KAON PRODUCTION IN RELATIVISTIC HEAVY ION COLLISIONS
AT 14.6 GeV/c PER NUCLEON

by

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Abstract

We present a systematic study of charged kaon production in Si+A collisions at
14.6 A·GeV/c. Using a 25 milliradian magnetic spectrometer at the Brookhaven
National Laboratory's Alternate Gradient Synchrotron, the high statistics data set
(≈ 80K K⁺s and 70K K⁻s for the Au target, ≈ 64K K⁺s and 30K K⁻s for Al target)
was made possible because of a second level trigger performing particle identification
online within 40 microseconds. Target and centrality dependencies are examined
for the two targets and for two centralities (central and peripheral). Central events
correspond to the upper 7% of the inelastic cross-section and peripheral events to the
lower 50%. Our analysis has included the extended particle identification detectors
which allows kaon identification up to a momentum of 3.0 GeV/c. This considerably
extends the limit of 1.8 GeV/c imposed if we only had the time-of-flight available.
We have measured over a broad region of phase space about midrapidity. The kaon
yields, \( dN/dy \), and inverse \( m_\perp \) slopes (T) are studied systematically as a function of
rapidity, centrality and target. We present the \( \Lambda \) yield and inverse \( m_\perp \) slope within
the rapidity range of 1.1 and 1.7. A measurement of the \( \Lambda \) to \( \Lambda \) ratio in the E802
spectrometer is also made.

Our results indicate that the inverse slopes of the kaons are explainable in terms of
the kinematics of their production mechanisms and multiple scattering. We observe
that in general, \( T_{K^+} > T_{K^-} \), and that the inverse \( m_\perp \) slopes for both particles increase
about equally in going from peripheral to central collisions. It is doubtful that the
inverse slope parameters are indicative of the existence of a phase transition, as has
been suggested.

The \( K^+ \) yields are more backward peaked than the \( K^- \) yields in central Si+Au
collisions, possibly reflecting different production mechanisms or absorption. We
estimate that some 80% of the \( K^+ \)s are from associated production, consistent with
p+p data. \( K^+ \) production in these collisions seems more dominated by N+N collisions,
rather than other mechanisms such as \( \pi+N \rightarrow K^+ + \Lambda \). The invariance of the \( K^+/K^- \)
ratio for either target or centrality is evidence for this. A comparison between p+A
and Si+A data indicates that the increase in the \( K^+/\pi^+ \) ratio is due in part to \( K^+ \)
production scaling faster than the number of projectile participants, whereas the pion
production saturates. Significant pion absorption seems to occur. Finally, the $K^-/\pi^-$
ratio increases by a factor of two from peripheral Si+Al to central Si+Au collisions.

Thesis Supervisor: Dr. Stephen Steadman
Title: Senior Research Scientist, Department of Physics
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Acknowledgements

And these are but the outer fringe of his works;
how faint the whisper we hear of him!
Who then can understand the thunder of his power?

Job 26:14

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Finally, I enjoyed working with the E802 collaboration and to all who made E859 a great success and special thanks the spokesmen: Bill Zajc, Lou Remsberg and Bob Ledoux.
Chapter 1

Introduction

1.1 A brief summary of the field of relativistic heavy ion physics

The field of relativistic heavy ion physics commenced with the acceleration of light nuclei \( A < 38 \) to a laboratory momentum of 2.1 GeV/c per nucleon at Lawrence Berkeley Laboratory's Bevalac in 1974. The Bevalac was soon followed by fixed target programs at Dubna \( A \leq 20, \ p_{lab} \leq 4.1A\cdot GeV/c \), Brookhaven National Laboratory \( A \leq 197, \ p_{lab} \leq 14.6A\cdot GeV/c \) and CERN \( A \leq 32, \ p_{lab} \leq 200A\cdot GeV/c \). The Relativistic Heavy Ion Collider (RHIC), presently under construction at Brookhaven, can accelerate Au nuclei up to 200A\cdot GeV/c per colliding beam. The proposed Large Hadron Collider (LHC), if built, will have beams up to 3.8A\cdot TeV/c per beam! These ultrarelativistic machines should take the heavy ion collisions to very different regimes than are presently being explored.

Under normal conditions, nucleons and nuclei are in their ground state. The primary goals of the Bevalac program were to determine the equation of state of nuclear matter and to study the fragmentation of the projectile. This was done by detecting particles and nuclear fragments as a function of reaction plane, centrality and projectile-target system. One of the results [Har92] was that a hot and fairly dense system was being formed. In an attempt to reach higher temperatures and
densities, higher energy and larger $A$ nuclei were used in the programs following the Bevalac.

The motivating force behind these new programs was to excite nuclear matter to a phase transition. The new state of matter, the quark gluon plasma (QGP), is one in which quarks are essentially unbound and form a relativistic gas of weakly interacting partons with the gluons. Such a transition has been predicted from lattice QCD calculations. For a recent summary see [Kar92]. We might expect unusual effects when the achieved densities imply an internucleon distance comparable to the nucleon size so that there is significant wave function overlap between neighboring nucleons. This occurs at about $5\rho_0$ to $7\rho_0$ where $\rho_0$ is normal nuclear matter number density, $0.17$/fm$^3$. Unusual effects may also be expected when the energy density exceeds that of the proton ($\approx 0.45$ GeV/fm$^3$). The collisions at Brookhaven and CERN produce the hottest and most dense states of matter achieved since the Big Bang.

In the last 5 years, the initial survey experiments have completed data taking and are in the final stages of analysis. The rapid evolution of the field is summarized in the Quark Matter proceedings from 1982 to the present year (for example, [JS82, LW83]). The results indicate that the QGP, if it is formed at Brookhaven energies, has a very weak signal which is dominated by the hadronic interactions. However, the systems studied so far have been small ($p+A$, $O+A$, $Si+A$ where $A = Be$, Al, Cu, Ag, Au). The $Au+Au$ data taken are expected [K+93] to produce the densest system yet created.

Most single particle production aspects of $Si+A$ collisions can be reproduced in detail by microscopic models incorporating standard hadronic physics. A recent summary of Brookhaven results (experimental and theoretical) can be found in [Sta93]. At CERN energies, the production of (multiply) strange baryons and antibaryons is not explainable by the same models without the incorporation of new mechanisms (such as "color ropes" for RQMD [Sor93]). While the verdict is still out as to the creation of the QGP at CERN, it seems that the best chance of observing something unusual occurs in the channels with the smallest cross-section.

The non-observation of the QGP has stimulated the development of hadronic
approaches to these collisions. An understanding of particle production in hot, dense nuclear matter is of crucial interest. Several authors [Cos91],[Ste93] have recently stressed the importance of understanding the characteristics of a "normal" hadronic system where no exotic phenomena occurs and the systematics of particle production from p+p to p+A to A+A. In fact, this point had been recognized as early as 1980 when only Bevalac data existed. Randrup [RK80] wrote,

"However, until now no striking signals have appeared, and it has become increasingly clear that the identification of possible exotic phenomena is conditioned on our ability to account well for the dominant processes of more conventional character. We must therefore try to understand in detail the overall collision dynamics."

As an example, the first exciting report of an enhanced $K^+/\pi^+$ ratio [A+90b] suggested that the QGP had been discovered. This was one of the predicted "smoking gun" signatures [K+86]. However, further theoretical investigation soon showed that such an enhancement was possible in a variety of hadronic gas scenarios [C+90, MBW92]. Hadronic cascade models with no exotic physics mechanisms also reproduce the data [M+89]. The lesson is simply that to observe a difference, we must have a reference level. Particle production from these hadronic scenarios can be compared in depth to production expected from a QGP to provide more robust signatures of the QGP.

There are thought to be two regimes of observational interest: the stopping regime and the baryon-free regime. The stopping regime refers to a range of incident beam energies where the projectile "stops" in the target, providing the best opportunity for high number and energy densities over a relatively "large" volume for a "long" enough time. A simple, classical picture of stopping is similar to the completely inelastic collisions in freshman mechanics, where one ball of putty hits another at rest and they go off as one merged mass. Two particle correlation studies may provide quantitative estimates of the size and duration over which particles are emitted [Sol94, Cia94]. Under these conditions, a unique opportunity is available to create extended, dense
matter in the laboratory. The experiments at Brookhaven and to some extent CERN encompass this stopping regime.

The baryon-free regime will be reached with the next generation of experiments at the Brookhaven Relativistic Heavy Ion Collider (RHIC) and at CERN's Large Hadron Collider (LHC). This regime is characterized by the projectile and target passing through each other and depositing energy in the vacuum. Particle production occurs in the absence of incident nucleons whereas in the stopping regime, both the initial and produced particles can interact. This makes the stopping region more complicated in deciphering particle production mechanisms. The exciting possibilities from the baryon-free regime must wait for a few more years until the start of RHIC.

1.2 The Brookhaven Program

The Brookhaven program occupies an ideal place in the study of these collisions. Baryon measurements in central Si+A collisions have indicated that almost the maximum amount of stopping possible is seen in central collisions [Par92]. Thus we expect to generate the highest baryon densities possible at Brookhaven energies. Furthermore, the $\sqrt{s}$ of the collisions allows for strangeness production significantly above threshold. Table 1.1 indicates the beam energy per nucleon and $\sqrt{s} - 2m_p$ (available energy for particle production) of each program. We note that the lowest threshold mechanism to produce a $K^+$ from N+N collisions, via $N + N \rightarrow N + \Lambda + K^+$, requires an energy of $m_\Lambda + m_{K^+} - m_N = 0.67$ GeV. In this thesis, N refers to a proton, neutron, or an excited state of either. We do not put a charge state on the pion to indicate that the $\pi$ and N must be chosen to ensure the appropriate conservation laws are maintained (charge, baryon number, isospin etc.). The production of a $\Lambda$ and $K^+$ in a reaction is termed "associated production" because the $K^+$ was originally observed to be produced with an associated, unknown neutral particle. Producing a kaon pair via $N + N \rightarrow N + N + K^+ + K^-$ costs $2 \times m_K = 0.988$ GeV. Thus the Bevalac is subthreshold for kaon production while Dubna is just above threshold for $K^+$ and below for $K^-$. Brookhaven energies are significantly above both thresholds.
Strange particle production at the lower energy facilities is dominated by subthreshold effects such as Fermi motion. The Brookhaven data should not be dominated by these effects. The difference between CERN and Brookhaven, while large in available energy, is smaller in terms of physics. For example, total charged particle multiplicity rises only logarithmically with $\sqrt{s}$. However, for particles which have large energy thresholds like the $\bar{p}$ or $\Lambda$, the difference between these programs is significant.

There are three major relativistic heavy ion experiments at Brookhaven National Laboratory's Alternate Gradient Synchrotron (BNL AGS) for the Si beam: E802/859 (henceforth, E859), E814 and E810. Each complements the others with a small overlap in phase space which allows for some cross-check between experiments. Such checks have confirmed very good agreement among the three experiments for the rapidity distribution of protons [Vid93]. To get a flavor of the AGS program, we provide a brief summary of E814 and E810 here. E859 will be discussed in chapter 3.

The two kinematic variables, $y$ and $m_\perp$, are useful because of their Lorentz invariant properties. Rapidity is defined as

$$y = \frac{1}{2} \ln \frac{E + p_x}{E - p_x},$$

where $E$ is the energy of the particle and $p_x$ the momentum component along the beam axis. The transverse “mass”, $m_\perp$ is

$$m_\perp = \sqrt{p_\perp^2 + m^2},$$

<table>
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<th>Location</th>
<th>Beam Energy (GeV)</th>
<th>$\sqrt{s} - 2m_p$</th>
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<td>2.1</td>
<td>0.5</td>
</tr>
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<td>Dubna</td>
<td>4.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Brookhaven</td>
<td>14.6</td>
<td>3.5</td>
</tr>
<tr>
<td>CERN</td>
<td>200</td>
<td>17.5</td>
</tr>
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Table 1.1: Program and beam energy per nucleon (GeV) and energy available for particle production (GeV) assuming fixed target experiments.
where $p_\perp$ is the transverse momentum and $m$ the particle mass. A nucleon with a momentum of 14.6 GeV/c has rapidity 3.44. This is termed the beam rapidity. The target (at rest) has a rapidity of 0.0. We note that if particle production were solely determined by N+N collisions at beam energy, the rapidity distributions of produced particles would be symmetric about $y_{cm}^{NN} = 1.72$. For asymmetric projectile-target combinations, one can assume that a thermalized source ("fireball") of particles is created from the participants of the collision. For fireballs from central Si+Au collisions, we would expect particle production to be symmetric about $y_{cm}^{part} = 1.3$.

While E802/859 measures particles with $y \leq 2.5$, E814 measures particle production above middle rapidity, $y \geq 1.7$. It consists of several calorimeters, a charged particle multiplicity detector and a forward spectrometer. The forward spectrometer can measure particle production to low $p_\perp (\approx 20$ MeV/c), enabling the exploration of regions of phase space inaccessible to E859 ($p_\perp \geq 120$ MeV/c). A particular feature of this experiment is its ability to measure neutrons with a forward calorimeter. E814 uses the measured transverse energy as a centrality trigger.

E810 consists of a time projection chamber (TPC) located within a dipole magnetic field. It measures all charged tracks forward of 20 degrees in the lab. It is uniquely able to measure neutral particle production by vertex reconstruction and has provided important information on the $K_S^0$ and $\Lambda$ production at AGS energies. It unfortunately lacks particle identification and so cannot unambiguously measure identified charged particle yields and $m_\perp$ distributions. If we assume, however, that all the negative tracks are $\pi^-$s (which is true to $\approx 5\%$), then the negative tracks give information on the negative pions. One can also assume that $\pi^+$ and $\pi^-$ have identical distributions. The difference between the positive tracks and negative then is an approximation of the proton distribution. Instead of an event characterization detector, they use the number of negative tracks reconstructed as their measure of centrality. For further details, see reference [E+89].
1.3 Motivation for this thesis

The parent experiment to E859, E802, has performed the most extensive measurement of particle production to date at Brookhaven energies, measuring the following particles: protons, $\pi^\pm$, $K^\pm$ and $\bar{p}s$. The results of that work have resulted in approximately 15 doctoral theses. E859 grew out of the motivation to provide a high statistics measurement of the rarer $K^\pm$ and $\bar{p}$ production as well as to perform the first two-kaon correlation measurement at these energies. To this end, a second level trigger, capable of on-line particle identification, was developed for E859. This enabled the experiment to run at a higher beam rate, permitting a high statistics measurement of the $K^\pm$ and $\bar{p}$. The fruit of this labor was even more bountiful than expected, allowing measurements of the $\Lambda$, $\bar{\Lambda}$ and the $\phi$. This thesis will concentrate on $K^+$ and $\Lambda$ data taken in E859.

Part of the motivation for studying $K^+$ production stems from Bevalac results. Since the early 1980's, strange particle production has been thought to be an important source of information regarding the dynamics of heavy ion collisions and an important signal of the hypothesized quark gluon plasma [K+86]. In particular, because the $K^+$ interacts weakly with nucleons (\(\approx 10\) mb as compared to $\approx 100-200$ mb for the pion-nucleon interaction), it has a mean free path of nearly 6 fm at the standard nuclear density of $0.17/fm^3$. In light of this, one expects that the $K^+$ would provide information about the initial, violent stage of the collision process. It is at this initial stage one expects the formation of the QGP. Nagamiya [Nag82] first used this reasoning to explain the momentum distributions of protons, pions and $K^+$s in the Bevalac data. In contrast, pions and protons, with much larger cross-sections, would rescatter significantly and so carry information about the later stages of the collision.

Other experiments have measured strange particle production in heavy ion collisions. At CERN energies, the NA35 collaboration has measured strange particle production in $p+$Au, O+Au, $p+$S and S+S systems at 60 and 200A·GeV/c. They report [B+90, B+89a] an excess $K_S^0$ production relative to negative particles in S+S...
compared to p+S but report no excess in O+Au relative to p+Au. This is in direct contrast to BNL results in which an enhanced K+/π+ ratio is found in Si+Al and Si+Au relative to p+Al and p+Au, respectively. Even the NA35 experimenters cannot explain their seemingly inconsistent results, although they cite the different phase space coverage for O+Au compared to S+S collisions as a possible problem. Given such a confusing situation, a detailed study over a broad range of phase space is warranted.

Further differences are found with CERN experiment NA36. In the rapidity interval from 1.0-1.5 (the beam rapidity is 6 for CERN beam energies) for S+W collisions, NA36 observes [A+92b] an enhanced K+/π+ ratio as a function of p⊥ as compared to p+p data. Their K−/π− ratio shows no such increase. AGS data from E859 indicates an increase in both ratios. More puzzling is the NA36 observation of no “significant relative increase in kaon production in high Et over low Et events in our p⊥ - y domain” [A+92b], whereas in E859 almost a factor 2 increase is observed in the K+/π+ ratio going from peripheral to central events.

The seemingly inconsistent situation at CERN may finally be resolved when the issues of different acceptances and triggering, for example, are taken into account. However, the need for a good statistics kaon measurement over a broad phase space acceptance by one detector is apparent. This is the motivation of E859 and the motivation for the data analysis performed in this thesis.

Another motivation is to distinguish between models. Many models were formulated to understand kaon production in these collisions at a time when the charged kaon data had relatively poor statistics (especially the K−s). This allowed for a proliferation of models which we hope to confirm or disprove with the large kaon data set and a careful analysis. We emphasize the requirement that a successful model must reproduce the differential cross-section behavior of all particles for all systems and all centralities. This is one of the motivating factors for obtaining a high statistics kaon data set for as many reactions as is feasible.
1.4 Introduction to this thesis

The Λ and K\(^+\) form a natural partnership because they are expected to be produced together via the same mechanism, associated production. We provide an analysis of the K\(^+\) and Λ data taken in E859. The detailed analysis of the K\(^-\), Λ, and φ can be found in the Ph. D. work of Dave Morrison, Peter Rothschild and Yufeng Wang, respectively [Mor94, Rot94, Wan94].

From p+p data at these energies, associated production (such as \(p+p \rightarrow p+Λ+K^+\) or \(π+p \rightarrow Λ+K^+\)) is expected to be the dominant mechanism for K\(^+\) and Λ production. In fact, about 76% of the strangeness producing p+p cross-section resides in associated production (\(p+p \rightarrow K+Y\) where \(Y=Λ,Σ\)) at an incident proton momentum (and fixed target) of 12 GeV/c [F+79]. At 24 GeV/c, this fraction drops to 60%, indicating the increasing importance of pair production. We are interested in each particle individually as well as the correlations between the two as indicators of this production mechanism. To this end, we present a systematic detailing of K\(^+\) production in Si+Al and Si+Au collisions of varying centrality. Both inverse \(m_⊥\) slopes and yields are discussed. Bevalac data indicated that the kaon cross-section was explainable after taking the production environment (protons and pions) into account with a simple model of kaon rescattering [Ran81]. It is therefore of interest to compare kaon production to protons and pions. Unfortunately, the Λ data set is not nearly as extensive. The first cross-section analysis in this experiment of a particle detected by its decay products is found here (Λ) and in the doctoral work of Yufeng Wang [Wan94] for the φ. Because of the narrow coverage of the E859 Λ data, we shall also utilize the Λ results of another Brookhaven experiment, E810.

The data shown here consist of the results of approximately 2 million events taken in two separate runs, February 1991 (Feb91) and March 1992 (Mar92), made at the Brookhaven National Laboratory’s Alternate Gradient Synchrotron (AGS). The Si projectile had an incident momentum of 14.6 GeV/c per nucleon. The data were taken using the E802 single arm magnetic spectrometer with extended particle identification and event characterization detectors. We have performed detailed studies of the
extended particle identification detectors. Although such detectors have been used in previous analyses \([A^+92a]\), a systematic study of the various efficiencies has not been done.

Another important aspect of this thesis we wish to emphasize is the capability of measuring the \(K^+\) and \(\Lambda\) yields with the same experimental apparatus. The measurement of the three strange particles \((K^\pm \text{ and } \Lambda)\) by a single experiment under identical conditions over the same region in phase space should remove possible systematic ambiguities in any comparison between experiments, such as different centrality triggers and definitions of minimum bias. We definitively show that the continuation of E802/E859 for the Au beam, E866, can fully map out the details of \(K^\pm\) and \(\Lambda\) production. Such a program has already commenced with the Au beam at the AGS.

We focus on the \(K^+\) production mechanisms. By combining the \(K^+\)'s with available \(\Lambda\) data, we address the issues of the overall strangeness production. In particular, we ask the following questions:

1) What are the mechanisms of \(K^+\) and \(\Lambda\) production? What can we learn from a comparison to \(p+p\) production and \(p+\Lambda\) production? What is the relative importance of associated production and pair production of kaons? How important are pion-nucleon and pion-pion collisions to kaon production?

2) How can the models help us understand the physics of these collisions?

3) How do the slopes of all particles change with centrality and target and can meaningful physics be extracted from them?

4) What experimental indications do we have to assess the idea of the \(K^+\) being a probe of the earlier stages of the collision?

5) Can we account for all the channels of strange particle production?
1.5 Summary of the upcoming chapters

Chapter 2 provides a brief overview of strange particle production in pp and pA collisions as well as at different energies. Chapter 3 provides a brief description of the experiment. We refrain from describing much of the experimental apparatus as it can be found elsewhere. Triggering, a crucial part of E859, is discussed in some detail, though. Chapter 4 follows with the analysis details involving the extended particle identification detectors. These are required so that appropriate corrections may be made. Chapter 5 is devoted to the cross-section generating process. It is included in order to facilitate the understanding of this crucial procedure. The final charged kaon results are presented in Chapter 6. Because of the significant differences in procedure, the Λ analysis is found in Chapter 7. Our final discussion is in Chapter 8, where we examine possible production mechanisms which account for the data. We also discuss what we can and cannot learn from $m_\perp$ distributions and yields. Finally, we conclude in Chapter 9 with a summary of the results and an outlook for future measurements.
Chapter 2

Overview of Strange Particle Production

We provide an overview of strange particle production as it pertains to our analysis. Basic kinematics and reaction mechanisms are discussed. We also summarize various types of models. Selected data from p+p, p+A and π+A collisions are used to see what one might expect in extrapolating to heavy ion collisions.

While we believe we know the production mechanisms, it is difficult to establish direct information from single particle spectra alone. From the experience gained at the Bevalac, Randrup wrote [RK80],

"So far it has not been possible to obtain an unambiguous view of the evolution of a high energy nuclear collision. The one-particle spectra, which form the main part of the data, have proved unsuitable for discriminating between widely different models."

We also find further warnings in [S80]. Regarding proton spectra, they wrote,

"Comparison is made with the intranuclear cascade calculations of ... and the two-fluid hydrodynamic calculations of ... . One is microscopic and the other a macroscopic calculation. The agreement is excellent for these two extreme models, showing, however, the insensitivity of the inclusive cross-section to the details of the reaction mechanism. More exclusive
data has to be used to probe the dynamics of the interaction."

We perform such exclusive measurements in this thesis.

2.1 Reactions and Kinematics

We provide a brief summary of the standard hadronic production mechanisms. Table 2.1 lists some of the possible mechanisms for producing kaons and $\Lambda$s. When an $s\bar{s}$ pair is created, the $s$ quark can combine to form a $\Lambda(uds)$, $K^-(us)$, $K^0(ds)$ or $\phi(s\bar{s})$. The $\bar{s}$ goes into a $K^+(us)$, $K^0(ds)$, $\Lambda(\bar{u}\bar{d}s)$ or $\phi$. Since the $\Lambda$ and $\phi$ production are small at these energies (down by at least a factor of 100 relative to the $\Lambda$), the $\bar{s}$ goes primarily into a $K^+$. The $s$ quark goes primarily into a $\Lambda$ or $K^-$. Exactly how the strange quarks are distributed is of interest experimentally.

We include here a brief section on the kinematics of strange particle production. The threshold energy for various reactions is given in Table 2.1 assuming $N$ refers to ground state nucleons. The collision between untouched incident nucleons has an available energy (after subtracting off the rest mass of the two nucleons, $\sqrt{s} - 2m_p$) of 3.5 GeV.

We first note the low threshold energy for associated production. This is well below the available energy for the initial NN collisions. If we take the average rapidity loss for projectile nucleons ($\approx 1.5$) found by Parsons [Par92] for central Si+Au collisions, we find that a subsequent collision has about 0.9 GeV available for particle production. Thus, second NN collisions can still contribute to $K^+$ production. The 0.9 GeV of remaining energy, however, is below the threshold for $K^-$ production. It may be possible to explain $K^-$ production using a first collision model. Such a model has had poor success explaining $\bar{p}$ production [Cos91, Rot94], possibly due to the very large absorption cross-section for $\bar{p}$. The $K^-$'s may be better explained because of their lower absorption cross-section compared to the $\bar{p}$s.

Secondly, $\pi+N$ collisions have the lowest threshold for producing $K^+$s. This mechanism was thought to be responsible for about 25% of the $K^+$s produced in AA collisions at the Bevalac [CL84]. Thirdly, with a threshold of 0.71 GeV, $\pi+\pi$ collisions
may play a role. And finally, \( \bar{\Lambda} \) production is also possible in these collisions.

We also note that the nucleons (\( N \)) in the above reactions may be replaced by \( \Delta s \) or even higher excited states. The dynamics of excited matter is expected to play a dominant role in strangeness production.

Taking a pion with rapidity, \( y_\pi \), and zero \( p_\perp \), and a proton with rapidity, \( y_p \), and also zero \( p_\perp \), then the available energy is given simply by

\[
\sqrt{s} - m_p - m_\pi = \sqrt{m_\pi^2 + m_p^2 + 2m_p m_\pi \cosh(|\Delta y|)} - m_p - m_\pi,
\]

where \( \Delta y = |y_p - y_\pi| \). This is shown in Fig. 2-1. We see that pions and protons with a rapidity difference of at least 2.5 have sufficient energy to create a (\( \Lambda, K^+ \)) pair.

To get an estimate of how many \( \pi+N \) collisions above threshold are possible, assume they all occur with nucleons at rest and that the pions have 0 \( p_\perp \). The \( \pi^+ \frac{dN}{dy} \) for central Si+Au collisions can be parameterized [Par92] as

\[
\frac{dN}{dy} = 20.0 e^{x_p(y-1.25)^2/2/0.91^2}.
\]

The fraction of \( \pi^+ \) with \( y > 2.5 \) is 9% of the total. If every \( \pi^+ + N \) collision produced a \( K^+ \) then these collisions could produce almost 1/2 of the \( K^+ \)s observed. However, \( \approx 8\% \) of the \( \pi+N \) cross-section results in strangeness production. Therefore, we do not expect this to be an important contribution to the \( K^+ \) yield.

Replacing the nucleon by a pion in Eq. 2.1 (still with 0 \( p_\perp \)), we show Fig. 2-
Figure 2-1: Available energy for particle production from $\pi + N$ collision versus $|y_p - y_\pi|$ assuming $p_\perp = 0.0$. The horizontal line is the $\pi + N \rightarrow \Lambda + K^+$ production threshold.
Figure 2-2: Available energy for particle production from a collision of two pions with rapidity difference $|\Delta y|$ assuming $0 \ p_\perp$. The horizontal line drawn is the threshold energy for kaon pair production by pion annihilation.

2. Only pions with rapidity differences larger than beam rapidity can create kaon pairs. This should exclude this mechanism. However, there are several caveats. We note that pions have been measured up to a rapidity of 5 [Hem93]. Of course, this is a very small fraction of the total pion multiplicity. Secondly, other theoretical possibilities exist, such as mass modifications in hot and dense media, which would lower the kaon mass significantly. This lowers the production threshold and increases the amount of available phase space [Ko93]. In fact, this mechanism purports to explain the enhanced $K^+/\pi^+$ ratio observed at BNL energies. Hadronic cascade models do not include this effect and yet still explain the ratio. One expects an increased $K^-/\pi^-$ ratio if pion annihilation contributed significantly to $K^+$ production via pair production.

Using a typical value of the $K^+/\pi^+$ of 20% for central Si+Au collisions, the kaons (both charged and neutral) amount to $\approx 15\%$ of the produced particles (assuming
\( \pi^- = \pi^+ = \pi^0 \) and \( \leq 5\% \) of all particles. Thus we expect that the kaons play little role in determining the overall dynamics. However, the kaon production should reflect the dynamics because their production is sensitive to the details of the proton and pion dynamics. It is therefore of interest to examine K\(^+\) production relative to other particles.

### 2.2 Is the K\(^+\) a probe of the early stages of the collision?

We briefly review one of the most oft quoted arguments for expecting the K\(^+\) to be a sensitive probe of the early stages of the collision. The Bevalac data indicated that at \( \theta = 90 \) degrees in the center of mass frame, the momentum distributions could be fit with an exponential \( (e^{-p/T}) \) whose inverse slope followed the trend: \( T(\pi) < T(p) < T(K) \). To explain this, Nagamiya [Nag82] suggested that the longer mean free path of the K\(^+\) should allow it to escape unscathed from the reaction volume and thus reflect the higher initial temperatures of the collisions. The cross-sections quoted by the above reference are the following:

- \( \sigma(K^+N) \approx 10 \) mb
- \( \sigma(NN) \approx 40 \) mb
- \( \sigma(\pi N) \approx 100 - 200 \) mb.

The numbers quoted are obtained from the momentum regime roughly between 0.3 and 0.5 GeV/c. At Brookhaven energies, a rough but more accurate determination of the average cross-section is obtained using momentum distributions generated using the RQMD model. For this exercise, we have chosen central Si+Au collisions with zero impact parameter. We restrict the rapidity range to \( 0.4 < y < 2.0 \) in order to select particles coming from the participant rapidity regime. We assume that the collisions occur with nucleons at rest. If we average the total cross-section (as obtained from the Particle Data Book [Gro90]) over these momentum distributions, we obtain,
\[ < \sigma (K^+ + N) > \approx 12 \text{ mb}\]
\[ < \sigma (N + N) > \approx 30 \text{ mb}\]
\[ < \sigma (\pi^+ + N) > \approx 73 \text{ mb}.\]

Although these numbers are clearly model dependent and are affected by the rapidity cuts, we only use them to indicate that the original argument made for Bevalac data still holds at Brookhaven energies but less strongly. We will examine the \( p_\perp \) slope parameters versus rapidity to see if we have evidence for the \( K^+ \) being a messenger from the early part of the collision.

Two particle correlations (pions and kaons) recently analyzed by the E859 collaboration [A+93, Cia94, Sol94] have indicated that the kaon source parameters (both in distance and in time) are smaller than the source parameters for pions. This is consistent with Nagamiya’s argument that kaons are expected to decouple from the participant volume earlier than the pions and hence come from a source with a smaller size and be emitted for a shorter time. An identical situation exists in the case of solar neutrinos which provide information about the processes deep inside the sun, whereas the photons are emitted from the solar surface.

We do remark here that Nagamiya’s attempt, while greatly simplified in many respects, is appealing because of its tangibility. We take what we know for pp data and extrapolate in a way where we have a concrete idea of why the result comes out as it does. The microscopic models to be discussed are so complex that it is difficult to untangle cause and effect and to single out, in our case, particular strangeness production mechanisms.

### 2.3 Models

We discuss several types of models on the market: microscopic, hybrid and hadronic gas. In particular, we describe the strange particle production mechanisms and how we might experimentally distinguish among them.
2.3.1 Microscopic

Microscopic models are the most complete particle production models available, tracing every incident and produced particle throughout the collision. Particles are treated as points traveling in straight lines. Interactions consist of binary collisions which occur if $2\pi b^2 < \sigma$ where $\sigma$ is the total cross-section and $b$ is the impact parameter between the two particles. This condition considers the cross-section to have a geometric interpretation. Certain problems do exist, however, for $p$ interactions. At 1 GeV/c, $\sigma(p + \bar{p}) = 100$ mb. This corresponds to a $b$ of about 4 fm, almost the diameter of the silicon projectile (6 fm). It seems questionable whether such a geometric interpretation is viable for two particles separated by 4 fm.

These models are useful because they track the space-time history of each particle. Most codes allow for particle rescattering, thought to be an important effect considering the densities being achieved in these models. These codes are by necessity CPU and computer memory intensive. The input data are taken from $e^+e^-$ or $pp$ data. Typically as much experimental data as possible are used as input. Various approximations must be made where no data are available. In particular, there are no data for interactions of excited states with other particles. The propagation of resonances and their interaction cross-section is of extreme interest and thought to be the dominant mechanism for rare particle production. Two popular models claim that a significant fraction of rare particle production (including charged kaons) come from interacting resonances. However, for lack of experimental information, these resonances are treated the same as ground state nucleons and given the same interaction cross-section. Another drawback is the fact that at high densities, the hypothesis of the collision being a sequence of binary collisions breaks down. For example, the models ARC and RQMD both predict a maximum number density of over 10 times normal nuclear density for central Au+Au collisions. If true, then the average internucleon distance is comparable to the nucleon size (0.8 fm) and the idea of binary collisions is suspect. Do the nucleons still act as point particles? How does one treat them?
Calculated and experimental meson rapidity distributions for minimum bias p+Be (left), p+Au (middle) and central Si+Au (right) reactions at a projectile energy of 14.5 A-GeV/c. The histograms represent the RQMD results: \( \pi^- \) (solid line), \( K^+ \) (dashed line) and \( K^- \) (dotted line). The experimental data are shown for \( \pi^- \) as circles, for \( K^+ \) as dots and for \( K^- \) as squares. The Si+Au distributions are divided by 28. The E802 pion data for Si+Au are multiplied with 1.2, because the RQMD calculations show 20% additional pions in the unmeasured low \( p_t \) region above a linear extrapolation in the transverse momentum spectra which was done by E802.

Figure 2-3: RQMD plots of their overall comparisons to E802 data (top) and the sources of \( K^+ \) production (bottom) [Sor93].
There are three models that will be discussed.

The first, Fritiof, is actually quite different from the next two. Particle production is based solely on its phenomenological string mechanism which is thought not to be applicable at the relatively low Brookhaven energies. It simply performs a superposition of the number of binary \(N+N\) collisions expected based on the impact parameter. Because there is no rescattering, it serves as a useful baseline when comparing to ARC and RQMD.

The Relativistic Quantum Molecular Dynamics (RQMD) model is probably the most complicated model [SSG89]. It does fairly well at explaining AGS data [SSG91, SSG92, M+89, S+90]. This model allows for multiple excitation of nucleons much beyond known resonances. These highly excited objects are called strings. While having strings as Fritiof does, it also acts as a hadronic cascade where only hadronic interactions occur. RQMD actually records the reaction mechanism at each collision and can categorize kaon production mechanisms. As an example, we include several plots in Fig. 2-3. The top plot shows the RQMD agreement to ES02 data for \(p+Be\), \(p+Au\) and \(Si+Au\) collisions. The agreement with \(p+Be\) is expected because the input to RQMD is \(p+p\). The separation of reaction mechanisms is shown in the lower plot. We see that RQMD predicts that \(\pi N\) collisions produce about 1/2 the number of \(K+\)s, equal to that produced from \(NN\) collisions. As the authors indicate [J+93],

"In RQMD, the process which enriches strangeness via associated production is meson rescattering in baryonic matter, mostly a meson (resonance) annihilating on a baryon and forming an s channel resonance."

The contribution to \(K+\) production from \(\pi\pi\) annihilation is very small. The large increase in \(K+\) production due to \(\pi+N\) in \(Si+Au\) compared to \(p+Au\) is noteworthy.

A Relativistic Cascade (ARC) [PSK92, P+92, K+93, S+92a] is a hadronic cascade code written specifically for Brookhaven energies. It does not include any string mechanisms. As the authors describe, "There can be only a pious hope that a strictly hadronic cascade will describe a relativistic ion collision." [PSK92]. Yet this model does amazing well at describing Si-A results for all the AGS experiments and even
for predicting the E866 Au-Au preliminary data [PSK92, P+92, Gon92].

We mention a few differences between ARC and RQMD which have consequences for strangeness production. ARC uses a single generic baryon resonance with the mass and quantum numbers of the $\Delta$. Very excited nucleons in RQMD are treated with a string phenomenology and these nucleons can be excited to very high internal energies. The advantage of propagating excited nucleons is that the $\sqrt{s}$ of the next collision is higher. A nucleon whose excitation energy exceeds three times the proton mass can decay to $p+p+\bar{p}$. This leads to a large difference in how rare particles such as $\bar{p}s$ are produced in these two models. (See [K+93] for further discussion.)

While both codes reproduce the excess $K^+$ production observed experimentally, the sources are distinct. "ARC obtains most of the $K^+$s from baryon-baryon interactions taking place at a significantly higher energy than in RQMD or other simulations. About two-thirds of the $K^+$s in a Si+Au collision at 14.6 GeV/c come from such interactions and the rest from meson-baryon and a small amount from meson-meson ($\approx 5\%$). ARC thus attributes the two puzzles mentioned above, proton temperature and $K^+$ enhancement to the same source, the dynamics of of resonances." [K+93]. As mentioned above, RQMD indicates that the meson-baryon interactions dominate $K^+$ production.

The major question is whether such a difference is experimentally detectable. The authors of the RQMD code have been extremely helpful in releasing their code. With it, we can generate events according to our own specifications and also pass these events through our experimental event selection and acceptance. Further details of this approach to understanding kaon production can be found in the doctoral work of David Morrison [Mor94].

2.3.2 Hybrids

There are less complicated models which use Monte Carlo and analytic techniques to simulate these collisions. They have the nice feature of being able to isolate a particular aspect of the physics and understand its implications. One such model by Chao [CGZ90] allows rescattering and in particular tries to quantify whether $\pi+N$
collisions can account for the $K^+/\pi^+$ ratio. They conclude that this mechanism is not sufficient to reproduce the observed ratio. Unfortunately, these types of models cannot account for all the possible dynamics. An important but neglected aspect is the propagation and collision of resonances. As an example of the importance of resonances, Fritiof predicts that about 90% of the total pion yield is from resonance decay products [Hua90]. The space-time evolution of a relativistic heavy ion collision must take resonances into account to be complete. Some have even termed the matter produced in Au+Au collisions as “$\Delta$ matter” because of the predicted predominance of resonances in the collision processes. These hybrid models are instructive but not exhaustive.

The hybrid model of Ko et al [HLRB87, LRBH88, Ko93] deals with the evolution of a quark gluon plasma and its subsequent hadronization. Starting with a fireball in thermal equilibrium, they use relativistic hydrodynamic equations to evolve the system. Chemical equilibrium is not assumed, rather they solve rate equations with production and annihilation terms included. This model is of particular interest because it actually makes predictions for the experimentally measurable momentum distributions of $K^+$s and $K^-$s. We reproduce their argument here.

If no phase transition is reached in these collisions, the system is much like a hadron gas and the $K^+$s escape much earlier than other particles because of their significantly smaller cross-section, as discussed previously. They are therefore messengers from the early, higher temperature part of the collision. If the QGP is formed, the $K^+$s hadronize more quickly than other particles because of the strangeness distillation effect. In a baryon rich QGP consisting of the incident $u$ and $d$ quarks plus any produced $q\bar{q}$ pairs, a $s$ quark will find it relatively easy to pick up a $u$ quark to form a $K^+$ compared to an $s$ finding a $\bar{u}$ to make a $K^-$. In fact, it may be easier for the $s$ to find both a $u$ and a $d$ quark and form a $\Lambda$. The $K^+$s will be more abundant than $K^-$s and leave the system earlier. This process, referred to as strangeness distillation, should be reflected in the energy spectra for the following reason. The QGP has many more degrees of freedom (quarks and gluons) than a hadron gas and therefore greater entropy. To conserve entropy, the system expands and heats up as
it hadronizes. The K⁺s are emitted at the beginning of this phase of mixed QGP and hadron gas. They therefore are produced at a lower temperature than the pions or protons. Furthermore, since they escape earlier, they do not feel the same collective flow effects as the pions, K⁻s and protons. In QGP formation the K⁺s should exhibit a smaller inverse slope parameter than the K⁻ mesons.

2.3.3 Hadron gas

The thermodynamic models calculate averages based on a statistical analysis of the collisions. One can make various assumptions about thermal (Fermi, Bose or Boltzmann momentum distributions) and chemical equilibrium (relating the chemical potentials of various particles) and use statistical mechanics to obtain yields and, more typically, ratio of yields. A nice example applied to E802 data can be found in [MBW92, Cos91]. While assumptions about thermal and especially chemical equilibrium are suspect, it is useful to apply these types of models because they represent one extreme of the possible scenarios. As was found by Asai's [ASS81] analysis of the Bevalac data, the assumption of chemical equilibrium resulted in an overestimate of the K⁺ yield by a factor of 40 while the pion and proton data were reproduced. This is not surprising since processes such as \( \pi + N \rightarrow K^+ + X \), which increase the K⁺ yield, are likely not to be in equilibrium and to assume so would lead to excess K⁺ production. Furthermore, K⁺s are produced but cannot be easily absorbed because there are no abundant anti-baryons (at our energies) with an \( \bar{s} \) quark. At AGS energies, various thermal models have been applied with the result that a temperature of \( \approx 110-130 \text{ MeV} \) is reached. The heavier Au+Au collisions are of particular interest because we expect them to be closest to equilibrium of all the A+A collisions. It will be interesting to see whether thermal models do better for these larger systems. A good summary of how these models work can be found in [Cos91].

Finally, we note that any model should reproduce the experimental distributions of all particle species under different centralities and projectile-target combinations. For example, the “firestreak” hadron gas scenario of Mader [MBW92] reproduces the observed ratio of K⁺/π⁺ but overpredicts the absolute K⁻ yield by a factor of two
to three. The assumption of global chemical equilibrium is strong and is difficult to justify.

2.3.4 Medium effects

An interesting alternative explored by Ko [KWXB91, Ko93] and others is the possible mass modifications in hot nuclear matter. It is possible that the temperature approaches that of the chiral phase transition in which the quark mass goes to zero and the meson and baryon masses accordingly decrease. This results in large increases in cross-section for near threshold reactions because of the enhanced phase space and lower energy threshold. In particular, $\pi + \pi \rightarrow K^+ + K^-$ could have a significant effect on the kaon abundances [KWXB91]. However, before pursuing this alternative, it is useful to use "standard" hadronic models to determine if the data can be simply explained. Other physics, such as in-medium mass modifications can be implemented if there is no other recourse.

2.4 What can we do experimentally?

The initial report [A+90b] of a $K^+/\pi^+ \approx 19\pm3\%$ and $K^-/\pi^- \approx 4\pm1\%$ for central Si+Au collisions at $y=1.4$ sparked great interest by theorists and even resurrected some dormant models from the Bevalac analysis. Remarkably, an enhanced ratio had even been predicted by [K+86] in a QGP scenario. It soon appeared that several models of various types, from hadron gases to the microscopic codes, could explain this one value. With the high statistics kaon data set, we wish to explore a systematic study of the absolute $K^+$ yields and also the $K^+$ yield relative to other particles. We will examine the ratio as a function of rapidity, integrated over rapidity and as a function of centrality. A systematic study over two systems (rather than 1), several centralities (rather than 1) and for a large rapidity window (rather than 1 point) should further constrain models.

Furthermore, motivated by the interest in the charged kaon $m_\perp$ distributions, we wish to examine the systematics of the $m_\perp$ slopes with changing centrality and
projectile-target system. Rescattering (scattering of produced particles with any other particle) was concluded to be a crucial mechanism affecting the K\(^+\) at the Bevalac energies [CL84, Ran81]. Here are some of the questions we can address with the high statistics E859 data set by examining the \(m_\perp\) distributions.

1) How well can we determine the \(m_\perp\) slopes, i.e. what is our sensitivity to slope differences between particle species?

2) We have observed that the proton inverse slope parameters increase with target mass and centrality while the pions remain essentially constant [Par92]. What happens with the kaons? Is the systematic behavior consistent with any of the above scenarios? If not, how do we explain the trends in the data?

3) Does rescattering give a coherent picture? Can we minimize the effects of rescattering by selecting peripheral collisions? If so, do peripheral collisions give us similar results to pp, where rescattering is not present?

4) How can the different production mechanisms affect the slope? Or in more general terms, what does the inverse slope measure? A temperature? Indications of flow?

5) Do particles which we might expect to be produced by rescattering, such as the K\(^+\) and \(\Lambda\), show any correlation in rapidity to the majority of scatterers (protons)? As indicated, RQMD predicts that \(\pi+N\) produces nearly one half of the K\(^+\)s [Sor93].

The effects of rescattering are thought to be most evident in the \(p_\perp\) (or \(m_\perp\)) inverse slope distributions. Rescattering tends to flatten \(m_\perp\) distributions since it is like a random walk in \(m_\perp\) space. Absorption can mimic rescattering. For example, since absorption increases at lower momentum for K\(^+\) + N and \(\bar{p}+N\) reactions, the spectra may flatten at low \(m_\perp\).
2.5 What can we learn from the past?

The importance of understanding the physics processes in the progression of p+p, p+A and A+A collisions has grown increasingly clear as the field of relativistic heavy ions has developed. To fully understand strangeness production in AA collisions, and to be able to distinguish the QGP from non-exotic physics, we must understand the progression from pp to pA and then to AA. While a comprehensive survey is not possible in this brief overview, we have chosen to discuss selected aspects of kaon production from p+p, π+p and p+A data. Our goal is to inquire as to how we might extrapolate our knowledge of kaon production in these simpler collisions to A+A collisions. A more comprehensive discussion of particle production in general is available in the thesis work of Brian Cole [Col92].

2.5.1 What can we learn from pp collisions?

The two primary sources of pp data at or near BNL energies are found in bubble chamber experiments of Blobel [B+74] and the spectrometer data of Amaldi [U+75]. Fortunately, Brookhaven experiment E802 has taken p+Be data [A+92a] with the same apparatus as used for the data used in this thesis. The results are similar to p+p data and we are fortunate to have the data.

We would first like to note here the rapid rise in kaon pair production at BNL energies. Firebaugh [F+68] notes that

"An interesting feature of these cross-section data, in combination with those at lower and higher momentum, is the rapidly rising value of the KK cross-section, both in absolute magnitude and relative to the total strangeness particle cross-section. To illustrate this, one can compute the percentage of the total identified strange particle cross-sections which occurs in the identified KK. At 5, 8, 10 and 25 GeV/c, the percentages are, respectively, 6, 12, 25, and 29%.”

So while pair production is becoming a significant contributor to K+ production at BNL energies, associated production still dominates. From these numbers, we
estimate that the K+/K− ratio should be approximately 4 and perhaps larger if there is enhanced K+ production and K− absorption. Because pair production and associated production result in different K+ rapidity dependencies, pair production complicates the analysis. We will try to estimate what fraction of K+s are coming from associated production in this thesis.

One important dynamical consideration at these energies to keep in mind is that the incident nucleons undergo several collisions, each having a smaller $\sqrt{s}$ than the previous one. Because of the sensitivity of the K− production cross-section to incident momentum, the relative yields of K+ to K− may depend on the abundance of lower energy collisions. Produced particle production is symmetric about $y_{cm}^{pp}$ and also peaks at $y_{cm}^{pp}$. The lower energy second (and third) collisions will have a lower $y_{cm}^{pp}$ and hence populate lower rapidity more than the first collisions. One may have a rapidity dependent K+ to K− ratio which increases at lower rapidities. We will examine this ratio to see what we can learn about K+ production.

Since the enhanced (relative to pp) K+/π+ ratio in central Si+Au collisions stimulated such theoretical activity, its rapidity dependence in pp collisions is of interest. We will include this in the following p+A discussion.

2.5.2 What can we learn from pA collisions?

One question of interest is whether the enhancement in kaons relative to pions observed in AA collisions is also found in pA collisions, and to what extent.

Specifically, one espoused mechanism in microscopic models for enhancing K+ production is via $\pi$+N. p+A collisions allow this mechanism because of the large amount of spectator matter (nucleons not hit by the projectile). With increasing A, one might expect larger contributions to K+ production because of the larger number of nucleons to scatter from. However, one also expects more K+s because there are more N+N collisions the larger the target A. Do we see an increase in kaon production with increasing A? Can we separate out the latter effect to determine whether the $\pi$+N mechanism increases with increasing A? What might this indicate about AA collisions?
One experimental work tried to estimate the contribution of $\pi+N$ rescattering in low energy $p+A$ collisions [HSZ58]. They measured the $K^+$ and $K^-$ yields at 0 degrees in $pBe$ and $pPb$ collisions with incident proton momenta between 1.7 and 3 GeV/c. While their measurements occur at a significantly different energy than ours and in a different phase space, their results, if applicable, are very interesting. They estimate that the fraction of observed $K^+$ mesons made by pions reinteracting increases with decreasing beam energy, from $\approx 0.06$ at 2.93 GeV/c to $\approx 0.08$ at 2.2 GeV/c to $0.37^{+0.3}_{-0.15}$ at 1.7 GeV/c. If this result applies to AGS energies at mid-rapidity, we might expect very little contribution of $\pi+N$ to $K^+$ and $\Lambda$ production in AA collisions, in contrast to RQMD's expectation. Unfortunately, there are many caveats.

At CERN energies, the total $\sigma$ for inclusive $\Lambda$ and $K_S^0$ production has been measured in $pA$ collisions ($A = S, Ar, Xe, Au$). If one writes

$$\sigma(pA) = \sigma(pp) \times A^\alpha,$$

the data give $\alpha$ from .87 to .93 (with an error of $\approx \pm 0.03$) for $K_S^0$ production and from .97 to 1.06 for $\Lambda$ production. An $\alpha$ value of 1 indicates a dependence on volume whereas $\alpha = 2/3$ indicates an areal dependence. Thus strange particle production seems to scale with nucleus volume in $pA$ collisions. Pion production studies give $\alpha \approx 0.76$ [C+79]. Thus we expect the absolute yield of kaons and the $K^+/\pi^+$ ratio to increase with $A$ in $pA$ collisions. If increasing the target $A$ and increasing the centrality of the collision results in a larger effective "$A"$, then we may expect this ratio to increase in heavy ion collisions. We will examine this trend in the data. While these numbers were determined for CERN energies, we might expect them to be similar at BNL energies because we are still well above threshold for $K^+$ and $\Lambda$ production.

The understanding and characterization of particle production in $p+A$ collisions has been greatly advanced by the E802 physics program, which measured particle production in $p+A$, $O+A$ and $Si+A$ collisions at the same incident beam energy. A summary of the $p+A$ data, shown in Fig. 2-4, is taken from [A+92a]. We make the
following observations of the rapidity distributions:

- The produced particle distributions peak at lower rapidities as the target A increases, reflecting the lower participant center-of-mass rapidity.
- Both pion and kaon production increases with A with the kaons increasing faster.
- The statistics on the K⁻'s make any conclusions difficult.

Figure 2-4: Rapidity distributions of particles from p+A data taken by the E802 collaboration.
The increase in yield is in part due to the higher number of NN collisions for larger A targets. To observe the differences relative to p+Be, the $dN/dy$ yields for p+A have been normalized to the p+Be $dN/dy$ yields. This is shown in Fig. 2-5. If we expected the yields to scale with the average number of N+N collisions, the ratio of yields would be flat and have values [Hua90] that are 1.40, 1.87 and 2.61 for p+Al, p+Cu and p+Au relative to p+Be, respectively. We observe that the pion yield is relatively flat and increases by less than that expected from a naive superposition of N+N collisions. The lack of increase is especially noticeable in p+Au where the increase is less than 1.6 and we had expected 2.61. This is consistent with the idea of the proton losing a significant amount of energy until it can no longer produce pions. On the other hand, the increase in kaons of both charges at low rapidities is unusual. Because the energy is being exhausted, one would expect less of an increase in the kaons because of their higher production thresholds. One could look at this as an unusual increase in kaon production or as an unusual non-increase in pion production starting in p+A collisions. Kaon enhancement or pion absorption (and likely both) is occurring. A similar trend is found in comparing Si+A to p+A data as will be discussed.

The final plot we reproduce from reference [A+92a] is the K+/π+ ratio for the p+A systems. This is shown in Fig. 2-6. This ratio is enhanced as A increases. There seems to be a slight increase in the ratio at low rapidity for p+Au collisions. The statistics for the ratio of the negatives preclude any conclusions about possible differences.

2.5.3 What can we learn from π+p collisions?

The motivation for investigating π+p collisions comes from the RQMD model. As just discussed, RQMD indicates that a significant (up to 50%) of K+ production arises from π+N collisions (the process of produced particles interacting is also called "rescattering"). This increase results in their matching of the K+/π+ ratio.

We examine here the expected impact of π+p collisions to the K+/π+ ratio using published data (almost all of which is from bubble chambers). An additional pro-
duction mechanism will of course add to the absolute yield of K+s. What we are concerned with here is whether π+p rescattering can increase the K+/π+ ratio.

We have taken π+p cross-section data [A+65] at an incident pion momentum of 4 GeV/c. The following formula is used to determine the average multiplicity of particle i,

\[ < n_i > = \frac{\sum_{k=1}^{k_{\text{max}}} k \sigma_k(i)}{\sigma_{\text{inel}}}, \]

where \( \sigma_k(i) \) is the partial cross-section for producing k particles of type i. Use of bubble chamber data is particularly appropriate as the channel-by-channel cross-sections are typically tabulated. The total π+p cross-section is 28 mb, of which 6.42 mb is elastic. Applying the results of Table 1 of [A+65] to the above equation yields

\[ < n_{\pi^+} > = 1.6. \]

Strange particle production has also been measured in these same π+p collisions at 4 GeV/c [J+66]. The observation of charged kaons is extremely difficult in bubble chambers. However, the K+ production cross-section may be related to the visible channels with some reasonable assumptions. (See [L+64] for the details.) They measure a total strange-particle production cross-section of 1.5±0.1 mb in these collisions. To establish an upper bound on the contribution of these collisions to the K+/π+ ratio, we make the extreme assumption that all this strangeness producing cross-section goes to producing K+. We would have

\[ < n_{K^+} > = 0.07 \]

and a maximum ratio of

\[ < n_{K^+} > / < n_{\pi^+} > = 0.044. \]

This analysis was performed at 4 GeV/c for π+p collisions. We have derived a fairly conservative upper limit to the K+/π+ ratio. Similar results are obtainable for
π⁻p collisions as the strangeness production cross-section is 2.1 mb at an incident momentum of 4 GeV/c [L⁺64]. The K⁺/π⁺ ratio from p+p collisions is ≈ 5%. We conclude that this mechanism, while increasing the absolute yield of K⁺s, cannot by itself be responsible for the enhanced ratio observed. If anything, it should lower it because of the significant number of pions produced in pion-nucleon collisions at these energies. We therefore are at a loss to understand how models can attribute their enhanced K⁺/π⁺ ratio to this mechanism. There must be more going on.
Figure 2-5: Rapidity distributions of particles from minimum bias p+A data normalized by the number of N+N collisions expected.
Figure 2-6: $K^+\pi^+$ ratio for p+A collisions.
Chapter 3

Experimental Setup

E859 is the second generation of Experiment 802 (E802). As a result, the main components of the experiment are the same. There are many excellent reviews of E802 to which I refer the reader [A+90a, Col92]. I will provide a brief summary of the experimental apparatus focusing primarily on the detectors used in this analysis. Event characterization and the various levels of triggering are discussed. A detailed discussion is made for the second level triggering as it is the major feature in E859.

3.1 A Brief Overview of Experiment 859

A diagram of E859 is given in Fig. 3-1. Detectors in E859 can be divided into four groups: detectors located on the spectrometer arm (see Fig. 3-2), event characterization detectors, a phoswich array and the Čerenkov Complex.

The purpose of the magnetic spectrometer is to identify particles within its acceptance ($\approx 25$ milli-steradians). Each particle is tracked and the bend angle through the magnet provides its momentum. To this end, the experiment includes sets of drift chambers (T1, T2) in front of the magnet and drift chambers (T3, T4) and wire chambers (TR1, TR2, T3P5) behind the magnet. The time of flight wall (TOF wall) consists of a wall of scintillator slats similar in design to a picket fence. It forms an arc about 660 cm from the target. In order to extend particle identification beyond what the TOF resolution provides, a segmented threshold gas Čerenkov counter, GASC,
Figure 3-1: A plan and gravity view of experiment 802/859. The AEROC detector was not present for E859. The F0 and PHOS detectors are not included.
Figure 3-2: A Plan and Gravity view of the spectrometer’s detectors. The F0 detector, used for triggering, is not included. It sits immediately in front of T1.
sits behind the TOF wall. Behind the GASC, a pad counter, BACK, verifies the passage of particles through the GASC.

Although not involved in tracking, a scintillator hodoscope, F0, sits in front of T1 approximately 90 cm from the target. Its signal indicates the presence of particles in front of the magnet and is used as part of the online level 1 trigger. More details can be found in the Ph. D. work of Kazu Kurita [Kur92].

The whole spectrometer sits on a sled which can rotate from 5 to 55 degrees relative to the beam axis. The primary angle settings are 5, 14, 24, 34 and 44 degrees, the inner angle of the spectrometer acceptance. The angular bite is $\approx 14$ degrees and covers 25 msr in $\Delta \Omega$. Rotating the spectrometer varies the rapidity and $p_\perp$ acceptance, with the larger angle settings corresponding to lower rapidities. These primary angle settings were chosen so that two adjacent settings have some overlap in $(y, p_\perp)$ space, allowing for systematic checks between settings.

There are two coordinate systems which will be mentioned in later sections. The beam coordinate system is defined with the z axis along the beam and the y axis up and perpendicular to the floor. The spectrometer coordinate system is the beam coordinate system rotated about the y axis with the new z axis being along the middle of the spectrometer. The z axis in the spectrometer system is perpendicular to the tracking chambers.

The Čerenkov Complex (ČC), behind the GASC, identifies very high velocity particles. Its greater distance ($\approx 10$ m) from the target allows for particle identification via time of flight and Čerenkov light information up to 14 GeV/c. Brian Cole [Col92] has performed a thorough analysis of the ČC and the interested reader is referred to his thesis for further discussion.

The Phoswich detector (PHOS) array is new to E859. It utilizes the energy loss through two layers of scintillators for particle identification of low momentum pions and protons. Located about 1 m from the target, it measures the particle spectra near target rapidity. The calibration and analysis details may be found in several internal E859 memos [C+92, Cos92].

The event characterization detectors include a lead glass calorimeter (PBGL), a
hadronic calorimeter at zero degrees (ZCAL) and a resistive pad array surrounding
the target to measure the charged particle multiplicity (TMA). Each of these detectors
is used for event selection purposes either in hardware or software. Their individual
distributions are also of interest, providing information about the geometry of the
collisions and the effect of multiple collisions [A+91b].

The data acquisition (DAQ) system is used to read out each event (FASTBUS
and CAMAC TDC's and ADC's), to format the events from these data and to write
them to permanent storage (9 track tape in our case). The details of this process
are summarized in [WL88, Col92]. We note that the DAQ provided a fundamental
limitation on the rate at which we took data because of its inability to write more
that \( \approx 100 \) events per 3-4 second long beam spill (the number of events depends on
the event size). This restricted our data taking at some level, especially at the lower
angle settings, where the size of the events is larger due to higher multiplicities.

### 3.2 Tracking Chambers

The tracking chambers are the four sets of drift chambers (T1, T2, T3, T4) used to
measure the space points of the particle's trajectory before and after the magnet. The
plane location provides the \( z \) position. The drift time to the nearest sense wire, in
combination with the information from other planes oriented in different directions,
provides the \( x \) and \( y \) coordinates. Each chamber consists of several wire planes ori-
ented in different directions. T2 through T4 use 4 orientations whereas T1 uses 5.
There are at least two planes per orientation to remove effects due to possible plane
inefficiencies and help resolve left-right ambiguities.

Table 3.1 includes a list of orientations and number of wires for each chamber.
The table starts with the planes closest to the target (T1X) and ends with the plane
furthest away (T4V). A positive wire angle is measured clockwise relative to the \( y \)
axis of the spectrometer coordinate system. Typical resolution depends on the wire
spacing and is about 200 \( \mu \)m. This resolution affects the momentum resolution. The
drift chamber times were read out with a multihit FASTBUS TDCs with 2 ns bins.
<table>
<thead>
<tr>
<th>Chamber</th>
<th>Module</th>
<th>No. of Planes</th>
<th>Angle (degrees)</th>
<th>Sense wire spacing (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>X</td>
<td>2</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>T1</td>
<td>V</td>
<td>2</td>
<td>-45</td>
<td>0.8</td>
</tr>
<tr>
<td>T1</td>
<td>Y</td>
<td>2</td>
<td>-90</td>
<td>0.8</td>
</tr>
<tr>
<td>T1</td>
<td>U</td>
<td>2</td>
<td>45</td>
<td>0.8</td>
</tr>
<tr>
<td>T1</td>
<td>W</td>
<td>2</td>
<td>-27</td>
<td>0.8</td>
</tr>
<tr>
<td>T2</td>
<td>X</td>
<td>3</td>
<td>0</td>
<td>1.4</td>
</tr>
<tr>
<td>T2</td>
<td>Y</td>
<td>3</td>
<td>-90</td>
<td>1.4</td>
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<td>3</td>
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<tr>
<td>T2</td>
<td>V</td>
<td>3</td>
<td>-45</td>
<td>1.4</td>
</tr>
<tr>
<td>T3</td>
<td>U</td>
<td>2</td>
<td>30</td>
<td>3.1</td>
</tr>
<tr>
<td>T3</td>
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<td>3</td>
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<td>3.1</td>
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</tr>
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<td>3.1</td>
</tr>
<tr>
<td>T4</td>
<td>U</td>
<td>2</td>
<td>30</td>
<td>3.3</td>
</tr>
<tr>
<td>T4</td>
<td>X</td>
<td>3</td>
<td>0</td>
<td>3.3</td>
</tr>
<tr>
<td>T4</td>
<td>Y</td>
<td>3</td>
<td>-90</td>
<td>3.3</td>
</tr>
<tr>
<td>T4</td>
<td>V</td>
<td>2</td>
<td>-30</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Table 3.1: Tracking Chamber Characteristics.
3.3 Trigger Chambers

Two refurbished multiwire chambers, denoted TR1 and TR2, were installed for E859 as part of the second level trigger. Table 3.2 provides the pertinent characteristics of these chambers. They were positioned with the following considerations in mind: 1) no chamber already on the spectrometer was to be moved, and, 2) the acceptance with the TR1 and TR2 sizes as constraints was to be maximized. Unfortunately, the best fit to this problem resulted in TR1 cutting off a significant part of the acceptance for tracks found by the LVL2 trigger. TR2 has no affect on the acceptance. A typical operating voltage was 2600 V for both TR1 and TR2.

The trigger chamber hits are read out via Lecroy's Proportional Chamber Operating System (PCOS). Details of the readout as well as diagnostic tests can be found in [C+91]. One detail worth mentioning is the PCOS' capability to provide a fast OR of all the channels. This is called the “prompt OR”. The presence of the prompt OR in TR1 or TR2 indicates a hit on one of the wires. A logical AND between the prompt OR from TR1 and TR2 and the first level trigger was made because the second level trigger requires such hits on both chambers. Because of its use in the LVL1 trigger, the efficiency of the trigger chambers is important to ascertain. We discuss this later.
### Table 3.3: GASC Momentum Threshold for various particles.

<table>
<thead>
<tr>
<th>Particle type</th>
<th>$P_{\text{threshold}}$ (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>0.0057</td>
</tr>
<tr>
<td>muons</td>
<td>1.12</td>
</tr>
<tr>
<td>pions</td>
<td>1.47</td>
</tr>
<tr>
<td>kaons</td>
<td>5.20</td>
</tr>
<tr>
<td>protons</td>
<td>9.88</td>
</tr>
</tbody>
</table>

3.4 Gas Čerenkov counter, GASC

3.4.1 Introduction

A particle with speed $\beta \geq 1/n$ emits Čerenkov radiation at an angle given by

$$\cos \theta = \frac{1}{\beta n},$$

where $\theta$ is relative to the particle’s direction of motion. The index of refraction of the medium is $n$. For our application, we used Freon 12 at 4 atmospheres, which has an index of refraction of 1.0045. The maximum $\theta$ of Čerenkov light is 5.3 degrees. The momentum at which a particle of mass, $m$, will start emitting Čerenkov light is

$$P_{\text{threshold}} = \frac{m}{\sqrt{n^2 - 1}}.$$

The momentum threshold of various particles is provided in Table 3.3. Typical values of energy loss and number of photons per cm vary with the type of radiator but an estimate can be made from the following formulas [Fer88]:

$$dE/dx = 1.2\sin^2(\theta) \text{ keV/cm}$$

and

$$dN/dx = 400\sin^2(\theta) \text{ photons/cm}.$$
For the \( \theta \) given above, a \( \beta = 1 \) particle has a \( \mathrm{d}E/\mathrm{d}x \) of 0.01 keV/cm and \( \mathrm{d}N/\mathrm{d}x \) of 4 photons/cm. By comparison, water as a radiator results in a \( \mathrm{d}N/\mathrm{d}x \) of about 170 photons/cm.

The small light yield indicates that the light collection efficiency needs to be maximized as well as the path length through the radiator. If we take a typical path length through the GASC of 100 cm, this means we have 400 photons per radiating particle. If total GASC efficiency (including effects such as light collection and phototube quantum efficiency) is 5\%, we obtain 20 photoelectrons per particle. Optimally, to avoid being dominated by fluctuations in photoelectron yield, a design goal of 20 photoelectron per particle is set. Another design consideration is that the radiator material should not be fluorescent. This is especially true for a threshold Čerenkov detector where just the presence of a signal is used.

### 3.4.2 Description

The segmented, threshold gas Čerenkov counter (GASC) was implemented to distinguish between pions and kaons (and to a lesser extent between electrons and pions) in a momentum region where the TOF provides ambiguous identification. It came online in 1988 and a detailed description by one of its builders can be found in [Kur92]. The forty cells built with aluminized Mylar are housed in a cylindrical tank held at 4 atmospheres of Freon-12. Each cell has an elliptical mirror located near the end of the cell which focuses the Čerenkov light to the surface of the phototube. A 5 inch RCA 8554 phototube detects the Čerenkov light and optical cones are used to enhance the photon collection efficiency between the inside of the GASC and the phototubes (which sit just outside the cells). Fig. 3-3 shows the schematic design of the GASC and its interior. The forty cells are divided into two types, long cells and short cells. The long cells have dimensions 23(H) x 23(W) x 101(L) cm and the short cells are 28(H) x 23(W) x 72(L) cm. There are 4 rows of 10 cells with the top and bottom rows made up of short cells and the two middle rows of long cells. The counting convention is to face the GASC from the target with cell 1 being the upper left cell, counting across, and cell 11 being the next-to-upper left cell.
Figure 3-3: A schematic of the GASC cell design.
The GASC housing was constructed to be able to contain Freon 12 at 4 atmospheres. Although built of aluminum to reduce the amount of material, both the Freon 12 and the aluminum amount to 10% of an interaction length. This makes it crucial to determine whether a particle has completely passed through the GASC. Particles which interact in the GASC may provide a signal which would cause misidentification unless some means were available to verify their passage through the GASC.

### 3.4.3 Calibration of Index of Refraction

The index of refraction, $n$, can be determined several ways. The first method requires measuring the Freon 12 pressure and using the Lorenz-Lorentz law [Jac75],

$$\frac{n^2 - 1}{n^2 + 2} = \frac{M}{\rho} = R,$$

where $M$ is the molecular weight and $R$ is the molecular refraction coefficient. $R$ is a constant. Letting $n = 1 + \delta$ where $\delta$ is a small number, we can approximate the above by

$$\delta = \frac{3}{2} \frac{R}{M} \rho.$$

Since $\rho$ is proportional (ideal gas law) to pressure, $P$, at constant temperature, we obtain

$$\frac{\delta_4}{\delta_1} = \frac{P_4}{P_1},$$

where the subscript 4 and 1 correspond to the values at 4 atmospheres and at 1 atmosphere. In other words, $\delta$ scales with pressure. At 1 atmosphere, 26 degrees C, $\delta_1$ is 0.001080 [Gro90]. Therefore, at 4 atmospheres

$$n = 1.00432.$$

The second method uses a Fabry-Perot interferometer. A small chamber containing Fabry-Perot plates is attached to the GASC through a small output pipe. The chamber has two windows allowing the passage of a laser beam. The laser light is
multiply reflected by the plates and the intensity read out on a photodiode. A vacuum pump slowly pumps down the chamber. As the pressure changes, the wavelength of the laser light in the chamber changes, thus changing the conditions for constructive interference. By measuring the number of fringes passed through, we can obtain the index of refraction at 4 atmospheres.

Let the subscript 0 and 4 be the values at 0 and 4 atmospheres, respectively. Let \( N \) be the number of fringes (peaks) measured. Then,

\[
N = n_4 - n_0.
\]

The condition for constructive interference for plates separated by \( D \) is just \( \frac{2D}{\lambda} \) (light must travel 2D until it is brought back to where it interferes). So

\[
N = 2D\left(\frac{1}{\lambda_4} - \frac{1}{\lambda_0}\right).
\]

Since

\[
c/n = \lambda \nu,
\]

where \( n \) is the index of refraction, we write

\[
n_4 = n_0 + \frac{Nc}{2D\nu}.
\]

The index of refraction of the vacuum is 1.0. We measured \( N \) to be 400. With \( D=2.786 \text{ cm} \) and \( \lambda_0 = 635.8 \text{ nm} \), this gives \( n_4 \) of 1.00456, in agreement with the simple scaling rule.

### 3.4.4 Calibration of the Single Photoelectron Peak

An externally triggered LED exists for each cell for calibration and diagnostic purposes. The LED alternately emits a large signal and a small signal. The small signal is adjusted to provide a single photoelectron response. This is done because we cannot resolve two photoelectrons. The large signal tests the full dynamic range of the
cell. It is used primarily to diagnose bad phototubes or even cells in which the mirror fell off its mounting.

Calibration is essential for the GASC cells because we must choose a threshold to decide when a cell fired (emitted Čerenkov light or not). During both running periods, pedestal and LED runs were taken. During the Feb91 running, a substantial amount of noise was observed as determined by the width of the pedestal. Since noise adds randomly, it should not affect the location of the pedestal and single photoelectron peak. The larger width of the pedestal distribution can be a problem, though, because it can cause the signal to be too large (or too small). One can gauge the size of the effect by noting that the single photoelectron peak is at least 3 to 4 $\sigma$ above the pedestal for all cells. Since we set the GASC threshold at 0.5 photoelectrons, this means the threshold is at least 1.5 $\sigma$ from the pedestal. The effect of the noise is small. Fig. 3-4 shows the pedestal and single photoelectron peak values obtained from various runs for the Feb91. The Mar92 data are identical. Pedestal runs taken throughout both running periods indicate the pedestal remains constant. The error bars on the pedestal are the rms of the pedestal distribution.

3.5 Back Counter

Because pions and kaons may decay between the TOF wall and the GASC or may be absorbed in the GASC, the BACK counter was placed immediately behind the GASC to verify passage through the GASC.

3.5.1 Description

Located about 9.3 m from the target, it covers an area from approximately -190 to +190 cm in x and -60 to +60 cm in y (relative to the spectrometer axis). The BACK counter consists of two layers of gas pads with the second layer staggered by one half a cell to eliminate dead regions due to the pad's wall. A charged particle ionizes the gas in a gas pad. This induces an image charge on the resistive plastic of the pad which is then read out. The BACK counter uses identical technology as the TMA
Figure 3-4: Pedestal and single photoelectron peak (in ADC channels) versus cell. The pedestal error bars are the rms of the pedestal distribution.
and the reader is referred to [Abb90] for further details. There is one readout plane which detects hits on either layer. The gas pad is smaller than the readout pad and so one readout pad may measure hits from several gas pads on the planes. The readout pad layer has 8 panels with 8 tubes per panel. Each tube has 24 pads for a total of 1536 readout pads, 64 in the x direction and 24 in the y direction. The readout pad is 6 cm long in the x direction and 5 cm high in the y direction.

The major problem for the BACK counter are pads which are dead or hot, i.e. they fire continuously regardless of the presence of a particle. Unfortunately, pads exhibit different degrees of 'hotness', firing at different rates. The dead and very hot pads were excluded from this analysis. Fig. 3-5 indicates the hot and dead cells for the Mar92(top) and Feb91(bottom) running, respectively. In Feb91 there were no hot cells. The worst case for Feb91 is shown. The effect is negligible, amounting to 36 pads. In Mar92, there were only 28 dead pads. Unfortunately, there were several time periods where whole panels would get warm. This makes the panel over-efficient. The example shown occurs at the 5 degree setting where the BACK counter is most needed.

How large an effect is expected? The dead pads are negligible, amounting to 36 out of 1536 pads at most. The hot pads are more serious. However, they are most important at the 5 degree spectrometer setting. Only 15 runs (all triggered on K⁻) out of the 100 taken at this setting are affected. Since the maximum number of hot cells constitutes no more than 10% of all pads, the size of the effect ≈ 2% (0.15 × 0.10). As this correction applies to kaons over a limited momentum range, we neglect this effect.
Figure 3-5: Hot and dead pads for the Mar92(top) and Feb91(bottom) running.
3.6 Event Definition and Characterization Detectors

3.6.1 Beam Counters

The beam counters provide the crucial normalization for cross-sections. Their two main tasks are to flag clean (i.e. well separated in time) beam particles of a specific charge and to flag interactions. The first task is accomplished by the upstream counters: UDEW, BTOF, BTOT and BVETO. The Bull's Eye counter (BE) determines whether an interaction has occurred. The exhaustive discussion in [Abb90] provides all the details. Only a brief discussion is supplied in the following paragraphs. Fig. 3-6 shows a sketch of the beam counter system. All counters consist of Bicron 448 scintil-
lator read out by phototubes (Hamamatsu 2431 or 1398). Both ADC and TDC values are recorded. The upstream counters are housed in vacuum tight compartments while BE sits immediately in front of the ZCAL, outside the beam pipe.

UDEW (Up, Down, East and West) is used to reject the beam halo. The gap in UDEW defines a preliminary aperture for the beam.

BTOT (or Beam Total) counts the number of beam particles. Its larger thickness compared to BTOF allows for more light and hence better charge resolution. It was primarily intended to protect against beam impurities (nuclei with different Z). However, its performance was frequently poorer than BTOF. This is possibly due to radiation damage and the fact that during the Mar92 run, the BTOT scintillator was not changed although the BTOF scintillator was. The charge resolution of BTOT, as monitored run by run, is $\sigma_Z = 1.1$ units of charge.

BTOF (or Beam Time of Flight) provides the start time for the experiment. In order to optimize the timing resolution, a very thin (50 $\mu$m) slice of scintillator is used. The intrinsic timing resolution, as measured by the sigma of the TDC difference between the two BTOF phototubes, is about 30 ps. The TDC and ADC signals are split and measured by the BEAM and by the TOF partitions. This eliminates about 100ps of jitter between the BTOF signal (the true start time of the event) and the signal indicating the acceptance of the event (the event start time used by the experiment). At best, BTOF's charge resolution was 0.8 units of charge measuring a Z of 14 (silicon). A more typical resolution was 1.0.

The BTOF signal is also used to flag beam particles which have another beam particle within 1 $\mu$sec after the first beam particle. These events are called "follow" events and are tagged, with the option of keeping these events left to the user. Checking the follow flag is important especially for rare particles. Assuming an interaction rate of 3%, the probability that two beam particles within the follow window will interact is small (0.03$^2$). This, however, can still constitute a significant background for very rare particles. For example, at the higher angle spectrometer setting where we ran at a very high beam rate (2x10$^6$ per spill), we can throw out up to 45% of $\bar{p}$ candidates when we cut on follow events! The extra beam particle in BTOF can also
affect the start time. A flag, called PRE, is also set if BTOF fires 1 \( \mu \)sec before a beam particle. Events with PRE set are rejected immediately.

The BVETO (Beam Veto) sits approximately 1 m in front of the target. With a 1 cm diameter hole in its center, any beam particle which has satisfied UDEW but was knocked out of BVETO’s aperture will be rejected.

Finally, sitting about 11 m downstream from the target, the Bull’s Eye (BE) measures the charge of the forward going fragments. A discriminator level was set in order to flag events with a Z of less than \( \approx 12.6 \) units of charge. This flag is used online as part of the minimum bias trigger. This threshold plays a role in the cross-section formation and so deserves some discussion.

The BE had problems, most probably due to radiation damage of the scintillator. As the signal drops with time, one either increased the phototube voltage or adjusted the discriminator threshold. This change in threshold changes the definition of an interaction trigger. Fluctuations in the interaction are evident in the data. For example, at the beginning of the Feb91 run, the total interaction rate (including target out) was almost 6% for a 3% Au target. The normal total interaction rate is 4%. Typically, the target out contributes 1% to the rate. The difference is the BE threshold level. As will be discussed later, knowing the target-out interaction rate is necessary for cross-sections and so an anomalously high interaction rate must be understood.

Other beam counters also had problems because of the high rates, which were up to \( 2 \times 10^6 \) per spill for E859 versus \( 10^5 \) per spill for E802; namely, light output of BTOF would decrease. This affects the start time because the time the BTOF pulse crosses the discriminator level depends on the pulse height. In order to mitigate this problem with BTOF, a new design for BTOF was installed between the Feb91 and Mar92 runs. It consisted of a strip of scintillator approximately 20 cm long attached to a remotely controlled motor which would move the strip down by a few mm. Whenever we saw evidence for any sag in BTOF, we would move the scintillator and thus ensure that the beam was incident upon new material.

Beam Z cuts are made on both BTOT and BTOF signals. Only events within
± 2 units of charge 14 on both scintillators were accepted as good in the offline analysis. We calibrated BTOF, BTOT and BE run by run to reduce some of the above mentioned effects.

### 3.7 Zero Degree Calorimeter (ZCAL)

Ideally, one would like to select events based on the impact parameter. Central events (with \( b \approx 0 \) fm) are of particular interest because it is for these events we expect to produce the most dense and longest lived excited state of nuclear matter. However, it is impossible to measure impact parameter directly and so we measure a quantity we expect is, on average, in one-to-one correspondence with impact parameter. Variables used in various heavy ion experiments include produced particle multiplicity, total transverse energy and total forward going energy.

The ZCAL measures the total forward going energy. Consider the intersection of two spheres as they pass through each other. The projectile nucleons lying outside the intersection are called the projectile spectators. The region outside of the intersection clearly depends on impact parameter in a one-to-one fashion. In a naive way, we think of the projectile spectators as not interacting whatsoever in the collision; they continue their trajectory down the beam line. By measuring their kinetic energy, one can then determine the number of projectile spectators and hence the centrality of the collision. The ZCAL was built for this purpose.

The ZCAL's 138 layers (60 cm by 60 cm) of plastic scintillator and iron constitute 8.9 interaction lengths. It is located about 11.7 meters downstream behind the Bull's Eye. The ZCAL detects particles within about 1.5 degrees of the beam axis and provides a very linear response as a function of incident number of nucleons \([A^+90a]\). The energy resolution is \( 0.76 \text{ (GeV)} \times \sqrt{T} \) where \( T \) is the kinetic energy measured in GeV.

Again we need to ask the question of how well the ZCAL measures the projectile spectators. Again several factors affect its performance. The first is that the ZCAL measures not just the projectile spectators but also very forward produced particles.
Also, we ran the experiment at a very high beam rate, reaching \(2 \times 10^6\) per spill at times. Because of the ZCAL signal’s long tail, at high rates, a new event frequently sat on top of this tail, falsely increasing the signal.

In my analysis, the ZCAL is used as a software trigger for peripheral events for Al and Au targets and for central events for the Al target. It does very poorly for Si-Au events because of the size asymmetry between the two nuclei. The Si nucleus can range over a few fm in impact parameter and yet still completely overlap the Au nucleus. This means the ZCAL will measure very little for impact parameter from 0 to about 2 fm. Clearly this makes it useless as an indicator of central events for this system. For symmetric systems, however, it is the ideal detector for both central and peripheral events. Fig. 3-7 shows the number of participant projectiles versus impact parameter as determined from the Fritiof model [Cos88]. The two sets of points correspond to a Si-Au collision and a Si-Al collision. We clearly see the insensitivity of the ZCAL to central Si-Au collisions. It is effective, though, for peripheral Si-Au and the preferred trigger for Si-Al collisions. Matt Bloomer ([Blo90]) and Dan Zachary([Zac94]) have done extensive work on understanding the ZCAL and I refer the reader to their work for further details.

3.7.1 Target Multiplicity Array (TMA)

The TMA measures the charged particle multiplicity. This is related to impact parameter with the following argument: smaller impact parameter means a larger geometrical overlap between projectile and target, more nucleon-nucleon collisions (i.e. more participants in the collision), and more particles produced. We emphasize that the TMA does not measure only the geometry of the collision but also the dynamics in an average sense. After the initial nucleon-nucleon collisions, the subsequent ones have less energy and therefore produce fewer particles. The observed multiplicities will depend on both geometry and how much energy is lost in succeeding nucleon-nucleon collisions. Since the TMA measures both produced and existing particles and the ZCAL primarily measures the projectile spectators, the latter provides a better measurement of the geometry (impact parameter) of the collision for symmetric
Figure 3-7: Number of projectile participants from Fritiof as a function of impact parameter.
systems. However, as discussed, the ZCAL loses sensitivity for asymmetric collisions such as Si+Au and the TMA proves very useful.

The TMA was built to measure the total charged particle multiplicity and hence provide a handle on the centrality of the collision. It consists of a barrel of resistive pads (identical to those used in the BACK counter) surrounding the target and a wall of such pads on the downstream side of the target. A gap in the wall allows particles heading for the spectrometer to propagate without interacting in it. The TMA covers from about 5 to 150 degrees in theta and almost $2\pi$ in phi. Fig. 3-8 shows a typical Si+Au collision. The TMA was designed so that the average occupancy per cell would be much less than one, thus reducing the probability of double hits.

An important question to ask is how well the TMA measures the produced particle multiplicity. Several factors can effect the TMA's abilities. Since the TMA is used
as a hardware centrality trigger, pads whose “hotness” (i.e., firing regardless of the presence of particles) varies causes changes in performance especially as the online TMA trigger was an analog sum of all the TMA pads. None of the data presented in this thesis is triggered in such a manner and so this will not affect our analysis. These hot pads are removed in the offline analysis. Secondly, the TMA also detects protons with kinetic energy above approximately 30 MeV. Because there are many protons for high A targets, the protons can constitute a significant fraction of what the TMA detects. Finally, the TMA also detects particles produced from beam interactions upstream from the target and from interactions in the target frame. Runs with the target out (but target holder in) are taken to estimate the effect of the target out contribution. This contribution is small for 3% Au targets but significant for 3% Al targets. Typical 3% Au, 3% Al and empty target TMA distributions are found in Fig. 3-9. We observe that the target-out contribution becomes comparable to that of 3% Al near a TMA multiplicity of 80.

More details, especially regarding TMA geometry, the corrections due to dead pads and other TMA inefficiencies, are presented very clearly in [Abb90].

### 3.8 Triggering

Because we wanted to accumulate statistics for rare particles (compared to protons and pions), we needed a selective trigger. We will discuss the three levels of triggering in E859: LVL0, LVL1, and LVL2.

There are two LVL0 triggers. They are BEAM and INT and are defined as

\[
BEAM \equiv UDEW \cap BTOT \cap BTOF \cap BVETO \cap PRE
\]

and

\[
INT \equiv BEAM \cap BE.
\]

Once formed, a trigger is sent to the front end electronics and a decision must be made whether to accept or reject the event. The many BEAM triggers (\( \approx 10^6 \) per
Figure 3-9: TMA distributions for Al 3%, Au 3% and no target normalized to the number of BEAM triggers.
spill) and INT triggers (≤ 6% of BEAM) would totally swamp the front end. Crucial for the normalization and for calibrating certain detectors, we need about 10% of events written to tape to be BEAM and INT triggers. The number we have available, though, is much larger and so we must have a way of removing many of them from being processed by the computer. Scaledowns are used for this purpose. They work as follows: if the BEAM scaledown is 1000 then every 1000th BEAM trigger is sent to the data acquisition system as a BEAM trigger. Typical scaledowns are 60000 for BEAM triggers and 1000 for INT triggers. All triggers are also counted on scalers and stored for each run. Because the amount of live beam is critical to the cross-section normalization, we would like a cross-check. We can do this by looking at the difference between the two numbers,

\[ N1 = (N_{\text{events}}^{\text{beam}} + 0.5) \times (\text{beam scaledown}) \]

and

\[ N2 = N_{\text{scaler}}^{\text{beam}} \]

Assuming the scale down of 1000 as above, the factor of 0.5 arises from the fact that the scaledown flags the 1000th trigger and not the 500th. Fig. 3-10 shows the difference over the average \( (100 \times \frac{N1-N2}{N1+N2}) \) between these two methods for the whole data set. Because of how the scale down works, we expect \( N1 \) slightly less than \( N2 \). This explains why the differences are slightly negative for the runs. In the E802 analysis, differences of up to 25% were found with this method [Par92] due to a hardware fault. We ignore differences of < 5% and find consistency in this data set and use the beam scaler for our cross-section normalization. Finally, we estimate a systematic error of \( \leq 1.0\% \) in our determination of the amount of beam for a given run.

Various detectors have a LVL1 trigger which can be enabled. For example, the TMA has its own LVL1 trigger as does the TOF wall (a particle hitting the TOF wall). Several triggers can be combined to form another LVL1 trigger. For example, our minimum bias trigger, SPEC, indicates the presence of a particle in the spectrometer.
Figure 3-10: Percentage difference (difference over average) between two methods of counting the amount of beam versus run (assembled in increasing order).
SPEC was defined in E802 as

\[ \text{SPEC}_{E802} \equiv \text{INT} \cap T1 \cap \text{TOF}. \]

The motivation for the \( \text{SPEC}_{E802} \) trigger comes simply from the fact that the spectrometer has a restricted acceptance and as we move to higher angle settings, the number of particles emitted at large angles drops off quickly. Therefore, most INT events will not have a particle in the spectrometer, making those events useless for particle production studies.

In E859, the minimum bias trigger was the logical AND of the SPEC trigger with the prompt-OR coming from trigger chambers TR1 and TR2. The prompt OR is a fast signal indicating the presence of hits on the chamber. Because the LVL2 trigger (to be discussed below) required TR1 and TR2 hits, it was pointless to accept events without any such hits. The E859 SPEC trigger thus consists of

\[ \text{SPEC} \equiv \text{INT} \cap F0 \cap \text{TOF} \cap (\text{TR1} \cap \text{TR2}). \]

The inclusion of F0 instead of T1 makes no difference.

In order to select central events with a particle in the spectrometer, another LVL1 trigger was formed with the AND of SPEC and TMA, or \( \text{SPEC}^*\text{TMA} \). For the kaon triggered data, we typically took a mixture of BEAM, INT, SPEC and \( \text{SPEC}^*\text{TMA} \). The \( \text{SPEC}^*\text{TMA} \) trigger allows an emphasis on central events. For kaon production, collisions producing kaons already tend to be central, so requiring a hardware TMA trigger adds bias. Because of the fact that most triggers were SPEC and that the \( \text{SPEC}^*\text{TMA} \) has the TMA bias in it, all the kaon data presented here is triggered on SPEC (plus a second level trigger to be discussed). This allows one to have more flexibility in how central one wants to make the software cut. We can also use ZCAL as a software trigger for the events taken only with SPEC.

The \( \Lambda \) data to be presented used \( \text{SPEC2}^*\text{TMA} \) for triggering where \( \text{SPEC2} \) is identical to SPEC except that the TOF wall was required to have at least two hits on it. Although one would like to have taken this data without TMA, time restrictions
required it.

3.9 LVL2 Trigger

The LVL1 SPEC trigger came online in 1988 during E802’s running period and provided increased statistics especially at the 34 and 44 degree settings. Compared to the INT trigger at these settings, one obtains approximately a ten-fold increase in number of events with tracks written to tape with this trigger. However, it was still difficult to accumulate statistics for very rare particles such as K⁻ and ď. The E802 ď paper [A+91a] included only 400 ďs. This clearly indicated the need for a more intelligent, second level trigger. The second level trigger (LVL2 trigger) was designed to allow momentum dependent mass cuts performed in real time. This requires a fast determination of momentum, pathlength and time-of-flight, \( p, L \) and \( t \). Lookup tables provide a means to quickly determine the first two. Using the known location of the trigger chambers, we can throw particles into the spectrometer acceptance over a range of \( p \) and \( \theta \) and record their TR1, TR2 and TOF hits. We accumulate the triplets, \( (\text{TR1}, \text{TR2}, \text{TOFSLAT}) \), which correspond to a track in the spectrometer. Each triplet of \( (\text{TR1}, \text{TR2}, \text{TOF}) \) uniquely identifies a possible track in the spectrometer. We also map the triplet to the momentum and pathlength of the track. We make a table whose indices include the triplet of numbers and whose output is the doublet \( (p, L) \). The Fast Encoding and Readout Time to Digital Converter (FERETs) digitized the time-of-flight. In another lookup table, we input \( (p, L, t) \) and get out \( m \). Then the momentum mass table (which contains the windows of particles we want) is queried with the found \( (p, m) \) to see if this particle is accepted. If no track satisfies the momentum mass table, the event is rejected.

The LVL2 trigger can also be used in a mode without the mass cuts and thus provides a track finding trigger. This is useful at the large spectrometer angle settings.

In Fig. 3-11 we include the logic/hardware diagram of the LVL2 trigger. We will not go into detail for this figure except to point out the complexity of the setup. Further details of the diagram and the exercising of the logic and hardware are found...
in [C+91, Mor91, Sol91, Zaj91]. It is amazing that it works and that it works well!
Figure 3-11: LVL2 hardware diagram.
In this chapter, we present the data analysis details. The analysis stages are described. The essential components are discussed with emphasis placed on the extended particle identification detectors. The various corrections to the data are detailed.

4.1 Analysis Staging

The data is analyzed in three stages, called passes. The three are PASS0, PASS12 and PASS3 and each will be described.

PASS0 consists essentially of transferring the data from the bulky 9 track tape format to the compact 8mm tape format. Typically the contents of eight 9 track tapes fit onto one 8mm tape.

PASS12 is a combination of two stages. The first stage is the conversion of the data to physical units, i.e. GASC ADC charge to photoelectrons or TOF TDC channels to nanoseconds. This requires that the calibration of the detectors has been performed. In the second stage, track reconstruction is performed and the output is again written to 8mm tape. The collaboration has chosen two tracking codes as the standard, AUSCON and TRCK3. Both have been compared in depth and yield similar results. I have chosen AUSCON for my analysis because of comprehensibility.
and the ease with which parameters can be changed.

A second TOF wall calibration is done before PASS3. This is a thorough calibration in order to remove any possible problems with experimental changes which could have caused a timing shift. This calibration was performed every 50 runs. Furthermore, any drifts between these calibrations were corrected for run by run. We therefore have confidence that the best possible timing is available for particle identification.

PASS3 performs the final particle identification on the tracks. It takes as input the PASS12 output and produces the final version of all the data. It also produces HBOOK4 \([B+93]\) ntuples used for cross-section purposes. A run-by-run global (i.e. applied to all slats) timing offset is calculated in case some changes were missed by the TOF wall calibration described above. The timing offset was typically very small (< 20 ps).

### 4.2 On the Road with AUSCON

The E802 tracking algorithm is called RECONSTRUCT. With the introduction of a modified T2 drift chamber, new trigger chambers (TR1 and TR2), and a wire chamber (T3P5), it became clear that either RECONSTRUCT be altered or a new algorithm written. Because of the difficulty in implementing these detectors in RECONSTRUCT and, more importantly, to implement the tracking insights gained from RECONSTRUCT, a new algorithm, AUSCON, was written by Peter Rothschild and Dave Morrison. A full description can be found in [Rot94] and I will here only give a brief description and details where relevant to my analysis.

Particle identification necessitates knowing the time-of-flight. AUSCON starts with a TOF hit and then gathers hits on chambers behind the magnet to form the T3T4 vector. This vector is then projected through the magnet to T1 and T2. Again, hits are gathered along the road and an independent vector is formed in front of the magnet. The two vectors are then compared and if they satisfy matching criterion (see [Rot94]) they are combined into one track. The process of finding the vector in
front of the magnet is the most time consuming part of track reconstruction because of the high hit multiplicity in T1 and T2.

AUSCON has many nice features including diagnostic ntuples and the ability to vary every cut parameter used in the code. This facilitates cut optimization and increases code flexibility. Because most particles of interest originate from the target, AUSCON's cuts partially depend (very reasonably) on the fact that the tracks come from the target. We require fully reconstructed tracks ("status 255") to project to within 2 cm in x and y of the average target position for each run. At the initial stages of reconstruction, a T3T4 vector formed behind the magnet is required to project back in y to within 2.4 cm of the average y target position. However, if we are searching for particles via their charged decay products, it is possible that the decay products no longer point to the target, especially if the parent has a characteristic decay distance of a few centimeters. This is certainly the case for the \( \Lambda \) and \( K^0 \). We examine this in the following chapter.

One important number which must be determined is the efficiency of AUSCON. That is, if we have a particle in the spectrometer, what is the probability that AUSCON will find it? The momentum and multiplicity dependence of this number is also important to know. For example, low momentum protons undergo a significant amount of multiple scattering which results in a momentum dependent efficiency. This correction is algorithm dependent and particle species dependent. Convoluted with other corrections, we present the final correction in the summary section of this chapter.

4.3 Particle Identification

The particle identification strategy is a crucial in determining accurate cross-sections. A significant amount of work has been done by the authors of this code, Shige Hayashi and Yoshito Tanaka, and the reader is referred to their memo [H+93]. We will frequently refer to the particle identification code as PICD, in reference to the data bank created by it. Because of the exhaustive description found in the above reference, I
only discuss the general particle identification strategy and discuss in detail those aspects which involve corrections or are of use in the kaon or $\Lambda$ analysis.

In order to appreciate what has been done in PICD, we outline the differences with the previous particle identification code, PIAD. The philosophy in PIAD was to identify every fully reconstructed track with a status word indicating the quality of the particle identification. For example, an unusually low energy loss in the TOF wall was flagged. The actual identification was done by calculating the mass of the track based on its momentum, time of flight and pathlength to the TOF wall: $p$, $t$ and $L$. Any particle with $350 < m < 750$ MeV/$c^2$ was called a kaon. Particles with a $\beta > 1$ were identified as “pseudo-pions” and assigned a special particle identification code.

The major drawback of PIAD is its use of mass as the cut parameter. One cannot inveigh enough against the danger of this method. The TOF calibration is done by finding the offsets to the $\Delta TOF (= TOF expected - TOF measured)$ distribution. However, cutting on equal values of mass above and below a particle's mass is not equivalent to a symmetric cut in time. Therefore, if tracks are identified as pions by the condition $30\,\text{MeV}/c^2 < m < 200\,\text{MeV}/c^2$, one does get rid of kaon contamination but poorly rejects electrons. This can significantly skew the $\Delta TOF$ distribution.

Furthermore, mass is not an experimentally measured quantity and so is not necessarily gaussian in its distribution. This makes it difficult to estimate what fraction of particles we discard by using a mass cut. We would rather like to select particles with a parameter that should be gaussian. In addition, PIAD does not allow for momentum dependant cuts. For example, it is well known that low momentum protons ($\leq 0.8$ GeV/$c$) suffer significant multiple scattering which deteriorates the momentum determination. This is true for low $\beta$ particles in general. We should have a larger window in the cut variable to account for this. In general, we need a momentum dependent window. Also, momentum resolution depends on the strength of the magnetic field. This is not accounted for in PIAD. Because of timing resolution, we expect some particles with $\beta > 1$. These particles were flagged as unphysical in PIAD. This problem worsens with increasing momentum. Ignoring $\beta > 1$ particles
can bias the particle identification in a momentum dependent manner which is difficult to correct. Finally, no provision was made in the PIAD code for using the GASC and BACK information.

PICD corrects all these shortcomings. We now go into some detail describing it. The cut parameter is $\Delta(1/\beta)$ (which is essentially $\Delta TOF$). Each track is subject to a mass hypothesis using masses of the electron, kaon, proton, deuteron and triton. Assuming $m$ and knowing $p$ determines $1/\beta^{exp}$ for a given mass hypothesis. For each track, $1/\beta = cx TOF/L$. The quantity $\Delta(1/\beta) = |1/\beta - 1/\beta^{exp}|$ is formed. If

$$\Delta(1/\beta) \leq 3 \times \sigma(1/\beta),$$

(4.1)

this mass hypothesis is kept. If tracks are in a momentum regime where the TOF wall does not provide unambiguous identification, the GASC and BACK information is used to decide. We detail $\sigma(1/\beta)$ in the next section.

This almost exhausts the TOF information. We also have the energy loss ($eloss$) of the particles in the slats. Too little $eloss$ may indicate a problematic slat or that the particle passed through two adjacent slats. A weak signal can affect the timing because of the walk effect (see the section on TOF details in this chapter). Secondly, a wrong $eloss$ determination will cause the correction for the walk effect to be off. This last effect can result in a maximum shift of 100 ps in the time-of-flight (compared to a typical shift for minimum ionizing particles of $\leq 10$ ps). A cut on $eloss$ has been observed to be especially important for rare particles [Par92, Rot94]. Less than 1% of full status tracks are lost because of this cut.

For each mass hypothesis satisfying the condition, the GASC and BACK information is checked if so requested. Table 4.1 indicates the possible (mass hypothesis, GASC, BACK) combinations. The momentum range dictates which (TOF, GASC, BACK) conditions are to be used. These momentum limits are determined by the $3\sigma$ separation in $1/\beta$. The particle's charge must match that shown in the charge column. Each reasonable combination of mass hypothesis is checked. The satisfied hypotheses are matched with that given by TOF_ID. The order of the bits is given...
at the top with the left most bit corresponding to an electron and the right most bit corresponding to He3. A “0” in the GASC column means that the GASC information is not used at all. A “1” in this column means that the GASC information is used and the GASC is required to have fired. A “2” means the GASC information is used and the GASC is required NOT to fire. The BACK counter simply has a “0” (information not used) and a “1” (information used and the track is required to BACK verify). For example, if a particle’s timing only satisfies a pion mass hypothesis in the momentum region (1.3,1.7897) then we do not need to use the GASC at all. We will discuss in detail how the GASC and BACK confirmation is performed.

4.3.1 \( \sigma(1/\beta) \)

The error in \( \Delta(1/\beta) \) arises from errors in the momentum and path length determination, and the resolution of the TOF wall.

In determining \( \beta \), one must know the track’s pathlength and time of flight. For the mass hypothesis, one needs the momentum. To compare the two, one needs to determine the errors associated with \( L, t \) and \( p \).

Propagating the errors in the formula \( \Delta(1/\beta) \) results in

\[
\sigma(1/\beta) = \sqrt{\left(\frac{c}{L} \sigma_{tof}\right)^2 + \left(\frac{-m^2}{p\sqrt{m^2 + p^2}} \frac{dp}{p}\right)^2},
\]

where we have dropped the error on \( L \) because we can measure path length very accurately (1 cm out of 670 cm). We see that the momentum dependence lies in the second term on the right hand side. We refer the reader to the PICD memo for details on how the momentum resolution \((\frac{dp}{p})\) is determined. The momentum resolution includes a term for multiple scattering (which correctly includes the effects for both different magnetic field settings, 0.2 T and 0.4 T) and a term due to the position resolution of the chambers. The TOF wall resolution was 120 ps.

The momentum dependence results in \( \sigma \) increasing as the momentum decreases. This is an important effect especially for protons. To get a feel for \( \sigma(1/\beta) \) as a function of momentum, we show Fig. 4-1 for a 0.4 T magnetic field setting and 120 ps TOF
Table 4.1: Table of particle identification parameters. The $\pi^+$ and $\pi^-$ particle identification schemes are identical so we omit that of the $\pi^-$. See the text for explanation.
resolution. At high momentum, $\sigma$ is dominated by the timing resolution, which is common to all the particles.

### 4.3.2 GASC and BACK algorithm

We go into some detail describing the extended particle identification algorithm because corrections are directly related to it. We raise several possible problems arising from the algorithm and will respond to them in the following sections. The following PICD parameters for the GASC/BACK algorithm are listed below with the values used in this analysis. The parameters are variables which PICD allows the user to set. We indicate their chosen values:

![Graph showing $\sigma(1/\beta)$ versus momentum for pions, kaons, and protons for a 0.4 T magnet setting and $\sigma$(TOF) = 120 ps.]

Figure 4-1: $\sigma(1/\beta)$ versus momentum for pions, kaons, and protons for a 0.4 T magnet setting and $\sigma$(TOF) = 120 ps.
- GASC threshold = 0.5 photoelectrons,

- GASC "dwallmax" (dx,dy) in cm (0.5,0.5),

- BACK search window (dx,dy) in cm (10.9,9.4).

A track's vector behind the magnet is projected to the GASC and BACK counter. Although the typical GASC's cell length is 70cm or 100cm, there is no segmentation along this length. In order to determine if the track remains in a given cell, we project the track to a front, center, and back plane of the GASC. The cell hit at each of these planes is recorded. If the front or back cell is different than the center cell, then the light output of the appropriate cell is added to the center cell's (or "hit" cell's) output. At the center plane, a check is make to see if the projection is within "dwallmax" of the nearest cell edge. If so, we consider that adjacent cell to be hit as well and its light output are added to that of the hit cell. The prejudice is that tracks which point this close to a cell’s edge are likely to have passed through the adjacent cell. Monte Carlo studies indicate that 7% of all tracks pass through two cells. Unfortunately, no checks are made to see if the adjacent cell being added in has another track pointing to it. This may be significant in a high multiplicity environment.

A projection to the BACK counter plane (z=935 cm) is made and the hit pad returned. All adjacent pads are also tested for hits. Verification is enabled if the hit or any adjacent pad has fired and the fired cell is neither hot nor dead. The BACK window size was chosen to maximize the BACK's efficiency as will be described.

One can separately require GASC and BACK confirmation. For kaons and pions, we require both, whereas for electrons, only GASC information is required, because electrons will likely not make it through the GASC. We have tried as much as possible to keep all the information that went into the particle identification decision. In this way we can vary some of these parameters and optimize them.
4.4 LVL2 Trigger Details

4.4.1 Mass cuts

One of the primary questions we need to answer is the possible bias due to the mass cuts used in the LVL2 trigger. Because the particle identification scheme just described was developed after the data taking, it is possible that what the PICD code calls a kaon would be rejected by the trigger. This would be a serious problem, which we now examine.

For the kaon data taking, we ran the LVL2 trigger in several modes: 1) K\(^{-}\) only, 2) K\(^{\pm}\) and 3) K\(^{+}\) only, where the names indicate the kaons accepted. The mass window for the K\(^{+}\) was from 320 to 750 MeV/c\(^2\) in the Feb91 running and 350 to 700 MeV/c\(^2\) in the Mar92 running. For the K\(^{-}\), we accepted any negative particle with \(m > 350\) MeV/c\(^2\). This allowed us to trigger on \(\bar{p}\)s as well. Any event with a track with momentum greater 2.5 GeV/c was accepted because we did not want to discard the higher momentum kaons which we could later identify with GASC and BACK.

Of primary concern is the possibility of losing events which actually had a kaon in the spectrometer but the LVL2 trigger indicated that there were no kaon candidates found. That is, we want to make sure that everything our particle identification code calls kaons were included in our LVL2 kaon mass cut. Otherwise, we may reject events with true kaons in them, biasing the data. To study this, we took runs triggering in LVL2 on kaons. The LVL2 decision was recorded but was not used to reject the event. This provides an unbiased sample of events. We then filtered these events by requiring that a kaon be found by our reconstruction/pid algorithm. Of these events, less than 2\% of them had a LVL2 decision which indicated no kaon existed, most of these at high momentum near 2 GeV/c.

The fraction missing is understandable for the following reason. Our particle identification scheme was developed after the LVL2 trigger. The LVL2 trigger defines a kaon candidate as a track with a mass between 0.32 and 0.75 GeV/c\(^2\), independent of momentum. Above a momentum of 2.5 GeV/c, all tracks were accepted as having been correctly been identified because our TOF resolution cannot distinguish pions
Figure 4-2: The momentum versus mass area what the LVL2 trigger and PICD scheme call kaons. The LVL2 trigger accepted any event if it contained any track with momentum above 2.5 GeV/c. The region enclosing the solid dot is where the particle identification scheme can identify a kaon by the LVL2 trigger would have not called it a kaon.

from kaons at a 3 σ level above 2 GeV/c. As we have just discussed, however, this is incorrect - the mass cuts should depend on momentum. We indicate this in Fig. 4-2. The PICD mass cuts were generated for a 0.4 Tesla magnetic field using our experimental TOF resolution of 120 ps. The region enclosing the solid dot is the region PICD accepts as a kaon but where LVL2 rejects. This is the source of bias. Fortunately, the bias is small and isolated to a small part of phase space. For the momentum range between between 1.9 and 2.5 GeV/c, there is at most a 2% bias.

One mitigating factor to this bias was found when visually displaying these events with a program called EDISP [C+89]. Some of the kaons identified with the particle
identification scheme and not identified by the LVL2 trigger had questionable reconstruction quality. For one event, all the other tracks seemed to originate from the target whereas the kaon track was off by almost 2 mm. Regardless of these mitigating factors, we assess a 2% systematic error to the LVL2 bias between 1.9 and 2.5 GeV/c. This is negligibly small compared to the errors associated with the GASC/BACK confirmation. We refer the interested reader to the Ph. D. work of David Morrison for further details regarding the LVL2 trigger and possible biases [Mor94].

4.4.2 Other possible biases in the LVL2 trigger

The SPEC trigger was first made in E802. The addition of TR1 and TR2 is strictly for E859 and so it is important to determine whether their inclusion into the trigger adds any bias which might make the SPEC trigger different between the two experiments. If so, it may have implications for comparisons between the data sets. In order to test this, we took data with (TR1 ∩ TR2) not in the SPEC trigger. We ignore the difference in the AND of T1 as done in E802 and the AND of F0 as in E859. We would like to know how many E859 SPEC triggers would also be defined as E802 SPEC triggers. Since we have the hit information from TR1 and TR2, we can look at the following ratio,

\[
\frac{\text{events with INT } \cap F0 \cap TOF \cap (TR1 \text{ hits } > 0 \cap TR2 \text{ hits } > 0)}{\text{events with INT } \cap F0 \cap TOF}.\]

This ratio is 1.0000 ± 0.0091 and so we conclude there is no bias to the SPEC trigger introduced by including TR1 and TR2. We do note that this may only mean that TR1 and TR2 are very noisy or have a large background so that they happen to have a hit for every SPEC trigger taken. At least we did not throw away events.

4.5 Trigger Chamber Details

A detector's efficiency is defined as the fraction of real particles passing through the detector which have a hit associated with them on the detector. To estimate the
efficiency, we must use tracks which do not require that detector's information for their reconstruction, or else the sample would be biased. Such a study is necessary because the prompt-OR is used in the first level triggering and because the second level trigger uses the trigger chamber hits to find particles. Inefficiencies in the chambers would lead to inefficiencies in the trigger and we would have to correct for them.

To study the trigger chamber efficiency, we took runs which did not include the prompt-OR in the triggering and which did not use the second level trigger. We also looked at data from higher angle spectrometer settings (24 and 44 degrees) so that we would have clean tracks and there would be less bias due to fake tracks which would point to a trigger chamber but of course leave no hit. We used the RECONSTRUCT algorithm because AUSCON requires the trigger chamber information. The method of determining whether a track had a TR1 or TR2 hit was to project the T3T4 vector to TR1 and TR2 with a varying search width from 0 to ± 2 wires away from the projected wire. The wire spacing is 0.635 cm for both chambers. If a hit was found within this search width, the track was considered to have a chamber hit. Two ratios were examined for each chamber. The first is the fraction of fully reconstructed tracks which have a LVL2 hit within the search width. These numbers are included in Table 4.2 for different search hit windows.

We also examine the efficiency as a function of wire number or a possible y dependence. Fig. 4-3 shows a plot of the fraction of LVL2 verified tracks as a function of wire number for TR1 and TR2 for a search width of 2 cm. Also, no y dependence was found. Although the runs used for the efficiency study were from the February 91 data set, we expect similar behavior for the Mar92 run.

<table>
<thead>
<tr>
<th>Search Width (in wires)</th>
<th>TR1</th>
<th>TR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 2</td>
<td>99.6</td>
<td>99.3</td>
</tr>
<tr>
<td>± 1</td>
<td>99.6</td>
<td>98.5</td>
</tr>
<tr>
<td>± 0</td>
<td>99.1</td>
<td>96.3</td>
</tr>
</tbody>
</table>

Table 4.2: Trigger chamber efficiency as a function of search width in wires. A search width of 0 means that the projected wire was required to fire to be counted as verified.
Figure 4-3: Trigger chamber wire efficiencies for TR1 (top) and TR2 (bottom). Acceptance restricts the number of hits at high TR2 wire number. The search width used here is ±2 wires.

We conclude that the wire chambers operated at a very high efficiency of ≈ 99.6% for TR1 and ≈ 98.5% for TR2 and so no correction for any trigger chamber inefficiencies is used.

4.6 TOF Details

The correct calibration of the TOF wall is crucial for reconstruction of tracks and for their identification. As discussed before, AUSCON starts with a hit on the TOF wall. The y position is determined from the difference in calibrated TDC up and down values. Therefore, the calibration of the y position is crucial for AUSCON. Similarly,
the PICD input parameter of the raw TOF resolution is based on the quality of the calibrations. In what follows we discuss the various details of the time of flight.

There were two calibrations done. The first one was done before PASS12 in order to have the y position calibrations and an adequate first timing calibration of the slats. This was part of my responsibility in this experiment. The y position at the TOF wall is simply given by the difference in times recorded by the top and bottom phototubes. Plotting this time difference versus the y position obtained independently by projecting the track to the TOF wall results in a straight line whose parameters are then used to convert time differences into y positions. The slope of this line is the inverse of the speed of light in the scintillators. A second calibration was done previous to PASS3, the particle identification pass. In the first pass, we typically calibrated when we changed angle setting or if something which could affect the timing happens, such as the beam being down for a day. Once a set of runs were selected to be calibrated, they were reconstructed with AUSCON and the TOF calibration program run on them. The values were stored in the database. Typically, an interval of about 100 runs separated calibration points. This can be a problem because of possible drifts. This was accounted for in the second calibration pass in which we calibrated the TOF wall about every 50 runs. Small (< 20ps) global shifts in timing were found run-by-run.

The slewing (or walk) effect is an important correction to the time of flight of a particle. The slewing correction is needed because two phototube pulses of different pulse height but exactly coincident in time cross a fixed discriminator level at different times. Pulses with larger signal height to fire the discriminator earlier than those pulses with lower pulse heights. It has been found that the correction to the time of flight is proportional to \( \frac{1}{\sqrt{\text{energy loss}}} \), [S+86] where \( \text{energy loss} \) is the energy lost in the hit TOF slat. While the average correction for a particle is typically about 5 to 10 ps, this has a large effect on the average resolution for the slat because it pulls particles on both sides of a \( \Delta \text{TOF} (= \text{TOF expected} - \text{TOF measured}) \) distribution toward zero and thus provides up to a 20 ps increase in the resolution relative to the raw, or uncorrected TOF.
4.7 GASC Details

In the various studies done, we have used the very handy feature of the PICD particle identification code which flags the various mass combinations. Because we want to find the GASC corrections, we need to identify particles another way. We identify particles as pions, kaons and protons if they satisfy only one mass hypothesis, i.e. their time-of-flight is at least $3\sigma$ away from the next closest mass hypothesis.

4.7.1 Threshold

A cell is considered as “fired” if its light output exceeds the threshold. Raising the threshold eliminates those kaons which may fire the GASC because of interactions or decay (into a $\mu^+$ or $\pi^+\pi^0$). However, it also labels pions which may not fire the GASC due to inefficiencies as kaons. Because the kaons and especially the $K^-$ are rare, this effect can constitute a significant fraction of the $K^-$s. It is difficult to correct for pion contamination. However, we can still correct if we throw kaons away. We therefore have chosen the threshold to be low, 0.5 photoelectrons.

4.7.2 Efficiency

The light yield efficiency of a cell strongly depends on where the particle is located in the cell. We determine the position in a cell by projecting the track to the mid-plane of the GASC with the plane perpendicular to the spectrometer axis. Less light is collected for pions which hit near the edge of the cell as opposed to the center. This was one of the motivations for the adjacent cell summing technique. Various tests measuring the light output characteristics were performed on individual cells in a test beam. Fig. 4-4 shows the photoelectron yield versus cell position along the $x$ directions. This variation complicates the GASC analysis considerably. We also need to consider how many photoelectrons a pion will create at the momentum which we start requiring GASC information. This momentum is approximately $1.8\text{ GeV/c}$ (depending slightly on the size of the magnetic field).

In Fig. 4-5 we show the photoelectrons as a function of pion momentum where
Figure 4-4: GASC light yield versus x position. The origin is the center of the cell.
the pions have been identified using the GASC information. An approximate shape of this distribution is given by [Gro90],

\[ N \sim 1 - \frac{1}{\beta^2 n^2}. \]

Superimposing this shape on the figure, we see a rather poor match (this is not a fit). Cole [Col92] observed a rather good match to the performance of the Cerenkov tanks of the CC complex. We expect that the inefficiencies, especially as a function of position in the cell, cause a distortion of this distribution which is difficult to characterize quantitatively. The variations in path length and the adjacent cell summing can complicate the observed response of the GASC. We note that the GASC starts firing at the threshold of about 1.5 GeV/c, as expected. At 1.8 GeV/c, the average number of photoelectrons emitted is about 12. Using Poisson statistics, the probability of measuring \( r \) counts when the average is \( \mu \) is

\[ P(r) = \frac{\mu^r e^{-\mu}}{r!}. \]

The probability of measuring no photoelectrons when the average is 8 is 6.1x10^{-6}. The probability of measuring 0 or just 1 photoelectron is just 8.0x10^{-5}. Since our threshold is 0.5 photoelectrons the probability of a pion not being identified because it does not produce a sufficient number of photoelectrons is extremely small. Despite the position dependent inefficiencies, we expect pion identification by the GASC to be extremely efficient.

### 4.7.3 Absorption

Fig. 4-6 plots the fraction of particles with BACK confirmation versus momentum for pions, kaons and protons within the BACK acceptance. Because the protons do not decay, their ratio indicates the particles lost between the TOF wall to the BACK counter. The loss comes from either interactions before the BACK wall, the multiple scattering out of the search window or a mis-positioning of the BACK wall. The
Figure 4-5: GASC light yield (in photoelectrons) versus momentum (GeV/c) for identified pions. The line drawn is an estimate of the expected shape of the distribution. This is not a fit. See the text for details.
multiple scattering is accounted for in the choice of search width (discussed below) and we assume that the survey positions are correct. The high momentum plateau is due to hadronic interactions. Cole [Col92] provides the radiation and interaction lengths for all the spectrometer media. The interaction length from the TOF wall (inclusive) to BACK counter is 10.2%. This corresponds well to the found ratio (see Fig. 4-6).

If one takes the protons which have BACK confirmation and multiplies by the decay factor for kaons of the same momentum and path length (from target to BACK counter),

$$\exp(-m_K \cdot L/(p \cdot c \tau)),$$

one duplicates the kaon curve. This indicates that the kaon distribution is explained by the same absorption as the protons plus their decay correction. Thus we can apply the same correction for absorption to all particles that use the BACK counter for particle identification. This correction is 1/0.9. Pions and kaons use the BACK counter for selected momentum ranges. We note that the kaon curve is consistently lower that the proton corrected kaon decay curve. We discuss the cause for this in the section on BACK details.

### 4.7.4 Misidentification

In this section we discuss problems with using the GASC for particle identification. In particular, we study the effects on kaon identification. There are similar effects with pions and protons, but because these are so much more abundant than kaons, and especially K\(^-\), we neglect the effects. As an example, a misidentification problem which adds 10% of the kaons to pions does not affect the pions significantly because pions are already about 5 times more abundant than kaons. On the other hand, an effect which adds 10% of the pions to kaons has a huge effect. K\(^-\)s are down by a factor of about 20 compared to \(\pi^-\)s. If we had 5 K\(^-\)s and 100 \(\pi^-\)s, a 10% misidentification rate would result in 15 K\(^-\)s and 90 \(\pi^-\)s: a 10% change for pions and a 200% change for the negative kaons! The size of any effect depends on the relative
Figure 4-6: Fraction of particles with BACK confirmation versus momentum (GeV/c).
abundances of possible contaminants.

With the help of simulations, we can identify the processes which cause kaons to be misidentified and correct for these losses. We therefore have chosen the GASC and particle identification parameters to reduce as much as possible the identification of other particles as kaons. Corrections for these effects depend in detail on the abundances and momentum distribution of the contaminants and are therefore complicated.

In using the GASC for particle identification, we can divide the particle identification corrections into two categories: 1) effects which cause true kaons to be called pions and, 2) effects which cause true pions to be called kaons. We need to determine the corrections for the first group and minimize the causes of the second category. We list conceivable effects for category 1.

a) electromagnetic interactions which produce particles above the GASC threshold, especially $\delta$ ray (or knock on electron) production.

b) hadronic interactions which produce particles above the GASC threshold.

c) decays to $(\mu, \nu_\mu), (\pi^+, \pi^0)$ which then fire the GASC.

d) a cell hit by a kaon is also hit by another particle which fires the GASC.

e) addition of an adjacent cell’s photoelectrons when the adjacent cell has been hit by a particle above the GASC threshold or has interacted in the GASC.

f) incorrect cell is pointed to and that cell was hit by another GASC firing particle.

We now list the conceivable effects for category 2.

a) a pion with both pion and kaon mass hypotheses hits a cell but does not fire because of inefficiencies.

b) a pion with both pion and kaon mass hypotheses decays or interacts before reaching the GASC and does not produce any light.
We note that some of the effects will be negligible once we require BACK confirmation. We will analyze these effects both with and without BACK counter verification to see how much an effect it is.

**Category 1, Item a and c**

As a particle traverses any medium, it loses energy via electromagnetic interactions with the medium’s electrons. If the incident particle and electron have a head on collision, one can have a large transfer of energy. Historically, these electrons are called delta rays.

The maximum possible energy transfer for a particle with speed, $\beta$, and $m >> m_e$, to an electron is given by

$$E_{\text{max}} = 2m_e\beta^2\gamma^2.$$ 

Any $\beta > 0.92$ particle can create a delta ray with sufficient energy to fire the GASC (use the thresholds found in Table 3.3). We can estimate the number of delta rays expected above the minimum firing energy, $E_{\text{min}}$ of 5.4 MeV. Fernow [Fer88] gives

$$N(E > E_{\text{min}}) = \Delta \left( \frac{1}{E_{\text{min}}} - \frac{1}{E_{\text{max}}} \right),$$

where

$$\Delta = 2\pi N_a r_e^2 m_e c^2 x / \beta^2 = 0.1535 x / \beta^2 \text{MeV cm}^2 / g.$$ 

Here $r_e$ is the classical electron radius, $N_a$ is Avagadro’s number, $x$ is the areal density (or $\rho \ast L$, $L =$ distance traversed, $\rho =$ mass density of medium). For the GASC aluminum tank front wall we have $x = 2.56 \text{ g/cm}^2 = 2.7 \text{ g/cm}^3 \times 0.9 \text{ cm}$ and for the Freon 12 we have $x = 1.97 \text{ g/cm}^2 = 4 \times 4.93 \text{ g/liter} \times 1 \text{ liter/1000 cm}^3 \times 100 \text{ cm})$. Thus we have

$$N(E > E_{\text{min}}) \approx 0.70 \frac{1}{\beta^2} \left( \frac{1}{5.4} - 0.98 \frac{1 - \beta^2}{\beta^2} \right).$$

The maximum number of delta rays ($\beta = 1$) is less than 1. Thus we expect delta ray contamination to be a small effect.
The above calculation is of course approximate. We must turn to simulations to give us a more quantitative answer. We performed a Monte Carlo calculation where we used a \((p, \theta)\) distribution approximating that obtained in central Si-Au collisions. The form of the distributions is not crucial. The result is that about 1.6\% of the kaons passing through the GASC and having BACK confirmation produce a delta ray above threshold (we have turned off decay so that the delta rays do not come from the decay products). Since we only use the GASC between 1.8 and 3.0 GeV/c, the momentum dependence of this effect is small. In our final simulation to determine particle identification efficiencies, we include delta ray production for completeness. However, if we now turn on kaon decay, we find that about 8\% of the kaons thrown produce light in the GASC. Subtracting off the contribution from kaons producing delta rays, about 6\% of the light produced arises from the decay muons. Since the kaons have momentum from 1.8 to 3 GeV/c, the decay muon typically has a momentum exceeding the GASC threshold (1.2 GeV/c for muons). The muons can also create delta rays. At most, 20\% of the muons will be BACK confirmed. We therefore expect the misidentification of kaons because of decay and delta ray production to be on the order of 3-4\%. This will be corrected for in the full efficiency study.

**Category 1, Item b**

As previously estimated, hadronic interactions should amount to about a 10\% effect. Here we are concerned with the frequency of a kaon interacting hadronically, producing light in the GASC, and still being BACK verified. We have no evidence of this occurring.

**Category 1, Item d, e and f**

This is difficult to determine from a simulation because it depends in detail on how the particle production characteristics of the data (i.e. \(p, \theta\) distributions and relative abundances of particles.) Because ARC [PSK92] events very accurately reproduce the E802/E859 data set for central Si-Au collisions, we have used this model to provide
events from which we estimate the effect of items d, e and f.

We define a double hit GASC cell as one in which at least two T3T4 vectors (status 120 or greater) point to it (a T3T4 vector is a well defined vector behind the magnet with T3, T4 and TOF hits). This is a generous definition of a double hit cell. For one thing, we do not check the track momentum or identity. We could, for example, disregard any particle with momentum less than 1.4 GeV/c because they would not fire the GASC unless they were electrons. Unfortunately, there are many "unless" scenarios. In Fig. 4-7 we display the fraction of time a cell has two hits as a function of cell number for various angle settings. We see that at the 5 degree setting we reach up to 18% of certain cells having double hits. If the effect was uniform over each cell, we would expect the distributions to be flat. However, we see that the effects are strongest on the beam side of the GASC. The \( \theta \) distribution drops with increasing \( \theta \) and so the probability of having a double hit decreases with increasing \( \theta \). We also observe the effect to be strongly spectrometer setting dependant, dropping a factor of 5 by the 24 degree setting.

The 18% effect for certain cells is the upper limit of this correction. We now use ARC events to determine the frequency of double hits which cause a misidentification. Since the frequency increases with multiplicity, we select ARC central events with impact parameter < 2 fm. This actually provides a more central trigger than the TMA cut used in the data. ARC events were put through the 5 degree spectrometer acceptance, passed through the detector Monte Carlo and the same analysis chain as the data. The average number of ARC particles per event was 3.6 with large fluctuations. We want to know how frequently a kaon will be called a pion because the particle to hit that GASC cell exceeded the threshold momentum to fire the GASC. Because relatively few kaons are produced, we examined protons because they are misidentified in the same manner as the kaons. We restricted the momentum range from 1.8 to 3.0 GeV/c, the range the GASC is used to identify kaons. We found that about \( \approx 4.5\% \) of the protons would be misidentified if GASC information were used. Of the small set of kaons present, the fraction misidentified was about 4%. About half of the misidentification resulted from the addition of the adjacent cell or cell's
Figure 4-7: Fraction of cells with double hits versus cell number for the 5, 14, 24 and 34 degree setting.
signal.

The numbers cited in the last paragraph were averages over the entire GASC. However, this effect is angle dependent and so we examine it cell by cell. Fig. 4-8 shows the cell-by-cell fraction of protons misidentified because of double hits and adjacent cell information being added. We note the strong dependence on cell number. Only cells 1 through 20 are shown because cells 1 through 10 and 31 to 40 are the top and bottom rows and the effect should be identical for both these rows. The same applies for the two middle rows. While this correction is derived from model results, it certainly brings us closer to the true correction. We estimate a systematic error of about 20% on this correction due to the model dependency and to geometry. The GASC is difficult to accurately survey. We have optimized its location in the simulation of the experiment to match the position obtained from the data. Mistakes in the cell's location result in differences in determining whether the adjacent cells be summed.

Another method is not to use any particle which had a double hit or had an adjacent cell's light output added. We then correct for the number thrown out on a cell-by-cell basis. While this method has the advantage of not being model dependent, it has the following drawbacks which preclude its use. We have noted that just from double hits, a peak correction of about 20% was obtained. If we threw away particles with double hits or adjacent cells being hit, we would lose up to 40% of the particles at the 5 degree spectrometer setting. This is a large fraction of our statistics in this momentum range. The second, more serious, problem is from inefficiency. The adjacent cell technique is used because of the GASC efficiency position dependence in a cell. The concern about not adding the adjacent cell's signal is that pions which hit the cell edges will not have as much signal and may be called kaons because the GASC did not fire. We try to avoid all effects which identify true pions as kaons because it is notoriously difficult to correct.
Figure 4-8: Fraction of ARC protons with p from 1.8 to 3.0 GeV/c misidentified using GASC information. Since the K⁺s bend in the same direction as the protons, we assume the same misidentification rate applies to them.
Category 2, Item a

Using Poisson statistics, we estimate a probability of $< 10^{-4}$ for a pion with momentum of 1.8 GeV/c not firing the GASC. This was based on the experimentally measured GASC response to identified pions. Therefore, the GASC is very efficient in identifying pions. If we assume that 1 pion out of every $10^{-4}$ does not fire the GASC, then assuming that there is 5 to 10 pions for every kaon yields a contamination to the kaons of 0.0005 to 0.001. This is negligible.

Category 2, Item b

We have thrown pions uniformly with momentum between 1.8 and 3.0 GeV/c. In our Monte Carlo simulation, we have turned on decay, hadronic interactions, multiple scattering and energy loss. An attempt to model the timing resolution was also implemented with the experimental TOF resolution of 120 ps being used. The fraction of pions which get identified as kaons is $<< 1\%$. Therefore, no pions which decay or interact in the spectrometer will be identified as kaons.

4.8 BACK Details

4.8.1 Efficiency

The efficiency is defined as the ratio of tracks passing through the GASC and through the BACK counter which have a hit in the search window on the BACK counter. The CC is conveniently located behind the BACK to allow such verification. Yuedong Wu has determined the BACK efficiency using tracks which are measured in the Cerenkov Complex [Wu92]. The efficiency depends on the size of the search window used. Three search windows were used: 1) the projected pad by itself, 2) the projected pad and pads above, below, to the right and to the left and 3) the projected pad and the surrounding 8 pads. Using E802 data and particles with momenta between 2 GeV/c and 5 GeV/c, the percentage efficiencies are given in Table 4.3. We estimate the amount of multiple scattering using the formula for the Gaussian approximation to
angular change, $\theta$ for a charge 1 particle with momentum $p$, velocity, $\beta c$ passing through a medium of thickness $x/X$ in units of radiation lengths [Gro90],

$$\Delta \theta = \frac{13.6 \text{MeV/c}}{\beta cp} \sqrt{x/X[1 + 0.2\ln(x/X)]}.$$ 

The number of radiation lengths corresponds to

$$x/X = 0.038 + 0.21 + 0.17 = 0.418,$$

corresponding to the TOF wall, GASC tank, and GASC freon, respectively. For a 2 GeV/c proton this corresponds to mean scattering angle of $\Delta \theta = 0.004$ radians. The distance between the TOF wall and BACK counter is about 300 cm and so the average scattering, $\delta$, in x or y, is $\delta = 300\text{cm} \ast \Delta \theta/\sqrt{3}$ or 0.7 cm. We again note that the pad size is 6 and 5 cm in x and y, respectively. Because of this multiple scattering it is better to take a search window larger than just the projected pad. Window type 3 is the obvious choice and indeed is what is used in the particle identification code to be discussed. We thus take the intrinsic BACK counter efficiency as 1.0.

Finally, a decay correction is needed for pions and kaons. If the BACK counter is used for particle identification, we apply the decay correction using the path length to the BACK counter (≈ 930 cm). Otherwise, we use the distance to the TOF wall (≈ 660 cm). Two cautionary notes are in order. BACK counter verification of a track does not necessarily guarantee that the particle passed through both the GASC and BACK counter. To wit, approximately 15% to 30% of kaons which decay to muons can have the muon verify on the BACK counter, thus falsely verifying the kaon. This means that the naive use of the decay correction would over-correct the number of

<table>
<thead>
<tr>
<th>Particles</th>
<th>Window Type 1</th>
<th>Window Type 2</th>
<th>Window Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$'s</td>
<td>83.1</td>
<td>98.5</td>
<td>99.4</td>
</tr>
<tr>
<td>$\pi^-$'s</td>
<td>83.4</td>
<td>98.9</td>
<td>99.7</td>
</tr>
<tr>
<td>protons</td>
<td>81.2</td>
<td>98.1</td>
<td>99.2</td>
</tr>
</tbody>
</table>

Table 4.3: Back Counter Efficiency.
kaons. However, if such a decay occurred before exiting the GASC, the GASC could fire and hence the particle would not be identified as kaon. The extent to which these two processes cancel each other is included in the Monte Carlo efficiency study.

Applying the decay correction to every kaon (pion) which is TOF identified assumes that every kaon (pion) which has decayed "disappears", i.e. is never reconstructed as a kaon (pion). This is certainly not the case. Indeed, the Monte Carlo indicates that approximately 7% of the identified kaons come from kaons which decayed in the spectrometer.

4.9 Reconstruction Efficiency

Particles decaying before and near to the TOF wall can be reconstructed. Because questions of reconstruction efficiency are linked with decay, multiple scattering and hadronic interactions, we cannot separate the individual factors. For this reason, we have chosen to use a global, momentum dependent global reconstruction efficiency correction. However, we have attempted here to get a handle on the relative sizes of various effects.

We have analyzed several effects which can cause misidentification of particles using the extended particle identification detectors. We note that some of these effects could be substantial (≈ 10%). Because of the complicated interplay between these effects, we use a Monte Carlo which includes these possibilities and use its output to determine the correction factors. We note that at some level, some of the effects cancel out. We observed in Fig. 4-6 that the kaons can be closely described by protons plus absorption plus a decay correction. This plot includes nothing else. Based on the earlier sections, we also estimate a 10% systematic uncertainty for the particles identified with the extended particle identification detectors. We note that this is in addition to the systematic errors arising from the normalization procedure and that this applies only for the range of momenta for which the extended particle identification detectors are used.

In Fig. 4-9 we show the final efficiencies for finding particles in the spectrometer.
as a function of species. All particles to be reconstructed were passed through the cross-section acceptance code. The data analysis chain then processed the simulated particles. Tracking chamber inefficiencies were estimated and applied to the simulated data. We use an 85% plane efficiency for T1 and 98% for T2 through T4. There is a few percent systematic error in the total reconstruction efficiency introduced due to the changes in T1 over the running period. We further estimate another 5% due to the fact that the hit multiplicity in front of the magnet is probably the dominant cause of tracking problems and we did not simulate this environment in our study. Thus all the reconstruction and particle identification efficiencies are accounted for. The Monte Carlo included the full contingent of physics effects such as decays, hadronic interactions, delta ray production and multiple scattering. The efficiencies thus include the loss from decay. Because of the convolution of all the effects in the reconstruction and particle identification efficiencies, we have not separated out the decay correction as was previously done. The efficiencies were evaluated by throwing particles at a specific momentum. We use a linear extrapolation between adjacent points to find efficiencies. The corrections applied are the inverse of the efficiency, which we now discuss.

The protons have a flat plateau of \( \approx 90\% \) at high momentum with the efficiency sharply falling for momentum \( \leq 800 \text{ MeV}/\text{c} \). Multiple scattering dominates at low momentum resulting in this drop. The pions have a slightly lower efficiency, due in part to the decay losses. The GASC information is required below 1.3 GeV/c and above 1.8 GeV/c. Anytime the GASC is used, further losses ensue. Above 1.8 GeV/c, one notes about a 10% drop in efficiency at 1.8 GeV/c compared to 1.5 GeV/c. This is because BACK counter confirmation is required above 1.8 GeV/c. Since the GASC amounts to a 10% interaction length, we observe the expected loss. For pions below 1.3 GeV/c, the BACK counter information is not used and hence we do not observe the same 10% loss.

The kaon efficiency mirrors that of the pions except for the behavior at 1.3 GeV/c. A much larger decay loss is consistent with the kaon decay constant, \( c\tau = 371 \text{ cm} \). In fact, dividing out by the decay correction results in approximately the same correction
Figure 4-9: Total efficiencies for identifying pions, kaons and protons claimed to be within the spectrometer acceptance. The loss from decays is included in this plot.
as for the protons below 1.8 GeV/c. We note that very low momentum kaons receive a large correction (a factor of 5 to 10). For all the species, the regions which require the largest correction are also the regions which dominate the systematics of fitting the $p_\perp$ distributions. The kaons are especially sensitive to the corrections obtained here.

We discuss the systematic errors involved in this correction procedure. A small (< 1%) error is made because we are applying an average decay correction and not using the pathlength for individual tracks. A more serious error ($\approx$2%) occurs in estimating the plane efficiencies. In particular, T1 has a history of problems and is crucial to the successful reconstruction of tracks. In the momentum region requiring the extended particle identification detectors, we estimate another 5% systematic error as discussed previously. Overall, to account for other effects difficult to correct for such as high hit multiplicities, we attribute a 5% systematic error to the reconstruction efficiency correction.

### 4.10 Summary of Systematic Errors

We discuss and summarize the systematic errors involved in the kaon analysis. These errors are phase space dependent. The use of GASC/BACK confirmation incurs a larger systematic error than if just TOF identification was required. Since the statistics at higher momentum are small, the total error is dominated by the statistical error. Also, it is not clear how these different errors affect the $dN/dy$ and inverse $m_\perp$ slopes. For example, the $dN/dy$ is not as sensitive to the high $m_\perp$ part of the spectra as the inverse slope is.

A large systematic error in $dN/dy$ occurs when using software centrality cuts. As discussed, we group runs until we have sufficient statistics to perform our cuts accurately. (Typically, this is 10 to 30 runs.) One concern is whether the centrality detector's performance changes over this short time span (this is about 1 to 2 days of running). However, if we do not have sufficient statistics, we will less accurately determine where the centrality cut is. We have analyzed central (as determined by
the TMA) Si+Au collisions using the following two methods: 1) determining the cut run-by-run and 2) determining the cut group-by-group (this is how our final results are obtained). In case 1) the statistics to generate the TMA threshold are poor but at least we can monitor run-by-run changes. In case 2), the statistics are great but we are clearly averaging the detector's behavior over a significant time period (1 or 2 days). The relative error on $dN/dy$ is given by the difference over the average of the sum. The relative error for the $K^+ dN/dy$ (inverse $m_\perp$ slope) averaged over rapidity is 4% (1%). The relative error for the $K^- dN/dy$ (inverse $m_\perp$ slope) averaged over rapidity is 3% (1%). We thus attribute a 4% (1%) systematic error to $dN/dy$ (inverse $m_\perp$ slope) due to our method of generating the software centrality cut.

The acceptance can have a systematic error in 1) the badslat correction and 2) the determination of the $\Delta\phi$ subtended. The correction for badslats is approximate and the edges of the acceptance affect the areas in phase space where spectrometer settings overlap. To test how sensitive we are to the choice of badslats and the range of accepted TOF slats, we have generated the cross-section for two cases 1) an acceptance used in our final results which includes badslats and accepts tracks within a TOF slat range of 20 and 150 and 2) an acceptance which ignores all badslats and accepts tracks within a TOF slat range of 17 to 160 (the maximum range). We have examined minimum bias Si+Al K$^+$ data. In order to isolate the angular dependence, we have plotted the differential yield as a function of $\theta$, the angle relative to the beam, for a slice in momentum. The difference in differential yield is typically less than 1% with a few points changing by as much as 1 to 2%. If we now estimate the effect on $dN/dy$ and inverse $m_\perp$ slope, we find the change in differential yield and inverse $m_\perp$ slopes is $< 1\%$ across our rapidity coverage. We thus do not assign a systematic error how we perform the acceptance. This is expected since we have few badslats overall and have little data from the ends of the TOF wall. However, the systematic error in determining the $\Delta\phi$ range is $\approx 5\%$.

Another systematic error can occur because of the varying $m_\perp$ coverage across rapidity. Because we do not have $p_\perp$ coverage to 0, an extrapolation is done to determine $dN/dy$ over the $p_\perp$ region where there is no data. There can be systematic
errors in \( dN/dy \) depending on how the data behaves at low \( p_\perp \). One way to estimate the systematic error on \( dN/dy \) is to fit with several functional forms which fit the data at higher \( p_\perp \) but behave differently at low \( p_\perp \). Three common fits are used to fit the differential yield:

- \( p_\perp \) fit, \( A e^{-p_\perp/T} \)
- \( m_\perp \) fit, \( A e^{-m_\perp/T} \)
- Boltzmann fit, \( A m_\perp e^{-m_\perp/T} \).

The \( p_\perp \) fit does a poor job fitting the kaons (\( \chi^2/d.o.f. \approx 4 \) compared to a \( \chi^2/d.o.f. \approx 1 - 2 \) for the \( m_\perp \) fit). A Boltzmann and \( m_\perp \) fit are comparable with the \( m_\perp \) doing slightly better in terms of \( \chi^2/d.o.f. \). The Boltzmann, however, turns over at low \( m_\perp \) and thus provides one extreme the \( dN/dy \) can take and still fit the data well. We have fit \( K^\pm m_\perp \) spectra over different rapidity slices using minimum bias Si+Al data. The deviations in \( dN/dy \) for \( K^+ \) and \( K^- \) are comparable and the average fraction deviation from the \( m_\perp \) \( dN/dy \) is shown in Table 4.4. The larger deviation at low rapidity is due to the larger \( m_\perp \) window over which we fit (see plots in first few pages of Chapter 6). For the Boltzmann fit over that large a range, it must reduce its intercept along the ordinate and hence decrease the \( dN/dy \) for that slice. We assign an average 3% systematic error for the extrapolation based on the errors in Table 4.4.

<table>
<thead>
<tr>
<th>Center of ( y ) window (0.2 wide)</th>
<th>( \frac{dN}{dy} m_\perp )</th>
<th>( \frac{dN}{dy} ) Boltzmann</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.050</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>0.042</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>0.038</td>
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<td>1.3</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>1.7</td>
<td>0.014</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: Average relative deviation in the \( dN/dy \) between a Boltzmann and \( m_\perp \) fit to minimum bias Si+Al K\(^\pm\) data.
Table 4.5: Summary of the systematic errors for the kaon analysis with comments as necessary. The total error is the sum of the errors added in quadrature. The total error in parenthesis is for data with rapidity $\geq 1.5$.

Finally, another rapidity dependent systematic error arises in the use of the GASC/BACK for extended particle identification. After a rapidity of about 1.5, all the kaon data requires extended particle identification and therefore includes the systematics in the GASC/BACK analysis. Using the values enumerated in the GASC analysis section, we estimate a 5% systematic error for rapidities of 1.5 and higher.

A summary of the systematic errors is given in Table 4.5 with comments. A total systematic error of $\pm 9\%$ on $dN/dy$ and of $\pm 5\%$ on the inverse $m_\perp$ slope is noted. We have estimated the total systematic error by adding the respective contributions in quadrature. Another method is to add their relative errors. We therefore expect the systematic error on $dN/dy$ to be between 9% and 17% and on the inverse $m_\perp$ slope to be about 5%.

4.11 Data Summary

The data is discrete, in units of runs. Four parameters characterize a run:

- Target: Au1, Au2, Au3, Al3, Al6, MT
- Spectrometer Setting: 5, 14, 24, 34, 44
- Magnet Field Setting: 0, 2, 4
- Magnet Polarity: A, B
<table>
<thead>
<tr>
<th>Angle</th>
<th>Au Events</th>
<th>K+</th>
<th>Au Events</th>
<th>K-</th>
<th>Al Events</th>
<th>K+</th>
<th>Al Events</th>
<th>K-</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>230</td>
<td>21.4</td>
<td>1900</td>
<td>49.8</td>
<td>140</td>
<td>4.5</td>
<td>550</td>
<td>6.5</td>
</tr>
<tr>
<td>14</td>
<td>230</td>
<td>18.7</td>
<td>240</td>
<td>7.5</td>
<td>240</td>
<td>13.0</td>
<td>320</td>
<td>7.9</td>
</tr>
<tr>
<td>24</td>
<td>54</td>
<td>4.4</td>
<td>140</td>
<td>7.3</td>
<td>110</td>
<td>9.9</td>
<td>270</td>
<td>10.9</td>
</tr>
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<td>22.6</td>
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<td>4.2</td>
<td>300</td>
<td>22.8</td>
<td>300</td>
<td>4.4</td>
</tr>
<tr>
<td>44</td>
<td>62</td>
<td>14.7</td>
<td>70</td>
<td>3.2</td>
<td>170</td>
<td>14.1</td>
<td>170</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 4.6: Number of SPEC events (x10^3), K^+(x10^3) and K^-(x10^3) for Au and Al targets.

The 0 field runs are used for calibrating the position of the detectors and for drift time calibrations. A typical run consist of ≈ 40,000 events and fills one 9 track tape. In E859, we used two targets, Al and Au. We also took runs with no target in place to estimate the contribution due to non-target interactions.

In Table 4.6 we summarize the total number of SPEC events at various angle settings which were included in this analysis. Optimally, we would like equal statistics for each angle setting, between each target and between K^+ and K^-, because in any comparison, we are always limited by the lowest statistics measurement. We have tried to accomplish this. As seen in Table 4.6, we have achieved this at some level with the large statistics for the 5 degree spectrometer setting originating from the $\phi$ data set.
Chapter 5

Cross-Sections and Yields

Data from particle and heavy ion experiments at relativistic energies are commonly presented as Lorentz invariant differential yields, $\frac{1}{\sigma_{\text{trig}}} E \frac{d^{3}N}{dp}$. Since we assume azimuthal symmetry, this is a function of two variables. Two common sets of variables, and the ones used in presenting the data in this thesis, are $(y, p_{\perp})$ and $(y, m_{\perp})$. For presentation purposes, one plots the transverse variable ($m_{\perp}$ or $p_{\perp}$) for slices of the longitudinal variable ($y$).

Although the concept of the cross-section is simple, the actual application to experimentally measured yields is complex. Complications occur because of our desire to select events based on the centrality of the collision. To facilitate an understanding of the issues, I will provide a simple derivation of the cross-section and use a concrete example in presenting the mechanics of generating a cross-section. This is a detailed business and in the name of clarification and future time savings, we present the details. We also discuss the mechanics of determining the software centrality cuts and the acceptance.

Calculating cross-sections has been the focus of numerous theses in the E802/E859 collaboration. The first cross-section code was written by Martin Sarabura [Sar89]. Several years later, Charles Parsons [Par92] completely rewrote the code and embedded it in the CERN standard analysis program, PAW (Physics Analysis Workstation) [B\textsuperscript{+}89b]. This is the interface for the code used in this analysis. It is upon the software structures he originally implemented that we have modified and optimized
various parts for application to E859. A review of this code, complete with statistical error analysis can be found in [SMRZ92]. A useful note on the cross-section analysis can be found in [D+89].

5.1 Introduction

A cross-section quantifies the probability of a collision occurring between two particles for which there can be several outcomes. In other words, the cross-section (or probability) can be separated into outcomes just as we separate the outcomes of a coin toss into orthogonal categories: heads or tails. The simplest breakdown of cross-section is into elastic and inelastic parts. These are called partial cross-sections for obvious reasons. The inelastic partial cross-section can be broken down even further depending on the type of particle produced. In this thesis, we will be showing partial inelastic cross-sections for producing particles such as $K^\pm$ and $\Lambda$. We note that the cross-sections discussed are even more restrictive by requiring the conditions on the centrality of the event producing a certain type of particle.

We will also be discussing the idea of a cross-section for producing a certain type of event. With our event characterization detectors, for example, we measure the centrality of an event with the TMA. We could then ask what is the cross-section (or probability) of getting an event with a TMA multiplicity greater than some level. In practice, we typically want to know the cross-section (or probability) for producing an event with a TMA multiplicity in the upper 7% of the minimum bias TMA distribution.

5.2 Cross Section Initiation

Applicable to particle production in general, we would like to make this discussion concrete and so we take the specific example of $K^+$ production. Let $\sigma_{K^+}$ be the cross-section for producing a $K^+$ in an AA collision. Since the collision is inelastic, there is a portion of $\sigma_{K^+}$ which corresponds to the probability of producing a $K^+$
with momentum \( p \) (in a window \( \Delta p \)) in a solid angle \( \Delta \Omega \) about the angle \( \theta \). We call this portion \( \Delta \sigma_{K^+} \). The differential cross-section is then defined as

\[
\frac{d^2 \sigma}{dpd\Omega} = \lim_{\Delta p, \Delta \Omega \to 0} \frac{\Delta \sigma_{K^+}}{\Delta p \Delta \Omega}
\]

as \( \Delta p, \Delta \Omega \to 0 \). \( \sigma \) is clearly a function of \( p \) and \( \theta \).

While we could readily use this formulation of the differential cross-section, its values are frame dependent. The quantity,

\[
E \frac{d^3 \sigma}{d^3 p},
\]

however, is easily verified to be Lorentz invariant. The Lorentz invariant differential cross-section does not change in shape or magnitude between frames, it just gets shifted along the rapidity axis.

We simply list the following definitions and relations between variables. A nice derivation of these and other kinematic relations can be found in [Han90]. Taking the beam axis to be the \( z \) axis with \( \theta \) the zenith and \( \phi \) the azimuthal angles, we have

\[
p_\perp = \sqrt{p_x^2 + p_y^2},
\]

\[
p_z = p \cos(\theta),
\]

\[
m_\perp = \sqrt{p_\perp^2 + m^2},
\]

\[
y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z},
\]

\[
m_\perp dm_\perp = p_\perp dp_\perp,
\]

and

\[
dp_x dp_y dp_z = E p_\perp dp_\perp dy d\phi.
\]

We thus can write

\[
E \frac{d^3 \sigma}{d^3 p} = \frac{d^3 \sigma(y, p_\perp, d\phi)}{p_\perp dp_\perp dy d\phi}.
\]
We will always assume azimuthal symmetry and integrate over $\phi$. The invariant differential cross-section becomes

$$\frac{d^2\sigma(y, p_\perp)}{2\pi p_\perp dp_\perp dy}.$$ 

Alternatively, we can write the cross-section as

$$\frac{d^2\sigma}{2\pi m_\perp dm_\perp dy}.$$ 

Because of the equivalence of the denominators, the two expressions are identical: they just allow one to plot data with different variables. In the discussion which follows, we will use $(y, p_\perp)$ for our variables, keeping in mind that we could have also used $(y, m_\perp)$.

We now have the equations we need. In the next section, we discuss how to calculate the cross-section from our experimental quantities.

### 5.3 Deriving the Cross Section

As discussed, the cross-section, $\sigma$, quantifies the probability of two particles interacting. It has units of area. A heuristic derivation of it is useful. We consider the case of a beam of particles incident on a thin slab of target material of area $S$, and thickness $d$. This is identical to the true experimental conditions. The total cross-section can be thought of as an effective area presented by the target nucleus. The larger the total cross-section, the larger the effective radius and the more probable an interaction. If $N$ is the number of target nuclei, then the total effective area is just $N \sigma$. Note that this assumes that there is no shadowing of the different target nuclei. This requires that $N \sigma / S$ is small. This number is just the probability, $P$, that an incident beam particle will hit the effective area. In this experiment, the largest interaction rate target was an aluminum 6% target. Most of the data, however, were taken with a 3% target. The 3% represents the probability of beam interacting with the target. Hence, the requirement that this probability is small is satisfied. With
$N_{\text{beam}}$ incident beam particles, we expect $N_{\text{beam}} P$ events of interest. If $\sigma$ is the $K^+$ production cross-section, we would expect $N_{\text{beam}} P K^+$s to be produced.

We now substitute in for some of the variables. Since $N$ is the number of target nuclei in the slab,

$$N = n S d,$$

where $n$ is the number density of target nuclei, which is related to $\rho$, the mass density, by

$$n = \rho N_{Av}/A'.$$

$N_{Av}$ is Avagadro’s number ($6.022 \times 10^{23}$) and $A'$ is the molar mass (atomic weight in grams/mole) of the target material. Substituting in for $P$ yields

$$P = \rho N_{Av} d \sigma/A'.$$

Here, $\rho d$ is the mass per unit area of the target, or $t$, in g/cm$^2$. We have measured this for each target. Therefore,

$$P = t N_{Av} \sigma/A'.$$

The number of interesting events is then

$$N_{ev} = N_{\text{beam}} t N_{Av} \sigma/A'.$$

For $K^+$ production, the L.H.S would simply be the number of $K^+$s in a $(y, p_\perp)$ bin and the $\sigma$ would be the cross-section for producing $K^+$s in that $(y, p_\perp)$ bin (which we have called $\Delta \sigma_{K^+}$). In the experiment, we measure the left hand side of this equation and then invert it to get the desired $\sigma$. Thus,

$$\Delta \sigma_{K^+}(y, p_\perp) = \frac{N_{K^+}(y, p_\perp)}{N_{\text{beam}} t N_{Av}} \frac{A'}{A'}.$$

In the following sections, we describe the quantities on the R.H.S of this equation.
5.4 Cross-section Details

Let us return to our original equation for the Lorentz invariant differential cross-section,
\[
\frac{d^2\sigma}{2\pi p_\perp dp_\perp dy}.
\]

We store information in histograms which have some finite bin size. Therefore, the differentials in the above equation become bin widths, signified by \(\Delta\). We continue our example of determining the cross-section for \(K^+\) production. We have
\[
\frac{d^2\sigma}{2\pi p_\perp dp_\perp dy} \rightarrow \frac{\Delta\sigma_{K^+}}{2\pi p_\perp \Delta p_\perp \Delta y},
\]

where, as before, \(\Delta\sigma_{K^+}\) is the cross-section for producing a \(K^+\) in a \((y, p_\perp)\) bin. Using the expression for \(\Delta\sigma_{K^+}\), we have
\[
\frac{d^2\sigma}{2\pi p_\perp dp_\perp dy} = \frac{N_{K^+}(y, p_\perp)}{2\pi p_\perp \Delta p_\perp \Delta y N_{\text{beam}} \ell N_{Ao}} \frac{A'}{A'}.
\]

Let us briefly describe the factors.

- \(N_{K^+}(y, p_\perp)\) is the total number of \(K^+\) in this \((y, p_\perp)\) bin. We discuss this further below.

- \(N_{\text{beam}}\) is the number of beam particles for which the data acquisition was active.

- \(\Delta y, \Delta p_\perp\) are the bin widths in the \((y, p_\perp)\) histograms used to store the run-by-run information. (They are set to 0.05 and 0.05 GeV/c, respectively.)

5.4.1 \(N_{K^+}(y, p_\perp)\)

We include a special section for this quantity because of the several important and sizeable corrections which are used in determining this number. This discussion is completely general but we use the example of a \(K^+\) for concreteness.

\(N_{K^+}(y, p_\perp)\) is the total number of \(K^+\) in the \((y, p_\perp)\) bin. The number of \(K^+\)s we measure, however, is only for those which fall inside the solid angle coverage of
our spectrometer. We lose some fraction of these due to decay, absorption, detector inefficiencies and effects due to cuts in reconstruction and particle identification algorithms. Each reason requires a correction to the number of $K^+$s. I will first write down the expression for $N_{K^+}(y,p_L)$ in terms of the number found and then explain the corrections. Please note that all corrections are done on a particle by particle basis and not a bin by bin basis. This is why we sum over all found particles. While the $(y,p_L)$ bins were chosen small so that the difference between these two methods is small, wherever possible we do things exactly rather than in an average way (as making corrections bin by bin does).

$$N_{K^+}(y,p_L) = \sum_{i=1}^{N_{\text{found}}(y,p_L)} \frac{1}{(\text{phi.accept}_i \times \text{decay}_i \times \text{rec.eff}_i \times \text{ypt.accept}_i \times \text{pid.eff}_i)}$$

- $N_{K^+}^{\text{found}}(y,p_L)$ is the raw number of $K^+$ in the $(y,p_L)$bin.

- $\text{phi.accept}$ is the $\phi$ coverage of the spectrometer for a given $p$ and $\theta$. Since we have integrated over $\phi$ in our expression for the cross-section, each $K^+$ detected must then be scaled by $\frac{2\pi}{\Delta\phi}$.

- $\text{decay}$ is the correction due to the decay of the $K^+$. For a particle with mass, decay time, momentum, and pathlength through the spectrometer of $m$, $\tau$, $p$, $L$, respectively, we expect $e^{-\frac{mL}{\tau p}}$ to decay before reaching the TOF wall (or BACK counter). We therefore correct by the inverse of this quantity. This correction reaches a maximum of 10 for low momentum kaons.

- $\text{rec.eff}$ is the correction for reconstruction inefficiencies caused by detector problems, multiple scattering, and mismatches between connecting the vectors on each side of the magnet and is tracking code dependent. We have chosen AUSCON [Rot94] for tracking and have corrected for the momentum and multiplicity dependence. See Section 4.9 for the details.

- $\text{pid.eff}$ is the correction for particle misidentification. For example, a certain fraction of particles do not deposit sufficient energy in the TOF wall and so are
discarded because it is thought their timing will be wrong.

- *ypt accept* is a correction due to the possibility that a \((y, p_\perp)\) bin may not fully be in the spectrometer’s acceptance. This is discussed more in detail in the section on acceptance. It only applies to bins on the edge of the acceptance. For the data presented here, we set a conservative requirement that 90% of the \((y, p_\perp)\) bin be in the acceptance.

We conclude by noting that the reconstruction efficiency, particle identification efficiency and decay are not necessarily disjoint. We have used a Monte Carlo program to combine these effects into one correction factor. The correction factors for each species are shown in the next chapter.

### 5.5 Cross-sections or Yields?

We have discussed in detail all the ingredients needed to form the invariant cross-section. Ironically, we now discuss the reasons why the cross-section is not necessarily the most useful or accurate way of merging the data. Indeed, data obtained with a trigger are almost always presented as invariant yields rather than as invariant cross-sections. The two are very closely related. This arises from the desire to present data of different centralities. We detail what this means below.

Because nuclei have significant sizes compared to nucleons (about 3-5 fm), collisions can occur over a range of impact parameters. If we have no way of determining the impact parameter of a collision, we will be observing an average over all impact parameters. Since one of the goals of relativistic heavy ion collisions is to create a large interacting system, it is useful to be able to select events where we know that all the projectile nucleons interacted with as many target nucleons as possible. This, of course, occurs at zero impact parameter. Intuitively, we expect the greatest particle production for the collisions with the most participants in the collision. Since the number of TMA hits is proportional to the number of produced particles, we anticipate that high TMA multiplicity corresponds to small impact parameter collisions.
We therefore select (i.e., cut on) events based on the TMA multiplicity. We have defined "central" events to be those events with a TMA multiplicity in the upper 7% of the TMA distribution. It is determining this 7% level that is the problem. In model calculations, a hard cut on events with a multiplicity in the upper 7% of the minimum bias distribution does indeed select low impact parameter events. However, the cut in impact parameter is rather broad and not a hard cutoff. This has implications in comparing to models. Typical TMA distributions are shown in Fig. 5-1.

With this selection criteria, we can now generate the cross-section according to the steps above. The only number that would change would be $N_{K^+}(y, p_{\perp})$ because we have reduced the number of events we use to count up the $K^+$s. In fact, the number of events passing the criteria is very sensitive. For example, if one changes the TMA multiplicity level from 7% to 6%, the number of events changes by 13%, as expected ($|0.06 - 0.07| = 0.14$). This means that the cross-section would change by 13%. But a change in the fraction of cross-section from 7% to 6% amounts to a change in TMA threshold multiplicity from 110 to 112: just two particles! Such changes in the TMA multiplicity level are likely and indeed are observed. This means that the cross-section is highly sensitive to the hardware. Of course, this is extremely undesirable because it introduces large, unknown systematics in merging data from many runs. Please note, however, that for minimum bias data there is no restriction in the TMA multiplicity and so merging cross-sections works.

In the same data set mentioned above, one should also note that while the number of events with TMA multiplicity above the set level changed rapidly with small changes in the set level, the number of $K^+$ selected per event above the TMA level changed by less than 1%! The reason is that events with a TMA multiplicity near the 7% level are very similar in their particle content and track multiplicity. So while the cross-section may fluctuate drastically with small variations in the TMA level the number of produced particles per event, or yield, exceeding the TMA level experiences very little change. Therefore, when it comes to merging data with software cuts on the event characterization detectors, merging a quantity which depends on the number of particles per event satisfying the cut is much more accurate than merging
Figure 5-1: TMA multiplicity distribution and the upper 7% cutoff for an Au 1% and Al 3% target. These distributions are target-out subtracted.
cross-section. The experimental conditions for which the yield is evaluated is known as a trigger.

5.6 The answer: yields

We define the Lorentz invariant differential yield as,

$$\frac{d^2 n(\text{trigger})}{2\pi p_\perp dp_\perp dy} = \frac{1}{N_{ev}(\text{trigger})} \frac{N_{K^+}(y, p_\perp, \text{trigger})}{2\pi p_\perp \Delta p_\perp \Delta y}.$$  \hspace{1cm} (5.1)

From our discussion of the Lorentz invariant cross-section, we readily see that this expression is also Lorentz invariant. It contains a ratio which changes little with the software cut (or trigger) on an event characterizing detector like TMA or ZCAL. The numerator is the number of K+ for those events satisfying the trigger in the \((y, p_\perp)\) bin and \(N_{ev}(\text{trigger})\) is the number of events satisfying the trigger. The definition is very similar to the cross-section and we could immediately use it except we do not know \(N_{ev}(\text{trigger})\).

The reason for not trivially knowing \(N_{ev}(\text{trigger})\) arises from how we trigger. As an example, let us take a run where we trigger online with SPEC and cut on the TMA multiplicity offline. The physics is in the cut on multiplicity. However, because we have only taken events which have a particle in the spectrometer (SPEC triggering), the number of events recorded is not \(N_{ev}(\text{trigger})\). \(N_{ev}(\text{trigger})\) in this case is the number of events which exceed the TMA threshold. We have available only those events which pass the TMA cut and have a particle in the spectrometer. There is no easy way to start with this latter number to obtain \(N_{ev}(\text{trigger})\). Note that if we just took data with the TMA hardware trigger, without SPEC, we could apply this formula directly. Thus the SPEC trigger requires us to determine \(N_{ev}(\text{trigger})\) in a different way. In what follows, we perform some manipulations to show how to find \(N_{ev}(\text{trigger})\).

Just as we derived the cross-section for particle production, we see that the cross-
section for a chosen trigger condition is

\[ \sigma(\text{trigger}) = \frac{N_{\text{ev}}(\text{trigger})}{N_{\text{beam}}} \frac{A'}{tN_A}. \]

We now substitute this into equation 5.1 to get

\[ \frac{d^2n(\text{trigger})}{2\pi p_L dp_L dy} = \frac{1}{\sigma(\text{trigger})} \frac{N_{K^+}(y, p_L, \text{trigger})}{2\pi p_L^2 \Delta y N_{\text{beam}} tN_A} A'. \]

The right hand side looks familiar and the above can be written as

\[ \frac{d^2n(\text{trigger})}{2\pi p_L dp_L dy} = \frac{1}{\sigma(\text{trigger})} \frac{d^2\sigma(\text{trigger})}{2\pi p_L dp_L dy}. \]

The only obstacle now is how to determine \( \sigma(\text{trigger}) \).

5.6.1 \( \sigma(\text{trigger}) \)

Our method for determining \( \sigma(\text{trigger}) \) is to first decide what fraction of the cross-section we want as a software trigger. The two software triggers used in this thesis are 1) a centrality trigger cutting on the upper 7% of the TMA distribution and 2) a peripheral trigger cutting on the upper 50% of the ZCAL distribution. Once we decide upon this fraction, \( f \), we have

\[ \sigma(\text{trigger}) = f\sigma(\text{minimum bias}). \]

Our minimum bias trigger, as previously described, is called INT. \( \sigma(\text{minimum bias}) \) is just

\[ \sigma(\text{INT}) = \frac{N_{\text{ev}}(\text{INT})}{N_{\text{beam}}} \frac{A'}{tN_A}. \]

In a run we take about 1000 INT triggers. Thus, for one run, or a set of combined runs with the same target, we can calculate \( \sigma(\text{minimum bias}) \). There are two cautionary notes. The first is that there is a significant amount of non-target material (about 1% of an interaction length) with which the beam particle can interact before hitting the
target. The two beam counters (BTOT and BTOF) constitute $\approx 1\%$ of an interaction length. This “target-out” rate is determined by taking INT triggers with no target in the target holder. We call this rate, $R_{\text{out}}^{\text{target}}$ and it is defined simply as

$$R_{\text{out}}^{\text{target}} = \frac{N_{\text{ev}}(\text{INT, target - out})}{N_{\text{beam}}}.$$  

The “target-in” rate is similarly define. We thus have

$$\sigma(\text{INT}) = (R_{\text{in}}^{\text{target}} - R_{\text{out}}^{\text{target}}) \frac{A'}{tN_A}.$$  

The second caution regards which target-out runs to use for which target-in runs. The INT trigger relies heavily on the Bull’s Eye counter threshold as discussed in the beam counter section of the experimental setup. This threshold can drift or it can be set wrong. In an extreme case, the target-out rates can change almost a factor of 2. Both target-in and target-out runs will both have the same variation if the target-out runs are near in time to the target-in runs. We have done this to the extent that the empty target runs are available.

Table 5.1 shows $\sigma(\text{INT})$ for each of the different targets. For comparison, Parsons [Par92] finds $\sigma(\text{Au}) = 3780$ mb and $\sigma(\text{Al}) = 1490$ mb. Bloomer [Blo90] finds $\sigma(\text{Au}) = 3822$ mb and $\sigma(\text{Al}) = 1423$ mb.

In Fig. 5-2 we plot the group-by-group determination of $\sigma(\text{INT})$ with the average given in the table superimposed. Each group was selected so that a sufficient number of INT triggers were available for determining the cross-section. The cross-section is independent of target thickness, and so different interaction rate targets should give the same cross-section if we know their thicknesses accurately. We note the stability of Aluminum and the Au 1\% cross-section. However, the Au 2\% target is systematically different and the Au 3\% has significant scatter. We note that the Au 1\% data were all taken in one week whereas the Au 3\% consist of Feb91 and Mar92 runs. A variation in the definition of INT could cause such fluctuations but we would expect Au3\% runs within one running period to be consistent. We can only explain the shift in Au2\% in a mismeasurement of the target thickness. Fortunately, we do not use any Au2\%
<table>
<thead>
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<th>Target</th>
<th>Thickness (g/cm$^2$)</th>
<th>$\sigma(INT)$ (millibarns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au1</td>
<td>0.944</td>
<td>3659</td>
</tr>
<tr>
<td>Au3</td>
<td>2.939</td>
<td>3941</td>
</tr>
<tr>
<td>Al3</td>
<td>0.817</td>
<td>1438</td>
</tr>
<tr>
<td>Al6</td>
<td>1.63</td>
<td>1430</td>
</tr>
</tbody>
</table>

Table 5.1: Minimum bias cross-section for the targets.

in this analysis. The variation in the Au 3% indicates another 5% systematic effect.

Because variations in the Bull's Eye threshold affects the definition of an INT trigger, we have decided to fix $\sigma(INT)$ at 3800 mb. This is between the averages obtained for the Au 1% and Au 3% target and also consistent with previous analyses. Because the Al target interaction cross-section is consistent between the Al 3% and Al 6% targets and also with previous analyses, we have used the measure $\sigma(INT)$ of 1430 mb.

After choosing the fraction, $f$, and now knowing $\sigma(minimum\ bias)$, we can find $N_{ev}(trigger)$ via

$$N_{ev}(trigger) = f\sigma(INT) N_{beam} \frac{tN_{Au}}{A'}.$$  

And so we have our final expression for the Lorentz invariant differential yield,

$$\frac{d^2n(trigger)}{2\pi p_\perp dp_\perp dy} = \frac{N_{K^+(y,p_\perp,trigger)}}{2\pi p_\perp \Delta p_\perp \Delta y} \frac{1}{f\sigma(INT) N_{beam} tN_{Au}} \frac{A'}{A'^{A}}.$$  

In terms of experimental quantities, we can replace $\sigma(INT)$ by the rates we measure and obtain

$$\frac{d^2n(trigger)}{2\pi p_\perp dp_\perp dy} = \frac{N_{K^+(y,p_\perp,trigger)}}{2\pi p_\perp \Delta p_\perp \Delta y} \frac{1}{f(R_{out}^{target} - R_{target}^{target}) N_{beam}}.$$  

We use the data to fix the target-in minus target-out rates (i.e. we fix the cross-section for the targets). The user chooses $f$ and the other quantities are measured.
Figure 5-2: Cross-section for INT triggers for various targets. Each point represents 5 to 10 runs. The arrows show the average value used in this analysis.
5.7 Determination of ‘Central’ and ‘Peripheral’

The only remaining item in generating the invariant differential yield is how to find the desired level for the TMA or ZCAL. The method is described in detail in [SMRZ92] and so will not be repeated here. The method relies on having a sufficient number of INT triggers. In order to achieve this, we have grouped the runs so that each group has at least 5000 INT triggers. We then find the TMA and ZCAL cuts for each group and store these. As we run through the data, the cuts applied for the TMA or ZCAL are done group by group. We show in Fig. 5-3 (and Fig. 5-4) the TMA (and ZCAL) level for the 7% (and 50%) central (and peripheral) cut as a function of group for the Al target. We note the drop in energy cut for several of the Al 3% runs. The runs are for the 5 degree spectrometer setting. At this setting, the beam pipe actually passes through the edge of the magnet yoke. To reduce the amount of material removed from the magnet yoke, a smaller beam pipe is used at this setting. The effective opening angle from the target to ZCAL decreases from 1.5 degrees to about 0.8 degrees. This essentially collimates the forward going energy and results in a smaller response as compared to other angle settings. A smaller response mimics a more central collision, where we expect less forward going energy. Since the rate of low energy ZCAL events is artificially increased, the energy at which we reach 50% of the cross-section is less. This explains the drop in threshold ZCAL energy for these runs.

5.8 Acceptance

The acceptances were generated on a run-by-run basis using a procedure developed by Charles Parsons [Par92]. A description of how to generate and use the acceptances is given in detail in [ZP92]. We therefore do not go into detail except to describe a few upgrades to the method found in [ZP92] and to explain how the GASC and BACK counter affects the acceptance.

For this analysis several modifications were made because of the addition of the two
Figure 5-3: TMA 7% threshold multiplicity as a function of Al 3% and AL 6% group-by-group.
Figure 5-4: ZCAL 50% peripheral energy threshold level as a function of Al 3% and Al 6% groups.
trigger chambers in E859. In order to incorporate these chambers into the acceptance, a scheme was developed in the Ph. D. thesis of Dave Morrison [Mor94]. It uses the detector size and location to determine the acceptance. This is an improvement because we had previously generated the acceptance boundary using the data as a guide. For consistency, geometry used is identical to that used by the reconstruction program. The improved accuracy of this method affects the low $p_L$ acceptance as well as the correction for bad TOF slats.

If we assume that the Henry Higgins' field can be approximated by a field of strength $B$ (Tesla) in a box of width $L$ (meters), the ideal dipole approximation, we have

$$\theta_{\text{bend}} = 0.3 q B L / p,$$

where $q$ is the particle's charge and $p$ the particle's momentum in GeV/c. We define $\theta_{xz}$, the angle of the momentum projected to the x-z plane relative to the spectrometer axis, as

$$\theta_{xz} = \sin(\theta_{\text{bend}}) \cos(\phi) - \theta_{\text{spectrometer}}.$$

We plot $\theta_{\text{bend}}$ vs $\theta$ in Fig. 5-5. The edges of the data are caused by various detector boundaries in the spectrometer. We also plot the hard boundaries expected for the detectors. These boundaries are determined by the location in $z$ of the detector and its size. We observe that they match well. This plot is useful in showing how each chamber contributes to the acceptance. We note that the lower left vertical boundary is caused by the first TOF slat. The data shown are from several E859 runs at the 14 degree spectrometer setting.

As discussed, TR1 restricts the acceptance of the spectrometer. Since TR1 hits are not required for reconstruction, we can still find particles outside TR1's acceptance. This explains the data shown in the acceptance plot. However, kaons found outside of TR1's acceptance could not be used because the LVL2 trigger was oblivious to them. We note that the high momentum particles near the beam side (negative $\theta$) are greatly affected. At the 5 degree spectrometer setting, where the particle spectra are the stiffest, up to 50% of the particles which bend toward the beam fall outside
of TR1's acceptance. TR2 has no affect on the total acceptance.

While the boundaries of the polygon shown in Fig. 5-5 determine the low $p_\perp$ edge of the acceptance, the particle identification code determines the upper momentum cutoff because we are only able to unambiguously identify particles up to a given momentum. This limit is particle dependent and depends on whether one is using the extended particle identification capabilities. Using the GASC and BACK counter, we can distinguish pions and kaons up to 3 GeV/c. Pions fire the GASC at about 1.5 GeV/c and kaons at 5.0 GeV/c. The reason we cannot distinguish kaons and protons up to 5 GeV/c is because neither fire the GASC.

To include the GASC into the acceptance several factors have to be considered. The first is that the GASC does have a smaller acceptance than the TOF wall. However, the particles which hit the TOF wall but miss the GASC are primarily low momentum particles which bend significantly in the magnet. Fig. 5-6 shows the TOF slat distribution for all fully reconstructed (called “status 255”) tracks. We have used the 5 degree (both magnet polarities) data here because the GASC is most important at this angle setting. The shaded histogram shows the distribution for the same set of tracks but requiring that they are within the GASC’s acceptance and BACK verified. We observe that requiring GASC and BACK hits reduces the TOF slat range from [17,160] to [19,151]. Are we therefore throwing away kaons above $p > 1.8$ GeV/c (when we start using the GASC) which hit the TOF wall but not the GASC?

Fig. 5-7 indicates the momentum distribution as a function of TOF slat for all fully reconstructed tracks. We see that the maximum momentum of a particle hitting these slats is less than 1.8 GeV/c. A particle must have momentum of at least 1.8 GeV/c to use the GASC to distinguish between pions and kaons. Therefore, we will never be called upon to provide GASC/BACK confirmation for those tracks which hit the TOF wall but miss the GASC/BACK system. We can thus just use the standard acceptance generated for the TOF wall but with an upper momentum cutoff determined by the GASC/BACK limit. For electrons and pions, however, the smaller GASC acceptance will have a significant affect. A different analysis is required for extended particle identification for these particles.
Figure 5-5: Data from several 14 degree runs plotted in variables defined in the text. The solid lines are labelled indicating the detector responsible for the boundary.
Figure 5-6: The solid line is the TOF slat distribution for fully reconstructed tracks at the 5 degree spectrometer setting (both magnetic field polarities). The shaded histogram is the same but requiring GASC and BACK confirmation. Vertical lines are drawn at slat 19 and 151.
Figure 5-7: Momentum (GeV/c) versus TOF slat for the same data as in the previous figure. The vertical lines are drawn at slats 19 and 151. The horizontal line indicates \( p = 1.8 \text{ GeV/c} \). Note that above slat 151 and below slat 19 there are extremely few (\(< 1\)\%) tracks (hence kaon candidates) which would require GASC or BACK verification. We can therefore use the TOF acceptance.
Throughout the run, diagnostic plots would occasionally show TOF slats missing. These slats malfunctioned because of loose connections to a discriminator. They consequently would show fewer hits than their adjacent cells. Such bad slats were traced by checking if the number of hits on a given slat was more than 3 sigma away from one half of the average of adjacent slats (taking into account that the double slats had twice the number of hits as single slats). Another condition on determining bad slats was to require that at least 0.04% of the 255 status tracks hit a slat. This number was determined empirically by examining the TOF distribution for a series of runs with all slats working. In order not to be affected by statistics, we accumulated 10000 status 255 tracks for determining the bad slats. Fig. 5-8 indicates the bad slat distribution run by run. We determined the bad slat distribution at every new timing calibration point (every 50 runs or so). We note the somewhat excessive number of bad slats at high slat number. For the series of runs between run 10600 and 10800, most of the data are taken at the 5 degree spectrometer setting at one magnet polarity. This causes one side of the TOF wall to be illuminated. Furthermore, the stiffer momentum distribution results in less bend in the magnet and thus less chance for the particles to reach the end slats. We note that the number of particles from these end slats is very small (<< 1%). While these tests will indicate whether a slat is functioning or not, they do not provide any information about whether a slat was correctly calibrated. However, the final TOF calibration was closely monitored and so we have confidence that the calibration is as good as it can get.

Only a fraction, $f$, of each $(y, p_\perp)$ bin is in the physical acceptance. We were conservative and required $f \geq 0.90$. This causes us to miss the lowest $p_\perp$ bins.

## 5.9 Merging

The merging of runs is discussed in detail in [SMRZ92]. As mentioned before, we merge the yields and not the cross-section, because the yields are more accurate for data cut on the TMA or ZCAL. In the case of minimum bias data, it is more accurate to merge cross-section. Since we are primarily interested in centrality triggered yields,
Figure 5-8: Bad slat distribution as a function of run number.
we sacrifice this accuracy for the minimum bias data.

We triggered on kaons in three modes: 1) at least one $K^{-}$, 2) at least one $K^{+}$ and 3) at least one $K^{+}$ and at least one $K^{-}$. Care was taken to insure that runs with similar triggering were merged. For example, the $K^{+}$ from a $K^{-}$ only run are extremely biased and should not be merged with the rest of the $K^{+}$ data.

Since $\pi$ combines both momentum and $\theta$, looking for differences between angle settings can be difficult using $p_{\perp}$ distributions. Therefore, we have modified the cross-section code to generate $(p, \theta)$ cross-sections. Taking bins in momentum, we plot the $\theta$ distribution. For diagnostic purposes, there are several advantages of studying $(p, \theta)$ distributions over $(y, p_{\perp})$. The first is that it is very clear where each angle setting contributes because the spectrometer’s natural boundaries are in $\theta$. Secondly, because the spectrometer angle settings do overlap slightly in $\theta$, we can easily compare the yields for the same $\theta$ but from two different spectrometer settings. Since the particles come from opposites sides of the spectrometer (near the beam side for the higher spectrometer angle setting and near the away-beam side for the lower angle setting), this is a strong consistency check on the cross-section as well as the consistency of the centrality cut.

Overall, we estimate a 10-15% systematic error arises in the merging of different spectrometer angle settings.
Chapter 6

Results

We present here our final K± results. The $m_\perp$ spectra in slices of rapidity are shown as functions of target and centrality. The rapidity distributions of $dN/dy$ and inverse $m_\perp$ slope parameter are included. Our final $\Lambda$ results are found in the following chapter. For all figures in this chapter, the errors shown are statistical only.

6.1 What Does the Extended Particle Identification Buy us?

We have spent significant effort in understanding the corrections to the extended particle identification detectors, GASC and BACK. We now indicate the benefits from this analysis. Fig. 6-1 shows the differential K$^+$ yield versus $m_\perp$ for various slices in rapidity for minimum bias Si+Au collisions. The line moving from the bottom left to upper right is the limiting value of $m_\perp$ if we did not have the extended particle identification detectors. The maximum momentum for separating pions and kaons by time-of-flight alone is 1.8 GeV/c. The rapidity dependent limit on $m_\perp$ is

$$m_\perp = \frac{E}{\cosh y},$$

where $E$ is the kaon energy at a p of 1.8 GeV/c. We note that GASC/BACK extends our $m_\perp$ range significantly for rapidities larger than about 1.3. For very forward
rapidities, the differential yields are dominated by this extension. A qualitative check on our corrections for the GASC/BACK is indicated by the absence of an obvious break in the $m_\perp$ spectra where GASC/BACK verification starts.

Along with the better statistics, the greater acceptance at low $m_\perp$ helps better determine the parameterization of the $m_\perp$ distribution. This allows for a more accurate determination of $dN/dy$ since the extrapolation to $m_\perp = m_0$ is better. Our systematic error on the determination of $dN/dy$ is accordingly smaller. We observe that the minimum bias $K^\pm$ spectra are significantly better fit with an exponential in $m_\perp$ versus an exponential in $p_\perp$. This was suggested from E802 data but is very evident in the high statistics E859 data set. For the minimum bias data shown here, the $\chi^2/d.o.f.$ for an $m_\perp$ fit is of order 0.5 to 1.5 whereas the $\chi^2/d.o.f.$ for a $p_\perp$ fit is on average $\approx 5$. The $K^-$ data exhibit similar results. For central triggering, the charged kaons remain better fit by an exponential in $m_\perp$, although the difference in $\chi^2/d.o.f.$ is smaller.

### 6.2 Consistency

A comparison to previous E802 results [A+94] is found in Fig. 6-2. Central Si+Au data are used. The E859 protons are consistent with previous results. Both kaons have slightly larger yields. All changes are $\leq 15\%$, within the quoted systematic error of 20%. A more obvious change occurs in the $\pi^+$ yields. (The E859 $\pi^-$ yields show similar behavior compared to the E802 $\pi^-$ yields and are omitted from this plot.) Below a rapidity of 1.4, the E859 yield is about 15\% higher than the E802 result. Above a rapidity of 1.4, the yields are similar.

The explanation is the expanded low $m_\perp$ coverage below a rapidity of 1.4 for E859. Above this rapidity, both E802 and E859 have comparable $m_\perp$ coverage. As an example, in Fig. 6-3 we show the $m_\perp$ spectra for E802 and E859 pions in the rapidity window from 0.8 to 1.0 (where the $dN/dy$ differ significantly) and in the rapidity window from 1.4 to 1.6 (where the $dN/dy$ differ little). In the region of overlap, the E859 data match the E802 data closely. The primary difference is the
Figure 6-1: $K^+$ $m_\perp$ distribution for minimum bias Si+Au collisions for various slices in rapidity. Each successive rapidity slice is divided by 10 for clarity.
$m_\perp$ coverage: the E859 data extend to much lower $m_\perp$ with much better statistics. The purposeful selection of a 0.2 Tesla magnetic field for the E859 data set as opposed to the 0.4 Tesla field used in E802 increased the low $m_\perp$ statistics in E859. Because of the larger $m_\perp$ coverage, we are better able to determine the pion $dN/dy$ with E859 data. We will therefore use the pion yields from E859 in the various ratios to be formed.

6.3 $m_\perp$ distributions

Figs. 6-4 to 6-11 show the invariant differential yields plotted against $m_\perp$ for rapidity slices of width 0.2. Both targets (Al and Au) and centralities (central and peripheral) are shown. As a reminder, central triggers are gated in software on the upper 7% of the TMA multiplicity distribution. The peripheral trigger is the upper 50% of the ZCAL energy distribution (more energy in the ZCAL implies a more peripheral collision). Successive windows in rapidity are scaled by factors of 10 for clarity. The average rapidity value for particles in the slice is shown next to the symbol used to plot that slice. Each rapidity slice is fit to an exponential of form

$$\frac{d^2n}{2\pi m_\perp dm_\perp dy} = Ae^{-m_\perp/T}.$$ 

The integral over $m_\perp$ from $m_0$ to $\infty$ is analytic and yields

$$\frac{dn}{dy} = 2\pi A(m_0T + T^2)e^{-m_0/T},$$

where $m_0$ is the mass of the particle being plotted. Instead of fitting to A and T, A was replaced by $\frac{dn}{dy}$ via the previous equation and both $\frac{dn}{dy}$ and T were returned as fit parameters. The error on both are then taken directly from the 1 $\sigma$ confidence level contours. The variables $(\frac{dn}{dy},T)$ were found to be less correlated than $(A,T)$ and because of the advantage of reading off $\frac{dn}{dy}$ (and its error) directly, we chose to fit in this manner.
Figure 6-2: $dN/dy$ distribution for central Si+Au collisions from E802 and this work.
Figure 6-3: $\pi^+ m_\perp$ distribution for $y$ between 0.8 and 1.0 from central Si+Au collisions from E802 and this work.
Figure 6-4: $K^+$ $m_L$ distribution for peripheral Si+Al collisions for various slices in rapidity. Each successive rapidity slice is divided by 10 for clarity.
Figure 6-5: $K^{-}$ $m_{\perp}$ distribution for peripheral Si+Al collisions.
Figure 6-6: K+ $m_{\perp}$ distribution for central Si+Al collisions.
Central Si+Al K$^-$ yields

Figure 6-7: K$^-$ $m_\perp$ distribution for central Si+Al collisions.
Figure 6-8: $K^+$ $m_\perp$ distribution for peripheral Si+Au collisions.
Figure 6-9: $K^-$ $m_\perp$ distribution for peripheral Si+Au collisions.
Figure 6-10: $K^+ m_\perp$ distribution for central Si+Au collisions.
Figure 6-11: $K^{-}$ $m_{\perp}$ distribution for central Si+Au collisions.
6.4 Slope Systematics

There has been much debate regarding the fitting of slopes [K+93]. We use the maximum log-likelihood ratio test for our fitting [BC84]. While the results differ little from a $\chi^2$ fit for high statistics data, we have chosen the log-likelihood ratio test in order to correct for low count $m_\perp$ bins which are difficult to correctly account for in a $\chi^2$ fit. The error estimate in a bin is $\sqrt{N}$, where $N$ is the number of counts in the bin. If $N=0$, the error on this bin is difficult to determine.

We summarize the inverse slope systematics in Fig. 6-12. Both targets and centralities are shown. A line is drawn at 0.150 GeV$/c^2$ as a common reference value. The various dependencies are isolated in the next few paragraphs. We also note that midrapidity is at $y=1.3$ for central Si+Au collisions. For Si+Al, midrapidity occurs at $y=1.72$ because of the approximate projectile-target symmetry.

To isolate the effects of centrality, we fix the particle type and target in each plot and vary the centrality. The results are shown in Fig. 6-13. For both targets and particles, we observe an increase in the inverse slopes with increasing centrality, with a somewhat larger difference for Si+Au collisions compared to Si+Al collisions. For Si+Al collisions, the increase in inverse slopes is approximately constant for both the $K^+$s and $K^-$s. $K^+$s from central Si+Au collisions show a larger increase near mid-rapidity than at lower rapidities.

Fixing the centrality and particle type and varying the target, we see in Fig. 6-14 that central Si+Al collisions yield different slopes than central Si+Au collisions. However, much of the difference for the $K^+$s is just a reflection of the different mid-rapidities for the two targets. For $K^-$s, the central Au collisions yield higher inverse slope parameters than the central Al collisions. This could be a reflection of more rescattering in central Si+Au collisions (because of multiple scattering) or a result of more $K^-$ absorption which preferentially depletes the low momentum. For peripheral collisions, the slopes are comparable for both sign kaons and targets. Regarding kaon production, peripheral Si+Al collisions seem identical to peripheral Si+Au collisions. Since peripheral collisions are expected to approximate p+p, the similarities are not
6.5 Yields

In Figs. 6-15 and 6-16 we show the $dN/dy$ for the Al and Au targets, respectively. Both the peripheral and central $dN/dy$ are shown for a given target. The error bars are statistical only and typically smaller than the plotting symbol.

For central Si+Al collisions, we note the faster fall off of the $K^-$ yield at lower rapidities. The drop off of both particles above a rapidity of 1.7 may be an artifact of the restricted $m_\perp$ acceptance at higher rapidity. There is a slight hint (1 bin) that the $K^-$ are peaking more forward than the $K^+$. In the Si+Al peripheral collisions, the $K^+$ peak at a rapidity of 1.3 and would show a gull shape if we reflect its $dN/dy$ about mid-rapidity (1.72). This is similar to the proton $dN/dy$ distributions [A+94] and may reflect the N+N dominance in peripheral Si+Al collisions. Ignoring the most forward rapidity point in the $K^-$ $dN/dy$ (it has large systematic errors), we see no evidence of peaking, in contrast to the positive kaons.

The $K^+$ yield peaks near 1.1 for central Si+Au collisions, slightly lower than expected from a fireball source sitting at the participant center-of-mass ($y=1.3$). The $K^-$ yield peak at a slightly higher rapidity and fall off faster than the $K^+$s at lower rapidity.

The $K^+$ and $K^-$ distributions from peripheral Si+Au collisions peak near 1.3. Interestingly, the $K^-$s fall off quickly for decreasing rapidities with the drop in $K^+$ being slower.

Because of the different $dN/dy$ scales, we plot the ratio of the yields between central and peripheral collisions in Fig. 6-17. For each target, we observe the same scaling of the $K^+$ and $K^-$, i.e., both kaons show the same rapidity-independent increase from peripheral Si+Al to central Si+Al collision. In going from peripheral Si+Au to central Si+Au collisions, we also observe the same increase for both $K^+$ and $K^-$, but the enhancement is rapidity dependent, increasing at low rapidity.
Figure 6-12: $K^\pm$ inverse $m_\perp$ slopes for central and peripheral Si+Al and Si+Au collisions.
Figure 6-13: $K^\pm$ inverse $m_\perp$ slopes as a function of centrality.
Figure 6-14: $K^\pm$ inverse $m_\perp$ slopes as a function of target.
The flatness of the ratios for Si+Al collisions is strongly suggestive that the kaon production mechanisms are the same in peripheral and central Si+Al collisions. If additional processes feed kaon production (such as π+N), one might expect them to show up by giving a different shape of the yields. While the ratio exhibits some shape, it is flat compared to the large changes in the Si+Au ratios. It is an interesting question as to whether this difference is a result of the larger spectator environment in central Si+Au collisions (and possibly new production mechanisms) or the larger stopping also occurring in these collisions. Something closer to a fireball may form for central Si+Au collisions, shifting the rapidity distributions to lower rapidity. The ratio would then be larger at low rapidities.

How similar are central collisions between these two targets in regards to kaon production? How similar are peripheral collisions for these two targets? The left plot of Fig. 6-18 shows the ratio of yields for Si+Al and Si+Au peripheral collisions. The second plot in this figure compares the ratio between Si+Al and Si+Au central collisions. We note that peripheral Si+Au collisions have higher yields (≈ 50%) than peripheral Si+Al collisions but are identical in shape for K+ and K−. This suggests that kaon production is dominated by the first N+N interactions for peripheral collisions. As a reminder, the first collision model attributes particle production to the N+N collisions where the N’s have not been previously struck. The peripheral Si+Au collisions have somewhat more first N+N collisions; hence, the ratio to peripheral Si+Al is about 1.5. To test this idea, we have taken the geometrical routines of the Fritiof model (see Chapter 2) and determined the number of first collisions in peripheral Si+Al and peripheral Si+Au collisions. The lower 50% of the minimum bias cross-section is used. We selected Fritiof events with impact parameter \( b > b_{0.5} \), where \( b_{0.5} \) corresponds the the impact parameter giving 50% of the geometrical cross-section. The ratio of the first collisions between peripheral Si+Au and peripheral Si+Al is 1.44, which duplicates the observed increase in both the K+ and K− yields.

In the right panel of this figure, we observe that the differences between central Si+Au and central Si+Al collisions are great indeed. This might have been anticipated for K+ production, since we expect π+N rescattering to feed K+ production at low y,
near the target rapidities. However, it is very surprising to see the same effect for the $K^-$s. In fact, the rapidity dependence contradicts any first collision model approach to $K^-$ production. As just discussed, such a model predicts a rapidity independent scaling of the yields, in clear distinction from what is measured. We also note a slightly larger increase in $K^+$ production than $K^-$ production in central Si+Au compared to central Si+Al collisions. To simulate the centrality cut, we selected Fritiof events with impact parameter $b < b_{0.07}$, where $b_{0.07}$ corresponds to the impact parameter giving the upper 7% of the geometrical cross-section. The ratio of the first collisions between central Si+Au and central Si+Al is 1.5, very different than observed. The first collision model cannot explain central Si+A kaon production.

### 6.6 $K^+/\pi^+$ and $K^-/\pi^-$ ratios

With the most complete coverage to date of $K^\pm$, we examine the ratios of yields as a function of rapidity. Figs. 6-19 and 6-20 show the two ratios for various centralities and targets. As shown in Fig. 6-3, E859 has greater coverage at low $m_\perp$ than E802. Thus, the extrapolation to $0\,p_\perp$ is also better. In calculating $dN/dy$ for these figures, we use the best fit to perform the extrapolation. This is an exponential in $m_\perp$ for the kaon data and an exponential in $p_\perp$ for the pions. The pion data used here are from the E859 data set.

In Fig. 6-19, we have also included the E802 determination of the $K^+/\pi^+$ ratio. We note that the E802 ratio was determined using the $dN/dy$ as determined from an $m_\perp$ fit applied to both the kaons and pions. The significant differences found with the E859 ratio are attributable to two effects: 1) the better extrapolation to low $m_\perp$ results in $\approx 10\%$ larger $dN/dy$ for E859 compared to E802 as seen in Fig. 6-2 and 2) the better fit of an exponential in $p_\perp$ gives up to another $10\%$ increase in $dN/dy$ than the best $m_\perp$ fit.

Discussion of the $K^-/\pi^-$ ratio has been limited because of the poor statistics. With the E859 data, we find just as large an increase in the $K^-/\pi^-$ ratio as in the ratio of the positives. The shape of the ratio, peaked near 1.3, is fairly constant
Figure 6-15: $K^\pm dN/dy$ for central and peripheral Si+Al collisions.
Figure 6-16: $K^\pm dN/dy$ for central and peripheral Si+Au collisions.
Figure 6-17: Ratio of central to peripheral kaon production for both targets and particles.
Figure 6-18: Ratio of $K^+$s and $K^-$s from Si+Au to Si+Al collisions for peripheral (left panel) and central (right panel) collisions. The horizontal line drawn in the left panel is the ratio between the number of first collisions in peripheral Si+Au to the number of first collisions in peripheral Si+Al collisions. The ratio between the number of first collisions in central Si+Au to the number of first collisions in central Si+Al collisions is similar to the ratio for peripheral collisions.
regardless of centrality or target. Generally, we note that both ratios increase with centrality and are larger for the larger target, at fixed centrality.

6.7 $K^+/K^-$ Ratios

The ratio of $K^+$ to $K^-$ is of interest theoretically [Koc90, K+86, K+83] as a measure of the baryon densities achieved in these collisions, assuming chemical and thermal equilibrium. We show this ratio for the two targets and two centrality cuts in Fig. 6-21. A ratio of nearly 4 is obtained at mid-rapidity ($\approx 1.3$ for central Si-Au and 1.7 for central Si-Al) regardless of target or centrality. The amazing fact is the nearly identical rapidity dependence of this ratio for different targets and centralities. We discuss its significance in the next chapter.

6.8 Comparisons to Other Experiments

No other BNL experiment measures charged kaons in the same phase space as E859. However, E810 has determined the $K_S^0$ yield as a function of rapidity for both Si and Pb targets. Unfortunately, there is no simple relation between $K^\pm$ and $K_S^0$ production except in isospin symmetric collisions. In such collisions, because of the equal numbers of $u$ and $d$ quarks available (isospin conservation), we must have

$$N(K^+) + N(K^-) = N(K^0) + N(\bar{K}^0).$$

The right hand side evolves into equal numbers of $N(K_{short}^0)$ and $N(K_{long}^0)$. Therefore,

$$N(K_{short}^0) = (N(K^+) + N(K^-))/2.$$
Figure 6-19: K$^+$/π$^+$ ratio for central and peripheral collisions in Si+Al and Si+Au collisions.
Figure 6-20: $K^- / \pi^-$ ratio for central and peripheral collisions in Si+Al and Si+Au collisions.
Figure 6-21: $K^+ / K^-$ ratio for central and peripheral collisions in Si+Al and Si+Au collisions.
Fig. 6-23. If the $K^0_S$ have the same rapidity distribution as the $K^+$s then the $K^+$ yield in central Si+Au collisions drops monotonically with increasing rapidity.
Figure 6-22: Average of the charged kaon yields from E859 superimposed on the $K^0_S$ yields from E810. Both data sets have been reflected about $y=1.72$. 

\[ (K^+ + K^-)/2, \text{E859, Si+Al central} \]

\[ K^0_S, \text{E810, Si+Si central} \]
Figure 6-23: E859 central Si+Au $K^+$ $dN/dy$ superimposed on E810's $K_S^0$ yields from central Si+Pb collisions.
Chapter 7

Λ Analysis

Because the analysis of Λs differs significantly from that of the charged kaons, we devote a separate chapter to it. The charged particle analysis is “mature” in the sense that many people have worked on it (about 8 doctoral theses so far). We discuss the Λ data set and experimental conditions. We then detail attempts to enhance the signal-to-background ratio. The acceptance calculation is explained and we determine the inverse $m_\perp^2$ slope and yield for our data. An estimate of the systematic error follows. We then compare to other experimental results and conclude with a short section on $\bar{\Lambda}$ production.

7.1 The Data

The Λ data set was taken over a 24 hour running period in the last days of the E859 Mar92 run. We used the SPEC2*TMA first level trigger, gating in hardware on approximately the upper 20% of the TMA multiplicity. In order to use the running time to collect Λ data and statistics for two pion correlation studies, the second level trigger required the event have a $(p, \pi^-)$ or $(\pi^-, \pi^-)$ pair in the spectrometer. We collected approximately 1100K events for Si+Au collisions at the 14 degree spectrometer setting with the magnetic field polarity chosen to optimize acceptance for negative particles (B polarity). This polarity is chosen because the negative pions from Λ decay have a significantly lower momentum compared to the protons. After
the reconstruction and particle identification analysis chain, \( \approx 580K \) events had at least 1 \( \pi^- \) and at least 1 proton in them. From this set, we collected \( \approx 3500 \) \( \Lambda \)s.

The LVL2 trigger was configured with the following cuts on the positive and negative particles accepted:

- negative tracks: \( p < 3.0 \text{GeV}/c, m_{LV L2} < 300 \text{MeV}/c^2 \),

- positive tracks: \( p < 4.0 \text{GeV}/c, 700 \text{MeV}/c^2 < m_{LV L2} < 1300 \text{MeV}/c^2 \).

For future \( \Lambda \) dedicated running, we would restrict the negative momentum to \( < 2 \) GeV/c and accept positive proton candidates up to 5 GeV/c. One can tune these cuts further by running a simulation for \( \Lambda \)s taken at a given spectrometer angle.

As in the kaon analysis, we have rejected "follow" events and discarded events which do not pass the beam \( Z \) cuts. On average, 70% of the events pass both these cuts. This reduces our sample of \( \Lambda \)s to about 2500. We lose the 30% because of the very non-linear beam spill structure found throughout the Mar92 running. This was due to the new injector used for the AGS ring. We could have disregarded these cuts in order to increase our statistics. However, the possible ambiguities involved in keeping these events are difficult to determine. For example, we have observed that removing the "follow" events from the March 92 data does not significantly affect the events which have a beam \( Z \) of larger than 16 (remember the beam \( Z \) is 14). We suspect that the nonlinear spill structure puts beam particles so close together that the later beam particle hits the beam scintillators before the "follow" gate has started. This affects the timing (and hence the particle identification) for that event since the start of the timing comes from the beam counters (specifically, BTOF). This could have a significant effect, especially on rare particles. While the \( \Lambda \)s are not rare, we have applied these cuts to remove as much ambiguity as possible.

Finally, we note that the measured \( \Lambda \) yield includes \( \Lambda \)s and \( \Sigma^0 \)s. The latter has a branching ratio of \( \approx 100\% \) to the \( \Lambda + \gamma \) decay channel, and so \( \Lambda \)s from this decay are indistinguishable from direct \( \Lambda \) production.
### 7.2 General Information

An invariant mass spectrum is formed by taking all possible combinations of $\pi^-$s and protons in the event. The background is formed by a method called event mixing. The protons of a given event are mixed with all the pions from the previous seven events. Only events which were used in the signal distribution are used to make the background. Finally, every event used for the signal and background was required to come from a SPEC2*TMA triggered event to provide identical event conditions for the signal and background.

In the top panel of Fig. 7-1, we show the $(p, \pi^-)$ invariant mass spectra for all events. The invariant mass is given by

$$M_{\text{inv}} = \sqrt{(E_p + E_{\pi^-})^2 - (p_p + p_{\pi^-})^2}. \quad (7.1)$$

We require the protons and pions to satisfy the momentum cuts imposed by the LVL2 trigger. Furthermore, all tracks were restricted to be within the TR1 and TR2 acceptance as the protons and $\pi^+$s we triggered on must have hit TR1 and TR2 to be accepted by the LVL2 trigger. The fit shown is a gaussian plus a scaled background generated from event mixing. The parameters from the gaussian fit are shown in Table 7.1. For comparison, we include results obtained from $\Lambda$s simulated in the spectrometer and passed through the same analysis chain as the real data. We especially note that the $\sigma$ obtained from the simulation is the best resolution possible. The $\Lambda$s (and their decay products) thrown through the Monte Carlo were not subject to any physics processes which would widen the invariant mass distribution. The bottom panel of Fig. 7-1 shows the background subtracted spectrum near $m_\Lambda$. The flat distribution on both sides of the peak indicates that the background is behaving as expected.

Our experimental $\Lambda$ mass resolution is 1.75 MeV/$c^2$. The mass resolution obtained for the $\phi$ is 2.2 MeV/$c^2$ [Wan93]. One explanation for the difference in mass resolution is where these particles decay. The $\phi$ decays in the target whereas the $\Lambda$ most often does not. Therefore, the charged kaons from the $\phi$ undergo multiple scattering
Figure 7-1: \((p,\pi^-)\) invariant mass. The lower plot is the mass region near \(m_A\) expanded after background subtraction. A bin width of 1.5 MeV/c\(^2\) is used. The fit parameters are shown in Table 7.1.

<table>
<thead>
<tr>
<th>Invariant mass parameters</th>
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<tbody>
<tr>
<td>(\mu \text{ (GeV/c}^2))</td>
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<tr>
<td>data</td>
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<tr>
<td>simulation</td>
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Table 7.1: Fit parameters of a gaussian plus background to the signal for data and for the simulation.
in the target, which can amount to a full radiation length for the Au3% target. This is about 10 times the total radiation length to the TOF wall. The neutral \Lambda does not undergo multiple scattering. For comparison, we note that the mass resolution for CERN experiment NA36, a time projection chamber, is 6 MeV/c² [A+92c]. Another CERN experiment, using a bubble chamber (which provides very accurate position information), obtained a mass resolution (\( \sigma \) from a gaussian fit) of 1.2 MeV/c² [B+92]. A BNL experiment using a large acceptance spectrometer (Multiparticle Spectrometer or MPS), obtained a resolution of 2 MeV/c² [B+88]. Although having a small acceptance for \( \Lambda \_s \), the E859 spectrometer does well in terms of mass resolution.

With no cuts, the signal to background ratio is about 15%. This compares with an experiment built to reconstruct \( \Lambda \_s \), where the signal to background ratio is 2000% (20 to 1) [A+92c]. The primary difference is the ability to determine that two tracks come from a vertex away from the target. The background reduction is tremendous in experiments designed for vertex detection. In E859, however, we must carefully understand the background distributions.

As an interesting byproduct, we can find the z position of the target in the spectrometer coordinate system at the 14 degree spectrometer angle setting by looking at the average z of any (p,\( \pi^- \)) pair in the data. We find that \( \left< z \right> = -0.61\, \text{cm} \). This is somewhat alarming since the target is taken as the origin of the coordinate system used in the experiment’s geometry. However, most quantities, including the detector z position, are adjusted based on relative positions and not absolute positions. While the discovery of the true z for the spectrometer at the 14 degree angle setting of the target has little implication for the experiment, it must be accounted for when we apply the acceptance because the simulation assumes the target is at the origin. Therefore, a cut of 3 cm on vertex position in the data translates as 3.61 cm when applying it to the simulation.

We note that all data shown here have passed the following event and track requirements:

- Event does not have the "follow" bit set,
• BTOT and BTOF scintillators see a charge, Z, such that |Z-14.0| <2,

• Event was triggered by the SPEC2*TMA trigger,

• All pion and protons in a candidate Λ pair were required to point within the TR1 and TR2 acceptance,

• All pion and protons in a candidate Λ pair were required to satisfy the LVL2 momentum cuts, \( p_{\text{pion}} < 3.0 \text{ GeV/c} \) and \( p_{\text{proton}} < 4.0 \text{ GeV/c} \),

• Monte Carlo studies indicate that no Λs decaying in our spectrometer at this angle setting (14 degrees) ever give a pion above 1.8 GeV/c. We therefore impose another cut on the data of \( p_{\text{pion}} < 2.0 \text{ GeV/c} \).

If further restrictions are made, they are indicated in the text. All decay particles from simulated Λs are required to satisfy the last two conditions.

### 7.3 General Strategy

The Λ cross-section generation is not automated as it is for the charged particle analysis. The data taken at one spectrometer setting enables us to determine the \( p_\perp \) distribution for one slice of rapidity from 1.1 to 1.7. We are restricted in our \( p_\perp \) segmentation by statistics. We have chosen to have four \( p_\perp \) bins of width 0.2 GeV/c centered at 0.8, 1.0, 1.2, 1.4 GeV/c, respectively. This corresponds in \( m_\perp \) to 1.37, 1.50, 1.64, and 1.79 GeV/c\(^2\). We will move interchangeably between \( p_\perp \) and \( m_\perp \).

We determine the acceptance for each \( p_\perp \) bin, as discussed later. This acceptance will incorporate any cuts we make on the data. Two factors guide the decision as to which cuts should be utilized. The first is to maximize statistics and the second is to maximize the signal to background ratio. We clearly want to maximize statistics. The advantage of the second criteria enters when we fit the data. A larger signal to noise ratio means that we should get a better fit to the peak than if the signal were just a little bump on a large background. This will reduce the systematics of fitting a gaussian to a small peak on a large background. Any cut we impose hurts
the first factor but helps the second. While our final analysis does not use or require
any cuts on the \((p, \pi^-)\) pairs, we do examine the effect of cuts in order to assess the
robustness of our acceptance calculation. This provides a handle on our systematic
error. Finally, we determine the number of \(A_s\) in each \(p_\perp\) bin, correct for acceptance,
fit the \(p_\perp\) distribution, integrate and obtain the \(dn/dy\) for this rapidity slice.

### 7.4 \(\Lambda\) Chops

Because of the significant background, we attempt to reduce the background with
various cuts. Before we investigate some of the more complicated cuts, it is natural
to ask how well we can reconstruct important kinematic quantities such as \(p_\perp\), rapidity
and vertex position.

Fig. 7-2 shows the difference between the thrown and reconstructed \(\Lambda\) rapidity
and \(p_\perp\). We note that the peak of the \(p_\perp\) distribution is off by only 4 MeV/c and with
width of a gaussian fit is 10 MeV/c. Thus the \(p_\perp\) resolution is much less than the bin
size (200 MeV/c). The same is true for the rapidity resolution \((\mu(\Delta y) = -0.002\) and \(\sigma(\Delta y) = 0.005\)). The main point of these distributions is that with the binning used
here, our results are not affected by the experimental resolution.

Another important variable is the reconstructed vertex. We will eventually use
this distance, \(R\), from the target to the vertex as the primary cut on the background
and so we would like to know how well we can determine \(R\). The proton and pion
tracks are approximately parallel because of the limited spectrometer range in \(\theta\) and
\(\phi\). It is therefore crucial to know how well we can perform this vertex determination.
We again use our simulated set of \(A_s\) and plot the difference between the thrown and
reconstructed \(R\). This is shown in Fig. 7-3. While the distribution is not gaussian in
the tails, we fit a gaussian around the peak (as shown) and obtain a peak position of
\(-0.05\) cm with a \(\sigma\) of 2 cm. This distribution is flat as a function of \(R\) and of the \(\Lambda\)
momentum. We can therefore reconstruct the vertex position with no obvious bias.

We now proceed to assess the feasibility of various cuts. We note that to be effective,
the cut should eliminate as much background as possible and, of course, as little
Figure 7-2: The difference between the thrown and reconstructed $\Lambda$ rapidity (left panel) and $p_\perp$ (right panel).
Figure 7-3: The difference (in cm) between the thrown and reconstructed \( \Lambda \) vertex position. The smooth curve is a gaussian fit to \( \pm 6 \) bins about the peak.
signal as possible. Furthermore, we would like the cut to remove background over the whole range of invariant mass. For example, it is a kinematic fact for our spectrometer at the 14 degree setting that the following relationship holds for simulated \( \Lambda \)s reconstructed in the spectrometer:

\[ p_{\text{proton}} > p_{\pi^-} + 0.5\text{GeV}/c. \]

If we apply this cut, it dramatically reduces the background for \( m_{\text{inv}} > m_\Lambda \) but does not affect the region below \( m_\Lambda \).

Here are the cuts we discuss in the following paragraphs:

- distance of closest approach of two tracks, \( d_{\text{min}} \),
- target related cuts
- coplanarity of the \( \Lambda, \pi^-, \) and proton momentum vectors.

**\( d_{\text{min}} \)**

The first cut we examine is the distance of closest approach between two tracks (\( d_{\text{min}} \)). Knowing the equation of two skew lines, one can analytically calculate \( d_{\text{min}} \). This occurs when a line connecting the two lines can be drawn such that it is simultaneously perpendicular to both lines. In Fig. 7-4 we show the distribution obtained from \( \Lambda \)s simulated and passed through the same analysis chain as the data. We also show the same distribution obtained from the data. The curves are arbitrarily normalized. From the simulation, we note that \( d_{\text{min}} \) falls off steeply and then starts to level off for \( d_{\text{min}} > 1 \text{ cm} \). The data fall off slightly less sharply. A more dramatic plot of the fall off is shown in Fig. 7-5. Here we plot the fraction of simulated \( \Lambda \)s found with \( d_{\text{min}} < \) abscissa. We observe that beyond 1 cm most of the simulated \( \Lambda \)s are found. At a \( d_{\text{min}} \) of 0.5 cm, we would reject approximately 7\% of the true \( \Lambda \)s but a larger portion of the background.

**target related cuts**

We expect that cuts on the target position of various quantities such as the projection of the \( \Lambda \) momentum vector back to \( z=0 \) will be useful. With the \( \Lambda \) originating
Figure 7-4: Distance (in cm) of closest approach of $(p, \pi^-)$ pairs from simulated $\Lambda$s (diamonds) and from the data (squares).
Figure 7-5: Fraction of simulated $A$s with $d_{min}$ less than the abscissa value.
from the target, we would expect the following relationship between the projections of the various particles originating from a \( \Lambda \) decay:

\[
R_{xy}(\Lambda) < R_{xy}(\text{proton}) < R_{xy}(\pi),
\]

where \( R_{xy} \) is the distance of the particle’s projection to the plane, \( z=0 \), relative to the target position. The increasing order is simply a result of the pion being so light that it is emitted at a larger angle (relative the the \( \Lambda \) direction) than the proton.

Unfortunately, both these possibilities depend on knowing the target position for that event. The target position wanders not only in a run but even within a spill. The beam can sweep over several millimeters in a spill. We can determine the average target position but it is problematic to apply that position event by event. We can exclude, for example, \( \Lambda \) candidates whose projection back to the target at \( z=0 \) is more than three sigma away from the average target position. However, with a typical sigma in target position of a few millimeters, this cut is ineffective.

**coplanarity**

A test can be made on the coplanarity of the decay. Because the \( \Lambda \) and its decay products lie in a plane, the scalar

\[
\vec{p}_\Lambda \cdot (\vec{p}_\pi \times \vec{p}_p)
\]

should be zero. In practice, we take the direction of the \( \Lambda \) as the vector from the target to the reconstructed vertex position. Thus we are dependent again on how well we know the target position. Fig. 7-6 shows the value as determined from the simulated \( \Lambda s \). Superimposed is the distribution for the \( (p,\pi^-) \) pairs from the data. The uncertainty in the target position is not included in the simulation. Because we use the direction to the vertex as the direction of the \( \Lambda \), this direction becomes more poorly determined the smaller the vertex distance is. It is not clear that this cut will be effective once we include the uncertainty in target position into the simulation. We have chosen not to use this cut.

To summarize, we have evaluated the possibility of various cuts. Most cuts have
Figure 7-6: Coplanarity as measured by $\vec{R}_A \cdot (\vec{p}_{\tau^-} \times \vec{p}_\mu)$. Both simulated (diamonds) and real (squares) data are shown.
limited usefulness because of the small spectrometer acceptance for two particles and a lack of target position information event-by-event. We have concluded that the two feasible cuts are the vertex position, R, and the distance of closest approach between two tracks, \( d_{\text{min}} \). While the analysis does not hinge on these cuts, we do wish to assess its robustness by performing the analysis with and without cuts.

### 7.5 Acceptance

A single arm spectrometer is not the ideal detector for identifying particles via their decay products. While having relatively large acceptance for single particles, detecting both decay products is an unlikely event. For a qualitative understanding of what the spectrometer can detect, we show in Fig. 7-7 the mean opening angle of the \( \Lambda \) decay products versus the momentum of the \( \Lambda \). To place us on the momentum axis, we note that RQMD calculations run for central Si+Au collisions at 14.6 GeV/c indicate that \( \langle p_\Lambda \rangle \approx 3 \text{GeV/c} \) for our rapidity slice (1.1<\( y \)<1.7). Since T1 dominates the \( \theta \) acceptance, we draw the maximum \( \theta \) opening of the spectrometer relative to the target at T1. Shown for comparison in Fig. 7-8 is the same plot for \( \phi \rightarrow K^+ + K^- \).

The mass asymmetry of the \( \Lambda \) decay products results in the pion coming off at a large angle relative to the proton. We note that the line drawn at 14 degrees is not a hard cutoff for \( \Lambda s \) because they characteristically decay away from the target. A \( \Lambda \) which decays 20 cm from the target sees a larger aperture than a \( \Lambda \) decaying in the target. The \( \phi s \) decay in the target; it is a hard cutoff for them. The mean opening angle in the lab frame of any decay is momentum dependent with the lower momentum having larger opening angles. We include Table 7.2 with the essential \( \Lambda \) characteristics.

<table>
<thead>
<tr>
<th>Quark content</th>
<th>uds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>1.1156 GeV/c^2</td>
</tr>
<tr>
<td>( c\tau )</td>
<td>7.89 cm</td>
</tr>
<tr>
<td>(p,π^-) branching ratio</td>
<td>0.641</td>
</tr>
</tbody>
</table>

Table 7.2: \( \Lambda \) characteristics.
Figure 7-7: $\Lambda$ opening angle versus momentum. The errors bar indicate the range of opening angle at a given momentum.
Figure 7-8: $\phi$ opening angle versus momentum. The errors bar indicate the range of opening angle at a given momentum.
With a decay length of 7.89 cm, and a typical $\gamma$ of about 3, for example, there are significant number of $\Lambda$s decaying away from the target. This is a double edged sword. On the positive side, the decay vertex provides the most effective cut on the data because most background $(p,\pi^-)$ pairs come from the target and will intersect there. A cut on vertex position eliminates a significant fraction of the combinatorial background.

The possible problem with the decay length is that a $\Lambda$ decaying, say, 10 cm from the target will create a pion which does not necessarily point back to the target. The target position, however, is a very useful way for the reconstruction algorithm to make initial cuts to evaluate if a track should be more fully reconstructed. Therefore, tracks not originating from the target may be dropped. This has the greatest effect for the pions since the proton essentially retains the $\Lambda$ $\vec{p}$, which already points back to the target.

One of AUSCON's strengths is the ability to vary any parameter which is used as a cut in reconstructing particles. We can estimate the effect of various cuts this way. Such a study has been done using the $\Lambda$ data. The various target cuts on a track were completely turned off. The result was an increase of less than 1% of events with at least one $\pi^-$ and at least one proton in them. The possible increase in the number of $\Lambda$s would have been less than 1% and so we did not bother reconstructing the data with the target cuts turned off but just used the PASS3 output as is.

With these thoughts in mind, we must determine the acceptance. We are fortunate that the $\Lambda$ data were taken at one spectrometer setting (14 degrees) with one magnet setting (4B). This simplifies our task immensely because we do not have to worry about merging different spectrometer settings, as we do for the charged particle analysis.

In order to determine the acceptance, we must use a simulation of our detector. This simulation, MCG315, uses GEANT315 [C+89]. We have included multiple scattering and decay (for the pions) as the physics processes in this simulation. Multiple scattering is responsible for a significant decline in reconstruction efficiency for low momentum protons ($p < 0.8$ GeV/c) [Par92]. Because of the small $\Lambda$ acceptance, we...
must throw many \( \Lambda \)'s. To save CPU time, the \( \Lambda \)'s are generated in the part of \((y, p)\) space covered by the 14 degree, 4B spectrometer setting for \( \Lambda \)'s. The spectrometer subtends at most 30 degrees in \( \phi \) and as it is symmetric about the x-z plane, we throw \( \Lambda \)'s from 0 to 15 degrees in \( \phi \) to save a factor of 2. We correct the total number thrown by 180/15 to account for the \( \phi \) region the spectrometer does not cover.

A total of \( 5 \times 10^6 \) \( \Lambda \)'s were thrown uniformly in rapidity between \( y=1 \) and \( y=2 \) and with an exponential distribution in \( m_\perp \) with an inverse slope of 200 MeV/c\(^2\). This value was obtained from initial estimates of the inverse slope. With some loose \( p, \theta \) and \( \phi \) cuts on the daughter proton and pion, only \( 2 \times 10^5 \) \( \Lambda \)'s remained to be passed to the simulation. If the \( m_\perp \) bin size is small, it is important to simulate the true \( m_\perp \) distribution as closely as possible. In reconstructing the data, there will be a certain resolution in finding the original rapidity and \( m_\perp \). The resolution will cause one to determine a \( \Lambda \)'s \( m_\perp \) above or below the true value with equal probability. The \( \Lambda \) \( m_\perp \) distributions are essentially exponential in \( m_\perp \). A given \( m_\perp \) bin will get a larger contribution from its smaller \( m_\perp \) neighbor bin than it gives to that same bin. The effect of the resolution would be to flatten the \( m_\perp \) distribution. In our case, the \( m_\perp \) bin size is much larger than the \( m_\perp \) resolution and this effect is negligible.

Once we have a \( \Lambda \) with a given \( y \) and \( p_\perp \), we then determine its momentum and decay it in its rest frame. Some caution is required here. The \( \Lambda \) decays with a characteristic time of \( c\tau \) where \( c \) is the speed of light. We need to create a distribution exponential in time, then boost the time to the lab frame and convert it to distance from the target. If \( t_0 \) is the time obtained from the exponential above, then boosting to the lab gives a factor of \( \gamma \) (of the \( \Lambda \)). To get the distance from the target, we then multiply by \( \beta \). Or,

\[
R_{\text{vertex}} = \gamma \times \beta \times t_0 = (p_\Lambda/m_\Lambda) \times t_0.
\]

If we threw the vertex position in the \( \Lambda \) frame according to an exponential with characteristic distance of \( c\tau \) and then boosted to the lab, we would only get a factor of \( \gamma \) and miss the \( \beta \).

The momentum 4-vector and vertex position are passed to MCG315 which prop-
agates the particles through the spectrometer and produces points in space along the trajectory of the particles. Another program, ZYBATCH [C+89], then digitizes the MCG315 output into a format identical to that of the real data. The ZYBATCH output is then processed in the same analysis chain as real data.

We reconstruct the simulated data with the same cuts as the experimental data. The \((y, p_{\perp})\) acceptance is then the ratio of the number of \(\Lambda s\) reconstructed in a \((y, p_{\perp})\) bin divided by the number thrown into that bin. This acceptance will thus correct for the geometrical acceptance (the region of \(\phi\) not covered by the spectrometer) and the decay corrections due to \(\Lambda\) decay. We also multiply by \(1/0.64\) to correct for the unseen decay mode into a \((n,\pi^0)\) pair. We must further correct for track reconstruction and particle identification efficiency. Assuming that the \(\Lambda\) reconstruction efficiency is factorable, we have

\[
\epsilon_\Lambda = \epsilon_{\text{proton}} \times \epsilon_{\text{pion}}.
\]

From our Monte Carlo studies, the protons from \(\Lambda\) decay have momentum \(\geq 1\ \text{GeV/c}\). The pions fall between 0.4 to 1.3 GeV/c. From Fig. 4-9, the proton efficiency is flat at 91%. The pion efficiency is momentum dependent. We have taken pions and protons from fully reconstructed, simulated \(\Lambda s\) and found the average efficiency

\[
< \epsilon_{\text{proton}} \times \epsilon_{\text{pion}} >= 0.69 \pm 0.04
\]

for each \(\Lambda\). The 0.04 is the rms value of the product, attributable to the efficiency variation of pions over their momentum range. Since we threw \(\Lambda s\) with a realistic \(m_\perp\) distribution, it is reasonable to use this value of the efficiency over the \(m_\perp\) range of our data. The \(m_\perp\) dependence of the reconstruction efficiency is less than the rms value and so we ignore it.

In Fig. 7-9, we show the \(\Lambda\) \((y, p_{\perp})\) acceptance. A box is drawn around the fiducial area in phase space we consider. Note than the entries have been scaled by \(10^6\). The acceptance changes rapidly in both rapidity and \(p_{\perp}\). We note that for our lowest \(p_{\perp}\) bin, we have acceptance for rapidities between 1.1 and 1.5, whereas the other 3 \(p_{\perp}\) bins have coverage to a rapidity of 1.7. This is because of the TR1 acceptance which
Figure 7-9: $\Lambda (y, p_{\perp})$ acceptance not including correction unseen decay mode or reconstruction/pid efficiency. Entries have been multiplied by $10^6$. The enclosed area corresponds to the fiducial area used for this analysis.

cuts off protons at forward rapidities. We note that this acceptance is the average over four bins of rapidly changing acceptance. This is not optimal - one would like, as we do for the single particle cross-sections, to have small $(y, p_{\perp})$ bins so that the acceptance changes little over one bin. Unfortunately, we are constrained by our lack of statistics.

7.6 Reality Check

In order to have confidence in our data, we need to compare to some physically known quantity. We should be able to reproduce the true $c\tau$ by boosting the "$\Lambda$" to its rest
frame and calculating the time it decayed. Since we do not positively identify $\Lambda$s we must generate a background and subtract it from the signal.

We have used a binned maximum likelihood method, which has also been used for determining the lifetime of short lived particles like the $\Xi^0$ [F+93]. We describe the method here.

Particles within $\pm 2\sigma$ of $m_\Lambda$ are binned as a function of the decay time in their rest frame as given by $R/(\gamma \beta)$, where $R$ is the vertex position in the lab frame. The background decay time distribution is made with particles falling in a window of the same width but $\pm 5\sigma$ away from $m_\Lambda$. We take $\sigma$ as 1.75 MeV/$c^2$, as determined from Table 7.1. Let $i$ be the $i^{th}$ time bin with time $t_i$. $b_i$ is the background and $n_i$ the signal for that bin. If $f(t_i)$ is the acceptance as a function of $t_i$, then we have

$$n_i = S \frac{f(t_i)e^{-t_i/\tau}}{\sum f(t_i)e^{-t_i/\tau}} + B \frac{b_i}{\sum b_i}.$$

This equation simply says that the number of counts in the signal histogram is a background plus the true number of $\Lambda$s we would see at time $t_i$. If we start with $S$ $\Lambda$s, at time $t_i$ we would expect to find $Se^{-t_i/\tau}$ remaining after decay. Of these, we would only see $Se^{-t_i/\tau}f(t_i)$ due to our acceptance.

Summing over $i$ yields $N = S + B$. Since $N$ is fixed from the signal histogram, we let $B$ vary and replace $S$ by $N - B$. We use the maximum likelihood method to find the best fit for $\tau$ and $B$. This is a strong test of whether the acceptance varies correctly with the data, i.e., that the data cuts are really reducing out the expected number of $\Lambda$s.

Table 7.3 indicates the variation in $c\tau$ for various cuts on the vertex position. We see that at 14 cm, the acceptance is starting to become questionable, whereas for 0 to 7 cm, we have some assurance that the acceptance is correct. The last cut listed in the table includes the effects of selecting a specific range of $d_{min}$. One other piece of information returned is the background scale factor. Since this fit presumably isolates the $\Lambda$ contribution to the timing distribution, we can sum over all bins and get the total number of $\Lambda$s in our sample via $S = N - B$. This is called method 1. It is an
Table 7.3: Fitted $c\tau$ for various cuts on R.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Fitted $c\tau$ (cm)</th>
<th>$N_\Lambda$, method 1</th>
<th>$N_\Lambda$, method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>7.98 ± .65</td>
<td>2112 ± 145</td>
<td>2165 ± 149</td>
</tr>
<tr>
<td>R&gt;7 cm</td>
<td>7.52 ± .53</td>
<td>1781 ± 178</td>
<td>1435 ± 75</td>
</tr>
<tr>
<td>R&gt;14 cm</td>
<td>8.78 ± .62</td>
<td>1338 ± 168</td>
<td>823 ± 48</td>
</tr>
<tr>
<td>R&gt;5 cm, $d_{min}$ &lt;0.5 cm</td>
<td>7.91 ± .73</td>
<td>1359 ± 112</td>
<td>1435 ± 72</td>
</tr>
</tbody>
</table>

An independent way of determining the total number of $\Lambda$s in our sample. The other method (method 2) is to plot the $m_{inv}$ distribution for the signal and event mixed background as was done for Fig. 7-1. We show these results in the Table 7.3 as well. The error in the number of $\Lambda$s for Method 1 is just that returned on the error for the background, $B$. Identical results are achieved for both methods and reasonable $R$ cuts, indicating a very small systematic error in determining the number of $\Lambda$s. Fig. 7-10 shows the background subtracted, acceptance corrected, timing distribution for our $\Lambda$ sample for the case of $R>0$ cm. The fit is superimposed.

### 7.7 $m_\perp$ Distribution and Yield

We have all the ingredients required for determining the $m_\perp$ distribution. The number of $\Lambda$s in each $m_\perp$ bin was determined by filling a histogram with the signal and a separate histogram with the mixed background. The signal was then assumed to be the background (scaled, of course) plus a gaussian distribution. The background scale factor, and height ($A$), mean ($\mu$) and $\sigma$ of the gaussian were left to vary. For a gaussian, the number of $\Lambda$s $N$, is simply

$$N = \sqrt{2\pi}A\sigma.$$

In practice, we replace $A$ by $N$ in the fit and so the fit parameters returned were $N$, $\mu$ and $\sigma$ of the gaussian. This allowed us to read off the errors on the number of $\Lambda$s directly.

No $R$ or $d_{min}$ cuts were applied to the $(p,\pi^-)$ pairs. Fig. 7-11 shows the signal
Figure 7-10: Background subtracted, acceptance corrected timing distribution of the \( \Lambda \) sample from the \( R>0 \) cm \( c\tau \) fit. Solid line is the fit result, \( c\tau = 7.98 \pm 0.65 \). The two dashed lines indicate how the fit looks \( \pm \) one \( \sigma \) change in \( c\tau \).
Table 7.4: Number of Λs for different $p_\perp$ bins obtained by binning the invariant mass distribution with two different bin sizes, 1.5 and 2.0 MeV/c$^2$. The rapidity range is 1.1<y<1.7.

<table>
<thead>
<tr>
<th>$p_\perp$ bin</th>
<th>1.5 MeV/c bins</th>
<th>2.0 MeV/c bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7-0.9 GeV/c</td>
<td>313 ± 71</td>
<td>322 ± 58</td>
</tr>
<tr>
<td>0.9-1.1 GeV/c</td>
<td>552 ± 75</td>
<td>540 ± 75</td>
</tr>
<tr>
<td>1.1-1.3 GeV/c</td>
<td>569 ± 66</td>
<td>526 ± 67</td>
</tr>
<tr>
<td>1.3-1.5 GeV/c</td>
<td>284 ± 50</td>
<td>281 ± 59</td>
</tr>
</tbody>
</table>

with fit superimposed for the four $p_\perp$ cuts. The right column shows the background subtracted signal. We examine this to see how well the background fits the signal distribution on either side of the Λ peak. The flat region on both sides of the peak indicate the consistency of the background. An excess on either side would indicate a problem. The fourth, highest $p_\perp$ bin shows some evidence of this problem.

We have chosen a bin size of 1.5 MeV/c$^2$. Because our mass resolution is 1.75 MeV/c, we estimate any systematic error due to our binning. To see how the number of Λs changes with bin size, we include Table 7.4 which shows the number of Λs for each $p_\perp$ bin with two different bin sizes, 1.5 and 2 MeV/c$^2$. For the latter, we have offset the bin so that the Λ mass is not in the center bin. The differences between the two bin sizes is consistent with the error bars. The average difference is about 3% but is within the statistical errors. We conclude there is no systematic error from binning.

Table 7.5 contains the information needed for generating the $m_\perp$ distribution. We plot the $m_\perp$ distribution in Fig. 7-12. The result, with all the corrections, is

- $dN/dy = 3.85 ± 0.58$.
- inverse $m_\perp$ slope, $T = 171 ± 13$ MeV/c$^2$.

We now estimate the systematic error due to the three possible major sources of uncertainty, 1) reconstruction/pid efficiency 2) the acceptance and 3) the normalization.
Figure 7-11: A invariant mass distribution for the 4 $p_\perp$ bins. The left column shows the signal plus fit superimposed. The right column shows the background subtracted signal. The lowest $p_\perp$ bin is the top row.
Figure 7-12: A $m_\perp$ distribution for central Si+Au collisions at $y = 1.4$.

<table>
<thead>
<tr>
<th>Center of $m_\perp$ bin</th>
<th>Acceptance (x10^3)</th>
<th>Recon./Pid Eff.</th>
<th>$N_A$</th>
<th>$\frac{d^2n}{2\pi m_\perp dm_\perp dy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.37</td>
<td>0.78</td>
<td>0.67</td>
<td>313 ± 60</td>
<td>0.234 ± 0.045</td>
</tr>
<tr>
<td>1.50</td>
<td>1.28</td>
<td>0.70</td>
<td>552 ± 75</td>
<td>0.134 ± 0.018</td>
</tr>
<tr>
<td>1.64</td>
<td>2.08</td>
<td>0.71</td>
<td>568 ± 66</td>
<td>0.071 ± 0.008</td>
</tr>
<tr>
<td>1.79</td>
<td>2.99</td>
<td>0.72</td>
<td>284 ± 51</td>
<td>0.021 ± 0.004</td>
</tr>
</tbody>
</table>

Table 7.5: Details for generating the differential yield. The acceptance does not include the correction for the unseen decay mode (1/0.64). The differential yield includes all effects.
7.8 Checks on Systematic Errors

The three major sources of systematic errors are the reconstruction efficiencies, the acceptance, and the uncertainties in normalization. We discuss each below.

7.8.1 Reconstruction Efficiency

The systematic error on the single proton reconstruction/pid efficiency is ± 3%. The systematic error on the single pion reconstruction/pid efficiency is ± 8%. The pion has a larger error because of the systematics involving the GASC/BACK part of the particle identification. We also assess a 2% systematic error due to multiplicity. The reconstruction efficiency is known to decrease with increasing particle multiplicity by \( \approx 2\% \) per additional particle after the first one. The average multiplicity for the \( \Lambda \) data is \( \approx 2 \). Adding the systematics in quadrature yields a systematic error of \( \approx 9\% \).

7.8.2 Acceptance

The acceptance is directly related to the Monte Carlo and so we discuss some of the possible differences between the real world and the simulation world. As mentioned, we ran the GEANT Monte Carlo with all the physics mechanisms disabled. This was done for CPU and memory savings because of the large number of \( \Lambda \)s needed for the acceptance. This, of course, is highly idealized, reflected in the differences in mass resolution between the data and simulation, \( \sigma_{\text{sim}} = 1.49 \text{ MeV}/c^2 \) while \( \sigma_{\text{data}} = 1.75 \text{ MeV}/c^2 \). In the following paragraphs, we enumerate some possible reasons for this difference which affect the acceptance.

The Monte Carlo geometry of the spectrometer is not identical to that used reconstructing real data. Although the differences are expected to be small, it may contribute to errors. The simulation includes smearing for the detector resolution but not noise in the chambers. Also, the simulation of the drift chambers planes is only an approximation to the wires. Each plane of wires is modeled as a plane with the same effective density rather than as true wires. Therefore, one does not get the large angle scattering occurring when a particle hits a wire. The largest difference
is the environment. In the experimental data, the reconstruction algorithm must pick out tracks from many hits in front of the magnet. The overall hit multiplicity increases the more forward the spectrometer and more central the events. The algorithm may pick up a hit not due to the particle. This would cause errors both in the momentum and angle determination. In the simulation, only two tracks are thrown and this problem does not exist.

In order to assess the systematic error due to the acceptance, we have determined the $A_{m_{\perp}}$ distribution under various cuts in $R$ and $d_{\text{min}}$. From the section on $A$ cuts, we concluded that these were the two most feasible cuts. They are also sensitive to the differences in the simulation and real world in that both quantities are sensitive to multiple scattering and how well we reconstruct the track in front of the magnet (see the previous discussion of $d_{\text{min}}$ and $R$). Table 7.6 shows the inverse $m_{\perp}$ slope and $dN/dy$ obtained under various $d_{\text{min}}$ and $R$ cuts. If the acceptance is correct, these values should be identical. The difference indicates the systematic error associated with the acceptance. From this table, we determine a $\pm 3\%$ systematic error on $T$ and a $\pm 8\%$ error on $dN/dy$ from the acceptance.

### 7.8.3 Normalization

A second source of uncertainty is the normalization. The effects of normalization has been tested in the following manner. The first test is to examine whether the TMA changed over the $A$ running time (24 hours). To do this, we ask for the number of minimum bias triggers (INT) which also indicated that the TMA would have triggered
this event (i.e. had a summed analog signal exceeding the hardware threshold). We examine this ratio run-by-run. As seen in Fig. 7-13, the TMA was stable over the one day running period. The two runs which have percentages near 100% are runs where we reduced the TMA threshold in order to simulate minimum bias events. These runs are not included in this analysis. We observe that the TMA threshold accepted approximately the upper 20% of the TMA multiplicity distribution.

A second method of testing the normalization is to recalculate the slope and dN/dy using a software TMA cut. We can make a tighter cut in software corresponding to the upper 10% of the TMA multiplicity distribution. Fig. 7-14 shows the TMA distribution normalized to BEAM for the minimum bias trigger (INT) and for the

Figure 7-13: The fraction of INT events with the hardware TMA bit set (from trigger word 2) as a function of run number.
Table 7.7: Summary of the systematic errors in the $\Lambda$ analysis.

<table>
<thead>
<tr>
<th>Cause of systematic error</th>
<th>% error in T</th>
<th>% error in $dN/dy$</th>
</tr>
</thead>
<tbody>
<tr>
<td>reconstruction efficiency</td>
<td>none</td>
<td>9</td>
</tr>
<tr>
<td>acceptance (R and $d_{\text{min}}$ cuts)</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>normalization</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>total (added in quadrature)</td>
<td>4</td>
<td>13</td>
</tr>
</tbody>
</table>

SPEC2*TMA trigger. The latter has been arbitrarily normalized to overlap in the upper TMA multiplicity region. We also show the empty target contribution. This last contribution is negligible in the determination of the 10% software cut. The level of the software cut (TMA multiplicity = 108) is indicated by the arrow. Only SPEC2*TMA events with TMA multiplicity $\geq$ 108 are used for the signal and mixed background. If we normalize in this manner, we obtain a yield of $4.00 \pm 1.0$ and an $m_\perp$ slope of $174 \pm 13$ MeV/c². The larger errors are due to the fact that the 10% software cut reduces our statistics by about a factor of 2. The consistency of the yield and slope is reassuring and is in accordance with our understanding that the number of particles per trigger stays constant for relatively small changes in centrality. Using the difference in values of $T$ and $dN/dy$ obtained with and without the hard TMA threshold, we assign a 2% systematic error to $T$ and a 4% systematic error to $dN/dy$ due to the normalization process.

### 7.9 Summary of the $\Lambda$ Analysis

We summarize our systematic errors in $T$ and $dN/dy$ in Table 7.7. These errors are assumed independent and the total is obtained by adding them in quadrature. We summarize our $\Lambda$ results for central (upper 10% of the cross-section) Si+Au collisions in Table 7.8. The first error is statistical and the second is systematic. The maximum possible systematic error is 5% for $T$ and 21% for $dN/dy$. 
Figure 7-14: TMA distribution from INT, target out, and SPEC2*TMA events and the software cut.

<table>
<thead>
<tr>
<th>Inverse $m_\perp$ slope (MeV)</th>
<th>dN/dy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$171 \pm 13 \pm 7$</td>
<td>$3.85 \pm 0.58 \pm 0.5$</td>
</tr>
</tbody>
</table>

Table 7.8: Final results of the $\Lambda$ analysis.
7.10 Comparison to Other Experiments

We compare to other experiments which have measured Λ production at these energies. Brookhaven experiment E810, using a time projection chamber (TPC), has performed the most complete measurement of neutral strange particle (Λ and Κ₀) production in relativistic heavy ion collisions at Brookhaven energies. Their central Si-Pb measurement is the closest system to that for central Si-Au collisions. While we expect little difference because of the different targets, there are other notable discrepancies. They measure centrality based on the number of negative tracks reconstructed in the TPC. It is unknown how well the E810 and the E859 measures of centrality correlate. Our expectation is that the correlation is passable and we must overlook any possible differences here.

With these caveats in mind, Fig. 7-15 [E+93] shows the \( \frac{dN}{dy} \) for Λs for E810 and our point superimposed. The errors shown are only statistical. Our value seems reasonable based on E810’s measurement. Fig. 7-16 [E+93] shows their measured inverse \( m_\perp \) slope as a function of rapidity with our point superimposed at \( y=1.4 \). Their value at \( y=1.5 \) is \( \approx 235 \pm 20 \) MeV/c², higher than ours. We note some discontinuities in E810’s slope distribution.

7.11 Other Λ Production Mechanisms: Pair Production

Since one of the mechanisms for Λ production is via pair creation with its antiparticle, we would like to estimate the contribution of this mechanism to the Λ yield.

A significant portion of the E859 running period was spent collecting central Si+Au collisions for the 2K⁺ correlation measurement [Cia94]. This data set was taken triggering on two kaons of any sign. Since the mass window for the K⁻ was set as \( m > 350 \) MeV/c², this trigger also accepted \( \bar{p}s \). A sample of \( \approx 5000 \) \( \bar{p}s \) were accumulated during the 2K⁺ correlation running. The first Λ measurement in heavy ion collisions at Brookhaven, reported in 1990 [Ho90], amounted to about 10
Figure 7-15: $\Delta dN/dy$ from AGS experiment 810 for central Si-Pb collisions. The E859 result is superimposed.
Figure 7-16: $\Lambda$ inverse $m_\perp$ slopes from AGS experiment 810 for central Si-Pb collisions. The E859 result is superimposed.
Λ's in Si+Al collisions. The \( \bar{p} \) identification requires significant study. We refer the reader to two Ph. D. theses devoted to this analysis [Cos91, Rot94]. Since the particle identification requirements are different for protons and \( \bar{p} \)s, we have required the protons to be identified in the same way as the \( \bar{p} \)s. The following requirements were imposed:

- Both decay products are required to be within the acceptance,
- Proton (anti-proton) momentum < 3.0197 GeV/c,
- \( \pi^+ (\pi^-) \) momentum < 1.8 GeV/c,
- \( \Lambda \) events triggered with SPEC2TMA and \( \bar{\Lambda} \) events triggered with SPECTMA. The centrality cut is \( \approx \) the upper 20-25% of the cross-section.
- Only fully reconstructed and identified tracks are used,
- No cuts of the vertices were made.

With these cuts, we have obtained \( 91 \pm 15 \pm 6 \) \( \Lambda \)'s in central Si+Au collisions at the AGS, where the first error is statistical and the second is systematic. The number of \( \Lambda \)s is \( 1265 \pm 112 \) with the error being statistical. Because of the small sample of \( (\bar{p}, \pi^+) \) pairs, a sufficiently smooth background could not be generated as we did for the \( \Lambda \) sample. The systematic error for the \( \bar{\Lambda} \)'s is due the different methods in normalizing the background to the signal. We did not have this problem for the \( \Lambda \)s. Fortuitously, the spectrometer angle setting (14 degrees) and magnet field (4A) were set so that the acceptance for \( \Lambda \)s in the \( \Lambda \) running is identical to that of the \( \bar{\Lambda} \)s taken in the two kaon data. We can thus determine the ratio of the spectrometer integrated cross-section, which largely cancels systematic errors. We obtain

\[
\frac{\sigma(\bar{\Lambda})}{\sigma(\Lambda)} = (3.96 \pm 0.56 \pm 0.24) \times 10^{-3},
\]

(7.2)

where the first is the statistical and the second the systematic error. This is the first measurement of its kind for heavy ion collisions at AGS energies.
While this is a ratio integrated over the spectrometer setting, we may estimate the $dN/dy$ by scaling this ratio by the measured $\Lambda dN/dy$ assuming the same $m_{\perp}$ distribution. We thus obtain

$$\frac{dN(\Lambda)}{dy} = (15.25 \pm 3.15 \pm 0.92) \times 10^{-3}.$$

We note that at this rapidity (1.4), the yield of antiprotons for central Si+Au collisions is $\approx 1.5 \times 10^{-2}$. The interesting implications of these comparable yields for $\bar{p}$ production is discussed in [Rot94].

As the $\Lambda$ yield is nearly 4 at a rapidity of 1.4, we observe that the contribution from pair production of $\Lambda$ and $\bar{\Lambda}$ is minuscule.

7.12 Future Prospects

We have shown the feasibility of a good statistics determination of the $\Lambda m_{\perp}$ distribution and yield with a single arm spectrometer. With the upcoming gold beam, it is my hope that we can perform such a measurement over the full range of spectrometer settings and determine the yield over a similar range of rapidity as the $K^+$ and $K^-$. We will thus have the most complete set of data from which we can decipher the mechanism of associated production in strange particle production.

Another prospect is to use the E859 spectrometer and the forward angle spectrometer (FAS) of E866 as a double arm spectrometer and to measure the $\Lambda$ cross-section at very forward rapidities. Furthermore, this two-arm system will probably be the only hope to find heavier strange baryons, such as the cascades or sigma baryons. Because of the multiplicity involved in Au-Au collisions, the E859 spectrometer cannot be moved closer than about 20 degrees relative to the beam. The FAS can approach 6 degrees. Therefore, with a minimum opening angle of about 26 degrees, we will be restricted to fairly low momentum ($p<3$ GeV/c) baryons. Using the LVL2 trigger for the E859 spectrometer arm may reduce the background sufficiently to see some of these rare strange baryons. The FAS presently does not have a second level trigger.
Chapter 8

Discussion

In this section, we address the issue of $K^+$ production and provide an understanding for the $K^+/\pi^+$ and $K^+/K^-$ ratios. We also discuss the inverse $m_\perp$ slope distributions and what physics can be extracted from them. We conclude with a discussion of the overall strangeness production in these collisions.

8.1 $K^+$ Production

A question central to heavy ion collisions is whether $A+A$ collisions can be understood as the superposition of $p+A$ collisions or even $p+p$ collisions. It has been observed that for certain global observables like neutral transverse energy, such a superposition picture reproduces the data [R+88]. It is of interest to see if this picture explains single particle yields. One particular approach is to see whether the yields scale with variables we expect to play an important role in determining particle production. A few such variables are the number of projectile participants, the number of total participants and the number of binary collisions.

We examine particle production scaled by the number of projectile participants, $A_{\text{part}}^\text{proj}$. Such a comparison was first made by Yasuo Miake [Mia90] and served as an effective way of showing the increase in kaon production compared to pion production. We have regenerated his plot in Fig. 8-1 using the most recent analysis of E802 pion and proton data [A+92a, A+94]. The central Si+Au collision kaons are from
this analysis. The Si+Au data have been scaled by 1/28, the number of projectile participants for central collisions. Three aspects of this plot standout.

1 Pion production peaks at a higher rapidity in the Si+Au collisions but the overall scale is the same as in p+Au collisions.

2 K\(^+\) production shows a similar shape in p+Au as in Si+Au collisions and also a marked increase in the absolute magnitude, by almost 50% at the peak.

3 Differences in the shape of the K\(^-\) distribution are difficult to determine but there is also about a 50% increase in the yield at the peak.

From p+Au to central Si+Au collisions, kaon production scales faster than pion production. We discuss possible reasons for this.

A possible mechanism for increasing the K\(^+\) yield is via \(\pi+N \rightarrow K^+ + \Lambda\). RQMD claims that this mechanism is responsible for about 1/2 of the K\(^+\)s produced (see the overview given in Chapter 2). However, we note that this mechanism does not explain the significant increase in the K\(^-\) yield. An increase in the \(\Lambda\) yield from p+Au to central Si+Au collisions would help confirm the \(\pi+N\) mechanism. Unfortunately, a measurement of the \(\Lambda\) yield in p+Au collisions has not been performed.

Since both charged kaons increase in central Si+Au collisions compared to p+Au collisions, the \(\pi + \pi \rightarrow K^+ + K^-\) mechanism is plausible. As discussed in Chapter 2, the kinematics of this reaction make this mechanism improbable. The occurrence of kaon mass modification is likely required to save this mechanism. Furthermore, annihilation would produce the kaons symmetric about the center-of-mass rapidity of the \(\pi + \pi\) system. Since pions must be separated by (at least) 4 units of rapidity to create kaons, the center-of-mass rapidity will be \(\geq 2\). The kaon pairs will be produced symmetric about this rapidity. It would be difficult to reproduce the K\(^+\) \(dN/dy\) shape by this mechanism because the K\(^+\)s peak near 1.1 in central Si+Au collisions. Therefore, we conclude that pion annihilation is an unlikely mechanism to explain the increase in K\(^+\) production.

For further insight into K\(^+\) production, we examine whether the effects just discussed are isolated to large targets (and much spectator matter) or whether we can
Figure 8-1: Particle production in p+Be, p+Au and central Si+Au/28.
observe this effect in collisions with the smaller Al target. Because of the smaller target thickness, central Si+Al collisions are not as central as Si+Au. The Fritiof model indicates that only \( \approx 22 \) projectile nucleons interact on average in central Si+Al collisions. Shown in Fig. 8-2 is \( dN/dy \) for p+Al, Si+Al/22 central, p+Au, and Si+Au/28 central. The p+A data are from [A+92a] and the central Si+Al pions are from [A+94]. The central Si+Al kaons are from this analysis. The proton yields have been omitted for clarity.

From this figure we see that the pions scale approximately as \( A_{\text{proj}}^{\text{proj}} \) for these systems. In contrast to using an Au target, kaon production in the p+Al system is very similar to that of the scaled central Si+Al collision. If \( K^+ \) production is dominated by pion rescattering with target spectator (at low rapidities), one might expect more \( K^+ \) production for the Au target than for the Al target, as we observe. However, we have just argued that the \( \pi+N \) cannot explain the increase in \( K^- \) production in central Si+Au collisions. Thus, while central Si+Au collisions have larger \( K^+ \) production compared to Si+Al collisions, it is unlikely this is due to rescattering.

Another possible explanation to the greater \( K^+ \) production in central Si+Au collisions arises from the greater stopping in these collisions than in central Si+Al collisions. Greater stopping translates into more \( N+N \) collisions and greater energy loss of the projectile. This energy goes into particle production and possibly into more kaons. As mentioned in Chapter 2, second \( N+N \) collisions can still create \( K^+ \)'s and even \( K^- \)'s. Thus, the increase in kaon production may be a reflection of the multiple \( N+N \) collision occurring in these reactions. We will expand on this idea later.

As a final topic under \( K^+ \) production, we estimate the contribution to the \( K^+ \) yield from \( \phi \) production. The \( \phi \) has been analyzed in depth for central Si+Au collisions [Wan94, Wan93]. \( \phi \) are of interest theoretically because of in-medium effects which can modify its mass and width [B+91]. Since the \( \phi \) decays to a \( K^\pm \) pair (with a branching ratio of \( \approx 50\% \)), it is natural to determine the \( \phi \)'s contribution to the \( K^\pm \) yield. The \( \phi \) contribution to the \( K^- \) yield is about 5\%. Its contribution to the \( K^+ \) yield is about 4 times smaller, or \( \approx 1\% \). Therefore, the \( \phi \) negligibly contributes to \( K^+ \) production.
Figure 8-2: Particle production in p+Al, central Si+Al/22, p+Au and central Si+Au/28.
8.1.1 $K^+/\pi^+$ ratio

The initial report [A+90b] of the $K^+/\pi^+$ at one rapidity value generated much excitement because it was thought that a QGP signature was found. In $p+p$ collisions, the $K^+/\pi^+$ ratio is $\approx 5-6\%$ and rises to $10\%$ for central $p+Au$ collisions. As shown in Fig. 6-19, the ratio is approximately $8-9\%$ for peripheral $Si+Al$ collisions (which are most like $p+p$) and increases to $\approx 10-12\%$ for central $Si+Al$ and peripheral $Si+Au$ collisions. The overall ratio is also about $15\%$, lower than the published value of $19\pm0.3\%$ [A+90b]. The primary difference is the larger pion yield below a rapidity of 1.1 due to the better fit at low $m_\perp$ for the E859 data. In general, the ratio increases with centrality and target size.

To understand this ratio, we must understand both $K^+$ and $\pi^+$ production individually. We would like to know whether the absolute yield of $K^+$ increases or the $\pi^+$ yield decreases or whether both effects occur. From Fig. 8-1, it seems that the kaon yields are increasing faster than $A_{part}^{proj}$ whereas pion production has saturated. To be more quantitative, we integrate the $\pi^+$ and $K^+$ yields in the rapidity interval, $[0.6,2.6]$ and $[0.4,1.8]$, respectively:

$$\frac{K^+, Si+Au, central}{K^+, p+Au, central} = 29 \pm 2.2,$$
$$\frac{K^+, Si+Au, central}{K^+, p+Au, min. bias} = 48 \pm 1,$$
$$\frac{\pi^+, Si+Au, central}{\pi^+, p+Au, central} = 18.5 \pm .2,$$
$$\frac{\pi^+, Si+Au, central}{\pi^+, p+Au, min. bias} = 19.5 \pm .2.$$

The central $p+Au$ pions are from the Ph. D. work of Parsons [Par92]. Note that the $p+Au$ data are both minimum bias and central, whereas the $Si+Au$ are just central. We want to “match” centralities as best we can. Minimum bias $p+Au$ is less “central” and $p+Au$ is more “central” than central $Si+Au$ collisions. Here central refers to the average impact parameter. Thus, we have bracketed the centrality by two extremes. In either extreme, we observe that $K^+$ production is near and most likely exceeds simple scaling by $A_{part}^{proj}$. Pion production, however, is saturated at $\approx 19$. One could conclude that the increase in the $K^+/\pi^+$ ratio seen in central $Si+Au$ collisions is due
Table 8.1: Fit parameters to fits of average particle multiplicities versus $s$ for p+p collisions. See text for details.

<table>
<thead>
<tr>
<th>Particle</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>-1.55±0.32</td>
<td>0.82±0.07</td>
<td>0.79±0.47</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>-2.98±0.22</td>
<td>0.94±0.05</td>
<td>3.31±0.33</td>
</tr>
<tr>
<td>$K^+$</td>
<td>-0.46±0.03</td>
<td>0.120±0.008</td>
<td>0.59±0.05</td>
</tr>
<tr>
<td>$K^-$</td>
<td>-0.45±0.03</td>
<td>0.100±0.007</td>
<td>0.70±0.06</td>
</tr>
</tbody>
</table>

To an increase of the $K^+$s. On the other hand, the saturation of the pion production suggests that significant pion absorption is occurring. This is quite possible in the baryon rich environment of the Au target. We now turn to p+p data for further insight.

How can we explain the $K^+/\pi^+$ ratio and its dependencies? Let us examine various possible mechanisms. Can we explain the ratio solely from independent NN collisions? Solely means that no final state interactions such as pion absorption are allowed. The $\pi^+$, $\pi^-$, $K^+$ and $K^-$ multiplicities for pp collisions at various energies have been measured and tabulated in [A+73]. They fit the data to

$$<\text{mult}>= A + B \ln s + C s^{\frac{1}{2}}$$

for $s$ from 7 to 2000 GeV$^2$ (our collisions have an $s$ of 29.2 GeV$^2$). The fit parameters shown in Table 8.1 are obtained from [R+75]. We show the various ratios versus $\sqrt{s}$ in Fig. 8-3. We observe that NN collisions with an $s$ less than the initial $s$ cannot increase the $K^+/\pi^+$ ratio. Both ARC and RQMD maintain the importance of resonance interactions as an important source of $K^+$s. The models treat the interactions of resonances as N+N collisions but with a larger $\sqrt{s}$. This would move us to greater $\sqrt{s}$ on this plot. It is clear that interactions of resonances cannot reproduce a $K^+/\pi^+$ ratio of 15%. If anything, a significant fraction of N+N collisions probably occur at a $\sqrt{s}$ of less than the incident beam energy of 5.4 GeV. This should reduce the $K^+/\pi^+$ ratio. N+N collisions do increase the absolute number of $K^+$s but not their
We conclude, then, that some other mechanism is responsible for increasing this ratio.

We examine another possible mechanism for increasing the $K^+/\pi^+$ ratio. RQMD [Sor93] claims that the reaction $\pi + N \rightarrow \Lambda + K^+$ is responsible for half of the $K^+$ yield. What is the $K^+/\pi^+$ ratio from $\pi + N$ collisions? We turn to existing $\pi + N$ data to see how the $K^+/\pi^+$ ratio changes as a function of $\sqrt{s}$. Unfortunately, we have not found the same type of data as is available for p+p collisions. However, in Chapter 2, we estimated the $K^+/\pi^+$ ratio from $\pi^+ + N$ collisions at 4 GeV/c and concluded that the maximum ratio possible under some extreme assumptions is at most 4%. Therefore, $\pi + N$ collisions alone should lower the ratio instead of increasing it.

We have just concluded that particle production from N+N or $\pi+N$ collisions without final state interactions cannot explain the large $K^+/\pi^+$ ratio in central Si+Au collisions. Both these mechanisms should work to lower the ratio. A remaining hypothesis is pion absorption. This is plausible given the large interaction cross-

Figure 8-3: $K^+/\pi^+$ and $K^-/\pi^-$ ratios from the fit to p+p data near our $\sqrt{s}$. $\sqrt{s} = 5.4$ GeV at Brookhaven energies. See text for the details.
section of $\pi + N$ interactions ($\approx 100$ mb compared to $\approx 12$ mb for $K^+ N$ interactions).

### 8.2 $K^+/K^-$ Ratio

The $K^+/K^-$ ratio was expected to be a possible signature for QGP formation [K+83]. However, recent theoretical studies [C+93] indicate the insensitivity of this signature to either a hadron gas or a QGP scenario. Regardless, this ratio has proven of interest experimentally. As observed in Fig. 6-21, the distribution falls as one approaches a rapidity of 2. This trend is remarkably independent of target or centrality. In fact, the invariance of this ratio indicates its usefulness as a QGP signature. This is one of the few quantities found invariant under different centralities and targets.

It was thought [Sun93] that the invariance of this ratio indicated that the dominant mechanism of $K^\pm$ production was solely $N+N$ collisions. If we think of varying centrality and target as equivalent to changing the number of $N+N$ collisions and assume these collisions dominate production, then the ratio of the yields remains constant. No rescattering effects need be employed. This would stand in marked contrast with RQMD results which indicate that $\approx 50\%$ of all $K^+$s come from $\pi+N$ rescattering [Sor93]. Certainly the rise at low $y$ of the $K^+$s for peripheral $Si+Al$ collisions, where we may not expect much $\pi+N$ rescattering, is puzzling.

A possible explanation arises from the dynamics of multiple collisions. Participant nucleons typically undergo more than one collision, especially for central collisions. Because energy is lost in each collision, subsequent collisions have less energy available for particle production. Since we are not that far from threshold for some reactions (see the review of reactions in Chapter 2) these second and third collisions will produce particles in different abundances compared to their first collision counterparts. The lower $\sqrt{s}$ means the center-of-mass rapidity of subsequent collisions decreases as well. Since the $p+p$ production of $K^-$ drops rapidly with $\sqrt{s}$, the ratio of $K^+/K^-$ increases for these second and third collisions and since these collisions occur at a lower rapidity, the overall ratio of $K^+/K^-$ increases there in accordance with the data. A more quantitative statement to the changing cross-section with $\sqrt{s}$ is shown in Fig. 8-
Figure 8-4: Ratio of $K^+/K^-$ versus $\sqrt{s}$ from p+p data. $\sqrt{s} = 5.4$ GeV at Brookhaven energies.

4. This ratio is derived from the fits to p+p data as mentioned above. The ratio increases with decreasing $\sqrt{s}$ since the $K^-$ production threshold is greater than the $K^+$ threshold.

It is questionable whether this can also explain the peripheral data. The peripheral trigger selects collisions closest to p+p collisions. We therefore do not expect the same number of multiple collisions for peripheral collisions. However, significant overlap between the two nuclei can exist for peripheral triggers and second collisions can still occur. It is uncertain whether this is sufficient to reproduce the $K^+/K^-$ ratio.
8.3 Strangeness Production

One can estimate the net strangeness production, which should be zero. We first must extrapolate our results over the full phase space. The net multiplicities are

\[ < K_{\text{net}} > = ( < K^+ > - < K^- > ) + ( < K^0 > - < \bar{K}^0 > ) \]

and

\[ < Y_{\text{net}} > = 1.6 \times ( < \Lambda + \Sigma^0 > - < \bar{\Lambda} + \bar{\Sigma}^0 > ), \]

where the 1.6 is a compensating factor for the unobserved hyperons such as the \( \Xi \)s (Y) [Wro85]. The \( \Lambda \) yields measured by E859 and by E810 already include the \( \Sigma^0 \) because they decay immediately to \( \Lambda \)s. The average, \( <> \), is simply

\[ \sum \frac{dN}{dy} \Delta y \]

for the desired particle species where \( \Delta y \) is the bin width of the rapidity distribution. The second factor in \( K_{\text{net}} \) is difficult to determine. However, for isospin symmetric systems, we have

\[ < K_{\text{net}} > = 2 \times ( < K^+ > - < K^- > ). \]

We therefore evaluate the net strangeness for our Si+Al system. This simplifies our calculation as we can use reflection symmetry in the rapidity distributions as well as E810’s results for their Si+Si collisions. We have fit the distributions of \( < K_{\text{net}} > \) and \( < Y_{\text{net}} > \) with gaussians and determined the above sum from the fit parameters. The result is consistent with strangeness conservation as expected,

\[ < K_{\text{net}} > = 4.48 \pm 0.18 \]

and

\[ < Y_{\text{net}} > = 4.02 \pm 0.70. \]
Since the $\bar{\Lambda}$ yield is measured to be $\approx 0.01$ of the $\Lambda$ yield, we have taken the anti-hyperon yield to be zero. The plot of E810’s $\Lambda$ yield for central Si+Si [E+93] collisions scaled by 1.6 and our $K_{net}$ are shown in Fig. 8-5.

Let us assume two mechanisms for $K^\pm$ production: associated ($K^+$ and $\Lambda$) and pair production ($K^+$ and $K^-\Lambda$). For these two mechanisms and isospin symmetric systems, every $K^-$ produced has a partner $K^+\Lambda$. This is only approximately true for asymmetric collisions. The fraction of $K^+$s coming from associated production is

$$f = \frac{N_{K^+} - N_{K^-}}{N_{K^+}},$$

where the N’s correspond to the total number of specified particles integrated over
the full phase space. We calculate this ratio for our two targets and centralities and obtain

- $f_{Si+Au}^{central} = 0.80 \pm 0.06$
- $f_{Si+Au}^{periph} = 0.80 \pm 0.11$
- $f_{Si+Al}^{central} = 0.77 \pm 0.09$
- $f_{Si+Al}^{periph} = 0.83 \pm 0.05$.

If the above assumptions hold true, then the relative strength of the strangeness producing mechanisms is consistent with that observed in p+p collisions. If $\pi+N$ collisions contributed to 50% of the $K^+$s without additional $K^-$ production via some other mechanism, the above fraction would be closer to 1.

8.4 $m_\perp$ distributions and physics

As discussed in Chapter 2, the inverse $m_\perp$ slope of various particles can be useful as a guide to see if there may be new physics processes appearing in these collisions. An interesting example applied to pion production is found in [Col92]. While it is hoped that some simple observations may be made, we do note that the $m_\perp$ distributions are the result of a complicated interplay between kinematics, different production mechanisms, rescattering and possibly flow. Despite these different contributing factors, the kaon distributions are surprisingly close to exponential in $m_\perp (p_\perp$ for pions) over the experimentally measured phase space.

Before comparing to other particles, we first discuss the $K^\pm$ inverse slope parameters. The most obvious observation is that regardless of centrality, for a fixed target, the $K^+$s have a larger inverse $m_\perp$ slope than the $K^-$s. Recalling the argument by Ko (Chapter 2), if the QGP is formed, the $K^+$ should have a smaller inverse slope than the $K^-$. The data indicate just the opposite for all systems and all centralities. The data, therefore, do not support the creation of a QGP in this scenario. Unfortunately,
the details of the hadronization of a QGP are little known and it is possible that the transition to the hadronic phase may wash out the initial signature.

We suggest one mechanism for understanding the inverse $m_\perp$ slopes. From the $p+$A data [A+92a], it is observed that

$$T_{K^+} \geq T_{K^-}$$

for all A. $p+$p data [U+75] at an incident proton momentum of 24 GeV/c also show that the $K^+$s fall off less quickly than the $K^-$s. We suspect, therefore, that the observed behavior in Si+A collisions is largely due to kinematics. Since the $K^+$ production threshold is lower than the $K^-$, the $K^+$ have more available energy and, therefore, larger $p_\perp$.

The drop in the $K^+$ inverse $m_\perp$ slope may also be linked with a multiple N+N collision picture of $K^+$ production. If $K^+$s are produced by second and third N+N collisions, these occur at a lower center-of-mass rapidity and leave a kaon with less energy than if the kaon was produced in one of the first N+N collisions. The inverse $m_\perp$ slopes therefore would decrease quickly at lower rapidities.

How do we explain the increase in inverse slopes from peripheral to central collisions? One likely mechanism which explained the $p_\perp$ slopes in Bevalac data is multiple scattering. The effects of multiple scattering are already evident in the progression from $p+$Be to $p+$Au [A+92a]. Both proton and $K^+$ inverse slopes increase by 10-20 MeV/c$^2$ near mid-rapidity. Since we expect multiple scattering to affect other particles as well, we summarize the inverse $m_\perp$ slopes for various particles in Figs. 8-6 and 8-7. The error bars are statistical only. The protons and $\pi^+$ data are from [A+94]. The behavior of $\pi^-$ is identical to that of $\pi^+$ and so only the later is shown.

The protons and kaons again show an increase in inverse $m_\perp$ slopes with centrality with the protons reaching a value of 250 MeV/c$^2$. This is believed [K+93] to be the result of the dominance of resonance interactions from which the protons emerge. There are a few resonances which decay to $K^+$s (the N(1650), for example). We doubt that the same mechanism which increases the proton's mean $p_\perp$ is at work with the
kaons. The pions are unusual in having the same inverse slope regardless of target
or centrality and, indeed, nearly the same as observed in p+A collisions [A\textsuperscript{+}92a].
Since pions have such a large cross-sections they should experience the most multiple
scattering. And yet they show little change in their behavior. It may be that because
pions are so abundant and have small masses that they are the closest to being in
equilibrium even in peripheral Si+Al collisions and thus show no change compared
to other targets and centralities. Multiple scattering can account for the target and
centrality dependence of the kaon inverse slope parameter.

Finally, we address the question of whether the K\textsuperscript{+} can be used as a probe of the
early part of the collision, as was suggested by Nagamiya [Nag82]. This possibility
was motivated by the experimental finding for heavy ion collisions at the Bevalac that

\[ T(K^+) > T(p) > T(\pi). \]

This is certainly not the case in Si+A collisions, where we have the following general
trend of

\[ T(p) > T(K^+) > T(K^-) \geq T(\pi). \]

Protons certainly have larger interaction cross-sections than K\textsuperscript{+}s and so an argument
based on path length through nuclear matter is inconsistent with the data. However,
if flow exists in these collisions, it would increase the proton inverse slopes more than
the kaons or pions because protons are slower at a given momentum.
Figure 8-6: Inverse $m_\perp$ slopes (MeV/c$^2$) for p, $\pi^+$, K$^\pm$ from central and peripheral Si+Al collisions. The error bars are statistical only.
Figure 8.7: Inverse $m_\perp$ slopes (MeV/c$^2$) for p, $\pi^+$, $K^\pm$ from central and peripheral Si+Au collisions. The error bars are statistical only.
Chapter 9

Conclusions

We have presented a systematic study of kaon production in Si+A collisions at 14.6 A·GeV/c using Al and Au targets. The high statistics data (≈ 80k K⁺s and 70k K⁻s for Au, ≈ 64k K⁺s and 30k K⁻s for Al) were obtained because of a second level trigger, which allowed online particle identification in 40 microseconds. Particle production has been studied for both central (upper 7% of the cross-section) and peripheral (lower 50% of the cross-section) software triggers. Our analysis has included the extended particle identification detectors which allows kaon identification up to a momentum of 3.0 GeV/c. This considerably extends the limit of 1.8 GeV/c imposed if we only had the time-of-flight available. We have measured over a broad region of phase space about mid-rapidity. The kaon $dN/dy$ and inverse $m_\perp$ slopes (T) have been studied systematically as a function of rapidity, centrality and target. Comparisons between p+A and Si+A collisions are made. We have also presented the Λ spectra over a limited range of phase space, obtaining results consistent with the Brookhaven experiment E810. Although not designed as such, we have proven the feasibility of performing a Λ measurement in the E802/859 spectrometer.

9.1 Summary

We summarize several aspects of the data here.
9.1.1 Spectra

The kaon invariant differential yields at fixed rapidity are best described by exponentials in $m_\perp$. We have also found that the pion invariant differential yields at fixed rapidity are best described by exponentials in $p_\perp$. This was observed by Parsons [Par92] and is confirmed in E859 because of the enhanced data set now available from measurements taken at a low magnetic field setting.

9.1.2 Inverse slopes

The inverse slopes, $T$, are always larger for $K^+$s than for $K^-$s in a given system and centrality. We believe this reflects the kinematics of their respective production mechanisms. Similar behavior is observed from $p+p$ to $p+A$ to $Si+A$ collisions. The slopes, $T$, increase with increasing collision centrality for both kaons while maintaining the relation, $T_{K^+} > T_{K^-}$. As with $K^+$ data from the Bevalac [Ran81], this is most likely due to multiple scattering of the $K^+$. This multiple scattering explanation is supported by the fact that the slopes for central collisions are larger than for peripheral collisions, i.e., $T_{K^+}^{central} > T_{K^+}^{periph}$ and $T_{K^-}^{central} > T_{K^-}^{periph}$.

9.1.3 $K^+$ and $K^-$ $dN/dy$

The high statistics data have been particularly helpful in determining the true shape of the kaon yields which have provided some unusual features. Kaon production in peripheral Si+Au and Si+Al collisions is very similar. The $K^+$ $dN/dy$ shows the same shape for both these two systems. Likewise, the $K^-$ $dN/dy$ is similar. Peripheral Si+A collisions seem to resemble $p+p$ collisions, as expected. However, central Si+Au collisions are very different from central Si+Al collisions regarding kaon production. $K^\pm$ production is markedly increased at low rapidities for central Si+Au collisions compared to central Si+Al. We believe this reflects the following mechanisms: the significantly larger stopping in central Si+Au collisions compared to Si+Al (see [Par92]) means more energy is available for particle production in general. There will be more kaon production from $N+N$ collisions taking place at a different
center-of-mass rapidity feeding the $dN/dy$ at low rapidity. We add that we cannot rule out further $K^+$ production being fed by $\pi+N$ collisions. However, we determined that approximately 80% of $K^+$ production was from associated production, consistent with p+p data. Therefore, if this mechanism contributes, it is at a small level (and certainly not at the 50% level that RQMD cites [Sor93]). Furthermore, if $\pi+N$ were responsible for the enhanced $K^+$ production, it cannot explain the large increase in $K^-$ yields. Unfortunately, we are hampered by a lack of p+A A data for comparisons which might help test this hypothesis.

We note that in central Si+Au collisions the $K^+$ yields possibly peak at a lower rapidity than the $K^-$ yields and certainly have different shapes. This is difficult for hadronic gas models to reproduce as particle production, by construction, is symmetric about the fireball's center-of-mass rapidity. Furthermore, for particles of the same mass, the fireball predicts yields of the same widths [S+92b]. The more forward peaking of the $K^-$s possibly indicates a different production mechanism than that of the $K^+$s. We add that because of the lower cross-sections, we do not expect the $K^+$s or $K^-$s to be in equilibrium.

Of particular interest is the ratio of $K^+$ to $K^-$, which is observed to be invariant for targets and centralities. The explanation for this amazing fact is still not completely understood. It could be a result of a conspiracy of several effects. The hypothesis of $\pi+N$ rescattering feeding $K^+$ production at low rapidity is discounted by the fact that the ratio is the same for peripheral Si+Al collisions, which we expect are just like p+p. The ratio indicates that regardless of whatever mechanisms are producing kaons, one just gets more of the same mechanisms (and not new ones) from peripheral Si+Al to central Si+Au collisions. Therefore, one suspects it is related to N+N collisions. Our hypothesis is that this ratio reflects the domination of the pair production mechanism ($\approx$80%) for $K^-$s and the domination of associated production for $K^+$ production. This associated production is related to the fragmentation of the nucleons. At low rapidities, we believe the $K^+$s are from target fragmentation. Production from fragmentation is known to be invariant of target or projectile. Hence the ratio of $K^+$ to $K^-$ is constant at these lower rapidities.
9.1.4 Relative yields

The $K^+/\pi^+$ and $K^-/\pi^-$ ratios have been systematically detailed. The $K^+/\pi^+$ ratio shows an increase with centrality and target rising to $\approx 15\%$ and generally flat versus rapidity. This was observed in E802. Mechanisms which feed $K^+$ production at low rapidities (such as pion rescattering with the target spectators) might tend to make this ratio increase at these rapidities, something not observed in the data. We have noted that the increase in the ratio with target mass may be attributable to an increase in the $K^+$ yields as well as to a saturation of pion production per projectile participant these collisions.

Interestingly, the $K^-/\pi^-$ ratio increases by the same relative amount as the $K^+/\pi^+$ ratio. This is a new finding and has important implications for models which have in the past only tried to reproduce the ratio of the positives.

9.1.5 Overall strangeness production

Not surprisingly, we observe that strangeness conservation is met in central Si+Al collisions. This is more of a check on the consistency between experiment E810 and E859. With the assumptions that $K^+$s are produced by $N + N \rightarrow N + K^+ + \Lambda$ and pair production and the $K^-$s are produced solely from pair production, we find that $\approx 80\%$ of $K^+$s are from associated production. The consistency with p+p results is another indication that strangeness production is dominated by N+N collisions.

9.2 Lessons learned and final remarks

As a final summary of the extent of the measurements made by the E802 collaboration, we show in Fig. 9-1 a plot of all observed particle production from central Si+Au collisions. The E802/E859 measurements have stimulated the theoretical community to develop various analytic and microscopic models such as ARC. As has been suggested [Ogi93], measuring particle production over a range of energies below 14.6 A·GeV/c may help unravel various physics effects and should constrain models which
Figure 9-1: All particle production measured by E082/859 for central Si+Au collisions.
match the data at this energy. Another possibility is to go up in energy so that we are further away from possible threshold effects.

We have attempted to understand the data by extrapolating from known data. While perhaps more intuitive, they can hardly be deemed conclusive because the collisions are so complicated. However, it is abundantly clear that we must have detectors which can do particle identification over a broad range of phase space. This has been the lesson learned from E802. Furthermore, we need to be able to gate on centrality. We eagerly await the results of measurements made recently for the Au beams at Brookhaven. The Au+Au collisions are expected to be significantly different than Si+Au collisions both in the higher densities achieved and for the longer duration of the compressed matter. This may be our best chance to form a QGP at these energies.
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