Search for Disoriented Chiral Condensates in 158 AGeV
$^{208}$Pb+Pb Collisions

by

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B.A. in Political Science, Yale University (1992)

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Abstract

The restoration of chiral symmetry and its subsequent breaking through a phase transition has been predicted to create regions of Disoriented Chiral Condensates (DCC). This phenomenon has been predicted to cause anomalous fluctuations in the relative production of charged and neutral pions in high-energy hadronic and nuclear collisions. The WA98 experiment has been used to measure charged and photon multiplicities in the central region of 158 AGeV Pb+Pb collisions at the CERN SPS. We measure charged multiplicity at mid-rapidity ($2.35 < \eta < 3.75$) with a Silicon Pad Multiplicity Detector (SPMD). We measure the multiplicity of "\(\gamma\)-like clusters" (which are 65% photons and 35% hadron background) in $2.8 < \eta < 4.4$ with the Photon Multiplicity Detector (PMD). The events selected have a measured transverse energy ($E_T$) in $3.5 < \eta < 5.5$ of greater than 300 GeV, corresponding to the most central 10% of the cross section. In a sample of 212646 events, the average multiplicities (not corrected for acceptance) are $\langle N_{ch} \rangle \sim 590$ and $\langle N_{\gamma-\text{like}} \rangle \sim 410$. The scatter plot of $N_{ch}$ vs. $N_{\gamma-\text{like}}$ reveals no clear DCC signal, which would appear as non-statistical outliers with respect to the bulk of the data, which respects the binomial partition of pion charge states. Using a simple DCC model, where we incorporate a DCC signal into a chosen fraction of the produced pions, we have set a 90% C.L. upper limit on the maximum DCC production allowed by the data. This result rules out the presence of large, single-domain DCCs in heavy-ion collisions at SPS energies. Suggestions for future analyses which can search for, or place upper limits on, smaller DCCs are discussed.

Thesis Supervisor: Boleslaw Wyslouch
Title: Associate Professor, Department of Physics
This thesis is dedicated to the memory of
my grandfather, Albert Hardy Newman (1903-1988)
and
my aunt, Carol Ruth Bransky (1940-1996).
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Chapter 1

Introduction

[Modern science tells us that] what should be examined are beings only, and besides that - nothing; beings alone, and further - nothing; solely beings, and beyond that - nothing.

What about this nothing?

- Martin Heidegger

At high temperatures and densities, Quantum Chromodynamics (QCD), the theory of strong interactions, is expected to undergo a phase transition from a state of matter where quarks are confined inside hadrons to one where quarks are free to move around within a large volume – the “quark-gluon plasma” (QGP). Lattice gauge theory calculations suggest that the critical temperature of full QCD, including quarks, is around $T_c = 150$ MeV, corresponding to an energy density of 2-3 GeV/fm$^3$ [Won94]. Bjorken estimated that the energy density achieved in the central region of nucleus-nucleus collisions could reach as high as 1-10 GeV/fm$^3$ [Bjo83], suggesting that such collisions could be used to create regions of QGP in the laboratory. This has inspired several generations of experiments at CERN (in Europe) and BNL (in the U.S.) searching for the creation of a QGP at ultra-relativistic energies (> 10 GeV/nucleon). The experimental searches have focused on isolating signatures of two types of phase transitions which may occur in extremely hot or dense nuclear matter. The “deconfinement” phase transition is expected to occur when the hot system of quarks and gluons no longer feels the long-range confining force that binds them into hadrons. The other type of phase transition, which is the main focus of this thesis, is associated with the restoration of chiral symmetry, which corresponds to the melting of the “quark condensate” that is found in the ground state of QCD.

Chiral symmetry refers to the fact that the QCD Lagrangian with massless quarks is symmetric under rotations of the quark fields in flavor space that independently act on right and left handed
quarks. This symmetry is explicitly broken in nature by the non-zero current quark masses, but it is also believed to be spontaneously broken in the QCD ground state by the formation of an isoscalar quark condensate [Koc97]. This explains many properties of low-energy hadronic states, including the light masses of the pions and the $\rho - \sigma_1$ mass splittings. The symmetry breaking is thought to arise dynamically, by a combination of the attractive force between quarks and anti-quarks (which spontaneously breaks the symmetry) and the small current masses of the light quarks (which explicitly breaks it). Thus, it has been thought that chiral symmetry may be effectively restored in hadronic matter at high enough temperatures such that the scale of the fluctuations becomes larger than the energy scale associated with the symmetry breaking.

Recent theoretical work using the linear $\sigma$-model, an effective theory of QCD at low energies, suggests that chiral symmetry may be restored via a second-order phase transition at a critical temperature estimated to be $T_c \sim 150$ MeV[Raj95]. Second-order phase transitions are characterized by long-range fluctuations in the relevant order parameter, which in this case are the pseudoscalar chiral fields ($\sigma, \pi^0$). However, in equilibrium, QCD has a correlation length scale given by the Compton wavelength of the pion $\hbar c/m_\pi \sim 1$ fm. And yet, calculations [RW93a] have found that given suitable initial conditions, the long-wavelength modes of QCD, i.e. low-$p_T$ pions, should be unstable as the system cools through the phase transition. These instabilities are expected to create “domains”, each with a well defined chiral direction, which may be different than the normal vacuum. Thus, these domains are called “Disoriented Chiral Condensates” (DCC). The normal vacuum, however, is not chirally symmetric, requiring us to project these states onto a basis of definite isospin. Doing such gives us the charge distribution of the emitted pions:

$$P(f) = \frac{1}{2\sqrt{f}}.$$  \hspace{1cm} (1.1)

where $f$ is the neutral fraction,

$$f = \frac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^+} + N_{\pi^-}}$$ \hspace{1cm} (1.2)

and $N_{\pi^0}, N_{\pi^+}$ and $N_{\pi^-}$ are the multiplicities of produced neutral, positive and negative pions. The emitted pions are expected to come from a region with radius $R \approx 3 - 5$ fm. Since they are emitted coherently, the momentum scale of the pions is set by the uncertainty principle to be $p_T \sim 1/R \approx 40 - 100$ MeV/c [Gav95].

Measurements of the correlations of pion charge states produced in high-energy $pp$ collisions suggest that while the total number of pions may be determined by the dynamics of particle production, the charge of each pion is chosen at random. This implies that the distribution of $f$ should be given by the binomial distribution, $\langle f \rangle = 1/3$ and $\sigma_f = \sqrt{2/9N_\pi}$, which is quite narrow in high multiplicity events. Although equation (1.1) also gives $\langle f \rangle = 1/3$, it is substantially wider ($\sigma_f \sim .18$) and
highly asymmetric, with a maximum at $f = 0$. This should allow for the production of events in high energy hadronic or nuclear collisions with $f$ far away from 1/3. Although cosmic ray experiments have found events which seem to show such behavior [FHL80], $pp$ collider searches have found no corresponding evidence [A+83, A+86b, Mel96, B+97].

In this thesis, we present the first search for DCCs in ultra-relativistic heavy-ion collisions. Equation 1.1 suggests that the most direct signal of DCC production is the existence of events with large charge fluctuations. We have used the WA98 experiment, studying 158 AGeV $^{208}$Pb+Pb collisions at the CERN SPS accelerator, to measure the multiplicity of charged particles and photons in the central rapidity region event-by-event. We measure charged particles (80% of which are charged pions) with a Silicon Pad Multiplicity Detector, covering $2.35 < \eta < 3.75$. We measure photons (85% of which are neutral pions) with a Photon Multiplicity Detector covering $2.8 < \eta < 4.4$. We furthermore restrict our search to the events with large amounts of transverse energy produced into $3.5 < \eta < 5.5$, as DCCs are expected to be produced in the most violent central collisions of two lead ions. The correlation of $N_{ch}$ and $N_\gamma$ in each event allows us to look for non-binomial behavior in the partition of pion charge states. Observation of a clear signal would be important for understanding the properties of hot QCD, as it would be direct evidence of a second-order chiral phase transition.

In Chapter 2 we present an overview of QCD, chiral symmetry, and the theoretical work on DCCs. In Chapter 3 we present the experimental history of the subject and outline the strategy for the DCC search at the CERN SPS. In Chapters 4 and 5 we describe the WA98 experiment and the event selection criteria. In Chapters 6 and 7 we describe the two main detectors used for the search (the SPMD and PMD) in detail, to describe how they function and what systematic errors they create for the DCC measurement. Finally, in Chapters 8 and 9 we present the results of the DCC search and discuss them in the light of the cosmic ray data.
Chapter 2

Theoretical Motivation

...The sad and amazing fact is that this crappy estimate is as close to phenomenology as DCC theorists have come.

- e-mail from Sean Gavin
  July 1997

2.1 Quantum Chromodynamics (QCD)

Quantum Chromodynamics (QCD) is a field theory of the strong interaction that has been experimentally verified in many different systems and CMS energies. It explains the interactions between quarks, the fundamental constituents of hadrons, by the exchange of gluons, which carry a color charge. This is analogous to the interactions of charged particles by photon exchange, as in Quantum Electrodynamics (QED). But while photons do not themselves carry charge, gluons also carry color and are thus able to interact with themselves. This has important consequences, some of which will be explored in this section.

2.1.1 The QCD Lagrangian

Although Gell-Mann’s quark model successfully described the known hadrons in terms of fractionally-charged constituent objects, it could not resolve the existence of the $\Delta^{++}$ state, composed of three spin-aligned up quarks, with the fact that fermi statistics should prevent three identical particles from being in the same state. Nambu’s hypothesis that quarks carried “color” quantum numbers resolved this puzzle and was further confirmed by the measured ratio $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, which is a factor of 3 higher than it should be given the number of quark flavors available.
Free color, however, has never been observed. This suggests that quarks are "confined" by the color force into the colorless hadronic states where all three colors are present, as with baryons, or by having one color and one anti-color, as with mesons.

Colorless states are invariant under invariant under SU(3) transformations of the quark colors. This led to a theory where color is required to be a local symmetry of the Lagrangian, just as in QED, where requiring a local symmetry under gauge transformations of the fermionic electron field gives rise to the photon field. This local color symmetry gives rise to quark interactions via a set of bosonic gauge fields respecting the same symmetry - the gluons. Since SU(3) has eight generators, there are eight corresponding gluons, which are orthogonal combination of color-anticolor pairs that transform into each other under color SU(3) transformations.

QCD, then, is a gauge theory described by the following Lagrangian density:

\[ \mathcal{L} = -\frac{1}{4} G^\mu_\alpha G^\mu_\alpha + \sum_{\text{flavors}} \bar{q} (i\gamma^\mu - m_q) q \]

where

\[ \gamma^\mu = \gamma_\mu D^\mu = \gamma_\mu (\partial^\mu + ig T_\alpha G^\mu_\alpha) \]

It contains two types of particle: the spin-1/2 quarks (represented by the \( q \) fields) and the spin-1 gluons (\( G \)) through which they interact strongly. Although the six known quarks are usually seen arranged in three isodoublets of increasing mass, QCD is "flavor independent", a hypothesis which has been borne out experimentally. Instead, the interactions involve the exchange of color charge (\( r, b, g \) and \( \bar{r}, \bar{b}, \bar{g} \)).

### 2.1.2 Perturbative and Non-perturbative QCD

To first order, gluons allow quarks to interact with one another via the Yukawa-type terms in the QCD Lagrangian, just as electrons interact by exchanging photons. SU(3) symmetry, however, requires that there are additional terms in the theory through which gluons interact with themselves. This makes the theory non-linear and thus extremely complicated to solve analytically, and makes it especially hard to define a perturbation theory. Fortunately, at large momentum transfer (\( Q^2 >> A_{QCD} \approx 200 \text{ MeV} \)), the renormalized QCD coupling becomes weak:

\[ \alpha_s(\mu) = \frac{12\pi}{(33 - 2N_F) \ln \left( \frac{Q^2}{\Lambda^2} \right)} \]

a phenomenon known as asymptotic freedom. This is the basis for "perturbative QCD" (PQCD), which allows the calculation of many quantities measurable at high-energy accelerators, such as jet properties.

At low momentum transfer, the QCD coupling becomes quite large and quarks and gluons form
tightly bound color singlet states which we observe as hadrons. The transition between the large and small coupling regimes is a subject of “non-perturbative QCD” (NPQCD). This includes attempts understand the properties of the known hadrons, how they form in fragmentation processes, and the properties of the QCD vacuum, the lowest energy state of the theory. NPQCD is a large subject whose tools include lattice simulations, effective theories, sum rules and perturbation methods based on various symmetries of the theory. One of the more fruitful symmetries which has been exploited to understand the theory at low energies is the so-called “chiral” symmetry.

2.2 Chiral Symmetry in Strong Interactions

In this section we will discuss the physical implications of chiral symmetry and its spontaneous breaking in the QCD vacuum. For an excellent review of the theory and phenomenology of chiral symmetry breaking, see [Koc97].

2.2.1 Chiral transformations for quarks and hadrons

Soft hadronic physics is characterized by energy scales on the order of $\Lambda_{QCD}$. This is much larger than the current masses of the light quarks (5-15 MeV) so it is often a good approximation to neglect them altogether and to work with massless quarks. The quark sector of massless QCD with two flavors can be written in terms of an isodoublet of quarks $\psi \equiv (\begin{pmatrix} u \\ d \end{pmatrix})$:

$$\mathcal{L} = i \bar{\psi}_j \gamma_j \psi_j$$

SU(2) rotations of the quark fields leave the total Lagrangian invariant. These are classified as “vector” and “axial” rotations of the fields, by the behavior of their conserved currents, $J_\mu$, under parity.

<table>
<thead>
<tr>
<th>Transformation</th>
<th>General</th>
<th>Infinitesimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector</td>
<td>$\psi \rightarrow \exp(-i \frac{\sigma}{2} \cdot \bar{\sigma}) \psi$</td>
<td>$(1 - i \frac{\sigma}{2} \cdot \bar{\sigma})(\psi_R + \psi_L)$</td>
</tr>
<tr>
<td>Axial</td>
<td>$\psi \rightarrow \exp(-i \frac{\sigma}{2} \cdot \bar{\sigma}) \gamma_5 \psi$</td>
<td>$(1 - i \frac{\sigma}{2} \cdot \bar{\sigma})\psi_R + (1 + i \frac{\sigma}{2} \cdot \bar{\sigma})\psi_L$</td>
</tr>
</tbody>
</table>

To make the connection between vector and axial transformation and the chirality of the quarks, we note that $\frac{1+\gamma_5}{2} + \frac{1-\gamma_5}{2} = 1$, so $\psi = \psi_R + \psi_L$. Since the Lagrangian is invariant under vector and axial transformations, it is also invariant under linear combinations. As an example, we see that

$$\frac{1}{2}(V + A)\psi = (1 - i \frac{\sigma}{2} \cdot \bar{\sigma})\psi = \psi_R + (1 - i \frac{\sigma}{2} \cdot \bar{\sigma})\psi_L$$

which clearly only rotates the left-handed component of the quark fields. Thus, invariance under $SU(2)_V \otimes SU(2)_A$ implies that it is also invariant under $SU(2)_L \otimes SU(2)_R$. 

17
Hadronic states, whether baryons or mesons, have definite properties under vector and axial transformations, depending on their spin and parity. To show this, we can define wave functions that carry the relevant quantum numbers of the lightest scalar and vector mesons:

- **pion-like state:** \( \vec{\pi} \equiv i \bar{\psi} \vec{\gamma}_5 \psi \)
- **sigma-like state:** \( \sigma \equiv \bar{\psi} \psi \)
- **rho-like state:** \( \vec{\rho}_\mu \equiv \bar{\psi} \gamma_\mu \psi \)
- **a1-like state:** \( \vec{a}_{1\mu} \equiv \bar{\psi} \gamma_\mu \gamma_5 \psi \)

It is straightforward to show that vector transformations transform “pion-like” states into other pion states, and that “sigma-like” states transform into themselves:

\[
\vec{\pi} \rightarrow \vec{\pi} + \vec{\Theta} \times \vec{\pi} \\
\sigma \rightarrow \sigma
\]  

(2.3)

Axial transformations rotate pion and sigma states into each other but with opposite signs:

\[
\pi \rightarrow \pi - \vec{\Theta} \sigma \\
\sigma \rightarrow \sigma + \vec{\Theta} \cdot \vec{\pi}
\]  

(2.4)

### 2.2.2 Chiral Symmetry Breaking (\(\chi SB\))

We have seen that massless QCD is invariant under vector and axial transformations of the quark fields, and hence of the light hadron states. Experimentally, we observe that isospin is a conserved quantum number of the strong interactions, implying that vector currents are conserved. Although axial currents cannot be conserved, due to the non-zero current quark mass, the smallness of \(m_q\) compared to \(\Lambda_{QCD}\) suggests that it may be nearly conserved, a hypothesis which is borne out by experimental observations. The PCAC (Partially Conserved Axial Current) relation relates the divergence of the axial current to \(m_\pi^2\), which is small compared to hadronic scales, e.g. the mass of the proton (1 GeV\(^2\)). This relation can be used to predict the pion-nucleon coupling constant, which differs from the experimental value only by about 10%, verifying that the axial current is nearly conserved. But if vector currents are conserved, and axial currents are partially conserved, then any two states related by chiral transformations should have the same mass, just as with pions which are symmetric under isospin have nearly the same mass. \(^1\) Instead, we see that while pions are

---

\(^1\)From the above discussion, it is obvious that these transformations can take us from an eigenstate of definite parity to a mixed state. However, the strong interactions are invariant under parity transformations so this is not a real concern.
light, there is no accompanying sigma state, indicating that it is substantially heavier. Furthermore, while the vector mesons \((\rho, a_1)\) also form a chiral multiplet, the \(\rho\) and \(a_1\) mass differ by \(\approx 500\) MeV. Thus, the ground state of the theory is not at all symmetric under axial transformation, although the vector symmetry remains intact. The way out of this apparent puzzle is if chiral symmetry is “spontaneously broken” in the ground state. While the Lagrangian is chirally invariant, the ground state is not.

2.2.3 Linear Sigma Model (LSM)

Given the transformation rules in equations 2.3 and 2.4, it is straightforward to write down an effective theory of low-energy QCD which is chirally invariant, but where the ground state symmetry is spontaneously broken, using the combination \(\sigma^2 + \pi^2\). This is the well-known linear sigma model (LSM), first introduced by Gell-Mann and Levy [GML60].

\[
\mathcal{L} = \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2} \partial^\mu \pi_a \partial_\mu \sigma^{\pi_a} - \frac{\lambda}{4} [(\sigma^2 + \pi_a^2)^2 - f_\pi^2]^2 \tag{2.5}
\]

The LSM has been found to be an appropriate theory of the strong interactions at low energies, even when extended to include the light strange mesons, but breaks down at energies large compared to \(\Lambda_{QCD}\).

2.2.4 Spontaneous Symmetry Breaking

In a field theory, physical particles are the low-lying excitations of the ground state field configurations. The properties of these particles, especially their masses, are determined by the effective potential, which in this case is

\[
V_{eff}(\sigma, \vec{\pi}) = \frac{\lambda}{4} [(\sigma^2 + \pi_a^2)^2 - f_\pi^2]^2 \tag{2.6}
\]

This is a familiar “Mexican hat” potential, which is shown in figure 2-1 for two of the pion fields set to zero. This potential has a continuum of minima, described by \((\sigma^2 + \pi_a^2)^2 = f_\pi^2\) so \((\sigma) \neq 0\) and/or \((\pi) \neq 0\). If nature chooses a minimum at \((\pi) = 0\) and \((\sigma) = f_\pi\), then we can render the Mexican hat in two dimensions, with \(\sigma\) in one direction and all of the \(\vec{\pi}\) fields in the other. Clearly, excitations in the \(\pi\) direction would cost no potential energy, indicating that pions are massless. On the other hand, \(\sigma\) excitations will require a minimum energy to overcome the restoring force, \(m_\sigma = 2\lambda f_\pi^2\). This is a specific example of the Goldstone theorem [Gol61], where the spontaneous breaking of a continuous symmetry results in the presence of massless modes. Interestingly, while this mechanism seems to be responsible for the near masslessness of pions, it suggests the while the \(\sigma\) is massive, its mass is proportional to \(\lambda\), which does not enter anywhere else. Thus, it can be
arbitrarily large, possibly explaining its non-observation in pion interactions. A similar mechanism occurs in the Higgs sector of the standard model, and there as well the mass of the Higgs boson is not constrained by other parameters of the theory, at least at tree level.

2.2.5 Explicit Symmetry Breaking

On the other hand, we know that pions are not massless, indicating that the spontaneous breaking of chiral symmetry is not the whole story. This is because we have been neglecting the non-zero quark mass, which enters QCD as a term proportional to $\bar{q}q$, which has the same quantum numbers as the $\sigma$ field. Thus, we add a term to the sigma model Lagrangian, $-H\sigma$ which lowers the potential slightly in the $\sigma$ direction. This is precisely the mechanism which chooses the $\sigma$ direction for the ground state. Otherwise, any other state satisfying $\sigma^2 + \pi^2 = f_\pi$ would lead to similar results, and we would be allowed to redefine our quark doublet, and even the parity operation itself, to arrive at the physical world. With the explicit symmetry breaking term added, we must rewrite the effective potential to require that the minimum of the potential is still at $f_\pi$:

$$V_{\text{eff}} = \frac{\lambda}{4} (\sigma^2 + \pi^2 - v^2)^2 - \epsilon \sigma$$  \hspace{1cm} (2.7)

To leading order in $\epsilon$, $v = f_\pi - \frac{\epsilon}{3\lambda f_\pi}$, $m_{\pi}^2 = 2\lambda f_\pi^2 + \frac{\epsilon}{f_\pi}$, and $m_{\pi}^2 = \frac{\epsilon}{f_\pi}$, fixing $\epsilon = f_\pi m_{\pi}^2$. 

Figure 2-1: The "Mexican hat" potential described by equation (2.6).
2.2.6 Phenomenology of $\chi$SB and connection with QCD

The above model of QCD, where the meson interactions are approximately chirally symmetric, but the ground state symmetry is spontaneously broken, is consistent with the world we see around us. Isospin has long been known to be a good symmetry of the strong interactions, the slight differences between the pion masses being due to the slightly different masses of and the electromagnetic interactions between the valence quarks inside the mesons. It also explains why the $\rho$ and $a_1$, which form a spin-1 analog of $\pi$ and $\sigma$ also have different masses, the difference being predictable under the assumption of a spontaneously broken axial current [Sak69].

The picture which emerges is that the vacuum state of QCD is not empty space, the notion one usually associates with a “vacuum”, but an isoscalar $(\bar{q}q)$ condensate resulting from an attractive force between quarks. Extending the LSM to include initially massless baryons, it can be shown that the same dynamical mechanism leads to the large masses of baryons. The simplest explanation of this is if interactions with the condensate are what give quarks a large constituent mass, which explains how a proton can be 1 GeV even if the electroweak current masses of the quarks inside of it are 5-15 MeV each. Based on this hypothesis, one can calculate sum rules which predict the hadron masses very well. Still, while the LSM model contains the essential symmetries and a mechanism for symmetry breaking, it does not explain the nature of this attractive force in terms of quarks and gluons. This is highly non-trivial, as the ground state of QCD is inherently non-perturbative, but there do exist several models which may give more insight into the mechanism than the LSM. One of the more promising lines of research concerns the role of instantons in QCD, but this will not be discussed here. For a review, see [SS].

2.2.7 Restoration of Chiral Symmetry at high temperatures and densities

Spontaneously broken symmetries can be effectively restored at high temperatures if the induced fluctuations are larger than the relevant symmetry-breaking scales of the ground state. In the sigma model, there are two such energy scales: $f_\pi \approx 92$ MeV related to SSB, and $m_q \approx 5$-10 MeV related to the explicit symmetry breaking. If one can “heat” the system to a temperature which is large compared to these various energy scales, the system is no longer constrained to sit in the ground state and the expectation value of $(\sigma) \rightarrow 0$, and chiral symmetry is effectively restored. Calculations [GL89] estimate the dependence of the chiral condensate with temperature to go as

$$
\langle \bar{q}q \rangle_T = \langle 0 | \bar{q}q | 0 \rangle (1 - \frac{T^2}{8f_\pi^2}) + f \left( \frac{T^2}{8f_\pi^2} \right)
$$

with $f$ containing higher powers of $\frac{T^2}{8f_\pi^2}$. The chiral condensate decreases quadratically with $T$ until the critical temperature, $T_c$, at which point $\langle \bar{q}q \rangle$ goes to zero and chiral symmetry is restored.

It is also possible to restore chiral symmetry by increasing the baryon density far above that of
nuclear matter \((\rho_0 \approx 0.15 \text{ GeV/fm}^3)\), since the chiral condensate decreases linearly with the density

\[
\langle \bar{q}q \rangle_\rho = \langle \bar{q}q \rangle (1 - 0.35 \rho / \rho_0)
\]  

(2.9)

In fact, the condensate is already 35\% lower at nuclear matter density.

### 2.3 Particle Production in Heavy Ion Collisions

In this section, we review the basic phenomenology of hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. The idea is to introduce the proper kinematic variables and to clarify the basic physics scenario being studied at the SPS.

#### 2.3.1 \(pp\) Collisions

Produced hadrons in high-energy \(pp\) collisions above \(\sqrt{s} = 10\) GeV, have been found to be described by several simple features.

**Thermal \(p_T\) slopes** The transverse momentum distributions of pions have been found to be approximately Boltzmann distributed (i.e. exponential) and nearly independent of energy. This implies that particles are, to some level, produced thermally from an equilibrated system, the inverse slope parameter \(T\) of \(dN/d(p_T^2) = (1/p_T)dN/d(p_T) = \exp(-p_T/T)\) acting as an effective temperature. The average \(p_T\) of hadrons is about 350 MeV, giving an effective temperature of \(\sim 180\) MeV.

**Rapidity plateau** In hadron-hadron (\(pp, \pi p, Kp\)) experiments, it has been observed that the distribution of produced particles, when measured as a function of *rapidity*, defined as

\[
y = \frac{1}{2} \log \left( \frac{E + p_z}{E - p_z} \right)
\]

(2.10)

which is approximated in experiments by measuring the *pseudorapidity*,

\[
\eta = -\log \tan(\theta/2)
\]

(2.11)

shows a plateau structure around \(y = 0\). Assuming that the average transverse momentum of hadrons is independent of the colliding system and that the total hadron-hadron cross section is constant, Feynman postulated [Fey72] that this plateau is composed of particles arising from soft partons \((\bar{n}(x) \propto 1/x)\) whose interactions have a finite range characteristic of the energy scale of the strong interactions (1-2 units of rapidity).
Figure 2-2: a.) Schematic description of high-energy hadron-hadron collisions, adapted from reference [Fey72]. The central plateau was expected to be “universal” and independent of incident energy. b.) pA collisions, showing the predicted universal plateau and the observed smearing due to the contribution from soft partons. c.) Central AA collisions, with minimal target and projectile fragmentation regions, and a large central rapidity peak.
Scaling of charged multiplicity  The average number of produced charged particles, \( \langle N_{ch} \rangle \), grows slowly with energy [Per91] as

\[
\langle N_{ch} \rangle = A + B \ln s.
\]  \hspace{1cm} (2.12)

At high energies, two colliding particles are separated in rapidity by \( \Delta y = \ln 2P + \ln 2P = \ln(s) \) where \( P \) is the beam momentum and \( s \) is the squared center of mass energy. If the particle density is mostly uniform, except at rapidities within 1-2 units from the colliding particles, and reaches a universal density at \( y = 0 \), then the multiplicity should scale with \( \ln(s) \). Instead, it has been found that the density at mid-rapidity

\[
\rho(0) = \frac{1}{\sigma_1} \frac{d\sigma}{d\eta}
\]  \hspace{1cm} (2.13)

grows with \( \sqrt{s} \) [A+86a]. This is understood to be due to the fact that the gluon structure function at low \( x \) rises faster than \( 1/x \).

Binomial Partition  At threshold, the charge of produced pions is highly correlated with the isospin of the colliding system. However, at sufficiently high energies and at central rapidities, such isospin constraints become less important. Measurements of the average number of \( \pi^0 \) produced given a measured number of \( \pi^- \) and the correlation functions between the two \( (f_{0-}) \) have been found to be consistent with a binomial partition of the charge states, with \( p_{ch} = 2/3 \) [GM75]. This indicates that the charge states of the pions are chosen independently (or at least pairwise, to conserve charge) by a statistical process.

These observations make clear predictions about \( N_{ch} \), \( E_T \), and \( N_\gamma \). The fact that \( \langle p_T \rangle \) is independent of energy means that \( N_{ch} \) will be strongly correlated with \( E_T \). Moreover, the fact that the charge states pions are chosen randomly implies that \( N_\gamma \) will be correlated with both \( E_T \) and \( N_{ch} \). It also predicts that while the rapidity plateau should appear at ISR energies or higher \( (\Delta y = 8) \) it will not appear at lower energies. For instance, SPS energies \( (\Delta y \approx 6 \) have only 1-2 units of rapidity available in the central region after cutting away the target and projectile fragmentation regions. Thus, they should have rapidity distributions that are approximately gaussian.

2.3.2 \( pA \) Collisions

Colliding proton beams with nuclear targets lets one understand how a proton loses energy travelling through nuclear matter. Observations of \( pA \) collisions at 200 GeV/c revealed several interesting features:

**Target dependence**  The multiplicity in the target fragmentation region for \( \pi, K \) and \( p + A \) collisions was found to depend linearly on the target "thickness" \( \nu = A\sigma_{hp}/\sigma_{hA}E^+80 \). No such
dependence was found in the projectile fragmentation region, consistent with the "limiting fragmentation" predicted by Yang [Y+69] and Feynman, which predicts that the target and projectile rapidity regions should be determined mainly by the characteristics of the target or projectile system.

**No Plateau** While the plateau was expected to be the same universal density as seen in pp collisions, the projectile was found to "drag" the soft particles along with it, creating a smooth interpolation between target and projectile regions, as shown in Figure 2-2b.

The overall multiplicities measured in pA reactions could be explained by the so-called "wounded-nucleon model" [BBC76], which assumes that an interacting nucleon is excited (wounded) and remains so until it leaves the interaction zone, although it can excite other nuclei on the way. In this model, the nuclear geometry dictates how many nucleons are wounded, but the particle production itself only depends on the properties of the excited nucleons. It was originally thought that the wounded nucleons would de-excite outside of the target nucleus, which would subsequently fall apart, creating a large peak at $\eta = 0$ extending 1-2 units of pseudorapidity and then a plateau extending out to the beam fragmentation region. In fact, the transition is smooth, again due to the buildup of low-$x$ partons in the central region.

### 2.3.3 AA Collisions

The geometry of nuclear collisions is shown in Figure 2-3. At high energies the nuclei are essentially Lorentz-contraction bags of nucleons, the longitudinal momentum of each given by $1/A$ of the CMS beam or target momentum and with transverse momentum deriving mainly from the Fermi momentum, $\hbar c/R \approx 30 \text{ MeV}/c$. At high enough momenta, the uncertainty principle $\Delta p \Delta x \approx 1$ indicates that the nucleons in the nuclei do not see the colliding nuclei, but just the nucleons inside them. Thus, the kinematics are given to first order by elementary pp (or NN) collisions. From pA collisions, however, we see that the presence of the nuclear medium modifies particle production by allowing the possibility of multiple collisions. Furthermore, AA collisions create a much larger reaction zone, where produced secondaries may in fact reinteract with nucleons, wounded nucleons, or even other secondaries, depositing even more energy at mid-rapidity. Thus, we see that the central rapidity region, shown in Figure 2-2c, is where we will find the highest multiplicities and the hottest temperatures in the collision. Moreover, the temperature of the nuclear system will thus depend on the "centrality" of the collision, i.e. how close the nuclei were as they interacted. Figure 2-3 shows a "peripheral" collision, with a large impact parameter. "Central" events are characterized by a small impact parameter.

It has already been noted for pA collisions that particle production is largely determined by the number of wounded nucleons. Thus, in a collision where the impact parameter $b \neq 0 \text{fm}$, while some
Figure 2-3: Geometry of a peripheral heavy ion collision in the center of mass frame, with the two Lorentz-contracted nuclei separated by a transverse distance $b$.

nucleons in the projectile collide with nucleons in the target nucleus, the remaining nucleons just act as spectators to the reaction. This suggests that one can directly measure the impact parameter of the collision by measuring the projectile spectators that continue in the beam direction, each carrying most of their original momentum. This is usually called the “forward energy” $E_F$ as it is measured by a Zero-Degree Calorimeter (ZDC). But since the number of participants in the projectile is approximately $A - N_{\text{spect.}}$, and $E_T$ goes as the number of participants, $E_T$ and $E_F$ should be tightly anti-correlated.

2.3.4 Thermodynamic Quantities

To describe the restoration chiral symmetry, we have invoked the language of “heating” the system. In fact, several thermodynamic quantities have their counterparts in experimental observables:

Temperature As discussed above, the temperature is defined as the inverse slope of the $p_T$ distribution of produced hadrons. It must be kept in mind that this is the freezeout temperature, and not the temperature of the initial, perhaps thermalized, state.

Energy Density Bjorken [Bjo83] has estimated the energy density for the central plateau, $\epsilon_{BJ}$ in
the high-energy limit as the measured rapidity density multiplied by the average transverse energy per particle divided by the space-time volume:

\[ \epsilon_{BJ} = \frac{dE_T}{dn} \frac{1}{\tau A} \]  

(2.14)

where \( A \) is the cross sectional area of the nuclei \( A = \pi (1.2 A^{1/3} \text{fm})^2 \) and \( \tau \) is the "formation time" of the hot region, estimated to be \( \sim 1 \text{ fm} \). Although this formula relies on the presence of a plateau in the central region, it is often applied even at SPS energies and gives energy densities around \( 3 \text{ GeV/fm}^3 \) [Mor96].

**Entropy** While \( E_T \) measures the energy available for particle production, this energy may be partitioned into physical particles differently depending on the structure functions in the central region (e.g. if there are many soft gluons which may hadronize into soft pions) and by the number of different kinematically accessible particle states. Thus, the multiplicity of produced hadrons is correlated with the number of degrees of freedom available to the system, which is the common definition of the entropy.

**Volume** The volume is measured experimentally using HBT correlations. Bose statistics gives us the result that \( P(n + 1) = (n + 1)P(n) \), implying that pion emission will be enhanced when several occupy the same state. By the uncertainty principle, \( \Delta p \Delta x \sim \hbar \), this gives rise to an enhancement at \( \delta p \equiv q \sim \hbar / \Delta x \approx R \), the spatial extent of the system. HBT measurements have been made at many energies in many different systems [Pra95] but will not be discussed in this thesis.

Obviously, if such measurables are going to truly measure their corresponding thermodynamic quantity, then the system should be in thermal equilibrium. This is a non-trivial property to measure, which is mainly achieved by comparing data to thermal models [BH97], and will not be discussed here. And yet, the correspondence is reasonable enough for us to be able to say that the best place to look for an environment hot enough to melt the chiral condensate will be in the most central collisions, with large \( E_T \) and small \( E_F \). Moreover, these will also be the highest multiplicity events.

### 2.4 Disoriented Chiral Condensates

#### 2.4.1 Description and formation

In the last eight years, several authors have suggested that the restoration of chiral symmetry may have observable consequences in high-energy hadronic and nuclear collisions if temperatures are sufficient to create regions of vacuum where chiral symmetry is restored by the disappearance of the chiral condensate. As this region cools, it may settle into a metastable state with a chiral condensate...
which not pointing in the sigma direction. As this “Disoriented Chiral Condensate” (DCC) realigns itself with the normal vacuum, it must radiate pions to balance out the difference in quantum numbers. Since the chiral order parameter may explore all of \((\sigma, \pi)\) space, its final isospin direction is random, leading to a neutral fraction of produced pions that can differ from 1/3. Instead, the neutral fraction of the pions produced by DCC decay has the distribution:

\[
P(f) = \frac{1}{2\sqrt{f}} \tag{2.15}
\]

where

\[
f = \frac{N_{\pi^0}}{N_{\pi^+} + N_{\pi^0} + N_{\pi^-}} \tag{2.16}
\]

where \(N_{\pi^+}, N_{\pi^0}\) and \(N_{\pi^-}\) are the numbers of positive, neutral, and negative pions produced in a particular collision process.

This can be derived (following the argument in [Raj95]) by writing \(f\) in terms of the cartesian pion fields:

\[
f = \frac{\pi^2}{\pi_x^2 + \pi_y^2 + \pi_z^2} \tag{2.17}
\]

and parametrizing the fields on the 3-sphere, \(\pi^2 + \sigma^2 = f\), as

\[(\sigma, \pi_x, \pi_z, \pi_y) = (\cos \theta, \sin \theta \cos \phi, \sin \theta \sin \phi \cos \eta, \sin \theta \sin \phi \sin \eta) \tag{2.18}\]

Thus,

\[
f = \cos^2 \phi. \tag{2.19}\]

Now, if all values on the 3-sphere are equally probably, then the CDF for \(f\) is determined by the integral

\[
P(f) = \int_{-1}^{1} P(f')df' = \frac{1}{2\pi^2} \int_0^{2\pi} d\theta \int_0^\pi d\sin^2 \theta \int_{\arccos \sqrt{f}}^\pi d\phi \sin \phi = \sqrt{f} + C \tag{2.20}
\]

so

\[
P(f) = \frac{dP}{df} = \frac{1}{2\sqrt{f}} \tag{2.21}
\]

as given in equation (2.15)

The process of chiral symmetry restoration and its subsequent breaking is shown in figure 2-4.
In a.) the ground state of the system lies in the global minimum selected by the H-term in the Lagrangian, given by the non-zero current mass of the quarks. In a high energy collision, it is hoped that a large, hot region is created where fluctuations are substantially larger than the SSB scale, $f_\pi$. At this point, the effective potential resembles b.) which has a single minimum at $(\phi) = 0$. After a time on the order of several fm/c, the system cools via longitudinal and transverse expansion. The condensate is then sensitive to the shape of the potential, but not yet to the influence of the quark mass. In other words, it is allowed to settle in a metastable state somewhere else in the valley, disoriented with respect to the normal vacuum. Finally, in d.) the system has cooled sufficiently that the quark mass forces the system back to the normal ground state. As the system relaxes from from b.) to d.), it radiates soft quanta, i.e. pions, to balance out the quantum numbers, the charge distribution obeying 2.15.

2.4.2 Theoretical work

Anselm and collaborators [AR91] were the first to suggest that a chirally symmetric classical pion field may be formed at high energies, which would emit pions coherently when it decays leading to unusual ratios of charged and neutral particles. The dynamics of such a field, called a Disoriented Chiral Condensate (DCC), was explored by Blaizot and Krzywicki [BK92], who first calculated Equation (2.15), among others. Bjorken, Kowalski, and Taylor [BKC93] developed a phenomenology relevant to $pp$ collisions, where a region of chirally restored vacuum would be protected from the outside world by a hot shell of debris expanding at the speed of light. If the shell remained intact for several fermi, the region could settle into a disoriented state and radiate as it is converted to normal vacuum. This model, called “Baked Alaska”, is generally not seen to be relevant for nuclear collisions since it is unlikely that such a shell shell could ever form in the complex environment of a nucleus-nucleus collision.

Rajagopal and Wilczek opened up a new line of inquiry by trying to study QCD at the critical point by exploiting the chiral symmetry of QCD and its similarity to the O(4) Heisenberg magnet, which has a second-order phase transition [PW84, RW93a]. Appealing to universality, they argue that calculations already done for the magnet model using renormalization group methods [BNM78] should also apply to QCD. They have applied these results directly to QCD at the critical point, calculating quantities like $m_\pi$ and $m_\sigma$ as the system goes through the phase transition. Lattice calculations have subsequently been used to confirm the assumption of universality [Raj95]. Of course, the correlation length of a system undergoing a second-order phase transition diverges at the critical temperature, This creates the possibility for coherent long- wavelength fluctuations of the order parameter, analogous to domains in a ferromagnet. The only problem is that this relies on the Goldstone mechanism to create massless pion modes, while real QCD has non-zero quark masses, making the pion modes massive. This gives the transition a characteristic length scale on
<table>
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<th>a.) Normal Vacuum</th>
<th>b.) Chirally Restored Vacuum</th>
<th>c.) Partially Broken Vacuum</th>
<th>d.) Normal Vacuum</th>
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Figure 2-4: Steps in the restoration of chiral symmetry in heavy ion collisions.
the order of the compton wavelength of the pion, \( \xi \approx 1/m_\pi = 1 - 2 \text{ fm} \), apparently precluding such long-wavelength modes from forming.

Rajagopal and Wilczek argue that such reasoning only applies when the system is in equilibrium as it passes through the critical point. Instead, they found that if the system is far out of equilibrium as it passes through the critical temperature, it is possible to dynamically enhance the probability of the formation of large coherent domains with well-defined values of the chiral order parameter. This led them to the "quench" scenario, where the system reaches equilibrium in the chirally symmetric state (the top of the Mexican hat) and is suddenly "frozen" in that state. In other words, the system begins in a completely disordered state, the fluctuations in all fields averaging out to zero, but subsequently evolves according to the \( T = 0 \) equations of motion, with the effective potential of Figure 2-4a rather than b.

Numerical simulations of the quench scenario show striking results [RW93b]. While the system begins in a completely random state, within about 20-30 fm most of the power is pumped into the long-wavelength modes, corresponding to pion momenta of 40-100 MeV/c. The short-wavelength modes showed no such amplification. Rajagopal explains this qualitatively by realizing that the masslessness of Nambu-Goldstone modes is the result of an algebraic cancellation \( m^2 = -\mu^2 + \lambda \phi^2 \), where the second term derives from an interaction with a condensate that takes the value \( \mu^2 / \lambda \) in the ground state. This can also be seen directly from the pion equations of motion if one makes a Hartree (mean-field) approximation, where the \( \phi^2 \) term in the EOM is replaced by its spatial average \( \langle \phi^2 \rangle \):

\[
\frac{\partial^2 \pi(\vec{k},t)}{\partial t^2} = (\lambda \phi^2 - \lambda (\phi^2) - k^2)\pi = -m_{\pi}^2 \pi(\vec{k},t)
\]

In a quench, the condensate begins at \( \langle \phi \rangle = 0 \) and oscillates to its final value \( \langle \phi \rangle = v \). Thus, sufficiently long-wavelength (i.e. low-k) modes will have a negative mass and the solutions will grow exponentially.

### 2.4.3 DCC "phenomenology"

Equation 2.15 sums up all that is definitively known about DCCs. It predicts that the event-by-event fluctuations of the ratio of neutral to all pions generated by a DCC follows a characteristic distribution qualitatively different than that predicted by the "generic" production described in Section 2.3.1. In this case, the measured distribution of \( f \) is determined by the binomial distribution and is thus Gaussian with \( \langle f \rangle = 1/3 \) and \( \sigma_f = \sigma_e/N = \sqrt{f(1-f)N}/N = \sqrt{2/9N} \). For \( N = 300 \), \( \sigma_f \approx 3\% \). Moreover, these pions are thermally distributed in momentum. Pions produced by a DCC, however, are produced coherently with the charge distribution shown in (2.15) which is asymmetric and substantially wider. The two are compared in figure 2-5. The momentum of these pions is given
by the Fourier transform of the domain, implying that the momenta are on the order of $1/R$. Thus, the larger the domain, the softer the pions.

In high-energy hadronic and nuclear reactions, more than 80% of produced particles are neutral or charged pions. Thus, the clearest signature of DCC production in such reactions would be the presence of non-statistical fluctuations in the ratio of produced charged pions and photons. Charged pions are easily detected through standard techniques (e.g. wire chambers or silicon detectors) and neutral pions, observed via their electromagnetic decay ($BR(\pi^0 \rightarrow \gamma + \gamma) \approx 98.7\%$), can be detected by calorimetric techniques.

And yet, there exists no fundamental theoretical model to predict the magnitude of the fluctuations induced by DCCs. Sean Gavin has made estimate [Gav95] of the multiplicity and momentum spectrum of pions produced by a DCC assuming a single domain of $R_{DCC} = 4$ fm and a vacuum energy density $\epsilon$ due to the disorientation of this domain with respect to the normal vacuum outside. The magnitude of $\epsilon$, essentially the depth of the Mexican hat, depends on $\lambda$ in the LSM and is thus a free parameter of the theory which must be constrained by experiment. However, the MIT bag model [CJJ+74] can predict many properties of mesons and baryons using a bag constant of $(146 \text{ MeV})^4$. Converting this to an energy density with $\hbar c = 200 \text{ MeV/fm} = 1$, we get $\epsilon \approx 60 \text{MeV/fm}^3$. This is the difference in energy density inside the proton, where chiral symmetry is restored and outside the proton where it is broken. Such an energy density inside a DCC of volume $V$ can create $\epsilon V/m_\pi$ pions. Thus, we have a model which predicts that about 120 low-$p_T$ pions are produced by a DCC. Although there are large uncertainties in this model (a factor of 4 in both directions), it suggests that a DCC effect may be large enough to be detected in an actual experiment.

Figure 2-5: $P(f)$ for a DCC and for 300 generically produced pions.
Chapter 3

Search for DCCs at the SPS

Research is what I'm doing when I don't know what I'm doing.

– Werner von Braun

3.1 Experimental History

By allowing the possibility of events with almost no electromagnetic energy or no charged hadrons, DCCs are an attractive hypothesis to explain the “Centauro” and “Anti-centauro” events seen in cosmic rays [FHL80]. A notable example of an anti-centauro, where a large region of phase space has many photons but no accompanying charged particles, has been shown by the JACEE collaboration (see Figure 3-1) who use balloon-borne detectors. Such events have already motivated searches for unusual charge fluctuations at the S$ar{p}$pS (by UA1 [A+83] and UA5 [A+86b]) and at the Tevatron (by Minimax [B+97] and CDF [Mel96]). None of these searches has yielded any candidate events or extracted a non-binomial component to pion production, whether at central rapidities or in the forward region (as had been predicted in [Gou86]). And yet, there have been no systematic studies utilizing the simultaneous measurement of charged and neutral multiplicities in heavy ion collisions at any energy.

3.2 DCC Search with WA98

The WA98 experiment at the SPS has the unique capability to measure both the multiplicity of charged particles at mid-rapidity (2.35 < η < 3.75) and of photons in a significant portion of the forward hemisphere (2.8 < η < 4.4). They are positioned such that a large, single-domain DCC formed in the hot central region of a collision would be seen as non-statistical anti-correlations, far away from the “bulk” of the events, characterized by the “generic” binomial partition of charge
states. However, we do not know a priori how the data will look in general, much less in rare events. Thus, it is critical to use an event generator to model the “standard” physics measured in experiments at lower energies and smaller systems.

3.3 **VENUS 4.12**

To describe the bulk of the data we use the VENUS 4.12 [Wer93] event generator with its default settings. VENUS simulates hadron-hadron interactions by using Gribov-Regge Theory to calculate elastic and total cross-sections and models the inelastic processes by “cutting” the diagrams which make up the elastic amplitudes. The picture which emerges is that when two high-energy nucleons interact, they exchange color between them, forming color strings which fragment into hadrons. This exchange can occur in four different ways, with different probabilities [Wer95].

**Non-diffractive scattering** (46%) wherein the colliding nucleons each exchange a single quark.

**Diffractive projectile excitation** (22%) where the target emits a colorless object that excites the projectile.

**Diffractive target excitation** (22%) where the projectile emits a colorless object that excites the target.

**Pomeron-pomeron scattering** (10%) where the projectile and target both emit colorless objects that interact.

Two strings are created in both cases, but they differ in the fate of the interacting nucleons. In diffractive scattering, the identity of the nucleon is unchanged.

VENUS models nucleus-nucleus collisions by assuming the nucleons in the colliding nuclei to be randomly distributed within the nuclear volumes. As the nuclei collide at a given impact parameter $b$, the nucleons exchange color as described above, forming hadrons and strings, which subsequently fragment. While early versions of the program performed no additional space-time evolution of the system, later versions (including 4.12) take account of interactions between the produced secondaries. Hadrons are evolved in space-time and when two come within a critical radius of one another, they are coalesced into “quark droplets”, which contain the sum of the quantum numbers of the colliding particles. The droplet decays statistically according to the available phase space constrained by the initial quantum numbers. Such a mechanism distinguishes VENUS from other cascade-type models like RQMD, which models the entire collision using two body collision cross-sections.

The acceptance of the charged particle and photon multiplicity detectors in WA98 are shown in Figures 3-2a and b superimposed upon the expected distributions from VENUS for events with $b < 6$ fm. The charged particle acceptance is large enough to observe about half of the produced
charged particles, with a similarly large fraction of produced photons observable with the photon detector.

3.4 Model of DCC production

To estimate the effect of DCC production in heavy ion collisions, we have modified several ensembles of VENUS events to include the characteristic fluctuations in the relative production of charged and neutral pions. As we have seen in Chapter 2, there are no detailed models incorporating DCCs into the context of real nuclear collision. Thus, we have devised a model to answer a simple question: how would a normal event appear in our apparatus if $\zeta\%$ of the pions in the final state of the event had a charge distribution characteristic of a DCC? We assume that only a single domain of DCC is formed in each central collision. A certain fraction $\zeta = N_\pi^{DCC}/N_\pi$ of the VENUS pions is associated with this domain, where $N_\pi^{DCC}$ is the number of DCC pions and $N_\pi$ is the total number of pions. A value of $f$ is then chosen randomly according to the distribution given in equation 2.15 and the charges of the pions are interchanged pairwise (e.g. we flip a $\pi^+\pi^-$ to a $\pi^0\pi^0$ pair) until the charge distribution matches the chosen value of $f$. A DCC created in this fashion has the same $p_T$ distribution of the original event, as the momentum of the pions is unchanged. Thus, this model simulates a DCC accompanied by the normal hadronic background in a way that conserves momentum and charge, and approximately conserves energy (up to the mass difference between charged and neutral pions).

The $N_{ch}$ vs. $N_{\gamma\text{-like}}$ distribution is shown for $\zeta = 60\%$ in Figure 3-3 compared to the reference distribution ($\zeta = 0$). The quantity $N_{\gamma\text{-like}}$ is closely related to the number of photons produced at mid-rapidity and will be described in detail in Chapter 7.
Figure 3-1: An "anti-centauro" event presented by the JACEE collaboration [LI92].
Figure 3-2: Acceptance of charged particles and photons (represented as $2 \times (\pi_0 + \eta)$) for VENUS events with $b < 6$ fm.

Figure 3-3: $N_{ch}$ vs. $N_{\eta\text{-like}}$ for 0% and 60% DCC.
Chapter 4

The WA98 Experiment at CERN

*Shut up and watch the lights.*

– B. Wyslouch to P. Steinberg

December 1994

4.1 General Motivation

The WA98 experiment, installed in the H3 beamline at the CERN SPS, has been designed to be a large acceptance, general purpose apparatus for measuring several possible signals of the quark-gluon plasma at the same time. Whereas some other CERN and AGS experiments are optimized to examine one particular aspect of the many collisions, WA98 attempts to take a broader view, with capabilities to measure several so-called “global” variables with full azimuthal coverage. This included the forward and transverse energy ($E_T$ and $E_F$), and the charged and neutral multiplicities ($N_\gamma$ and $N_{ch}$) in the central region ($2 < \eta < 4$). It was the only CERN experiment to directly measure photons with a large electromagnetic calorimeter, and thus was one of only two experiments (along with the electron experiment NA45) capable of measuring direct thermal photons created by hard quark-quark and quark-gluon processes. Finally, two spectrometer arms measuring positively and negatively charged hadrons were situated behind a large dipole magnet. These spectrometers had large enough acceptance to measure several particles in each event, allowing for studies of HBT interferometry and strangeness production. The hope was to classify each event by means of the global measurements (e.g. centrality or correlations in $N_\gamma$ and $N_{ch}$), and to look for modifications in the charged and neutral hadron spectra or the two-particle correlation function.

This chapter will briefly describe the experimental setup of the full experiment. The charged and photon multiplicity detectors will be discussed in greater detail in Chapters 6 and 7.
4.2 Experimental Setup

For completeness, the full apparatus will be briefly described in this section. The arrangement of the detectors is shown in Figure 4-1 and a close-up of the target region is shown in Figure 4-2. In the latter, we show the target, the Silicon Drift Detector (SDD) which is not used in this analysis, and the Silicon Pad Multiplicity Detector (SPMD). Arrows show the trajectories followed by particles with $\eta = 2.3, 3$ and $3.8$, which correspond respectively to the outer, mid-rapidity and inner region of the SPMD.

4.2.1 Beam and Target

WA98 is a fixed-target experiment in the H3 beamline at the CERN SPS, which delivers $^{208}$Pb beams at 158 AGeV, or 32.8 TeV for the total beam energy. The full CERN accelerator complex is shown in Figure 4-3, with the path travelled by the lead ions indicated on the figure. The acceleration stages, the kinetic energy at each stage, the efficiency, and the number of ions accelerated in each SPS cycle are listed in Table 4.1. The SPS cycle lasts 19.2 seconds, with 14.4 seconds of acceleration and 4.8 seconds of extraction, called a “spill”.

Lead ions are produced by evaporation of the metal from a 'micro-oven' and are fed into an ECR (electron cyclotron resonance) ion source. The source is a plasma generator which confines a plasma longitudinally with two solenoids and radially with a Fe-Nd-B permanent sextupole magnet. Plasma electrons at the cyclotron frequency are heated and cause additional ionization. The ions which escape longitudinally out the ends of the source can be extracted using electrostatic techniques.

Figure 4-1: The WA98 Experiment at the CERN SPS. Only a subset of these detectors are used in this analysis.
each SPS cycle $2.85 \times 10^{10}$ Pb$^{28+}$ ions are extracted from the source with energies of 2.5 keV/nucleon and sent into a radio-frequency quadrapole (RFQ) that accelerates the ions up to 250 keV/nucleon and feeds them into the Linac 3. This accelerates the ions up to 4.2 MeV/nucleon and sends them through a stripper foil to increase the charge from Pb$^{28+}$ to Pb$^{53+}$, but with only a 16% efficiency. From here the ions head into the PS Booster (PSB) a synchrotron that gives them a kinetic energy of 95.4 MeV/nucleon and then feeds them into the PS accelerator, which takes them up to 4.25 GeV/nucleon. Finally, the ions are fully stripped (to Pb$^{82+}$) by another foil and the SPS accelerates the $^{208}$Pb beam to 33 TeV, or 158 GeV/nucleon. At this point, accelerating slow ions in synchrotrons designed for faster particles and the transfer process between acceleration stages has eliminated 98% of the ions from the source. Acceleration in the SPS loses about 30% of what remains, and then these are divided up among up to six experiments, who demand very different beam rates. The typical rates seen by WA98 varied depending on the experimental configuration but reached a maximum of

<table>
<thead>
<tr>
<th>Accelerator/Element</th>
<th>Output $T(\beta)$</th>
<th>Efficiency</th>
<th>Pb Ions/cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECR Source</td>
<td>2.5 keV/u (.0023)</td>
<td></td>
<td>$2.85 \times 10^{10}$</td>
</tr>
<tr>
<td>RFQ</td>
<td>250 keV/u (.023)</td>
<td>.9</td>
<td></td>
</tr>
<tr>
<td>Linac 3</td>
<td>4.2 MeV/u (.094)</td>
<td>.9</td>
<td>$2.31 \times 10^{10}$</td>
</tr>
<tr>
<td>Stripper Foil</td>
<td></td>
<td>.16</td>
<td>$3.70 \times 10^{9}$</td>
</tr>
<tr>
<td>PSB</td>
<td>95.4 MeV/u (.421)</td>
<td>.24</td>
<td>$8.88 \times 10^{8}$</td>
</tr>
<tr>
<td>PS</td>
<td>4.25 GeV/u (.984)</td>
<td>.67</td>
<td>$5.91 \times 10^{8}$</td>
</tr>
<tr>
<td>SPS</td>
<td>158 GeV/u ($\sim 1$)</td>
<td>.67</td>
<td>$3.93 \times 10^{8}$</td>
</tr>
</tbody>
</table>

Table 4.1: Stages in the acceleration of lead ions in the SPS complex. The overall efficiency between the ion source and the SPS extraction is $\eta = .014$ [A+93].
Figure 4-3: The CERN accelerator complex. Heavy ions are generated by an ECR source (1), accelerated through Linac 3 (2), the PSB (3), the PS (4), and finally the SPS (5) up to energies of 158 GeV/nucleon. (Figure courtesy of CERN)
The lead targets used are 210 and 436 μm thick and mounted on an aluminum wheel with five spaces for targets. In the various beamtimes during which WA98 took data, there were also carbon, nickel and niobium targets.

4.2.2 Start and Veto counters

The incident beam is measured by a gas Čerenkov counter designed and built by the Tsukuba group [C+96] and positioned 3.5 meters upstream of the target. Incident particles travelling faster than the speed of light in a medium produce light in a cone characteristic of the velocity of the particle. This light is collected and read out through photomultiplier. The timing resolution achieved in WA98 was better than 30ps. To reject against accidental triggers from muons in the beam halo, we use the Inner and Outer Halo counters, which are scintillator arrays positioned about 5.7 and 6 meters upstream of the target. To reject further against halo particles close to the beam axis, a Little Veto counter, consisting of a piece of scintillator with an 8 mm diameter hole, was positioned 3 meters upstream of the target, 50 cm downstream of the start counter.

4.2.3 Plastic Ball

The Plastic Ball detector, originally built for experiments at the Bevalac accelerator at Berkeley, measures particles in the target fragmentation region (−1.7 < η < 0.5) in full azimuth, allowing for detailed studies of directed and elliptical flow as well as particle correlations [B+82]. It consists of 655 ΔE − E detector modules, where the ΔE counter is a CaF₂(Eu) crystal and the E counter is a plastic scintillator. These are read out by a photomultiplier system in conjunction with a LeCroy TDC system. Comparison of the energy deposited in the ΔE and E layers of scintillator allow the identification of pions, protons, and heavier fragments (d,t) up to kinetic energies of 250 keV. By using the TDCs to look for the muons from stopped π⁺s which decay in the scintillator, these particles can also be identified and their energy measured. Due to the high particle densities in the forward direction, the Plastic Ball is only able to resolve single particles in the target fragmentation region (−0.7 < η < .1). This is a region particularly sensitive to the directed flow of target spectator matter, including protons and fragments, makes the Plastic Ball a useful tool to study the reaction-plane dependence of many observables. In this thesis, we only use the detector as an interaction trigger, as described below.

4.2.4 MIRAC and ZDC

The produced transverse energy flow in 3.5 < η < 5.8 was measured in the MIRAC calorimeter, located 24 meters downstream of the target. The detector consists of 30 stacks, each divided verti-
cally into six 20cm × 20cm towers and segmented longitudinally into electromagnetic and hadronic sections. The electromagnetic section is 15.6\(X_0\) deep (8 absorption lengths) and was constructed of alternating layers of lead (3 mm) and scintillating plastic (3 mm). The hadronic section is 6.1 absorption lengths deep and is constructed of layers of iron (8 mm) and scintillator. The showers in both sections were read out through wavelength shifter coupled to photomultipliers. The resolution was 17.9%/\(\sqrt{E}\) for the electromagnetic section and 46.1%/\(\sqrt{E}\) for hadronic energy. Further details of the construction and operation of this calorimeter have been described elsewhere\[A+89\]. In this thesis, \(E_T\) refers to the corrected sum of transverse energy deposited in 3.5 < \(\eta\) < 5.5, where the azimuthal acceptance is more than 50%.

The Zero-Degree Calorimeter (ZDC) is constructed of 35 modules (7 × 5) consisting layers of lead and scintillator also read out by wavelength shifter. The full assembly is 105 cm × 75 cm × 202 cm and was positioned 30 meters downstream of the target. The ZDC is tilted 3° with respect to the beam direction in order to distribute the showers from 33 TeV Pb ions over several modules.

4.2.5 Multiplicity Detectors

To perform the DCC search, we measure the charged and neutral multiplicities at mid-rapidity. WA98 uses two types of silicon detectors, the Silicon Pad Multiplicity Detector (SPMD) and the Silicon Drift Detector (SDD), to measure charged particles at mid-rapidity. Both are made from 300 \(\mu m\)-thick silicon wafers and radial geometry, although the detection principles are somewhat different. To measure photons, we use the Photon Multiplicity Detector (PMD), a high-granularity “preshower” detector that measures electromagnetic showers before they have developed to their full spatial extent.

**Silicon Pad Multiplicity Detector**

The Silicon Pad Multiplicity Detector (SPMD) is a circular pad detector used to detect the passage of charged particles in 2.35 < \(\eta\) < 3.75. It is composed of four quadrants, each segmented into 22 bins in pseudorapidity and 46 bins in \(\phi\). The segmentation increases with increasing radius, making the acceptance of each pad uniform in pseudorapidity. The detector is a 300 \(\mu m\) n-type wafer implanted with \(p^+\) pads. This creates a p-n junction across which 50V is applied to fully deplete the silicon. When a charged particle traverses the silicon wafer, the most probable value for the energy loss is about 84 keV. This corresponds to about 24000 electron-hole pairs produced in the depletion zone. The liberated charge induces a signal on aluminum pads which are separated by ONO dielectric from the \(p^+\) pads. As the readout electronics are mounted next to the outermost pads, it is necessary to read out the signals through traces cut from a second aluminum layer, separated from the first by 1 \(\mu m\) of SOG (spun-on glass). Traces on the inner pads run over the outer pads until they reach the electronics. The readout is done using the IDE VA-1 chip, which has a 128-channel charge sensitive
amplifier and storage capacitors. The geometry and operation of the SPMD will be described in more detail in Chapter 6.

**Silicon Drift Detector**

The SDD [GR84] is a circular detector, fashioned from a single 3" silicon wafer, with a hole cut out from the middle to allow the beam to pass through. The wafer is implanted with $p^+$ rings on both sides, with one replaced by $n^+$ ring at the outer edge of the detector. The $p^+$ implants create two depleted regions, one on each side, that present a parabolic potential to the electrons liberated by the minimum ionizing particle. A longitudinal voltage (typically 1000-2500V) is then applied to several rings via the $p^+$ implants, which act as voltage dividers, to drift the electrons outward to the edge of the detector. The drift time then gives the radial position of the impinging particle. This can give an extremely precise two-dimensional image of the pattern of particles impinging on the detector, although the precision is limited by the knowledge of the drift speed, which depends strongly on the applied voltage. The silicon drift detector was operational during the 1996 run, but several technical problems have prevented the analysis from reaching the final stage. Thus, it is not included in this analysis, although it extends the charged multiplicity measurement to $\eta \approx 2$.

**PMD**

The Photon Multiplicity Detector (PMD) is a large preshower detector that measures photon multiplicity from $2.8 < \eta < 4.4$. Photons convert in $3X_0$ of lead and leave an appreciable amount of energy about $\approx 70\%$ of the time, while hadrons only convert $15\%$ of the time. The converter is thin enough that the showers do not develop to their full width $2R_M$, where $R_M$ is the Molière radius [Leo94] which is about $2X_0$ (1 cm) for lead. The shower secondaries are collected in $\sim 40000$ scintillating tiles read out through wavelength shifting fibers and digitized by a system of Image Intensifiers (IIs) coupled to CCD cameras. The digitized data is filtered through a cluster algorithm and the number of resolved clusters for each event is $N_\gamma$-like, which contains an admixture of primary photons, photons from target and air conversions, and background from hadrons that interact strongly and mimic a photon signal. Further details and results from the PMD are presented in Chapter 7.

4.2.6 LEDA and CPV

To measure the energy of photons produced in $2. < \eta < 3.$ we use the LEadglass Detector Array (LEDA). To reject hadron-induced showers in the leadglass, we use the Charged Particle Veto (CPV) positioned directly in front of LEDA.

LEDA consists of 10080 TF1 lead glass modules of cross section $4 \text{ cm} \times 4 \text{ cm}$. These are glued into arrays of $6 \times 4$ modules, called supermodules, using carbon fiber and epoxy. Each supermodule
contains 24 photomultiplier tubes with individual high-voltage generators and an independent gain monitoring system based on LEDs and PIN-diodes. The supermodules are themselves stacked into two large subunits containing 5040 modules each. Photons impinging on the detector shower in the lead glass and the charged particles produced are detected via the Čerenkov effect. By setting thresholds properly, one may reject hadrons, which are slower than electrons and photons of the same momentum. The resolution for electromagnetic showers measured with an electron beam at the CERN SPS was \( \frac{0.8\% + 5.5\%}{\sqrt{E}} \).

The CPV consists of two sets of 86 Iarocci-type plastic streamer tubes that overlap the LEDA acceptance and allow the rejection of showers stemming from charged particles rather than from photons. The tubes cover 19 m\(^2\) are filled with a mixture of Argon(10%), Isobutane (30%) and \( CO_2 \) (60%). A charged particle traversing the tube creates a thin discharge channel (called a “streamer”) which start from the anode wire and propagates a few millimeters toward the cathode. A streamer discharge induces a signal on externally mounted pads, which are 42 mm \( \times \) 7 mm. Groups of 16 pads are connected to a charge-sensitive amplifier chip that integrates the charge and stores it as a voltage level in sample-and-hold units that are digitized by a 6-bit FADC when a trigger arrives. For the WA98 CPV, 17 chips are read out in series and the digitized signals are processed by a DSP that adds addressing information, subtracts pedestals, and can remove hits below a set threshold. 49120 pads and 3070 chips are necessary to read out the full CPV acceptance.

4.2.7 Tracking and TOF systems

To measure the momentum of charged particles, we analyze the produced particles with a dipole magnet and measure their trajectories with tracking chambers positioned downstream of the magnet. Combined with the momentum measured in the tracking chambers, the velocity measured with a Time-of-Flight (TOF) detector allows the calculation of the mass of the incident particle.

The WA98 tracking system is composed of two spectrometer arms and the large Goliath dipole magnet, which delivers .8 Tm of bending power. The negative particles are measured in 6 Multi-step Avalanche Chambers (MSAC) with optical readout built by a Lund-Geneva collaboration and a Time-of-Flight (rTOF) wall build by a group from JINR, Dubna. Each MSAC plane contains a series of parallel meshes preceded by a gas-filled conversion gap, in which impinging charged particles liberate electrons. These are amplified by a large electric field and then allowed to drift. If a trigger signal arrives, then a reverse bias voltage is removed from a gate layer that normally prevents the amplification process from continuing. After three amplification and two drift stages the amplified electrons are converted into light by TEA (triethylamine), a photoemissive vapor mixed with the ambient gas. The emitted light is wavelength-shifted toward the blue range and is reflected by a thin mylar mirror towards a CCD camera mounted below the detectors.

The rTOF is a large hodoscope consisting of scintillator slats with PMT readout at both ends.
It has a time resolution of $\sim 120$ ps.

The positive tracking arm has two planes of streamer tubes, similar to those used for the CPV, and two planes of Lund-built Pad Chambers, which are similar to the MSACs but employ a pad readout to read out the charge directly instead of with CCDs. This readout system has proven to be very reliable, as noise hits were confined mainly to one pad while real hits to two or more. The TOF wall on this arm built by the Tsukuba group, developed for the PHENIX detector at RHIC, achieved a time resolution of $\sim 80$ps.

4.3 Trigger and Data Acquisition

4.3.1 The WA98 Trigger

The full WA98 experiment utilizes detectors of different readout speeds, from the nanoseconds achievable by the PMT-based detectors, to the milliseconds needed by the SPMD and PMD, to the very slow MSACs. Thus, the trigger system has been designed to interleave different trigger types, in order to read out the faster detectors while the slower detectors are busy.

In Table 4.2 we summarize the main trigger conditions referred to in this thesis. Coincidence is indicated by "+", anti-coincidence by "-", and a blank indicates that this signal is not relevant to the particular trigger. The main "beam" trigger condition is a signal in the start counter with no coincident signal in the Little Veto, which would indicate the passage of an off-axis beam halo particle. The hardware sum of the MIRAC energy, the signal in each tube weighted to simulate the $\sin \theta$ calculation, is fed into three discriminators with thresholds set to define three further event classes. The lowest threshold defines a "minimum-bias" physics event, where an interaction is thought to have occurred. The next highest threshold defines the upper bound on "peripheral" (large impact-parameter) events. The highest threshold then defines the lower bound on "central" (small impact-parameter) events. Events which satisfy the peripheral condition but not the central condition are classified as "not-so-central". A stronger interaction trigger is provided by a threshold on the hardware sum of energy signals from the forward two rings in the Plastic Ball detector. Requiring this signal to be present lets us reject downstream interactions, where a beam particle or part of the halo strikes the beam pipe, causing a shower of significant energy that satisfies the minimum-bias trigger conditions. To optimize the use of the output tape drives, the different triggers are "scaled down", i.e. rejected randomly by factors of $2^n$, to enrich various samples by decreasing the number of events of other types written to tape. Typically, peripheral events were scaled down by a factor of 16, NSC by a factor of 8 and centrals were left alone, since they contain the rare high-multiplicity events.
Table 4.2: Main WA98 trigger conditions. On the top are listed the various detectors incorporated into the trigger logic. In the table, '+' indicates coincidence, '-' indicates anti-coincidence, and ' ' indicates that the status of this detector does not matter for this trigger.

<table>
<thead>
<tr>
<th>Start Counter</th>
<th>Little Veto</th>
<th>In/Out Halo</th>
<th>Plastic Ball</th>
<th>$E_T$ Low</th>
<th>$E_T$ Peri.</th>
<th>$E_T$ Cent</th>
<th>Trigger Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accepted:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Beam</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Clean Beam</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
<td>Min. Bias/Per. Interaction</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>NSC Interaction</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>Central Interaction</td>
</tr>
<tr>
<td>Rejected:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td>Upstream Interaction</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>Downstream Interaction</td>
</tr>
</tbody>
</table>

4.3.2 Data Acquisition

The WA98 data acquisition (abbreviated as DAQ) is based upon the QDAC system, originally designed as a “Quick Data ACquisition” for test beams, which was found to have a low enough overhead to be adequate for the full setup. Detectors are read out independently by OS9-based front-end processors running a Sub-Event Builder (SEB) program. While each SEB process is capable of reading out every detector on the experiment, the program running on a particular processor is configured externally by reading in a “CAMAC Definition File” (CDF) that instructs the program which detector to read, how to read it, and assigns a subevent ID which uniquely identifies the subevent on the data structure written to tape. The SEB processors are used for buffering as well as readout, a fact which allows one to distribute the data acquisition load more evenly by adding additional processors as needed.

The processors communicate among themselves via TAXI (Transparent Asynchronous transmitter/receiver Interface) units connected by fiber-optic cables. Upon receiving a hardware trigger, a “trigger” process running on the main event builder requests the SEBs to read their subevents and store them in memory. When this is finished, they tell the trigger process that they are ready for the next event. SEBs are read out on any of three conditions: 1) The SEB memory is 80% full, which happens only rarely, 2) A spill-on event arrives, 3 seconds ahead of the actual spill, to flush the buffers of calibration events taken between spills, or 3) A spill-off event arrives, indicating that no physics events will happen for 14 seconds. At these times the main event builder (located near the tape drive) reads out the SEB buffers, constructs the full events, and writes out the events to a DLT2000 Digital Linear Tape. Thus, a minimum amount of data is written to tape during the spill, minimizing the arbitration overhead on the front-end processors, and maximizing the number of written events.
The WA98 data was written out in 400 MB segments, called "runs", each containing from 7000-10000 "events". The events were divided into three "trigger types", listed in Table 4.3. The trigger types are ordered by the integration time and readout speed of the detectors included. Type 1 events contain the various PMT-based detectors. Type 2 contains the multiplicity counters which have large event sizes. Type 3 is mainly for the optical-readout MSACs which had to be run at a lower rate than the other detectors. Each trigger type includes those detectors of lower types, i.e. Type 2 contains the Type 1 detectors, and Type 3 contains Types 1 and 2. This arrangement allows the faster detectors to collect data while the slower detectors are busy, optimizing the use of the data acquisition. In the data presented in this thesis, the magnet was switched off and the tracking detectors removed from the DAQ. Thus, there are no type 3 events, and about half of them were Type 2.

### 4.4 Data Production

The data used in this thesis was processed using the WA98 analysis package (ANPACK) on a DEC AlphaServer 8400. M. Purschke and B. Kolb designed the basic structure of the package, and created the ANPACK[Pur] libraries which handle file access and access to the events in a run. H. Kalechofsky compiled the various detector offline codes and put them into the WA98_PB95 package, which was updated in 1996 to include the second tracking arm but kept the older name. The output of the WA98_PB95 package was intended to be a DST file that would contain the processed data in a compressed form, using the CERN ZEBRA[CERc] package. However, these files proved to be quite large (150% of the raw data size) and were thus unwieldy when trying to analyze large amounts of data. Thus, it was decided not create DSTs at all, but to make Column-Wise Ntuples (CWN) for use with PAW[CERb], the standard analysis package. A third package (DST) was developed to create HBOOK CWNs directly from the raw data processed by WA98_PB95. Whereas the raw data is stored in files of 400 MB each, the produced CWNs were 20-60 MB each, depending on the detector configuration for a particular run, as the stored data could be compressed bitwise to avoid unused space in the common blocks.

ABACUS, the MIT AlphaServer, managed by W. Wander and S. Galley of the MITLNS Scientific Computing Facility, consisted (in 1997) of 12 437MHz 64-bit Alpha CPUs and 4GB of RAM arranged...
in an SMP architecture. Digital UNIX 4.0 is able to distribute processes to the different processors in real time, dynamically balancing the load. The system also included a tape robot with six DLT4000 drives and the capacity to hold 176 tapes. The entire WA98 1996 data set fit onto 130 DLT2000 cartridges, so all of it could be accessible from ABACUS at any time.

The data production is managed by two separate processes. The staging process loads and reads in as many tapes as there are free tape drives onto a large capacity scratch disk, until the free space on disk is less than $N_{\text{Drives}} \times 400$ MB. In that case, it waits until more space is freed, as the raw data is deleted after it is processed. The production process waits for runs to be fully loaded, whereupon ANPACK is started and produces the final CWN. Since the staging and production processes are independent of one another, it is often necessary to check log files by hand to see if runs were not processed for reasons of disk space, system crashes, or tape malfunctioning. Still, the resources available on ABACUS are usually large enough that this only happens a few percent of the time. Instead, with the tapes reading at 1MB/second and a SCSI bus with only 7MB/second bandwidth, the system is usually limited more by the speed of reading the tapes rather than the processing speed. This is especially true when analyzing only a subset of the detectors.

For this thesis, we use only 350 runs out of 4000 produced in 1996. Moreover, these runs do not contain any of the tracking detectors, keeping down CPU needs. Thus, we are able to reanalyze the subset of the full data set (140GB of data) in less than a day.
Chapter 5

Event Selection

5.1 Introduction

As shown in Figure 3-3, DCCs can lead to large event-by-event fluctuations in the relative multiplicity of charged and neutral multiplicities. We thus require the data to be as free from pileup events and systematic distortions as possible. To do this we have

1. made tight cuts using the trigger detectors to eliminate double events and non-target interactions
2. chosen a subset of the full data set where the spectrometer magnet is turned off.

Using MIRAC, we have also selected the 10% most central events in order to enhance the possibility of a DCC signal, which we call the “central sample”

5.2 Trigger Cuts

With $5 - 10 \times 10^5$ lead ions per spill passing through the target during an effective spill of 2-3 seconds and an interaction probability of about 1%, we expect an interaction to happen every 300 $\mu$s on the average and to trigger on it about 80% of the time (see D. Morrison’s WA98 report [Mor96]). The PMD integration time is slightly longer than the SPMD (see Chapter 7), so it is possible that a pileup event will be detected by the PMD and not by the SPMD. Such events would precisely mimic a DCC signal. Thus, it is critical to reject such events using other detectors.

The WA98 trigger system has been designed to reject beam pileup by two methods. The first is by using the signal pulse height from the start counter, as this integrates the total charge within a 50 ns window. Double interactions are removed by using the cuts listed in Table 5.1.

The second method uses several TDCs which separately see signals coming from the trigger detectors. “Early” TDCs are able to detect events coming before the recorded event, while “delay”
TDCs detect events coming after it. Both TDCs are restarted by the event trigger and stopped by a signal in a window $d = 100 \text{ ns}$, $500 \text{ ns}$, or $10 \mu\text{s}$ before or after the actual event. The signal coming to the early TDC is delayed by the length of time equal to the full range of the TDC. If an event occurs at time $t$ before the triggered event, the earlier event will appear after the event at time $d - t$.

Distributions of the early and delay TDCs for the $E_T(\text{low})$ signal are shown in Figure 5-1.

The geometry of the trigger detectors is shown in Figure 5-2 and their properties are listed in Table 5.2. They cover a substantial amount of the solid angle around the target, allowing us to distinguish interactions which originate upstream or downstream of the target.

While a second event in a $10\mu\text{s}$ window is not a problem for LEDA, the SPMD and PMD integrate two events which occur within a few $\mu\text{s}$ from each other. Thus, for the analysis in this thesis, we have chosen the cuts shown in Tables 5.3 and 5.4. After these cuts, we estimate that .02% of the remaining events are due to pileup.
Figure 5-2: Geometry of the WA98 Detectors, not drawn to scale

<table>
<thead>
<tr>
<th>Name</th>
<th>Detector Type</th>
<th>Position</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Halo</td>
<td>Large Scintillator Slats</td>
<td>-6m</td>
<td>TDC</td>
</tr>
<tr>
<td>Inner Halo</td>
<td>Small Scintillator Slats</td>
<td>-5.7m</td>
<td>TDC</td>
</tr>
<tr>
<td>Start Counter</td>
<td>Gas Cerenkov</td>
<td>-3.5m</td>
<td>ADC/TDC</td>
</tr>
<tr>
<td>Little Veto</td>
<td>Scintillator</td>
<td>-2.7m</td>
<td>TDC</td>
</tr>
<tr>
<td>Plastic Ball</td>
<td>Phoswich</td>
<td>-1.7 &lt; η &lt; 0.5</td>
<td>Forward/Backward sum</td>
</tr>
<tr>
<td>MIRAC</td>
<td>Lead/Iron-Scintillator</td>
<td>+25m</td>
<td>( E_T(\text{Low,Per,Cent}) )</td>
</tr>
<tr>
<td>ZDC</td>
<td>Lead-Scintillator</td>
<td>+30m</td>
<td>( E_F(\text{Low}) )</td>
</tr>
</tbody>
</table>

Table 5.2: Trigger detectors used in this analysis to eliminate event pileup.

<table>
<thead>
<tr>
<th>Trigger Detector</th>
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<td>lveto</td>
</tr>
<tr>
<td>Inner Halo</td>
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<td>ihalo</td>
</tr>
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<td>0 - 600</td>
<td>zdc</td>
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<tr>
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<td>Pileup</td>
<td>0 - 591</td>
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Table 5.3: Early TDC cuts used to eliminate pileup events occurring before the event trigger. TDCs falling into the indicated ranges fail the cut.

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<tr>
<th>Cut name: etd</th>
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<th>Purpose</th>
<th>Delay TDC cut</th>
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<td>0 - 617</td>
<td></td>
</tr>
<tr>
<td>( E_T ) Low</td>
<td>Pileup after event</td>
<td>0 - 600</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4: Delay TDC cuts used to eliminate pileup events occurring after the event trigger. TDC values falling in the indicated ranges fail the cut.
Several additional cuts are applied even after all pileup has been removed using the trigger ADCs and TDCs. These are listed in Table 5.5, which also lists the section where each condition is described. We can cut even harder on pileup by requiring the sum of energy deposited in the MIRAC ($3.5 < \eta < 5.5$) and ZDC ($\eta > 6$) to be consistent with a single event. This is done by linearizing the $E_T$ vs. $E_F$ correlation plot, with the formula $|E_T - (33 - E_{ZDC}) \times \frac{\text{E}_T}{35}|$, which is Gaussian distributed, and requiring that an event fall within $5\sigma$ from zero.

Table 5.6 is a truth table showing various combinations of the aforementioned cuts and the types of events they reject. Requiring all events to be “good events” removes 30% of the data sample on tape. This leaves us with .01% of the event sample which may contain pileup events with less than 70 additional particles at mid-rapidity. These events are too small to satisfy the minimum-bias $E_T$ trigger and would thus be missed by our cuts.
5.3 Data Selection

5.3.1 DCC Run II

The data analyzed in this thesis is from WA98 Runs 11245-11573, which is called the “DCC Run II”. During the time this data was taken, the Goliath magnet was switched off. This makes the data analysis easier as it removes distortions in the angular distributions of the PMD arising from charged particles swept sideways by the dipole field, which would otherwise have to be simulated and understood in great detail before it could be corrected.

5.3.2 “Central” sample

When all of the cuts are applied to the minimum-bias data, around 480000 events are left. About half of these are central events, as the peripheral and NSC events have been scaled down (as discussed in 4.3.1). For the DCC search, we will concentrate on the most central events, defined by a measured transverse energy of at least 300 GeV in $3.5 < \eta < 5.5$. These correspond roughly to 10% of the Pb+Pb minimum bias cross section $\sigma_{mb} = 6200 \pm 620$ mb. After all cuts are applied, there are 212646 events in this sample, which we will refer to as the “central” sample in the rest of this thesis.
Chapter 6

Silicon Pad Multiplicity Detector

Remember ...
They're going to buy it,
We're going to build it,
And it's going to be beautiful!

- e-mail from Bernie Wadsworth
  December 4, 1994

6.1 Introduction

The Silicon Pad Multiplicity Detector (SPMD), built by a collaboration between MIT and National Central University (NCU), Taiwan, was designed in the summer of 1994; assembled, tested, and installed in WA98 by October 1995; and used for lead beamtimes in 1995 and 1996. A photograph of the detector is shown in Figure 6-1.

The SPMD detector has been designed to serve several purposes. Primarily, it would serve to measure the multiplicity of charged particles at mid-rapidity. However, it can also act as an important cross-check on multiplicity and position for the Silicon Drift Detector installed in WA98. While the spatial resolution of the SDD is much better, there can be large uncertainties in the absolute position measurement due to uncertainties in the drift speed and it is useful to have a detector which gives a fixed space point with every hit. Finally, the SPMD pad design and readout are similar to that intended for the PHOBOS detector at RHIC, so in some sense it has turned out to be a prototype for future experiments.
Figure 6-1: Photograph of the SPMD placed next to a 5" compact disc (photo courtesy of Peter Berges, MIT).
Figure 6-2: a.) Subset of a SPMD silicon wafer, showing a detector quadrant and several test structures. Pad rows 1, 10 and 22 are indicated to show the numbering system used in this chapter. b.) C-V curves as a function of pad radius for wafer 4, φ = 1.

6.2 Detector Design

6.2.1 Silicon Wafer

The design requirements were to cover a significant part of the phase space explored in heavy ion collisions at the SPS in pseudorapidity (η) and azimuthal angle (φ) while keeping the occupancy below 20%. Although silicon detectors fabricated from a single circular 4” wafer existed at the time, it was realized that by splitting the active area into four separate quadrants, each cut from a single 4” wafer, one could cover a larger area as well as simplify the construction. The final wafer design was made by ERSO, Taiwan and is shown in Figure 6-2a. This also shows some of the test structures on the 4” wafer including several other small silicon detectors as well as structures used study the bulk properties of the wafer itself. The active surface of each SPMD quadrant is divided into 46 φ-wedges and 22 slices in η, making 1012 channels in all. The radial spacing is such that the Δη is approximately 0.06 for all bins. This keeps the occupancy fairly uniform over the detector surface in normal physics events.

The geometrical parameters of the SPMD pads, starting from the inner pads and moving outward (i.e. Row 1 is the innermost row), are listed in Table 6.2.1. In this table, \( r_{in} \) and \( r_{out} \) refer to the inner and outer radius (in mm) of the pad. These numbers were obtained from the AutoCAD files used to fabricate the lithographic masks for the silicon production. Converting these radii to a polar angle, assuming \( z_{SPMD} = 328.5 \) mm, we get \( η_{out} \) and \( η_{in} \) which are “reversed” due to the definition of η = − log tan(θ/2). Δη gives the difference of the two, which is the pseudorapidity...
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<th>Row</th>
<th>( r_{\text{in}} ) (mm)</th>
<th>( r_{\text{out}} ) (mm)</th>
<th>( \eta_{\text{out}} )</th>
<th>( \eta_{\text{in}} )</th>
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Table 6.1: Parameters of the SPMD pads. These are explained in the text.

bin size needed in section 6.4.3 to calculate the pseudorapidity density. We define the geometrical acceptance \( \epsilon_{\text{geom}, \eta} \) as the ratio of the number of good pads to the total number in each radial bin. The criteria used to decide if a pad is working will be described in Section 6.4.2. It is clear that this number is quite small in row 22, where many of the pads are disconnected. Finally, we list the factor which relates the Landau mean to the Landau peak, \( C_\eta \), which will also be described in Section 6.4.2.

An automated procedure was created for testing the overall quality of the wafers and obtaining C-V curves for each channel, which are used to check for proper depletion with increasing voltage and are sensitive to disconnected or shorted pads, which have an anomalously small or large capacitance relative to the nearby pads. The behavior is predicted to be \( C \propto A/\sqrt{V_B} \) \cite{Leo94} where \( A \) is the area of the pad, and \( V_B \) is the applied bias voltage. A family of C-V curves for one \( \phi \)-wedge (\( \phi = 1 \)) of one wafer (wafer #4) is shown Figure 6-2b. Two features can be immediately seen: 1) The capacitance rises with increasing pad radius, and 2) it falls with increasing voltage. From 50-70V, the capacitance seems to saturate, thus we chose to run the detector at \( V_B = 50V \) during the experiment.
6.2.2 Mounting

The SPMD sits very close to the lead target, in front of the photon detectors (LEDA and PMD) which are positioned about 20m farther downstream. To avoid excessive conversions in the SPMD care has been taken to minimize the amount and density of material in the regions which overlap the other detectors. For the PMD, this is not a problem as it subtends $\eta > 2.8$, which is overlapped only by 300 $\mu$m of silicon. LEDA, however, subtends $2. < \eta < 3.$ and is also overlapped by the electronics and their mounting. Thus, it was chosen to mount the chips and associated electronic components on a 700$\mu$m-thick piece of beryllium glued to two 1mm-thick ceramic “octant” pieces. The silicon is in turn glued to the beryllium quadrant. Signals from the sensitive area of the silicon wafer are brought to the edge of the wafer by top metal traces, are amplified by the preamp/shaper chips sitting on the beryllium quadrant, pass through bonding wires connected to the inner edge of the octants and then pass through an inner layer of the ceramic to the connectors on the outer edge. A cross section of an SPMD quadrant is shown in Figure 6-3.

6.2.3 Readout System

Electronics

Signals from the depleted silicon wafer are read out via aluminum signal lines bonded to VA-1 chips (produced by IDE, Norway). Each chip contains 128 charge preamplifiers with a gain of 12.5 mV/fC, followed by a CR-RC shaper, sample-and-hold, and an analog multiplexer with a differential output buffer. While the intrinsic rise-time in the silicon is on the order of a nanosecond, it requires shaping to facilitate the speed of the external readout system. The shaping time is adjustable and was set to 0.6$\mu$s in order to minimize pileup at the higher beam rates. In Figure 6-4 we show a schematic drawing of the shaped pulse. Note that while the rise time is short, the signal falls over a much longer interval. This is a potential hazard at high beam rates, as new signals appearing several
Figure 6-4: Signal pulse output by the VA-1 chip, after shaping. The peak arrives 600 ns after the particle impinges on the detector.

...microseconds after the triggered pulse may be superimposed on top of pedestals pulled below the baseline by the decaying signal pulse.

The VA-1 can be read out in two modes: “trigger” mode, which is the normal mode of operation, and “test” mode where a selected amount of charge can be delivered to each channel by a common capacitor. A schematic diagram of the SPMD readout system is shown in Figure 6-5. Ribbon cables connect each quadrant to Hybrid Adaptor Boards (HAB), mounted in an aluminum box about 1m from the detector itself. The HABs supply the necessary power, the control bias voltages and the currents for the chips. They also act as buffers for digital control signals from the sequencer.

The readout is controlled by the “sequencer” which sits in a separate box close to the HABs. It contains the optically decoupled trigger input and sends and receives control signals from a Fiber-Optic Link (FOL) which has input and output ports. The digital FOL is based on multimode fibers and TAXI chips and is capable of sending only digital codes. One cable receives clock signals from a clock module 45m in the electronics room. The other transmits synchronization signals for the Flash-ADC system. The sequencer is initialized by a VME-based output register (AVME9412). It also contains the DAC which provides the required voltage for calibration mode.

**Readout sequence**

The VA-1 chip has two readout modes. “Trigger” mode is used in the normal readout of the detector. “Test” mode is used for calibration by injecting charge into the readout capacitors.

The output of the chips on a particular quadrant are multiplexed, and the signals read-out by a daisy chain connection. In trigger mode, the sequencer is initialized by a trigger signal from external logic (e.g. the WA98 trigger). A hold signal is then sent to the VA-1 chips 600ns after the original trigger, just when the shaped signals have reached their peak. The stored signals from eight VA-1s
are then read out sequentially, one chip at a time. The sequencer sends "shift-in" signals one at a
time, each time receiving the signal from the next channel. When it reads out the 128th channel,
the chip sends a "shift out" signal to the sequencer, at which point it reads out the next chip. The
incoming signals pass through the buffer amplifier in the HABs and are finally sent via the 45m
signal cable to the Struck 750 FADC system in the electronics room. This takes place at 2.5 MHz,
so the full digitization time is .4ms in trigger mode.

Since a common capacitor is used for the calibration of 128 channels in a single VA-1 chip, one
can obtain information concerning the relative gain of each channel. In test mode, a calibration
signal is determined by the DAC on the sequencer and is applied to input of each preamplifier in
serial order using an input multiplexer. The control synchronization signals are sent by the VME
output register through the FOL. After each signal, the sequencer provides the appearance of an
analog output signal and the corresponding synchronization signal for the FADC. Thus, the readout
timing in this mode is determined by the VME-based processor, as opposed to the clock module, as
in trigger mode. The measured noise in the VA1 channels in test mode are somewhat larger than
trigger mode, 2.4 and .92 channels respectively. This depends on the length of the cable between
the HAB and hybrid.
6.3 Assembly & Installation

6.3.1 Testbeam installation and performance

To measure the efficiency for charged particle detection, we put one quadrant of the SPMD (Sub-assembly # 4) in a testbeam at the H3 beamline at the CERN SPS. The detector was surrounded by a silicon hodoscope from NCU and two small scintillator paddles to define a trigger. Instead of using the WA98 data acquisition, we used a LabView-based system developed at MIT. With this, we were able to read 15-20 events per SPS spill. Thus we could saturate our data acquisition with just the muons that penetrated the beam stops when the beam was nominally off, illuminating the detector surface uniformly. We took 120000 events in this configuration. By finding events with one good track in the hodoscope, we measured an efficiency of greater than 99% for working pads and found that approximately 1% of the particles shared charge between two or more pads, the rate given by the effective inter-pad spacing of 15 μm, rather than the design spacing of 50 μm. For additional details, see the Senior Thesis of Ryan Caveney [Cav96].

6.3.2 Installation in WA98

A pre-condition of installing the SPMD in WA98 was that it had to be capable of running in vacuum down to $10^{-4}$ mbar, in order to minimize $\gamma$ conversions in air. To achieve this, special flanges had to be designed and machined that would allow o-ring sealing wherever possible. Additional gaps were sealed with silicon putty. Using 2.5mm rubber o-rings, we achieved vacuum of down to $8 - 9 \times 10^{-4}$ mbar in a very large evacuated region, including the whole magnetic field region (a volume of several cubic meters).

The SPMD sits 328.5 mm from the target position, with the readout chips facing away from the target itself. The quadrants are mounted such that the boundaries fall at roughly 45° with respect to the vertical axis. The top and bottom quadrants sit 1mm closer to the target than the left and right (as indicated by “upper” and “lower” in Figure 6-6). The $z$ positions of the upper and lower quadrants are determined by the position of the alumina shim shown in Figure 6-3. While a temperature monitor was set up to measure the temperature of the detector, it was not used during the run. However, the leakage current for each quadrant could be measured via four cables stretched from the detector to the control room. It was sampled roughly once every eight hours and the currents were recorded in the experimental logbook. Typically, currents were between 3 and 7 $\mu$A and varied slowly over the course of each day.
6.4 Principles of SPMD Data Analysis

Analyzing the SPMD requires three passes through the data. In the first, we extract pedestals and channel noise. In the second, we extract the gain of each channel by fitting the signal distribution to a Landau distribution convoluted with a gaussian. In the third pass, we can extract hits by looking for signals with energy above a threshold. Finally, with the hits from each event, we can calculate the charged particle multiplicity and the pseudorapidity density of charged particles.

6.4.1 Pass 1: Pedestals and Noise

We measure the pedestals and noise for each SPMD channel by analyzing 'pulser' events, which are taken in between SPS spills. The mean ADC in each channel gives the pedestal ($p_i$), which is subtracted from each signal in data events, and the standard deviation ($\sigma_i$) gives us the convolution of various sources of noise in the detector and readout. The distribution of pedestal and noise for each channel is shown in Figure 6-7a and 6-7b.
Figure 6-7: a.) Pedestal value (in ADC counts) for each channel, b.) Pedestal noise in each channel.
It is clear from Figure 6-7 the pedestals have characteristic ranges and channel-to-channel variations which vary from chip to chip. Because we use the analog signal to determine the charged multiplicity in each event, we store the 4096 pedestal values in a database (HEPDB, from CERN) for each experimental run and use the set of values in a particular run when doing the offline analysis. The variation is not more than 5% over long periods of time, but this can change the effective gain by a similar amount, which is critical for the multiplicity measurement described below.

The distribution of noise as a function of channel number is uniform across the detector and is on average slightly less than 1 ADC channel. It has a structure which is correlated with the pad radius, the noise increasing with increasing pad size. This is related to the differences in input capacitance, shown above. The disconnected channels in Preamp 4 on each quadrant show up as adjacent channels with a noise of approximately .6. In principle, they see just the noise from the electronics and no capacitive load from the silicon and the metal traces. However, they are also sensitive to the correlated noise observed in the SPMD, discussed below.

There are also several channels with a large noise, far greater than the average. These have been hypothesized to come from imperfections in the silicon itself, which lead to large leakage currents as charge builds up in the imperfection site. This hypothesis was borne out by the fact that the noise would decrease after turning off the detector and the bias voltage for a period of time and then restoring it. The noise also varies slightly run-to-run but since this is not critical for the multiplicity measurement, no run-by-run correction is applied.

6.4.2 Pass 2: Gains

Charged particles passing through matter deposit a small fraction of their energy which depends on the Z of the projectile and the target material, the incident velocity, the thickness of material traversed, and several other properties of the material. The average energy deposited \( \langle \Delta \rangle \) is given by the Bethe-Bloch formula (from [Leo94]):

\[
\langle \Delta \rangle \equiv \xi = 2\pi N a r_e^2 m_e c^2 \rho Z (\frac{\rho}{A})^2 x. \tag{6.1}
\]

However, since the energy is lost through a statistical collision process, the fluctuations become important for thin slabs of material. Landau performed this calculation and found the energy distribution to be:

\[
f(x, \Delta) = \phi(\lambda)/\xi \tag{6.2}
\]

where

\[
\phi(\lambda) = \frac{1}{\pi} \int_0^\infty \exp(-u \ln u - u\lambda) \sin(\pi u) du
\]
Figure 6-8: a.) Sample Landau distribution plotted using DENLAN.F from CERNLIB. The parameters have been chosen to be similar to the SPMD data. The mean and variance for the distribution truncated at \( x = 5 \) are shown at the upper right. b.) Double-Landau fit to the signal distribution in channel 1000.

\[ \lambda = \frac{1}{\xi} [\Delta - \xi (\ln \xi - \ln \epsilon + 1 - C)] \]

and

\[ \ln \epsilon = \ln \left( \frac{(1 - \beta^2) \xi}{2mc^2 \beta^2} + \beta^2 \right). \]

The distribution \( f(x, \Delta) \) has a strong peak, but it also has a large tail, due to the production of \( \delta \)-rays. The position of the peak, \( \Delta_{mp} \) (which is also referred to as the “most probable value”), has been found to be:

\[ \Delta_{mp} = \xi [\ln(\xi/\epsilon) + 0.198 + \delta], \]

where \( \delta \) is the density effect coefficient. This function can be evaluated numerically, and has been made into a CERN Fortran library function, an example of which is shown in Figure 6-8.

Assuming that the energy loss distribution can be described by a convolution of Landau fluctuations and Gaussian electronic noise [H+83], we can normalize the response of each channel by finding the most probable energy loss and normalizing the measured signals such that this peak lies at 1. A program gains.f was written to do the fits. In Figure 6-8b we show the raw signal distribution for central events in channel 1000, and a fit with a multi-parameter function which includes contributions from a noise peak, a single Landau peak convoluted with a Gaussian, and the convolution of two such Landau peaks with a Gaussian. The signal-to-noise ratio (S/N) is defined using this plot as the ratio of the position of the peak divided by the width of the noise. To be conservative, we eliminated all channels with \( S/N < 14 \) Any channel below this cut was considered
Figure 6-9: a.) Gains($g_i$) (in units of FADC channels) for all of the channels in the SPMD. We divide the signal in each channel by this value to normalize the response of the detector according to the position of the Landau peak. b.) Gains and noise (from Gaussian fit, and multiplied by 10 to put it on the same scale as the gain) for the first two preamps of quadrant 1 (channels 1 to 256) “dead” and removed from the analysis. A visual scan of all 4096 channels eliminated several others, which showed excessive noise, or no signal at all.

The peak position of the measured Landau peaks are shown in Figure 6-9. We will refer to these values as $g_i$, where $i$ is the channel number.

They also show a structure correlated with the pad radius, with the smaller pads associated with larger gains and lower noise, as seen in Figure 6-9b which is a closeup of the first two preamps in quadrant 1. The gains are the closed circles, while the noise (multiplied by a factor of 10) are closed triangles. We see a clear correlation between the noise and the gain, the higher noise implying a lower gain. This is because both are related to the pad capacitance.

To normalize the response of different pads, we define the normalized signal $s_i$

$$s_i = \frac{a_i - b_i}{g_i}$$ (6.3)

In principle, $s_i$ should be Landau distributed, with the peak exactly at 1 and the mean given by the Landau formula above. However, when we plot the distribution of $S_i$ integrating over all channels in the same $\phi$-wedge, we find (Figure 6-10) that while the most probable value is very close to 1, the mean of the distribution varies almost 15% between the innermost and outermost row. We will return to this point below.
6.4.3 Pass 3: Charged Multiplicity and $dN/d\eta$

Charged Multiplicity

From Figure 6-9b, we see that the separation of the signal from the noise occurs around $s_i = .5$. Thus, we define a "hit" as a pad which contains more than 1/2 of the most probable energy loss. In principle, we could determine the true charged multiplicity in the region $2.35 < \eta < 3.75$ by just counting the number of hits found in each event. However, with increasing occupancy, we expect an increasing rate of double hits. We can calculate the relationship between the true and observed occupancy ($\epsilon \equiv N_{ch}/N_{pads}$ and $\epsilon' \equiv N_{hits}/N_{pads}$) if one assumes that particles are distributed uniformly in $\eta - \phi$ space, which is a reasonable assumption for the SPMD given the non-uniform segmentation in $r$. In this case, $\epsilon'$ is given by Poisson statistics as the probability that one or more hits are found in any particular pad:

$$P(n) = \frac{e^n \epsilon - \epsilon}{n!}$$

$$\epsilon' = P(n > 0) = 1 - P(0) = 1 - e^{-\epsilon} \approx \epsilon(1 - \frac{\epsilon}{2}) + O(\epsilon^2).$$  (6.4)

Thus, the measured occupancy is somewhat lower than the true occupancy, e.g. at 20% true occupancy, the measured occupancy is 18%. Even with "small" occupancies like we have in the SPMD, we would undercount the true multiplicity by at least 10% if we considered merely the number of pads to be the actual charged multiplicity. Thus, we have chosen to estimate the number of charged particle hitting the detector using an alternative method, which takes advantage of the fact that we
count a large number of particles and that the width of the of the Landau distribution is relatively small. We can estimate the number of charged particles impinging on the detector surface as:

\[
N_{ch} = \frac{N_{\text{hits}}}{\sum_{i=1}^{N_{\text{hits}}} \frac{dE/dx}{(dE/dx)}}
\]

Since we have seen that the Landau distribution has a dispersion of roughly 55-60%, the resolution on this method is just that of a sum of N individual Landau distributions: \(60%/\sqrt{N_{ch}}\). While this method is straightforward in principle, it requires a good knowledge of the detector pedestals and gains as well as a good measurement of the average of the measured Landau distribution, to properly normalize the energy sum to the number of particles impinging on the detector. We have already seen how this average varies with the pad size, for reasons which are discussed below. Thus we calibrate using low-multiplicity events \((N_{ch} < 50\), giving \(\approx 1%\) occupancy\) and plot the energy sum vs. the pad multiplicity. This gives a linear trajectory, the slope of which is precisely the factor we seek. These factors are given as \(C_{\eta}\) in Table 6.2.1. With these parameters determined, we calculate \(N_{ch}\) with the formula:

\[
N_{ch} = \sum_{\eta=1}^{22} \frac{1}{C_{\eta} \times \epsilon_{\text{geom},\eta}} \sum_{i=1}^{N_{\text{hits}}} \left( \frac{a_i - p_i}{g_i} \right).
\] (6.5)

### Pseudorapidity Density \((dN_{ch}/d\eta)\)

To calculate the pseudorapidity density of charged particles between \(2.35 < \eta < 3.75\) as a function of \(\eta\), we count the average number of charged particles in different bins and then divide by \(\Delta\eta\), the width of the bin in \(\eta\). To do this, we need to know the physical size of the various pads as accurately as possible. Measurements of \(\Delta\eta\) from the AutoCAD drawings are also listed in Table 6.2.1. These are accurate down to about 5 \(\mu\)m, which limits our precision and introduces a systematic error. With these determined, the \(dN_{ch}/d\eta\) in each bin is determined by:

\[
\frac{dN}{d\eta} (\eta \pm \Delta\eta/2) = \frac{1}{\Delta\eta \times C_{\eta} \times \epsilon_{\text{geom},\eta}} \sum_{i=1}^{N_{\text{hits}}} \left( \frac{a_i - p_i}{g_i} \right)
\] (6.6)

We will show results for \(N_{ch}\) and \(dN_{ch}/d\eta\) in Section 6.6

### 6.5 Detector simulation

Although silicon detectors are relatively straightforward to operate and analyze, a full simulation incorporating a physics model and the experimental apparatus is indispensible. More importantly, the SPMD is situated far upstream of many of the other detectors in WA98 and it is crucial to at least have the material present in the full simulation in order to estimate the rate of photon conversions
Figure 6-11: a.) The SPMD geometry implemented in the WA98 GEANT package. The silicon, VA-1 chips, beryllium quadrants, ceramic octants and aluminum rings are indicated. b.) Comparison of ADC distribution in data (closed circles) and the SPMD simulation for high-multiplicity events (shaded histogram).

and the multiple scattering of charged particles. We have used the GEANT 3.21 package to model all of the pieces shown in Figure 6-3. This includes the silicon quadrant, the beryllium hybrid, the PC board octants, and the aluminum mounting rings. A view of the geometry implemented is shown in Figure 6-11a. The particle types interacting in the SPMD are shown in Figure 6-12.

As discussed above, particles passing through the silicon leave energy according to the Bethe-Bloch formula and the energy straggling is handled according Landau calculation. Furthermore, the production of δ-ray electrons is enabled in the simulation, telling the simulation to generate actual δ-electrons if the energy deposition is sufficiently high. The ADC distribution for charged particles passing through the silicon in simulated central events is shown in figure 6-11b. While the overall shape is similar to the data, the systematic broadening of the distribution with increasing pad size is not seen in the simulation. Thus, we only need one calibration factor \( C_\eta = 1.297 \) to relate the Landau mean to the peak. This is found by taking the mean of the ADC distribution in low-multiplicity events, the maximum being set at 5 MIPS, as with the data.

Two simple checks can be made to estimate how well one is actually measuring the number of charged particles produced in a heavy ion collision. The first is to test the soundness of the multiplicity measurement purely within the simulation, by comparing the number of particles incident on the SPMD which leave energy in the silicon with the reconstructed multiplicity. The two quantities are compared in Figure 6-13a. and while the relationship is linear, the slope is off by about 2%. This is a contribution to the overall systematic error on the measured \( N_{ch} \). Another important check of the
formula above correcting the number of hits to the number of charged particles is the comparison with the simulated events. The average $N_{ch}$ is plotted against $N_{hit}$ for data and simulation in Figure 6-13b.

In addition to the particles produced by the Pb+Pb collision itself, the SPMD is also sensitive to the $\delta$-rays generated by the Pb$^{52+}$ ion passing through the lead target. We can get a conservative estimate of the $\delta$-ray multiplicity in physics events by studying events that satisfy the conditions for a beam trigger but not the interaction trigger. These “beam” events have a mean multiplicity in the SPMD of 11.4±.5 and a width of 5.9±.3. The angular distribution is consistent with a spatially uniform illumination of the detector surface. To include these ion-induced $\delta$-rays in the simulation, we sample the measured charged multiplicity distribution for beam events and add it to the charged particle multiplicity for each simulated event. They are not, however, included when calculating $dN_{ch}/d\eta$. Instead, we subtract them from the measured distribution.

Another potential source of background is the presence of the Silicon Drift Detector (SDD) 12.5cm from the target. Particles passing through the silicon can knock out $\delta$-rays and even nuclear fragments that might deposit energy in the SPMD. The magnitude of this effect is small and has been included in the GEANT simulation by including the geometry and material of the SDD used in the experiment.
Figure 6-13: a.) Comparison of the number of particles leaving energy in the SPMD with the reconstructed multiplicity. A linear fit is shown. b.) Comparison of $N_{ch}$ with $N_{hits}$ for data and simulation. The line $N_{ch} = N_{hits}$ is drawn to guide the eye.

6.6 Performance in lead beam

6.6.1 Software

DAQ and data structure

The data acquisition code was first written by P. Kulinich and adapted by M. Purschke for use in WA98. The routine `init.event.f` contained instructions to reset the VA-1 chips via the sequencer. It also set up the Struck 750/1 FADC unit to read out the next event. This code can be found in Appendix C.

The routine `sub.event.f` was used to read out the FADC after a valid event had been triggered and encode it in QDAC subevent 1701. The subevent was encoded in a straightforward way. The first six words contained the subevent ID, the number of words (1030), the date, the time, and the encoding method. The next 1024 words encoded the ADC values of the n-th channel of all four quadrants by packing channel n of quadrant 1 into the first 8 bits of the n-th word, quadrant 2 into the next 8 bits, and so on. Decoding the subevent involves extracting four 8-bit numbers from each 32-bit word into a list of 4096 bytes. This is done with the ANPACK routine `uxdcdi.c`. In the SPMD offline code, one further “unwraps” the data, grouping together the information in each quadrant. The order of the quadrants corresponds to the numbering system of the HABs written on the outside of the HAB housing. The connection between the quadrant number and the detector geometry is shown in Figure 6-6 by the roman numerals, so Quadrant 1 is indicated by "I". Within a quadrant, the channels are grouped into 8 sets of 128 channels, each corresponding to a single VA-1 chip. The numbering convention dates from the 1995 C-V measurements and associates the
first 128 channels with preamp 7, the next with preamp 6 and so on.

Monitoring

To monitor the SPMD during the experimental runs, we used the LISA program developed at Berkeley in the early 1980's for use with the Plastic Ball detector. When the data acquisition is momentarily idle and is writing out events to tape, events are taken at random stored in a “ring buffer” on the VAX running MONA, the DAQ front-end. A LISA process running on a separate VMS machine located near the control room continually checks this buffer for new events and if found, runs a stripped-down version of the offline code on the event, subtracting pedestals and extracting hits. For these events, we generate ADC, multiplicity, $\eta$ and $\phi$ distributions online. This allows the monitoring of the detector system, e.g. to check if smaller segments were malfunctioning, in real time. A detailed event-display image (an example of which is shown in Figure 6-14) was created every few minutes and shipped to the CERNSP SP2 cluster, where it was put on the World Wide Web, allowing for remote monitoring at any time from any computer equipped with a web browser.

Vertex Shift

Since the SPMD is located so close to the target, it is very sensitive to the vertex position. In Figure 6-15a, we show two SPMD $dN/d\phi$ spectra, one for events in the first 500 ms of the spill and one for events 4000-4500 ms into the spill, towards the end. This behavior is consistent with the beam moving slightly during the spill, as the particle density in the inner part of the detector is higher than the outer part. Assuming that the particles are distributed uniformly in $\eta$, the acceptance in $\phi$ will change by the ratio $\Delta \eta'/\Delta \eta$, where $\Delta \eta$ is the nominal pseudorapidity region covered by the detector and $\Delta \eta'$ is the acceptance of the shifted detector, which is clearly a function of $\phi$:

$$\Delta \eta'(\phi) = \log \tan(\Theta_{out}/2) - \log \tan(\Theta_{in}/2)$$

(6.7)

where

$$\Theta_{i}(\phi) = \arctan \frac{|r_{i}(\phi) - \vec{R}|}{z_{SPMD}}$$

(6.8)

and $\vec{R}$ is the transverse offset of the beam parametrized by $(|R|, \phi_{o})$; $r_{in}(\phi)$ and $r_{out}(\phi)$ are vectors pointing out from the center of the detector to the inner and outer radii of the detector at a given $\phi$; and $z_{SPMD}$ is the z-position of the SPMD. By finding the $\phi_{o}$ and $|R|$ which give the best fit with the data, one gets a reasonable estimate of the beam position. In Figure 6-15b, we show the radial position of the vertex as a function of run number and time within the spill. The vertex starts about 1mm off-axis and gradually moves toward the axis, a behavior which is reasonably stable over several
Figure 6-14: A typical online event display from the 1996 lead run.
hundred runs. When the beam position moved far away from the nominal center of the experiment, we adjusted the SPS steering magnets to bring it closer to the desired position.

Despite the sensitivity of the azimuthal distribution to the vertex position, we have found no significant time dependence for the charged multiplicity integrated over full azimuth. A simple Monte Carlo simulation shows that shifts of \( \sim 1 \) mm only change the average multiplicity by \( .1\% \) and induce resolution of \( .8\% \). Thus, we do not correct for this effect in the data analysis presented in Chapter 8.

6.6.2 Trigger Cuts

Due to the high beam rates, we expect a certain number of double events. Also, beam particles may interact upstream and downstream of the target, creating non-target interactions that happen to satisfy the minimal trigger conditions. We must then use information from the trigger detectors themselves to remove the undesired events. Now, MIRAC has a much shorter integration time than the SPMD and is thus less sensitive to pileup events. However, it is also positioned 24m downstream of the target, so it is more sensitive to downstream interactions. Conversely, the SPMD is so close to the target that it is sensitive to upstream events which are created in front of the target. The effect of the trigger cuts, described in Chapter 5, on the SPMD multiplicity can thus best be seen in the correlation between \( N_{ch} \) and \( E_T \) as shown in Figure 6-16. Several regions have been isolated and we have counted how many times they fail the different trigger cuts.
Region I (high $N_{ch}$ and low $E_T$) is dominated by double interactions upstream or near the target (triggering the Little Veto).

Region II (high $N_{ch}$ and high $E_T$) is dominated by several types of double interactions.

Region III (high $E_T$ and low $N_{ch}$) consists of low multiplicity events that triggered MIRAC but not the Plastic Ball. This is indicative of downstream interactions.

6.6.3 SPMD Pathologies

In this subsection, we detail several “pathological” effects in the SPMD response. These effects are common, but have a small effect on the multiplicity, or very rare, with a large effect.

“Lines”

One unexpected effect noticed quickly on the online event display is the presence of non-statistical “lines” of hits along a $\phi$-wedge, usually illuminating the entire $\eta$-range but confined to only one wedge, as shown in Figure 6-17a. These are most likely caused by a nuclear interaction in the silicon that deposits such a large amount of charge that it affects neighboring pads by capacitive crosstalk. However, it also seems to affect the VA-1 directly, since in most cases, all of the pedestals in the preamp associated with the line are pulled down, as the chip cannot supply enough current to stabilize them. Still, this effect can be distinguished event-by-event and subsequently corrected with minimal distortion to the measured multiplicity.

A “line” is detected by counting the number of hits in each phi wedge, $N^\phi_{ch}$, for every wedge in every event. This distribution is shown in Figure 6-18. There are clearly two components in this distribution, one which falls off by around 12 hits, and one which rises after 17 hits. This suggests that any wedge with:

$$N^\phi_{ch} > \frac{18}{22} \times N^\phi_{good},$$

where $N^\phi_{good}$ is the number of good pads in the wedge, is caused by a line. The number of lines per event in central events is shown in the Figure 6-17b.

When a line has been distinguished using the cut 6.9, the line is removed by setting its ADC values to zero, as all of the information in the line is lost, but the line no longer contributes $\approx 22 \times 5$ to $N_{ch}$. To restore the baseline, which may have been pulled down, we sort the ADC values of the remaining channels of the preamp and calculate the average of the lowest 80% of the channels. This procedure removes most of the hits from the remaining channels and thus gives the shifted pedestal for this chip. The distribution of the shift is shown in Figure 6-19a scaled by the channel gains, to put it into MIP units. The average shift is about -0.5 MIPs, but it can be as much as 3, which
Figure 6-16: Scatter plot of $N_{\text{ch}}$ vs. $E_T$, with several regions of outliers isolated and studied in detail. Region I is dominated by double interactions upstream or near the target (triggering the Little Veto). Region II is also dominated by a whole range of double interactions. Region III is made of low multiplicity events that triggered MIRAC but not the Plastic Ball. This is indicative of downstream interactions.
Figure 6-17: a.) A particular event showing a "line" of hits in the top half. b.) Histogram of number of lines per event in central events. The average is around .3/event.

would effectively remove all of the hits from this preamp if not for the correction. In Figure 6-19b we show the average number of lines per event as a function of the final SPMD multiplicity. The average number of lines increases approximately linearly with multiplicity, with a slope of $5.6 \times 10^{-4}$, implying that the number of lines is proportional to the number of particles incident on the detector. Converting the slope to a rate, we get $P = 1 \text{ Line} / 1779 \text{ Particles}$. We can convert this into a cross section by the formula:

$$
\sigma_{\text{line}} = \frac{PA}{\rho N_A} \times 10^{27} \text{ mb} = 11\text{mb}
$$

(6.10)

where $A$ is the atomic number of silicon (28), $\rho$ is the density of silicon (2.33 g/cm$^2$) and $N_A$ is Avogadro's number ($6 \times 10^{23}$). The total $\pi Si$ cross section should be around 230 mb at 1 GeV, derived by taking measured $\pi p$ cross sections at a few GeV/c and scaling by $A^{2/3}$. To compare these numbers, we would need to better understand the angular distribution of nuclear fragments.

"Pull-down"

Alternatively, we can sort the ADC values in each 128-channel preamp, highest to lowest, take the average of channels 55-110 and call this the "preamp baseline" (PBL) for each event. This should have an intrinsic resolution of 10%. This gives us the ability to study common noise within a quadrant by correlating the PBL's for preamps in the same quadrant and in different quadrants. It also allows us to extract the contribution of common noise to the measured detector pedestal noise.
"Tracks"

Even after applying trigger cuts and cutting away the lines within each event, several high-multiplicity events remain which appear to be inconsistent with the shape of the tail. Visual inspection of these events show the presence of what appear to be charged tracks penetrating large distances in the silicon, depositing huge amounts of charge as they traverse the detector. Each pad in the path of these particles shows an ADC value at the top of its range, thus greater than 5 MIPS. One example of this is shown in Figure 6-20.

A scatter plot of $N(>5\text{MIPS}) \equiv N(\text{overflows})$ vs. $N_{ch}$ shows that while some overflows are obviously expected from the Landau distribution itself, there is a separate class of events with an anomalously high number of such hits. These are perfectly correlated with the presence of tracks in the SPMD and are removed from the data sample by a cut of $N(\text{overflows}) < 21$. However, one must be careful when doing event-by-event physics, as the track probability per event does scale with the incident particle multiplicity.

6.6.4 Measurement of δ-rays

As described above, we call events with a valid start signal and no subsequent nuclear interaction in the target "beam" events. The multiplicity distribution for beam events is shown in Figure 6-21a. The mean multiplicity in the SPMD of 11.4±.5 and the width is 5.9±.3. The angular distribution $dN/d\eta(\text{beam})$ is shown in Figure 6-21b and is consistent with either $dN/d\theta \propto \theta$ or a uniform distribution in the x-y plane.

6.6.5 Results for $N_{ch}$ and $dN_{ch}/d\eta$

The final distribution of $N_{ch}$ is shown in Figure 6-22a. The distribution of $dN_{ch}/d\eta$ is presented in several centrality bins, defined by ranges in $E_T$, in Figure 6-22b. To correct for the presence of δ-rays in physics events, we have already subtracted the $dN_{ch}/d\eta$ measured in beam events, shown in the previous section. In principle, this is an over-correction, as the average beam particle will interact halfway through the target. Still, this is difficult to model. Thus we take the raw beam distribution as the best estimate and use half of the beam distribution as a first order estimate on the systematic error induced by making these assumptions.

6.6.6 Error on $N_{ch}$ and $dN_{ch}/d\eta$

The known sources of systematic error, stemming from the detector itself, on $N_{ch}$ are shown in Table 6.2. The three largest source of systematic error are:

Uncertainty in gains The uncertainty in the determination of the gains can be seen by the integrated normalized energy distributions, which should have a peak at exactly 1. Instead, the
Effect Systematic Error

<table>
<thead>
<tr>
<th>Effect</th>
<th>Systematic Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel-by-Channel Gain Determination</td>
<td>2%</td>
</tr>
<tr>
<td>Average of Landau distribution</td>
<td>2%</td>
</tr>
<tr>
<td>&quot;Lines&quot; from nuclear interactions</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Charge Sharing</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Total</td>
<td>3%</td>
</tr>
</tbody>
</table>

Table 6.2: List of known systematic errors and their effect on the overall scale of \( N_{ch} \).

peak is slightly higher, indicating some slight biases in the method.

**Average of the Landau distribution** From the previous section, we see that the multiplicity depends critically on the Landau average, which goes into the denominator of the energy sum. The abovementioned fits to determine these factors have errors on the order of 2%.

"Lines" As described in Section 6.6.3 we have an average of 0.3 lines in central events, and fewer for event with lower multiplicity. As each line removes 1 \( \phi \)-wedge out of 180, it reduces the effective acceptance of the SPMD by \( 0.3/180 = 0.2\% \) per event.

6.6.7 Total systematic error

The systematic error is dominated by the uncertainty in gains and the average in determining the average of the Landau distribution. Combined in quadrature, these give slightly less than 3% systematic error on the scale of \( N_{ch} \). The other sources are not significant, so we estimate that we have a 3% uncertainty. Furthermore, we estimate the relative uncertainty between data and VENUS to be less than 2%, by the close agreement of data and simulation. In the systematic error on \( dN_{ch}/d\eta \), we fold the 3% uncertainty on the overall multiplicity scale and the \( \delta \)-ray contribution together, as shown by the dotted lines. It must be emphasized, however, that both sources of uncertainty affect all of the bins in a correlated fashion.
Figure 6-18: $N_{ch}^{\phi}$ for minimum bias events. A secondary contribution clearly appears around 17 hits.

Figure 6-19: a.) Measured shift of preamp pedestal. b.) Average number of lines per event vs. the number of particles impinging on the SPMD.
Figure 6-20: a.) X-Y view of a "track" event in the SPMD. Such events are eliminated by cutting out events with more than 20 such overflows. b.) \( N(\text{overflow}) \) vs. \( N_{ch} \), but I need to relax the overflow cut for this plot.

Figure 6-21: a.) Multiplicity of \( \delta \)-rays measured in beam events. b.) \( dN_{ch}/d\eta \) for beam events, which gives the angular distribution of the \( \delta \)-rays.
Figure 6-22: a.) Minimum-bias distribution of $N_{ch}$. Peripheral and NSC events have been entered with weights to correct for the trigger scaledowns. The histogram shows the minimum bias distribution for the simulation. b.) Pseudorapidity distribution of charged particles in different centrality bins, as selected by the total transverse energy deposited into $3.5 < \eta < 5.5$. The plot on the left shows the uncorrected distribution, while the right plot shows the distribution after correcting for $\delta$-ray contamination. The distribution from VENUS, for $E_T > 300$ GeV, is shown as open squares and compared to the corrected distribution.
Chapter 7

Photon Multiplicity Detector

I'm beginning to see the light.

— Lou Reed

7.1 Introduction

We count photons in the preshower Photon Multiplicity Detector (PMD) situated 21.5 m from the target, covering the region $2.8 < \eta < 4.4$. A photo of the PMD in WA98 is shown in 7-1. In this chapter, we will describe the principles of photon detection with a preshower detector, the physical design of the detector, how the data is analyzed, the GEANT detector simulation, and finally PMD results from the lead beam. We will not describe the various corrections that can be applied to the data to measure $dN_\gamma/d\eta$ or even a corrected $N_\gamma$ rather than $N_\gamma$-like. This information can be found in the thesis of Jan Urbahn and in reference [A+97a]. Most of the technical details and the rationale for the various detector parameters are discussed in the original WA93 NIM paper [A+96].

7.2 Principle of photon detection

The principle of photon identification makes use of the fact that photons are more likely to shower in the lead converter and produce a large signal in the scintillator pads, while non-showering hadrons will produce a signal corresponding to a single minimum ionizing particle (MIP). The reason for this is simple. The relevant length scale for an electromagnetic interaction is set by the pair production mean-free path

$$\lambda_{\text{pair}} \approx \frac{9}{7}X_0 = .72\text{cm}$$
while the similar scale for hadrons is set by the nuclear interaction length

\[ \lambda_f = 17.1\text{cm} \]

Thus, the probability of photon interactions per radiation length of lead is a factor of 23 higher than for hadrons. Instead, hadrons will more often “punch through” the converter, while photons will shower. Choosing \( 3\lambda_0 \) of lead and \(.34\ \lambda_0 \) of iron (the support structure discussed later) gives an intrinsic photon conversion efficiency of around 90\%, and a hadron conversion probability of about 10-15\%.

The Moliere radius, \( R_M \), which sets the scale for the size of electromagnetic showers [Leo94], for lead is quite small (1.24 cm) and with only \( 3\lambda_0 \), showers are confined within \( 1 - 2R_M \). Thus, it is feasible to design a detector which can convert most of the photons which impinge upon it while rejecting most of the hadrons, detecting the secondaries from the electromagnetic shower in scintillator pads. This was the guiding principle behind the design of the PMD, as detailed in [A+96] and illustrated in figure 7-2
Figure 7-2: Photon detection principle and general readout design for the PMD.

7.3 Detector Design

7.3.1 Detector Hardware

For the WA98 run, the PMD consisted of 28 nearly identical “boxes” shown in 7-3a, mounted on an iron support structure, shown in 7-1. The photons impinging on the detector are converted in $3.34 X_0$ thick lead and iron and the secondaries are detected in 3mm-thick square plastic scintillator (BC400) pads of varying sizes (15mm, 20mm and 23mm). A matrix of $50 \times 38$ pads is placed in one light-tight box module and read out individually via 1mm diameter wavelength shifting optical fibers (BCF01) coupled to an image intensifier and CCD camera system similar to that described in [A+96] and shown in figure 7-4. The modules with smaller pads were mounted in the forward angle region to minimize cluster overlap at large multiplicities and to provide reasonably uniform occupancy. Out of a total of 28 box modules implemented in the PMD, the data presented in this thesis correspond to 19 box modules having 35524 pads. The average occupancy for the part of the detector considered in the present case is around 15% for central events.
7.3.2 Readout

The fibers are attached to a Fiber End Coupler plate attached to a 3-stage Image Intensifier (II) and CCD camera system. The image of the fibers is reduced from 80mm to about 7mm, and the light is amplified by a factor of nearly 40,000. Since the fibers are in a $38 \times 50$ grid, while the CCDs have a $145 \times 218$ pixel grid, a "pixel-to-fiber" map is required to associate sets of CCD pixels to a given pad on the PMD surface. The CCD charge is stepped across its surface and digitized by a FASTBUS-based 8-bit 20MHz flash ADC controlled and read out by an Aleph Event Builder (AEB). The digitizer system runs in three modes:

Mode 1 Pedestal-unsubtracted pixel data.

Mode 2 Pedestal-subtracted pixel-level information

Mode 3 Pedestal-subtracted pad-level data

Mode 1 data is taken several times per day and the pedestals are loaded into the digitizer memory so it can perform pedestal subtraction and zero suppression during the readout. Mode 2 data is taken at the beginning of each lead run in order to create the pixel-to-fiber map (PFM) that corrects for optical distortions in the II system. Mode 3 data uses the PFM to record the information at the pad level only, compacting the data by a factor of around 15. During normal running, we used Mode 3 data only, as the data volume in high-multiplicity events would be too large for our data writing speed.
7.3.3 Timing

The PMD digitizers are always open, integrating events as they come. Thus, they must be cleared at a reasonable rate to avoid superimposing several events. The PMD timing diagram is shown in Figure 7-5. A 1μs-wide pulse is sent every 10μs to the CCD to clear it using anti-blooming electrodes. During this, a 2μs wide BUSY inhibits further triggering by the data acquisition. Upon the arrival of an event trigger, a 600μs gate generates a 430V reverse bias voltage on one of the II stages, blocking further electrons from getting through as the pixel data is transferred into memory. Then the CCDs are digitized over a period of 5 ms. The clear clock is vetoed for the 5.6ms of the whole readout sequence, preventing the PMD from being cleared during readout. However, events which are triggered just before or after the clear clock trigger veto may be partially cleared. These events can be identified by using the PMD TDC information which is read out with every event.

7.4 Data Analysis and definition of $N_{\gamma}$-like.

After decoding, a typical event looks like Figure 7-6a. Here we see ADC value as a function of position, the magnitude represented in log scale by shades of grey. Signals from several neighbouring pads are combined to form clusters. The clustering algorithm searches for local maxima within $7 \times 7$
submatrices in each camera matrix. Single clusters are written out immediately, while multiple clusters are split using a gaussian weighting function that moves the deposited energy towards the local maxima, resolving clusters that lie close together.

Those clusters with energy deposition larger than that corresponding to 3 MIPs are considered to be "γ-like" clusters, the total number of which in an event we call \( N_{\gamma\text{-like}} \). One can define a MIP signal as the average energy left by a charged hadron that punches through the lead converter and just leaves a signal in the 3mm of scintillating tile (corresponding to an energy deposition of about 600 keV). In this analysis, however, we do not extract a MIP signal. Instead we choose a cut near to where 3 MIPS would lie, but the main criteria is to optimize the photon efficiency while maintaining a reasonable photon purity.

In Figure 7-7a., we see the energy deposited in the PMD converter and collected by the scintillator
for photons and hadrons produced in 2871 central VENUS events. The energy is converted to an ADC scale similar to what appears in the data analysis. Only about 15% of hadrons deposit enough energy to fall into the region above ADC=90. Conversely, around 70% of the photons do fall into this region. However, the ratio of produced photons to produced hadrons is such that the ratio $N_\gamma/N_{all}$ is only around 65% if we average over all ADC values, as seen in 7-7b.

### 7.5 Detector Simulation

The photon counting efficiency, hadron contamination and the associated errors can be calculated using test beam data and a GEANT simulation using a method similar to the ones described in [A+96, A+97b]. In this thesis, however, we do not use these parameters to correct this data in order to compare it with a model. Instead, we rely heavily on the GEANT simulation to simulate all of the important physics processes that occur when hadrons and photons interact with the lead converter and iron and the secondaries deposit energy in the scintillating tiles. The PMD geometry has been fully implemented, as shown in figure 7-3b.

As particles impinge upon the PMD, a $26 \times 50 \times 38$ matrix of sensitive pads is filled with the energy loss, in MeV. At the end of the event, the energy is converted to ADC and smeared according to conversion and resolution functions derived in part from a testbeam and in part from making sure that the simulated ADC distribution is reasonably compatible with the measured dis-

---

1. The conversion is $ADC=21+47000 \times DEACT$. $DEACT$ is the energy deposited in the scintillator after the passage of the particle.
Figure 7-7: a.) Simulated "ADC" distribution for photons (solid line) and hadrons (dotted line). The dashed line shows the 90 ADC cut over which we define γ-like clusters. The event sample consists of 2871 high multiplicity (> 1000) events. b.) Ratio of γ-induced clusters to all clusters as a function of ADC counts.

7.6 Efficiency and hadron background

To study the efficiency and background, we have used the detector simulation above and written out the full history of 50 central VENUS events. We first study the average multiplicity of each particle type on the PMD active area in each event. This is shown in figure 7-8. The histogram shows the average multiplicity before we consider how much energy the particle deposits in the lead. When we apply a cut on the amount of deposited energy for each particle, similar to the 3 MIP cut applied to the real and simulated data clusters, the average multiplicity decreases, as indicated by the closed circles. We see that the efficiency for photons is far larger than for hadrons and that only the pions create significant background.

The 3 MIP selection gives an average photon counting efficiency of about 70% which is almost uniform over the range of centrality and pseudorapidity considered. It also creates an effective lower $p_T$ cutoff of 30 MeV/c, at which point the efficiency falls below 35%. About 15% of the produced hadrons impinging on the PMD interact in the converter, generating secondaries which also deposit...
large energy on the detector. This contamination constitutes a background to photon counting. In order to minimize effects due to variations in the angular distributions of charged particles, we only use data with the Goliath magnet turned off.

Although we can establish the intrinsic photon efficiency of the PMD, we can also use the simulation to establish source of the photons shown in Figure 7-8a. The cluster information is not sufficient to determine if they came from the event vertex. Thus, we show the parent particle of the photons hitting the PMD in Figure 7-8b. We see that while most of the photons come from π⁺'s and η's decaying at the vertex, about 25% come from other sources, including $K_S^0$ decays ($BR(K_S^0 \rightarrow \pi^+\pi^-) = 31.39\%$) and from charge conversion in the magnet exit window and the air gap between the magnet and the PMD, which add up to 10%X₀. Although the non-vertex photons are somewhat softer than the primary photons, the 3MIP cuts does not remove more than ~ 30% of them.

7.7 Calibration

We also use the simulation to address the complicated issue of detector calibration, which is used to make the PMD response uniform over the detector surface. Despite the fact that the PMD position is reasonably well known and the voltages were monitored during the experiment, the number of clusters and the sum of the energy deposited (i.e. the sum of cluster ADC values) varies by almost a factor of two in boxes that are geometrically similar (e.g. 1, 4, 7 and 10). Since the ADC distribution is approximately exponential, the multiplicity in each box is strongly dependent on the 3MIP cut. Thus, overall differences in camera gain can lead to large differences in multiplicity. In principle, measuring a clear MIP signal in the scintillator can give an absolute calibration of the ADC scale. However, it has proven difficult to measure the MIP signal directly, due to noise in the readout and because we are unable to track the pedestal, which is suppressed in the Mode 3 data.

It is not correct to tune the multiplicity itself by a scale factor $N' = aN$. Fluctuations should scale as $\sigma \propto \sqrt{N}$, but scaling changes the fluctuations linearly: $\sigma' \propto a\sigma$. Instead, one should tune lower-level parameters, such as detector response and resolution, until the shape of the energy spectra are in resonable agreement with the Monte Carlo. Thus we have adopted a method to normalize the response of the detector assuming that VENUS gives a reasonable description of the pseudorapidity and energy distribution of photons produced in the collisions. For each event with $E_T > 320$ GeV, whether in simulation or in actual data, we add up the ADC value of the clusters for each camera and call this value an “ADC sum”. We then consider the average ADC sum for each camera in the full VENUS sample to be the “MC sums” (listed in Table D.1) and in each data run to be the “data sums”. The overall ADC scale for each camera in each data run is then corrected by the ratio of the MC sum divided by the data sum.
The ADC distribution in each camera is compared for the simulation and calibrated data in Figure 7-9. We see that after the calibration, a uniform 3 MIP cut can be applied for all clusters in all cameras. We also use this method to correct for time-dependent gains, since we use a different camera sum for each run. This requires a full pass through the data and to extract the camera ADC sums for each run and to put them in the HEPDB a database. These are subsequently read in at the beginning of the analysis of each run. Once the gains are fixed at a particular point in time, the camera sum in each run will track the overall gain as it changes. However, the presence and absence of the magnetic field changes the hadron distribution in the PMD, changing the sum in most of the cameras. Thus, we have also run the Monte Carlo with the field on to acquire a separate set of gain factors for use in the systematic checks in Section 7.10.

It is true that correcting the data sums to agree with the MC sums in some sense tunes the overall multiplicity distributions to agree as well. However, it should be kept in mind that the PMD measures the number of photon clusters, not the sum of their energy. Thus, the clearest way to justify this procedure is to vary the input camera sums and observe how the resultant multiplicity changes. In fact, we have observed that a 10% change in camera gains changes the multiplicity by 5%, reassuring us that we are not just tuning the multiplicity directly.

7.8 Performance in lead beam

7.8.1 Trigger cuts

To understand the effect of different trigger cuts, described in Chapter 5, we have divided the events in the $N_{\gamma-\text{like}}$ vs. $E_T$ into several regions where events seem to cluster away from the main correlation trend, as outlined in Figure 7-10.

Region I includes events which have a huge number of PMD clusters, clustering around 2000. Of the 14 trigger cuts considered, none seem to characterize these events. However, the rate seems to be independent of centrality so we remove all events with $N_{\gamma-\text{like}} > 1800$.

Region II are events which fail various double interaction cuts in a 10 $\mu$s before the recorded event, and not the cut against simultaneous double interactions, which would fail the start counter cuts (stadc and sttdc). In these events, the PMD multiplicity looks “high” given the amount of measured $E_T$.

Region III These are events recorded as the PMD was clearing, failing the PMD TDC cuts, listed in Table 7.1. These events have a negligible PMD multiplicity although $E_T$ is large.

Region IV are events where $N_{ch}$ is exactly zero. These events show a slightly low $N_{\gamma-\text{like}}$ compared to $E_T$ although both of these quantities are inconsistent with $N_{ch}$.
<table>
<thead>
<tr>
<th>PMD TDC</th>
<th>Purpose</th>
<th>TDC cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDC1</td>
<td>Reject cleared events</td>
<td>850 - 1300</td>
</tr>
<tr>
<td>TDC2</td>
<td>&quot;</td>
<td>950 - 1350</td>
</tr>
</tbody>
</table>

Table 7.1: PMD TDC cuts used to make sure that we use no event recorded as the PMD is being cleared.

7.8.2 Results for \(N_{\gamma-\text{like}}\)

The final PMD cluster multiplicity \(N_{\gamma-\text{like}}\), is composed of 70% of the incident photons and 15% of the hadronic background. It is formed by counting the number of clusters in each camera and summing over the different cameras. Several cameras, mainly those on the “wings” (camera number > 22), were not instrumented during the WA98 experimental run. Other cameras, in particular 10, 13 and 16, have been excluded from the analysis in this thesis since their response is not uniform over time. The DCC analysis is a large statistics search for anomalous events. Thus, it is better to eliminate bad cameras from both data and simulation rather than attempt to isolate the periods in which these cameras were working properly. This leaves 19 cameras included in the global PMD multiplicity. The minimum-bias distribution of \(N_{\gamma-\text{like}}\) and the correlation of \(N_{\gamma-\text{like}}\) and \(E_T\) are shown in Figures 7-11a and b respectively. To check the detector uniformity, we plot the PMD clusters in \(\eta-\phi\) space, as shown in 7-12. The jagged structures in the cluster distribution arise from projecting the rectangular boxes into \(\eta-\phi\) space. When we consider only from 3.4 < \(\eta\) < 3.9, where the distortions due to camera boundaries are minimal, we find that the \(\phi\) distribution is reasonably uniform, as seen in Figure 7-13a. We can also plot the raw \(dN_{\gamma-\text{like}}/d\eta\) distribution for both data and simulation, achieving a good match over most of the acceptance, as seen in Figure 7-13b. This justifies the calibration method at least as a method of establishing the relative gains between geometrically non-similar cameras.

7.9 Systematic error on \(N_{\gamma-\text{like}}\)

We estimate the uncertainty on the absolute multiplicity scale of simulated \(\gamma\)-like clusters, due to uncertainties in various parameters of the simulation and data analysis, to be 15%, and that the relative uncertainty between data and VENUS is 5%. The main source of uncertainty derives from the determination of the 3MIP cut, as the multiplicity drops by 3.5% when we raise the cut from 90 to 100.
7.10 Systematic Checks

The level of hadron contamination in the PMD was verified by comparing the azimuthal distribution of hits for magnet-on and magnet-off data [vH96]. The azimuthal distribution of charged tracks becomes very non-uniform in the presence of the magnetic field, the amount of non-uniformity indicating the magnitude of the hadron contamination. Thus, if the hadron contamination is correctly modeled, and the hadron/photon ratio is reasonably well described by VENUS, then the ratio of \( dN/d\phi \) for magnet-on and -off should be the same in both cases. This method has the distinct advantage of cancelling out systematic distortions in the \( \phi \) spectrum due to edges and other local effects. Instead, since the detector response is the same, it factors out only the relative differences due solely to the presence of the magnetic field in front of the PMD.

The results are shown in Figure 7-14. Figure 7-14a shows the raw \( \phi \) spectra for simulation and data with the magnet on and off. The simulation is quite smooth, unlike the data, which has several camera-related effects not properly introduced into the GEANT model. The ratio is shown in Figure 7-14b and is quite smooth even for the data. More importantly, the amount of sweeping in the data and simulation is very similar. Thus, either the data and Monte Carlo are in good agreement in 1) the ratio of neutral to charged and 2) the conversion, or the two are both wrong, but in such a way as to cancel their effects.
Figure 7-8: a.) Average multiplicity of each particle type in the PMD for central VENUS events. The histograms show all particles, the filled circles show the multiplicity after applying the 3MIP cut. b.) Average multiplicity of the parent particle of the photons. The histogram is for all photons, and the filled circles are for photons above the 3MIP cut.
Figure 7-9: Camera ADC distributions for the calibrated data and the simulation, in which we have converted the deposited energy in MeV to ADC by the functions described in Section 7.5.
Figure 7-10: Study of which cuts are not satisfied in different regions of the $N_T$-like vs. $E_T$ plot.
Figure 7-11: a.) Minimum-bias distribution of $N_{\gamma\text{-like}}$ for data (open circles) and simulation (histogram). b.) Correlation of $N_{\gamma\text{-like}}$ with $E_T$ for the minimum bias sample.

Figure 7-12: Integrated number of clusters for events with $E_T > 300$ GeV as a function of $\eta$ and $\phi$. 
Figure 7-13: a.) Raw $dN_{\gamma\text{-like}}/d\eta$ distribution for $E_T > 300$ GeV. b.) Raw $dN_{\gamma\text{-like}}/d\phi$ distribution for $E_T > 300$ GeV and clusters in $3.4 < \eta < 3.9$.

Figure 7-14: a.) Raw $dN/d\phi$ for simulation (magnet on and off) and data (magnet on and off). b.) Ratio $dN/d\phi(\text{on})/dN/d\phi(\text{off})$ normalized to the number of bins so the average value is 1.
Chapter 8

Data Analysis

8.1 Introduction

In this section we describe the "global" search for DCCs, where we study the fluctuations in the correlation of $N_{ch}$ and $N_{\gamma}$-like. There are two basic approaches for such an analysis. The **inclusive** approach tries to identify a DCC signal by studying the detailed shape of the joint multiplicity distribution, projected across the clear correlation axis present in the data. The **exclusive** approach focuses instead on isolating individual events that sit far away from the main correlation trend. It relies on fewer assumptions about the inclusive distribution, separating "DCC candidates" by a simple cut. Thus, it is a clean method to set an upper limit on DCC production in the absence of a signal.

8.2 Simulation of full setup

As described in section 3.3, we use the VENUS 4.12 [Wer93] event generator with its default settings to describe the bulk of the data. To compare VENUS with our data, we propagate the raw generator output through a full simulation of our experimental setup using the GEANT 3.21 [CERa] package from CERN, as shown in Figure 8-1. In Chapters 6 and 7 we presented the simulations for the individual detectors. For this analysis, we have combined the SPMD and PMD detector simulations in the same GEANT code. The simulation incorporates the detector physics effects and folds them into the generated data, which is then analyzed using the same code used for the raw experimental data. In the rest of this chapter, the term "VENUS" refers to the combination of VENUS 4.12 and the full GEANT 3.21 detector simulation, not to the raw generator output, unless otherwise specified.

We have also created a "fast simulation" of the MIRAC calorimeter, indicated by the annulus in
Figure 8-1: The subset of WA98 detectors used for the global DCC search, as represented in the GEANT simulation. The magnet is present in order to simulate photon conversion in the experimental apparatus between the target and the PMD.

Figure 8-1, in order to get a reasonable estimate of the transverse energy produced in $3.5 < \eta < 5.5$ without doing the full calorimeter simulation. To calculate $E_T$, we stop all particles reaching $z = 25m$ downstream of the target in the angular region $0.5^\circ < \theta < 3.45^\circ$. Each particle then deposits a certain amount of its energy smeared by a detector resolution function depending on the particle type, as detailed in Table 8.1. The smeared deposited energies are then weighted by $\sin \theta$ and summed to calculate $E_T$ for each event. In Figure 8-2 we show the minimum bias distribution of $E_T$ (in GeV, closed circles). Overlaid are simulated distributions for minimum-bias events (solid histogram) and for $b < 6$ fm (dashed histogram).

In Figures 8-3a and 8-3b we present the minimum-bias multiplicity distributions for charged particles and $\gamma$-like clusters. The correlation between the charged and neutral multiplicities is presented in Figure 8-4 with the minimum bias distribution outlined, the central VENUS events hatched, and the central data events shown as scattered points, each point corresponding to a single event. The most distinctive feature of the scatter plot is the strong correlation between the charged and neutral multiplicities. A reasonable explanation of this would be if most of the produced particles are pions with their charge states partitioned binomially, as measured in $pp$ experiments at similar
<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Energy Deposited ($\Delta E$)</th>
<th>Resolution ($R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma, e^+, e^-$</td>
<td>All</td>
<td>$1.4% + 11%/\sqrt(\Delta E)$</td>
</tr>
<tr>
<td>$\mu^+, \mu^-$</td>
<td>2 GeV</td>
<td>None</td>
</tr>
<tr>
<td>Baryons</td>
<td>$E - m$</td>
<td>$3% + 34%/\sqrt(\Delta E)$</td>
</tr>
<tr>
<td>Anti-baryons</td>
<td>$E + m$</td>
<td>$3% + 34%/\sqrt(\Delta E)$</td>
</tr>
<tr>
<td>Mesons</td>
<td>All</td>
<td>$3% + 34%/\sqrt(\Delta E)$</td>
</tr>
</tbody>
</table>

Table 8.1: Energy deposited and resolution functions for different particle types incident on the fast simulation of MIRAC.

Figure 8-2: Minimum bias distribution of $E_T$ (in GeV, closed circles). Overlaid are simulated distributions for minimum-bias events (solid histogram) and for $b < 6$ fm (dashed histogram).
Figure 8-3: The charged and neutral multiplicity distributions are shown in a) and b). The open circles represent the minimum-bias distribution. The “central” sample ($E_T > 300$ GeV) is represented by closed circles for the data and by histograms for VENUS.

energies [GM75]. A binomial distribution leads to a correlation width $\sigma(N_{ch} - N_\gamma) \propto \sqrt{N_{ch} + N_\gamma}$, which would explain the very tight correlation, since the relative fluctuations are proportional to $1/\sqrt{N_{ch} + N_\gamma}$. As this is seen in both data and VENUS, we can study the contributions to the different multiplicities to verify this hypothesis. We have already seen (Sections 6.5 and 7.5) that about 80% of the charged particles produced in VENUS are pions, the rest being protons and kaons, and about 85% of detected photons come from $\pi^0$ decays. Thus, by simply counting the charged particles and photons produced in a heavy ion collision, we have a reasonable estimate of the number of charged and neutral pions created.

We verify the binomial nature of the charge fluctuations in VENUS by studying its “binomiality”:

$$B = \frac{N_{\pi_{ch}} - p_{ch}N_{\pi}}{\sqrt{p_{ch}(1-p_{ch})N_{\pi}}}$$

(8.1)

where $N_{\pi_{ch}}$ and $N_{\pi}$ are number of charged pions and the total number of pions for each event, and $p_{ch} = N_{\pi_{ch}}/N_{\pi}$ is the probability that a pion is charged. For a pure binomial distribution, $p_{ch} = 2/3$ and B is Gaussian with a mean at zero and an RMS of one. For VENUS without GEANT we find (Table 8.2) that $p_{ch} = .65$ and the RMS of the B distribution is .94 for pions produced in the central rapidity region in events with an impact parameter less than 6 fm. This is consistent with the hypothesis that the correlation arises mainly from the binomial partition of $N_\pi$, the total pion multiplicity. The slight divergence from perfect isospin symmetry reflects the isospin asymmetry of the Pb+Pb system, each nuclei with 82 protons and 126 neutrons. It is also interesting to note that
Figure 8-4: a.) This is the scatter plot showing the correlation between $N_{ch}$ and $N_{\gamma-like}$. The solid outline shows the trend of the minimum bias data. The central sample (with $E_T > 300$ GeV) is shown as points for the data and as a hatched region for VENUS (with much lower statistics). Overlaid on the plot are the Z axis and the $D_Z$ axis at a particular value of Z as explained in the text. b.) Profile plot of the same with a fit to the “banana” function, described in Section 8.3.2.
### Table 8.2: Charged pion fraction and the width of the B distribution ($\sigma_B$) for all VENUS pions ($b < 6$ fm) and for only pions produced in the central region covered by the SPMD and PMD.

<table>
<thead>
<tr>
<th></th>
<th>All pions</th>
<th>$2.3 &lt; \eta &lt; 3.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{ch}$</td>
<td>.651 ± .001</td>
<td>.650 ± .001</td>
</tr>
<tr>
<td>$\sigma_B$</td>
<td>.900 ± .001</td>
<td>.939 ± .001</td>
</tr>
</tbody>
</table>

$\sigma_B$ is smaller when we include all pions, including target and projectile rapidities.

### 8.3 Data Analysis

DCCs should modify the binomial partitioning of $N_\pi$ into charged and neutral pions. Events in which a DCC is produced (henceforth referred to as “DCC events”) will show up as deviations from the binomial behavior and appear as outliers with respect to the bulk of the data. We have already discussed that the charged and neutral multiplicities are directly sensitive to the charged and neutral pion multiplicities in each event. Thus, DCC events should appear in the correlation of charged and neutral multiplicities, while the individual distributions will be mainly unaffected.

#### 8.3.1 Charged-neutral correlation

The strong correlation between charged and neutral multiplicities described above suggests a more appropriate coordinate system with one axis being the measured correlation axis and the other perpendicular to it. If all detected particles were pions and the detectors were perfect and had identical pseudorapidity acceptance, then the correlation axis would be a straight line. Instead, we must account for the fact that at high multiplicities, the pseudorapidity distributions tend to narrow, changing the relative acceptance of charged and neutral particles due to the non-identical apertures of the SPMD and PMD. Moreover, the large occupancies in the PMD lead to a slight saturation effect, which we call the “banana” effect.

#### 8.3.2 The “banana” effect

In hadron-hadron and nucleus-nucleus scattering, several global quantities are well known to be linearly correlated. The best example of this is the correlation between $N_{ch}$ and $E_T$, which comes about mainly due to the limited $p_T$ available to produced hadrons. However, one must be careful with so-called “global” variables when they are measured in a limited region of phase space. In WA98, $N_{ch}$ is measured over $2.35 < \eta < 3.75$ which covers the central peak. $E_T$ is measured from $3.5 < \eta < 5.5$, well down the peak and into the forward rapidity region. Now, it has been measured in Au+Au collisions at the AGS that the width of the $dN_{ch}/d\eta$ distribution in AA collisions...
decreases with increasing centrality [Vol95]. We have observed the same effect in VENUS 4.12 for Pb+Pb collisions at SPS energies, the magnitude of the effect increasing as one increases the effective meson-baryon cross section. This leads us to suggest the following hypothesis: as more particles pile up in mid-rapidity, the ratio of the number of particles in the central region compared to the number in the forward region rises, causing $N_{ch}$ to rise faster than $E_T$. This hypothesis can be confirmed by splitting MIRAC into two regions in pseudorapidity, $E_T(\text{SPMD})$ ($3.3 < \eta < 3.7$) which overlaps the SPMD, $E_T(\text{Forward})$ ($4.8 < \eta < 5.5$) which covers a more forward region. Comparison of $N_{ch}$, $N_\gamma$, $E_T(\text{SPMD})$, and $E_T(\text{Forward})$ are shown in Figure 8-5, each combination fit with a function $y = p_1 x (1 + p_2 x)$, $p_2$ indicating the deviation from linearity. The solid line indicates the fit region, the dashed line extrapolates the fit to the full range of the plot, and the dotted line is the same function with $p_2 = 0$. In these plots, two main features stand out. First, one can achieve a “banana” effect purely by correlating the two different regions of $E_T$, as seen in Figure 8-5a. Second, correlating the SPMD or PMD with $E_T(\text{SPMD})$ gives a more linear correlation than correlating it with $E_T(\text{Forward})$, as seen in Figures 8-5c-f. These two facts suggest that the original hypothesis is true.

Although the SPMD and PMD have similar acceptance, the PMD covers $2.8 < \eta < 4.4$, which is somewhat off-peak, so we expect that the correlation of these two detectors should show the same effect, albeit with a smaller magnitude. However, we must also worry about the fact that the PMD analysis does not perform an event-by-event occupancy correction, unlike with the SPMD. Fortunately, VENUS events propagated through GEANT describe the data quite well, suggesting that we can decompose the curvature purely within the simulation. To make things quantitative, we fit each plot of $y$ vs. $x$ with the function

$$y = p_0 + p_1 x (1 + p_2 x)$$  \hspace{1cm} (8.2)$$

where $p_0$, $p_1$ and $p_2$ are the offset, slope, and curvature coefficients. As before, a significantly non-zero $p_2$ indicates the presence of a quadratic term, which leads to a “banana” effect.

The integrated $N_{ch}$ vs. $N_{\gamma-\text{like}}$ plot (the fit is shown in Figure 8-4b) gives a $p_2 = (65 \pm 4.6) \times 10^{-5}$, which translates into a 24-28% effect at $N_{\gamma-\text{like}} = 400$. The SPMD is linear with the number of incident charged particles. This is confirmed in Figure 6-13a which gives $p_2 = (5 \pm 5) \times 10^{-6}$, consistent with being perfectly linear. However, the number $\gamma$’s incident on the PMD which deposit an amount of energy greater than the “3 MIP” cut (defined by the Mev-ADC conversion formula discussed above) versus the measured $N_{\gamma-\text{like}}$ (Figure 8-6a) gives $p_2 = (23.5 \pm 1.3) \times 10^{-5}$, which indicates a 9-10% saturation effect. However, this is only about 35% of the effect measured above. Another component of the effect is extracted by comparing $N_{ch}$ to $N_{\gamma+\mu}$ and $N_{h+\mu}$, the raw numbers of photons/electrons or hadrons/muons actually impinging on the PMD (Figure 8-6b). We see that
Figure 8-5: Comparison of $N_{ch}$, $N_{\gamma}$, $E_T$(SPMD) ($3.3 < \eta < 3.7$), and $E_T$(Forward) ($4.8 < \eta < 5.5$). The fit is to the function $y = p_1 x (1 + p_2 x)$. The solid line indicates the fit region, the dashed line extrapolates the fit over the full range, and the dotted line shows the same function but with $p_2 = 0$. 

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there is a banana effect in both cases, indicating that the effect is not due to any inefficiency but due to the slightly different acceptance of the PMD. The 12-13% effect observed for $\gamma + e$ and 7-8% for $h + \mu$ adds up to a 10-12% effect (since $35\% \times 7.5\% + 65\% \times 12.5\% = 10.75\%$). All together, we have explained about 18-22% of the 24-28% effect. This indicates that the SPMD-PMD banana is due to a combination of saturation and acceptance effects that are well described by the Monte Carlo.

### 8.3.3 Change of Variables

We have seen that the correlation between $N_{ch}$ and $N_{\gamma-\text{like}}$ is not a straight line. It is then useful to define a new coordinate system consisting of a correlation axis ($Z$) described by a second-order polynomial, and the perpendicular distance ($D_Z$) from it, which is defined to be positive for points below this $Z$ axis.

The Z-function, which is nothing but a parametrization of $(N_{ch})(N_{\gamma-\text{like}})$, can be determined in three ways:

<table>
<thead>
<tr>
<th>Method</th>
<th>Function</th>
<th>$p_0$</th>
<th>$p_1$</th>
<th>$p_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least-squares</td>
<td>$P^2$</td>
<td>$4.7 \pm 1.8$</td>
<td>$1.10 \pm 0.01$</td>
<td>$0.0063 \pm 0.0002$</td>
</tr>
<tr>
<td>M.R. fit 1 ($A &gt; 0$)</td>
<td>$P^2$</td>
<td>$0.0000 \pm 0.0001$</td>
<td>$1.10 \pm 0.01$</td>
<td>$0.0007 \pm 0.0001$</td>
</tr>
<tr>
<td>M.R. fit 2</td>
<td>$P^{2'}$</td>
<td>$-12 \pm 1$</td>
<td>$1.19 \pm 0.01$</td>
<td>$0.0004 \pm 0.0001$</td>
</tr>
</tbody>
</table>

Table 8.3: Fits to the $N_{ch}$ vs. $N_{\gamma-\text{like}}$ data to obtain the Z-function by three different methods. $P^2$ is a standard 2nd-order polynomial, $y = p_0 + p_1 x + p_2 x^2$. $P^{2'}$ is of the form $y = p_0 + p_1 x (1 + p_2 x)$.
Figure 8-7: Minimum bias distribution of $N_{ch}$ vs. $N_{\gamma-like}$ with three Z-functions overlaid. The red line is from a fit to a second order polynomial with $\chi^2$ defined as the sum of $D_Z$. The blue line is a similar fit with different limits on the parameters. The green line is from a standard least-squares fit to a profile histogram.

1. By a standard least-squares fit on $(N_{ch})(N_{\gamma-like})$ ("Least-squares")

2. By a fit which adjusts the parameters until it minimizes the residuals in $D_Z$ with $A > 0$ ("M.R. fit 1")

3. By the same fit, with no restriction on $A$ ("M.R. fit 2")

We have used these different methods to fit to two slightly different functions:

1. "$P2$" $y = p_0 + p_1 x + p_2 x^2$

2. "$P2'$" $y = p_0 + p_1 (1 + p_2 x)$

The results of the three fits are shown in Table 8.3 and the resultant functions are shown in Figure 8-7. They are quite similar and we have chosen to use "M.R. fit 1".

$D_Z$ is determined by numerically finding the closet point on the Z-function to the data point. For convex functions ($d^2f/dx^2 > 0$ for all $x$), the closest distance is also the perpendicular distance. To prove this, one defines the euclidean distance from a point $(x_0, y_0)$ to $y = f(x)$ as $D(x) = \sqrt{(x - x_0)^2 + (f(x) - y_0)^2}$. The value $x$ which minimizes $D(x)$ is found by solving the equation
Figure 8-8: a.) This figure shows the distribution of $Z$, with the same conventions as in figure 8-3. b.) This shows the distribution of $D_Z$ in the “central” sample for the data (closed circles) and for VENUS (histogram). The difference in the mean between the two distributions arises due to the overall scale differences discussed in Section 3.

$f'(x) = -(x - x_0)/(f(x) - y_0)$. But this tells us that the slope of the line connecting $(x, f(x))$ is $1/f'$, so this line is perpendicular to the slope of $f(x)$ at $x$.

These axes are shown superimposed and labelled on Figure 8-4 and the projection along the $Z$-axis is shown in Figure 8-8a. The full projection along the $D_Z$-axis is shown in Figure 8-8b. To a very good approximation, the data are Gaussian distributed, which is consistent with binomial partition. The VENUS results, shown by the histogram, are also Gaussian, but with a slightly smaller width. In both cases, $\sigma_{D_Z}$, the standard deviation of a gaussian fit in the $D_Z$ direction, increases with increasing $Z$, as seen in Figure 8-9. We have chosen to work with the scaled variable $S_Z = D_Z/\sigma_{D_Z}$ in order to compare relative fluctuations at different multiplicities. While binomial partition leads to fluctuations that grow as $\sqrt{N}$, the data and VENUS follow a slightly different power law. This may be due to the presence of contaminating particles, like nucleons kaons, and etas. It also may result from the hadron conversion in the PMD, which tends to correlate $N_{ch}$ and $N_{\gamma}$-like. A reasonable parametrization of $\sigma_{D_Z}$ for $Z > 200$ has been found to be $\sigma_{D_Z} = C + Z^\beta$ where $C = 7.5 \pm .1$ for the data, and $C = 4.8 \pm .1$ for the simulated events, and $\beta = .46$. This function is superimposed upon the data and VENUS in Figure 8-9a.

The discrepancy between VENUS and the data can be seen more clearly by measuring the width of the $S_Z$ distribution with the $\sigma_{D_Z}$ in the denominator taken from the simulation. The VENUS distribution is a gaussian of width $0.998 \pm 0.002$ (fit error only) and the data is also gaussian, of width $1.13 \pm 0.07$ (error from relative scale uncertainties included) as shown in Figure 8-9b. In this figure, the means of the distributions have been shifted to zero to show the difference in shape.
8.3.4 Systematic checks on $\sigma_{DZ}$

The discrepancy in $DZ$, while within the estimated systematic error due to scale uncertainties, is not negligible. Moreover, it is asymmetric, with a slightly longer tail in the high-$N_\gamma$-like direction. This is precisely how a small and frequent DCC would appear in an inclusive approach to the DCC search. Thus, although we will not carry out this analysis here, it is important to check the detector response in more detail, to see if there is a simple explanation for this effect. The first hypothesis to test is if a part of either detector is creating persistent local fluctuations that influence the global multiplicities. This can be checked by dividing the detector into different sized pieces in phase space. The other major hypothesis to check is if GEANT correctly simulates hadrons in the PMD. If too many hadrons are detected, it causes extra charged-neutral correlations that would be manifest precisely in a larger width.

Octants

To check for the presence of local fluctuations, we have divided the SPMD and PMD into eight octants, "wedges", that cover the overlap region of the two detectors, $3.4 < \eta < 3.9$. They are numbered according to Figure 8-10a. Using these octants, we can create subdetectors with 8 different sizes in $\Delta \phi$ (45, 90, 135,... degrees) at 8 different positions $\phi_o$. For each $\Delta \phi$ and $\phi_o$, we calculate
Figure 8-10: a.) Numbering system for the octants. Octant 1 ranges from $\phi = 0$ to 45 degrees, etc. b.) Width of octant distributions as a function of octant position and $\Delta \phi$.

the distribution of $X$, where

$$X \equiv \frac{N_{\gamma-like}}{\langle N_{\gamma-like} \rangle} - \frac{N_{ch}}{\langle N_{ch} \rangle}$$

(8.3)

and determine its width, $\sigma_X$. If the fluctuations are purely binomial, $\sigma_X$ should decrease as

$$\sigma_X \propto 1/\sqrt{\Delta \phi}.$$  

(8.4)

Figure 8-10b shows $\sigma_X$ for 8 different values of $\phi_0$, data as a clear histogram, and simulation as a shaded histogram. We draw the function 8.4 with the constant set to go through the points at $\Delta \phi = 45^\circ$. No real discrepancy from the expected behavior is shown for any value of $\Delta \phi$ or $\phi_0$.

Magnet-on data

In Section 7.10 we checked the level of hadron contamination by comparing the magnet-on with magnet-off $dN/d\phi$ distributions in data and simulation. If the simulation was to overestimate the amount of hadron conversion in the PMD, this would cause extra charge-neutral correlations that would show up precisely as a smaller width. The good agreement between data and simulation suggests that this is not a substantial contribution to the effect.
Figure 8-11: $S_Z$ distribution for the experimental data is shown, overlaid with VENUS simulations incorporating 0%, 25% and 60% DCC in every event. All of the distributions are normalized to the total number of data events.

8.3.5 Comparison of data with DCC model

In Figure 8-11, we compare the $S_Z$ distribution in the data (closed circles) with the DCC model described in section 3.4 for the $\zeta = 0\%$, 25\% and 60\% DCC hypotheses. It is clear that the distributions get wider as $\zeta$ is increased.

8.3.6 Upper Limit Calculation

DCC events would show up as non-statistical tails on the $D_Z$ axis. We see no such events in our data sample. Thus, we are faced with the possibilities that single-domain DCCs are very rare, very small, or both. To check which hypotheses are consistent with our data, we determine upper limits on the frequency of DCC production as a function of its size, as represented by $\zeta$.

We have computed $S_Z$ distributions for several values of $\zeta$, ranging from 15\% to 90\%. To define an efficiency for detecting DCCs, we start from the observation that the distribution assuming the null hypothesis is Gaussian. With our statistics, we expect few events farther than 5 to 6 $\sigma$ from the mean. An event containing a DCC, however, has an enhanced probability of being found in this region. The cut $|S_Z| > S_{\text{cut}}$ then defines a two-dimensional region in the scatter plot in which all
Table 8.4: DCC efficiencies and 90% C.L. upper limits on DCC production as a function of $\zeta$ for $S_{\text{cut}} = 5$ and 6.

<table>
<thead>
<tr>
<th>$S_{\text{cut}}$</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC $\zeta$ (%)</td>
<td>$\epsilon(5, \zeta)$</td>
<td>Limit</td>
</tr>
<tr>
<td>15%</td>
<td>.1%</td>
<td>$1.7 \times 10^{-2}$</td>
</tr>
<tr>
<td>25%</td>
<td>1%</td>
<td>$7.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>40%</td>
<td>11%</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>60%</td>
<td>33%</td>
<td>$3.2 \times 10^{-5}$</td>
</tr>
<tr>
<td>90%</td>
<td>60%</td>
<td>$1.8 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

events are considered to be “DCC candidates”. Once the cut is set, the DCC efficiency is defined, for $N_{\text{MC}}$ VENUS events, as

$$\epsilon(S_{\text{cut}}, \zeta) = \frac{N(|S_Z| > S_{\text{cut}}, \zeta)}{N_{\text{MC}}}$$

which is a function of both the DCC fraction and the cut position, and is shown in Figure 8-12a.

The background is determined by a Gaussian fit to the VENUS distribution, in order to extrapolate beyond the Monte Carlo statistics. With the efficiency and background determined, we calculate the Poisson upper limit $N_{U.L.}$ for a 90% confidence level, which is $2.3 \cdot (N_{U.L.} = -\log(1 - CL))$ if there are no measured events over the cut and no background events are expected, as is the case for our cuts. These three numbers are combined into an upper limit, for $N_{\text{Data}}$ events, via the formula:

$$\frac{N_{DCC}}{N_{\text{Central}}(S_{\text{cut}}, \zeta)} \leq \frac{N_{U.L.}}{\epsilon(S_{\text{cut}}, \zeta)} \frac{1}{N_{\text{Data}}}$$

where $N_{\text{Central}}$ is the number of central events in our sample and $N_{DCC}$ is the number of DCC events.

We have calculated limits for two scenarios. The first is based upon the conservative assumption that VENUS should describe the data perfectly in the absence of a DCC signal. Under these assumptions, $S_Z = D_Z / \sigma_{D_Z}$ as obtained from VENUS (as it was in Figure 8-11b) and $S_{\text{cut}} = 6$, which is well away from the data point with the largest $S_Z$. The 90% C.L. limit is presented in Figure 8-12b as a solid line. The other scenario assumes that the difference between the data and VENUS is due to detector effects and that the widths should be the same. In this case, $S_Z = D_Z / \sigma_{D_Z}$, with $\sigma_{D_Z}$ taken from the data, and we choose a tighter cut $S_{\text{cut}} = 5$. This limit is presented in the same figure as a dashed line. The two limits are quite different at $\zeta = 15\%$ but get closer at $\zeta > 30\%$. In both cases, the uncertainty in the absolute comparisons between the data and VENUS have not been included in the upper limit estimate. The efficiencies and limits are listed in Table 8.4.
Figure 8-12: 90% C.L. upper limit on DCC production per central event as a function of the fraction of DCC pions under two assumptions. The thick line gives the upper limit obtained by assuming the $\sigma_{DZ}$ in $S_Z$ is completely given by the VENUS calculation requiring to make a cut at 6$\sigma$. The dashed line shows a less conservative limit obtained by using the $\sigma_{DZ}$ measured in the data itself. This allows us to make a tighter cut at 5$\sigma$, increasing the DCC detection efficiency.
Chapter 9

Discussion

In the previous chapter, we have established a 90% C.L. upper limit on DCC production in Pb+Pb collisions at 158 AGeV. In this chapter we compare our result with theoretical predictions. We also discuss the relevance of our search method in light of the JACEE anti-centauro event.

9.1 Comparison with Gavin model

In reference [Gav95], Sean Gavin makes an estimate of the number of pions produced by a DCC, already discussed in Chapter 2. He works with slightly different initial conditions than the quench scenario discussed previously. Instead of evolving the chirally restored state using the zero temperature $V_{eff}$, the “annealing” scenario (from Gavin and Müller [GM94]) assumes that the potential returns to its original form slower than the time scale associated with the development of unstable pion and sigma modes. This leads to the formation of somewhat larger domains than predicted in the quench scenario. Gavin’s conservative estimate is that a DCC radius could reach sizes up to $R \approx 3 - 4$ fm. With the MIT bag constant setting the overall scale, he derives a vacuum energy density $\rho$ of 60 MeV/fm$^3$ - although with large uncertainties of up to a factor of 4. We shall assume it can be as high as 120 MeV/fm$^3$. The $p_T$ of the produced pions should go as $p_T \sim 60$ MeV/c which is small. Thus, in this model a DCC can generate $\frac{4}{3}\pi R^3(\rho/m_\pi) \approx 50 - 230$ pions.

Assuming that all of these pions are produced into the central region of the collision, we can calculate $\zeta$, the fraction of DCC pions relative to all produced pions. The SPMD sees all of the charged particles produced in the central rapidity region, 80% of which are pions. Since $\langle N_{ch} \rangle \sim 600$ this lets us estimate the total number of centrally produced pions in an average event to be about

$$0.8 \langle N_{ch} \rangle \times \frac{3}{2} = 720.$$ 

Thus, we would expect a DCC created at the SPS to have a $\zeta$ of approximately 5 - 30%. Our
analysis clearly rules out anything larger than about 25% within the scope of the assumed model, thus ruling out the larger end of Gavin's estimate. However, it is unable to directly rule out the presence of smaller domains.

9.2 $\sigma_{Dz}$ as a signal for DCCs

Still, although we do not observe any central events with large multiplicity fluctuations, a small and frequent DCC-induced effect might also appear as a slightly enhanced correlation width, similar to what we observe in our data when compared to VENUS. However, this apparent enhancement could also result from uncertainties in the detector modeling or the underlying physics model itself. For instance, theoretical uncertainties might arise because no model has ever been used to study charge correlations in heavy ion collisions. Rescattering phenomena, resonances, or Bose-Einstein effects may have predictable effects on the expected binomial distribution. These issues should be addressed in future studies.

9.3 Discussion of the JACEE event

The JACEE experiment is a balloon-borne detector consisting of stacks of emulsions sandwiched with heavy absorbers. It has the advantage over ground-based experiments of being able to measure the vertex and charge of the incoming cosmic ray as well as the secondaries. The anti-centauro event, presented by the JACEE collaboration in 1992 [LI92] is one of the more striking events in the existing cosmic ray data. It has served as "inspiration" [BKC93] for experimental DCC searches, although it has not been formally presented as a DCC candidate.

Event 4LIIG-27, previously shown in Figure 3-1 has 119 photons and 52 charged particles. This event is one out of 70 events with leading photon clusters, the rest of which have $R \equiv N_{ch}/N_{\gamma} \sim 1$ [BKC93]. Using the discussion presented in Chapter 2.4.3, $N_{x} \approx 52 + \frac{112}{2} \approx 112$ so $f = 60/112 = .53$. Moreover, $\sigma_{f} = \sqrt{2/(9 \times 112)} = .044$, so this event is 4.5$\sigma$ from $f = 1/3$. This suggests that the global multiplicity of this event should be far away from the main cluster of events.

However, this effect may be the result of different efficiencies for detecting charged and neutral particles in the emulsion stacks. Or it may be a "pathology" in the measurement of either the charged or neutral particles, just as we found for the SPMD in Chapter 6 using our high statistics. The important thing to keep in mind here is that such anomalous events can only be understood with respect to an large ensemble of similar events, preferably with as little trigger bias as possible.

However, it is ironic that while large statistics allow better characterization of the background, improving the estimate of the statistical significance of an outlier, very large statistics make this a very difficult task. If the production rate is relatively small and background is gaussian distributed,
with sufficient statistics the gaussian tails are guaranteed to fall into the region where a signal the size of the anti-centauro event has been found, effectively swallowing the signal. To do high statistics searches for small signals where the background is gaussian, one must understand the detector response extremely well all the way out to the tails of the distribution, including all the possible rare detector anomalies.

Another reason this event is important for DCC studies is because of the presence of a region of size $\Delta \eta \Delta \phi \sim 6-7$, which we call the "DCC region", where there are $\sim 25$ photons and only 1 charged particle. An important question is if our method would be sensitive to this event if it occurred in our acceptance. Thus, we have extracted the phase space positions of the charged particles and photons by hand. “Our” JACEE event is shown in Figure 9-1. Although the position of the showers is not exactly the same as the original event, this should not affect the discussion. To establish the properties of the JACEE event outside the DCC region, we divide the JACEE lego space into four regions, defined in Table 9.1, and count the charged and neutral clusters in these regions. Region II includes the DCC region, which is clear from the very low $R \equiv N_{ch}/N_\gamma$. However, region IV is also shows a low value of $R$ relative to regions I and III. This can be seen more clearly in Figure 9-2.
Table 9.1: $N_{ch}$ and $N_\gamma$ and their ratio for four regions in the lego space of the JACEE anti-centauro event (Figure 3-1).

<table>
<thead>
<tr>
<th>Region</th>
<th>Phase Space</th>
<th>$N_{ch}$</th>
<th>$N_\gamma$</th>
<th>$R = N_{ch}/N_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\phi &lt; 180^\circ$ and $\eta &lt; 7$</td>
<td>13</td>
<td>21</td>
<td>.62</td>
</tr>
<tr>
<td>II</td>
<td>$\phi &lt; 180^\circ$ and $\eta &gt; 7$</td>
<td>2</td>
<td>32</td>
<td>.06</td>
</tr>
<tr>
<td>III</td>
<td>$\phi &gt; 180^\circ$ and $\eta &lt; 7$</td>
<td>27</td>
<td>38</td>
<td>.71</td>
</tr>
<tr>
<td>IV</td>
<td>$\phi &gt; 180^\circ$ and $\eta &gt; 7$</td>
<td>9</td>
<td>28</td>
<td>.32</td>
</tr>
</tbody>
</table>

which shows the density of charged and neutral particles separately as a function of $\eta$. The charged and neutral particles seem to be separated in phase space, the charged particles clustering around $\eta \sim 6$ and the photons around $\eta \sim 7.5$. This suggests that what is interesting about this event is not just the presence of a “patch” in a particular region, but the overall anti-correlation in phase space between the charged and neutral densities. The global analysis would not be sensitive to this, as it integrates over the full detector acceptance. However, there are methods under development [HSTW96], using the discrete wavelet transform, that may be sensitive to such charged-neutral structures within a particular event. They will not be attempted here, as that should be for another thesis.
Figure 9-2: Distribution of charged and neutral particles (represented as hollow and hatched histograms respectively) in pseudorapidity.
Chapter 10

Conclusions

In this thesis, we have used the WA98 experiment to measure charged and photon multiplicities in the central region of 158 AGeV Pb+Pb collisions at the CERN SPS in order to search for Disoriented Chiral Condensates (DCC). The presence of DCCs should modify the binomial partitioning of pion charge states according to $P(f) = 1/2\sqrt{f}$, where $f$ is the neutral fraction of produced pions. This is the first such search in heavy-ion collisions at any energy.

The experimental procedure consists of the event-by-event measurement of:

- Charged multiplicity at mid-rapidity.
- The multiplicity of photons in a similar acceptance.
- Transverse energy ($E_T$) in the forward hemisphere.

For the DCC search, we have selected events corresponding to the most central 10% of the minimum-bias cross section. In a sample of 212646 events, $\langle N_{\text{ch}} \rangle \sim 590$ and $\langle N_{\gamma-\text{like}} \rangle \sim 410$ (without acceptance corrections) and the full distributions agree well with simulated multiplicity distributions. However, the scatter plot of $N_{\text{ch}}$ vs. $N_{\gamma-\text{like}}$ reveals no clear DCC signal.

Using a simple DCC model, incorporating a DCC signal into a randomly-chosen fraction $\zeta \equiv N_{\text{DCC}}/N_{\pi}$ of the pions produced by VENUS 4.12, an event generator which has been used to describe S+S and S+Au collisions at the SPS, we have set a 90% C.L. upper limit on the maximum DCC production allowed by the data as a function of $\zeta$. This result rules out the presence of large, single-domain DCCs in heavy-ion collisions at SPS energies.
Chapter 11

Acknowledgements

All the ladies and gentlemen
Who made this all so probable

− Alex Chilton

This thesis would not have been possible without the support, advice and friendship of many people.

First, I would like to thank Bolek Wyslouch, my thesis supervisor at MIT, who, with his infallible intuitions and subtle management style, was influential on my development as a physicist and instrumental in making my four-and-a-half years at MIT a rewarding experience. Professors Wit Busza, Robert Birgeneau and Ernest Moniz supported MIT's involvement in WA98, which would have been impossible without them. Special thanks also goes to the management of LNS, especially Patrick Dreher and Bob Redwine, whose involvement was critical to our success.

Before coming to MIT, Professor Steve Manly at Yale University took a chance in hiring me, an already-graduated political theory major, as a summer student. That year of working with him was critical for me in gaining the experience, knowledge, and confidence to continue in physics.

My collaborators in WA98 made my years of research and living at CERN a great pleasure. I would like to thank our spokesmen, Hans Gutbrod and Terry Awes, for allowing us to join the collaboration so late and supporting our work there. I would also like to thank the local CERN crowd and the occasional visitors Tony, Martin, Burkhard, Paul, Glenn, Frank, the Lund group (Hans-Ake, Karim, Sten, Tom), Hal (and Belis), Jan, Yuk-Yan, Stephan, Birgit, Irmgard, Thomas, Dave, Gerrit, Tapan, the Muenster students (Hubertus, Christoph, Christof, Damian, Klaus, Stefan), and Tsukuba gang (Shunji, Susumo, Mizuki) for their collaboration and comradery over three experimental runs. Finally, I would like to thank the PMD group, led by Dr. Y.P. Viyogi, for their great detector, for their warm hospitality during my trip to India in 1995, and for their collaboration on as well as their
sharp criticisms of the DCC analysis, responding to which led to a much better work.

The secretaries in the PPE division and in the Users Office, especially Rose-Marie Audria and Christine, were very generous with their time and patience and helped make a foreigner feel a little more at home.

After the experiment was decommissioned in 1996, I returned to the U.S. and the major research and writing in this thesis was done amidst the excellent intellectual and technical resources of MIT, the Physics Department, and the MIT Laboratory for Nuclear Science. Among the excellent scientists, engineers, and computing staff working at LNS, I would like to thank Mark Baker, Jerry Friedman, Stu Galley, Piotr Kulinich, Marge Neal, Gerrit van Nieuwenhuizen, Craig Ogilvie, Heinz Pernegger, Leslie Rosenberg, Larry Rosenson, John Ryan, Paris Sphicas, Steve Steadman, George Stephans, Frank Taylor, Robin Verdier, Bernie Wadsworth, Wolfgang Wander, and Dave Woodruff for their help at various stages of the research and writing. I would also like to thank Peggy Berkovitz, the Education Coordinator of the MIT Physics Department, as well as Sandy and Barb, the PPC and Heavy Ion Group secretaries, who were always helpful and patient with administrative issues, especially during my long absences from MIT.

Further thanks go out to friends on both sides of the ocean: the Brothers Roland (Christof and Günther) and Sonja; The Cirrhosis/Charly’s/Segny Axis (Andre, Clara, Deni, Joel, Jon, Jim, the Milicic sisters, Mike, Sarah, Sabine, Theo, Tome, Werner and I’m sure I forgot someone...); the Fifth Floor (Ed, Heinz, Patrick, and Tushar); the Fourth Floor (George and Jamie); the G-1 crew (Ibo, Jason, Sandra, and Rich [and Patricia]); the New Yorkers (Anna, Caitlin, Cyrus); the St. Croix folks (David K., Domizia, Günther, Gustaaf and Sotirios); and the Traymore Institute (Cat, Kei, Martie, Rory, Jamie and Souheil). Needless to say, I could never have gotten through this whole process without Liz M., Liz A., Liza, Madeleine, and Emma.

Finally, without the love and support of my parents, Judith and Glenn Steinberg; my grandparents Muriel Newman and Sara and Louis Pellar; my sister Ellen; and my extended family Allen, Mary, and Walter; the Tanner family (Uncle Harold and Aunt Nicki and my cousins James, David and Karen); and the families of my aunts Randy, Donna and Carol in Chicago, this work would have been impossible. Sadly, my aunt Carol passed away on December 18, 1996, the day before I returned to the U.S. from CERN, after a long battle with cancer. This thesis is dedicated to her memory.

This thesis is also dedicated to my grandfather, Albert Hardy Newman. My grandfather had an enormous curiosity about many facets of the natural world, but physics always held a special magic for him. According to my grandmother, he even enrolled at the University of Chicago in the fifties to train as a nuclear physicist. Although his physics career never materialized, he always found a use for his considerable analytical skills and endless patience in many arenas, whether it was running a successful golf course in the suburbs of Chicago, searching for the perfect bread recipe, developing
the perfect color print, or trying to explain Einstein’s theory of relativity to his young grandson over a game of chess.
Appendix A

Glossary of acronyms and notations

B  "Binomiality", the distribution of which measures how well the production of pions by a particular generator approximates a binomial distribution

C_\eta  Correction factor for each \eta-ring to account for the different widths of the measured Landau distribution as a function of pad size

D_Z  Distance across the N_{ch} vs. N_{\gamma-like} correlation axis

E_T  Transverse energy produced in each event, which acts as a measure of the impact parameter

N_{ch}  Charged multiplicity produced in an event

N_{ch}^\phi  Number of SPMD hits in a particular \phi-wedge. From the pad geometry of the SPMD, this can take values from 0 to 22.

N_{hit}^\phi  Number of working SPMD pads in a particular \phi-wedge.

N_{hit}  Number of working SPMD pads hit by one or more charged particles in an event

N_{pads}  Number of working SPMD pads

N_\gamma  Multiplicity of photons produced in an event

N_{\gamma-like}  Multiplicity of "photon-like" clusters produced in an event. While most of these are created by electromagnetic showers, a certain fraction of these clusters are caused by hadrons interacting strongly in the converter.

N_\pi  The multiplicity of pions produced in a collision

N_{\pi, ch}  The multiplicity of charged pions produced in a collision

N_\pi^{DCC}  The number of pions in the final state which follow the DCC charge distribution rather than the binomial distribution.

N_{central}  Number of central events in our sample

N_{DCC}  Number of events in a given sample containing a detectable DCC signal
NUL. 90% C.L. upper limit on the number of DCC events past a specified cut given the expected background and the number of measured events over the cut

Nspect  Number of projectile spectators in a heavy ion collision

\( P(f) \)  Probability distribution for \( f \), the neutral fraction of produced pions

\( R \)  The ratio \( N_{ch}/N_{\gamma} \) defined in Chapter 9

\( \bar{R} \)  The distance of the interaction from the nominal WA98 vertex

\( R_{M} \)  The Molière radius, which sets the scale for the size of electromagnetic showers in a material

\( S_{Z} \)  Defined as \( D_{Z}/\sigma_{D_{Z}} \), this quantity measures the fluctuations of \( D_{Z} \) in units of \( \sigma_{D_{Z}} \) at a given \( Z \)

\( T_{c} \)  Critical temperature of the QCD phase transition

\( V_{eff} \)  Effective potential of the linear \( \sigma \)-model

\( X \)  A quantity similar to \( D_{Z} \) discussed in Subsection 8.3.4

\( Z \)  Distance along the \( N_{ch} \) vs. \( N_{\gamma} \)-like correlation axis

\( \Delta \eta \)  Pseudorapidity of the full SPMD.

\( \Delta \eta_{\eta} \)  Pseudorapidity of each \( \eta \)-ring.

\( \delta \)-ray  Electrons ejected from a material by the passage of a charged particle

\( \epsilon(S_{cut}, \zeta) \)  DCC detection efficiency as a function of the cut in \( S_{Z} \) and the chosen \( \zeta \)

\( \epsilon_{Bj} \)  Energy density in the central region, as calculated using the Bjorken formula.

\( \epsilon_{geom,\eta} \)  Fraction of good pads in each \( \eta \)-ring.

\( \eta \)-ring  The set of SPMD pads covering the same range in pseudorapidity

\( \eta \)  Pseudorapidity, defined by \( \eta = -\log \tan(\theta/2) \), where \( \theta \) is the angle of the produced particle. At high energies \( \eta \approx y \), and is less difficult to measure.

\( E_{F} \)  Forward energy produced in each event, which also acts as a measure of the impact parameter

\( \lambda_{I} \)  Nuclear interaction length

\( \lambda_{pair} \)  Pair production mean-free path for a photon in a material

\( \langle \bar{q}q \rangle \)  Expectation value of the chiral condensate

\( \phi \)-wedge  The set of SPMD pads at the same azimuthal angle

\( \rho(0) \)  Charged particle density at midrapidity

\( \rho \)  Baryon density

\( \rho_{0} \)  Baryon density of normal nuclear matter

\( \sigma_{i} \)  Pedestal noise for SPMD channel \( i \)

\( \sigma_{D_{Z}} \)  Variance of \( D_{Z} \) as a function of \( Z \)

\( \sigma_{line} \)  Cross section per particle of creating a “line” in the SPMD

\( \zeta \)  Fraction of final-state pions which are changed to agree with the DCC distribution

\( a_{i} \)  ADC value for SPMD channel \( i \)
\( dN_{ch}/d\eta \) Pseudorapidity density of charged particles

\( f \) The fraction of neutral pions produced in a collision

\( f_\pi \) The pion decay constant, which determines the rate of pion decay

\( g_i \) Measured gain value for SPMD channel \( i \)

\( p_0, p_1, p_2 \) Parameters used in several different polynomial fits in Chapter 8. The functional forms used are specified there.

\( p_i \) Pedestal value for SPMD channel \( i \)

\( p_{ch} \) The fraction of charged particles produced in a collision

\( s_i \) Pedestal-subtracted, gain-normalized ADC value for SPMD channel \( i \)

\( u \) Vacuum energy density in the Gavin model

\( y \) Rapidity variable, defined as \( y = \frac{1}{2} \log(E + p_z/E - p_z) \). At the SPS, beam rapidity is around 6.

ADC Analog-to-digital converter, which outputs a digital value proportional to an input signal level

Box A single PMD camera, with 50 x 38 pads

Central A “central event” is one where two nuclei collide almost head-on, producing a large number of secondaries and a large amount of \( E_T \). The central rapidity region is the region separated by 1-2 units of rapidity from the target and projectile rapidities.

DCC Disoriented Chiral Condensate, a region of hadronic matter where the chiral fields (\( \sigma, \pi \) - see LSM) are, on average, disoriented with respect to the normal vacuum. This is expected to lead to large fluctuations in the relative production of charged and neutral pions in high-energy collisions of hadrons or nuclei. For a more detailed discussion, see Chapter 2

LEDA Lead-glass detector array, an electromagnetic calorimeter which predominantly measures photons produced into \( 2. < \eta < 3. \)

LSM Linear Sigma Model, a low-energy effective theory of the strong interactions

MIRAC Mid-Rapidity Calorimeter, measuring transverse energy produced into \( 3.5 < \eta < 5.5 \)

NSC Not-so-central, i.e. not a peripheral or central event

Peripheral Events where the two nuclei do not collide head-on, producing little \( E_T \) and only a few secondaries

PMD Photon Multiplicity Detector, a preshower detector which detects photons produced into \( 2.8 < \eta < 4.4 \)

PS The Proton Synchrotron at CERN

Participants Nucleons which undergo collisions during a heavy ion collision

Projectile In the lab frame, this is the nucleus impinging on the target nucleus with momentum \( P \)

SPMD Silicon Pad Multiplicity Detector, which detects charged particles produced into \( 3.5 < \eta < 5.5 \)

SPS The Super Proton Synchrotron at CERN, which accelerates lead ions up to 158 GeV/nucleon

Spectators Nucleons which do not undergo collisions during a heavy ion collision
TDC Time-to-digital converter, which outputs a digital value proportional to the time interval between successive signals above a certain threshold.

Target In the lab frame, this is the nucleus at rest.

ZDC Zero-Degree Calorimeter, measuring energy produced in the far-forward direction ($\eta > 6$).
Appendix B

Rejected Events

In the course of this analysis, several events were removed by hand from the event sample. In this appendix, we list these events and show the full event display for each. The points show hits for the SPMD (crosses) and PMD (open circles). The closed circles show overflow hits in the SPMD. The dotted lines outline the boundaries of the PMD cameras, the number in the middle referencing it to the numbering system shown in Figure 7-3a.

1. Run 11329, Event 139 ($N_{ch} = 707, N_{\gamma\text{-like}} = 331, E_T = 341.3$) In this event, we see two "tracks" around $\eta \sim 3.3, \phi \sim 200$ that were not removed by the cut on the number of overflows.

2. Run 11445, Event 6309 ($N_{ch} = 101, N_{\gamma\text{-like}} = 307, E_T = 371.4$) In this event, cameras 14 and higher show no clusters while the other cameras show an average amount for a central event.
3. Run 11531, Event 4520 ($N_{ch} = 16, N_{\gamma-like} = 11, E_T = 437.0$) This event shows only several clusters in both the SPMD and PMD although the trigger reported this to be a central event. The $E_T$ is quite high even for a central event so it is possible that the trigger is for the previous event while a second, minimum bias event, was seen in the slower detectors.

These events are shown relative to the others in Figure B-1.
Figure B-1: The three events removed from the central sample after examination of the event display. The full event and their distinguishing features are discussed in the text.
Appendix C

SPMD readout codes

init_event.fp which initializes the sequencer and detector at the end of reading out an event:

```fortran
if (device.eq.'STR750') then ! set up a STR750 flash adc
  read (string,*) b,c,words,id,subid
  if(b.ne.my_branch) goto 1
  b = 0
  c words are ignored for the moment
  s_out = 'STR750 flash ADC'
  write(s_out(40:),15) c,words,id,subid
  print *, s_out
  if (str750_length .ge. max_entries ) then
    call space_warning ('MIZAR', str750_length)
    goto 1
  endif
  str750_length = str750_length + 1
  str751_base(str750_length) = 'ffff0000'x ! c*....
  str755_base(str750_length) = 'FF400000'x ! c*....
  str750_id(str750_length) = id
  str750_subid(str750_length) = subid
  str750_ft(str750_length) = iflat
  i2adr = str751_base(str750_length) + 2
  i2adr = 4
  i2adr = 2
  i2adr = 7
  i2adr = str751_base(str750_length) + 4
  i2adr = 400
  do i = 0,7
    iadr = str755_base(str750_length) + 4*i
    iadr = 0
  end do
  i2adr = str751_base(str750_length)
```

```fortran
else if (device.eq.'STR750') then ! set up a STR750 flash adc
  read (string,*) b,c,words,id,subid
  if(b.ne.my_branch) goto 1
  b = 0
  c words are ignored for the moment
  s_out = 'STR750 flash ADC'
  write(s_out(40:),15) c,words,id,subid
  print *, s_out
  if (str750_length .ge. max_entries ) then
    call space_warning ('MIZAR', str750_length)
    goto 1
  endif
  str750_length = str750_length + 1
  str751_base(str750_length) = 'ffff0000'x ! c*....
  str755_base(str750_length) = 'FF400000'x ! c*....
  str750_id(str750_length) = id
  str750_subid(str750_length) = subid
  str750_ft(str750_length) = iflat
  i2adr = str751_base(str750_length) + 2
  i2adr = 4
  i2adr = 2
  i2adr = 7
  i2adr = str751_base(str750_length) + 4
  i2adr = 400
  do i = 0,7
    iadr = str755_base(str750_length) + 4*i
    iadr = 0
  end do
  i2adr = str751_base(str750_length)
```
c print*, 3, @i2adr
i2adr = 'f800'x
@i2adr = str751_base(str750_length) + 2

c print*, 4, @i2adr
i2adr = 2
i2adr = 7
i2adr = 9

max_event_length = max_event_length + 4096 !?

sub_event.fp which reads out the detector after a trigger is accepted:

sub event fp which reads out the detector after a trigger is accepted:

do i = 1, str750_length
   if ( event_id .ne. str750_id(i) ) goto 170 ! not our ID

   if (str750_ft(i).eq.0 .or. (str750_ft(i).eq.1).and.(not.flat_top_off).or.
      + (str750_ft(i).eq.-1).and.flat_top_off) then
      ibuf(ibeg_sub+1)=str750_subid(i) ! sub event id
      ibuf(ibeg_sub+2)=4 ! integer*2 data follow
      ibuf(ibeg_sub+3)=IDS750 ! decode method

   @i2adr = str751_base(i) + 2
   icount = 0
   do while ( iand( i2adr,'80'x ).eq.0 .and. icount.le.10000 )
      icount = icount + 1
   end do
   ibuf(ibeg_sub+5) = i2adr ! get CSR

   @i2adr = str751_base(i)
   ibuf(ibeg_sub+4) = i2adr ! Get Mar

   @i2adr = str751_base(i) + 2
   i2adr = 8 ! disable front input

   if (icount.ge.10000) then
      ibuf(ibeg_sub+4) = ior( ibuf(ibeg_sub+4), '8000'x)
      words = 6
   else
      @iadr = str755_base(i) + '1000'x
      call _movl( iadr, ibuf( ibeg_sub+6 ), 1024 )
      words = 1024 + 6
   endif
   ibuf(ibeg_sub)=words
   ibeg_sub=ibeg_sub+words
   event_length = event_length + words

   @i2adr = str751_base(str750_length)
i2adr = 'f800'x
i2adr = str751_base(str750_length) + 2
i2adr = 2
i2adr = 7
i2adr = 9

end if
continue

end do
Appendix D

PMD Gains

In Table D.1, we list the PMD gains used for the analysis in this thesis. The sums labelled "MC" have been extracted from the PMD GEANT simulation using VENUS 4.12 events with $E_T > 320$ GeV. The statistical error on each of these values is about 2% and the systematic error from changing parameters in the simulation is about 10%, contributing to the overall PMD systematic error. The magnet on sums were taken with lower statistics, giving a statistical error on the order of 3%. The magnet-off data sums are taken from run 11250 and the magnet-on from run 11800, the number of events per run such that the statistical error is also about 2-3%.

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<th>Box Number</th>
<th>Magnet-off</th>
<th>Magnet-on</th>
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<td>MC</td>
<td>Data</td>
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<tr>
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<td>8930</td>
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</tr>
<tr>
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<td>16430</td>
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<td>3</td>
<td>16550</td>
<td>19793</td>
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<td>4</td>
<td>9119</td>
<td>26533</td>
</tr>
<tr>
<td>5</td>
<td>17870</td>
<td>24769</td>
</tr>
<tr>
<td>6</td>
<td>17760</td>
<td>20401</td>
</tr>
<tr>
<td>7</td>
<td>9255</td>
<td>24206</td>
</tr>
<tr>
<td>8</td>
<td>16360</td>
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<td>20271</td>
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<tr>
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<td>10605</td>
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</tbody>
</table>

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This figure shows the distribution of $Z$, with the same conventions as in figure 8-3. This shows the distribution of $D_Z$ in the "central" sample for the data (closed circles) and for VENUS (histogram). The difference in the mean between the two distributions arises due to the overall scale differences discussed in Section 3.

$\sigma_{D_Z}$ as a function of $Z$. Closed circles indicate the data while open circles are for VENUS. The data and simulation have been parametrized by the function $\sigma_{D_Z} = C + Z^{0.6}$ with $C = 7.5$ for the data and 4.8 for the simulation. $S_Z$ distributions for data and simulation. The means of both distributions have been shifted to lie at zero, to show the difference in shape.

Numbering system for the octants. Octant 1 ranges from $\phi = 0$ to 45 degrees, etc. Width of octant distributions as a function of octant position and $\Delta\phi$.

$S_Z$ distribution for the experimental data is shown, overlaid with VENUS simulations incorporating 0%, 25% and 60% DCC in every event. All of the distributions are normalized to the total number of data events.

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