Particle Production and Collectivity in High Multiplicity pp and pPb at the LHC

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Particle Production and Collectivity in High Multiplicity pp and pPb at the LHC

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Abstract. Recent unexpected evidence for collectivity in high multiplicity pp and pPb collisions at LHC energies has challenged the notion that such small systems do not exhibit any of the properties that have been used to study the quark gluon plasma in heavy ion collisions. An overview of recent results concerning particle production and collectivity in such collisions using the CMS detector at the LHC is presented.

1 Introduction

For roughly the first decade of heavy ion physics at RHIC and the first few years of similar studies at the LHC, heavy ion physicists assumed that no interesting physics (in the quark gluon plasma, QGP, sense) happened in pp collisions and almost no interesting physics happened in pA (or dA) collisions. These systems were viewed as too small for any possibility of forming a system of quarks and gluons that could be considered a medium. Data from pp collisions were used almost exclusively as references to determine what similar heavy ion data (for example jet spectra) would look like in the absence of the QGP. Results from pA were studied to look for cold nuclear matter effects in order to verify that any interesting observations seen in AA were not due to initial state effects. More recently, some pA data were found to be useful to constrain nuclear PDFs, but this usage served more as a fine tuning of assumptions about the initial state, as opposed to being directly related to QGP physics.

These attitudes towards these small systems have been challenged by recent observations of evidence for collectivity, first in very high multiplicity pp collisions [1] and later in high multiplicity pA collisions [2]. Studies of two-particle correlations of charged particles found a clear "ridge", a peak at small relative azimuthal angle, $\Delta\phi$, that extended over the entire accessible range of relative pseudorapidity, $\Delta\eta$. Collecting sufficient quantities of these very rare events is only possible through the use of a dedicated online high multiplicity selection implemented in the CMS trigger system.

This paper will summarize what has been learned recently about the properties of pp and pA collisions using the CMS detector at the LHC. For the sake of brevity, only the major conclusions will be described, additional information can be found in the references. Details of all heavy ion results from CMS can be found on the heavy ion physics website [3].

2 Properties of the Pb nucleus

Recent pPb data from CMS at $\sqrt{s_{_{NN}}}$ = 8.16 TeV has pushed the study of the properties of charged particle multiplicity in collisions involving projectiles larger than a proton to the highest nucleon-nucleon

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center-of-mass energy ever [4]. Combined with data at lower energies, these results can constrain the physics processes in various particle production models and thereby improve our understanding of using similar models to describe the soft background in AA. As just one example, it is found that models without shadowing significantly overpredict the observed multiplicities [4].

In addition, various observables from pA collisions can be used to constrain the nuclear PDFs used in modeling the initial state in AA interactions. The differences between parton properties in nuclei and in protons can modify, in particular, the production of heavy particles and therefore must be taken into account in interpreting the nuclear modification factor, R_{AA}, for example for J/Ψ or Z bosons. One observable that has been found to be particularly sensitive is the differences between dijet pseudorapidity distributions in various p_T ranges for pp and pPb [5]. While calculations including the EPS09 nPDFs give a better agreement than other options, some discrepancies remain, suggesting that some additional tuning is needed. The asymmetry of these collisions has also been exploited by looking at the forward-backward asymmetry as a function of the rapidity in the nucleon-nucleon center-of-mass frame, $|y_{cm}|$, where again the data are better matched by EPS09 [6]. Similar studies have been done using the rapidity dependence of the yield of prompt J/Ψ [7], although in this case the effect of comovers might also be important.

3 High p_T suppression (or not) in pPb

Initially, the study of R_{AA} in pA was motivated by the need to determine the influence of initial state effects on the large suppressions observed in AA. In all cases, it was found that such effects were small, and in many cases went in the wrong direction. For example, the R_{AA} of charged particles in pPb shows an *enhancement* of about 5-15% over a broad range of p_T for $|\eta| < 1$ [8]. For jets, small effects are seen as a function of η and p_T and it is found that next-to-leading order calculations including EPS09 are able to match the data [9]. Expanding these studies to rarer objects such as jets tagged as containing a c quark have shown R_{AA} values consistent with 1.0 [10], although the statistical and systematic uncertainties are still large.

In light of the evidence for collective effects in small systems at high multiplicities (see next section), renewed interest has been paid to looking in more detail at the possibility of quenching in pA. However, three caveats need to be kept in mind. First, all studies to date have used inclusive pA collisions containing the high p_T particle of interest. Extending these studies to higher multiplicity events remains to be done. Furthermore, essentially all models of quenching assume some length dependence. It is quite possible that even if a QGP-like medium is formed in some high multiplicity pA events, the length traversed by emerging partons will be too small to generate a measurable energy loss. Finally, when comparing particle production in high multiplicity pA to either scaled pp or to AA, the question of the correct reference data arises. High multiplicity AA events typically result from a large number of incoherent NN interactions, each of which produces multiplicities similar to inclusive pp. However, similar multiplicity events in pA must arise from a small number of highly unusual NN collisions that produce many more particles than a typical pp interaction. It's not at all clear whether comparing particle production in such events to that in scaled inclusive pp is meaningful.

It should be stressed, however, that these recent discoveries do not shed doubt on the previous uses of pp and pA collisions as reference systems to normalize or interpret the results from AA data. As mentioned previously, even when quite peripheral, a typical heavy ion collision consists of a very large number of independent nucleon-nucleon interactions. Therefore, taking minimum bias pp or pA data as a reference system for comparing to data from AA collisions remains appropriate.

4 Recent results in small system collectivity

After the early discoveries of evidence for collectivity in high multiplicity pp and pPb, more recent work has focussed on exploring other aspects of these events. Particular emphasis has been put on observables that are expected to be sensitive to the presence of a collective evolution of the system.

The earliest example from CMS work on pPb data is the finding that triangular flow, v_3, has essentially identical magnitudes in pPb and PbPb events having the same charged particle multiplicity [11]. Unlike elliptic flow, v_2, which in AA is sensitive to the lenticular overlap region for the colliding nuclei, v_3 results from fluctuations in the initial energy density. The fact that this is a collective effect relating the entire system, and not some unusual feature of correlations between a few particles is established by using cumulants and Lee-Yang Zeroes to extract v_2 for correlations of larger groups of particles. The results show that when correlating 4 or more particles, the elliptic flow magnitudes do not change [12]. Finally, as expected for pressure-driven hydrodynamic flow, v_2 as a function of p_T shows a clear mass ordering when comparing charged particles to K^0_S and Λ [13].

Recent CMS work finds that these collective features seen in pPb, including both mass ordering and higher-order cumulants for v_2, are also present in high multiplicity pp data [14]. Another observation expected for a pressure-driven expansion is a mass ordering of the yields as a function of p_T with heavier particles being enhanced at higher transverse momenta. Again using K^0_S and Λ, the expected pattern is found in both pp and pPb, with the ratios of the yields of the two particles for a given p_T and event multiplicity being very similar for the these two systems, as well as for PbPb [15].

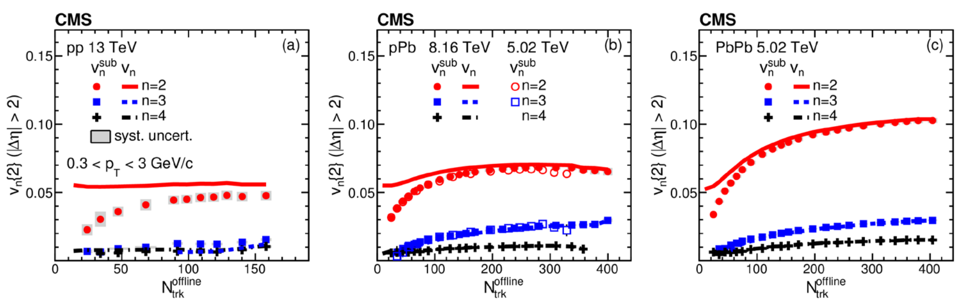

Figure 1. The v_2, v_3, and v_4 flow coefficients found using long-range ($|\Delta\eta|$ >2.0) two-particle correlations for charged particles with $0.3 < p_T < 3$ GeV/c as a function of total event particle multiplicity, $N_{trk}^{offline}$, in collisions of pp at $\sqrt{s}$ = 13 TeV (a), pPb at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV (b), and PbPb at $\sqrt{s_{NN}}$ = 5.02 (c). The results with (without) correction by subtraction of correlations in low-multiplicity events are denoted as v_n^{sub} (lines v_n). The gray boxes represent systematic uncertainties [16]. Note that the abscissa range is expanded for the pp data.

Comparisons of similarities and differences of Fourier coefficients of various orders for pp, pPb, and PbPb over a very broad ranges of multiplicity have continued. Extending the previous comparisons of v_2 and v_3 for pPb and PbPb, very similar values of both v_3 and v_4 are found for these two systems, as well as for pp, when studied at the same multiplicity (see Fig. 1) [16]. As these analyses are extended to somewhat lower multiplicities, and especially in the case of v_2 for pp, it is critical to perform a careful subtraction of the contributions of other sources of particle correlations such as jets. In the CMS work, these effects are accounted for using the lowest multiplicity events studied. As expected due to contributions from the shape of the initial nuclear overlap region, v_2 in PbPb shows increasing deviations from the other two systems at the higher multiplicities studied. To investigate what is happening in even more detail, event-by-event correlations between the different orders have been extracted. When normalized by the product of the average values, the correlations between v_2

and v_3 do not show a strong system dependence (although the statistical precision of the pp data is still poor), while the v_2/v_4 correlation, which can be affected by initial shape effects, does show differences [16]. Finally, studying properties of the particles at freeze-out, system sizes found using HBT correlations of identified identical particle pairs, for both pions and kaons, are in many cases quite similar for all three systems at lower multiplicites [17]. Small differences for the radii found at higher multiplicities may be related to differences in temperature or lifetime of the various systems. Even in these cases, the dependence of the radii on the pair average transverse momentum, another effect of radial expansion, is independent of multiplicity and does not depend on the system studied.

Many current interpretations of the collective signals in pp and pA data begin with assuming a non-uniform energy density formed at the earliest stages of the interaction. That non-uniformity must arise almost exclusively from fluctuations in the initial state of the proton in the case of pp and such fluctuations also contribute for pA (see [18] for a recent review). Investigating the properties of these exotic events opens a new window in the study of QCD matter under extreme conditions.

5 Summary

In conclusion, it is now clear that studies of both pp and pA collisions can serve many uses beyond simple reference systems for the "more interesting" AA data. Detailed studies of production of various particles in pA can help constrain the nuclear PDFs which are important input to interpretation of AA results. When explored in the realm of very high particle multiplicity, both pp and pA exhibit evidence for some unexpected collective phenomena. In addition to expanding the scope of studies of the formation and evolution of QGP (or "QGP-like") media, these data can provide insight on additional interesting physics, for example fluctuations in the initial state of the proton. Finally, comparing and contrasting results from the various systems provides the opportunity to explore the onset of collectivity in small systems over a broad range of conditions, which may provide insight into similar transitions in systems other than QCD matter.

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