Systematics of Soft Particle Production at RHIC: Lessons from PHOBOS

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The PHOBOS experiment has measured the properties of particle production in heavy ion collisions between $\sqrt{s_{NN}}$ of 20 and 200 GeV. The dependencies of charged particle yield on energy, system size, and both longitudinal and transverse momentum have been determined over close to the full kinematic range. Identified charged particles emitted near mid-rapidity have been studied over about 2 orders of magnitude in transverse momentum. This broad data set was found to be characterized by a small number of simple scalings which factorize to a surprising degree. This study has recently been extended by the addition of new data for Cu+Cu as well as new analyses of Au+Au data, including more peripheral collisions. In addition, the exploration of global properties has been expanded with the use of new techniques, including two-particle correlations, more sensitive searches for rare events, and more detailed studies of particles emitted at very forward rapidity. The characteristics of particle production which are revealed by this extensive data set will be described along with the implications for future data from the LHC.

1 Introduction

The PHOBOS experiment took data at RHIC starting with the first beam in June of 2000 and continuing through Run 5 in the spring of 2005. Data were taken for a broad range of systems, namely p+p at two energies, d+Au at one energy, Cu+Cu at three energies, and Au+Au at five energies. Results from PHOBOS and the three other RHIC experiments have shown that heavy ion collisions at the highest RHIC energies result in the formation of a new state of matter, characterized by a high energy density and dominated by partonic degrees of freedom.[1]

One of the primary goals of the PHOBOS experimental program was the characterization of the properties of particle production over a very broad range in energy and system size, as well as over several orders of magnitude in transverse momentum and all or a very large fraction of the pseudorapidity distribution. While not necessarily evidence for, or a direct probe of, the exotic partonic state, these observables set constraints on models of the formation and subsequent hadronization of the novel medium. Final state particle distributions can also set limits on basic properties of the system such as energy density and entropy. In addition to contributing significantly to our understanding of the systems formed at RHIC, this extensive data set has revealed a number of surprising results.

2 Energy Dependence of Particle Production

The first physics result from RHIC was the PHOBOS publication of the charged particle pseudorapidity density, $dN/d\eta$, near mid-rapidity at nucleon nucleon center of mass energies ($\sqrt{s_{NN}}$) of 56 and 130 GeV.[2] This early result had three immediate and profound impacts on the field of relativistic heavy ions. First, the numerical value invalidated the majority of the theoretical predictions in existence at the time. Second, the data lent support to concepts of parton saturation, which if validated could describe the dominant physics process controlling the low-x region at high energies, even in p+p collisions. Finally, the fact that these values were significantly lower than many of the theoretical predictions, combined with the first PHOBOS $dN/d\eta$ data at $\sqrt{s_{NN}}$=200 GeV which was also on the low side of the revised theoretical predictions,[3] suggested that tracking and other measurements in heavy ion collisions at the LHC might not be as formidable as originally thought. This realization helped to spawn a significant expansion in the planned LHC heavy ion program.

Later analysis revealed an intriguing similarity between the particle multiplicities per pair of participating nucleons in nucleus-nucleus collisions when compared to proton-(anti)proton interactions at twice the center of mass energy (i. e. (p+p)$\sqrt{s}$=2×(A+A)$\sqrt{s_{NN}}$). Further, these multiplicities were similar to those seen in e^++e^- at the same energy.[4] The comparison of p+p and e^++e^- was known previously and assumed to be due to the fact that only about half of the center of mass energy in p+p was available for particle production. The new comparison with Au+Au implies that nucleus-nucleus collisions can convert a much larger fraction of the available energy into particles. Data from the LHC (p+p at 14 TeV and Pb+Pb at 5.5 TeV) will reveal whether or not this correspondence extends to much higher energies.

3 Pseudorapidity Dependence of Particle Production

The uniquely broad pseudorapidity coverage of the PHOBOS multiplicity detector allowed measurement of all or almost all of the $dN/d\eta$ distribution, even at the highest RHIC energies. In addition to producing total multiplicity data with relatively small systematic errors, these results made possible a detailed comparison of the shape of the distribution at different center of mass energies. When the $dN/d\eta$ distributions for Au+Au ranging from $\sqrt{s_{NN}}$=19.6 to 200 GeV were plotted as a function of $\eta - y_{beam}$, thereby effectively viewing them in the rest frame of one of the colliding nuclei, it was found that data from all energies followed a common curve (see top left panel of Fig. 1).[5, 6] Furthermore, preliminary data for Cu+Cu over roughly the same range in energy reveal that they follow exactly the same curve.[7] Thus, the “limiting fragmentation” or “extended longitudinal” scaling seen previously in small systems was found to apply also in heavy ion collisions. Assuming that this observation and the energy dependence described in the previous section extend up to LHC energies, an empirical prediction of the full $dN/d\eta$ shape can be made.[8]

A related, but much more surprising, result was found when a similar analysis was applied to the pseudorapidity dependence of elliptic flow. When the data for v_2 from Au+Au were plotted in the effective rest frame of one of the colliding nuclei, a pattern of “extended longi-

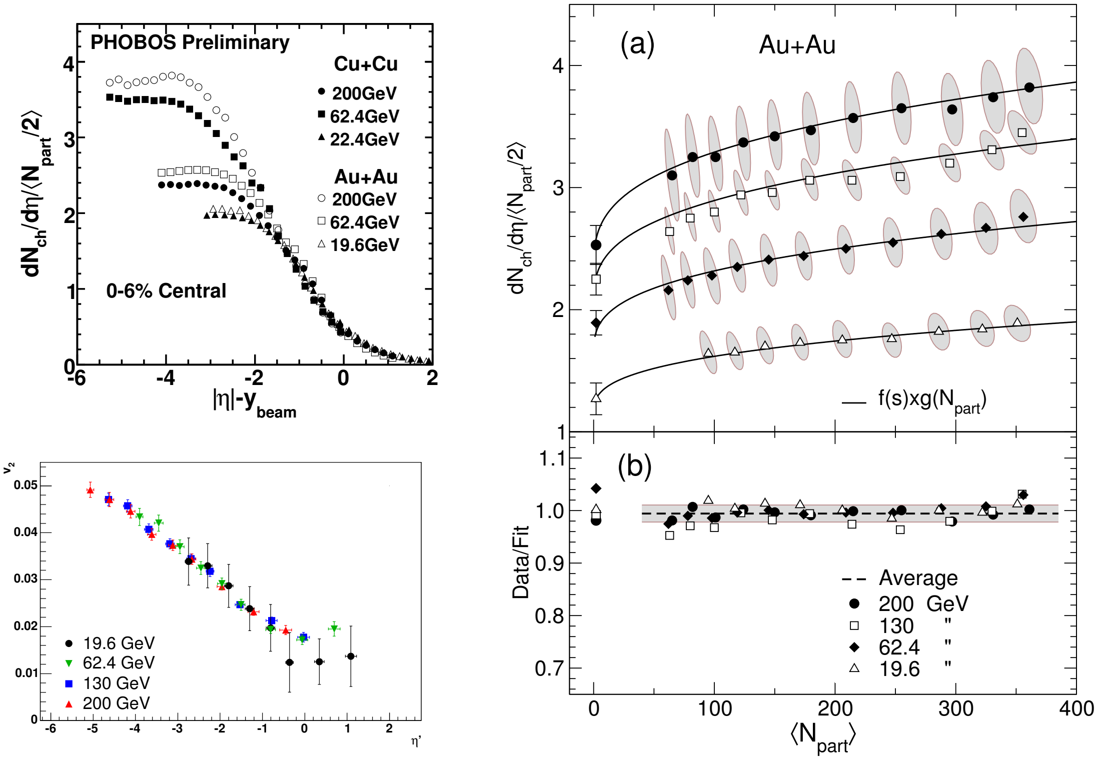

Figure 1: (Top left) Charged particle $dN/d\eta$ for various systems and energies effectively viewed in the rest frame of one of the colliding nuclei. (Bottom left) A similar plot for elliptic flow. (Right) $dN/d\eta$ per participant pair versus centrality for Au+Au at four energies fit using a product of separate functions of energy and centrality.

tudinal scaling" was again revealed (see bottom left panel of Fig. 1.[9] This adds an additional intriguing element to the experimental results for the pseudorapidity dependence of elliptic flow, data which have presented a considerable challenge to existing theories (see for example [10]). Again, an extrapolation to LHC energies can be done but the interpretation of the result is unclear. The magnitude of v_2 at midrapidity in Au+Au at $\sqrt{s_{NN}}$=200 GeV is claimed to saturate the hydrodynamical limit but, if the observed trend continues, the value at the LHC will be significantly larger.

4 Centrality Dependence of Particle Production

By analyzing heavy ion collisions at varying impact parameter, the effect of system size on particle production can be explored. This variation does not represent simply "more of the same" since central collisions with small impact parameters have a larger average number of collisions per participant and therefore might differ more significantly from elementary p+p interactions. A common claim is that "harder" processes should scale with the number of collisions while "softer" process should scale with the number of participants. If true, this belief, combined with the expectation that the ratio of "hard" over "soft" processes should increase with collision energy, implies that the centrality dependence must be energy dependent. In stark contrast to this prediction, the centrality dependence is found to be identical at all energies studied.[11] [6] In fact, it can be shown quantitatively that the data factorize by fitting them with the product of separate functions of energy and the number of participating nucleons (see right panel of Fig. 1).[12] Far from being a property solely of bulk particle production at lower transverse momentum, this factorization was found to extend up to p_T of almost 4 GeV/c in Au+Au data.[13] Again, Cu+Cu results are observed to follow the same trend.[14] As with many of the PHOBOS observations, it will be very interesting to follow this trend to the LHC where "hard" processes are expected to make a much more dominant contribution to particle production.

5 Continuing PHOBOS Analysis

Although no further data are being taken by the PHOBOS collaboration, analysis work continues. One goal is to fully incorporate all results, including those for smaller systems such as p+p and nucleus-nucleus collisions over an extended range of centrality. Simultaneously, the analysis is expanding beyond event-integrated single-particle distributions to the consideration of more complicated observables such as fluctuations, correlations, and rare event topologies. Results for elementary systems, to be used as a baseline comparison for nucleus-nucleus data, have already been published.[15]

6 Summary

Analysis of the characteristics of particle production in nucleus-nucleus collisions at RHIC energies have revealed a number of unexpectedly simple dependencies. Observables considered range from the most basic such as total multiplicity to the fairly complex such as elliptic flow. In many cases, the dependencies on collision energy, centrality, pseudorapidity, and transverse momentum factorize to a surprising degree. To paraphrase a comment originally made about star formation in galaxies[16], "Particle production in heavy ion collisions follows a quite simple pattern and simple patterns often mean that there are only [a] few basic physical mechanisms at work. . . . We can now find out what these mechanisms are by measuring how particle production behaves with energy, centrality, η, and p_T and compare that behavior to models". Extrapolation of these trends to LHC energies suggest that interesting discoveries may well be made using only these simply global observables.

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