Particle Multiplicities and Correlations

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Abstract. Studies of charged hadron multiplicities have provided important information about the physics of ultra-relativistic heavy ion collisions. The systematics of charged particle multiplicities in high energy collisions, i.e. nucleon-nucleon, \(e^+e^-\) and nucleus-nucleus reactions, as a function of collision energy and centrality, suggest that in heavy ion collisions the multiplicity distributions are determined in the initial collision stage and that the overall produced multiplicity is limited by coherence or destructive interference in this early stage. In this paper, I will present some of the experimental results supporting these conclusions and point out features of the data that still await an explanation in dynamical models of the collision process. I will discuss future possibilities to help answer these questions, including measurements at the Large Hadron Collider and studies of multiplicity correlations.

1. Introduction

Heavy-ion collisions provide the best opportunity to test the predictions of QCD for matter under conditions close to the expected QCD phase-transition or resembling the conditions in the early universe. However, the system created in a heavy-ion collision is different from that simulated in lattice calculations or the early universe in several important aspects. The small size of the available nuclei sets the scale of the temporal and spatial extent of the high-density system created in the collision. The asymmetry of the incoming system, with its momentum in the direction of the incoming beams, is reflected throughout the evolution of the collision process. Most estimates suggest a lifetime of the collision system of 10-20 fm/c, from the initial high density state until freeze-out occurs, i.e. the collision density becomes so low that the produced particles essentially enter a free-streaming motion and are finally detected by the experiments.

The main experimental and theoretical challenge is then to reconstruct the properties of the earlier stages of the system from experimental observables based on the final-state particles. It is therefore essential to study collision systems that specifically probe the different stages of this evolution by varying the system size and collision energy.

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In the past three years, RHIC has delivered Au+Au collisions at $\sqrt{s_{NN}} = 19.6, 56, 130$ and 200 GeV and $d+Au$ and proton-proton collisions at 200 GeV. As the results shown below will illustrate, the information from these systematic surveys, in combination with data from the AGS and CERN fixed target programs, is essential in forming a consistent dynamical picture of the evolution of a heavy ion collision.

The emphasis in this paper is on the systematics of particle multiplicities in these collisions. A priori, a mapping of the observed multiplicity to a specific stage of the collisions seems difficult, as in principle all stages of the collision could contribute to particle production. A close examination of the available data however, suggests that the multiplicity of charged particles and the distribution in pseudo-rapidity are determined very early on in the collision and provide a window into the dynamics of the initial state.

### 2. Multiplicity Systematics

#### 2.1. Particle Density near Mid-Rapidity

The first physics results from RHIC were measurements of pseudo-rapidity densities of charged hadrons, $dN_{ch}/d\eta$, near mid-rapidity in central Au+Au collisions at collision energies of $\sqrt{(s_{NN})} = 56$ and 130 GeV [1]. Like many of the RHIC data published since then, these first results proved surprising, showing a much smaller increase over multiplicities from lower energies than expected in the vast majority of theoretical approaches. Further measurements at the full RHIC energy of 200 GeV showed that in fact the mid-rapidity particle density appears to rise logarithmically from the AGS to the highest RHIC energies [2]. A summary of these measurements for central Au+Au (Pb+Pb) collisions as a function of collision energy is shown in the left hand plot of Fig. 1, while the left plot shows a compilation of predictions in comparison to data at 200 GeV [3, 4].
Figure 2. Ratio of the charged hadron mid-rapidity multiplicities at 200 and 19.6 GeV as a function of collision centrality.

Clearly, the charged hadron pseudo-rapidity density is related to the initial energy density of the system, as the initial volume of the system can be determined from the known size of the nuclear overlap region, in combination with an estimate of the longitudinal size at the time of equilibration, which is typically taken to be $\approx 1 \text{ fm}$. The corresponding energy density can be estimated to be on the order of 3-5 GeV/fm$^3$ or higher, if one assumes faster equilibration. While this estimate is still comfortably higher than the predictions for the critical energy density from lattice QCD of 1 GeV/fm$^3$, it was a surprise that the data fell at the lowest end of the range of predictions.

It has been suggested that the relatively low multiplicity seen at RHIC is a consequence of parton saturation, based on the idea that at high energies the density of low-$x$ gluons in the transverse plane of the colliding nuclei will no longer allow them to interact independently. Rather, they will form a “Color Glass Condensate” [5], with the resultant coherent interaction of the constituents of the nuclei limiting the growth of particle multiplicity as a function of collision energy. Model calculations based on the idea of parton saturation, in combination with local parton-hadron duality, have had impressive success in describing the energy, centrality and rapidity dependence of charged hadron production in nucleus-nucleus collisions.

The importance of these ideas is illustrated in Fig. 2, which shows the ratios of the charged hadron mid-rapidity multiplicities at 200 and 19.6 GeV as a function of centrality[6]. This ratio is found to be flat, in sharp contrast to predictions of models like HIJING that describe charged particle production as a superposition of an empirical soft component and energy- and centrality dependent contributions from hard scattering processes. In this model, as shown in Fig. 2, the experimentally seen factorization of energy and centrality dependence is strongly violated. In contrast, parton saturation model calculations include this factorization approximately [5] or explicitly [7].
2.2. Limiting Fragmentation

One of the interesting observations in multiplicity distributions at RHIC was first pointed out by the BRAHMS collaboration. They found [8] that the pseudo-rapidity distributions for charged particles over a large range of pseudo-rapidity were independent of the collision energy, when viewed in the restframe of one of the colliding nuclei. This observation was confirmed and extended by PHOBOS [9] and recently by STAR [10]. Measurements from PHOBOS are shown in Fig. 3. The observed extended longitudinal scaling of particle production is known from p+p collisions over a large range of collision energies, as well as from p+A collisions. It is usually termed “limiting fragmentation”. What is surprising in nucleus-nucleus collisions is that the scaling behavior seen in these elementary collisions is preserved in the complicated dynamical environment of A+A collisions. It in fact appears to control particle production over a large part of longitudinal phase space, several units away from what is normally considered the fragmentation region. Furthermore, the longitudinal scaling seen in pseudo-rapidity distributions is also observed in the anisotropy of azimuthal particle distributions relative to the reaction plane of peripheral Au+Au collisions. Data from PHOBOS have shown that $v_2$ drops quickly for particles away from mid-rapidity. Although qualitative arguments can be made that this is related to the dropping particle density and resulting incomplete thermalization, no dynamical 3-dimensional calculations exist that successful describe these data. Comparing data from 4 different energies at RHIC, shows that the average $v_2$ parameter follows a very simple scaling behavior, as shown in Fig. 4. This observation suggests that at LHC even higher values of $v_2$ will be observed. Eventually, a complete understanding of the dynamical evolution of the system will need to explain this remarkably simple scaling behavior.
Based on these scaling observations, the data taken at RHIC allow an empirical prediction of the expected $dN/d\eta$ distribution at LHC. This prediction, shown in Fig. 5, is based on the logarithmic energy dependence of the mid-rapidity pseudo-rapidity (Fig. 1), in combination with the observed “limiting fragmentation” scaling of charged particle $dN/d\eta$ distributions. The resulting mid-rapidity charged hadron $dN/d\eta$ for central Pb+Pb collisions at the LHC is only $\approx 1200$, far below most model expectations (and the design specifications of the experiments). It is important to note that a higher mid-rapidity multiplicity, e.g. following a power-law energy dependence, would either imply a violation of limiting fragmentation, which has been found to hold up to collision energies of 900 GeV in $p+p$ collisions, or a radically different shape of the $dN/d\eta$ distributions at the LHC. If however this empirical prediction holds, it will imply an even stronger “destructive interference” in the initial state particle production than suggested in parton saturation models. Clearly, the contribution to particle production from hard processes is expected to increase rapidly when going to LHC energies. A test of the factorization observed at low energies will be one of the fascinating day-1 measurements once the LHC comes online.
2.3. Multiplicity and the Initial State

As mentioned before, the multiplicity of charged hadrons could be expected to be a convolution of contributions from all different stages of the collision process. In this case, few conclusions could be drawn from the measurements directly, and the data could at best be used to test or calibrate models of the collision. However, several observations suggest that in fact the particle multiplicities are defined in the very early stage of the collision process and are little changed in the further evolution of the collision, in accordance with the idea of an isentropic expansion of the initial system.

Support to this claim is given by the success of pure initial state models based on the idea of parton saturation in describing the overall energy dependence of particle densities, the evolution of multiplicity distributions with centrality and the factorization of energy and centrality dependence. As such models can account (after normalization at one energy) for the relatively low overall multiplicities, it is reasonable to conclude that the contribution from further stages of the collision to the overall particle multiplicity is small. Further evidence comes from the survival of scaling behavior like e.g. limiting fragmentation seen in p+p and p+A collisions in the A+A environment, which would require a fortuitous cancellation of dynamical effects, if particle production was dominated by the later collision stages.

Finally, it was observed that the energy-dependence and absolute magnitude of the mid-rapidity particle density per participant pair in central Au+Au collisions coincide, within the experimental uncertainties, with those in $e^+e^-$ collisions at the same collision energies [11]. Similarly, the total charged particle multiplicity per pair of participating nucleons for A+A collisions above $\sqrt{s_{NN}} \approx 20$ GeV is within 10% of the total charged particle multiplicity in $e^+e^-$ collisions at the same collision energy and that of p+p collisions, if those are corrected for the leading particle effect.
In summary, these observations naturally hint at an universal mechanism of particle production in the strong interaction, defining particle multiplicities early on in the collision process. Measurements at the LHC, with a factor 30 higher collision energies, might yield the final clues for understanding these connections.

3. Multiplicity Correlations

The study of high $p_T$ particle production has played a central role in developing our understanding of heavy-ion collisions. One of the most promising directions is the development of correlation studies that elucidate the how the fast partons interact with the medium [12]. Obviously, the energy of the fast partons is not lost, but redistributed inside the collision system. Differential studies of this transport process are beginning to emerge [13]. Studies of multiplicity fluctuations, as seen in Fig. 6 [14], show that the features of these fluctuations as a function of centrality, rapidity and size of the rapidity bins can be approximately reproduced in models like HIJING, provided that the correlations due to initial hard scattering processes are included. The studies suggest that the event-wise fluctuations in the multiplicity distributions are dominated by particle correlations introduced through initial hard scattering processes. Similarly, fluctuations in event-by-event average transverse momentum can be explained as results of the correlations at intermediate $p_T$ from the same processes. In essence, most of the dynamical fluctuation signals observed at RHIC can be traced to the same physical origin.

One of the major tasks for the next years will therefore be to develop a phenomenology that will allow us to relate the observed final state correlations to the known seeds of fluctuations provided by the initial hard scattering processes and to use this to quantitatively extract properties of the dense medium. A good analogy for this experimental and theoretical program is given by recent...
progress in cosmology, where the final state correlation structure of e.g. the cosmic microwave background is used to quantitatively constrain parameters of the cosmic evolution. This analogy also suggests that this will be a long-term program, requiring input from a systematic survey of collision energies and collision systems, as well as a close connection between theory and experiment to find a common language in which to express the observed and calculated correlation structure.

4. Conclusions

The results from nearly two decades of experimental high-energy heavy-ion physics demonstrate convincingly that a unique, high-density medium is formed in these collisions. Many of the properties of the medium, such as the universality of entropy production, the presence of coherent effects limiting particle production, the large initial energy density, the isentropic nature of the expansion and the dominance of correlations originating from initial hard scattering processes can be inferred from studies of multiplicity distributions and multiplicity fluctuations. Still, many experimental and theoretical questions remain. Of highest importance are measurements related to the nature of the medium before hadronization and a theoretical understanding of how the initial equilibrated medium is formed and how the eventual decay into hadrons proceeds. Many of the answers will come from tests of our present models at the much higher collision energies accessible at the LHC. In addition, a comprehensive study of particle correlations over the full accessible phase space and using tagged initial hard processes, will help us to develop a more complete picture of the collision dynamics. At the same time, we can probably expect that the rich harvest of surprising experimental results will continue in these future studies.

[1] B B Back et al. Phys. Rev. Lett. 85, 3100 (2000)
[2] B B Back et al. Phys. Rev. Lett. 88, 22302 (2002)
[3] K J Eskola, Nucl. Phys. A698 (2002) 78, arXiv:hep-ph/0104058.
[4] B B Back et al. arXiv:nucl-ex/0410022.
[5] L D McLerran, R Venugopalan, Phys. Rev. D49 2233 (1994),
    D Kharzeev and B Levin, Phys. Lett. B523 79 (2001),
    A Krasnitz, R Venugopalan, Phys. Rev. Lett 86 1717 (2001),
    D Kharzeev, E Levin, L. McLerran, arXiv:hep-ph/0210332.
[6] B B Back, et al., Phys. Rev. C 70 (2004) 021902R.
[7] N Armesto, C A Salgado and U A Wiedemann, arXiv:hep-ph/0407018.
[8] I G Bearden et al. Phys. Rev. Lett. 88 202301 (2002).
[9] B B Back et al., Phys. Rev. Lett. 91, 052303 (2003).
[10] J Adams et al. arXiv:nucl-ex/0502008, submitted
[11] B B Back et al., arXiv:nucl-ex/0301017, submitted to Phys. Rev. C.
[12] C Adler et al., Phys. Rev. Lett. 90 082302 (2003).
[13] see M Kopytine, these proceedings.
[14] K Wozniak et al. J Phys G30 1377 (2004)