The Remarkable Simplicity and Universality of Multiparticle Production Data

Wit Busza
Massachusetts Institute of Technology

DOI: http://dx.doi.org/10.3204/DESY-PROC-2009-01/35

Abstract

A discussion is given of the remarkable simplicity and universality of multiparticle production data at high energies, in particular in heavy ion collisions.

The question is raised if the reason for this simplicity and universality is trivial or profound and consequences for LHC are considered.

In this talk I will present no new results. It is aimed at those of you who are not experts on heavy ion collisions but who are interested in soft collisions, in particular in the phenomenology and mechanism of multiparticle production in pp and e^+e^- collisions. I want to bring to your attention the fact that there exists today a vast amount of high quality data on multiparticle production in relativistic heavy ion collisions [1–4] and that these data exhibit great similarity to the pp and e^+e^- data [1, 5], and that therefore trends observed in AA data may throw light on our understanding of soft processes in general and not just in AA collisions.

The most remarkable feature of multiparticle production data is its simplicity and universality [6, 7]. It is probably fair to state that as a rule the data exhibit features and trends that are much simpler than the explanations.

In our current understanding of the multiparticle production process in e^+e^-, pp, pA, and AA collisions there are some similarities but overall our picture of each process is quite different. In e^+e^- for example we view the initially produced virtual photon as evolving, through sequential pair production and radiation, into a system of partons that fragment (and/or combine) into the multihadron final state. On the other hand, in the highest energy head-on (central or small impact parameter) heavy ion collisions, the conventional picture is that, viewed in the center of mass frame, two Lorentz contracted disks collide. Each is essentially a dense wall of low momentum strongly interacting gluons together with their sources, the high momentum weakly interacting partons. The gluon walls are the so-called colored glass condensate or CGC [8]. In a very short time ($\leq \frac{1fm}{c}$) after the collision the two gluon walls stop each other and produce a hot equilibrated strongly interacting system with high pressure. At RHIC energies there is general consensus [9] that at the time of equilibration the temperature, pressure and energy density of the system are higher than the critical values obtained in lattice QCD calculations for the hadronic/partonic phase transition. There is also general consensus that the hot system is more like a strongly interacting liquid with extremely low value of the ratio of viscosity to entropy, then that of a weakly interacting gas. The final multihadron state is the last stage of this system as it expands and cools.

The surprising fact is that most of the global trends observed in the collision of all these systems and at all energies are the same. Bringing these trends to your attention is the main aim of my talk.

Before discussing the heavy ion data, I wish to point out that the most extensive set of AA data on multiparticle production of particles into almost the full 4π solid angle comes from the PHOBOS experiment at RHIC [1]. In PHOBOS only charged particles are measured and for the majority of these only the polar and azimuthal angles. Thus only $\frac{d^2N}{d\eta d\phi}$, the particle density in pseudorapidity η and azimuthal angle ϕ space, is measured. In this talk I will not distinguish between rapidity and pseudorapidity. The two are almost identical for particles with speed close to that of light except for polar angles close to zero. Nevertheless it should be remembered that pseudorapidity distributions do distort true rapidity distributions, and conclusions based on pseudorapidity distribution might sometimes be misleading.

The first universal trend worth pointing out is that in AA collisions, as in e^+e^- and pp, for all impact parameter and colliding systems studied, the mid rapidity particle density $\frac{dN}{d\eta}$ increases linearly with the logarithm of the energy of the collision [1], with no signs of any change in the trend as the energy increases. This is despite the fact that the energy range studied to date covers energies low enough where the conditions are such that the initial energy density must be well below critical and furthermore dominated by baryons, and high enough that, almost certainly the initial energy density is above critical and the system created is essentially baryon free.

As proof that this observed simple rate of increase of particle density is neither obvious nor well understood is the observation that the predictions of various authors [10] for the expectations at LHC differ by more than a factor of 2.

At mid rapidity not only does the particle density increase with energy as $ln\sqrt{s}$ ($\sqrt{s}$ is the nucleon-nucleon center of mass energy) but also the amplitude of azimuthal anisotropy of particle production [11], ie. of v_2, the second Fourier coefficient in $\frac{d^2N}{d\phi d\eta} = N_0(1 + 2v_2cos2\phi)$ with v_1 and higher coefficients neglected.

One of the most prominent universal features of all multiparticle production data is "extended longitudinal scaling" [1], an extended (in rapidity) version of "limiting fragmentation". Plotting $\frac{dN}{d\eta}$ as a function of η, boosted to the rest frame of either of the two colliding systems, we find that as $\sqrt{s}$ increases, $\frac{dN}{d\eta}(\eta)$ is independent of $\sqrt{s}$ for a bigger and bigger range of η. Extended longitudinal scaling appears to be valid not only for $\frac{dN}{d\eta}(\eta)$ but also for $v_2(\eta)$ [1]. An instructive way of visualizing and obtaining an intuitive understanding of extended longitudinal scaling is to consider the outcome of the collision of two beams, say yellow and blue, whose energies can be set independently. Extended longitudinal scaling would manifest itself as follows. For a given energy of the yellow beam, as the energy of the blue beam is increased $\frac{dN}{d\eta}$ and v_2 increases until it reaches a maximum value. Once this value is reached, increasing the blue beam energy further, even to infinity, has no effect on $\frac{dN}{d\eta}$ or v_2. The maximum values of these quantities (ie. point on the limiting curve) can be increased only by increasing the energy of the yellow beam. This phenomenon is seen for all colliding systems and is a direct manifestation of some kind of universal saturation phenomenon.

It is interesting to note that the limiting curve for $\frac{dN}{d\eta}$, to within the precision of the data, is a straight line with $\frac{dN}{d\eta}$ close to zero at a value of η corresponding to one of the colliding systems at rest. This fact, together with the fact that the difference of rapidity between the colliding systems $\sim ln\sqrt{s}$ and also $\frac{dN}{d\eta}|_{y=0} \sim ln\sqrt{s}$ (with $\sqrt{s}$ in GeV), imply that the shape of the $\frac{dN}{d\eta}(\eta)$ distributions are independent of energy. This similarity of $\frac{dN}{d\eta}(\eta)$ distributions at all energies, to fairly high precision, is seen in e^+e^-, pp, pA, and AA collisions. From these facts it also follows that the total charged particle multiplicity increases linearly with $ln^2\sqrt{s}$ (with $\sqrt{s}$ in GeV), which again is consistent with observation for all colliding systems studied [7].

Another prominent feature in AA collisions is that the energy dependence and system dependence are to a large degree independent of each other. For example, at all energies, the total charged particle multiplicity scale in the same linear manner with the total number N_{part} of nucleons participating in the collision [1](the so-called participant scaling first observed in pA collisions [12]), and the fractional increase with N_{part} of the mid rapidity particle density is independent of the energy [1,13]. These two features are quite surprising. Naively one would expect the fraction of soft and hard collisions to change with energy and therefore so also the N_{part} dependence. Furthermore it is hard to understand what mechanism gives rise to the apparent number conservation of produced particles per participant under conditions when the distribution with rapidity of the produced particles changes significantly. For example, how is it that by changing the impact parameter of the collision one exchanges, one for one, a 100 GeV particle for one 1 GeV particle (the energy being conserved through increases in transverse momentum of many particles)?

Below I give other examples of facts that can be simply stated but that have no simple explanations.

In both AA and in pp there are hard collisions. There is one difference: in AA per nucleon-nucleon collision fewer high transverse momentum particles are produced. This is the so-called “jet quenching” phenomenon [14]. All theoretical estimates, based on the hypothesis that jet-quenching is due to energy loss of the recoiling parton in the high density medium, predict a weak P_t dependence of the suppression of the high P_t particles. In reality the suppression, up to the highest P_t values measured ($\leq 20\frac{GeV}{c}$), seems to be independent of P_t [15]. Furthermore the magnitude of this suppression is not that different from the suppression of the high $x_{Feynmann}$ forward particles in pA collisions at all energies studied [16]. In both cases, as a first approximation, one can qualitatively explain the data with the simple assumption that the central part of the nucleus is totally absorbing and only particles originating along the periphery of the nucleus survive.

A final example is the striking observation that for a given impact parameter of an AA collision at a given energy, if $\frac{v_2}{n}$ is plotted as a function of $\frac{KE}{n}$, where n is the number of valence quarks in the produced particle and KE is its kinetic energy, the data for all produced particles fall on a universal curve [17]. This is taken as evidence of the existence in the intermediate state of a system with quark degrees of freedom followed by coalescence. This interpretation of the general features of this data is highly plausible, however it is difficult to understand why all the data fall with such high precision on one curve.

To conclude, through this talk I have attempted, on the one hand to bring to your attention the fact that there exists a large body of very high quality data on multiparticle production in AA collisions, and on the other, to point out the interesting curiosity that on the whole the data is simpler and more universal than the current explanations of it.

I do not understand this fact and I am intrigued by it. Is the remarkable simplicity and universality of the data an accident? If not, is it trivial or profound? Is it possible that we are simply wrong or missing something fundamental in our current interpretation of the facts?

In the not too distant future, multiparticle production data in PbPb collisions will become available at an energy 27 times higher than the highest energy data at RHIC. The trends discussed in this talk, when extrapolated to LHC energies suggest that the following will be seen at LHC [7, 10]: 1) extended longitudinal scaling and N_{part} scaling, 2) for PbPb collisions with N_{part}=386 (top 3% centrality) at $\sqrt{s}$=5500 GeV, $N_{charged}$=15000 $\pm$ 1000, 3) for PbPb collisions at $\sqrt{s}$=5500 GeV, for the 40% most central collisions, v_2=0.075 $\pm$ 0.005, 4) $\frac{v_2}{n}$ will continue to be a universal function of $\frac{KE}{n}$, 5) the suppression of high P_t hadrons at mid rapidity, will continue to be independent of P_t (with $R_{AA} \sim 0.2$ for the most central PbPb collisions), 6) for non-single-diffractive pp collisions at $\sqrt{s}$= 14000 GeV (10000 GeV), $N_{charged}$=70±8 (65±8), 7) for inelastic pp collisions at $\sqrt{s}$ = 14000 GeV (10000 GeV), $N_{charged}$=60±10 (56±9).

If most of these extrapolations turn out to be consistent with LHC data, more than ever it will become crucial that a coherent explanation can be found for the continued simplicity and universality of the data.

On the other hand, if some or all of the results turn out to be very different from these extrapolations, it will be a strong indication of the onset of new physics at LHC.

References

[1] PHOBOS Collaboration, B. B. Back *et al.*, Nucl. Phys. **A757**, 28 (2005). `nucl-ex/0410022`.

[2] STAR Collaboration, J. Adams *et al.*, Nucl. Phys. **A757**, 102 (2005). `nucl-ex/0501009`.

[3] BRAHMS Collaboration, I. Arsene *et al.*, Nucl. Phys. **A757**, 1 (2005). `nucl-ex/0410020`.

[4] PHENIX Collaboration, K. Adcox *et al.*, Nucl. Phys. **A757**, 184 (2005). `nucl-ex/0410003`.

[5] UA5 Collaboration, G. J. Alner *et al.*, Z. Phys. **C33**, 1 (1986).

[6] W. Busza, Acta Phys. Polon. **B35**, 2873 (2004). `nucl-ex/0410035`.

[7] W. Busza, J. Phys. **G35**, 044040 (2008). `0710.2293`.

[8] L. McLerran. Talk given at ISMD08;
K. Itakura. Talk given at ISMD08.

[9] E. . Rischke, D. and e. . Levin, G. Prepared for Workshop on New Discoveries at RHIC: The Current Case for the Strongly Interactive QGP, Brookhaven, Upton, New York, 14-15 May 2004.

[10] E. . Armesto, N. *et al.*, J. Phys. **G35**, 054001 (2008). `0711.0974`.

[11] NA49 Collaboration, C. Alt *et al.*, Phys. Rev. **C68**, 034903 (2003). `nucl-ex/0303001`.

[12] W. Busza *et al.*, Phys. Rev. Lett. **34**, 836 (1975);
W. Busza *et al.* Invited paper presented at Topical Meeting on High Energy Collisions involving Nuclei, Trieste, Sep 9-14, 1974.

[13] PHOBOS Collaboration, B. B. Back *et al.*, Phys. Rev. **C74**, 021902 (2006).

[14] PHENIX Collaboration, K. Adcox *et al.*, Phys. Rev. Lett. **89**, 212301 (2002). `nucl-ex/0204005`.

[15] PHENIX Collaboration, A. Adare *et al.* (2008). `0801.4020`.

[16] D. S. Barton *et al.*, Phys. Rev. **D27**, 2580 (1983).

[17] PHENIX Collaboration, A. Adare *et al.*, Phys. Rev. Lett. **98**, 162301 (2007). `nucl-ex/0608033`;
STAR Collaboration, J. Adams *et al.*, Phys. Rev. Lett. **92**, 052302 (2004). `nucl-ex/0306007`.