Proc. 20th Winter Workshop on Nuclear Dynamics (2003) 000–000

20th Winter Workshop on Nuclear Dynamics
Trelawny Beach, Jamaica
March 15–20, 2004

Multiparticle Production in pp, pA, dA, and AA Collisions

Wit Busza[1]

[1] Massachusetts Institute of Technology,
Cambridge, MA USA

Abstract. A discussion is given of the principal features observed in pp, pA, dA, and AA collisions at high energies. In particular it is pointed out that the rapidity distributions for all these colliding systems exhibit great similarity, and furthermore they all show the same evolution with energy.

Keywords: multiparticle production, heavy ion collisions, RHIC, rapidity distributions
PACS: 25.75Dw, 13.85Hd

In high energy heavy ion collisions a fascinating strongly interacting system is produced. The aim of this talk is to look at the main longitudinal features in pp, pA, dA, and AA multiparticle production, to see if we can get some insight into what is happening during the AA collsion process, and perhaps even into the nature of the produced system. As a by product, I hope the talk will serve as a reminder of some old but probably relevant facts in pA collisions. Intentionally I make no comparisons with theoretical models. The whole idea is to focus on what the data is trying to tell us in the most simple terms possible. For the same reason I am not focusing on details.

It is my firm belief that the final correct theoretical description of AA collsions will automatically contain all these basic features. They will not turn out to be the consequences of detailed calculations or accidental coincidences.

From the beginning I should stress that in this talk my aim is to emphasize features in the phenomenology, it is not to survey all the existing data. I have made no attempt to choose data equally from different experiments. In general I chose those results to which I had the most easy access.

1. The overall shape of rapidity distributions

Since it is much easier to measure the pseudorapidity ($\eta = \tanh^{-1}\cos\theta = \tanh^{-1}\frac{P_l}{p}$) rather than the rapidity ($y = \tanh^{-1}\beta = \tanh^{-1}\frac{P_l}{E}$) of a particle, there is much more information available on pseudorapidity distributions $\frac{dn}{d\eta}$ than on rapidity dis-

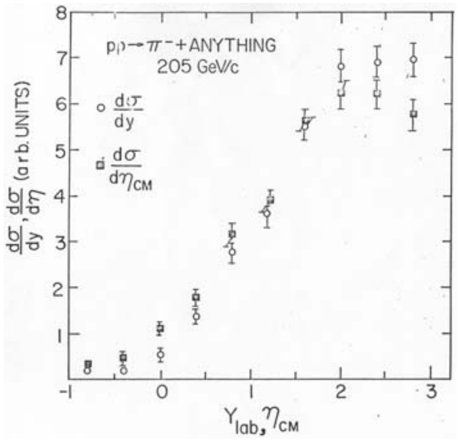

Fig. 1. Same data plotted as $\frac{dn}{dy}$ or as $\frac{dn}{d\eta}$ from ref. 1

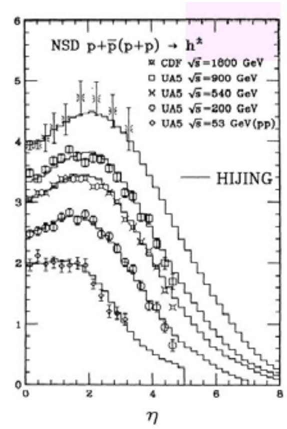

Fig. 2. Pseudorapidity distributions for $p\bar{p}$ collisions at several energies from ref. 2

tributions $\frac{dn}{dy}$. It is only the latter, of course, that can relatively easily be interpreted and gives some kind of a picture of the process that takes place during the collision. Fortunately for the majority of particles the difference between $\frac{dn}{d\eta}$ and $\frac{dn}{dy}$ is small. This difference, for example, is illustrated in figure 1. This figure not only points out that the basic shape of the $\frac{dn}{d\eta}$ and $\frac{dn}{dy}$ distributions are quite similiar, but also makes apparent some significant differences. Near mid-rapidity $\frac{dn}{d\eta}$ develops a plateau or even a dip that is not seen in $\frac{dn}{dy}$. This depletion of particles near mid-rapidity is balanced by an increase at values of pseudorapidity close to the rapidity of the incident particles.

Keeping the above distortions in mind let's now look at $\frac{dn}{dy}$ distributions (and $\frac{dn}{d\eta}$ distributions when the former are not available) and see what are the main characteristics of the shape of these distributions. Example of such distributions for pp, pA, dA, and AA collisions are given in figures 1 - 6.

The pp and AA rapidity distributions are very similiar in shape and, contrary to naive expectations, they show no significant boost-invariant central plateau even at the highest energies. In fact, to a good approximation, as can be seen in fig. 6 at all energies $\frac{dn}{dy}$ distributions can be described by gaussians[6]. Although Fermi and Landau, based on the assumption that strong interactions are "really strong", predicted gaussian distributions for ultra high energy hadronic collsions, with today's knowledge of the partonic structure of hadrons and of asymptotic freedom, it is not obvious why rapidity distributions have an approximately gaussian shape.

Not surprisingly, for asymmetric collsions such as pA and dA, the rapidity distributions are asymmetric. However what is surprising is the range in rapidity of correlations between the produced and incident particles. The correlations span the

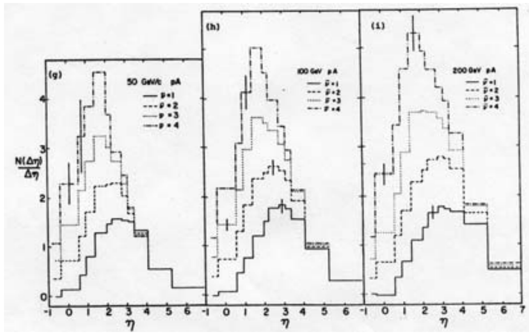

Fig. 3. Energy and centrality dependence of pseudorapidity distributions in pA collisons (from E178, ref. 3) $\bar{\nu} = N_{part} - 1$ is the number of participants in the nucleus.

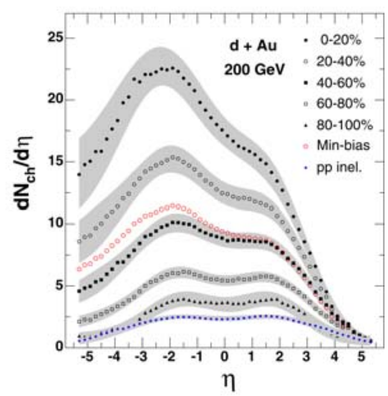

Fig. 4. Centrality dependence of pseudorapidity distribution for dAu collisions from Phobos ref. 4

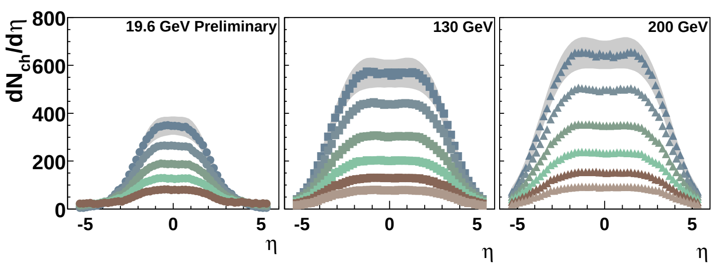

Fig. 5. Energy and centrality dependence of pseudorapidity distributions in AuAu collisions from Phobos ref. 5

full available rapidity range. This is apparent if we look at the ratio of the particle density in pA or dA and pp. In figure 7 we see that over most of the rapidity range this ratio is linear. I will briefly come back to this fact later.

2. Dependence of Multiparticle Production on Energy

If we look at the evolution with energy of pp or AA rapidity distributions [figures 2, 5 and 6] two features stand out: the density of particles at midrapidity increases logarithmically with energy[7], and the width of the distributions increases proportionally to the rapidity of the incident projectiles. The origin of such a uniform logarithmic increase of particle production with $\sqrt{s_{NN}}$ over such a broad range of energies and colliding systems is not well understood. For example, before measure-

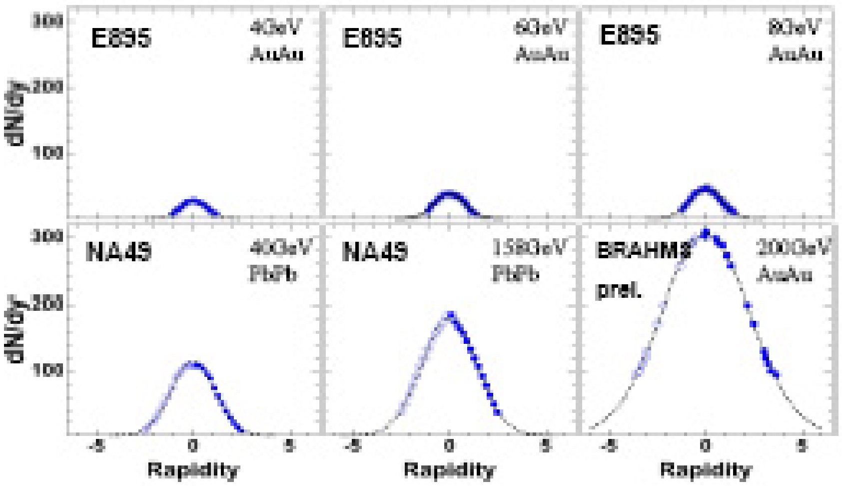

Fig. 6. Compilation by G. Roland (ref. 6) showing that the shape of AA rapidity distribution is approximately gaussian for $\sqrt{s_{NN}}$ from 4GeV to 200GeV.

ments were made, most models predicted a higher multiplicity at RHIC. If we plot the pseudorapidity distributions as a function of $\eta\prime = \eta \pm y_{beam}$, ie. plot the results in a frame at rest with respect to one of the projectiles, see figures 8 and 9, we immediately see that the observed width of the rapidity distributions reflects the fact that the data are consistent with the hypothesis of "limiting fragmentation". The independence with energy of distributions near $\eta\prime = 0$ is not too surprising. It is seen in all hadronic collisions and is used as a classic example of the "short range order" of soft hadronic interactions. Briefly, the target fragments as a consequence of an interaction with the approximately energy independent slow components of the projectile. However what is intriguing in all multiparticle production data (ranging from e^+e^- to AA) is the continuous increase with energy of the maximum value of $|\eta\prime|$ up to which energy independence of $dN/d\eta\prime$ is seen.

Fig 10 shows that "limiting fragmentation" and the increase of the extent of region of the "limiting fragmentation" also occurs in asymmetric collisions. These data are very suggestive of some kind of saturation phenomenon. If it wasn't for the fact that this phenomenon is seen at low energies (even at $\sqrt{s_{NN}} = 67$) and in e^+e^-, it would be natural to interpret it in the language of the Color Glass Condensate (CGC) scenario. Whatever the explanation, the data in figs 8, 9, and 10 are very suggestive that the same system, with the same particle density, is produced at mid

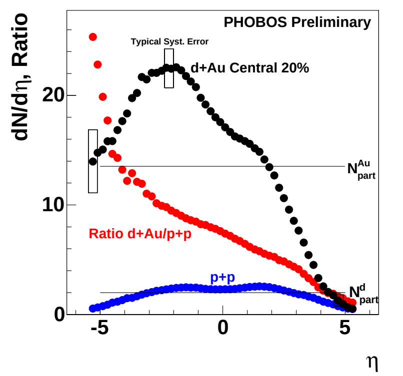

Fig. 7. Evidence of long range correlations in dAu collisons. The dAu and pp data are from Phobos ref. 4

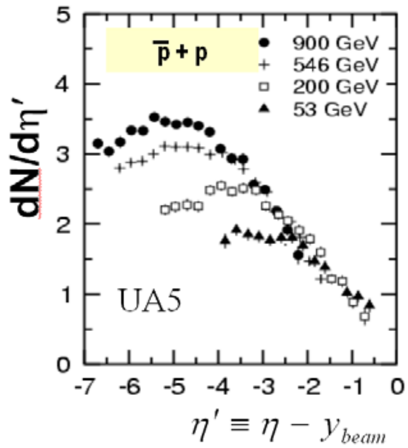

Fig. 8. Same data as shown in fig. 2 plotted in the rest frame of one of the beams.

rapidity for a lower energy collision as is produced in a higher energy collision at the appropriate rapidity away from midrapidity. [eg from fig 10 we conclude that the produced system moving with rapidity $(\eta + y_{target}) = 2$ will be the same for p-emulsion collisions at all energies $\sqrt{s_{NN}} \geq 11.2 GeV$.] A striking confirmation of this equivalence is provided by the comparison of the flow, both directed and elliptic [see fig 11], at different energies.

3. Dependence of Multiparticle Production on the Incident Systems or on the Centrality in the Case of AA Collisions

The increase in the fragmentation region with energy discussed above is an indication of very long range correlations. The unexpected importance of such correlations is even more apparent if we compare pA and/or dA collisions with pp collisions. In fig. 7 I compared such distributions and also showed their ratio. I noted that the correlation of particle production with the nature of the incident particle spans the whole available range in rapidity. Not only that, the strength of the correlation decreases slowly: the ratio of the particle production dAu/pp drops only linearly in magnitude from a value approximately equal to the number of gold participants at the rapidity of the Au projectile, to a value equal to the number of deuteron participants at the rapidity of the deuteron.

One of the most amazing features of hadron-nucleus and nucleus-nucleus scattering is the scaling of the number of produced particles with the number of participants. This is illustrated, for example, in fig. 12 and 14. It should be pointed out that a priori there is no obvious reason why N_{part} is such an important parameter

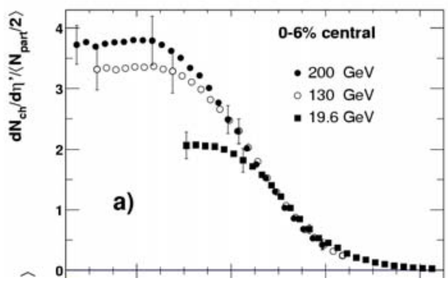

Fig. 9. Same data as shown in fig. 5 but plotted in rest frame of one of the beams.

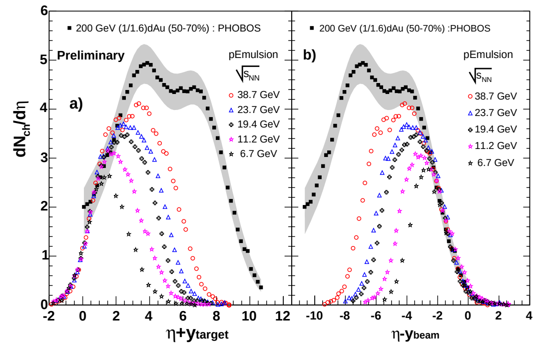

Fig. 10. "Limiting Fragmentation" seen in dAu and pA data. The pA data are a compilation of a very large number of experiments. It includes all produced particles ($n_s + n_g$). The centrality of the dAu data (from ref. 4) is selected and the data normalized so that in both dAu and pEmulsion there are the same number of participants in both projectiles.

for describing hA or AA collisions. N_{part} is a construction based on a very naive classical picture of the collison of single hadrons or a set of nucleons with many nucleons in a nucleus, with the added assumption that the size of each incident hadron remains unaltered during the complex collision process. N_{part} is used partly because, with approximation, it is a parameter with relevance to the Glauber model, but more important because it seems to be useful in describing data. See E178 data in ref 9 which, for the first time, showed that the collision of different hadrons with nuclei, eg πA, KA or PA, exhibit a simplicity if compared at the same value of N_{part}.

As one changes the size of the colliding system, another prominent feature is the decrease in the magnitude of the slope of the sides of the rapidity distribution. This is clearly visible in fig. 13. It should be noted that since the total multiplicity scales with N_{part}, as N_{part} increases the redistribution in rapidity of particle production consists of one for one reduction of particles at high rapidity and increase near mid rapidity. As far as I can tell, no conservation law requires such a simple conservation of the number of particles.

Fig. 14 compares total charged particle production in pp, dAu, and AuAu collisions. For the latter two N_{part} scaling is again clearly visible. At first sight the data suggests that the number of particles produced per participant pair for pp and dAu is lower than for AuAu. However, there is probably a simple explanation for this difference, suggesting that the actual production mechanism is the same for the three. The most likely explanation for the observed difference is as follows. In pp, pA or dA collisions, the typical collision of one of the participants is not "head on",

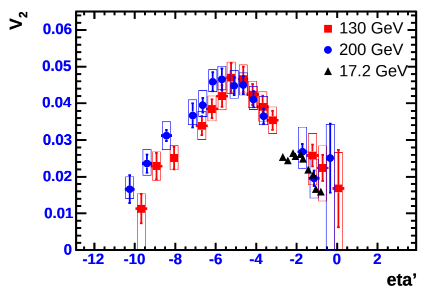

Fig. 11. Energy dependence of elliptic flow in AuAu collisions plotted in the rest frame of one of the nuclei data from ref. 8

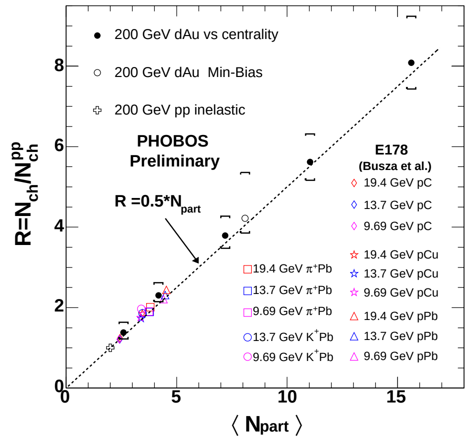

Fig. 12. N_{part} scaling of the total charged particle multiplicity in pA (from E178 ref. 3) and dA (from Phobos ref. 4) collisions.

most collisions are effectively "peripheral". Now we know from the detailed study of pp collisions that on average 50% of the energy does not go into particle production, it is taken up by the leading baryon. Furthermore as is shown in ref 10. if a fraction of initial energy E goes into the leading baryon the rapidity distribution of the produced particles is the same as that of a pp collision at a lower energy $(l-f)E$. (Note: this is consistent with extrapolated $p\bar{p}$ data in fig. 13.) If we take the above into account we find that for $\sqrt{s_{NN}} \geq 20GeV$ the multiplicity per participant pair in AA is the same as in pp. What is even more surprising is that it is also equal to the multiplicity of the produced particles in e^+e^- annihilations! (ref. 11)

I now return to a discussion of the change of shape with centrality (or with incident systems) of the last two units or so in y (or η) of the rapidity distributions. Since there is a significant amount of data on this part of phase space for pA collision, I will base my discussion on pA results. Fig. 15 and 16 illustrate some results that have been obtained in the study of the process $pA \to hX$ at low transverse momenta and positive Feynmann x_F. [Note that the last two units of rapidity approximately correspond to $0.2 < x_F < 1.0$] These results lead to two observations. First, the A-dependence of all processes studied, to a good approximation, are energy independent. Second, the A-dependence is independent of the produced particle [eg in fig 15 we see that the ratio of the production of such very different particles as $\bar{\Lambda}$ and Λ is the same for a Be and Pb target!] The first observation is nothing other than "limiting fragmentation". The simplest explanation of the second observation, and one consistent with the measured A^α dependence of the cross-section, is that the particles going into the forward one or two units of rapidity are only produced on the periphery of the nucleus. This is a surprising result since one would expect

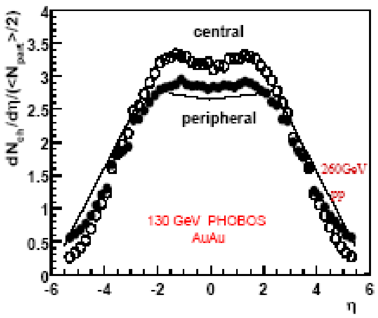

Fig. 13. AuAu pseudorapidity distriburtions for two centralities (same data as in fig. 5). Also shown, as a broken line, is the distribution for pp at 260GeV extrapolated from the data in fig. 8.

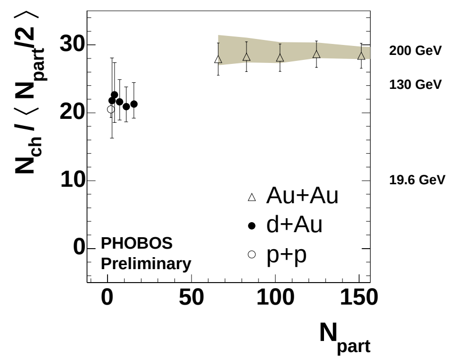

Fig. 14. Comparison of total charged particle production in pp, dAu and AuAu collisions (ref. 4).

the high rapidity particles to be fragments of penetrating fast partons, whilst this result implies that the inner part of the nucleus is totally absorbent or "black". In short, the fast partons seem to be "quenched" as they traverse the nucleus. Though in completely different domains of p_t (one soft and the other hard) the similarity of this "quenching" and "jet quenching" naturally leads one to wonder if the two phenomena are related in any way.

To conclude, as is evident from the extensive data on the distribution of particles in longitudinal phase space the same basic features occur in pp, pA, dA, AA and in some respects even in e^+e^- collisions, for collision energy as low as $\sqrt{s_{NN}} \sim 10GeV$ to the highest energies studied. The most prominent features are: approximately gaussian rapidity distributions, logarithmic increase of mid rapidity multiplicity density with energy, ever increasing region of "limiting fragmentation", importance of long range correlations, scaling with number of participants, and "quenching" of leading particles. Considering that, as the energy and the complexity of the colliding system increases the particle production process must be undergoing a change, it is a curious fact that the basic features remain unaltered. I do not believe that this is accidental. I am convinced that these features are one of the more important clues as to the nature of the processes that take place in multiparticle production in high energy collisions.

Acknowledgement(s)

I wish to particularly thank my colleagues from experiments E178 and E451 at Fermilab and from Phobos at RHIC for numerous discussions related to the subject of this talk, and above all for much of the data presented

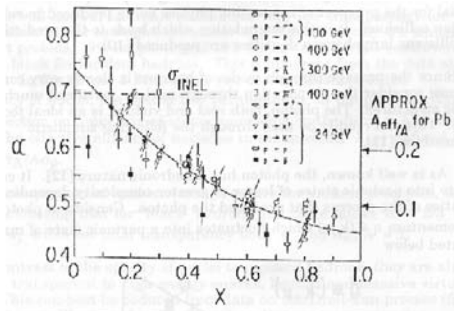

Fig. 15. A dependence of the production of particles in the forward two units of rapidity for the process $pA \rightarrow hX$. (from E451, ref. 12) α is the power of A for a $\sigma_0 A^\alpha$ parameterization of the invariant cross section. $x \equiv p_l/p_{inc}$.

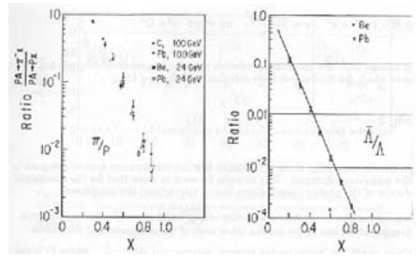

Fig. 16. Data showing that the ratios of particles produced in the forward two untis of rapidity in pA collisions do not depend on A. $x \equiv p_l/p_{inc}$ from ref. 13.

References

1. J. Whitmore, NAL - Pub - 73/70 - Exp. **63** (1973) figure 63.
2. Review of Particle Physics.
3. J. E. Elias *et al.*, [E178 or "Phobos 1"] *Phys. Rev.* **D22** (1980) 13.
4. R. Noucier, (Phobos) *Proceedings Quark Matter 2004*, Oakland, CA.
5. B. Back *et al.*, (Phobos) *Phys. Rev. Lett.* **91** (2003) 052303.
6. G. Roland, *Proceedings Quark Matter 2004*, Oakland, CA.
7. B. Back *et al.*, (Phobos) *Phys. Rev. Lett* **88** (2002) 022302.
8. S. Manly (Phobos), *Twentieth Winter Workshop on Nuclear Dynamics*, Jamaica, 2004.
9. J. E. Elias *et al.* (E178) *Phys. Rev. Lett.* **41** (1978) 285.
10. A. E. Brenner *et al. Phys. Rev.* **D26** (1982) 1497.
11. B. Back *et al.* nucl-ex/0301017v1 (28 January 2003).
12. D. S. Barton *et al.* (E451) *Phys. Rev*, **D27** (1983) 2580.
13. W. Busza compilation, *Proceedings Quark Matter 1991*, Gatlingburg, TN.