The Color Glass Condensate, Glasma and the Quark Gluon Plasma in the Context of Recent pPb Results from LHC.

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Abstract. This paper describes some of the implications of the LHC pPb experimental results for understanding the Color Glass Condensate, the Glasma and the thermalized Quark Gluon Plasma. I attempt to outline the scientific issues, various possible explanations about what has been seen, and present ideas on how some of the alternative explanations might be resolved.

1. Introduction

The major goal of the heavy ion programs at RHIC and the LHC is to understand various forms of high energy density matter[1],[2],[3],[4],[5] . Matter in thermal equilibrium is the Quark Gluon Plasma[6]-[7]. High density, coherent gluonic matter in the colliding nuclei is the Color Glass Condensate[8],[9] [10],[11]. This matter controls the high energy limit of the interactions of hadrons, and provides initial conditions for the matter produced in such collisions. At early times after the collision, matter is in a Glasma[12],[13],[14][15]. This is highly coherent largely gluonic matter. It is strongly interacting matter even though the coupling is weak. The strength of the coupling is determined by a dimensional scale, the saturation momentum, which grows with increasing energy and increasing multiplicity of produced particles. The phase space occupation number of gluons is of order

$$\frac{dN}{d^2r_T dy d^2p_T} \sim \frac{1}{\alpha_s(Q_{sat})} \gg 1 \quad (1)$$

which enhances the effect of interactions due to coherence of the gluon field strength. (This is not unlike in gravity where an intrinsically weak gravitation field of nucleons is enhanced by the coherent interaction of many protons.)

The Glasma as it evolves ultimately will thermalize into a thermalized Quark Gluon Plasma[16]-[17]. Once thermalized, the QGP expands further producing particles, and evolving to a good approximation by the laws of perfect fluid hydrodynamics[18].

As the Glasma expands it interacts with itself, and will produce particles[19]-[20] . It will also generate flow patterns due to these interactions. In many ways, the transition between a Glasma and a thermalized Quark Gluon Plasma is more qualitative than abrupt. It should also be thought of as a Quark Gluon Plasma, but not a thermalized one. Electromagnetic plasmas need not be thermalized to be called plasmas and in this sense the Glasma is a Quark Gluon Plasma. Viewed from this perspective, the investigation of the Quark Gluon Plasma becomes an issue of understanding the properties of a Quark Gluon Plasma and focuses practical issues related to determining its properties of matter "as it is" rather than hard to define ideological issues about what matter "should be" .

In the remainder of this talk, I will discuss various aspects of the forms of matter described above in terms of what might be learned from experiment. I will comment on issues which are not yet so well resolved from either a theoretical or experimental view.

2. The Color Glass Condensate

The Color Glass Condensate is weakly coupled, but strongly interacting highly coherent gluonic matter in the wave function of a nucleus. It can be probed directly in ep and eA interactions at high energies. Assuming that final state interactions can either be computed or that they are in some circumstances small corrections, it can also be studied in high energy pp, pA and AA collisions.

The CGC determines the initial multiplicity of produced particles as a function of beam energy and centrality of collisions[21]. It is usually assumed that the multiplicity of produced gluons is equal to that of produced pions by using approximate entropy conservation during the evolution of the Glasma and the thermalized QGP. There are surely corrections associated with entropy production. Under this assumption, the saturation picture does a fair job of explaining pp and pA multiplicities at RHIC through LHC energies, Fig.1[23]. The CGC also predicts negative binomial distributions for produced particles, and provides a good description of the fluctuations in the pp multiplicities seen at CERN, Fig. 2[22].

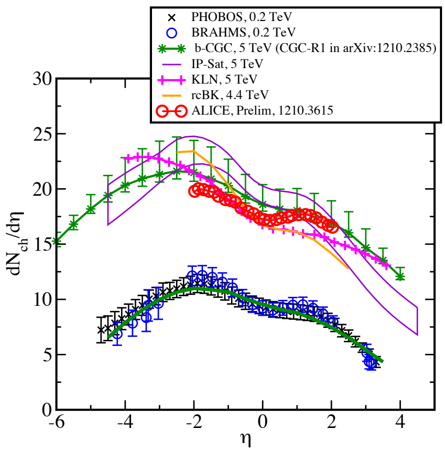

Figure 1. Multiplicity in minimum bias pPb collisions at LHC energy and various theoretical predictions.

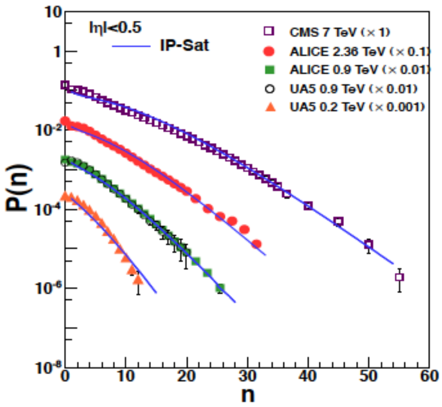

Figure 2. Distribution of multiplicity fluctuations in pp collisions at LHC energy.

The transverse momentum distributions for charged particle productions pp collisions at LHC energies are well described by the geometric scaling hypothesis motivated by the CGC description[24] . The transverse momentum broadening predicted by the CGC as a function of particle multiplicity is clearly seen in the data. There is also unpublished analysis of CMS data for identified particle productions which shows that such scaling works for the pp data on identified particles when the scaling variables is expressed in terms of M_T for massive particles[25],[26],[27]. Whether or not such scaling works for pp and pA collisions as a function of multiplicity for identified particles is not yet tested. It is more difficult to apply such reasoning

Journal of Physics: Conference Series **458** (2013) 012024 doi:10.1088/1742-6596/458/1/012024

to pA collisions because in general there are two saturation scales, that of the proton and that of the nucleus.

The behavior of single particle distributions at high multiplicity in pA and pp collisions might allow discrimination between the CGC hypothesis and hydrodynamic descriptions advocated by some. The CGC hypothesis predicts a growth of average p_T of produced particles with the saturation momentum, and the saturation momentum itself $Q_{sat}^2 \sim dN/dy/\pi R^2$ grows with multiplicity per unit area in the collision[24]. This is clearly seen in multiplicity fluctuations in the pp data, as shown in Fig. 3. There are also detailed predictions for the shape of the p_T distribution in pPb collisions as a function of centrality, energy and rapidity, an example of which is shown in Fig. 4 [29].

Another issue related to this is the measurement of radii of last interaction for high multiplicity pp and pA collisions[28]. Radii determined by HBT pion interferometry should grow as $R \sim (dN/dy)^{1/3}$. This is seen in nucleus-nucleus collisions. In pp collisions, there is only weak growth with multiplicity, and the radius is not much changed at high multiplicity compared to low multiplicity, which is a size typical of the proton, as shown in Fig. 5. Hydrodynamic simulations would suggest a trend similar to that of nuclear collisions, and a radius for high multiplicity events significantly larger than the proton size. It should be noted that if a hydrodynamic description works for the pA collisions at some multlplicity, it would be quite difficult to argue that it would not also work for pp collisions, since even if the production size region is initially smaller in a pp collision, eventually the matter will expand to a size typical of that of a larger system, and if it is already assumed that hydrodynamics describes the larger system, one would therefore expect it to describe it for a pp collisions at least from the point of time where the pp volume becomes equal to that of the pA.

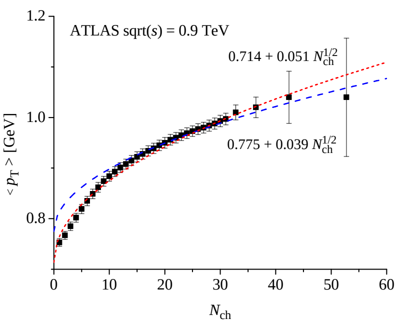

Figure 3. Tranvserse momenta of charged particles as a function of multiplicity compared to a simple model based on the CGC.

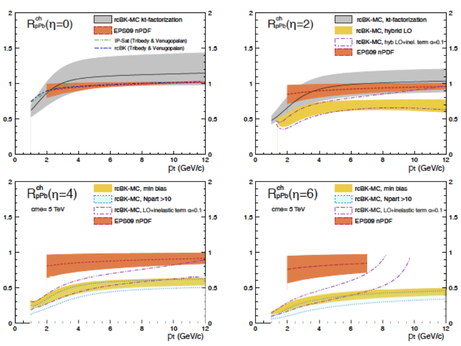

Figure 4. Predictions for the transverse momentum distributions in pPb collisions as a function of rapidity.

The CGC description predicts some broadening of transverse momenta distribution of produced particles as a function of centrality[30]. At RHIC energies, this was observed in the forward particle forward-backward angular correlation of charged particles[31][32], as shown in Fig. 6. In the backward direction there is a noticeable brooding and disappearance of the backward peak in dA collisions.

3. The Glasma

The Glasma is formed very quickly after the collision of two nuclei. It is initially an ensemble of lines of longitudinal color electric and color magnetic flux, as shown in Fig. 7. The typical

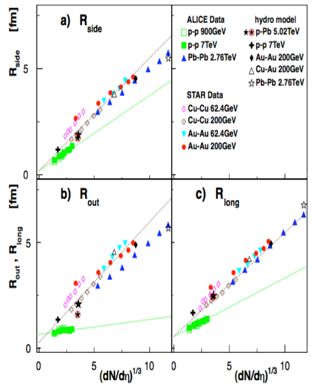

Figure 5. HBT radii in pp and AA collisions as a function of charged particle multiplicity.

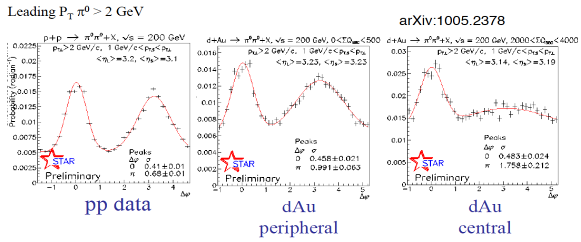

Figure 6. Two particle correlation at forward rapidity as measured in STAR..

transverse size scale of these flux lines is of the order of the inverse saturation scale (more properly the transverse correlation lengths for color and magnetic charge).

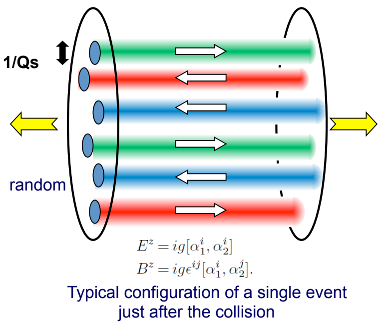

Figure 7. The colored fluc lines produced in hadron collisions immediately after a collision.

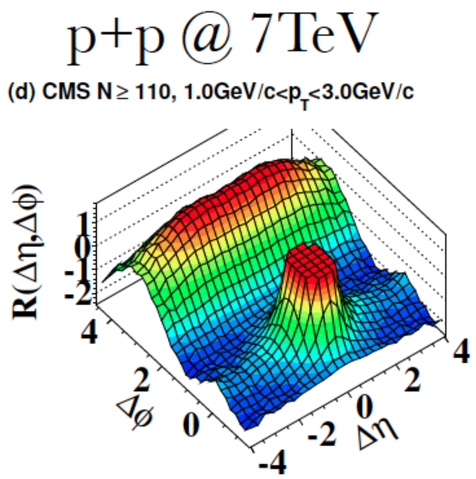

Figure 8. The ridge as seen in two particle correlations in pp collisions by the CMS experiment

These fields have a nonzero and maximal value of the topological charge density FF^d, and may be responsible for a number of interesting effects associated with charge correlations in the presence of a magnetic, field. The interested reader is referred to Refs. [33],[34],[35] for a discussion of the chiral magnetic effect and chiral magnetic wave.

One has observed two particle correlations over long distances in rapidity in pp, pA, dA and AA experiments[36],[37],[38],[39],[40],[41]. To have such an effect, one must both have fluctuations in the transverse positions of scattering centers, and a long rang structure such a as a flux line in the longitudinal space which is attached to the coordinate of the scattering center[42]. In AA collisions, such fluctuations in the transverse position might be generated by fluctuations in nucleon-nucleon scattering transverse positions[43]. In pp collisions, the fluctuations must be generated by quarks and gluons at the end of flux lines[44]-[45]. The CGC provides a theory of such fluctuations. Since this exists in pp collisions, there must at least be some component associated with quark and gluon fluctuations in AA collisions. Such fluctuations provide a good description of high order flow moments in AA collisions.

After such fluctuations have been formed in the initial state, they must somehow appear in the final state distribution of produced particles. This can happen either by initial state effects associated with the decay of a a flux tube, or by hydrodynamics effects which evolve initial energy density fluctuations into the momentum space distributions of produced particles, or perhaps by final state interactions which are not strong enough to generate fully developed hydrodynamic flow. In various regions of phase space, effects from of initial state or final state might dominate. For ridge measurements at low transverse momenta in AA collisions, almost certainly hydrodynamic effects play a dominant role. For pp collisions at high multiplicity, or high transverse momentum measurements, there is no consensus on this issue, and it is a subject of intense theoretical and experimental work, and needless to say, much controversy.

There are multiple issues to be settled in this controversy:

- Are the fluctuations that generate the ridge in pA collisions largely at the subnucleonic scale or at the lager scale sizes?
- How is the initial state structure which generates the ridge translated into particle distributions in the final state? Is this by initial state quantum mechanical correlations, by fully developed hydrodynamics, or by relatively weak final state interaction?
- What are the implications of understanding the ridge for our understanding of heavy ion collisions, and their interpretation as a nearly perfect fluid?

4. Summary and Conclusions

The pp and pA program at the LHC has generated much more scientific interest than anyone had originally envisaged. It may allow us to to resolve fundamental issues concerning the nature of interactions of high energy hadrons.

5. Acknowledgements

The research of L. McLerran is supported under DOE Contract No. DE-AC02-98CH10886. L. Mclerran gratefully acknowledges discussions with Adam Bzdak, Bjoern Schenke, Vladimir Skokov and Raju Venugopalan concerning the interoperation of LHC results about p-Pb collisions.

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