The Nuclear Fragmentation Region of High Energy Nucleus-Nucleus and Hadron-Nucleus Collisions

Work in progress with Soeren Schlichting and Srimoyee Sen

When can we begin to use a high energy description for nucleus-nucleus collision?

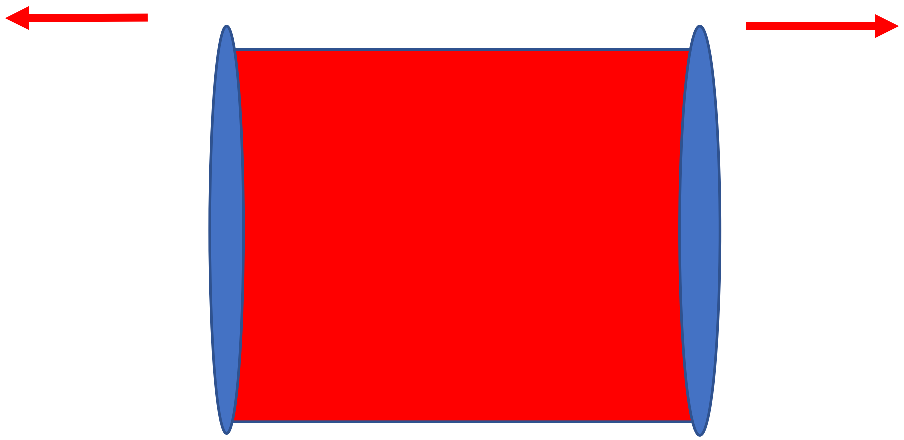
When there is a central region

Particle not formed within the nucleus:

$$\gamma\ t_{formation} >> R \qquad E/M_T^2 >> R$$

$$\delta y > lnA^{1/3} \qquad E_{CM} > 30\ GeV$$

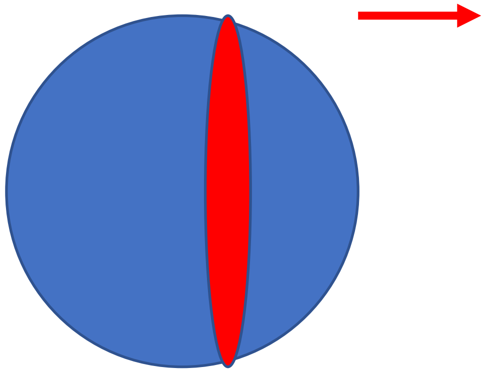
This is the conventional region of CGC studies where the nuclei can be treated as two Lorentc contracted sheets with particles produced by the color fields that connect them



There is another region where the High Energy Limit Works:

$$\gamma_{proj} >> A^{1/3}_{target} \qquad 15\ GeV << E_{lab} << 100\ GeV$$

or center of mass energies greater than about 5 GeV



Physical picture, which we shall review is that the high energy projectile compresses the baryon number and heat the target. Anishetty, Koehler and McLerran argued that the energy densities were sufficient to make quark matter. I put this in a modern context with saturation physics ideas, so that theory of fragmentation region works at high energy. Set up problem of Baryonic CGC

Want to:

Review computation of energy density in modern saturation context (see McLerran 2016)

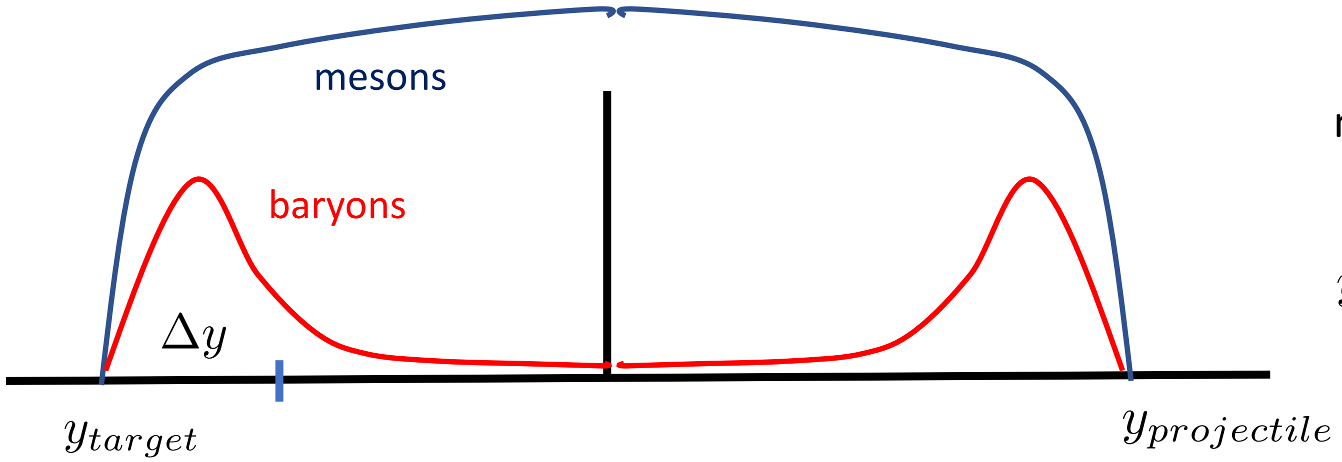
Develop a theory of the classical fields and baryon density produced in the collision (in spirit similar to the recent work of Schenke and Shen)

I will consider the fragmentation region at extremely high energies, where there is a fully developed central region. In principle such a description might also be applied at lower energies where the nuclear fragments do not separate, but where a high energy description is valid, but that problem is more complicated.

In the fragmentation region there is an asymmetry between the saturation momentum of the target and projectile

Target saturation momentum is evaluated at

Δy



Projectile saturation momentum is evaluated at

$y_{target} - \Delta y$

$$Q_{sat}^{projectile} >> Q_{sat}^{target}$$

Saturation momenta are

$$Q_{target}^{sat\ 2} \sim A^{1/3}\Lambda_{QCD}^2 e^{\kappa \Delta y}$$

$$Q_{projectile}^{sat\ 2} \sim A^{1/3}\Lambda_{QCD}^2 e^{\kappa(y_{projectile} - y_{target} + \Delta y)}$$

$$\kappa \sim 0.2 - 0.3$$

At LHC energies, the target saturation momenta is of the order of a GeV but the projectile is of order 5-10 GeV
This means that the projectile is "black" to the partons in the target up to a scale of momentum which is the projectile saturation momentum. The dominant particle production occurs in the region of momentum between these two saturation momenta. This is a region where the color sources produce a weak field A << 1/g and there is not much interaction of produced particles in this kinematic region, at least when the degrees of freedom correspond to classical fields. At momenta scales less than the saturation momenta of the target, there are strong fields and classical time evolution of classical fields. This latter region is that of the Glasma.

The multiplicity at low p_T is not much changed due to very high energy

$$\frac{dN}{dyd^2p_T} \sim cons, \quad p_T < Q_{sat}^{target}$$

But the dominant contribution comes from intermediate momenta

$$\frac{dN}{dyd^2p_T} \sim \frac{Q_{sat}^{target\ 2}}{p_T^2}, \quad Q_{sat}^{target} < p_T < Q_{sat}^{proj}$$

And at very high momenta the distribution smoothly goes to a perturbative dependence

$$\frac{dN}{dyd^2p_T} \sim \frac{Q_{sat}^{target\ 2} Q_{sat}^{proj\ 2}}{p_T^4}, \quad Q_{sat}^{proj} < p_T$$

$$\frac{dN}{dy} \sim Q_{target}^2$$

Does not change up to logarithms

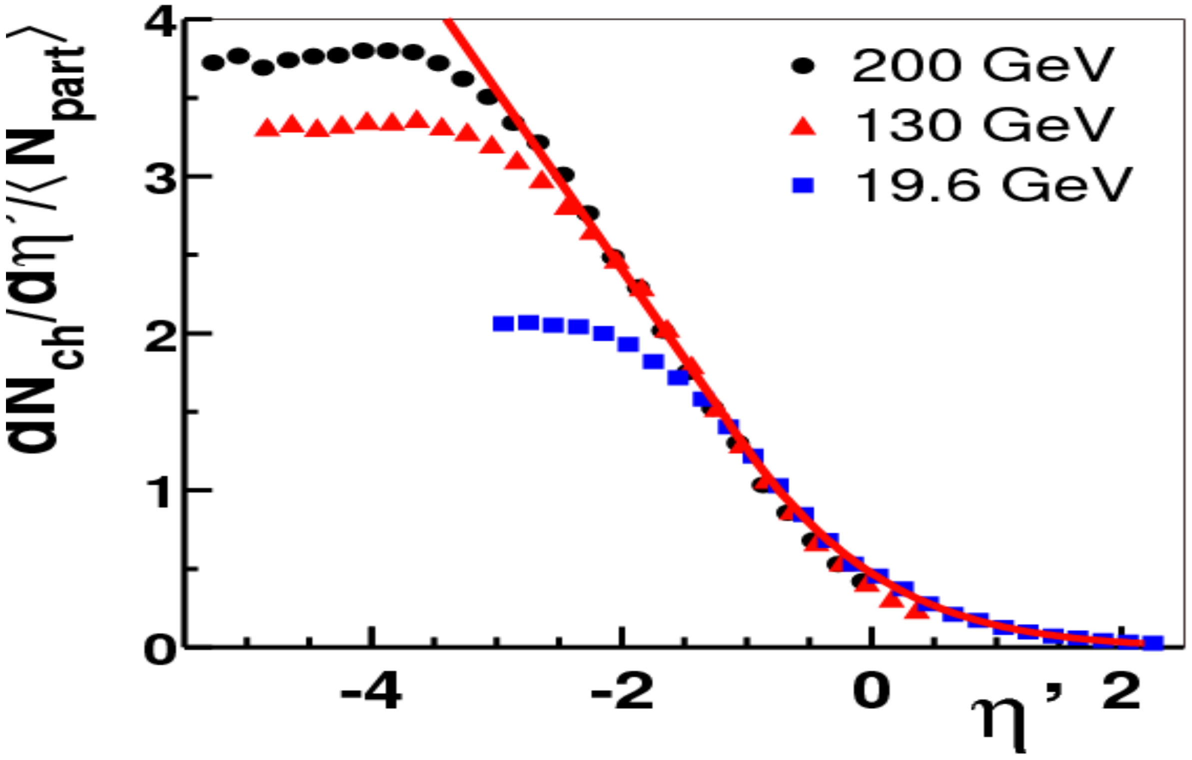
$$< p_T^2 > \sim Q_{proj}^2$$

Is about 100 times bigger at LHC than at RHIC since

$$x_{rhic}^{proj} \sim 10^{-2} \qquad x_{lhc}^{proj} \sim 10^{-9}$$

The CGC and Limiting Fragmentation:

Empirically, limiting fragmentation works quite well



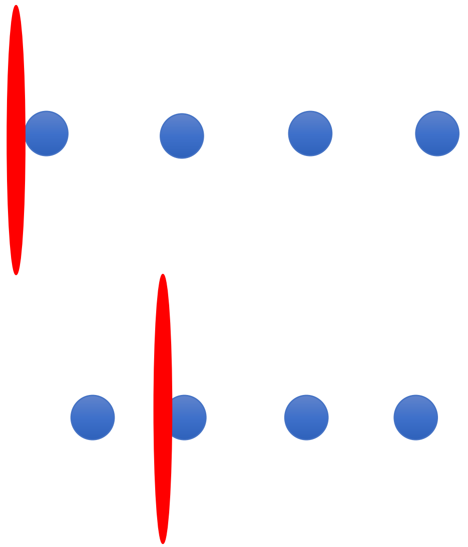
Phobos Data

The projectile nucleus is dark up to a resolution scale of order the inverse saturation momentum. Therefore the target nucleus is stripped of sea quarks and gluons up to a momentum scale of order this inverse resolution scale. As beam energy increases, there is smaller x probed of the projectile, and momentum scale increases, so there should be some weak breaking of scaling for multiplicity distributions

In addition there is baryon number compression

Why is high energy fragmentation regions somewhat simple?

Anishetty, Koehler and McLerran, Ming and Kapusta



$$\Delta z \sim 1 - v$$

In boosted fame of struck nucleon, compression

$$\Delta z_{comoving} \sim 1/\gamma_{nucleon}$$

The compression gamma factor should be of the order of the gamma factor for produced particles

$$\gamma / M_T \sim R$$

$$\gamma \sim Q_{proj} R$$

So the initial baryon density is of order

$$N_B / V \sim Q_{targ}^2 Q_{proj}$$

The number multiplicity of produce particles per unit area scales as

$$\frac{1}{\pi R^2} \frac{dN}{dy} \sim Q_{targ}^2$$

The initial longitudinal size scale is set by the typical transverse momenta of produced gluons

$$Q_{proj}$$

$$N_{gluon}/V \sim Q_{targ}^2 Q_{proj}$$

$$N_B/N_g \sim cons$$

However, gluons are not in thermal equilibrium

$$E/S \sim Q_{proj}$$

but

$$s \sim Q_{targ}^2 Q_{proj}$$

How might expansion change this?

Interactions and thermalization?

Can one set up CGC-Glasma initial conditions in the fragmentation region including the effects of baryon number density?

How do we set up the problem for CGC-Glasma

Before the collision, the nucleons in the target all have momentum space rapidity Y_{target}

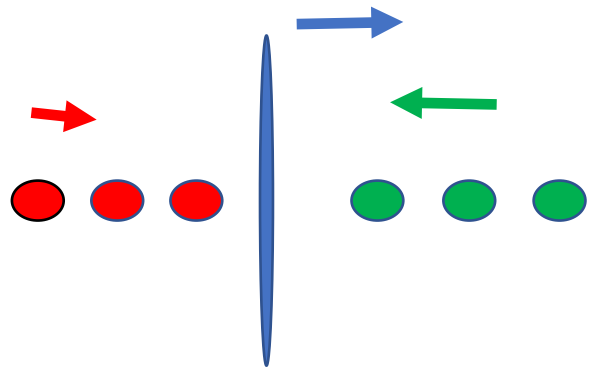
They sit initially at various longitudinal positions between 0< z < 2L where L is the nuclear radius, in the rest frame of the target

The width of the fragmentation region in momentum space will eventually be

$$\Delta y \sim lnA^{1/3}$$

Let us boost to a frame where 1 << y –y{target} << Δy

In this frame the nucleons are moving fast in one direction and the projectiles move fast in the opposite direction



As the projectile moves through the target, there are more nucleons to the left of the projectile. This means that the color sources associated with the target are increasing with time.
Therefore the classical field problem induced by the sources is that of a time dependent projectile charge.
This mans the classical solution is not boost invariant.
The space-time rapidity of the classical solution remains correlated with the space time-rapidity of the produced particles.

What happens to the projectile nucleus quarks that pass through the target. In any finite width in rapidity, the number of quarks should be small compared to that in the total fragmentation region of the target. The “local quarks” generate a small field compared that of the “ source quarks”
This means we can compute the classical fields only from the ”source quarks” and the ”local quarks” propagate in the background field generated by the “source quarks”

When the quarks first pass through the projectile nucleus, they acquire a transverse momentum of order the projectilesaturation momentum. This generates a rapidity shift of order Δy
and a compression of order $Q^{sat}_{proj}/\Lambda_{QCD}$

This is what we estimated before. Note however that the nucleons initially are propagating with a velocity different than the gluonic field in which they were produced, so there will be modifications of this density with time due to interactions with the gluonic fluid

This should allow a proper treatment of the baryon rich Ba-Glasma. One could either treat the quarks as classical particle propagating in the background field, or perhaps as Dirac particles in such a field. In either case, this treatment shows how to set up the initial condition for the Baglasma

Does the Ba-Glasma thermalize?

A number of interesting questions arise: Due to the uniform shift in quark momentum space rapidities which does not appear to be the same as that of the gluons with which is it is produced, how do the quarks adjust their momentum space rapidities? How long does the baryon number density stay highly compressed? How is the baryon to meson ratio modified due to thermalization or partial thermalization?

How does one apply such picture to lower energies appropriate for a high energy collision but where there is not complete separation of fragmentation regions