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?

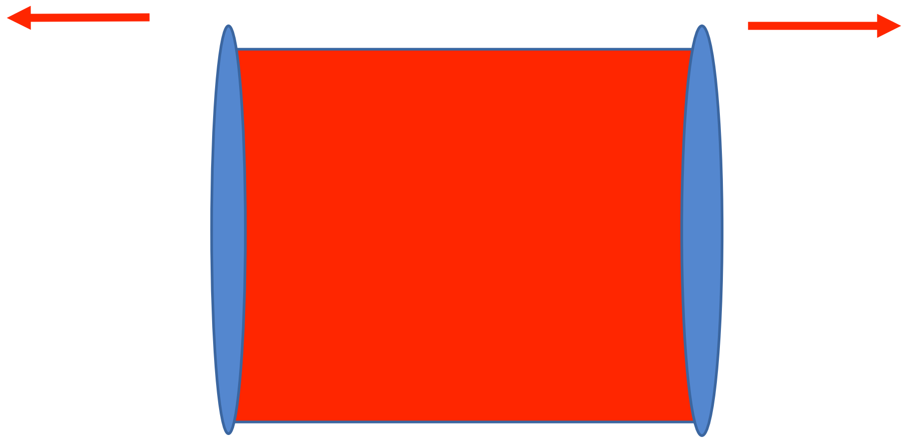
When there is a central region

Particle not formed within the nucleus:

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

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

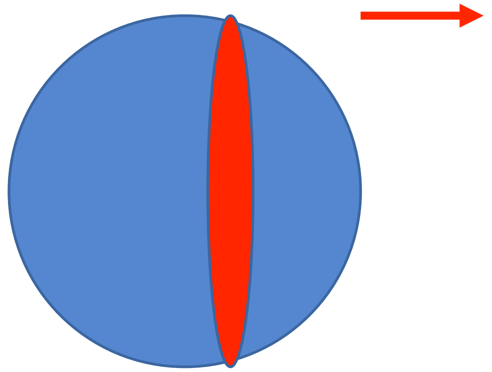
This is the conventional region of CGC studies where the nuclei can be treated as two Lorentz contracted sheets with particles produced by the color fields that connect them



There is another region where the High Energy Limit Works:

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

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)

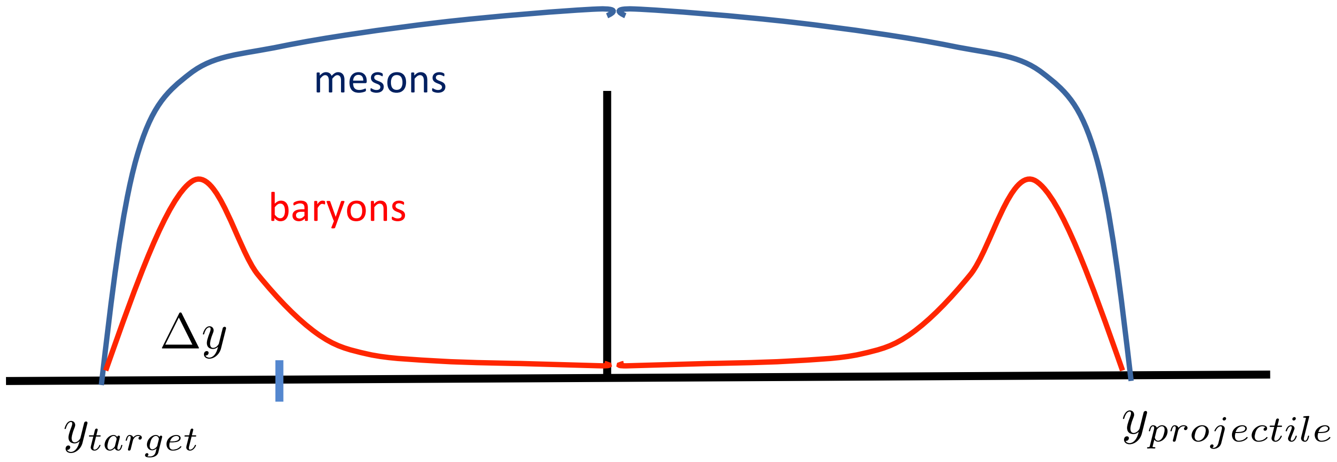
Develop a theory of the classical fields and baryon density produced in the collision (in spirit similar to the recent work of Schenke and Shen)

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

$$Q^{sat\ 2}_{target} \sim A^{1/3}\Lambda^2_{QCD}e^{\kappa\Delta y}$$

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

$$\kappa \sim 0.2 - 0.3$$

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

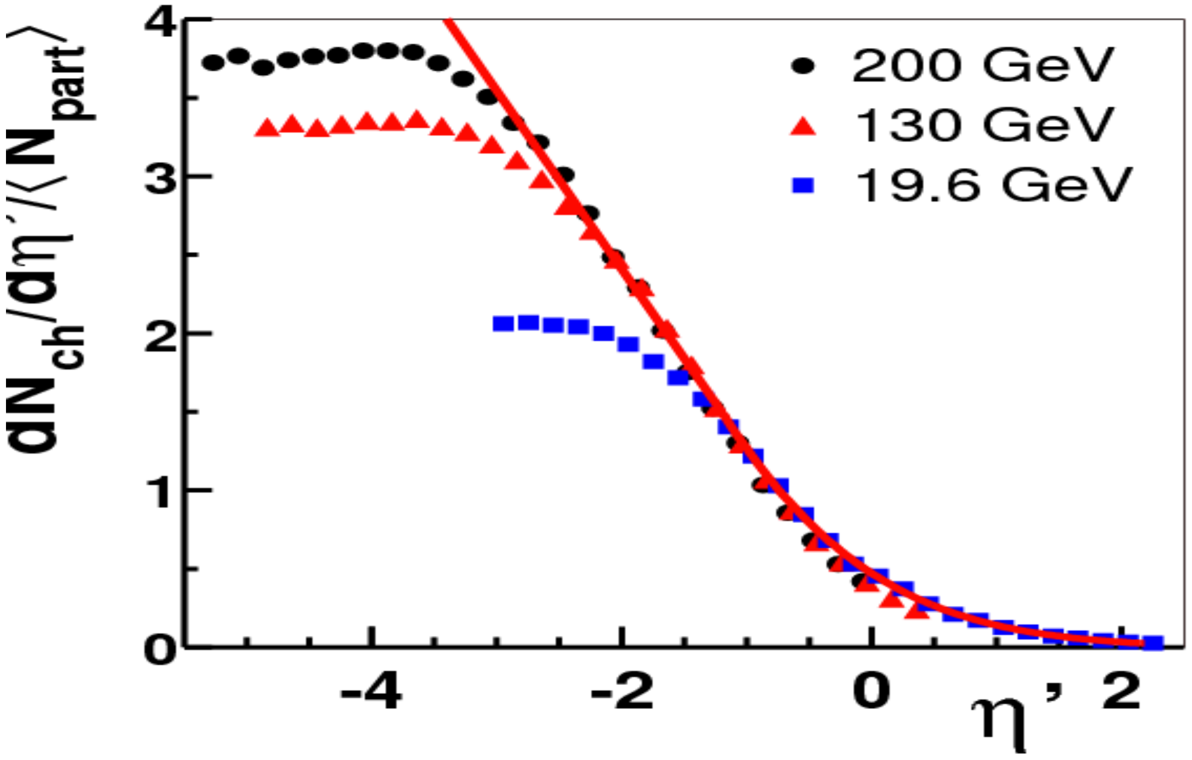
$$< p_T^2 > \sim Q_{proj}^2$$

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



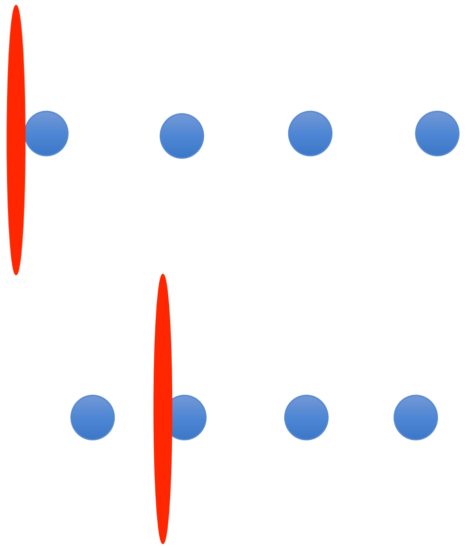
Phobos Data

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 produced 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?

Another argument for the rapidity shift of low momentum quark as it passes through the thins sheet of the projectile nucleus

$$p^2 = 2p^+p^- - p_T^2 = m^2$$

$$p^+ = (p_T^2 + m^2)/2p^-$$

$$p_i^+ = m^2/2p^-$$

$$p_f^+ = (Q_{proj}^2 + m^2)/2p^- \sim Q_{proj}^2/2p^-$$

$$\Delta y = \frac{1}{2} ln(p_f^+/p^-) - \frac{1}{2} ln(p_i^+/p^-) = ln(Q_{proj}/m)$$

How to Set up Problem:

Thin sheet passes through a uniform distribution of quarks at rest with random color charges

Quarks at rest are boosted by the interaction with the sheet, and their orientations in color charge are determined by Yang Mills equation for their interaction with the sheet

Therefore the current of the quarks is known.

This current together with that of the thins sheet now determines Yang Mill equations an can compute gluon production. Can be doe analytically for the region where most of the gluon are produced:

$$p_T > Q_{target}$$

Will find a typical rapidity of produced gluons of the order of the rapidity of the quarks and a large transverse momentum enhancement

Is this relevant for the highest energy cosmic rays?
(w M. Strikman)

Claim in the highest energy cosmic rays, by comparison to shower simulations that there is a change in composition from protons to protons and nuclei.

At a fixed total energy, the nucleons in a nucleus have a lower energy per nucleon than for a proton, so the starting point in rapidity for showers is down shifted in rapidity.

For our saturation description, the down shift is caused by the saturation momentum of the air nuclei at very small x.

Needs detailed simulation since nothing is as simple as it seems in cosmic rays.
Need to simulate shower shape in first few interactions and distribution of starting points for shower in the air (total cross section).

The Ba-Glasma

Computing the gluonic fields.

Does it thermalize?

Can one see the rapidity shift?

The increased transverse momenta?

It is challenging because the forward region at LHC is hard to measure since particles go down the beam pipe and have very high energy