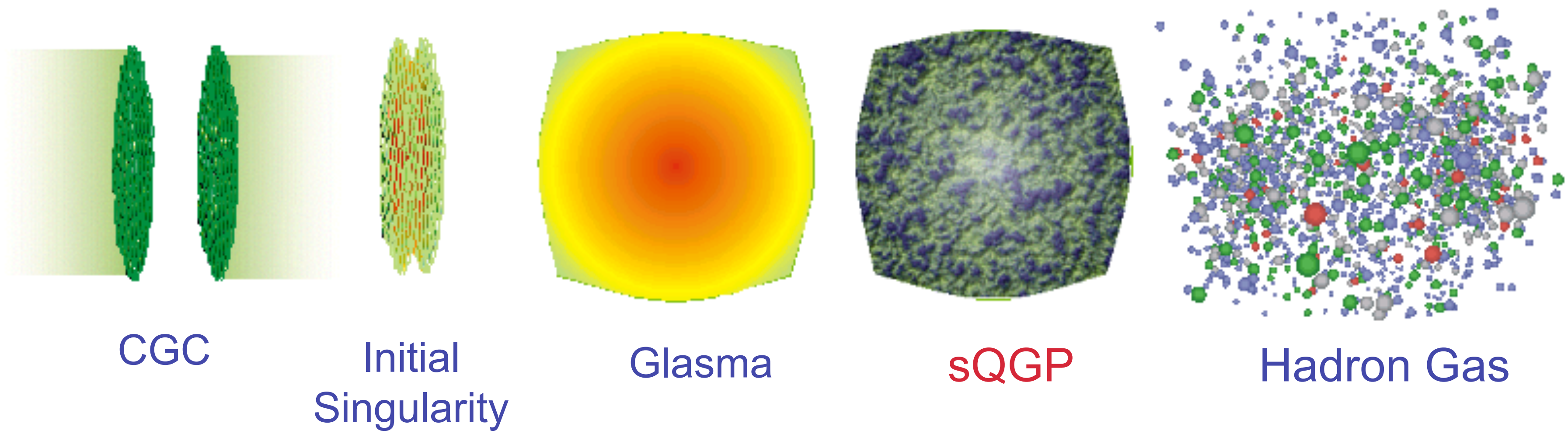
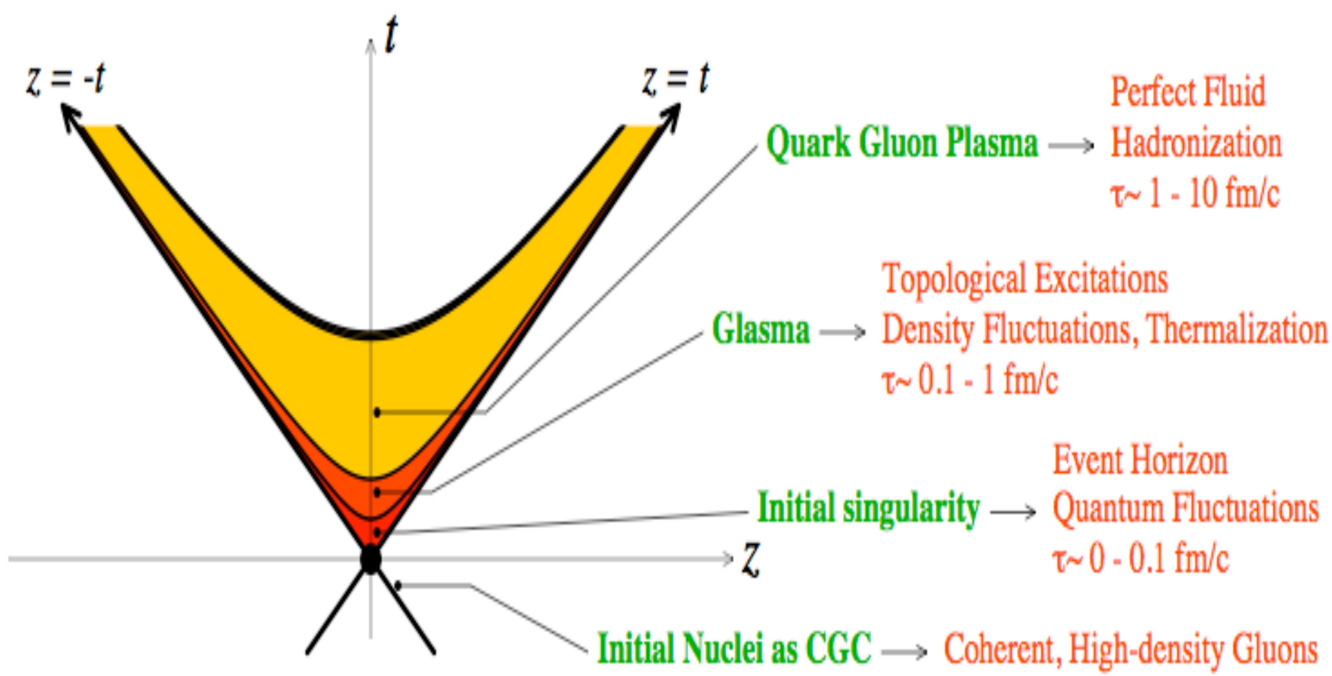
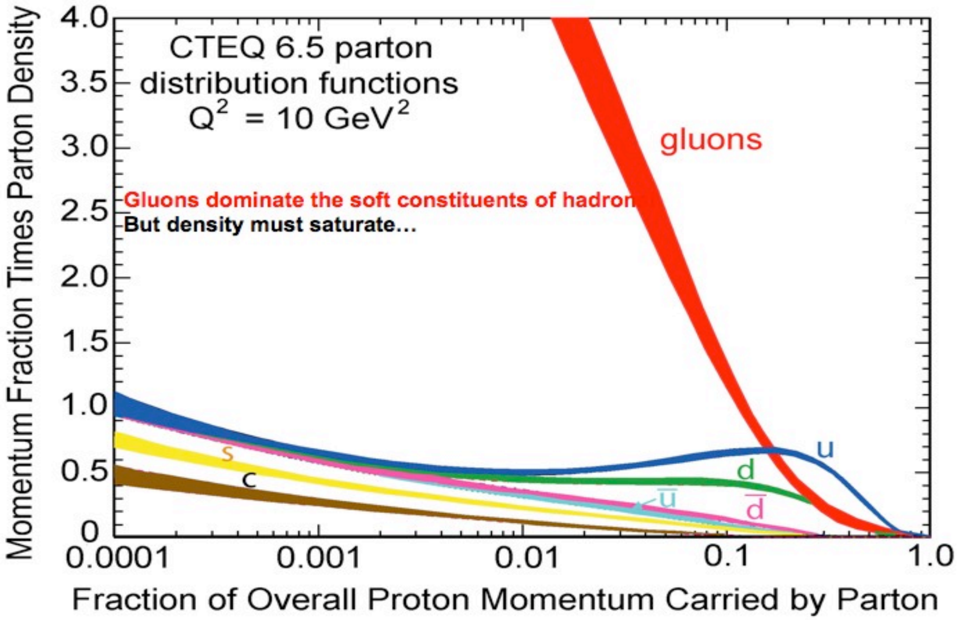
The Color Glass Condensate and Glasma

Art due to S. Bass





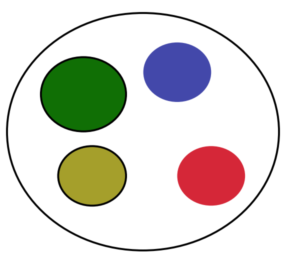
The Hadron Wavefunction at High Energy



Small x limit is high energy limit

$$x = E_{gluon}/E_{hadron}$$

Where do all the gluons go?

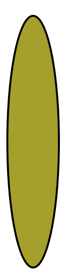


Baryon:

3 quarks

3 quarks 1 gluon

.....



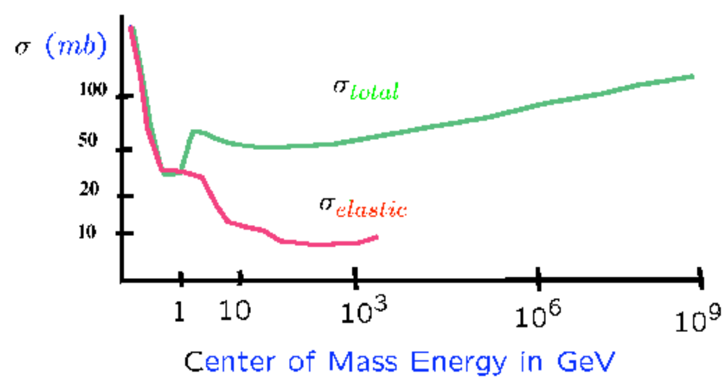
3 quarks and lots of gluons

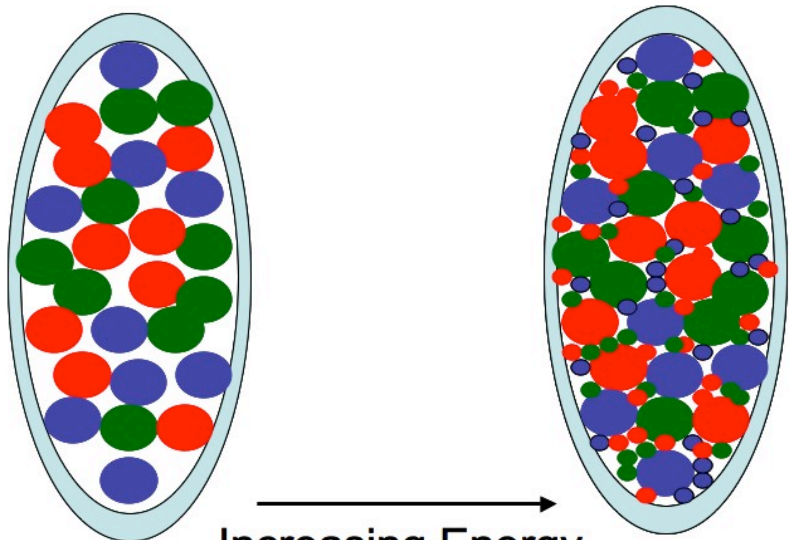
Cross sections for hadrons rise very slowly with energy

$$\sigma_{tot} \sim ln^2(E/\Lambda_{QCD})$$

$$\Lambda_{QCD} \sim 200\ MeV$$

The total hadronic cross section:





But the gluon density rises much more rapidly!

The high energy limit is the high gluon density limit.

Surely the density must saturate for fixed sizes of gluons at high energy.

Color Glass Condensate

Color: Gluons

Glass:

The partons which make the CGC fields are moving fast => Lorentz time dilation => fields evolve slowly compared to natural times scales

Condensate:

$$\frac{dN}{dy d^2p_T d^2x_T} = \rho$$

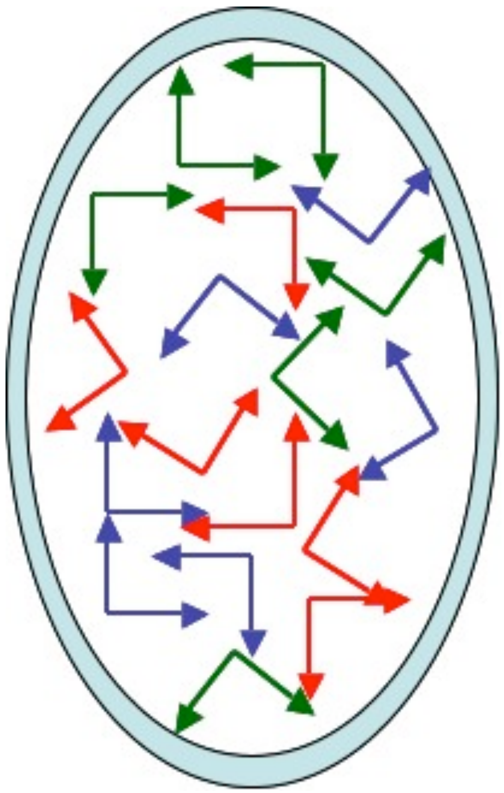
Phase space density

$$E = -\kappa\rho + \kappa' \alpha_S \rho^2 \quad \Rightarrow \quad \rho \sim 1/\alpha_S$$

Coupling weak because density is high

Fields are coherent and classical

What does a sheet of Colored Glass look like?



On the sheet $x^- = t - z$ is small

Independent of $x^+ = t + z$

F^{i+} is big F^{i-} is small

F^{ij} is 0(1)

so that the big fields are

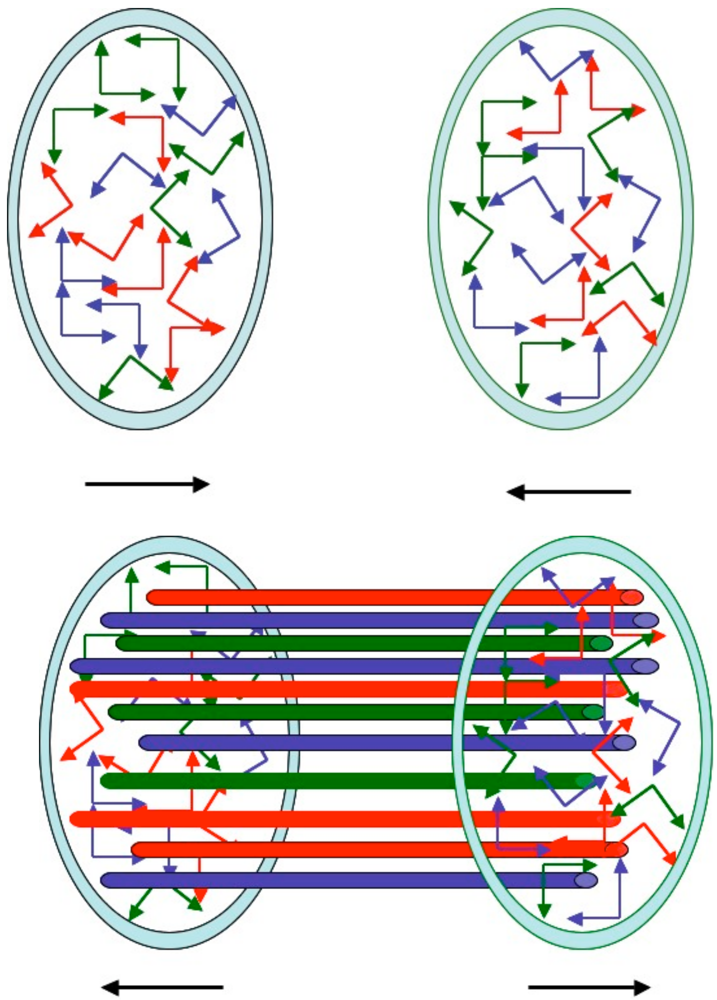
$$\vec{E} \perp \vec{B} \perp \vec{z}$$

Lienard-Wiechart potentials

Random Color

Density of gluons per unit area $\frac{1}{\pi R^2} \frac{dN}{dy} \sim \frac{1}{\alpha_{strong}} Q^2_{sat}$

CGC Gives Initial Conditions for QGP in Heavy Ion Collisions

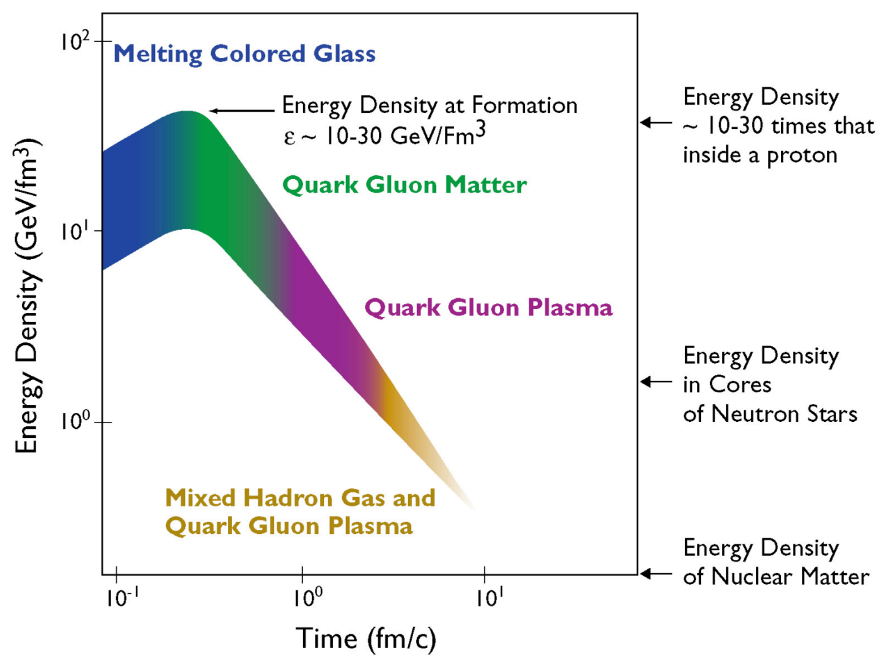


"Instantaneously" develop longitudinal color E and B fields

Two sheets of colored glass collide

Glass melts into gluons and thermalize

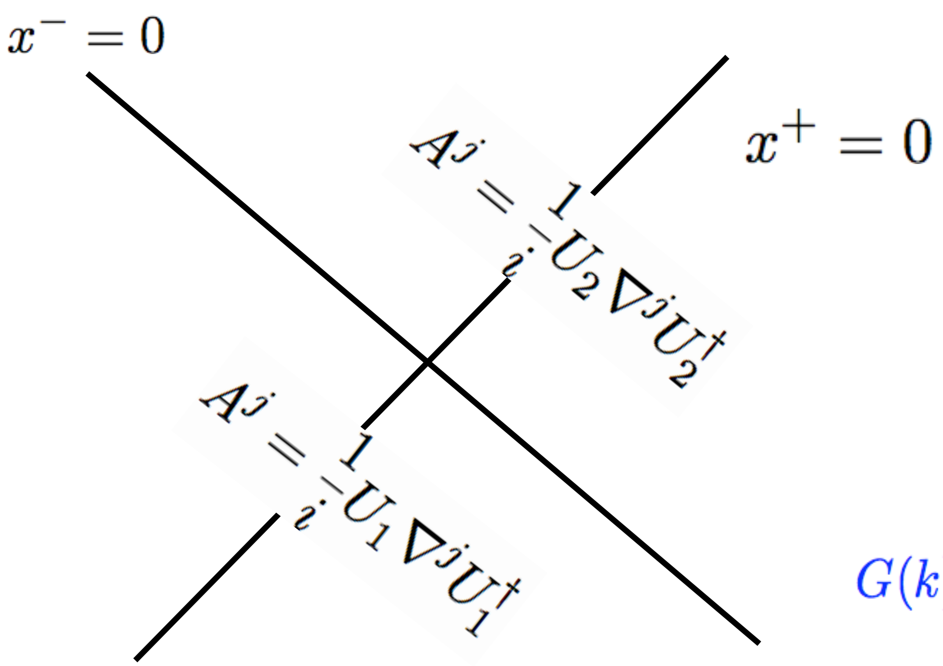
QGP is made which expands into a mixed phase of QGP and hadrons



Fields in longitudinal space:

$$F^{i+}$$

is a delta function on scales less than the inverse longitudinal cutoff



Gluon distribution is at scales larger than the cutoff

$$G(k) \sim 1/p^+$$

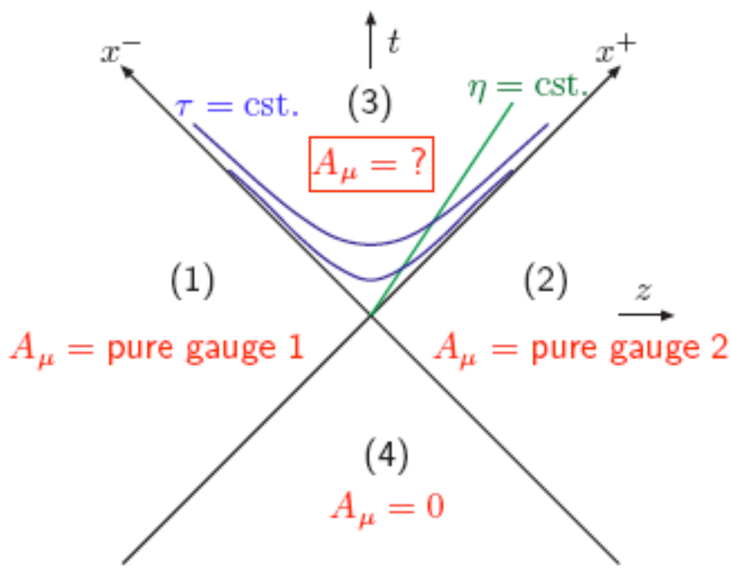
$$G(k) =< a^\dagger(k) a(k) >\sim< A(k) A(-k) >$$

The Glasma:

Before the collision only transverse E and B CGC fields

Color electric and magnetic monopoles

Almost instantaneous phase change to longitudinal E and B



In forward light cone

$$A_1^i + A_2^i$$

generates correct sources on the light cone

$$\nabla \cdot E = A \cdot E$$

$$\nabla \cdot B = A \cdot B$$

$$A_1 \cdot E_2$$

$$A_1 \cdot B_2$$

Equal strength for magnetic and electric charge on average!

Glasma and Long Range Correlations

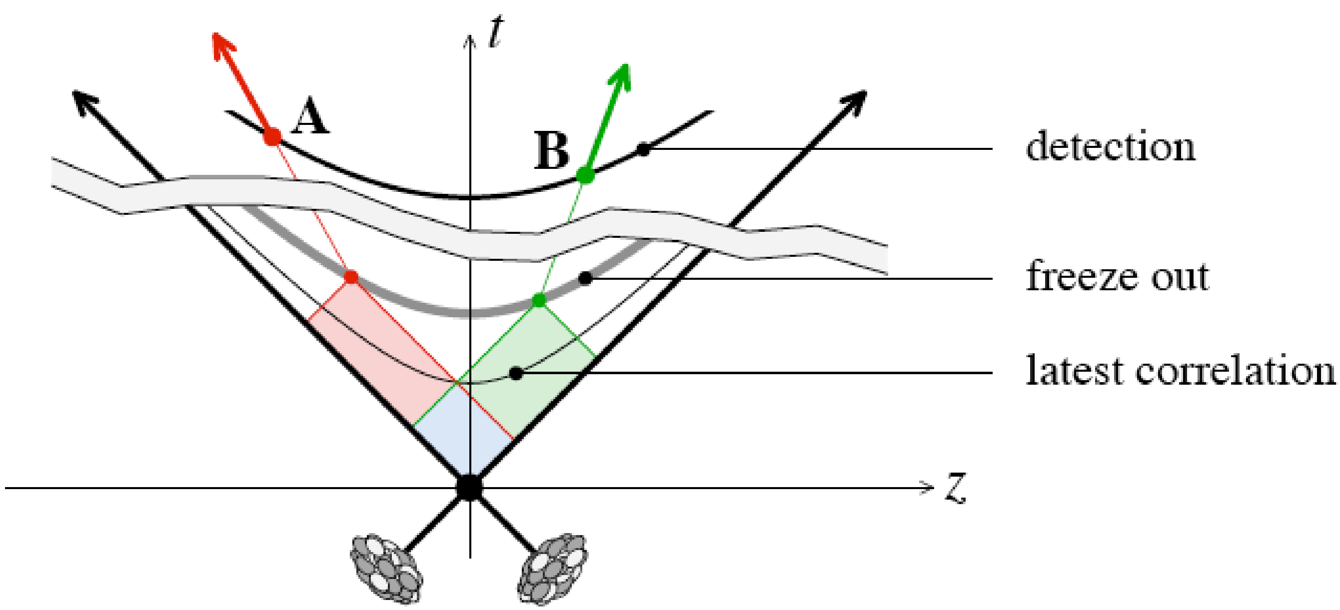
Glasma flux tubes formed at very early times

Long range correlation in rapidity

$$\tau_i = \tau_f e^{-\Delta y/2}$$

Impossible to set up long range correlations by final state interactions!

Long range correlation cannot be destroyed by final state interactions



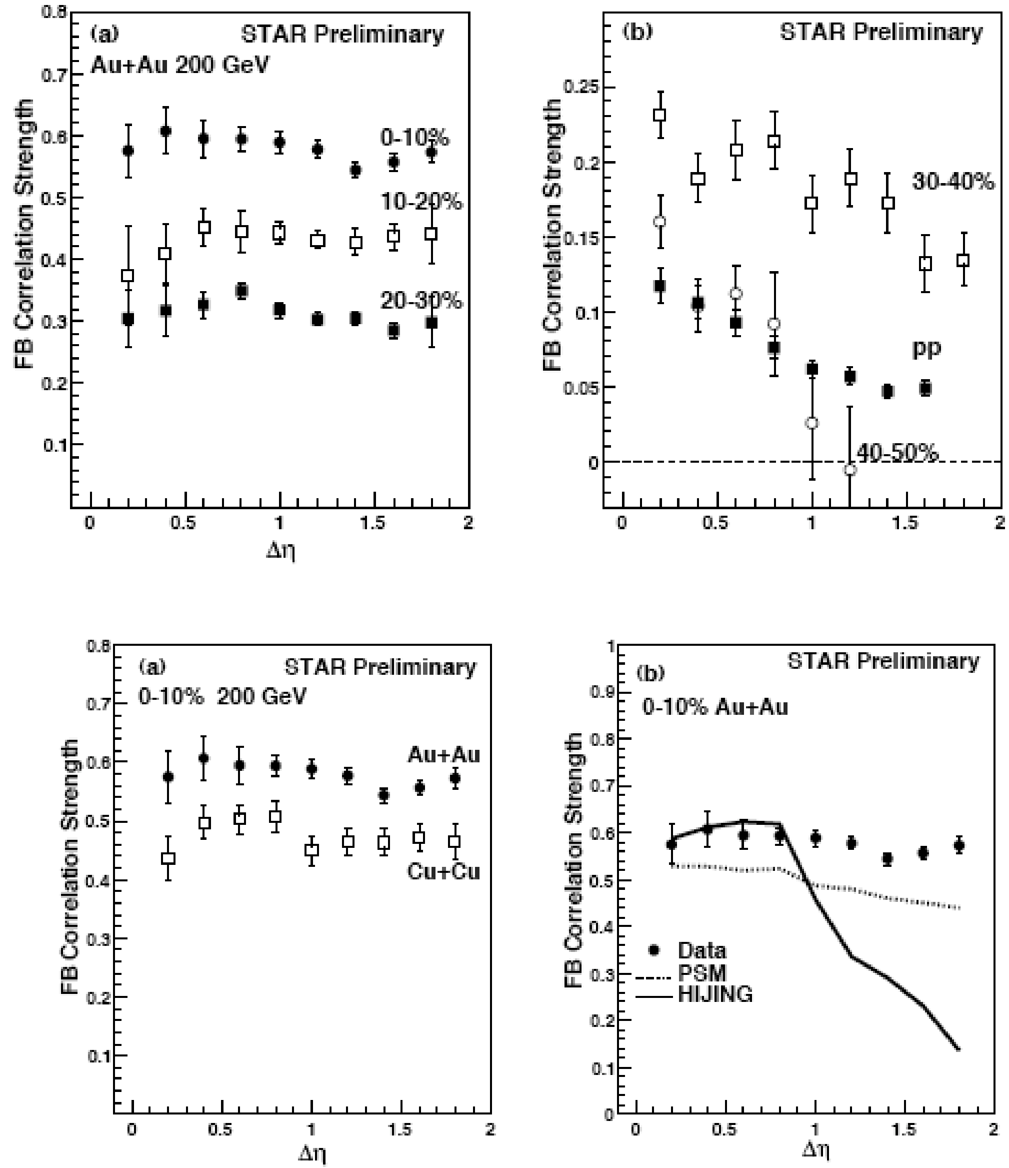
Forward-Backward Correlations: $$\frac{< N_F N_B > - < N_F >< N_B >}{< N_F^2 > - < N_F >^2}$$

Long range correlation present in proton-proton and proton-antiproton data.

Impact parameter effect

Correlation increases as function of centrality and of ion size

Hijing cannot explain the long range correlation



Intuitive Glasma Explanation:

Classical decay of a flux tube.

LDM and Kovchegov,

Armesto, Pajares and LDM

Venugopalan and Gelis,

Fukishima and Hidaka

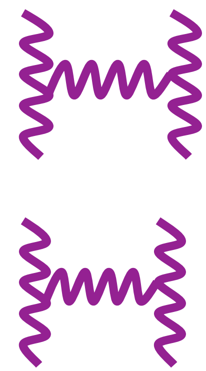
$$\frac{dN_{FT}}{dy} \sim R^2/R_{FT}^2 \sim Q_{sat}^2 R^2$$

Multiplicity of each flux tube

$$1/\alpha_S$$

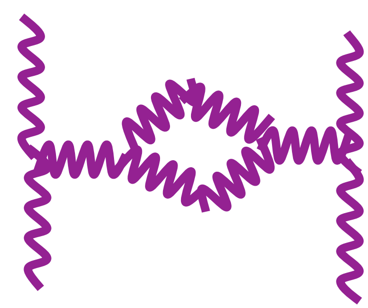
=>

$$\frac{dN_{gluons}}{dy} \sim \frac{1}{\alpha_S} \; Q_{sat}^2 R^2$$



Classical contribution is leading order and is strongly correlated:

$$< N_F N_B > \sim < N_F >^2 \quad \sim 1/\alpha_S^2$$



Short range correlation

$$O(1)$$

(Interference?)

Forward-Backward Correlation

$$\frac{< N_F N_B > - < N_F >< N_B >}{< N_F^2 > - < N_F >^2} \sim \frac{A/\alpha_S^2}{A/\alpha_S^2 + B} \sim \frac{1}{1 + \kappa \alpha_S^2}$$

Correlation strongest when centrality largest, since coupling is weakest for larger saturation momentum

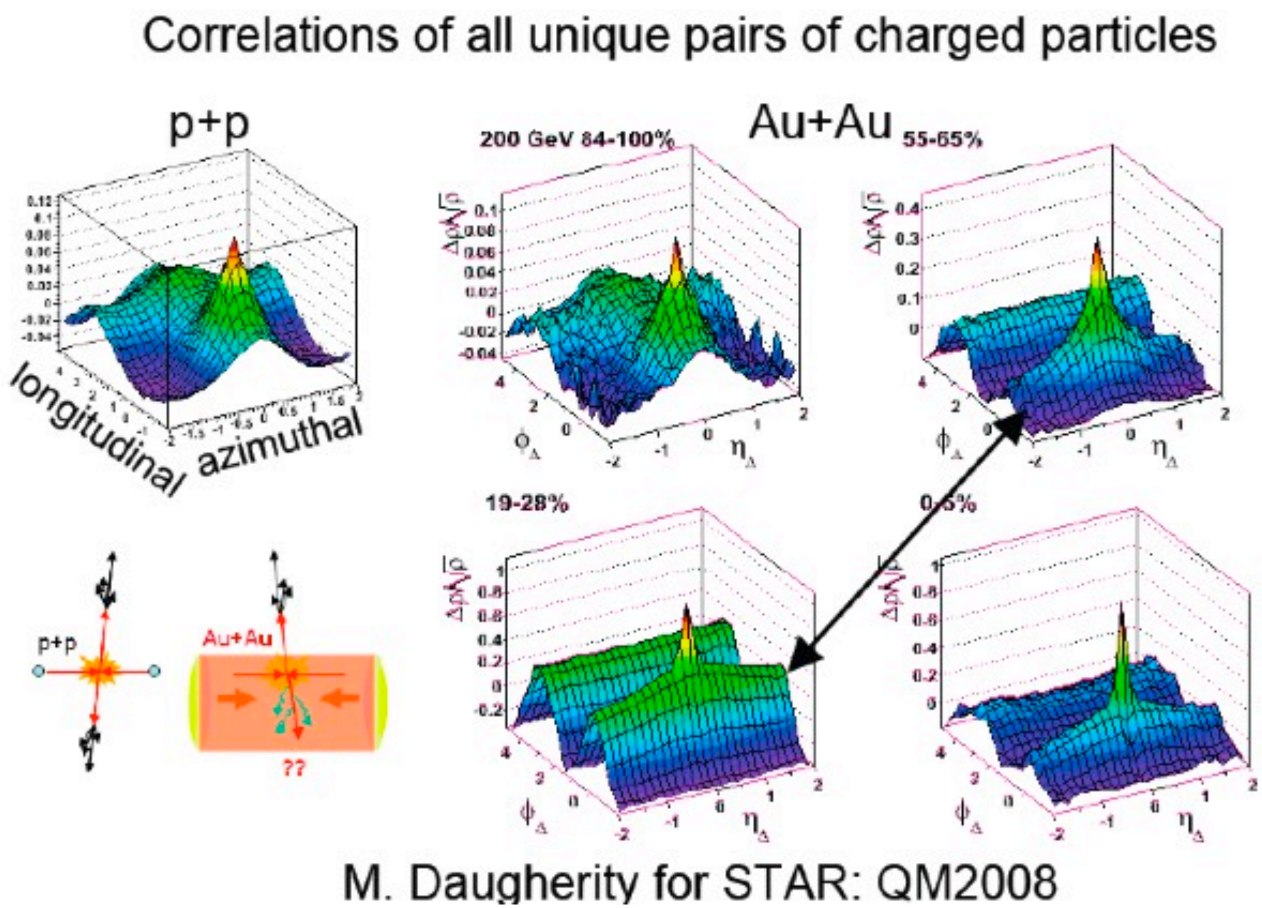
Gluons are enhanced by inverse coupling squared because of Bose coherence in the Color Glass Condensate

Baryons are Fermions and there is no enhancement. For central collisions there is little change relative to less central collisions

For baryons we therefore expect

$$\left\{ \frac{< N_F N_B > - < N_F >< N_B >}{< N_F^2 > - < N_F >^2} \right\}_{baryons} \sim \frac{1}{1 + \kappa'}$$

The Ridge in Heavy Ion Collisions:



Is this evidence for Glasma flux tubes?

The Ridge

High p_T Ridge and Inclusive Ridge: Will analyze inclusive ridge

First compute the two particle spatial correlation:

$$r(x_1, x_2) = n_2(x_1, x_2) - n_1(x_1)n_1(x_2)$$

Convolute with hydrodynamic expansion via blast wave with parameters from Phenix

Scale resulting multiplicity distribution by total multiplicity to define $\frac{\Delta\rho}{\sqrt{\rho}}$

$$r \sim \frac{1}{\alpha_S^2} \frac{dN_{fluxtubes}}{dy} \qquad \frac{dN}{dy} \sim \frac{1}{\alpha_S} \frac{dN_{fluxtubes}}{dy}$$

$$\frac{\Delta\rho}{\sqrt{\rho}} \sim \frac{1}{\alpha_S}$$

Ridge correlation is strong!

LM and Kovchegov,

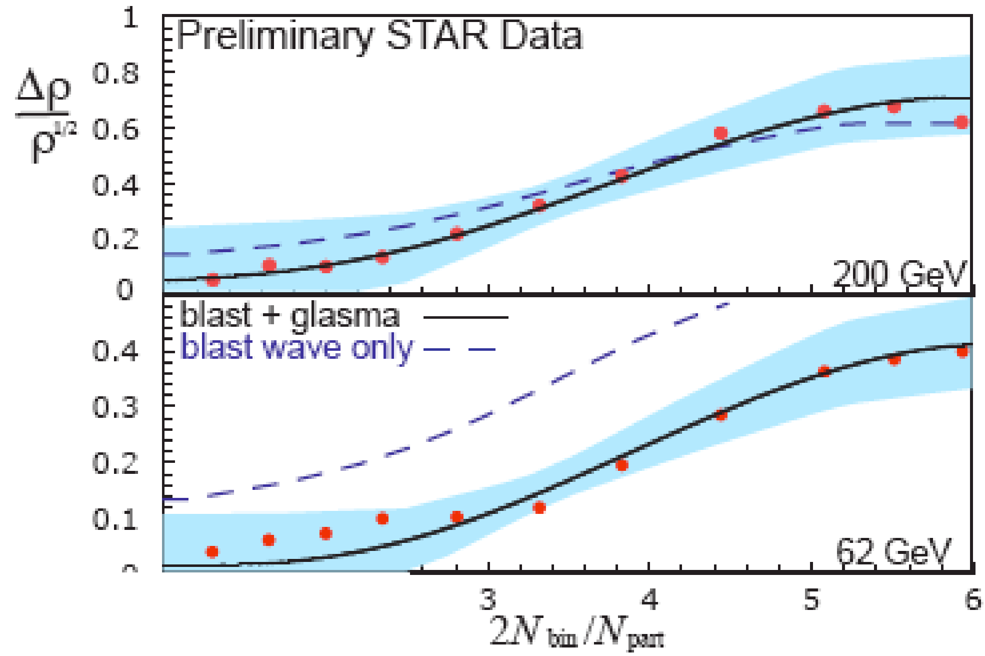
Dumitru, Gelis, LM and Venugopalan

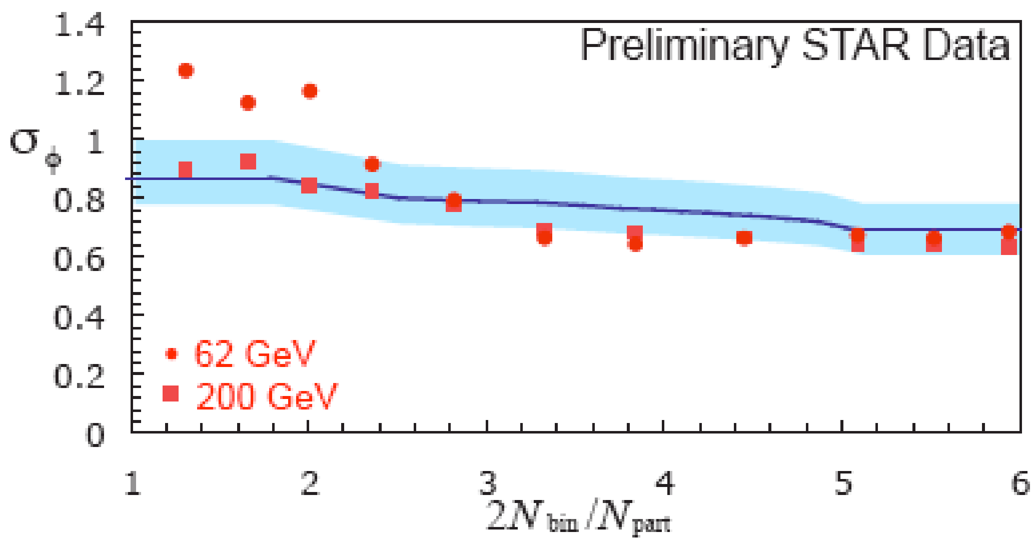
Gavin, LM and Moschelli

Assuming delta function in transverse size, flat in rapidity:

Naturally get right magnitude.

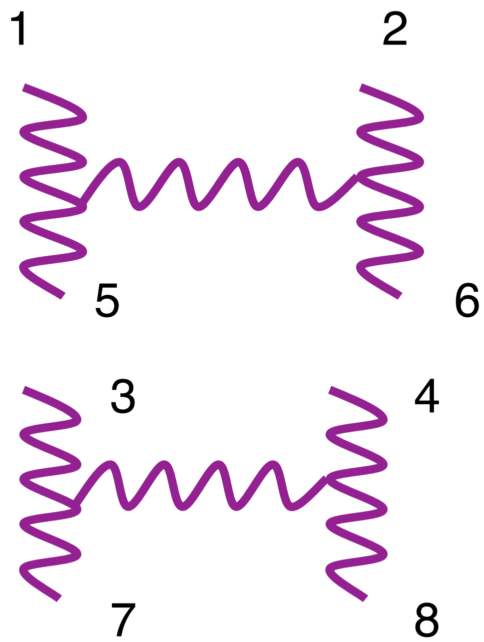
Normalization fixed at one energy and centrality





Two particle correlation in angle from flow effects

How is correlation generated ?



Naively disconnected,

But CGC averages over sources at positions 1-8

Sources 1-4 can be contracted in pairs as can 5-8

The contraction 1-2, 3-4, 5-6, 7-8

gives a disconnected diagram which cancels the mixed event subtraction

There are however other contractions which do not cancel.

These correspond to interference diagrams associated with the classical field, and are intrinsic to the classical field description

Questions:

How to describe the backwards ridge (associated with momentum conservation)?

Rapidity dependence of the ridge?

Experimentally is it truly long range?

What is the value of the un-detemined numerical coefficient?

Can one compute the short range piece of the correlation to get a full description?

How to describe the high p_T ridge?

What can be done in LHC?

How is this related to forward-backward correlations seen in pp and pbar-p?

Could the effect be due to biasing arising from flow? (Akiba)