Strongly Interacting Matter at High Energy Density

Matter at high temperature and baryon density:

The Quark Gluon Plasma and Quarkyonic Matter

The matter which controls the high energy limit of QCD:

The Color Glass Condensate

The matter which is produced in hadronic collisions which decays into the QGP

The Glasma

Related Questions:

How do strongly interacting particles acquire mass?

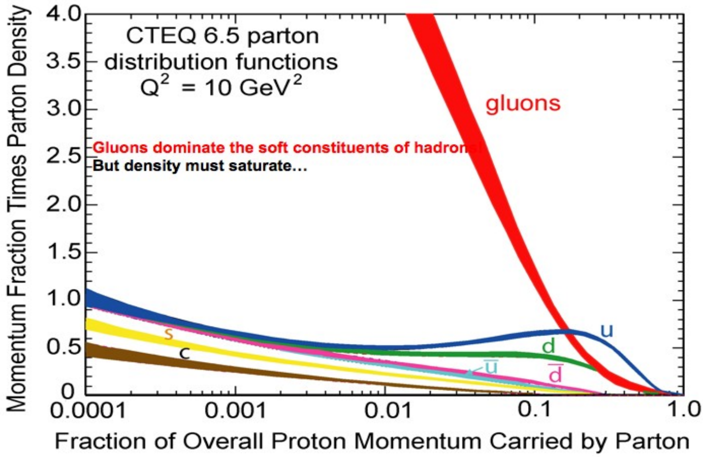
What is the nature of glue?

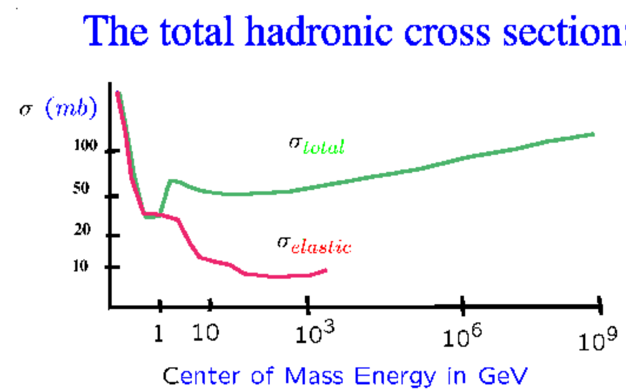
Can we see effects of topological charge?

What are the properties of matter which might appear in high energy astrophysical sources

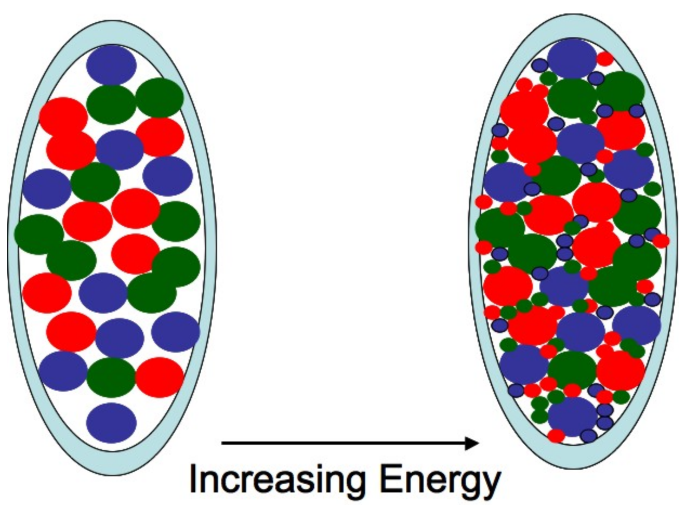
Saturation: The Color Glass Condensate,Glasma and the High Energy Limit of QCD

As one evolves the gluon density, the density of gluons becomes large:





Gluons are described by a stochastic ensemble of classical fields, and JKMMW argue there is a renormalization group description



In target rest frame: Fast moving particle sees classical fields from various longitudinal positions as coherently summed

In infinite momentum frame, these fields are Lorentz contracted to sit atop one another and act coherently

Density per unit rapidity is large

Mueller and Qiu, Nucl. Phys. B268, 427 (1986)

L. Gribov, Levin and Ryskin, Phys. Rept. 100, 1 (1983)

McLerran & Venugopalan, Phys. Rev. D49, 2233 (1994); 3352 (1994)

Leads to name for the saturated gluon media of Color Glass Condensate:

Color: Gluon Color

Glass: V. Gribov's space time picture of hadron collisions

Condensate: Coherence due to phase space density

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

Derivation JIMWLK evolution equations that for correlators is BK equation

The theoretical description overlaps:

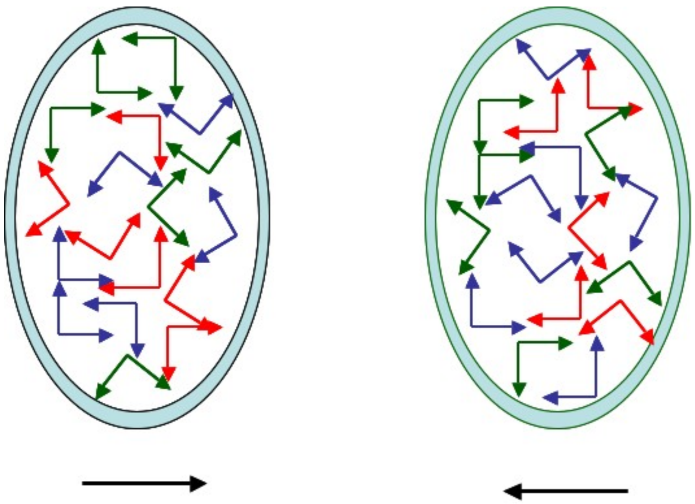
Perturbative QCD at large momenta (low density)

Includes the Pomeron and Multi-Reggeon configurations of Lipatov

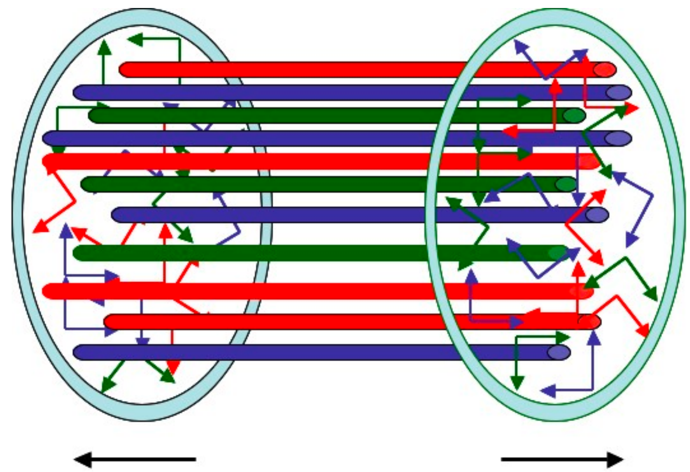
In various approximations, "Pomeron loop" effects can be included.

Theoretical issue is more when the approximations used are valid, not whether framework is valid

CGC Gives Initial Conditions for QGP in Heavy Ion Collisions



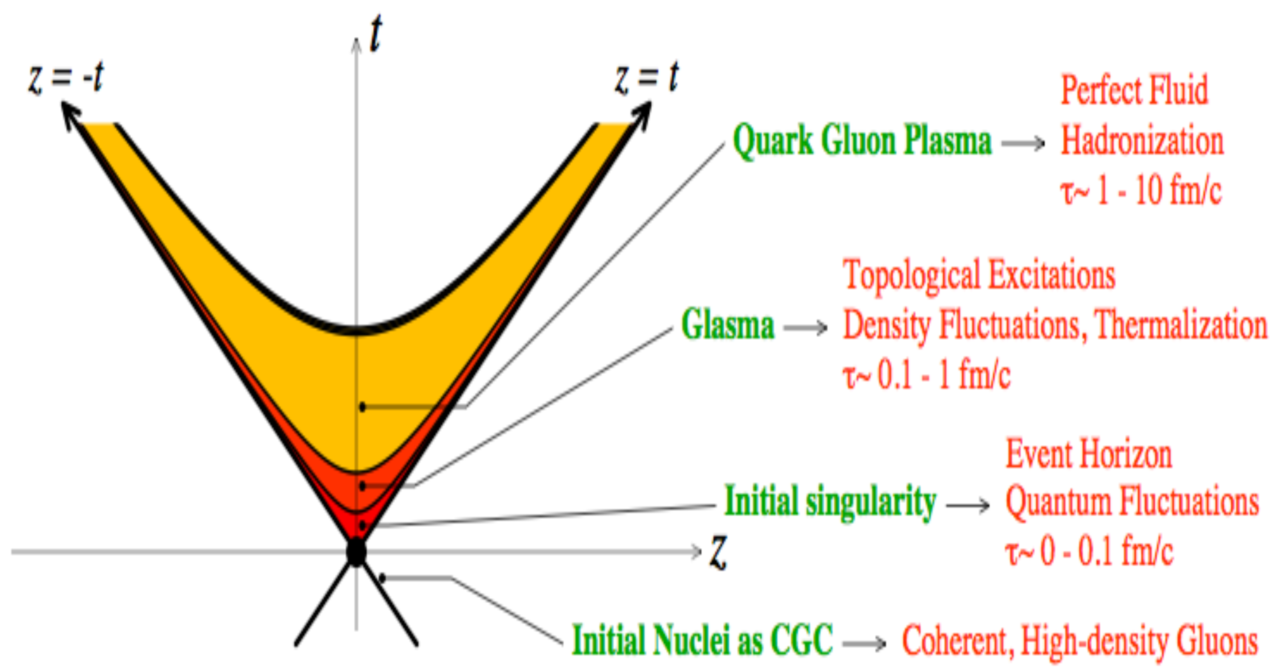
Longitudinal electric and magnetic fields are set up in a very short time



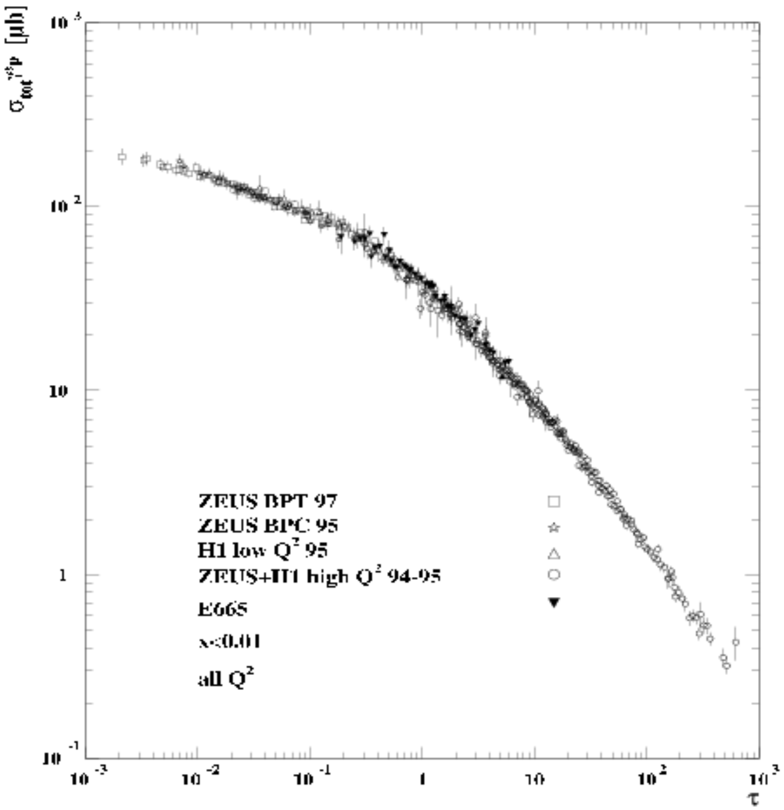
$$t \sim \frac{1}{Q_{sat}} e^{-\kappa/\alpha_S} << \frac{1}{Q_{sat}}$$

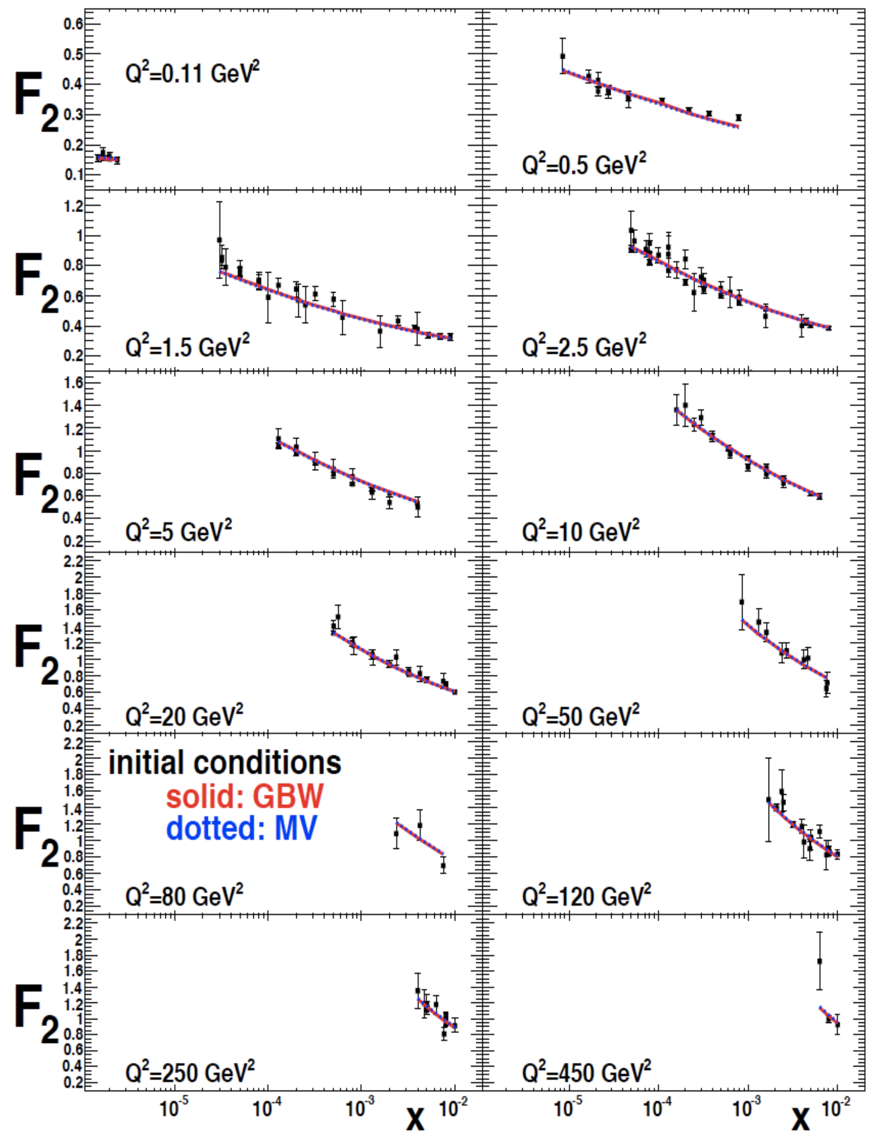
Bjorken

Phys.Rev.D27:140-151, 1983.



Experimental Evidence: ep Collisions





$$\sigma_{\gamma^* p} \sim F(Q^2/Q^2_{sat}(x))$$

$$x < 10^{-2}$$

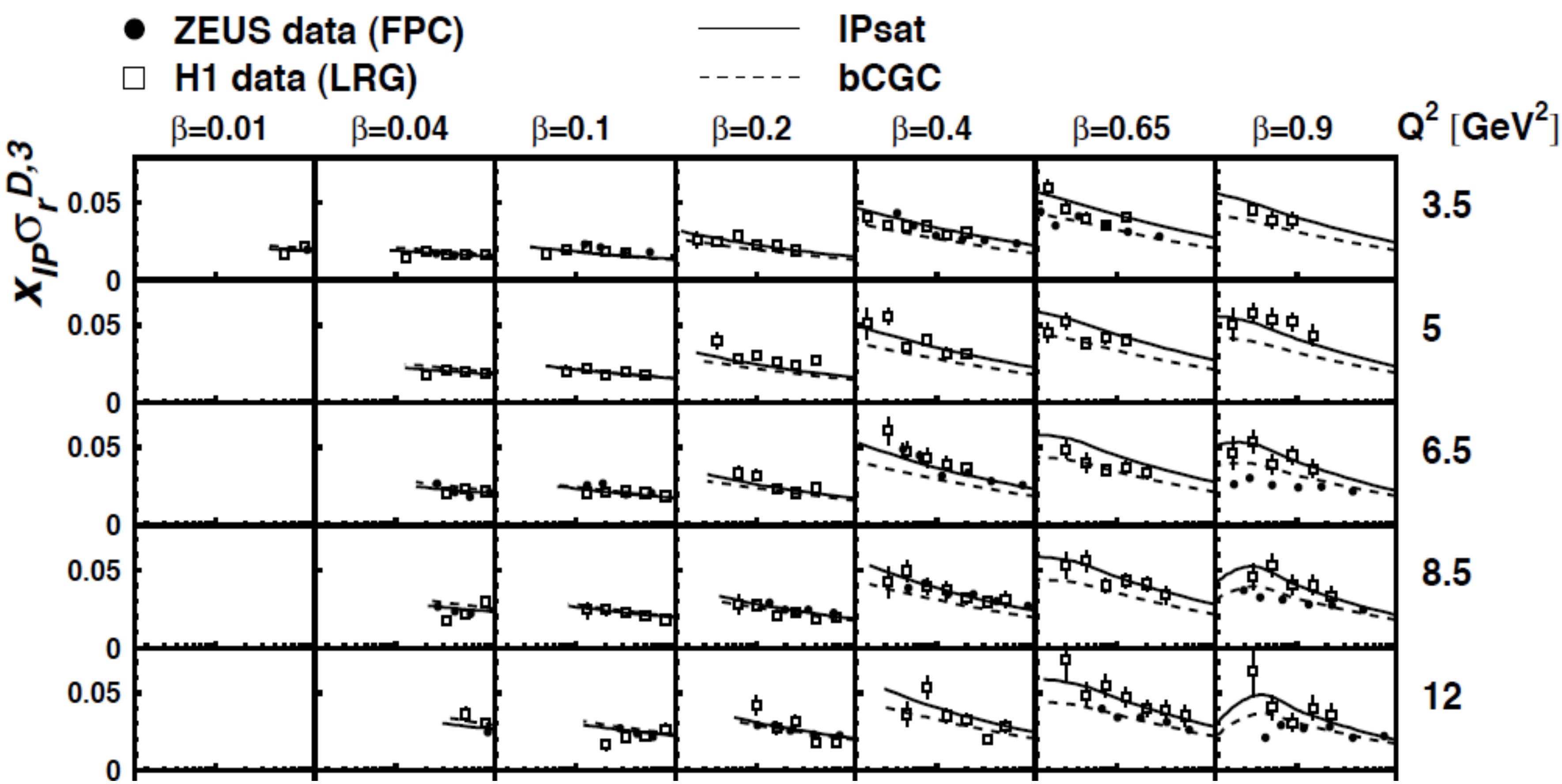
Computed saturation momentum dependence on x agrees with data

Simple explanation of generic feature of data

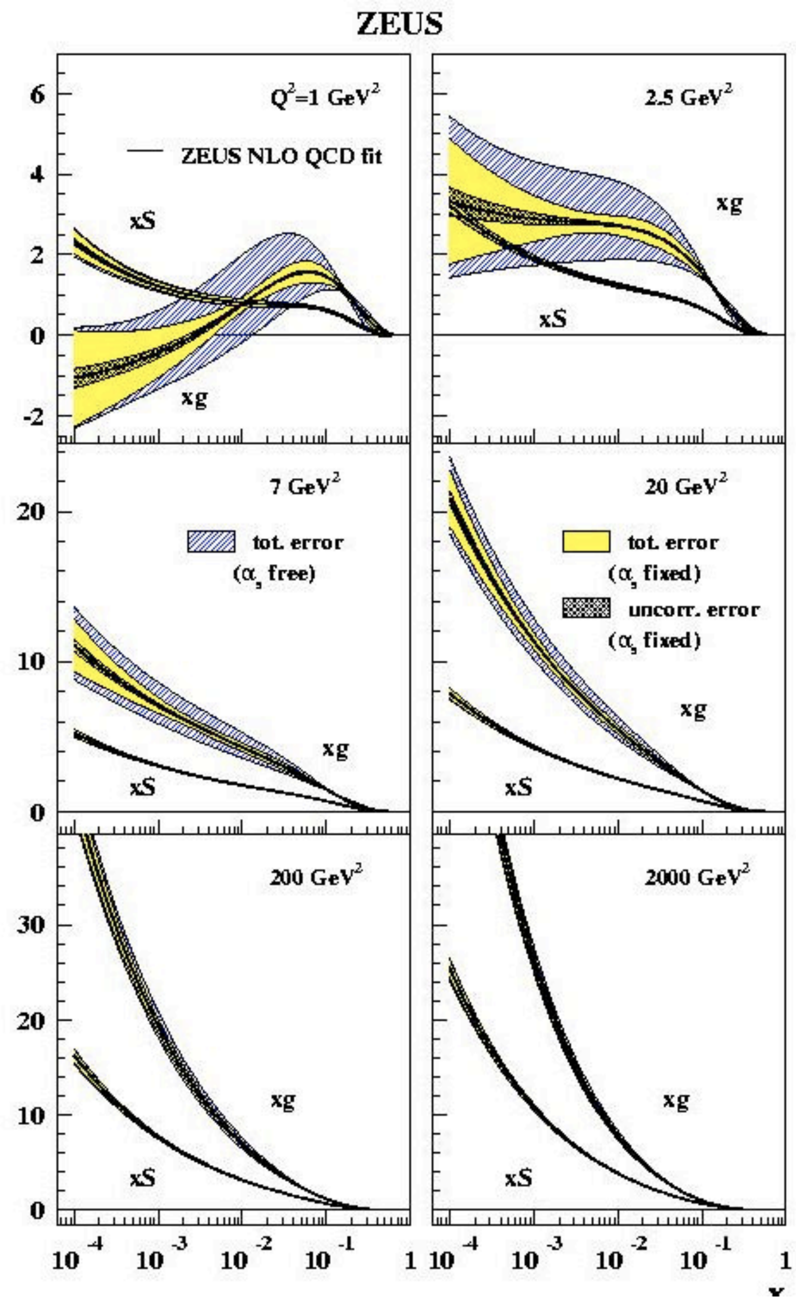
Allows an extraction of saturation momentum

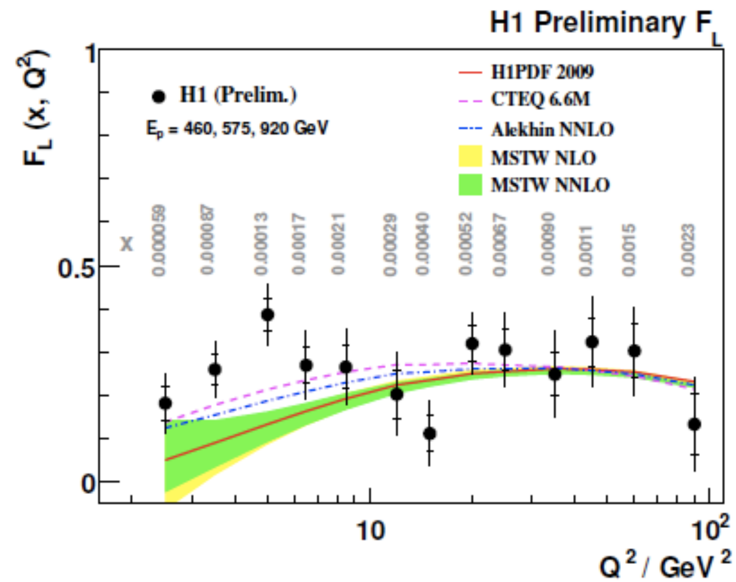
Experimental Evidence: ep Collisions

Diffraction

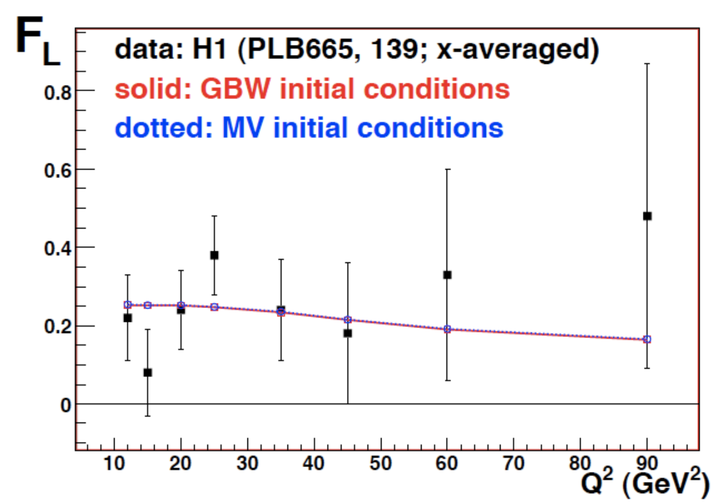


Experimental Evidence: ep Collisions





But there exist other non-saturation interpretations. Are there really no or even a negative number of "valence gluons" in the proton for small x?

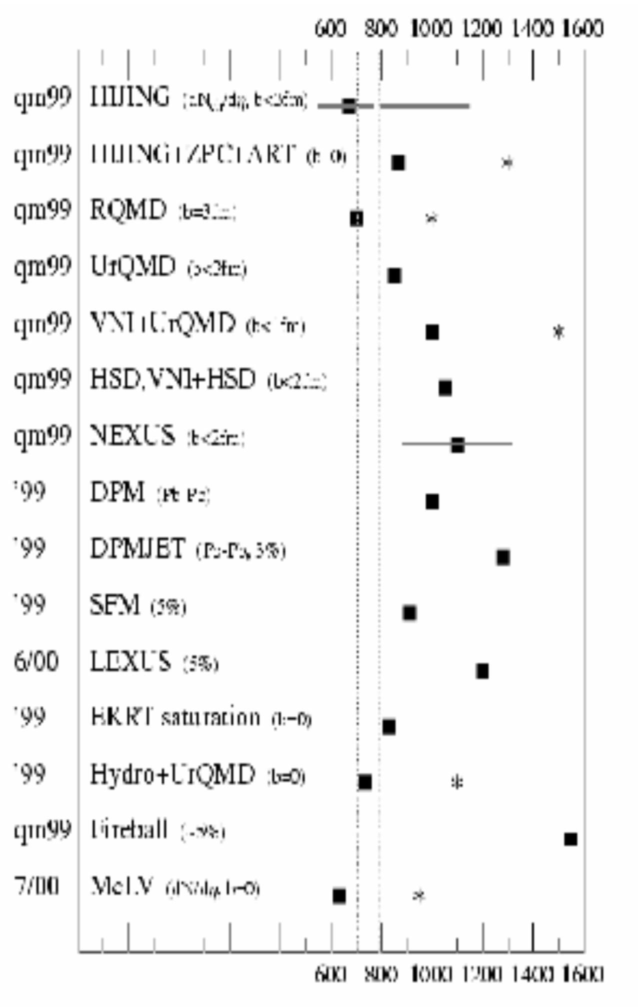


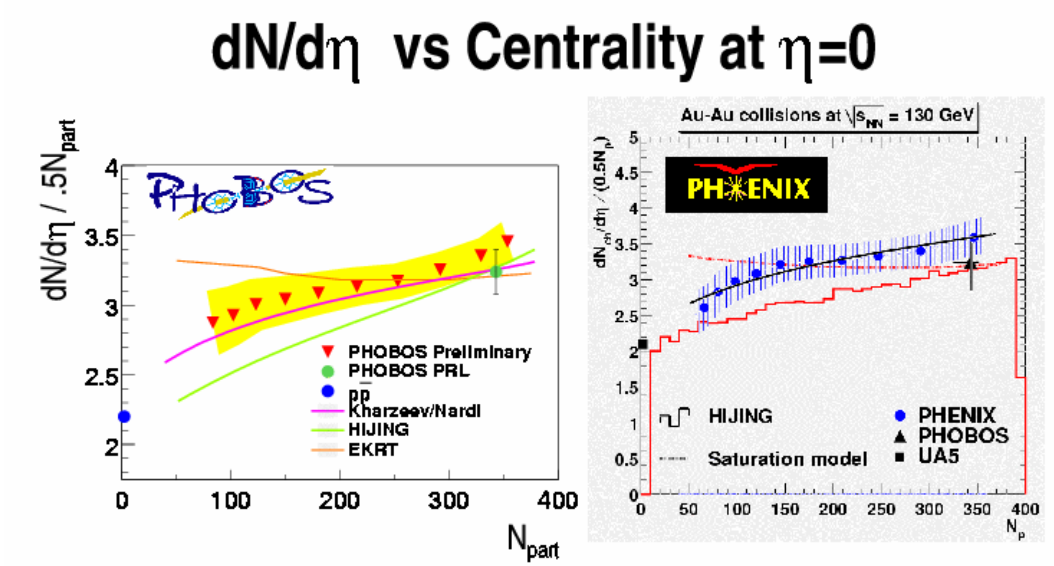
Saturation and Nuclei: Multiplicity

$$\frac{1}{\pi R^2}\frac{dN}{dy} \sim \frac{1}{\alpha_S}\, Q^2_{sat} \sim A^{1/3}/x^{.3}$$

Increasing A corresponds to decreasing x, or increasing energy

Early results on multiplicity:





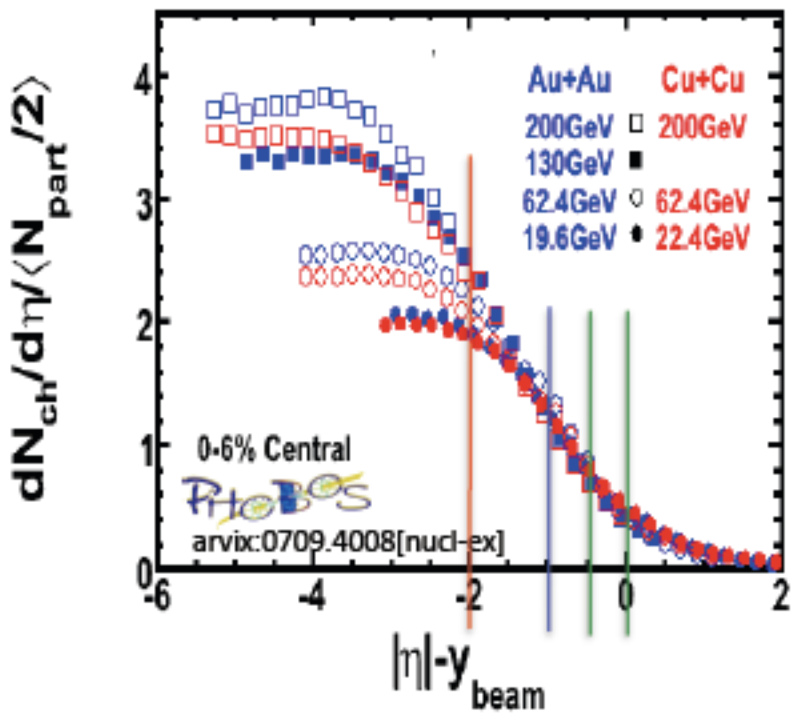
Saturation based models predicted the centrality and energy dependence of the data

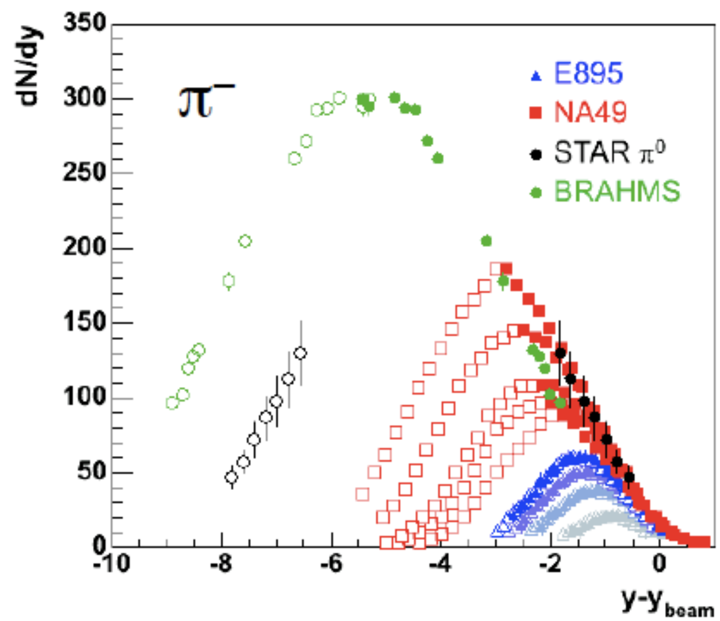
Extended Longitudinal Scaling:

Large x parton (projectile) sees saturated disk of low x partons from target:
Partons up to saturation scale are stripped from projectile.

Approximate scaling well described in CGC

Important for renormalization group description of CGC





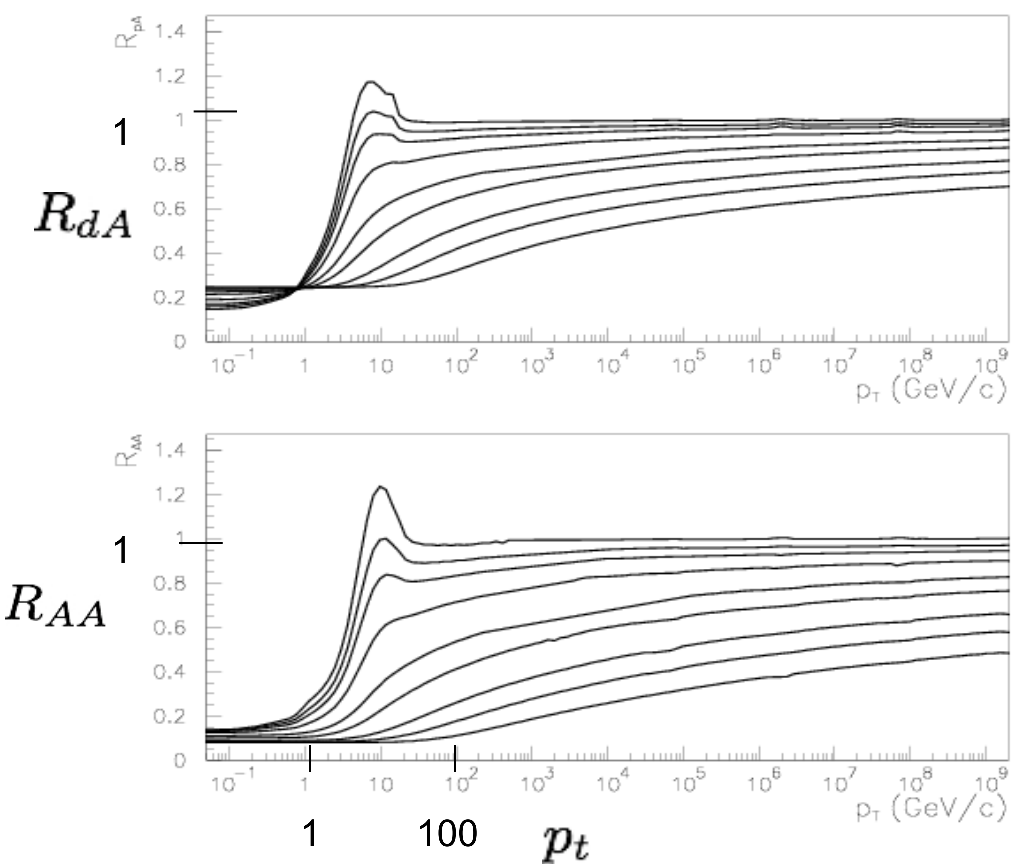
Single Particle Distributions in dA Collisions:

Two effects:

Multiple scattering: more particles at high pT

CGC modification of evolution equations => less particles

It also includes DGLAP and BFKL evolution

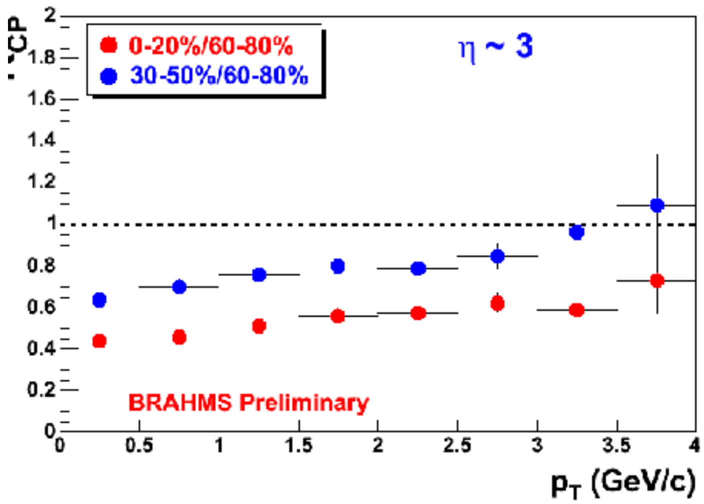


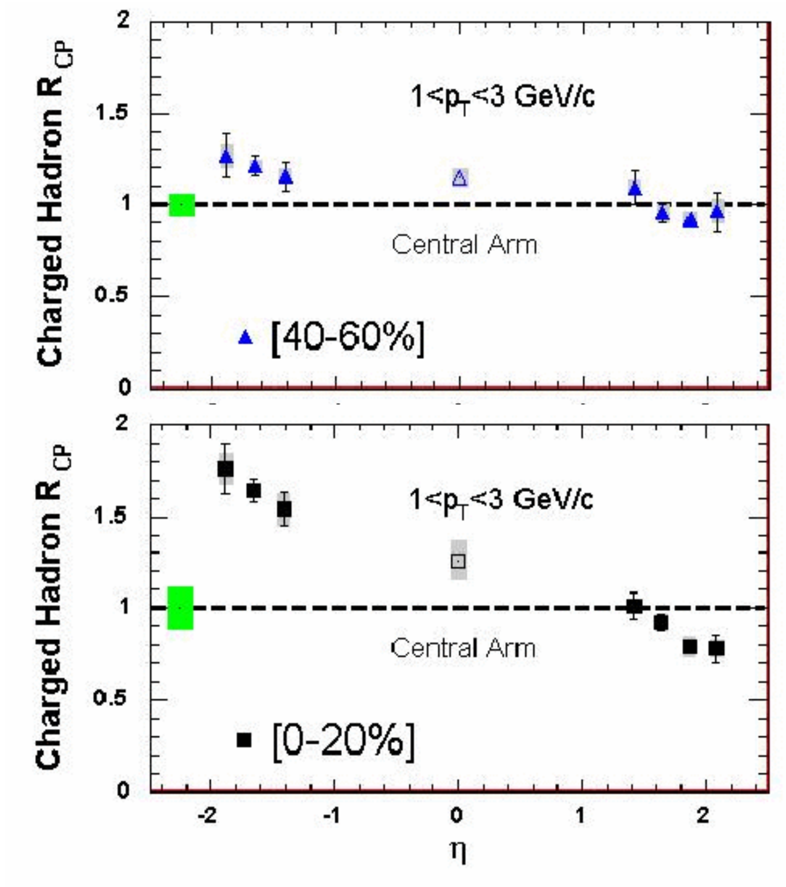
Upper Curves:

Ratio of deuteron gold to pp distribution as function of transverse momentum for various x values

Lower Curves:

Same plot for initial state modifications for the ratio of gold-gold to pp





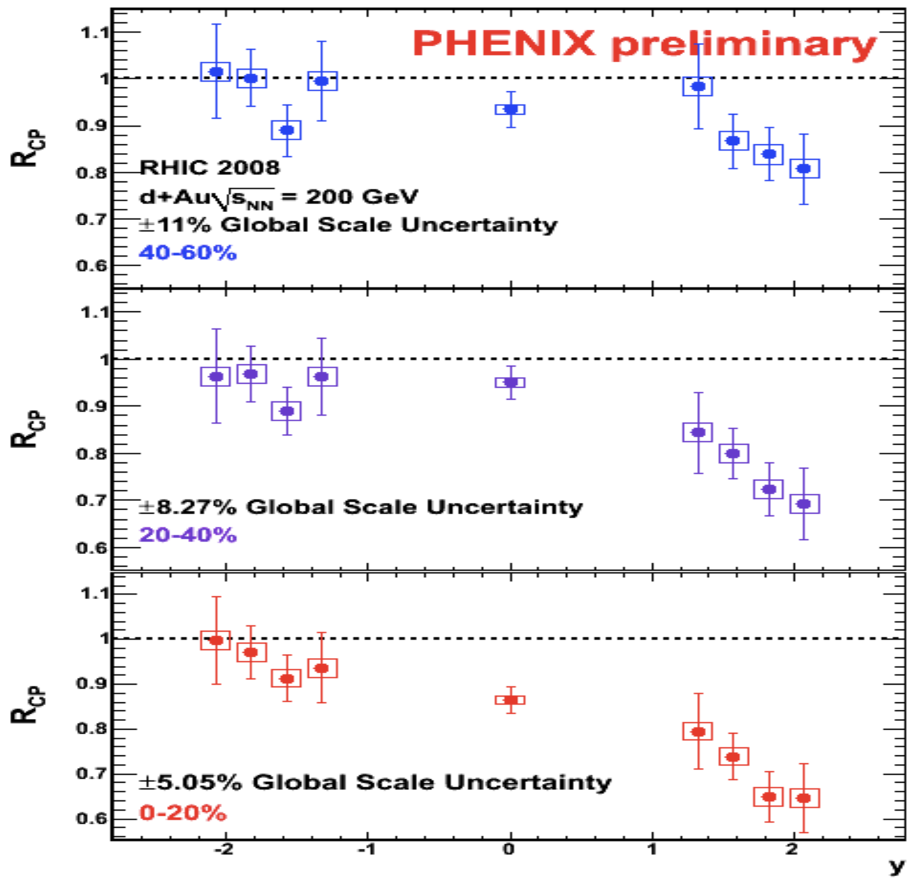
Single Particle Distributions in dA Collisions:

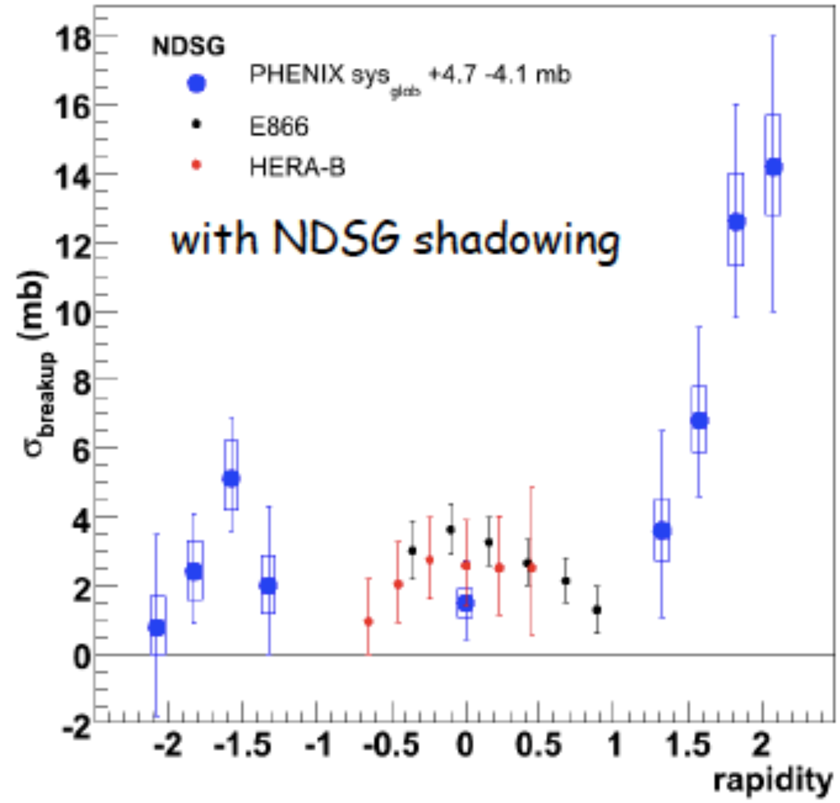
Only CGC correctly predicted suppression at forward rapidity and suppression with increasing centrality seen in Brahms, Phenix and Star

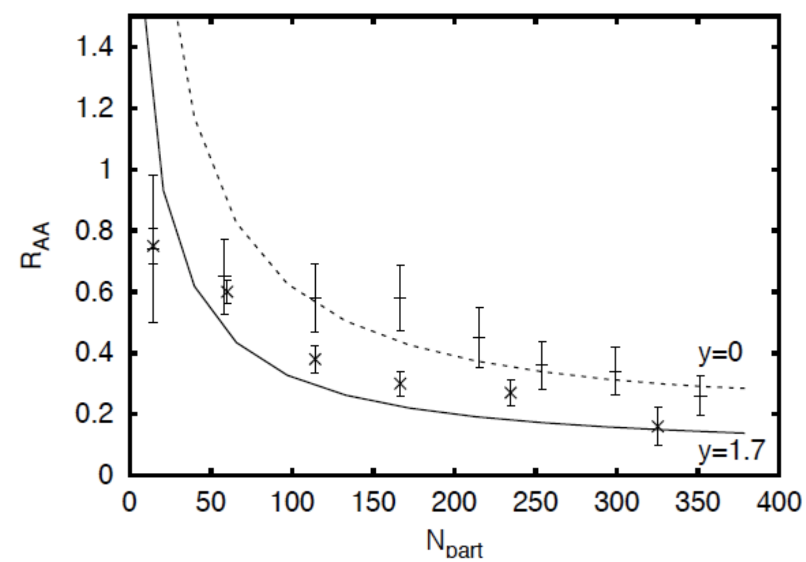
Leading twist gluon shadowing does NOT describe the Brahms data!

Non-leading twist at small x is saturation.

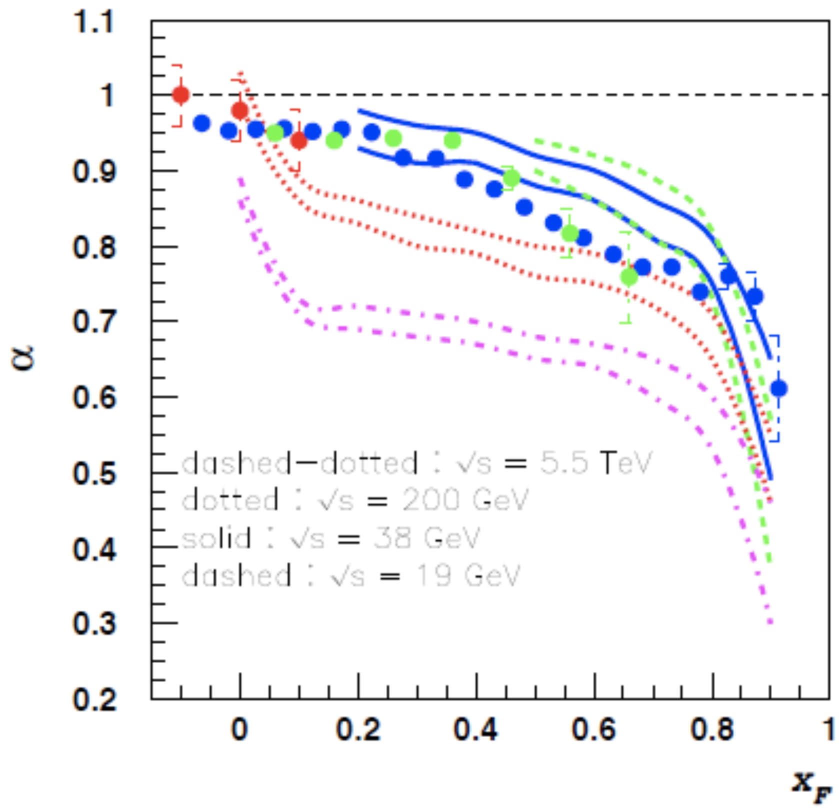
J/Psi Production in dA and AA







CGC description a realization of intrinsic charm ideas of Brodsky



Can be interpreted as nuclear absorption but with a strong rapidity dependence and huge cross section in forward region

CGC: If saturation momentum exceeds charms quark mass, then charm is similar to a light mass quark: Feynman scaling and cross section like

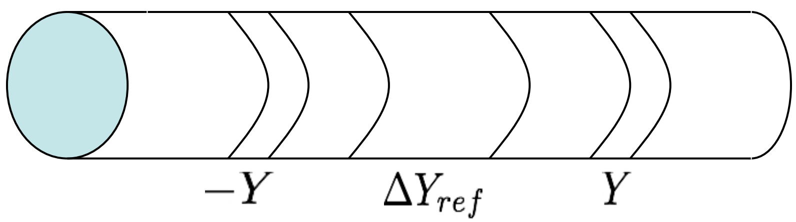
$$A^{2/3}$$

Good intuitively plausible description of data

Two Particle Correlations

If the relative momentum between two particles is large, the two particle correlation must is generated at a time t ~ 1/p

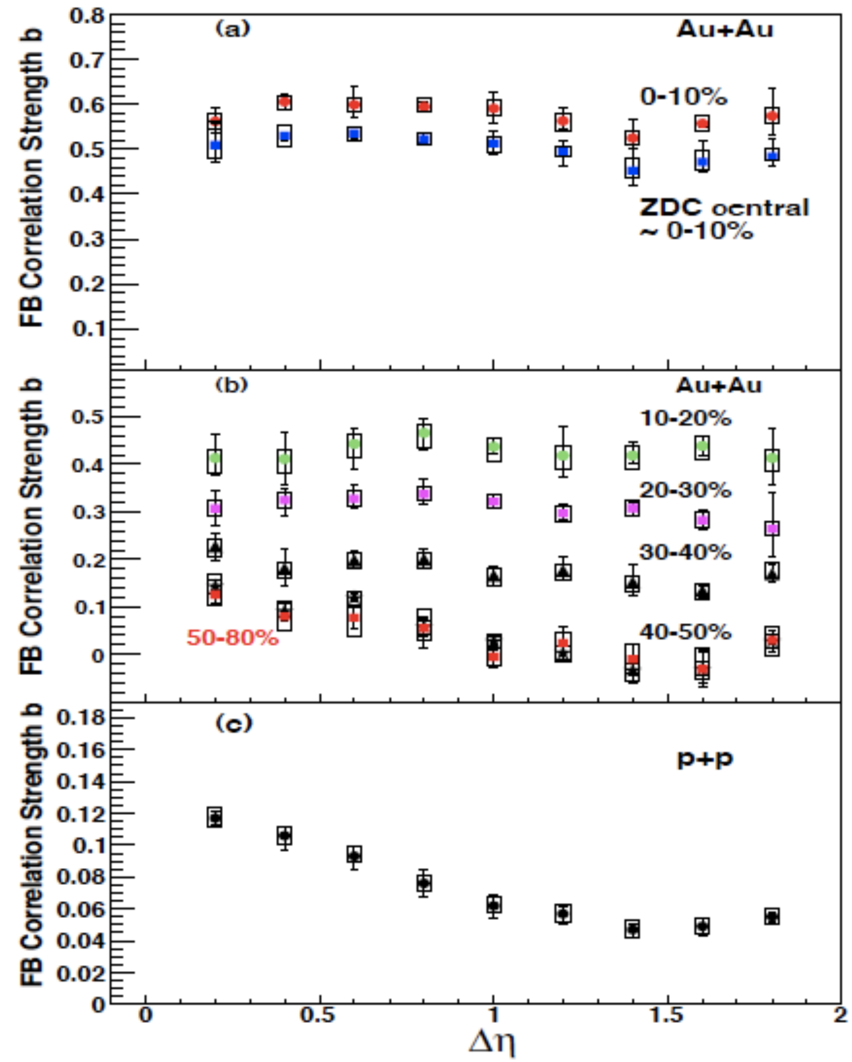
STAR Forward Backward Correlation



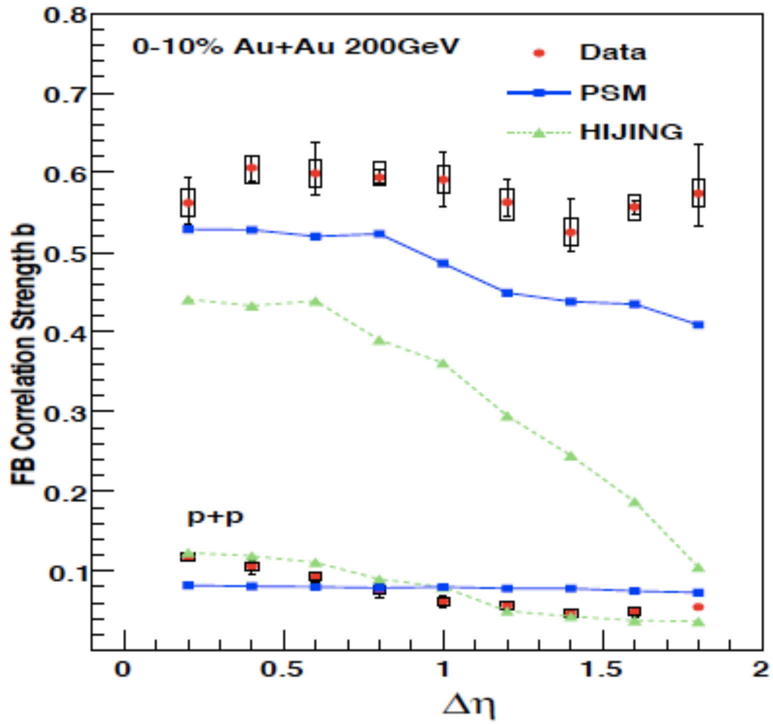
$$b = \frac{< N_F N_B > - < N_F >< N_B >}{< N_F^2 > - < N_F >^2}$$

Correlations measured for fixed reference multiplicity and then are put into centrality bins

Correlation is stronger for more central collisions and higher energy



Two Particle Correlations



Impact parameter correlation give b = 0.16

Most central highest energy correlation strength exceeds upper bound of 0.5 from general considerations

$$b \sim \frac{A_{longrange}}{A_{longrange} + A_{shortrange}}$$

Long-range correlation from Glasma flux

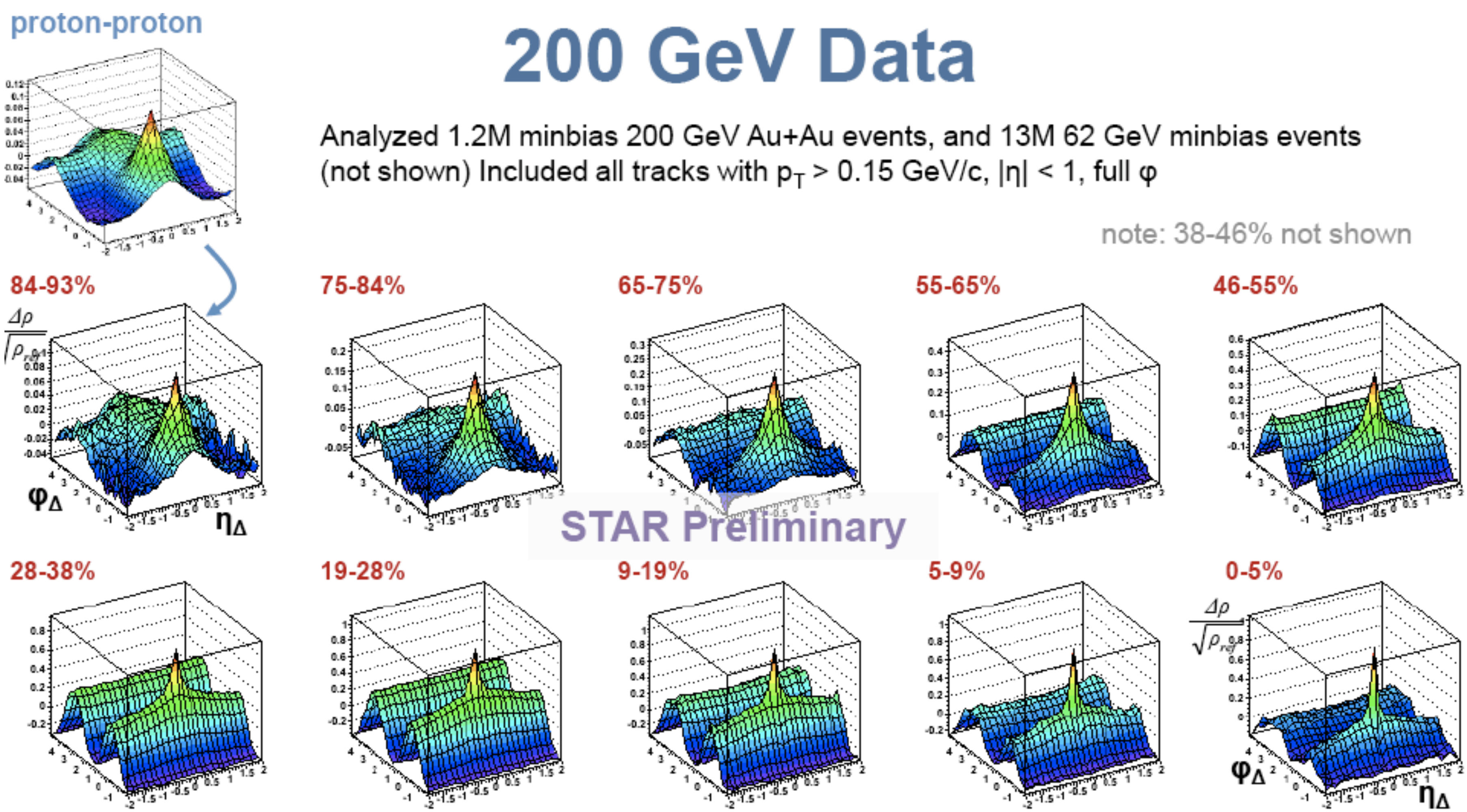
Short-range from higher order corrections

$$b \sim \frac{1}{1 + c\alpha_S^2}$$

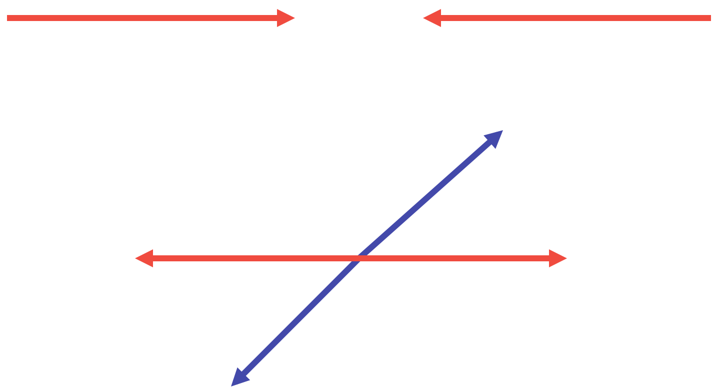
Glasma provides qualitatively correct description, and because of long range color electric and magnetic flux

Two Particle Correlations

The Ridge

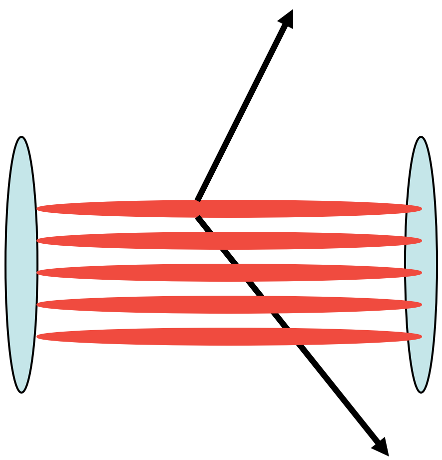


Two Particle Correlations



In perturbative QCD, there is in addtion to the high p_T jet, a "beam fragmentation jet" caused by image charges

Glasma includes perturbative QCD processes for hard ridge



Multiple Pomeron emission: In non saturated region Lipatov hard Pomeron

CGC includes Lipatov hard Pomeron, but also allows one to extend to dense region for inclusive ridge

Two particle correlation is suppressed by

$$1/N_c^2$$

relative to inclusive production.

Need a color correlation!

Decay of Lines of Flux:

Long range in rapidity

Narrow in angle due to flow

Hydro gives “mach cone” structure

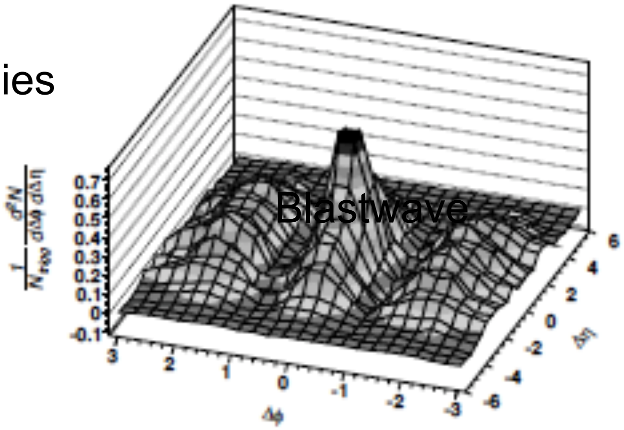
Beam jet fragmentation in perturbative QCD,

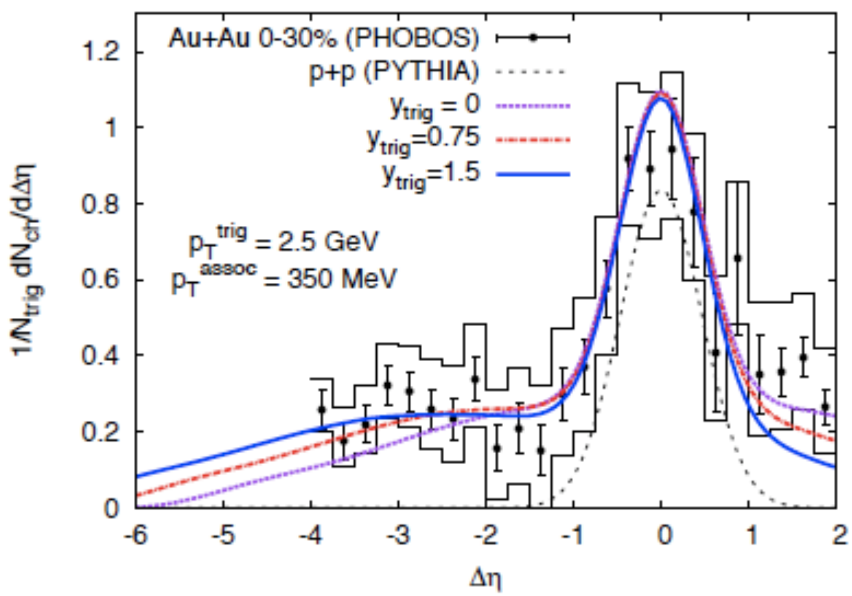
Glasma “flux tube”

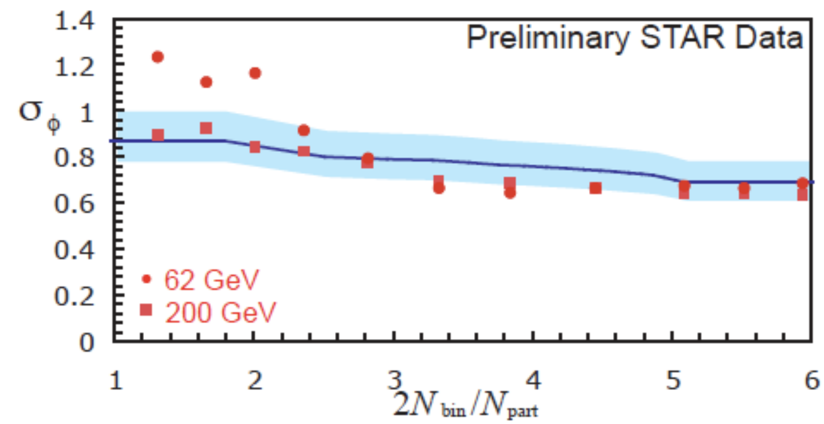
Pomeron decays

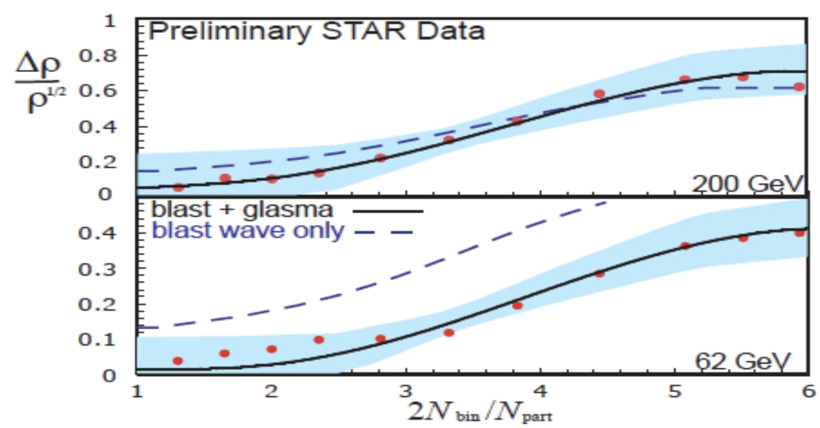
Glasma description is inclusive

Hydro-studies









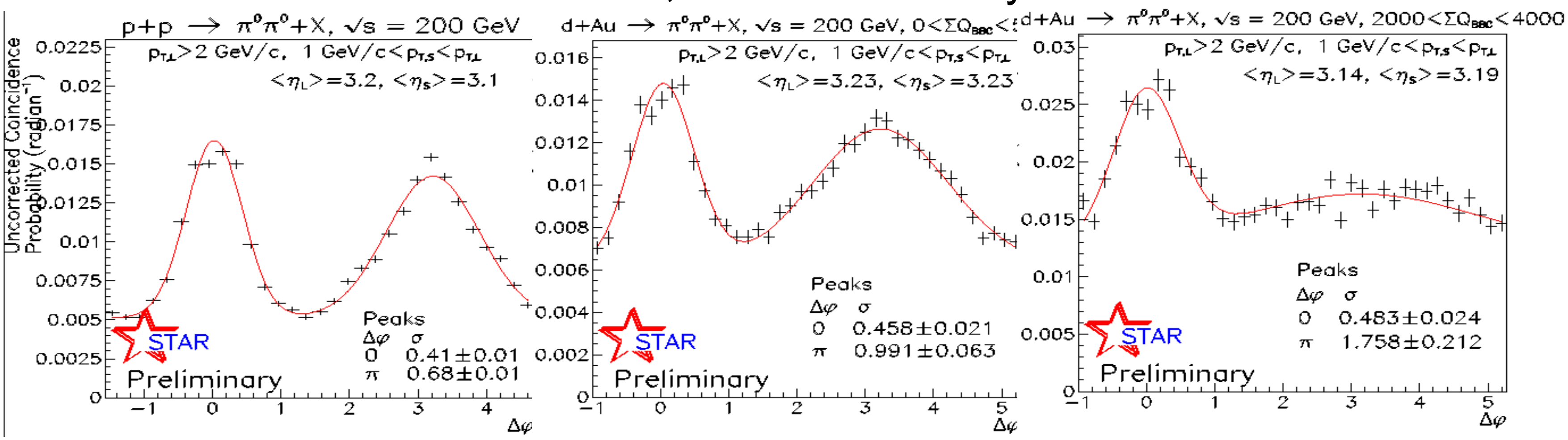
Jet quenching CAN NOT explain the long range rapidity correlation!

“Jet Quenching” in dA Collisions:

Forward backward angular correlation between forward produced, and forward-central produced particles

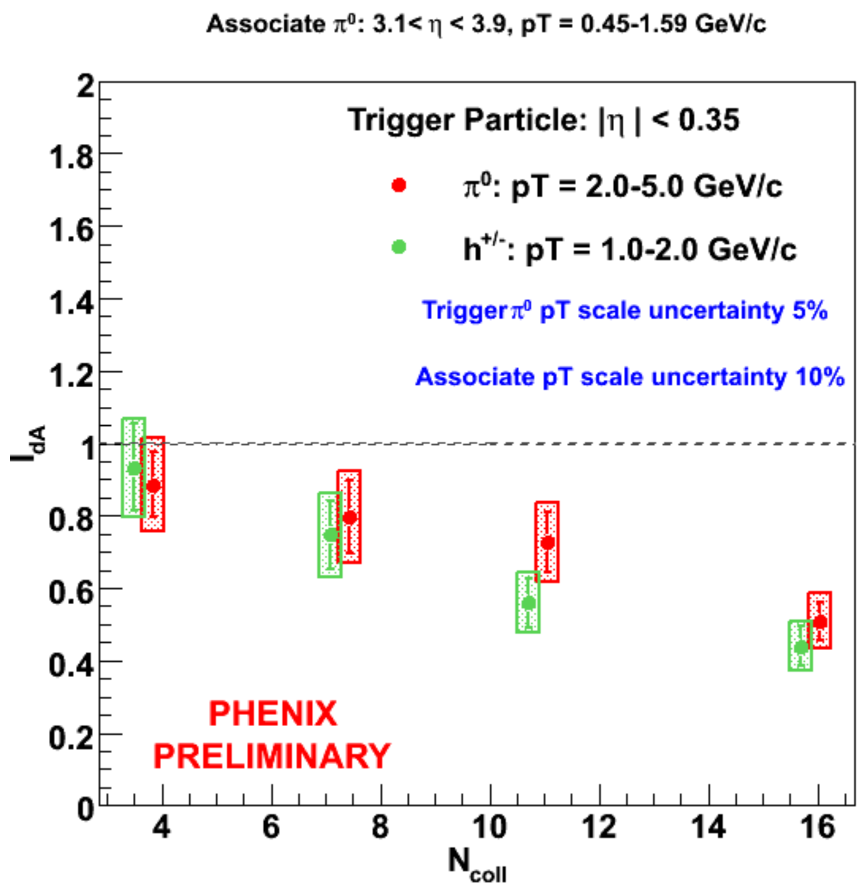
Conclusive evidence that the CGC is a medium!

200 GeV ***p+p*** and ***d + Au*** Collisions
Run8, STAR Preliminary



pp ***d+Au (peripheral)*** ***d+Au (central)***

Two Particle Correlations



PHENIX data is well described by the saturation based computation.

"Jet Quenching" in dA Collisions:

Forward backward angular correlation between forward produced, and forward-central produced particles

STAR and PHENIX

Conclusion:

Large number of tests of saturation hypothesis: Experimental results from Brahms, Phenix, Phobos and Star are consistent with that predicted for Color Glass Condensate and Glasma

Most recent data:

dA Correlations: There is a saturated media present in the initial wavefunction of the nucleus that is measured in the two particle correlations of PHENIX (and STAR).

The Ridge: In the collisions of two nuclei, “flux tube” structures are formed and are imaged in the STAR, PHOBOS and PHENIX . They are well described as arising from a Glasma produced in the collisions of sheets of Colored Glass Condensate.

Question:

Is it “strongly” or weakly coupled?

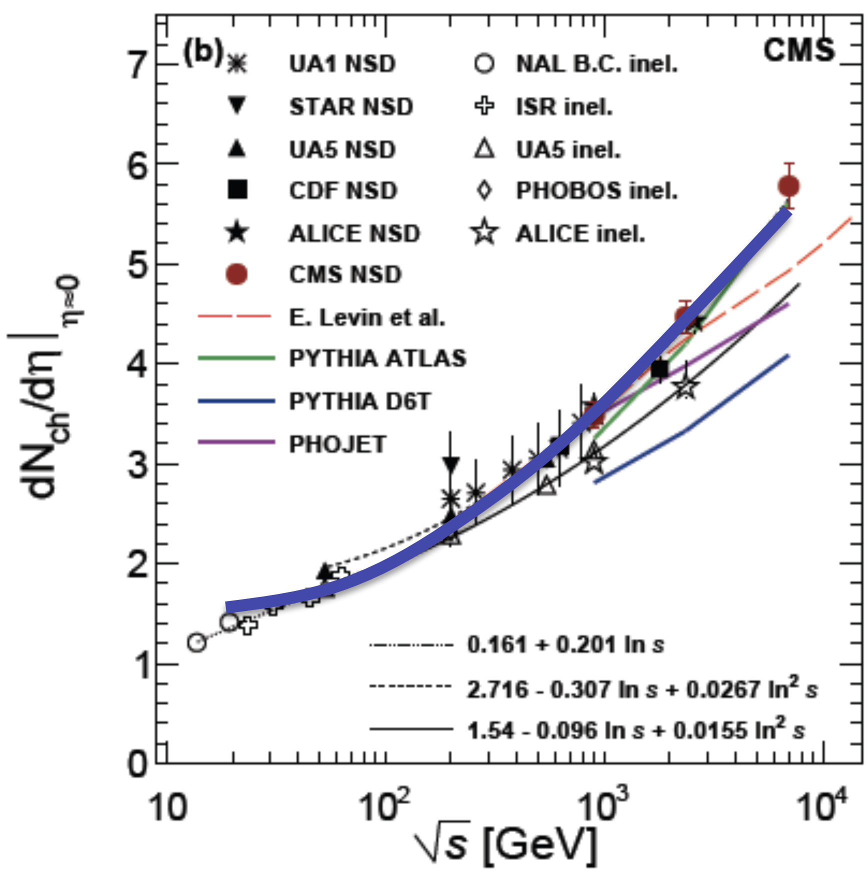
The accumulated data from RHIC provides compelling confirmation of the CGC hypothesis for gluon saturation

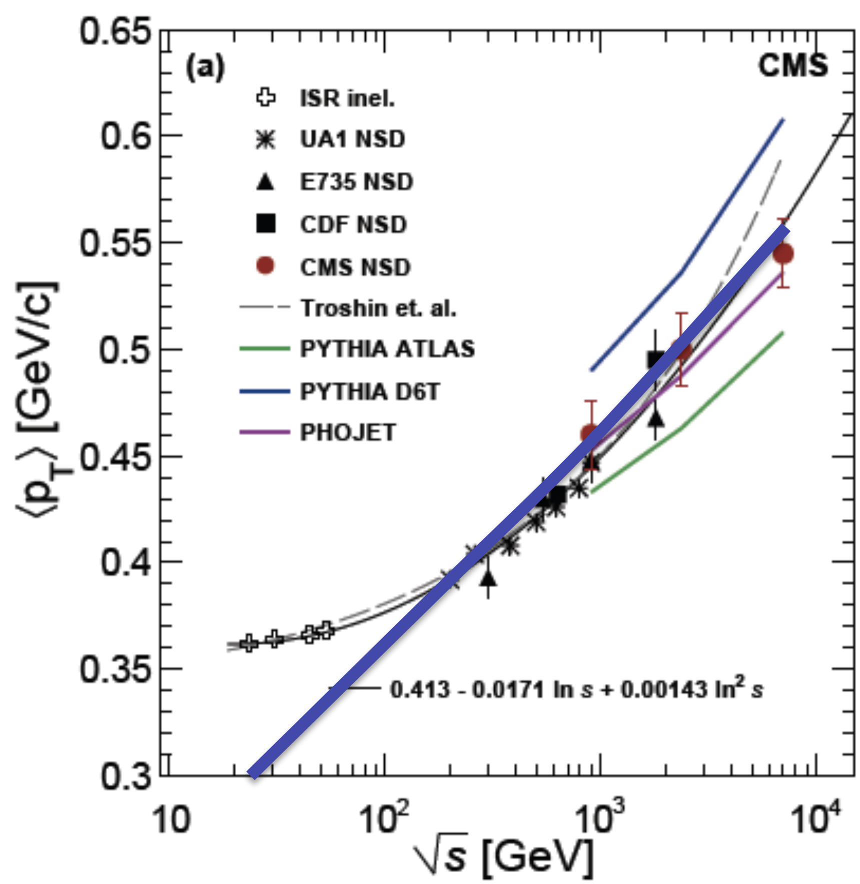
Saturation and the LHC

Ignoring slow variation of coupling constant and total cross section with energy

$$\frac{1}{\sigma}\frac{dN}{dy} \sim Q_{sat}^2 \sim E^a \qquad\qquad < p_T > \sim Q_{sat} \sim E^{a/2}$$

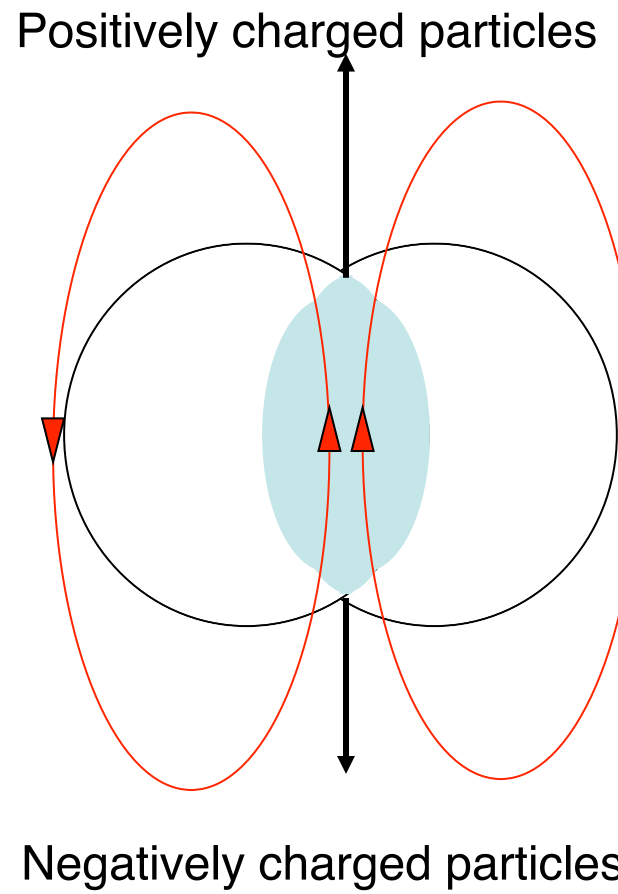
$a \sim .2 - .3$ from HERA, take $a = 0.22$





Topological Charge Changing Processes and Event by Event P and CP Violation

$$\partial^\mu J^5_\mu = \kappa \; E \cdot B + O(m_{quark})$$



Glasma generates a large topological charge density.

Perhaps the observed “P and CP Violating fluctuations” due to topological charge fluctuations?

Do these arise from the Glasma?