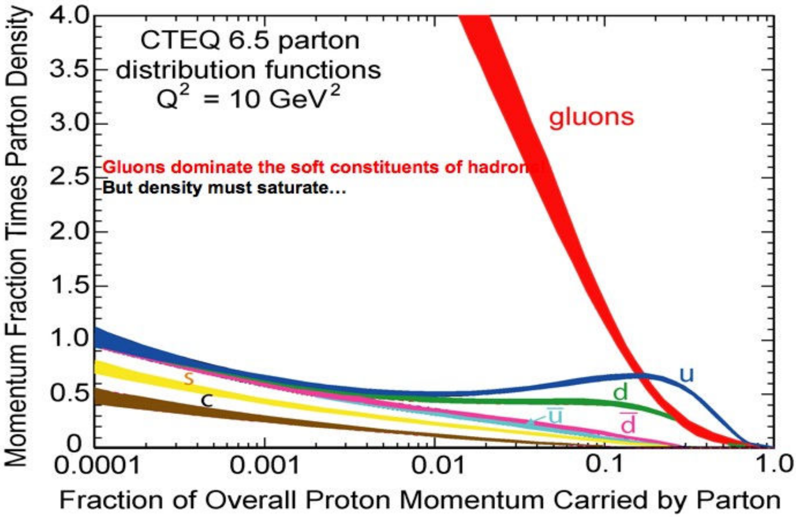
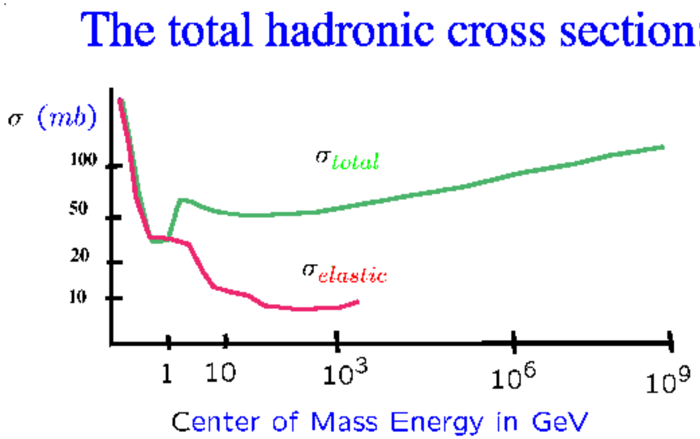
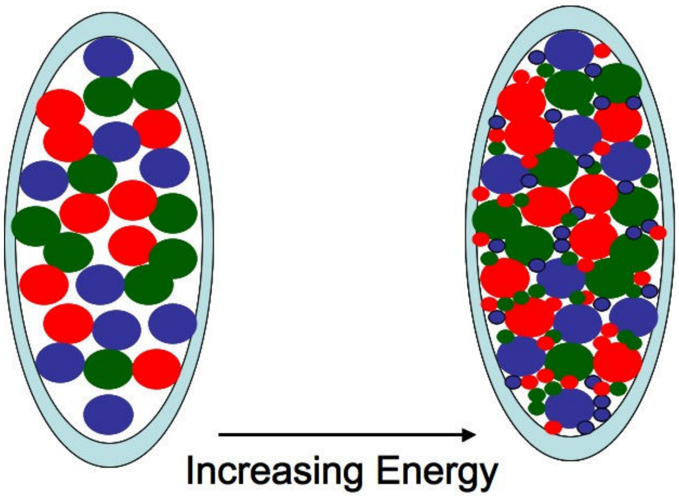
Saturation: The Color Glass Condensate,Glasma and RHIC

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

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

QuickTime™ and a
decompressor
are needed to see this picture.

Derivation JIMWLK evolution equations that for correlators is BK equation

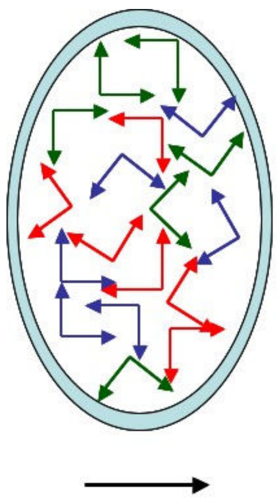
The theoretical description overlaps:

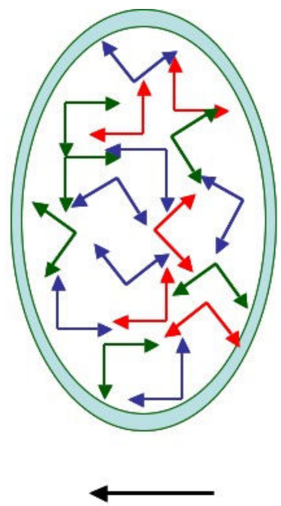
Perturbative QCD at large momenta (low density)

Includes the Pomeron and Multi-Reggeon configurations of Lipatov

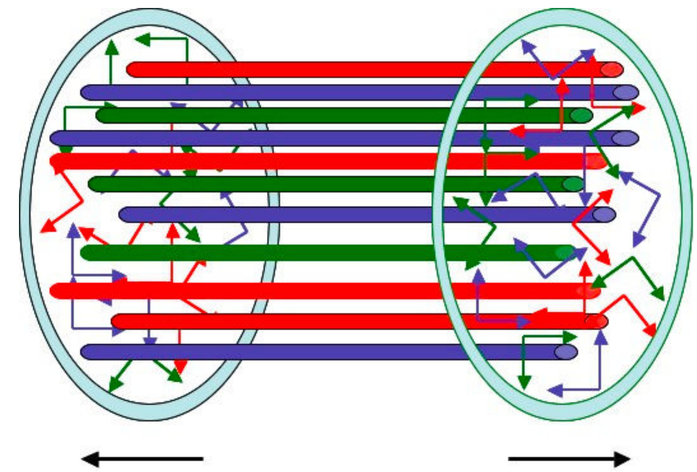
In various approximations, "Pomeron loop" effects can be included.

CGC Gives Initial Conditions for QGP in Heavy Ion Collisions

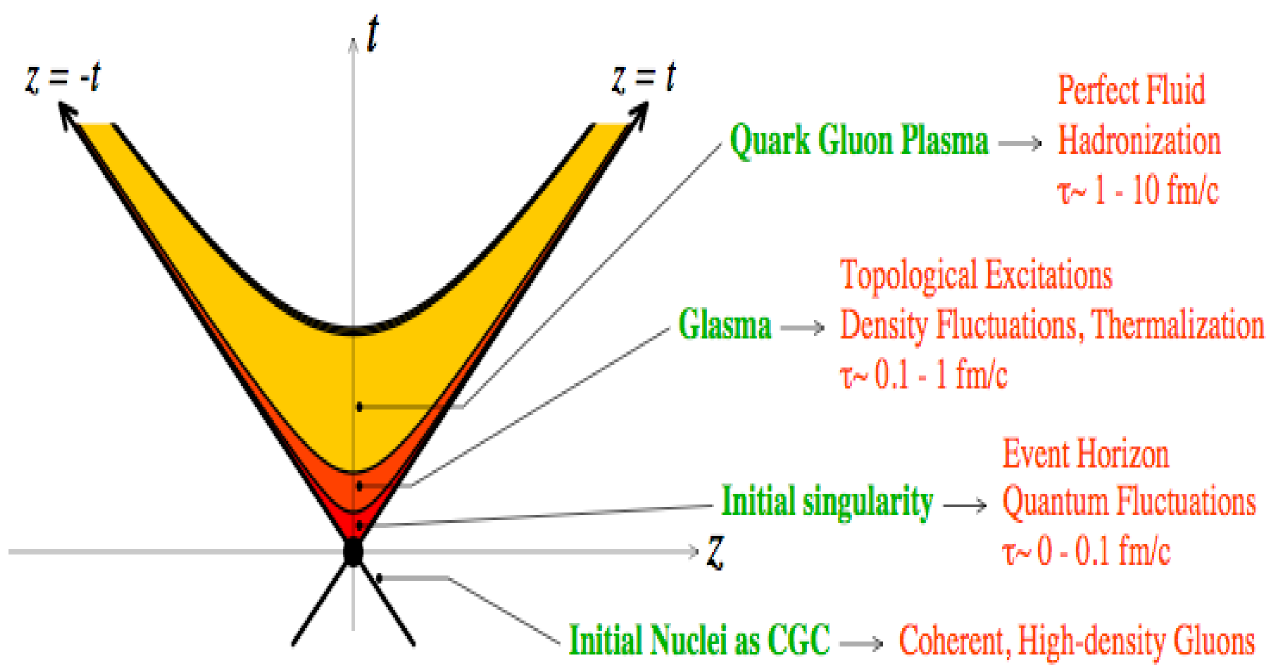




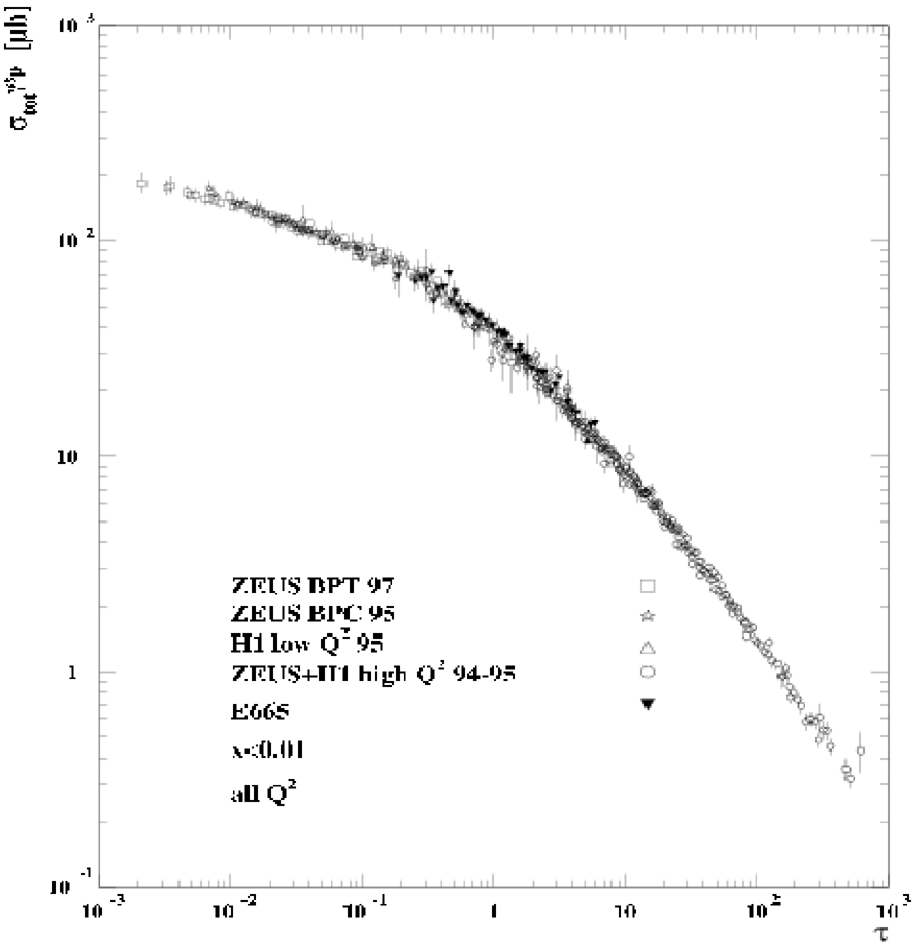
Longitudinal electric and magnetic fields are set up in a very short time



QuickTime™ and a decompressor are needed to see this picture.



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

Valid for

QuickTime™ and a
decompressor
are needed to see this picture.

Mueller and Triantafylloupoulos

Golec-Biernat and Wustoff

A. Mueller

Stasto, Golec-Biernat, Kwiecinski

Iancu, Itakura and LM

Experimental Evidence: ep Collisions

QuickTime™ and a
decompressor
are needed to see this picture.

Good and simply
motivated
description
inclusive deep
inelastic data
(includes running
coupling effects)

Albacete, Armesto,
Milhana and Salgado

Experimental Evidence: ep Collisions

QuickTime™ and a
decompressor
are needed to see this picture.

Kowalski and Teaney;

Iancu, Itakura and Munier

Kowalsk, Motyka and Watt

Provides a good and simple description of diffraction

Experimental Evidence: ep Collisions

QuickTime™ and a
decompressor
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QuickTime™ and a
decompressor
are needed to see this picture.

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?

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decompressor
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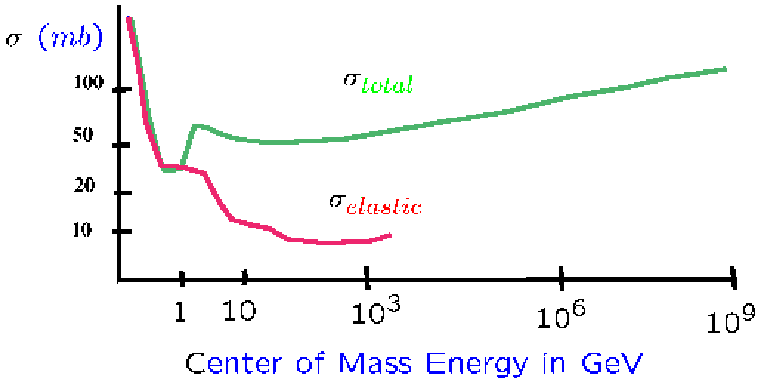
pp Collisions: Heuristic Explanation of Slow Growth of Total Cross Section

The total hadronic cross section:



Transverse distribution of gluons:

$$\frac{dN}{dy d^2 r_T} = Q^2_{sat}(y) e^{-2m_\pi r_T}$$

Transverse profile set by initial conditions

Size is determined when probe sees a fixed number of particles at some transverse distance

$$e^{\kappa y} e^{-2m_\pi r_T} \sim constant$$

$$\sigma \sim r_T^2 \sim y^2 \sim ln^2(E/\Lambda_{QCD})$$

Kovner and Wiedemann

Ferreiro, Iancu and LM

Saturation and Nuclei: Multiplicity

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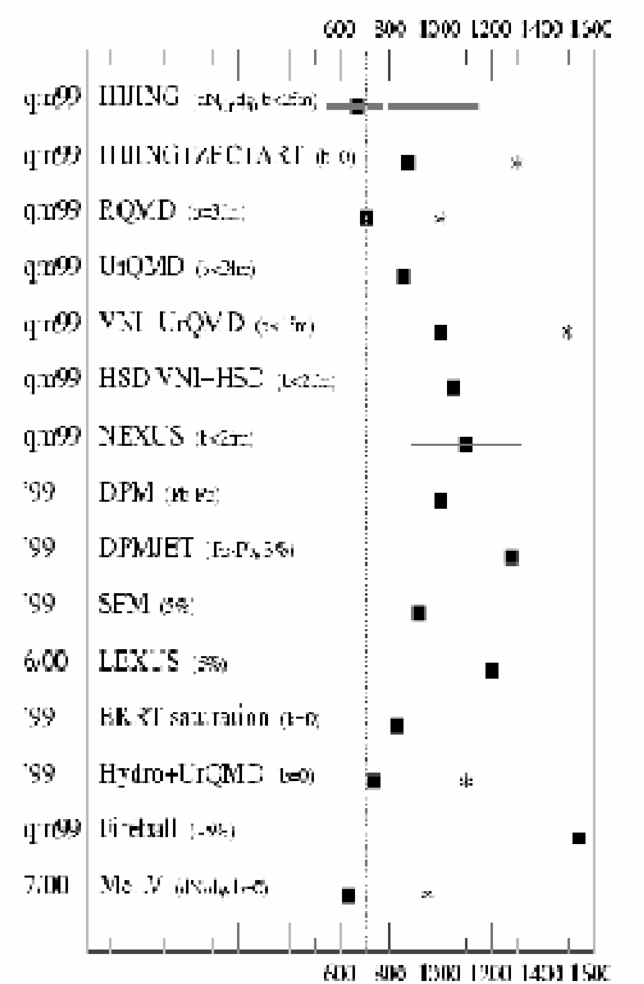
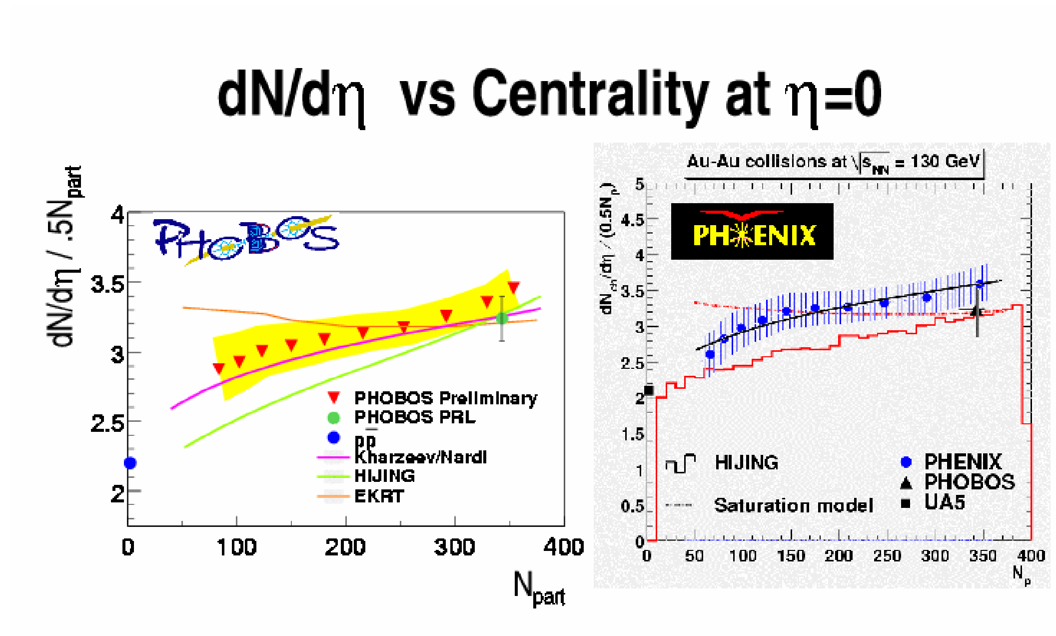
Increasing A corresponds to decreasing x, or increasing energy

Early results on multiplicity:





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

Kovchegov and Mueller

Krasnitz and Venugopalan

Kharzeev and Nardi

Saturation and Nuclei: Multiplicity Fluctuations

Glittering Glasma: Negative Binomial Distributions

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decompressor
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QuickTime™ and a
decompressor
are needed to see this picture.

Poisson Statistics is Limit of NB as k => infinity at fixed average multiplicity

Poisson corresponds to decay of classical field

NB does not fall off like 1/n! at large n

“Completeness relationship” for negative binomial:

Sum of negative binomial emitters with parameters

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Gives a negative binomial distribution with

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decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

Saturation and Nuclei: Multiplicity Fluctuations

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decompressor
are needed to see this picture.

Interpret

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decompressor
are needed to see this picture.

In paper with Gelis and Lappi, show that a single Glasma flux tube is a NB source.

Phenix results:

Multiplicity distribution is negative binomial

K proportional to the number of participant

RHIC Experiments:

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decompressor
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Transition from Poisson to NB at around 10 GeV, roughly when nuclei being to penetrate through one another, and when flux tube description might become usable

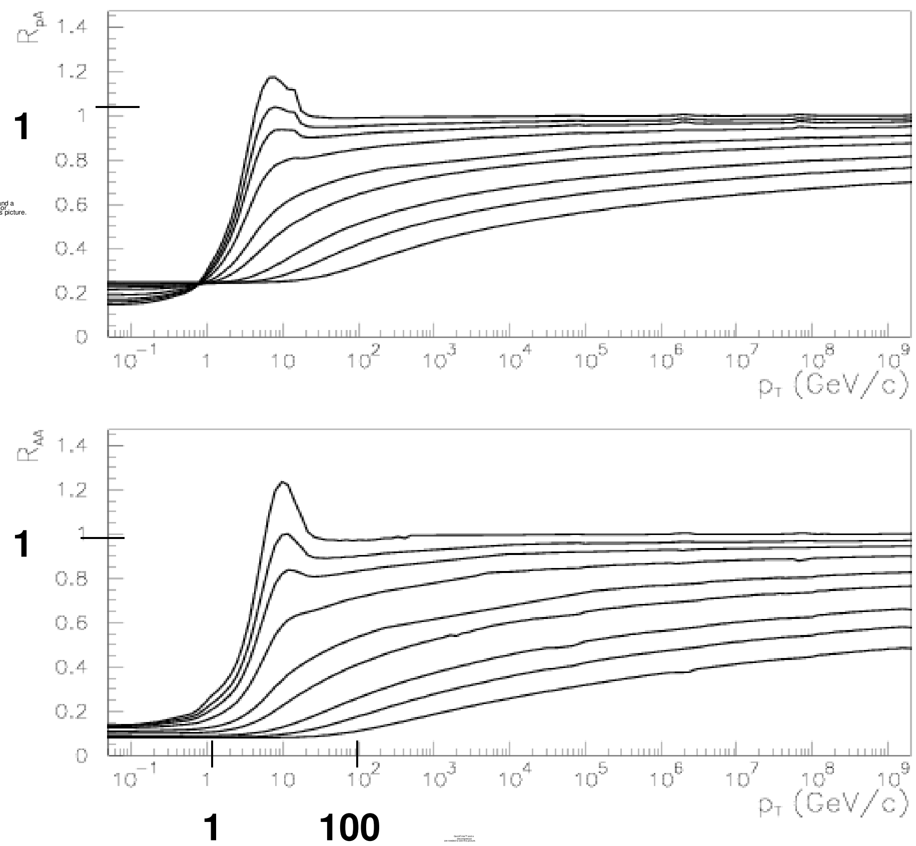
Single Particle Distributions in dA Collisions:

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

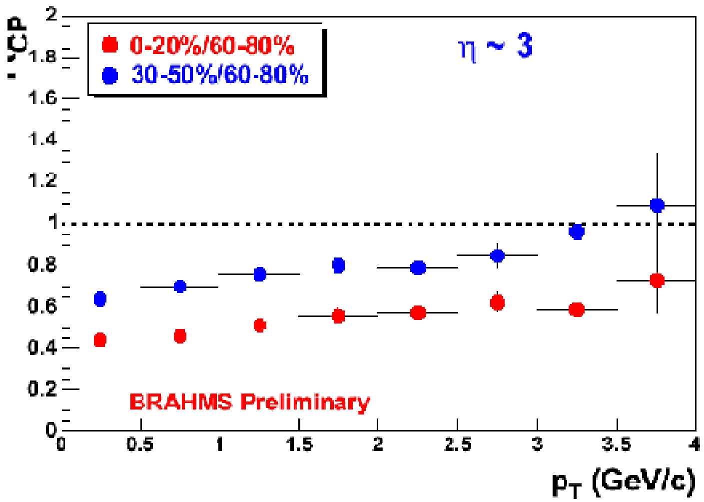
Lower Curves:

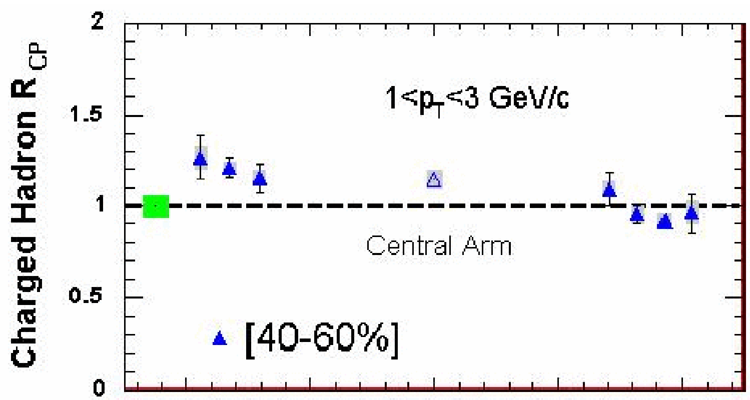
Same plot for initial state modifications for the ratio of gold-gold to pp

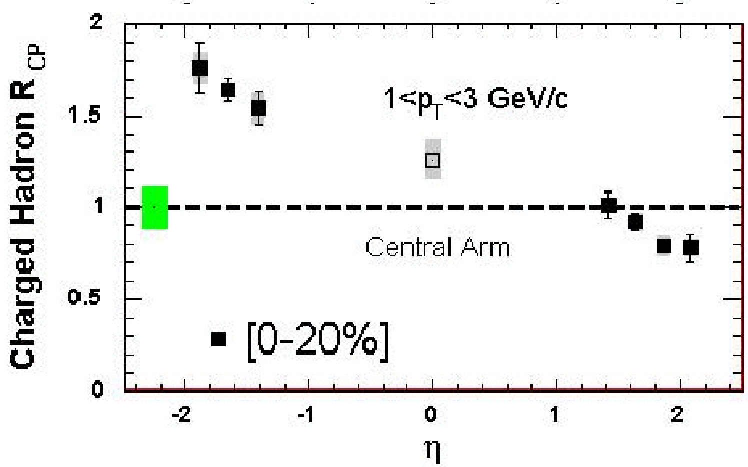
Albacete, Armesto, Kovner, Salgado, Wiedemann

Kovchegov, Jalilian Marian, Tuchin and Kharzeev

Single Particle Distributions in dA Collisions:







Only CGC correctly predicted suppression at forward rapidity and suppression with increasing centrality

Leading twist gluon shadowing does NOT describe the Brahms data!

Eskola, Paukunnen and Salgado, JHEP 0904:065,2009

Guzey, Strikman and Vogelsang, Phys.Lett.B603:173-183,2004

Non-leading twist at small x is saturation.

J/Psi Production in dA and AA

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

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

A simple explanation in terms of CGC

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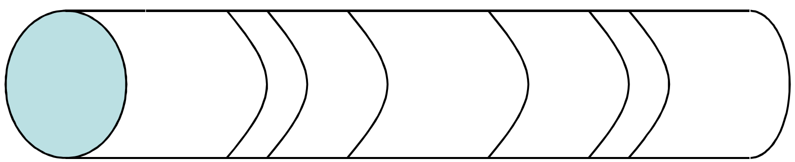
decompressor
are needed to see this picture.

Kharzeev and Tuchin

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



QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

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

QuickTime™ and a
decompressor
are needed to see this picture.

Impact parameter correlation give b = 0.16

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

QuickTime™ and a
decompressor
are needed to see this picture.

Long-range correlation from Glasma flux

Short-range from higher order corrections

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

Armesto, LM and Pajares
Nucl.Phys.A781:201-208,2007

Lappi and LM, arXiv:0909.0428

QuickTime™ and a
decompressor
are needed to see this picture.

Two Particle Correlations

The Ridge

QuickTime™ and a
decompressor
are needed to see this picture.

Decay of Lines of Flux:

Long range in rapidity

Narrow in angle due to flow

Beam jet fragmentation in perturbative QCD,

Glasma “flux tube”

Pomeron decays

Glasma description is inclusive

Hydro-studies

QuickTime™ and a decompressor are needed to see this picture.

Blastwave

QuickTime™ and a decompressor are needed to see this picture.

QuickTime™ and a decompressor are needed to see this picture.

Shuryak, Phys.Rev.C76:047901,2007

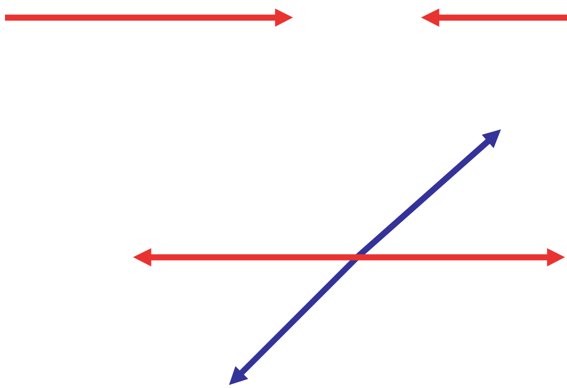
Takahasi, Tavares, Qian, Grassi, Hama, Kodama, Xu, arXiv:0902.4870

Dumitru, Gelis, Mclerran,and Venugopalan Nucl.Phys.A810:91,2008

Gavin, McLerran and Moschelli, Phys.Rev.C79:051902,2009

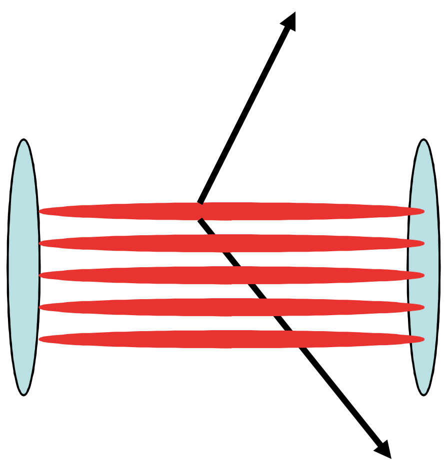
Jet quenching CAN NOT explain the long range rapidity correlation!

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

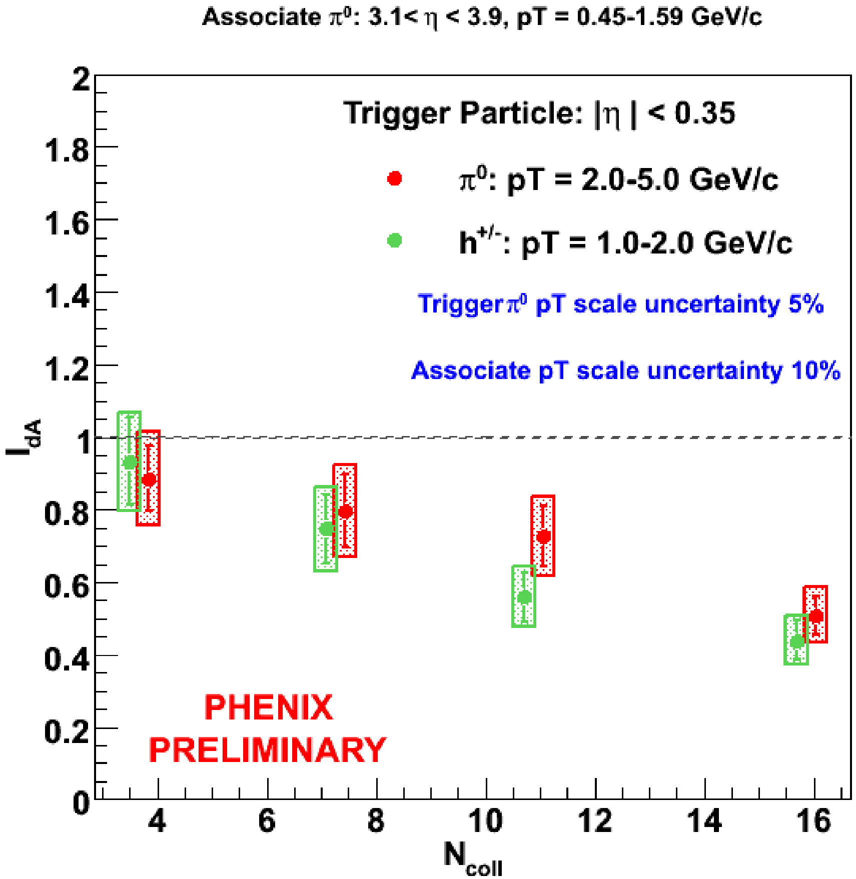
Two particle correlation is suppressed by

QuickTime™ and a decompressor are needed to see this picture.

relative to inclusive production.

Need a color correlation!

Two Particle Correlations



Evidence that the CGC is a media!

PHENIX data is well described by the saturation based computation of Qiu and Vitev

Kovchegov and Tuchin, Nucl.Phys.A708:413-434,2002

Kharzeev, Levin and LM, Nucl.Phys.A748:627-640,2005

Qiu and Vitev, Phys.Lett.B632:507-511,2006

Marquet (in preparation)

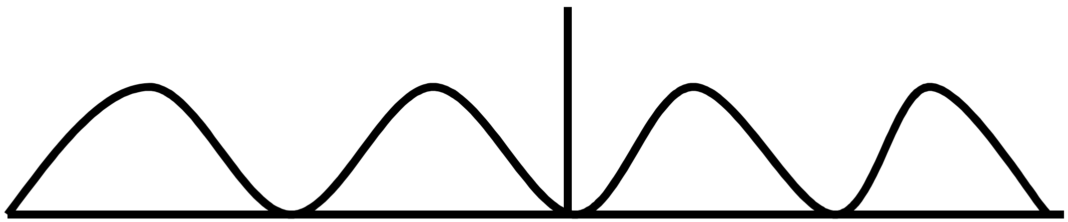
"Jet Quenching" in dA Collisions:

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

STAR and PHENIX

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

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



QuickTime™ and a
decompressor
are needed to see this picture.

Changes in topological charge change helicity of quarks

In Glasma, net Chern-Simons is zero initially but can be generated by time evolution

Such fluctuation may be source of nucleon mass

Analogous processes in electroweak theory may be responsible for baryon asymmetry

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

Can we see topological charge changing transitions in heavy ion collisions?

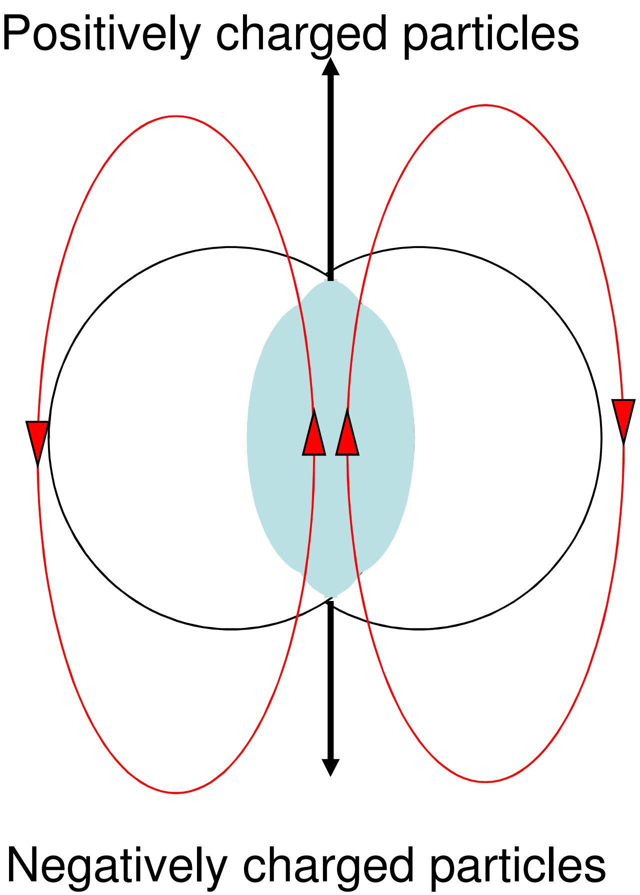
Strong sphaleron flips helicity at high temperature. Can generate net topological charge =>

Net vorticity and helicity of the fluid => correlation between spin and momentum

Strong QED magnetic field can polarize quark spins, and therefore generate net flow of the fluid, because spin is correlated with momenta.

Strong QED magnetic field perpendicular to reaction plane caused by net charge of nuclei as they collide generating net flow

Event by event CP violation



Kharzeev, Pisarski and Tytgat, Phys.Rev.Lett.81:512-515,1998

Kharzeev, LM and Warringa, Nucl.Phys.A803:227-253,2008Fukushima, Kharzeev and Warringa, Phys.Rev.D78:074033,2008

Conclusion:

Large number of tests of saturation hypothesis:
Experimental results 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.