Saturation: The Color Glass Condensate,Glasma and RHIC

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

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

L. McLerran and R. Venugopalan, Phys. Rev. D49, 2233 (1994); 3352 (1994)

Total of 4222 citations

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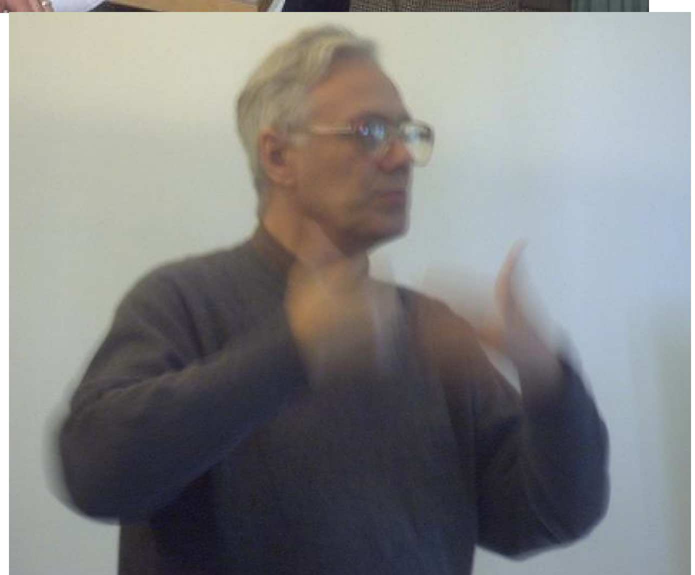

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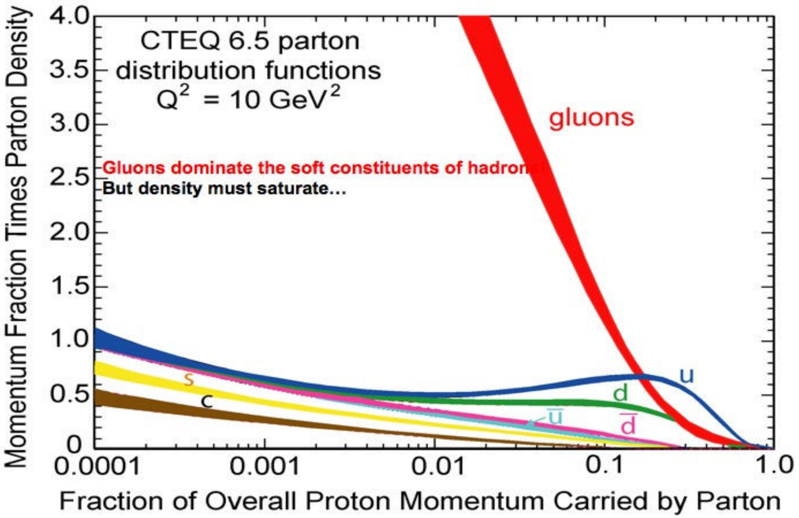
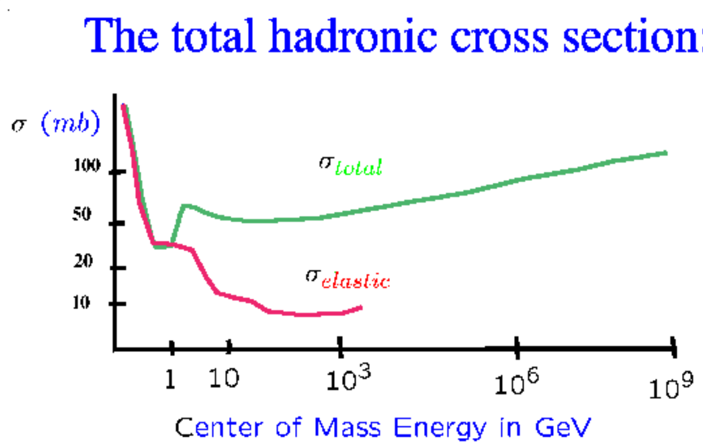
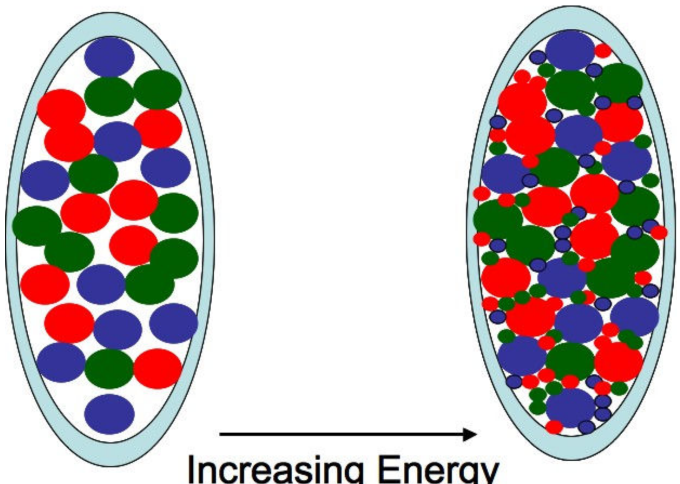
GLR and MQ argue that as one evolves in x, the density of gluons becomes large:





MV: Gluons are described by a stochastic ensemble of classical fields, and JKMW 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

A. Mueller,Nucl.Phys.B335:115,1990

Jalilian-Marian, Kovner, LM and Weigert ,PR D55, 5414 (1997)

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

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BK = JIWMLK for correlators

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V. Gribov, Sov.Phys.JETP 30:709-717,1970, Zh.Eksp.Teor.Fiz.57:1306-1323,1969;

Jalilian-Marian, Kovner, Leonidov and Weigert, Nucl.Phys.B504:415-431,1997;

E. Iancu, A. Leonidov and LM; Nucl.Phys.A692:583-645,2001;

E. Ferreiro, E. Iancu, A. Leonidov and LM, Nucl.Phys.A703:489-538,2002;

Y. Kovchegov, Phys.Rev.D60:034008,1999. Phys.Rev.D61:074018,2000

I. Balitsky

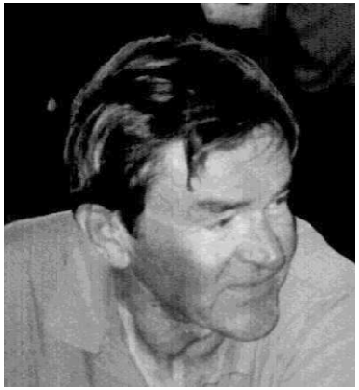
Nucl.Phys.B463:99-160,1996

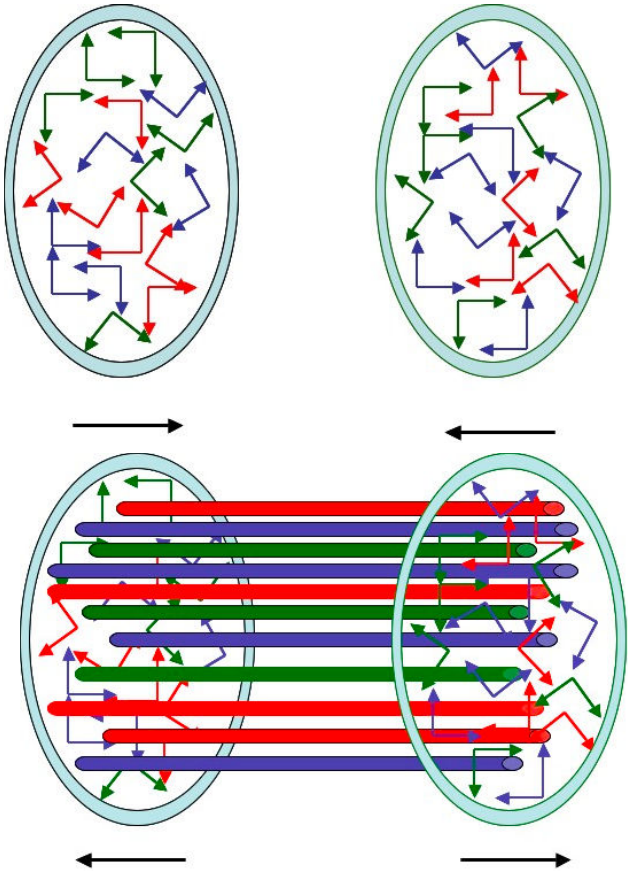
CGC Gives Initial Conditions for QGP in Heavy Ion Collisions

Bjorken

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

1664 Cites





Blaizot and AM, Nucl.Phys.B289:847,1987.

Jalilian-Marian, Kovner and LM, Phys.Rev.D52:6231-6237,1995;Phys.Rev.D55:5414-5428,1997.

Krasnitz and Venugopalan, Phys.Rev.Lett.84:4309-4312,2000.

T. Lappi Phys.Rev.C67:054903,2003

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

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Theoretical Status:

First principles formalism that follows directly from QCD

and is rigorous in the high density limit,

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Factorization theorem as in perturbative QCD.

Includes in various limits:

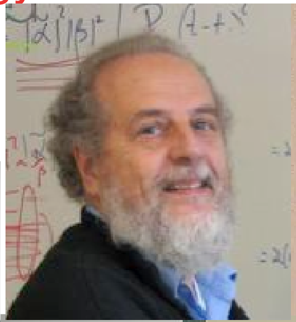
Perturbative QCD

BFKL Pomeron

Odderon and Reggeons

As yet incomplete treatment of Pomeron Loops

At what energy does the description become valid?

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Gelis, Lappi and RV, Phys.Rev.D78:054019,2008.

Kovner and Lublinsky, Phys.Rev.D71:085004,2005, Phys.Rev.Lett.94:181603,2005.

Hatta, Iancu, Itakura and LM, Nucl.Phys.A760:172-207,2005.

Hatta, Iancu, McLerran and Stasto, Nucl.Phys.A764:423-459,2006

Brodsky, Frankfurt, Gunion, Mueller and Strkman,

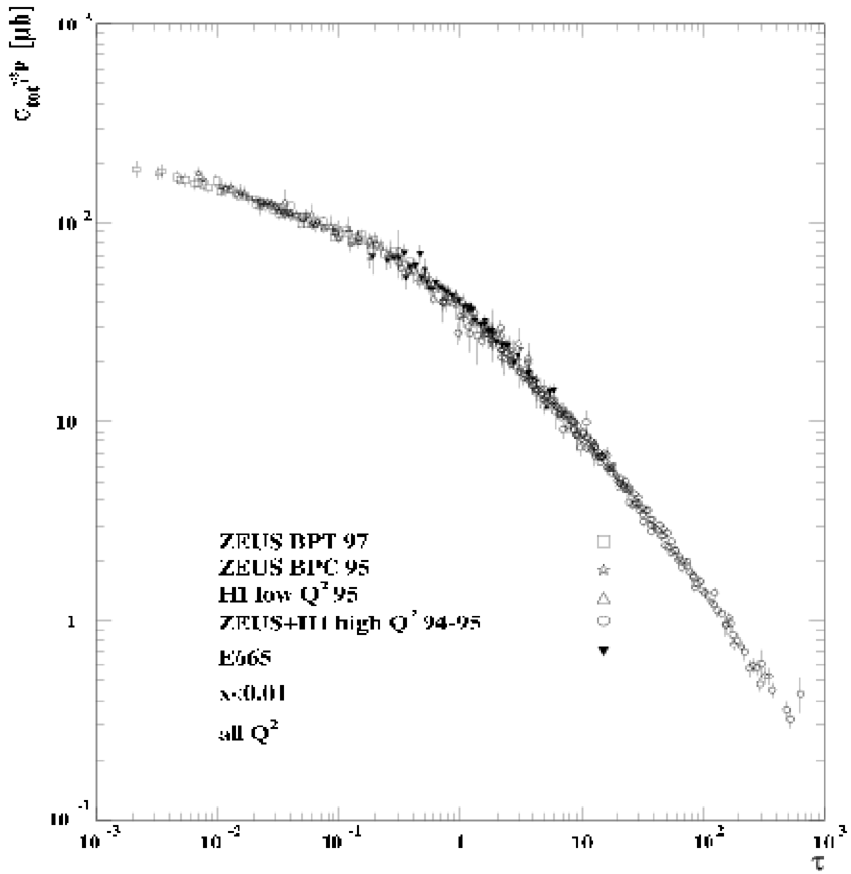
Phys.Rev.D50:3134-3144,1994

Kuraev, Lipatov and Fadin,Sov.Phys.JETP 45:199-204,1977, Zh.Eksp.Teor.Fiz.72:377-389,1977

Balitsky and Lipatov, Sov.J.Nucl.Phys.28:822-829,1978, Yad.Fiz.28:1597-1611,1978

J. Bartels, Nucl.Phys.B151:293,1979; Nucl.Phys.B175:365,1980

S. Munier and R. Peschanski, Phys.Rev.Lett.91:232001,2003



Experimental Evidence: ep Collisions

$$\sigma_{\gamma^* p} \sim F(Q^2/Q^2_{sat}(x))$$
$$x < 10^{-2}$$

A. Mueller, Nucl.Phys.B415:373-385,1994

Stasto, Golec-Biernat, Kwiecinski, Phys.Rev.Lett.86:596-599,2001.

Iancu, Itakura and LM, Nucl.Phys.A708:327-352,2002

Computed saturation momentum dependence on x agrees with data

Mueller and Triantafylloupoulos, Nucl.Phys.B640:331-350,2002

Provides good description of deep inelastic data

Albacete, Armesto, Milhano and Salgado, Phys.Rev.D80:034031,200

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

Describes diffractive structure functions

Golec-Biernat and Wustoff, Phys.Rev.D59:014017,1999, Phys.Rev.D60:114023,1999.

Kowalski and Teaney, Phys.Rev.D68:114005,2003

Experimental Evidence: ep Collisions

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decompressor
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But there exist other non-saturation interpretations.

Are there really zero or even a negative number of “valence gluons” in the proton for small x?

F2 yes, FL no

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Saturation and Nuclei:

Increasing A corresponds to decreasing x, or increasing energy

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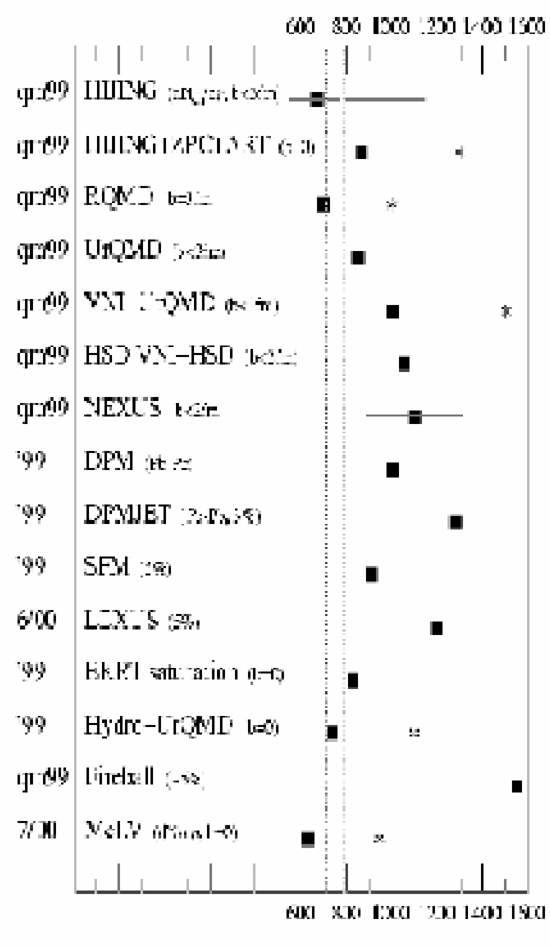
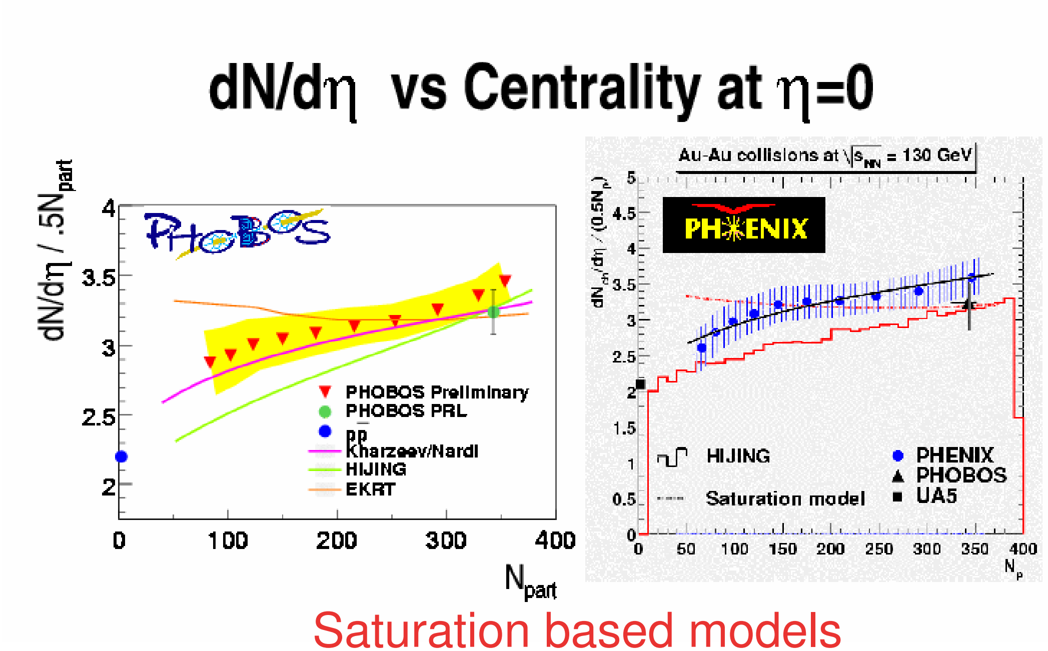
Early results on multiplicity:





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

Kovchegov and Mueller, Nucl.Phys.B529:451-479,1998

Krasnitz and Venugopalan, Phys.Rev.Lett.84:4309-4312,2000.

Kharzeev and Nardi, Phys.Lett.B507:121-128,2001

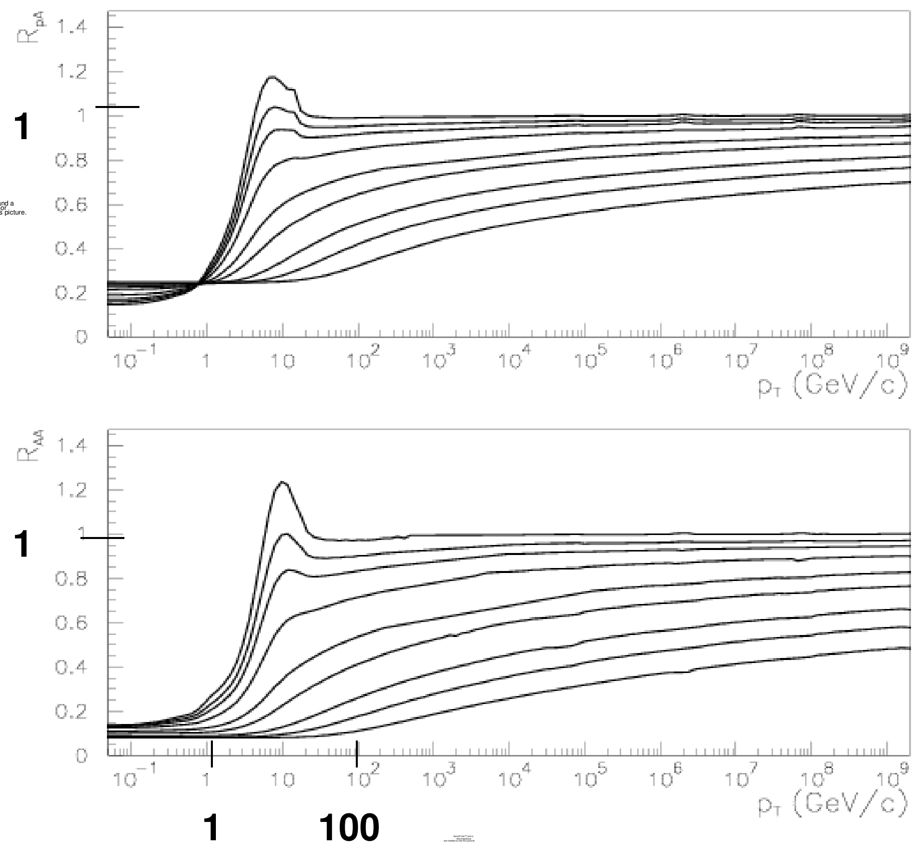
Single Particle Distributions in dA Collisions:

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:

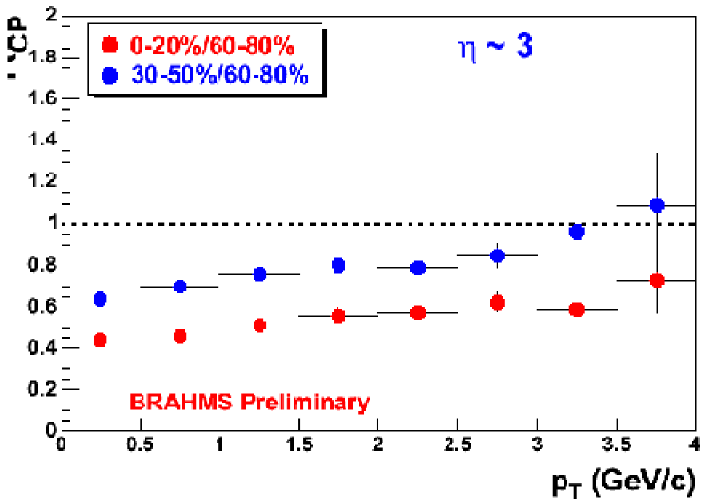
Ratio of deuteron gold to pp distribution as function of transverse momentum for various x values

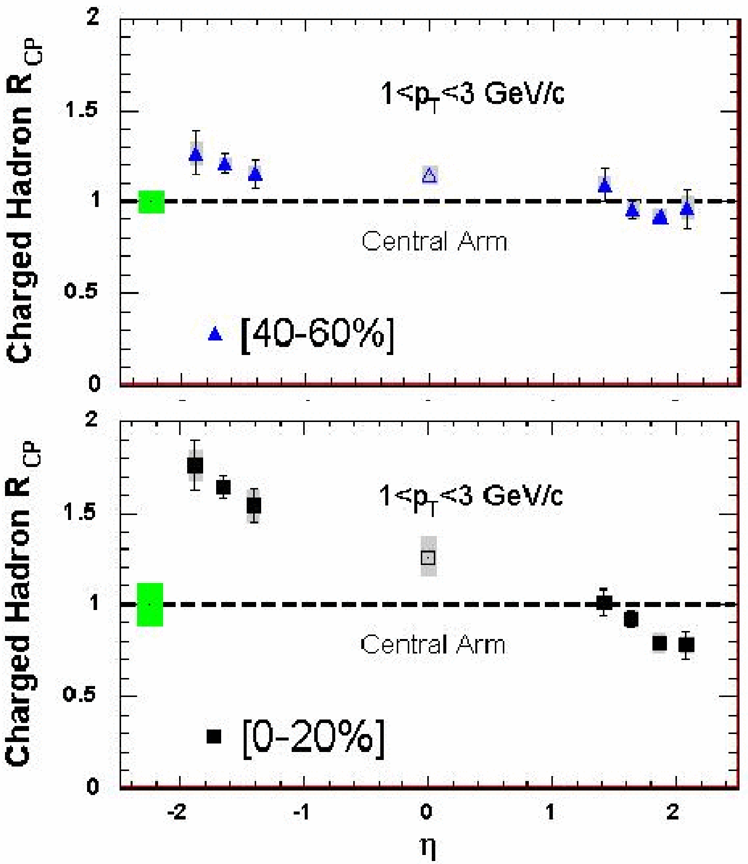
Lower Curves:

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

Albacete, Armesto, Kovner, Salgado, Wiedemann; Phys.Rev.D68:054009,2003,Phys.Rev.Lett.92:082001,2004

Kovchegov, Jalilian Marian, Tuchin and Kharzeev,Phys.Rev.D68:094013,2003Phys.Lett.B599:23-31,2004





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.

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J/Psi Production in dA

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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

Looks like limiting fragmentation, not

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scaling. Limiting fragmentation For the deuteron is natural in CGC if saturation momentum exceeds charm quark mass, but hard for shadowing description.

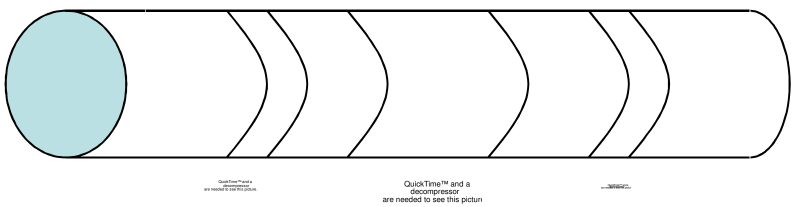
Kharzeev and Tuchin,
Phys.Rev.Lett.102:152301,2009,
Nucl.Phys.A826:230-255,2009

Gelis,Stasto and Venugopalan,
Eur.Phys.J.C48:489-500,2006

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



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

Correlation is stronger for more central collisions and higher energy

Impact parameter correlation give
b = 0.16

Most central highest energy correlation strength exceeds upper bound of 0.5 (y > 1) from general considerations

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Long-range correlation from Glasma flux

Short-range from higher order corrections

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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

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The Ridge

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Decay of Lines of Flux:

Long range in rapidity

Narrow in angle due to flow

Blastwave

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Beam jet fragmentation in perturbative QCD,

Glasma “flux tube”

Pomeron decays

Glasma description is inclusive

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Hydro-studies

Jet quenching cannot explain the long range rapidity correlation!

Voloshin, Phys. Lett. B632, 490 2006

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

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“Jet Quenching” in dA Collisions:

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

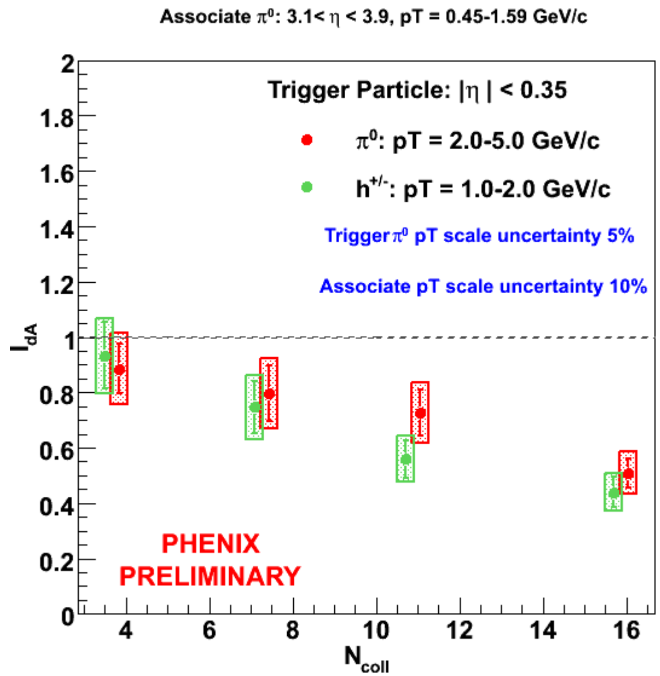
Conclusive evidence that the CGC is a medium!

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

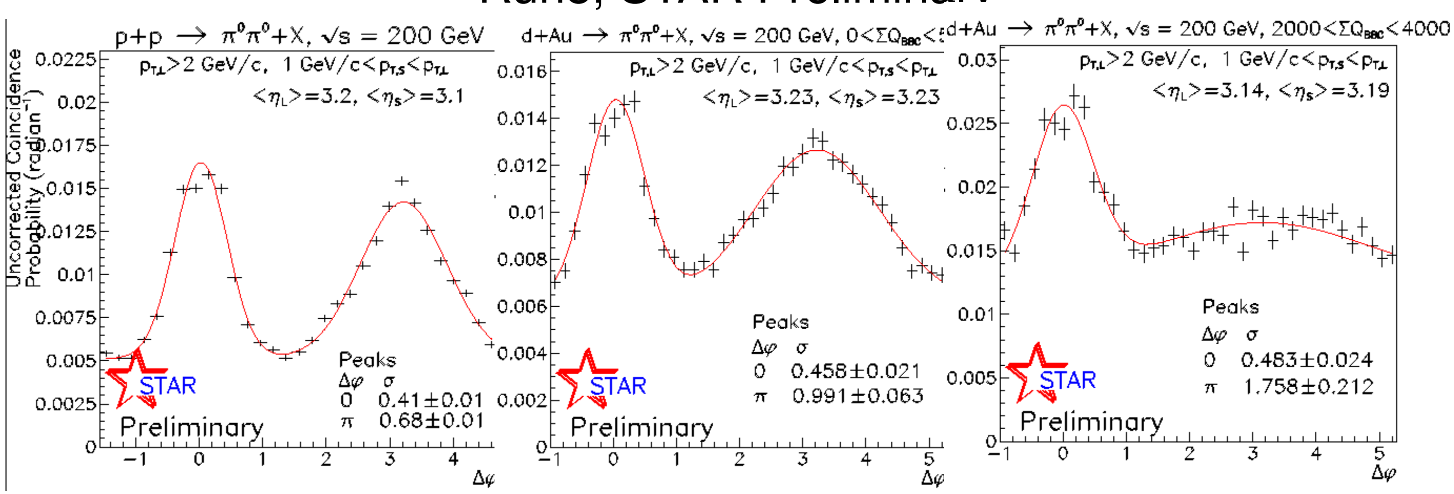
Kharzeev, Levin and LM, Nucl.Phys.A748:627-640,2005

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

Marquet (in preparation)



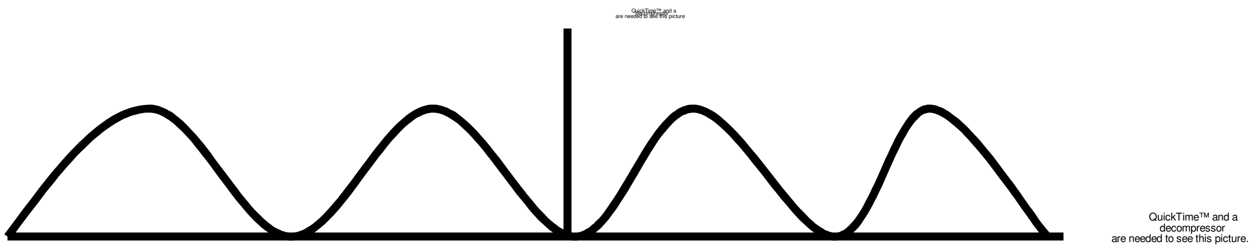
200 GeV ***p+p*** and ***d + Au*** Collisions
Run8, STAR Preliminary



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

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

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



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

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.

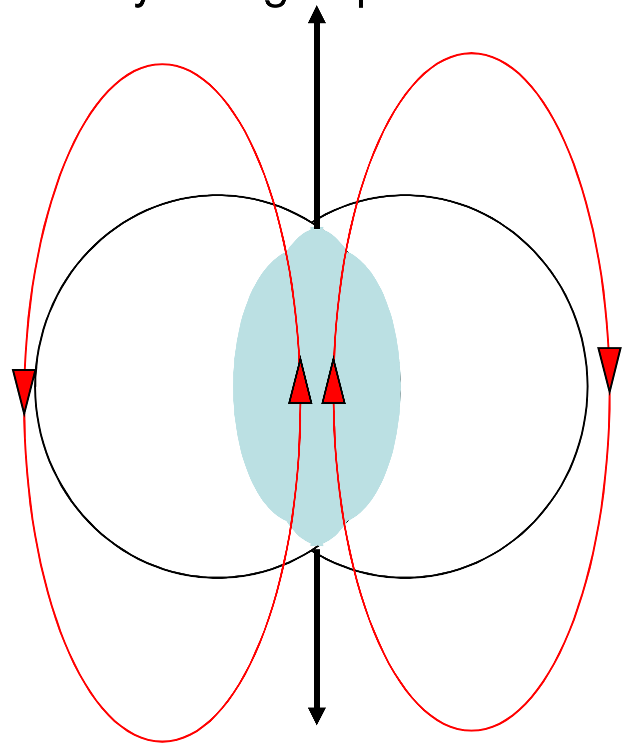
Strong QED magnetic field perpendicular to reaction plane caused by net charge of nuclei as they collide generating net flow

Event by event CP violation: STAR

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

Positively charged particles



Negatively charged particles

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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.

Question:

Is it “strongly” or weakly coupled?

The accumulated data from RHIC is compelling.

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