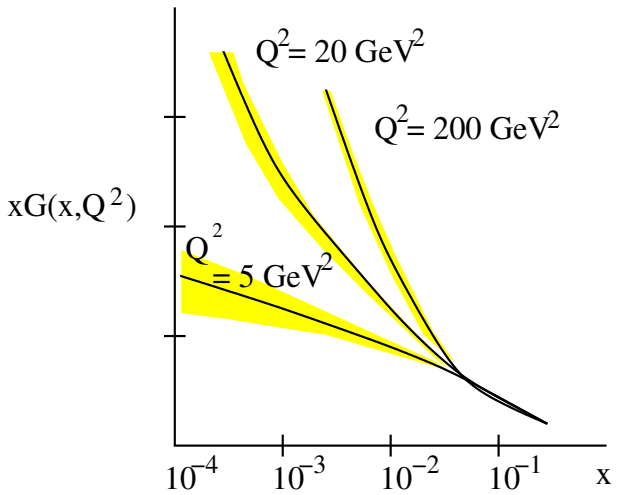
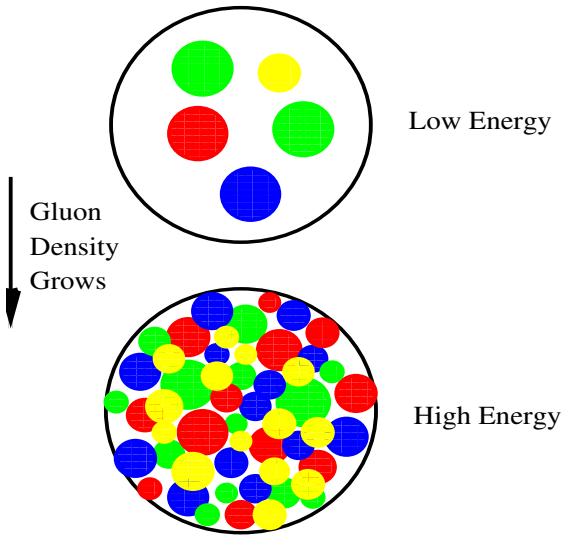
# What is the Evidence for the Color Glass Condensate?

## Motivation:




G,L,R
M,Q
M,V
BFKL

HERA




I,L,M

Density high $\rightarrow$
Separation small $\rightarrow$
$\alpha_S << 1$

# What is Color Glass Condensate?

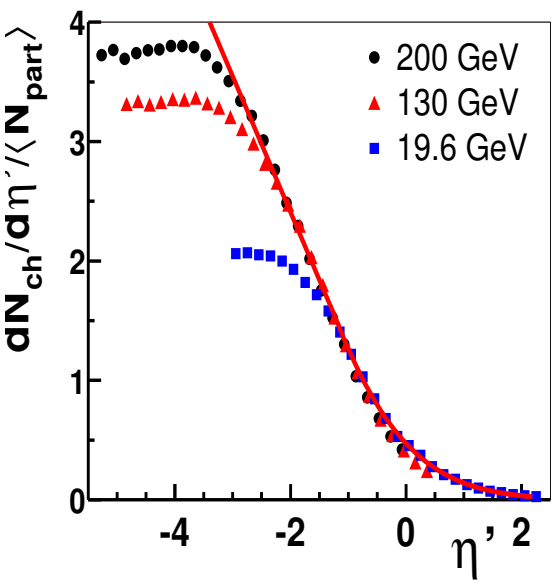
Glue at large x generates
glue at small x

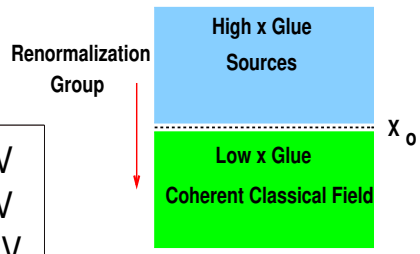
Glue at small x is classical field
Time dilation $\rightarrow$ glassy
High phase space density $\rightarrow$ condensate

Phase space density $\rho$
Negative mass term $\sim -\rho$
Repulsive interactions $\sim \alpha_S \rho^2$

$$\rho = \frac{1}{\pi R^2}\frac{dN}{dyd^2p_T} \sim \frac{1}{\alpha_S}$$

Separation of longitudinal scales
Renormalization Group
Limiting Fragmentation




Total multiplicity is
$\sim N_Q + N_{\overline{Q}} + N_G$
for projectile evaluated at
$Q^2 \sim Q^2_{sat}(x_{target})$

Jalilian-Marian

# Theory (Not Model) of CGC

Mathematically similar to a spin glass

$$Z = \int_{X_0} [dA][d\rho]\ exp\left(iS[A,\rho] - \chi[\rho]\right)$$

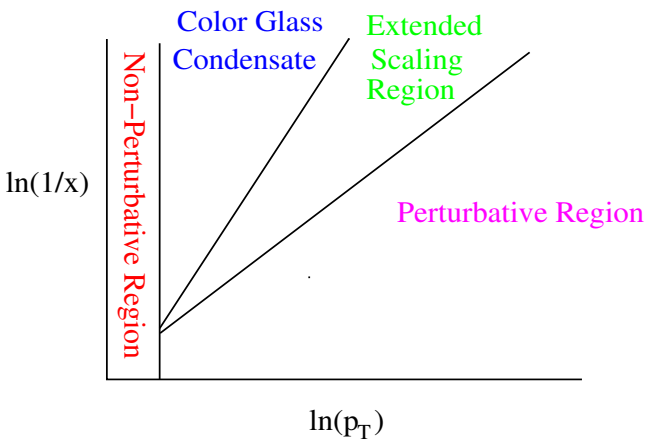
$\rho$ is the source
$X_0$ is the cutoff in x
$\chi[\rho]$ is the weight function
for the fields

M,V; K;B
JIMWLK; F;

$\chi[\rho]$ satisfies RG equation
derived from QCD

JIMWLK equation
Equaivalent in limits to
DGLAP, BFKL and BK equations

$\chi[\rho]$ quadratic is MV model



# Why CGC is Important:

It is a new universal type of matter.

Matter:
Separation of gluons is
small compared to size.

New:
Can only be probed
at high energy and it is produced
in heavy ion collisions.

Universal:
Independent of hadron
Fundamental
(Universality also applies in scaling region)

It is a theory of:

The origin of glue and sea quarks
in hadrons.

The origin and nature of cross
sections and particle production

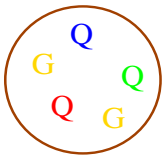
The distribution of valence quantum
numbers at small x

Provides initial conditions for
the QGP as produced in heavy ion collisions.

# Infinite Momentum Frame:

In rest frame

Valence quarks and occasional glue and sea quarks




Nucleon is made of
states with 3 quarks
3 quarks with one gluon
3 quarks with two gluons
.....
3 quarks with 1000 gluons
.....

In infinite momentum frame

Wall of lots and lots of glue at near light speed



At low energy:
3 quarks and few gluons

At high energy:
Lots of gluons

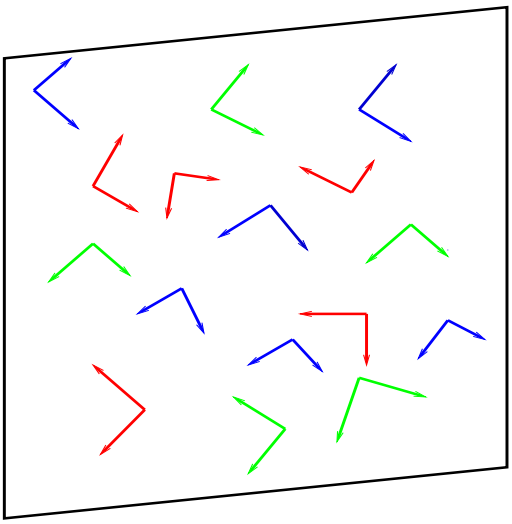
Description is frame independent:

Mueller-Kovchegov Duality:
Infinite momentum frame multigluon states are important.

Target rest frames:
Coherent multiple scattering.

Dipole Model Included in CGC Framework
Iancu-Mueller

# What does the gluon wall look like?



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

Independent of $x^+ = t + z$

$F^{i+} \sim \partial/\partial x^- A^i$ is big.

$F^{i-}$ and $F^{ij}$ are small

$F^{i\pm} \sim E^i \pm \epsilon^{ij} B^j$

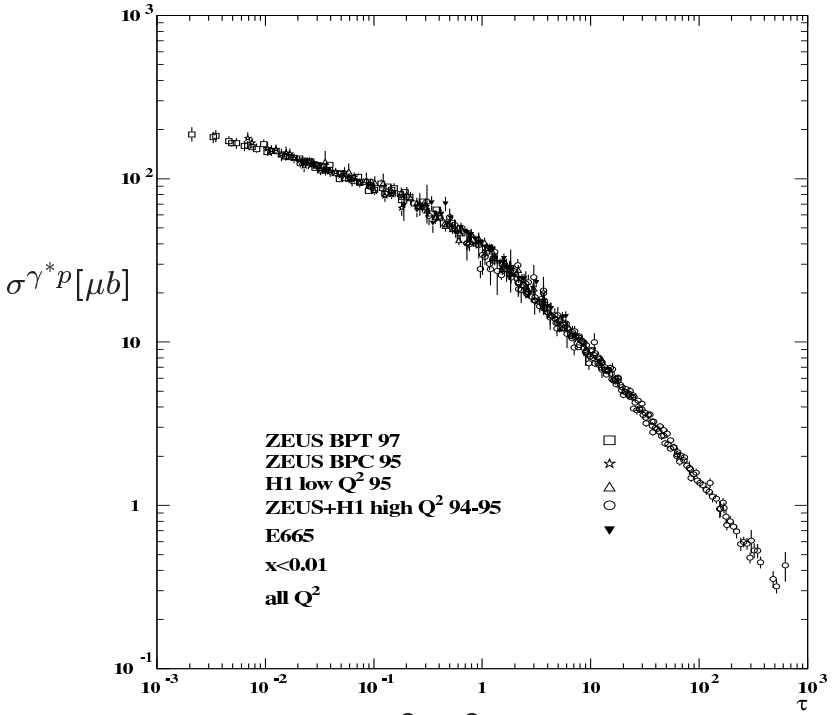
$\vec{E} \perp \vec{B} \perp \vec{z}$

Fields random in color

The density of gluons per unit area:

$$\frac{1}{\pi R^2}\frac{dN}{dy} \sim \frac{1}{\alpha_S} Q_{sat}^2(x)$$

# Experimental Evidence: HERA




$\sigma \sim F(Q^2/Q^2_{sat}(x))$

$Q^2_{sat}(x)$ dependence on x computed by Mueller and Triantafyllopoulos

First observed by G-B,K,S. Geometric scaling shown to be property of CGC by IIM

For $Q^2 << Q^2_{sat}$ trivial

Works til $Q^2 \sim Q^4_{sat}/\Lambda^2$

Needs $x \leq 10^{-2}$

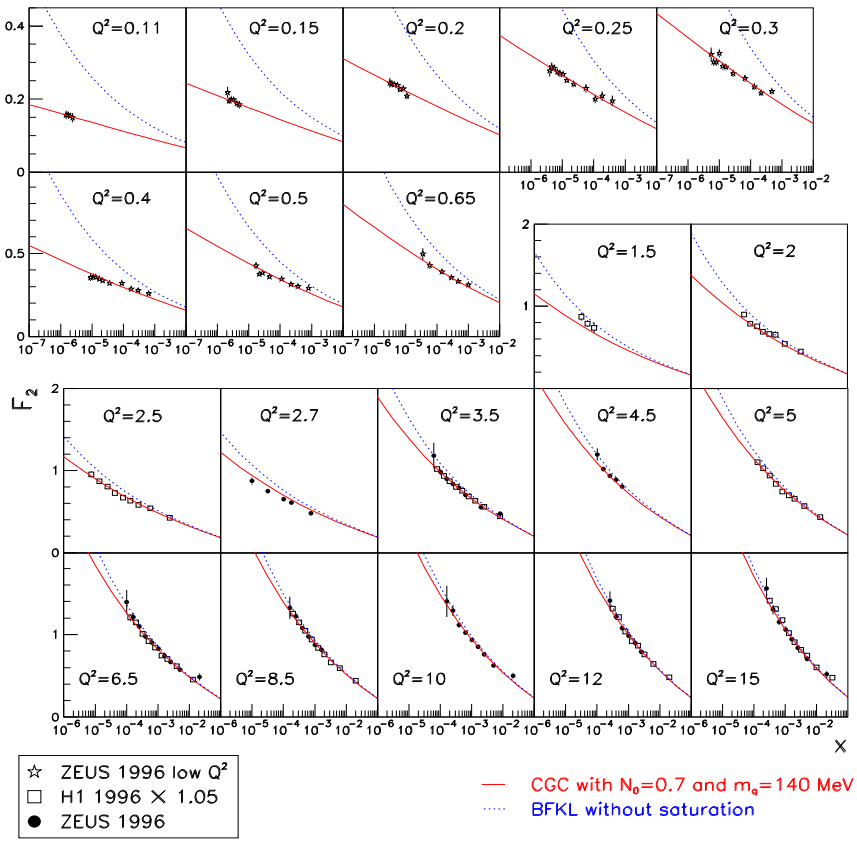
# Experimental Evidence:

$F_2$ for $x < 10^{-2}$ and $Q^2 < 50\ GeV^2$

Must include computable deviations from geometric scaling

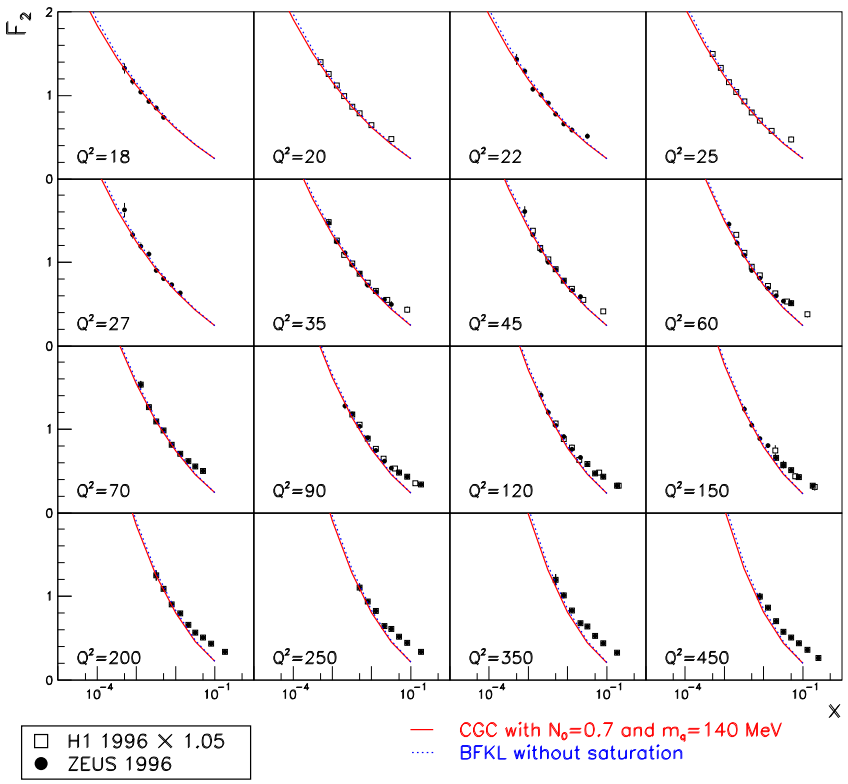
3 parameters: $R, x_0, \lambda$

$$N(x, r_T) = N_0 (r_T^2 Q_{sat}^2)^{\gamma} exp\left\{ -\frac{1}{2\kappa\lambda ln(1/x)} ln^2(1/r_T^2 Q_{sat}^2) \right\}$$



# Experimental Evidence:

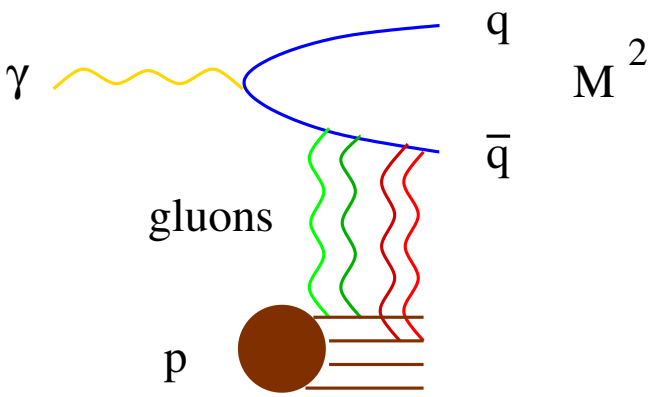
$F_2$ for $x < 10^{-2}$ and $Q^2 < 50 GeV^2$

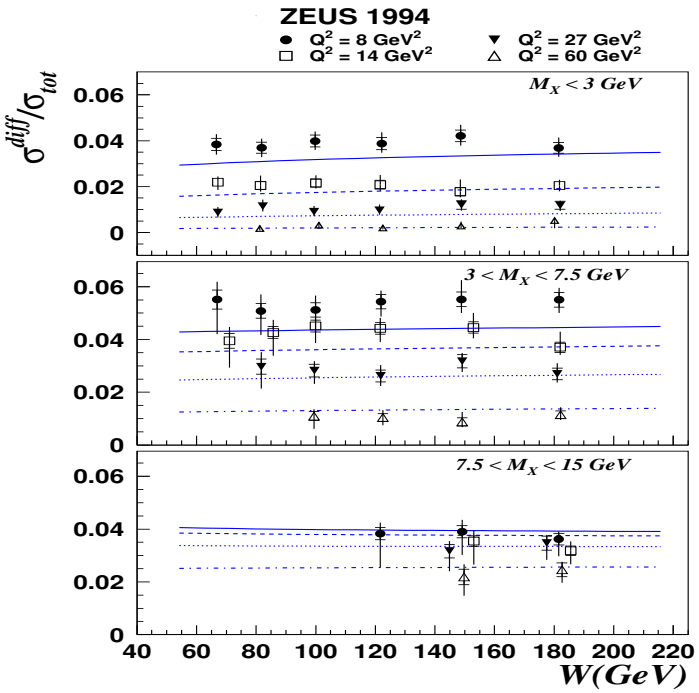



Early work by Golec-Biernat, Wustoff, Stasto Kwiecinski,Kowalski, Bartels, Teaney.
Work above by Iancu, Itakura and Munier

# Experimental Evidence:

## Diffraction and Quasi-Elastic

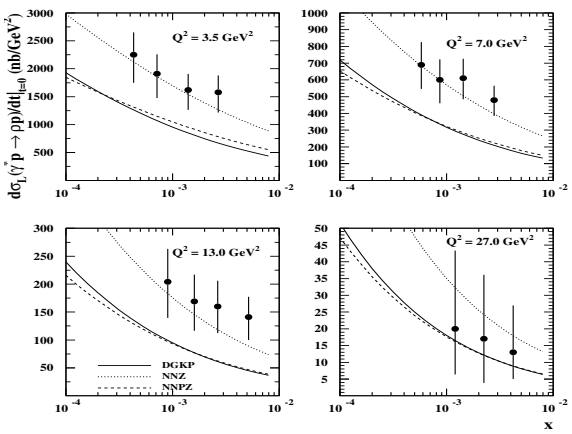



G-B, W; M,H; K,M; G-B,B; K,T;

# Experimental Evidence:

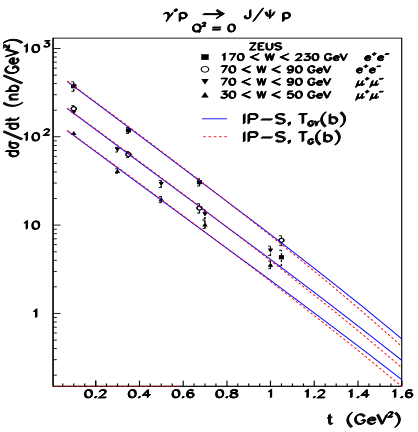
## Diffraction and Quasi-Elastic

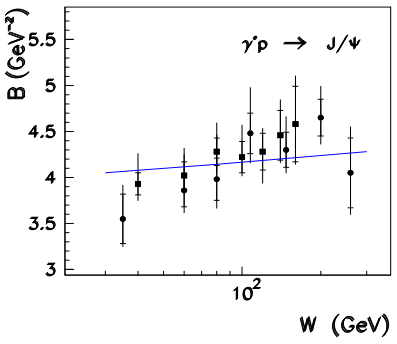



$\gamma^* p \to \rho p$

Some sensitivity to
$\rho$ wavefunction

Mueller, Munier and Stasto



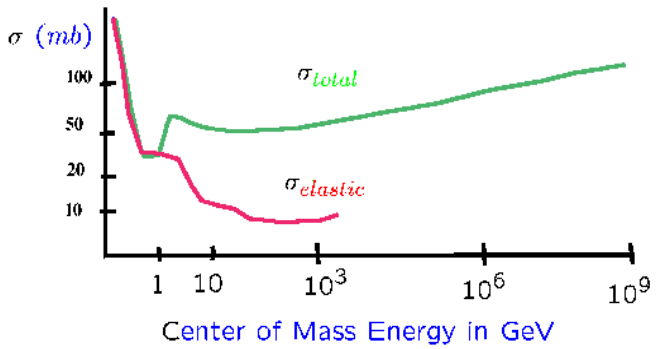




$\gamma^* p \to J/\Psi p$; Teaney and Kowalski

# Experimental Evidence:

## Qualitative Understanding of Hadronic $\sigma^{tot}$

**The total hadronic cross section:**




F,I,I,M
K,W

Nucleon becomes dark at some impact parameter b when the probability to scatter is of order one

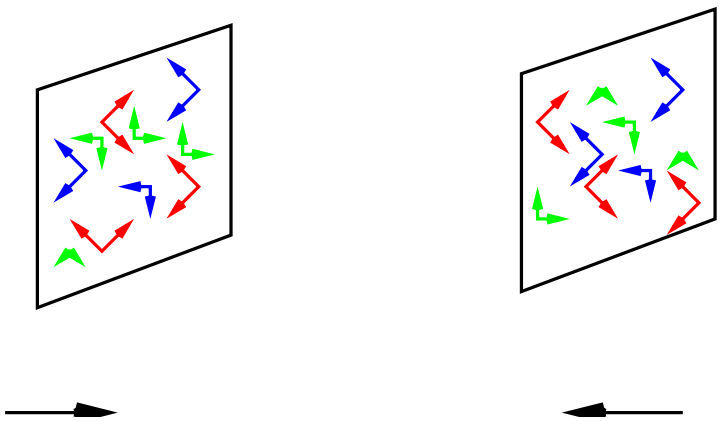
The number of gluons increases as
$(x_0/x_{min})^{\lambda}$
$x_{min} \sim \Lambda_{QCD}/E$

The impact parameter distribution is
$exp(-2m_{\pi}b)$.

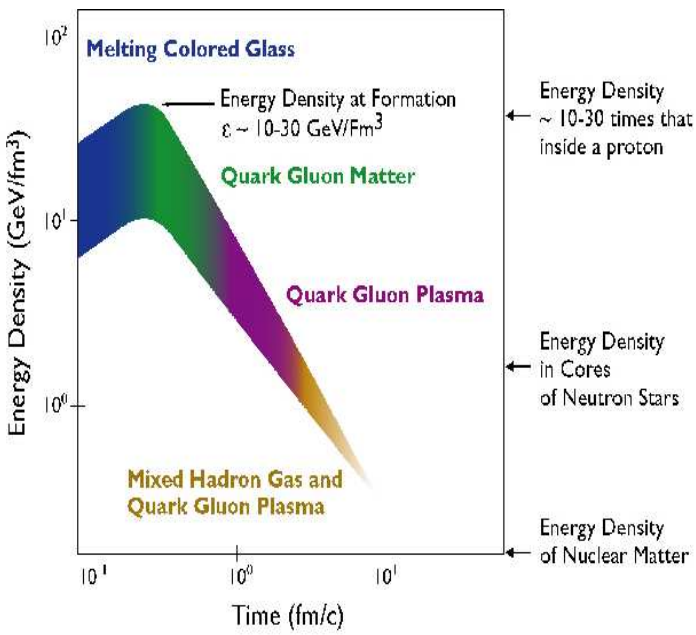
$(x_0/x_{min})^{\lambda} exp(-2m_{\pi}b) \sim 1$
or
$\sigma \sim b^2 \sim ln^2(1/x_{min}) \sim ln^2(E)$

Froissart Bound Saturation

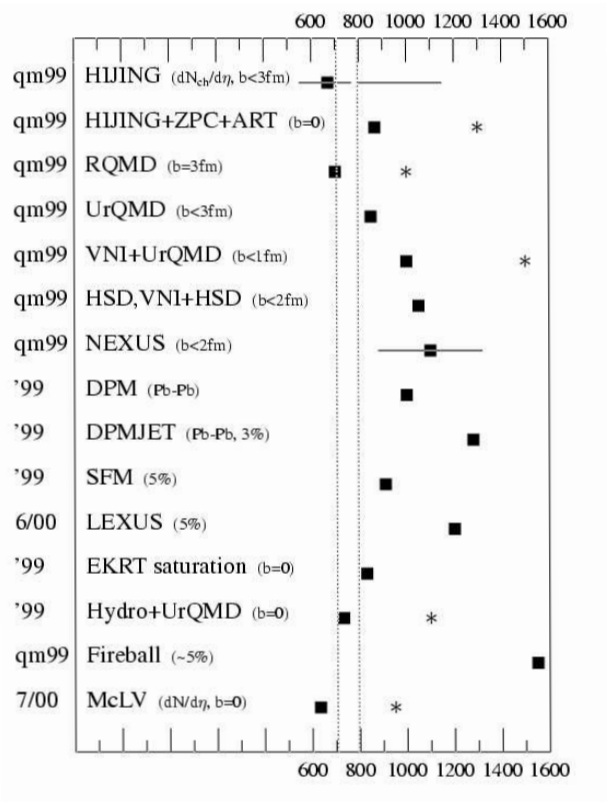
# Heavy Ion Collisions



M,K,W; G, M; Krasnitz, Nara, Venugopalan



# Evidence from Heavy Ions:




Krasnitz and Venugopalan

CGC is only theory which allows consistent computation of multiplicity

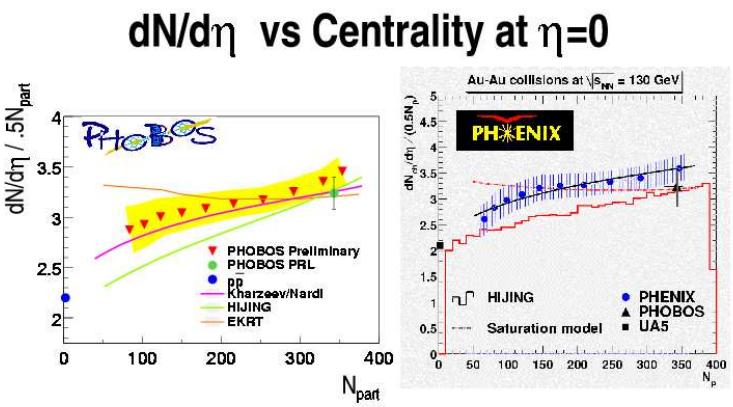
$$\frac{1}{\pi R^2}\frac{dN}{dyd^2p_T} \sim \frac{1}{\alpha_S}\frac{Q_{sat}^4}{p_T^4}$$

for $p_T >> Q_{sat}$

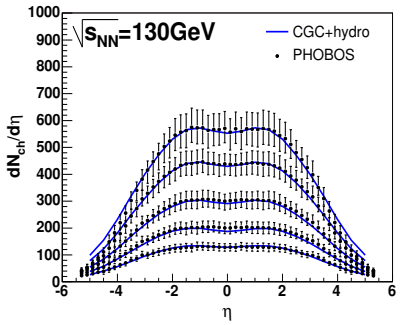
For $p_T \leq Q_{sat}$, the distribution softens and becomes integrable:

$$\frac{dN}{dy} \sim \frac{1}{\alpha_S}Q_{sat}^2$$

# Global Features of Heavy Ion Collisions

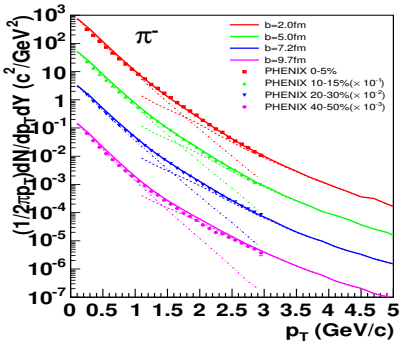



Kharzeev and Nardi



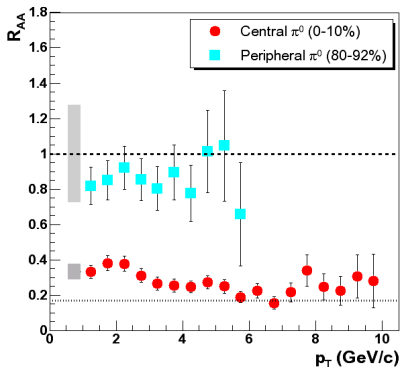

$$\frac{1}{N_{part}}\frac{dN}{dy} \sim \frac{1}{\alpha_S}$$

CGC initial conditions ala Kharzeev, Levin and Nardi lead to good rapidity and $p_T$ distributions
Nara and Hirano




Not so much processing of $dN/dy$

# AA and dA Collisions: Probing the Nuclear Wavefunction

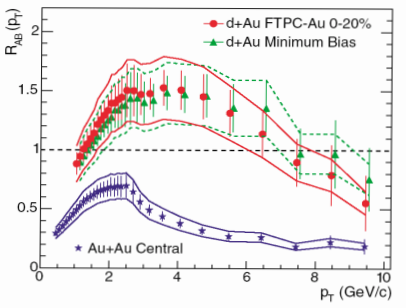


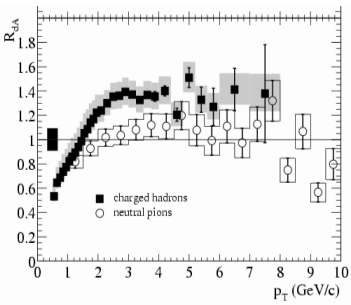

Heavy Ion Experiments at central rapidities give evidence of strong suppression relative to incoherent scattering

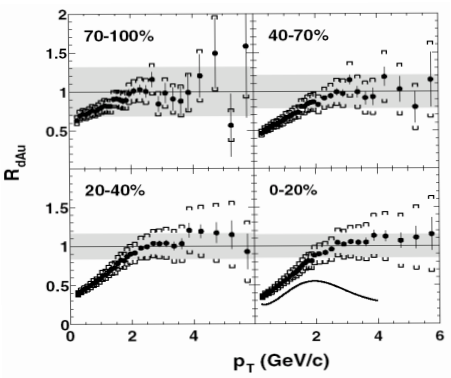
Is it an initial state effect (CGC) or final state (QGP)

Gluons and quarks come from $x \sim 10^{-1}$ Not small x

Some features of data look like geometrical scaling: K,L, M




Conclusively established: Jet quenching at central rapidity is largely a final state effect (QGP).

# dA Collisions and Shadowing:

What about the rapidity dependence of $R_{dA}$?

Cronin enhancement at nuclear rapidity

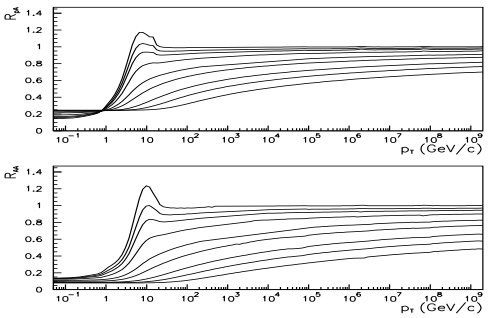
Small effect at zero rapidity

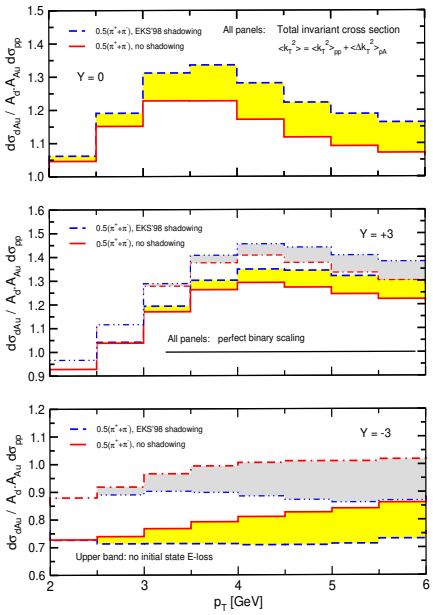
Forward rapidity? $x \sim 10^{-3}$.

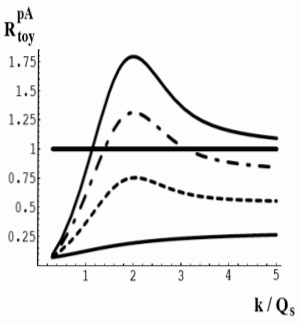
Quantum evolution plus classical rescattering for CGC give suppression

Centrality and rapidity dependence different

Very rapid evolution in Color Glass Condensate




K,K

A,A,K,S,W

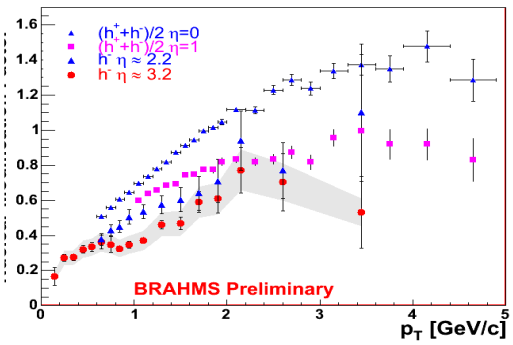
Classical multiple scattering gives Cronin enhancement

More matter at small x bigger Cronin enhancement

G,V,W

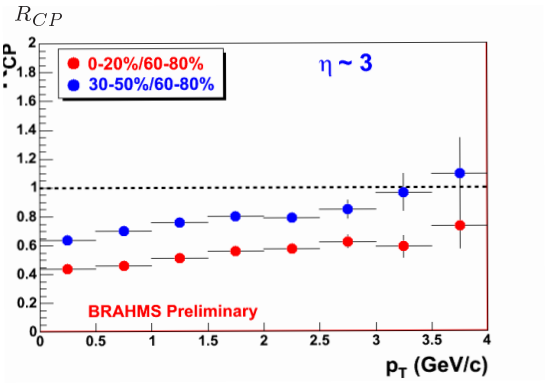
# dA Collisions: Data

$R_{CP}$

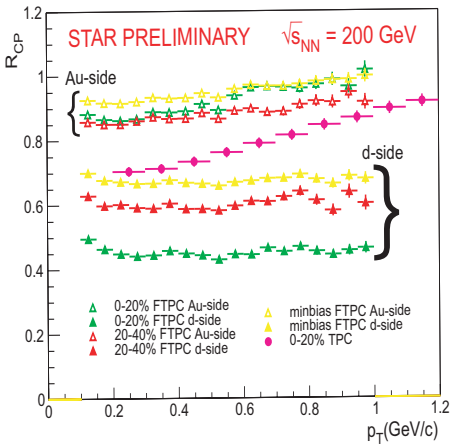



Brahms shows Cronin enhancement turn into suppression in deuteron fragmentation region

$R_{CP}$




Brahms shows suppression increase as function of centrality




At lower $p_T$ star shows suppression increase as one goes to fragementation region of deuteron