The Color Glass Condensate and the Glasma

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What is the high energy limit of strong interactions?

How do we compute the gluon and quark distributions relevant for asymptotically high energy interactions?

What are the possible states of high energy density matter?

Is there a simple unified description of lepton-hadron and hadron-hadron interactions?

Where?

Deep inelastic scattering and diffraction at $x < 10^{-2}$

Heavy ion collisions and dA collisions at RHIC energies and above

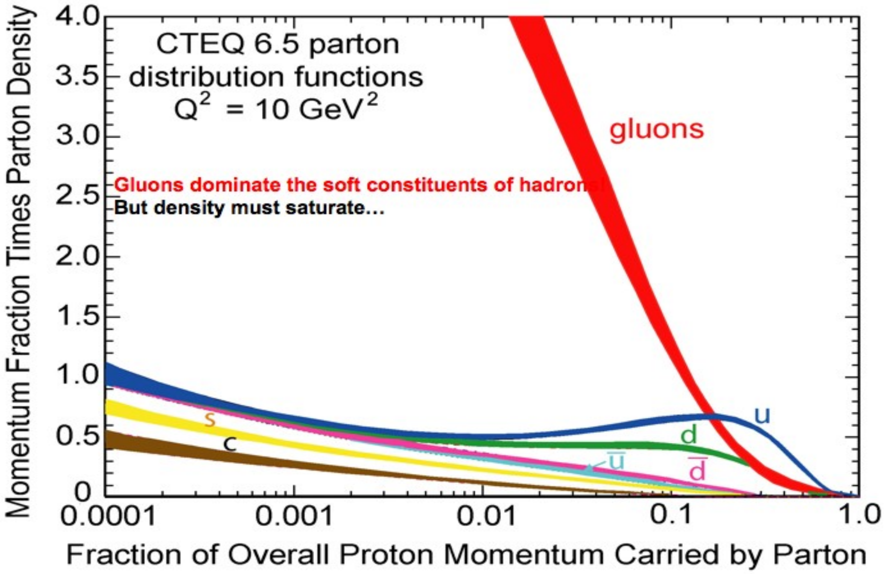
LHC

November 2010

The gluon density is high in the high energy limit:

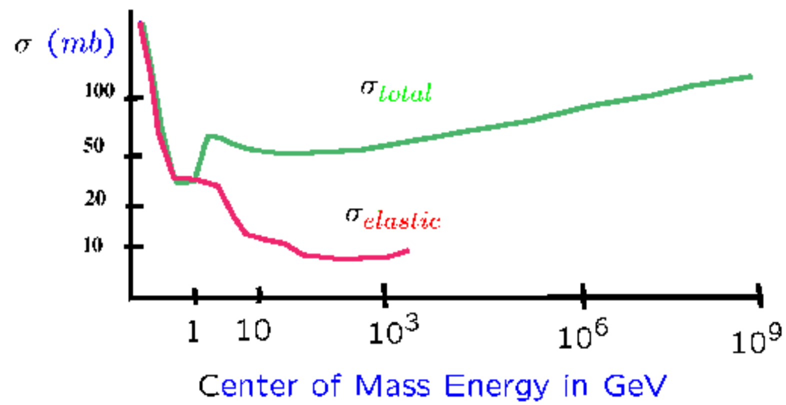
$$x = E_{gluon}/E_{hadron}$$

$$x_{min} \sim \Lambda_{QCD}/E_{hadron}$$

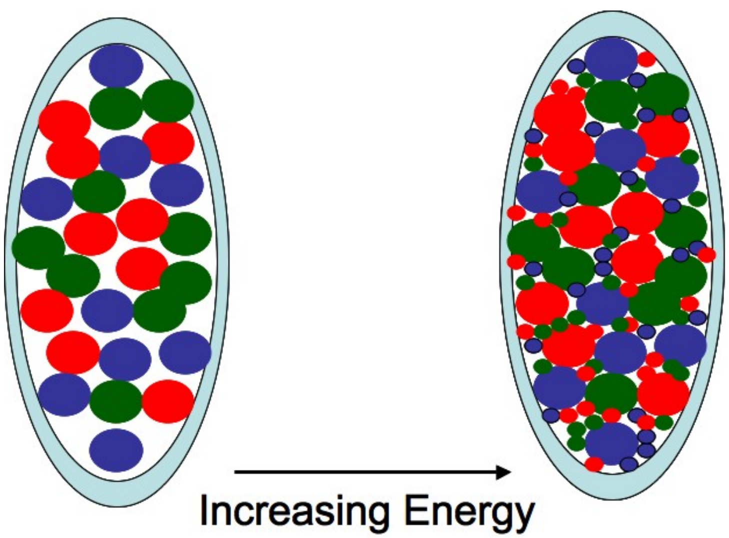


Gluons dominate the proton wavefunction

The total hadronic cross section:



Proton size grows slowly



Asymptotic Freedom: High density systems are weakly coupled because typical distances are short

$$\alpha_S << 1$$

Should be possible to understand from first principles

Increasing gluon density seen in DGLAP and BFKL evolution equations

Typical gluon size 1/Q

DGLAP:
From momentum Q_0 compute distribution at Q at fixed x
Number of gluons grows but gluons decrease in size rapidly:
Dilute limit

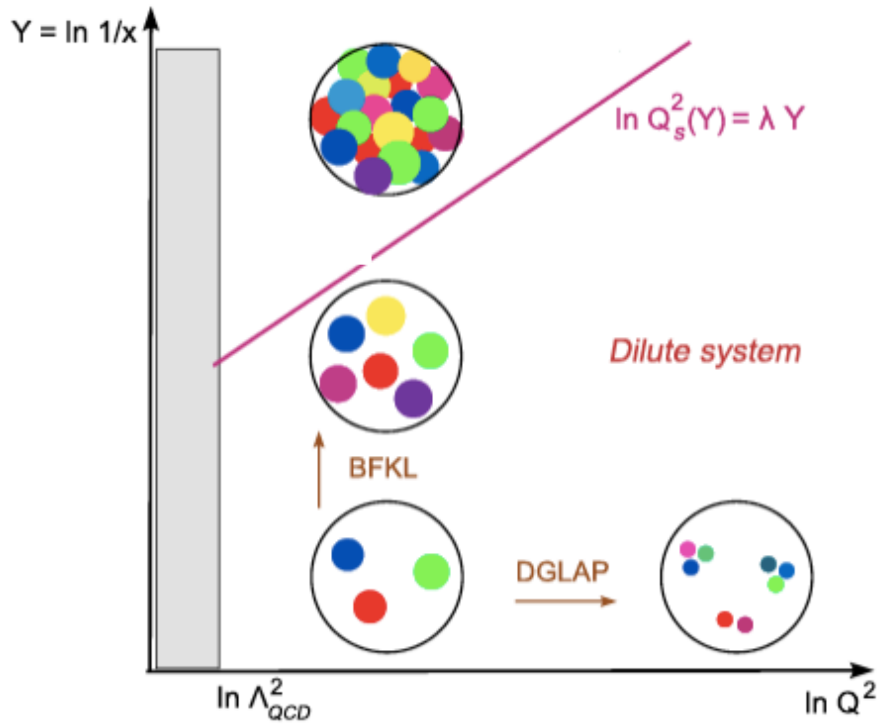
BFKL:
From x_0 to x at Q:
Number of gluons grows but gluons of fixed size:
High density limit

$$q < Q_{sat}$$

Gluons Saturated.

$$Q^2_{sat} \sim Q_0^2 \left(\frac{x_0}{x} \right)^\delta \qquad \delta \sim 0.2 - 0.3$$

Grows



How does density at fixed size stop growing?

$1/\alpha_s$ gluons with interaction strength α_s are a hard sphere.

When all gluons with

$$q < Q_{sat}$$

are filled, then begin filling with higher momentum

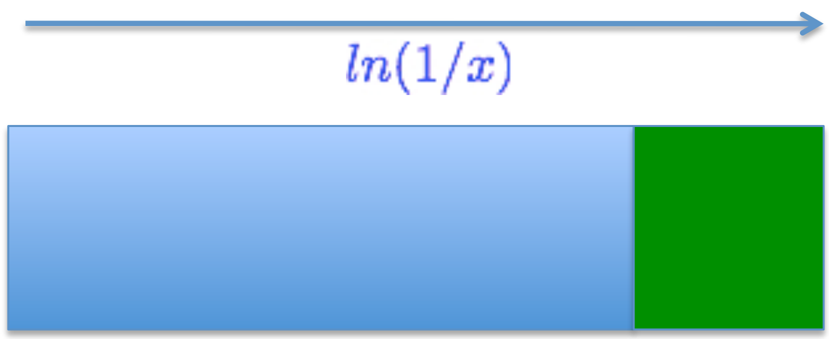
Effective Theory of Color Glass Condensate

$$\frac{dN}{dy\,d^2p_T\,d^2r_T} \sim \frac{1}{\alpha_S} \qquad p_T < Q_{sat}$$

Classical gluon fields at small x
Static sources of gluon fields at large x

Renormalization group changes what is source and what is field as energy increases.
Renormalization group determines distribution of sources

Fixed point of renormalization group => Universality of CGC

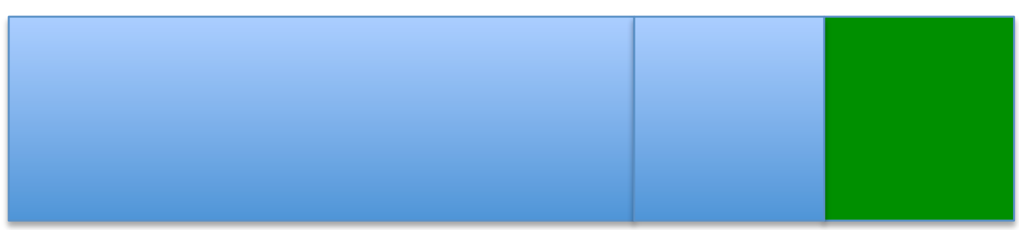


$x \sim 1 \qquad x_1 \qquad x_0 \sim Q_{sat}/E_{hadron}$

$$\alpha_s ln(x_1/x_0) << 1$$

Required to treat fields as classical for

$$x_1 > x > x_0$$



$x \sim 1 \qquad x_1 \qquad x_2 \qquad x'_0 \sim Q_{sat}/E'_{hadron}$

Evolution equations to all orders in the strength of gluon fields: JIMWLK; Balitsky-Kovchegov

Color Glass Condensate

Color:
Gluons are colored

Condensate:
Gluon occupation number $1/\alpha_S$ is as large as can be, like Higgs condensate or superconductor
High density of gluons is self generated

Glass:
The sources of gluon field are static, evolving over much longer time scales than natural one
Resulting theory of classical field and real distribution of stochastic source is similar to pin glass

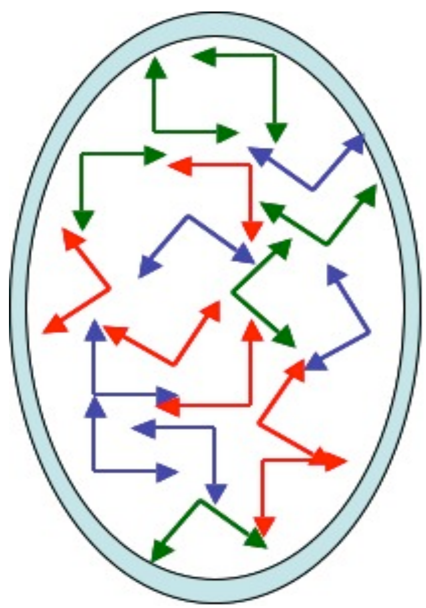
A sheet of Colored Glass:

$$z - t\ small; \quad z + t\ big$$

$$F^{i+}\ big; \quad F^{i-}\ small; \quad F^{ij} \sim O(1)$$

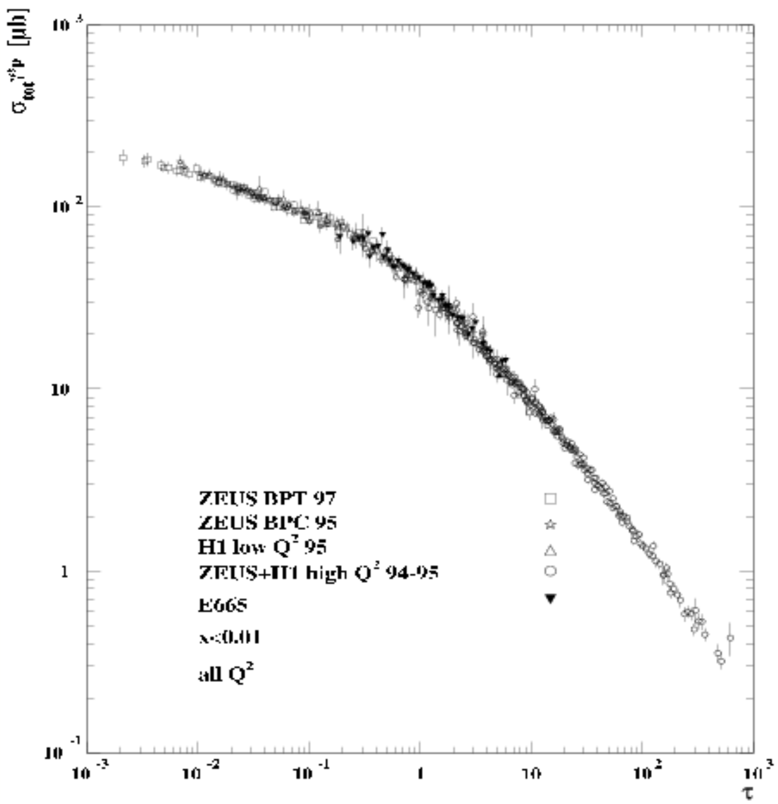
$$\vec{E} \perp \vec{B} \perp \hat{z}$$

Stochastic Lorentz boosted
Coulomb fields

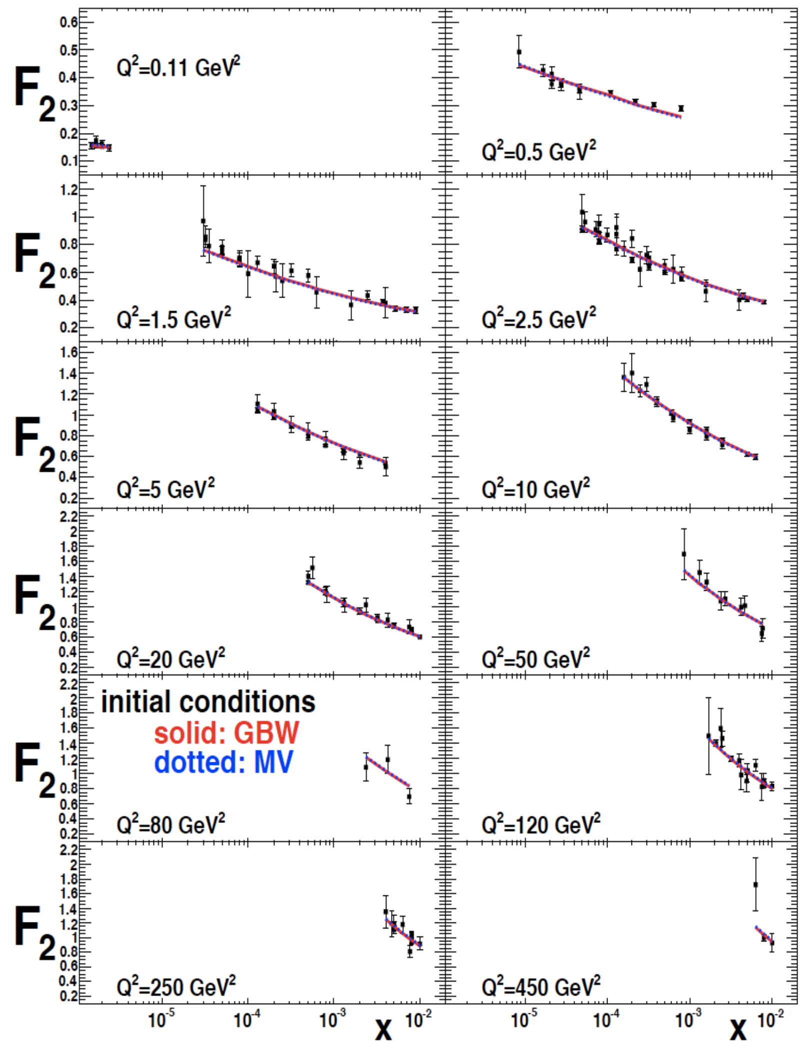


Theory of CGC: First Principles from QCD

Requires saturation momentum $Q_{sat} >> \Lambda_{QCD}$ When is it true?



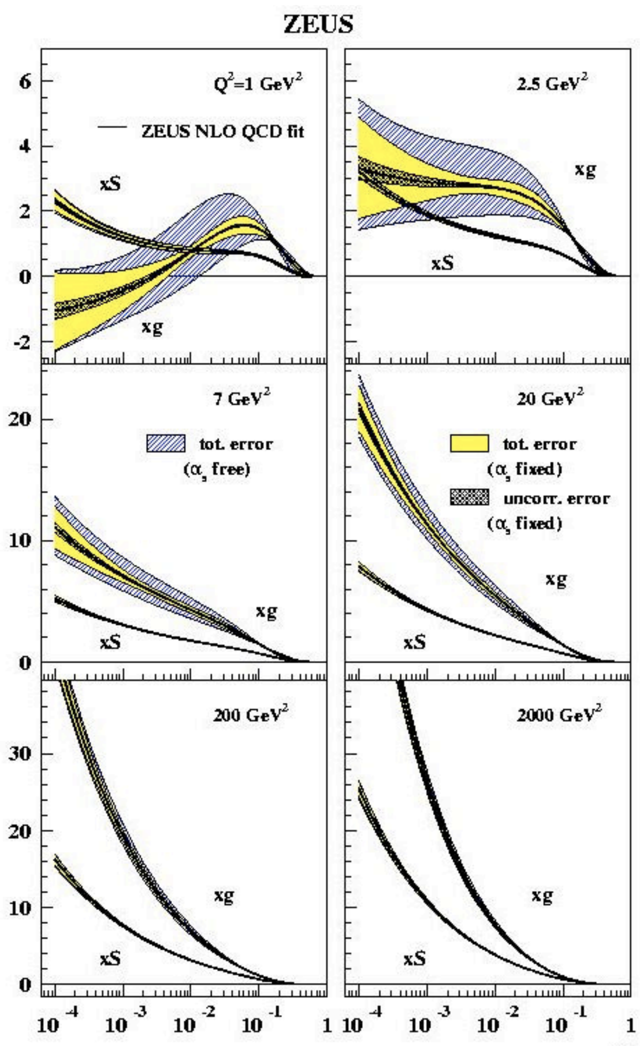
Experimental Evidence: ep Collisions

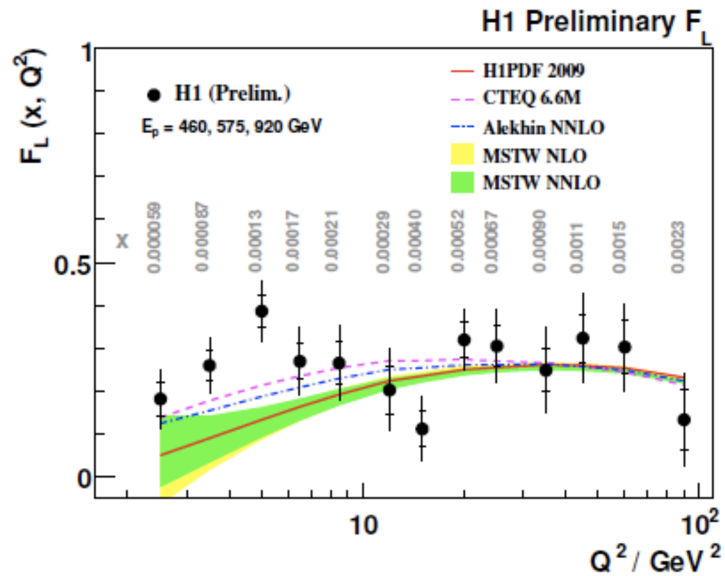


Computed saturation momentum dependence on x agrees with data

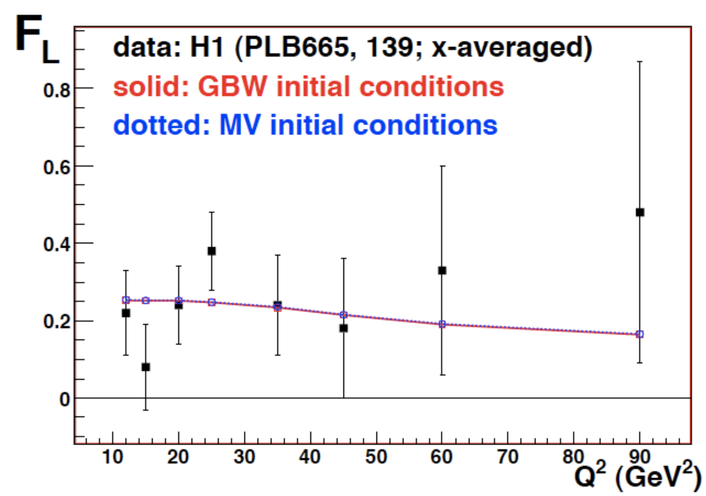
Simple explanation of generic feature of data

Allows an extraction of saturation momentum

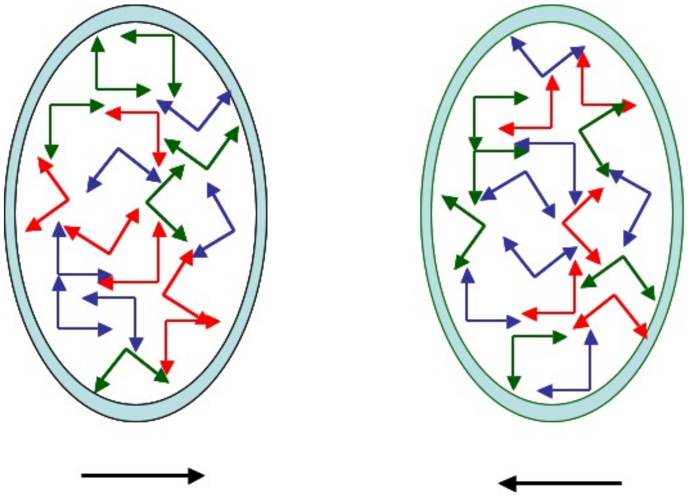




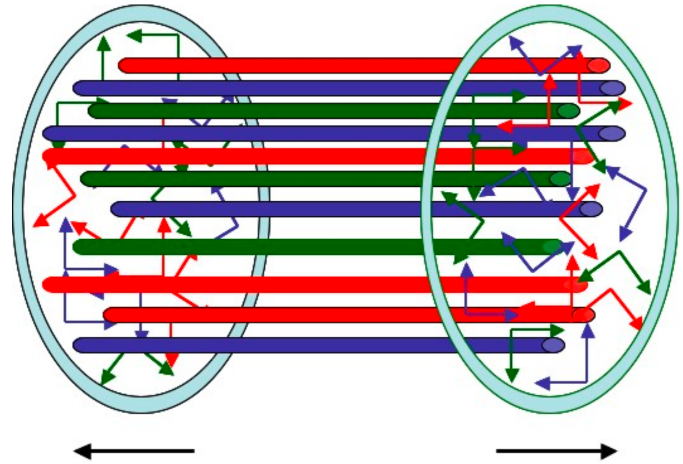
But there exist other non-saturation interpretations. Are there really no or even a negative number of “valence gluons” in the proton for small x?



Hadron-Hadron Collisions and the Glasma



Two sheets of CGC collide



Sheets charge up with color electric and color magnetic charge

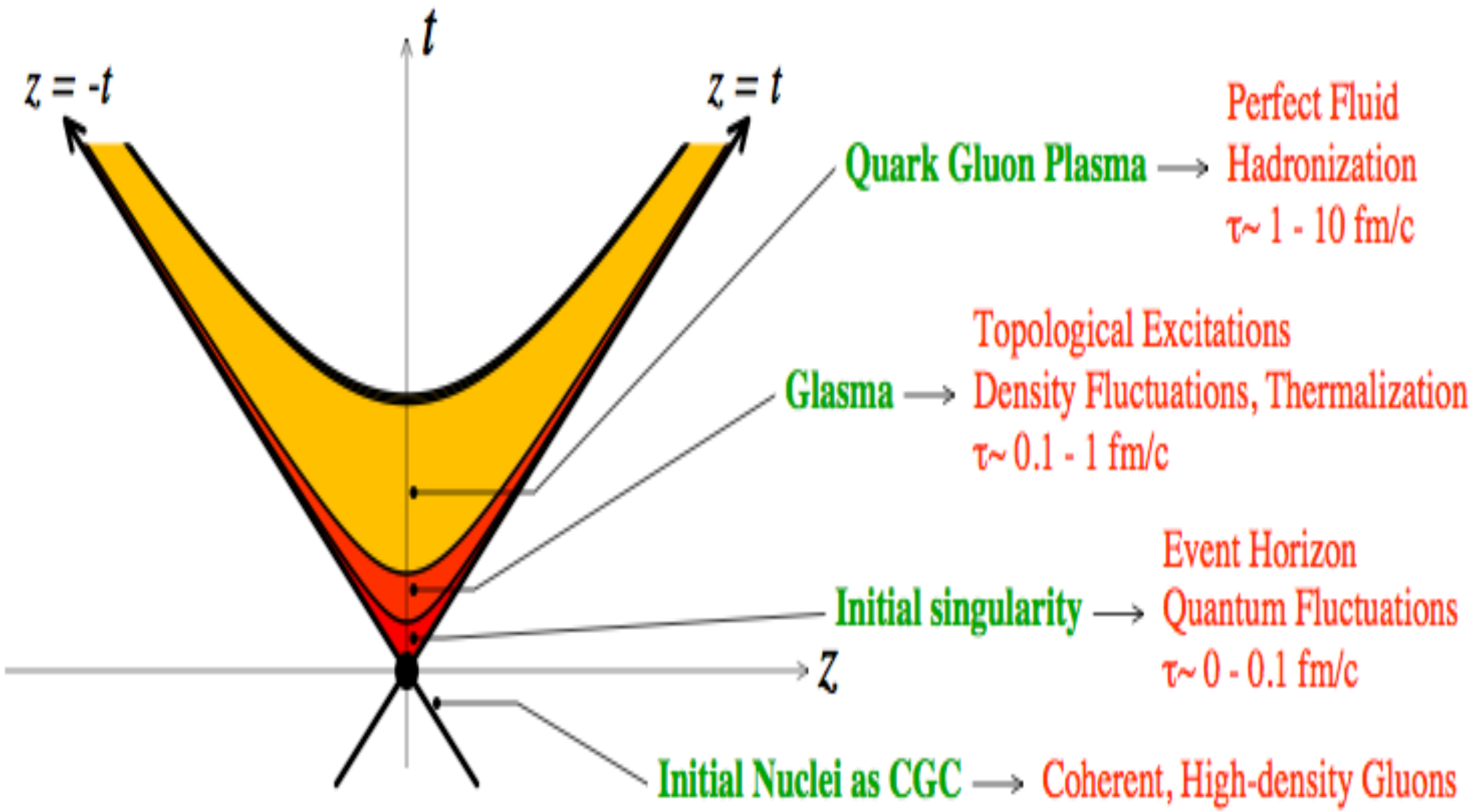
Long range color fields form in time

$$t \sim e^{-\kappa/\alpha_S}$$

Maximal local density of topological charge

$$\vec{E} \cdot \vec{B}$$

Glasma: Matter making the transition for Color Glass Condensate to Quark Gluon Plasma



Space Time Picture of Hadron Collisions very similar to that of Big Bang Cosmology

Time scales much smaller

What Can CGC and Glasma Do?

Deep Inelastic Scattering

Quark and Gluon Distribution Functions
Diffractive structure functions

Hadron Collisions:

Initial gluon transverse momentum and rapidity distributions in collisions
Heavy quark production
Two particle correlations in angle and rapidity
Fluctuations in multiplicity.

First principles framework if

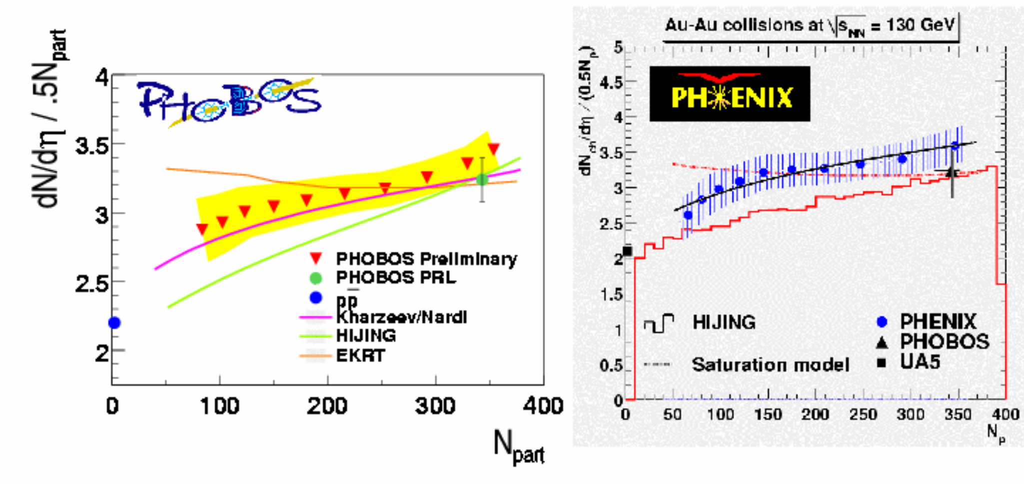
$$Q_{sat} >> \Lambda_{QCD} \sim 200\ MeV$$

When and if it is true must be established by experiment.

AdSCFT suggests a saturation phenomenology even in strong coupling

Multiplicity Distributions in pp, dA and AA

dN/dη vs Centrality at η=0



Tribedy and Venugopalan

Multiplicity and Centrality at RHIC

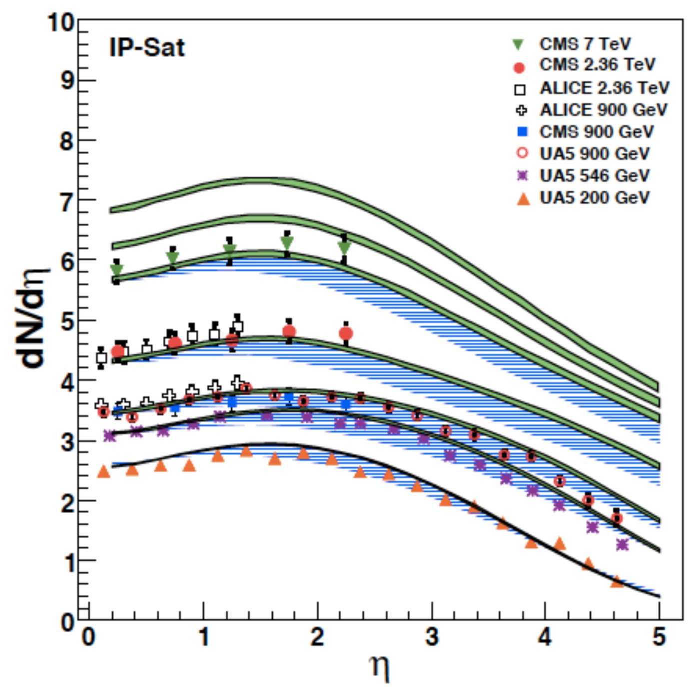
Kharzeev-Nardi

$$\frac{dN}{dy} \sim \frac{1}{\alpha_{strong}} \pi R^2 Q_{sat}^2 \sim A ln(A)$$

Rapidity distributions and initial conditions for hydrodynamic models

Impact Parameter Saturation Model of Kowalski and Teaney:

Comprehensive description of HERA data on deep inelastic scattering and diffraction

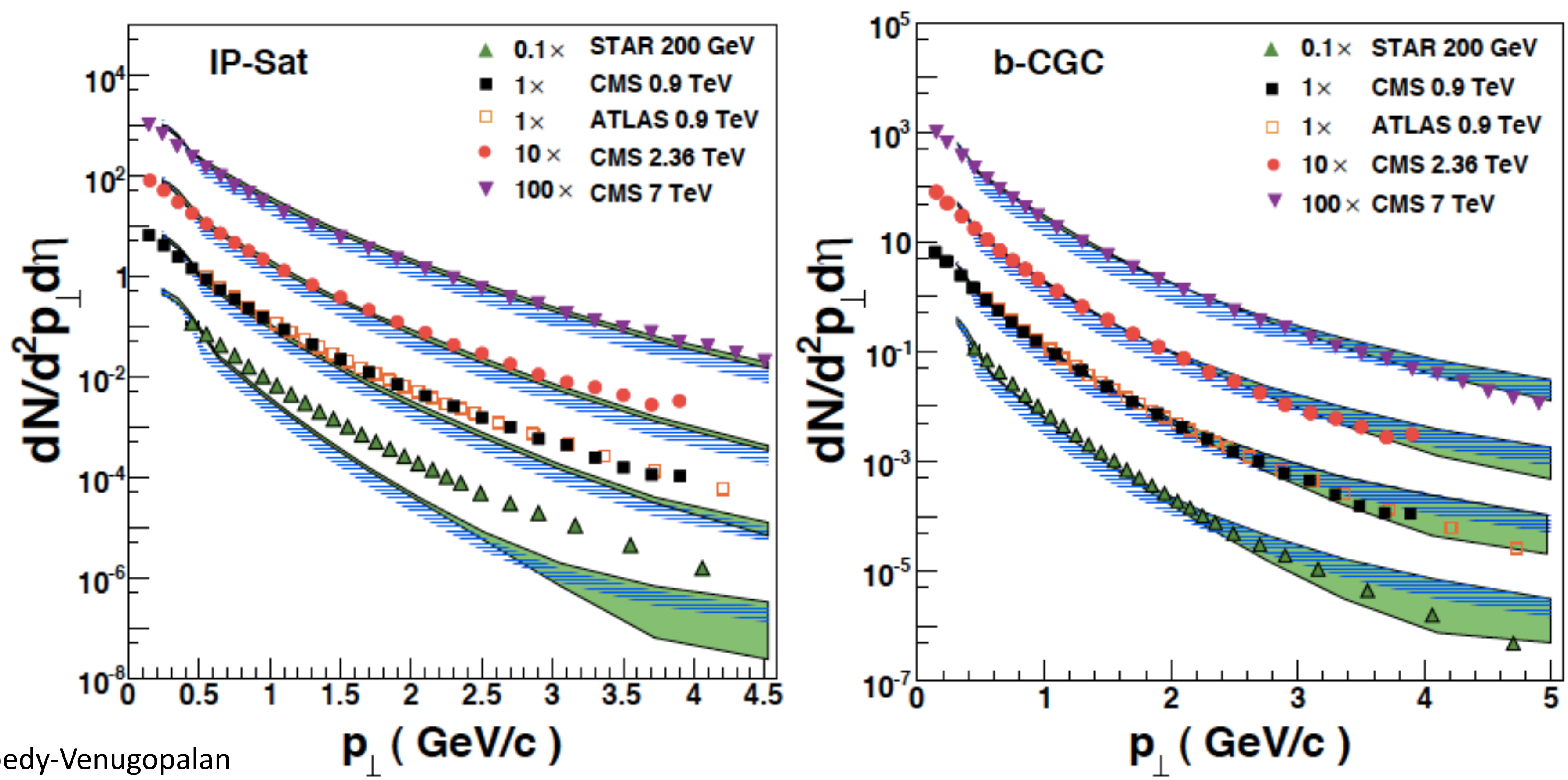


Transverse Momentum Distributions in pp

Geometric scaling? $p_T/Q_{sat}(p_T/E)$

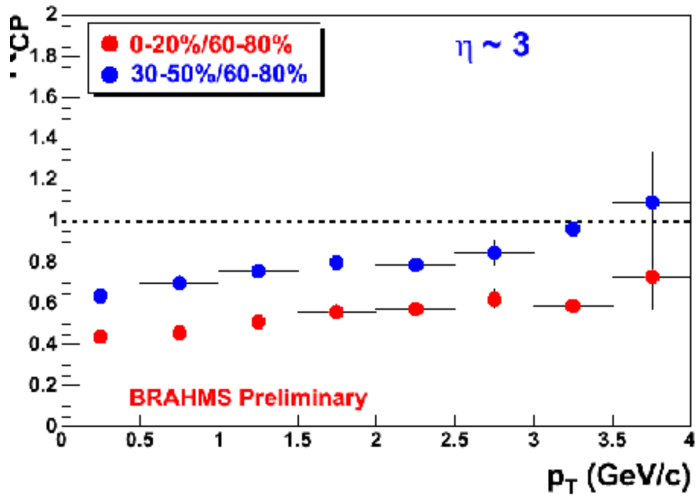
Large initial state effects in heavy ion collisions: $p_T \sim n/Q_{sat}$

N about 6-7 from Tsallis fit



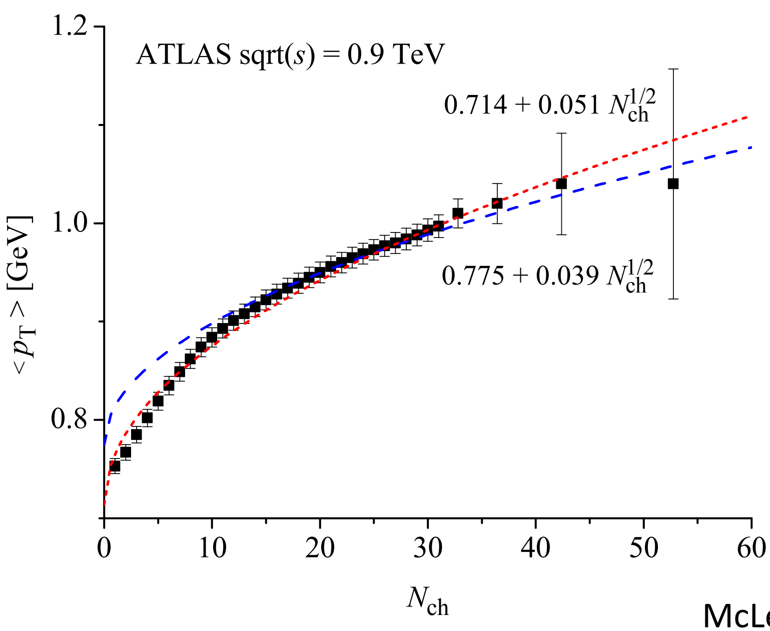
Tribedy-Venugopalan

Relations between multiplicity and transverse momentum



In dA collisions, gluons are suppressed at high transverse momentum at small x:

Saturation momentum cuts off gluon evolution



In pp collisions: transverse momentum is enhanced in multiplicity fluctuations

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

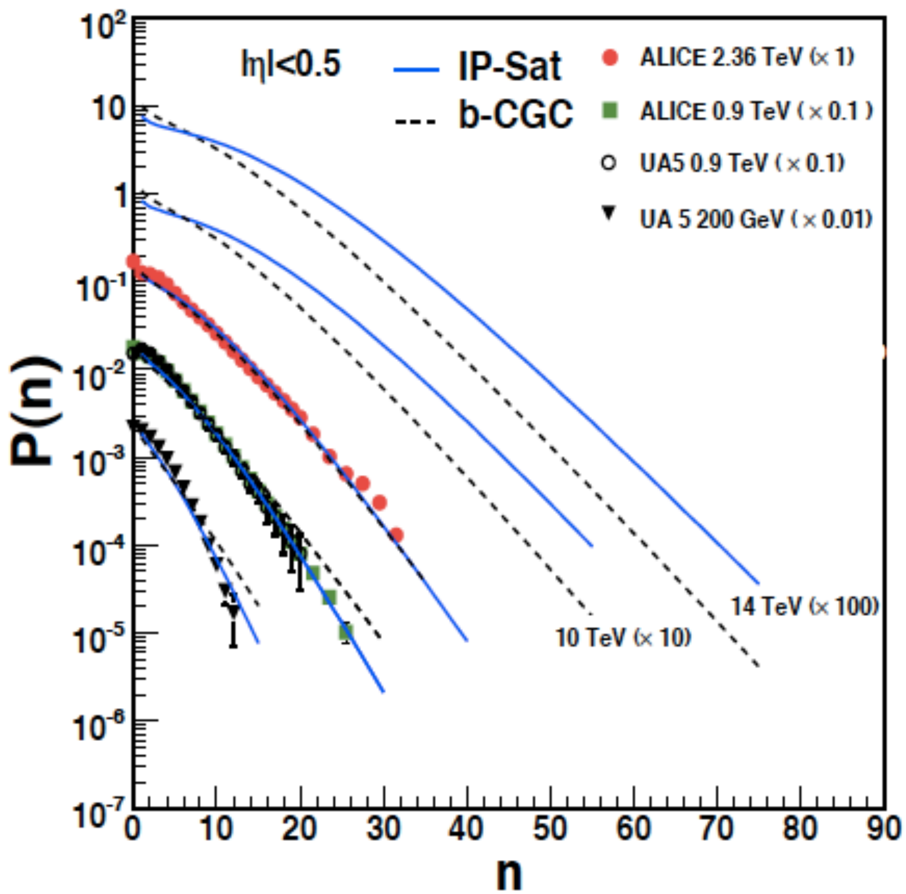
$$< p_T^2 > \sim Q_{sat}^2$$

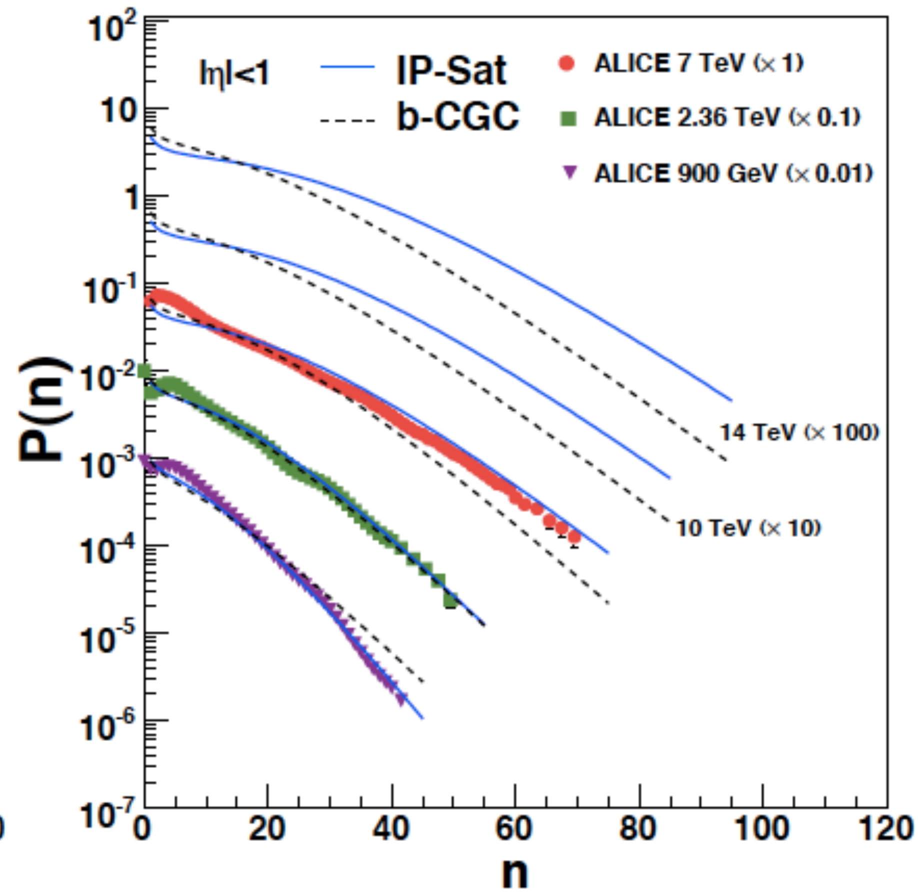
McLerran-Praszalowicz

Multiplicity Fluctuations

The decay of a single line of color electric or color magnetic flux give a negative binomial distribution

The sum of negative binomial distributions is a negative binomial distribution



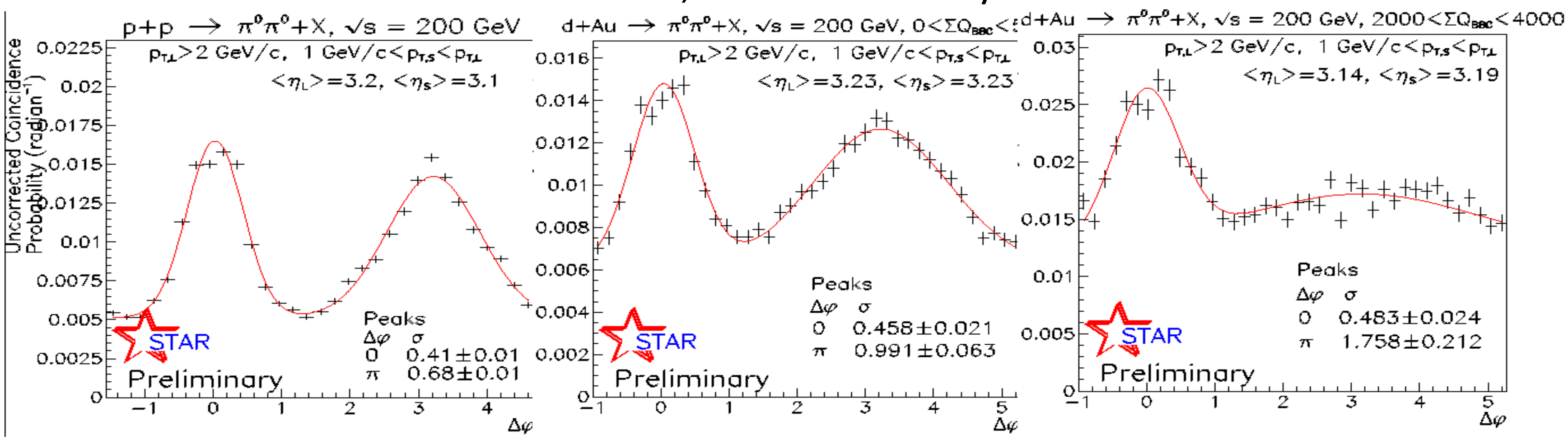


“Jet Quenching” in dA Collisions:

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

200 GeV ***p+p*** and ***d + Au*** Collisions

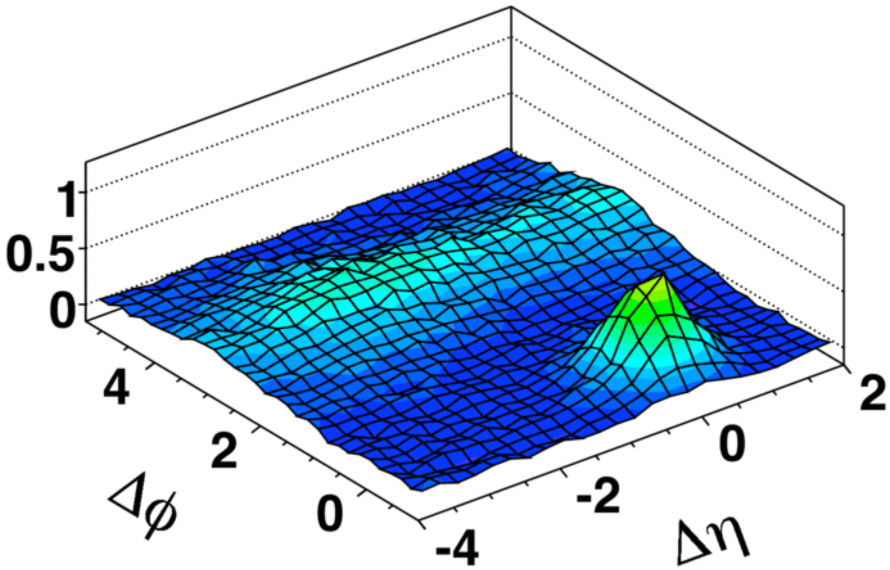
Run8, STAR Preliminary



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

No such backward suppression was found in dA at central rapidity

Near-side correlations, $\Delta\Phi \ll \pi$
(the "ridge")

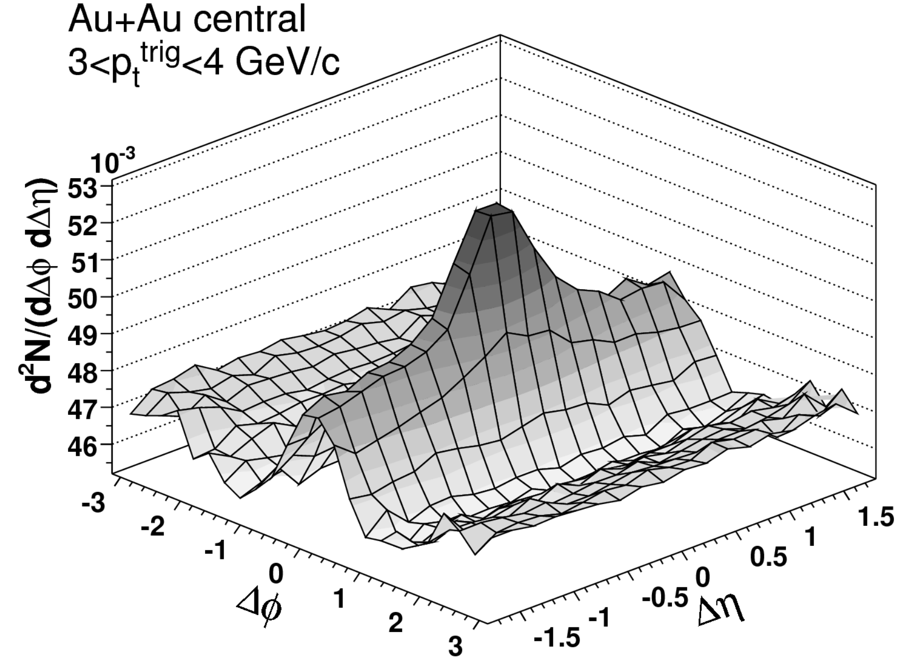


PYTHIA pp, $p_T^{trig} > 2.5$ GeV

STAR (arXiv:0909.0191)

PHOBOS (arXiv:0903.2811):

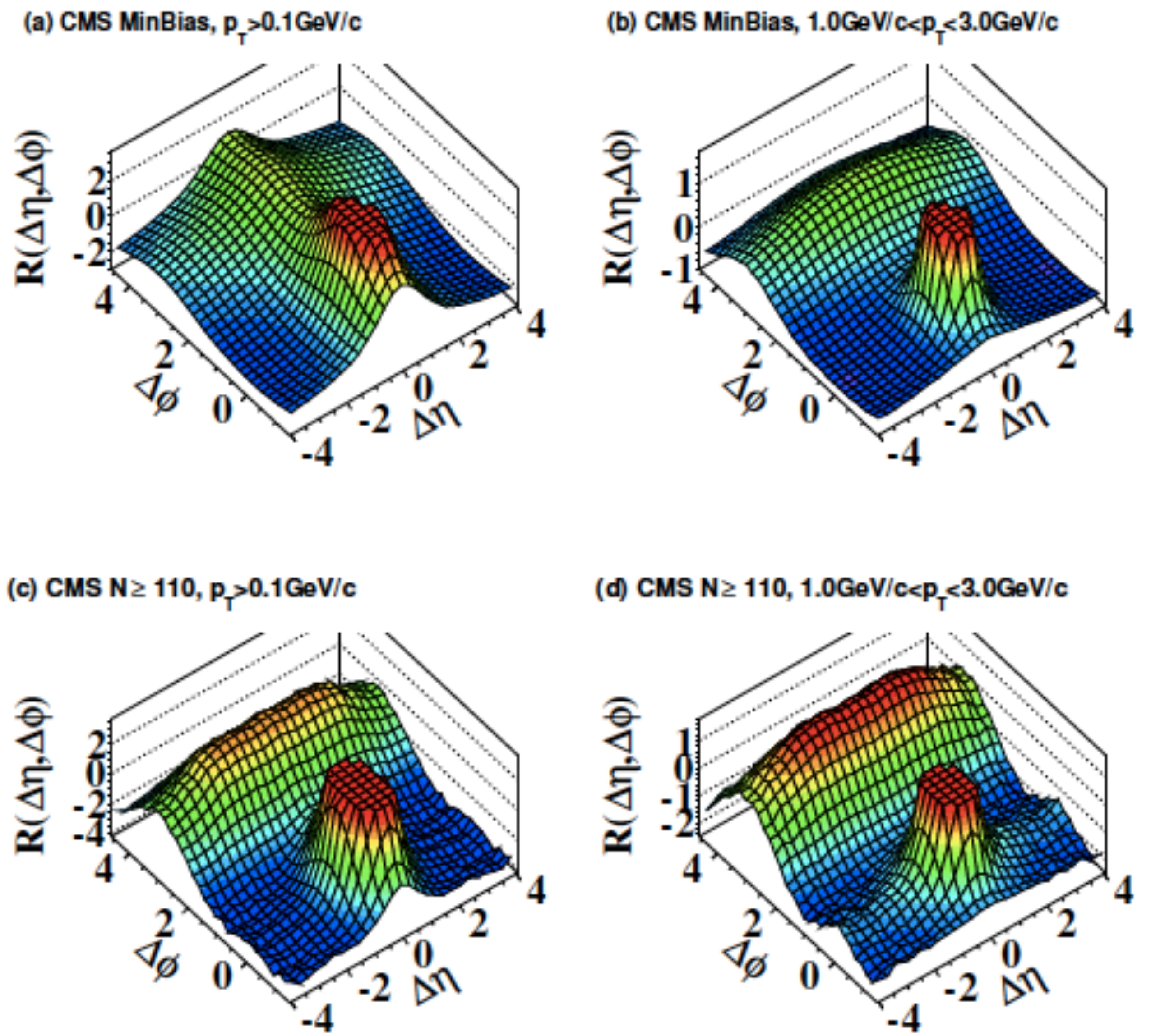
$$ln(z\Lambda_{QCD}) \sim \Delta\eta$$

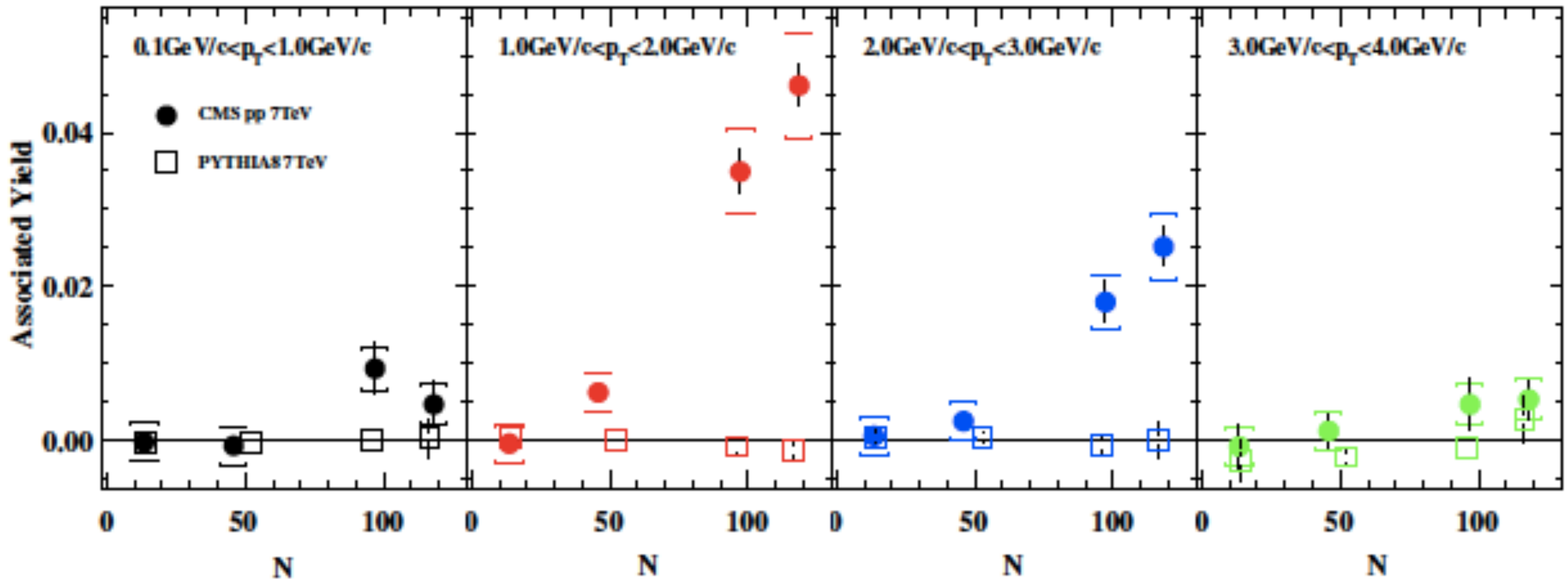


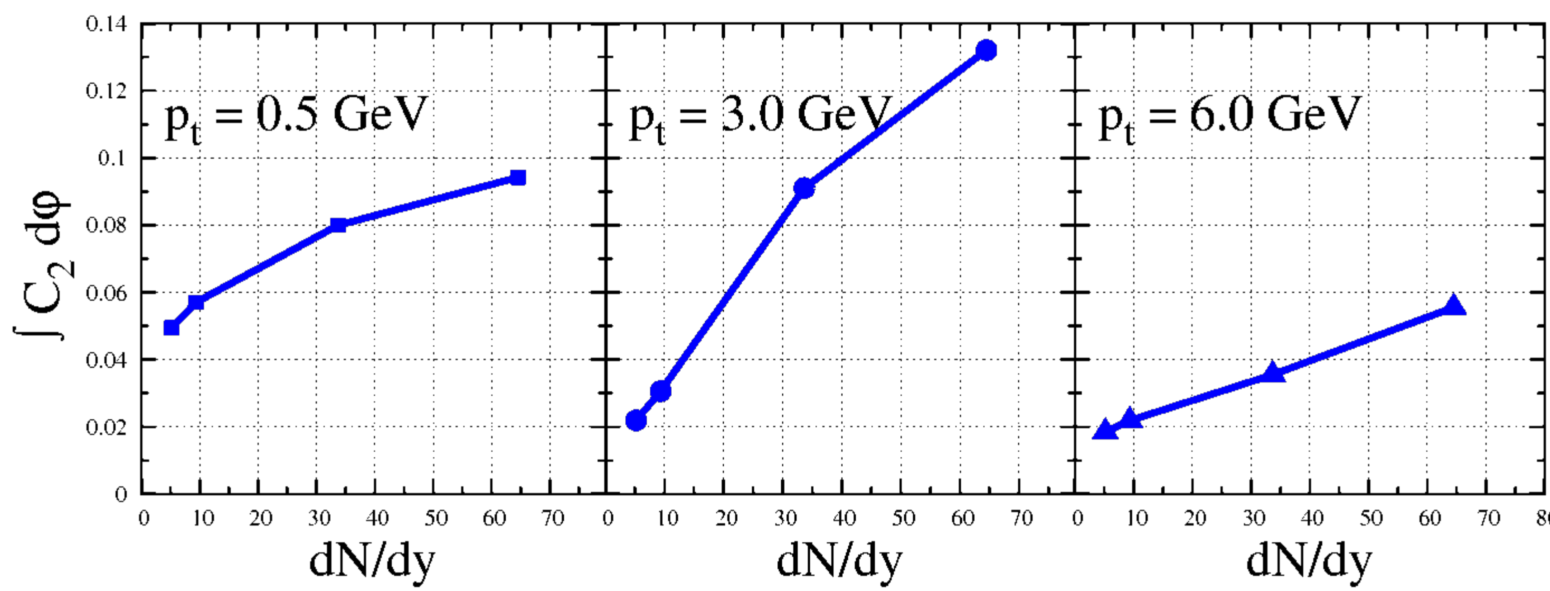
Causality requires that correlations of long range in rapidity must be made very early:
Not originating in QGP
Not jet interactions

CMS Sees Ridge over 8 units of rapidity! High Multiplicity Events

p_T ~ 1-3 Gev







Dumitru, Dusling, Gelis, Lappi, Vemugopalan

The Ridge is a Snapshot of a Color Electric or Magnetic Flux

LHC:

Tubes exist on sub-fermi transverse size scale
Perhaps as small as .2 Fm
They are formed very early in the collision

Angular peaking:

Intrinsic peaking at emission?
Opacity?
Flow or nascent flow effects?

Probably different combination of mechanisms:

High multiplicity pp
High transverse momentum AA
Inclusive AA

Unsolved Problem: Transition between Glasma and Thermalized QGP

Strongly Interacting QGP

Glasma
or
Thermalized QGP

Glasma hypothesis might help with:
Jet Quenching
Flow
Enhanced dilepton production