The Color Glass Condensate: Theory, Experiment and the Future

Physics Issues:

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

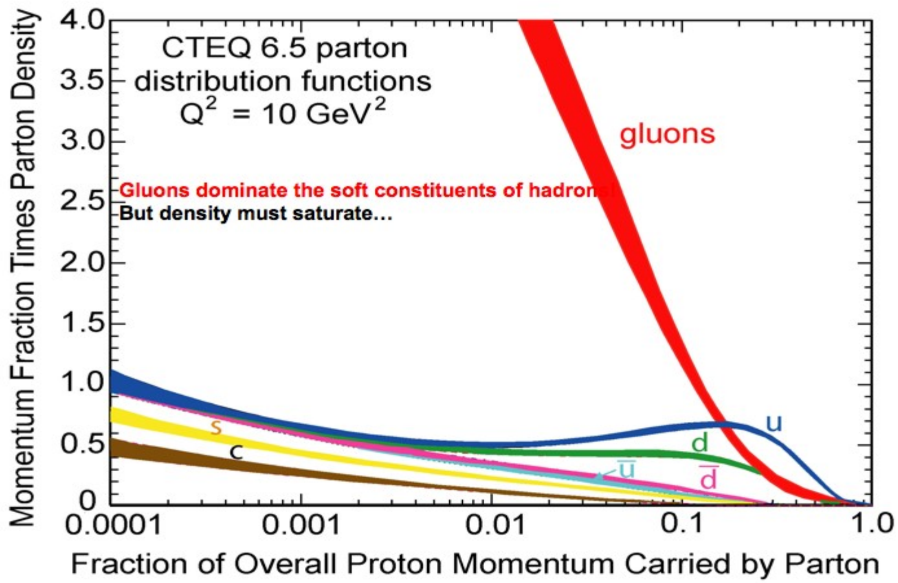
$$x < 10^{-2}$$

Heavy ion collisions and dA collisions at RHIC energies and above

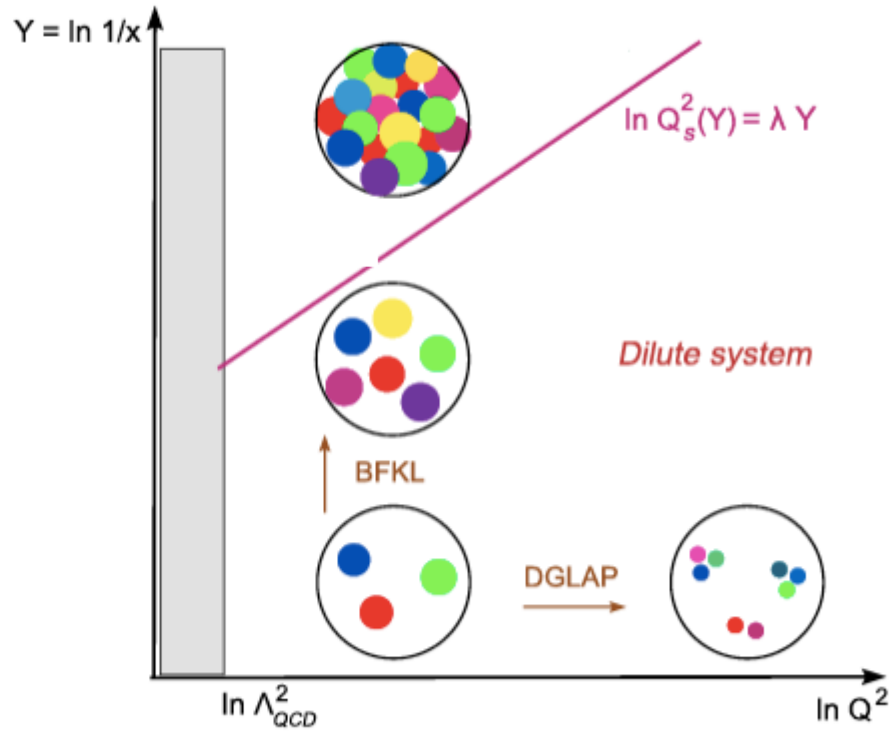
LHC

The gluon density is high in the high energy limit:

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



Gluons dominate the proton wavefunction

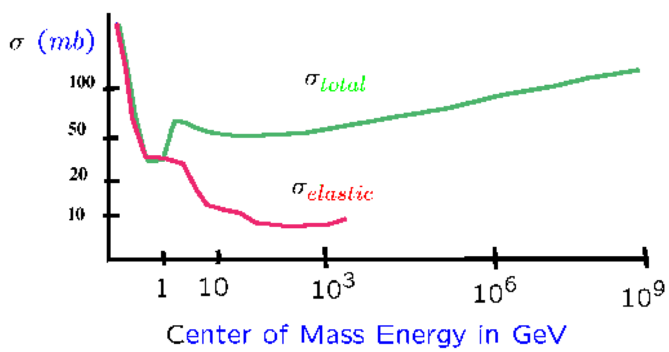


Evolution at fixed resolution scale is towards high density

Evolution at fixed x is towards dilute distribution of large numbers of partons

Gribov, Levin and Ryskin;
Mueller, Qiu

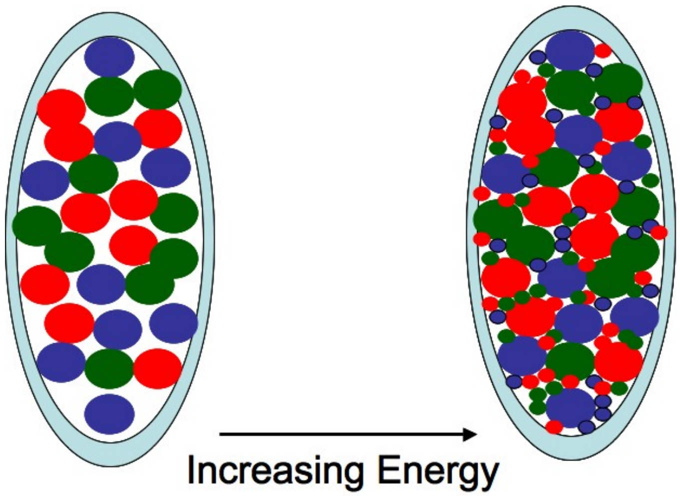
The total hadronic cross section:



But proton size grows slowly

Mclerran and Venugopalan

At high gluon density the coupling is weak, so should be able to compute the properties of this high gluonic density state using weak coupling methods within QCD



Imagine gluon as a sphere of size $1/p_T$

$1/\alpha_s$ act like a hard sphere

At fixed resolution scale pact until the phase space density

$$\frac{dN}{dyd^2p_Td^2r_T} \sim \frac{1}{\alpha_S}$$

Once the phase space density is saturated, then begin to fill up hadron with smaller size gluons

The Bjorken-Feynman parton model of incoherent quark and gluon distributions is generalized to classical gluon fields

High phase space density => Classical Limit

Color: Gluons are colored

Condensate: The phase space density of gluons is high and is self-generated

Glass: The classical field corresponding to slow moving partons arises from fast moving partons and therefore evolves on time scales long compared to natural ones: Distribution is incoherent distribution of sources like spin glasses

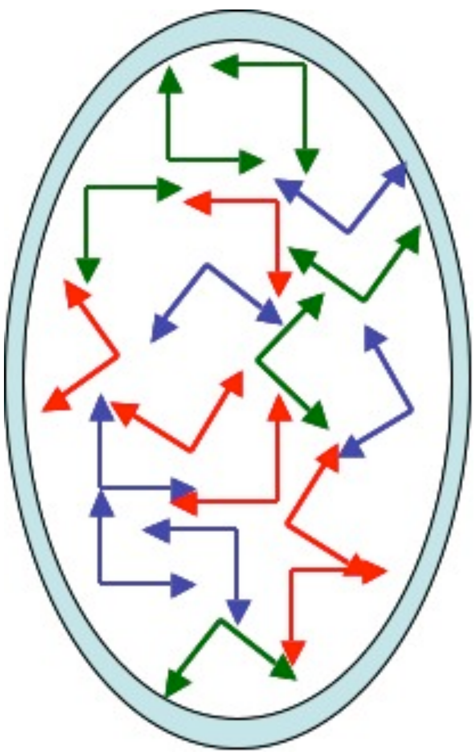
Theoretical Developments:

Well developed and intuitive formalism for computing deep inelastic scattering and diffraction. Good and simple description of data.

JIMWLK Evolution equations to all orders in the background fields that for correlation functions is Balitsky-Kovcehgov hierarchy. NLO computations performed.

Evolution equations predict universal solution at small x

Is it weakly coupled? How coherent?



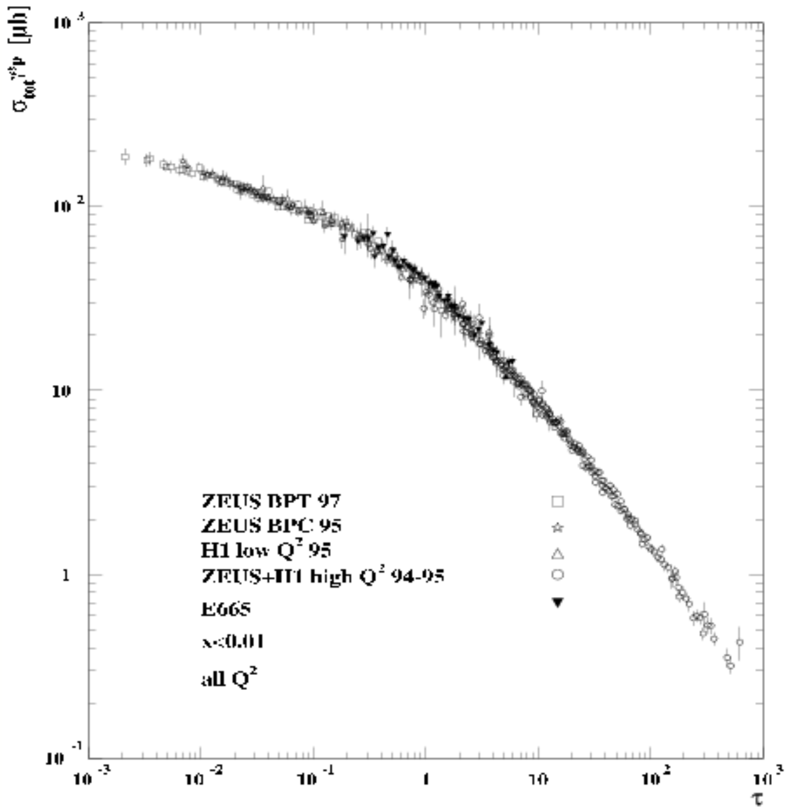
Color Glass Condensate:

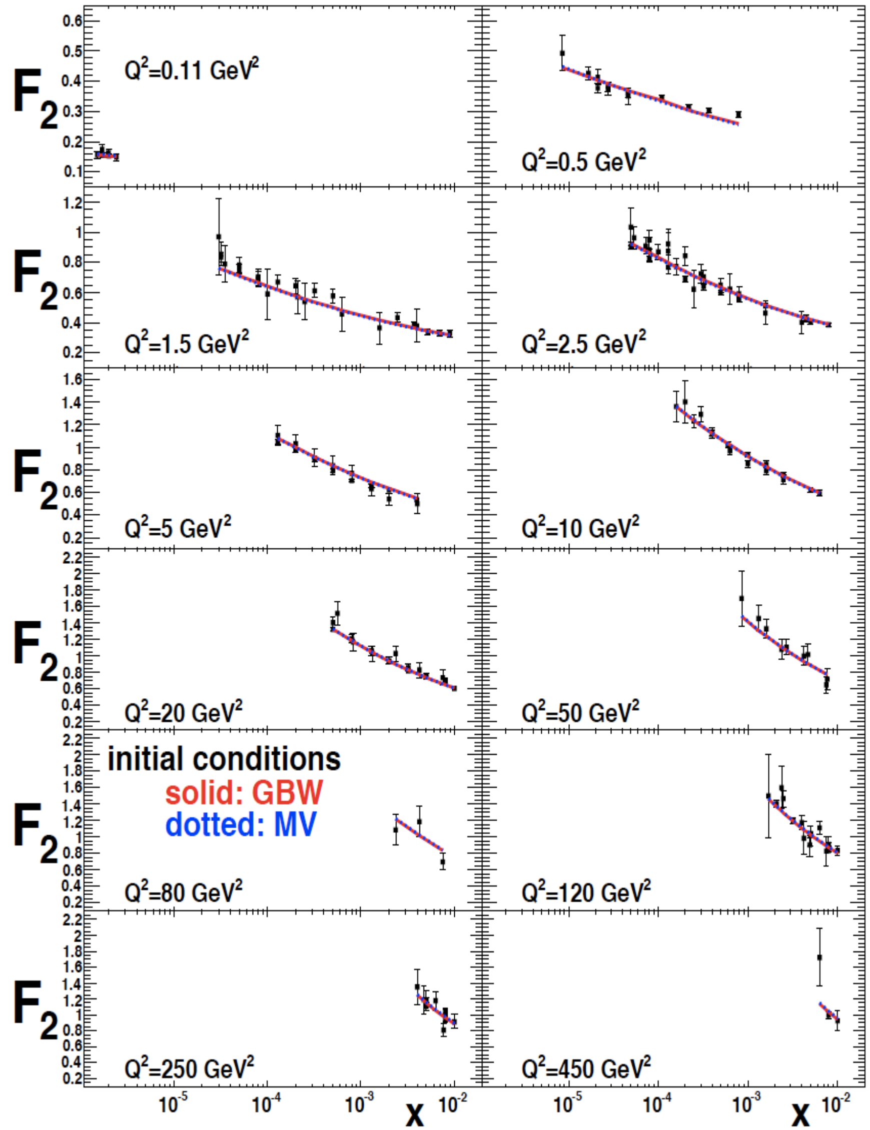
Theory of source of color charge

Source produces stochastic distribution
Of non-abelian Lorentz boosted Coulomb fields.

Gluonic operators are expressed in terms of classical field and averaged over incoherent distribution of sources

McLerran-Venugopalan model is Gaussian distribution of sources





Experimental Evidence: ep Collisions

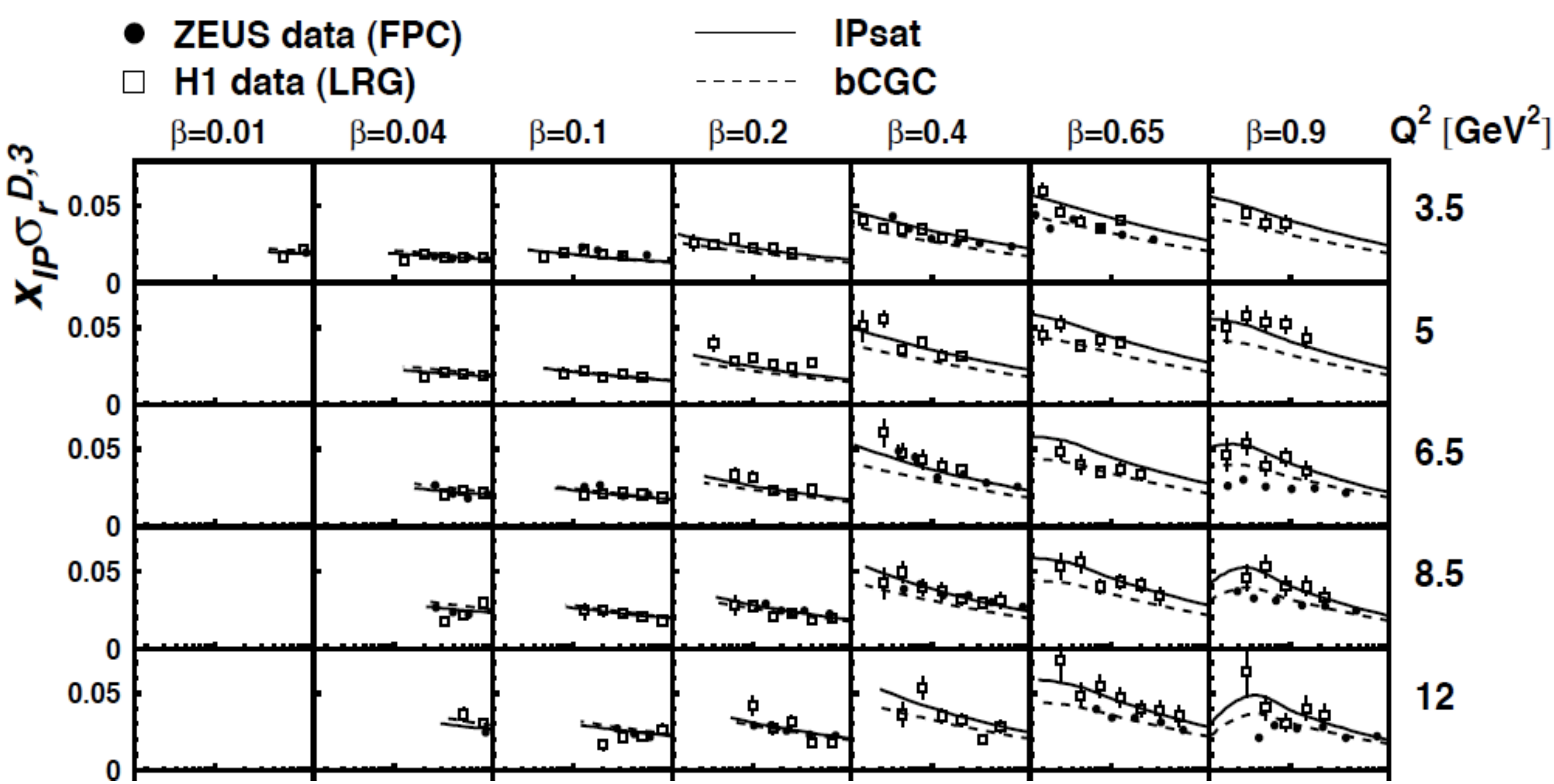
Computed saturation momentum dependence on x agrees with data

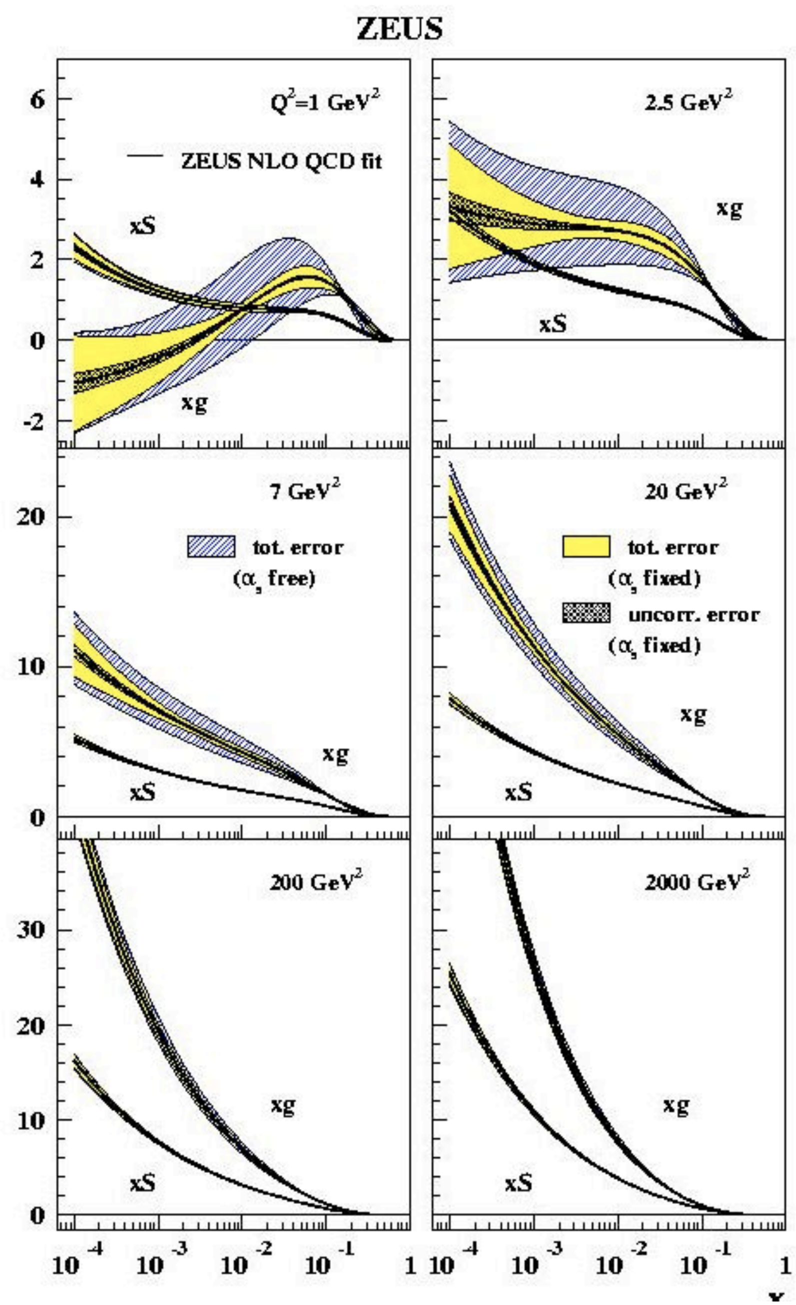
Simple explanation of generic feature of data

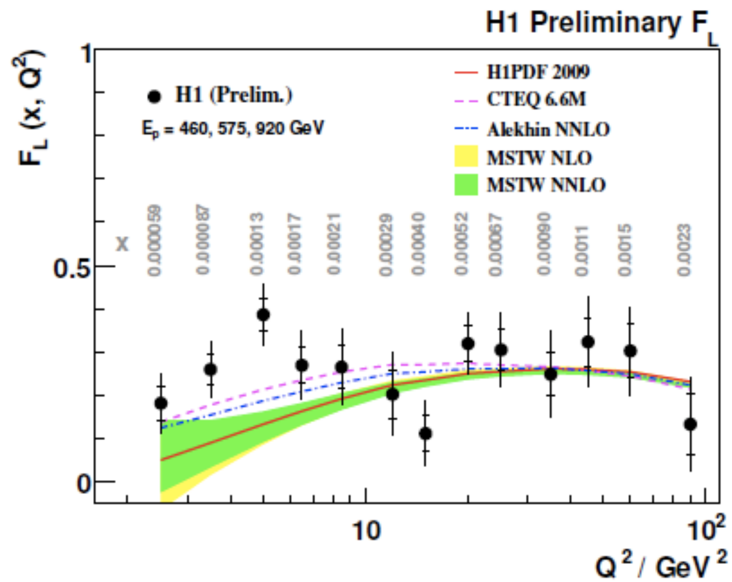
Allows an extraction of saturation momentum

Experimental Evidence: ep Collisions

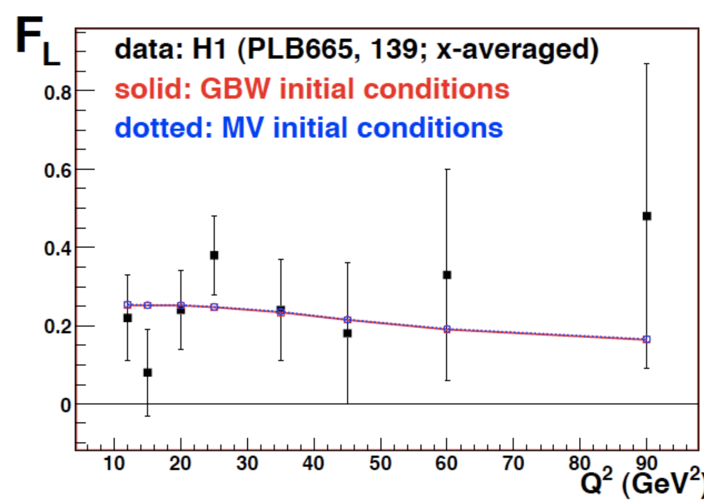
Diffraction



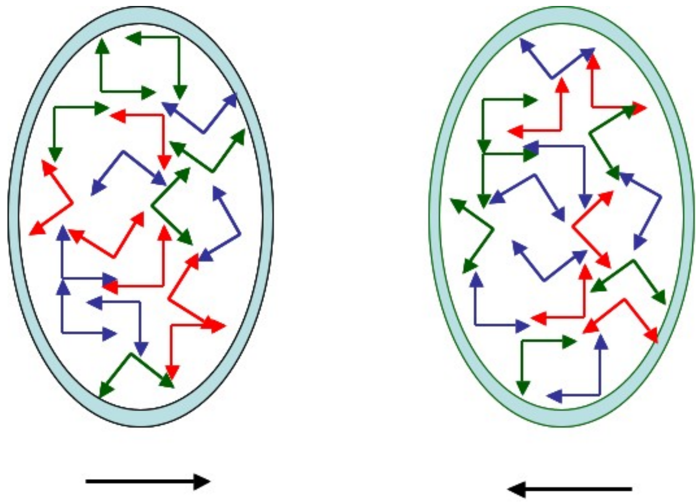




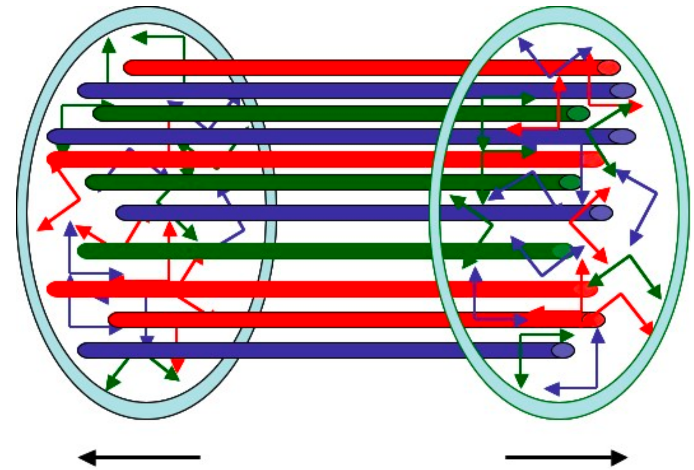
But there exist other non-saturation interpretations.
Are there really no or even a negative number of
"valence gluons" in the proton for small x?



High Energy Collisions:



Explicit realization of Bjorken space-time picture

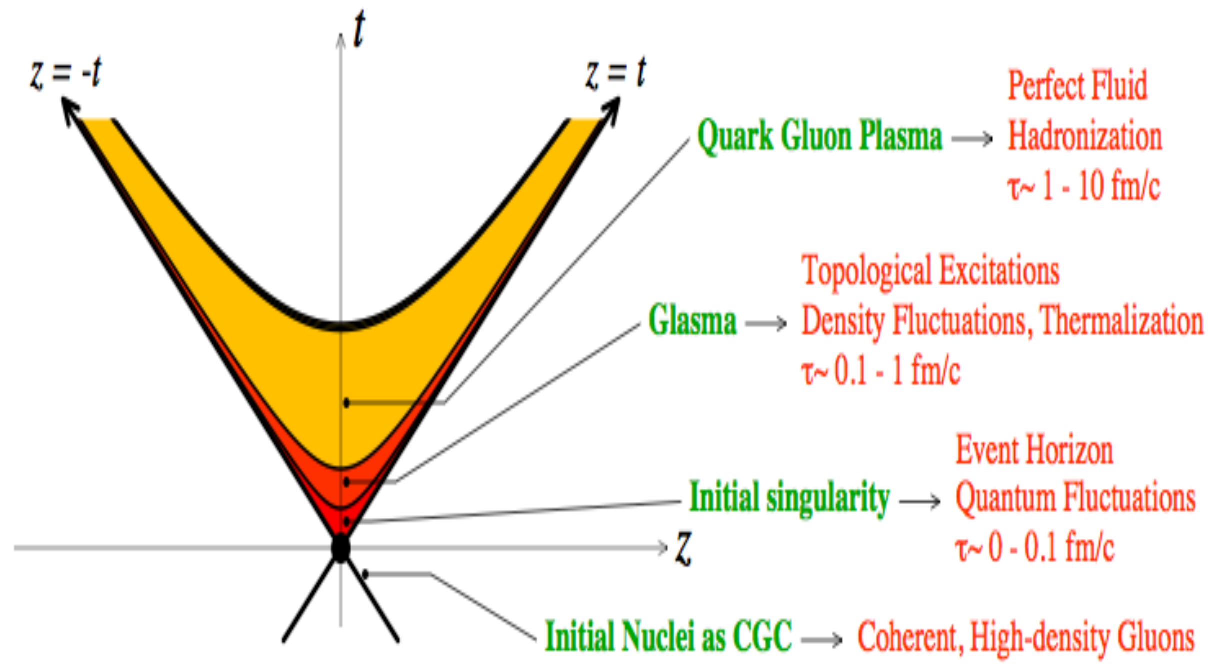


“Instantaneously” develop longitudinal color E and B fields

Two sheets of colored glass collide

Glass melts into gluons and thermalize

QGP is made which expands into a mixed phase of QGP and hadrons



The Glasma and CGC allow a theoretically consistent prediction of:

Initial gluon multiplicity and transverse momentum distributions
Shadowing and dependence on participant number in heavy ion collisions
Heavy quark dependence upon participant number in heavy ion collisions
Fluctuations in the multiplicity distribution
Long range rapidity correlations
Two particle correlations

Provides a framework for addressing issues such as:

Thermalization

Topological charge fluctuations and even by event violations of P and CP

First principles derivation e.g.:

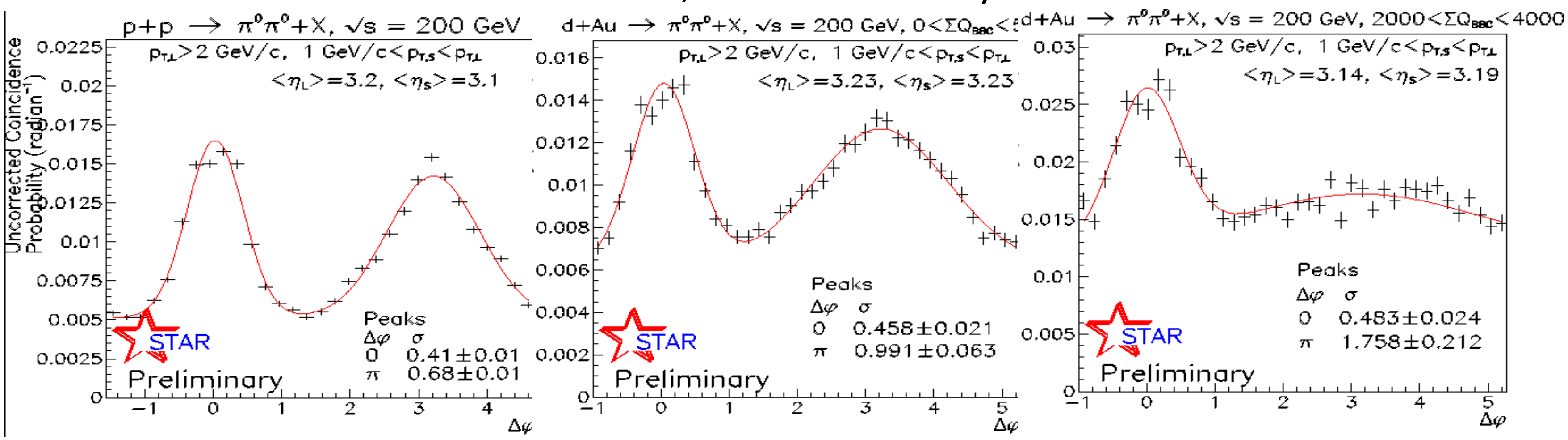
Factorization theorems that generalize those of perturbative QCD into the saturated region

“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



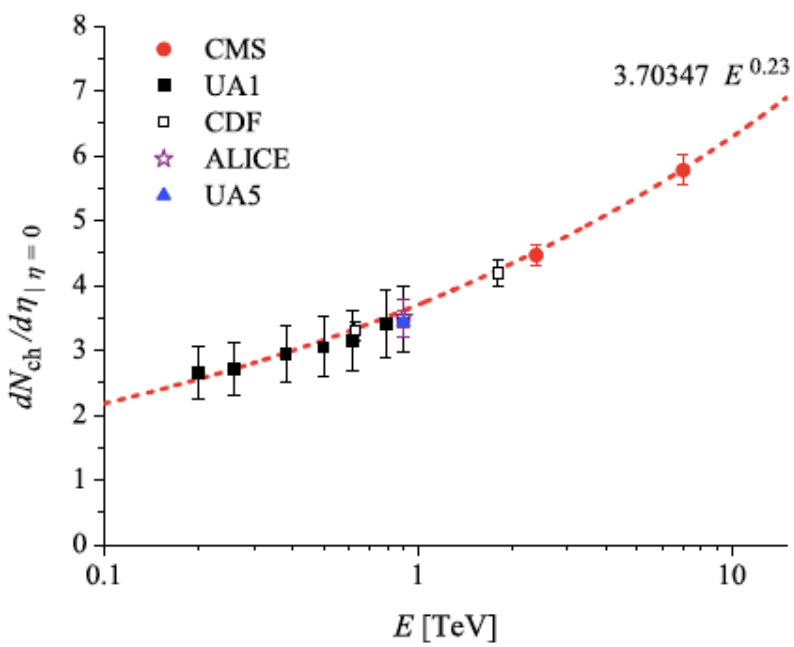
pp ***d+Au (peripheral)*** ***d+Au (central)***

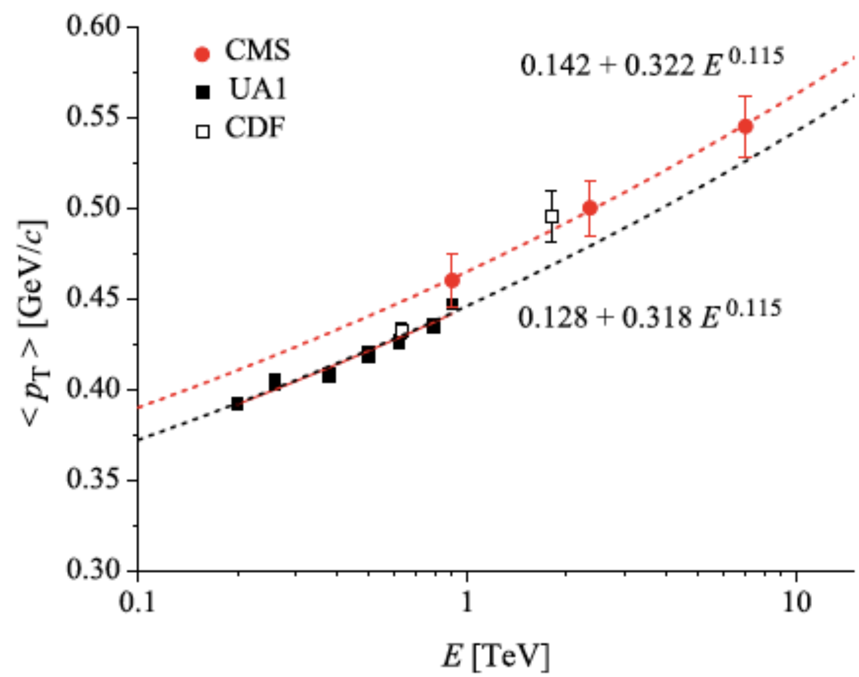
Saturation and the LHC

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 $a = 0.22$



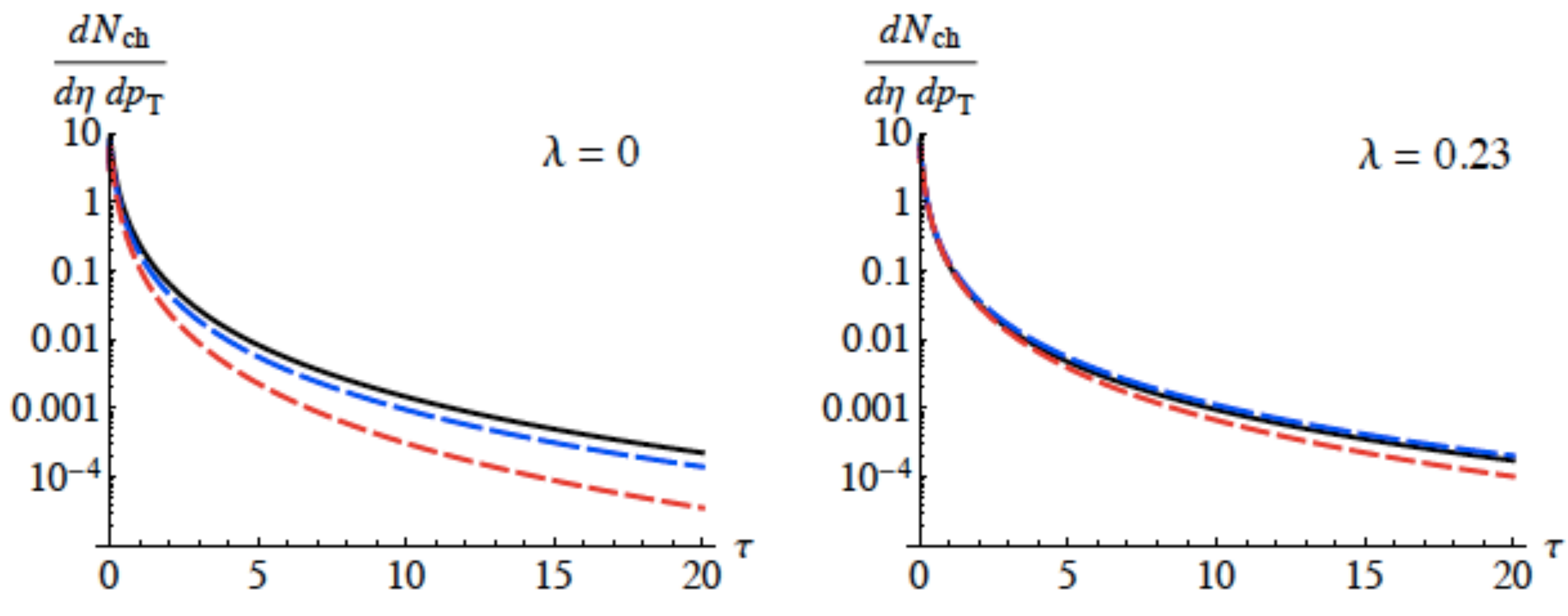


Geometric Scaling of transverse momentum distributions

$$\frac{1}{\sigma}\frac{dN_{\rm ch}}{d\eta d^2p_{\rm T}} = F\left(\frac{p_{\rm T}}{Q_{\rm sat}(p_{\rm T}/\sqrt{s})}\right)$$

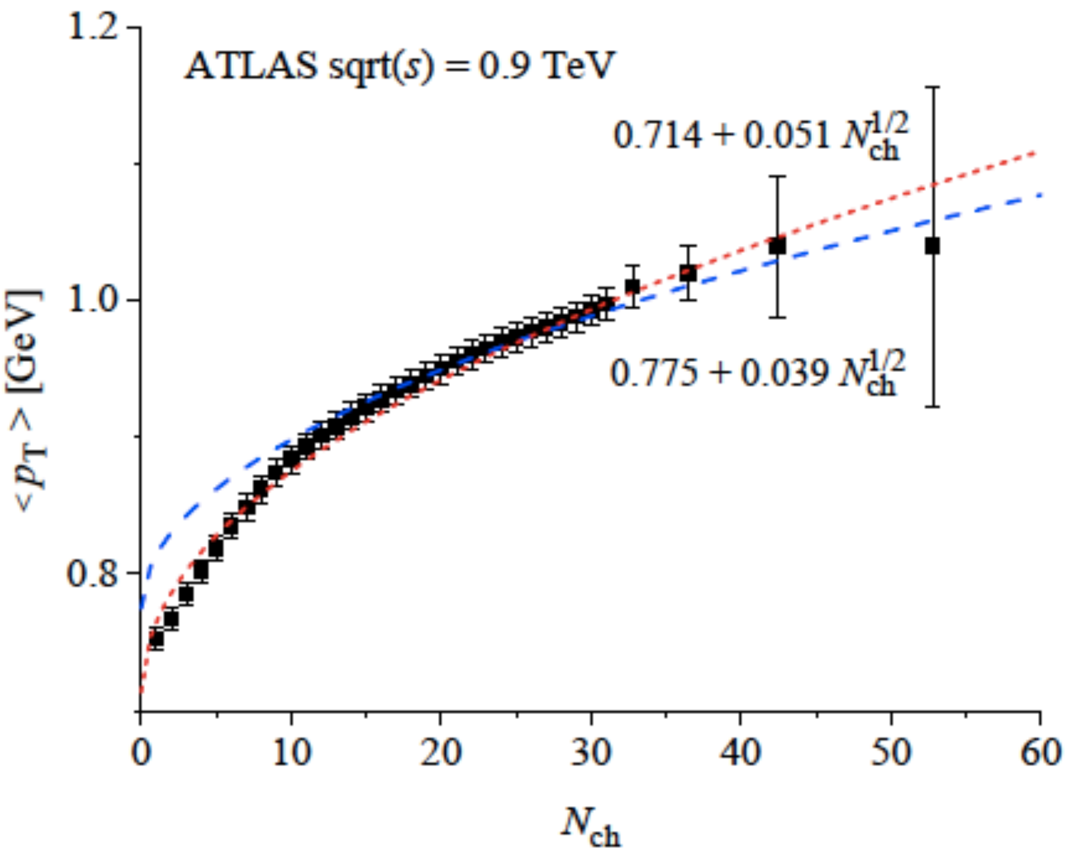
$$\tau = \frac{p_{\rm T}^2}{Q_{\rm sat}^2(p_{\rm T}/\sqrt{s})} = \frac{p_{\rm T}^2}{1\,{\rm GeV}^2}\left(\frac{p_{\rm T}}{\sqrt{s}\times 10^{-3}}\right)^{\lambda}$$

$$\frac{dN_{\rm ch}}{d\eta d^2p_{\rm T}} = C\frac{p}{E}\frac{dN_{\rm ch}}{d\eta}\left(1+\frac{E_T}{nT}\right)^{-n}$$



Multiplicity Fluctuations and Transverse Momentum

$$< p_T >\sim Q_{sat} \sim \sqrt{N/\sigma}$$



The EIC

Data for RHIC indicate that for

$$x \sim 10^{-2} - 10^{-3}$$

a number of effects that can be ascribed to saturation are rapidly turning on for large nuclei

Would like precise tests of the CGC hypothesis.

Is the theory capable of precise computations for such values of the saturation momentum?

$$Q_{sat} \sim 1 - 2GeV$$

Is it possible to get precise results for nuclei on interesting quantities such as the longitudinal structure function?