Probing the Properties of QCD with Atomic Nuclei: Theoretical Aspects

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Outline

- The big picture
- Small-x Physics and Saturation
  - Main Saturation Concepts
    (Strong Fields, Weak Coupling, Nonlinear Effects)
  - Relevant Observables
- Large-x Physics in e+A
- Connections to other fields
- Conclusions

The Big Picture

Fundamental Questions in QCD

- Confinement, chiral symmetry breaking, quantitative understanding of hadron masses, structure of the nucleon and the nucleus.

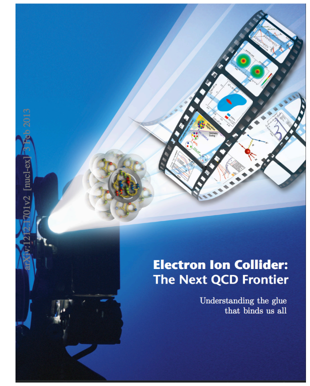
- QCD under extreme conditions: finite-T (heavy ions, Early Universe), finite-μ (neutron stars), high energy QCD asymptotics.

Fundamental Questions of QCD **at EIC**

- Confinement, chiral symmetry breaking, quantitative understanding of hadron masses, **structure of the nucleon and the nucleus**.

- QCD under extreme conditions: finite-T (heavy ions, Early Universe), finite-μ (neutron stars), **high energy QCD asymptotics**.

Big Questions EIC Would Address



- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
- Where does the saturation of gluon densities set it? What is the dynamics? Is it universal?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

Fundamental Questions in e+A

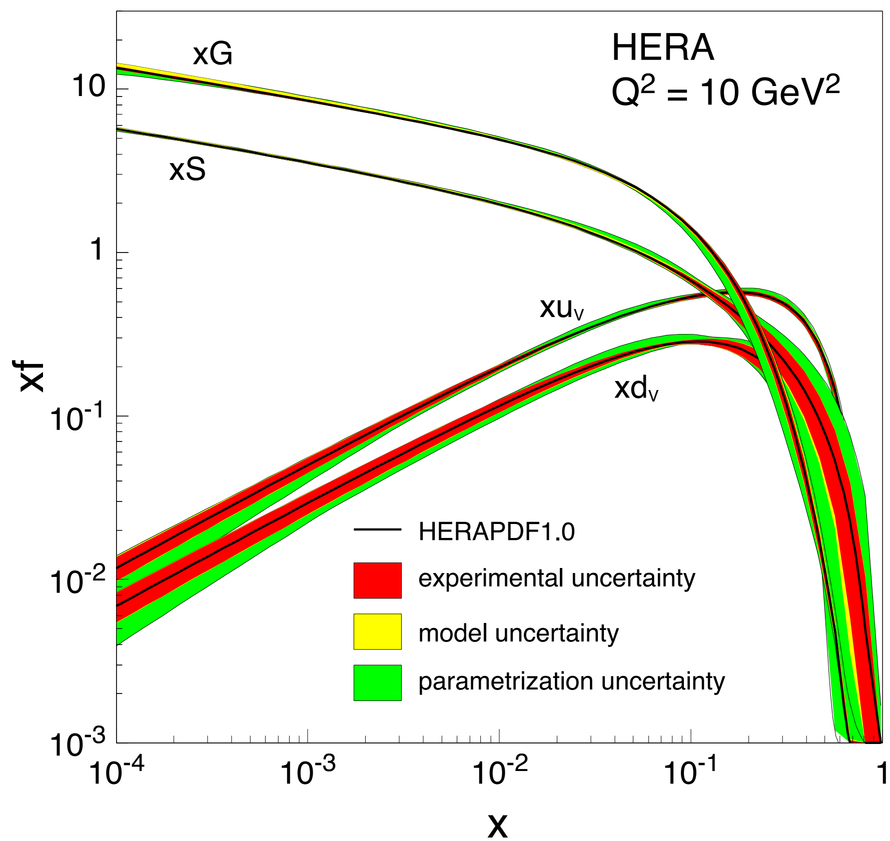
- What is the role of strong gluon fields, parton saturation effects, and collective gluon excitations in nuclei?
- Can we experimentally find evidence of nonlinear QCD dynamics in the high-energy scattering off nuclei?
- What is the momentum distribution of gluons and sea quarks in nuclei? What is the spatial distribution of gluons and sea quarks in nuclei?
- Are there strong color (quark and gluon density) fluctuations inside a large nucleus? How does the nucleus respond to the propagation of a color charge through it?

Small-x Physics and Saturation

A. Main Concepts

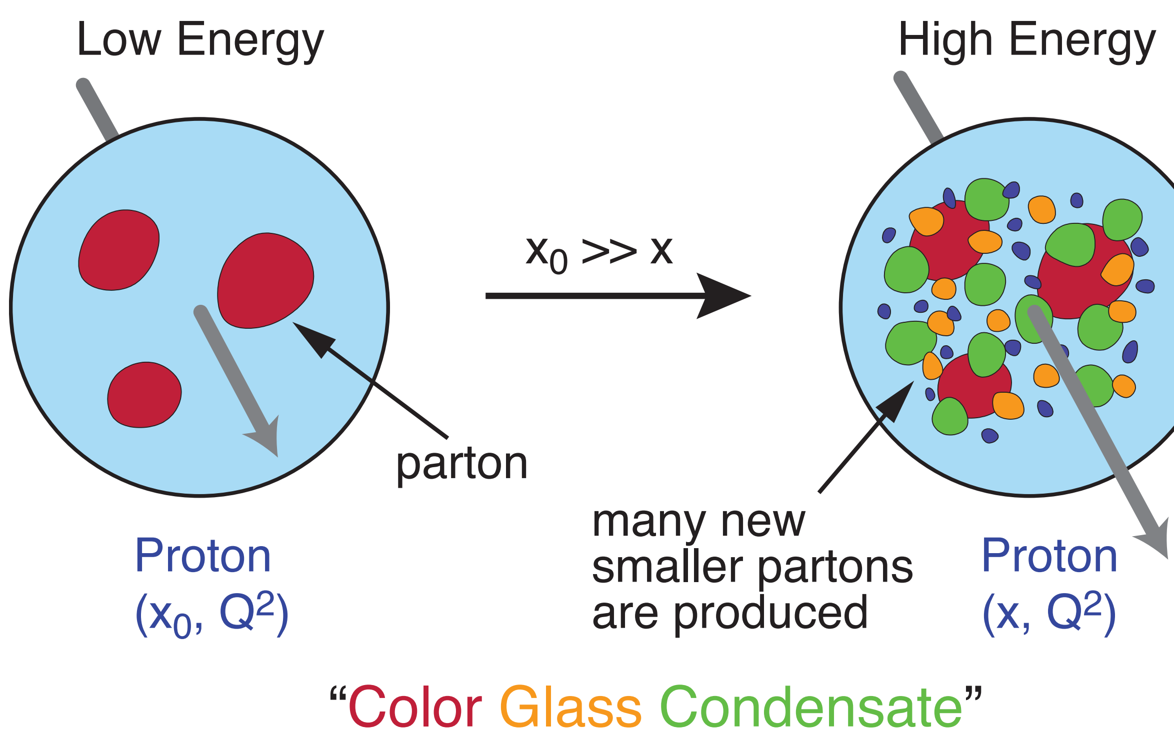
Gluons at Small-x

- There is a large number of small-x gluons (and quarks) in a proton:



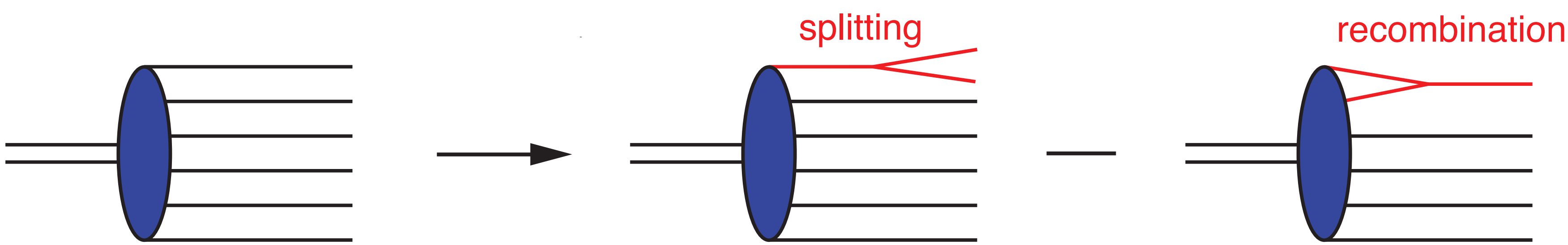
High Density of Gluons

- High number of gluons populates the transverse extent of the proton or nucleus, leading to a very dense saturated wave function known as the Color Glass Condensate (CGC):



Nonlinear Equation

At very high energy gluon recombination becomes important. As energy (rapidity) increases, gluons not only split into more gluons, but also recombine. Recombination reduces the number of gluons in the wave function. Here Y~ln s~ln 1/x is rapidity, s is cms energy.

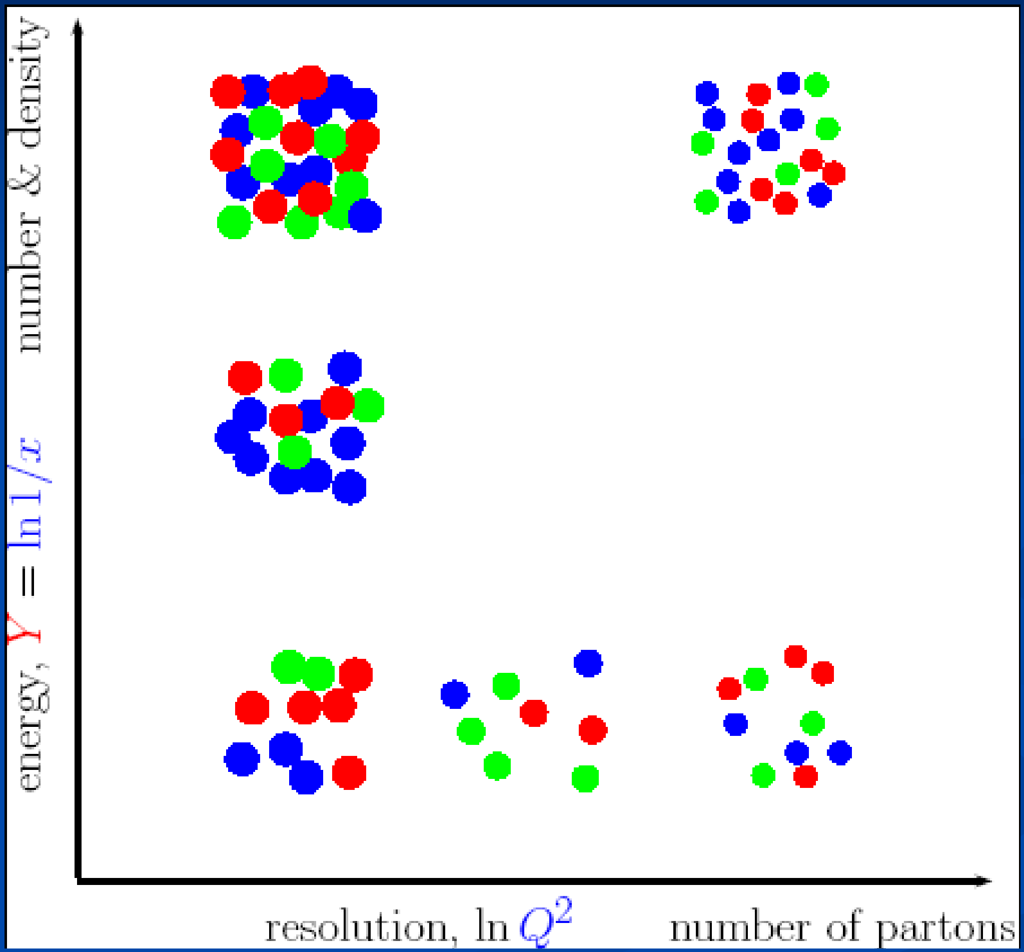


$$\frac{\partial}{\partial Y} N(x, k_T^2) = \alpha_s K_{BFKL} \otimes N(x, k_T^2) - \alpha_s [N(x, k_T^2)]^2$$

Number of gluon pairs ~ N^2

I. Balitsky ’96, Yu. K. ’99;
JIMWLK ‘98-’01

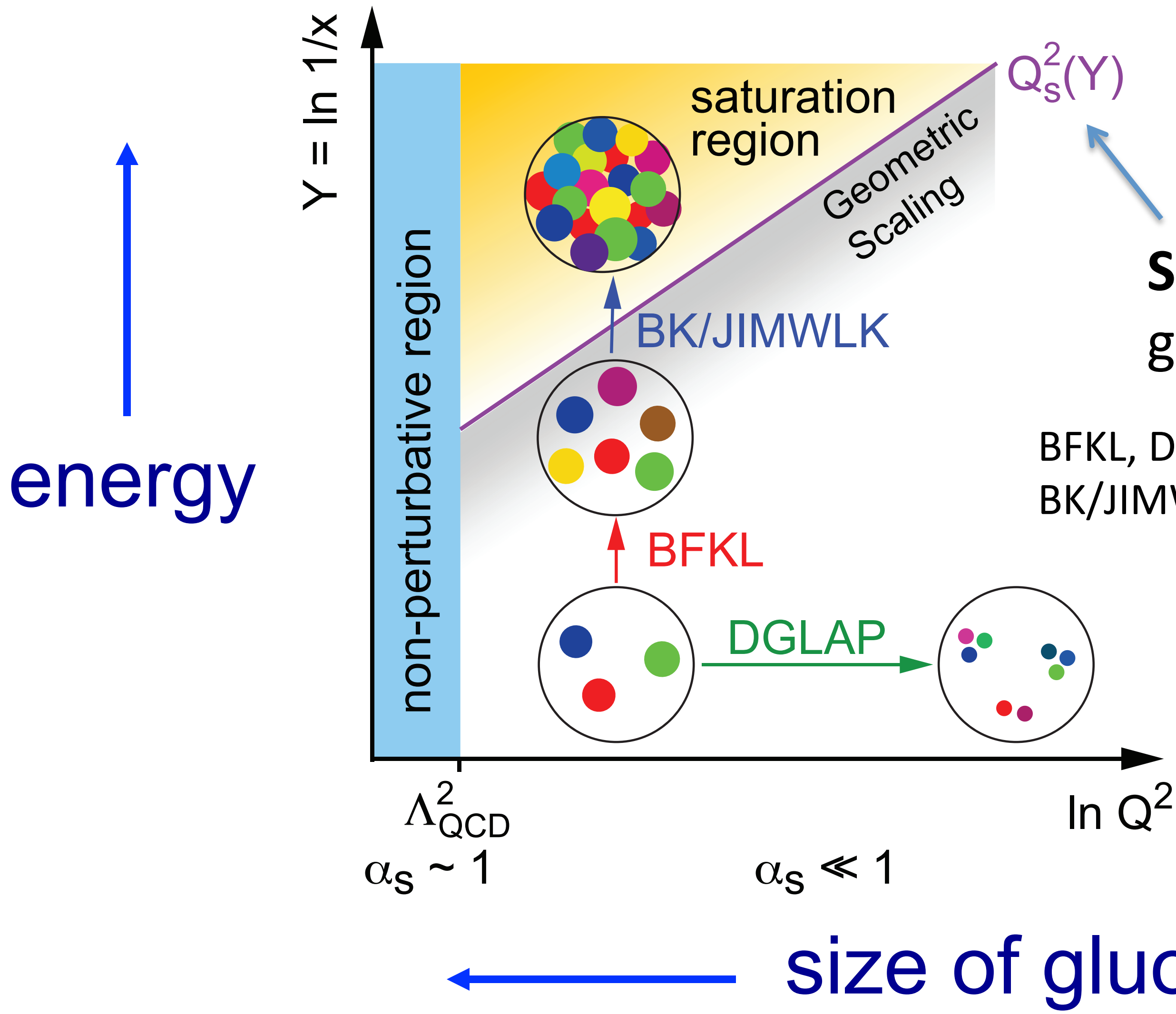
Map of High Energy QCD



energy

size of gluons

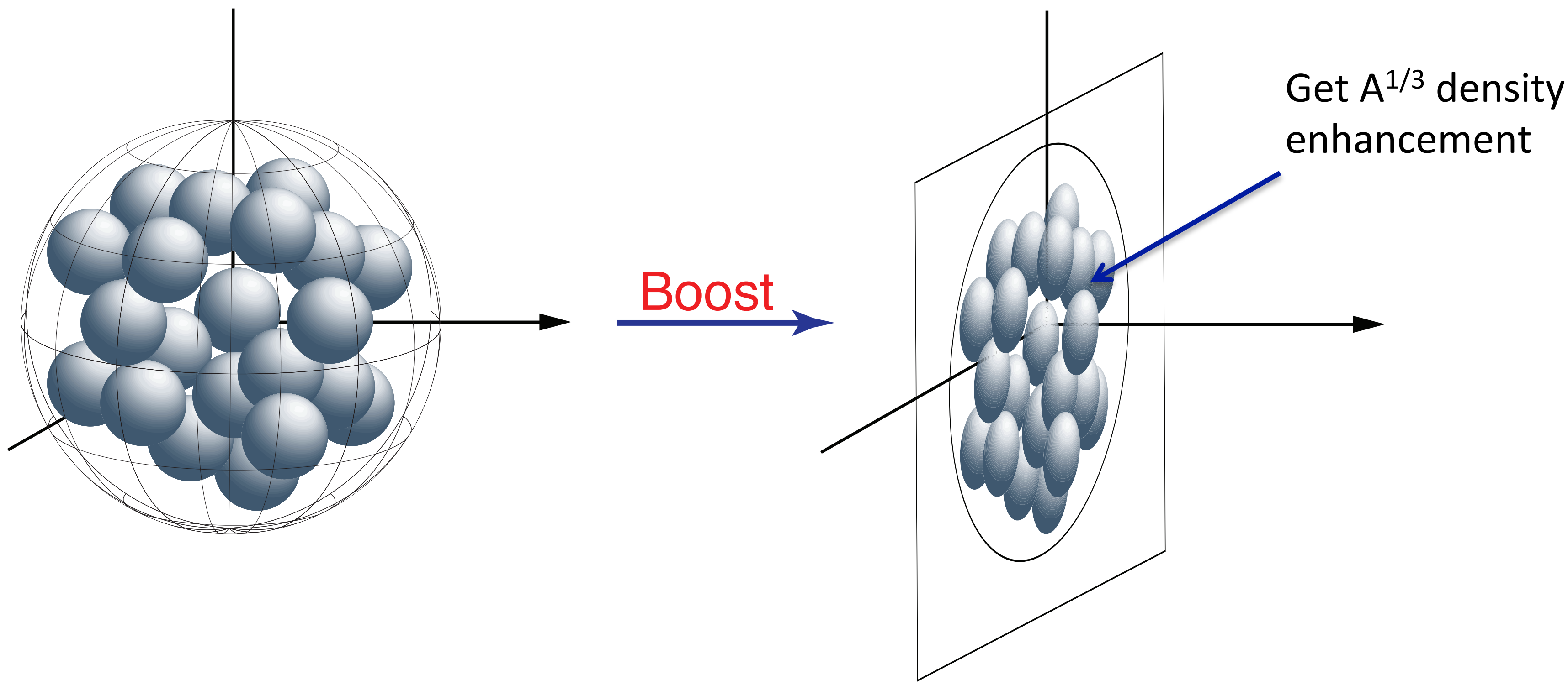
Map of High Energy QCD



Saturation Scale
grows with energy

BFKL, DGLAP – linear equations
BK/JIMWLK – nonlinear

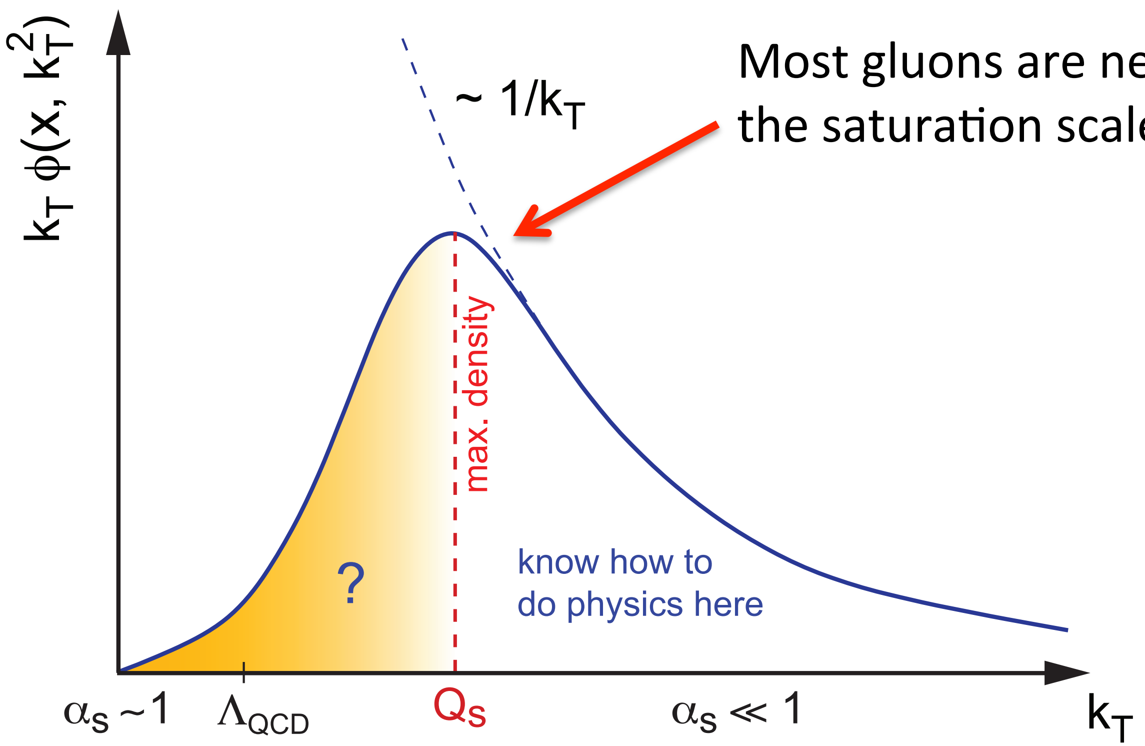
McLerran-Venugopalan Model



- Large gluon density gives a large momentum scale Q_s (the saturation scale): Q_s^2 ~ # gluons per unit transverse area ~ $A^{1/3}$.
- For $Q_s >> \Lambda_{QCD}$, get a theory at weak coupling $\alpha_s(Q_s^2) \ll 1$ and the leading gluon field is classical.

Typical gluon "size"

Number of gluons (gluon TMD) times the phase space



Most gluons are near the saturation scale Q_s.

momentum transverse to the beam

Gluon "size" = 1/transverse momentum

= $1/Q_s$

High Energy QCD: saturation physics

- The nonlinear BK/JIMWLK equations and the MV model lead to a large internal momentum scale Q_S which grows with both the decreasing x / increasing energy s ($\lambda \approx 0.3$) and the increasing nuclear atomic number A

$$Q_S^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

such that

$$\alpha_S = \alpha_S(Q_S) << 1$$

and we can calculate total cross sections, particle multiplicities, correlations, etc. , from first principles.

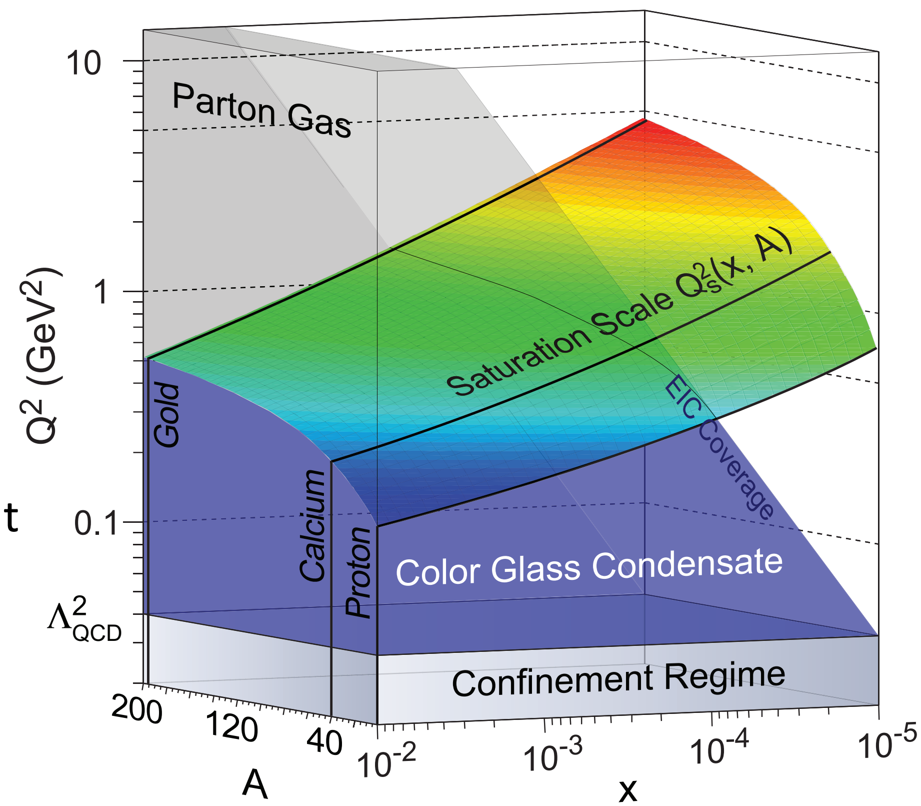
- Bottom line: coupling is weak, Feynman diagrams work.
But: the system is dense and physics is nonlinear!

Saturation Scale

To summarize, saturation scale is an increasing function of both energy (1/x) and A:

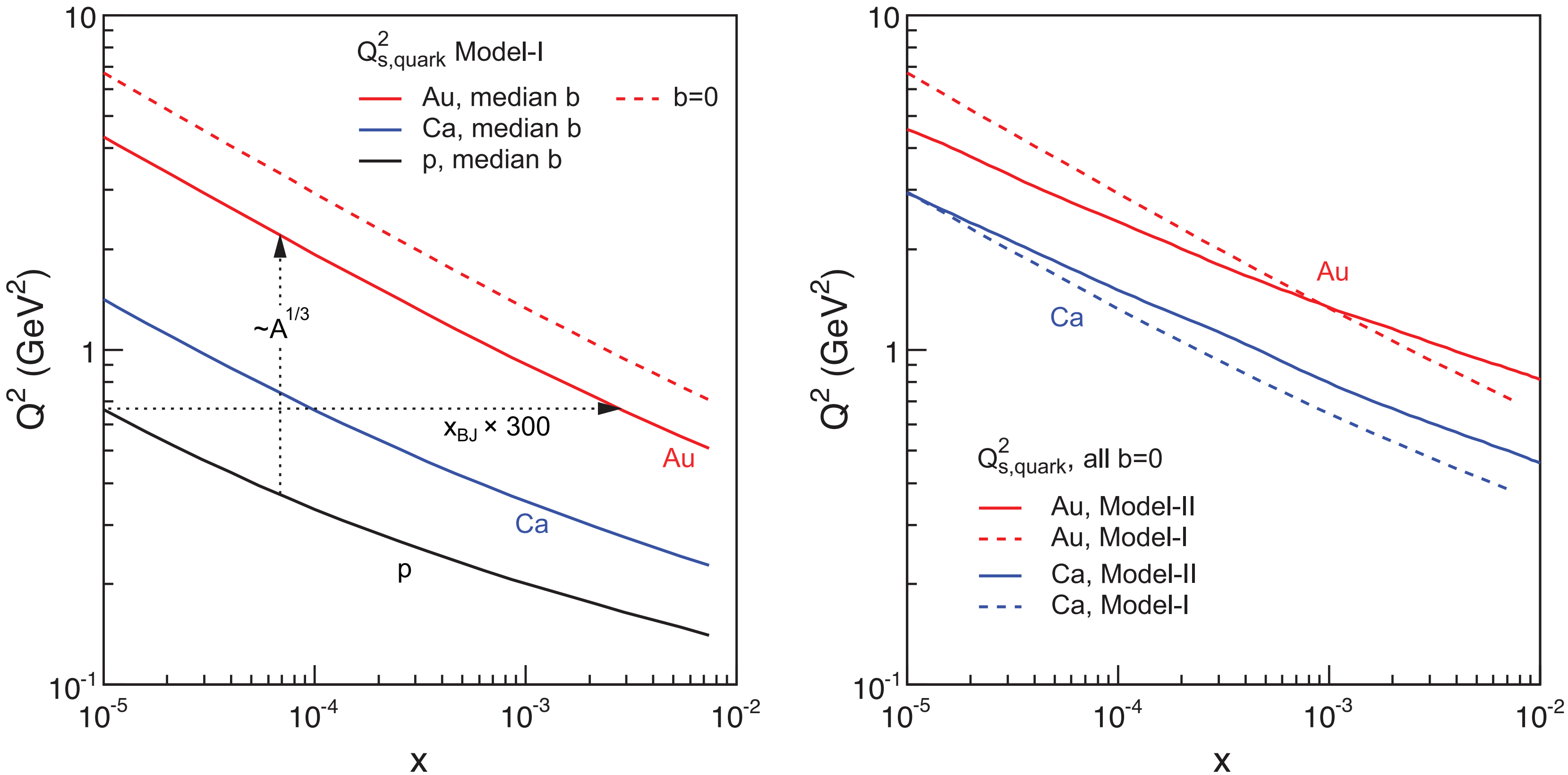
$$Q_s^2 \sim \left(\frac{A}{x}\right)^{1/3}$$

Gold nucleus provides an enhancement by $197^{1/3}$, which is equivalent to doing scattering on a proton at 197 times smaller-x / higher-s!



Saturation Scales at EIC

Model I = MV-inspired dipole model
Model II = running-coupling BK evolution (rcBK)

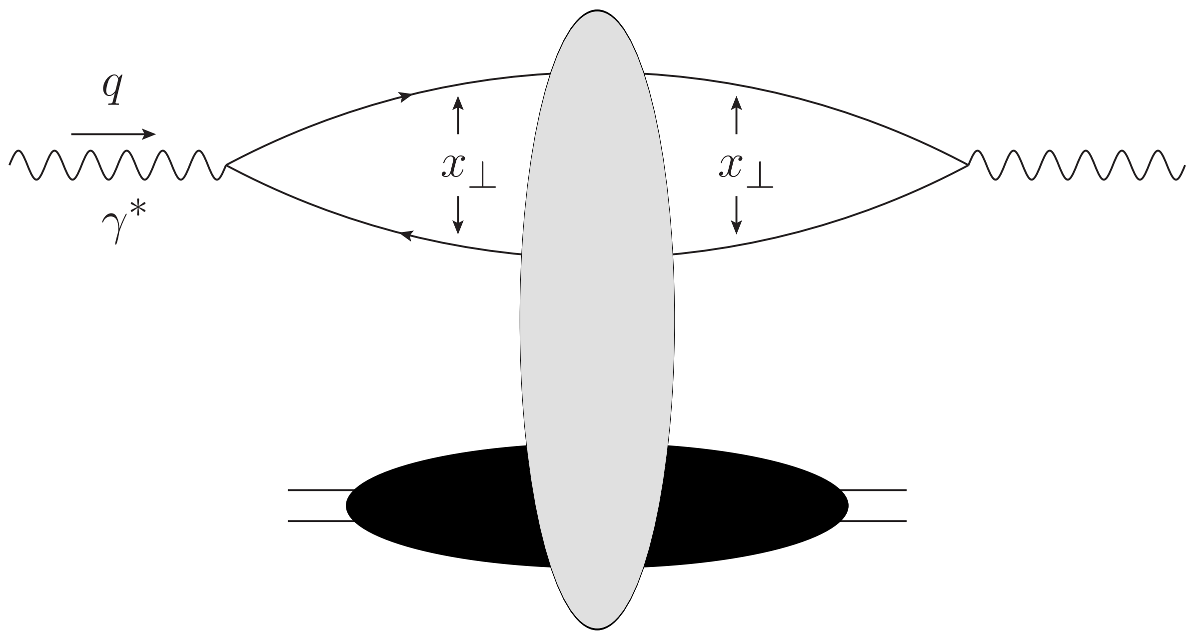


The difference in Q_s values is minimal in the EIC range.
Still theoretical uncertainty remains.

B. Relevant Observables

Dipole picture of DIS

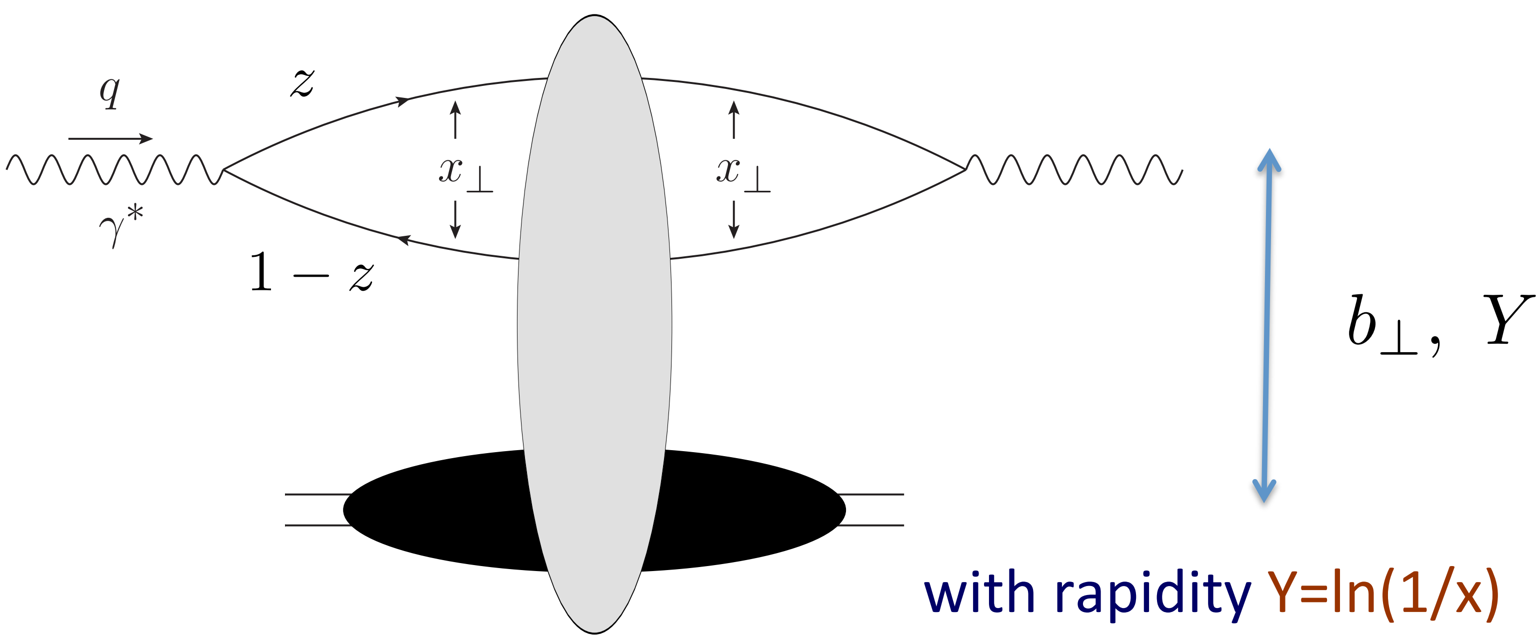
- In the dipole picture of DIS the virtual photon splits into a quark-antiquark pair, which then interacts with the target.
- The total DIS cross section and structure functions are calculated via:



Dipole Amplitude

- The total DIS cross section is expressed in terms of the (Im part of the) forward quark dipole amplitude N:

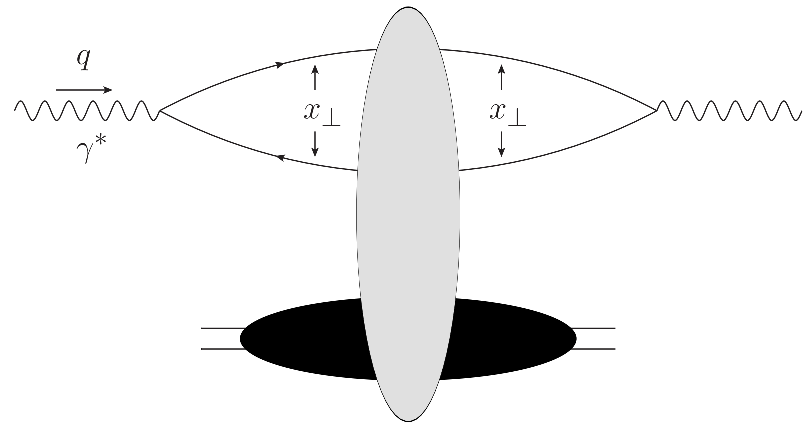
$$\sigma_{tot}^{\gamma^* A} = \int \frac{d^2 x_\perp}{2\,\pi}\, d^2 b_\perp \int_0^1 \frac{dz}{z\,(1-z)}\; |\Psi^{\gamma^* \to q\bar{q}}(\vec{x}_\perp, z)|^2\; N(\vec{x}_\perp, \vec{b}_\perp, Y)$$

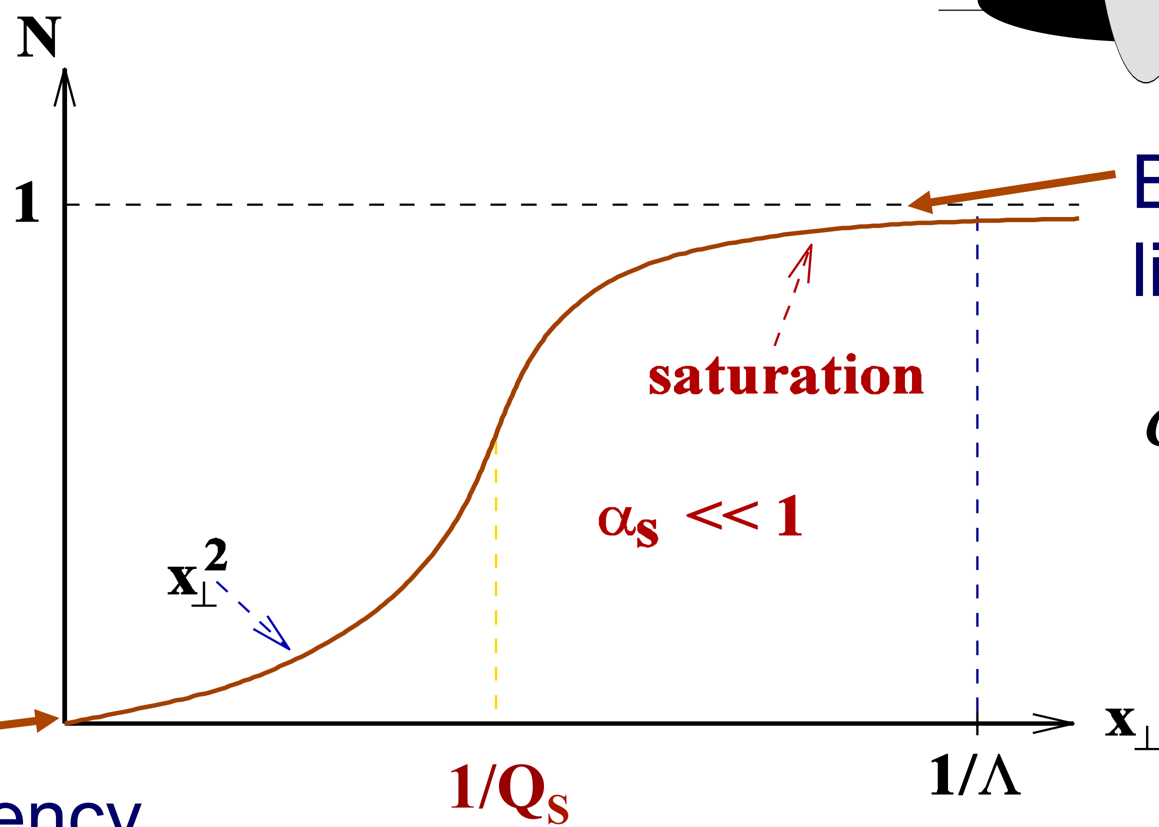


with rapidity Y=ln(1/x)

Dipole Amplitude

The dipole-nucleus amplitude
as a function of the dipole size is



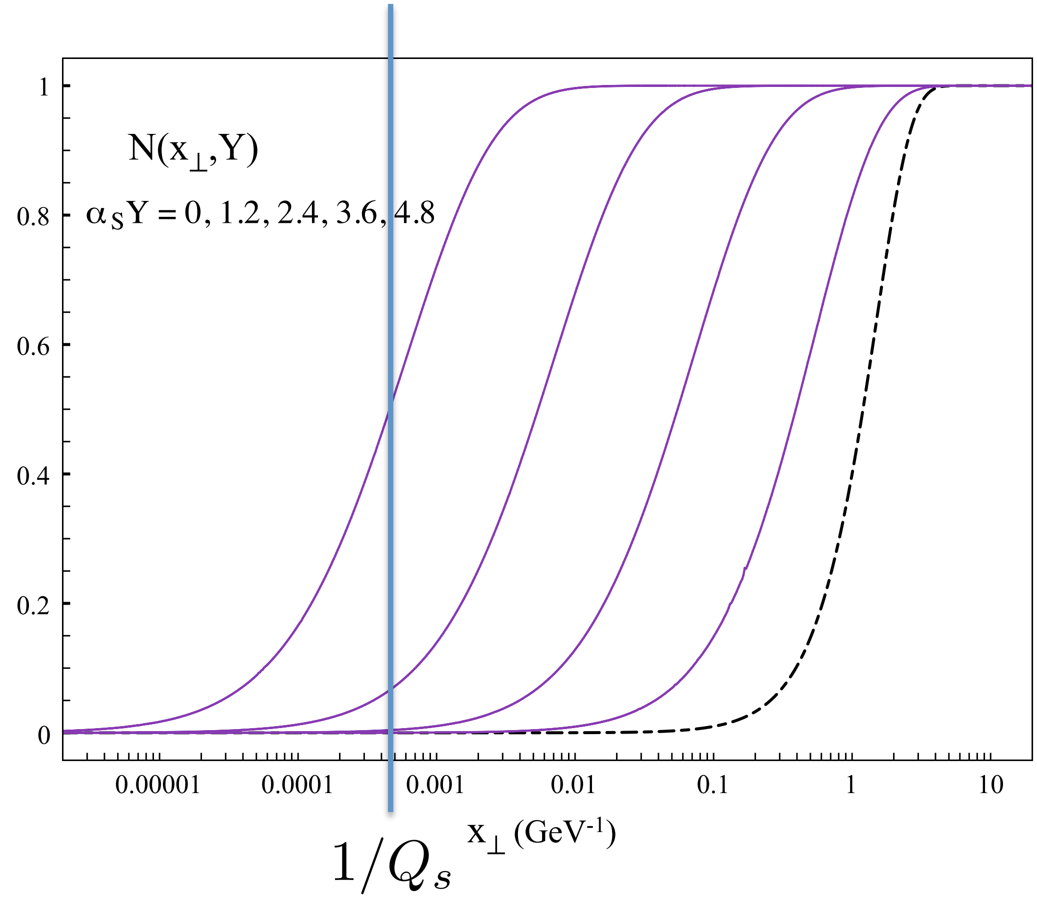


Black disk limit,

$$\sigma_{tot} < 2\pi R^2$$

Color transparency

Evolution of the Dipole Amplitude with Rapidity

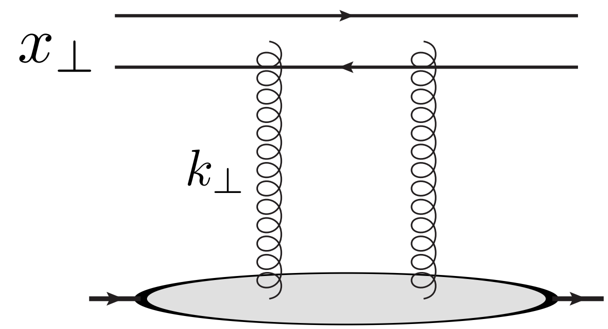


numerical solution
by J. Albacete '03

BK solution preserves the black disk limit (N<1):

$$\sigma^{q\bar{q}A} = 2 \int d^2b \, N(x_\perp, b_\perp, Y)$$

Dipole Amplitude as a Probe of Spatial Gluon Distribution



- Dipole amplitude is related to gluon distribution.
- It is related to the Wigner distribution for low-x gluons:

$$N(\vec{x}_\perp, \vec{b}_\perp, Y = \ln 1/x_{Bj}) \Leftarrow (\text{Fourier transform}) \Rightarrow W(\vec{k}_\perp, \vec{b}_\perp, x_{Bj})$$

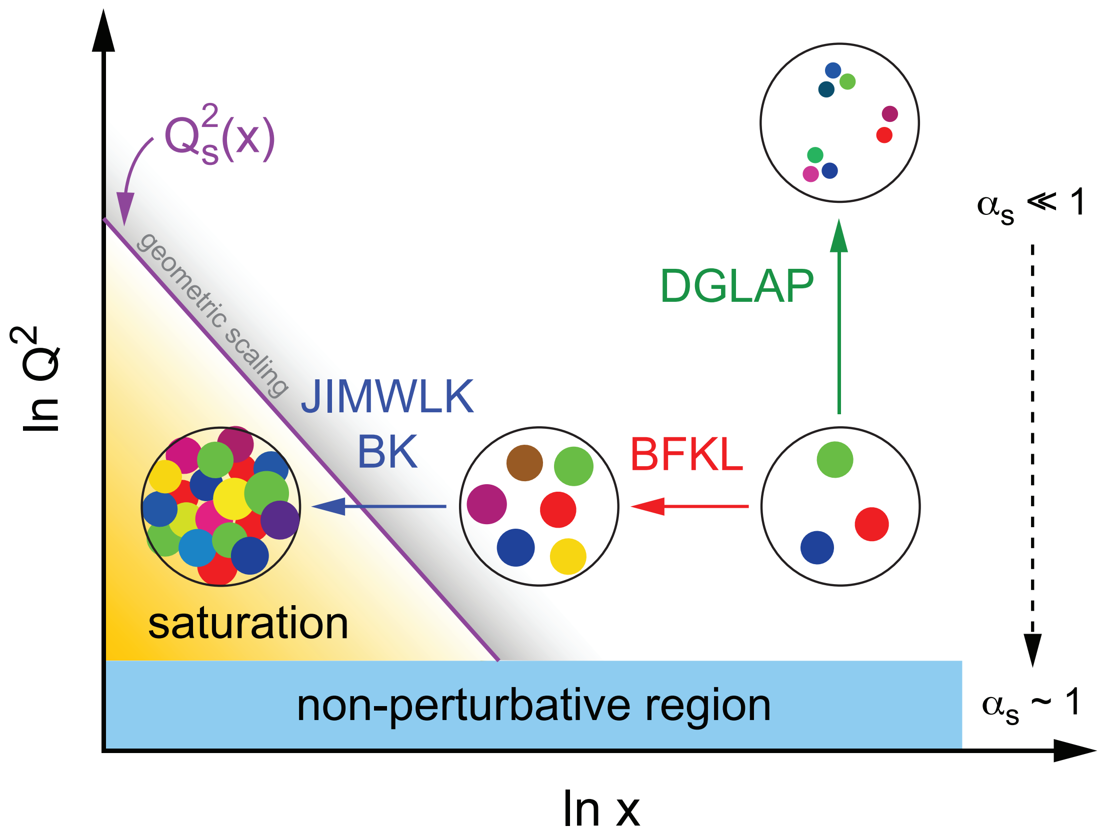
- Just like for the Wigner distribution, one can extract the gluon transverse momentum distribution (TMD) out of it:

$$\int d^2 b_\perp \, N(\vec{x}_\perp, \vec{b}_\perp, Y = \ln 1/x_{Bj}) \Leftarrow (\text{Fourier transform}) \Rightarrow f(\vec{k}_\perp, x_{Bj})$$

- Dipole amplitude gives us information about the spatial distribution of small-x gluons.

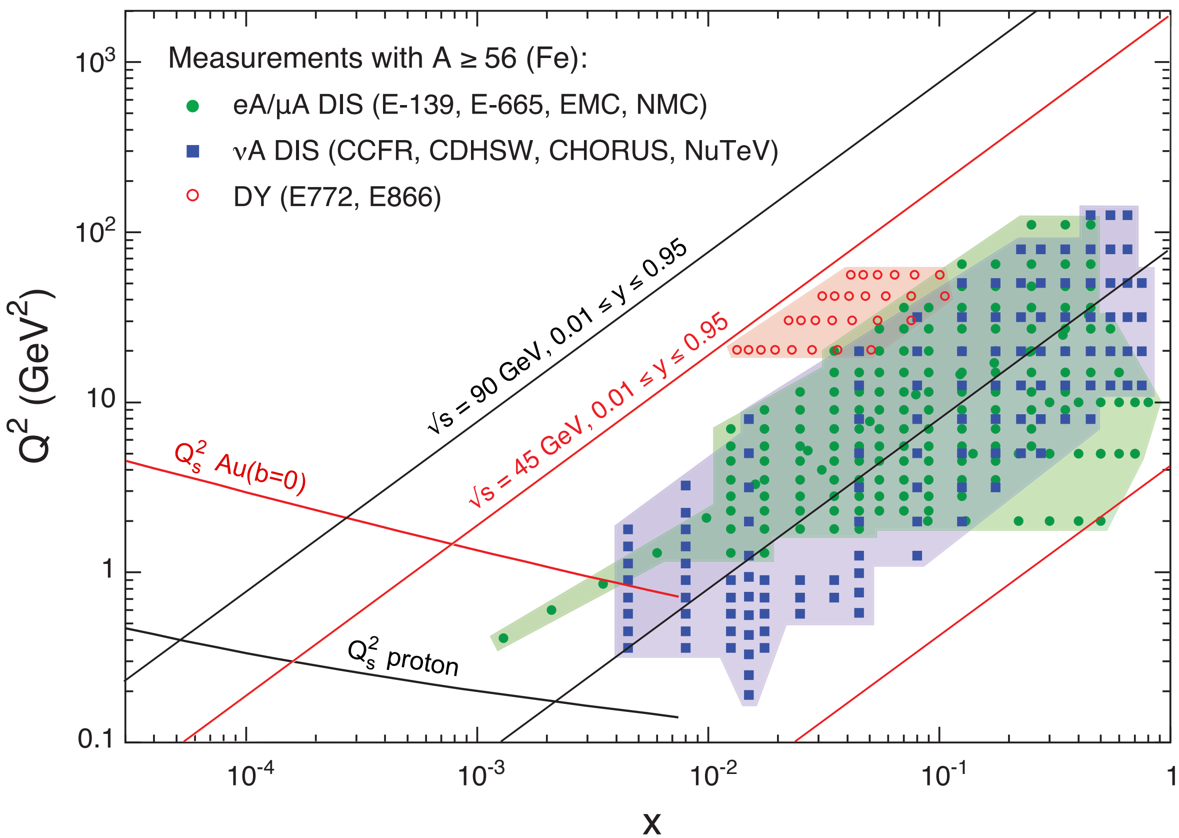
Can Saturation be Discovered at EIC?

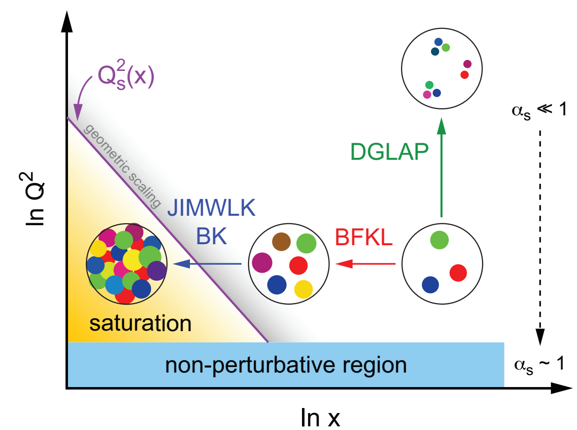
EIC has an unprecedented small-x reach for DIS on large nuclear targets, allowing to seal the discovery of saturation physics and study of its properties:



Can Saturation be Discovered at EIC?

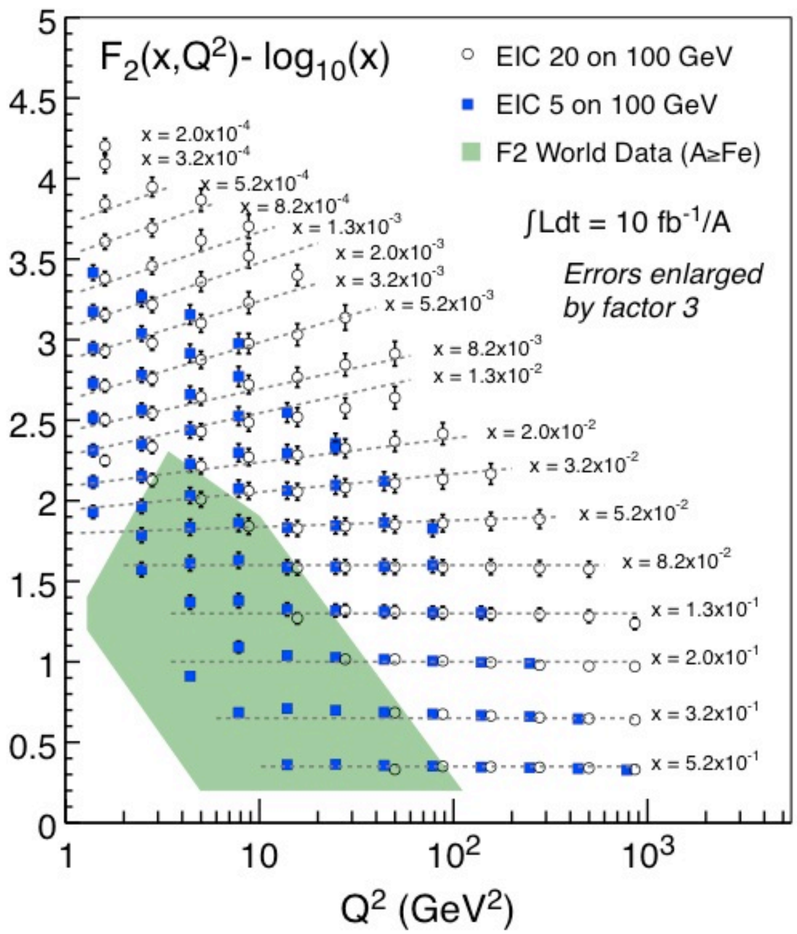
EIC has an unprecedented small-x reach for DIS on large nuclear targets, allowing to seal the discovery of saturation physics and study of its properties (see Thomas Ullrich's talk):



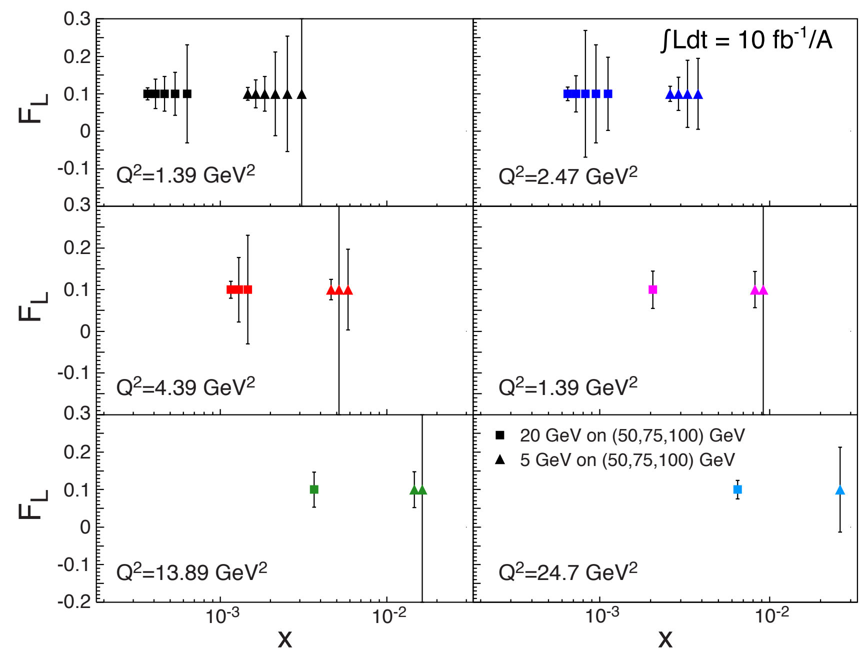


(i) Nuclear Structure Functions

Structure Function at EIC

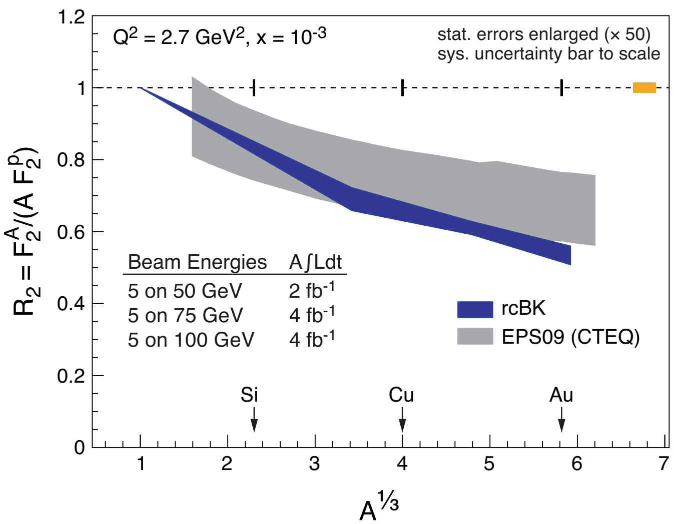


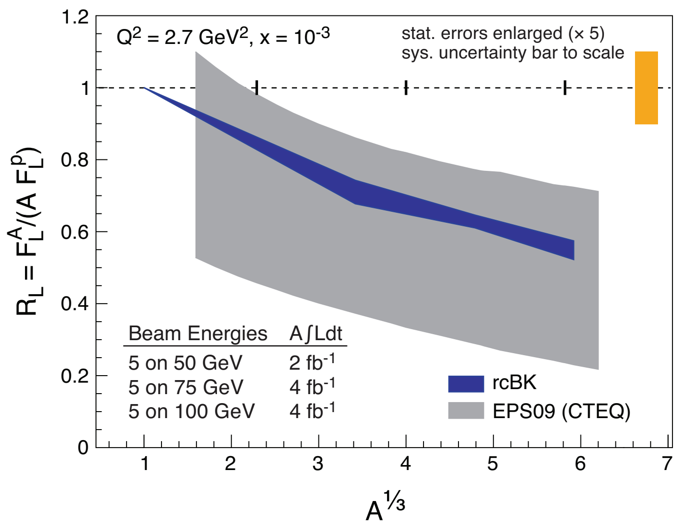
Nuclear structure functions F_2 and F_L which could be measured at EIC (values = EPS09+PYTHIA). Shaded area = (x, Q^2) range of world e+A data.

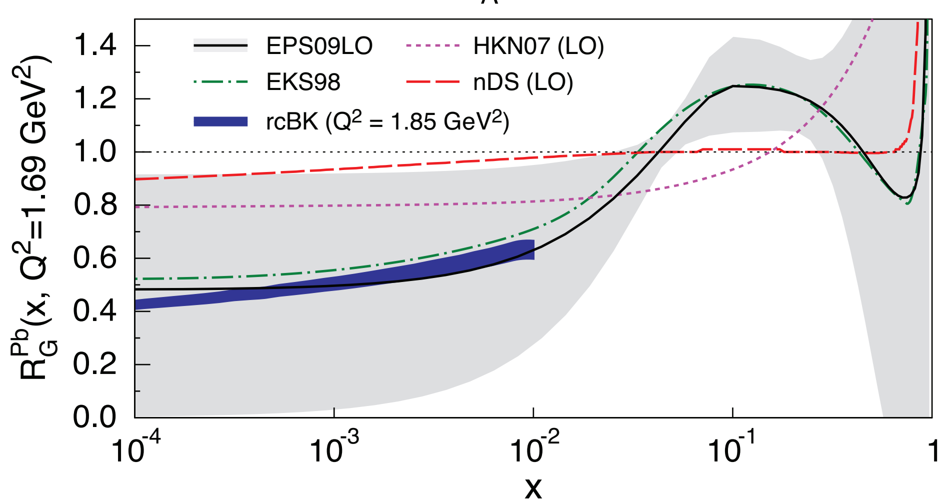


Nuclear Shadowing

- Saturation effects may explain to nuclear shadowing: reduction of the number of gluons per nucleon with decreasing x and/or increasing A:







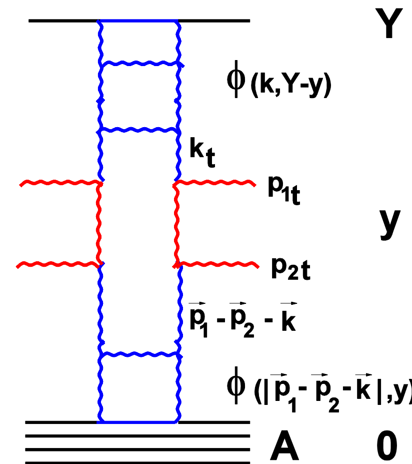
But: as DGLAP does not predict the x- and A-dependences, it needs to be constraint by the data to distinguish DGLAP from nonlinear evolution.

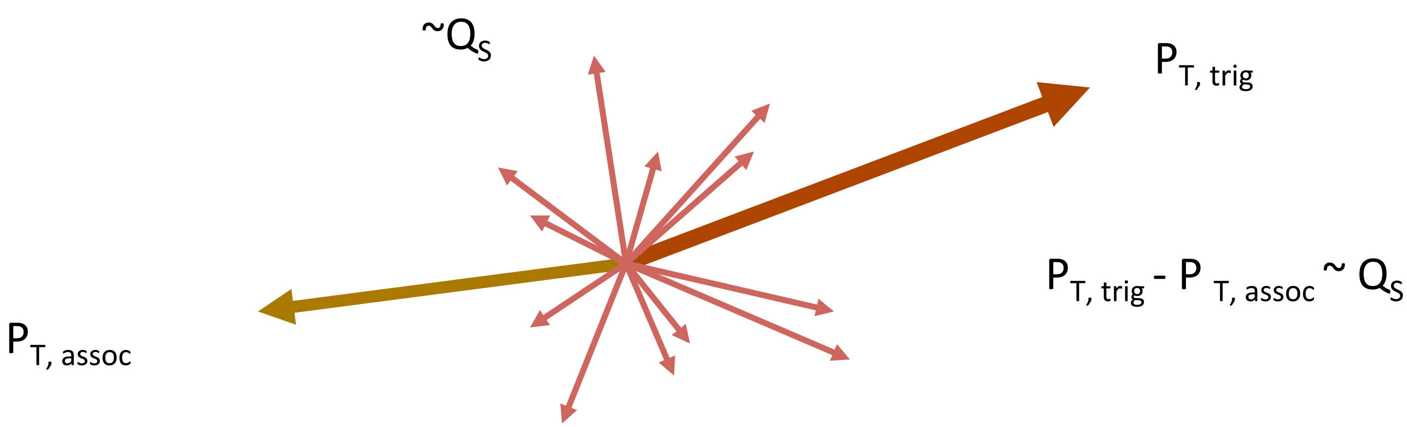
Note that including heavy flavors (charm) for F_2 and F_L should help **distinguish between the saturation versus non-saturation predictions** (see Thomas Ullrich's talk).

(ii) Di-Hadron Correlations

De-correlation

- Small-x evolution ↔ multiple emissions
- Multiple emissions → de-correlation.

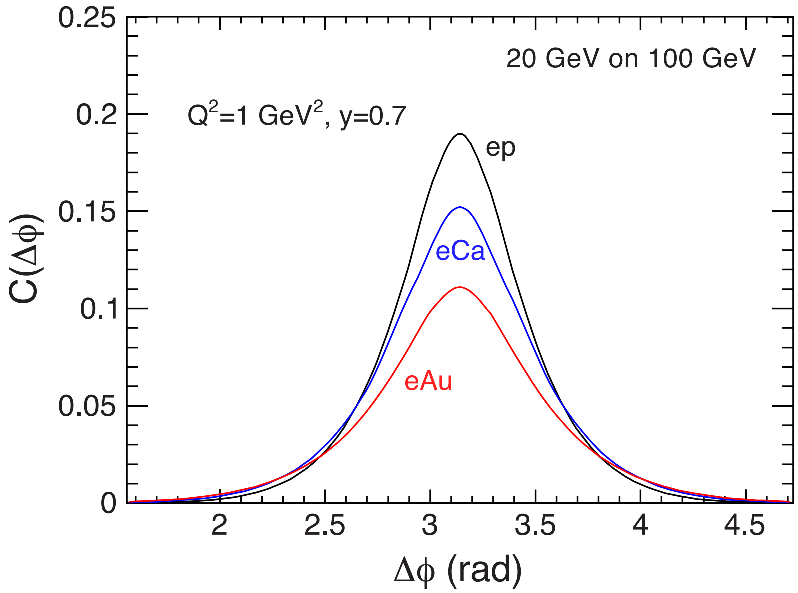


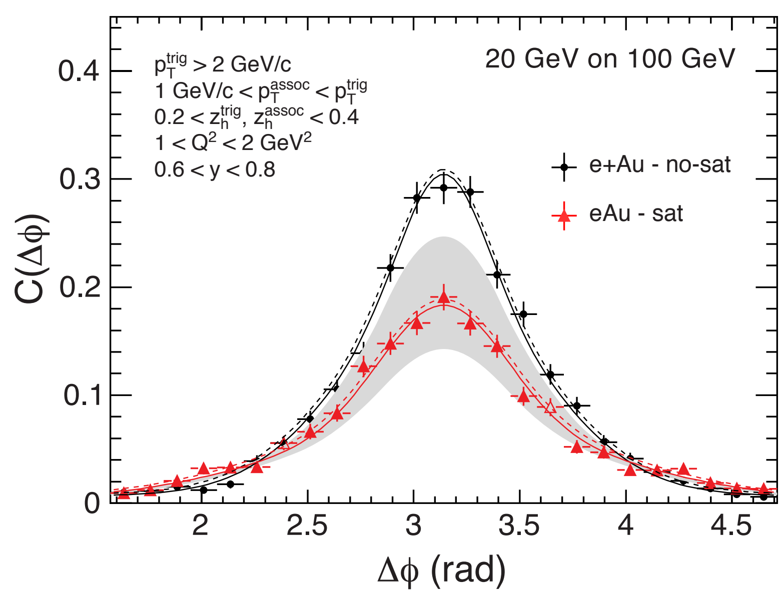


- B2B jets may get de-correlated in p_T with the spread of the order of Q_S

Di-hadron Correlations

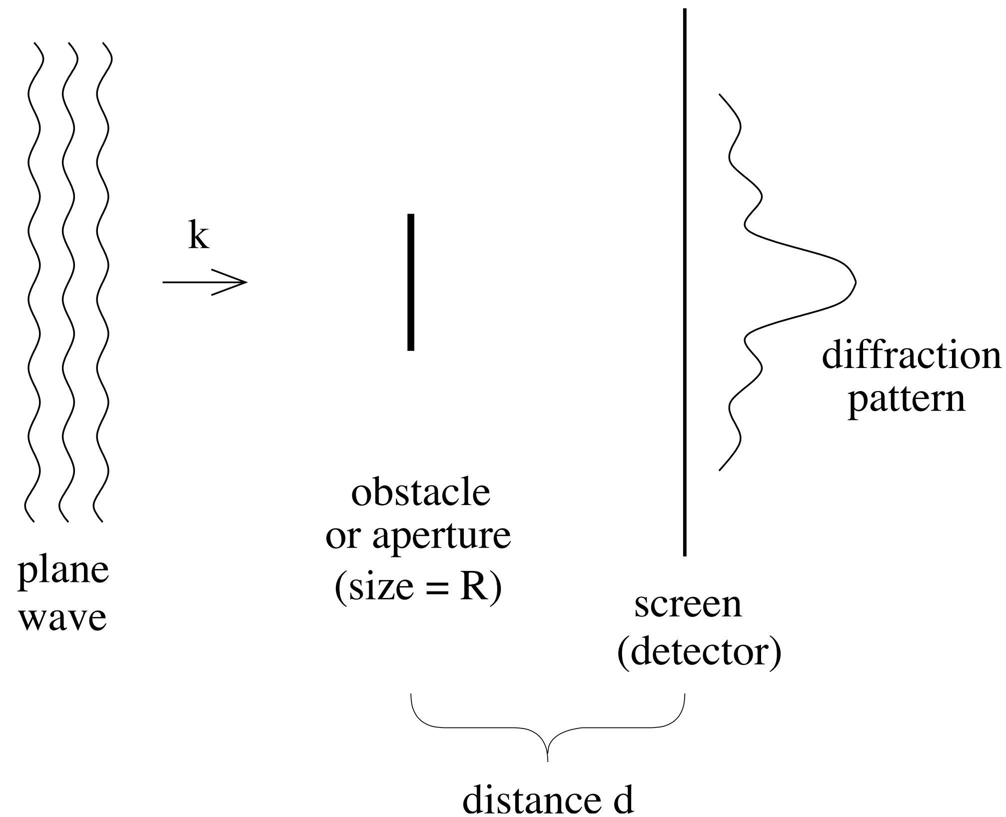
Depletion of di-hadron correlations is predicted for e+A as compared to e+p. (Domingue et al '11; Zheng et al '14). This is a **signal of saturation**.





(iii) Diffraction

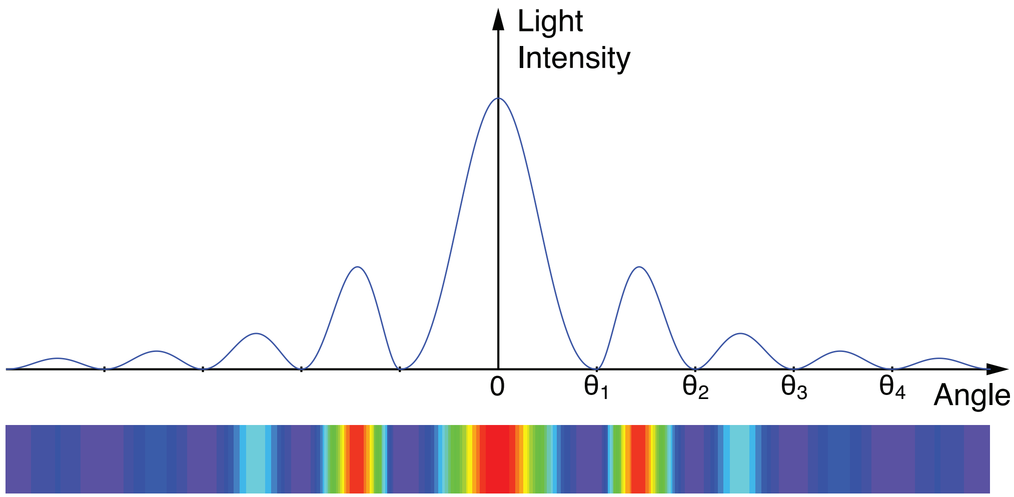
Diffraction in optics

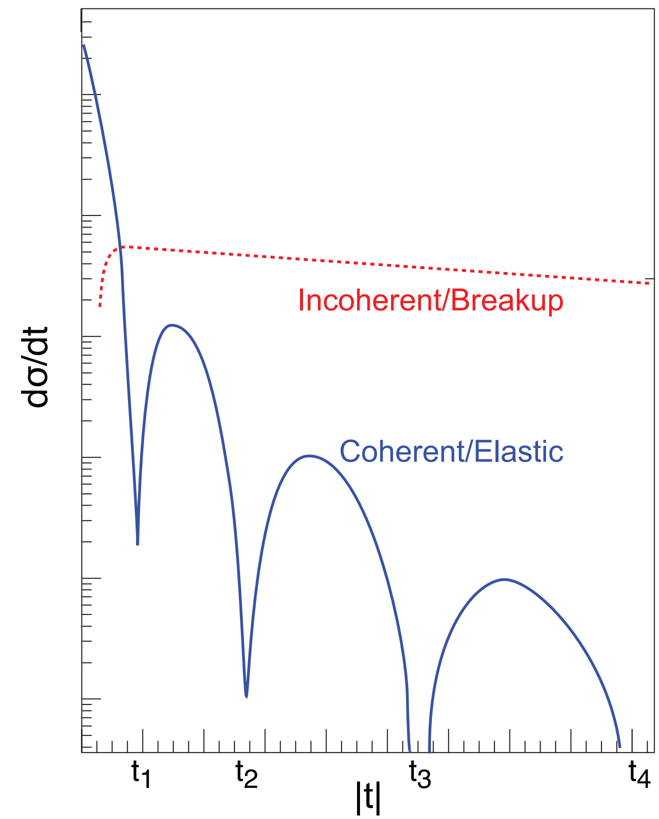


Diffraction pattern contains information about the size R of the obstacle and about the optical "blackness" of the obstacle.
In optics, diffraction pattern is studied as a function of the angle θ. In high energy scattering the diffractive cross sections are plotted as a function of the Mandelstam variable $t = k \sin \theta$.

Optical Analogy

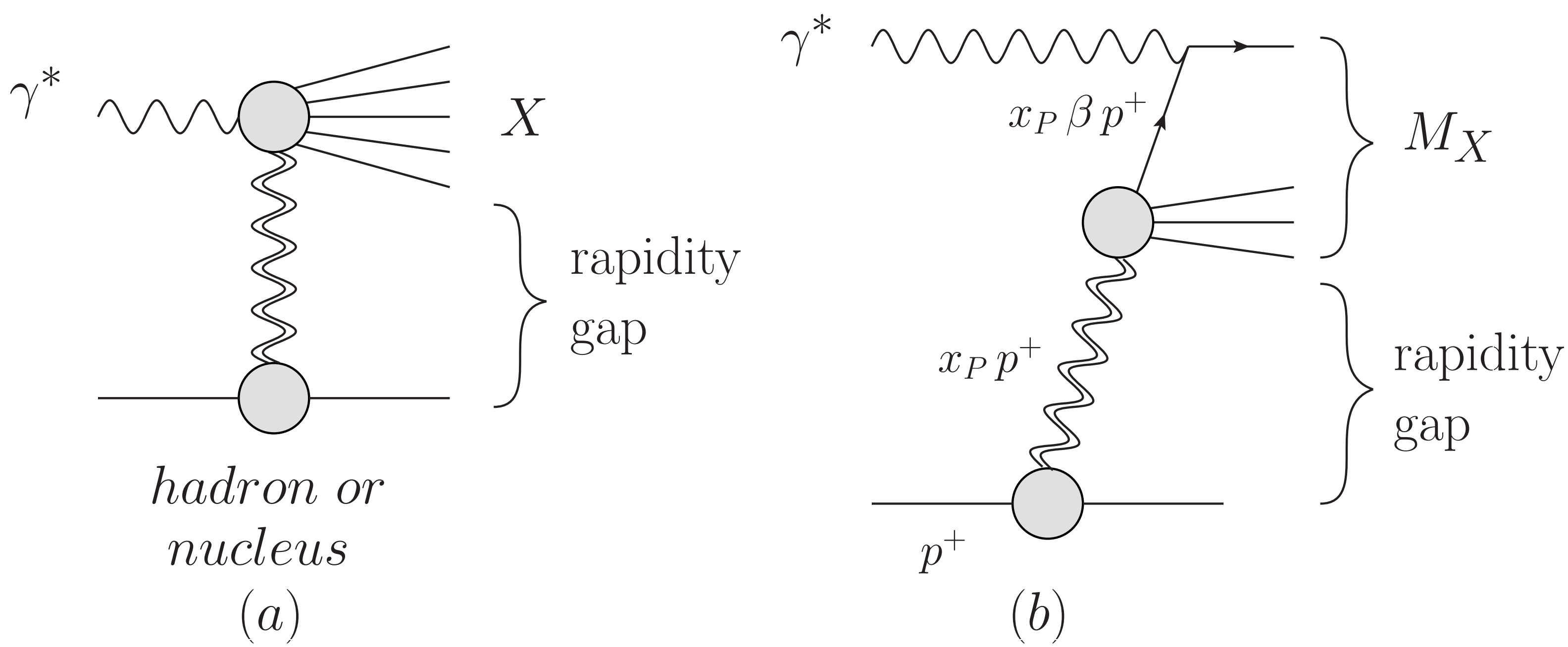
Diffraction in high energy scattering is not very different from diffraction in optics: both have diffractive maxima and minima:





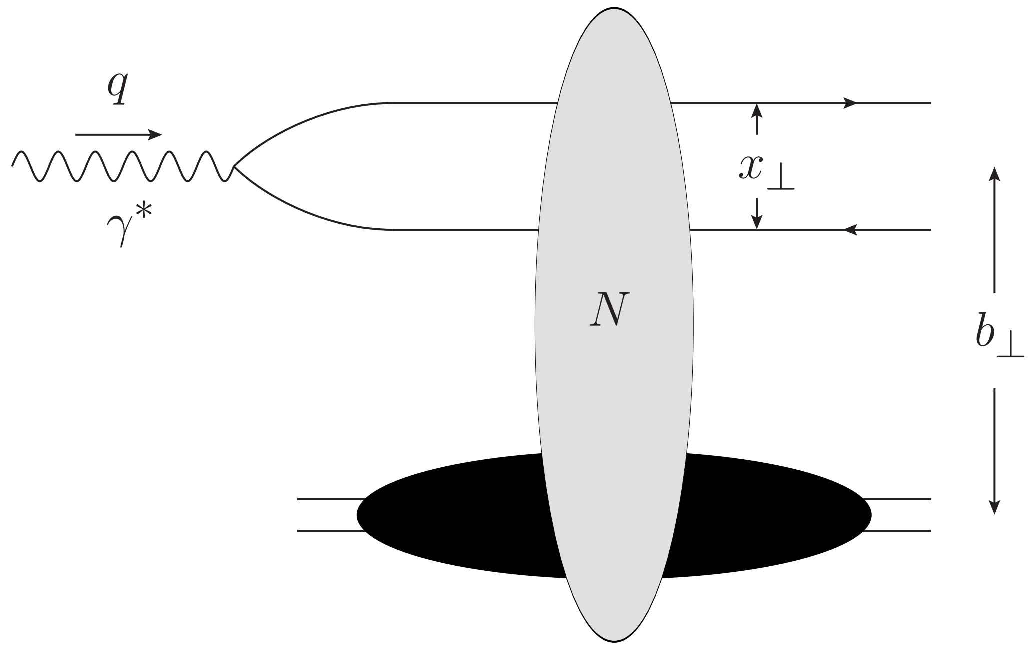
Coherent: target stays intact;
Incoherent: target nucleus breaks up, but nucleons are intact.

Diffraction terminology



Quasi-elastic DIS

Consider the case when nothing but the quark-antiquark pair (pions) is produced:



The quasi-elastic cross section is then

$$\sigma_{el}^{\gamma^* A} = \int \frac{d^2 x_\perp}{4\,\pi}\, d^2 b_\perp \int\limits_0^1 \frac{dz}{z\,(1-z)}\ |\Psi^{\gamma^* \to q\bar{q}}(\vec{x}_\perp, z)|^2\ N^2(\vec{x}_\perp, \vec{b}_\perp, Y)$$

Buchmuller et al '97, McLerran and Yu.K. '99

Diffraction on a black disk

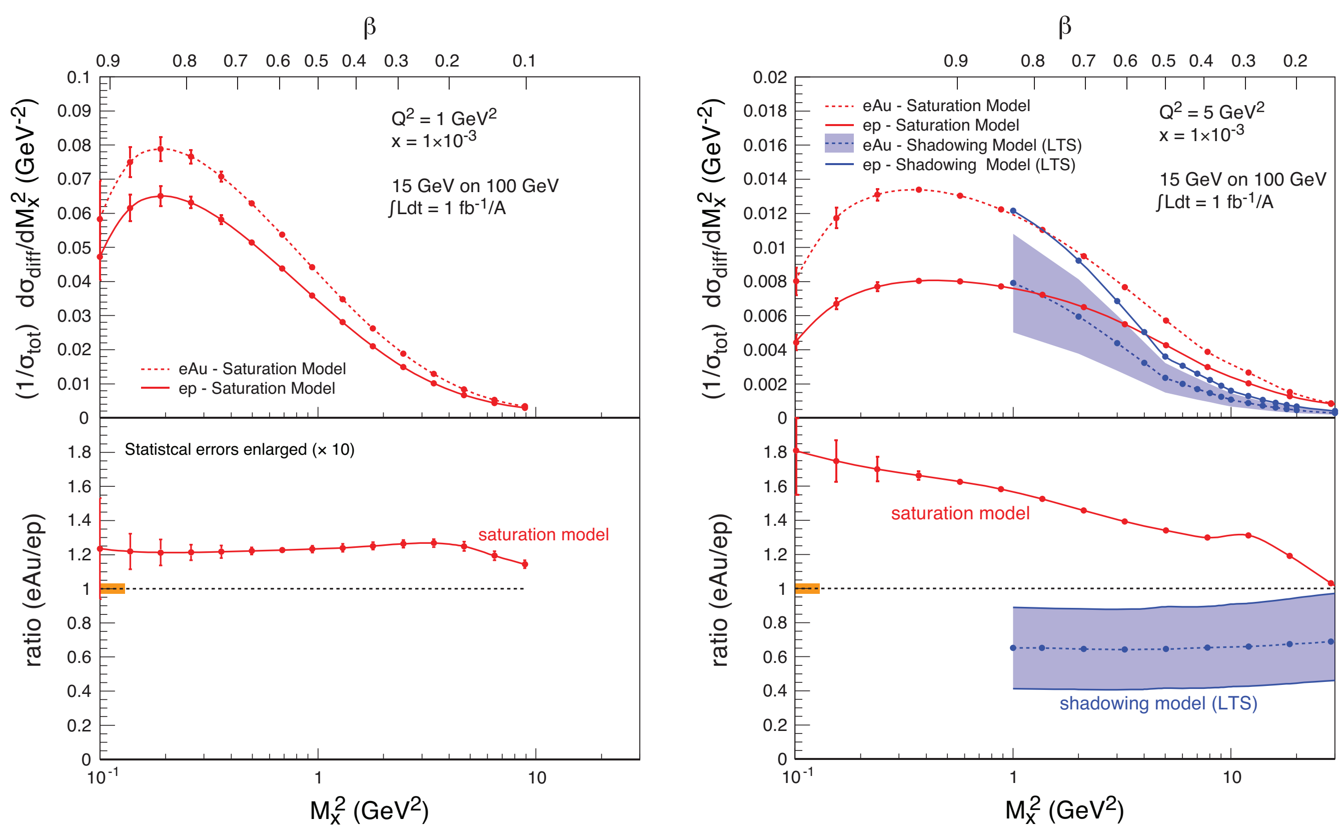
- For low Q^2 (large dipole sizes) the black disk limit is reached with N=1
- Diffraction (elastic scattering) becomes a half of the total cross section

$$\frac{\sigma_{el}^{q\bar{q}A}}{\sigma_{tot}^{q\bar{q}A}} = \frac{\int d^2b\, N^2}{2\int d^2b\, N} \longrightarrow \frac{1}{2}$$

- Large fraction of diffractive events in DIS is a signature of reaching the black disk limit!
- HERA: ~15% (unexpected!) ; EIC: ~25% expected from saturation

Diffractive over total cross sections

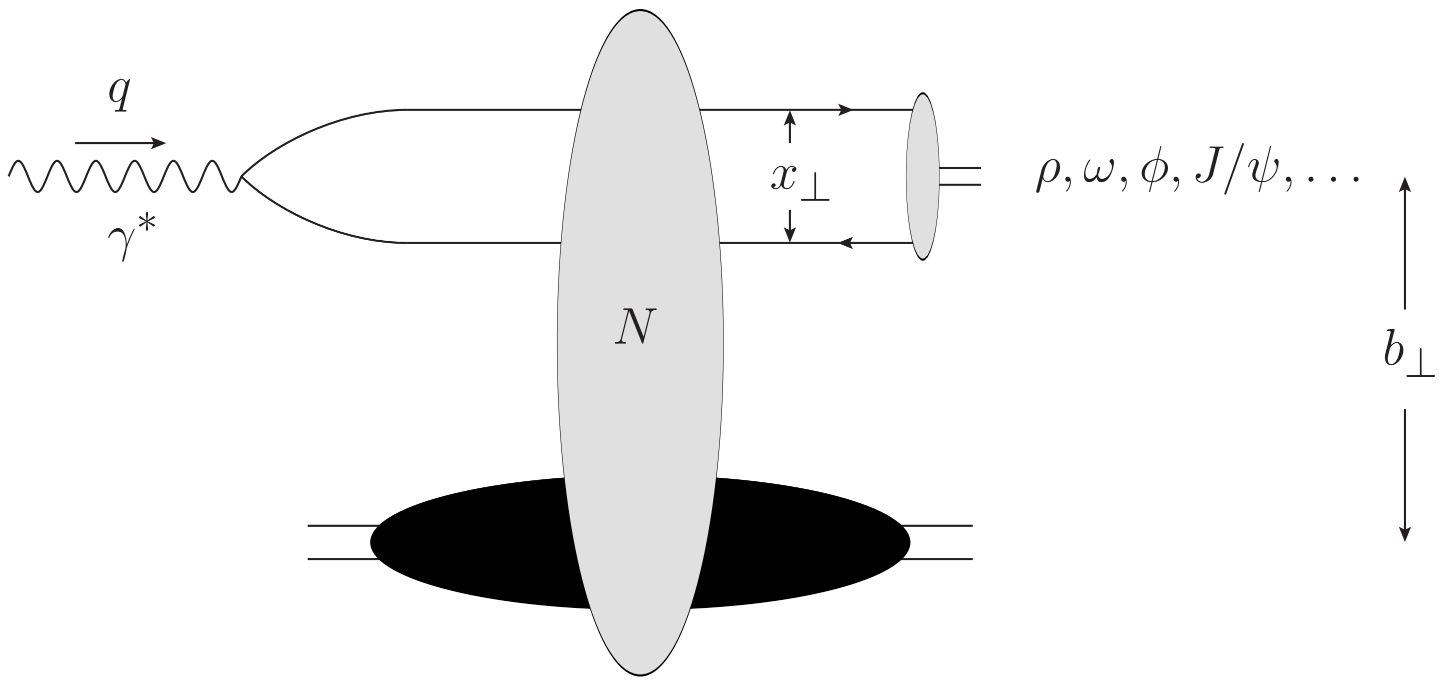
- Here's an early EIC measurement which may **distinguish saturation from non-saturation** approaches:



sat = Kowalski et al '08, plots generated by Marquet
no-sat = Leading Twist Shadowing (LTS), Frankfurt, Guzey, Strikman '04, plots by Guzey

Exclusive Vector Meson Production

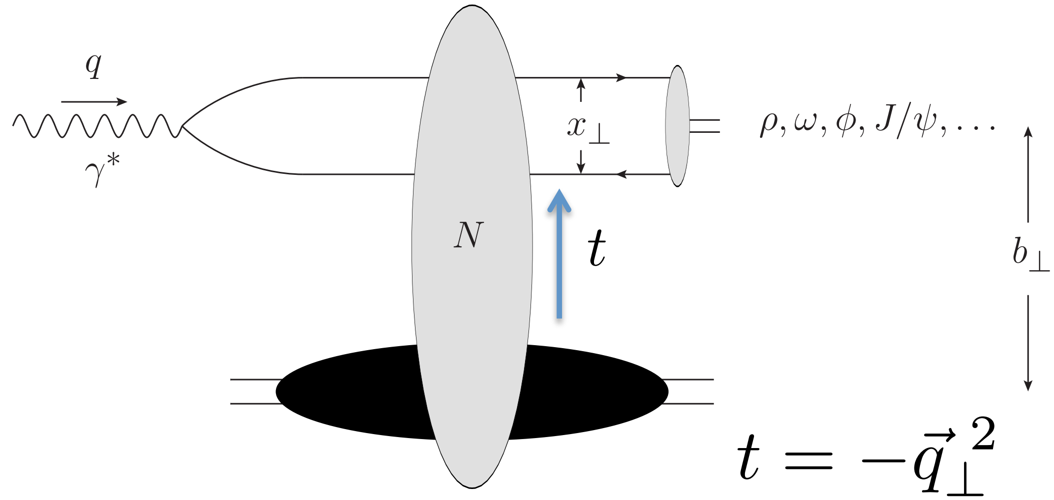
- An important diffractive process which can be measured at EIC is exclusive vector meson production:



Exclusive VM Production: Probe of Spatial Gluon Distribution

- Differential exclusive VM production cross section is

$$\frac{d\sigma^{\gamma^*+A\to V+A}}{dt} = \frac{1}{4\pi}\left|\int d^2b\, e^{-i\,\vec{q}_\perp\cdot\vec{b}_\perp}\, T^{q\bar{q}A}(\hat{s},\vec{b}_\perp)\right|^2$$



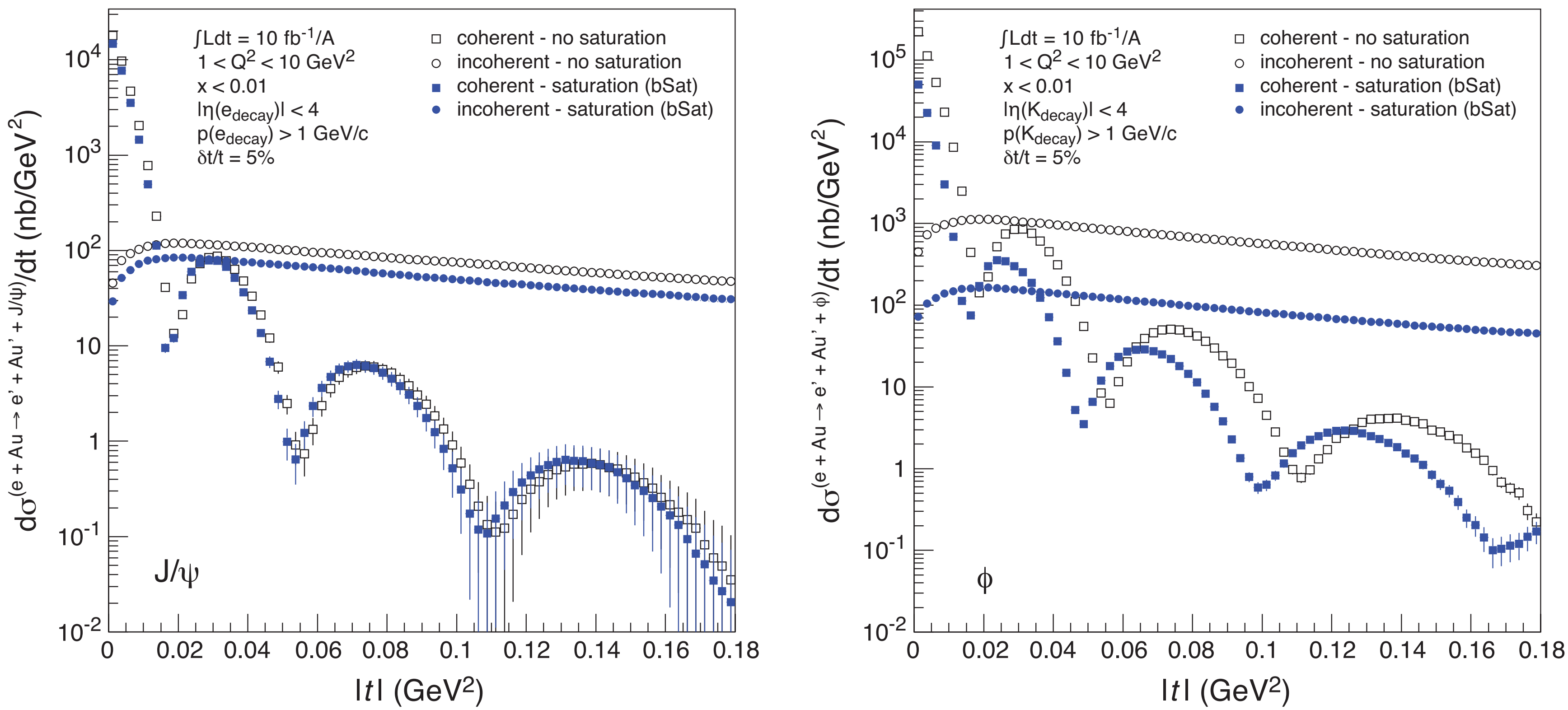
- the T-matrix is related to the dipole amplitude N:

$$T^{q\bar{q}A}(\hat{s},\vec{b}_\perp) = i\int \frac{d^2x_\perp}{4\pi}\int_0^1 \frac{dz}{z\,(1-z)}\;\Psi^{\gamma^*\to q\bar{q}}(\vec{x}_\perp, z)\;N(\vec{x}_\perp,\vec{b}_\perp, Y)\,\Psi^V(\vec{x}_\perp, z)^*$$

Brodsky et al '94, Ryskin '93

- Can study t-dependence of the dσ/dt and look at different mesons **to find the dipole amplitude N(x,b,Y)** (Munier, Stasto, Mueller '01).
- Learn about the **gluon distribution in space**.

Exclusive VM Production as a Probe of Saturation



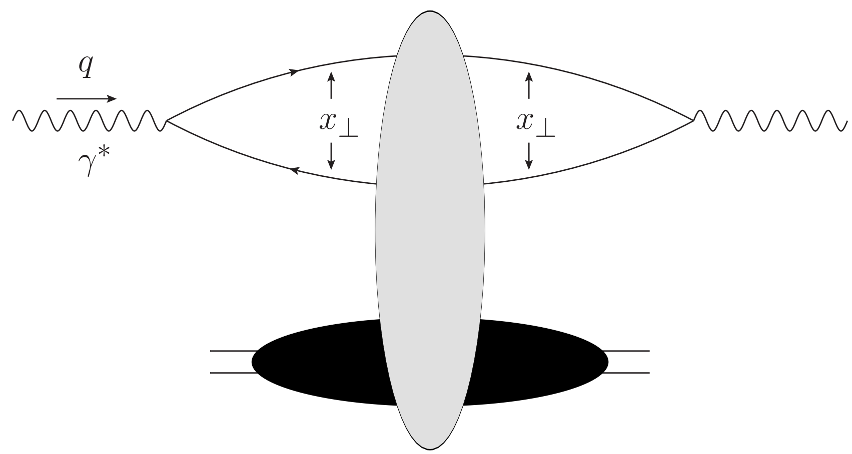
Plots by T. Toll and T. Ullrich using the Sartre event generator (b-Sat (=GBW+b-dep+DGLAP) + WS + MC).

- J/psi is smaller, less sensitive to saturation effects
- Phi meson is larger, more sensitive to saturation effects

See talk by Thomas Ullrich for an in-depth discussion of e+A observables

Dipole Amplitude and Other Operators

- Dipole scattering amplitude is a universal degree of freedom in saturation physics.
- It describes the total DIS cross section and structure functions:



- It also describes single inclusive quark and gluon production cross sections in DIS and in p+A collisions. <- **Universality!**
- Works for diffraction in DIS and p+A. <- **Universality!**
- For correlations need also quadrupoles (J.Jalilian-Marian, Yu.K. ’04; Dominguez et al ‘11) and other Wilson line operators.

Large-x Physics in e+A

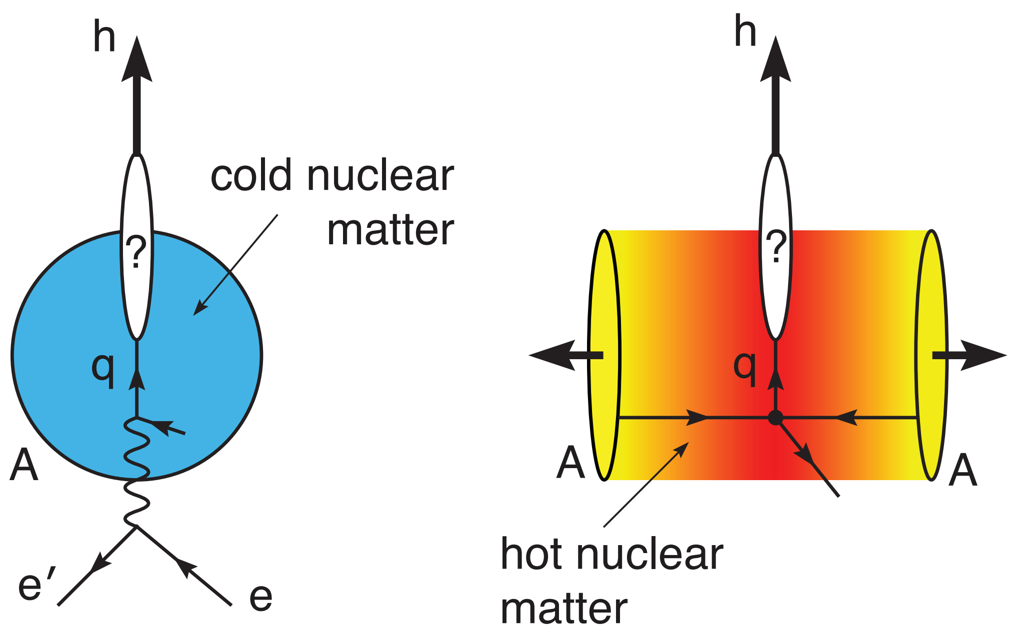
e+A at Large-x

- In e+A at EIC one could measure quark and gluon distributions (PDFs, GPDs, TMDs) and determine their spatial distributions at all values of Bjorken-x.

- We would also learn more about the properties of hadron formation in the cold nuclear matter.

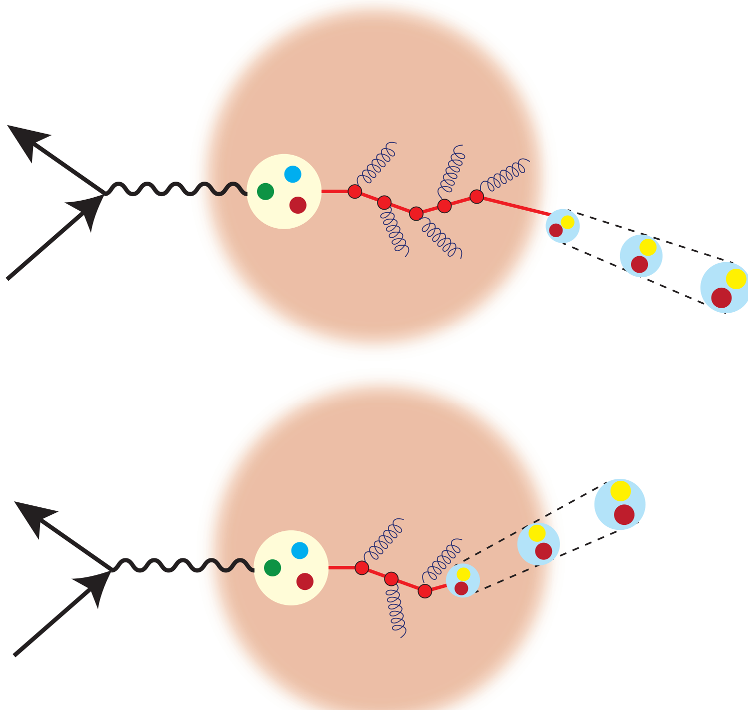
Energy Loss in Cold Nuclear Matter

- EIC would be able to measure the energy loss of quarks in a cold nuclear matter, complementing the RHIC and LHC measurements of energy loss in hot QCD plasma:

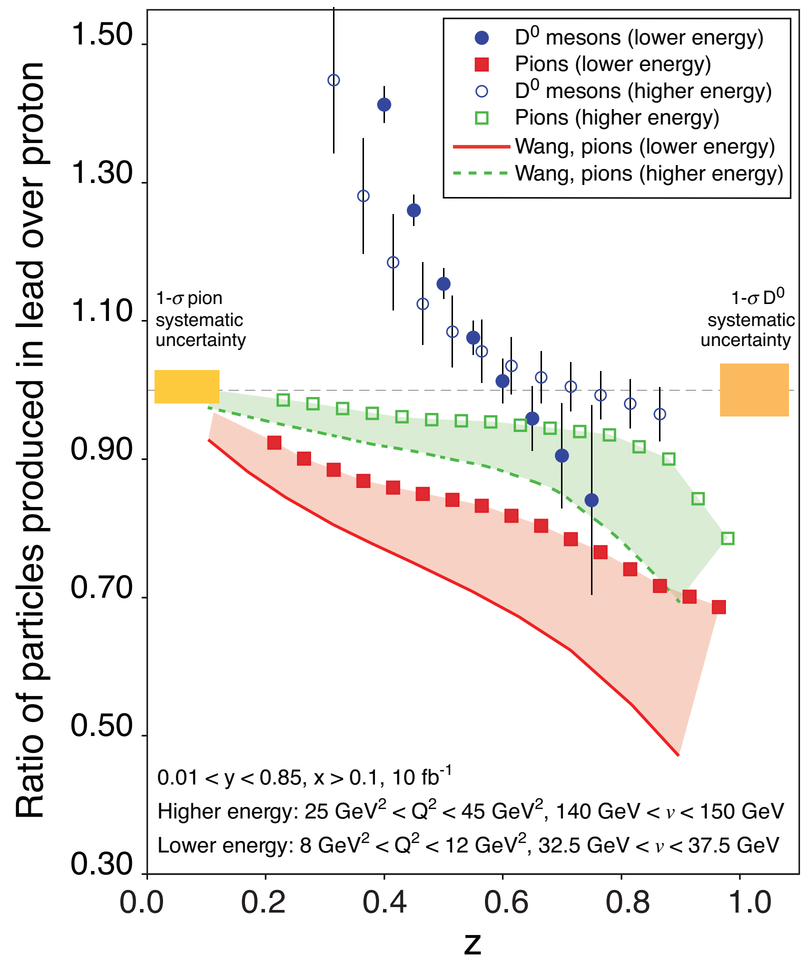


Energy Loss in Cold Nuclear Matter

- By studying quark propagation in cold nuclear matter we can learn important information about hadronization and may even measure qhat in the cold nuclear medium (see more in Thomas's talk):



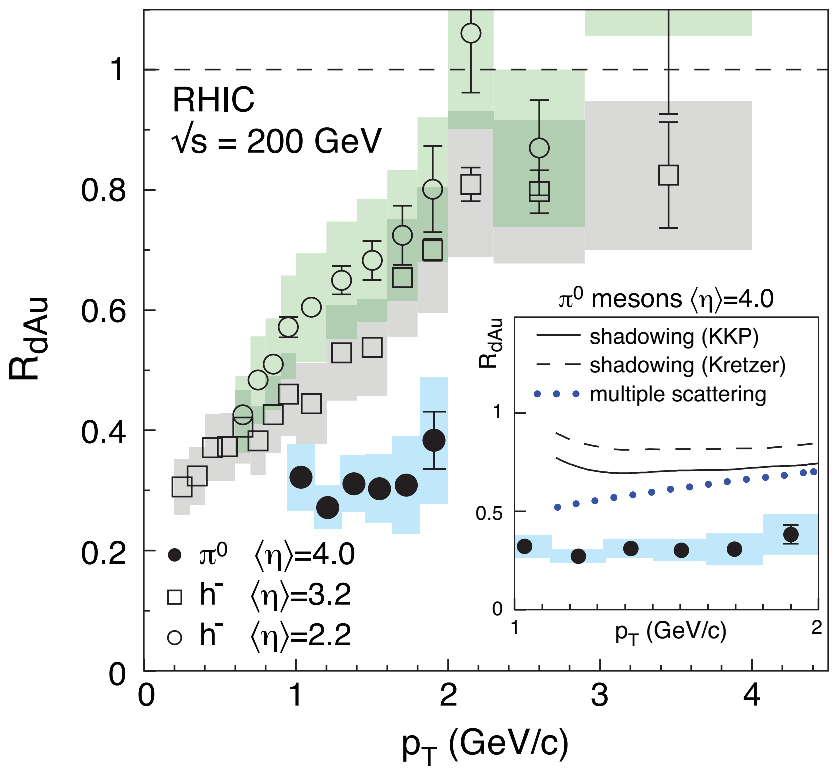
$$z = \frac{E_h}{\nu}$$



Connections to p+A and A+A collisions

Connections to p+A

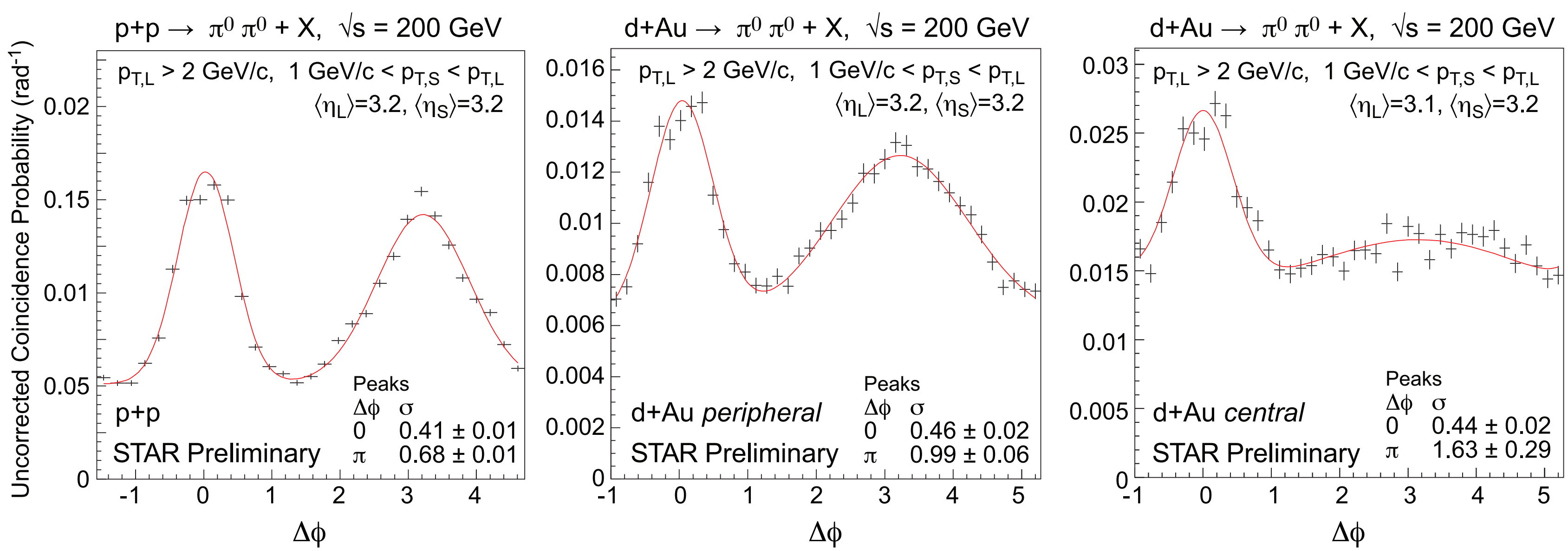
- In the saturation framework particle production in p+A is described by the dipole amplitude, just like structure functions in DIS. (**Universality!**)
- Correlations in both processes are described by other Wilson line operators like quadrupoles. (**Universality!**) – see Z. Kang's talk
- Some evidence of saturation has been seen in d+Au collisions at RHIC:



$$R_{pA} = \frac{1}{N_{coll}} \frac{dN^{pA}/d^2p_T\,dy}{dN^{pp}/d^2p_T\,dy}$$

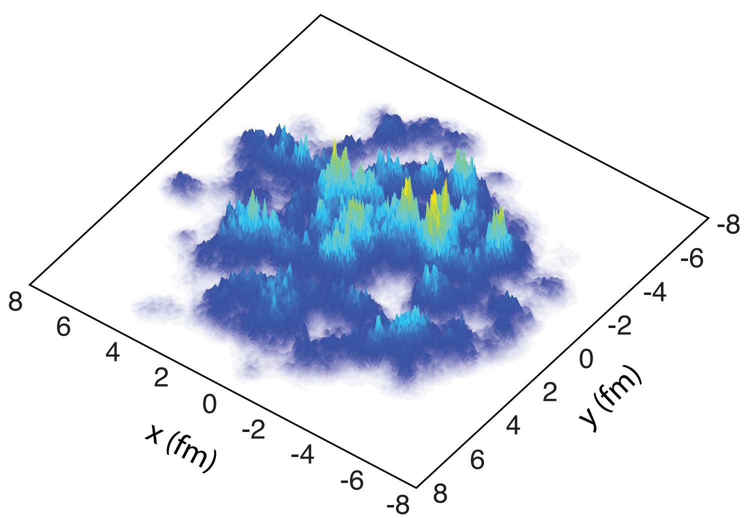
Connections to p+A

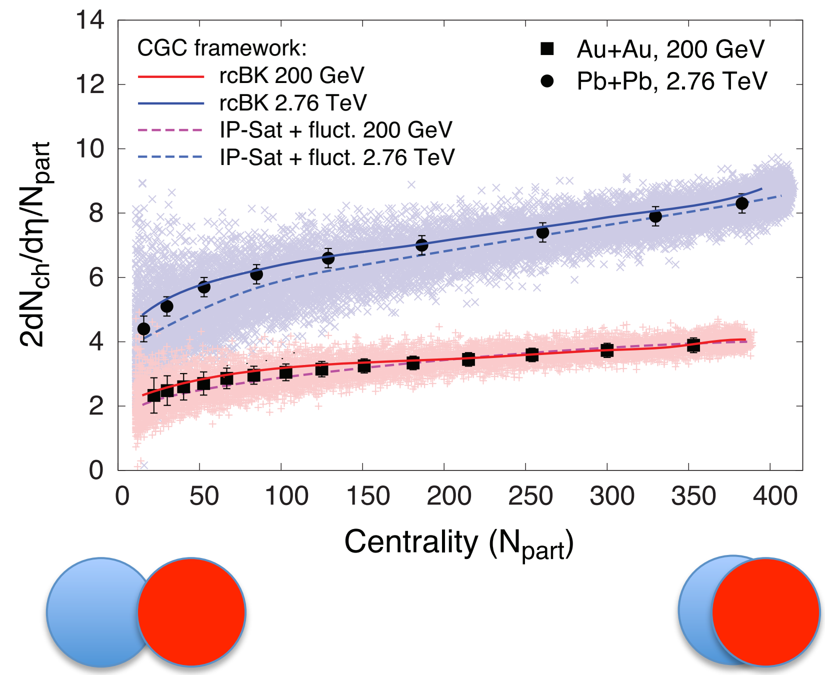
Di-hadron back-to-back azimuthal correlation function decorrelates for central d+Au collisions in agreement with saturation predictions (cf. e+A):



Connections to Heavy Ion Physics

- CGC Physics also plays important role in the early-time dynamics of heavy ion collisions
- By exploring it at EIC we would get a better handle on formation of QGP and on fluctuations, including multiplicity and azimuthal harmonic flow coefficients v_n.





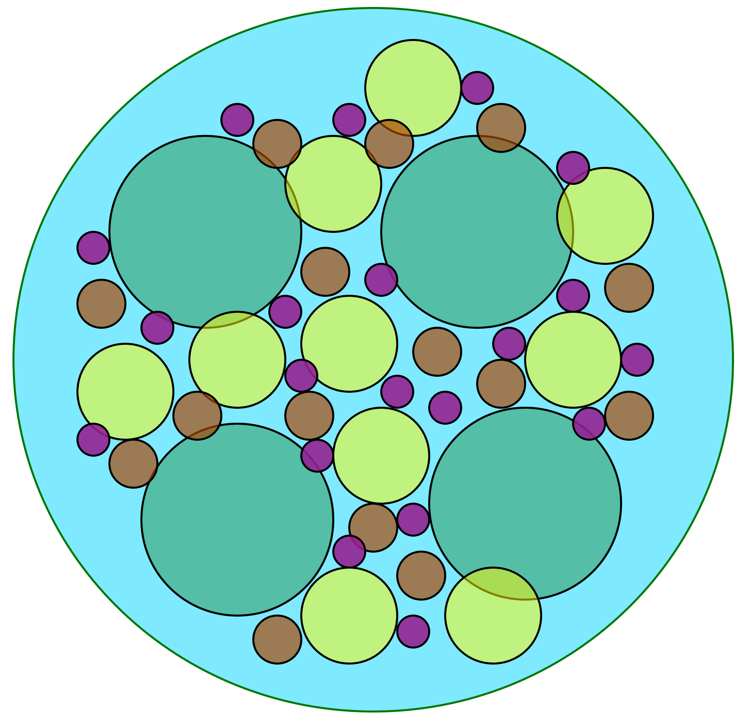
Conclusions

- EIC is a unique opportunity to complete the **discovery of saturation/CGC physics** and to study its properties. Strong gluon fields and nonlinear dynamics may be found only in e+A collisions.
- EIC would help us understand **spatial distribution of gluons and quarks** in the nuclei.
- Saturation physics extends our understanding of both QCD under extreme conditions and of the nucleon structure/TMD physics.
- By discovering saturation, we would make a significant progress in **understanding high-energy QCD**, answering one of the fundamental questions in the field and paving the way for better understanding of strong interactions at the future accelerators.

Backup Slides

Nonlinear Evolution at Work

Proton



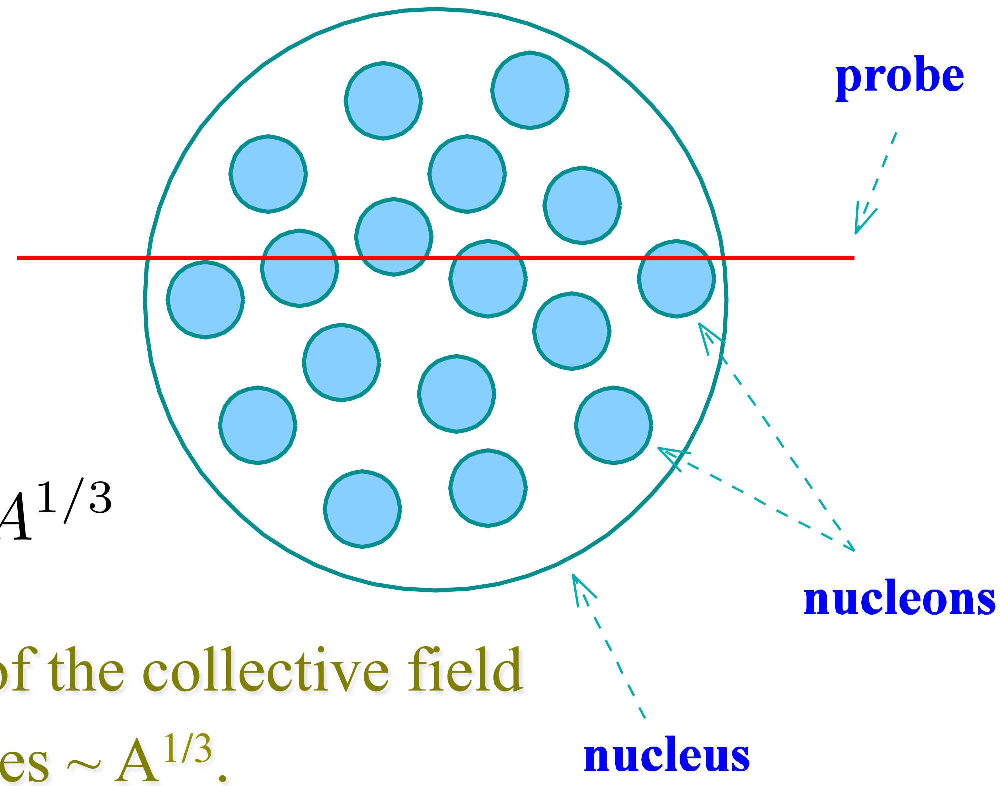
✓ First partons are produced overlapping each other, all of them about the same size.

✓ When some critical density is reached no more partons of given size can fit in the wave function. The proton starts producing smaller partons to fit them in.

Color Glass Condensate

Saturation Scale

To argue that $Q_S^2 \sim A^{1/3}$ let us consider an example of a particle scattering on a nucleus. As it travels through the nucleus it bumps into nucleons. Along a straight line trajectory it encounters $\sim R \sim A^{1/3}$ nucleons, with R the nuclear radius and A the atomic number of the nucleus.

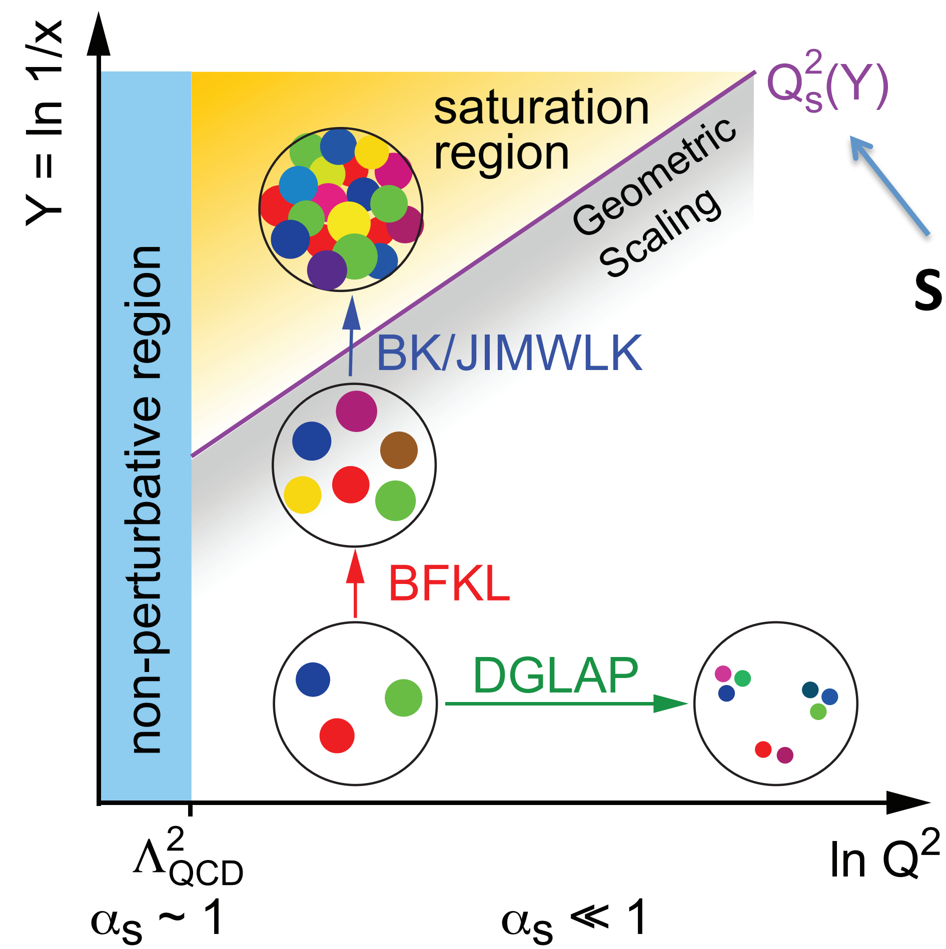


The particle receives $\sim A^{1/3}$ random kicks. Its momentum gets broadened by

$$\Delta k \sim \sqrt{A^{1/3}} \Rightarrow (\Delta k)^2 \sim A^{1/3}$$

Saturation scale, as a feature of the collective field of the whole nucleus also scales $\sim A^{1/3}$.

Map of High Energy QCD



$$Q_s^2 \sim \left(\frac{A}{x}\right)^{1/3}$$

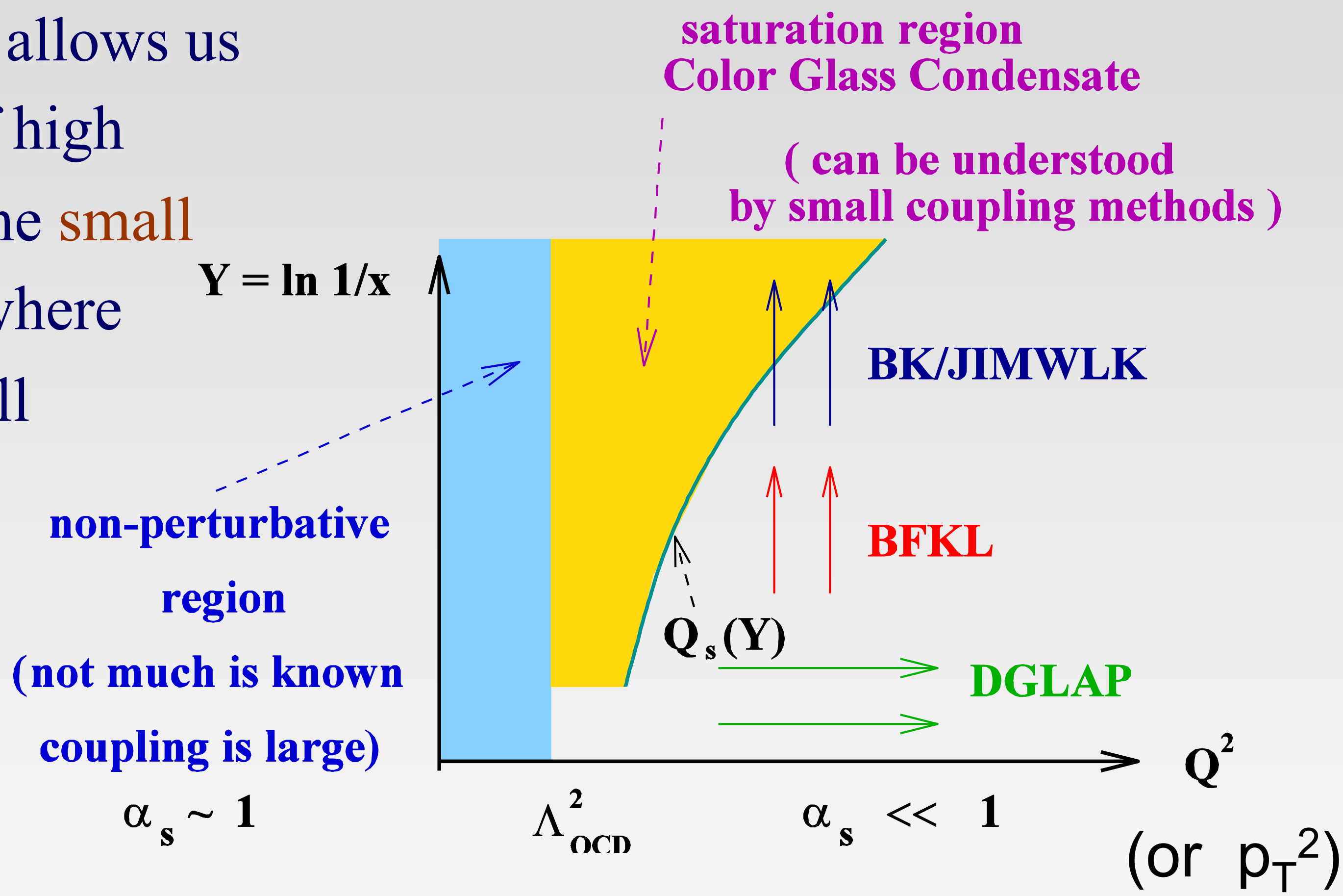
Saturation Scale

energy

size of gluons

Map of High Energy QCD

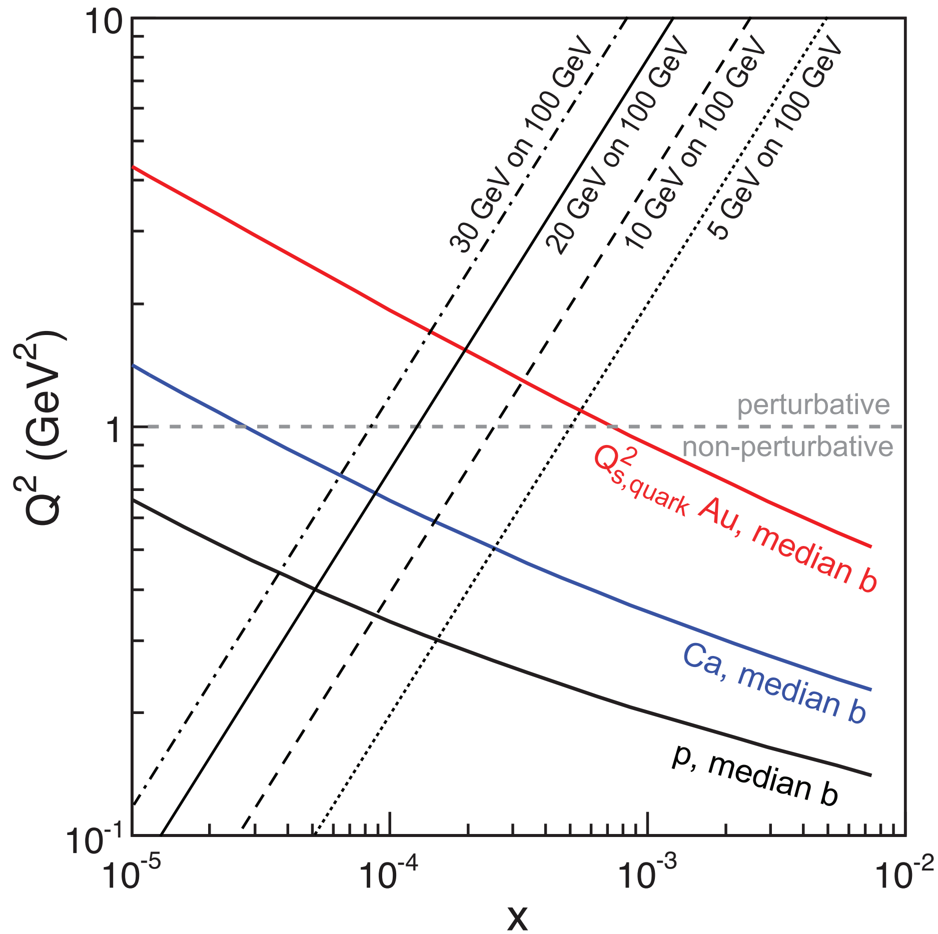
Saturation physics allows us to study regions of high parton density in the small coupling regime, where calculations are still under control!



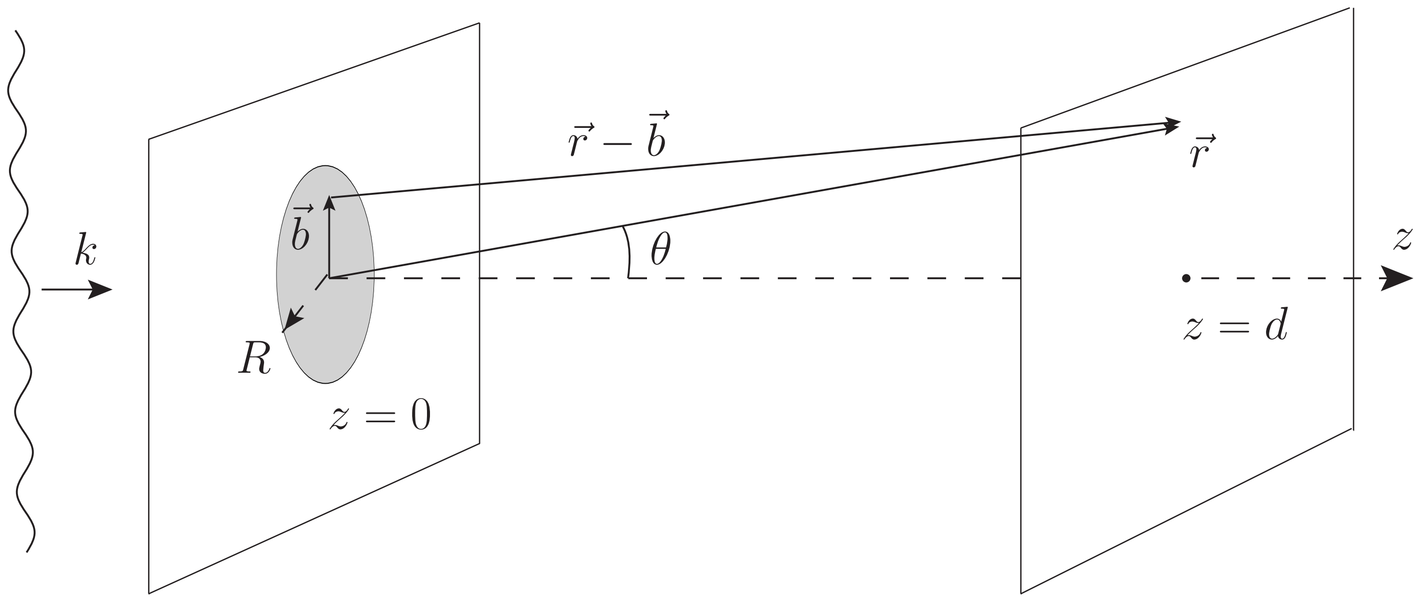
Transition to saturation region is characterized by the saturation scale

$$Q_S^2 \sim A^{1/3} \left(\frac{1}{x} \right)^{\lambda}$$

Saturation Scales at EIC



Diffraction in optics and QCD



- In optics, diffraction pattern is studied as a function of the angle θ.
- In high energy scattering the diffractive cross sections are plotted as a function of the Mandelstam variable t = k sin θ.

Impact Parameter Dependence

- Using exclusive VM production one can study the b-dependence of the T-matrix since inverting the above formula one gets (Munier, Stasto, Mueller '01)

$$T^{q\bar{q}A}(\hat{s}, \vec{b}_\perp) = \frac{i}{2\,\pi^{3/2}} \int d^2q\, e^{i\,\vec{q}_\perp \cdot \vec{b}_\perp} \sqrt{\frac{d\sigma^{\gamma^* + A \to V + A}}{dt}}$$

- The amplitude T is related to N and to the vector meson and γ* wave functions:

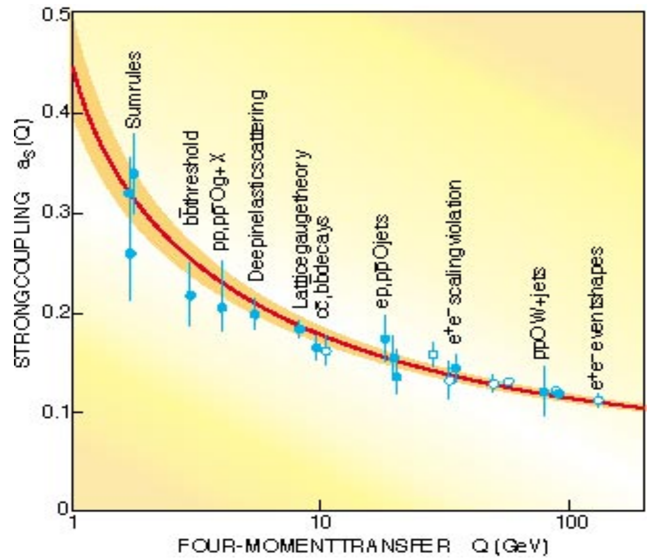
$$T^{q\bar{q}A}(\hat{s}, \vec{b}_\perp) = i \int \frac{d^2x_\perp}{4\,\pi} \int_0^1 \frac{dz}{z\,(1-z)}\; \Psi^{\gamma^* \to q\bar{q}}(\vec{x}_\perp, z)\; N(\vec{x}_\perp, \vec{b}_\perp, Y)\, \Psi^V(\vec{x}_\perp, z)^*$$

- Diffraction (elastic VM production) can help us figure out the b-dependence of the T-matrix, and hence see if saturation has been reached. It would also give us the b-dependent gluon distribution in the nucleus.

Strong Coupling Scenarios

Strong Coupling

- What if the realistic saturation scale at the EIC is not large enough for the coupling to be small?



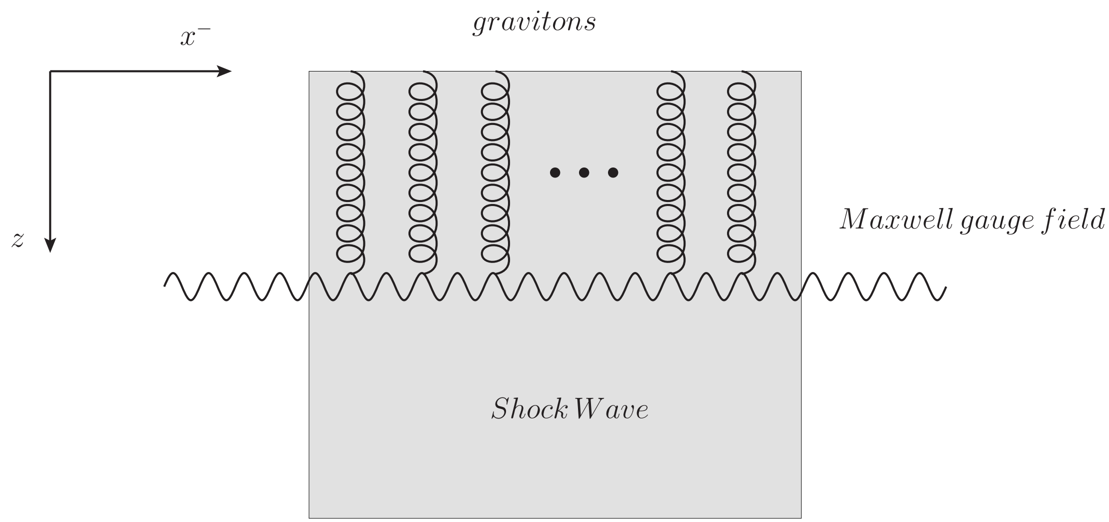
- The theoretical tool would then be AdS/CFT correspondence.
- Problems: N=4 SYM is not QCD, not clear how to obtain QCD in a controlled way; there is no E&M current in N=4 SYM, hence not clear what to calculate to describe DIS, etc.

DIS in AdS/CFT: Currents Correlator

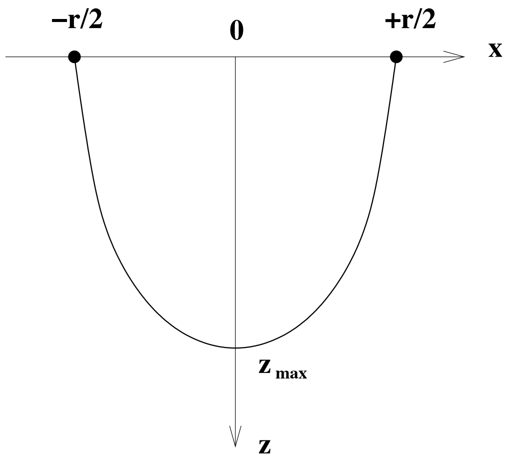
- DIS can be modeled in AdS/CFT by calculating correlator of two *R*-currents in the background of a thermal medium or a shock wave (Levin et al '08, Mueller et al '08, Avsar et al '09). The saturation scale is then

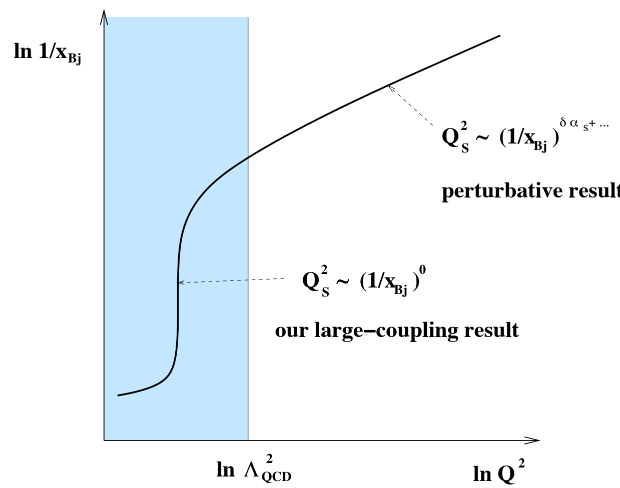
$$Q_s^2 \sim \Lambda^2 \frac{A^{1/3}}{x}$$

- Very fast x-dependence, such scale has not been observed. Moreover, if it grows with x this fast, it would quickly get into pQCD region making the coupling small…



DIS in AdS/CFT: Dipole Amplitude





- One can directly calculate the dipole amplitude in DIS obtaining (Albacete et al '08)

$$Q_s^2 \sim \lambda \, \Lambda^2 \, A^{2/3}$$

  (more plausible x-dependence (none), but strong A-dependence – not observed)

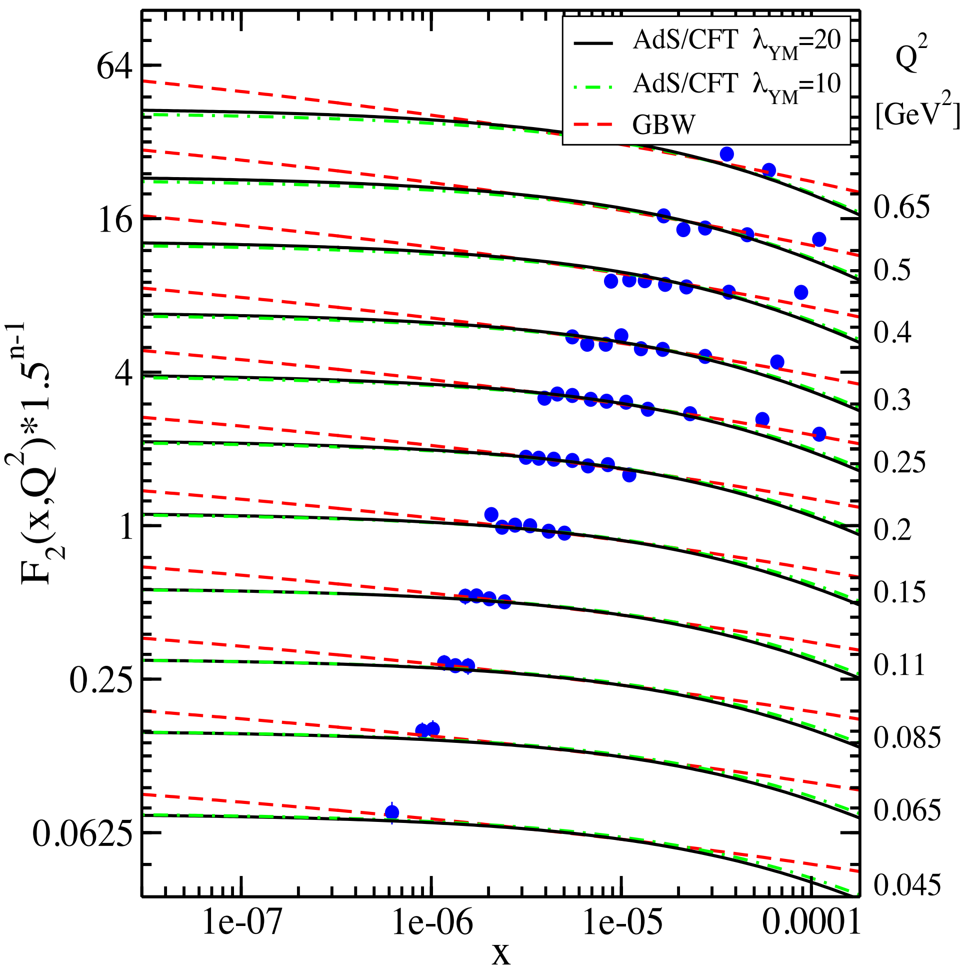
- or (Dumitru and Noronha '14, more realistic A-dependence)

$$Q_s^2 \sim \lambda \, \Lambda^2 \, A^{1/3}$$

- More work is needed to sort things out. This may be an opportunity.

AdS/CFT vs the Data

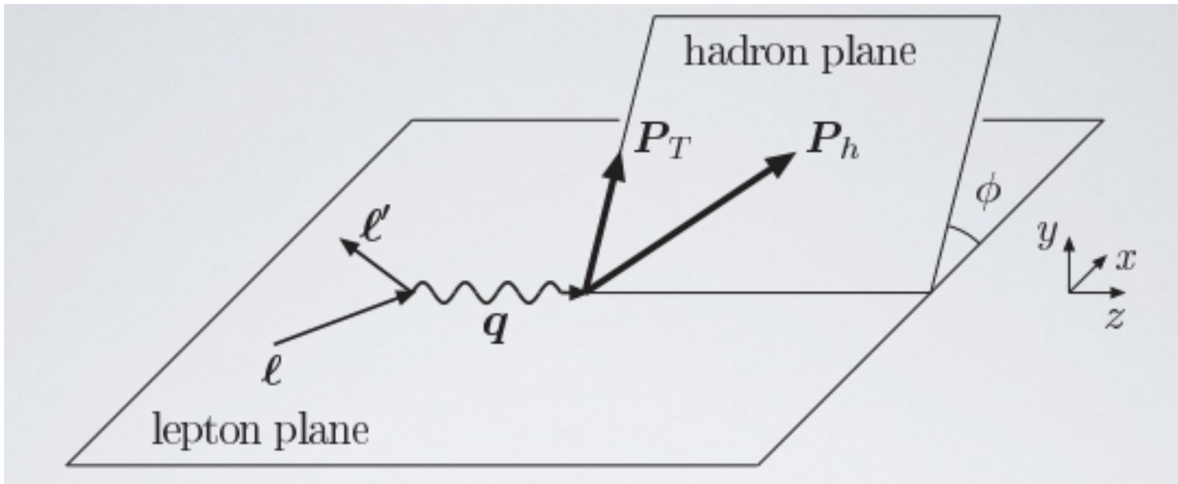
- One can describe the low-Q^2 F_2 HERA data using AdS/CFT approach (YK, Lu, Rezaeian, '09):



Strong vs Weak Coupling

- Can experiments distinguish between strongly vs weakly-coupled saturation scenarios at an EIC?
- This is largely an open question.
- Purely large-coupling scenario at all momentum scales unlikely – in heavy ions AdS predicts stopping of heavy ions in the collision (not observed at RHIC or LHC) and very strong growth of hadron multiplicity with energy. Most likely early-time dynamics in A+A is weakly-coupled.
- A combination of weakly and strongly-coupled dynamics is possible at an EIC since Q_s is not huge. This would be hard to tackle theoretically.

Strong Color Fluctuations



One could study the pT-broadening of produced hadrons in DIS on a nucleus as a function of the angle ϕ between the lepton and hadron planes. The broadening

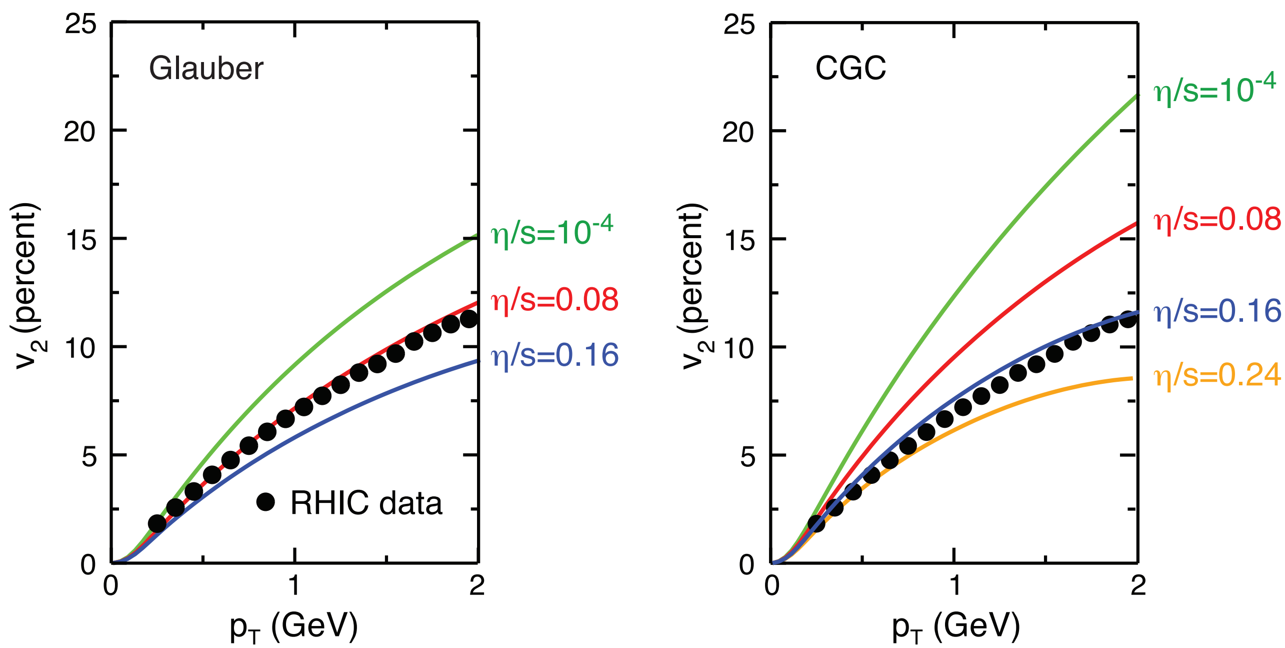
$$\langle \Delta p_T^2(\phi) \rangle_{AN} = \langle p_T^2(\phi) \rangle_A - \langle p_T^2(\phi) \rangle_N$$

would be sensitive to strong color fluctuations in the density of partons.

Connections to Heavy Ion Physics

Harmonic flow coefficients are sensitive probes of the dynamics of quark-gluon plasma and the initial conditions for its formation:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + \sum_n 2\, v_n\, \cos(n\phi)\right]$$



A comparison of data vs theory using viscous hydrodynamics with Glauber-like initial conditions (left) or the saturation-inspired ones (right).

Connections to Cosmic Rays

- There is a known problem in Auger data indicating that cosmic rays behave like protons at lower energies and like nuclei at higher energies, according to the existing QCD Monte-Carlos.

- X_{max} = atmospheric depth of the cosmic ray shower maximum

- It could be that the problem is with our understanding of QCD at this super-high energies.

- Perhaps saturation physics, with input from EIC, could help improve our understanding of the Auger data.