Color Glass Condensate for EIC (experiment)

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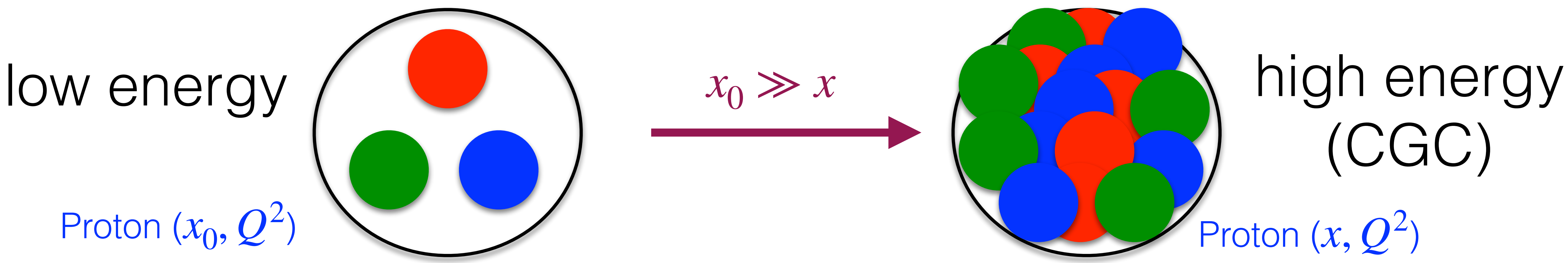
Outline

- Basic introduction to color glass condensate (CGC)
- Current status: results from HERA, RHIC, LHC
- Measurements required for the EIC discovery of CGC

Materials are collected from various talks and papers

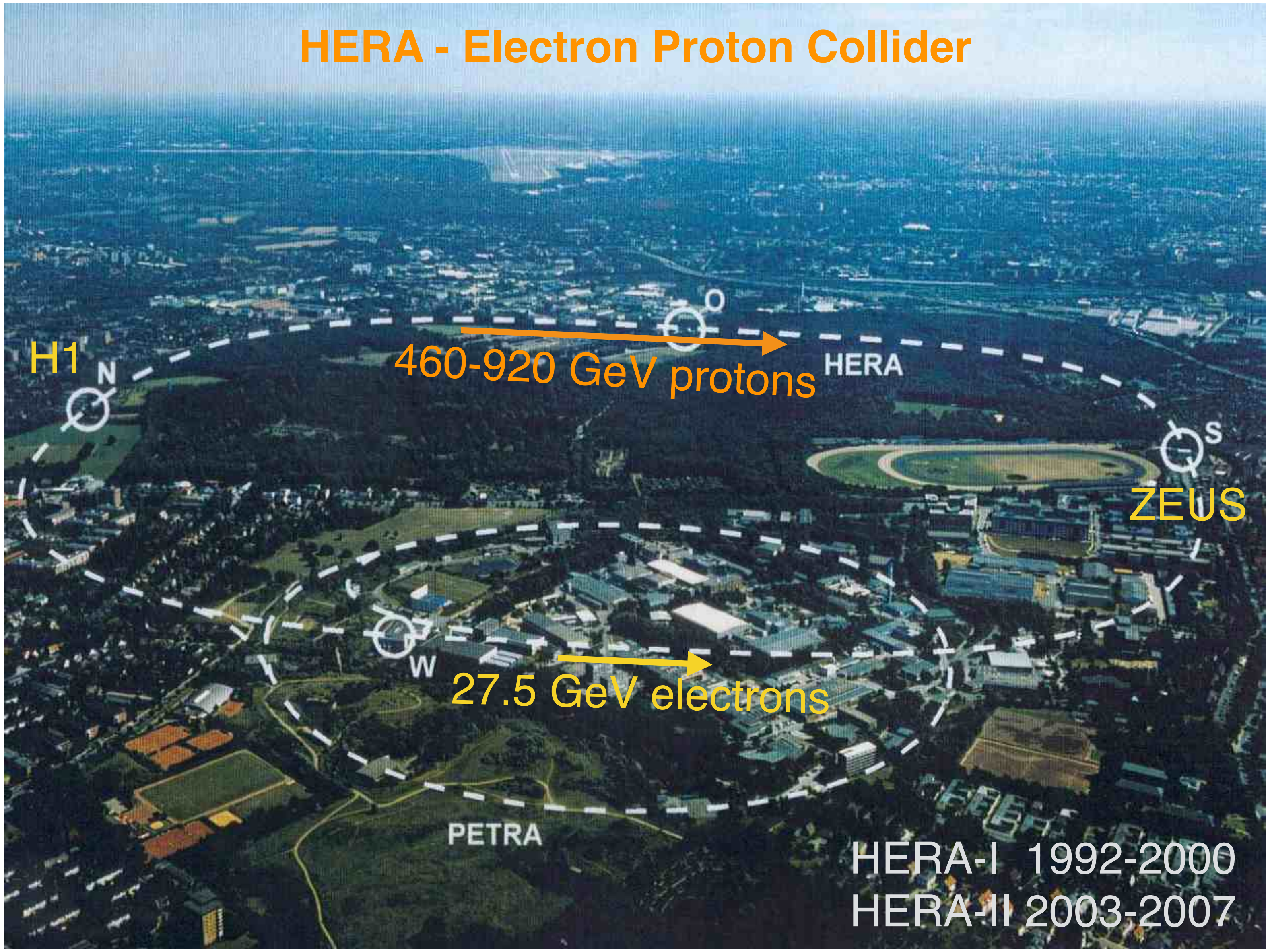
What is the CGC ?

- Dense gluonic states in hadrons which universally appear in the **high-energy** limit of scattering
  - **Color**: gluons have “colors”
  - **Glass**: gluons with small longitudinal momentum fractions ($x \ll 1$) are produced by long-lived patrons randomly distributed over the transverse extension of protons or nuclei → borrowed from condense matter that the materials are disordered and act like solids on short time scales but liquid on long time scales
  - **Condensate**: gluon density is very high and saturated → gluons may interact and form a coherent state reminiscent of a Bose-Einstein condensate.
- CGC can be probed directly in ep and eA scatterings at high energies
- It can also be studied in high energy pp, pA and AA collisions, assuming the final state interactions are calculated, or in some cases they are small corrections

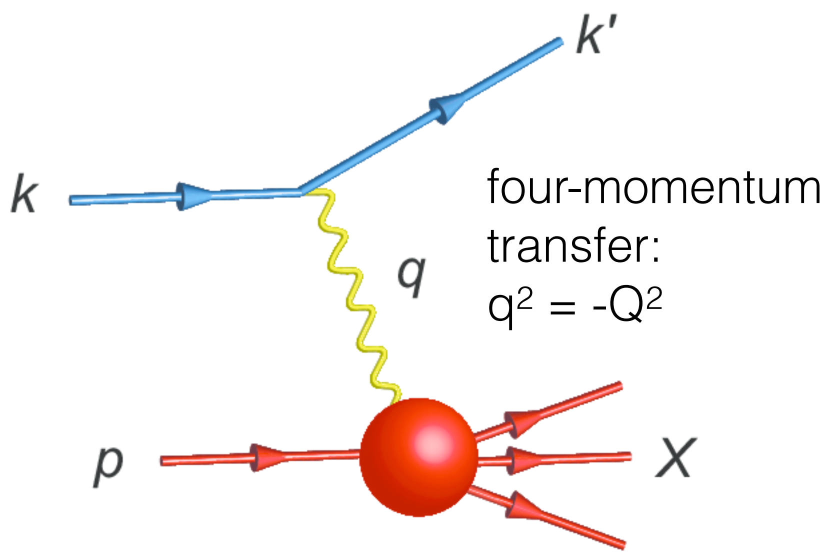


Study of small-x

- Accurate experimental study of small-x with good precision was achieved in the DIS at HERA



An experimental picture of ep scattering



M. Hentschinski
JPCS 651:012011

- Electron-proton scattering (ep→eX) can be described as an exchange of a virtual photon

- The result of ep scattering depends strongly on

$$\lambda = \frac{hc}{E}$$

  - At low Q^2 (momentum carried by photon is low), $\lambda >> r_p$ → the proton as a point

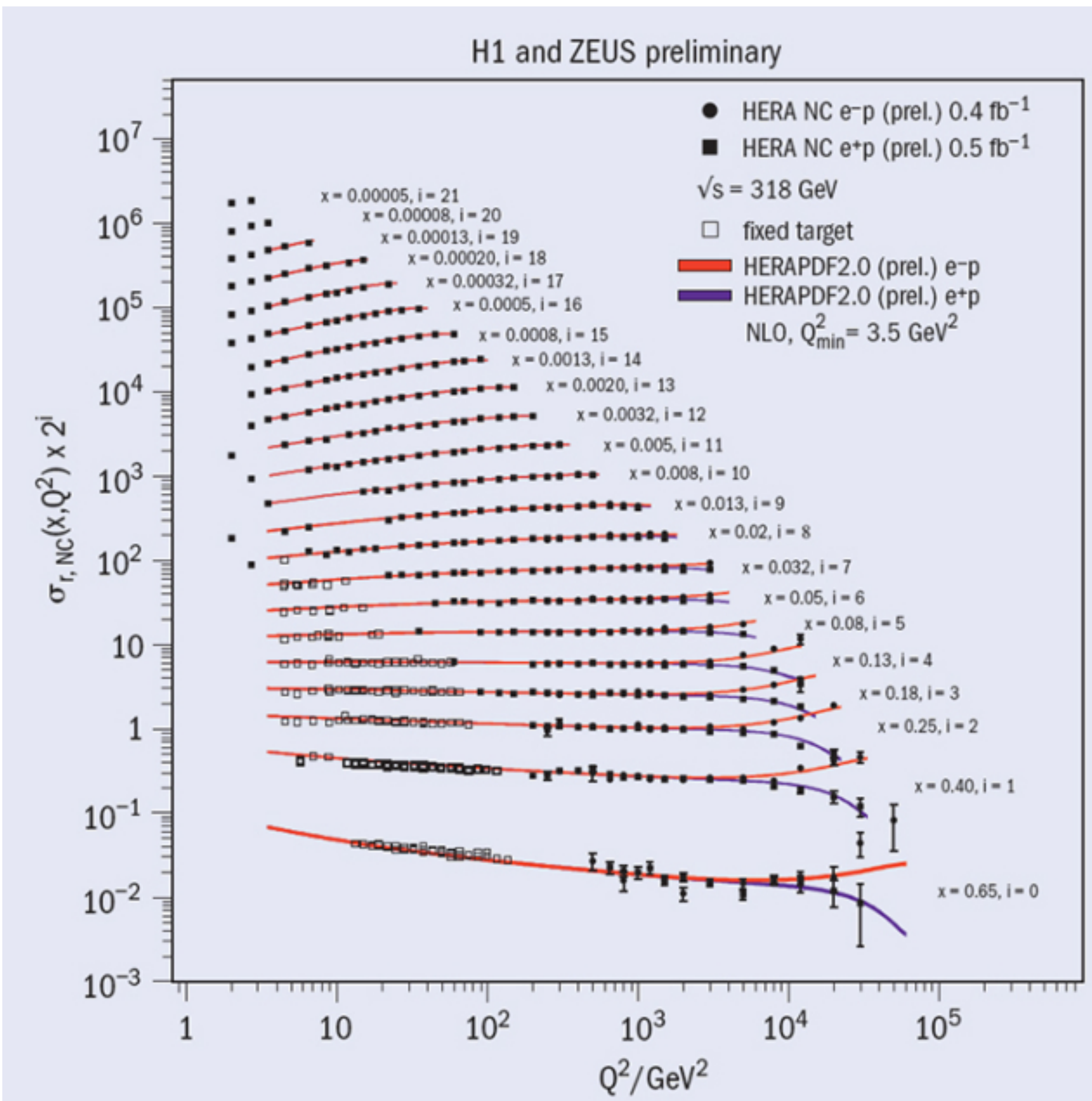
  - At medium Q^2, $\lambda \sim r_p$ → photon starts to resolve the finite size of the proton

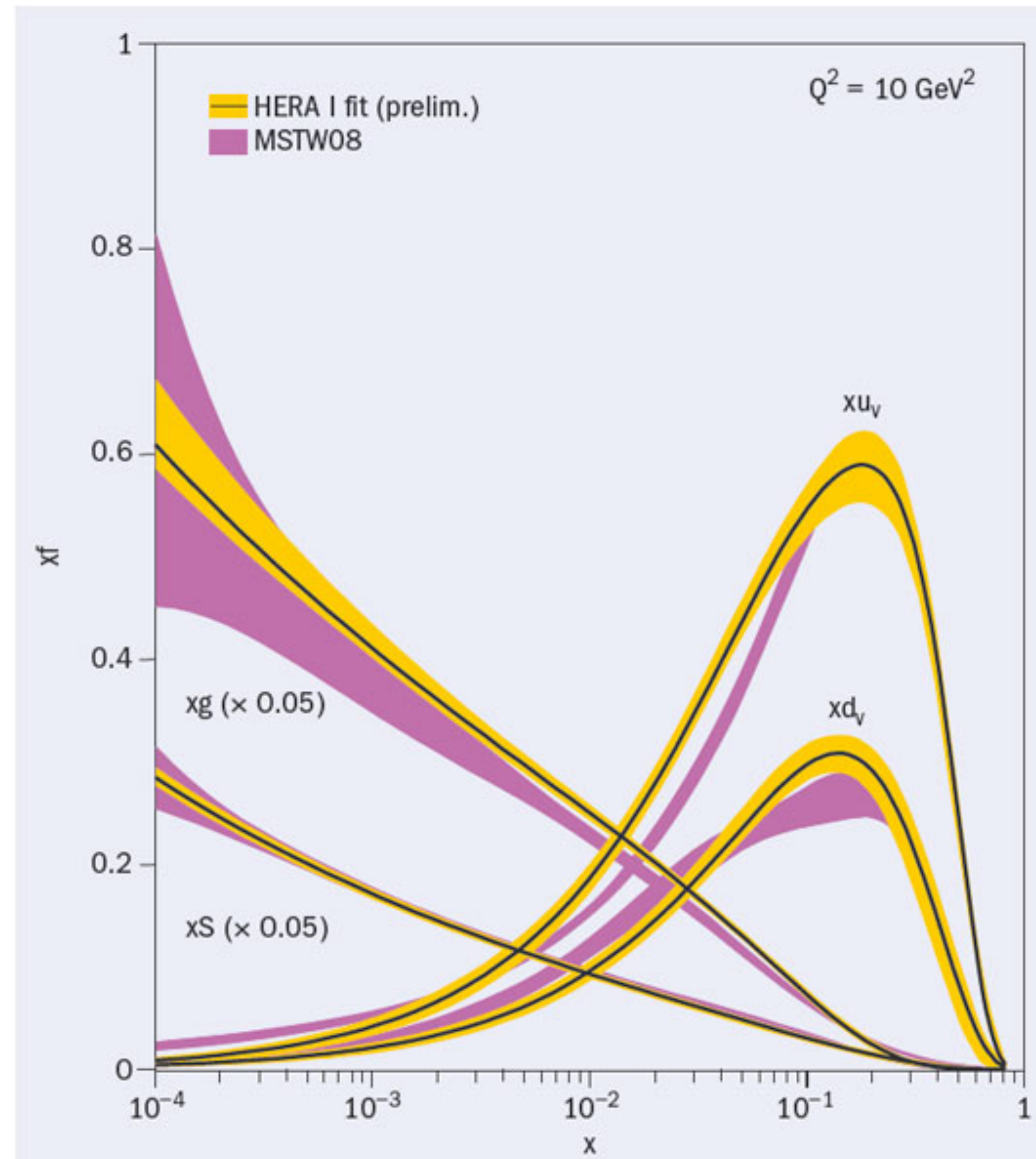
  - At high Q^2, $\lambda << r_p$ → photon resolves the internal structure of the proton

- Proton composition changes with energy

Two kinematic variables:
Q^2: transverse resolution
x: longitudinal momentum fraction of partons

HERA results





higher energies

σ vs Q^2 at fixed x

parton densities vs x

What we learnt from HERA ?

- Gluons dominate the proton wave function at high energy
- The gluon density is large and increases with decreasing x
- The density depends on the scale or resolution with which one probes the proton
- If one increases the resolution, by increasing Q^2, the parton density increases as one “sees” more and more patrons

QCD evolution in the $x - Q^2$ phase diagram (1/5)

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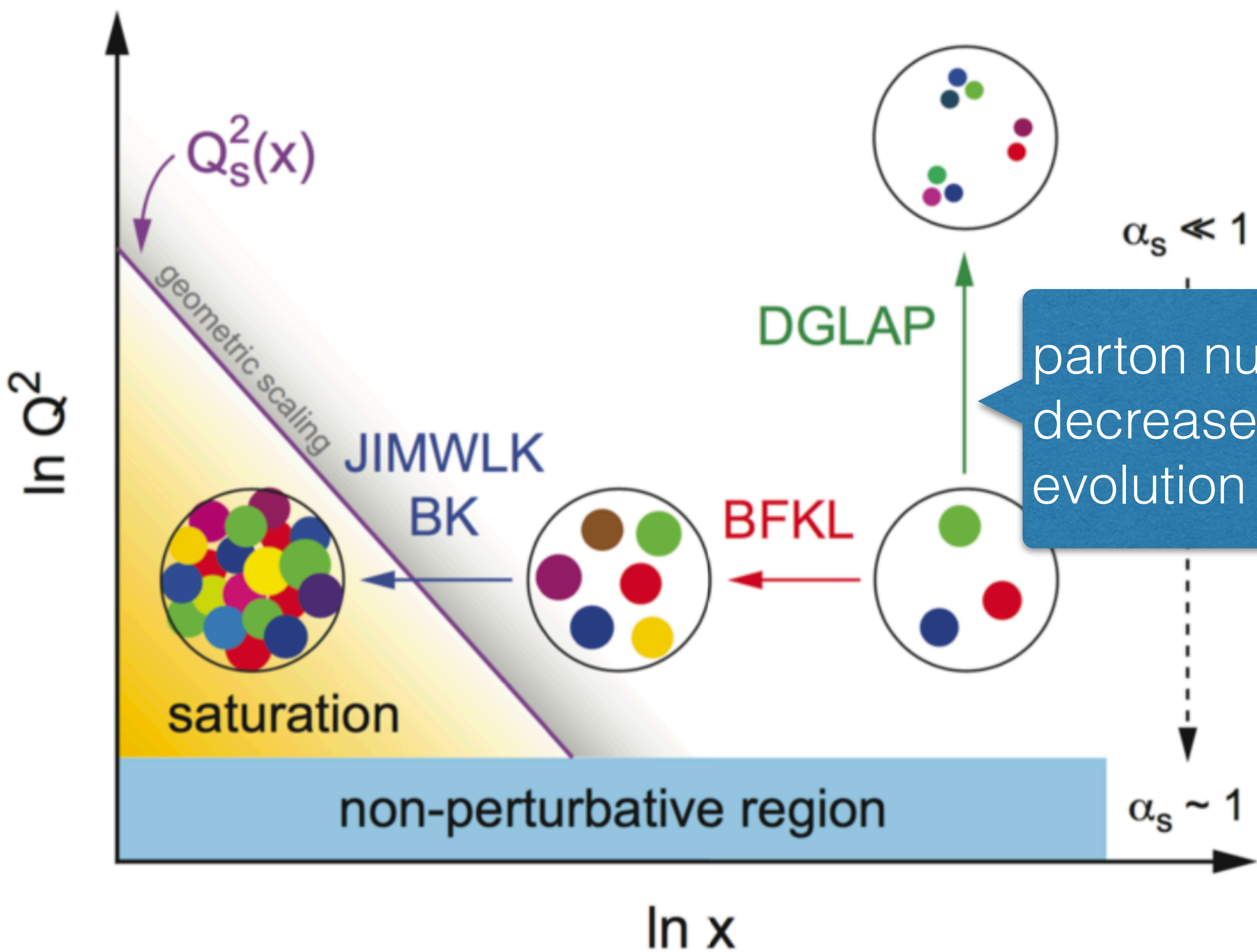
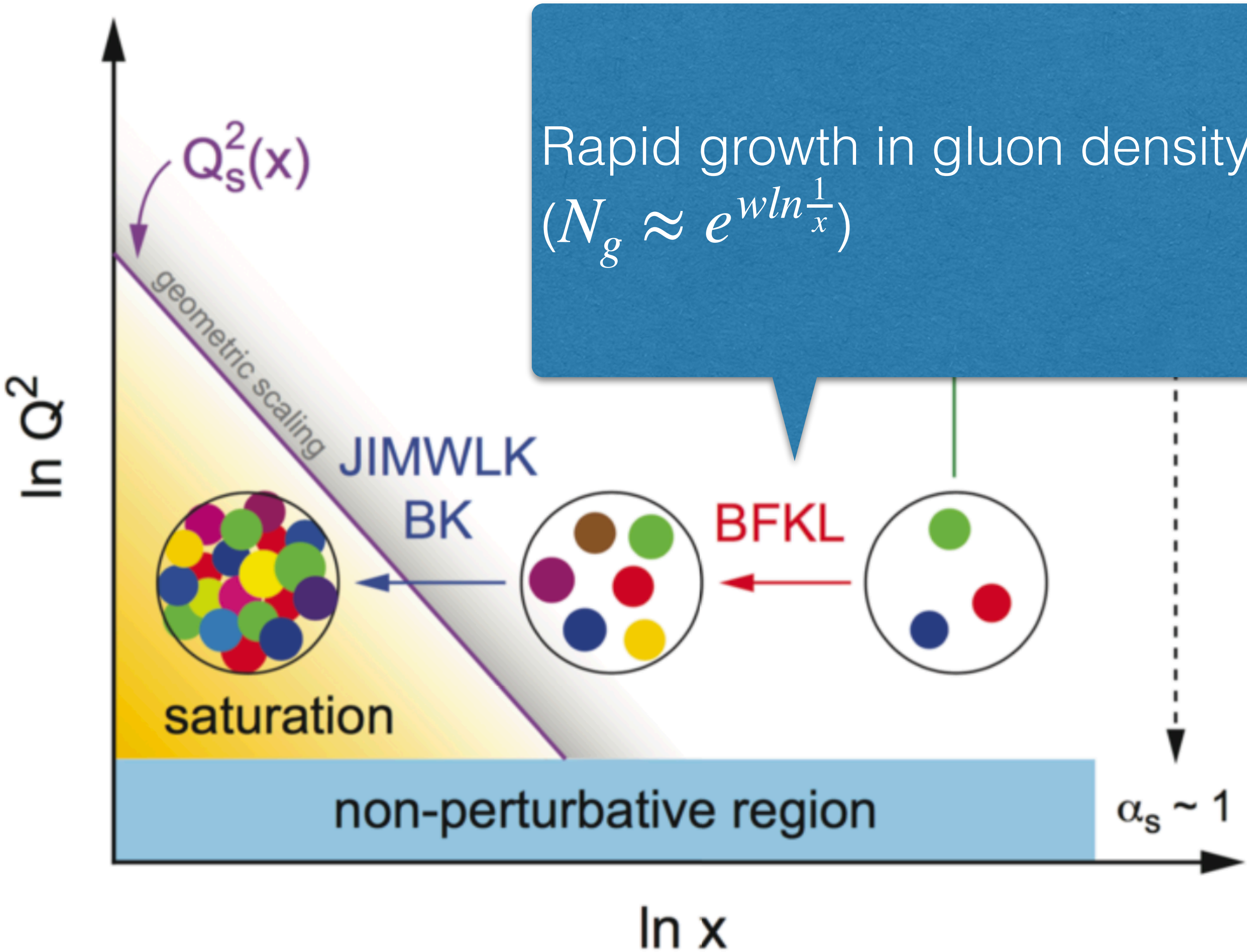


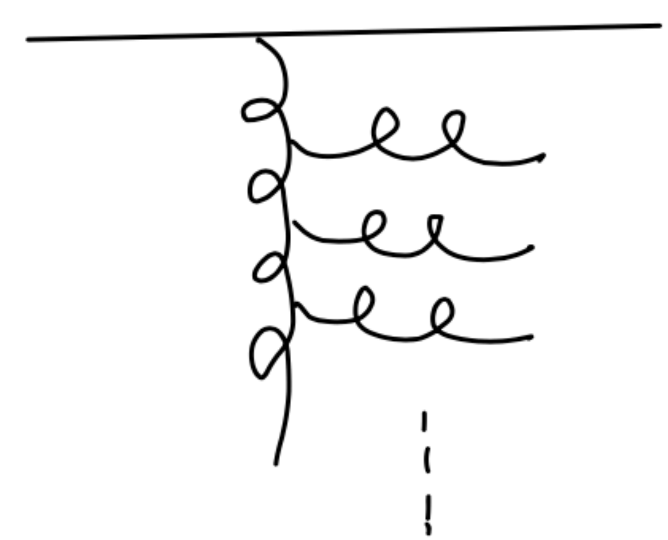
parton number increases, but density decreases; the system produced by DGLAP evolution becomes dilute and weakly coupled

- Perturbative theory is very successfully in this regime and has broad applicability, for example the inclusive production of jets over a wide range of p_T at the hadron colliders
- Measurements of jet production at the Tevatron improved the knowledge of the gluon content of the production at moderate and high x

QCD evolution in the $x - Q^2$ phase diagram (2/5)

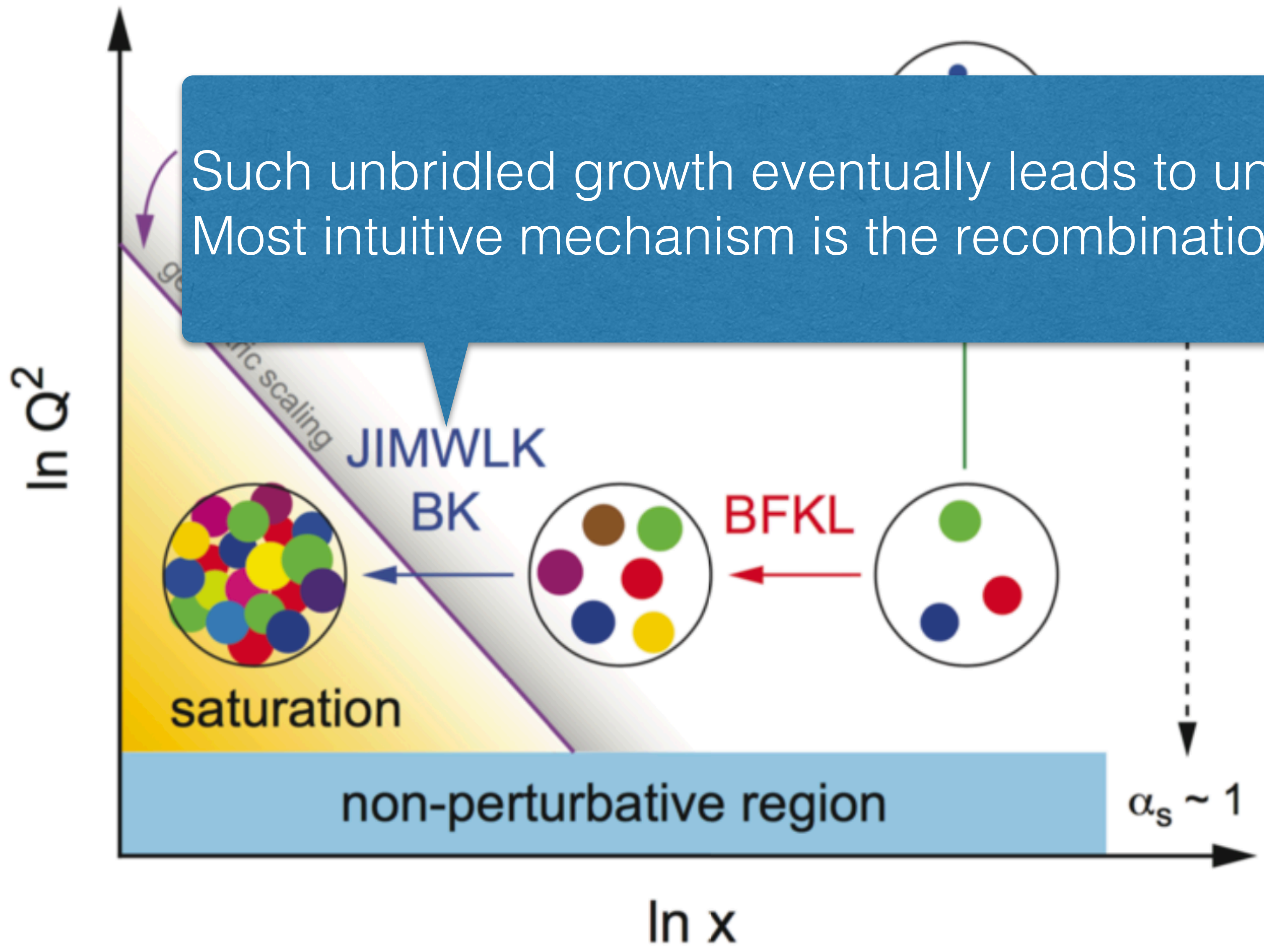
Rapid growth in gluon density due to multiple gluon emissions ($N_g \approx e^{wln\frac{1}{x}}$)

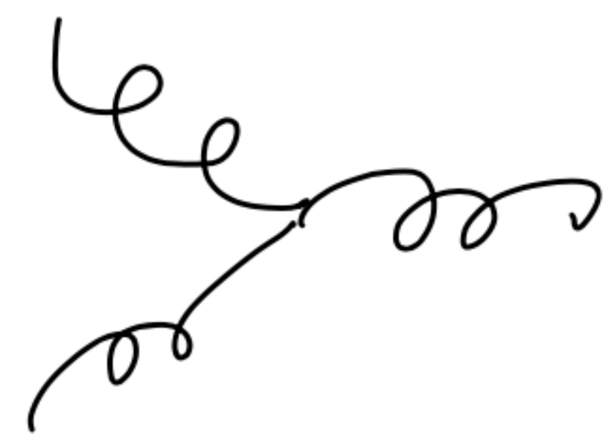




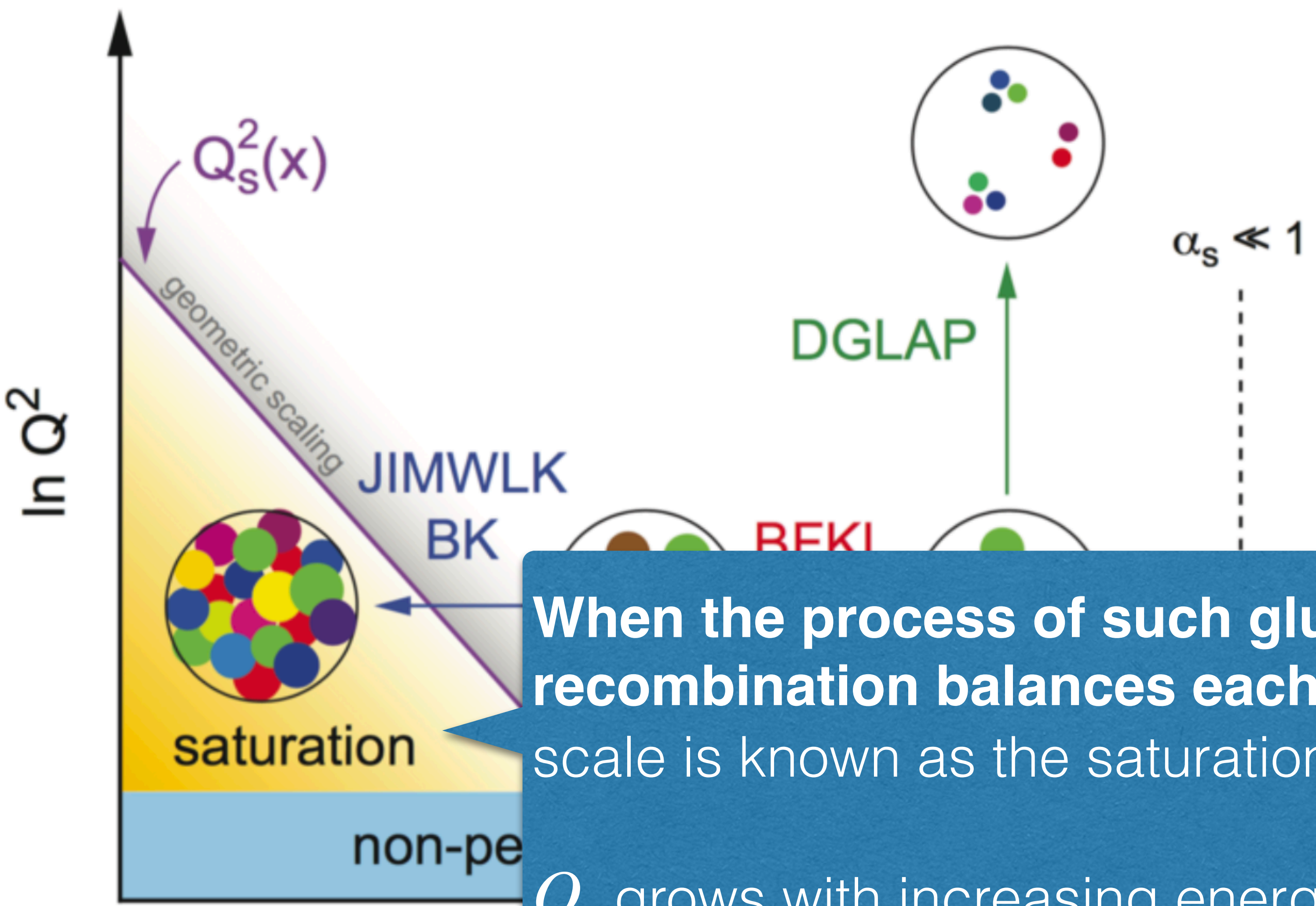
QCD evolution in the $x - Q^2$ phase diagram (3/5)

Such unbridled growth eventually leads to unphysical cross sections.
Most intuitive mechanism is the recombination of gluons ($N_g \leq 1$)





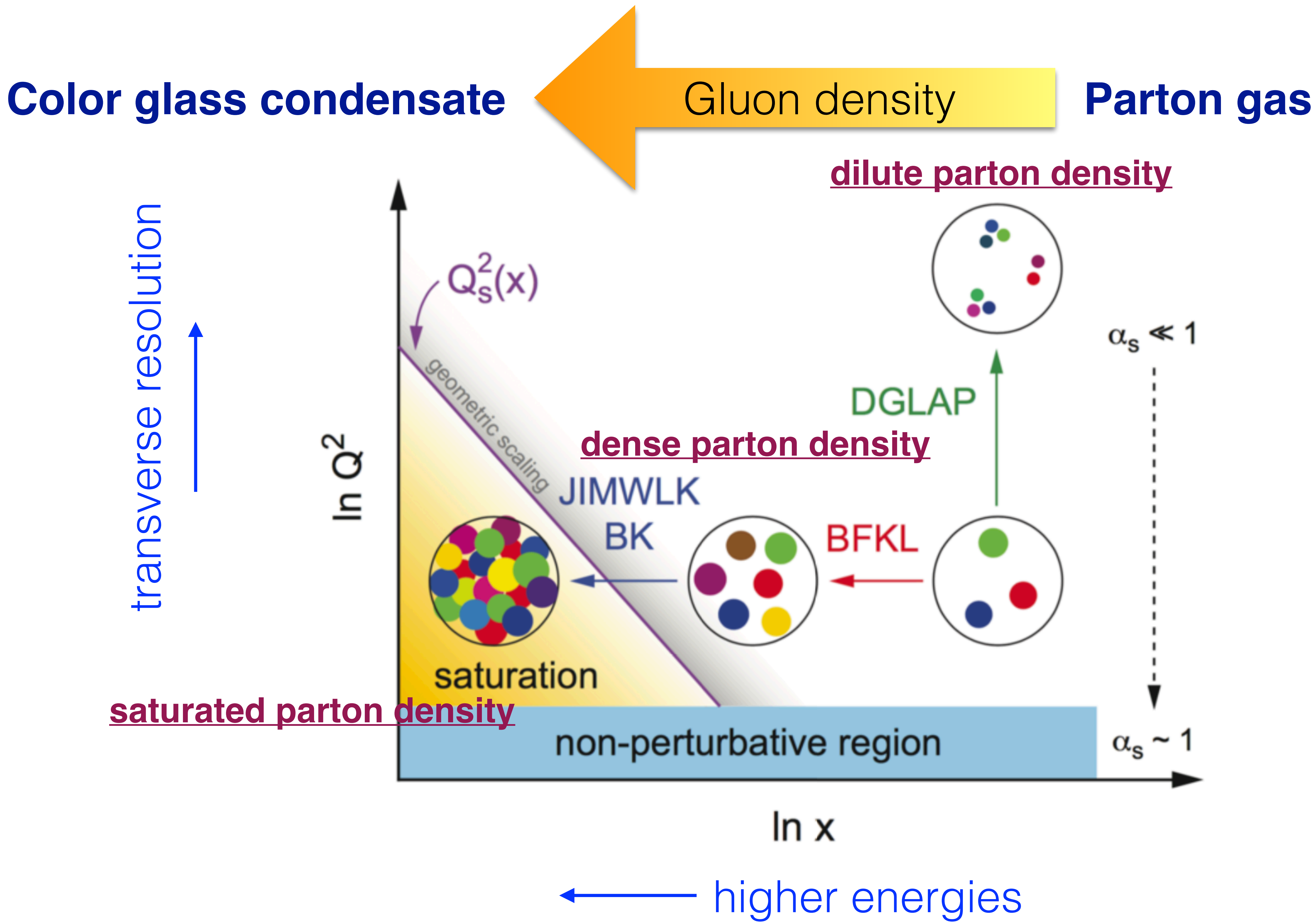
QCD evolution in the $x - Q^2$ phase diagram (4/5)



When the process of such gluon emission and recombination balances each other, this momentum scale is known as the saturation scale Q_s^2

Q_s grows with increasing energy (decreasing x) → weak coupling at high energies

QCD evolution in the $x - Q^2$ phase diagram (5/5)



Geometric scaling evidence from HERA data

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Stasto, Golec-Biernat, Kwiecinski
PRL 86 (2001) 596

ep

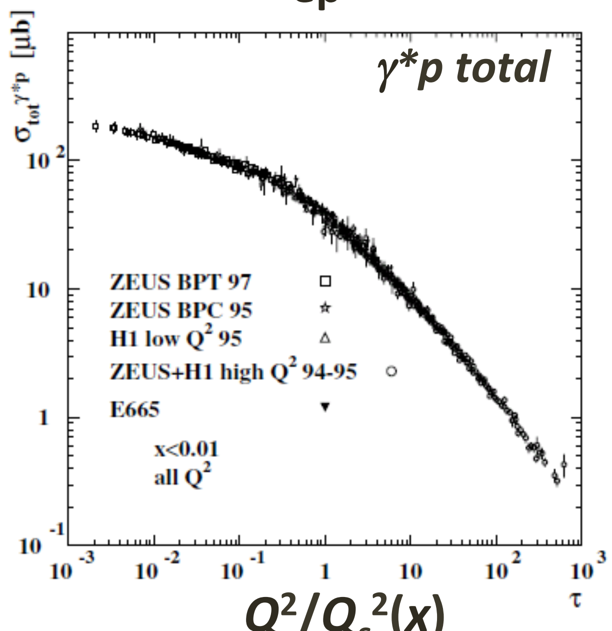


FIG. 1. Experimental data on $\sigma_{\gamma^* p}$ from the region $x < 0.01$ plotted versus the scaling variable $\tau = Q^2 R_0^2(x)$.

Freund, Rummukainen, Weigert, Schafer
PRL 90 (2003) 222002

eA

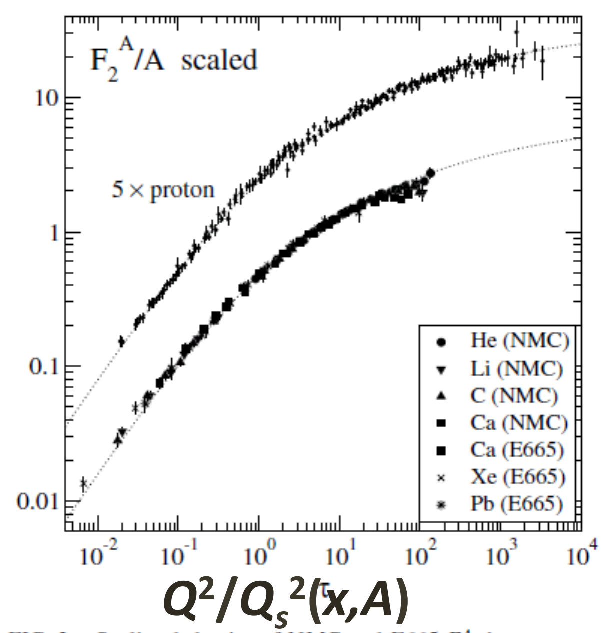


FIG. 3. Scaling behavior of NMC and E665 F_2^A data vs $\tau = (\frac{x_{Bj}}{x_0})^{2\lambda} \frac{Q^2}{A^{1/3}}$. The vertical axis corresponds to the left-hand side of Eq. (5). The dashed line corresponds to the geometric scaling curve obtained from HERA data. These are shown offset by a factor of 5.

Marquet, Schoeffel
Phys. Lett. B639 (2006) 471

Diffractive ep

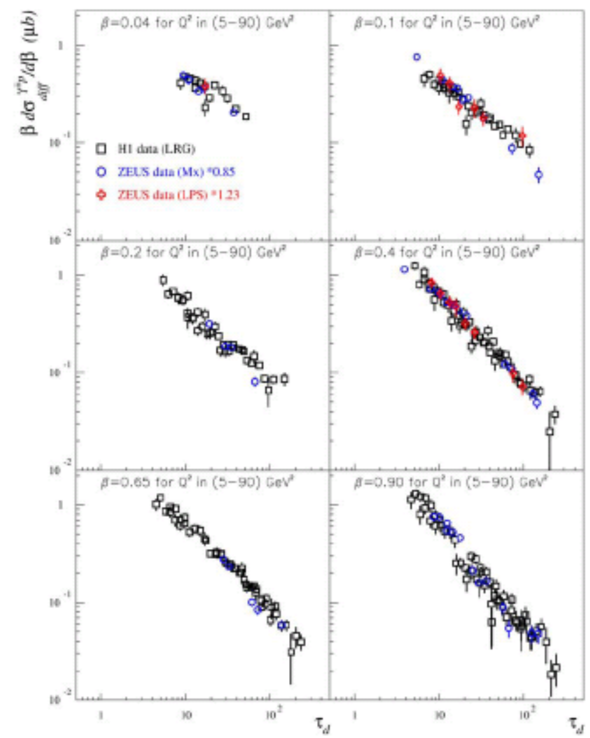


Fig. 2. The diffractive cross-section $\beta d\sigma_{diff}^{\gamma^* p \to Xp}/d\beta$ from H1 and ZEUS measurements, as a function of τ_d in bins of β for Q^2 values in the range [5; 90] GeV^2 and for $x_P < 0.01$. Only statistical uncertainties are shown.

credit: Kazu Itakura (KEK)

- HERA data exhibit geometric scaling with respect to $\tau = Q^2/Q_s^2(x)$ for $x < 10^{-2}$ at all moderate Q^2
- This is not seen in prior fixed-target experiments and HERA data at larger x
- ~15% of events is diffractive → suggestive of an underlying physics mechanism of gluon saturation

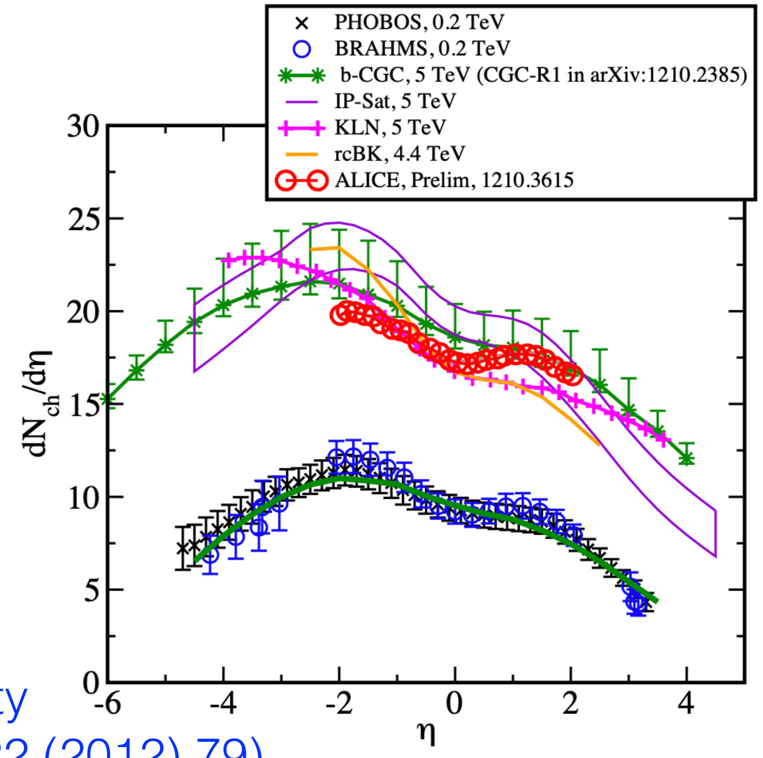
Saturation at HERA?

- However, it has been shown that DGLAP evolution
  - preserves the geometric scaling if the initial parton distributions follows its characteristic shape (Nucl. Phys. A 854 (2011) 32)
  - can itself generate such scaling behavior for moderate values of Q^2 (PRL 101 (2008) 022001)
- Despite significant progress, theoretically as well as experimentally with complementary processes, the situation remains inconclusive to date and further studies are needed!

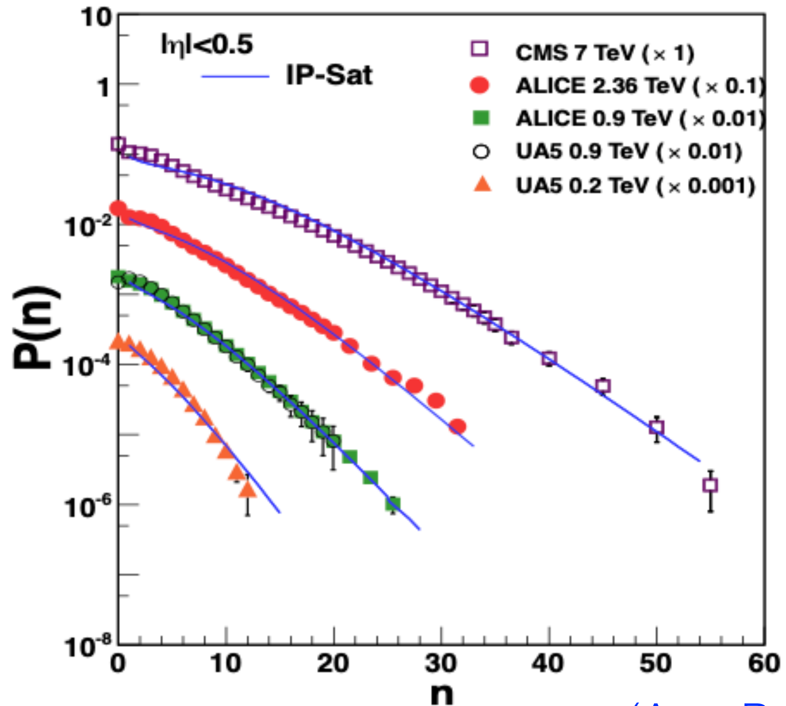
Some studies from RHIC and LHC (1/5)

- CGC determines the initial multiplicity of produced particles as a function of beam energy and centrality of collisions

- It is usually assumed that the multiplicity of produced gluons is equal to that of produced pions

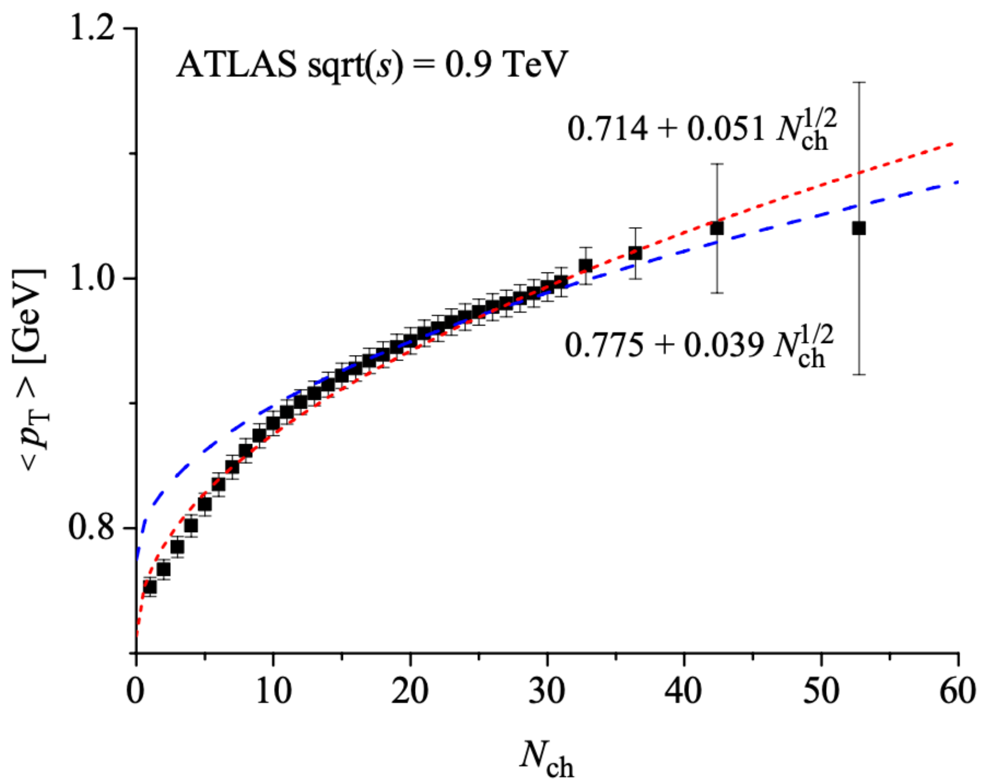


Multiplicity
(AIP Conf. Proc. 1422 (2012) 79)

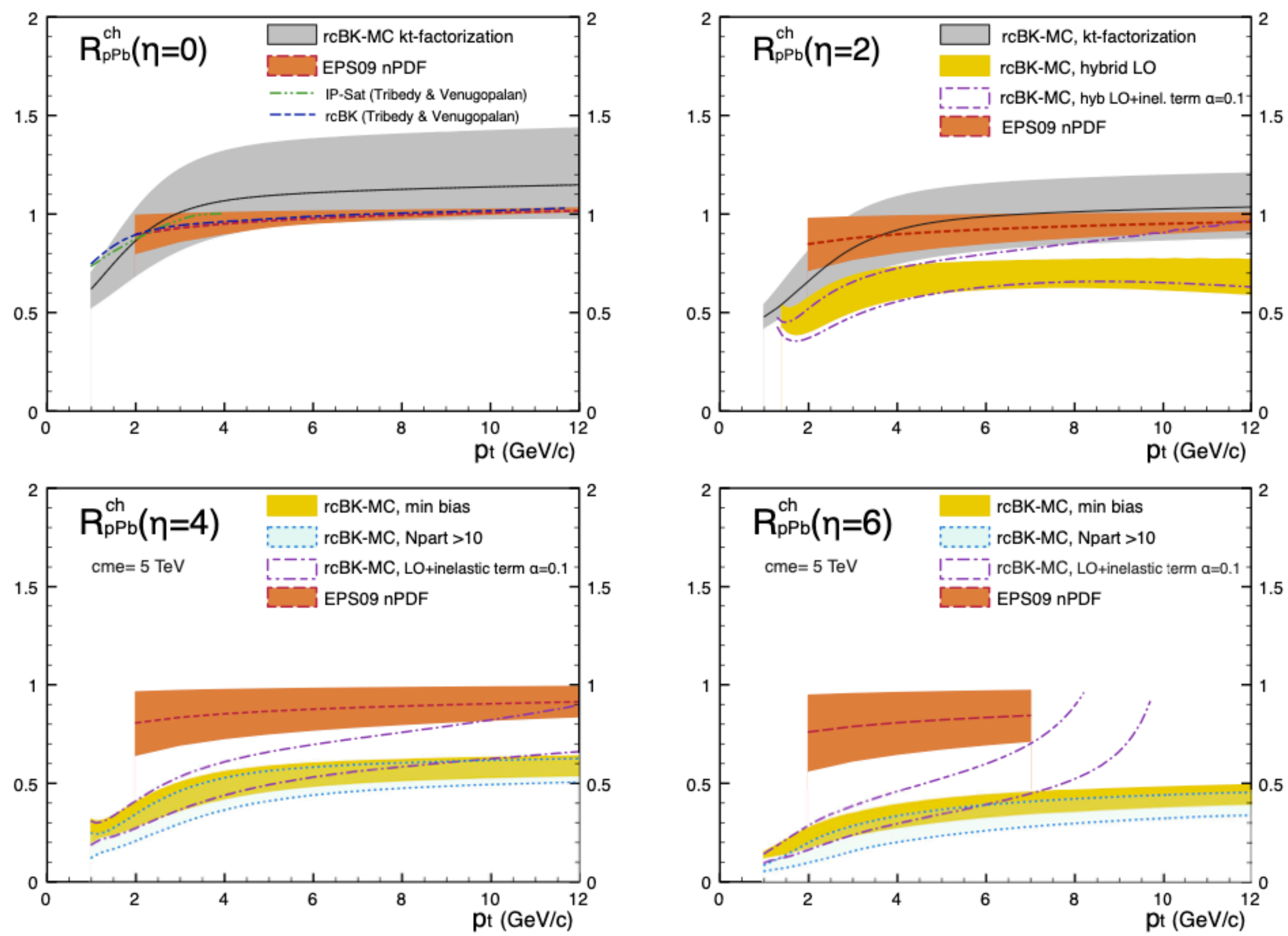


Distribution of multiplicity fluctuations
(Ann. Rev. Nucl. Part. Sci. 60 (2010) 463)

Some studies from RHIC and LHC (2/5)

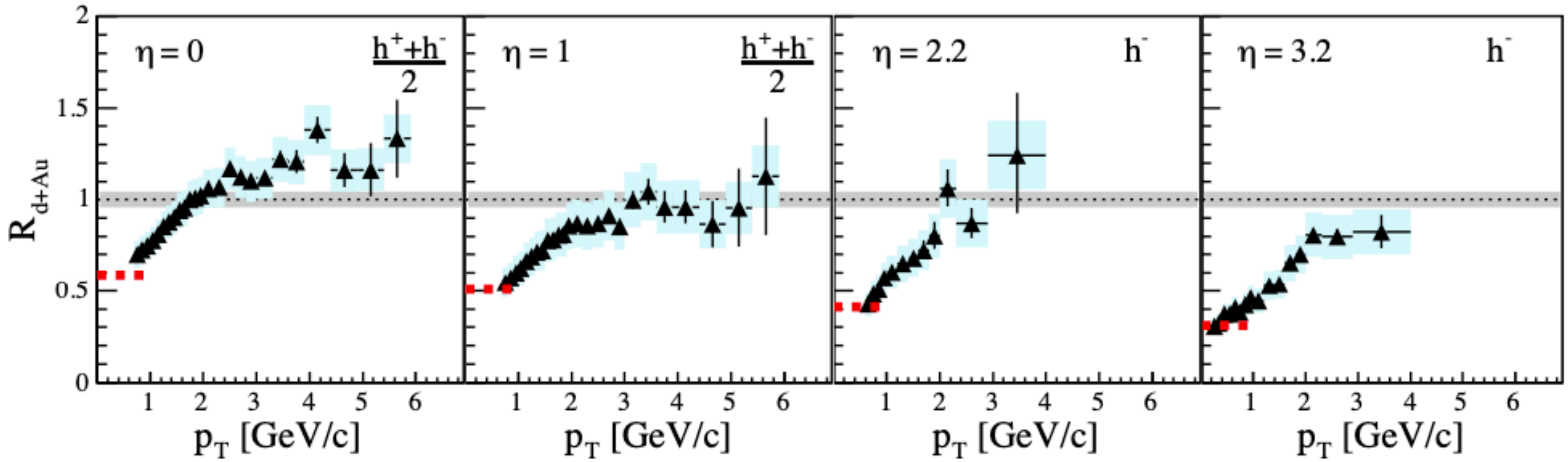


Transverse momenta vs multiplicity
(data vs simple model based on CGC)
(Acta. Phys. Polon. B 41 (201) 1917)



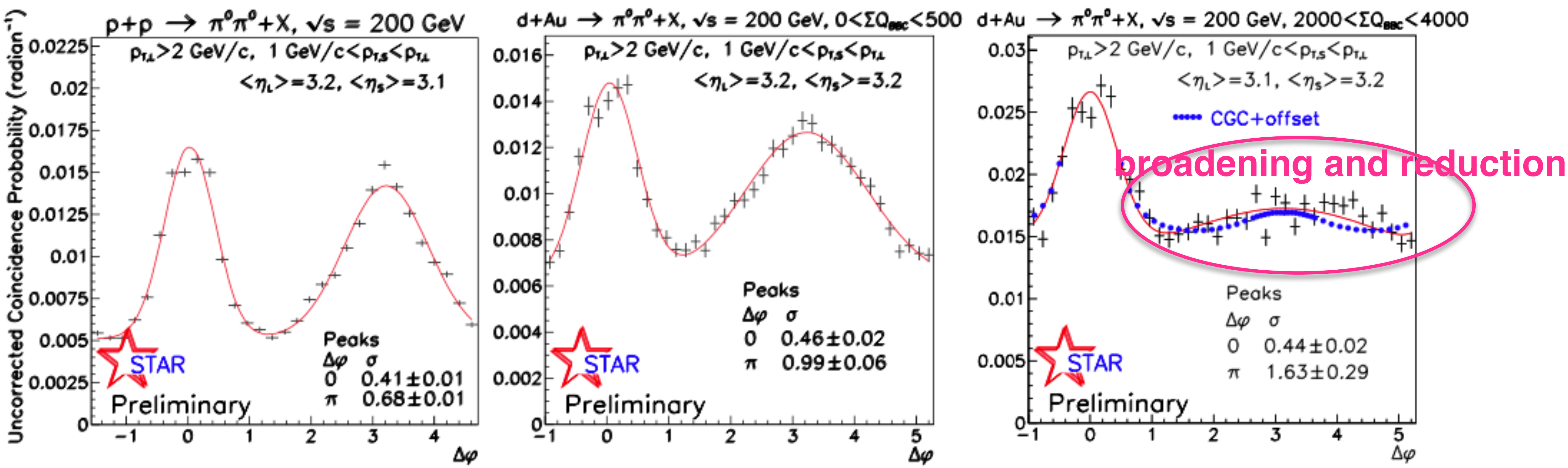
CGC predictions in p+Pb collisions
(Nucl. Phys. A 897 (2013) 1)

Some studies from RHIC and LHC (3/5)



- A conventional multiple scattering model based on Glauber's theory predicts the enhancement of the Cronin effect in the forward rapidity region
- BRAHMS data show marked suppression in the forward region consistent with the CGC predictions

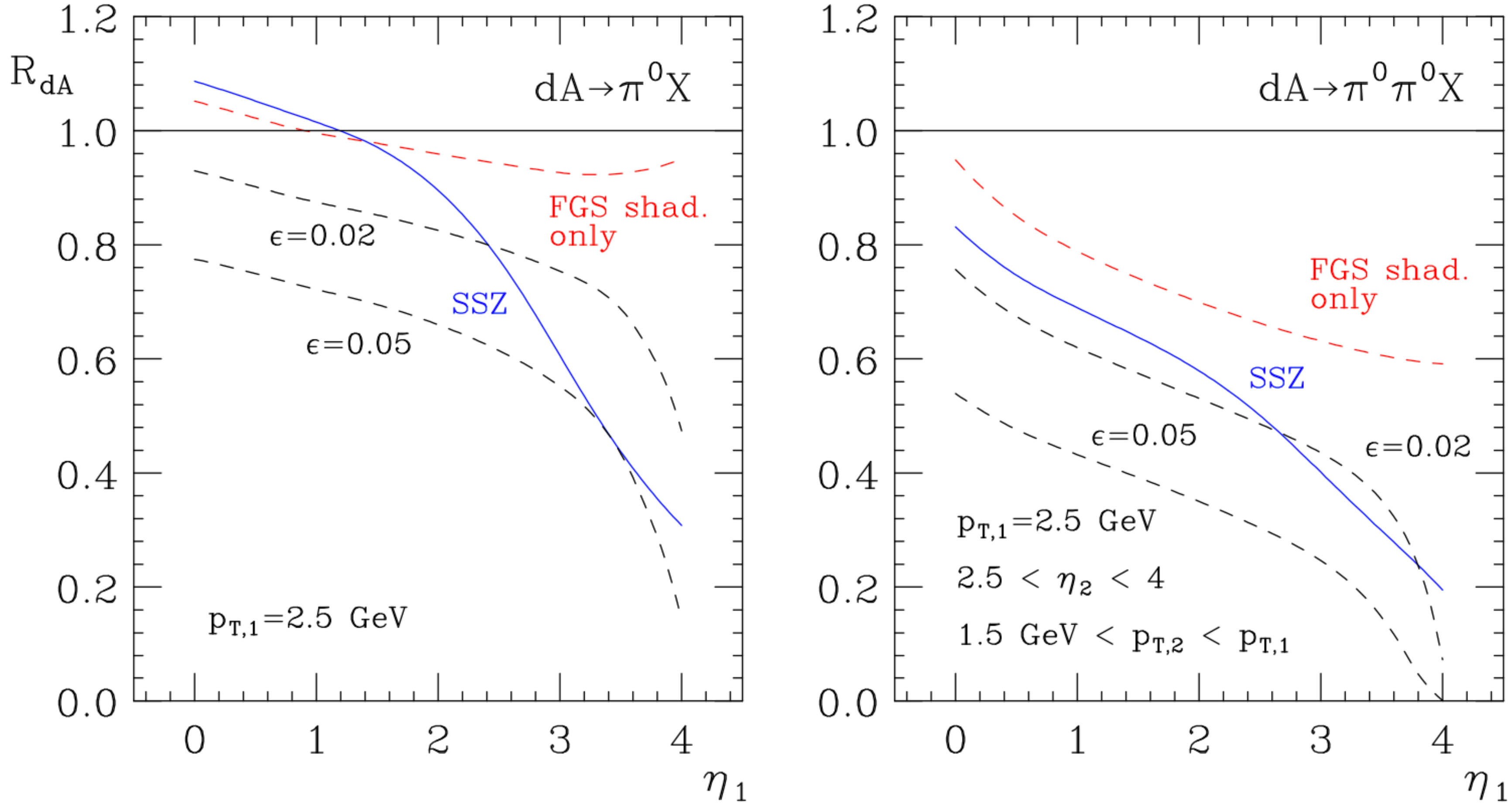
Some studies from RHIC and LHC (4/5)



pp dAu peripheral dAu central

- Forward-backward angular correlation of two forward neutral pions
- In the backward direction, the backward peak in the collision of the dA center has obvious settling and disappearance

Some studies from RHIC and LHC (5/5)



- The approach of multiple parton interactions was shown to be quantitatively consistent with the forward suppression of R_{dAu} (PRD 83 (2011) 034029)
- a short conclusion: alternative descriptions (such as multiple parton interactions) are not excluded

EIC: key questions and key measurements

- Key questions:
  - **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus ?**
  - **Where does the saturation of gluon densities set in ?**
  - **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei ?**

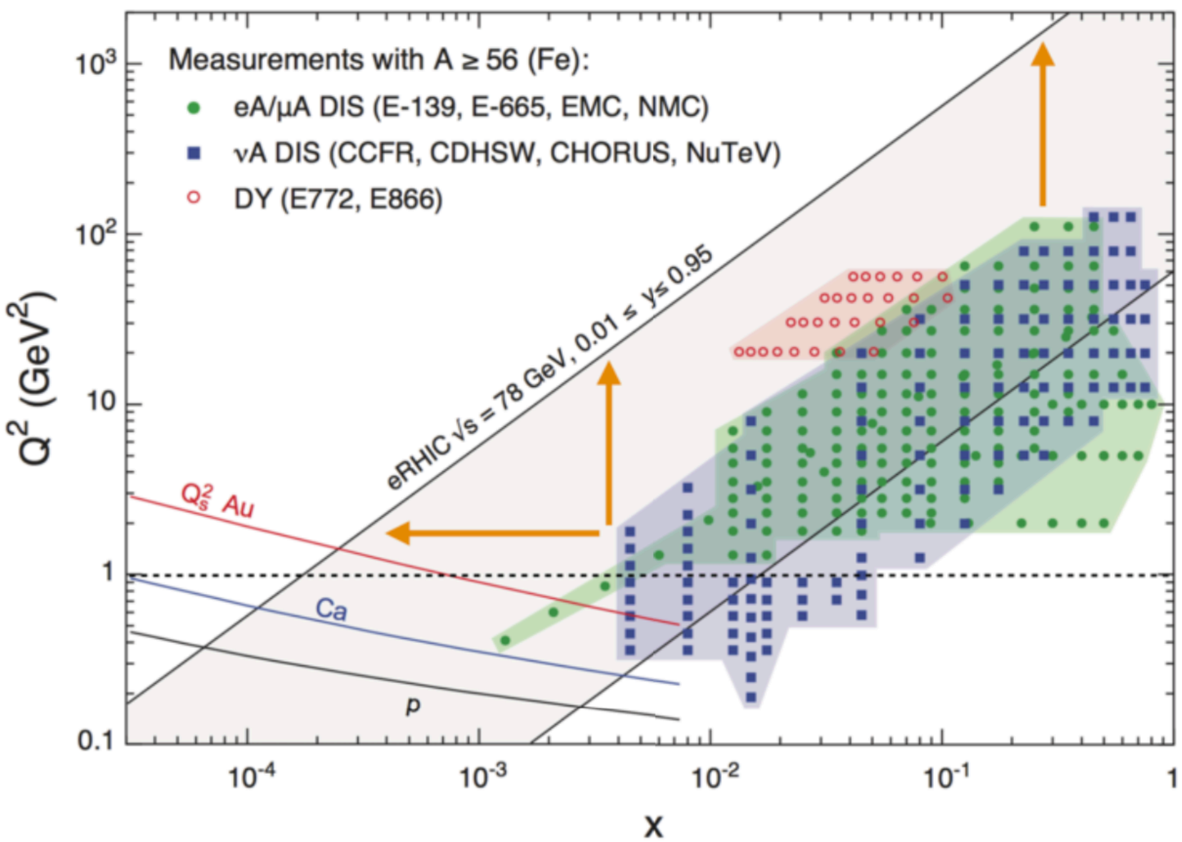
- Key measurements:
  - Inclusive deep inelastic scattering
  - Semi-inclusive deep inelastic scattering with one or two of the particles in the final state
  - Exclusive deep inelastic scattering
  - Diffraction

EIC: key measurements and key requirements

- Key requirements:
  - Electron identification - scattered lepton
  - Momentum and angular resolution - x, Q^2
  - $\pi^+, \pi^-, K^+, K^-, p^+, p^-, \ldots$ - identification, acceptance
  - Rapidity coverage, t-resolution

- Key measurements:
  - Inclusive deep inelastic scattering
  - Semi-inclusive deep inelastic scattering with one or two of the particles in the final state
  - Exclusive deep inelastic scattering
  - Diffraction

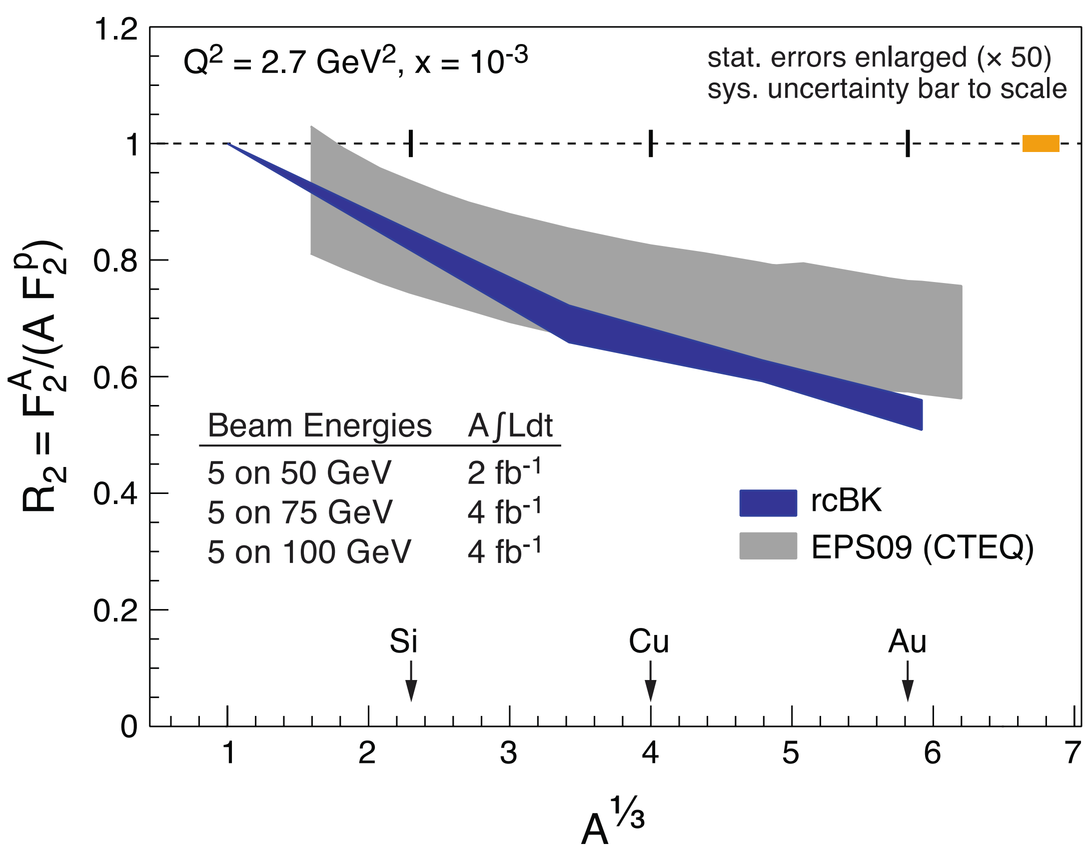
EIC kinematic range

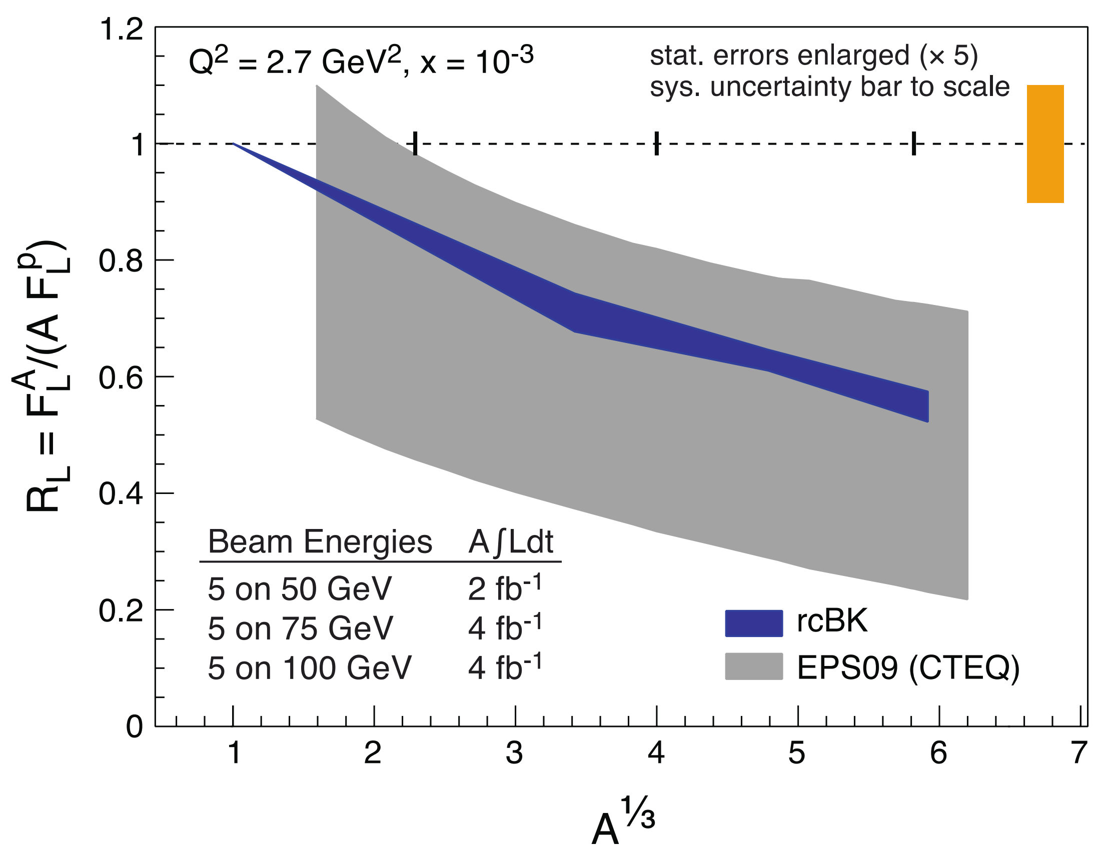


- EIC will delve into the unmeasured region of large Q^2 and the uncharted territory of nucleon distribution for small x
- The requirement of heavy nuclei serves to enhance saturation phenomena compared to proton beams at the same $\sqrt{s}$ per nucleon
- Compared to HERA, it not only compensates for the lower center-of-mass energy of the EIC, but also reduces the range of x accordingly

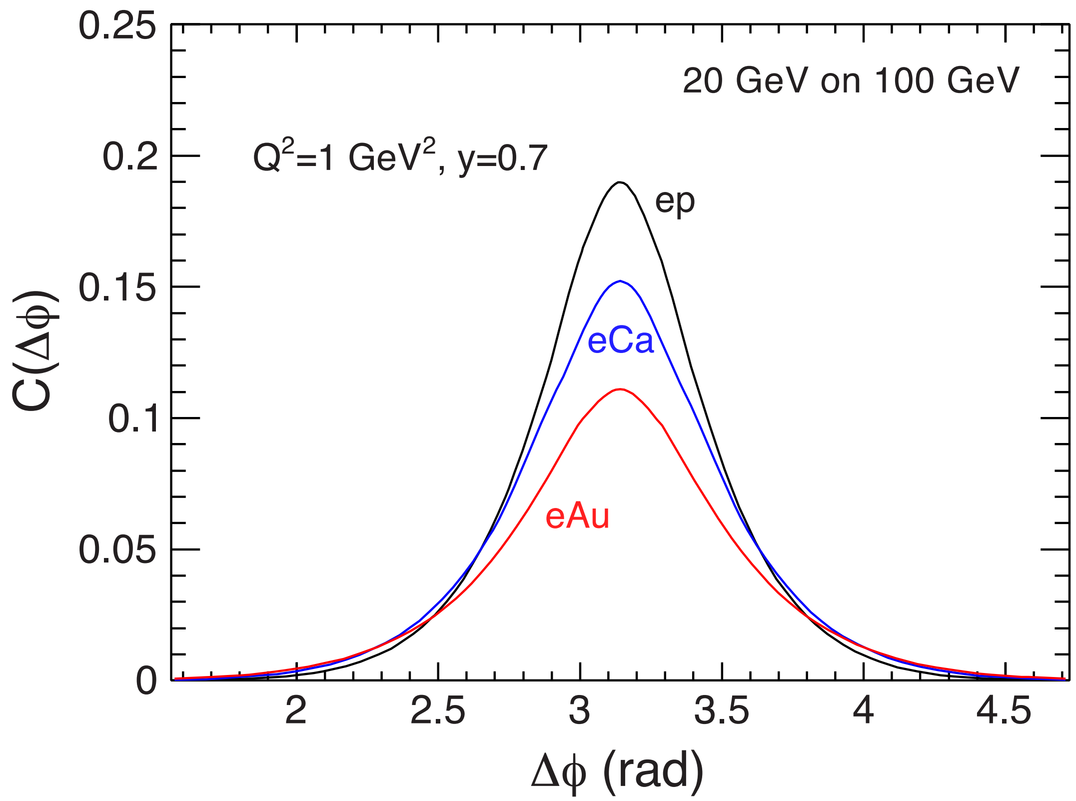
Saturation measurements at EIC

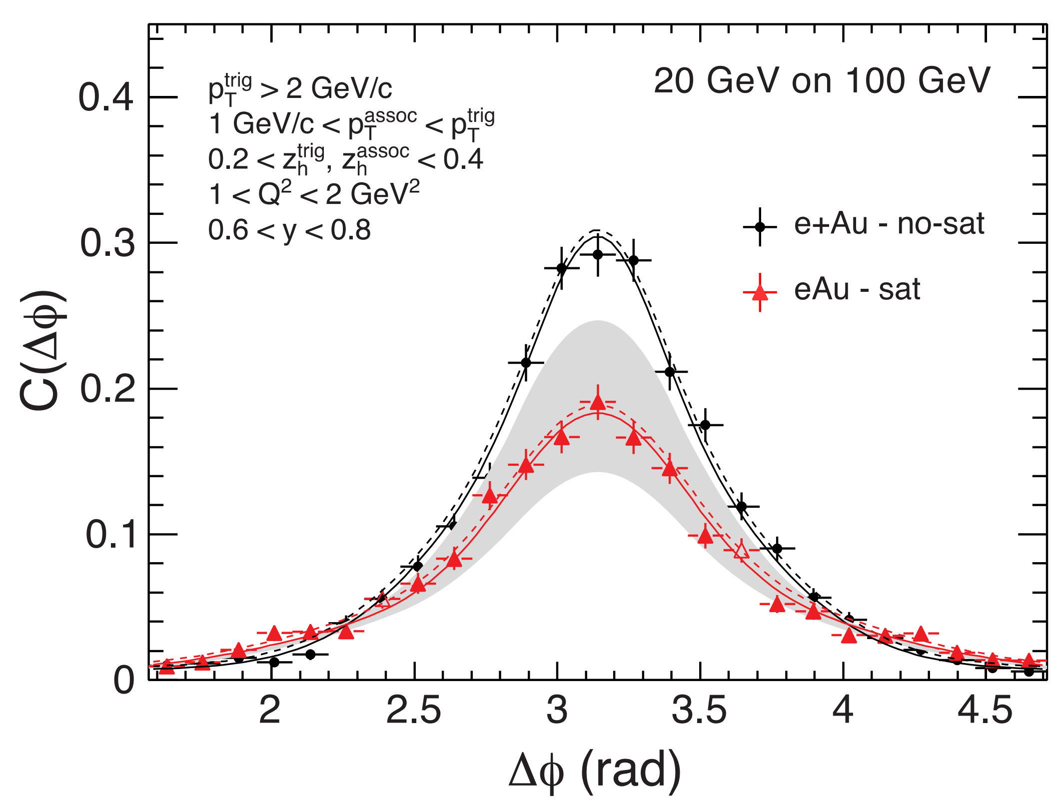
- Saturation physics predicts the x-dependence of structure functions with BK/JIMWLK equations and their A-dependence through the MV/GM initial conditions, though the difference with models for DGLAP initial conditions is modest





Di-hadron correlations (1/2)





- Di-hadron correlation depletion predicted for e+A compared to e+p

Di-hadron correlations (2/2)

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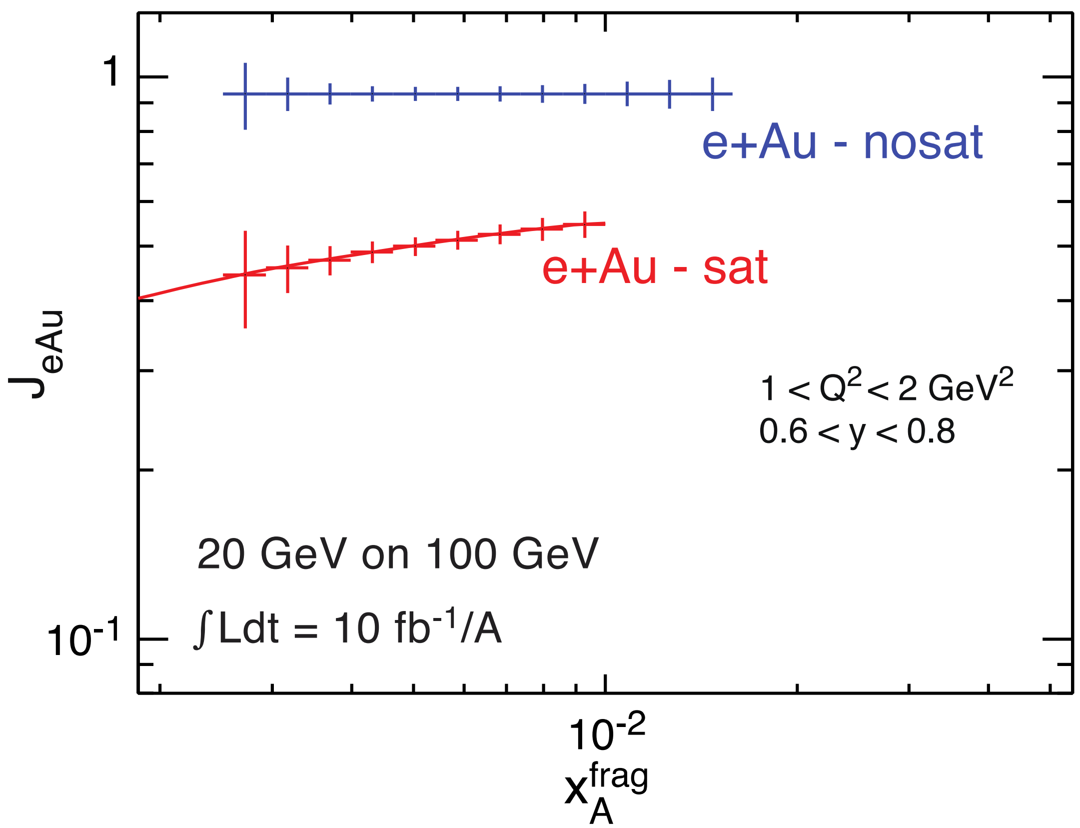

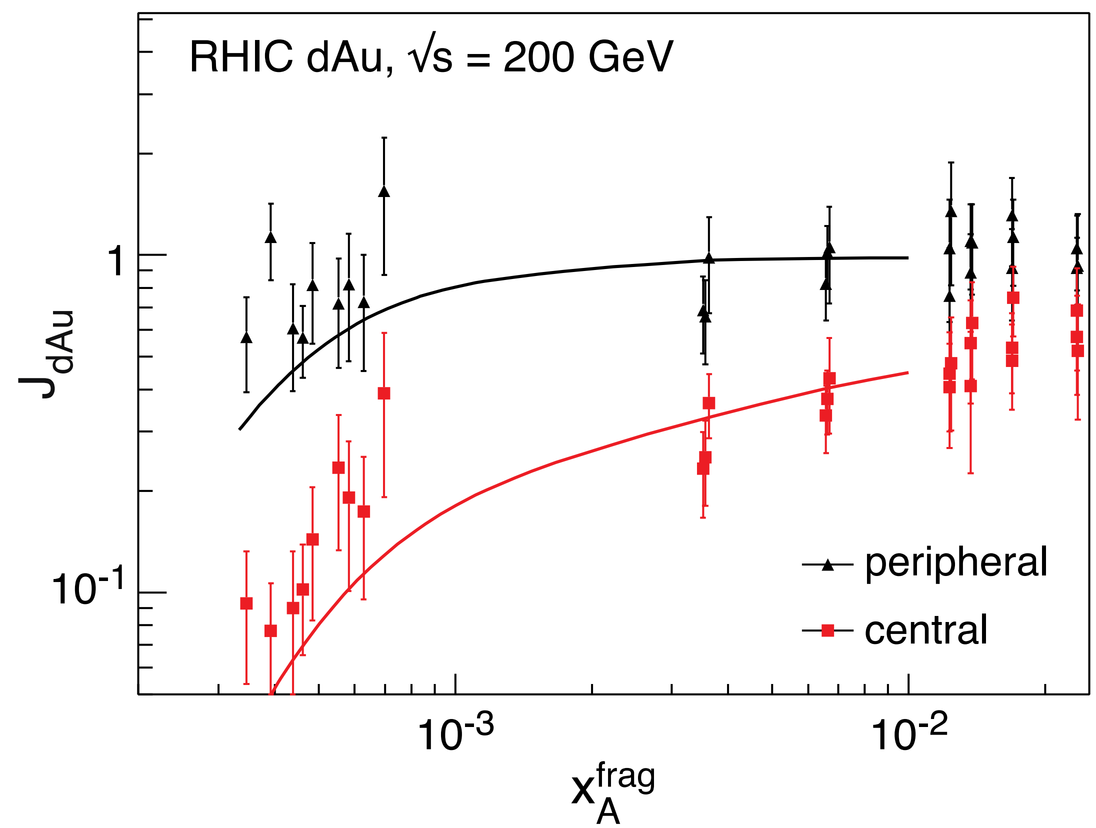

- Away-side yield J_{eA} is also expected to decrease in e+A compared to e+p

Diffraction

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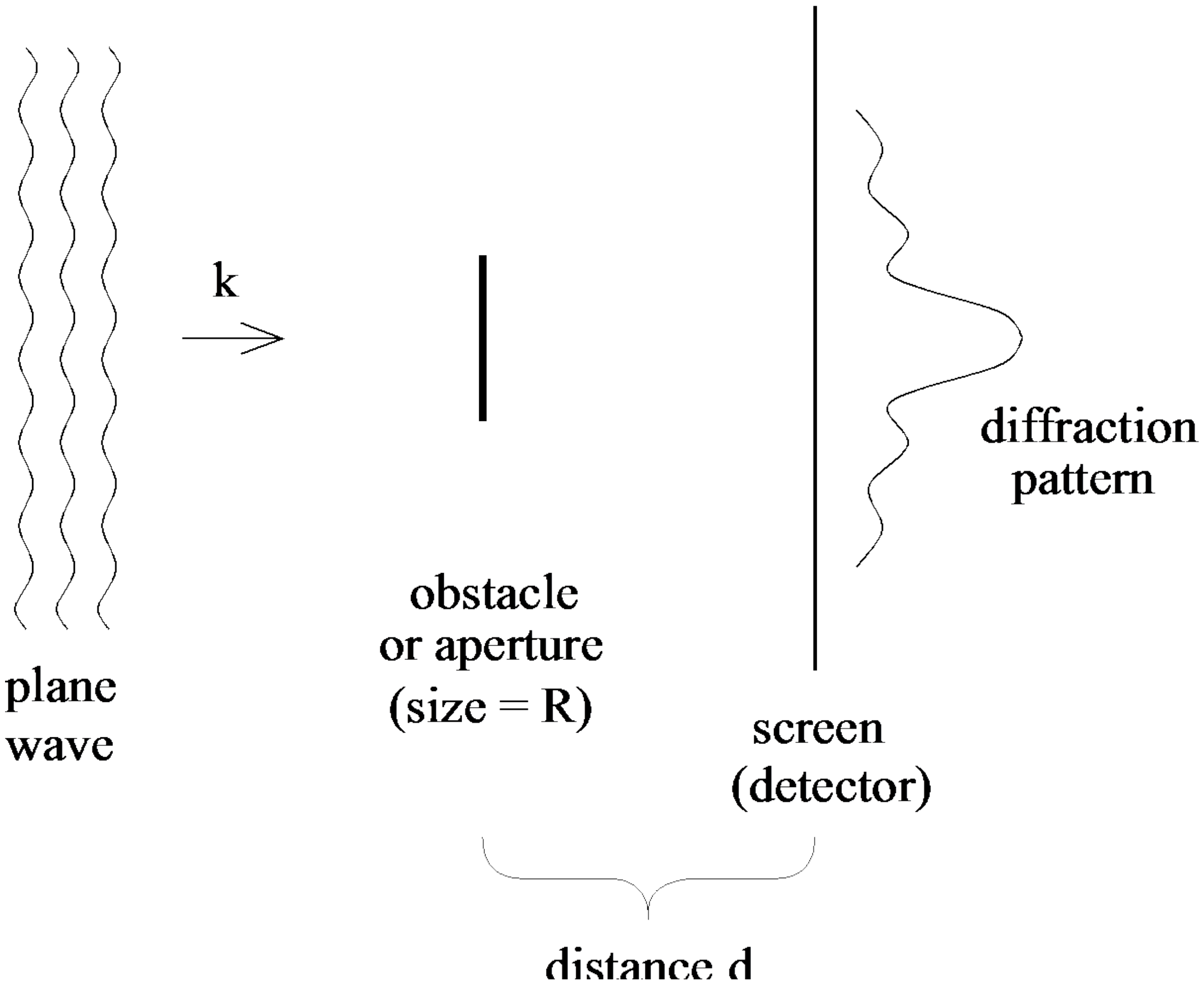
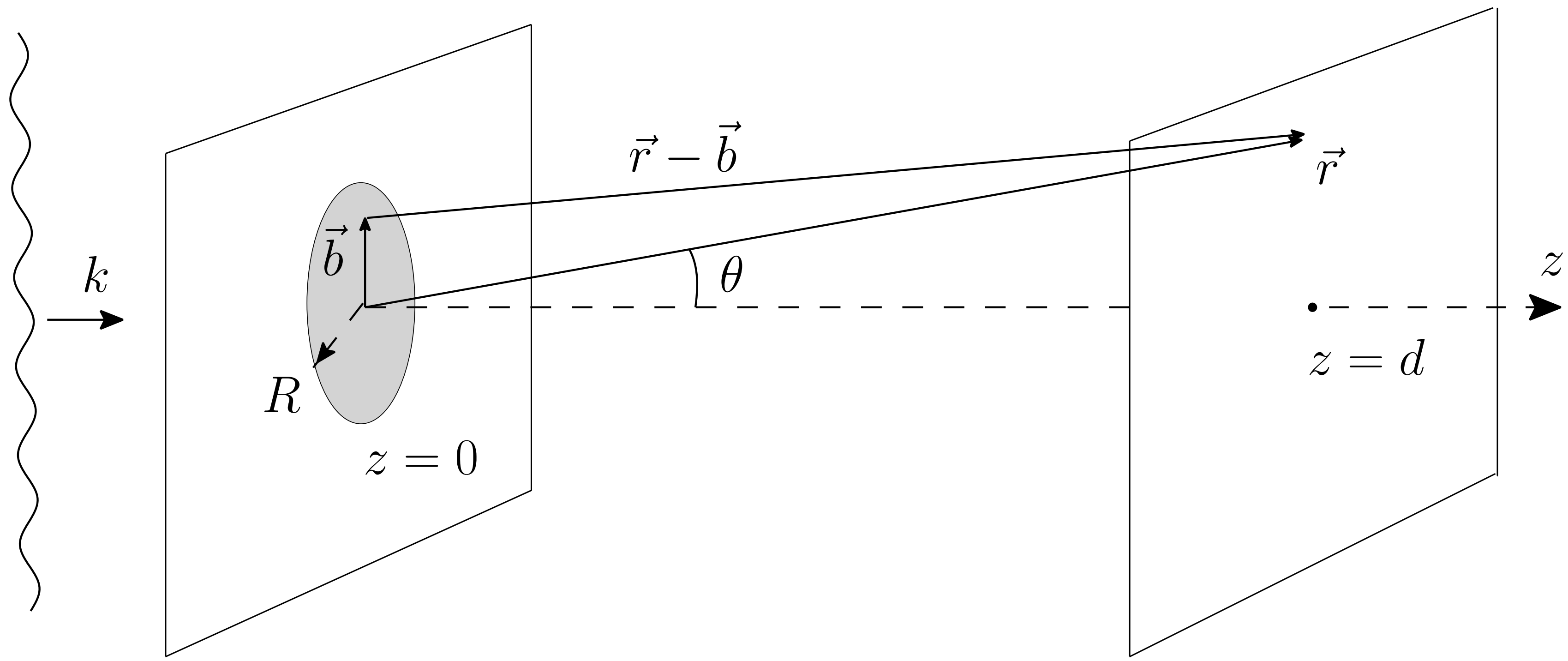
- One of the key signatures of diffractive events in deep-inelastic scattering events is the existence of a large rapidity gap between the scattered proton or nuclei traveling at near-to-beam energies and the final-state particles produced at mid-rapidity
- The diffraction cross section is particularly sensitive to the underlying gluon distribution
- It is found surprisingly large at HERA, where about 15% of the events are diffractive, and is expected to be even larger in the e+A collision of the EIC
- The measurement of the diffractive cross sections and their dependence on the invariant mass of the produced particles in e + p and e + A collisions is also crucial to be studied

Diffraction in optics



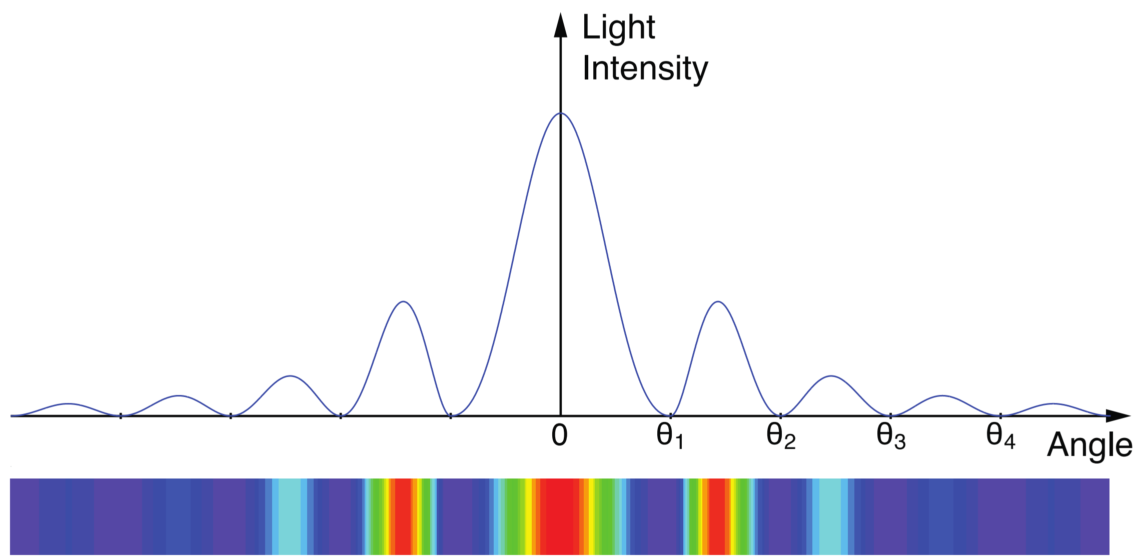
- The diffraction pattern contains information about the obstacle size R and the optical "blackness" of the obstacle

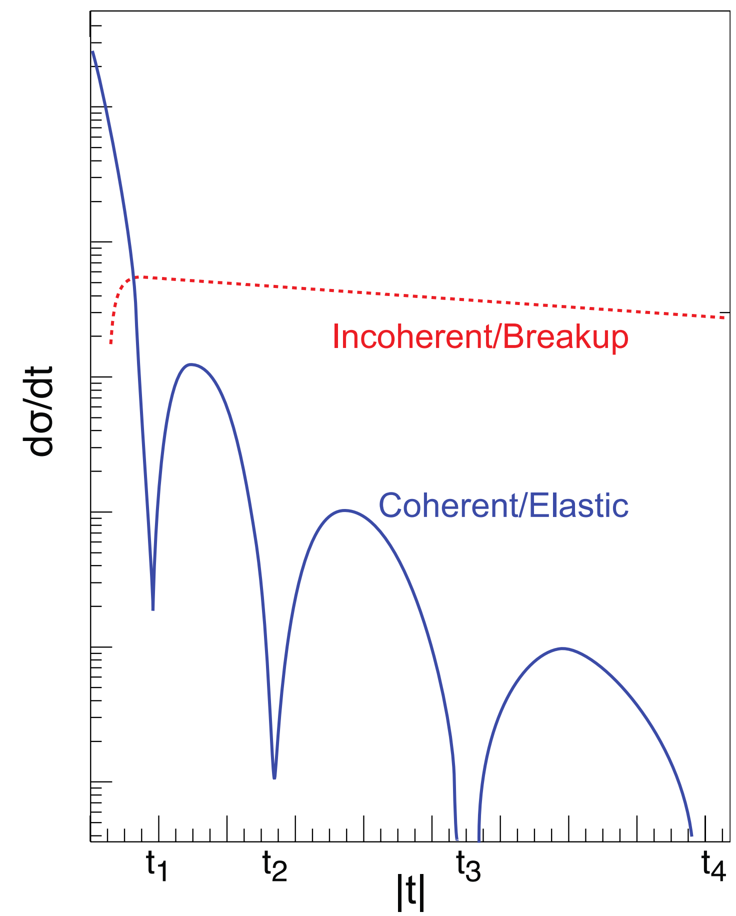
Diffraction in optics and QCD



- 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 $t = -(k sin\theta)^2$

Optical analogy





- Diffraction in high energy scattering is not very different from diffraction in optics: both have diffractive maxima and minima
- In diffractive e + A collisions one distinguishes coherent events, in which the nucleus stays intact, and incoherent events, in which the nucleus breaks up but the nucleon stays intact
- Two processes can be distinguished experimentally with good efficiency by using tagging techniques with a very forward zero-degree-calorimeters in combination with the observation of a rapidity gap

Exclusive vector meson production as a probe of saturation

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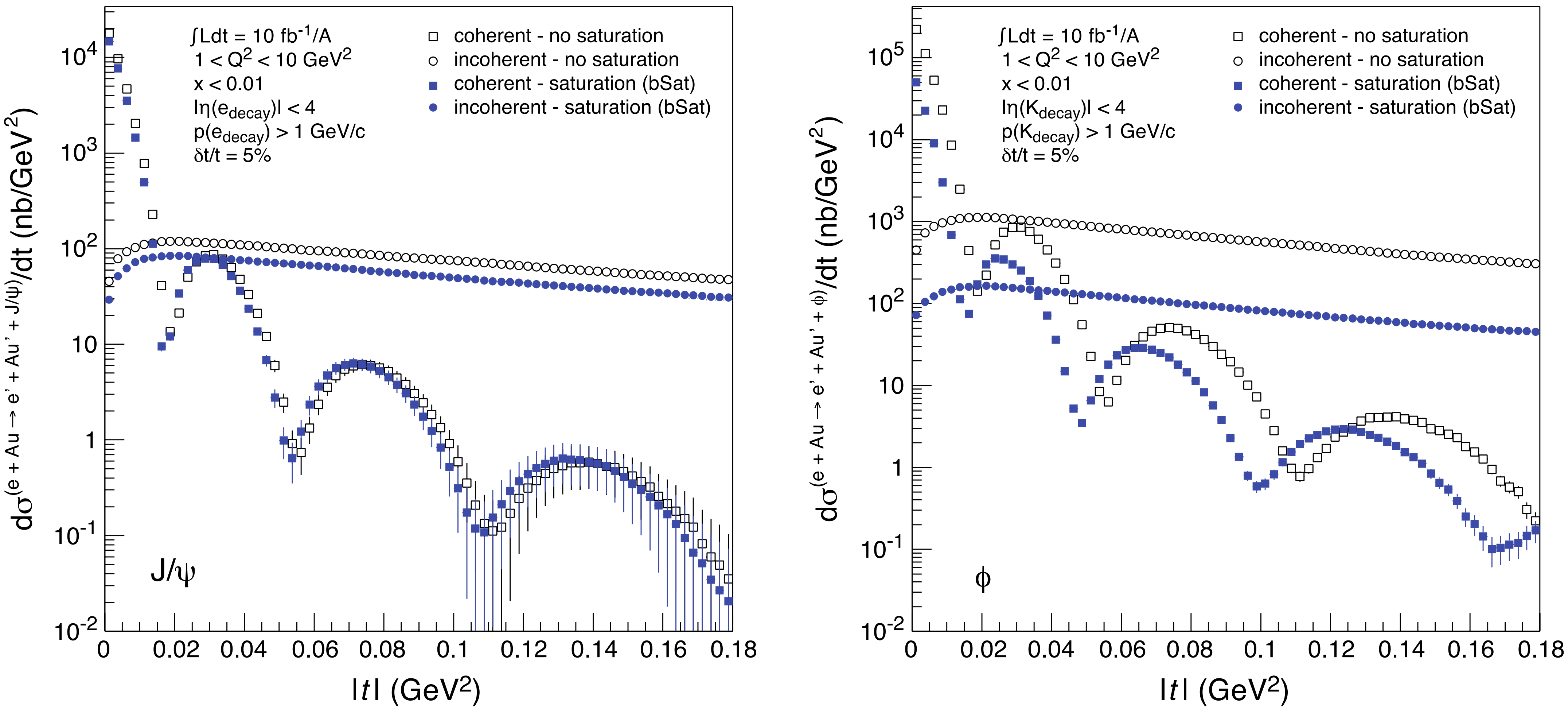

- It is experimentally very clean and allows the reconstruction of the momentum transfer, t
- J/Ψ is smaller, less sensitive to saturation effects
- Φ meson is larger, more sensitive to saturation effects

Summary

- The structure of nuclear matter is increasingly dominated by gluons when we probe it at higher and higher energies
- The gluon saturation has yet to be observed conclusively
- EIC has been proposed to observe and study the saturated gluon density regime

References

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- Yuri Kovchegov, Gluon saturation (oral presentation)
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- L. McLerran, The color glass condensate, glasma, and the quark gluon plasma in the context of recent pPb results from LHC, JPCS 458 (2013) 012024