Opportunities in low x physics at a future Electron-Ion Collider (EIC) facility

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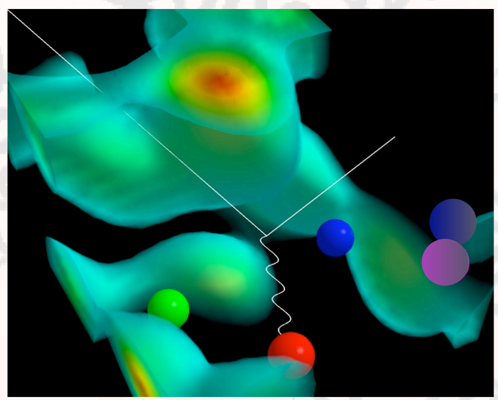
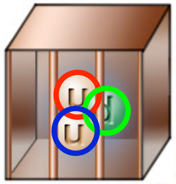
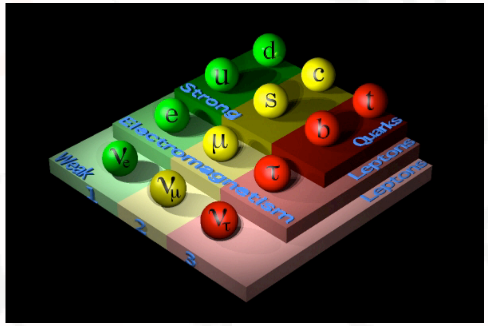
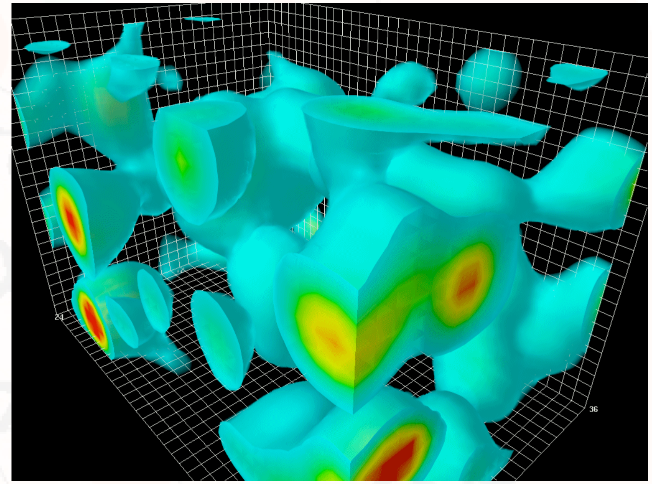


Quantum Chromo Dynamics



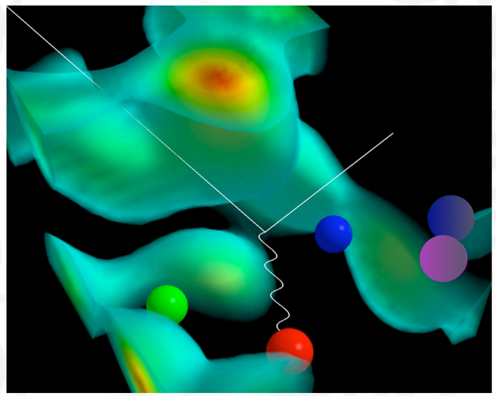
Proton=uud





Visible Universe

Galaxies, stars, people,...



Protons & Neutrons

3 valence quarks +...

Silent Partners:

Virtual quark-antiquark pairs ($\Delta E\ \Delta t \sim h$)

Gluons!

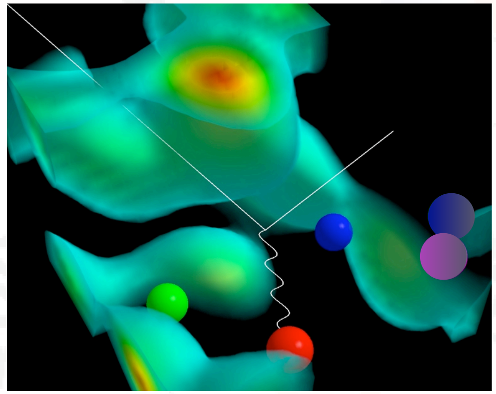
Structure and dynamics of proton (**mass**) (→ visible universe) originates from QCD-interactions!

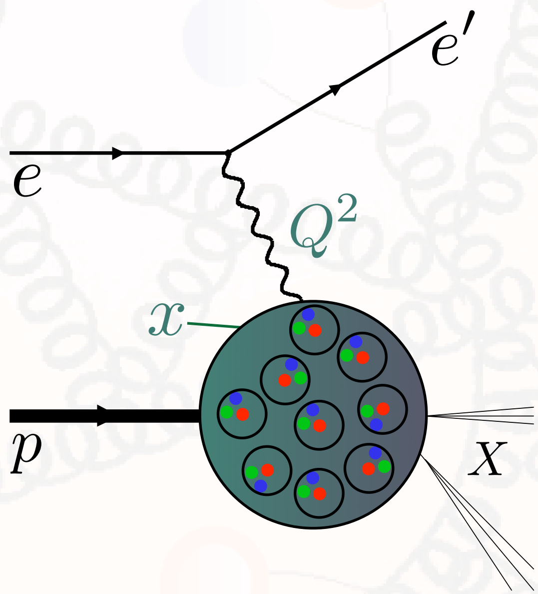
What about **spin** as another fundamental quantum number?

- The silent (low x) partners...: Gluons and QCD-Sea

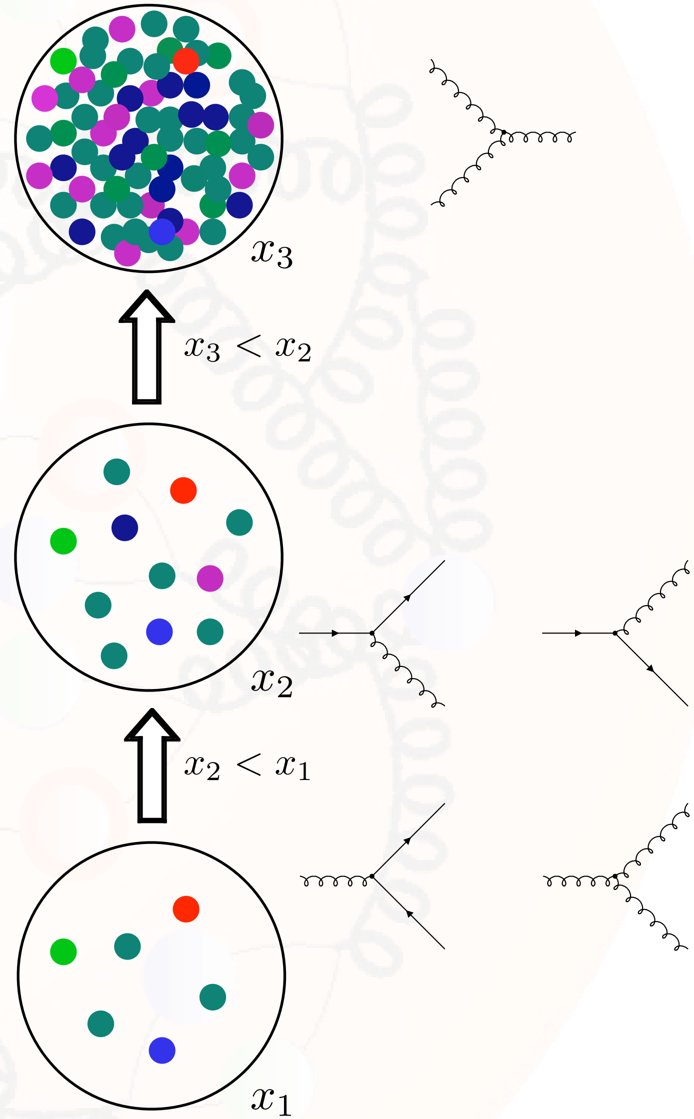
- Fundamental questions:

  - What are the properties of gluons that bind strongly interacting particles?
  - What is the quark-gluon internal structure of nucleons?
  - What are the properties of quark-gluon matter at high density?



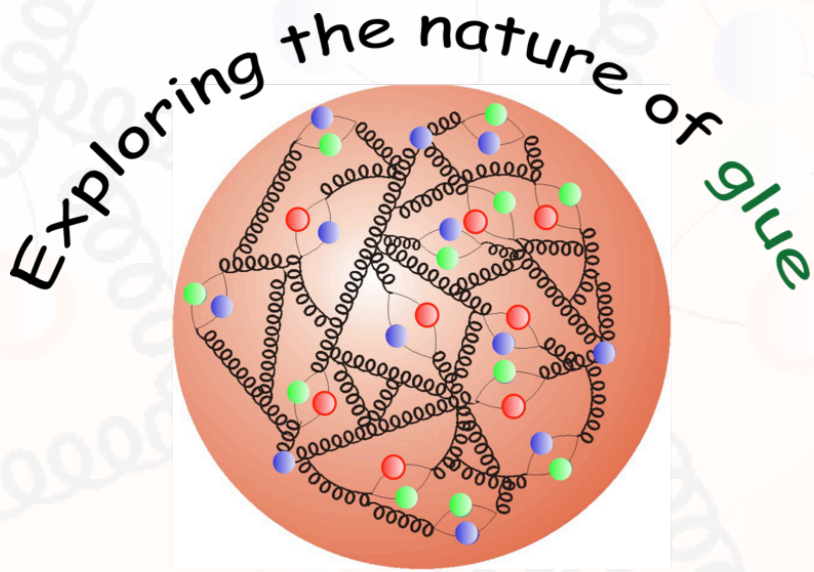


$W^2 \simeq Q^2/x$



Outline

- Low-x physics: Future opportunities



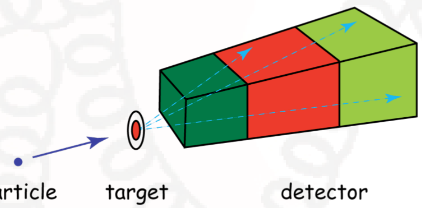
- Low-x physics: Concepts and Status
- Summary and Outlook

Low-x Physics - Concepts and Status

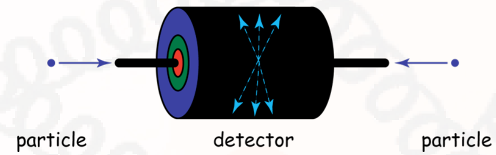
- Low-x basics
  - Access higher parton density system
    - Larger center-of-mass energy (√s): Smaller x at larger √s!

fixed-target

$\sqrt{s} = \sqrt{2E_B m}$



$x \sim \frac{Q^2}{s}$

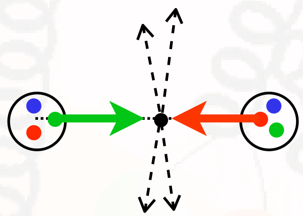


collider

$\sqrt{s} = \sqrt{4E_{b_1}E_{b_2}}$

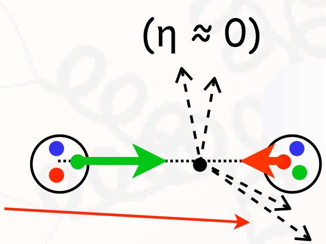
- Forward direction: Smaller x at larger at larger η!

central
(η ≈ 0)

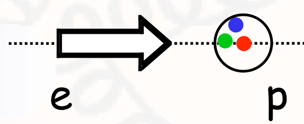


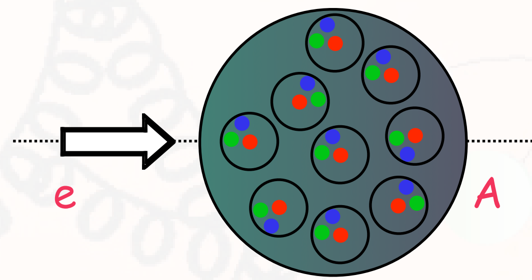
$x \sim \frac{2p_T}{\sqrt{s}} e^{-\eta}$

forward
(η large)



- eA vs. ep scattering: Probe higher parton density system in eA compared to ep!



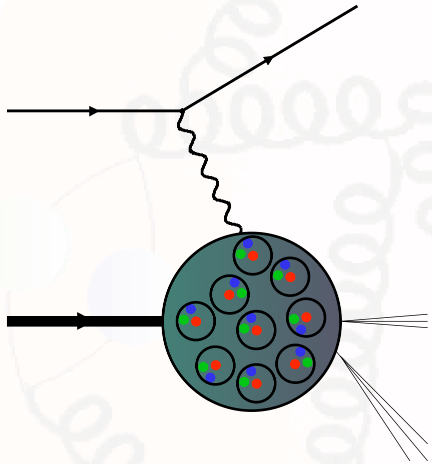


$\sim A^{1/3}$

Low-x Physics - Concepts and Status

- Low-x basics
  - Cross-sections and structure functions

$$Y_+ = 1 + (1-y)^2$$



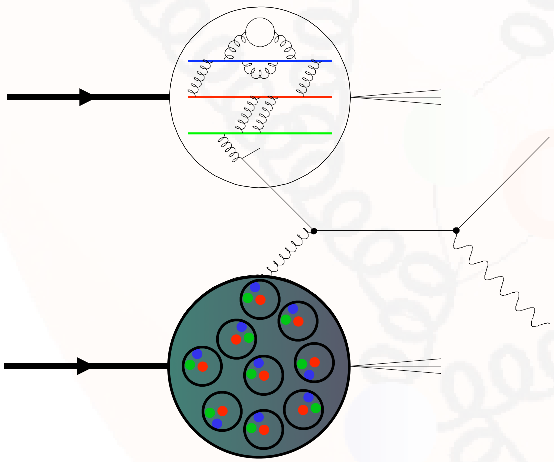
$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

$$\sigma_{tot}^{\gamma^* p} = \sigma_T^{\gamma^* p} + \sigma_L^{\gamma^* p}$$

$$F_2 = \frac{Q^2}{4\pi^2\alpha}\sigma_{tot}^{\gamma^* p} = \sum_{f=q\bar{q}} x e_q^2 f$$

$$F_L = \frac{Q^2}{4\pi^2\alpha}\sigma_L^{\gamma^* p} \propto xg$$

Universality



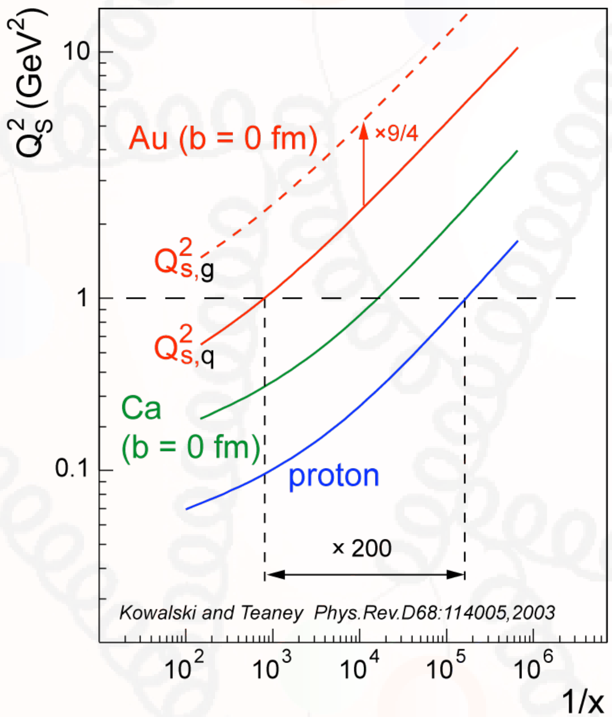
$$d\sigma = \sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \rightarrow f X} \otimes D_f^h$$

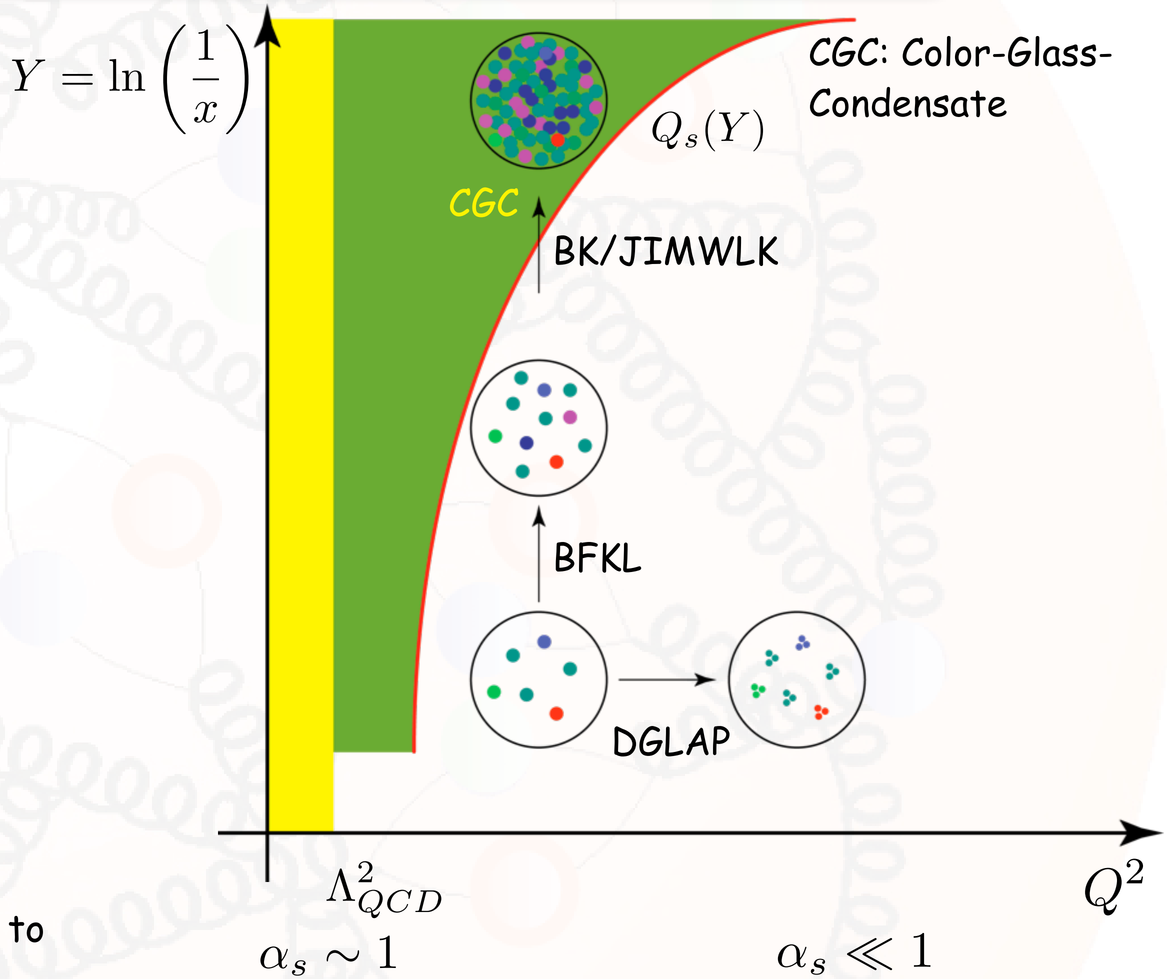
Factorization

Important: Complementary probes are required for unambiguous extraction of observables in high-energy density QCD region!

Low-x Physics - Concepts and Status

- Low-x basics
  - Dynamics: DGLAP / BFKL and CGC





Q_s^2: Saturation scale ⇒ Characterize transition to saturation region!

$$Q_s^2 \simeq \alpha_s \frac{1}{\pi R^2} xG(x, Q^2) \sim$$

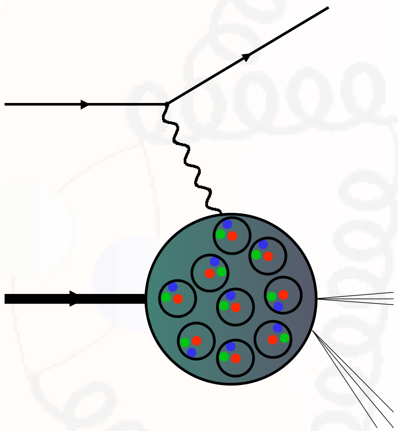
Enhanced for eA compared to ep: $A^{1/3} x^{-\delta}$

DGLAP: Evolution in Q^2

BFKL: Evolution in x

Low-x Physics - Concepts and Status

- Low-x basics
  - Dipole model



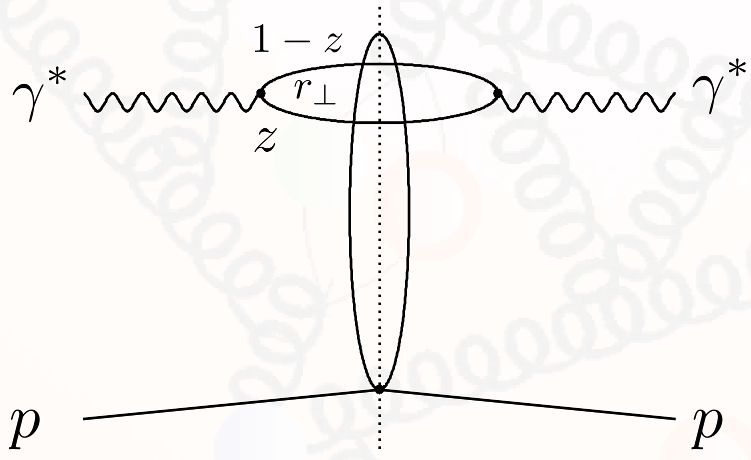
Consider virtual photon-proton cross-section

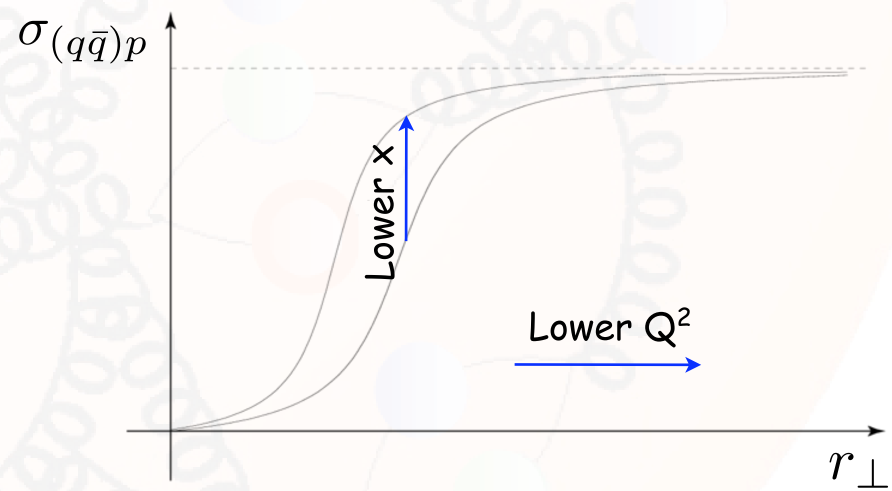
Frame: Proton rest frame

Interaction time < Fluctuation time at low x

Dipole model: Interaction of quark/anti-quark pair with proton

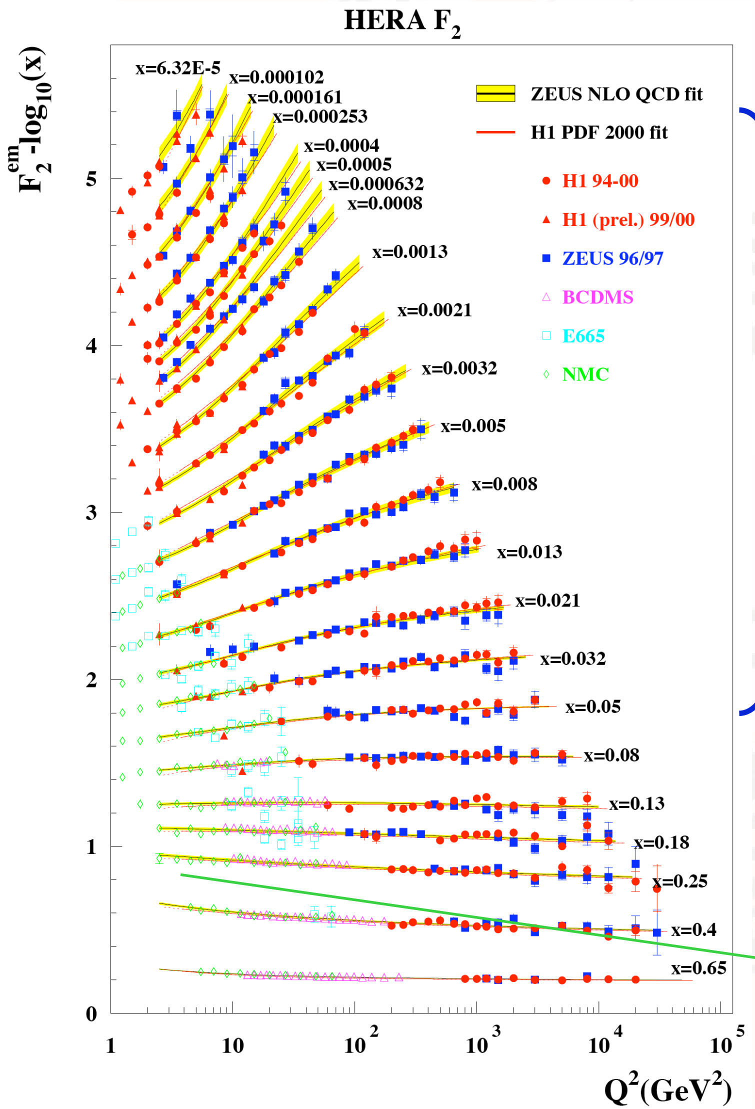
$$\sigma_{tot}^{\gamma^* p} = \int dz \int d^2_{r_\perp} |\Psi|^2 \sigma_{(q\bar{q})p}$$





Low-x Physics - Concepts and Status

HERA: F_2 at low x

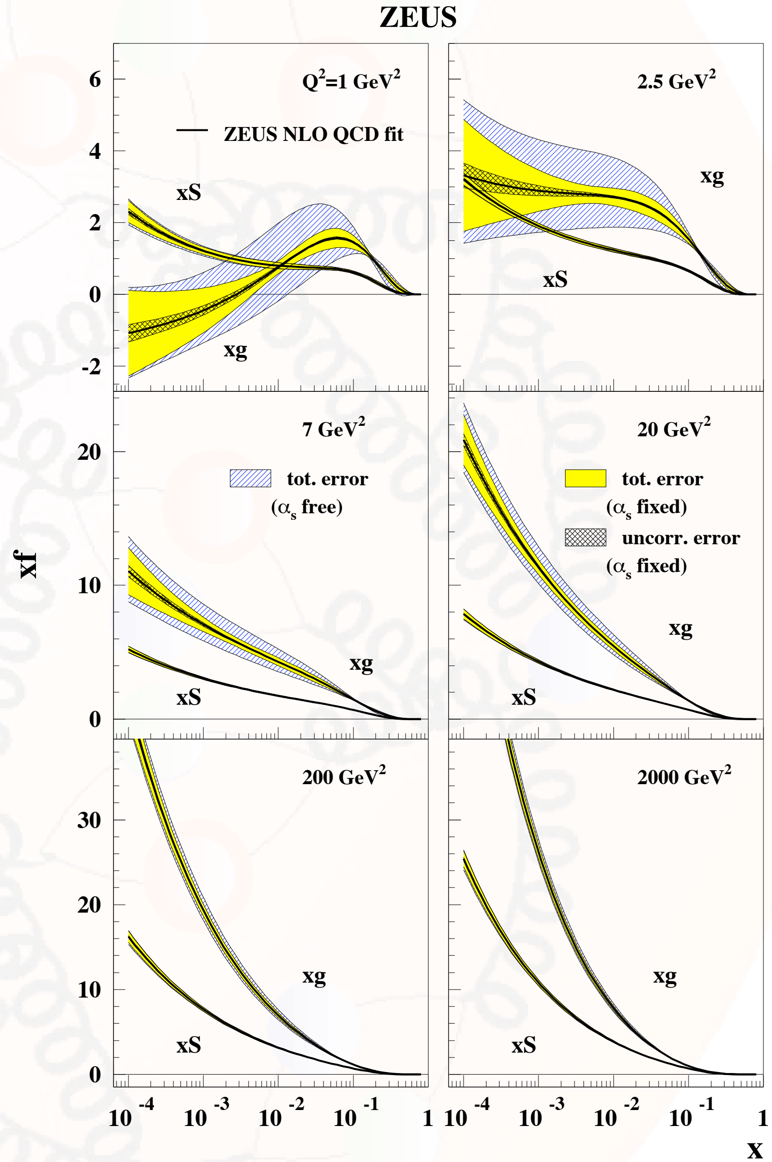


$$xg \sim \left(\frac{dF_2}{d\ln Q^2}\right)$$

Strong violation of scaling at low x and high Q^2

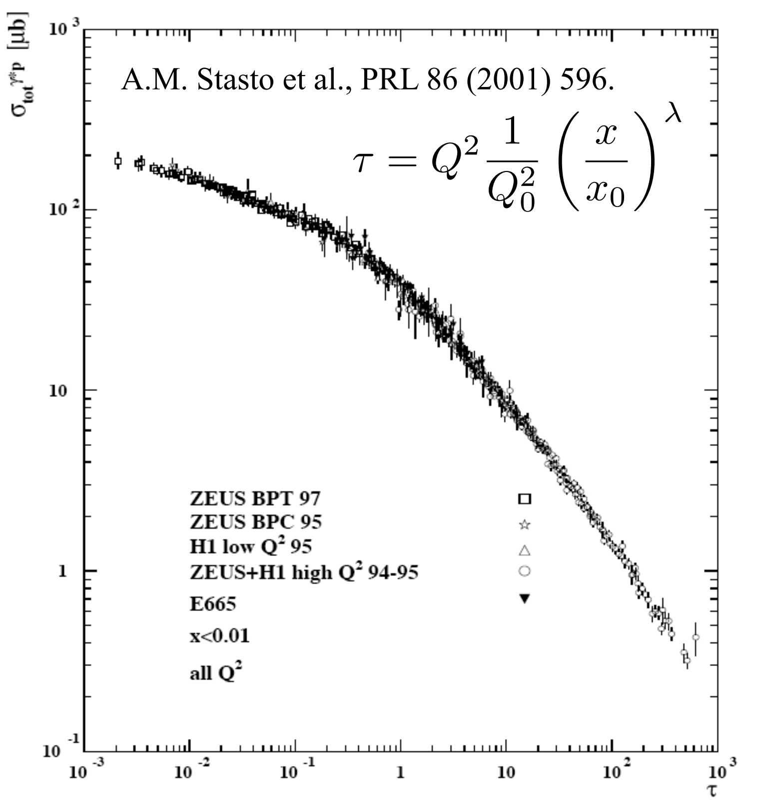
In contrast to:

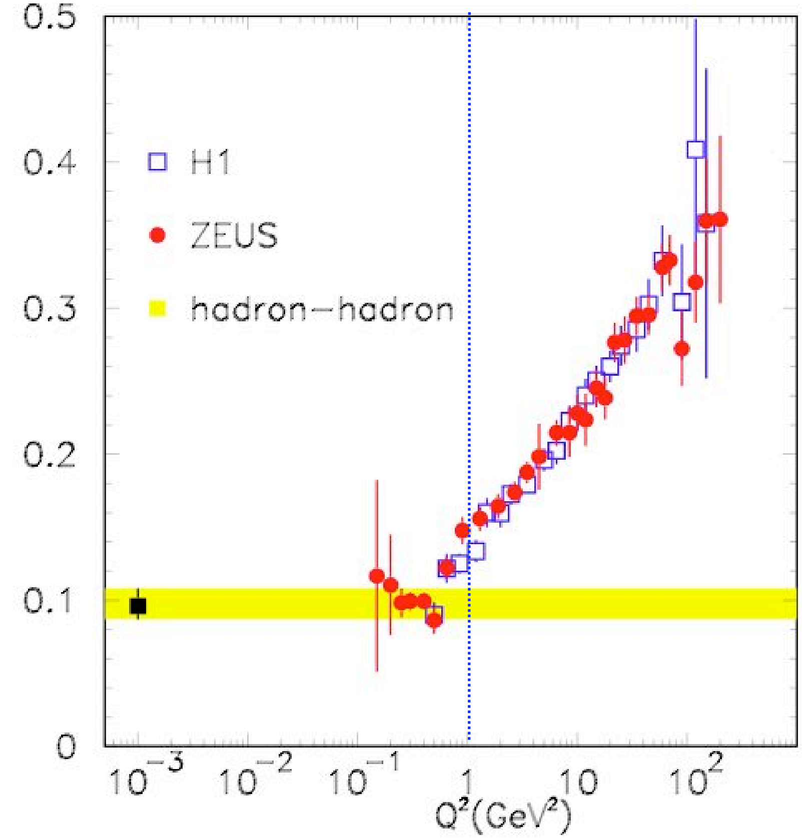
Low Q^2 high x!



Low-x Physics - Concepts and Status

- HERA: $\gamma^{*}p$ cross-section

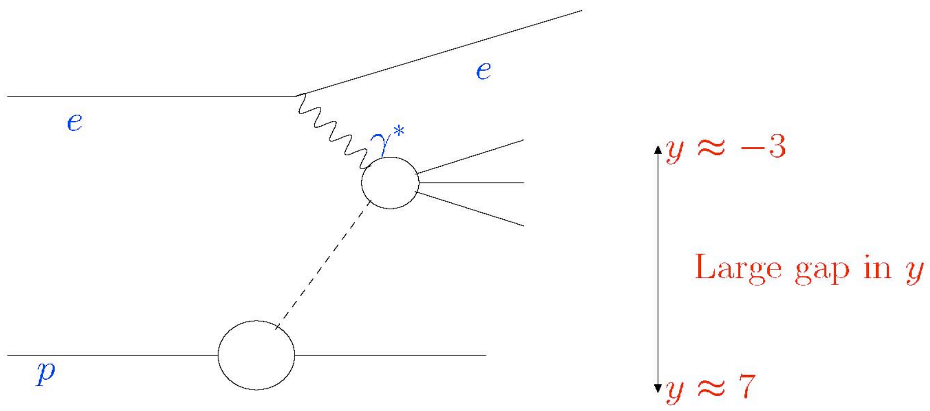


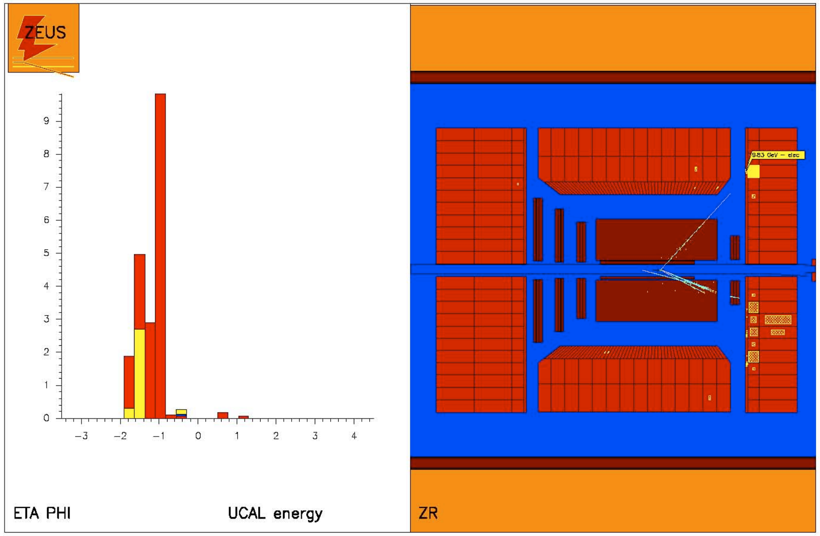


- Dipole-model approach: Successful description of both inclusive and diffractive processes at low x
- Change of Q^2 dependence around $1GeV^2$!

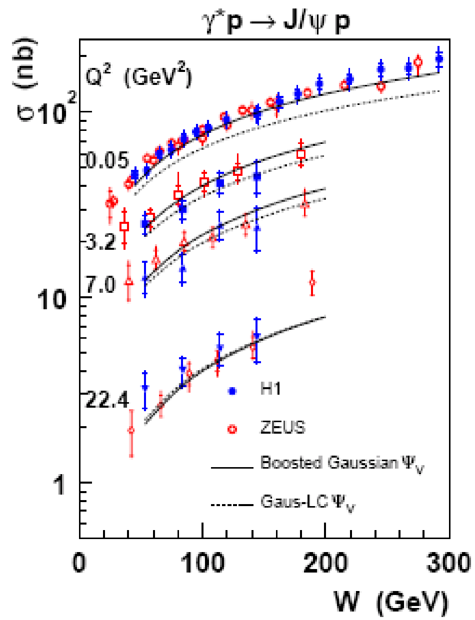
Low-x Physics - Concepts and Status

Diffraction





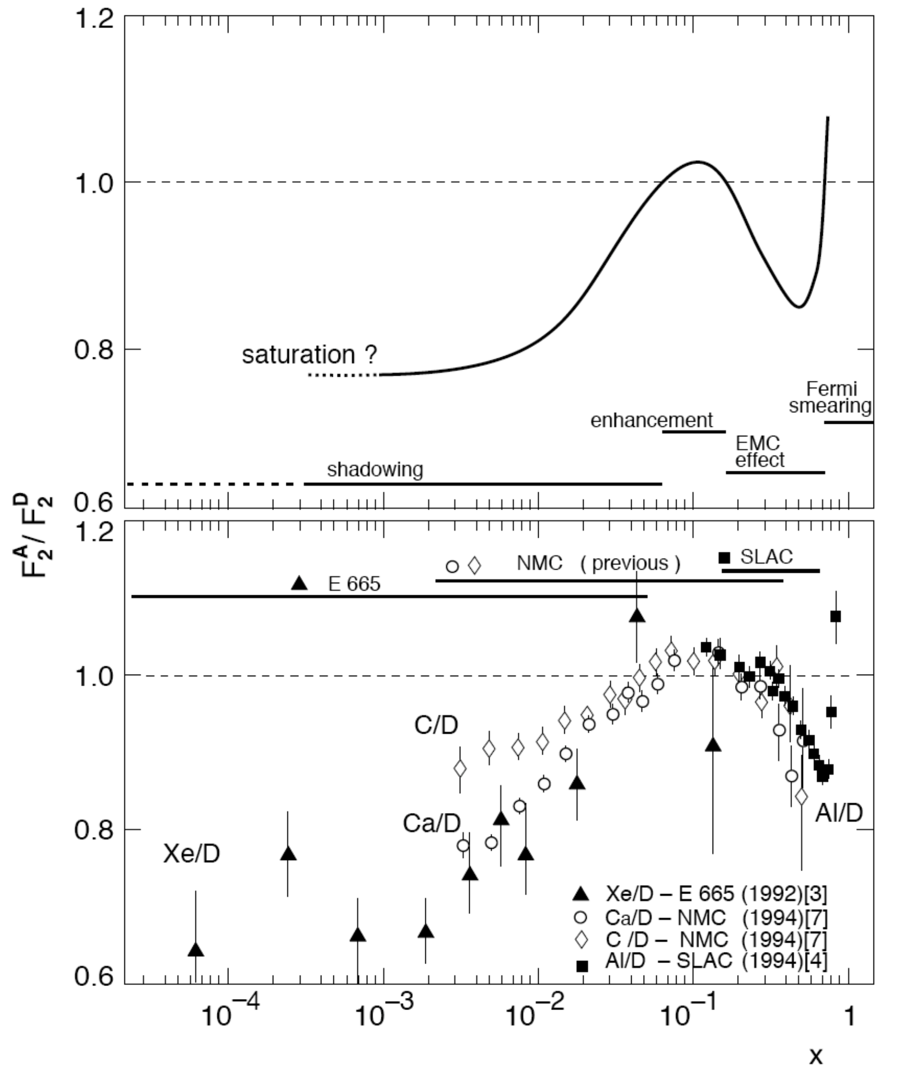
- Ratio of diffractive to total cross-section (200<W<245GeV): 15% at Q^2=4GeV^2
- Dipole models: Successful description of inclusive and various diffractive measurements (e.g. Ratio of diffractive to inclusive cross-section, Diffractive Vector-Meson production)

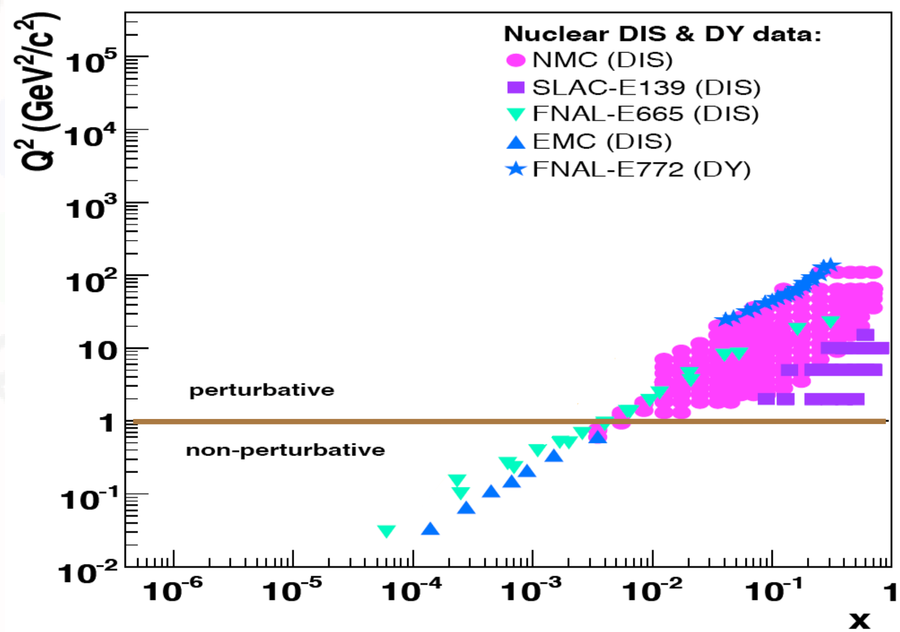


$$\propto \alpha_s^2 \left[g(x, Q^2)\right]^2$$

Low-x Physics - Concepts and Status

- Fixed-target scattering

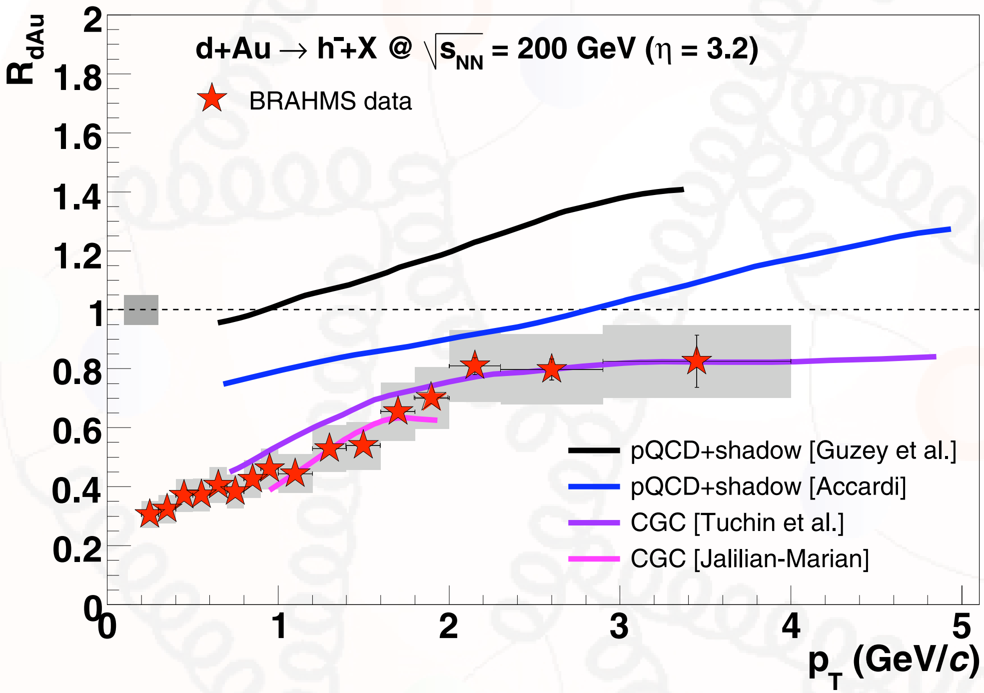


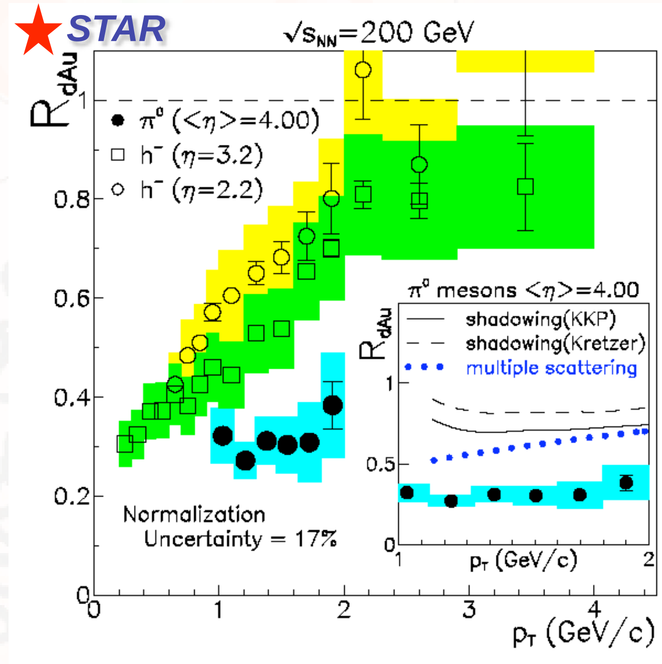


- Inclusive structure function ratio important to constrain nuclear modifications to gluon density
- World data (Fixed target) are concentrated above $x>0.01$ in pQCD region
- For $x<0.01$ only data in non-pQCD region

Low-x Physics - Concepts and Status

- RHIC dA scattering at forward η





- Forward identified hadron production at RHIC in dAu collisions: Sizable suppression of yields for charged hadrons and neutral pions observed
- pQCD+shadowing calculations over-predict hadron yield suppression. Is this an indication for gluon saturation in Au nuclei?
- More RHIC dAu are expected with enhanced detector capabilities (PHENIX/STAR)

Low-x Physics - Future Opportunities

- Key questions in low-x physics for a future ep/eA facility
  - How do strong fields appear in hadronic or nuclear wavefunctions at high energies?
  - How do they respond to external probes or scattering?
  - What are the appropriate degrees of freedom?
  - Is this response universal? (ep, pp, eA, pA, AA)

  (QCD Theory Workshop, DC, December 15-16, 2006)

  Required measurements:
  - What is the momentum distribution of gluons in matter?
  - What is the space-time distributions of gluons in matter?
  - How do fast probes interact with gluonic matter?
  - Do strong gluon fields affect the role of color singlet excitations (Pomerons)?

A future EIC facility can provide definite answers to these questions!

Low-x Physics - Future Opportunities

- Facilities
  - EIC (US): Electron-Ion Collider
    - eRHIC: ep and eA (light to heavy nuclei, up to U)
      - Linac-Ring: ep (20GeV / 250GeV): $2.6 \cdot 10^{33}$ cm^{-2}s^{-1}

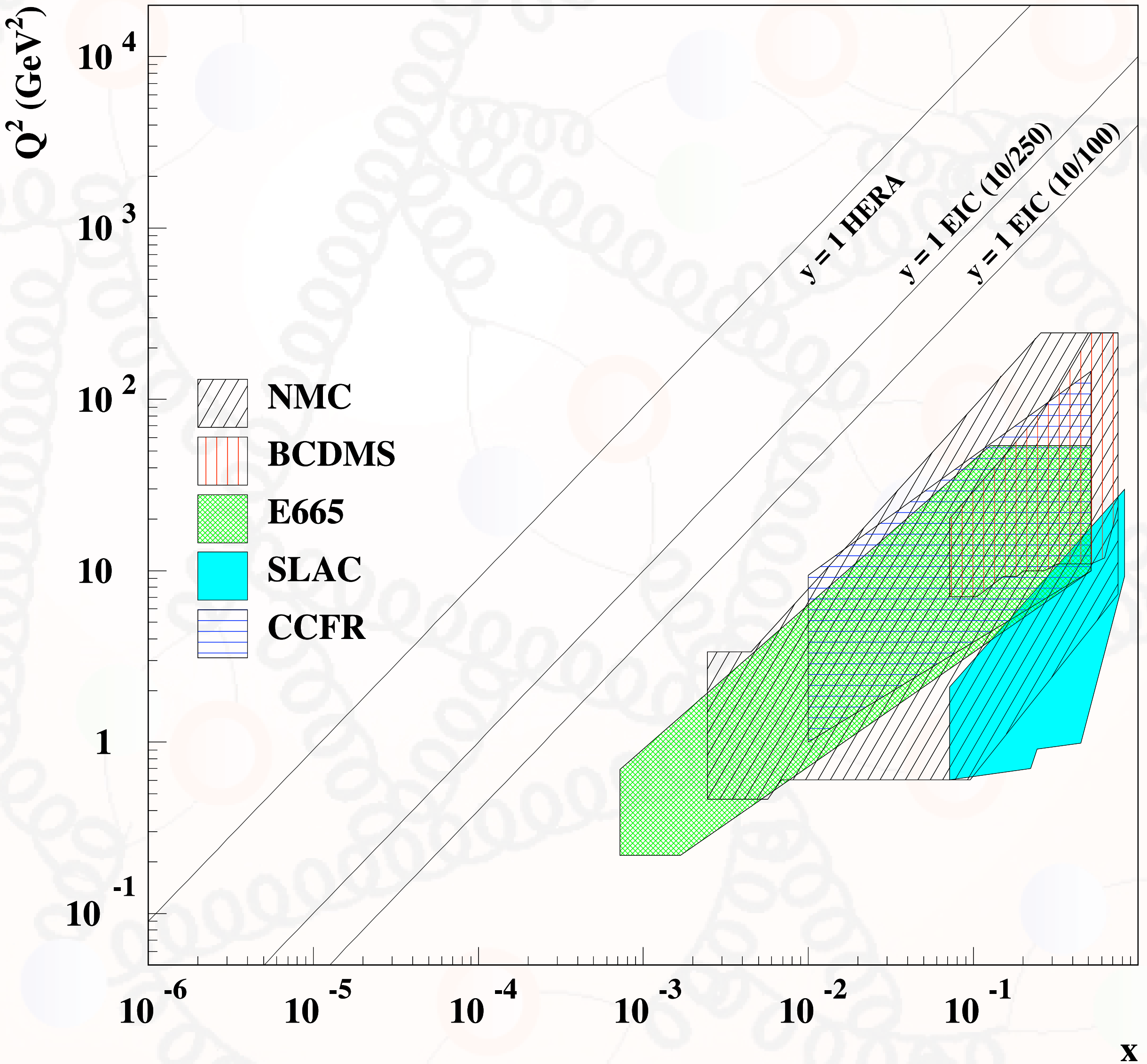
        eA (20GeV / 100GeV/n): $2.9 \cdot 10^{33}$ cm^{-2}s^{-1} / n
      - Ring-Ring: ep (10GeV / 250GeV): $0.47 \cdot 10^{33}$ cm^{-2}s^{-1}

        eA (10GeV / 100GeV/n): $0.52 \cdot 10^{33}$ cm^{-2}s^{-1} / n
    - ELIC: ep and eA (light nuclei)
      - Linac-Ring: ep (7GeV / 150GeV): $7.7 \cdot 10^{34}$ cm^{-2}s^{-1}

        eA (7GeV / 75GeV/n): $1.6 \cdot 10^{35}$ cm^{-2}s^{-1} / n

Low-x Physics - Future Opportunities

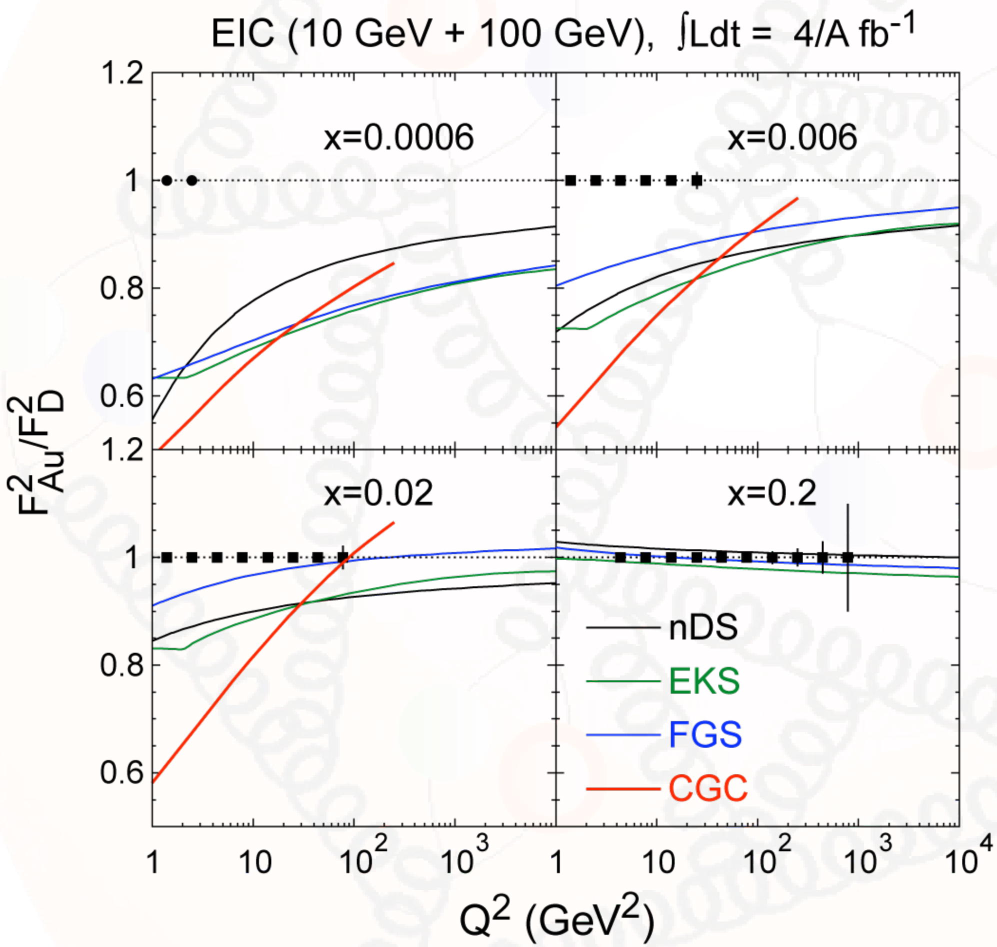
- Kinematics



- Key observables in electron-proton and electron-nucleus scattering at low x
  - Gluon distribution:
    - F_L (Variable center-of-mass energy) and F_2
    - Jet rates
    - Inelastic vector meson production (e.g. J/Psi)
  - Space-Time distribution of gluon:
    - F_L (Variable center-of-mass energy) and F_2
    - Deep virtual compton scattering (DVCS)
    - Exclusive final states (e.g. Vector meson production)
  - Interaction of fast probes with matter:
    - Hadronization, Fragmentation studies
    - Energy loss (Heavy quarks)
  - Impact of strong gluon fields on the role of color neutral excitations:
    - Diffractive structure functions
    - Diffractive vector meson production

Low-x Physics - Future Opportunities

- Observables: Nuclear structure function ratios



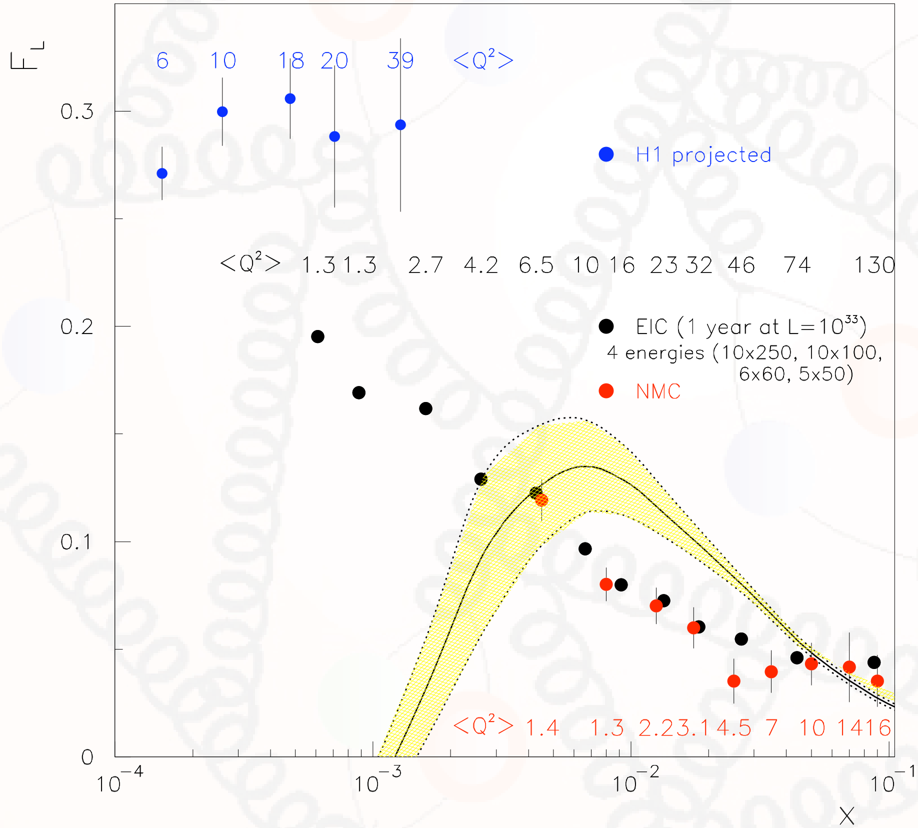
$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

- F_2 will be one of the first measurements at EIC
- nDS, EKS, FGS: pQCD models with different amounts of shadowing

EIC will allow to distinguish between pQCD and saturation model predictions

Low-x Physics - Future Opportunities

- Observables: Longitudinal structure function



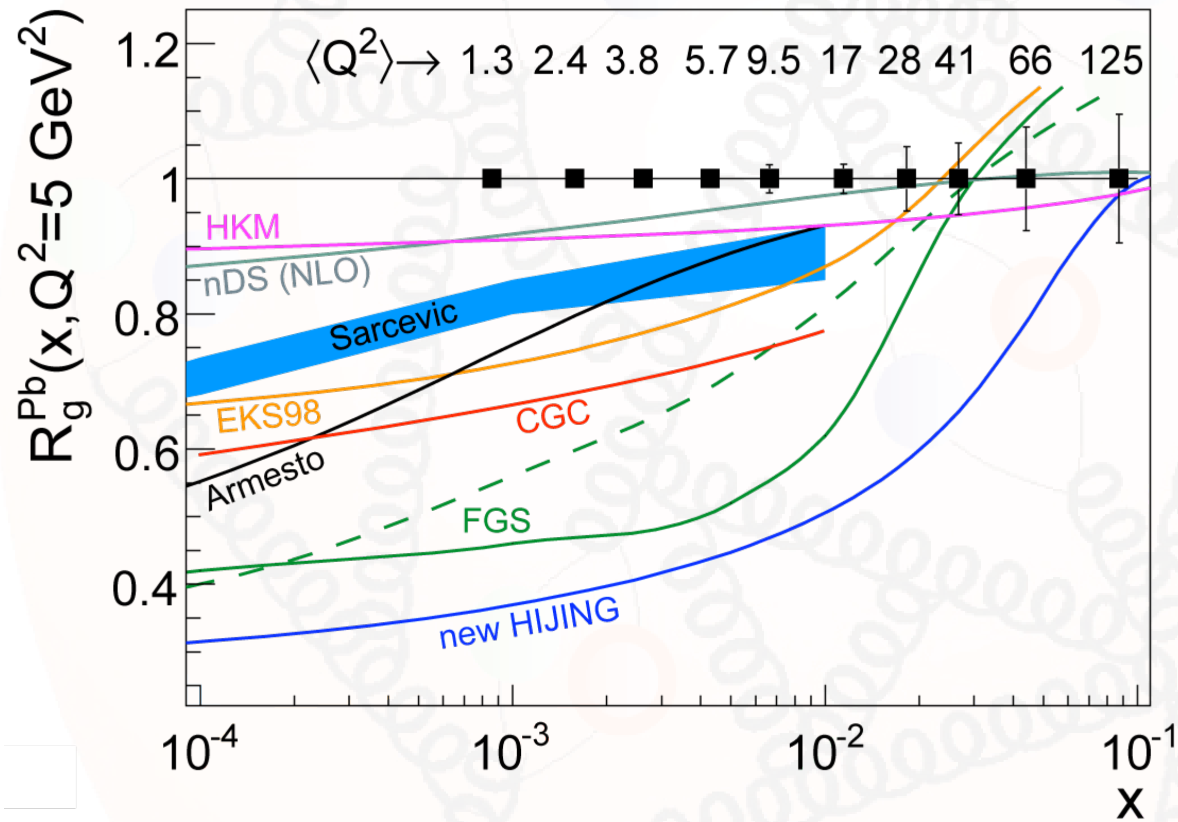
- F_L measurement requires operation of EIC at different center-of-mass energies ($\sqrt{s}$)
- Precise measurement from low to high Q^2 region

$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right) \quad F_L = \frac{Q^2}{4\pi^2\alpha}\sigma_L^{\gamma^* p} \propto xg$$

Unique measurement at EIC of F_L with high precision in ep collisions to constrain gluon distribution

Low-x Physics - Future Opportunities

- Observables: Ratio of nuclear gluon distribution function



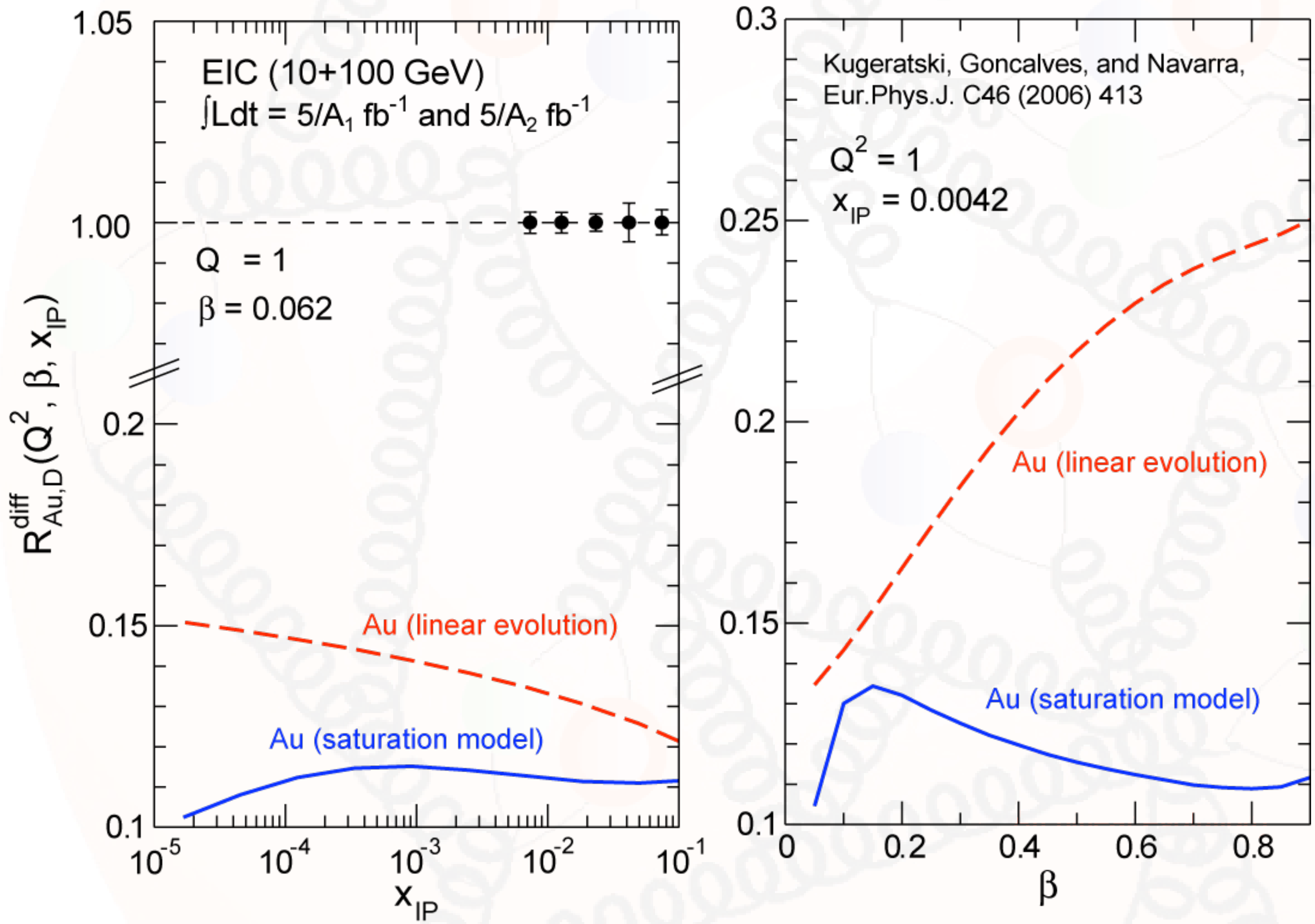
- EIC will reach the unmeasured low-x region (<0.01) with high precision for Q^2>1GeV^2
- Constrain gluon modification due to nuclear effects in comparison to large range of models

$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right) \quad F_L = \frac{Q^2}{4\pi^2\alpha}\sigma_L^{\gamma^* p} \propto xg$$

EIC will measure modification of gluon distribution with high precision!

Low-x Physics - Future Opportunities

- Observables: Diffractive measurements



x_{IP} = momentum fraction of the Pomeron with respect to the hadron

β = momentum fraction of the struck parton with respect to the Pomeron

$x_{IP} = x/\beta$

EIC allows to distinguish between linear evolution and saturation models in diffractive scattering with high precision

Summary and Outlook

- Status and Concepts
  - HERA: Precision structure function measurements (F_2) at low x
  - At low Q^2 and low x: DGLAP (Leading twist) approach leads to valence-like gluon behavior
  - Diffraction: Important contribution to overall ep event yield
  - Dipole model: Allows to describe inclusive and diffractive measurements. Reach of saturation region at low x not conclusive
  - Lesson: Optimize any future EIC efforts for acceptance and luminosity
  - eA: No information in low-x region
  - dAu results at RHIC: Can saturation account for observed behavior? Complementary probes important (RHIC/LHC)!

EIC important to answer outstanding questions in high-energy QCD physics

Summary and Outlook

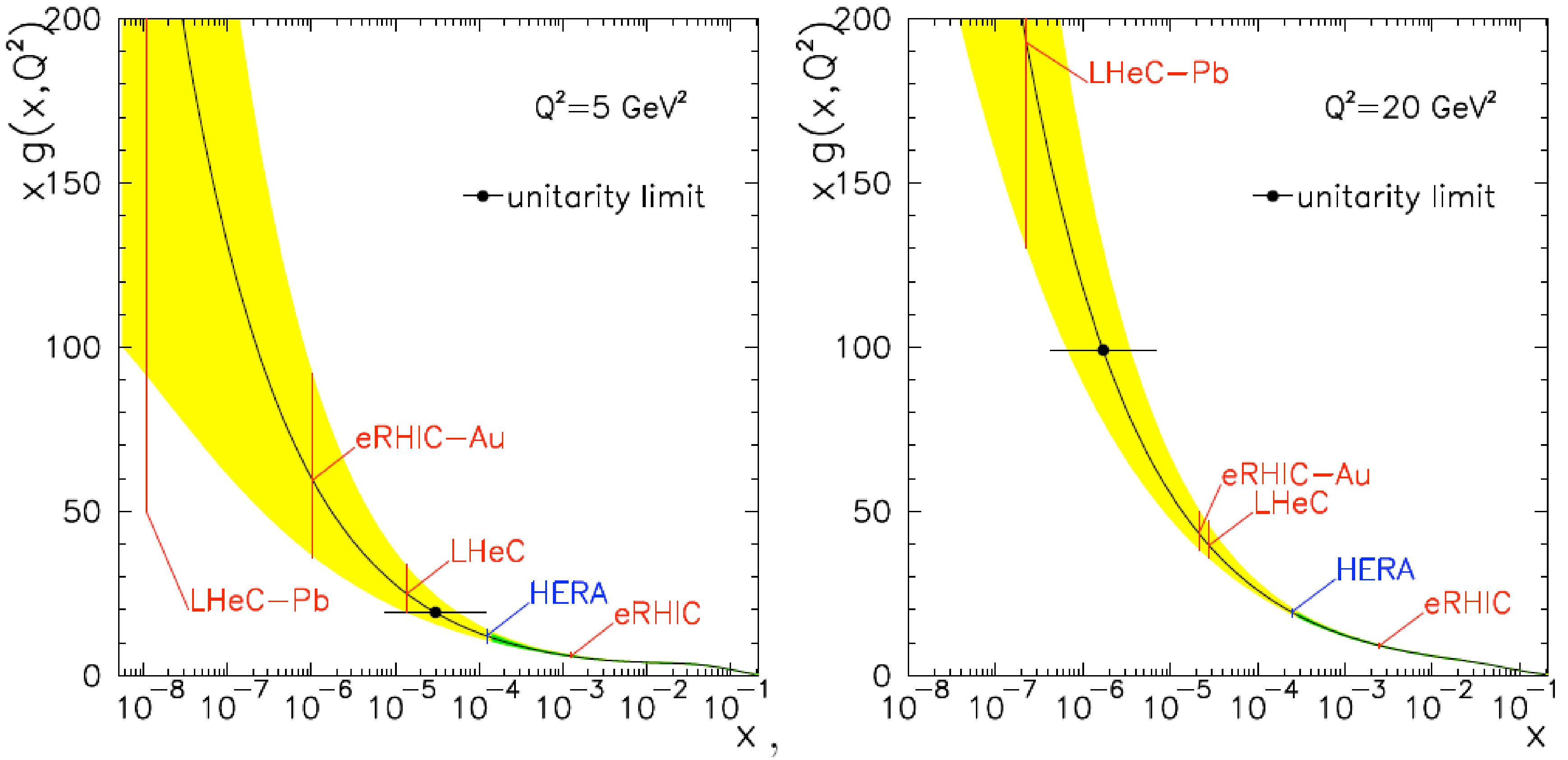
- Future Opportunities
  - EIC will allow to study the physics of strong color fields:
    - Explore existence of saturation regime
    - Measurement of momentum and space-time gluon distributions
  - Study the nature of color singlet excitations (Pomeron)
  - Study nuclear medium effects
  - Test and study factorization / universality
  - Required: EIC at high luminosity and optimized detector
  - EIC will allow to bridge several QCD communities (Hadron structure and Relativistic Heavy-Ion)
  - Unique opportunity: US leadership in precision QCD physics (The QCD LAB) complementary to other next generation facilities in Europe (LHC at CERN, FAIR at GSI) and Asia (J-PARC)

Urgency to establish next-generation ep/eA collider facility

Fundamental QCD studies

Backup

- Observables: Extraction of gluon distribution function

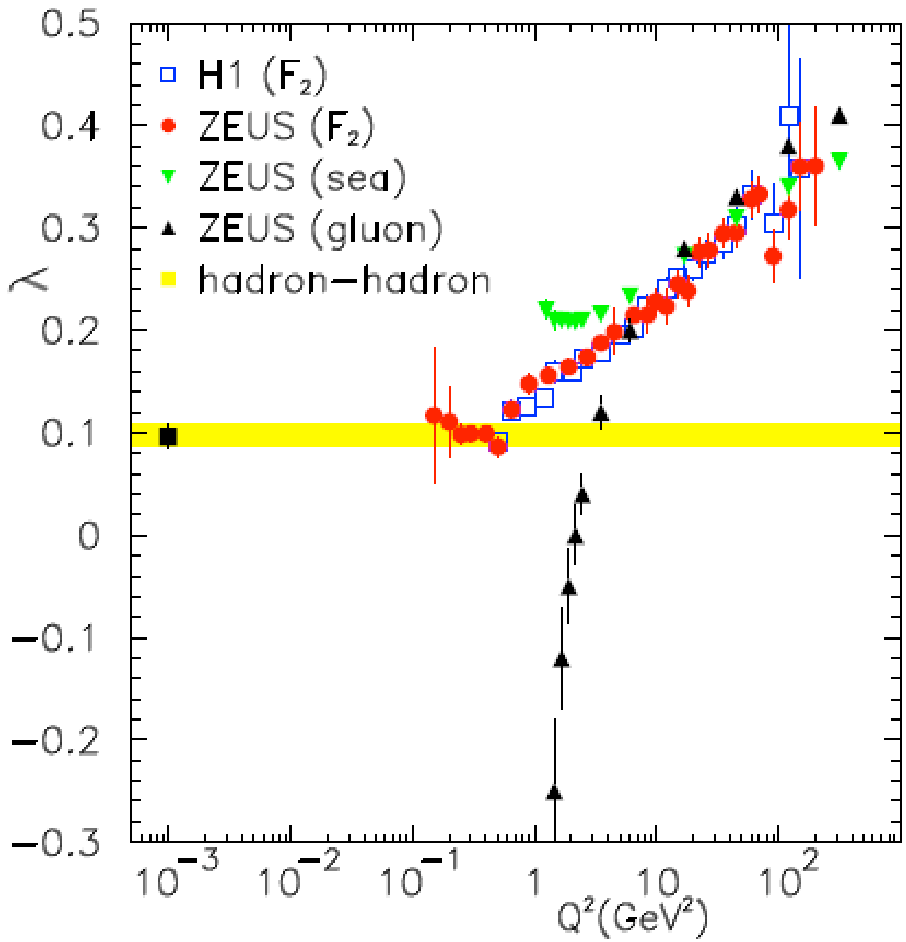


J. Dainton et al., hep-ex/0603016

eA operation at EIC allows to reach very low-x region competitive with LHeC (ep)

Backup

- Rise of F_2 and parton distribution functions



$$F_2(x,Q^2) \sim x^{-\lambda}$$

$$xG(x,Q^2) \sim x^{-\lambda_G}$$

$$xq_{sea}(x,Q^2) \sim x^{-\lambda_q}$$