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

Bernd Surrow

Massachusetts Institute of Technology

The Electron-Ion Collider

Rutgers

Joint Town Meetings on Quantum Chromodynamics
APS Division of Nuclear Physics:
2007 Long Range Plan

January 12 - 14, 2007
Rutgers University

QCD and Hadron Physics Town Meeting:
Simon Capstick (Florida State University)
Lawrence S. Cardman (Jefferson Lab)
Abhay L. Deshpande (SUNY Stony Brook)
Xiangdong Ji (University of Maryland), Co-Chair
Cynthia Keppel (Hampton University)
Curtis Meyer (Carnegie-Mellon University)
Zein-Eddine Meziani (Temple University), Co-Chair
John Negele (MIT)
Jen-Chieh Peng (Illinois)

Phases of QCD Matter Town Meeting:
Peter Jacobs (Lawrence Berkeley National Laboratory), Co-Chair
Dima Kharzeev (BNL)
Berndt Mueller (Duke University), Co-Chair
Jamie Nagle (Colorado)
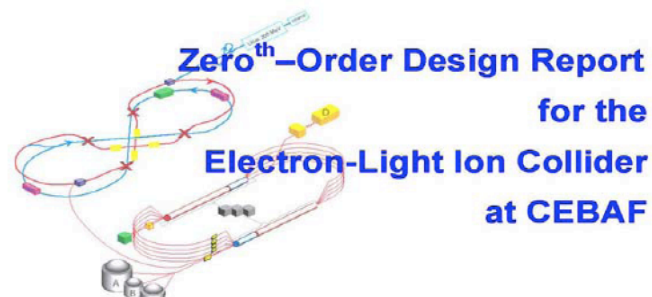Krishna Rajagopal (MIT)
Steve Vigdor (Indiana)

Local Organizing Committee:
Ronald Ransome (Rutgers University)
Ronald Gilman (Rutgers University)

http://www.physics.rutgers.edu/np/2007lrp-home.html

Jefferson Lab

BROOKHAVEN
NATIONAL LABORATORY

NSF

Unanimous recommendation of the
QCD Town Meeting,
Rutgers University, NJ,
January 13, 2006

A high luminosity Electron-Ion Collider (EIC) is the highest priority of the QCD community for new construction after the JLab 12GeV and RHICII luminosity upgrade. EIC will address compelling physics questions essential for understanding the fundamental structure of matter:

☐ Precision imaging of the sea-quarks and gluons to determine the spin, flavor and spatial structure of the nucleon.

☐ Definitive study of the universal nature of strong gluons fields in nuclei.

This goal requires that R&D resources be allocated for expeditious development of collider and detector design

The Electron-Ion Collider

☐ EIC - Accelerator Design

The Electron-Ion Collider

Physics Opportunities
with
e+A Collisions
at an
Electron Ion Collider

e+A White Paper Draft 2.0
EIC Collaboration
March 9, 2007

The EIC Collaboration*

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The Electron-Ion Collider

http://www2.lns.mit.edu/eic

Outline

Low-x physics: Future opportunities

Exploring the nature of glue

Low-x physics: Concepts and Status

Summary and Outlook

Bernd Surrow
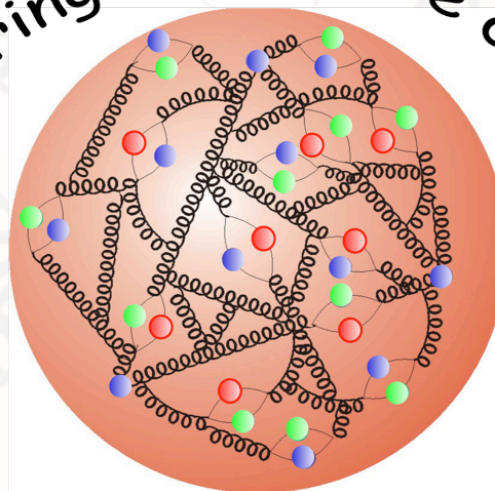
Low-x Physics - Concepts and Status

□ **Low-x basics**

　○ **Cross-sections and structure functions**

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

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

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

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

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

Universality

$$d\sigma = \sum_{f_1, f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^h$$

Factorization

Important: Complementary probes are required for unambiguous extraction of observables in high-energy density QCD region!
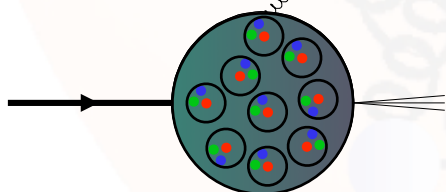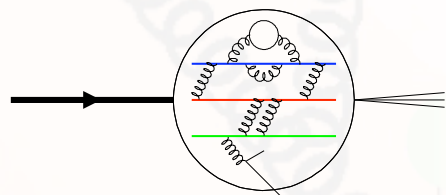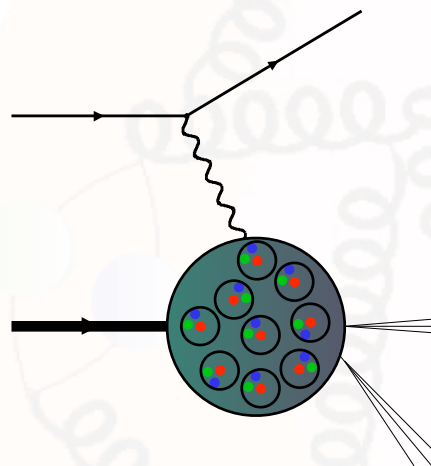
Low-x Physics - Concepts and Status

□ **Low-x basics**

   O **Dynamics: DGLAP / BFKL and CGC**

$$Y = \ln\left(\frac{1}{x}\right)$$

Kowalski and Teaney Phys.Rev.D68:114005,2003
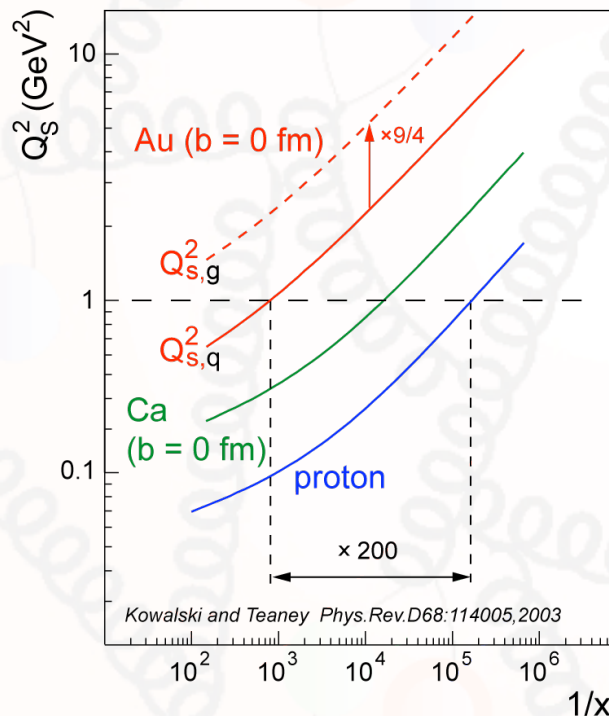
$Q_s{}^2$: Saturation scale ⇒ Characterize transition to saturation region!

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

Enhanced for eA compared to ep:

$$A^{1/3} x^{-\delta}$$

CGC: Color-Glass-Condensate

$Q_s(Y)$

CGC

BK/JIMWLK

BFKL

DGLAP

Λ_{QCD}^2

$\alpha_s \sim 1$ $\alpha_s \ll 1$

Q^2
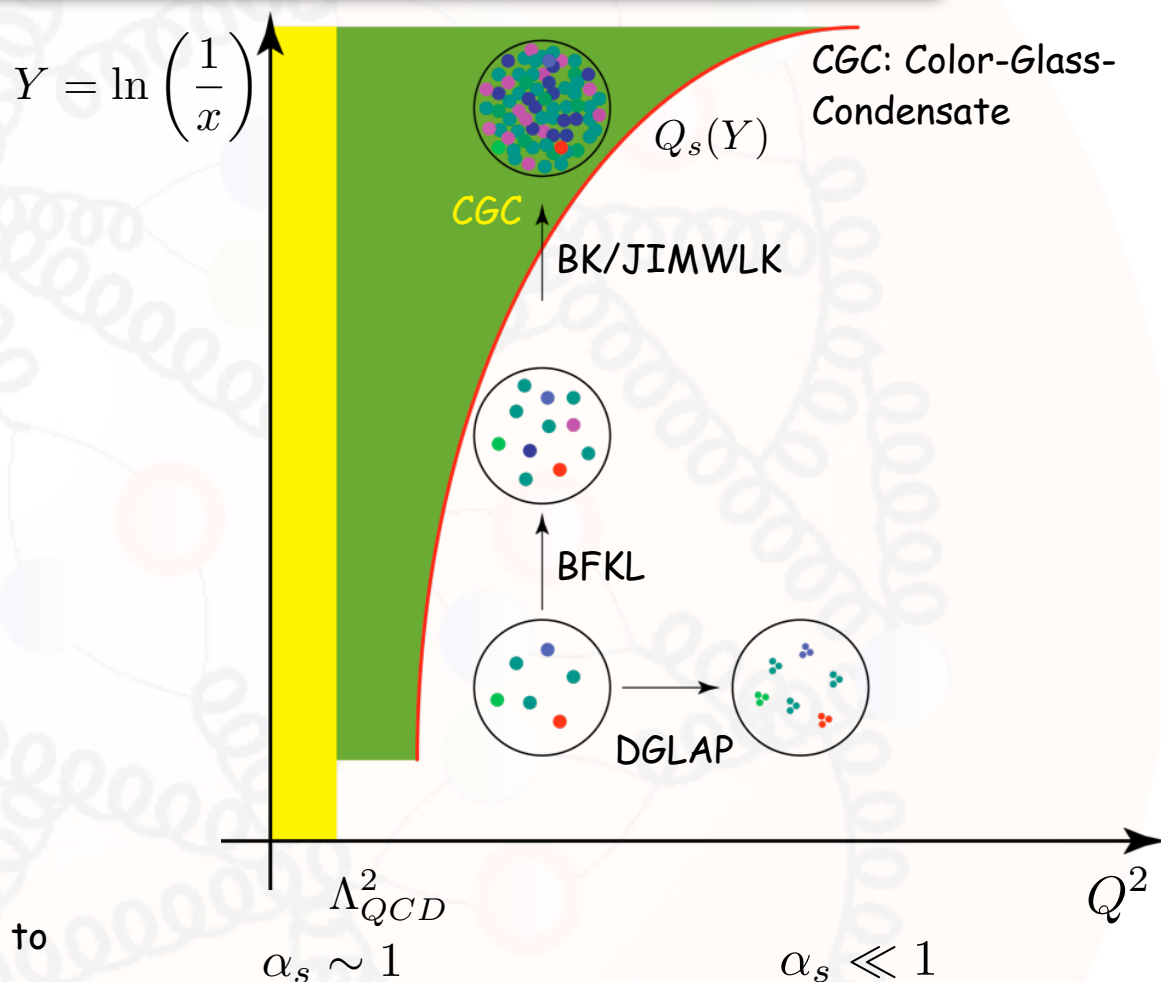
DGLAP: Evolution in Q²

BFKL: Evolution in x

Low-x Physics - Concepts and Status

□ **HERA: F_2 at low x**

HERA F_2

ZEUS NLO QCD fit
H1 PDF 2000 fit

- H1 94-00
- H1 (prel.) 99/00
- ZEUS 96/97
- BCDMS
- E665
- NMC
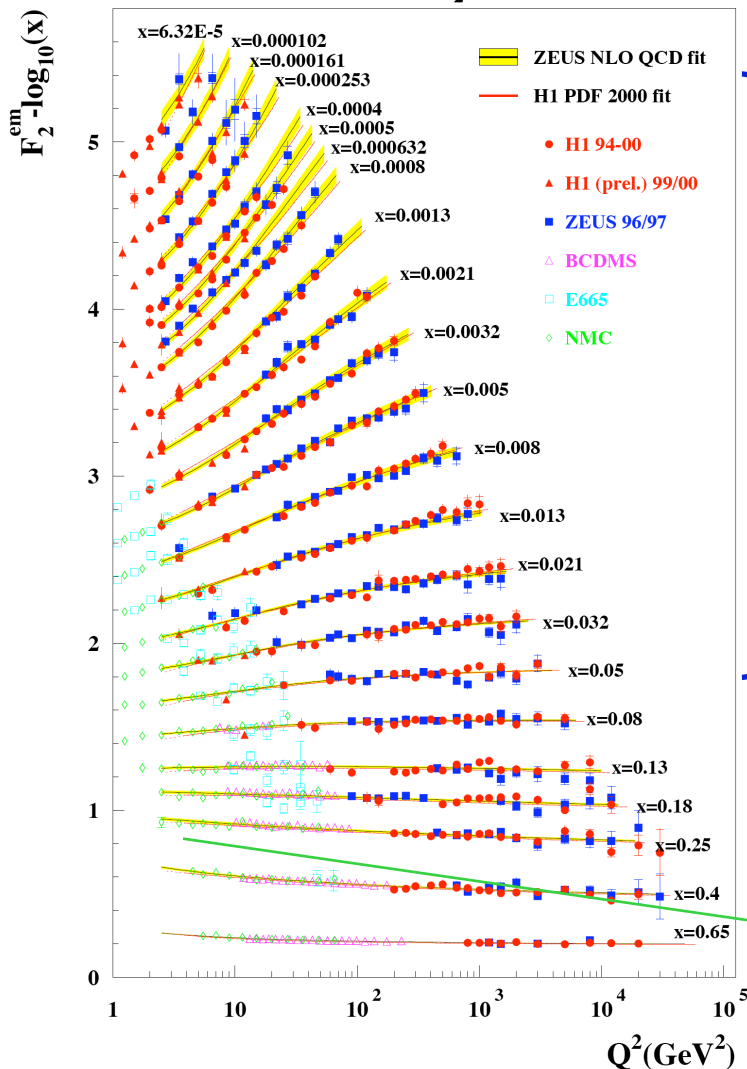
$$xg \sim \left(\frac{dF_2}{d \ln Q^2} \right)$$

ZEUS

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

In contrast to:

Low Q^2 high x!
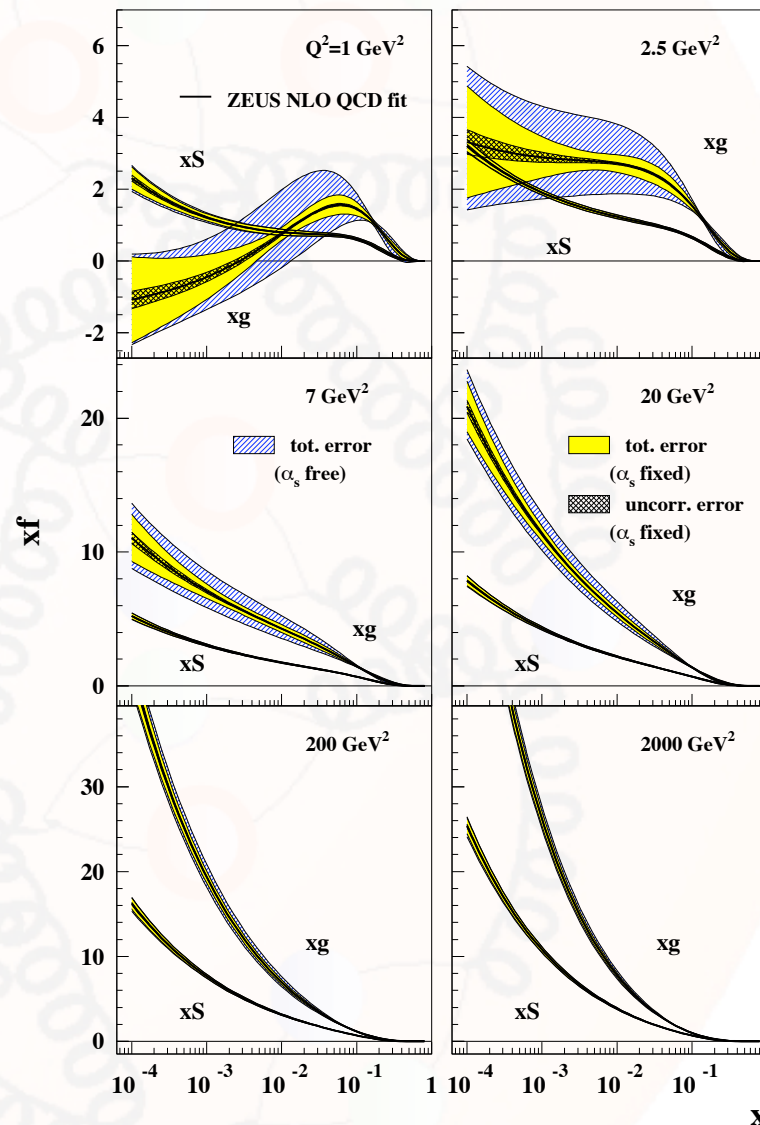
Low-x Physics - Concepts and Status

□ **Fixed-target scattering**
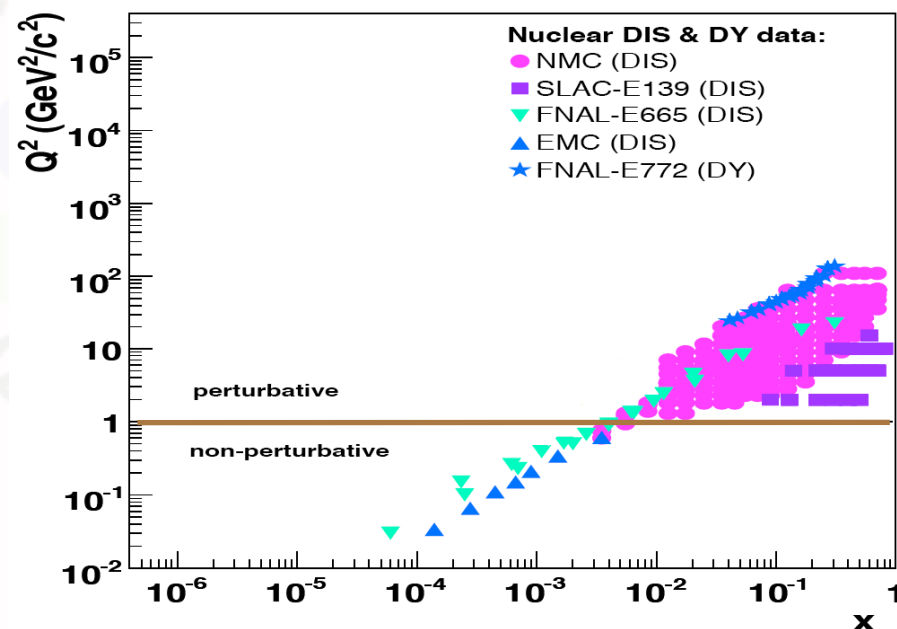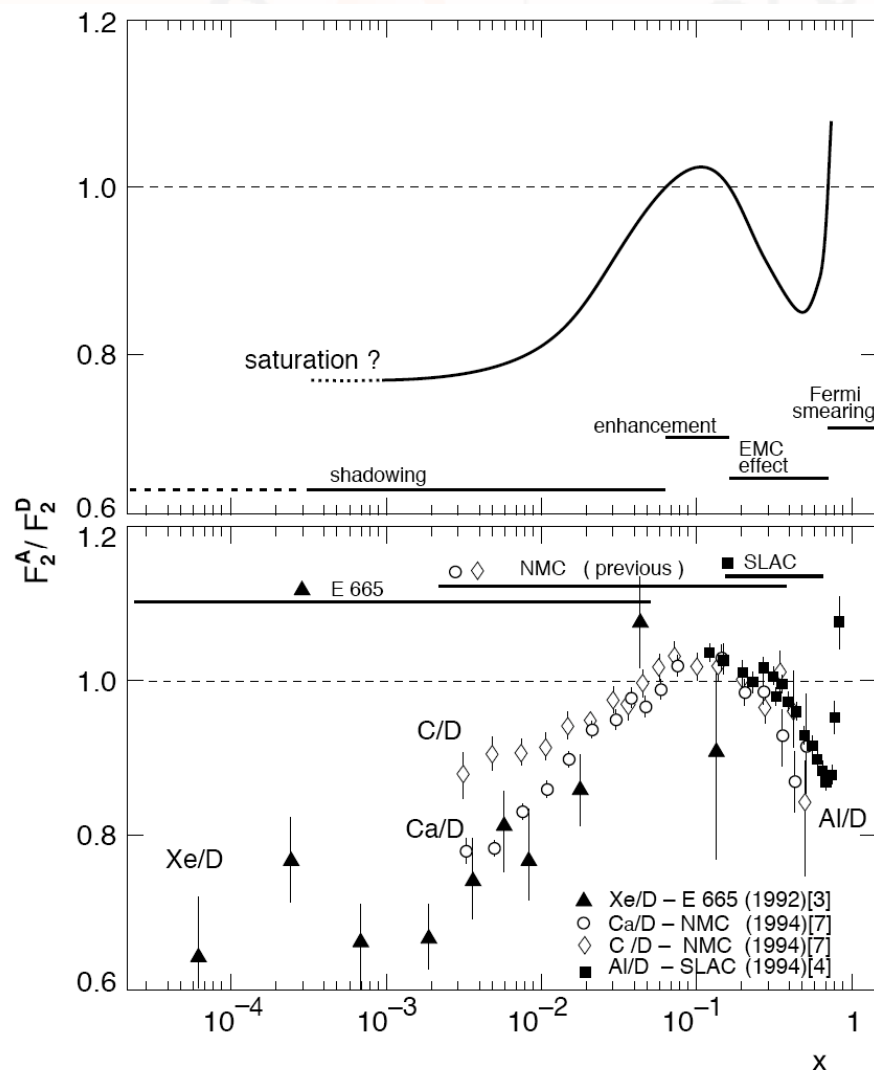
○ **Inclusive structure function ratio** important to constrain nuclear **modifications to gluon density**

○ 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

d+Au → h⁻+X @ $\sqrt{s_{NN}}$ = 200 GeV (η = 3.2)
★ BRAHMS data

pQCD+shadow [Guzey et al.]
pQCD+shadow [Accardi]
CGC [Tuchin et al.]
CGC [Jalilian-Marian]

R_{dAu} — p_T (GeV/c)

★ STAR $\sqrt{s_{NN}}$ = 200 GeV

R_{dAu}
● π^0 (<η> = 4.00)
□ h⁻ (η=3.2)
○ h⁻ (η=2.2)

π^0 mesons <η>=4.00
shadowing(KKP)
shadowing(Kretzer)
multiple scattering

Normalization
Uncertainty = 17%

p_T (GeV/c)
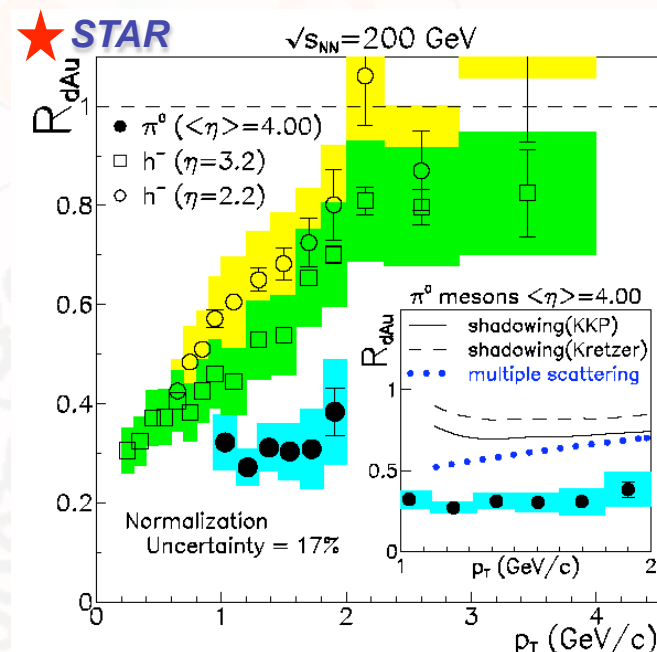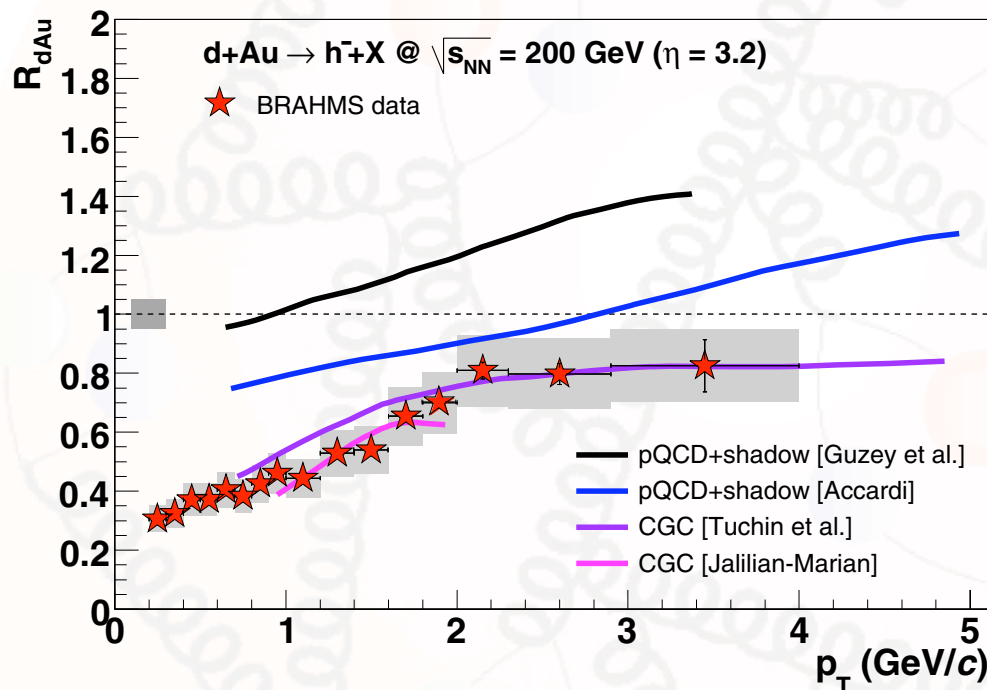
○ **Forward identified hadron production at RHIC in dAu collisions:** Sizable suppression of yields for charged hadrons and neutral pions observed

○ 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)

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

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)?

Low-x Physics - Future Opportunities

- ☐ Facilities - EIC (US): Electron-Ion Collider

  - ☐ eRHIC (BNL): 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
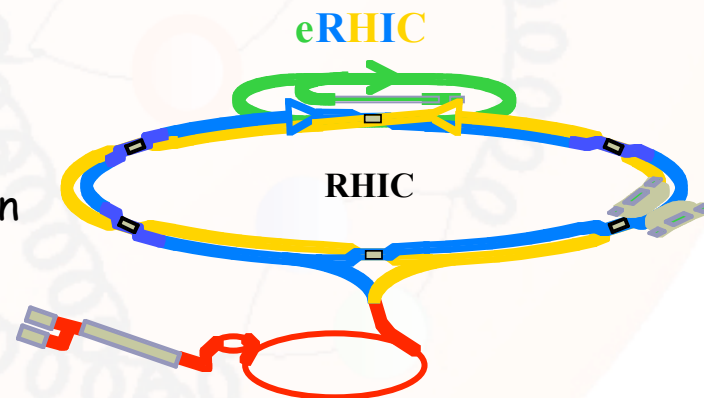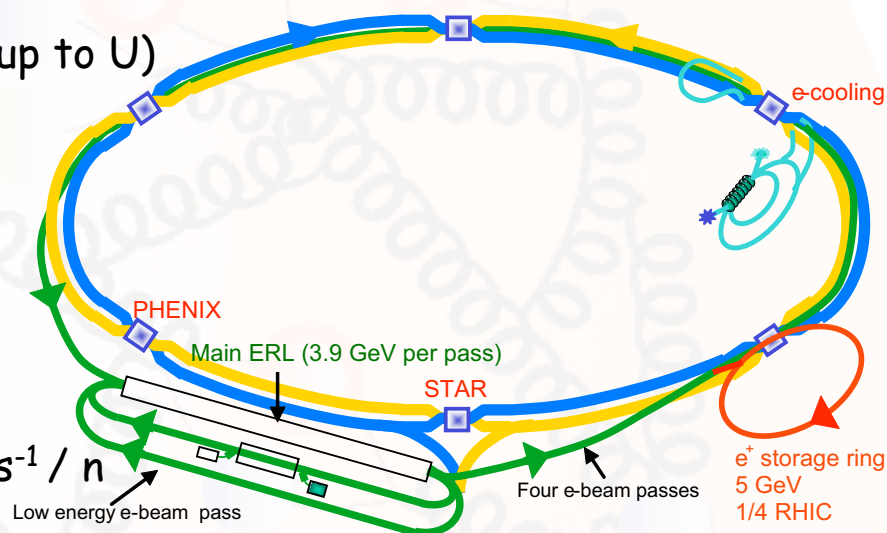
Low-x Physics - Future Opportunities

☐ Facilities - EIC (US): Electron-Ion Collider

☐ ELIC (JLab): 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

Ion Linac and Pre-Booster

Electron Cooling

Solenoid Snake

3-7 GeV electrons   30-150 GeV light ions

Electron Injector

CEBAF with Energy Recovery

A B C

Beam Dump

D
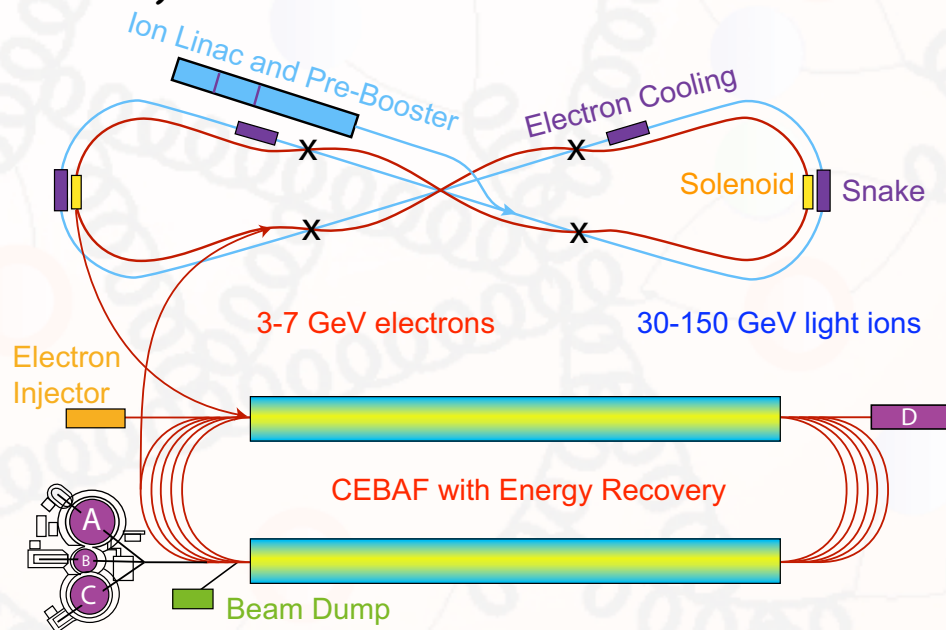
Low-x Physics - Future Opportunities

☐ Kinematics
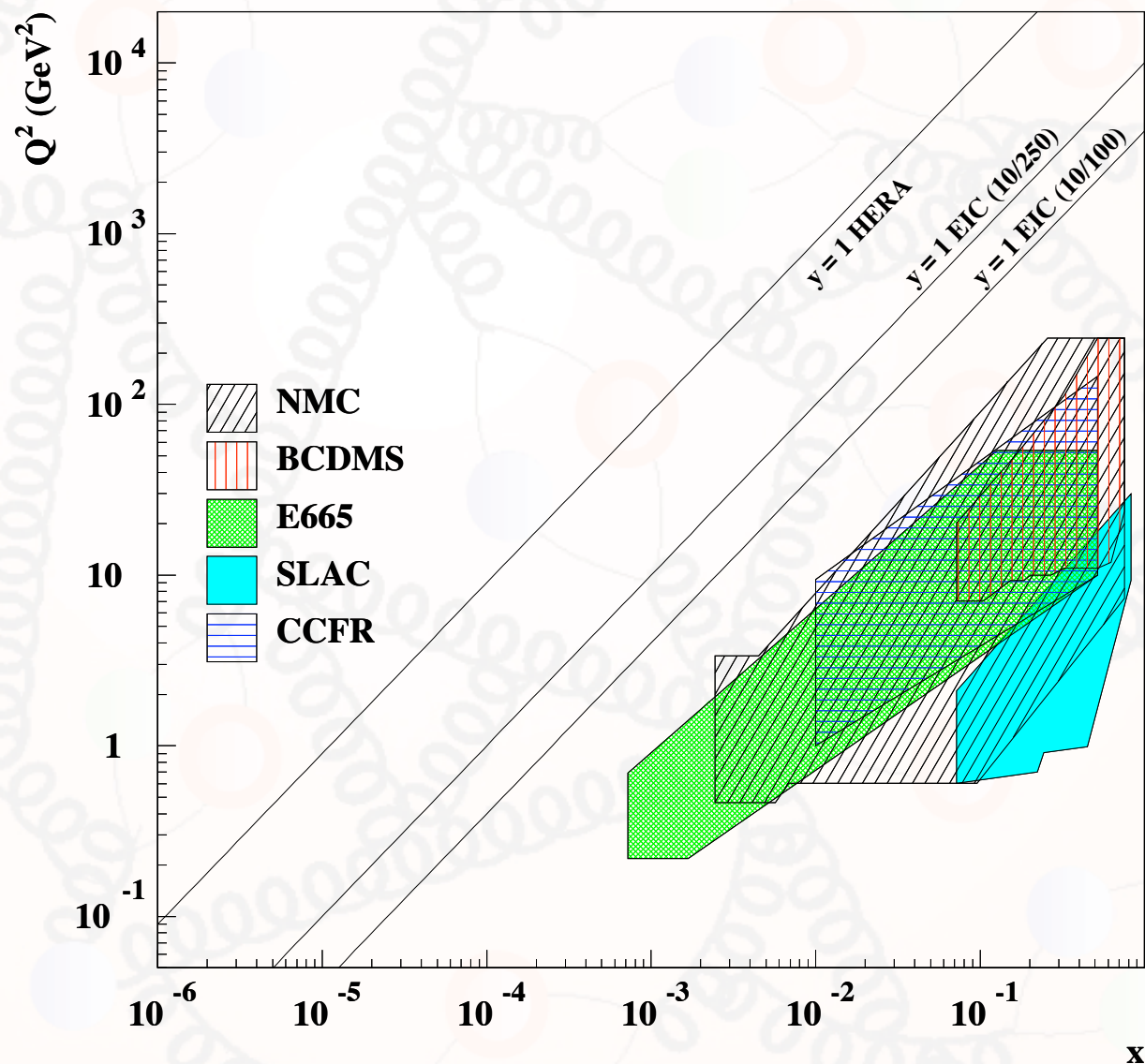
Low-x Physics - Future Opportunities

□ Facilities - Detector concepts (Kinematics)
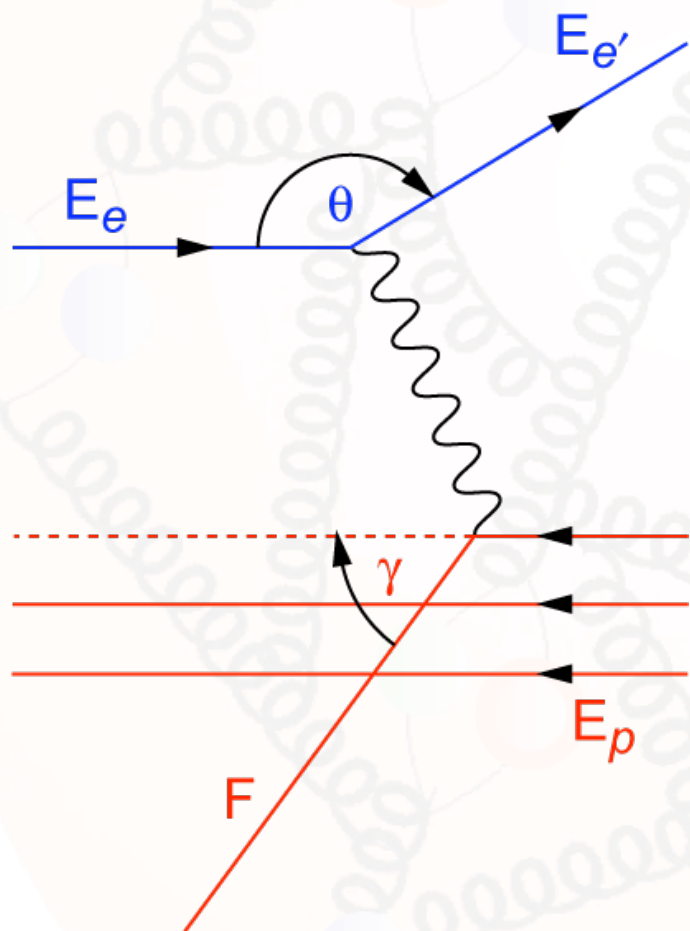
EIC (eA) event topology (E_e=10 GeV, $E_{h/A}$=100 GeV)
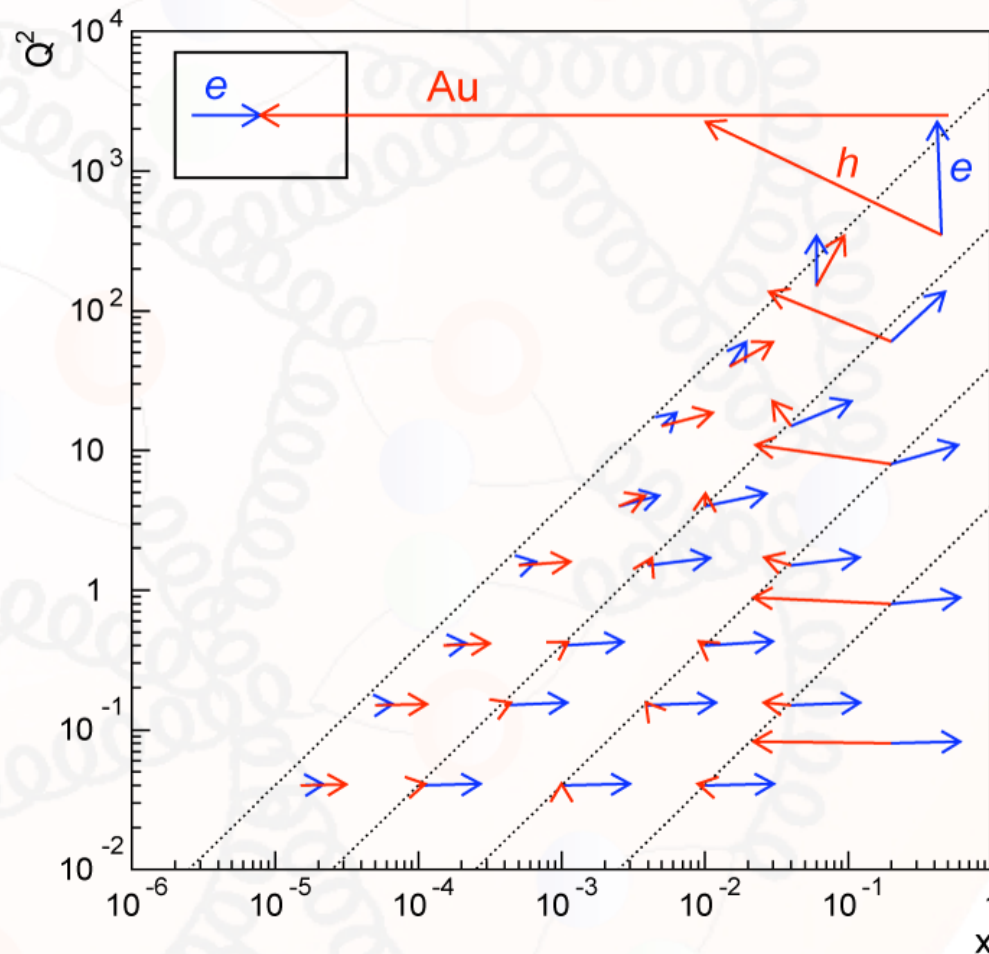
Low-x Physics - Future Opportunities

Facilities - Detector concepts
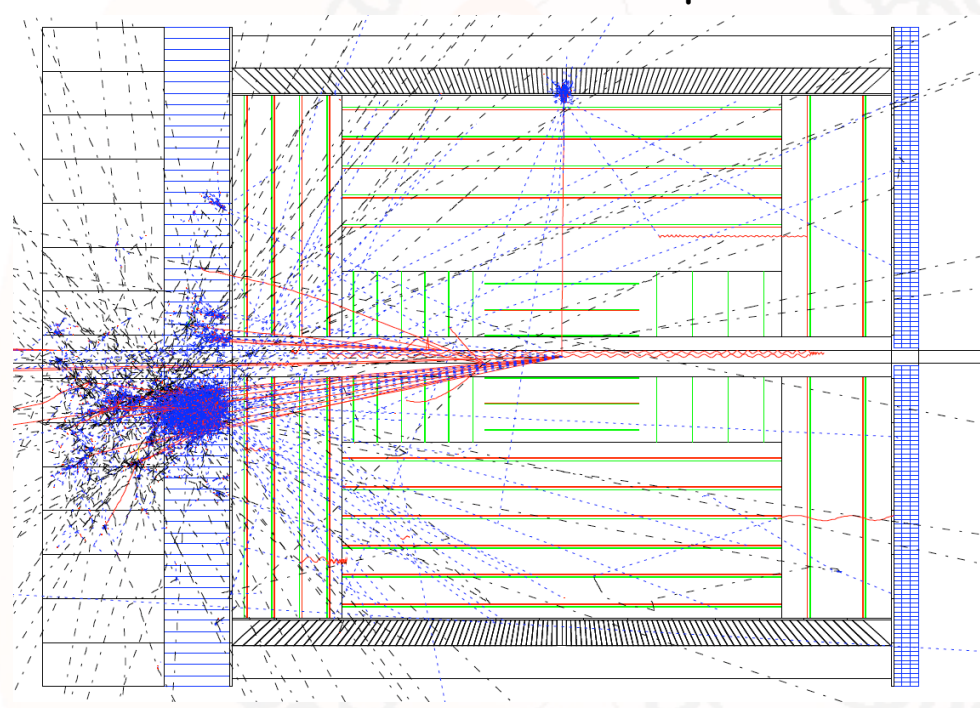
J. Pasukonis, B.S. , physics/0608290

Positron Hemisphere
EM calorimeter end-wall at -360cm

EM barrel calorimeter
covering z=±70cm

EM catcher calorimeter
at z=-110cm

EM catcher calorimeter
at z=+110cm

Proton Hemisphere
EM and hadron calorimeter
end-wall at +360cm

I. Abt, A. Caldwell, X. Liu,
J. Sutiak, hep-ex 0407053

Concepts:

O Focus on the rear/forward acceptance and thus on low-x / high-x physics (Compact system of tracking and central electromagnetic calorimetry inside a magnetic dipole field and calorimetric end-walls outside

O Focus on a wide acceptance detector system (Compact calorimeter system)

Low-x Physics - Future Opportunities

□ 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**

EIC (10 GeV + 100 GeV), $\int L dt = 4/A \text{ fb}^{-1}$
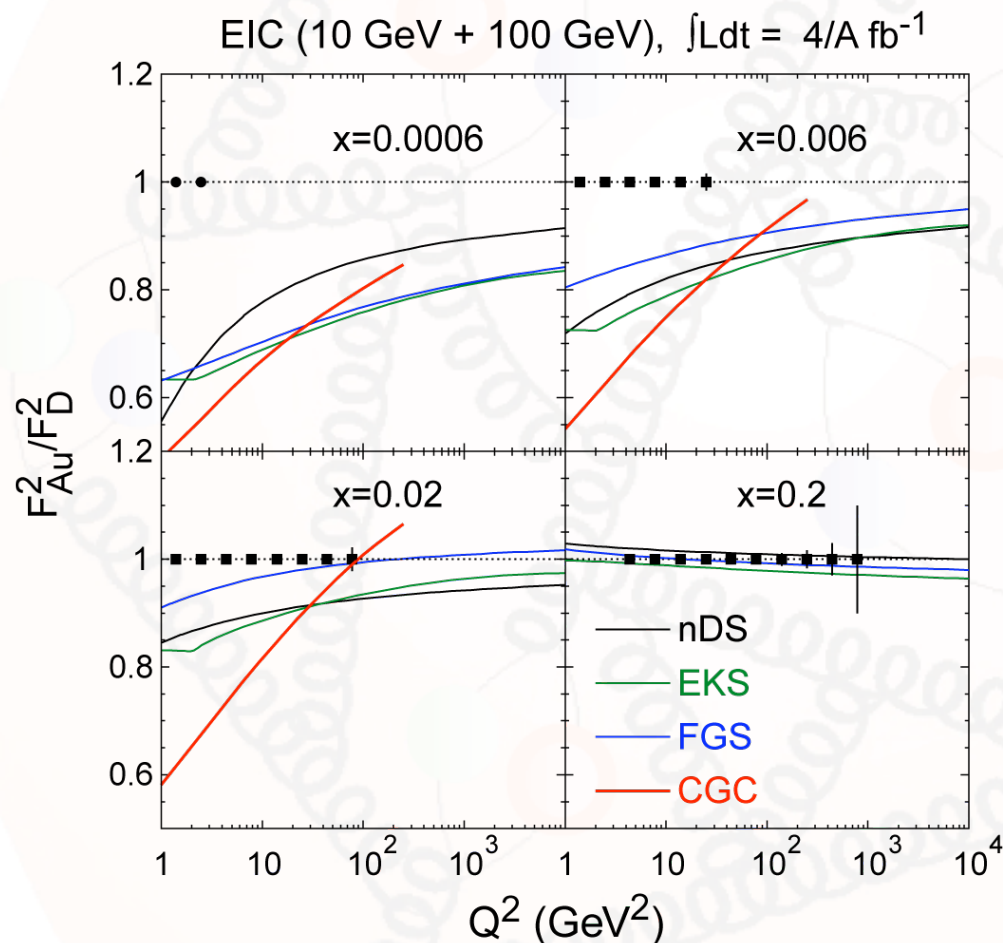
○ F_2 will be one of the first measurements at EIC

○ nDS, EKS, FGS:

pQCD models with different amounts of shadowing

EIC will allow to distinguish between pQCD and saturation model predictions

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

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

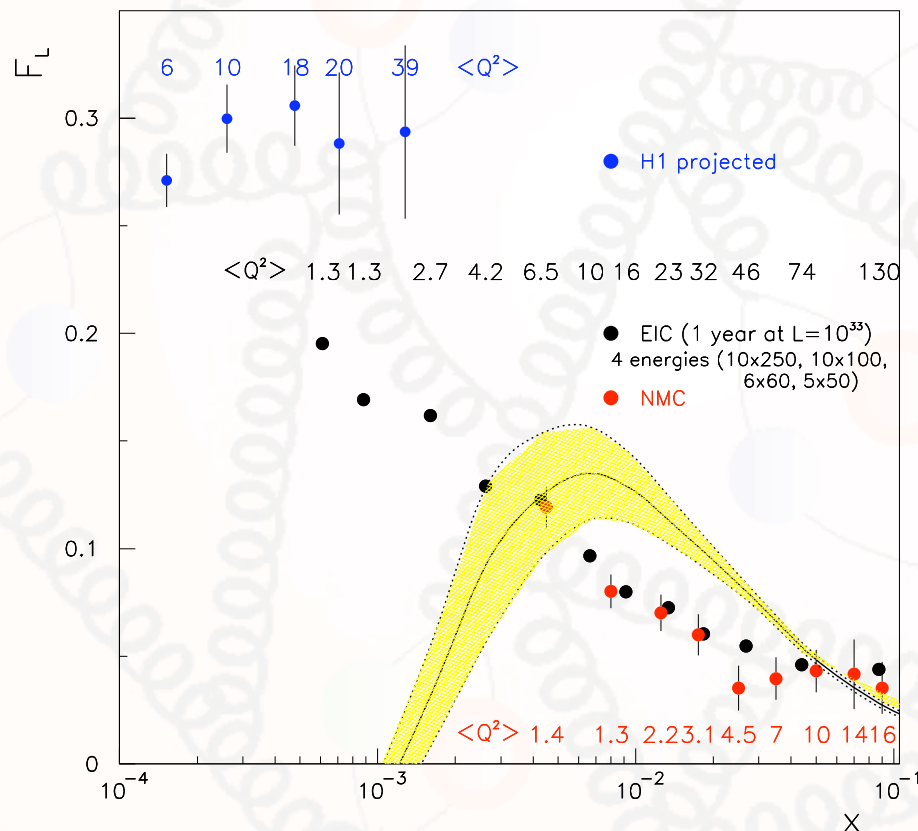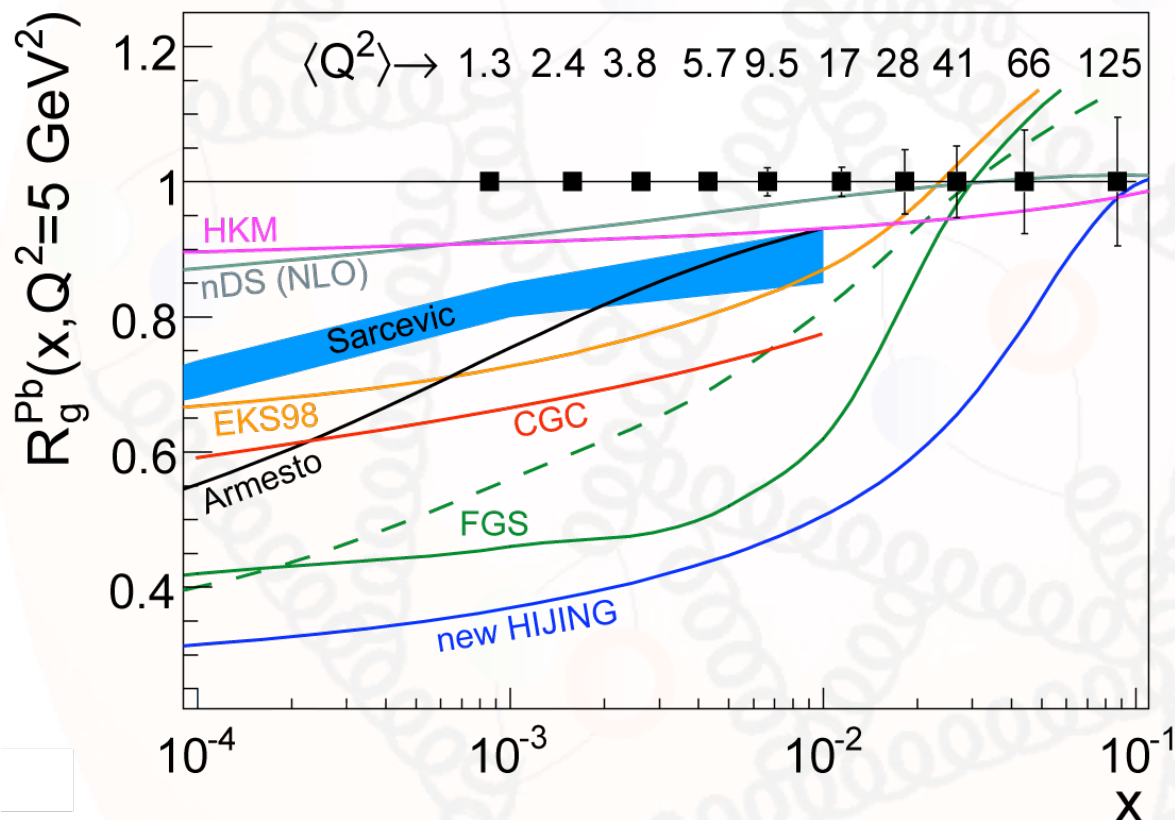Unique measurement at EIC of F_L with high precision in ep collisions to constrain gluon distribution

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

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

EIC will measure modification of gluon distribution with high precision!

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

Low-x Physics - Future Opportunities

☐ Observables: Diffractive measurements

EIC (10+100 GeV)
$\int L dt = 5/A_1 \text{ fb}^{-1} \text{ and } 5/A_2 \text{ fb}^{-1}$

$Q = 1$
$\beta = 0.062$

Au (linear evolution)

Au (saturation model)

Kugeratski, Goncalves, and Navarra,
Eur.Phys.J. C46 (2006) 413

$Q^2 = 1$
$x_{IP} = 0.0042$

Au (linear evolution)

Au (saturation model)
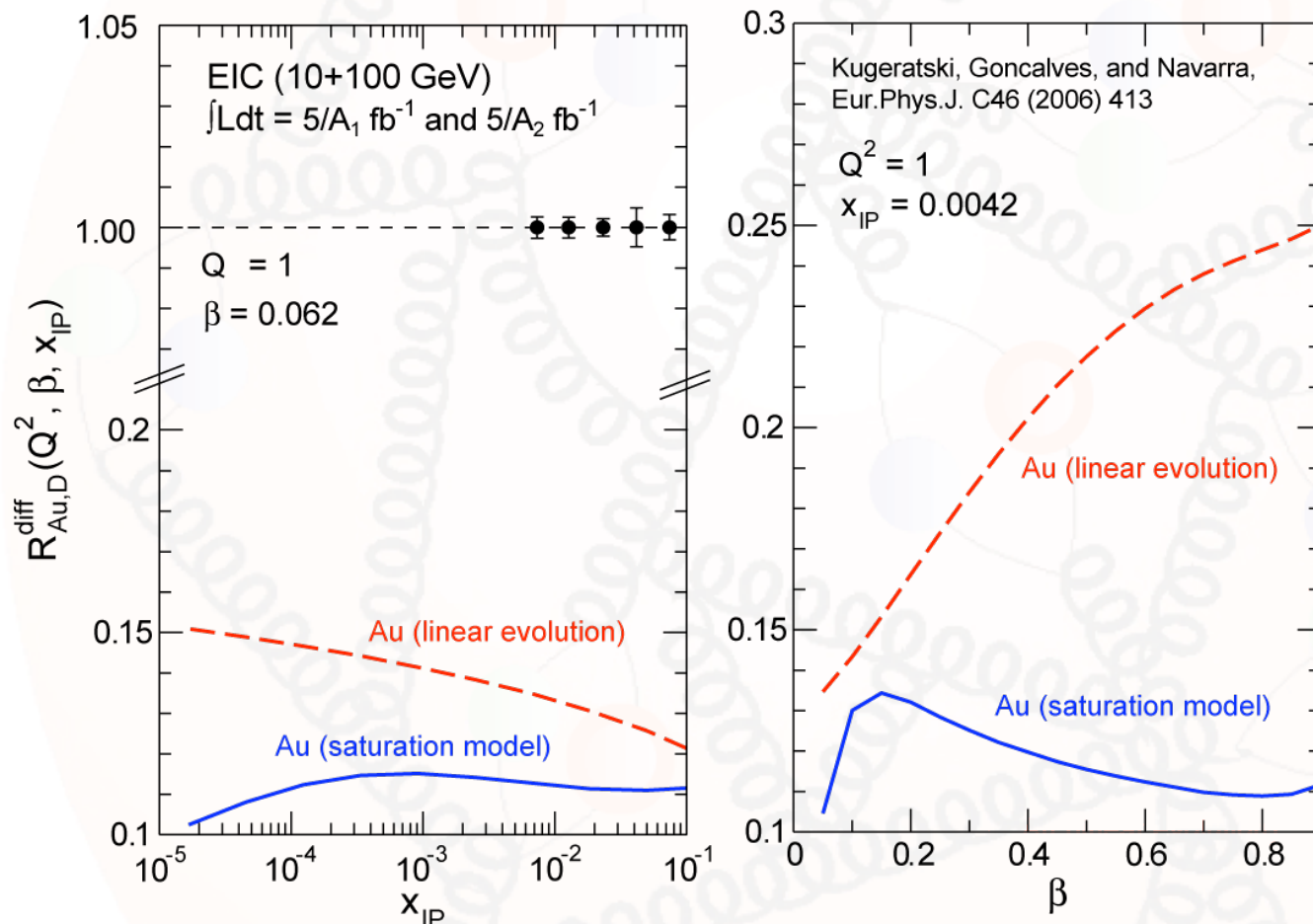
x_{IP} = momentum fraction of the Pomeron with respect to the hadron

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)