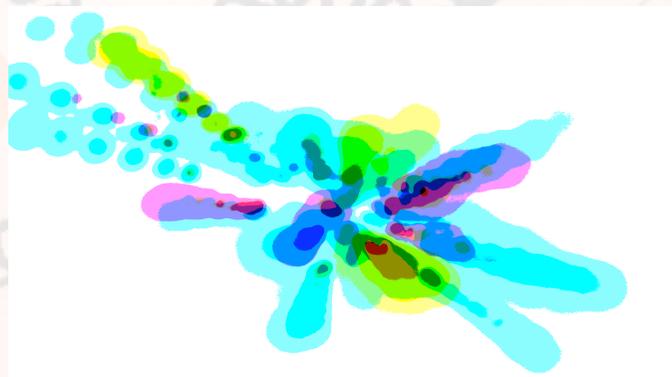


Opportunities in low x physics at a future Electron-Ion Collider (EIC) facility

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 E. 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-Chiieh 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 Vignor (Indiana)

Local Organizing Committee:

Ronald Ransome (Rutgers University)
Ronald Gilman (Rutgers University)

Jefferson Lab

BROOKHAVEN
NATIONAL LABORATORY

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

Unanimous recommendation of the
QCD Town Meeting,
Rutgers University, NJ,
January 13, 2007

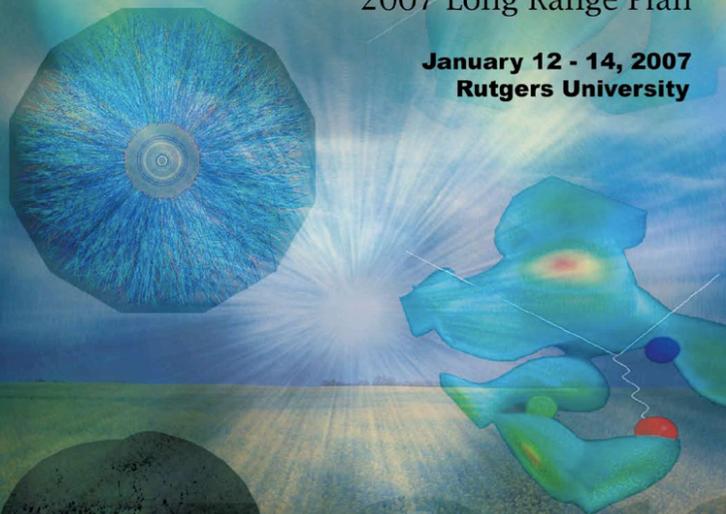
A high luminosity **Electron-Ion Collider (EIC)** is the **highest priority** of the **QCD community** for **new construction** after the **JLab 12GeV** and **RHICII upgrades**. EIC will address compelling physics questions essential for understanding the fundamental structure of matter:

- 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.

The Electron-Ion Collider



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- 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

eRHIC Accelerator Position Paper
For NSAC Long Range Plan 2007

BNL:
J. Beebe-Wang, I. Ben-Zvi, A. Fedotov, W. Fischer, Y. Hao, D. Kayran, V. N. Litvinenko, W.W. MacKay, C. Montag, E. Pozdeyev, V. Ptitsyn, T. Roser and D. Trbojevic

MIT-Bates:
K. Dow, W. Franklin, J. van der Laan, R. Milner, R. Redwine, C. Tschalär, E. Tsentalovich, D. Wang and F. Wang

January 2007

The image shows a stylized yellow 'E' logo with a vertical arrow pointing upwards through its center, set against a background of colorful, abstract patterns. Below the logo is a diagram of a particle collision process involving a virtual photon, a quark, a gluon, and a nucleon, with various labels like 'incident electron', 'incident nucleon', and 'hepton pair'.



A. Afanasev, A. Bogacz, A. Bruell, L. Cardman, Y. Chao, S. Chattopadhyay, E. Chudakov, P. Degtiarenko, J. Delaysn, Ya. Derbenev, R. Ent, P. Evtushenko, A. Freyberger, J. Grames, A. Hutton, R. Kazimi, G. Krafft, R. Li, L. Merminga, M. Poelker, A. Thomas, C. Weiss, B. Wojtsekhowski, B. Yunn, Y. Zhang
Thomas Jefferson National Accelerator Facility
Newport News, Virginia, USA

W. Fischer, C. Montag
Brookhaven National Laboratory
Upton, New York, USA

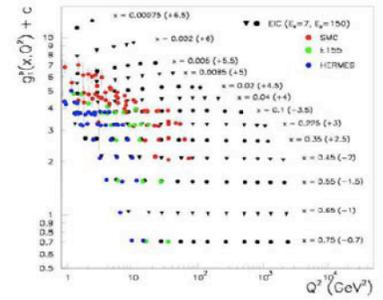
V. Danilov
Oak Ridge National Laboratory
Oak Ridge, Tennessee, USA

V. Dudnikov
Brookhaven Technology Group
New York, New York, USA

P. Ostroumov
Argonne National Laboratory
Argonne, Illinois, USA

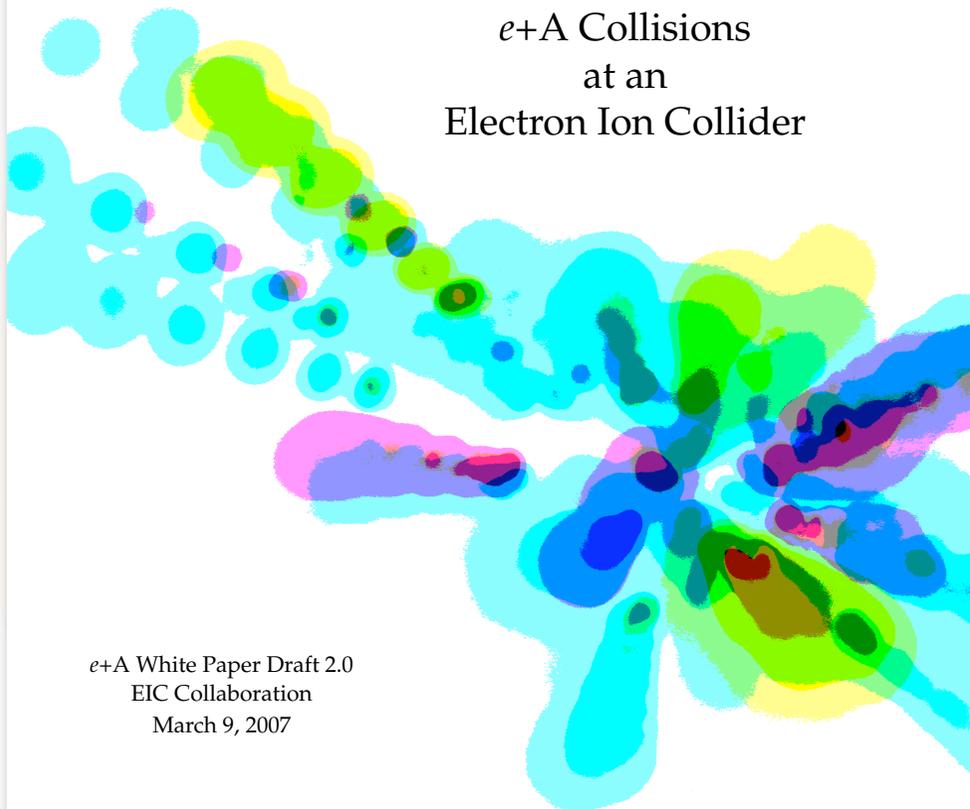
V. Derenchuk
Indiana University Cyclotron Facility
Bloomington, Indiana, USA

A. Belov
INR, Moscow-Troitsk, Russia
Editors: Ya. Derbenev, L. Merminga, Y. Zhang



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*

⁸J. Annand, ¹J. Arrington, ²⁴R. Averbeck, ³M. Baker, ²⁶W. Brooks, ²⁶A. Bruell, ¹⁷A. Caldwell, ²⁶J.P. Chen, ²R. Choudhury, ⁹E. Christy, ⁷B. Cole, ⁴D. De Florian, ²⁴A. Deshpande, ¹⁶K.Dow, ²⁴A.Drees, ³J.C. Dunlop, ²D. Dutta, ²⁶R. Ent, ¹⁶R. Fatemi, ¹⁶W. Franklin, ²⁶D. Gaskell, ¹⁴G. Garvey, ¹⁰M.Grosse-Perdekamp, ¹K. Hafidi, ¹⁶D. Hasell, ³T. Hemmick, ¹R. Holt, ⁷E. Hughes, ²⁰C. Hyde-Wright, ⁵G. Igo, ¹²K. Imai, ⁸D. Ireland, ²⁴B. Jacak, ¹³P. Jacobs, ²⁶M. Jones, ⁸R. Kaiser, ¹⁵D. Kallow, ⁹C. Keppel, ⁶E. Kinney, ¹⁶M. Kohl, ²V. Kumar, ¹⁵K. Kumar, ¹⁹G. Kyle, ¹¹J. Lajoie, ¹⁴M. Leitch, ²⁵J. Lichtenstadt, ⁸K. Livingstone, ¹⁸W. Lorenzon, ¹³H. Matis, ¹⁰N. Makins, ¹⁶M. Miller, ¹⁶R. Milner, ²A. Mohanty, ³D. Morrison, ²⁴Y. Ning, ¹³G. Odyniec, ¹¹C. Ogilvie, ²L. Pant, ²⁴V. Pantuyev, ¹⁹S. Pate, ²⁴P. Paul, ¹⁰J.-C. Peng, ¹⁶R. Redwine, ¹P. Reimer, ¹³H.-G.Ritter, ⁸G. Rosner, ²³A. Sandacz, ⁶J. Seele, ¹⁰R. Seidl, ⁸B. Seitz, ²P. Shukla, ¹³E. Sichtermann, ¹⁶F. Simon, ³P. Sorensen, ³P. Steinberg, ²²M. Stratmann, ²¹M. Strikman, ¹⁶B. Surrow, ¹⁶E. Tsentalovich, ⁹V. Tvaskis, ³T. Ullrich, ³R. Venugopalan, ³W. Vogelsang, ¹³H. Wieman, ¹³N. Xu, ³Z. Xu, ⁷W. Zajc

¹Argonne National Laboratory, Argonne, IL

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⁴University of Buenos Aires, Argentina

⁵University of California, Los Angeles, CA

⁶University of Colorado, Boulder, CO

⁷Columbia University, New York, NY

⁸University of Glasgow, Scotland, United Kingdom

⁹Hampton University, Hampton, VA

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¹¹Iowa State University, Ames, IA

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¹³Lawrence Berkeley National Laboratory, Berkeley, CA

¹⁴Los Alamos National Laboratory, Los Alamos, NM

¹⁵University of Massachusetts, Amherst, MA

¹⁶MIT, Cambridge, MA

¹⁷Max Planck Institut für Physik, Munich, Germany

¹⁸University of Michigan Ann Arbor, MI

¹⁹New Mexico State University, Las Cruces, NM

²⁰Old Dominion University, Norfolk, VA

²¹Penn State University, PA

²²RIKEN, Wako, Japan

²³Soltan Institute for Nuclear Studies, Warsaw, Poland

²⁴SUNY, Stony Brook, NY

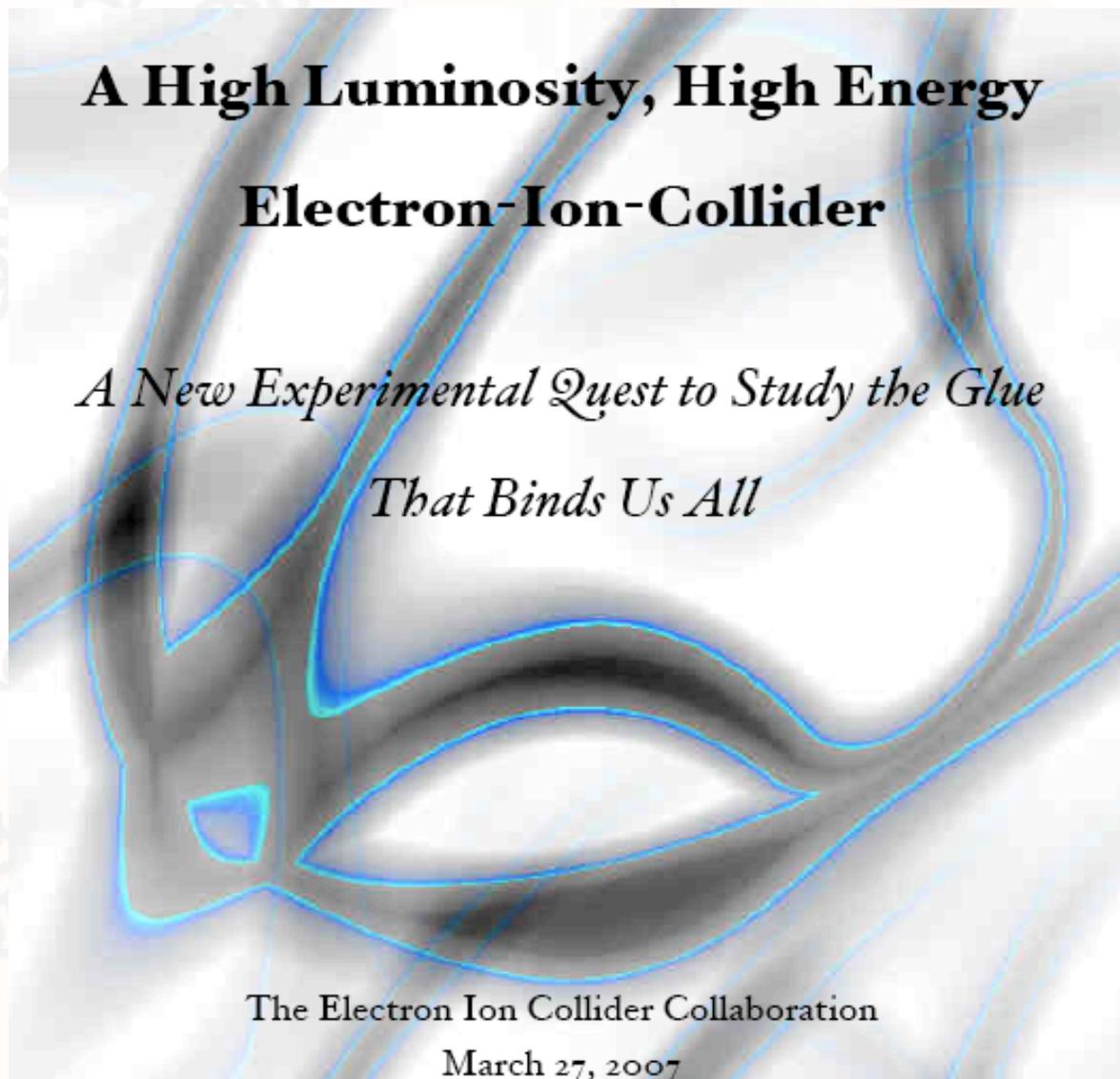
²⁵Tel Aviv University, Israel

²⁶Thomas Jefferson National Accelerator Facility, Newport News, VA

*with valuable contributions from: ¹¹Alberto Accardi, Vadim Guzey (Ruhr-Universität Bochum, Germany), ³Tuomas Lappi, ³Cyrille Marquet, ¹¹Jianwei Qiu.

The Electron-Ion Collider

- EIC Whitepaper
 - Input for the NSAC LRP 2007 process



NSAC: Nuclear Science Advisory
Committee

LRP: Long-Range Planning

The Electron-Ion Collider

Electron - Ion Collaboration Meeting

Massachusetts Institute of Technology - Laboratory for Nuclear Science

6-7 April, 2007

Home

Agenda

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Useful Links

Welcome to the Electron-Ion Collider Collaboration Meeting

Massachusetts Institute of Technology

Laboratory for Nuclear Science

6-7 April, 2007

The meeting is hosted by the **Laboratory for Nuclear Science** at MIT with support from **Brookhaven National Laboratory** and **Thomas Jefferson National Accelerator Facility**.

The primary aim of this meeting is to discuss the science case and accelerator parameters for a future electron-ion collider in preparation for the Long Range Plan Writing Group meeting in early May. We also hope that this will be the first in a series of regular meetings in realising the future electron-ion collider and experiments.

Please register as soon as possible as space may be limited and we need to make plans according to the number of participants expected. In particular the special rate negotiated with the hotel is only guaranteed until 9 March. When you register please indicate whether or not you would be interested in attending a no-host, group dinner Friday evening.

Introductory documentation and copies of presentations will be available from the **Presentations** page as they become available.

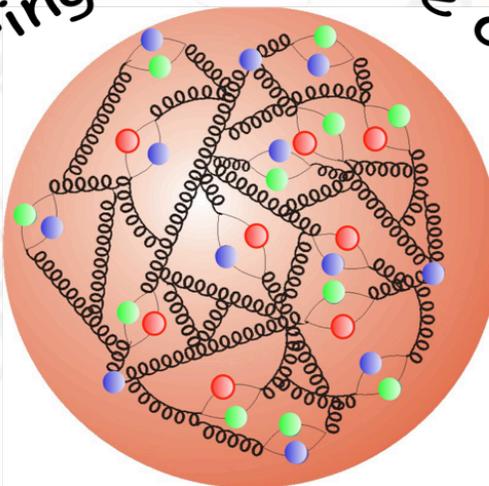
The links in the menu to the left should provide all the information necessary. Otherwise please contact us directly.

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

Outline

- Low-x physics:
Future
opportunities

Exploring the nature of glue



- Low-x physics:
Concepts and
Status

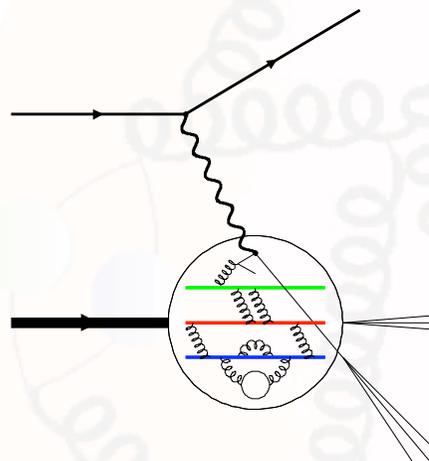
- Summary and
Outlook

Low-x Physics - Concepts and Status

Low-x basics

Cross-sections and structure functions

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



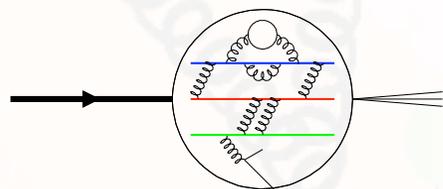
$$\left(\frac{d^2\sigma}{dydQ^2} \right) = \frac{2\pi\alpha^2 Y_+}{yQ^4} \left(F_2 - \frac{y^2}{Y_+} F_L \right)$$

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

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

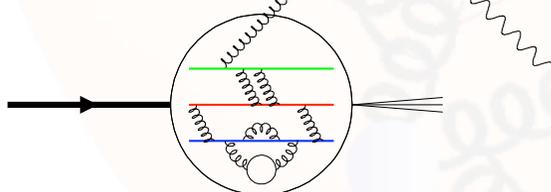
$$F_L = \frac{Q^2}{4\pi^2\alpha} \sigma_L^{\gamma^*p} \propto xg$$

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

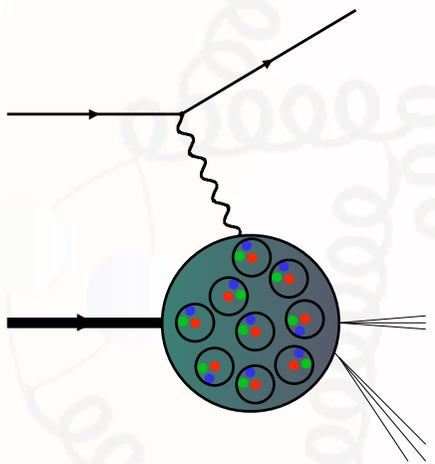


Low-x Physics - Concepts and Status

□ Low-x basics

○ Cross-sections and structure functions

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



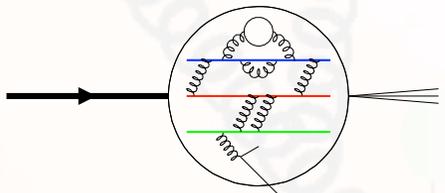
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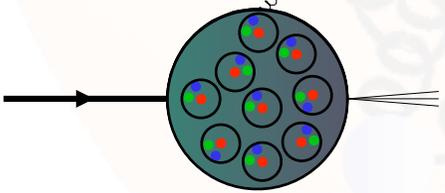
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Factorization



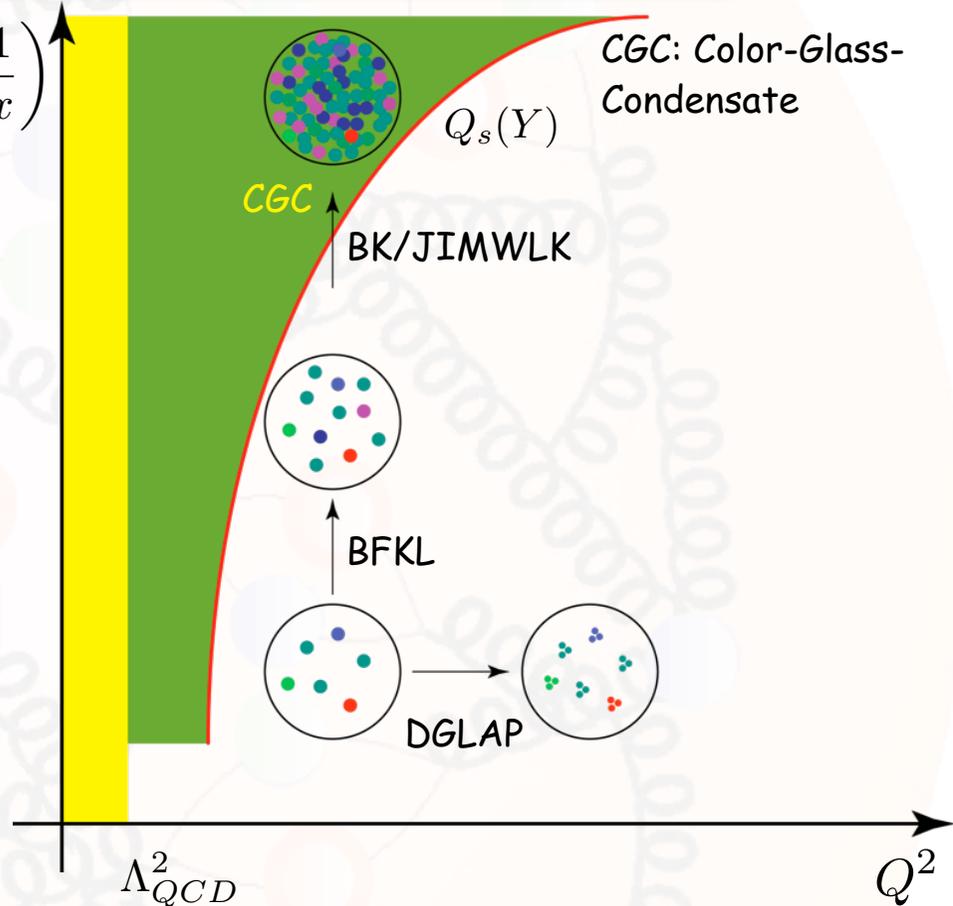
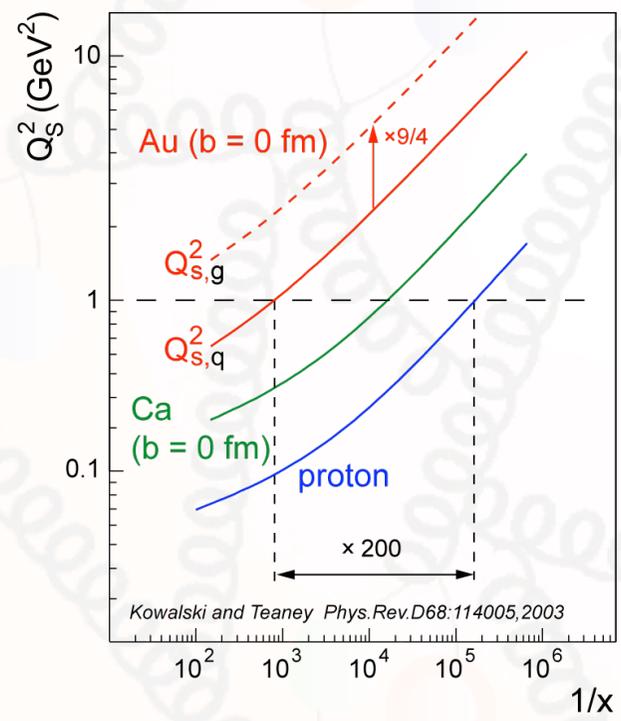
Important: Complementary probes are required for unambiguous extraction of observables in high-energy density QCD region!

Low-x Physics - Concepts and Status

□ Low-x basics

○ Dynamics: DGLAP / BFKL and CGC

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



Q_s^2 : **Saturation scale** \Rightarrow 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:

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

$\alpha_s \sim 1$

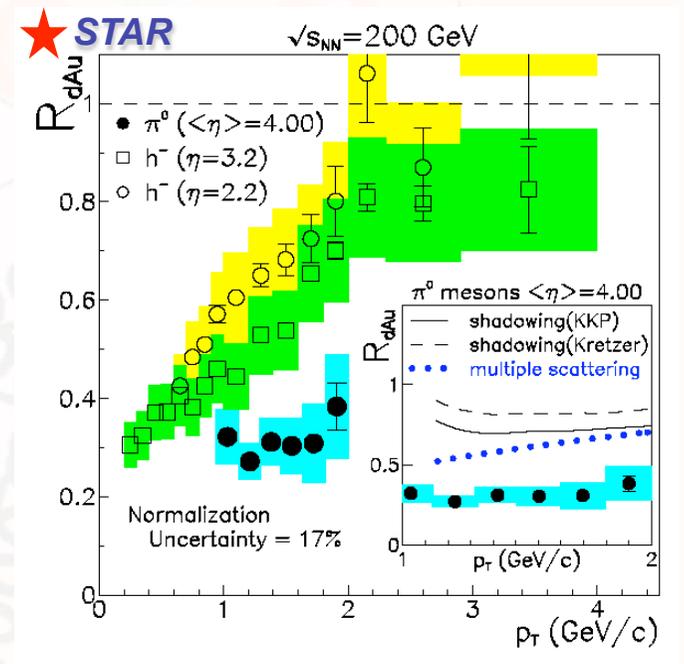
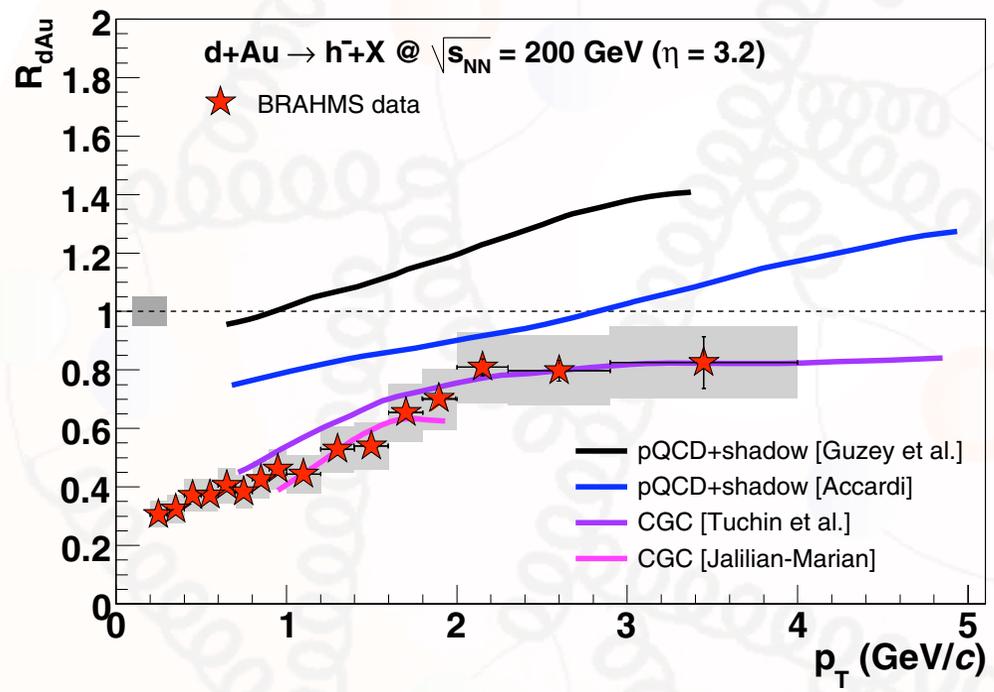
$\alpha_s \ll 1$

DGLAP: Evolution in Q^2

BFKL: Evolution in x

Low-x Physics - Concepts and Status

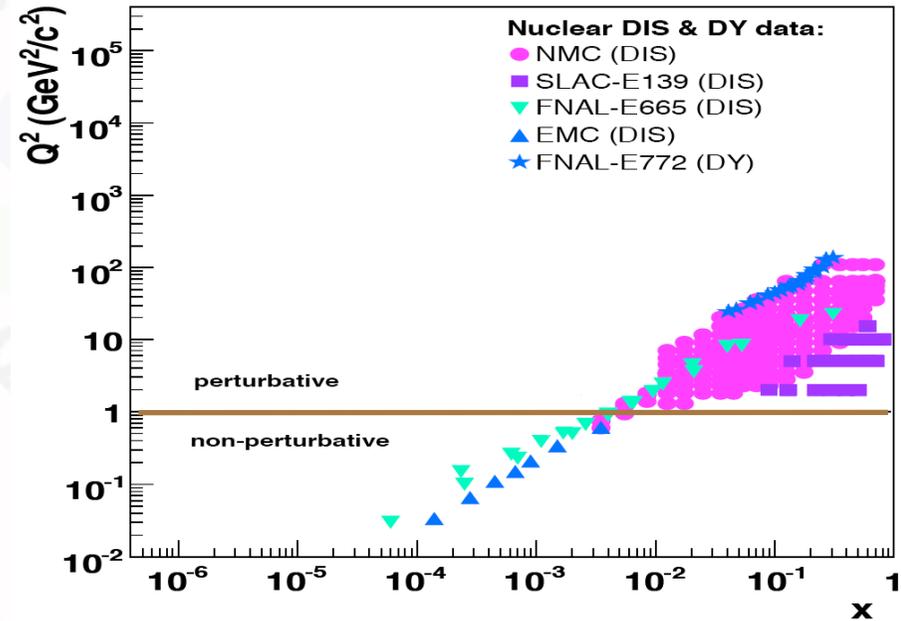
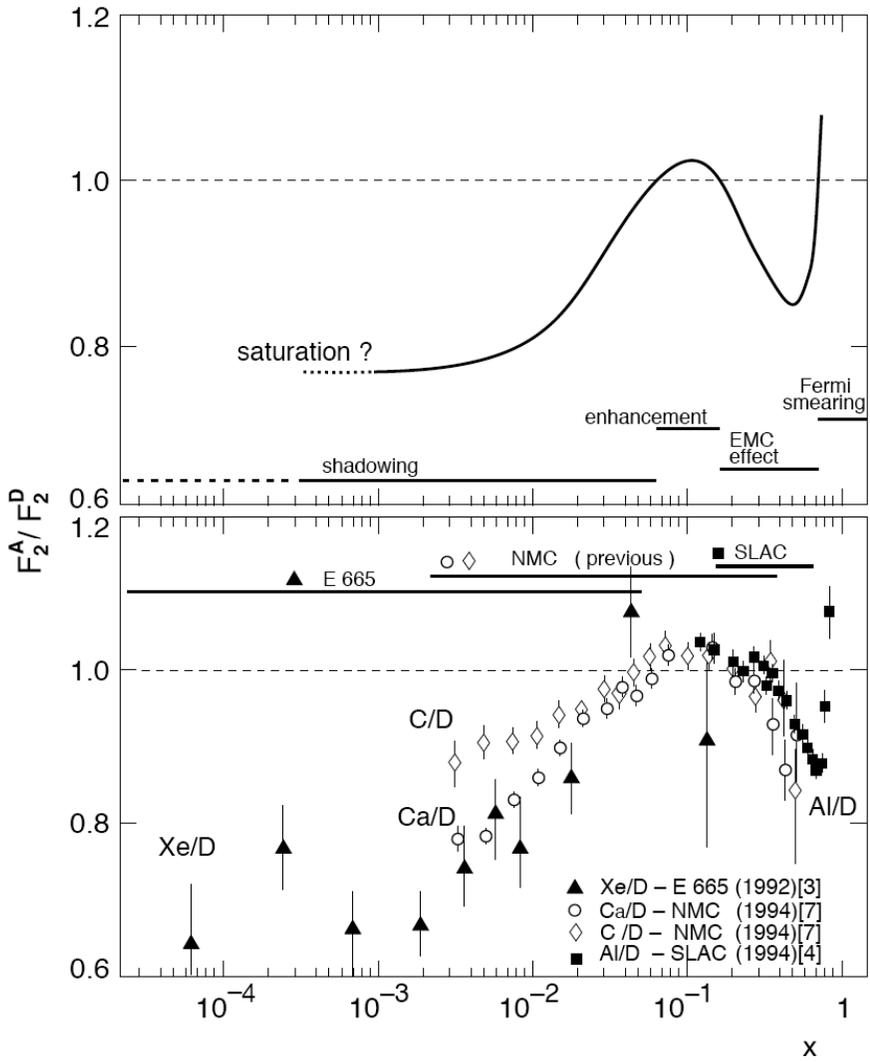
□ RHIC dA scattering at forward η



- **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 - 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 - 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!

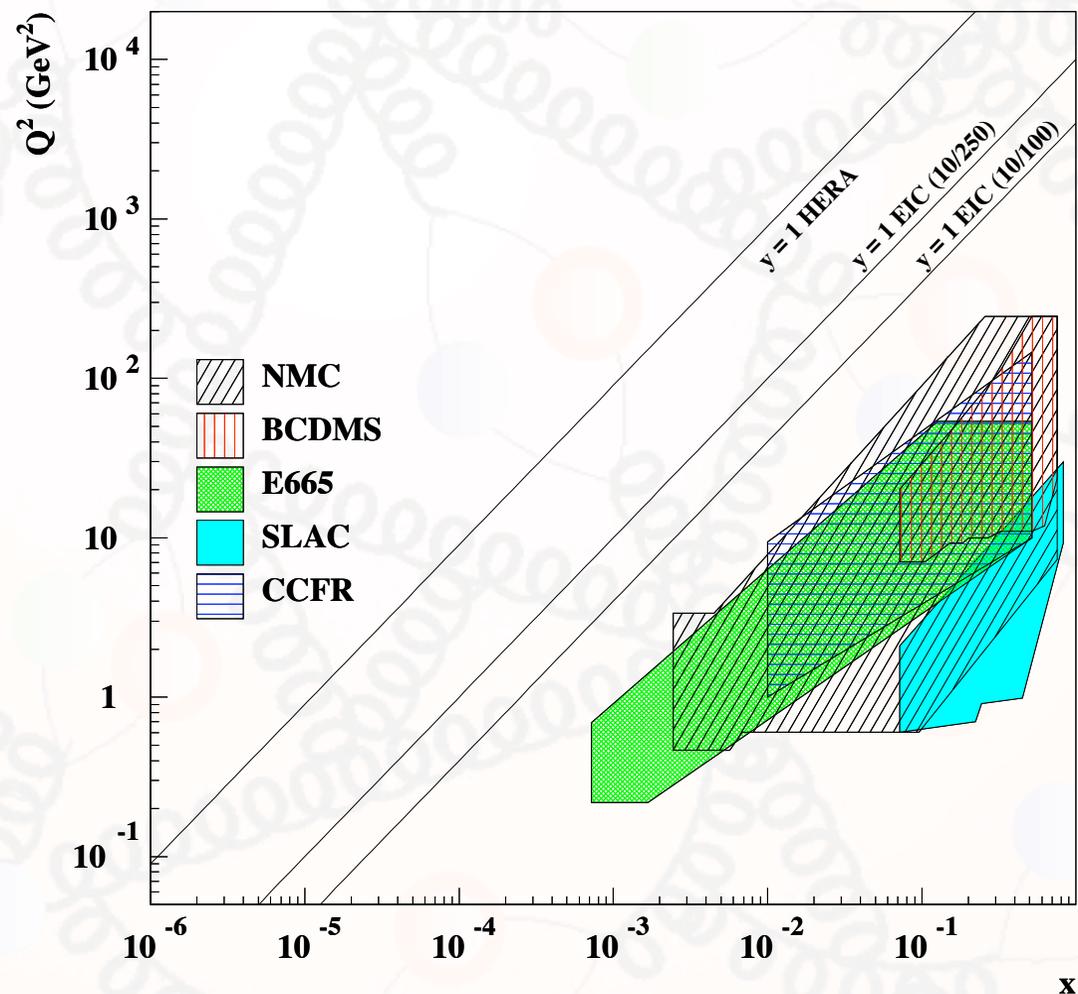
Required measurements:

- 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

□ Kinematics

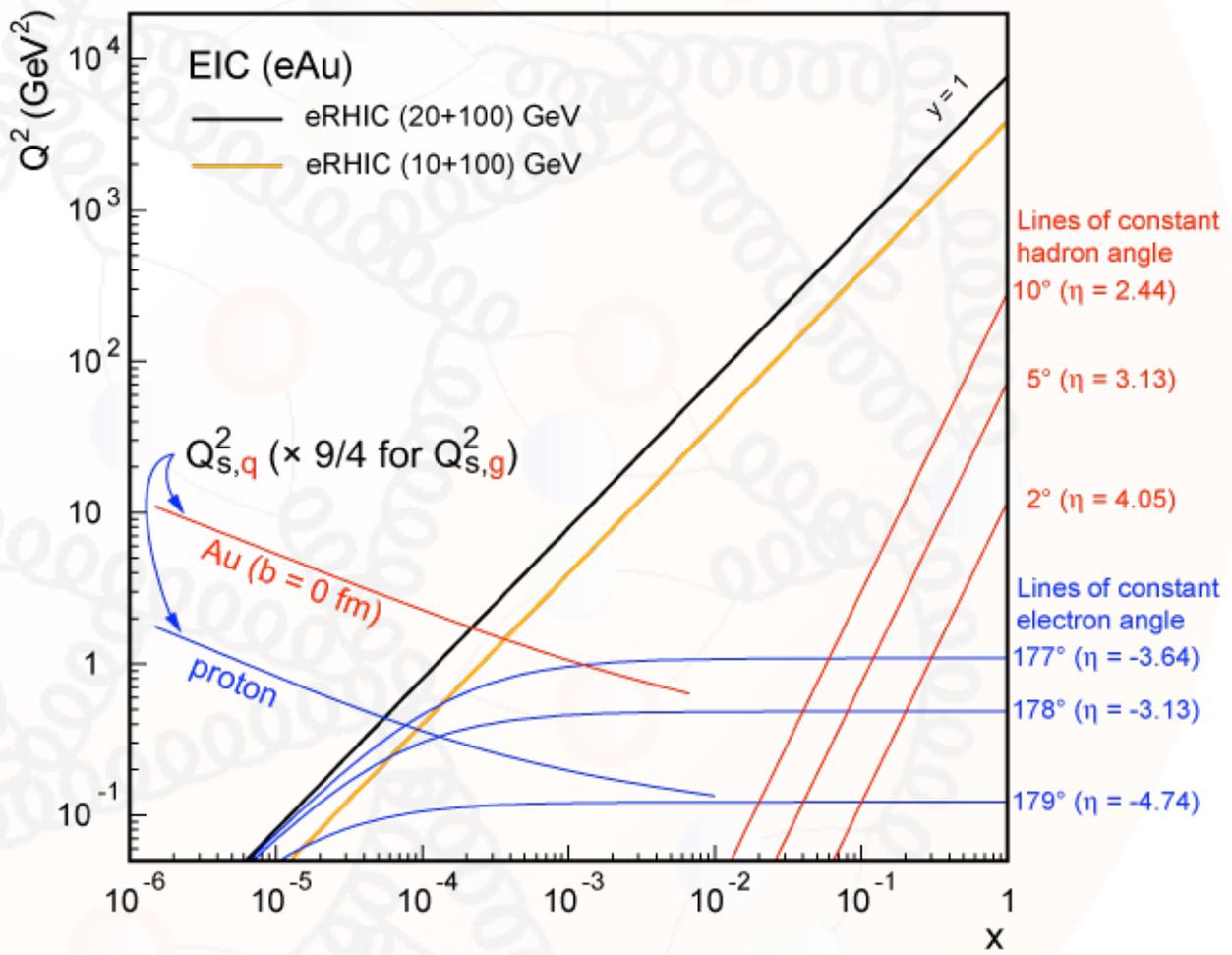
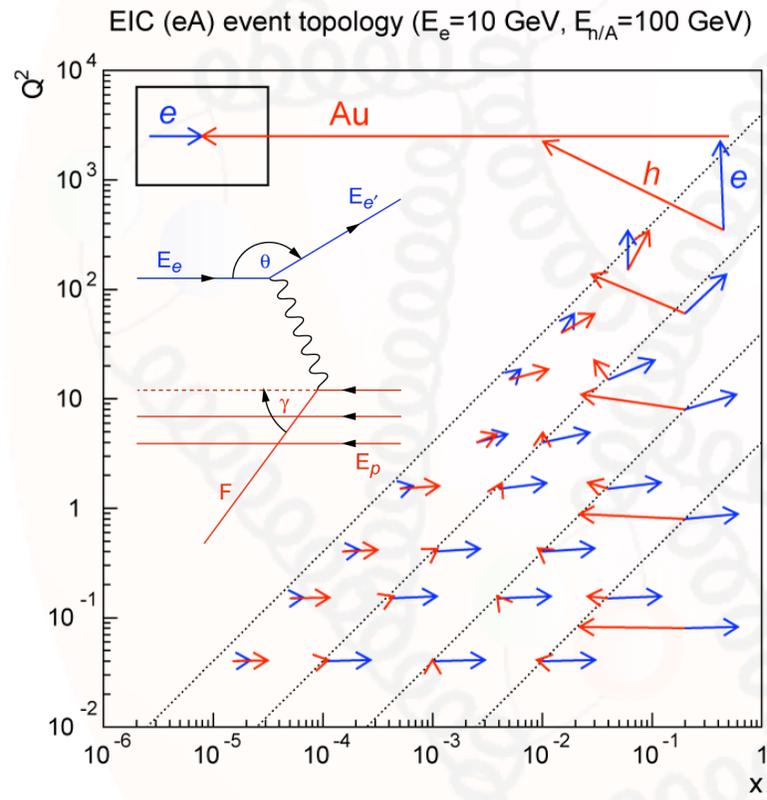
○ Comparison HERA / EIC / Fixed-target experiments



Low-x Physics - Future Opportunities

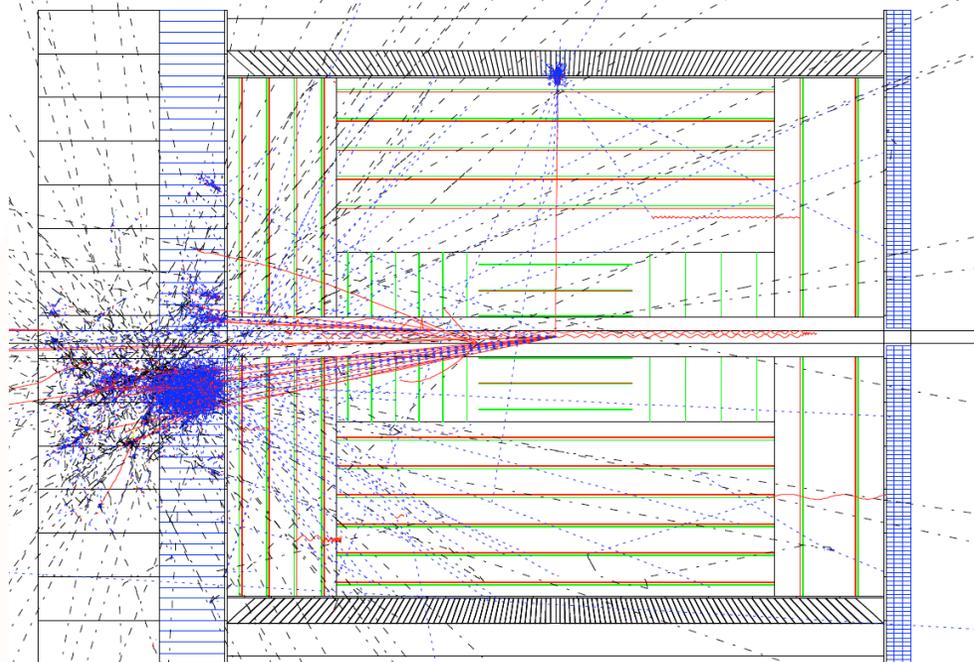
□ Kinematics

○ Acceptance



Low-x Physics - Future Opportunities

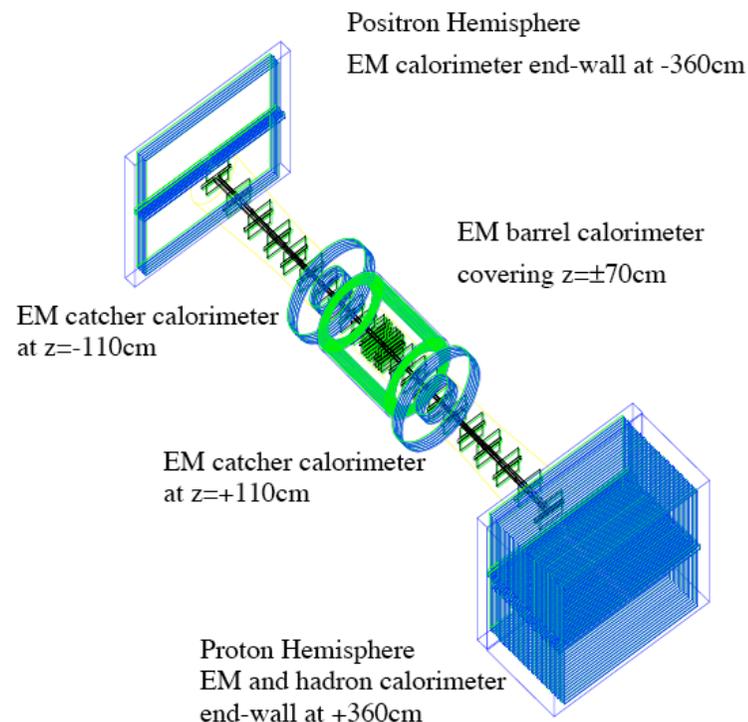
Facilities - Detector concepts



J. Pasukonis, B. Surrow, physics/0608290

Concepts:

- 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)
- Focus on a **wide acceptance** detector system (Compact calorimeter system)



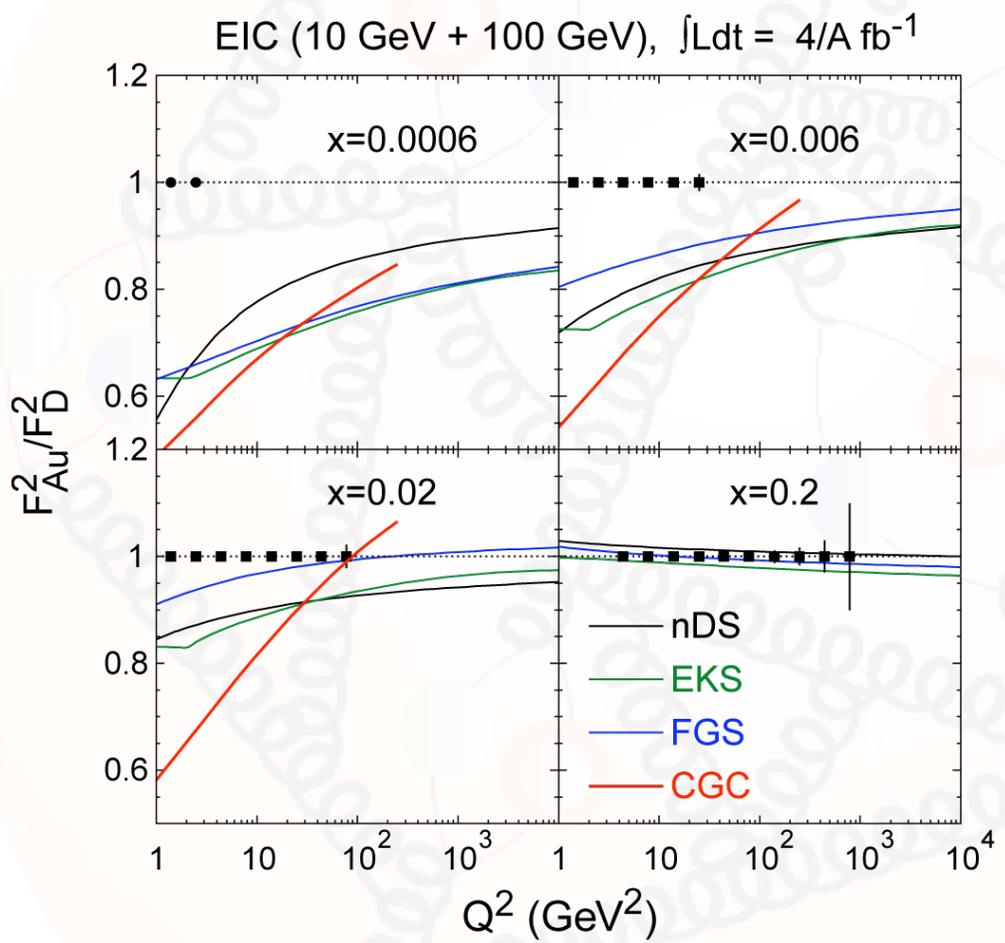
I. Abt, A. Caldwell, X. Liu,
J. Sutiak, hep-ex 0407053

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



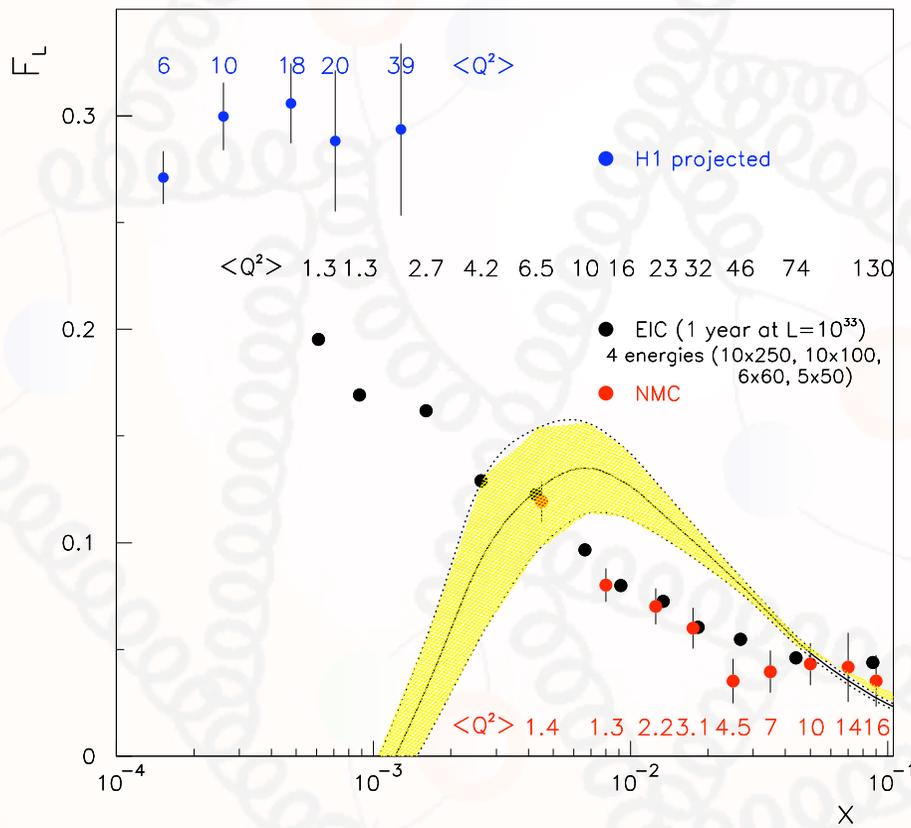
- F_2 will be one of the first measurements at EIC
- nDS, EKS, FGS: pQCD models with different amounts of shadowing

EIC will allow to distinguish between pQCD and saturation model predictions

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

Low-x Physics - Future Opportunities

□ Observables: Longitudinal structure function



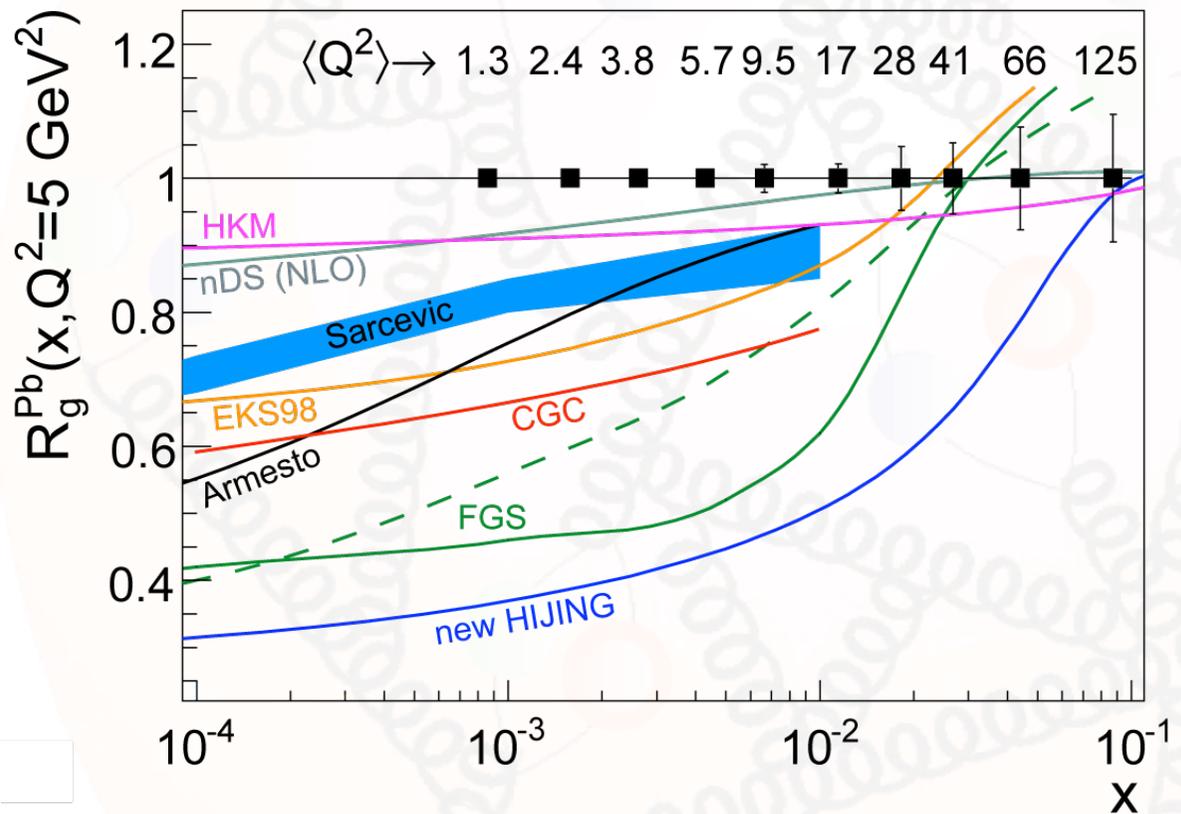
- F_L measurement requires operation of EIC at different center-of-mass energies (\sqrt{s})
- Precise measurement from low to high Q^2 region

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



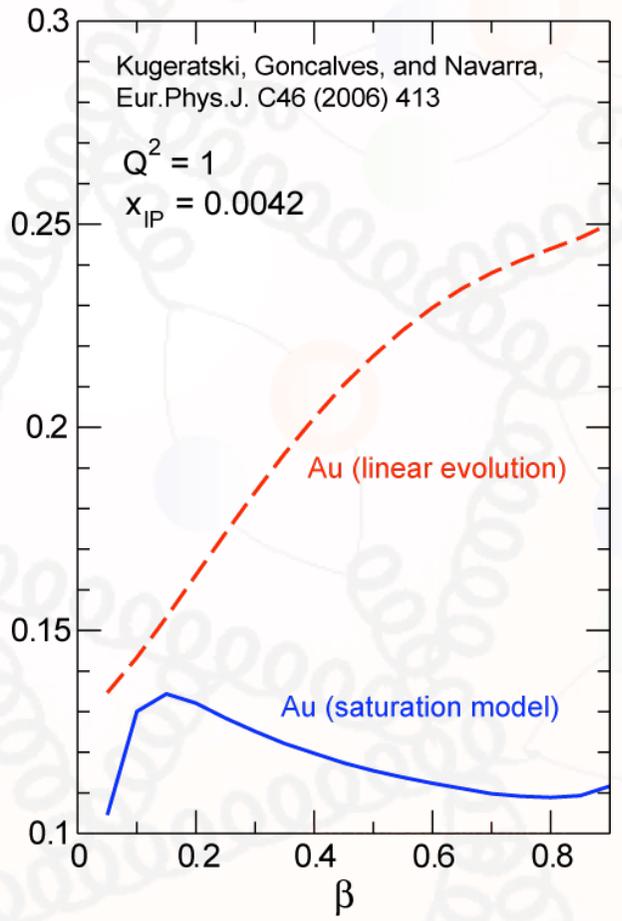
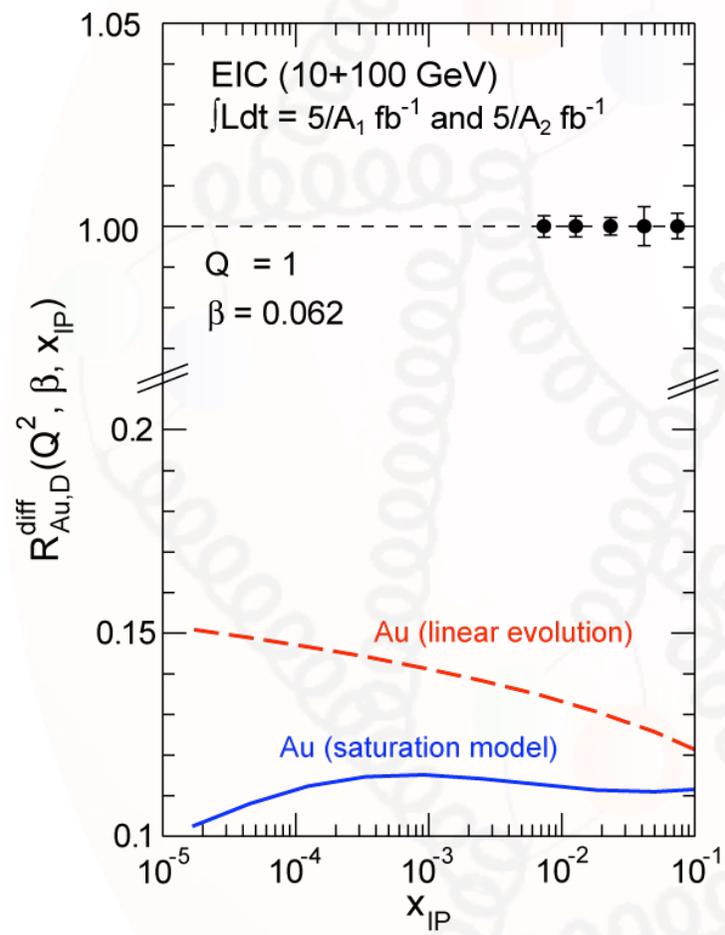
- EIC will reach the unmeasured low-x region ($x < 0.01$) with high precision for $Q^2 > 1 \text{ GeV}^2$
- Constrain gluon modification due to nuclear effects in comparison to large range of models

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



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** 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)

Backup

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

□ eRHIC (BNL): ep and eA (light to heavy nuclei, up to U)

■ Linac-Ring:

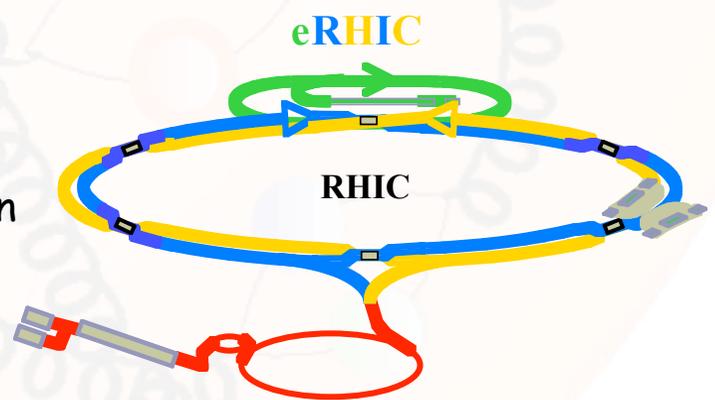
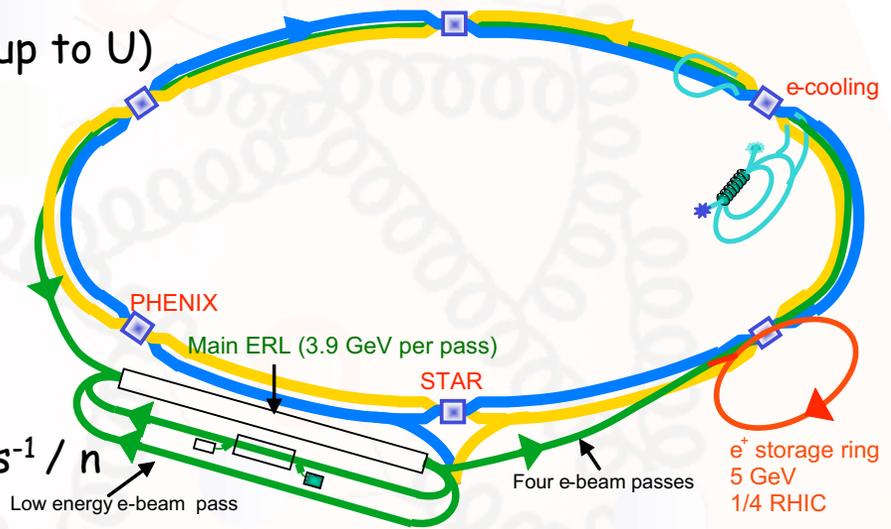
■ ep (20GeV / 250GeV): $2.6 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

■ eA (20GeV / 100GeV/n): $2.9 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1} / n$

■ Ring-Ring:

■ ep (10GeV / 250GeV): $0.47 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

■ eA (10GeV / 100GeV/n): $0.52 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1} / n$



Backup

Facilities - EIC (US): Electron-Ion Collider

ELIC (JLab): ep and eA (light nuclei)

Linac-Ring:

ep (7GeV / 150GeV): $7.7 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

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

