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

Bernd Surrow

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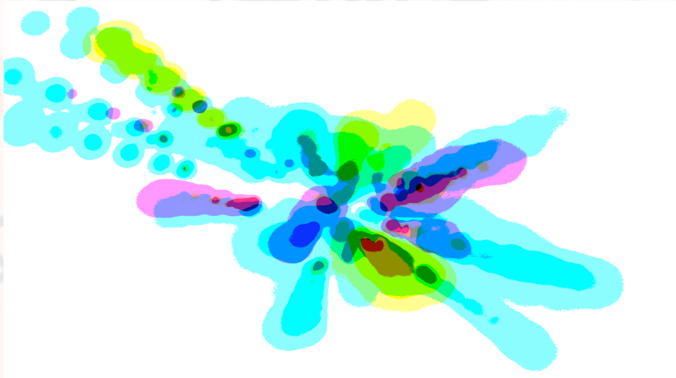

The Electron-Ion Collider

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.

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- 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

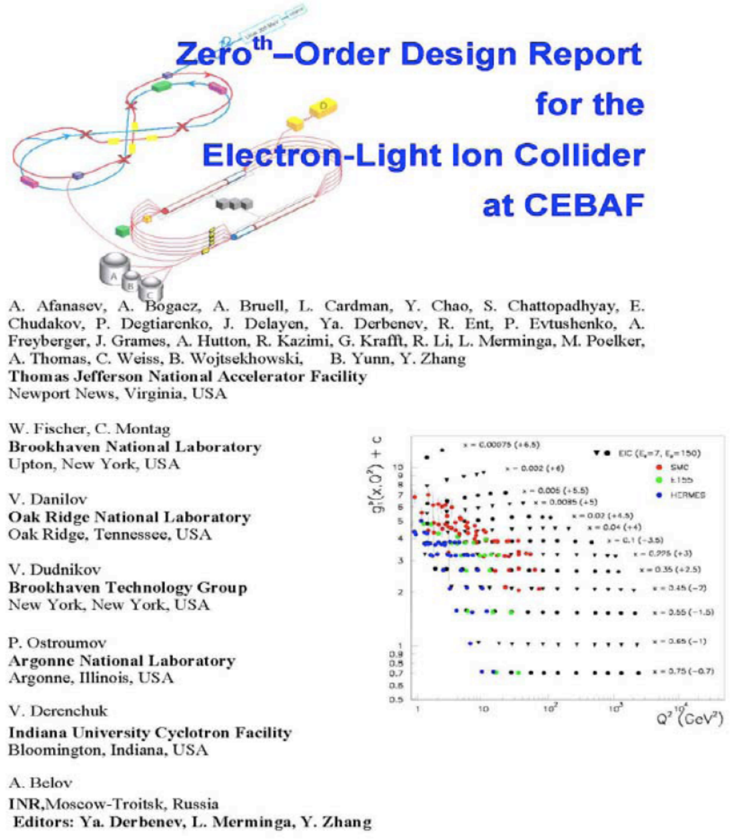
eRHIC Accelerator Position Paper

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



Zero[th]–Order Design Report for the Electron-Light Ion Collider at CEBAF

A. Afanasev, A. Bogacz, A. Bruell, L. Cardman, Y. Chao, S. Chattopadhyay, E. Chudakov, P. Degtiarenko, J. Delayen, 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

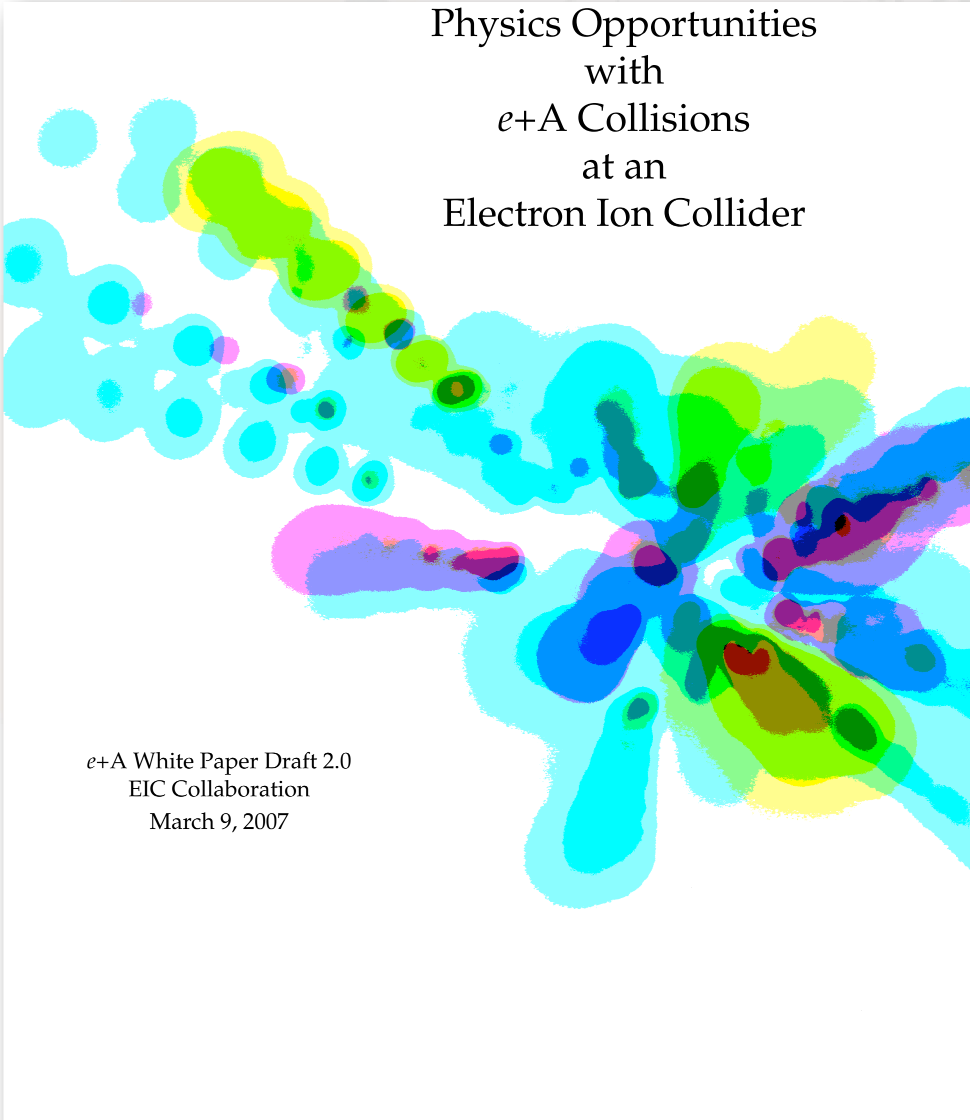
V. Dudnikov
Brookhaven Technology Group
New York, New York, USA

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



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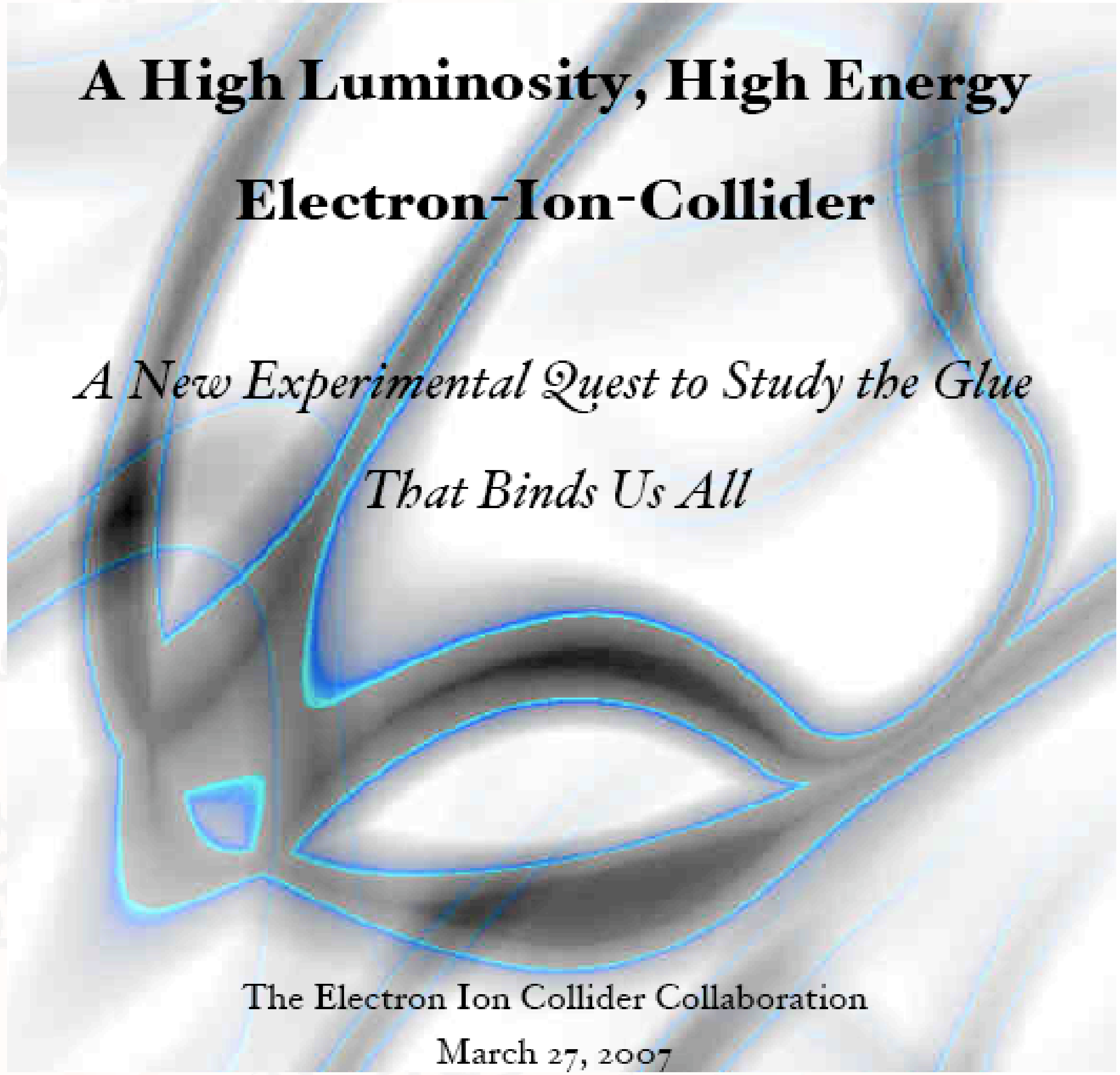
*with valuable contributions from: [11]Alberto Accardi, Vadim Guzey (Ruhr-Universität Bochum, Germany), [3]Tuomas Lappi, [3]Cyrille Marquet, [11]Jianwei Qiu.

The Electron-Ion Collider

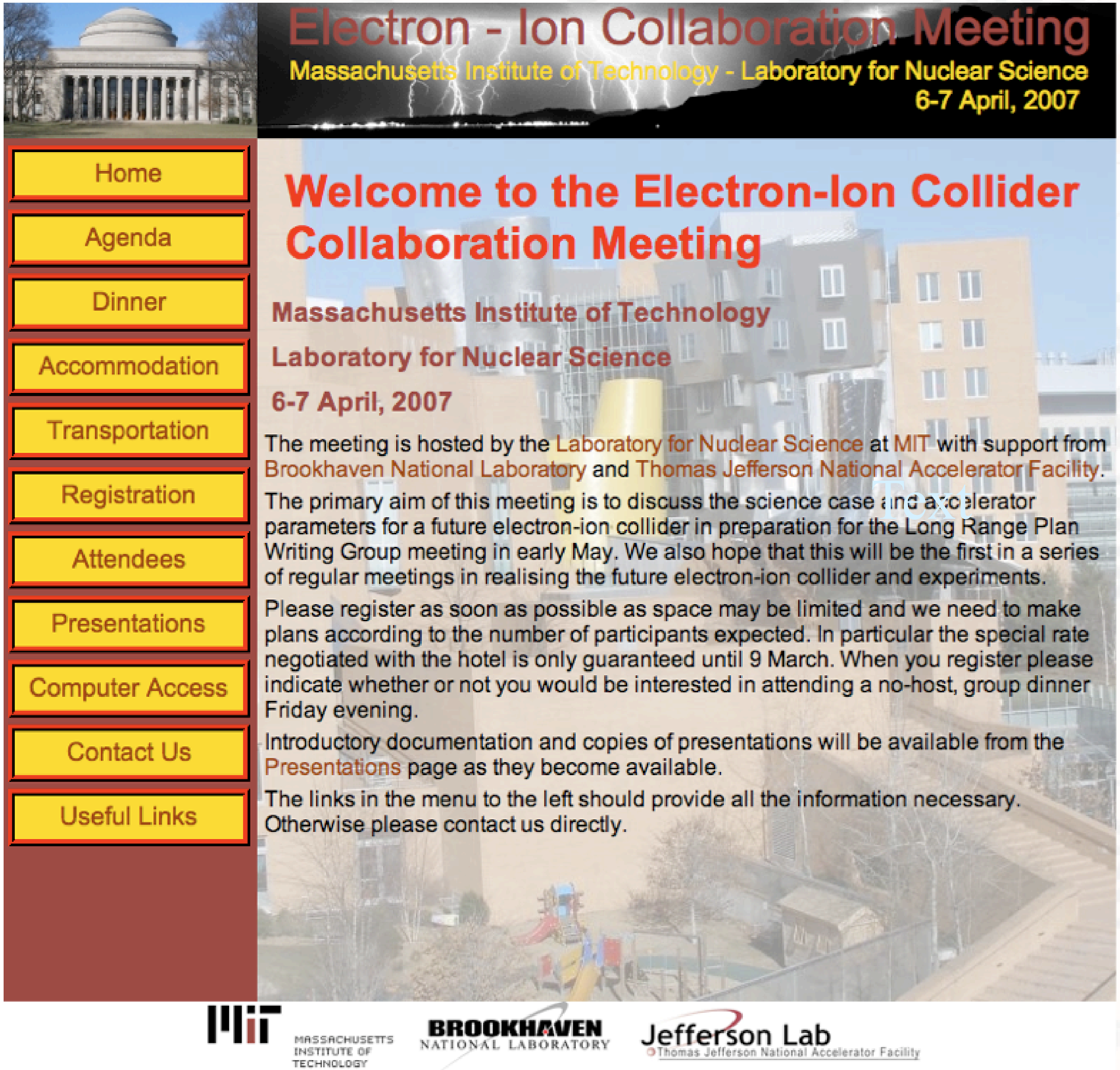
- EIC Whitepaper
  - Input for the NSAC LRP 2007 process



NSAC: Nuclear Science Advisory Committee

LRP: Long-Range Planning

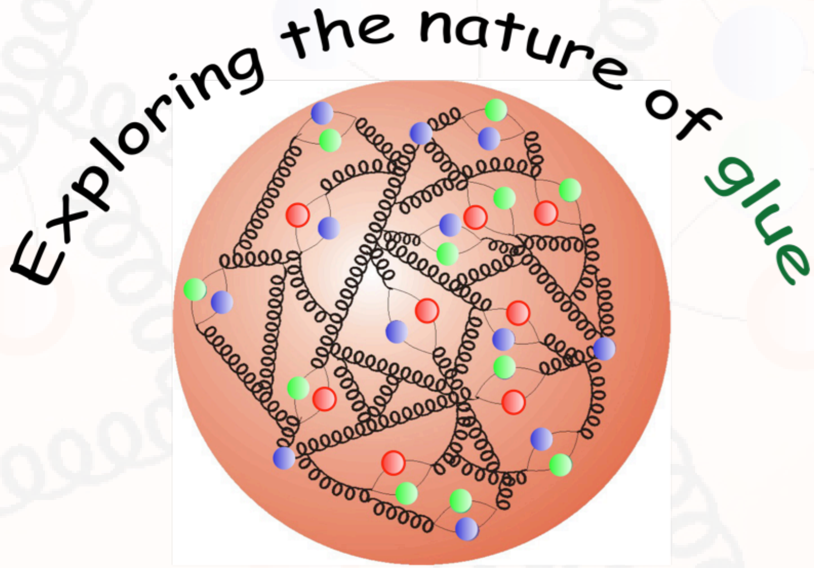
The Electron-Ion Collider



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

Outline

- Low-x physics: Future opportunities



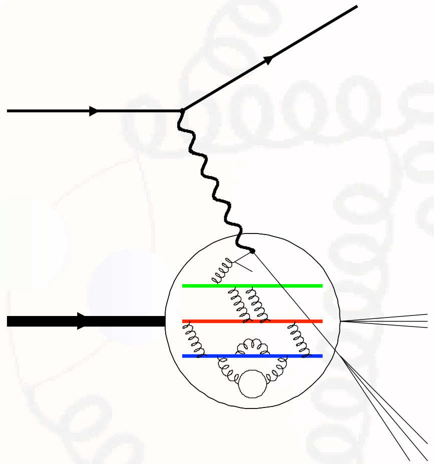
- Low-x physics: Concepts and Status

- Summary and Outlook

Low-x Physics - Concepts and Status

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

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



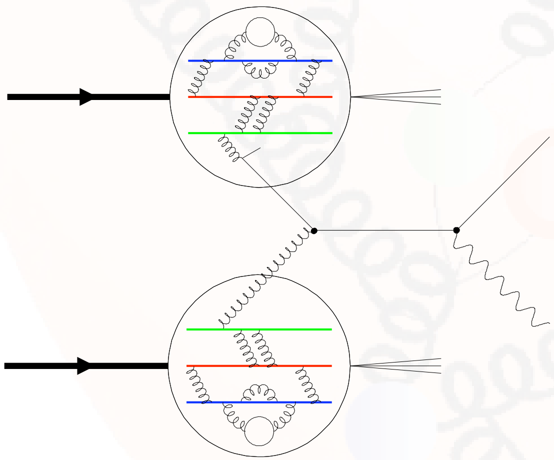
$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

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

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

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

Universality



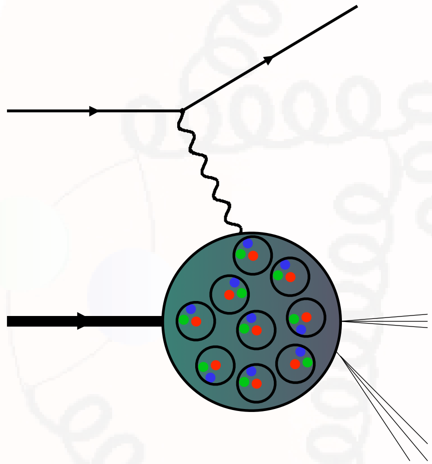
$$d\sigma = \sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to f X} \otimes D_f^h$$

Factorization

Low-x Physics - Concepts and Status

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

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



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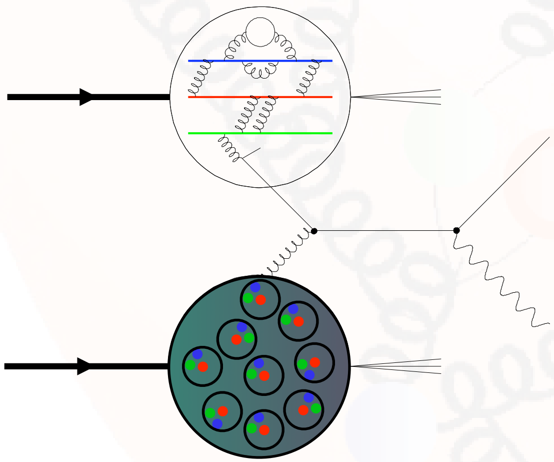
Universality



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

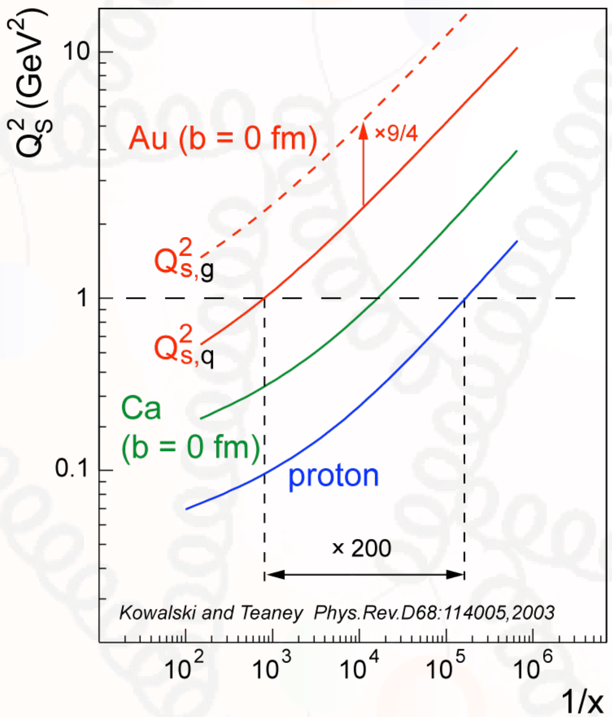
Factorization

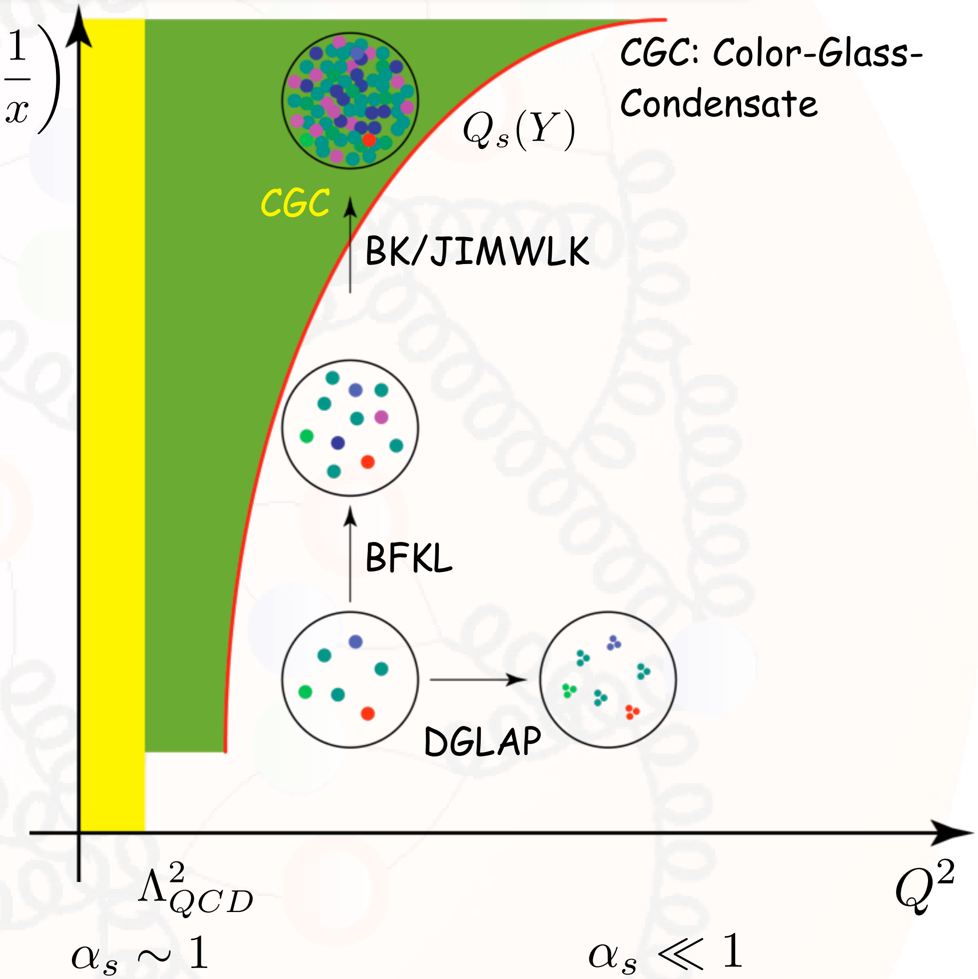
Important: Complementary probes are required for unambiguous extraction of observables in high-energy density QCD region!

Low-x Physics - Concepts and Status

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

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





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

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

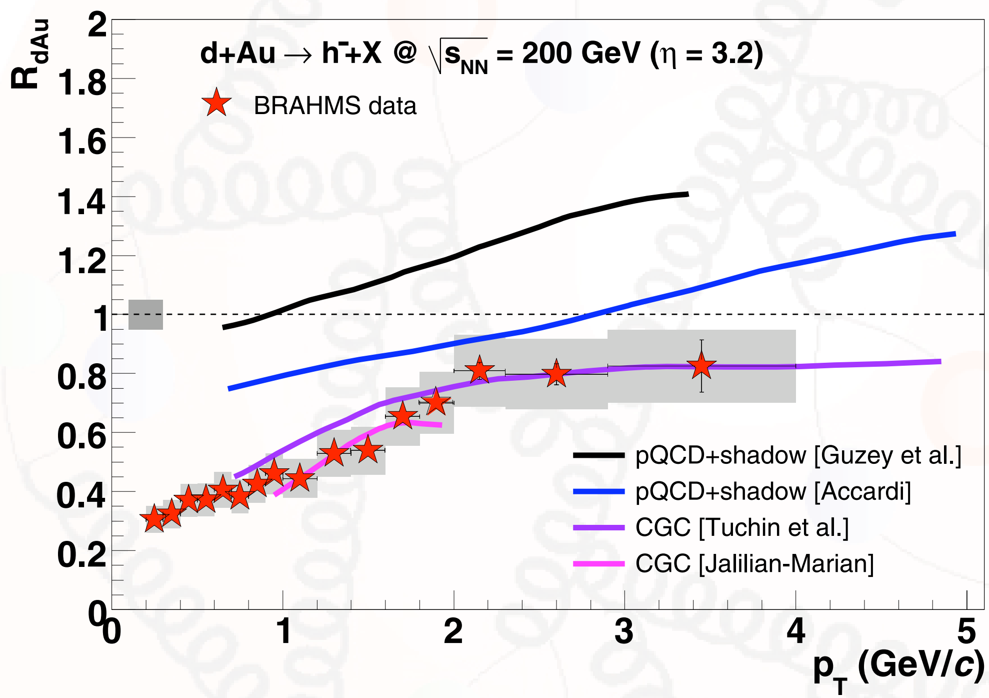
Enhanced for eA compared to ep: $A^{1/3} x^{-\delta}$

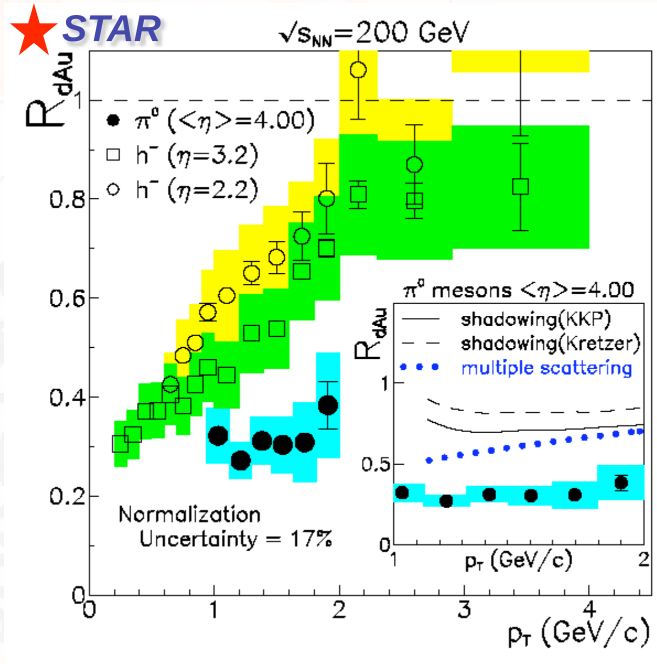
DGLAP: Evolution in Q^2

BFKL: Evolution in x

Low-x Physics - Concepts and Status

- RHIC dA scattering at forward η

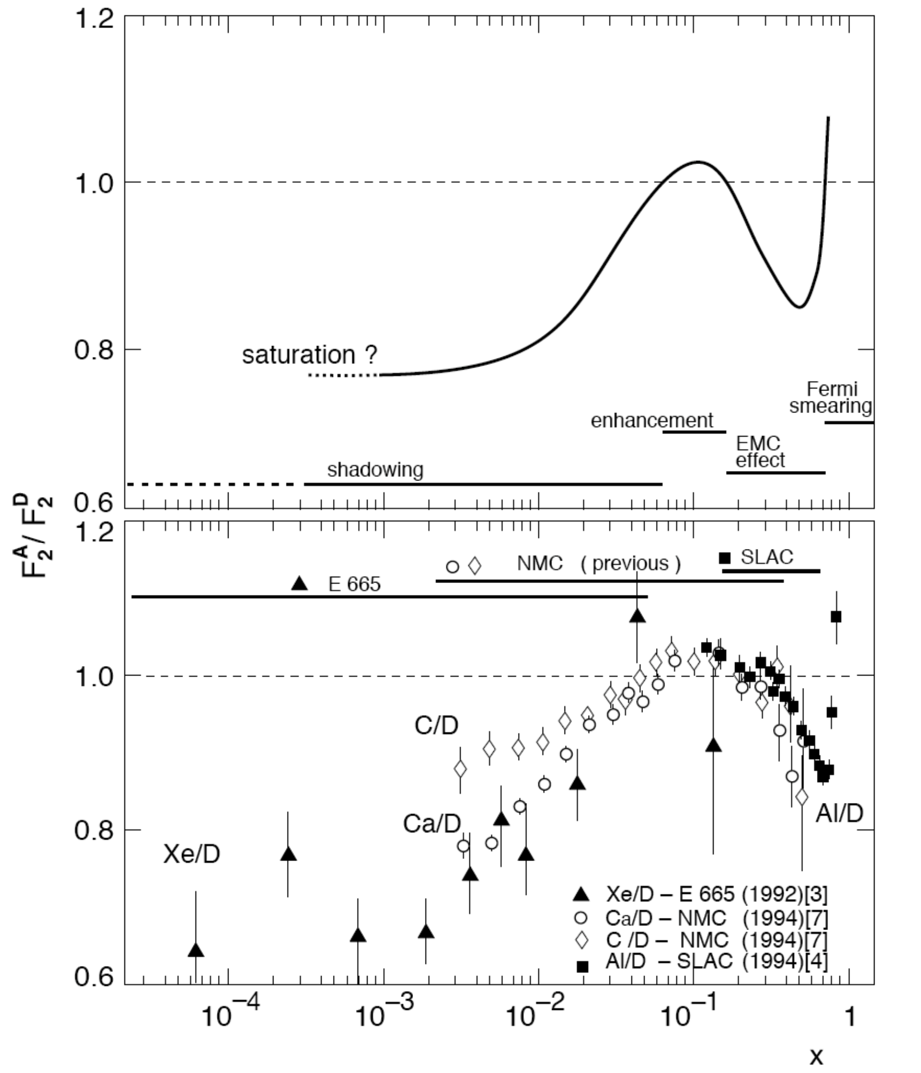


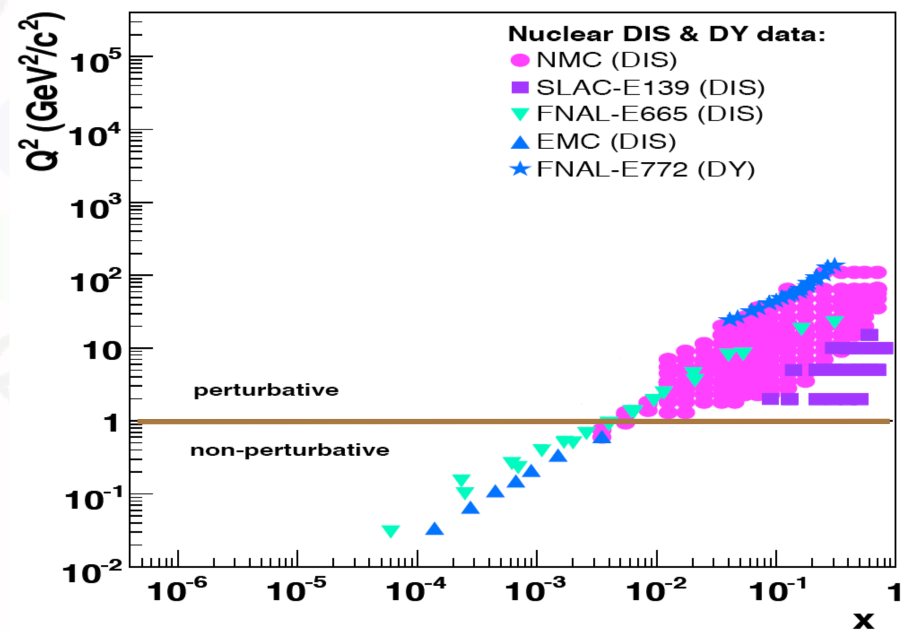


- Forward identified hadron production at RHIC in dAu collisions: Sizable suppression of yields for charged hadrons and neutral pions observed
- pQCD+shadowing calculations over-predict hadron yield suppression. Is this an indication for gluon saturation in Au nuclei?
- More RHIC dAu are expected with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

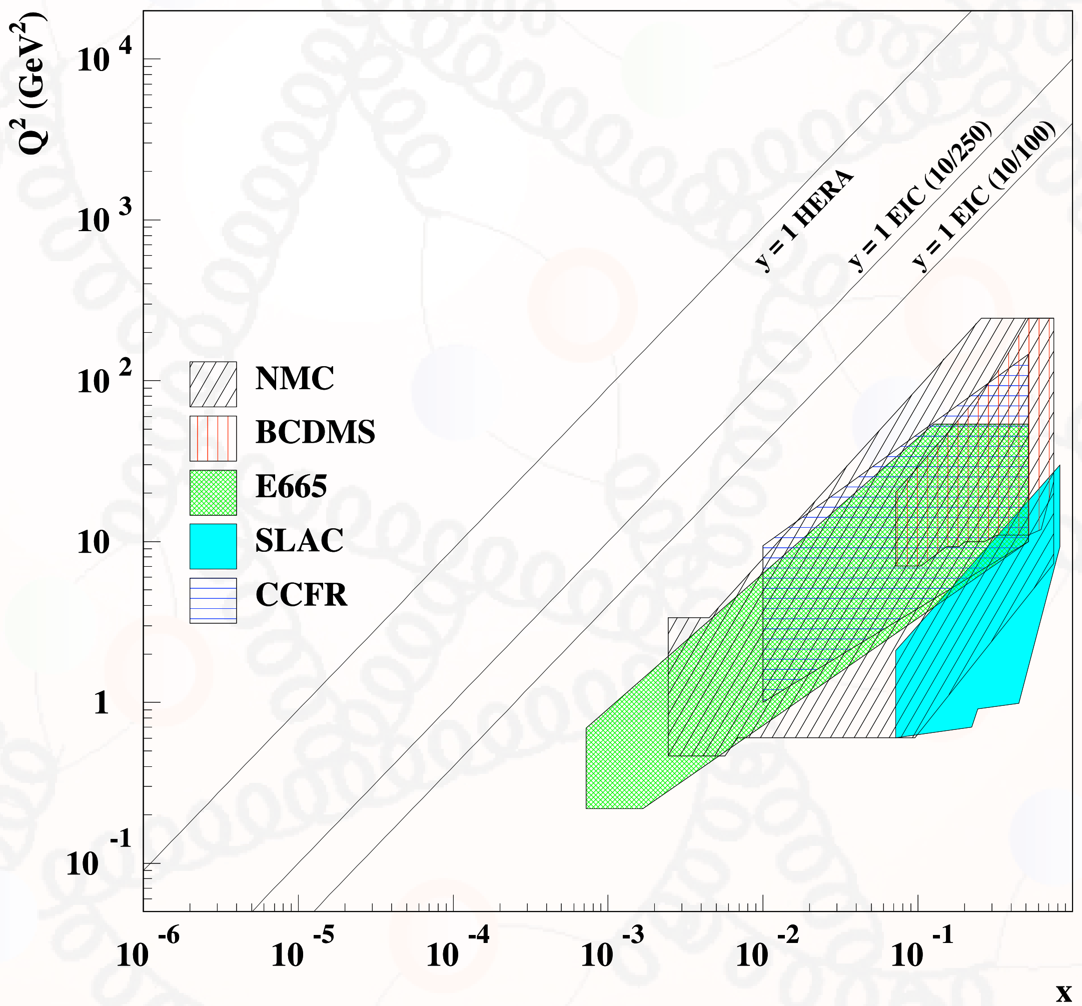
  (QCD Theory Workshop, DC, December 15-16, 2006)

  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!

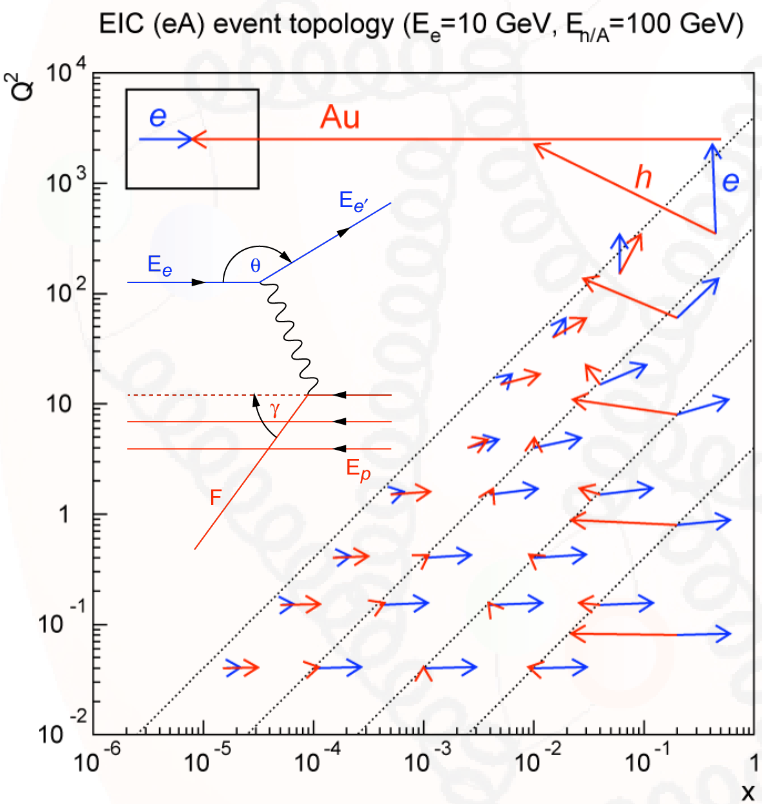
Low-x Physics - Future Opportunities

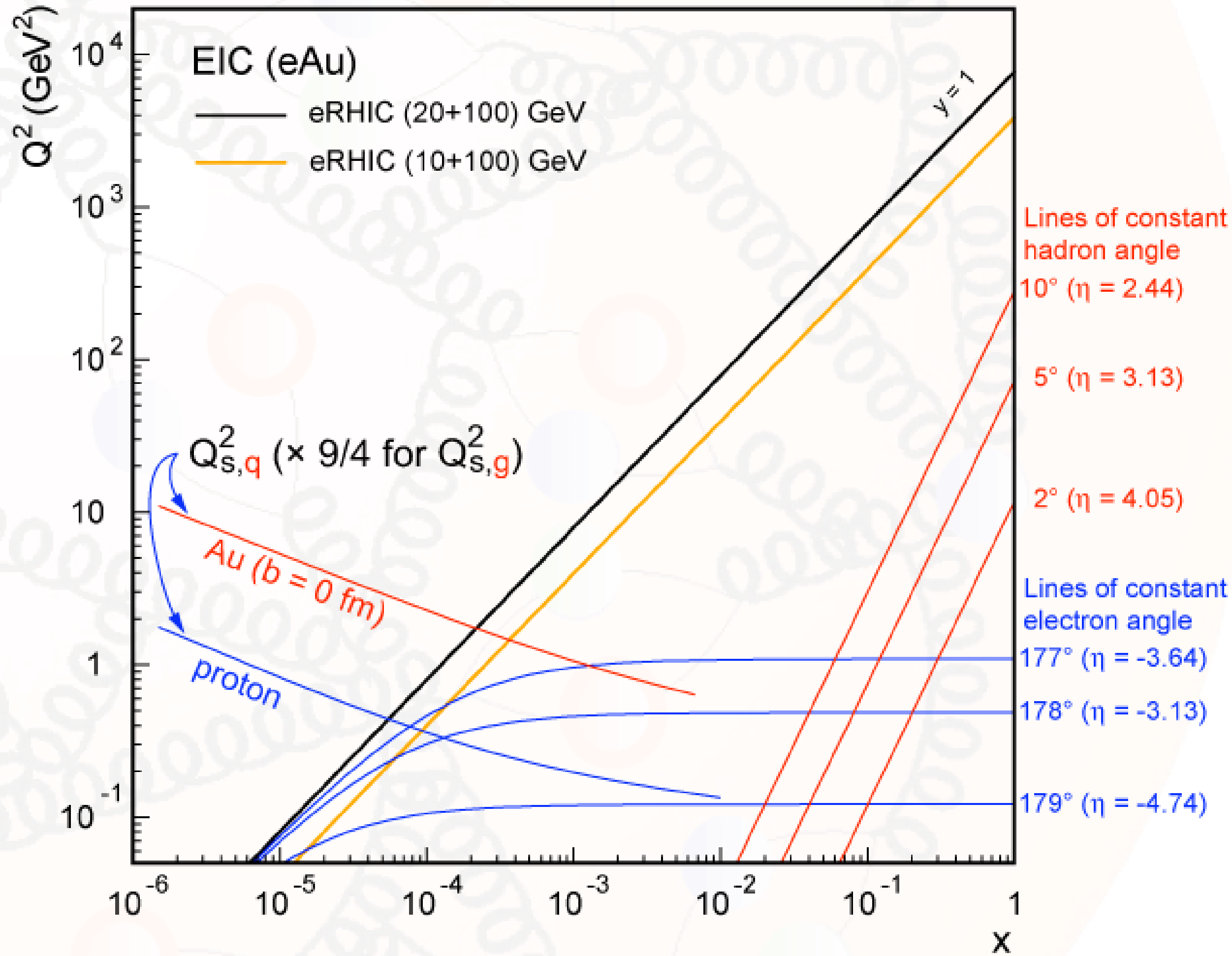
- Kinematics
  - Comparison HERA / EIC / Fixed-target experiments



Low-x Physics - Future Opportunities

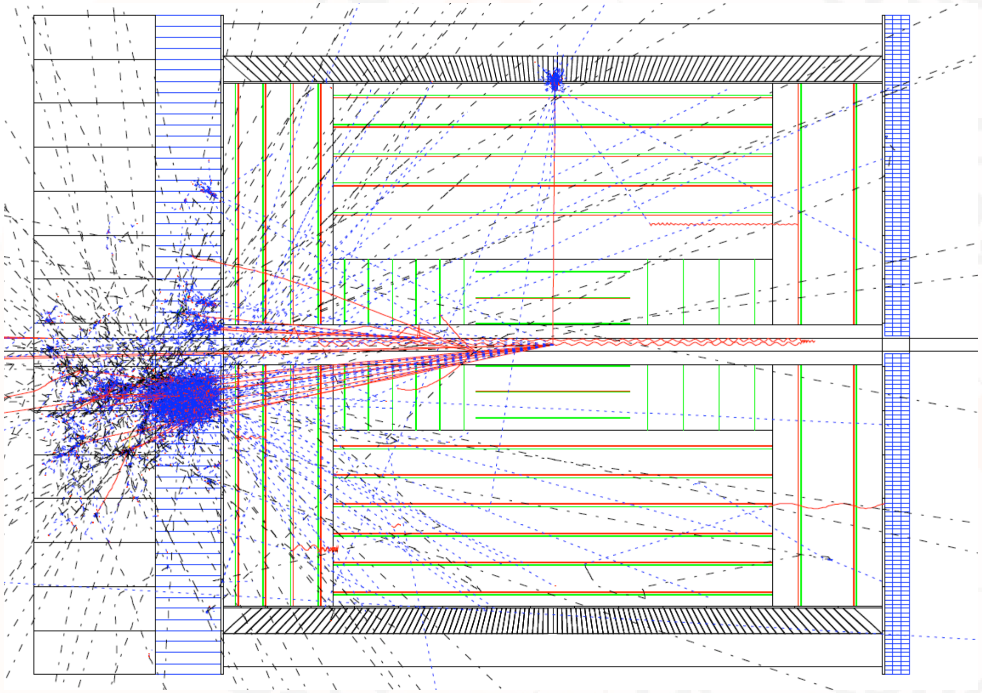
- Kinematics
  - Acceptance



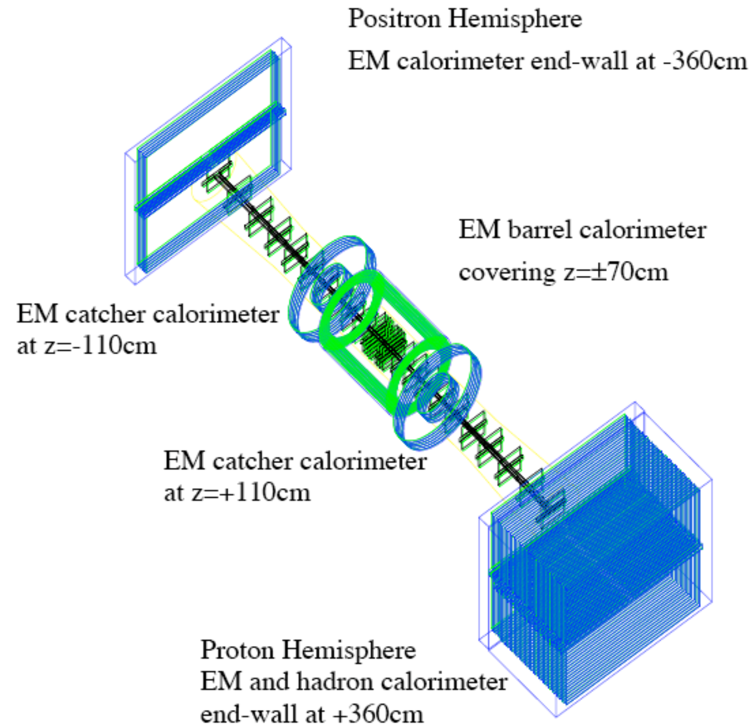


Low-x Physics - Future Opportunities

- Facilities - Detector concepts



J. Pasukonis, B. Surrow, physics/0608290



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

Concepts:

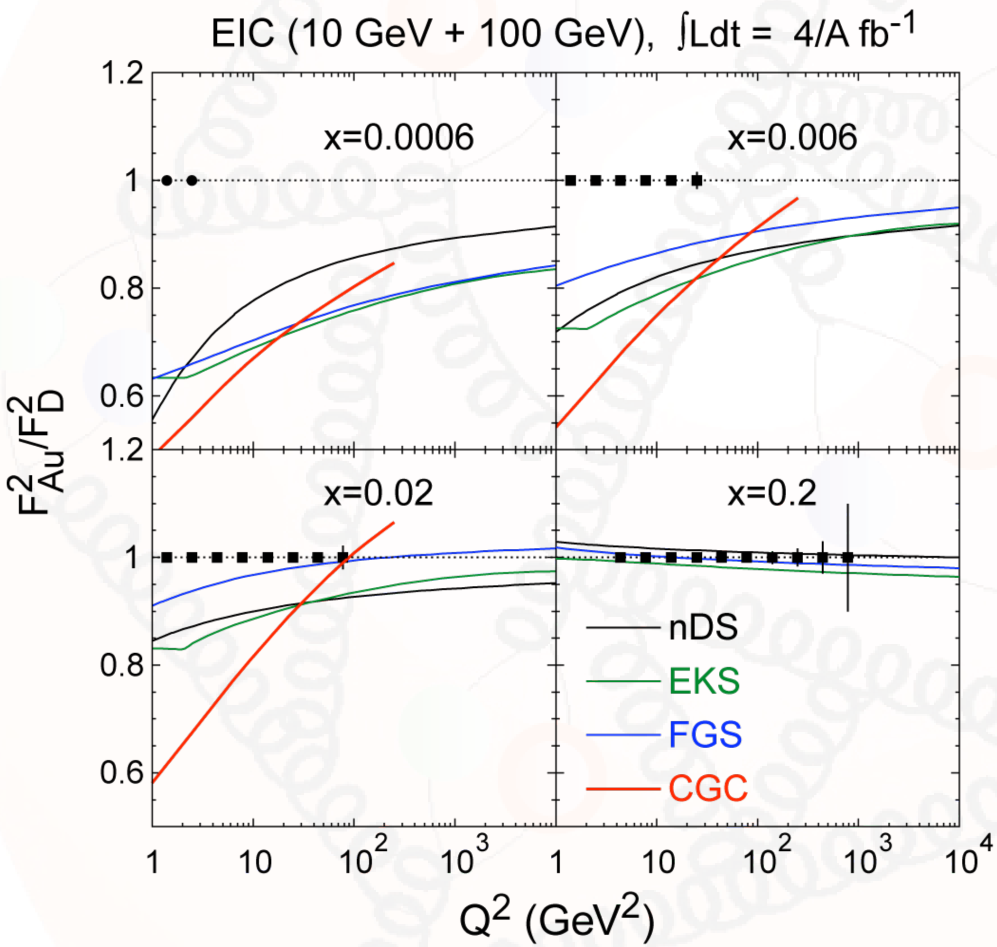
- Focus on the rear/forward acceptance and thus on low-x / high-x physics (Compact system of tracking and central electromagnetic calorimetry inside a magnetic dipole field and calorimetric end-walls outside
- Focus on a wide acceptance detector system (Compact calorimeter system)

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



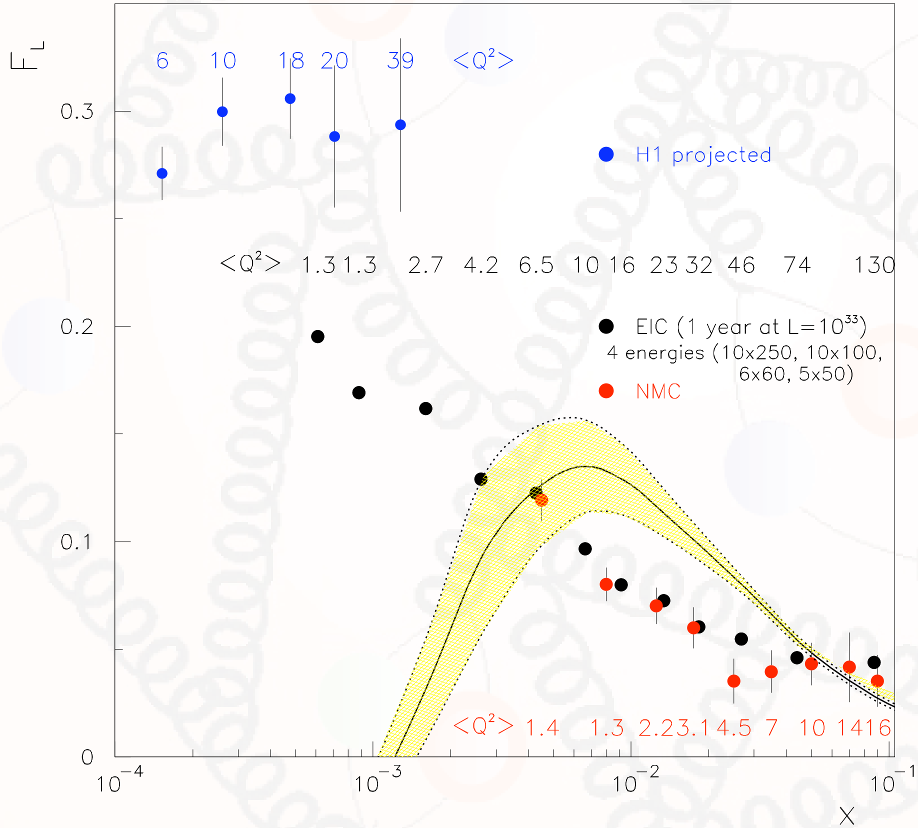
$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

- 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



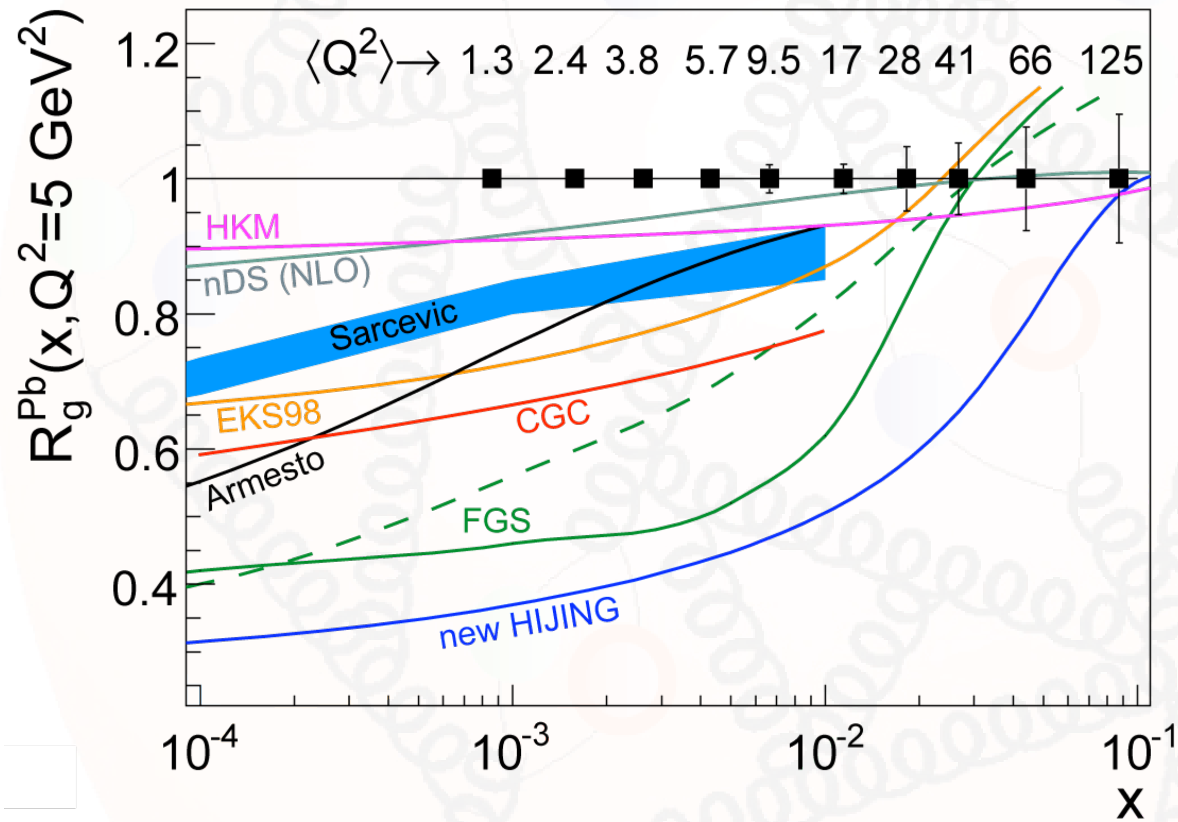
- F_L measurement requires operation of EIC at different center-of-mass energies ($\sqrt{s}$)
- Precise measurement from low to high Q^2 region

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

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



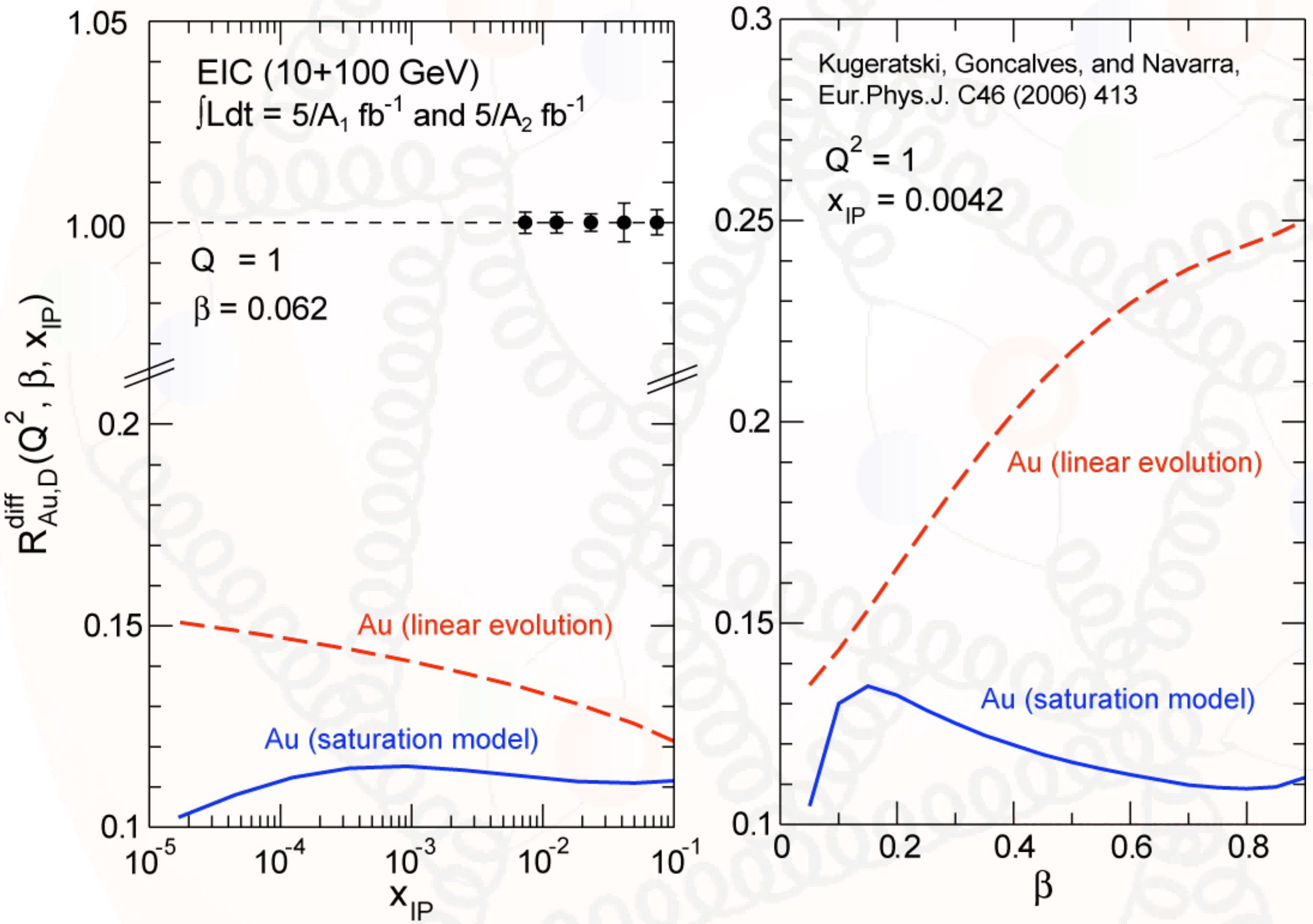
- EIC will reach the unmeasured low-x region (<0.01) with high precision for Q^2>1GeV^2
- Constrain gluon modification due to nuclear effects in comparison to large range of models

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

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)!

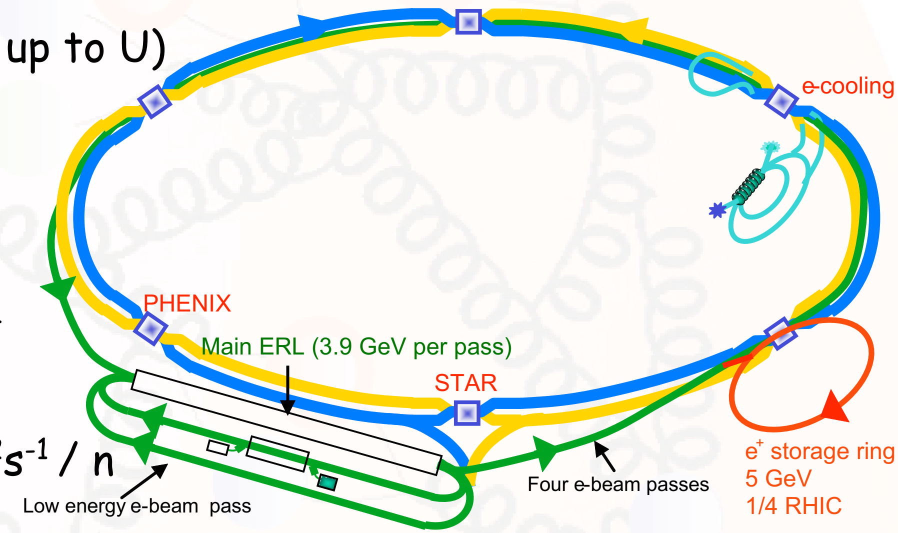
EIC important to answer outstanding questions in high-energy QCD physics

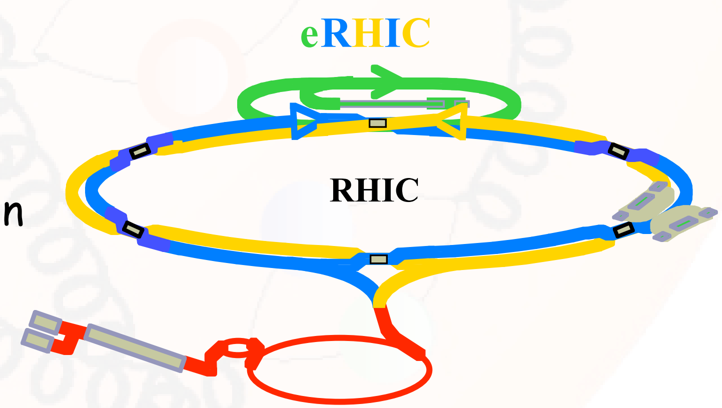
Summary and Outlook

- 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 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): $2.6 \cdot 10^{33}$ $cm^{-2}s^{-1}$
      - 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





Backup

- 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