Physics of the future Electron-Ion Collider

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Seminar at HEP Division, PNPI, Gatchina
November 25, 2008

Outline

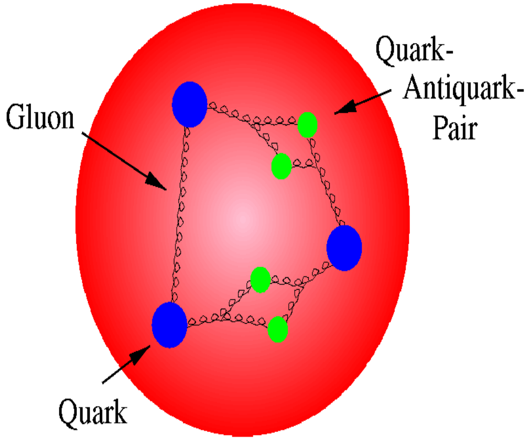
- Introduction
- Status of the partonic structure of hadrons, open questions and key measurements at the EIC
- Collider concepts
- Status of the EIC project
- Summary

The theory of strong interactions: QCD

The modern theory of the strong interactions is Quantum Chromodynamics, a quantum field theory of point-like quarks interacting by the exchange of gluons.

The color force which governs the strong interactions explains the structure of all matter in the Universe: from nucleons to nuclei to neutron stars.

It is a central goal of nuclear physics to understand the structure of the nucleon and nuclei in terms of quarks and gluons.



Partonic structure of hadrons

The partonic structure of matter is studied in high-energy collisions involving a large momentum transfer between the participants.

Decades of experiments at SLAC, CERN, Fermilab and DESY verified many predictions of QCD and explored the internal structure of hadrons. Some highlights include:

- the quark momentum and spin distributions in the nucleon
- the gluon momentum distribution in the nucleon
- nuclear medium modifications of the parton distributions
- discovery of jets
- discovery of the running coupling constant
- discovery of hard diffraction in DIS

Open questions

However, there are still many open questions:

- What is the gluon momentum distribution in nuclei?
- What are the properties of high-density gluon matter?
- How do fast quarks or gluons interact as they traverse nuclear matter?

- How do partons contribute to the spin structure of the nucleon?
- What is the spacial distribution of partons in the nucleon?
- How do hadrons final state form in QCD?

Electron-Ion Collider

The Electron-Ion Collider (EIC) is a proposed new facility to collide high-energy beams of electrons with nuclei and polarized protons/light ions, which will attempt to address the above open questions.

Two main goals of the future EIC:

- **eA program**: explore strong gluon fields in nuclei
- **ep program**: precisely image the sea quarks and gluons in the nucleon

Basic requirements for EIC

- **Lepton Beam**

  Provide clean and well-understood probe

- **Range of center-of-mass energies**

  -- for the parton description, minimal c.m. energy=10 GeV is required;
  to utilize QCD Q^2-evolution equations, c.m. energy=100 GeV is desirable;
  E_e=9-20 GeV, E_p=250 GeV,
  E_A=100 GeV/n

  -- variable energy to study F_L

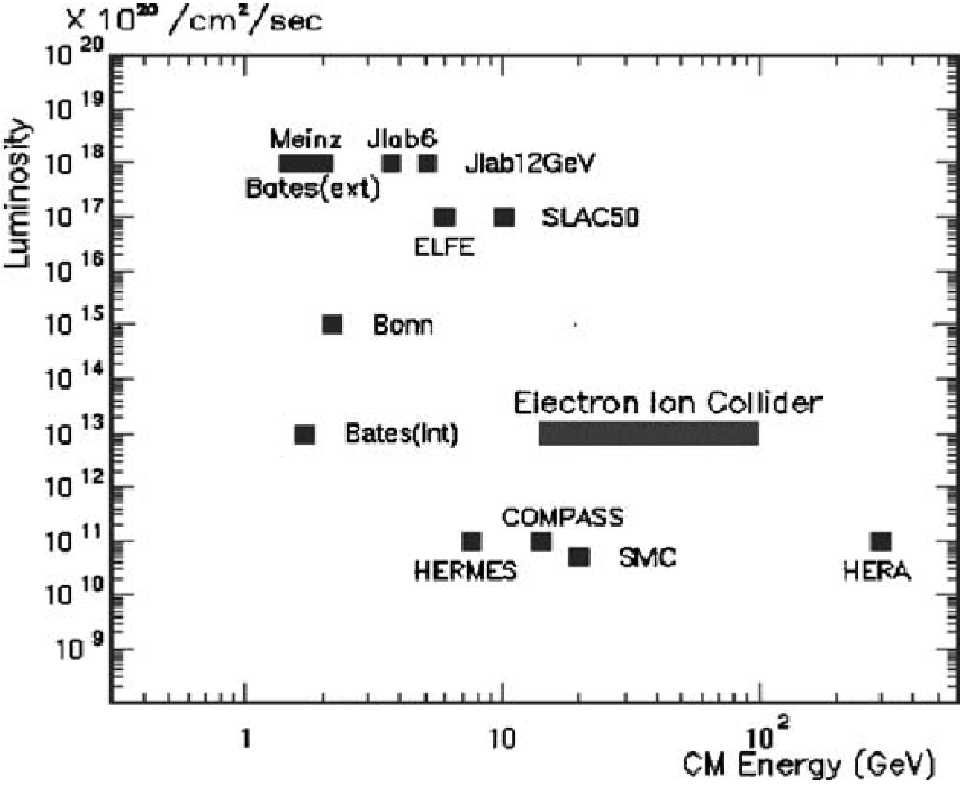


Figure 1 The center-of-mass energy vs. luminosity of the proposed Electron-Ion Collider eRHIC compared to other lepton scattering facilities.

- **High luminosity**

  The desired luminosity $L > 10^{33}$ cm^{-2} s^{-1}

Basic requirements for EIC (cont.)

- **Polarized beams**

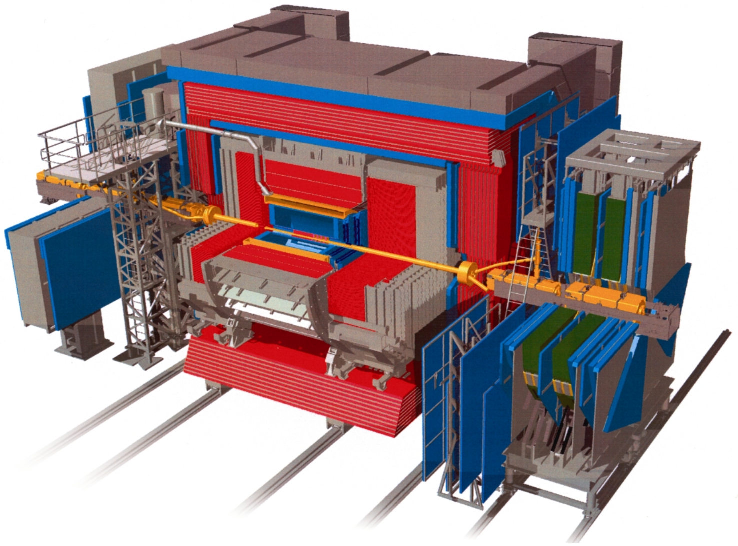
  Essential to study the spin structure; polarized D or ^{3}He required for Bjorken sum rule

- **Nuclear beams**

  Light nuclei are useful for probing the spin and flavor content of parton distributions. Heavy nuclei are essential for probing nuclear modifications and studying high-density gluon matter.

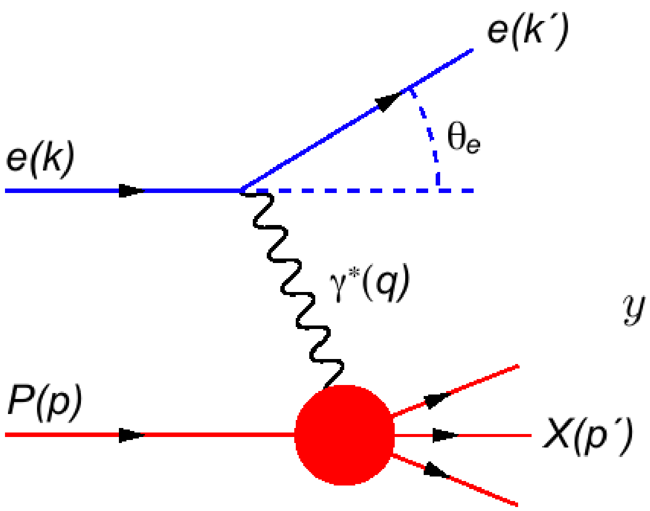
- **Detector considerations**

  similar to H1 and ZEUS detectors



Deep-Inelastic Scattering (DIS)

Most of our understanding of the parton structure of hadrons comes from Deep Inelastic Scattering (DIS) experiments.



$$Q^2 = -q^2 = -(k-k')^2$$

$$Q^2 = 4E_eE'_e\sin^2\left(\frac{\theta'_e}{2}\right)$$

Measure of resolution power or "Virtuality"

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

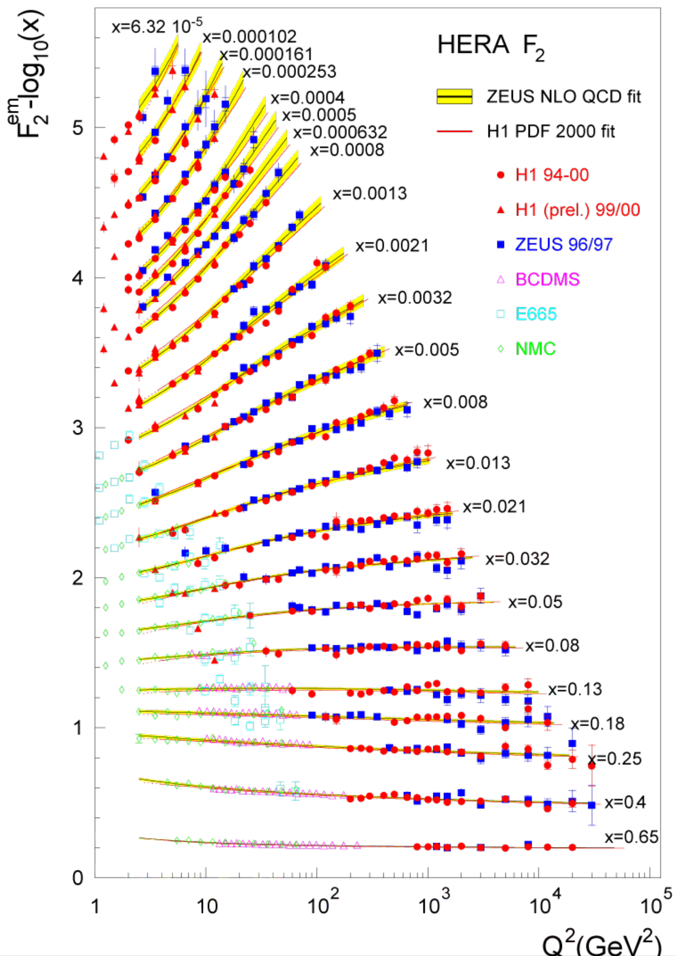
$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

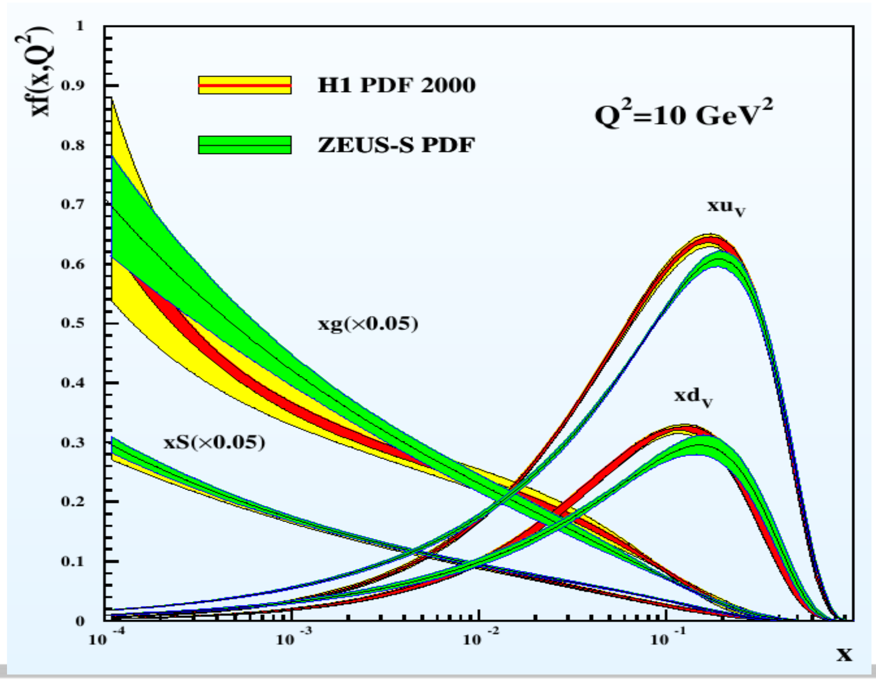
DIS and proton PDFs

A huge amount of data on DIS on the proton have been collected and analyzed in terms of parton distribution functions (PDFs) using QCD factorization and DGLAP evolution eqs:



$$F_2(x,Q^2) = \sum_{q=u,d,s,c,b,t} e_q^2 (xq(x,Q^2) + x\bar{q}(x,Q^2))$$

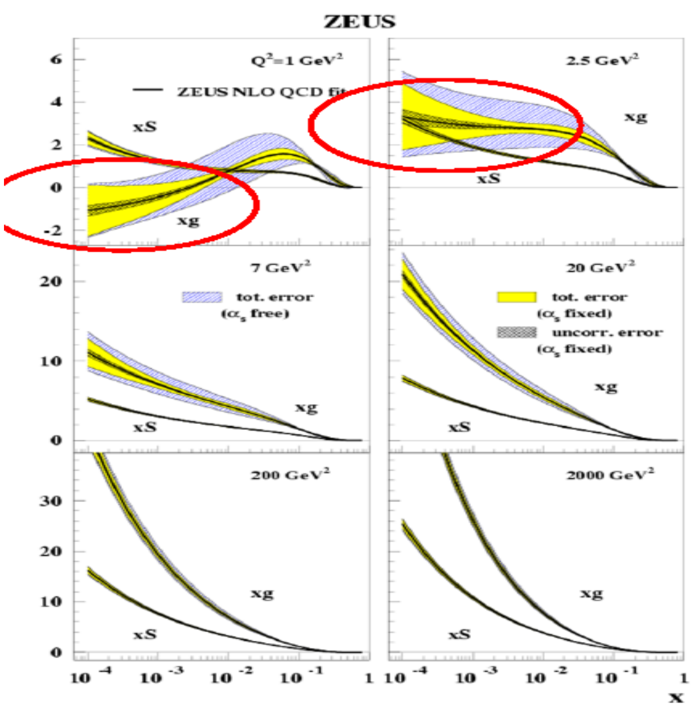
$$\frac{d}{d\ln Q^2}\begin{pmatrix} q \\ g \end{pmatrix}(x,Q^2) = \begin{pmatrix} P_{qq}(\alpha_s,x) & P_{qg}(\alpha_s,x) \\ P_{gq}(\alpha_s,x) & P_{gg}(\alpha_s,x) \end{pmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}(x,Q^2),$$

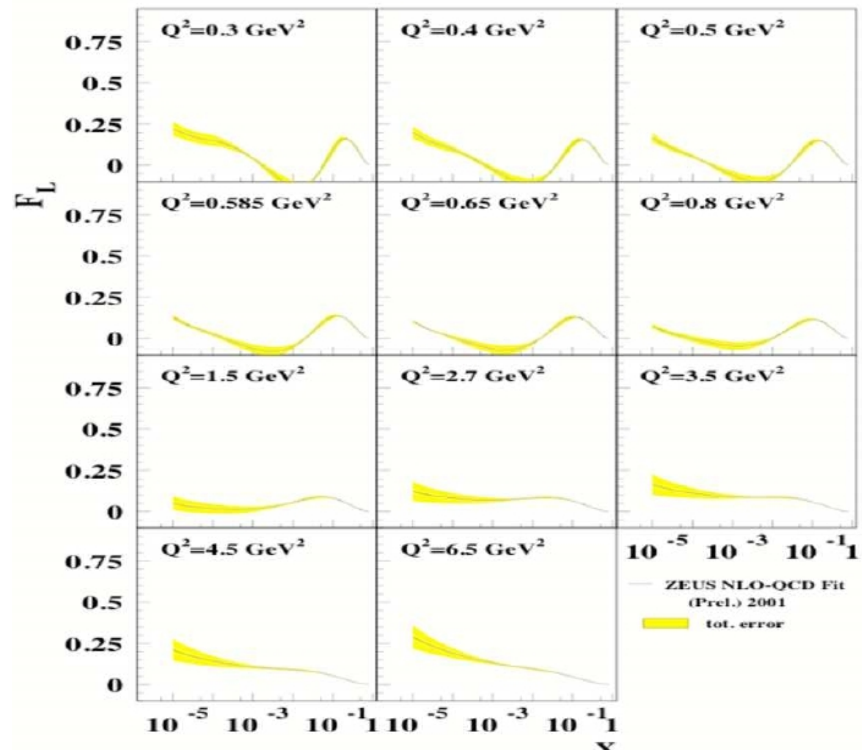


Problems with gluon distribution

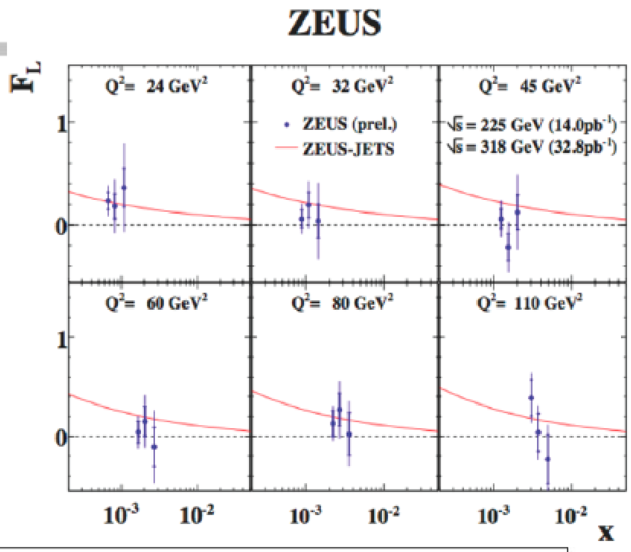
1) Small-x puzzle: the fast growth of $xg(x,Q^2)$ at small x and high Q^2 should eventually violate the Froissart (unitarity) bound -> effects beyond DGLAP (non-linear effects/saturation amplified in nuclei).

2) Low-Q^2 puzzle: some global fits give negative gluons at low x and Q^2, which leads to unphysical negative $F_L(x,Q^2) \sim \alpha xg(x,Q^2)$





F_L at the EIC

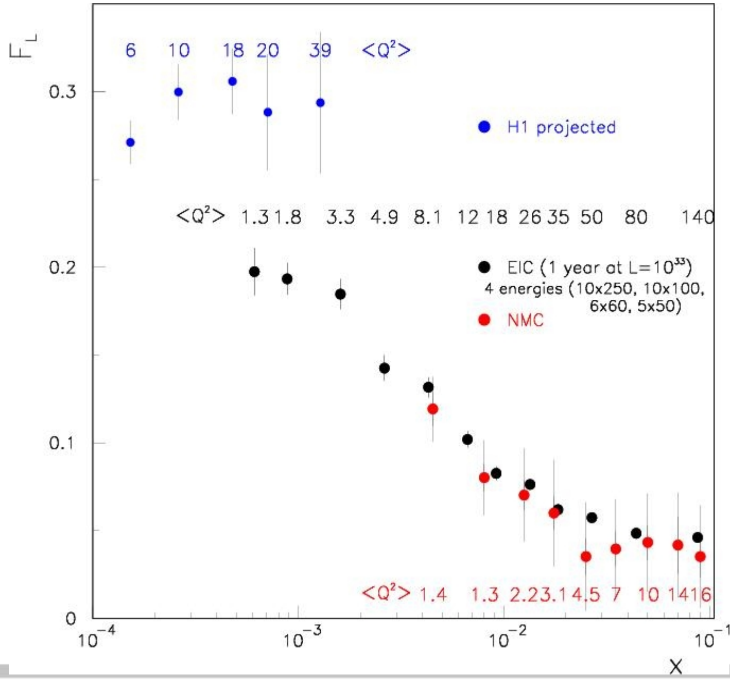


Measurements of the longitudinal F_L at HERA are challenging:

- require large y or low electron energy
- performed at large Q² and with large errors

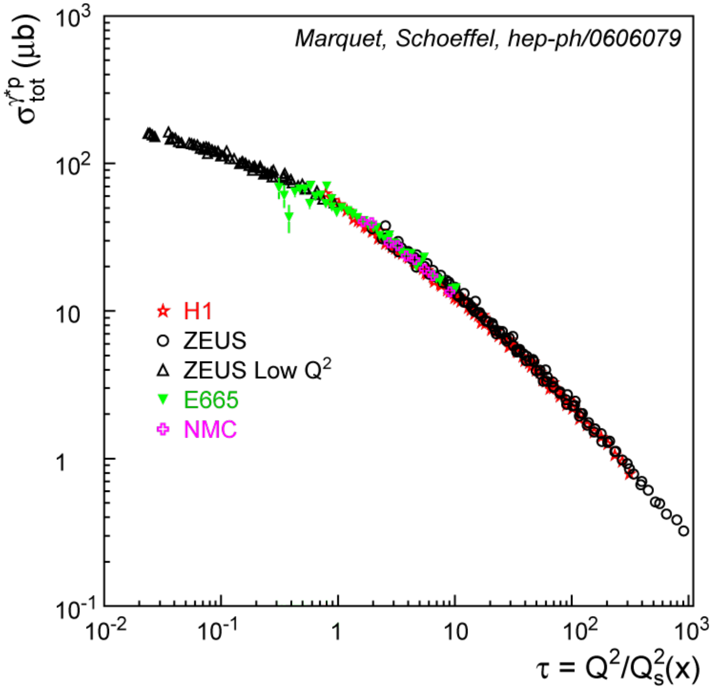
At EIC, the direct extraction of F_L will be possible due to the variable energies!

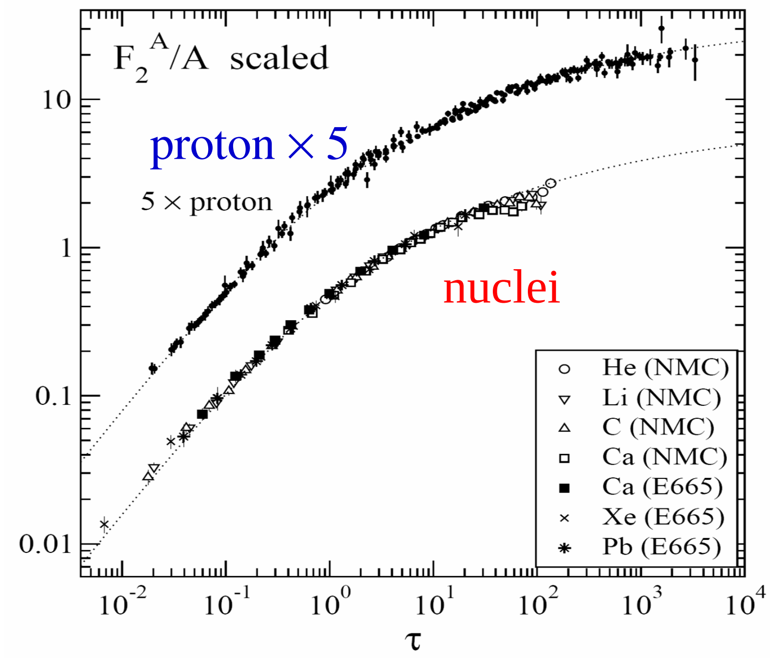
The gluon distribution will be measured directly via $F_L \sim \alpha x g(x,Q^2)$



Geometric scaling

At small x and Q^2, structure function $F_2(x,Q^2)$ depends on one variable $\tau=Q^2/Q^2_s$ instead of x and Q^2: geometric scaling



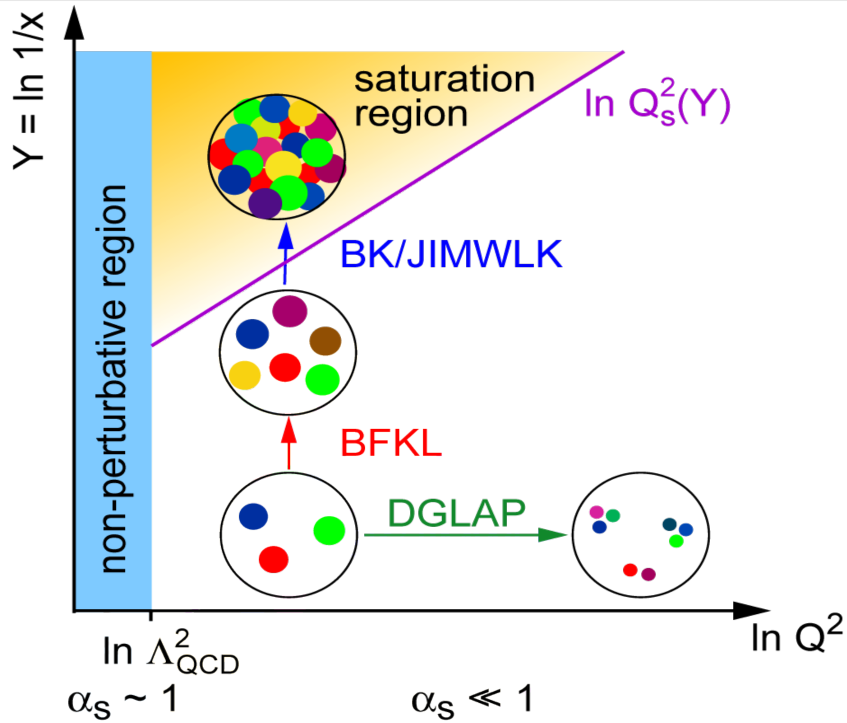


Does this mean an onset of a new regime of strong interactions characterized by some saturation scale Q_s?

Non-linear QCD: Saturation

- In DGLAP, one fixes x and increases Q^2 resolving more partons of decreasing transverse size

- Fixing Q^2 and decreasing x, one allows for emission of extra partons (gluons) of fixed size. At some density, these gluons start to recombine which compensates for emission -> saturation



- The saturation (high-gluon-density) regime of QCD is described by the Color Glass Condensate effective theory.

- Evolution in x is governed by non-linear JIMWLK/BK equations.
- Essential feature of saturation – the saturation scale $Q_s(x,A)$

Saturation scale

Criterion for gluon recombination

Gribov, Levin, Ryskin (1983)

Number of gluons per unit area :

$$\rho \sim \frac{xG_A(x, Q^2)}{\pi R_A^2}$$

Recombination cross-section :

$$\sigma_{gg\to g} \sim \frac{\alpha_s}{Q^2}$$

Recombination happens if $\rho\sigma_{gg\to g} \gtrsim 1$, i.e. $Q^2 \lesssim Q_s^2$, with :

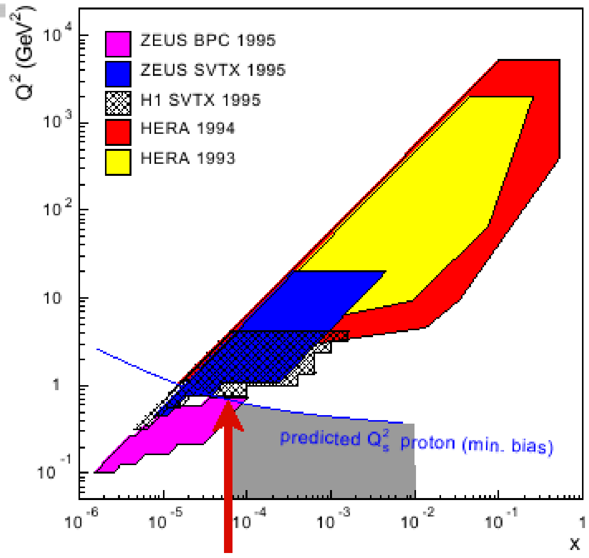
$$Q_s^2 \quad \sim \quad \frac{\alpha_s xG_A(x, Q_s^2)}{\pi R_A^2} \quad \sim \quad A^{1/3}\frac{1}{x^{0.3}}$$

Note: At a given energy, the saturation scale is larger for a nucleus (for $A = 200$, $A^{1/3} \approx 6$)

Saturation at EIC vs. HERA

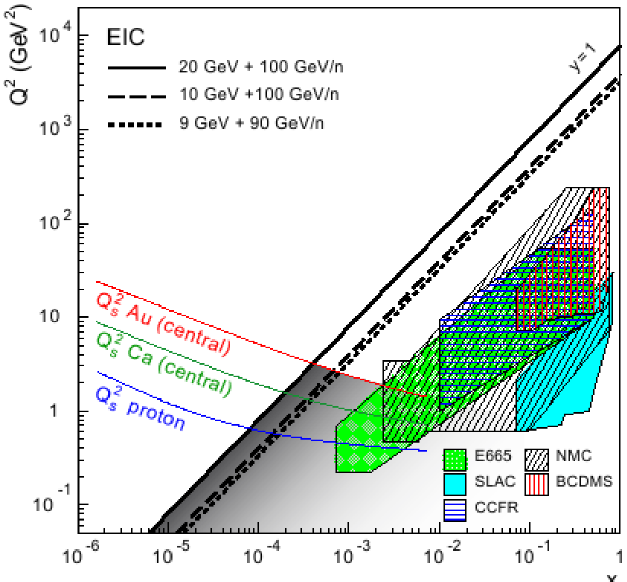
HERA:

- e+p: 30+920 GeV, √s=330 GeV
- despite much large energies than EIC, most of HERA kinematics is not sensitive to saturation



EIC:

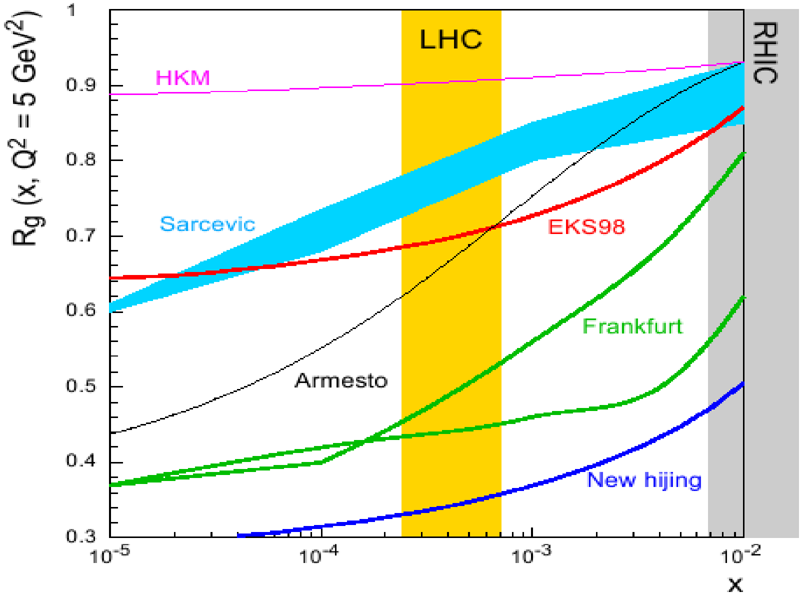
The idea to study high-density gluon matter at EIC is based on the enhancement of $Q^2_s \sim A^{1/3}$



Uncertainty in nuclear PDFs

Besides exploring the saturation and testing the predictions of the Color Glass Condensate model, it is important to determine the poorly known at small x nuclear Parton Distribution functions (PDFs).

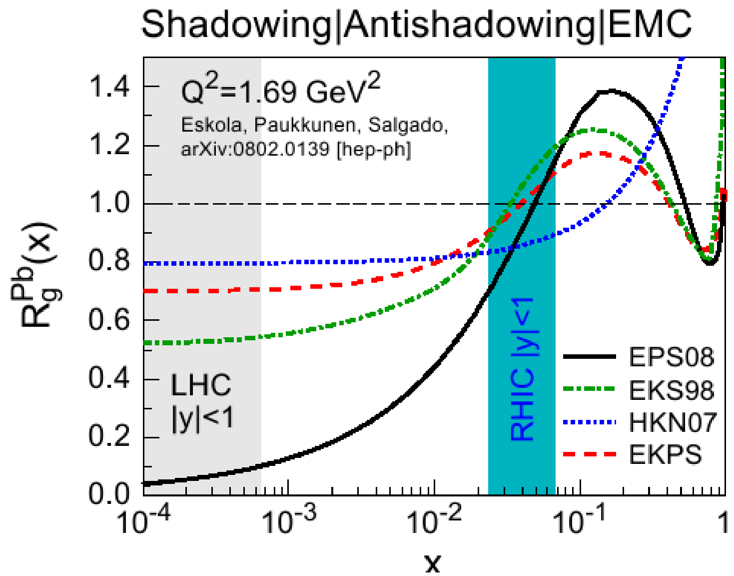
- Nuclear PDFs are measured in DIS on fixed nuclear targets
- In fixed-target kinematics, small x are either unaccessible or correspond to low Q^2 (HT effects?)
- Large uncertainties in extrapolations to low x
- Gluons are through the QCD evolution



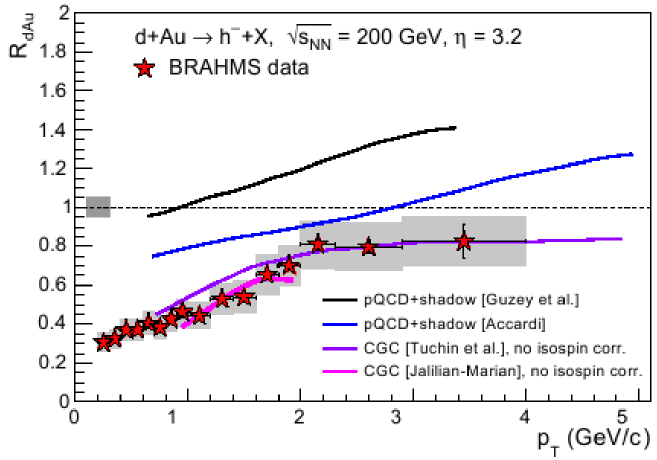
Nuclear PDFs are interesting in its own right (test of models and nuclear shadowing) and essential for pQCD analysis of RHIC and LHC

Connection to RHIC and LHC

1) Saturation effects at forward rapidities at RHIC and midrapidities at the LHC



Saturation (initial state) effects
(RHIC fwrd, LHC mid-rapidity)

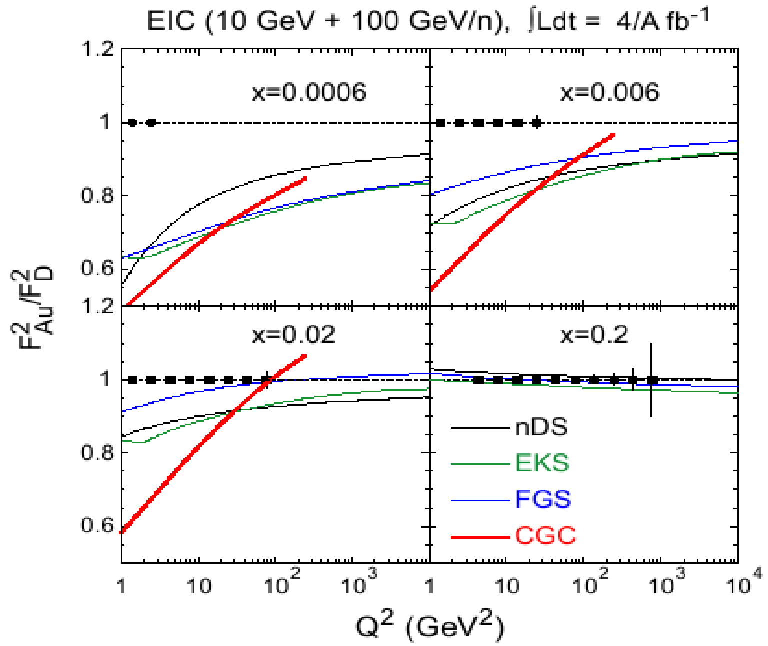


2) Energy loss and hadronization in hot nuclear matter: precise nuclear PDFs are needed to separate the initial state effects from final state effects (parton energy loss) and test different models of fragmentation.

Key measurements of e+A program

1) Inclusive structure functions F_2 and F_L

- F_2 will measure quarks directly and gluons via scaling violations
- F_L will access directly gluons



2) Charmed structure functions F_2 and F_L

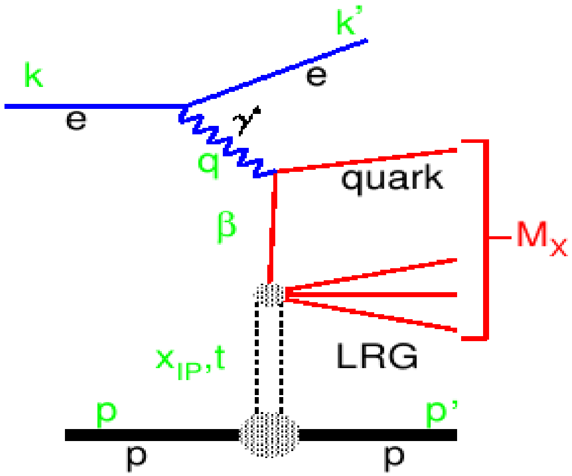
- by detecting charmed D-mesons
- will access charm quark and gluon PDFs

3) Light and heavy quark jets in DIS

- will probe quark and gluon PDFs
- cleanest environment to study nuclear modifications of hadron production
- simultaneous studies of light and heavy quark jets will test models of hadronization (energy loss vs. absorption) in cold nuclear matter (relevant for RHIC and LHC)

Key measurements of e+A program

4) Hard inclusive diffraction



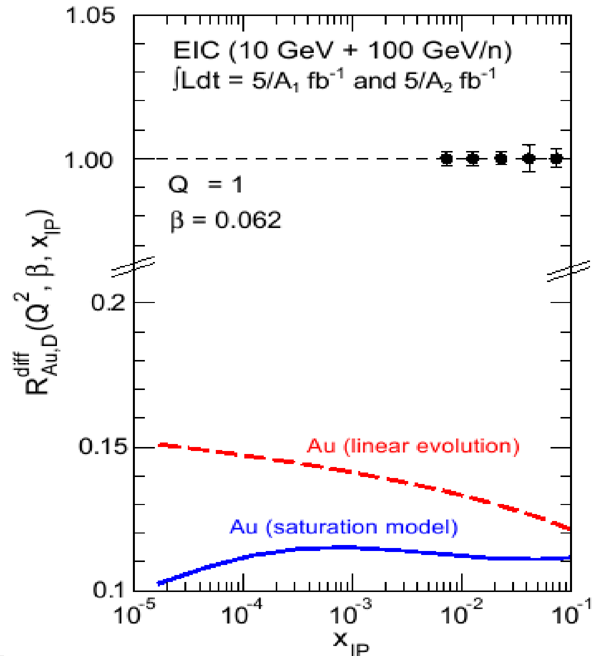
$$\frac{d^4\sigma}{dx\,dQ^2\,d\beta\,dt} = \frac{4\pi\alpha^2}{\beta^2 Q^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^{D,A}(x,Q^2,\beta,t) - \frac{y^2}{2}F_L^{D,A}(x,Q^2,\beta,t)\right]$$

$$t = (p-p')^2\,,$$

$$x_{I\!P} = \frac{q\cdot(p-p')}{q\cdot p} \simeq \frac{M_X^2+Q^2}{W^2+Q^2}\,,$$

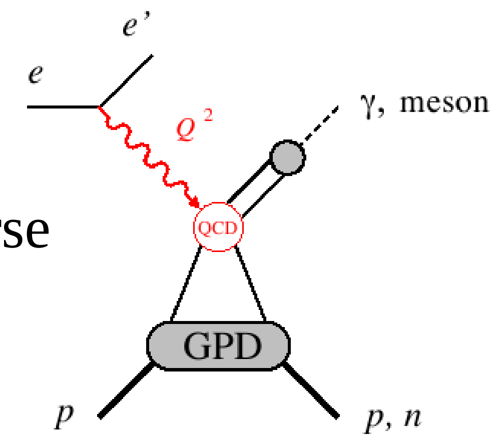
$$\beta = \frac{Q^2}{2q\cdot(P-P')} = \frac{x}{x_{I\!P}} \simeq \frac{Q^2}{Q^2+M_X^2}$$

- Hard diffraction in DIS on nuclei has never been measured
- More sensitive to saturation effects than inclusive measurements since $F_2^D \sim [xg_A(x,Q^2)]^2$
- Nature of the Pomeron



Key measurements of e+A program

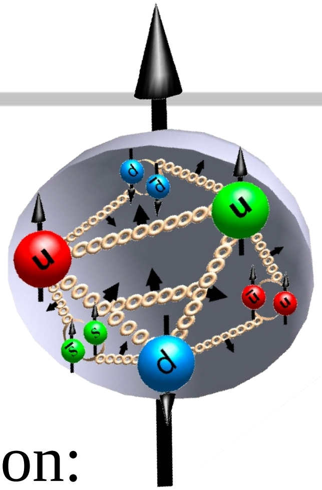
5) Exclusive electroproduction of mesons and real photon
(Deeply Virtual Compton Scattering-DVCS)



- measures Generalized Parton Distributions (GPDs) of the target, which give both longitudinal and transverse distribution of partons
- sensitive to saturation since $\sigma \sim [xg(x,Q^2)]^2$
- requires large luminosity since $\sigma_{DVCS} \sim \alpha^3/Q^6$
- sensitive to saturation: $\sigma_{DVCS} \sim 1/Q^6 \rightarrow 1/Q^2$

A very similar set of key measurements is discussed for the unpolarized e+p program.

Spin structure of the nucleon



Proton helicity sum rule:

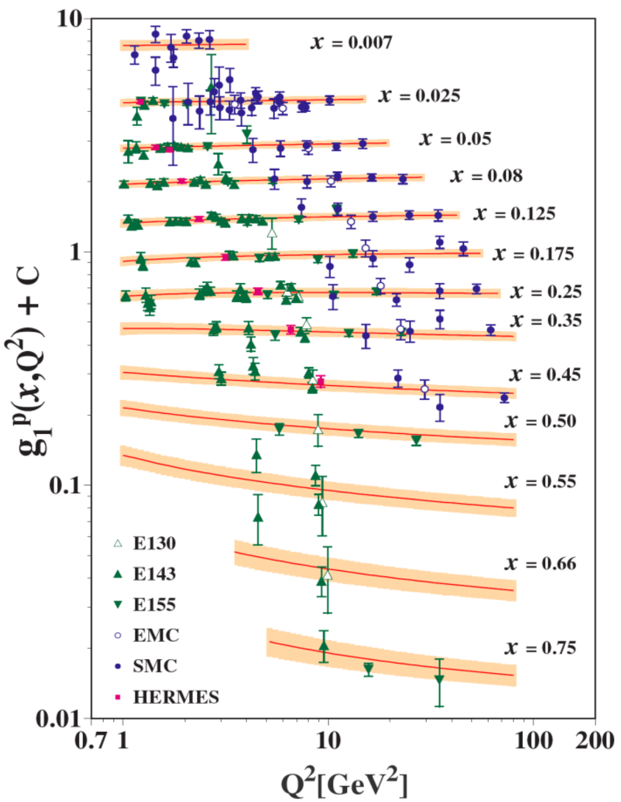
$$1/2 = 1/2\,\Delta\Sigma + \Delta g + L_q + L_g$$

From inclusive and semi-inclusive polarized DIS on the proton:

- quark contribution $\Delta\Sigma=0.3$ -- proton spin crisis
- $\Delta u>0$, $\Delta d>0$, $\Delta s\approx 0$
- gluon contribution from scaling violations is very uncertain: $\Delta g=1 \pm 1$
- The goal of the RHIC spin program is to extract Δg;
  the current RHIC data favors small $|\Delta g|$
- $L_u+L_d\approx 0$ from lattice QCD calculations of moments of GPDs

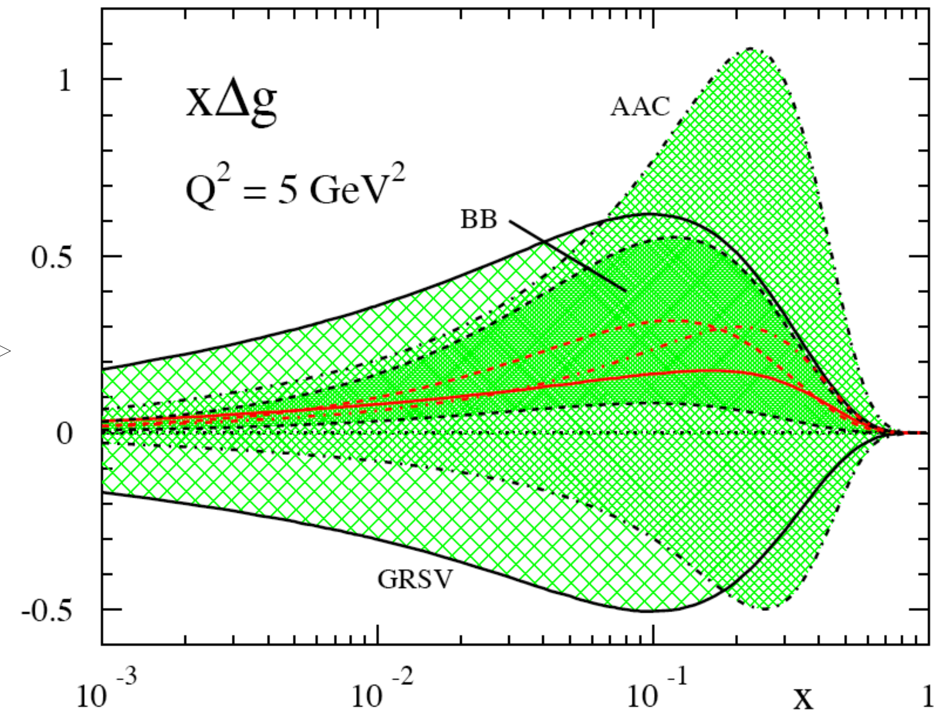
Nucleon Δg from g_1

$g_1(x,Q^2) = \Sigma_q \, e_q^{\,2} \, \Delta f^q(x,Q^2)$



Use scaling violations to extract Δg:

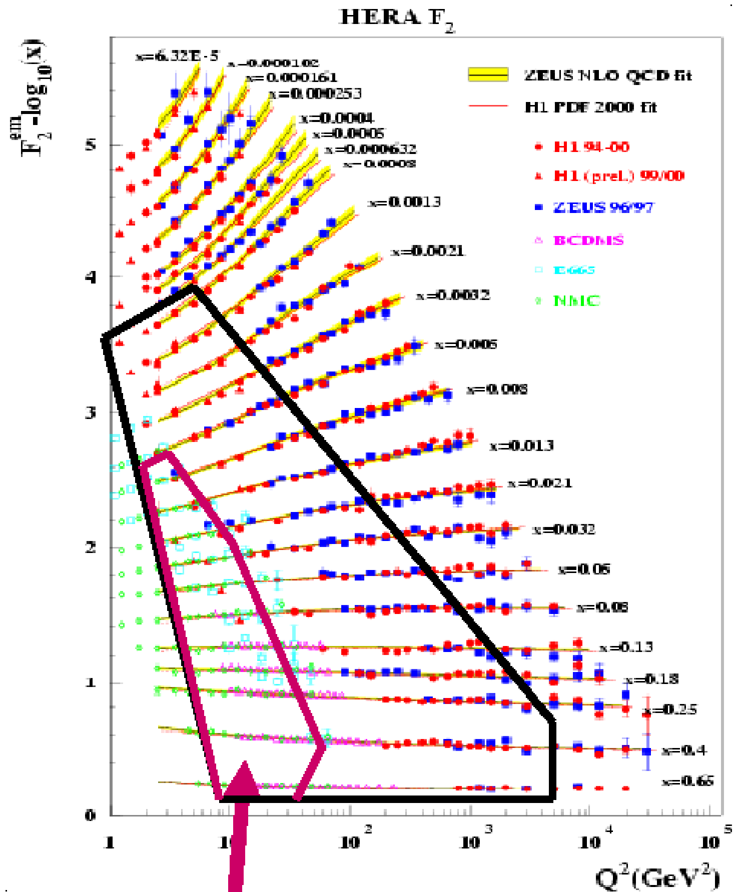
$$\frac{d\,g_1}{d\log(Q^2)} \;\propto\; -\,\Delta g(x,Q^2)$$



Not enough range in x and Q^2

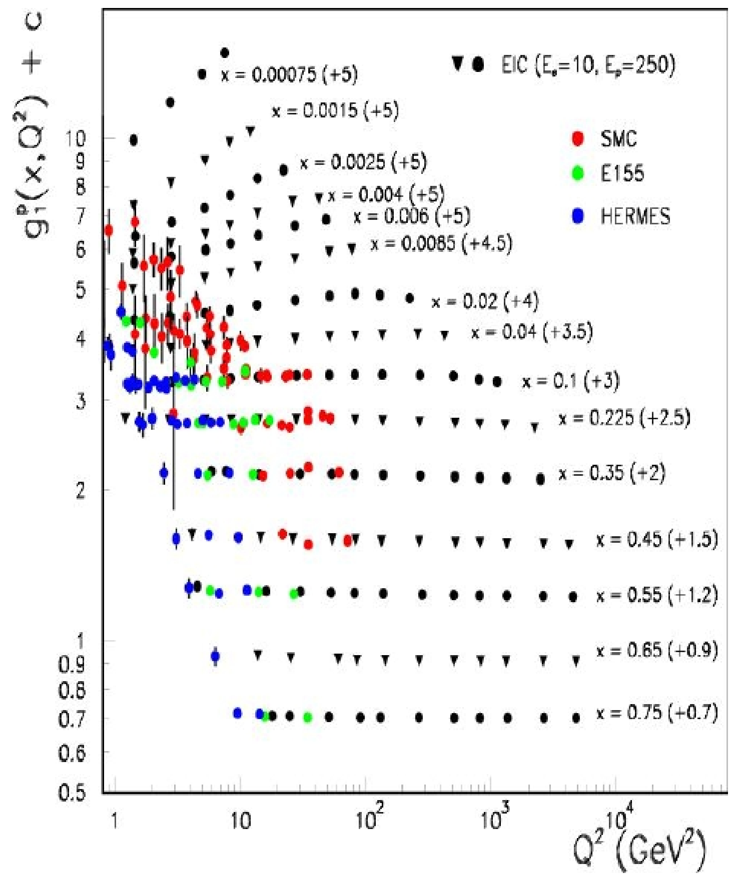
Polarized DIS and EIC

World Data on F_2^p



Region of existing g_1^p data

World Data on g_1^p

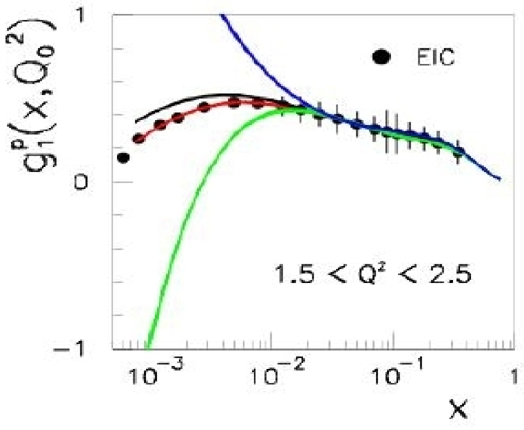


An E … kes it possible!

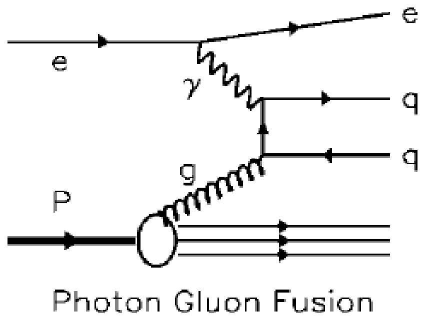
Nucleon Δg at EIC

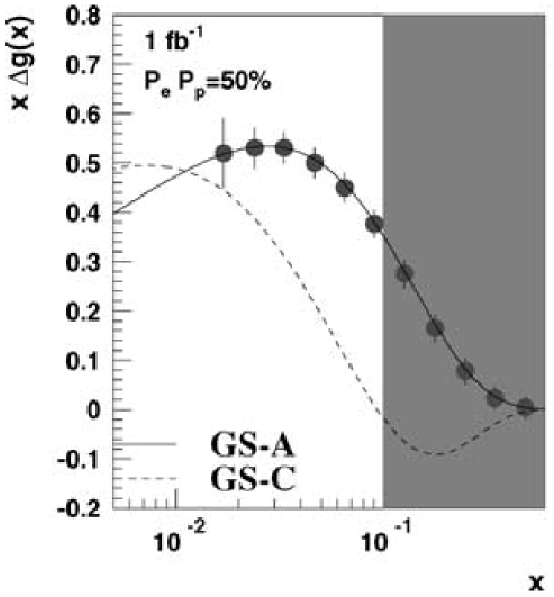
1) From $g_1(x,Q^2)$

$$\frac{d\,g_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$



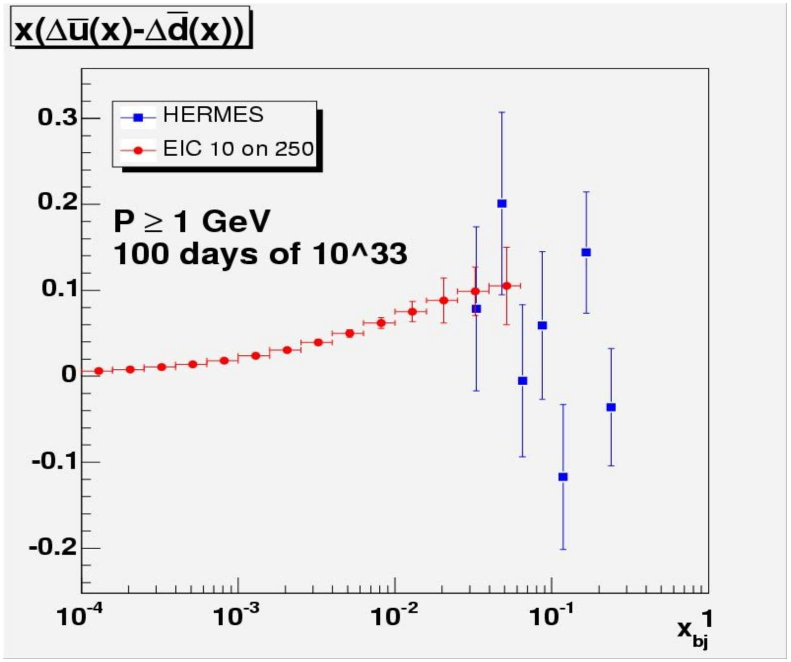
2) Via open charm and dijet production

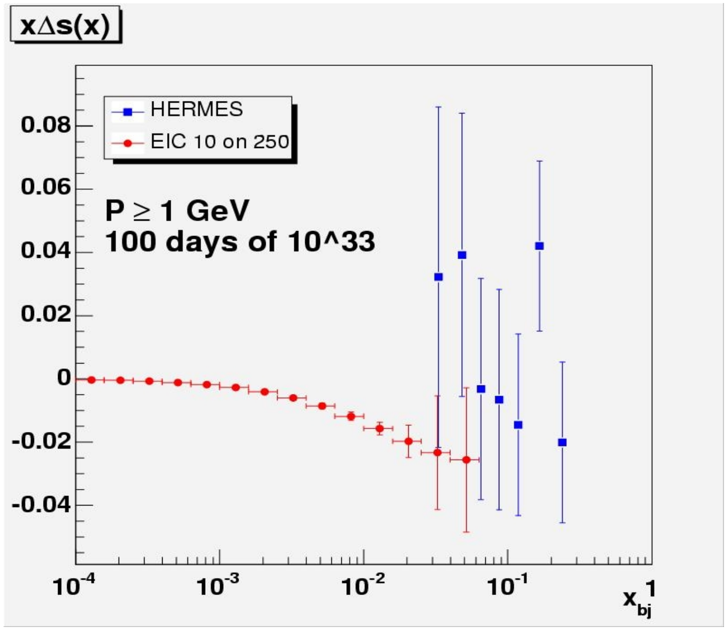




Additional measurements with polarized ep program

1) Semi-inclusive ep -> ehX DIS and polarized quark flavor decomposition





2) Studies of transversity with the transversely polarized target.

Electron-Ion Collider Concepts

eRHIC (BNL): Add energy recovery linac to RHIC

- higher energy, lower luminosity

E_e=10 (20) GeV

E_A=100 GeV (up to U)

$\sqrt{s_{eN}}$=63 (90) GeV

L_{eAu}(peak)/n=2.9•10^{33} cm^{-2} s^{-1}

ELIC (JLab): Add hadron beam facility to existing CEBAF

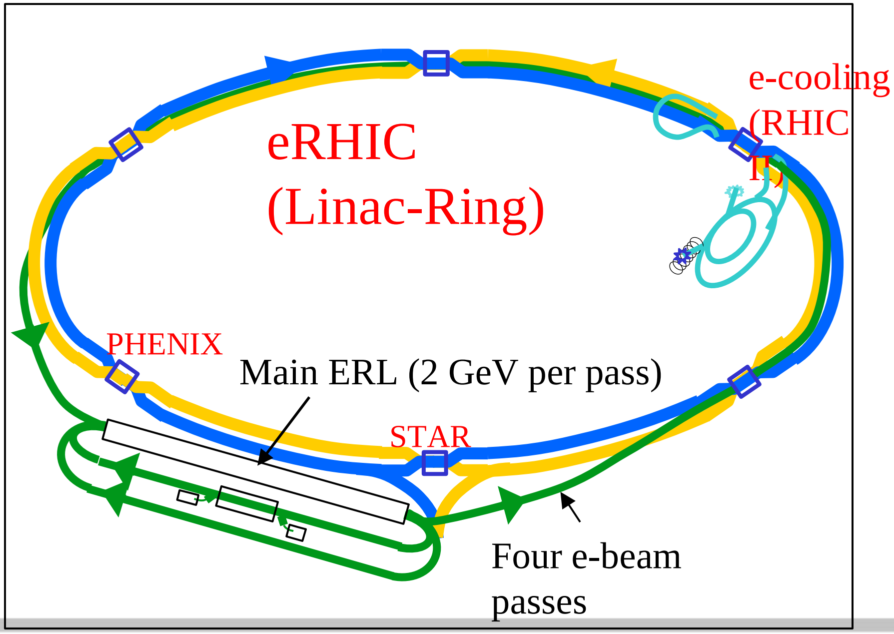
- lower energy, higher luminosity

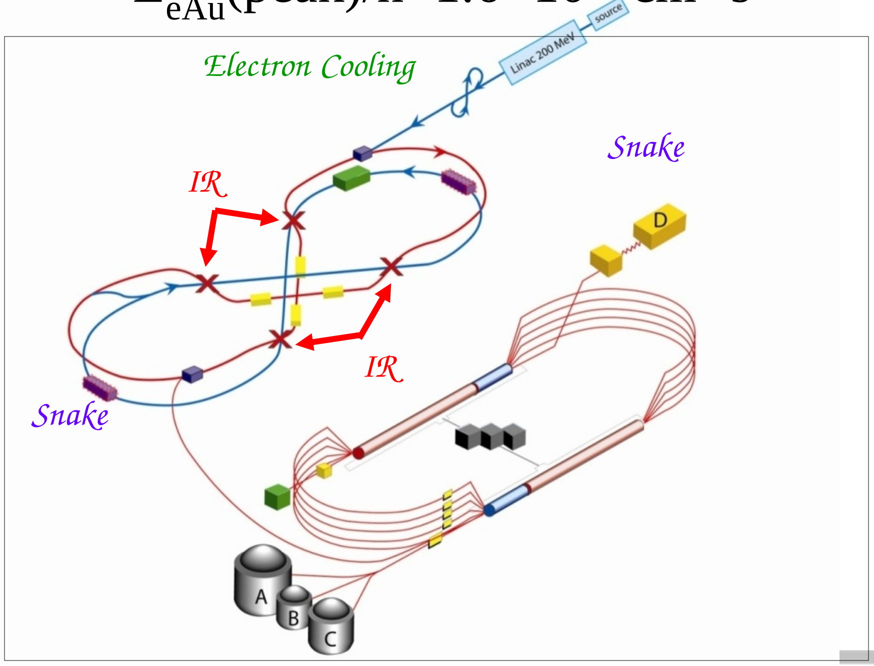
E_e=9 GeV

E_A=90 GeV (up to Au)

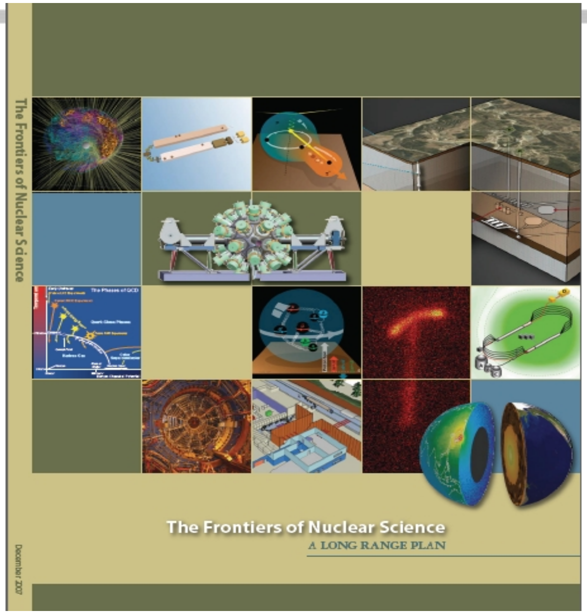
$\sqrt{s_{eN}}$=57 GeV

L_{eAu}(peak)/n=1.6•10^{35} cm^{-2} s^{-1}





EIC Timeline and Status



- NSAC Long Range Plan 2007
  - Recommendation: $6M/year for 5 years for machine and detector R&D

- Goals for Next Long Range Plan 2012
  - high-level recommendation for construction

- EIC Roadmap
  - finalize detector requirements from physics 2008
  - conceptual detector designs 2010
  - EIC design decision 2011

The EIC Collaboration

- ~100 Scientists, 30 Institutions, 9 countries

- 4 Working Groups:
  - accelerator - detector
  - ep - eA

- Publications:
  - The Electron Ion Collider (EIC) White Paper
  - The GPD/DVCS White Paper
  - Position paper: e+A Physics at an Electron-Ion Collider
  - The eRHIC Machine: Accelerator Position Paper
  - ELIC Zeroth Order Design Report

- More info: http://www.bnl.gov/eic

Summary

• The proposed Electron-Ion Collider (EIC) is a new high-energy and high-luminosity electron-ion and electron-polarized proton (light ion) collider.

• The EIC physics program has two main goals:

- to explore strong gluon fields in nuclei
- to precisely image the sea quarks and gluons in the nucleon (including spin)