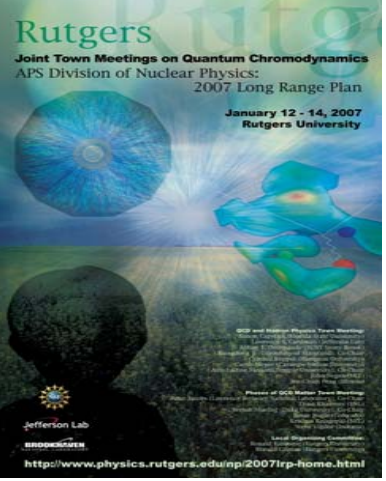
# Studying the Glue which Binds Us All

## A High Luminosity Electron-Ion Collider (EIC) to Study the Fundamental Structure of Matter

- Update
- Highlights of nucleon structure
- Summary




# Unanimous recommendation of the QCD Town Meeting Rutgers University, New Jersey January 13th 2007

*A high luminosity Electron-Ion Collider (EIC) is the highest priority of the QCD community for new construction after the JLab 12 GeV and RHIC II luminosity 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;* **R. Milner**

*- Definitive study of the universal nature of strong gluon fields in nuclei.* **T. Ullrich**

*This goal requires that R&D resources be allocated for expeditious development of collider and detector 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
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Newport News, Virginia, USA

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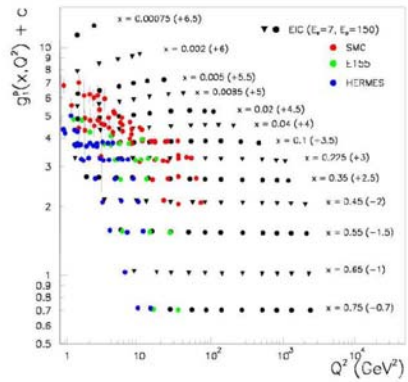
A. Belov
INR,Moscow-Troitsk, Russia
**Editors: Ya. Derbenev, L. Merminga, Y. Zhang**

DRAFT V2.0 08-MAR-07

# Exploring the 3D quark and gluon structure of the proton: Electron scattering with present and future facilities*


H. Abramowicz,[1] A. Afanasev,[2] H. Avakian,[3] M. Burkardt,[4] V. Burkert,[3] A. Camsonne,[3] A. Deshpande,[5,6] F. Ellinghaus,[7] L. Elouadrhiri,[3] R. Ent,[3] M. Garçon,[8] G. Gavalian,[9] M. Guidal,[10] V. Guzey,[11] C. E. Hyde,[9,12] X.–D. Ji,[13] A. Levy,[1] S. Liuti,[14] W. Melnitchouk,[3] R. G. Milner,[15] Ch. Montag,[16] D. Müller,[17] C. Muñoz Camacho,[18] R. Niyazov,[3] B. Pasquini,[19] S. Procureur,[8] A. Radyushkin,[3,9] J. Roche,[20] F. Sabatié,[8] A. Sandacz,[21] A. Schäfer,[17] M. Strikman,[22] M. Vanderhaeghen,[3,23] E. Voutier,[24] and C. Weiss[3]

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Understanding the structure of the nucleon in terms of the quark and gluon degrees of freedom of QCD is one of the key objectives of nuclear physics. During the last 10 years a comprehensive framework for describing the quark and gluon structure of the nucleon has been developed, based on the concept of Generalized Parton Distributions (GPDs). GPDs unify the momentum–space parton densities measured in inclusive deep–inelastic electron scattering with the spatial densities (form factors) measured in elastic scattering. They describe correlations between the momentum and spatial distributions of quarks, which are revealed in exclusive processes in electron scattering at large momentum transfer (deeply virtual Compton scattering, meson production). GPDs are the basis for novel representations of the nucleon as an extended object in space (2–dimensional tomographic images, 3–dimensional Wigner phase space distributions), and provide access to fundamental static properties such as the quark orbital angular momentum. In this White Paper we summarize the scientific motivation for nucleon structure studies based on GPDs, and outline what measurements with present and future facilities can contribute to our knowledge of these functions. We specifically focus on the GPD program planned with the 12 GeV Upgrade of Jefferson Lab, and on GPD studies with a future electron–ion collider (EIC).


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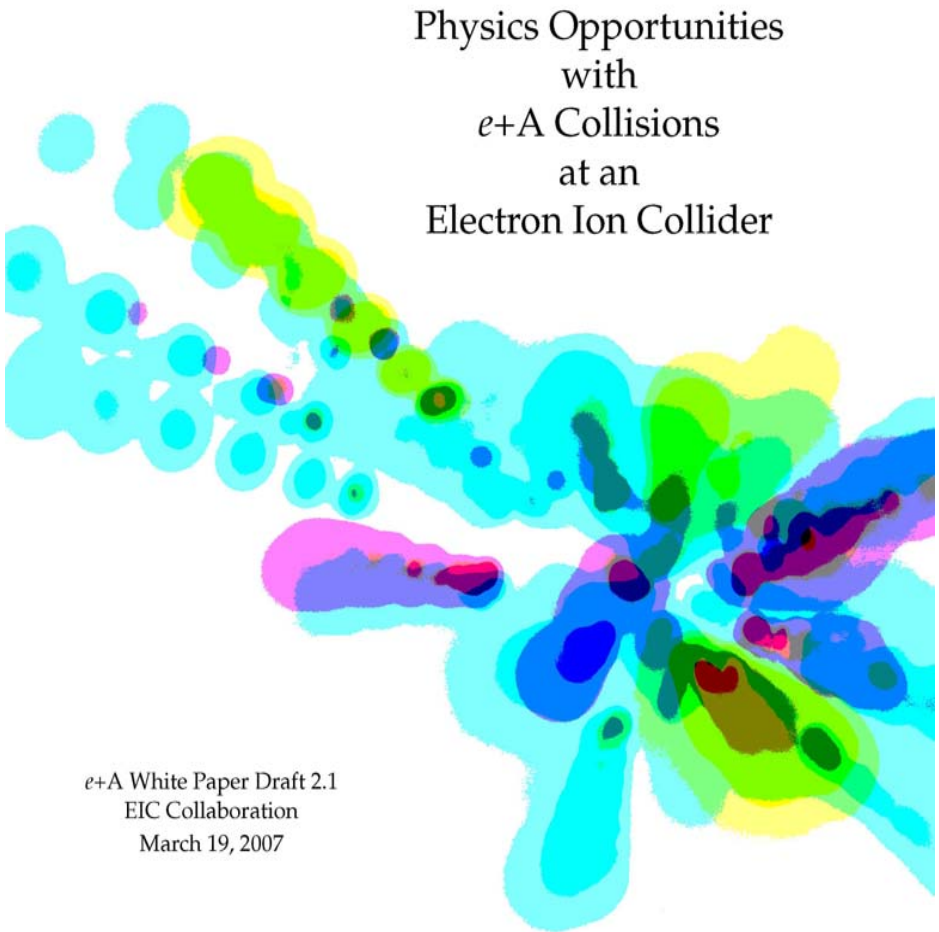
* White Paper prepared for the discussion of the National Science Advisory Committee's Long–Range Plan (2007). Drafted at the Workshop "Hard exclusive processes with JLab 12 GeV and a future EIC," University of Maryland, Oct. 29–30, 2006, organized jointly by the Institute of Nuclear Theory, Jefferson Lab, and Brookhaven National Lab. The individual contributions to the Workshop are available at `http://www.physics.umd.edu/tqhn/GPD.html`.


Physics Opportunities
with
e+A Collisions
at an
Electron Ion Collider
e+A White Paper Draft 2.1
EIC Collaboration
March 19, 2007

A White Paper prepared for the 2007 Long Range Plan

# A High Luminosity, High Energy Electron-Ion Collider

## *A New Experimental Quest to Study the Glue which Binds Us All*

**The EIC Collaboration**

**March 25th 2007**

# The EIC Collaboration

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# EIC Steering Committee

- A. Caldwell (MPI Munich)
- A. Deshpande (Stony Brook) (Co-chair)
- R. Ent (JLab)
- G. Garvey (LANL)
- P. Reimer (ANL)
- E. Hughes (Columbia)
- K.-C. Imai (Kyoto Univ.)
- L. Merminga (JLab)
- R. Milner (MIT) (Co-chair)
- P. Paul (Stony Brook)
- J.-C. Peng (Illinois)
- T. Roser (BNL)

# Electron - Ion Collaboration Meeting

Massachusetts Institute of Technology - Laboratory for Nuclear Science
6-7 April, 2007


- Home
- Agenda
- Accommodation
- Transportation
- Registration
- Attendees
- Presentations
- Computer Access
- Contact Us
- 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 non-hosted, group dinner Friday evening.

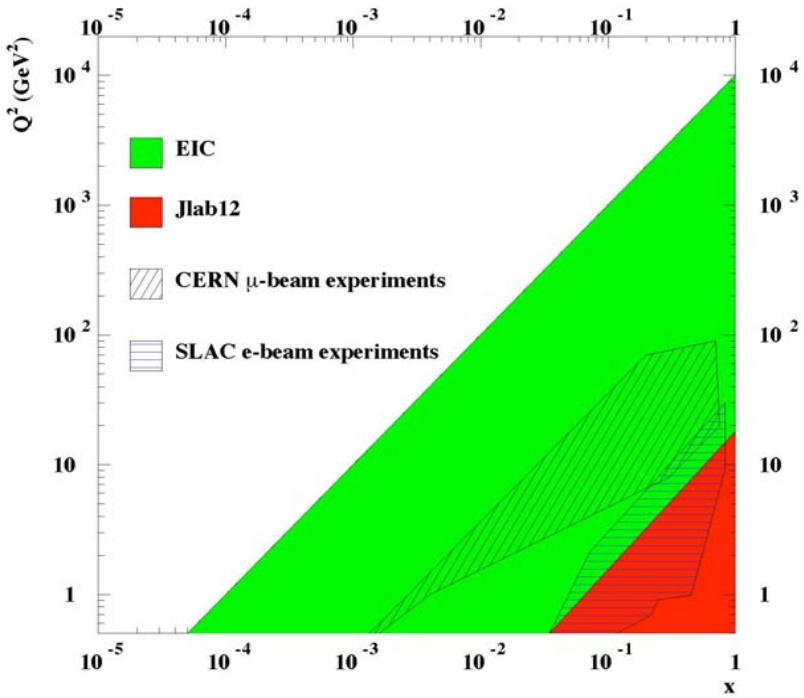
Introductory documentation and copies of presentations will be available from the Presentations page as they become available.

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/

MIT Massachusetts Institute of Technology · Brookhaven National Laboratory · Jefferson Lab Thomas Jefferson National Accelerator Facility

# EIC Design Parameters



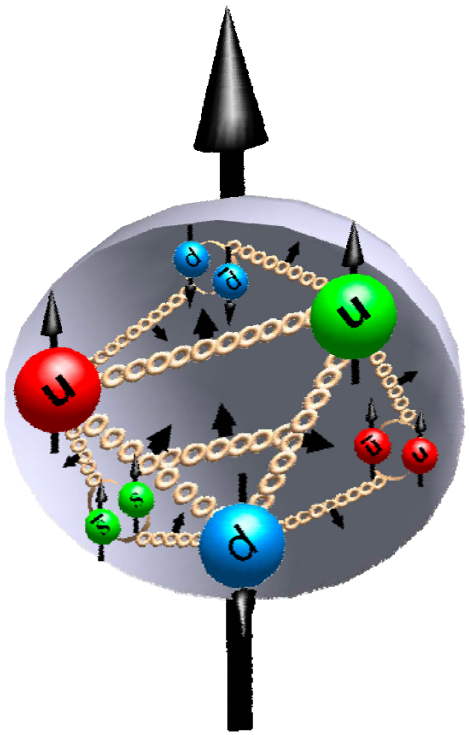

- $E_e$=5-10 GeV
- $E_p$=30-250 GeV
- $s^{\frac{1}{2}}$=25-100 GeV
- $x_{Bj}$=$10^{-4}$ to 0.7
- $Q^2$=0 to $10^4$ $(GeV/c)^2$
- polarization of $e^{\pm}$, p, $^3$He ~ 70%
- heavy ion beams of all elements
- high luminosity ~ $10^{33}$ $cm^{-2}$ $s^{-1}$
- 50 $fb^{-1}$ integrated luminosity over a decade, i.e. x 100 above HERA

# Luminosity Arithmetic

- Assume an average data taking luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$
- In 11.6 days of 100% efficient data taking,
  $10^{6}$ x $10^{33}$ cm$^{-2}$ = $10^{39}$ cm$^{-2}$ = 1 fb$^{-1}$ integrated luminosity is acquired.
- The goal for EIC is to acquire ~ 5 fb$^{-1}$ per year, i.e. the equivalent of ~ 58 days (8 weeks) of continuous 100% data taking at an average luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$.
- With 70% efficiency each for accelerator and detector, overall efficiency should be ~ 50%, i.e. 5 fb$^{-1}$ would be acquired in ~ 16 weeks.
- HERA will have acquired ~ 0.5 fb$^{-1}$ in its lifetime before it ceases operation this summer.
- Over its lifetime, EIC should acquire x 100 times the integrated luminosity acquired with HERA with polarized nucleon and heavy nuclear beams.

# The Spin Structure of the Nucleon

$$\tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$




We know from lepton scattering experiments over the last three decades that:

- quark contribution $\Delta\Sigma \approx 0.25$
- gluon contribution $\Delta G \approx 1 \pm 1$
- valence quark polarizations as expected
- measured anti-quark polarizations are consistent both with zero and also with sizable negative sea polarization => significantly more precise data required

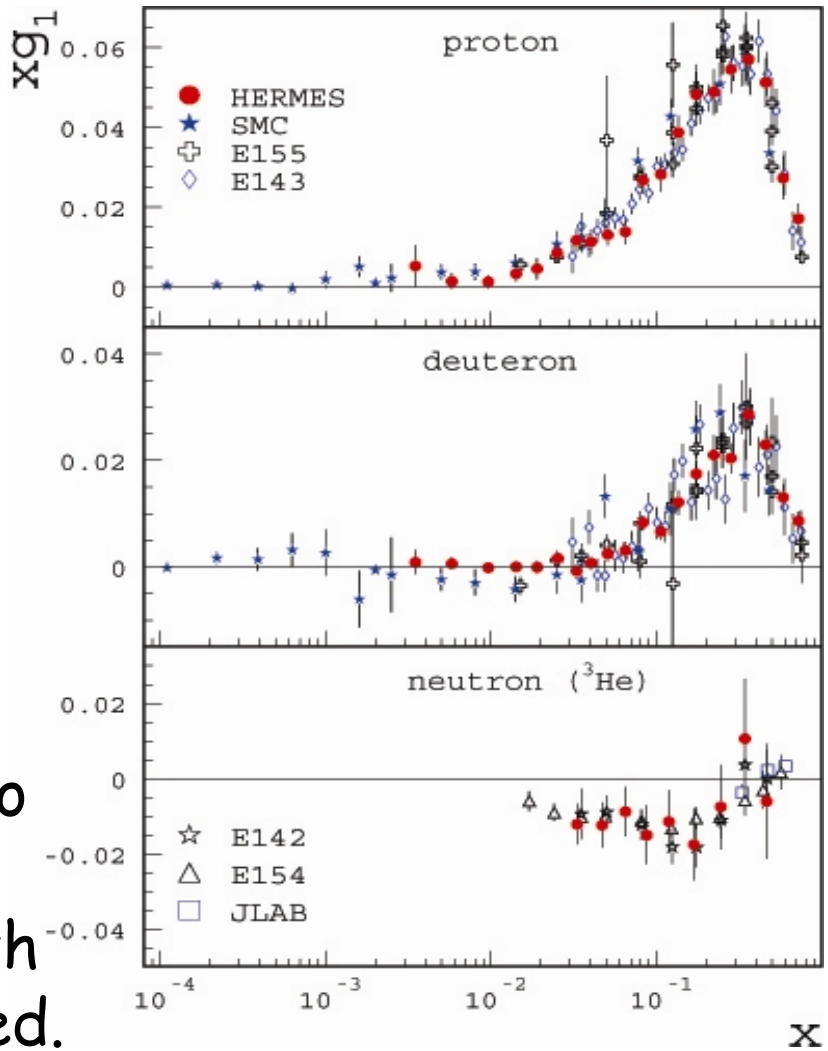
# EIC will allow access to all aspects of nucleon spin

- $g_1^{p,n}(x,Q^2)$ precisely measured at lower x and higher $Q^2$
- $\Delta G(x,Q^2)$ precisely determined over $10^{-3} < x_{gluon} < 0.5$ through several independent channels
- Quark polarizations accurately determined
- Transverse spin fully explored
- Access to processes over a large and unprecedented range of x and $Q^2$
- Possible determination of the contribution of orbital angular momentum $L_{q,g}$

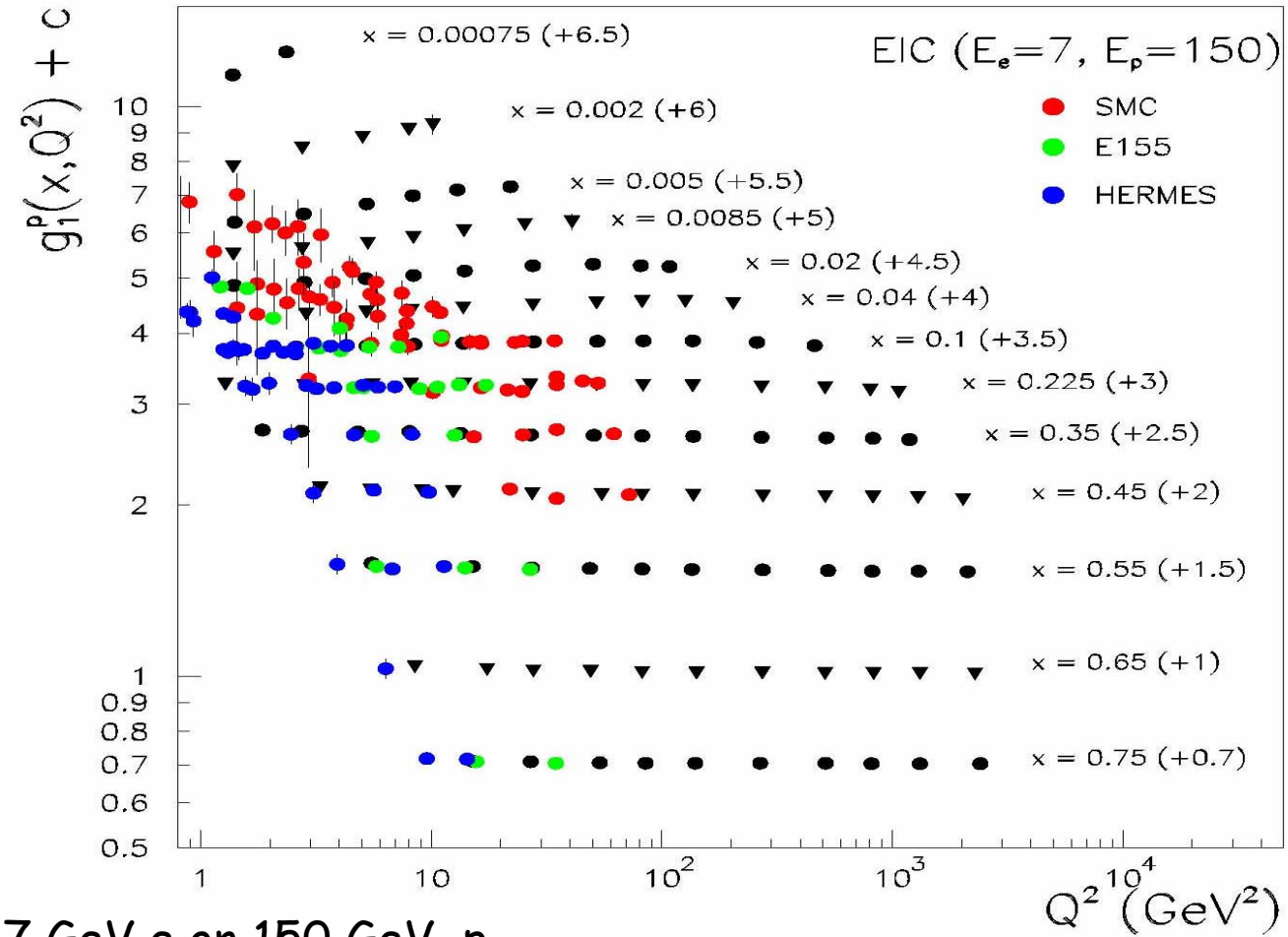
# Spin-dependent inclusive DIS

- Measurements on neutron and proton with assumptions yield quark polarizations vs. x
- $Q^2$ dependence yields gluon spin
- Neutron and proton data can be combined to test QCD Bjorken Sum Rule:

  $\Gamma_1^p - \Gamma_1^n = 1/6\ g_A\ [1 + O(\alpha_s)]$
- Sum rule verified at present to $\pm 10\% \rightarrow 1\%$ with EIC
- Kinematic range accessible with existing accelerators exhausted.



# EIC will extend reach of spin-dependent inclusive measurements by several orders of magnitude

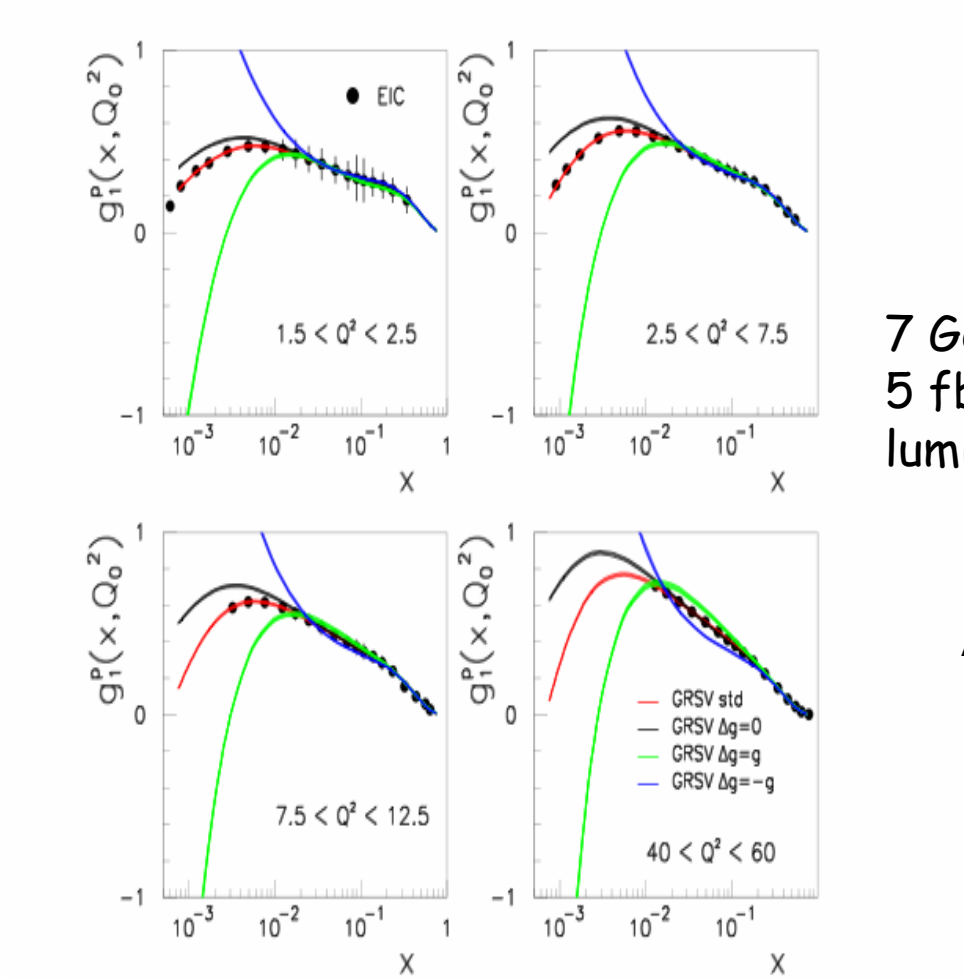



A. Bruell
R. Ent

7 GeV e on 150 GeV p
5 fb$^{-1}$ integrated luminosity

Scaling violations directly observed!

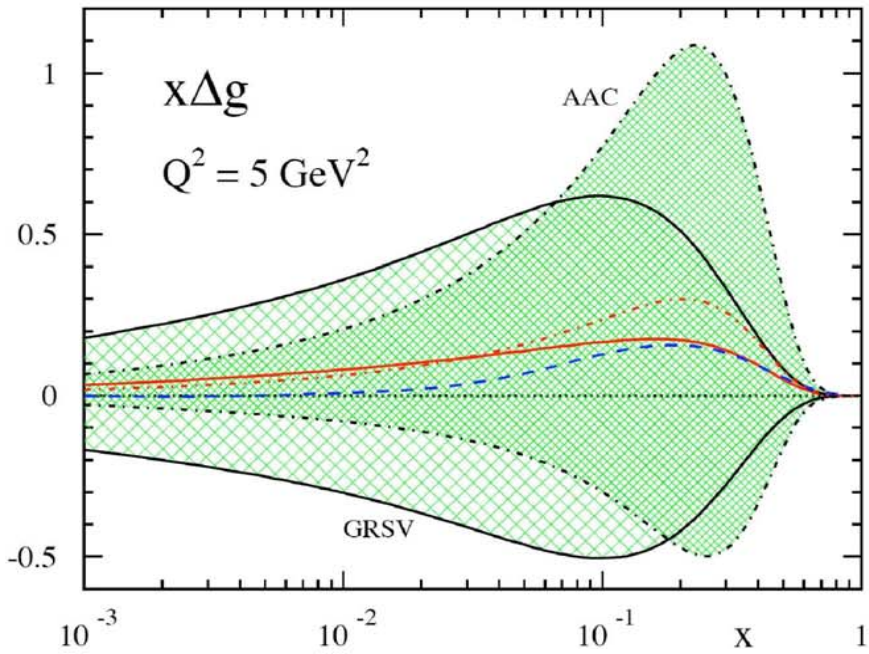
# Unprecedented inclusive spin-dependent DIS measurements




7 GeV e on 150 GeV p
5 $fb^{-1}$ integrated luminosity

A. Bruell
B. R. Ent

# x-dependence of gluon polarization

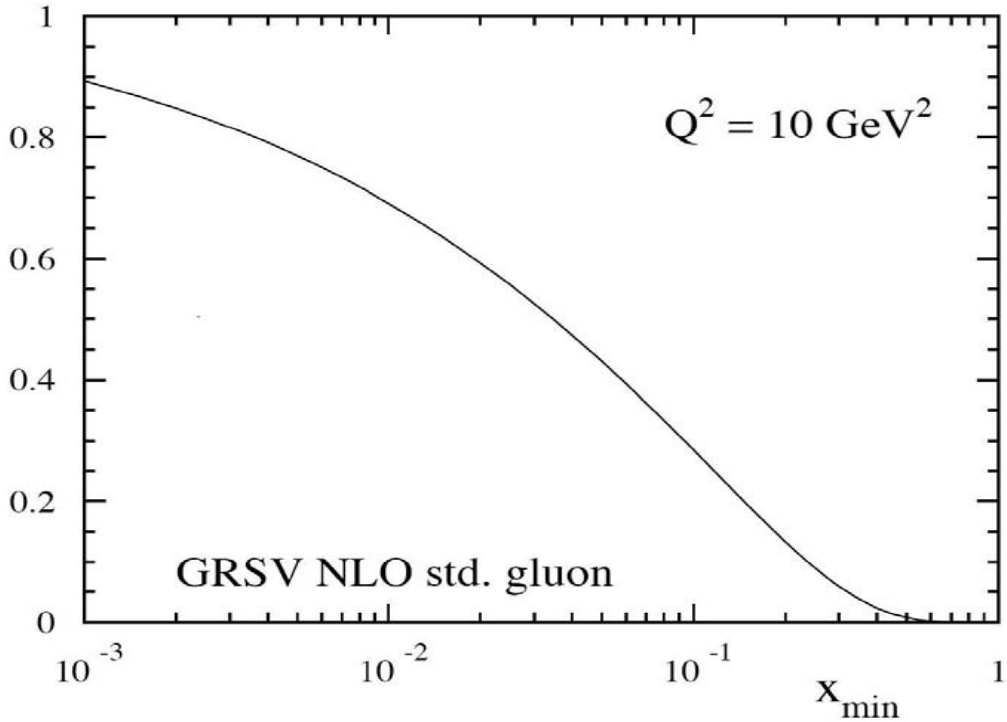



Note substantial gluon polarization in some models at high x ~ 0.5

Stratmann and Vogelsang
hep-ph/07020831

# Integral of gluon spin: ΔG

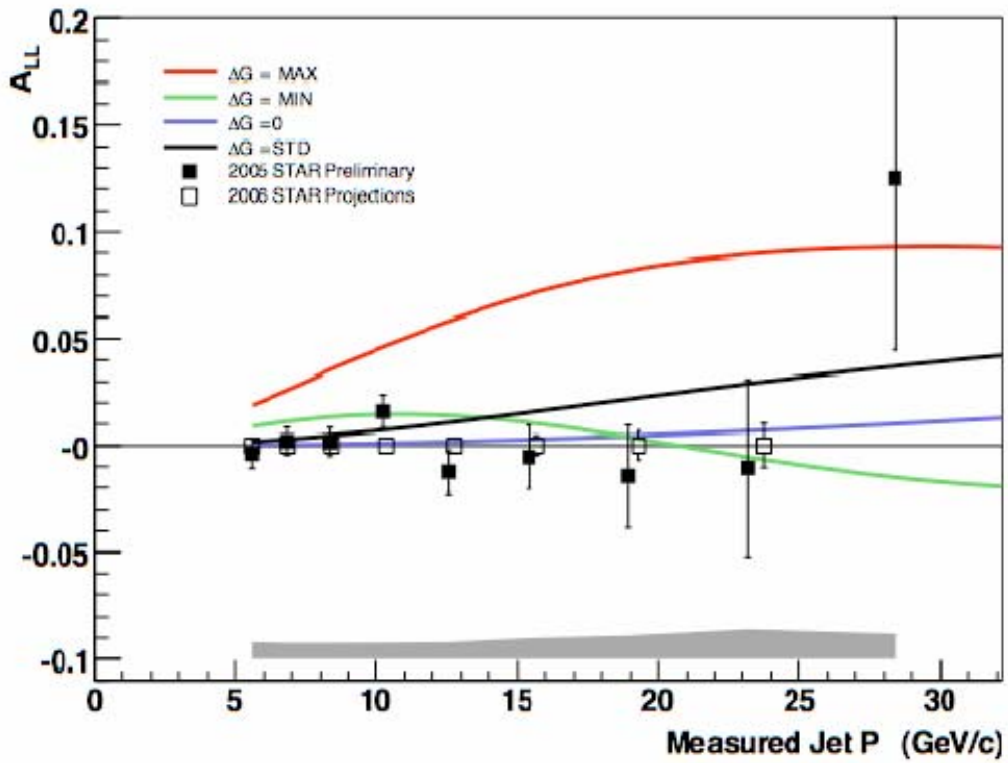
$$\frac{\int_{x_{\min}}^{1} dx\, \Delta g(x, Q^2)}{\Delta G(Q^2)}$$




Stratmann and Vogelsang, hep-ph/07020831

# RHIC-spin: gluon polarization

2005 STAR preliminary from inclusive jets
1.6 $pb^{-1}$ integrated luminosity



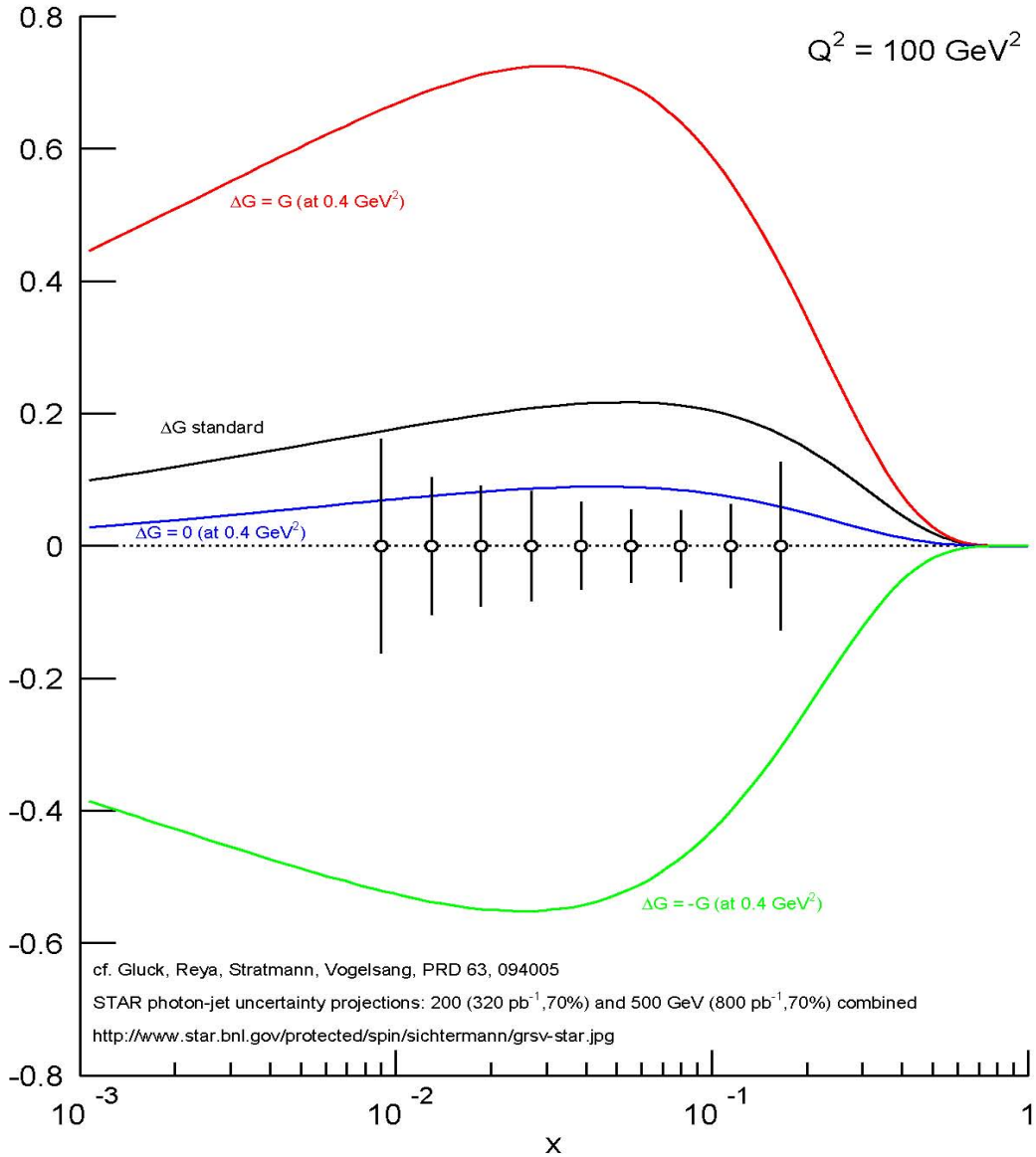

STAR collaboration

# RHIC-spin: future projection

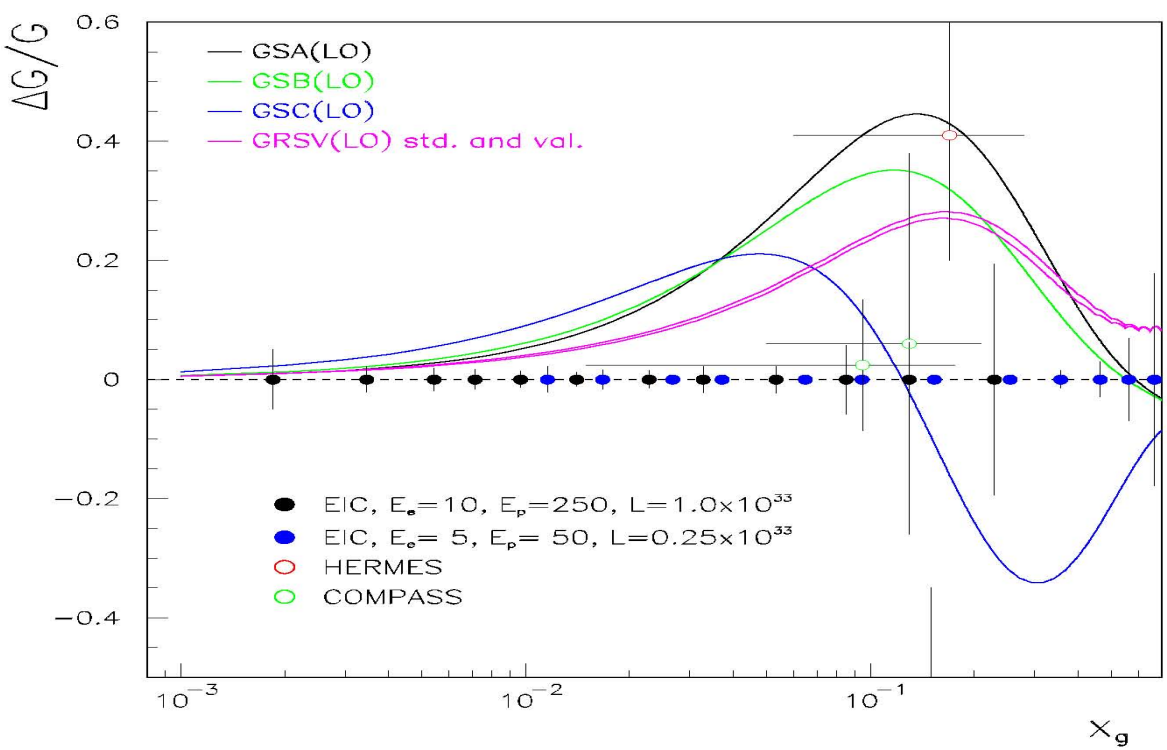
200 GeV : 300 pb$^{-1}$
500 GeV : 800 pb$^{-1}$

E. Sichtermann

Richard G. Milner



# $\Delta G(x,Q^2)$ from charm production



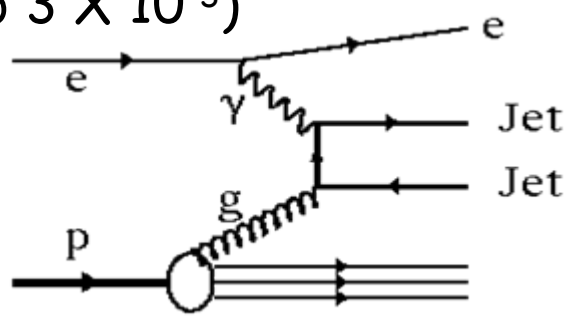

$D^0 \rightarrow K^- \pi^+$

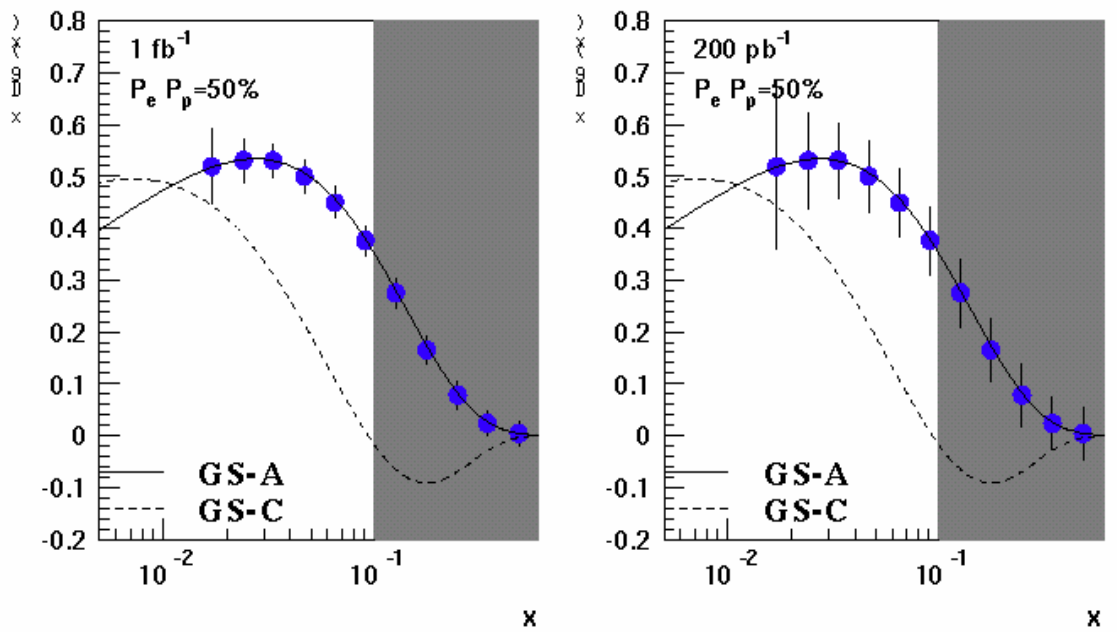
A. Bruell
R. Ent

10 GeV e on 250 GeV p: 10 $fb^{-1}$ integrated luminosity
5 GeV e on 50 GeV p : 2.5 $fb^{-1}$ integrated luminosity
$Q^2$ = 9 $(GeV/c)^2$

# $\Delta G(x,Q^2)$ at EIC

- Best determination from scaling violations of $g_1(x,Q^2)$
  - EIC will extend range in x ( down to 1 $x10^{-4}$) and $Q^2$
  - improve existing measurements by a factor of 3 in 1 week!
- Direct measure via photon-gluon fusion (down to 3 X $10^{-3}$)
  - di-jets, high $P_T$ hadrons
  - Successfully used at HERA
  - NLO calculations exist
  - Constrains shape in mid x region



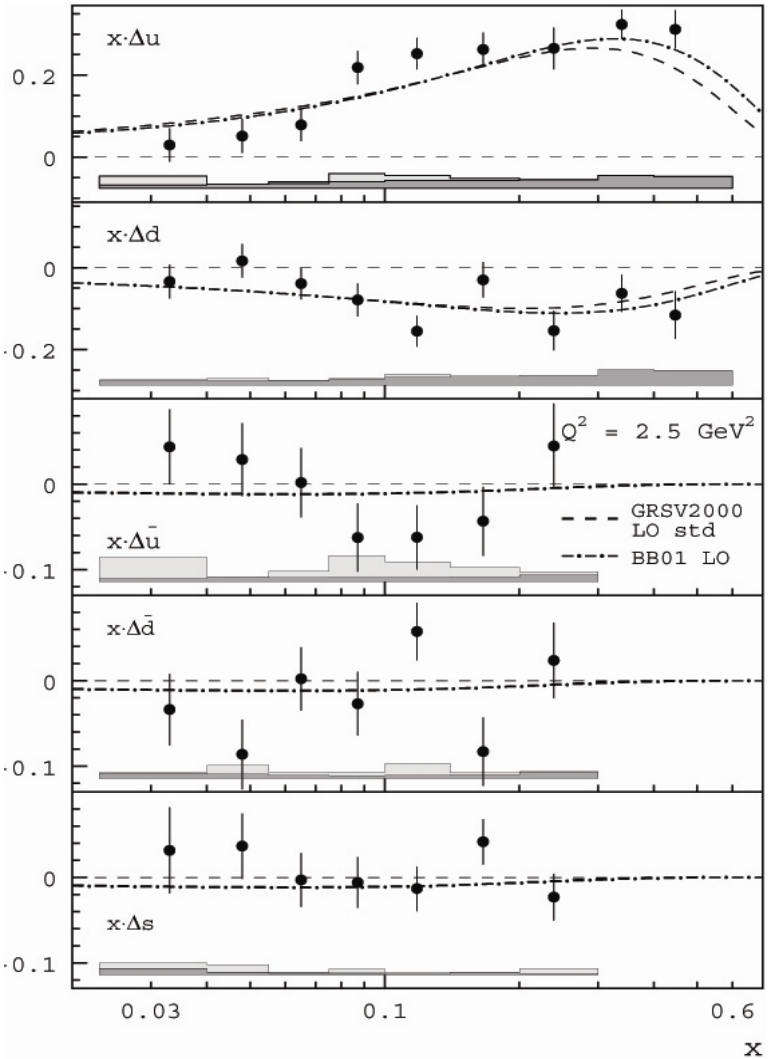

**1 $fb^{-1}$ integrated luminosity**

**Scaling violation data plus di-jet analysis will yield total uncertainty ~ 5% after 1 year**

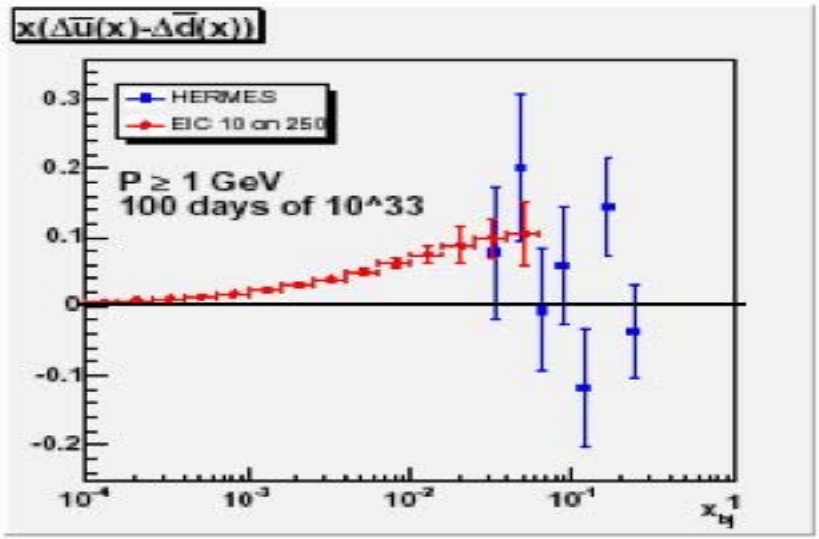
**A. DeRoeck et al., Eur. Phys. J. 121, C6 (1999)**

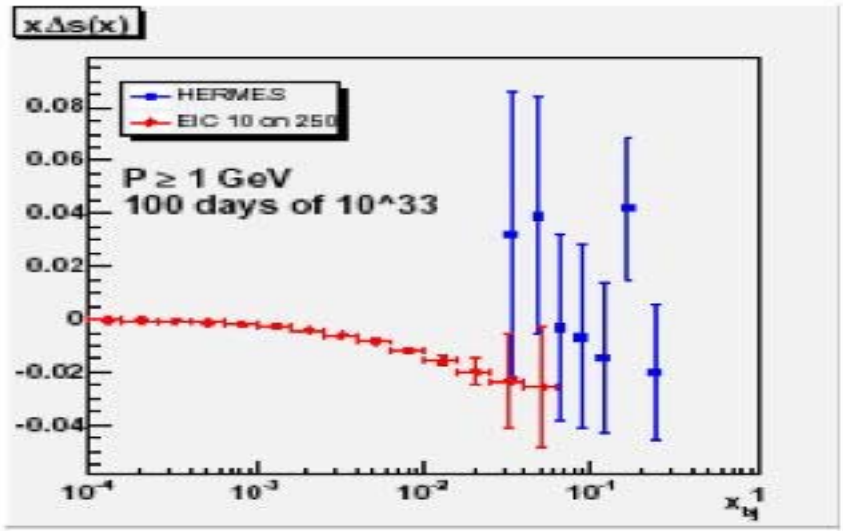
# HERMES Flavor Decomposition of Quark Spin

Semi-inclusive DIS



# EIC determination of polarized quarks and anti-quarks

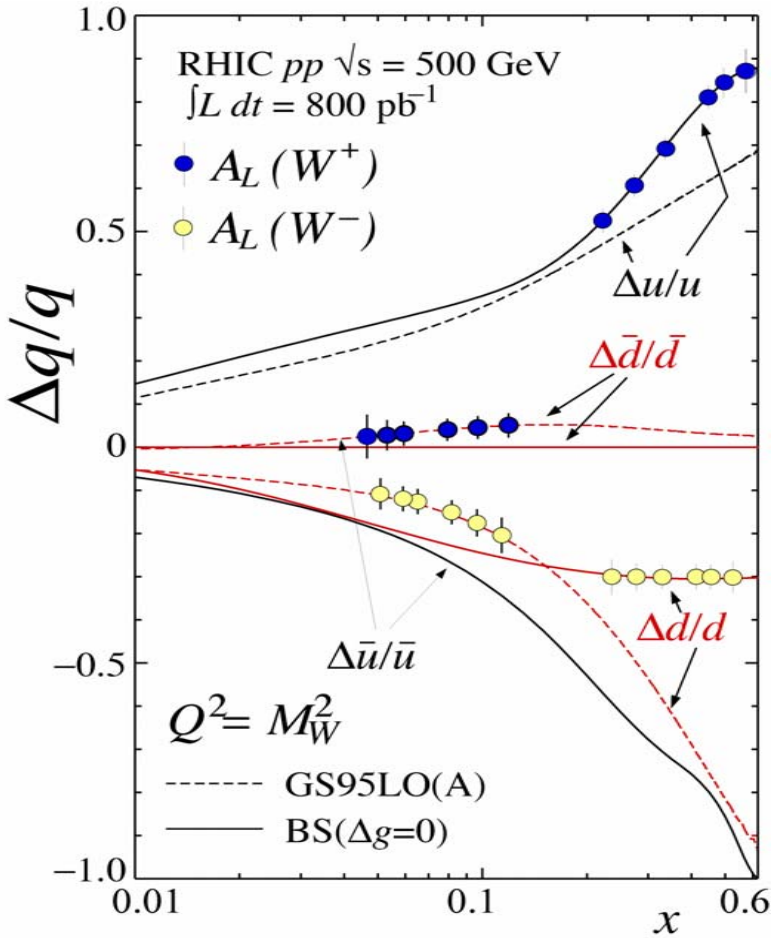



10 GeV e on 250 GeV p
10 $fb^{-1}$ integrated luminosity

E. Kinney et al.

# Quark flavor decomposition RHIC-spin projection

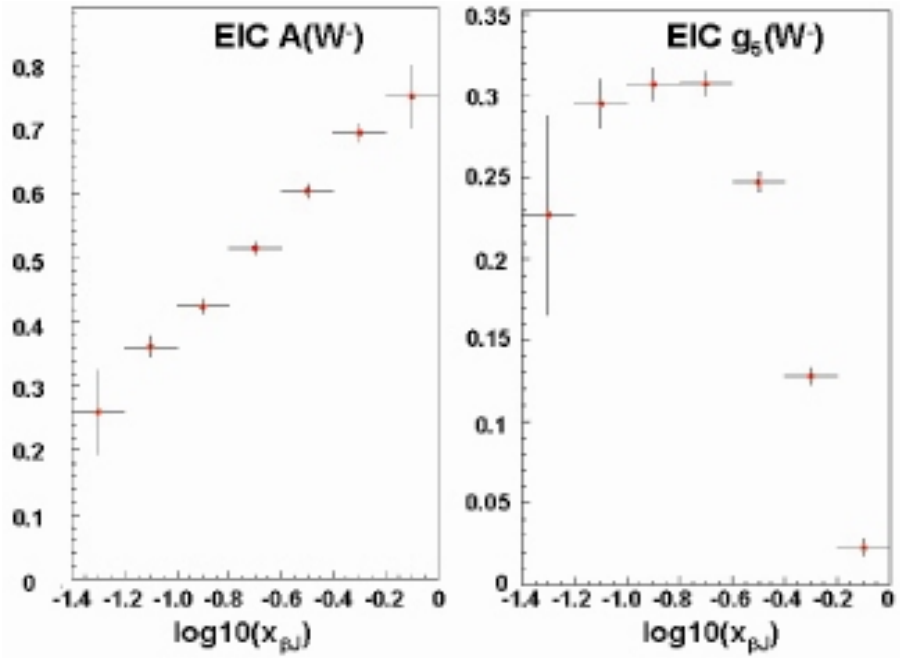



C. Aidala et al.
Research Plan for Spin Physics at RHIC, February 2005

$$A_L^{W^+} \approx \frac{\Delta u(x_1)\,\bar{d}(x_2) - \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)}$$

Eliminates fragmentation function
Uncertainties of SIDIS

# Parity violating lepton scattering



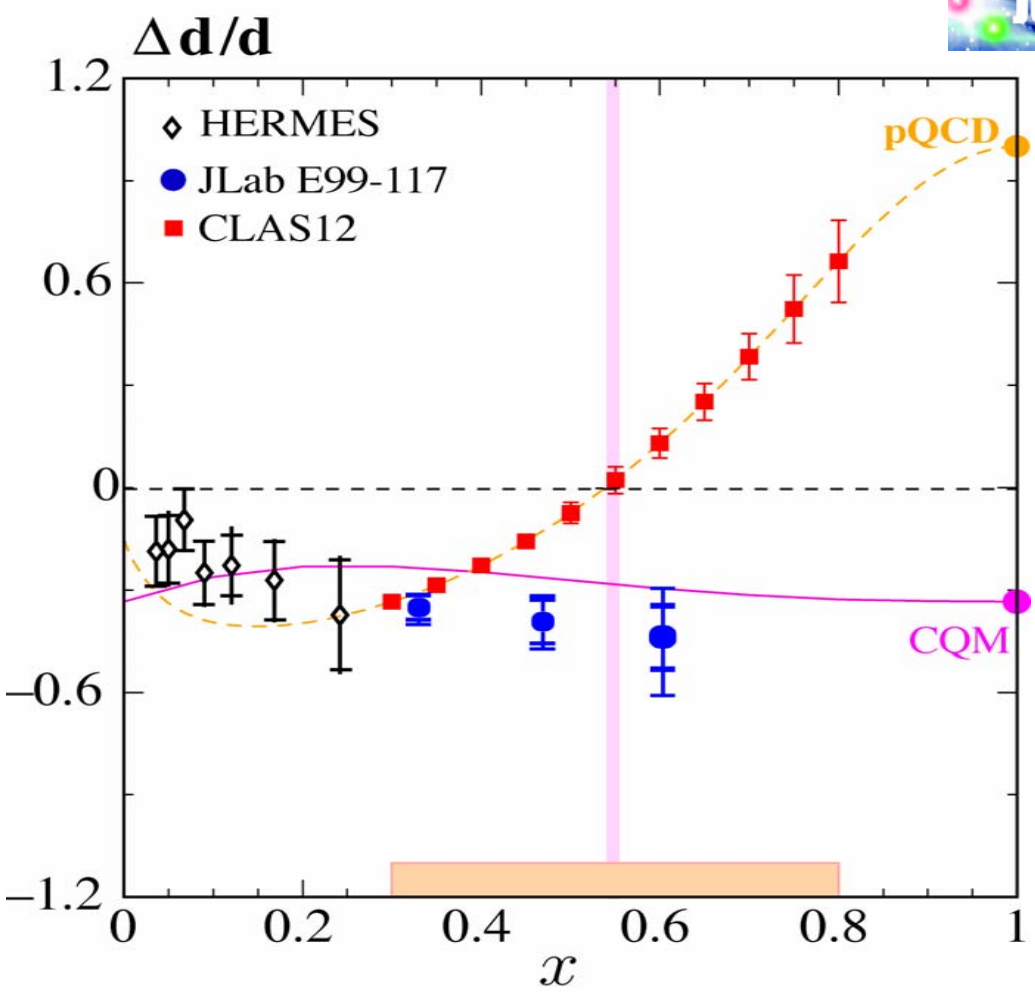

10 GeV e on 250 GeV p
4 $fb^{-1}$ integrated luminosity

A. Deshpande et al.

- $W^+$ and $W^-$ exchange probed via parity violating scattering
- This measurement requires a polarized positron beam.
- It will provide new combinations of $\Delta u$, $\Delta \bar{u}$, $\Delta d$, $\Delta \bar{d}$, $\Delta s$, $\Delta$sbar etc.
- There is an analog sum rule to the Bjorken Sum Rule.

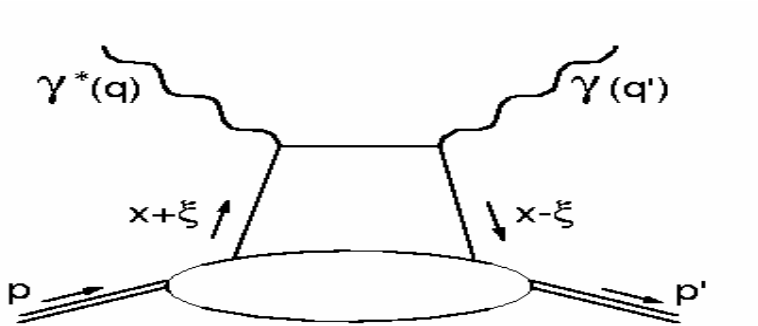
# Flavor Decomposition

## At JLab 12 GeV with (SI)DIS




R. Ent

# Orbital Angular Momentum

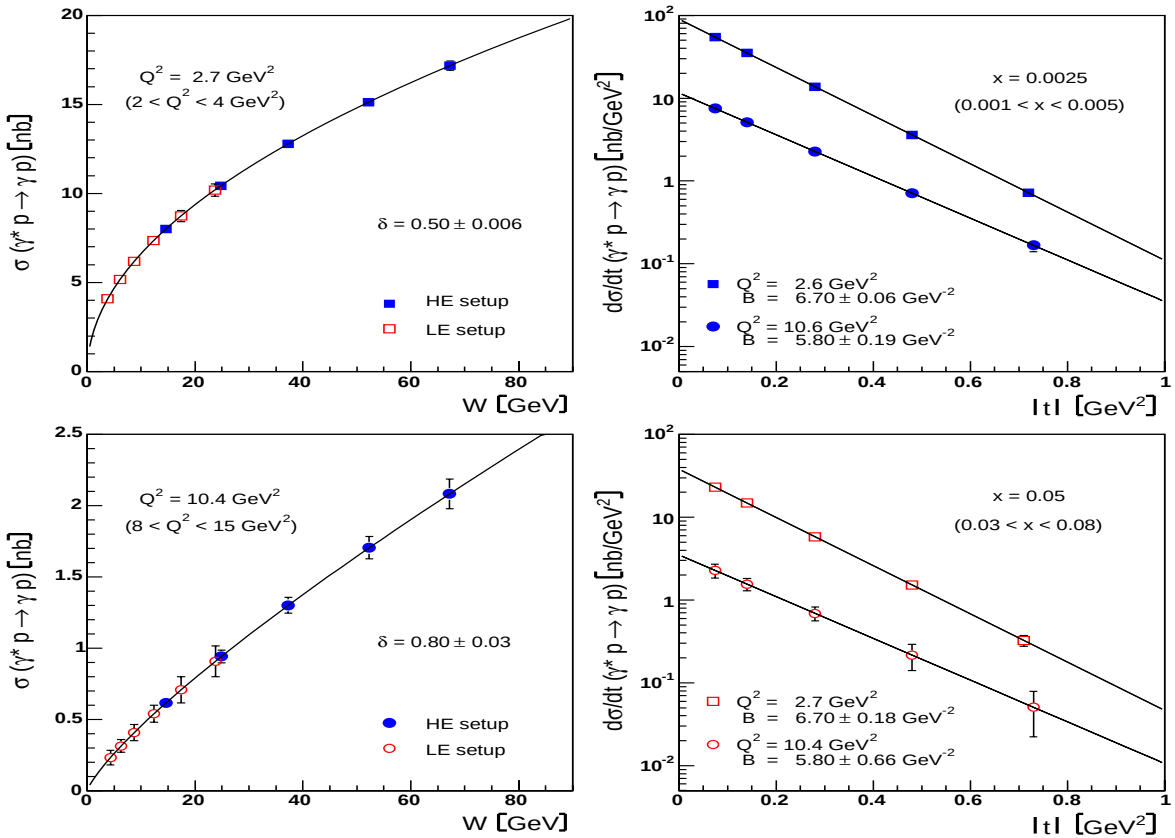



- Generalized parton distributions offer a means to measure the spatial distribution of the nucleon.
- One promising avenue being pursued is to measure a photon or meson in coincidence with the scattered lepton.
- JLab@12 GeV will explore this avenue in the valence quark region at low $Q^2$
- EIC will carry out measurements complementary to those at JLab at higher $Q^2$ – focus on sea quarks and gluons.
- Study of this important issue by both theorists and experimentalists continues

# Deeply Virtual Compton Scattering

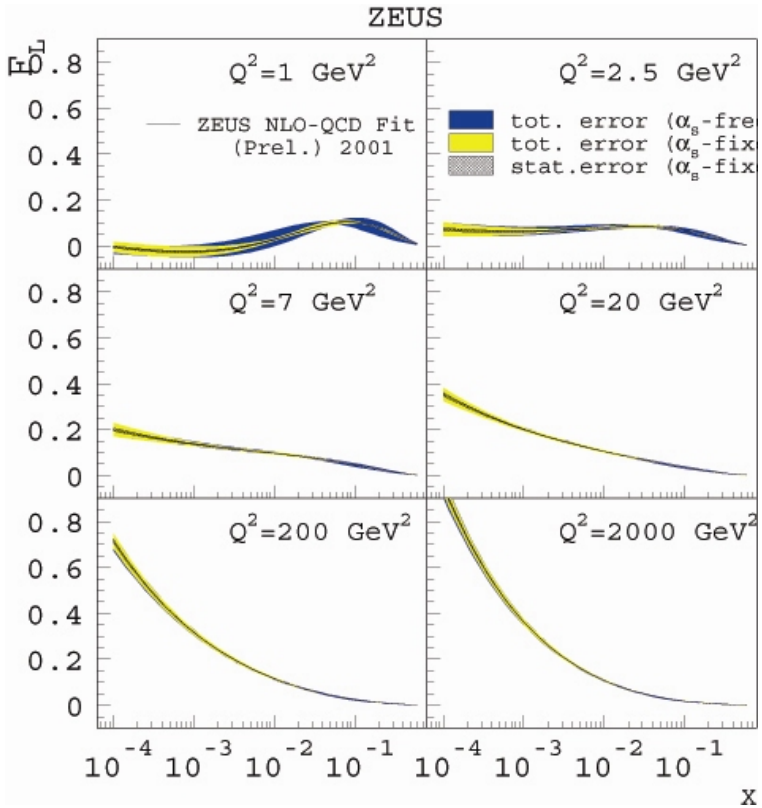
10 GeV e on 250 GeV p : 0.5 $fb^{-1}$
5 GeV e on 50 GeV p : 0.2 $fb^{-1}$

A. Sandacz



# Longitudinal structure function $F_L$

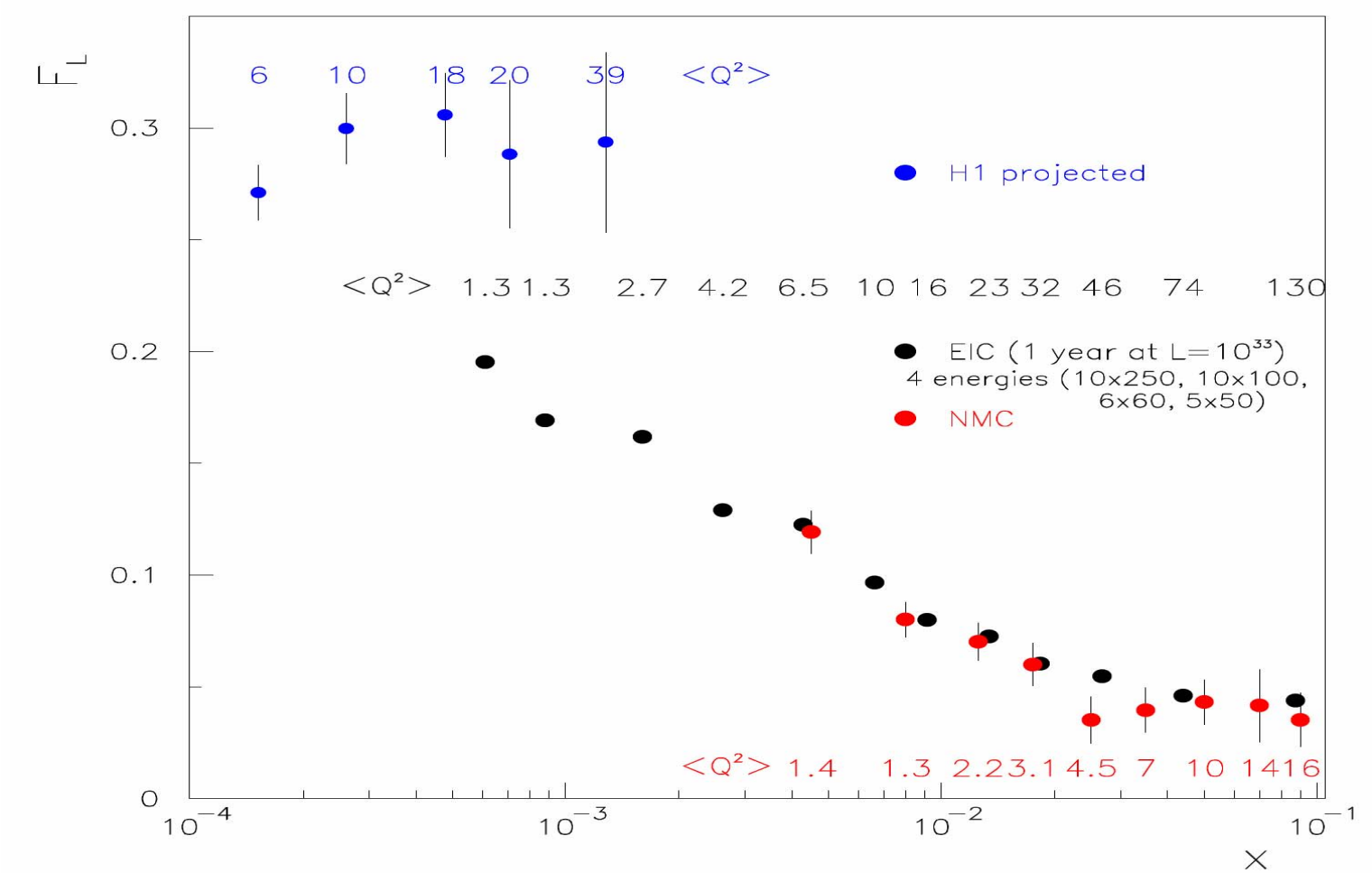
- Extracted from scaling violations of $F_2$
- Experimentally can be determined directly
- Highly sensitive to effects of gluon
- With precise enough $F_2$ and $F_L$ one can extract the coefficient λ of the saturation scale
- Logarithmic derivatives of $F_2$ and $F_L$ with Q will be sensitive to CGC



# $F_L$ projected measurements at EIC

10 fb$^{-1}$ integrated luminosity

A. Bruell, R. Ent



# Summary

- A high luminosity Electron-Ion Collider has been established as the highest priority for new construction by the U.S. QCD community after the 12 GeV JLab and RHIC II luminosity 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 gluon fields in nuclei
- There is a strong, energetic and motivated EIC collaboration drawing from both the hadron and QCD phase communities in the U.S. as well as from the international community.
- The EIC collaboration will meet at MIT on April 6$^{th}$ and 7$^{th}$ to prepare for the Galveston meeting.