Studying the Spin Structure of the Nucleon with a High Luminosity Electron-Ion Collider

A presentation to convince a nuclear physicist colleague that the science is compelling

"Exploring new territory with precision instrumentation is the key to discovery" – S.C.C. Ting

- EIC will explore *terra incognita* well beyond the present frontiers in understanding the fundamental building blocks of atomic nuclei.
- EIC will explore new landscape in terms of gluon/sea quark structure of nucleon spin and atomic nuclei.
- Precision is key:
  - lepton probe
  - polarized beams
  - high luminosity
  - optimized detectors
- Past indicates potential for unexpected new insight, e.g.

  SLAC – discovery of quarks

  CERN – modification of quark momentum in nuclei, `spin crisis'

Spin – intrinsic angular momentum

- Spin arose from quantum mechanics and relativity and is an essential element of our understanding of the structure of matter
- **Atoms and nuclei**

  The shell structure of atoms and nuclei can be well understood in terms of their spin-$\frac{1}{2}$ constituents in a mean potential and the Schrödinger equation
- Constituents can be directly observed in scattering experiments and the spin structure verified
- We understand in a fundamental way the stability of matter and why chemical elements and nuclear isotopes have their rich structure observed in our physical world.

Spin structure of the proton

- Most of the mass in the world around us arises from QCD, predominantly from the gluons.
- QCD tells us that the proton consists of spin-$\frac{1}{2}$ quarks interacting via exchange of spin-1 gluons.
- This is a highly relativistic system described by a non-Abelian gauge theory, completely unlike an atom or nucleus.
- The quark model has had great success in predicting the spins of baryons.
- We have learned that the quark model breaks down in understanding proton structure from scattering experiments.

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

- It is essential to understand how the proton spin-$\frac{1}{2}$ arises from its quark and gluon constituents and their orbital angular momentum contributions.

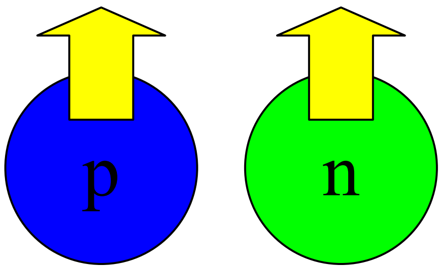
Lepton Scattering

- Uses the extremely well understood electroweak probe to scatter from the constituents.
- At low energies (< 1 GeV) the scattering process is well understood in terms of scattering from hadrons.
- At high energies (> 20 GeV) the scattering is directly interpretable in terms of scattering from the pointlike quarks – *deep inelastic scattering.*
- The spin asymmetry when detecting the scattered lepton and the coincident "constituent" is directly sensitive to the polarization of the "constituent".
- This works well for atoms and nuclei, at the nucleon level. It is drastically different in lepton scattering from the proton at high energies.

Example: The Spin Structure of the Deuteron

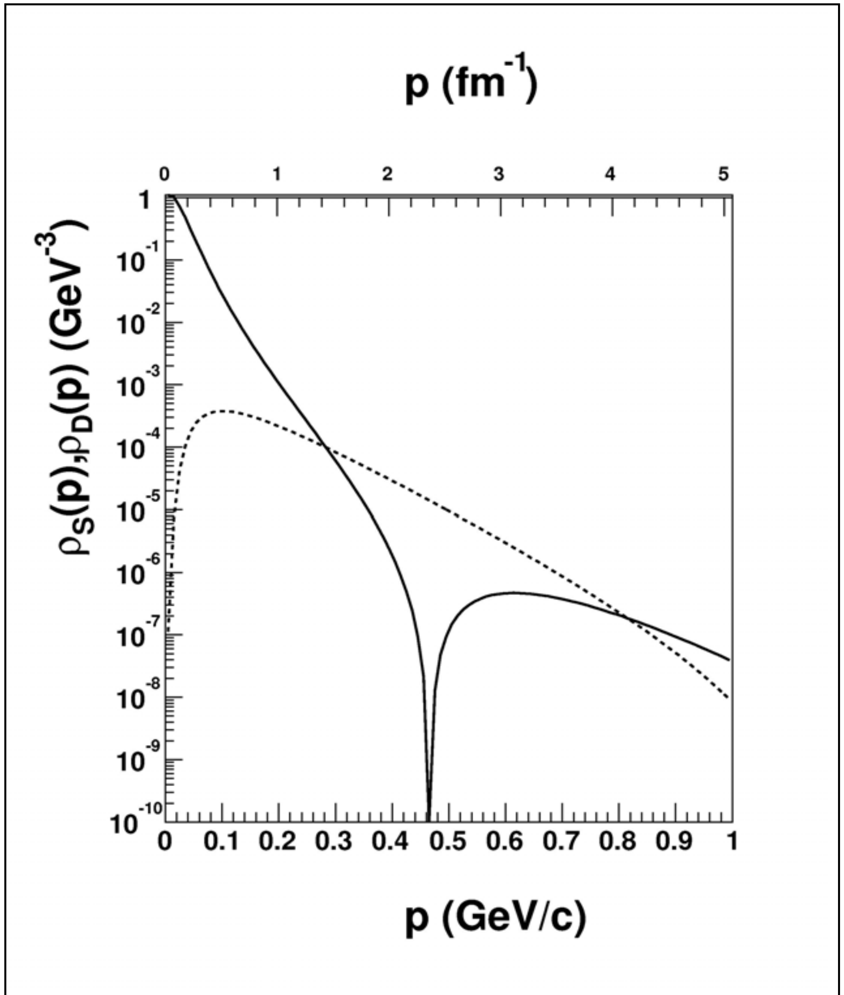
J=1

L=0
S=1

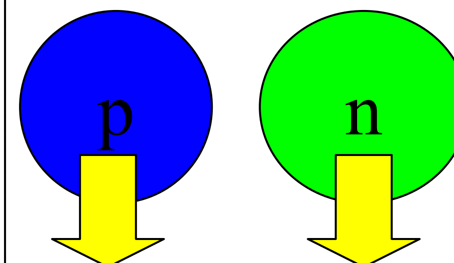


S-state
96% of g.s.
wave
function

1 = L + S



L=2
S=1

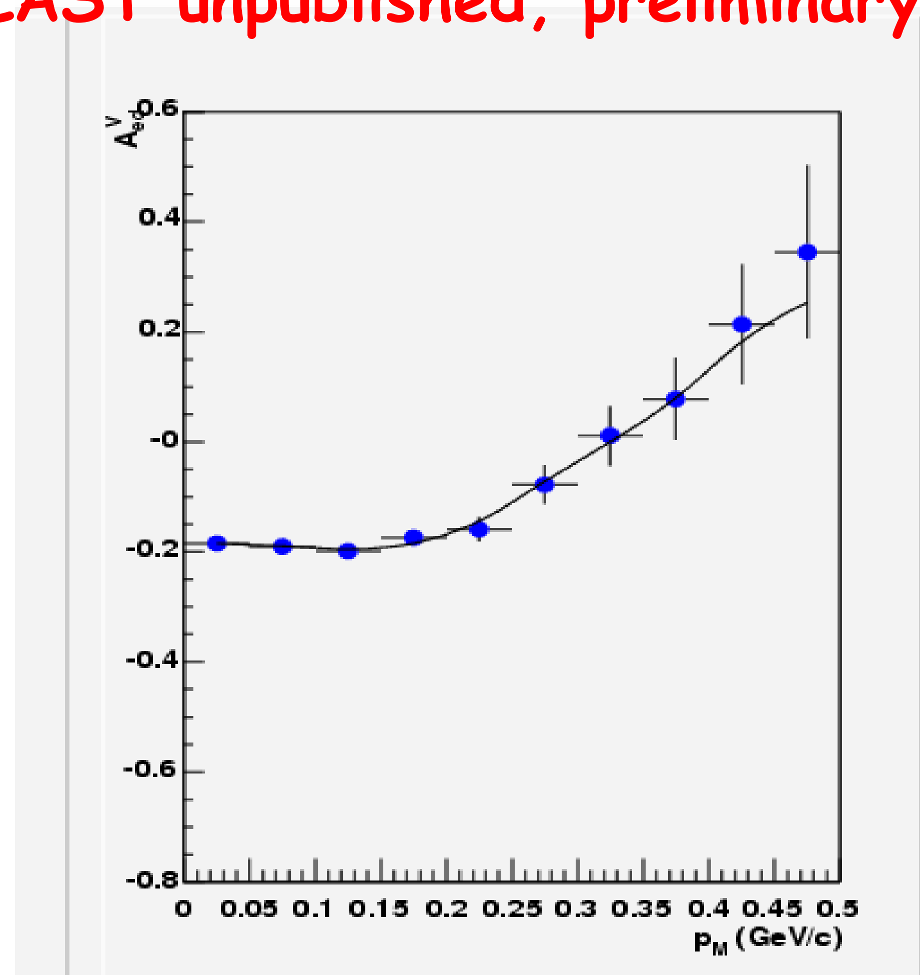


D-state
4% of g.s.
wave
function

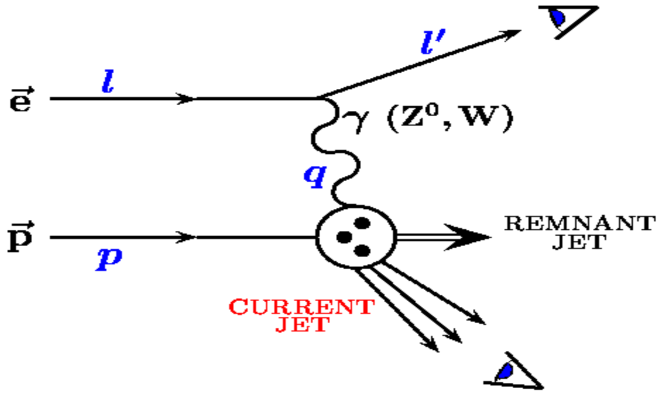
850 MeV (e,e'p) Scattering from Polarized Deuterium

BLAST unpublished, preliminary

- Scattering asymmetry shown vs. initial momentum p_m of detected proton
- The solid line is the theoretical prediction using Monte-Carlo (Arenhövel)
- At low p_m, the scattering is dominated by the S-state in the deuteron
- At high p_m, the asymmetry changes sign and is predominantly due to the D-state of the deuteron.



Deep Inelastic Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot l}$$

$$s = 4E_e E_p = E^2_{CM}$$

$$W = (q+p)^2$$

- Directly interpretable in terms of QCD
- Struck quark hadronizes, typically to a meson
- Quark momentum fraction is $0<x<1$
- Valence quarks: $0.1 \leq x \leq 1$
- Sea quarks and gluons: $x \leq 0.1$
- $Q^2 = E^2_{CM} \cdot x$ => low x reached with high E_{CM}
- Forty years of data has provided a precise determination of the momentum distribution of the quarks and gluons in the proton.

Determining quark distributions

$$cross-section \sim F_2(x)$$

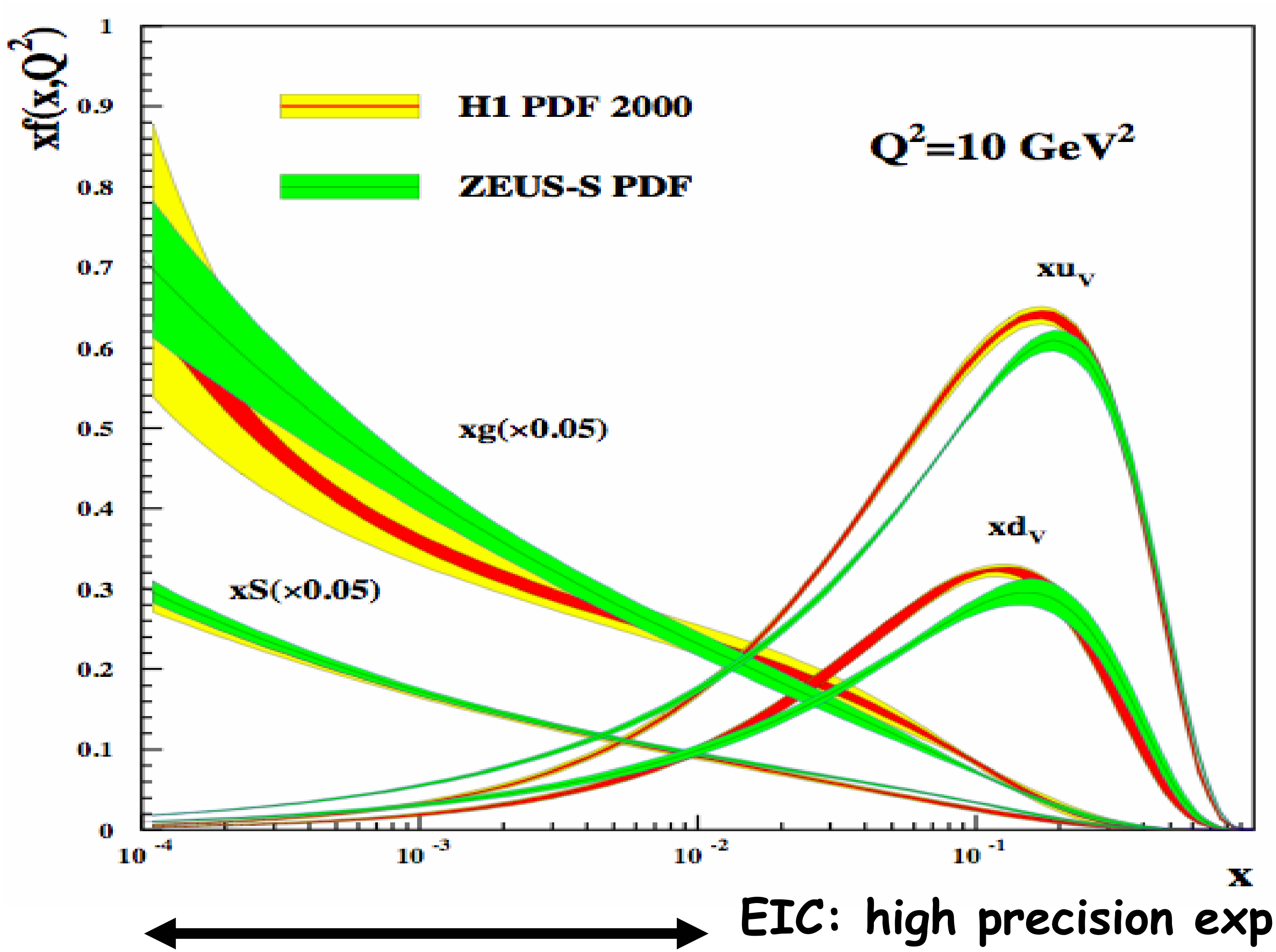
$$spin-asymmetry \sim \frac{g_1}{F_2}$$

$$F_2(x) = \sum_{i=u,d,s....} e^2{}_i[f_i^{\uparrow}(x) + f_i^{\downarrow}(x)]$$

$$g_1(x) = \sum_{i=u,d,s,...} e^2{}_i[f_i^{\uparrow}(x) - f_i^{\downarrow}(x)]$$

$f_i^{\uparrow}(x)$ = probability to find a quark with momentum x and flavor i polarized along the nucleon spin

Unpolarized structure of the proton



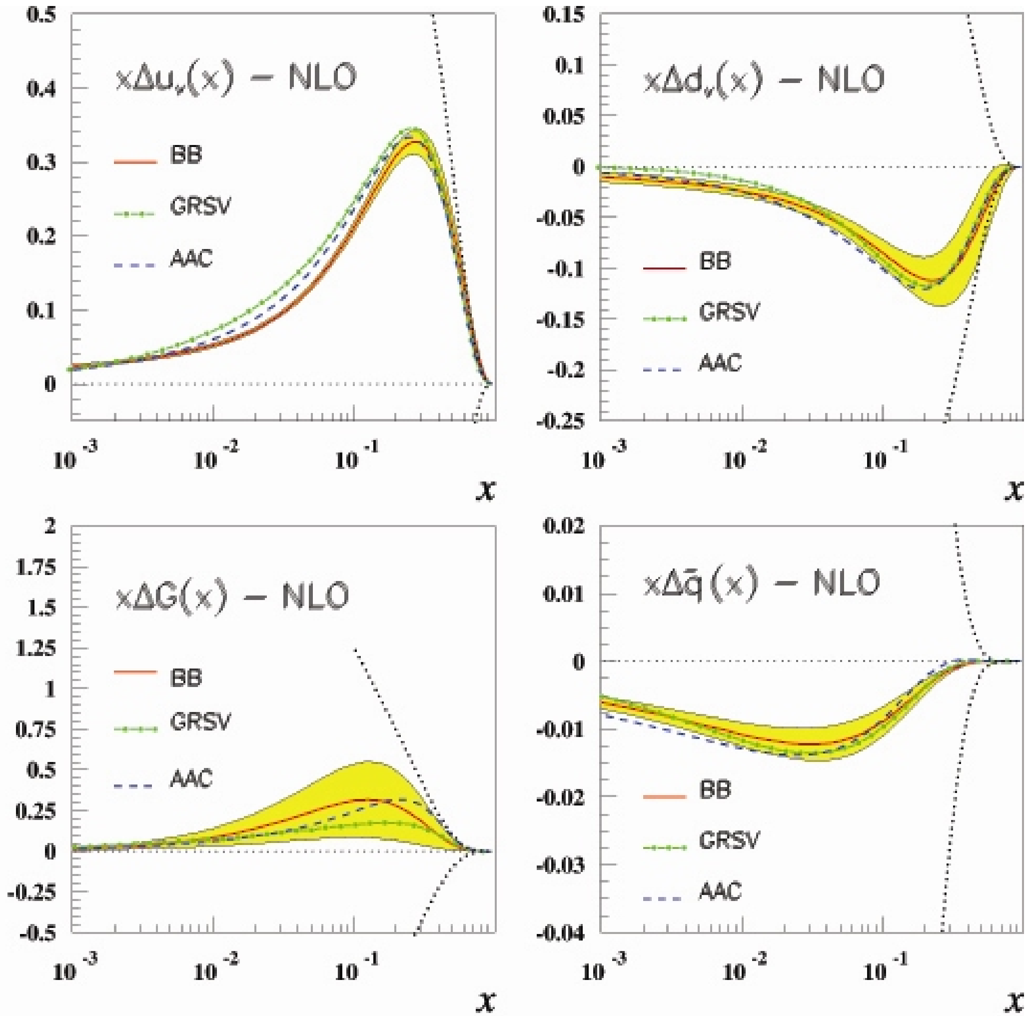
EIC: high precision exploration with spin and nuclei

Spin-dependent DIS

- Spin polarize longitudinally both the proton and lepton
- Measure the spin scattering asymmetry in DIS
- Inclusive asymmetry directly interpretable in terms of QCD => polarizations of quarks (both valence and sea) under some assumptions
- Pioneering experiments initiated at SLAC and CERN in the 1980's.
- Surprising result that the quark model breaks down motivated a second generation of experiments at SLAC, CERN, and DESY.
- Scientific interest has motivated a tremendous technical development: polarized electron beams, polarized proton and neutron targets, world's first polarized proton collider as well as intensive theoretical developments.

Polarized parton densities of the proton

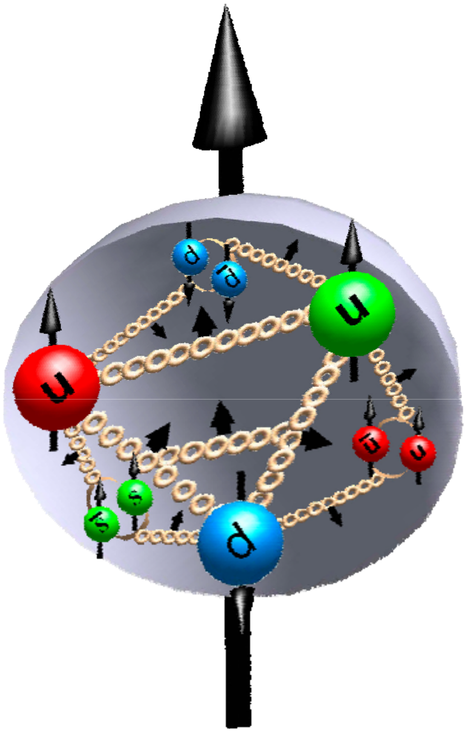
SU(3) flavor symmetry for sea quarks assumed



Blümlein and Böttcher

The Spin Structure of the Nucleon

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



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

- quark contribution $\Delta\Sigma \approx 0.2$
- gluon contribution $\Delta G \approx 1 \pm 1$
- valence quark polarizations as expected
- measured anti-quark polarizations consistent with zero

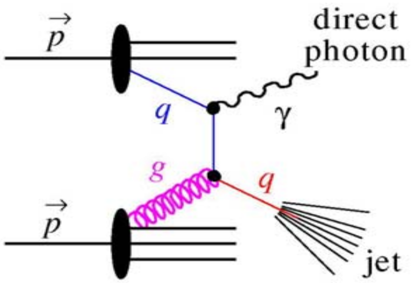
RHIC-spin

- **Gluon polarization**

  Measure asymmetry in long. polarized proton-proton scattering

  Sensitive to $0.01 < x_{gluon} < 0.2$

  Definitive, new results anticipated in 2007

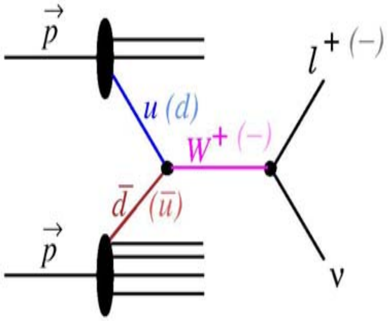


- **Flavor dependence of sea quark polarization**

  Measure parity-violating asymmetry in proton-proton scattering with a $W^{\pm}$ boson in the final state

  anti-u, anti-d quark polarizations

  Measurements in 2012 and beyond



Caution

Elastic proton-proton scattering at high energy: Big mystery in spin asymmetry

Beyond RHIC-spin

Looking to the future, we require:

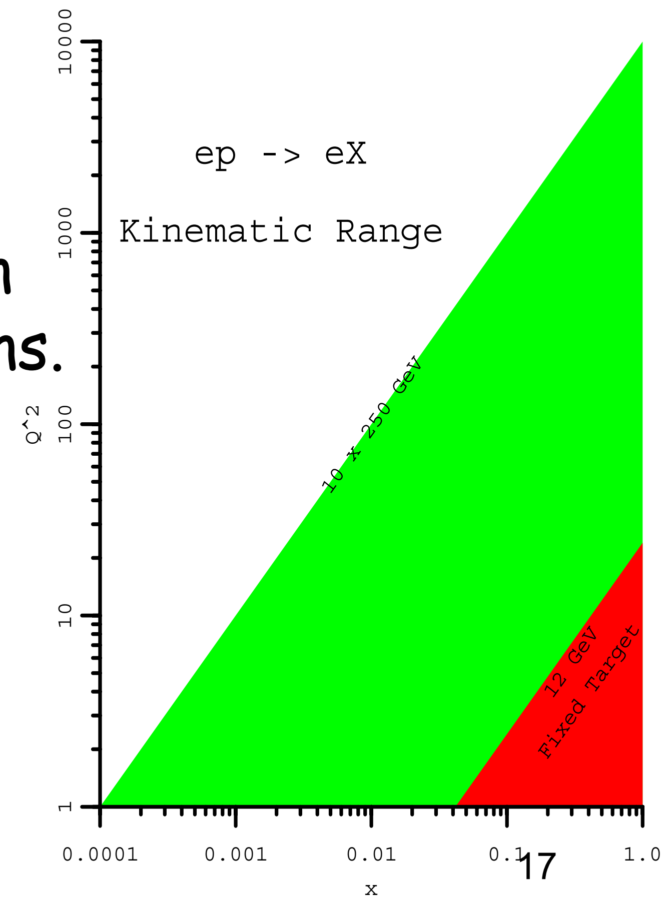
- ΔG precisely determined
- x and Q^2-dependence of gluon polarization $\Delta G(x)$ and sea quark polarization determined
- Anti-quark polarization precisely determined
- Precision test of QCD
- Transverse quark polarization understood
- A firm theoretical understanding of how we might measure the contribution of orbital angular momentum.
- If understood, determination of the contribution of orbital angular momentum.

In summary:

- Understanding the spin structure of the nucleus of the hydrogen atom is the direct culmination of the last century of tremendous progress by physicists in understanding the fundamental structure of matter.
- In the last several decades there has been substantial progress.
- Over the next ~ 5 years, RHIC-spin should be a rich source of new insights, maybe surprises!
- However, lepton scattering at low x at existing facilities will shortly come to an end.
- It is certain that many central issues in understanding the spin structure of the proton will remain unresolved.
- A new experimental capability which explores the role of gluons and sea quarks over an extended range in momentum and spatial resolution is urgently required.

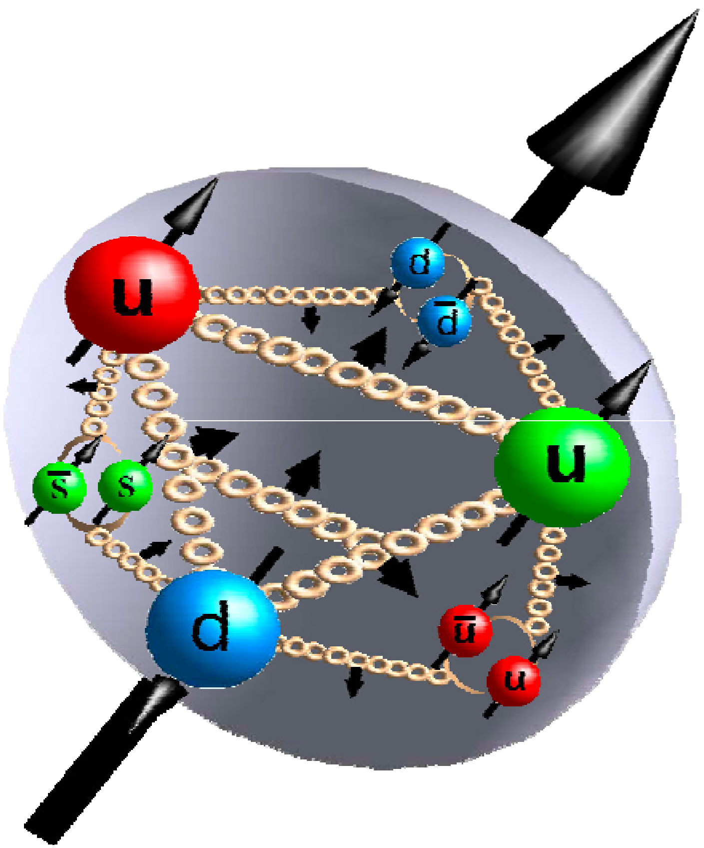
Experimental considerations

- A new accelerator which directly probes the quarks and gluons is required
  - Lepton probe
  - Undiluted lepton-nucleon scattering
  - High center of mass energy => low x
  - High luminosity ⇒ precision
  - Polarized lepton, nucleon
  - Optimized detectors
- At HERA, collider topology has proven ideal in accessing sea quarks and gluons.
- EIC goal is to realize 100 times the luminosity of HERA with polarized nucleon.
- $10^{-4} < x$ 1 $\quad 1 < Q^2 < 10^4 \quad (\mathrm{GeV}/c)^2$
- Note that valence quarks are also accessible over a large region in Q^2



The Spin Structure of the Nucleon

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

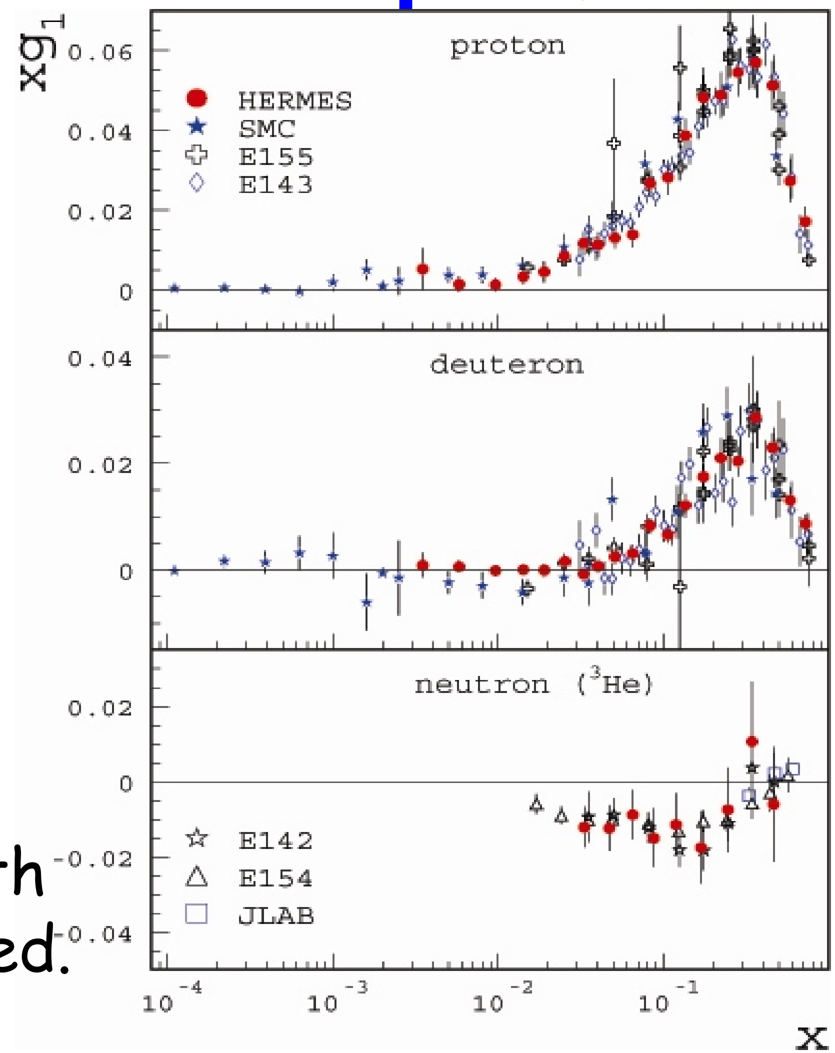


EIC is the first machine to allow access to all the contributions to the spin of the nucleon

- $g_1^p(x)$ measured at lower x
- ΔG accurately determined through several independent channels simultaneously
- quark polarizations accurately determined
- Transverse spin fully explored
- Access to DVCS process over a large range of x and Q^2 => possible determination of the contribution of orbital angular momentum $L_{q,g}$

Spin-dependent DIS detecting only the scattered lepton

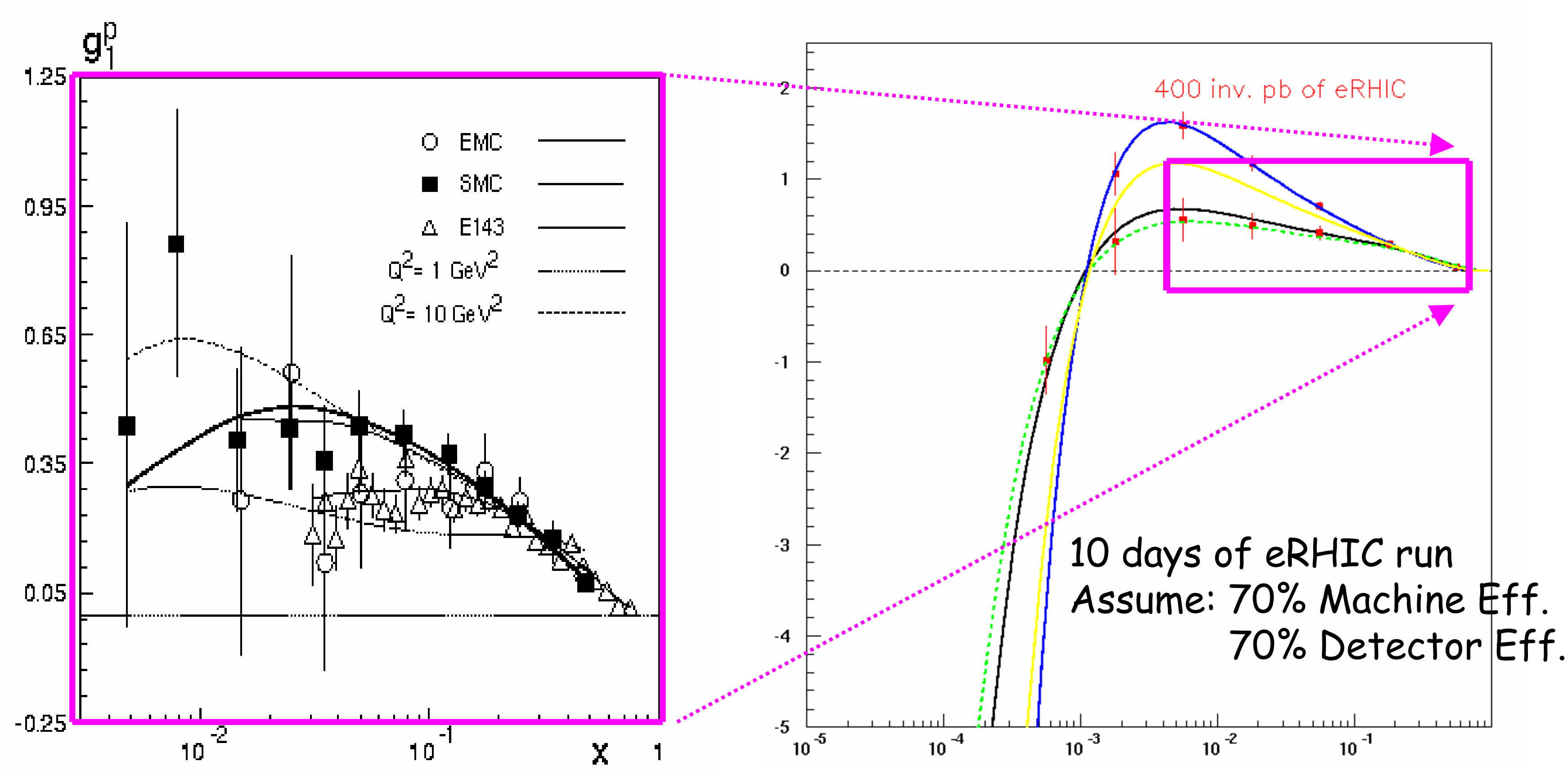
- Measurements on neutron and proton with assumptions yield quark polarizations vs. x
- Q^2 dependence yields gluon spin
- Neutron and proton data can be combined to test QCD Bjorken Sum Rule:
  $\Gamma_1^p - \Gamma_1^n = 1/6\ g_A [1 + O(\alpha_s)]$
- Sum rule verified to ±10%
- Kinematic range accessible with existing accelerators exhausted.



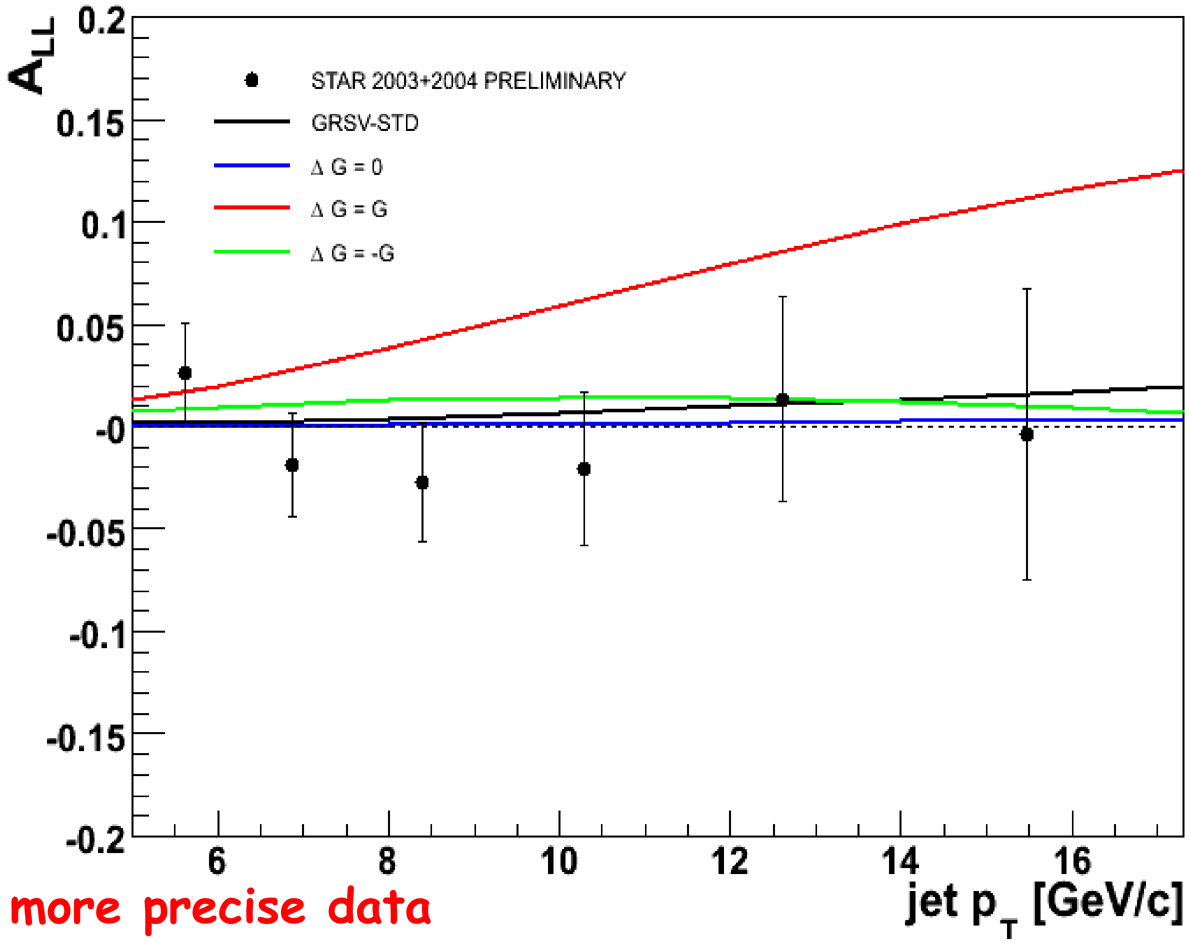
g^p_1 at low x related to $\Delta G(x)$

$x = 10^{-3} \rightarrow 0.7$
$Q^2 = 0 \rightarrow 10^3$ GeV
Fixed target experiments
1989 – 1999 Data

$x = 10^{-4} \rightarrow 0.7$
$Q^2 = 0 \rightarrow 10^4$ GeV
EIC 250 x 10 GeV
Lumi=85 pb^{-1}/day



Gluon polarization from STAR

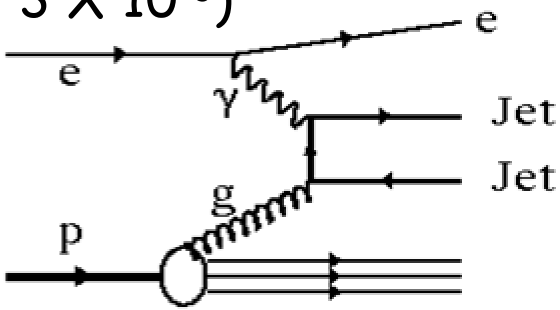


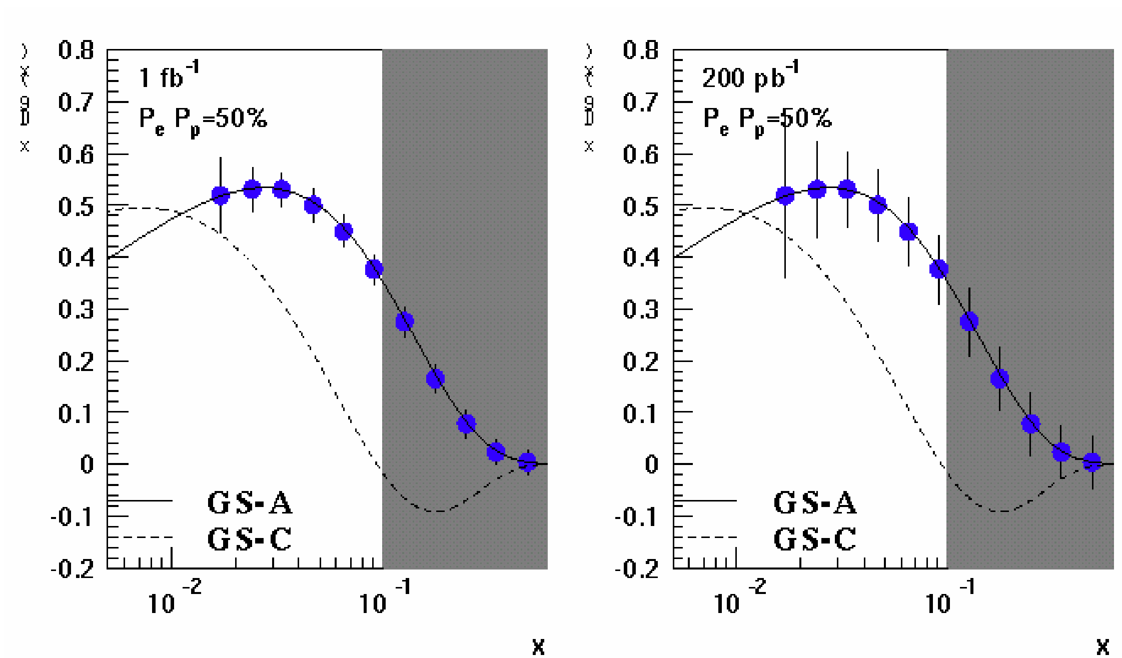
New more precise data

STAR preliminary 2003+4 results for double longitudinal spin asymmetry A_{LL} versus jet p_T in p + p → jet + X, compared with NLO pQCD

$\Delta G(x,Q^2)$ 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



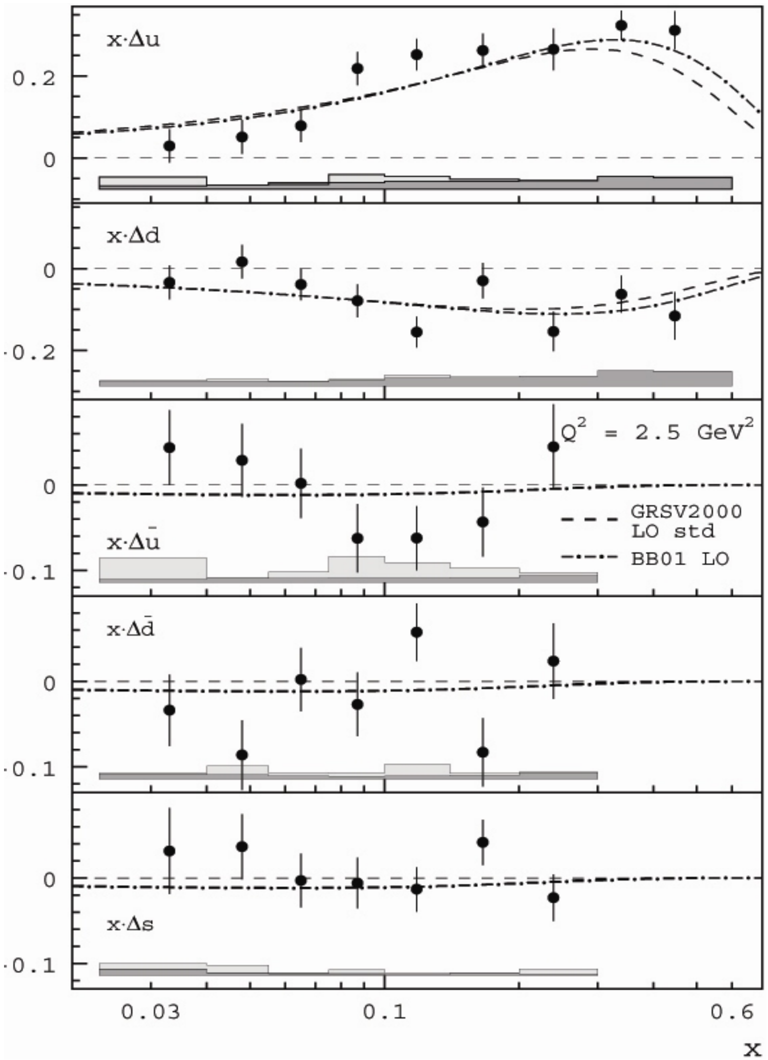


1 fb^{-1} in ~2 weeks at EIC

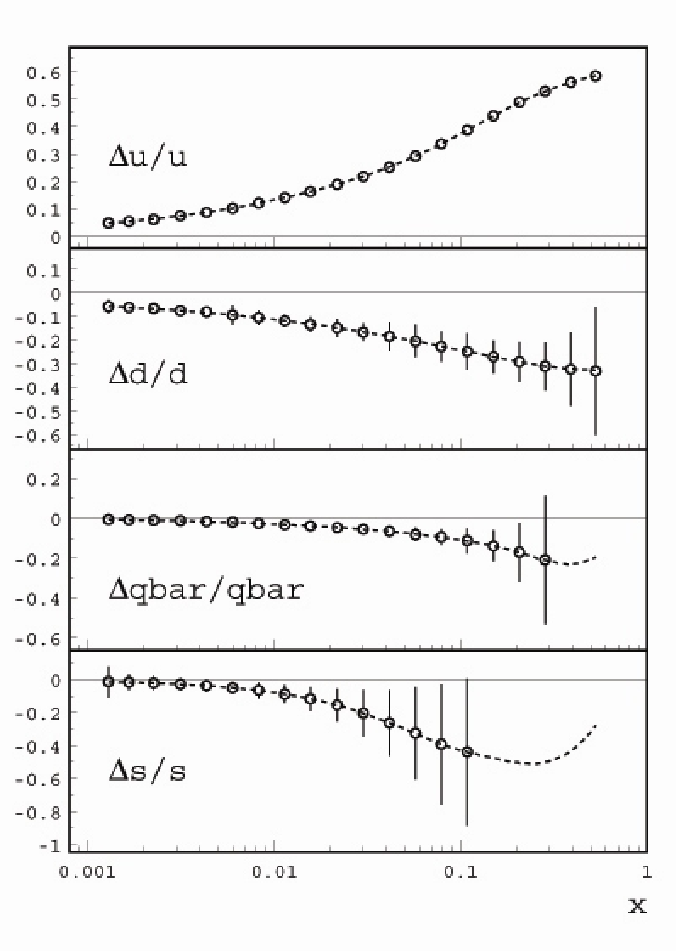
Scaling violation data plus di-jet analysis will yield total uncertainty ~ 5% after 1 year

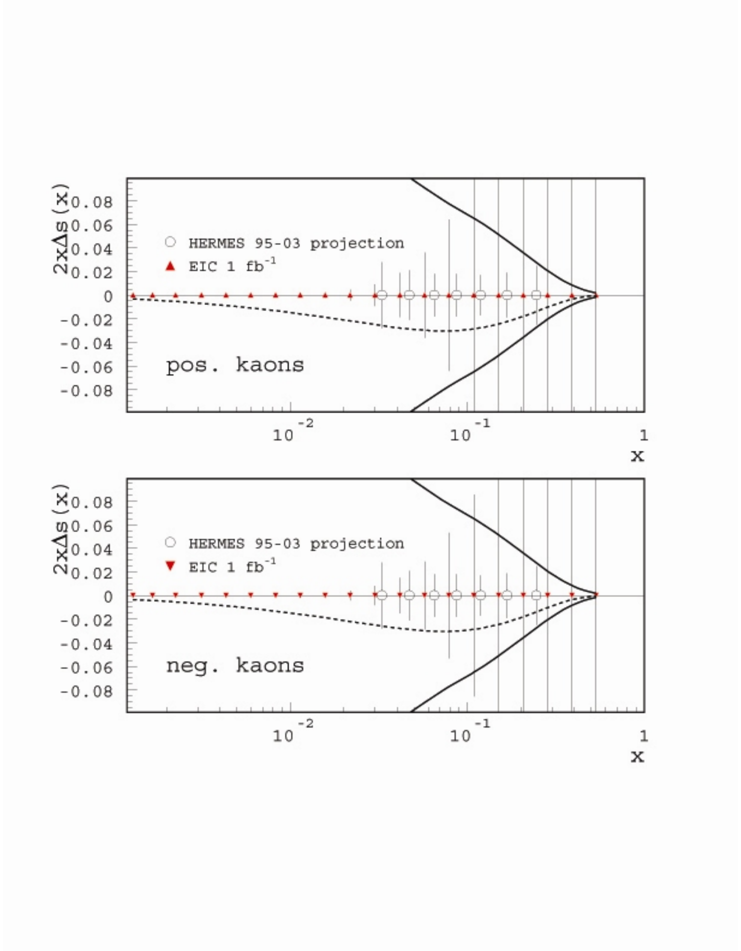
HERMES Flavor Decomposition of Quark Spin

Semi-inclusive DIS

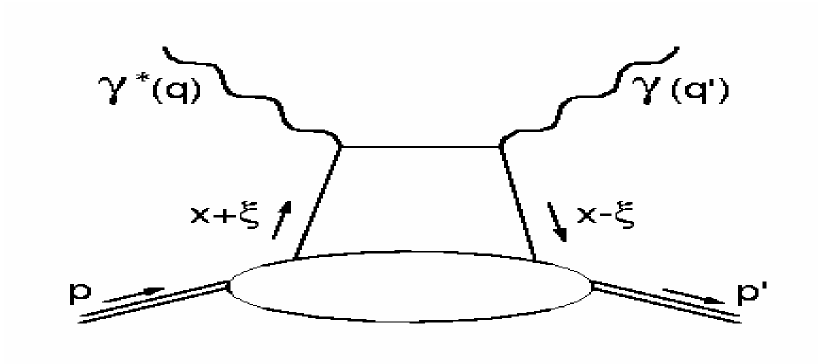


EIC determination of polarized quarks and anti-quarks



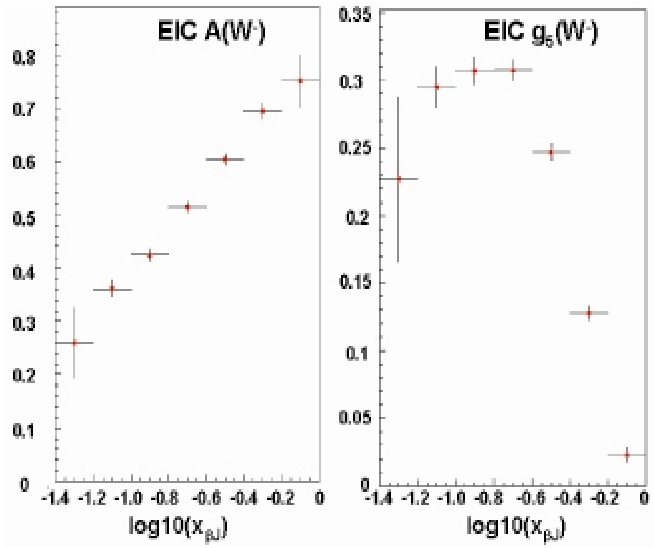


Orbital Angular Momentum



- At this time, it is not known how to determine the contribution of orbital angular momentum.
- One promising avenue being pursued is to measure a photon or meson in coincidence with the scattered lepton.
- New types of quark distribution functions arise.
- 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.
- Study of this important issue by both theorists and experimentalists continues

Parity violating lepton scattering



- W^+ and W^- exchange probed via parity violating scattering
- This measurement requires a polarized positron beam.
- It will provide new combinations of Δu, Δd, Δs etc.
- **Δs and Δsbar can be isolated**.
- There is an analog sum rule to the Bjorken Sum Rule.

Summary

- Spin plays an essential role in our understanding of the structure of matter
- Spin in atomic and nuclear systems is well understood.
- The spin of the proton is not understood in terms of the quarks and gluons of QCD.
- The capabilities of present lepton scattering facilities have been exhausted. JLab@12 GeV will continue study of the valence quark region at low Q^2. RHIC-spin will provide new insight into the role of gluons and sea quarks in a limited x-region.
- Polarized $e^{\pm}$ probes in collider geometry will offer unprecedented access to the sea quarks and gluons of the nucleon.