

Polarized Physics with an Electron-Ion-Collider

Antje Bruell, Jlab
DIS2007

- What is the EIC ?
- Central Questions in Nucleon Structure
- The longitudinal structure function F_L
- The Gluon Contribution to the Nucleon Spin
- TMDs and GPDs at EIC

What is the EIC ?

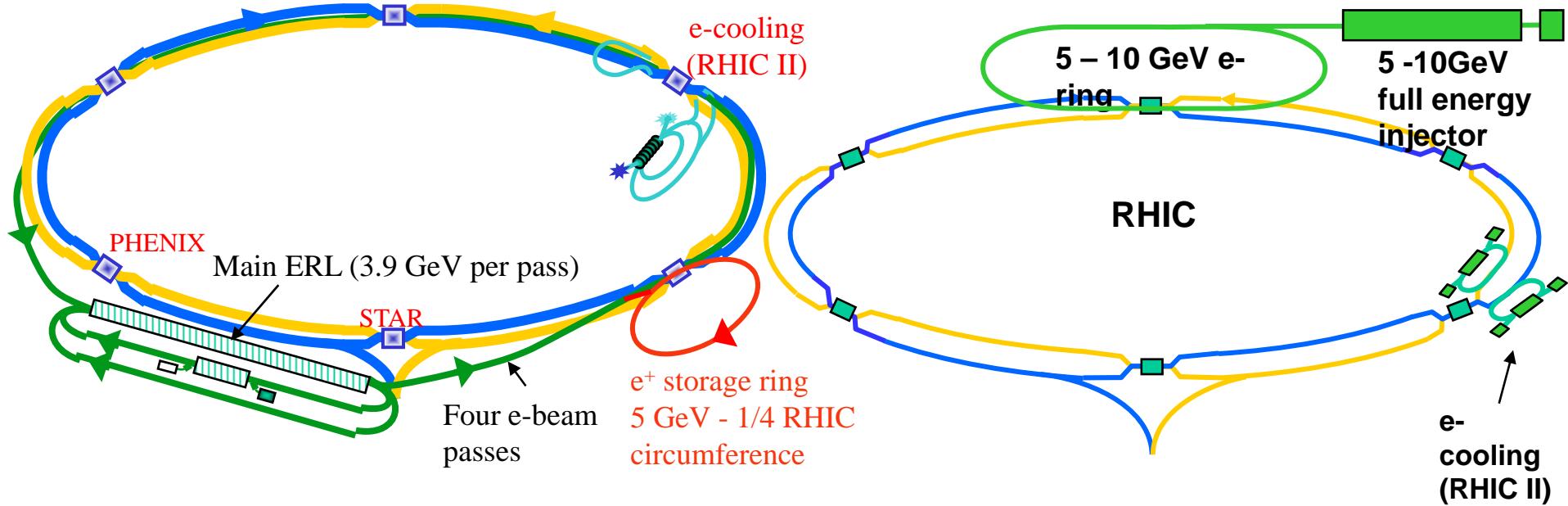
Electron Ion Collider as the ultimate QCD machine

- Variable center of mass energy between 20 and 100 GeV
- High luminosity
- Polarized electron and proton (deuteron, ${}^3\text{He}$) beams
- Ion beams up to $A=208$

**Explore the new QCD frontier:
strong color fields in nuclei**

**Precisely image the sea-quarks
and gluons in the nucleon**

2 different eRHIC Design options



- Electron energy range from 3 to 20 GeV
- Peak luminosity of $2.6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- high electron beam polarization (~80%)
- full polarization transparency at all energies
- multiple electron-hadron interaction points
- ± 5 meter “element-free” straight section(s)
- ability to take full advantage of electron cooling of the hadron beams;
- easy variation of the electron bunch frequency to match the ion bunch frequency at different ion energies.

- Based on existing technology
- Collisions at 12 o’clock interaction region
- 10 GeV, 0.5 A e-ring with 1/3 of RHIC circumference (similar to PEP II HER)
- Inject at full energy 5 – 10 GeV
- Polarized electrons and positrons

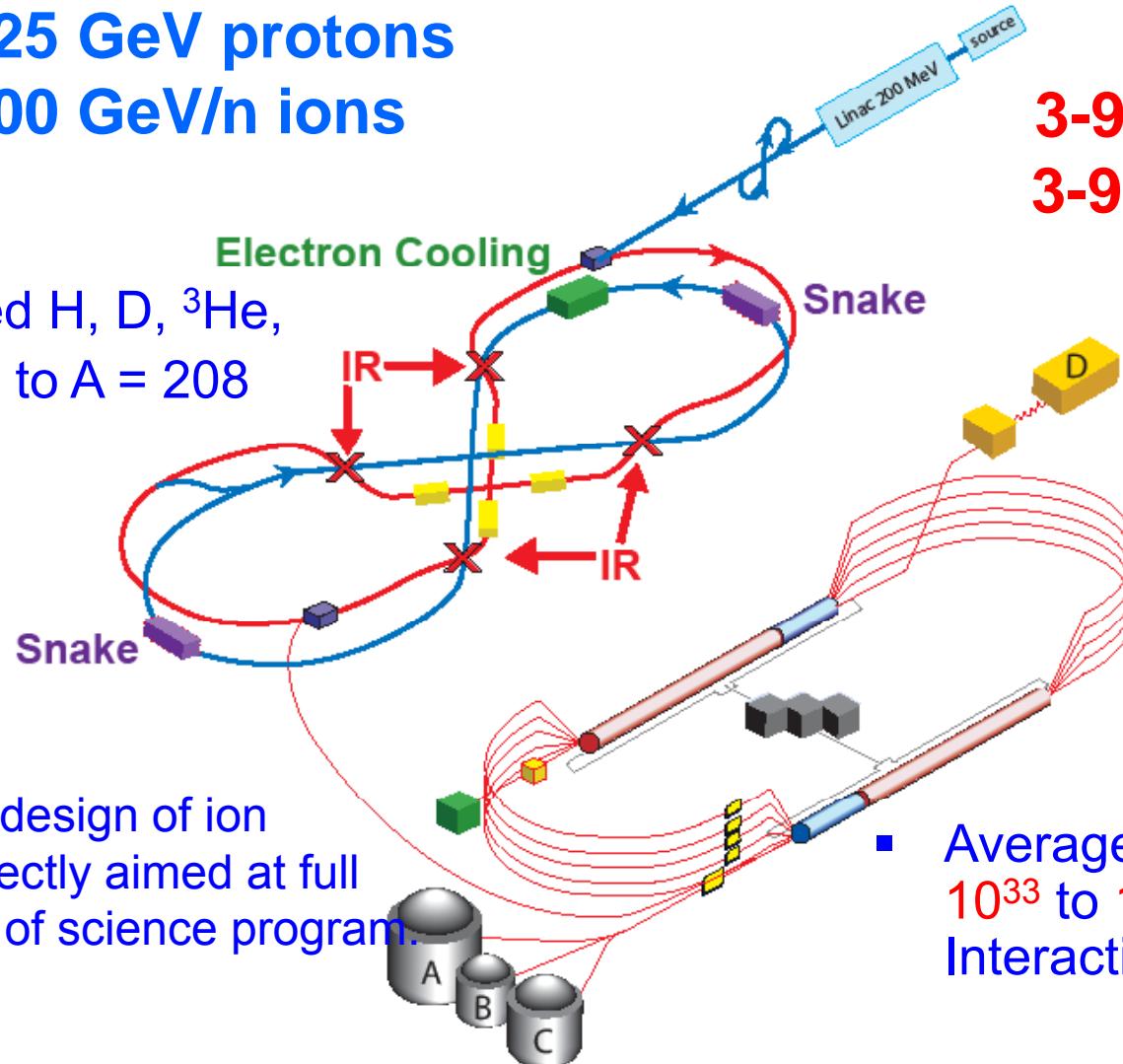
ELIC design at Jefferson Lab

30-225 GeV protons

30-100 GeV/n ions

3-9 GeV electrons
3-9 GeV positrons

- Polarized H, D, ^3He ,
- Ions up to A = 208

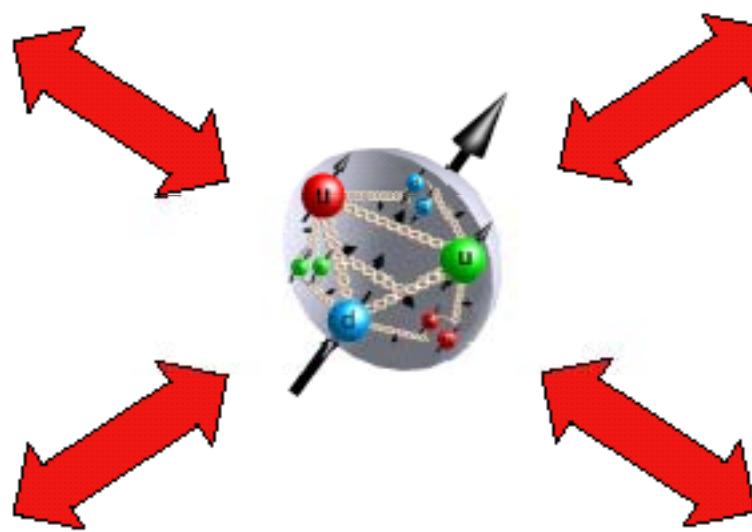


Green-field design of ion complex directly aimed at full exploitation of science program.

- Average Luminosity from 10^{33} to $10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$ per Interaction Point

Exploring the nucleon: Of fundamental importance in science

Know what we
are made of !

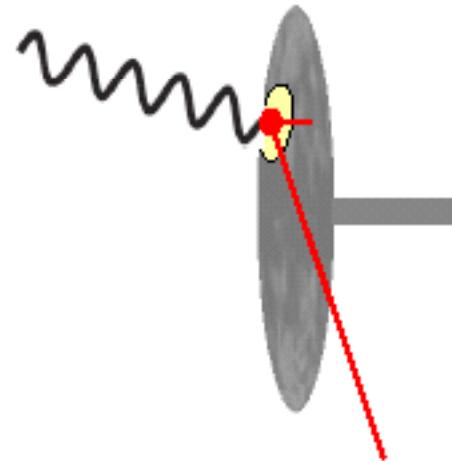


Explore and
Understand QCD:
Lattice, Models

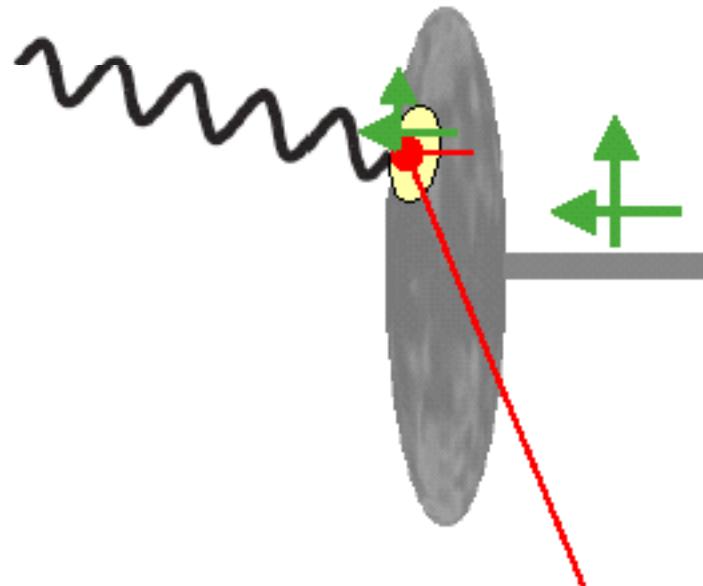
Test our ability
to use QCD:
Asymptotic Freedom,
Factorization

Nucleon as tool for
discovery:
RHIC Heavy Ions, LHC
Tevatron High- E_T jets
NuTeV anomaly, ...

Questions to ask:

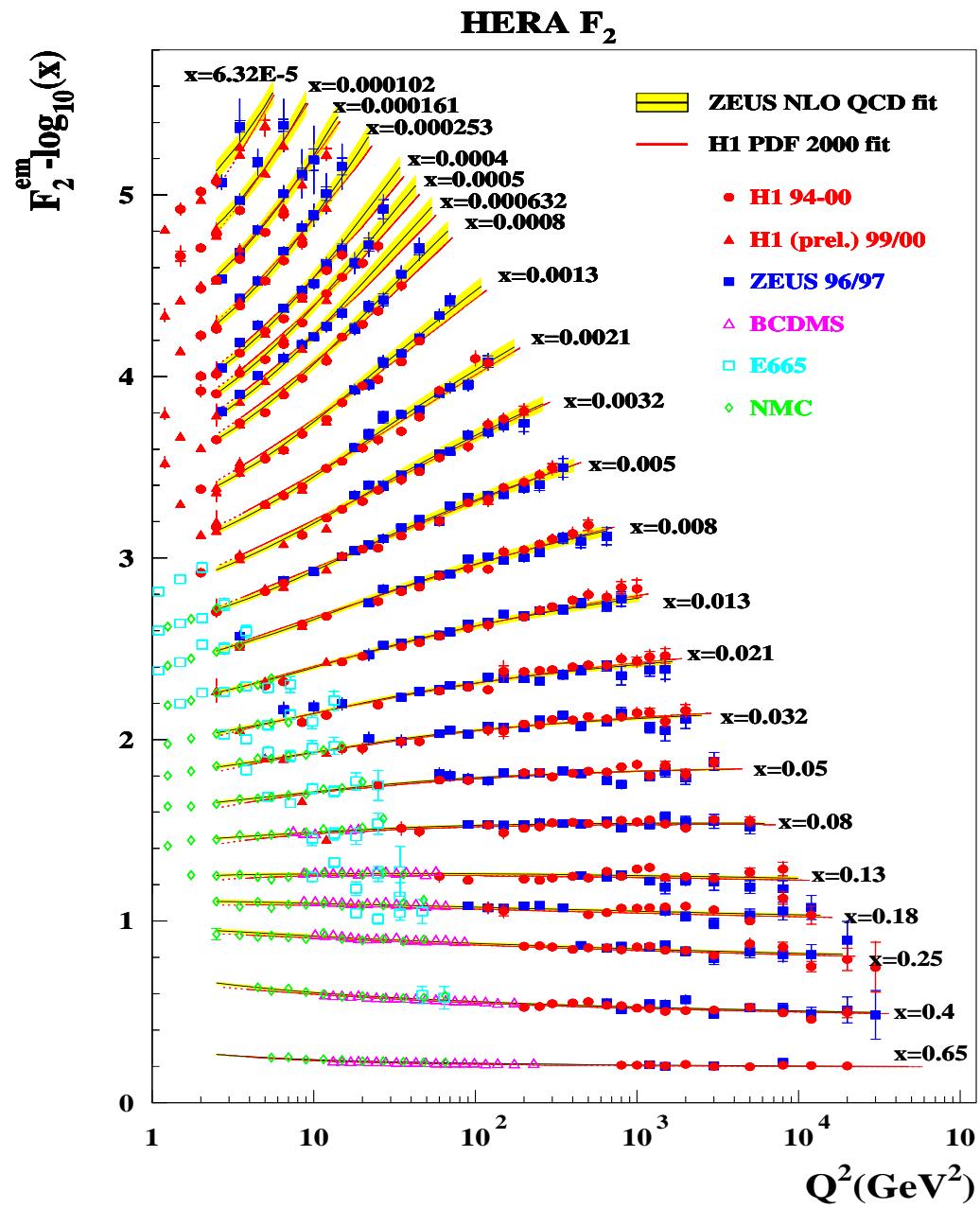


- What are the momentum distributions of quarks, anti-quarks, and gluons ? $p = x P$
- What flavor symmetries hold-- or how are they broken ? \bar{u} vs. \bar{d} s vs. \bar{s} ?
Isospin-symmetry between p and n ?
- How are quarks and gluons distributed spatially ?

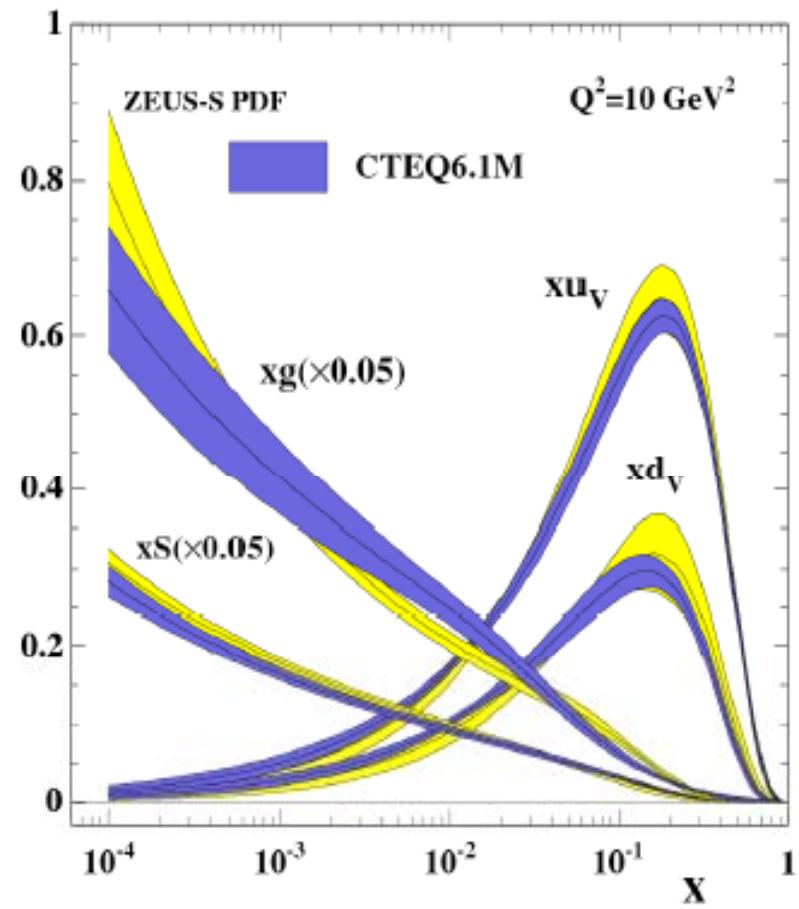


- How do partons carry the proton spin-1/2 ?
(Spins & orbital angular momenta)
- What difference does \leftarrow vs. \uparrow make ?
What novel features arise ?
- How are quarks and gluons correlated ?

World Data on F_2^p Structure Function



Next-to-Leading-Order (NLO)
perturbative QCD (DGLAP) fits

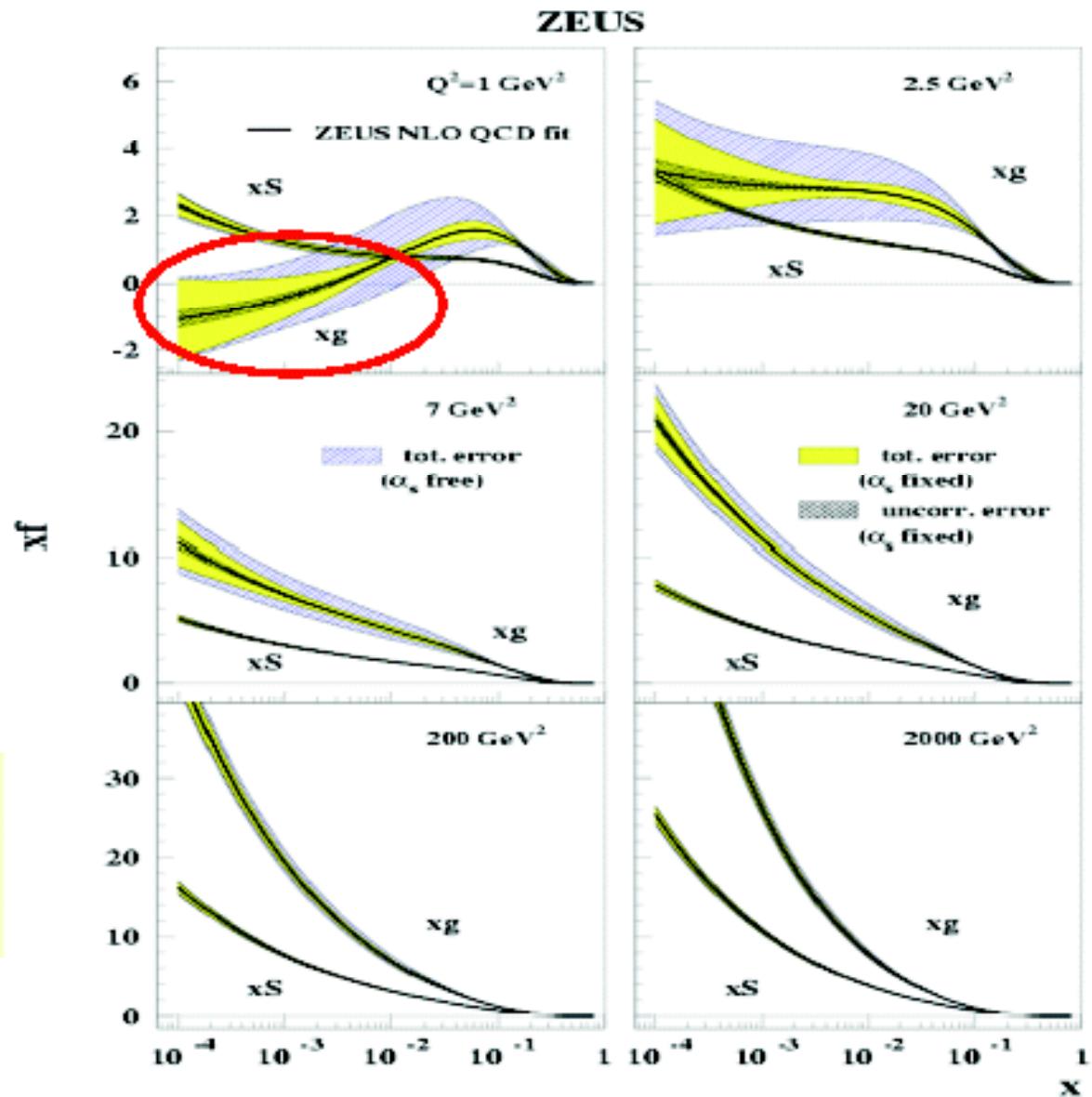


Negative gluon distribution!

- NLO global fitting based on leading twist DGLAP evolution leads to negative gluon distribution
- MRST PDF's have the same features

Does it mean that we have no gluons at $x < 10^{-3}$ and $Q=1 \text{ GeV}$?

No!



F_L

Need better data to test whether our parton densities are reasonable. The structure function F_L will provide an important test.

negligible at small Q^2

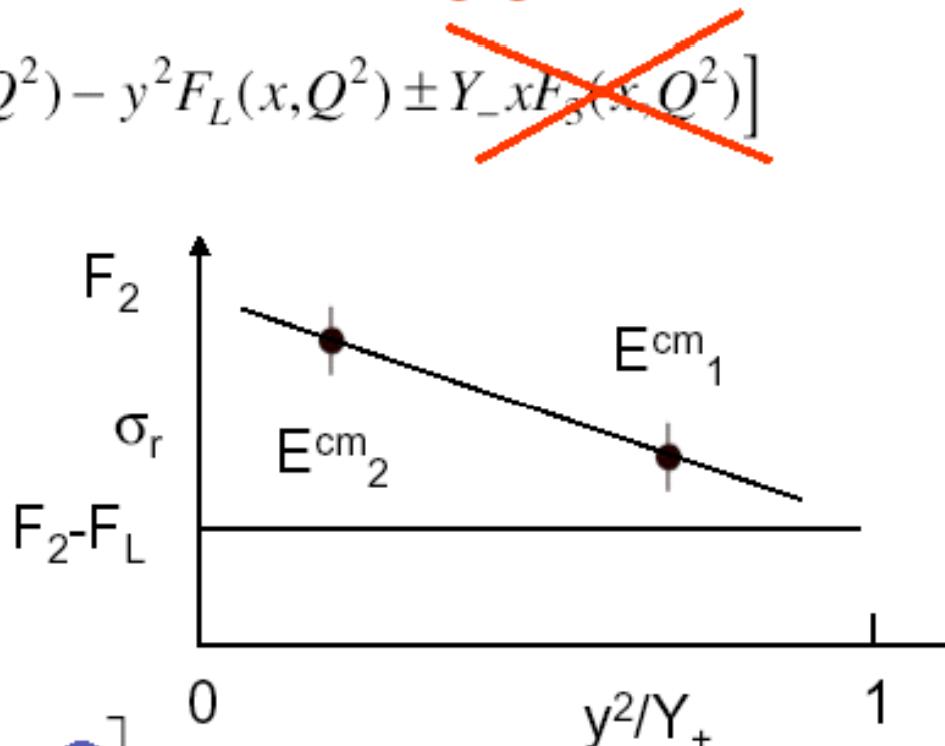
$$\frac{d^2\sigma(e^\mp p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} [Y_+ F_2(x, Q^2) - y^2 F_L(x, Q^2) \pm Y_- x F_S(x, Q^2)]$$

$$Y_\pm = (1 \pm (1-y)^2)$$

Need two beam energies to measure F_L

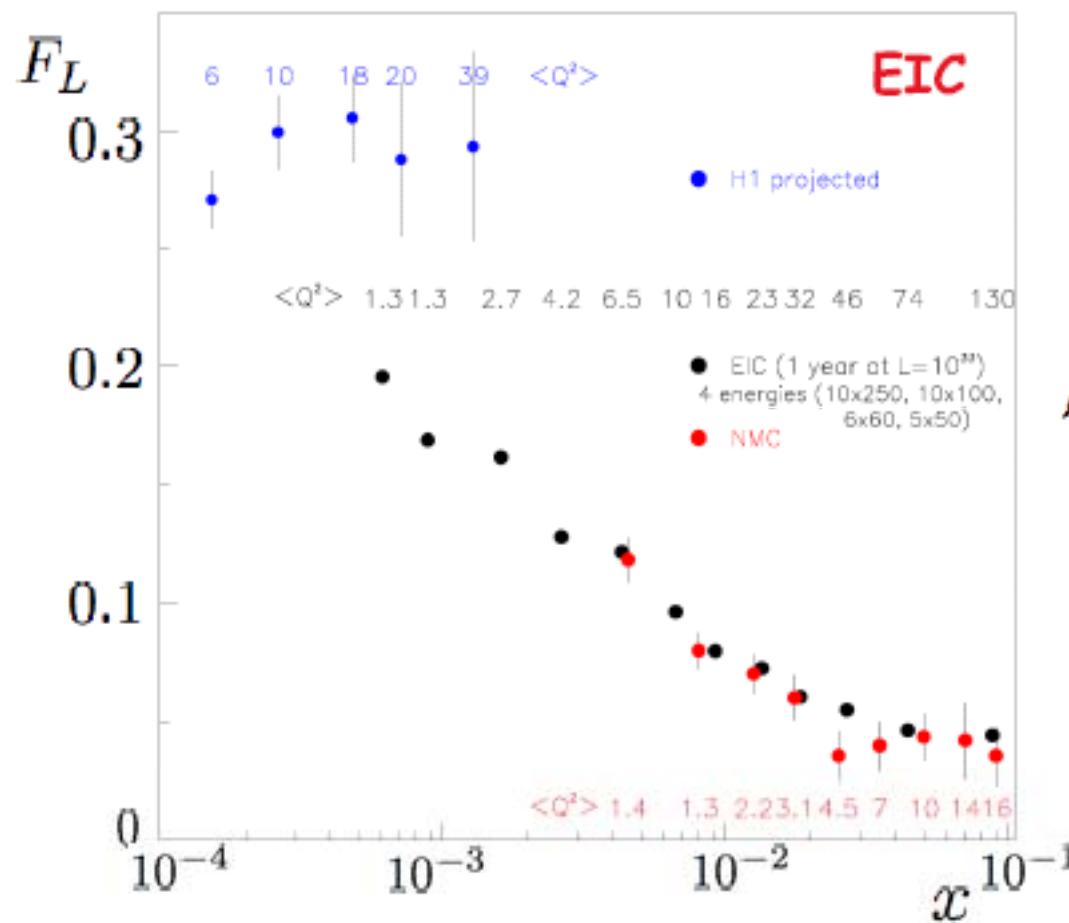
$$F_L = \left(\frac{Q^2}{4\pi^2\alpha} \right) \sigma_L$$

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^z \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum e_q^2 \left(1 - \frac{x}{z} \right) g \right]$$



Directly sensitive to xg at small- x

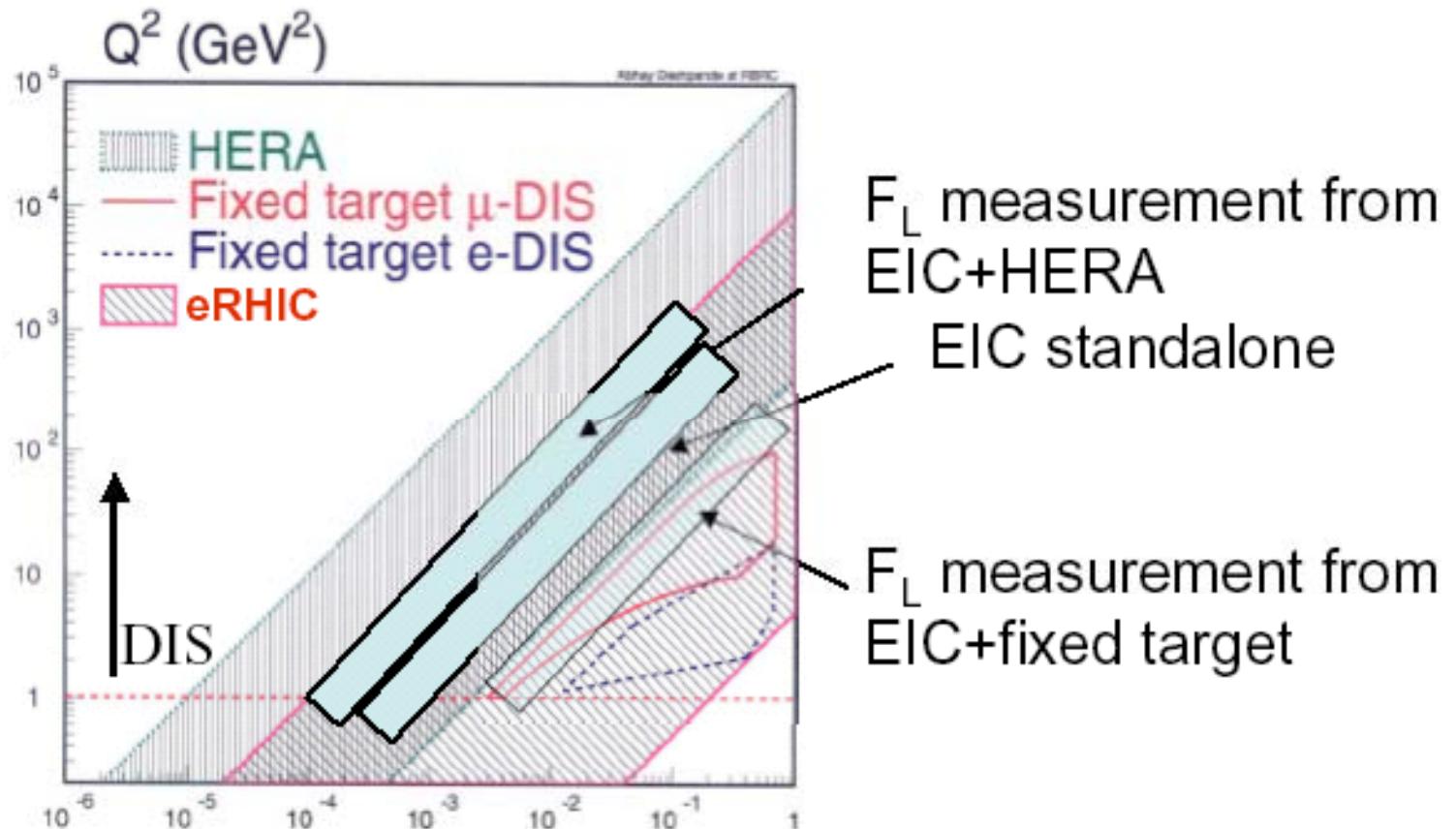
$$F_L \propto \frac{\alpha_s}{2\pi} x \int_x^1 \frac{d\xi}{\xi} \xi(1-\xi) g\left(\frac{x}{\xi}, Q^2\right) + \dots$$



A. Bruell, R. Ent

One observable among many: $dF_2/d\log(Q^2)$, $e p \rightarrow \text{jet+jet+X}$, charm, ...

F_L : EIC & other Measurements



EIC is in an optimal energy range to extract F_L via cross section comparisons to previous experiments.

Where is the nucleon spin ?

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

~ 0.25

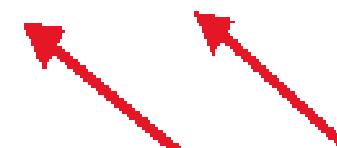
$q+\bar{q}$ spin contribution



Gluon spin contribution

$$\int_0^1 dx \Delta g(x)$$

Orbital ang.
momenta

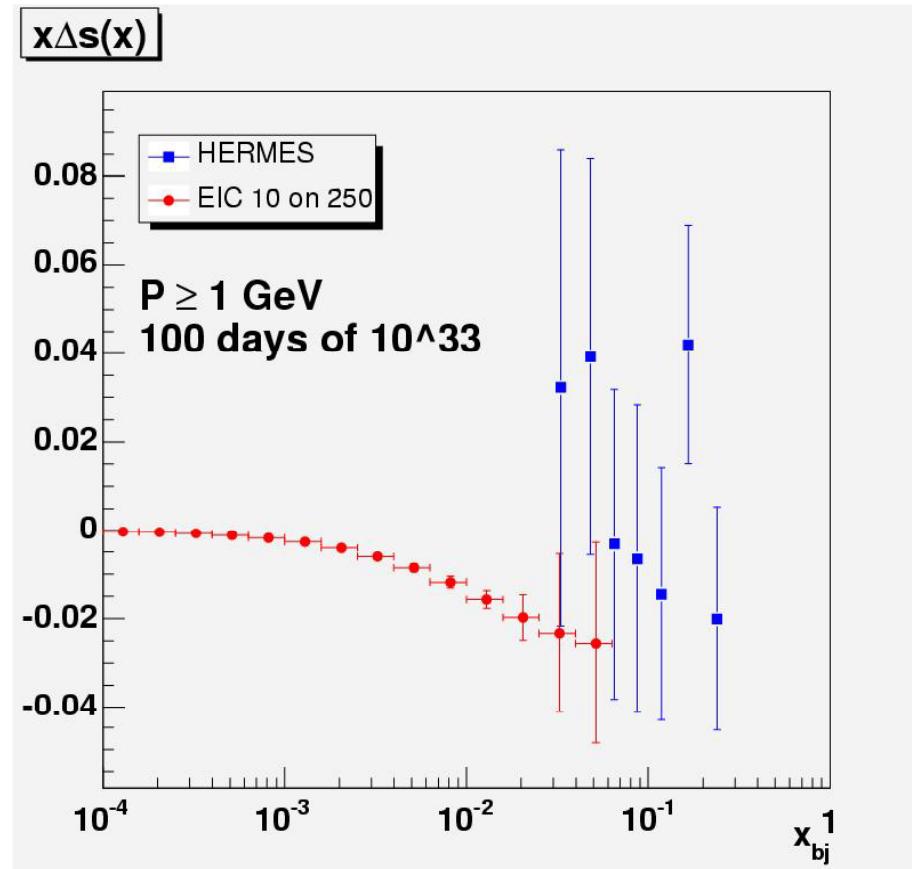
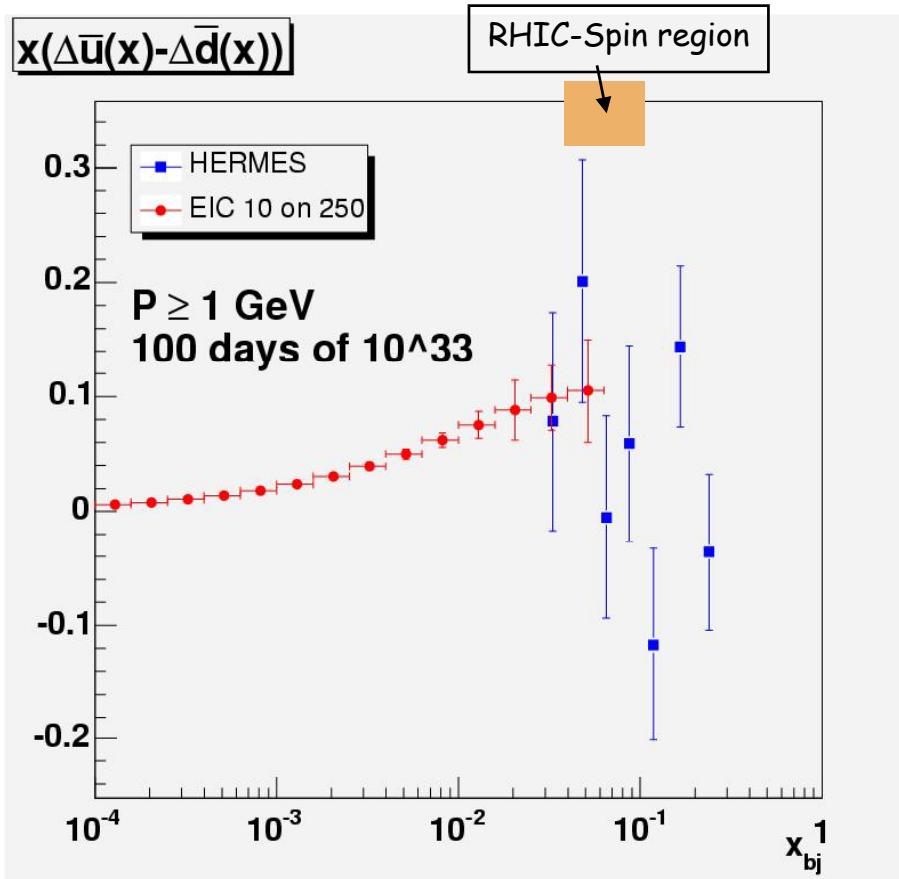
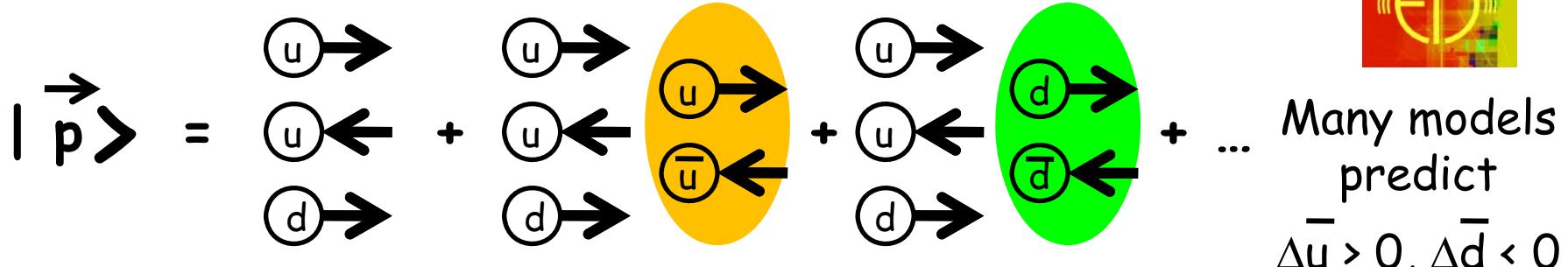


?

$$\frac{1}{2} \int_0^1 dx [\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}]$$

Precisely image the sea quarks

Spin-Flavor Decomposition of the Light Quark Sea

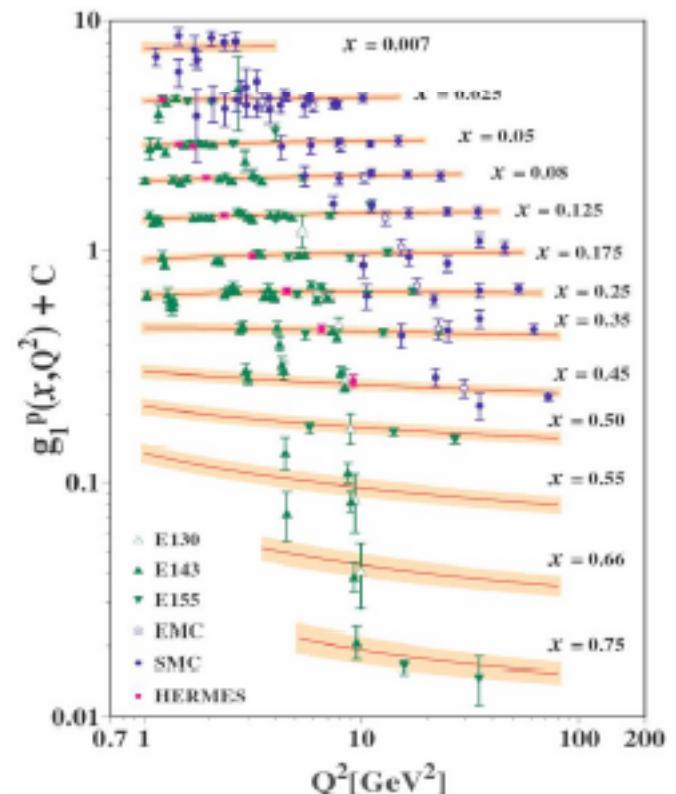
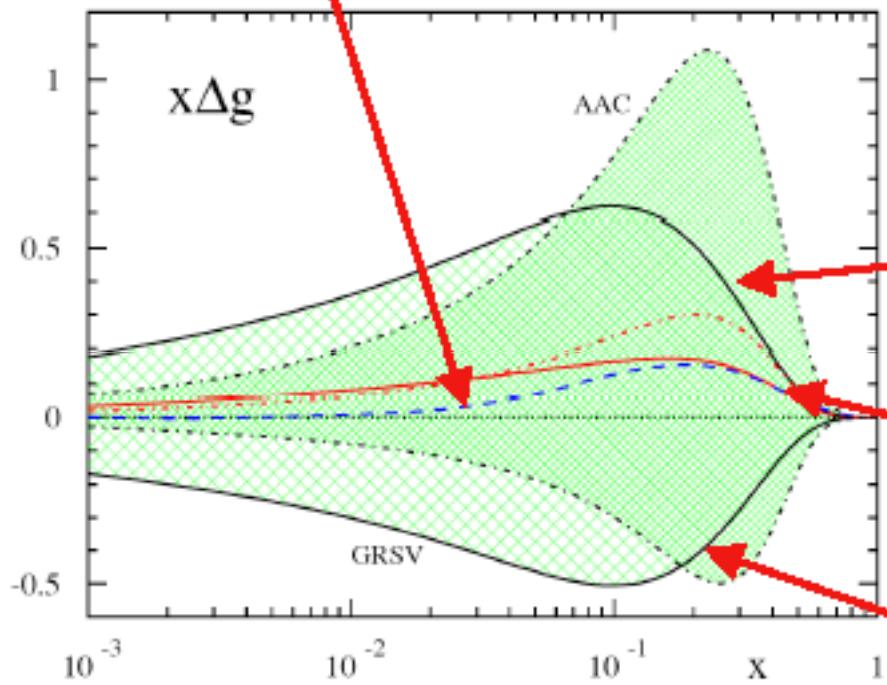


The gluon spin distribution Δg

Not much information until recently:

$$\frac{dg_1}{d\log(Q^2)} \propto \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x, Q^2) + \text{quark contrib.}$$

Bag model Chen, Ji $\Delta G \approx 0.3$



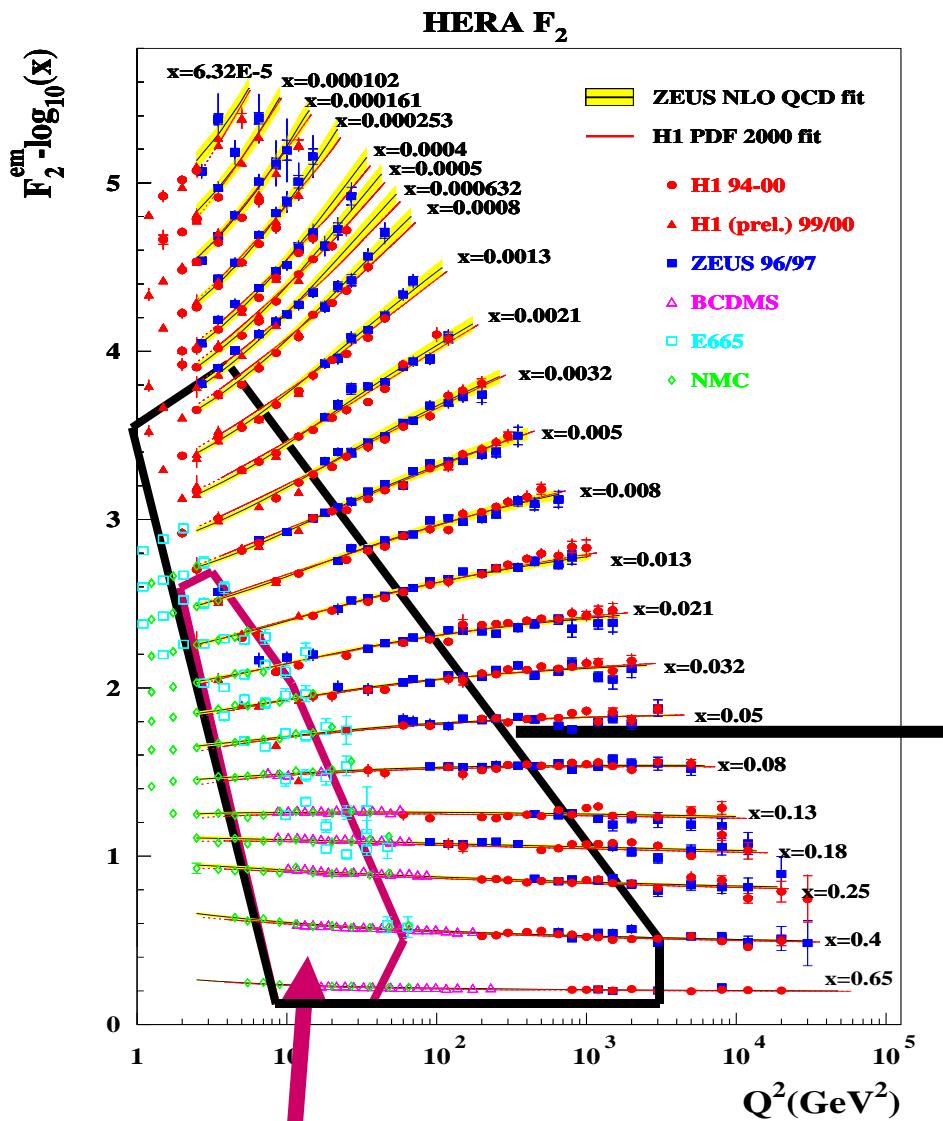
$\Delta G \approx 1.8$ (@ 1 GeV 2)

"axial anomaly" Altarelli et al.

$\Delta G \approx 0.4$

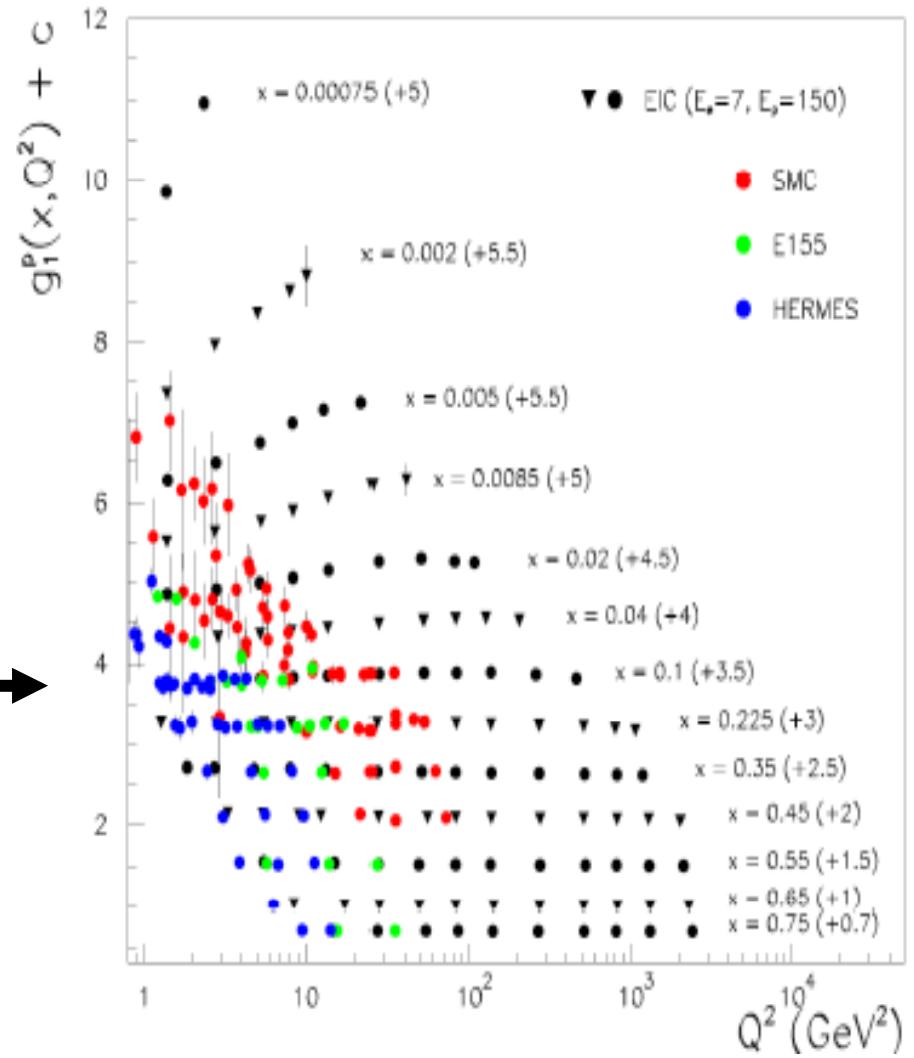
$\Delta G \approx -1.7$

World Data on F_2^p



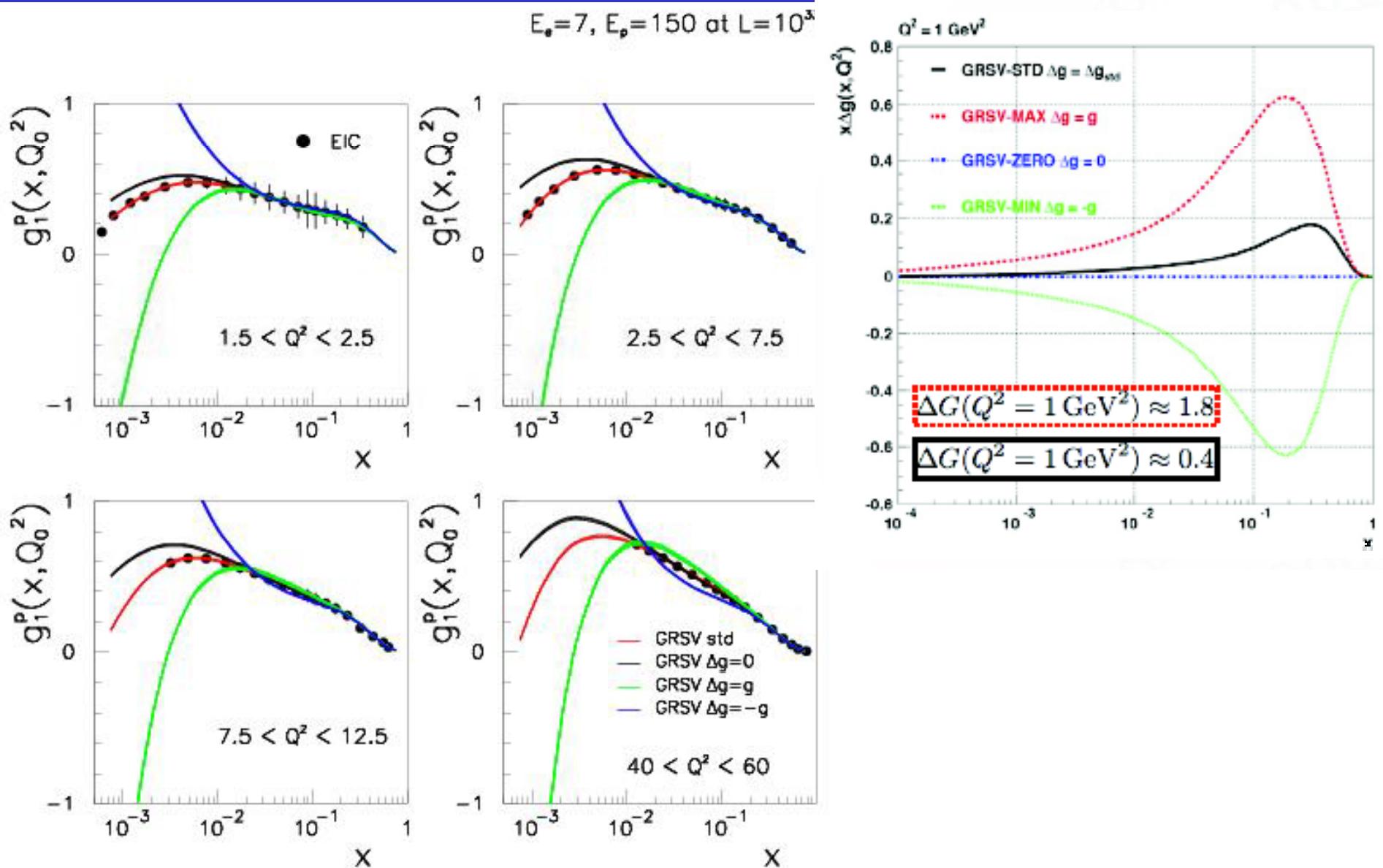
Region of existing g_1^p data

EIC Data on g_1^p



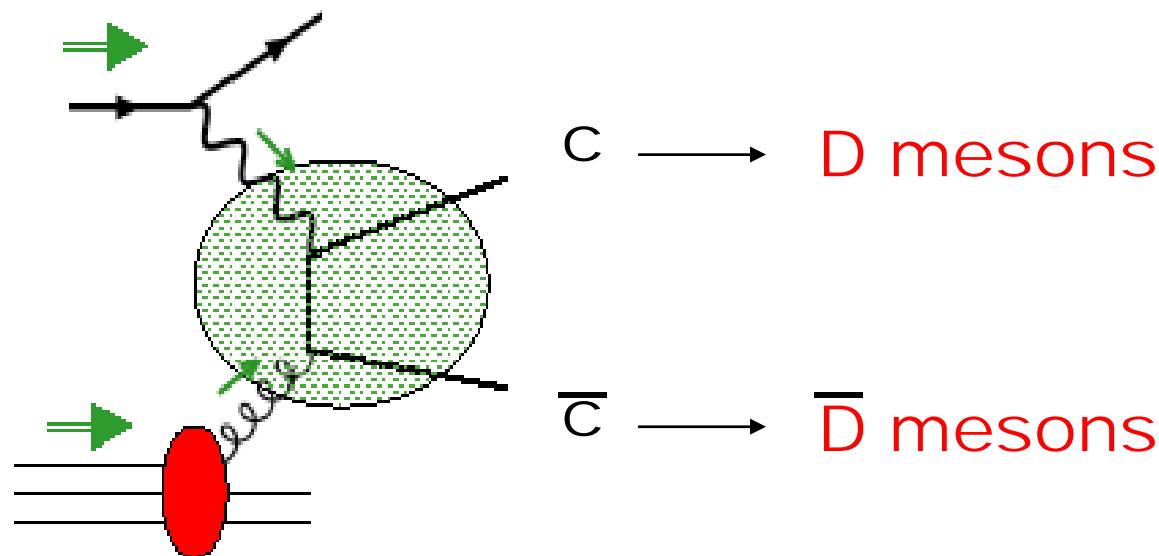
An  makes it possible!

ΔG from scaling violations of g_1



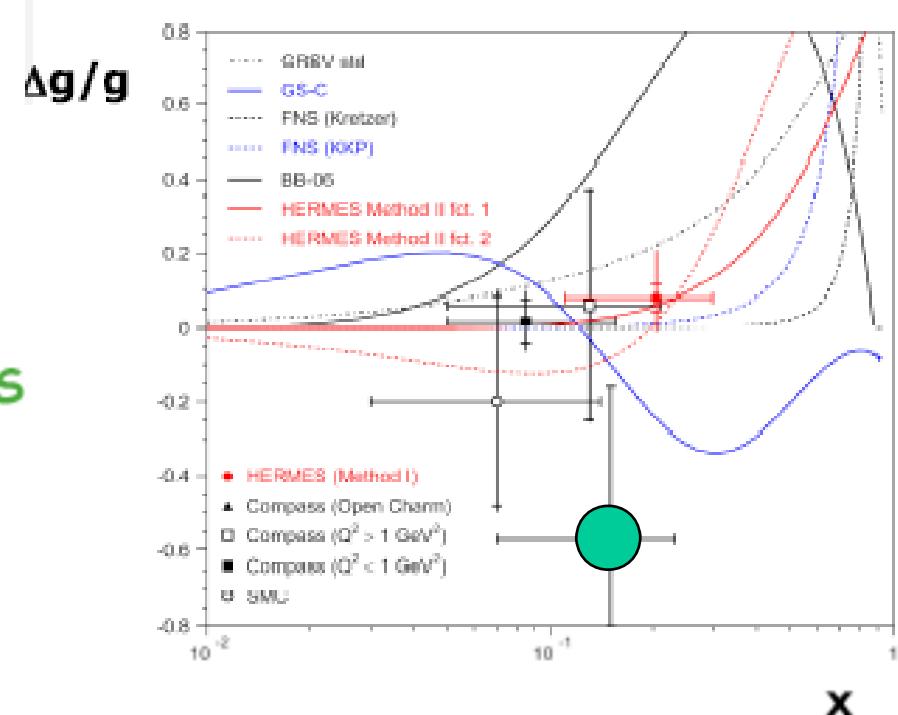
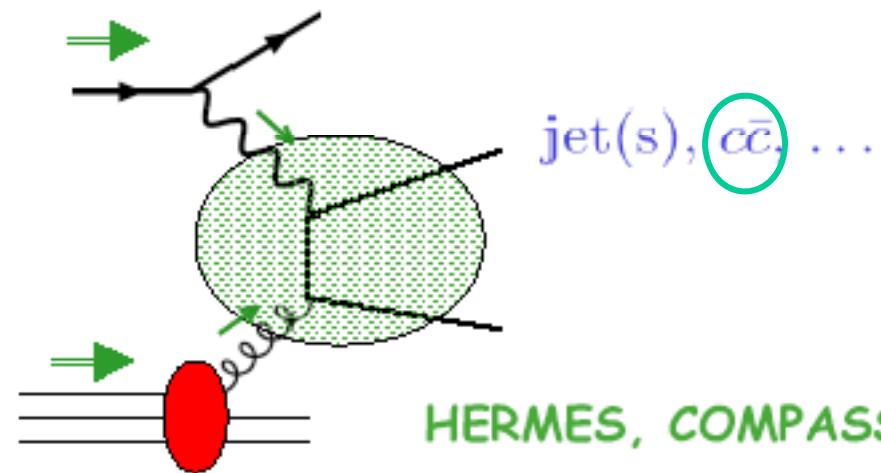
Polarized gluon distribution via charm production

very clean process !



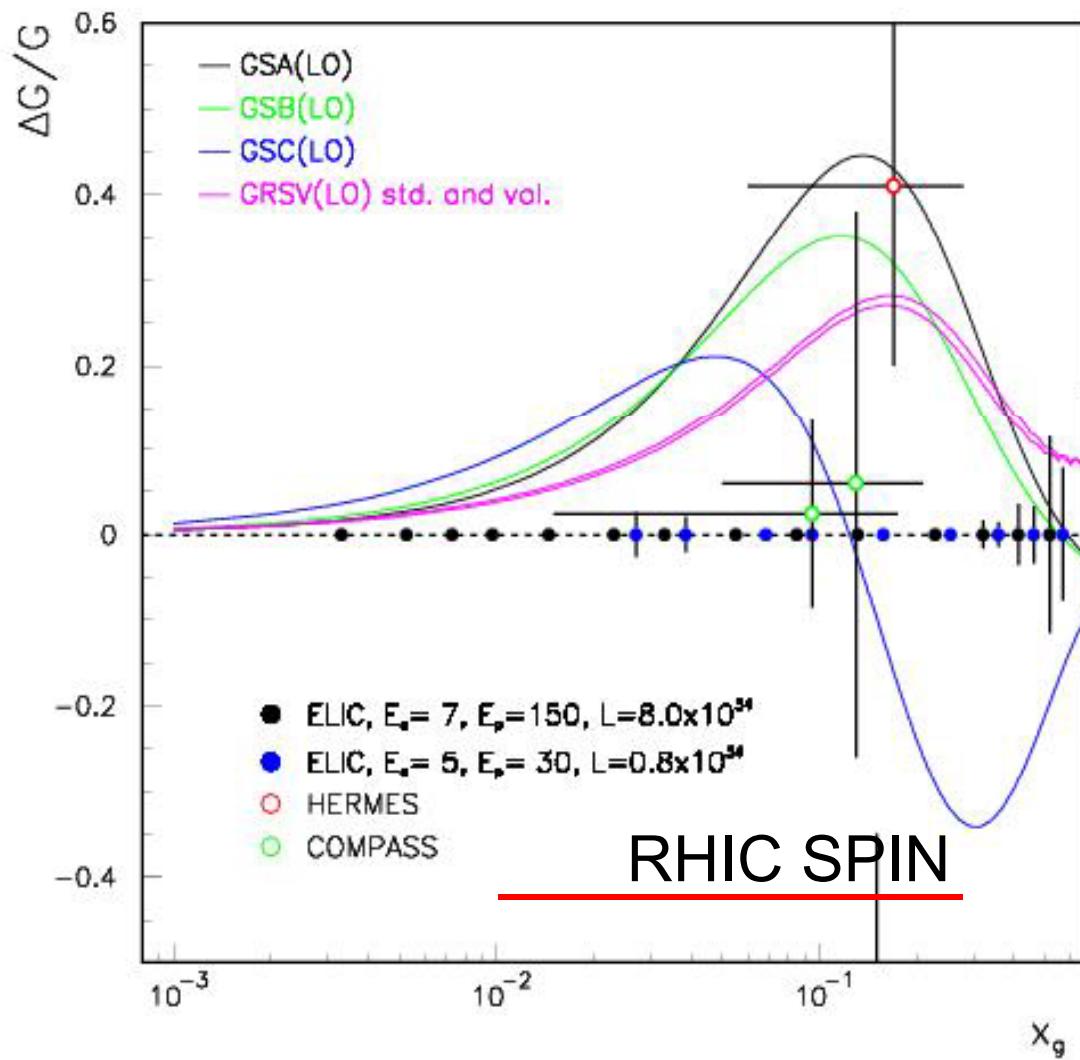
LO QCD: asymmetry in D production directly
proportional to $\Delta G/G$

Polarized gluon distribution via charm production



problems: luminosity, charm cross section, **background !**

Polarized gluon distribution via charm production



Precise determination of $\Delta G/G$ for $0.003 < x_g < 0.4$ at common Q^2 of 10 GeV^2

however...

Polarized gluon distribution via charm production

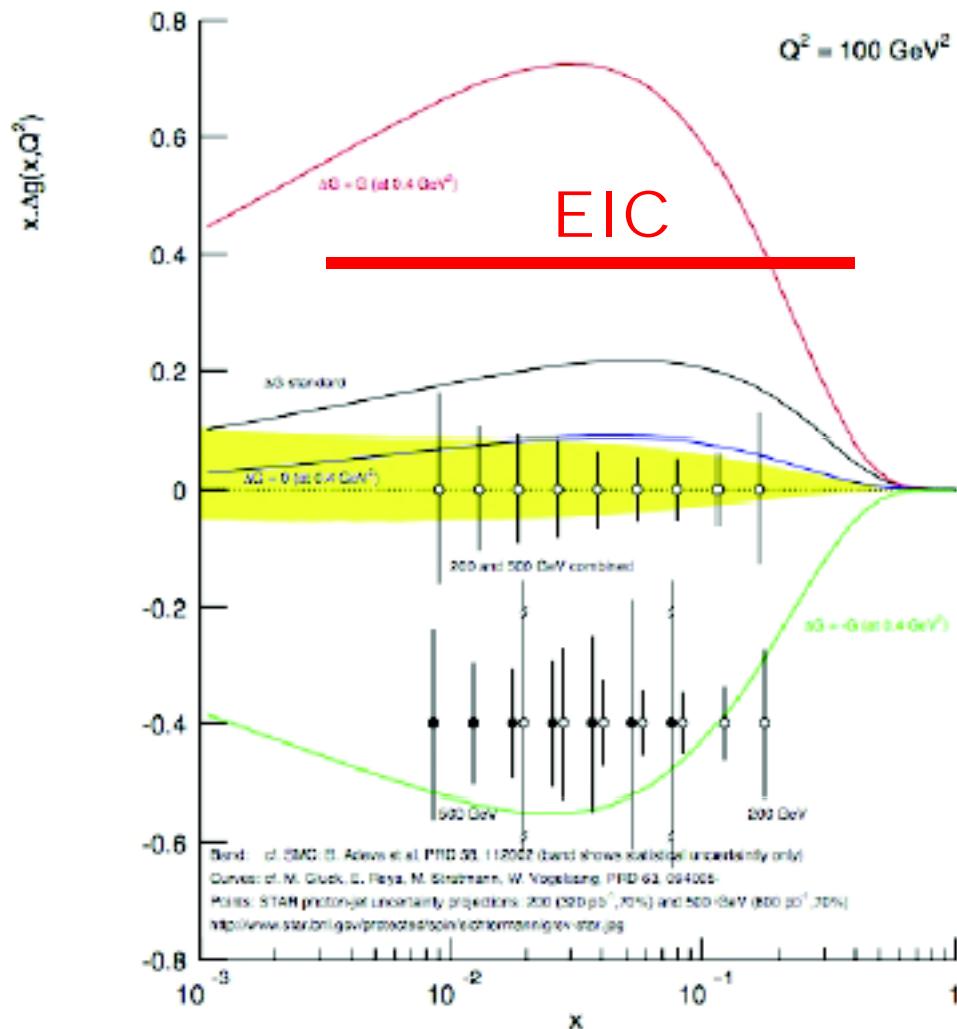
Precise
determination
of $\Delta G/G$ for
 $0.003 < x_g < 0.4$

at common Q^2
of 10 GeV^2

If:

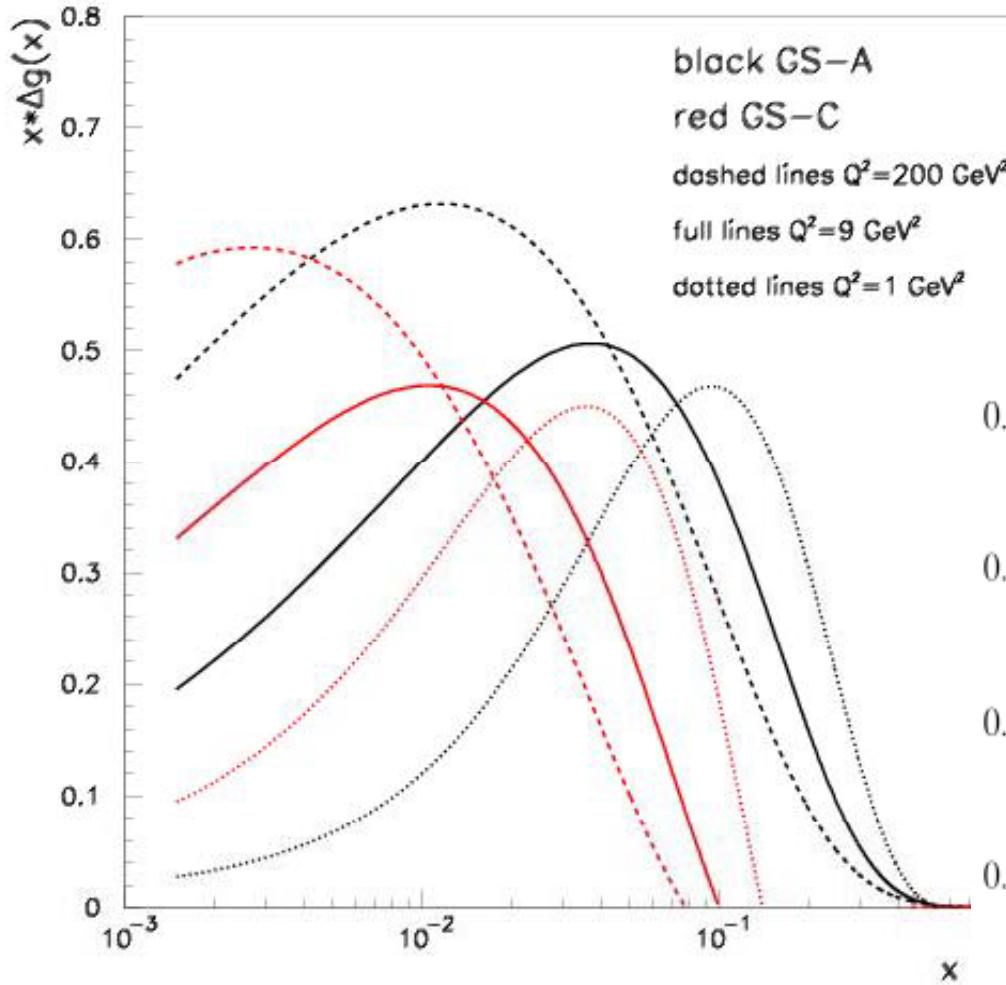
- We can measure the scattered electron even at angles close to 0° (determination of photon kinematics)
- We can separate the primary and secondary vertex down to about $100 \mu\text{m}$
- We understand the fragmentation of charm quarks (file icon)
- We can control the contributions of resolved photons
- We can calculate higher order QCD corrections (file icon)

Future: $x \Delta g(x, Q^2)$ from RHIC and EIC

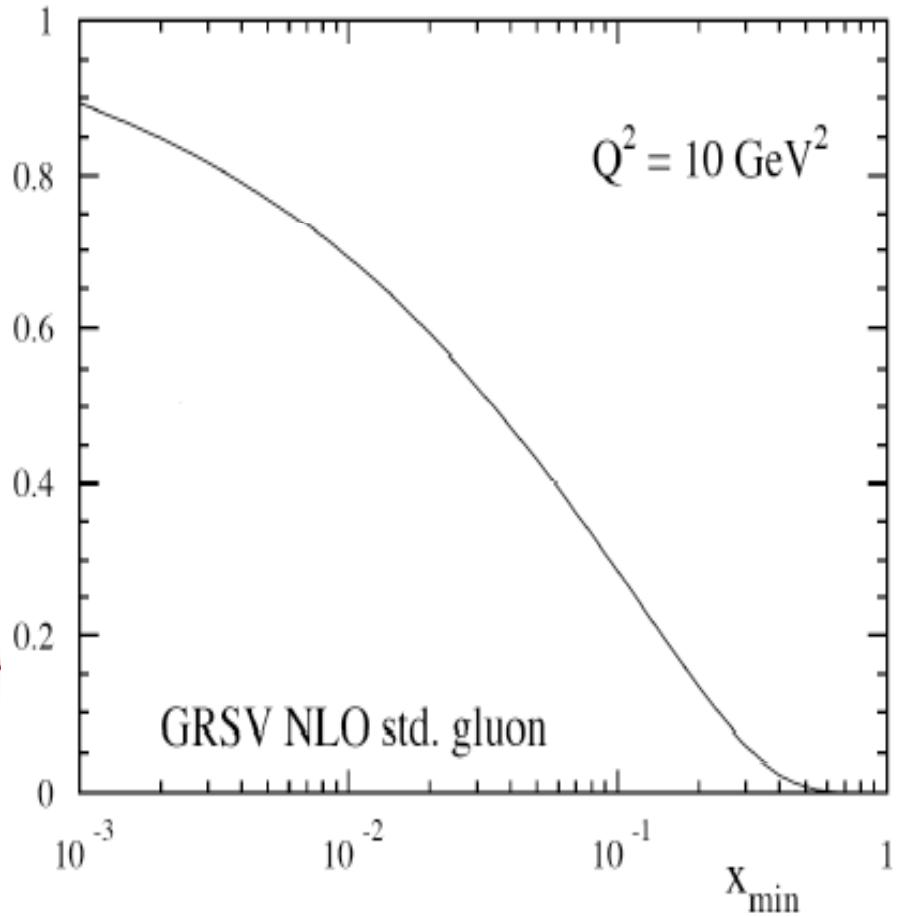


EIC
 $0.003 < x < 0.5$
uncertainty in $x\Delta g$
typically < 0.01
!!!

Polarized gluon distribution vs Q^2



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



- **Bjorken's sum rule**

$$\int_0^1 dx g_1^{ep-en}(x, Q^2) = \frac{1}{6} \frac{g_A}{g_V} \left\{ 1 - \frac{\alpha_s(Q^2)}{\pi} - \frac{43}{12} \frac{\alpha_s^2(Q^2)}{\pi^2} - 20.215 \frac{\alpha_s^3(Q^2)}{\pi^3} \right\}$$

high-order perturbation theory

$$+ \frac{M^2}{Q^2} \int_0^1 x^2 dx \left\{ \frac{2}{9} g_1^{ep-en}(x, Q^2) + \frac{1}{6} g_2^{ep-en}(x, Q^2) \right\}$$

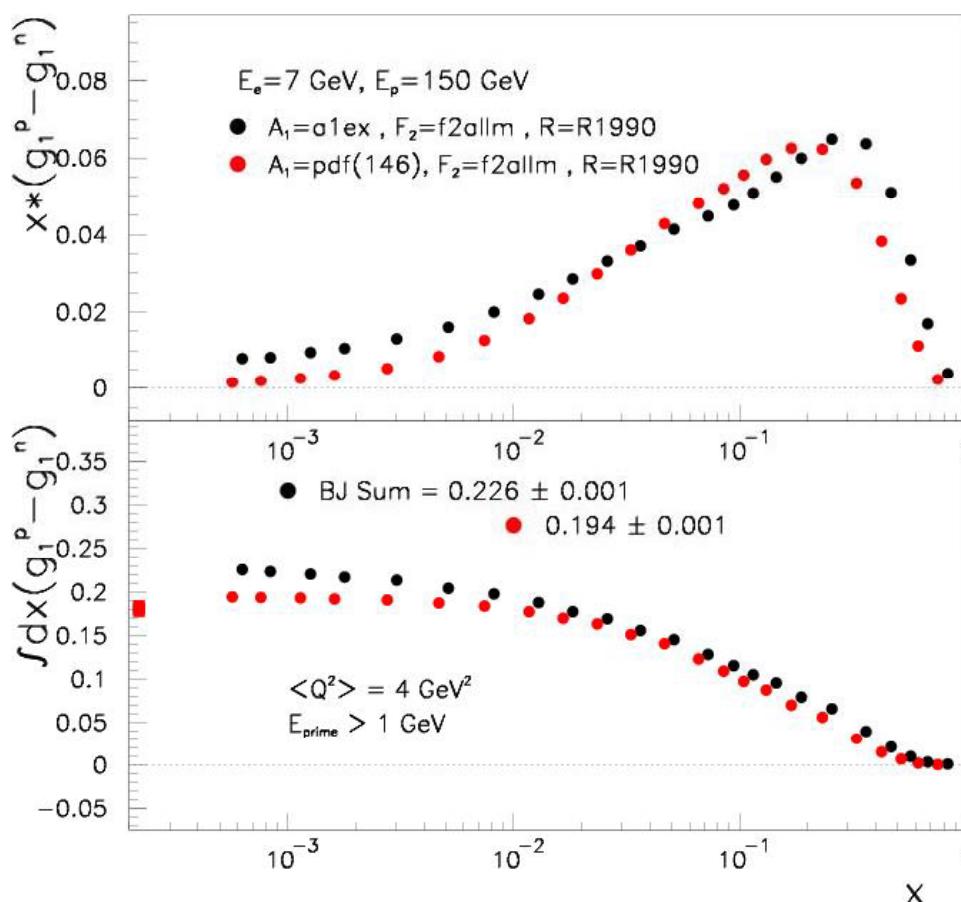
target-mass corrections

$$- \frac{1}{Q^2} \frac{4}{27} \mathcal{F}^{u-d}(Q^2)$$

Twist-4 matrix elements $\sim \langle \bar{q} \tilde{F} q \rangle$

- Precision QCD. Currently tested at $\sim 10\%$.
Can it be tested at ~ 1 or 2% ?

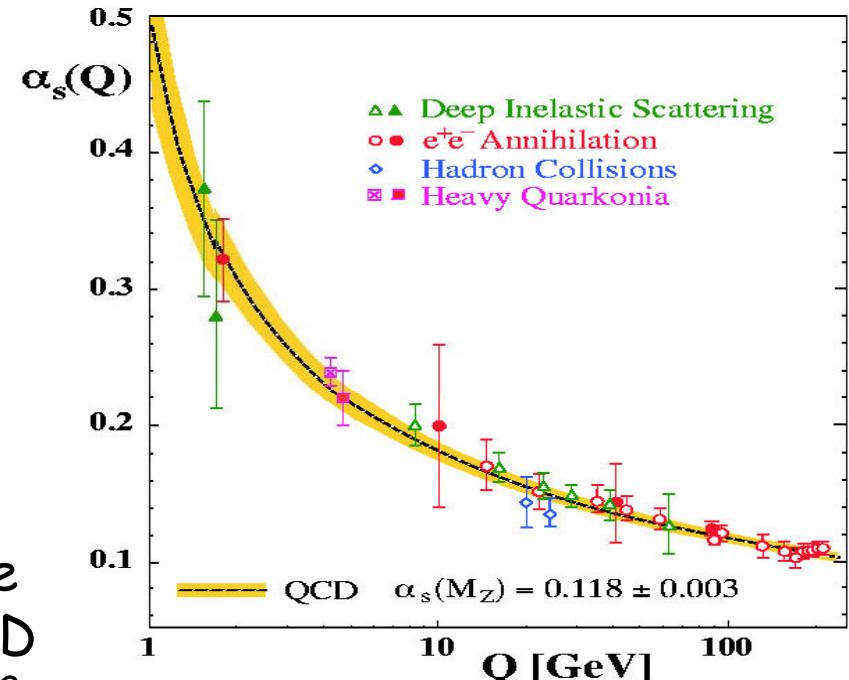
$$\text{Bjorken Sum Rule: } \Gamma_1^P - \Gamma_1^n = 1/6 g_A [1 + O(\alpha_s)]$$



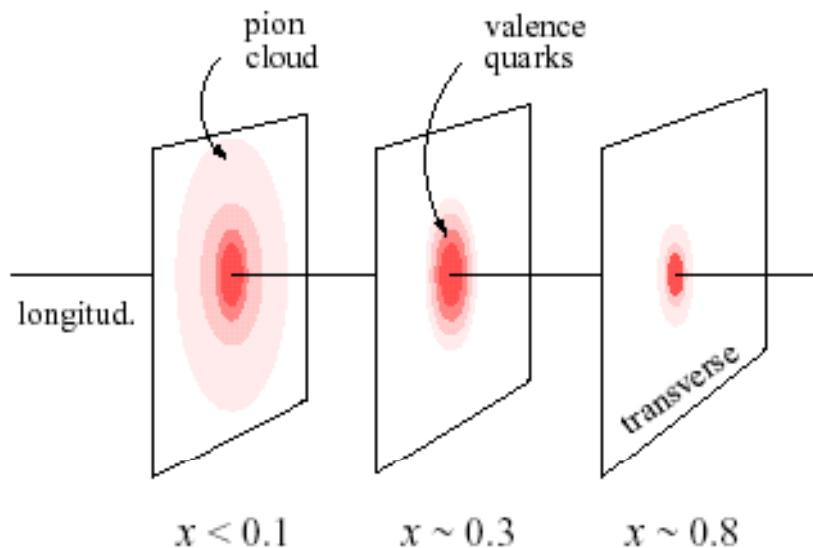
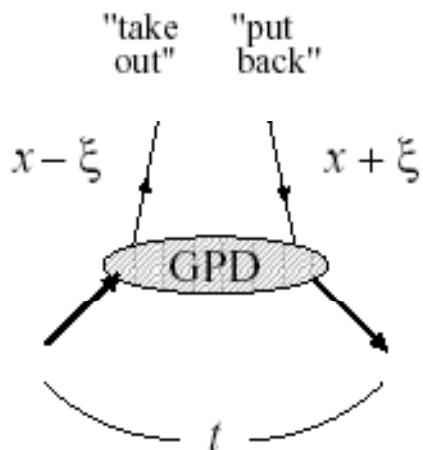
- Sub-1% statistical precision at ELIC (averaged over all Q^2)
- 7% (?) in unmeasured region, in future constrained by data and lattice QCD
- 3-4% precision at various values of Q^2

Needs:
 $O(1\%)$ Ion Polarimetry!!!

Holy Grail: excellent determination of $\alpha_s(Q^2)$



GPDs and nucleon structure



- Unify concepts of parton density and elastic form factor
- Describe correlation of longitudinal momentum and transverse position of quarks/gluons
 - Transverse quark/gluon imaging of nucleon ("tomography")
[Burkardt 00; Diehl 02]
- Moments (x -integrals) related to fundamental static properties:
 J_q quark angular momentum [Ji 96]
 - Lattice

Hard exclusive processes at collider energies

$$W^{\gamma^* p} > 10 \text{ GeV}$$

- “Diffractive” channels: $J/\psi, \phi, \rho^0, \gamma$ (DVCS)

- Cross sections grow with energy
- Probe gluon and singlet quark GPDs
- Need to be studied together!

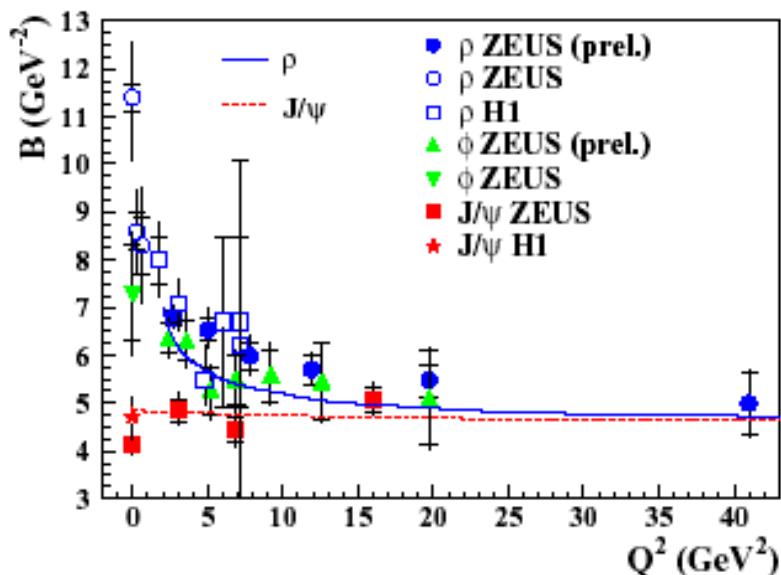
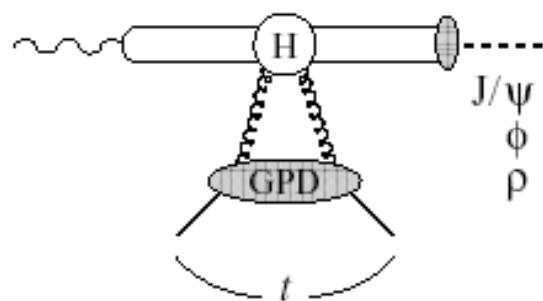
“Transverse gluon imaging of nucleon”

- “Non-diffractive” channels: $\pi, \eta, K, \rho^+, \dots$

- Cross sections small, do not grow with energy
- Probe spin/flavor/charge non-singlet GPDs
- Comparisons between different channels

“Spin/flavor structure of nucleon”

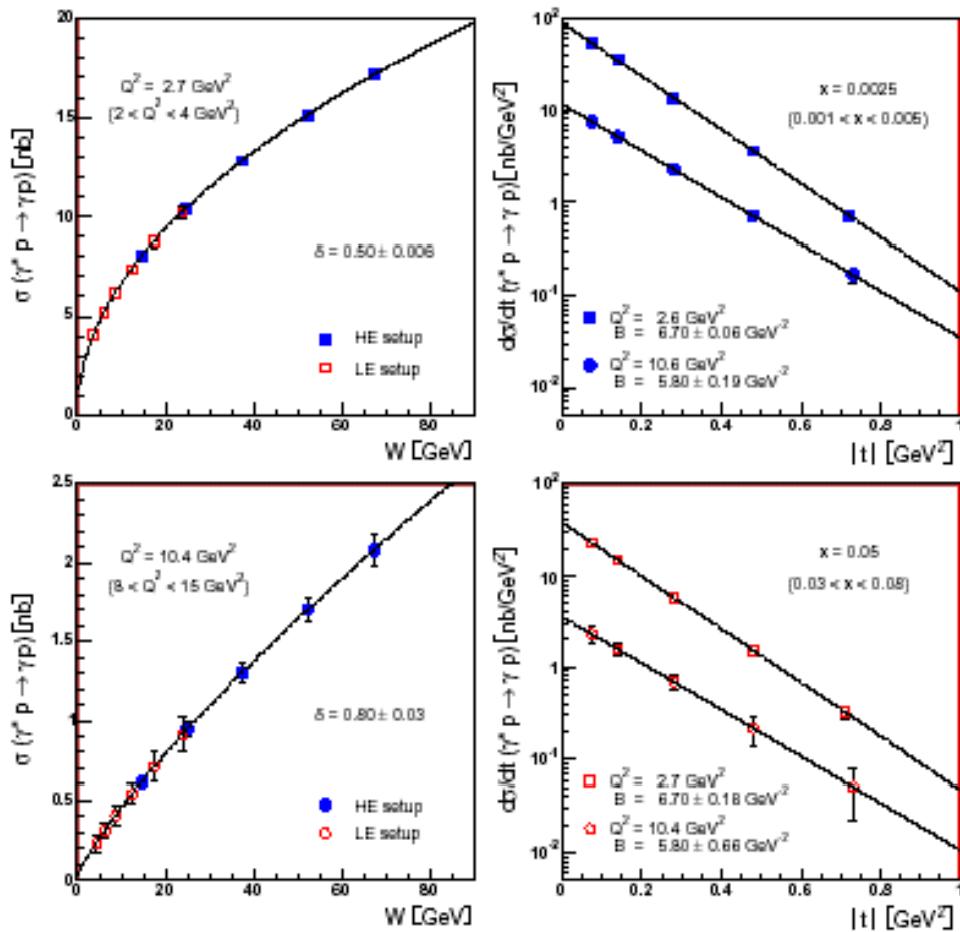
Diffractive channels: HERA results



- LO QCD factorization \leftrightarrow Dipole picture
Gluon GPD \leftrightarrow Color dipole moment
- Measurements of diffractive channels (J/ψ , ϕ , ρ , γ) have confirmed applicability of QCD factorization:
 - Energy dependence changes with Q^2
 - t -slopes universal at high Q^2
 - Flavor relations $\phi : \rho$
- Transverse gluonic size of nucleon . . . essential input for small- x physics!

[Levy, Frankfurt, Strikman, CW 05]

Diffractive channels: EIC projections

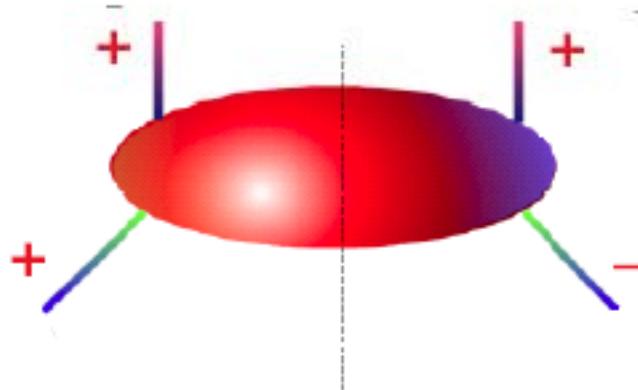


- Aim: Transverse gluon/singlet quark imaging of nucleon over wide range $10^{-3} < x < 10^{-1}$
- Requirements:
 - $Q^2 \sim 10\text{--}20 \text{ GeV}^2$: Factorization
 - Wide Q^2 -range: Leading/higher twist, QCD evolution
 - Wide W -range: x -dependence, overlap with fixed-target
 - Luminosity: Differential measurements in W, Q^2, t

[DVCS with eRHIC HE/LE, 530/180 pb $^{-1}$
A. Sandacz, GPD White Paper (2007)]

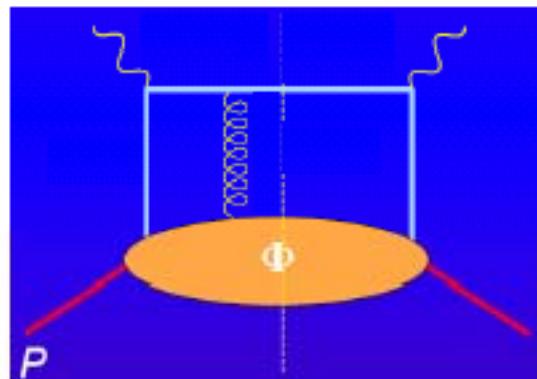
Feasible with high-luminosity EIC;
need to work out details

What's the physics of the Sivers functions ?



Probes overlap of proton
wave fcts. with $J_z = \pm 1/2$

- → involves orbital angular momentum
- T-invariance of QCD: they involve a “rescattering”
in the color field of the remnant

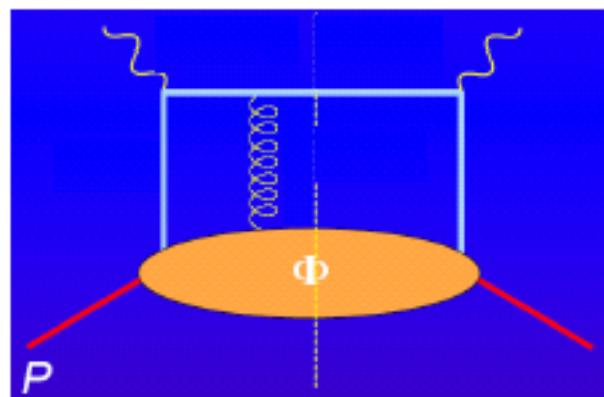


Brodsky, Hwang, Schmidt; Collins;
Belitsky, Ji, Yuan;
Boer, Mulders, Pijlman

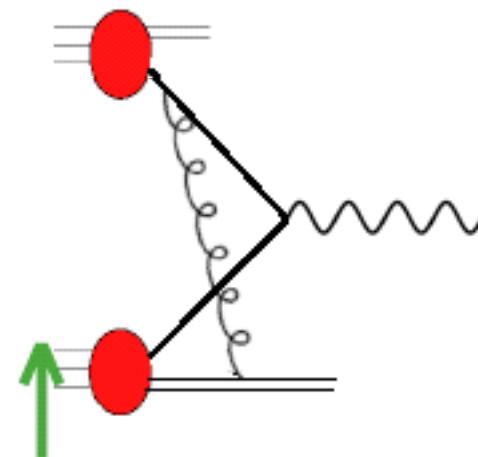
Attractive !

- profound physics implication:
→ process-dependence of Sivers functions

DIS: “attractive”



DY: “repulsive”

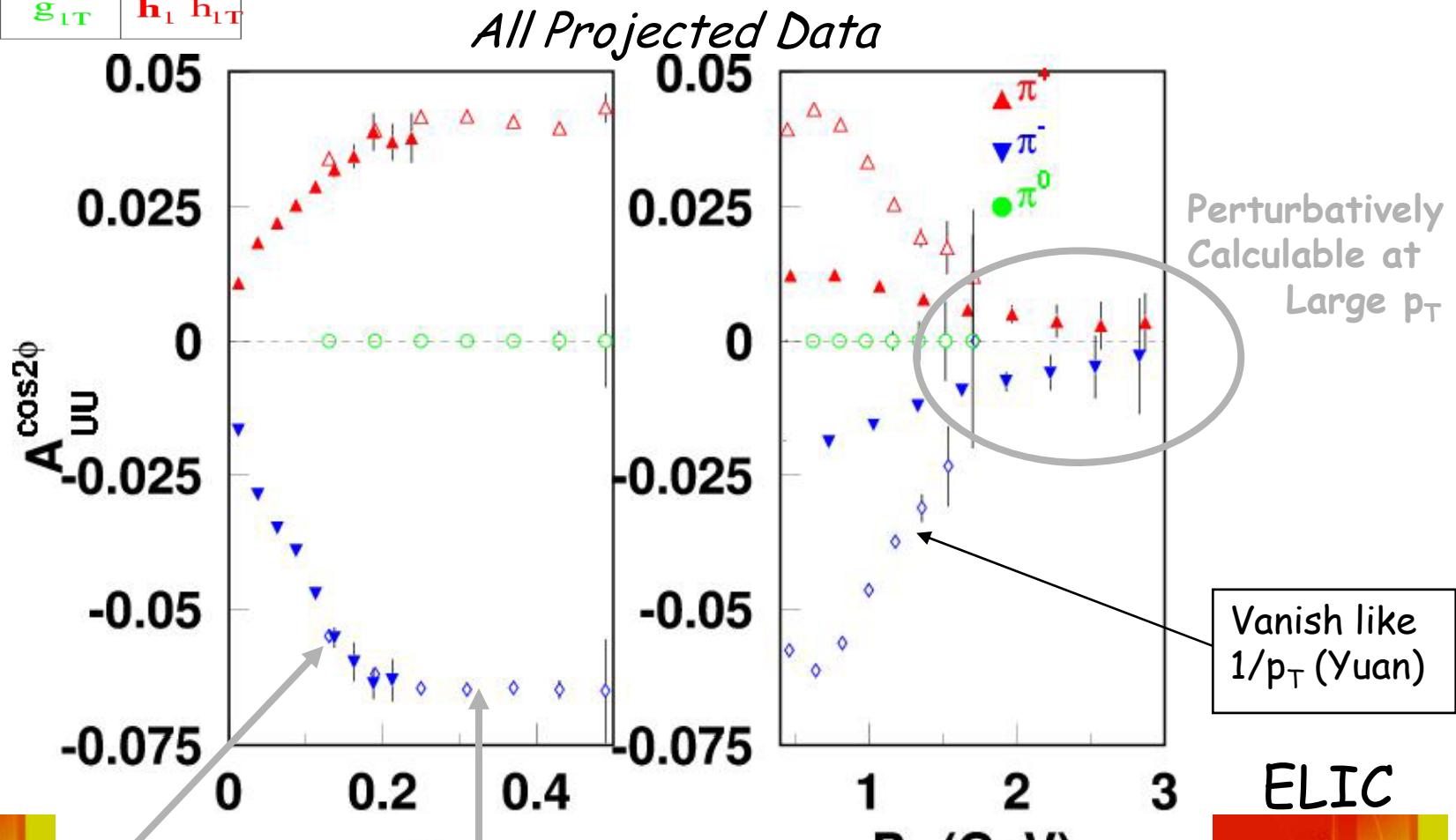


$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

- hugely important in QCD -- tests much of what we know about description of hard processes

N_q	U	L	T
U	f_U		h_U^\perp
L		g_L	h_{UL}^\perp
T	f_{UT}^\perp	g_{UT}	$h_U h_{UT}^\perp$

Correlation between Transverse Spin and Momentum of Quarks in Unpolarized Target



Perturbatively
Calculable at
Large p_T

Vanish like
 $1/p_T$ (Yuan)

ELIC



Jefferson Lab 12
Exploring the Nature of Matter



Summary

**EIC is the ideal machine to provide the final answers
on the structure of the proton at low x**

It will allow to :

- measure precisely the gluon distribution at low x and moderate Q^2
- determine the polarized sea quark distributions in the nucleon
- map out the polarized gluon distribution in the nucleon
- perform a precision test of the Bjorken Sum Rule ---> α_s
- do gluon “tomography” via exclusive processes
- determine transverse spin effects and orbital momenta
- provide a understanding of the fragmentation process
- + investigate the low x physics of saturation in the nucleus

Backup slides

Backup slides

ELIC Accelerator Design Specifications

- Center-of-mass energy between 20 GeV and 90 GeV
 - with energy asymmetry of ~10, which yields
 $E_e \sim 3 \text{ GeV}$ on $E_A \sim 30 \text{ GeV}$ up to $E_e \sim 9 \text{ GeV}$ on $E_A \sim 225 \text{ GeV}$
- Average Luminosity from 10^{33} to $10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$ per Interaction Point
- Ion species:
 - Polarized H, D, ^3He , possibly Li
 - Ions up to A = 208
- Longitudinal polarization of both beams in the interaction region (+Transverse polarization of ions +Spin-flip of both beams)
 - all polarizations >70% desirable
- Positron Beam desirable

Design Features of ELIC

Directly aimed at addressing the science program:

- “Figure-8” ion and lepton storage rings to ensure spin preservation and ease of spin manipulation. No spin sensitivity to energy for all species.
- Short ion bunches, low β^* , and high rep rate (crab crossing) to reach unprecedented luminosity.
- Four interaction regions for high productivity.
- Physics experiments with polarized positron beam are possible. Possibilities for e^-e^- colliding beams.
- Present JLab DC polarized electron gun meets beam current requirements for filling the storage ring.
- The 12 GeV CEBAF accelerator can serve as an injector to the electron ring. RF power upgrade might be required later depending on the performance of ring.
- Collider operation appears compatible with *simultaneous* 12 GeV CEBAF operation for fixed target program.

Achieving the Luminosity of ELIC

For 225 GeV protons on 9 GeV electrons, $L \sim 7 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
compatible with realistic Interaction Region design.

Beam Physics Concepts

- Beam – beam interaction between electron and ion beams
($\xi_{i/e} \sim 0.01/0.086$ per IP; 0.025/0.1 largest achieved)
- High energy electron cooling
- Interaction Region
 - High bunch collision frequency ($f = 1.5 \text{ GHz}$)
 - Short ion bunches ($\sigma_z \sim 5 \text{ mm}$)
 - Very strong focus ($\beta^* \sim 5 \text{ mm}$)
 - Crab crossing

F_L from EIC, HERA comparison

