Selected Physics Topics at the Electron-Ion-Collider

Antje Bruell, JLab
JLab Users Meeting, June 18, 2008

- **What is the EIC ?**
- **The Gluon Contribution to the Nucleon Spin**
- **TMDs and GPDs at EIC**
- **Gluon saturation at EIC ?**
- **Summary**

What is the EIC ?

Electron Ion Collider as the ultimate QCD machine

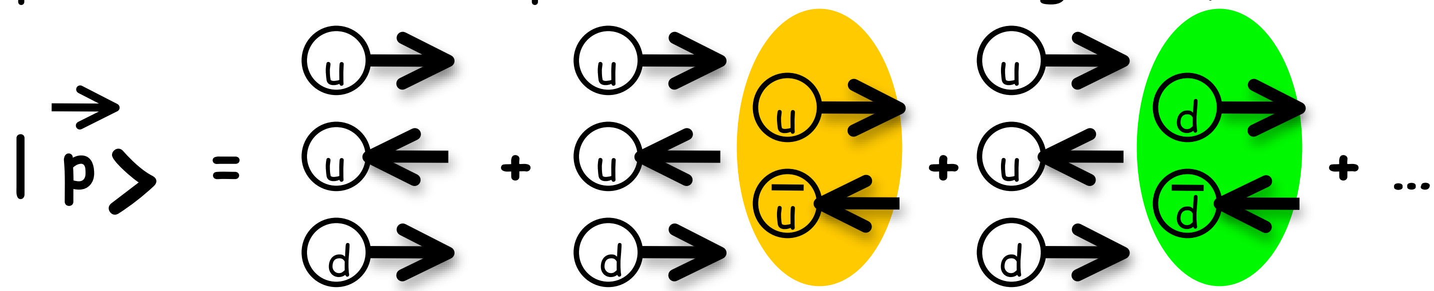
- Variable center of mass energy between 20 and 100 GeV
- High luminosity
- Polarized electron and proton (deuteron, 3He) beams
- Ion beams up to A=208

Explore the new QCD frontier: strong color fields in nuclei

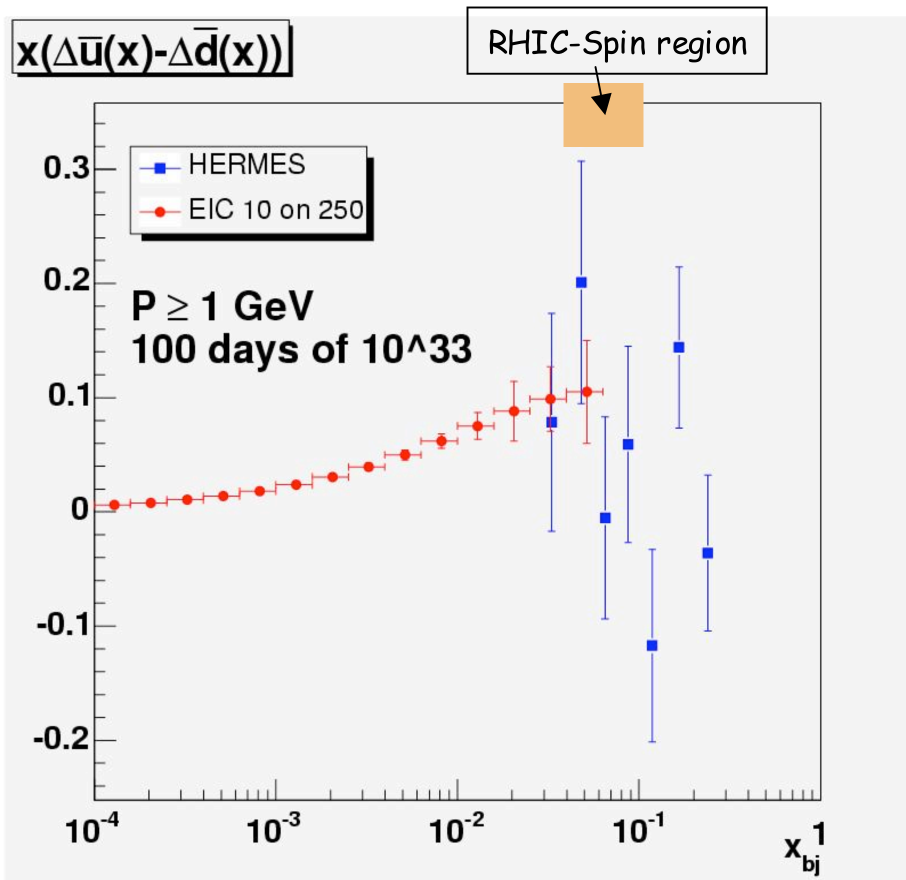
Precisely image the sea-quarks and gluons in the nucleon

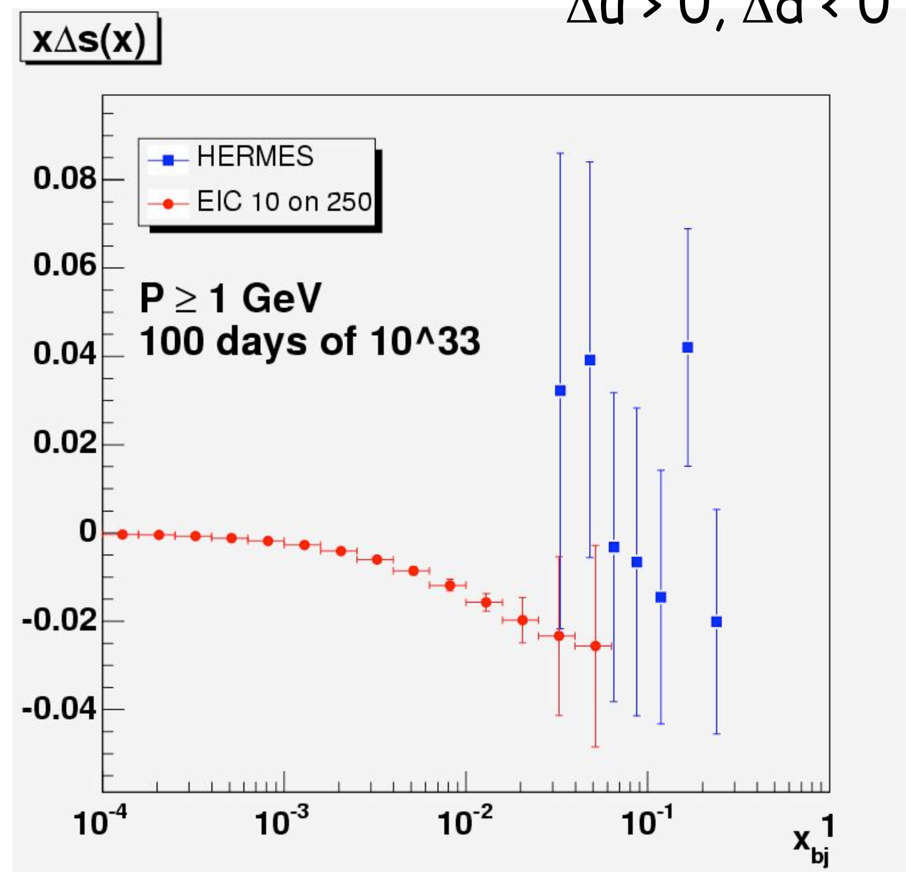
Precisely image the sea quarks

Spin-Flavor Decomposition of the Light Quark Sea



Many models predict $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

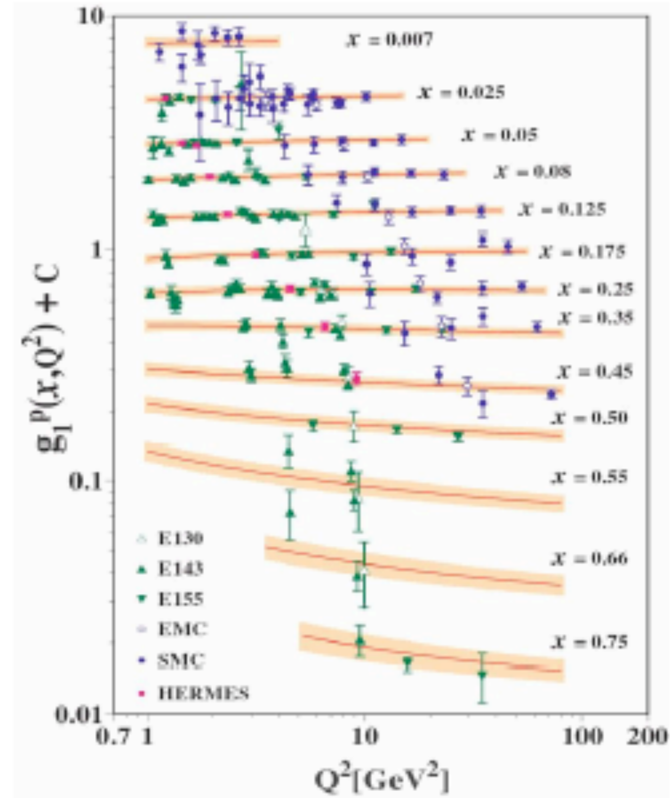




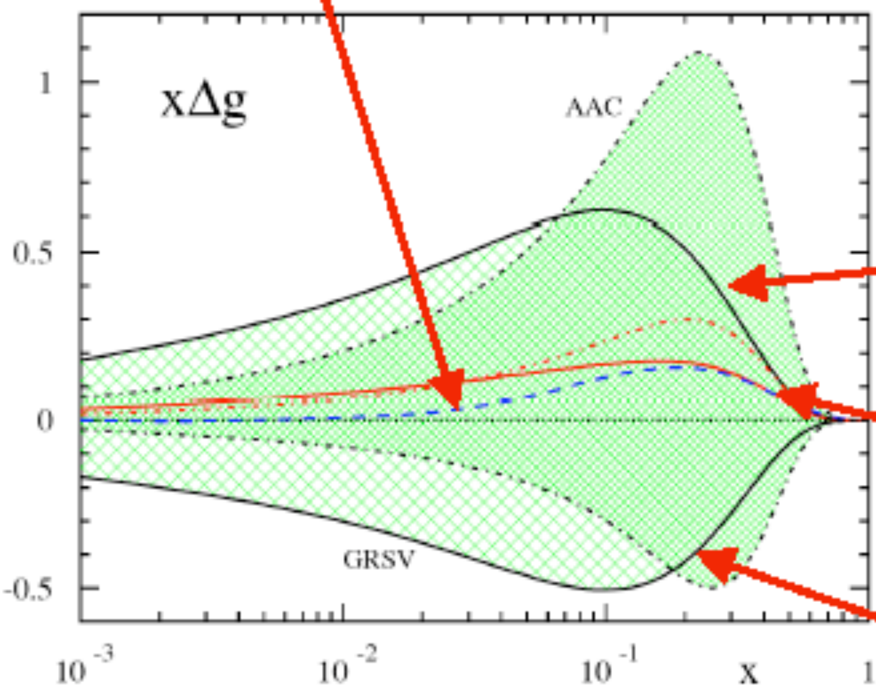
The gluon spin distribution Δg

Not much information until recently:

$$\frac{d\,g_1}{d\log(Q^2)} \propto \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x, Q^2) \ + \ \text{quark contrib.}$$



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



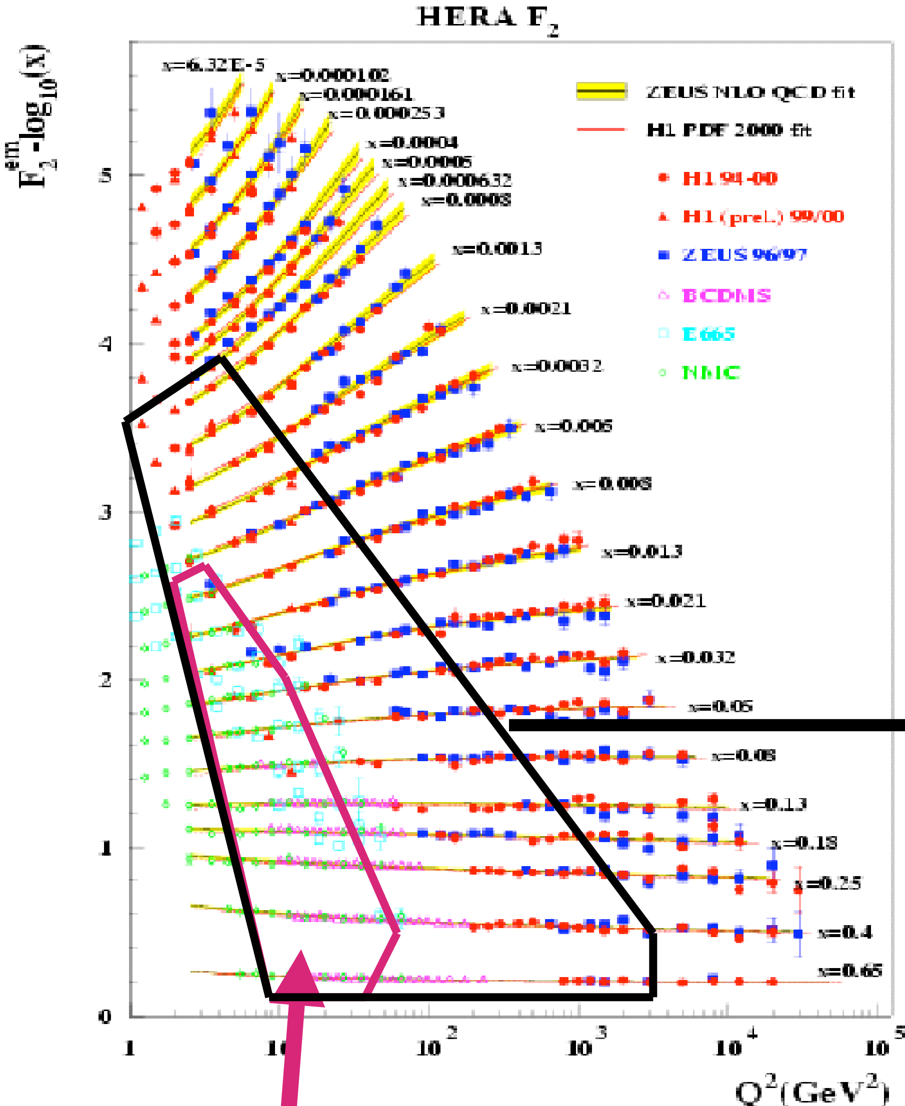
$\Delta G \approx 1.8 \ (@\,1\mathrm{GeV}^2)$

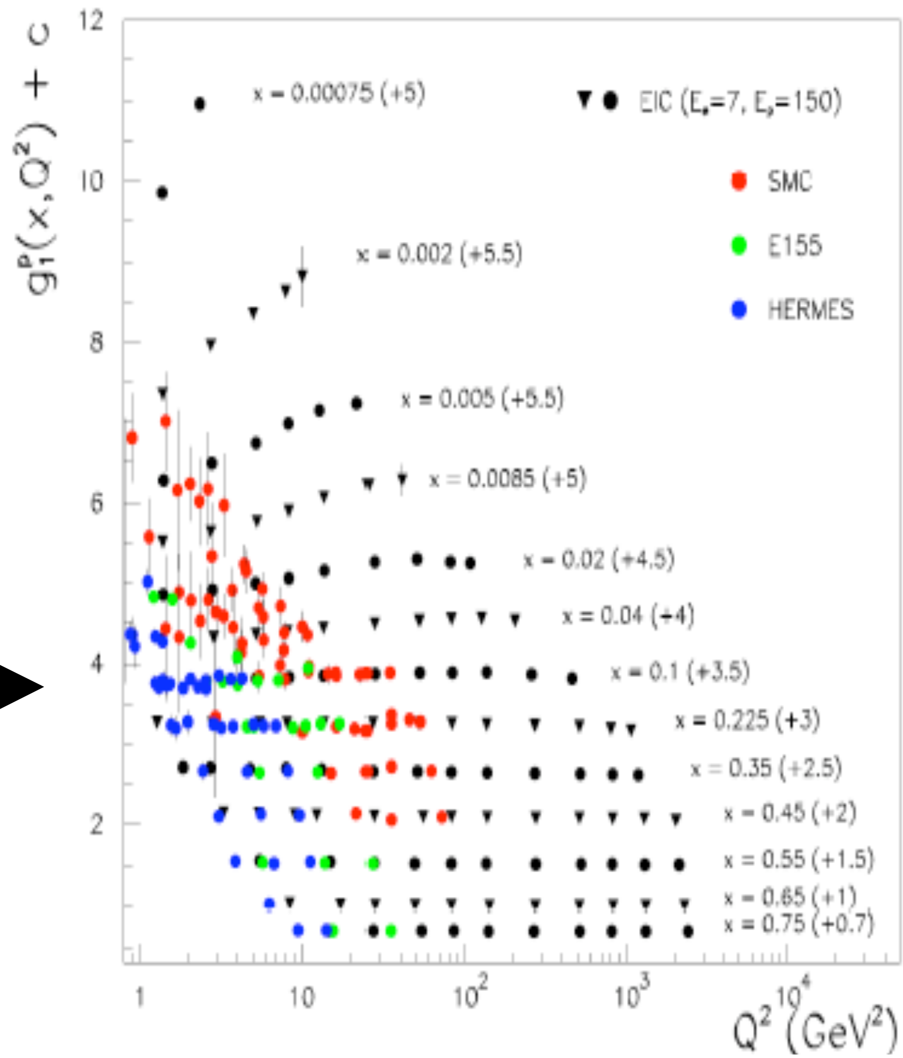
"axial anomaly" Altarelli et al.

$\Delta G \approx 0.4$

$\Delta G \approx -1.7$

World Data on F_2^p | EIC Data on g_1^p

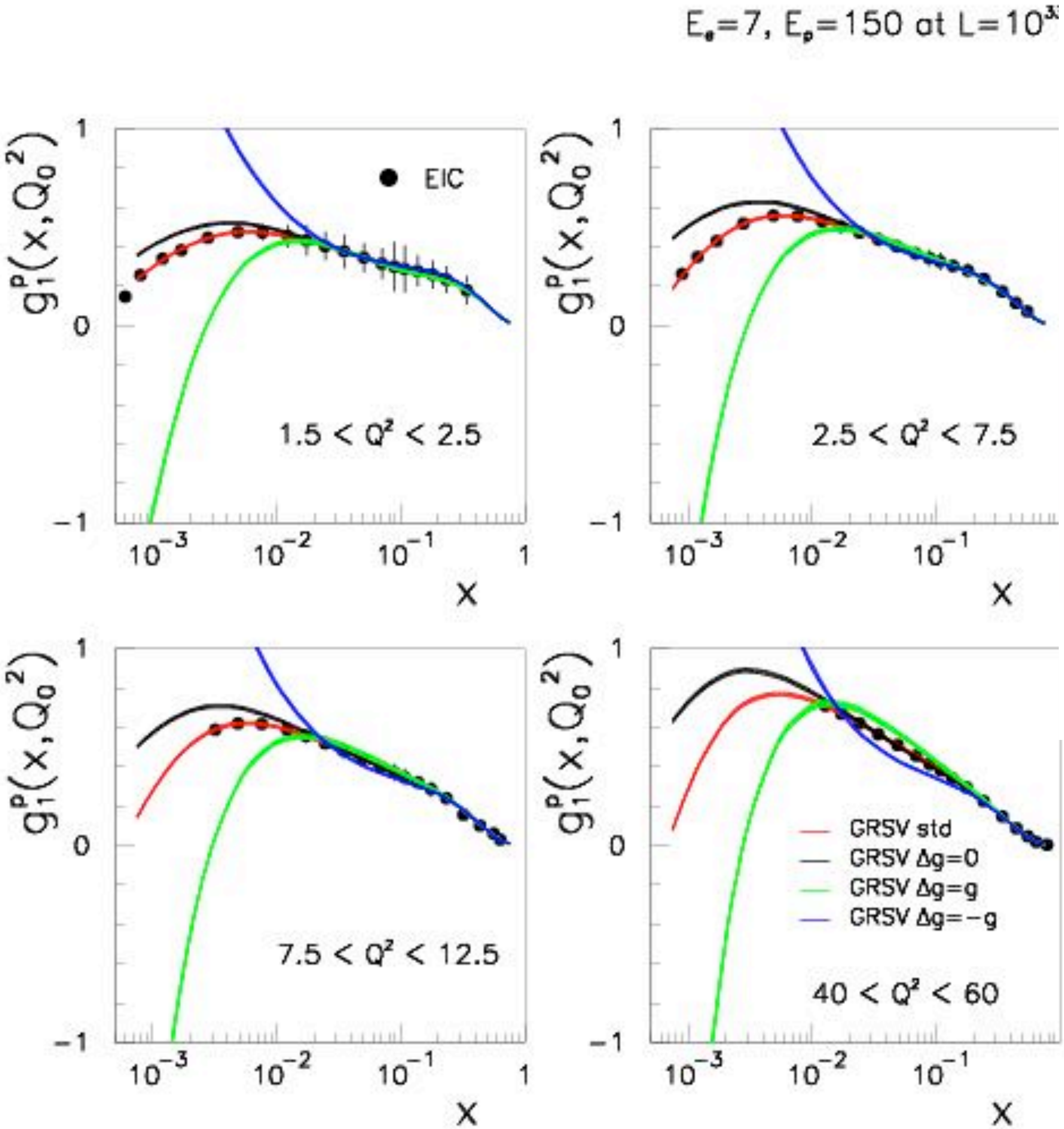


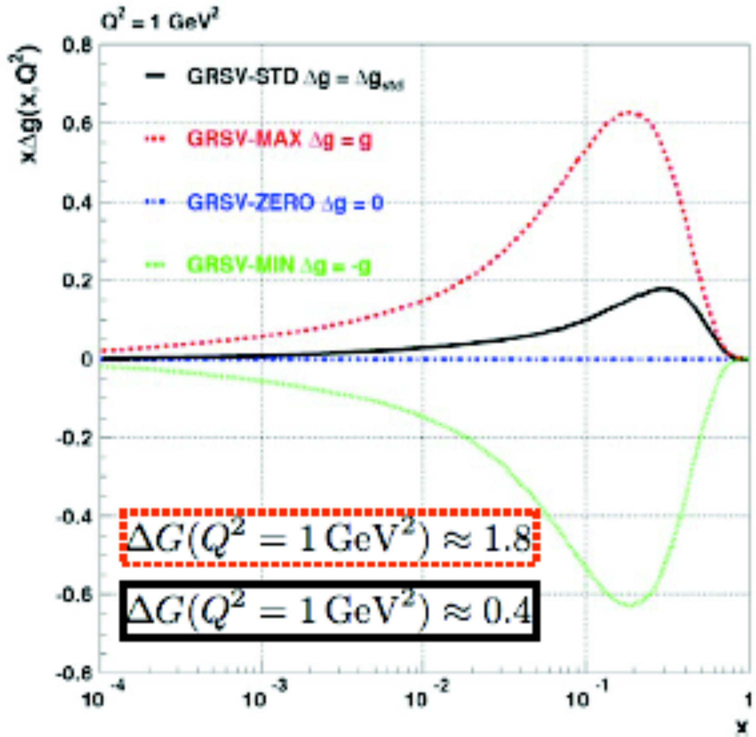


Region of existing g_1^p data

An EIC makes it possible!

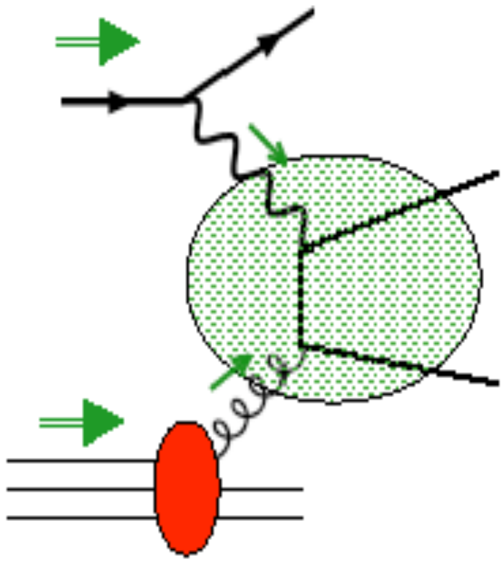
ΔG from scaling violations of g_1





Polarized gluon distribution via charm production

very clean process !

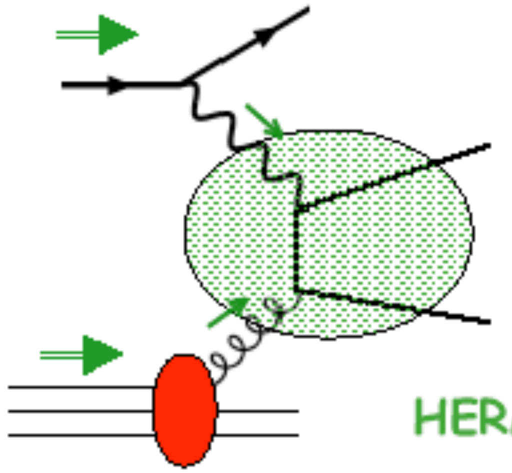


c → **D mesons**

$\bar{c}$ → $\bar{D}$ **mesons**

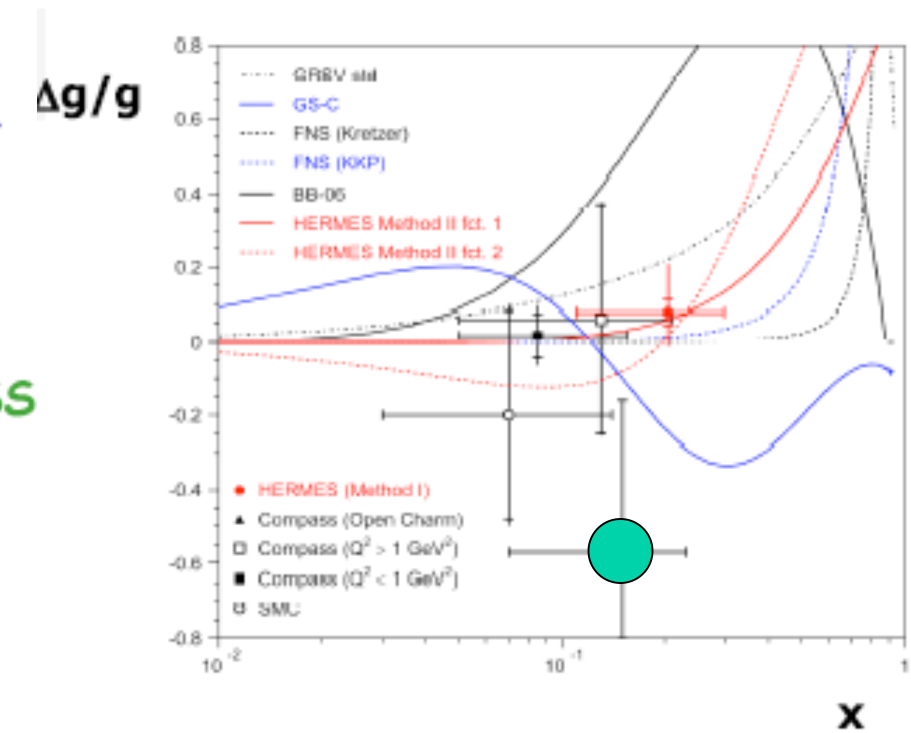
LO QCD: asymmetry in D production directly proportional to Δ G/G

Polarized gluon distribution via charm production



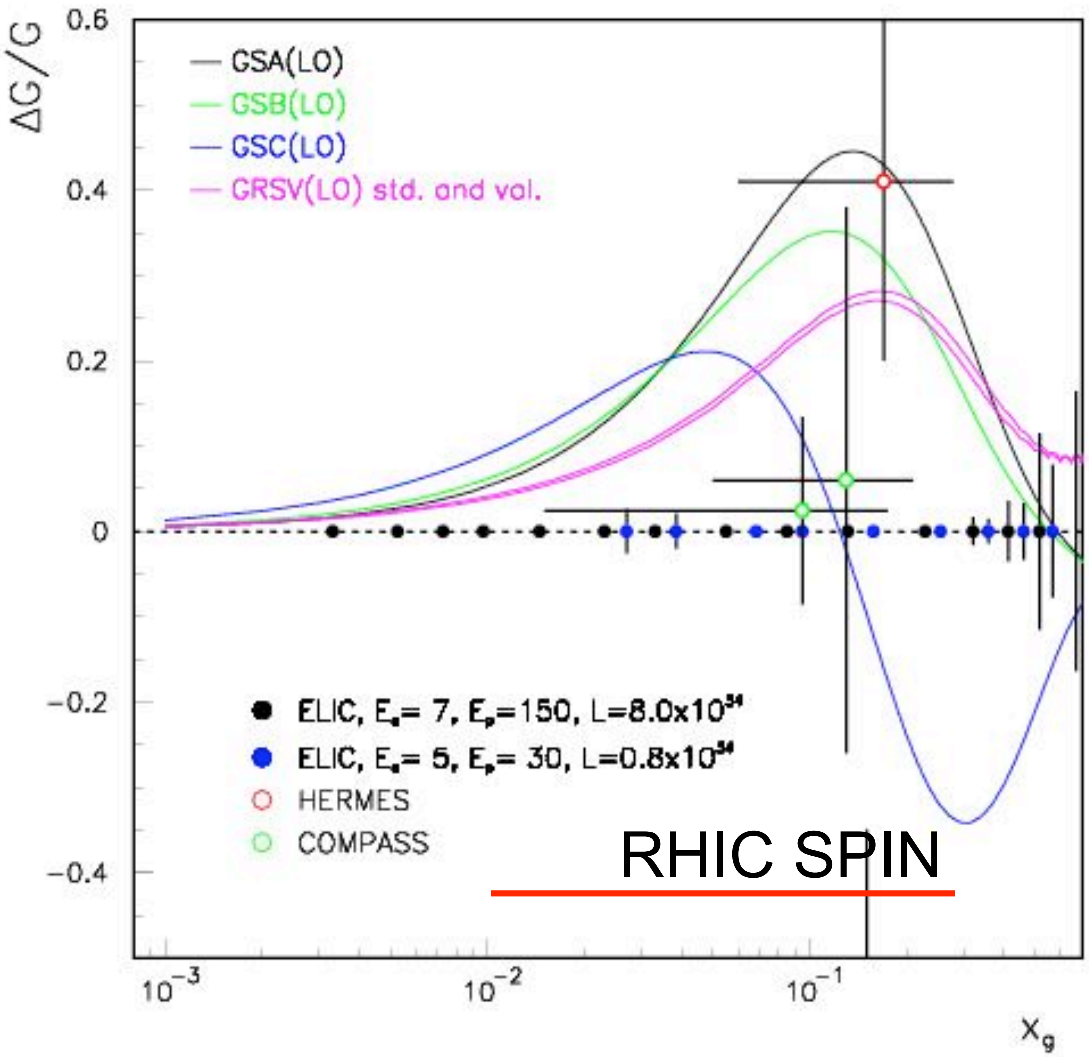
jet(s), $c\bar{c}$, . . .

HERMES, COMPASS



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

Polarized gluon distribution via charm production



Precise determination of Δ 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 Δ 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 0^0 (determination of photon kinematics)
- We can separate the primary and secondary vertex down to about 100 μm
- We understand the fragmentation of charm quarks (✔)
- We can control the contributions of resolved photons
- We can calculate higher order QCD corrections (✔)

- **Bjorken's sum rule**

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

high-order perturbation theory

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

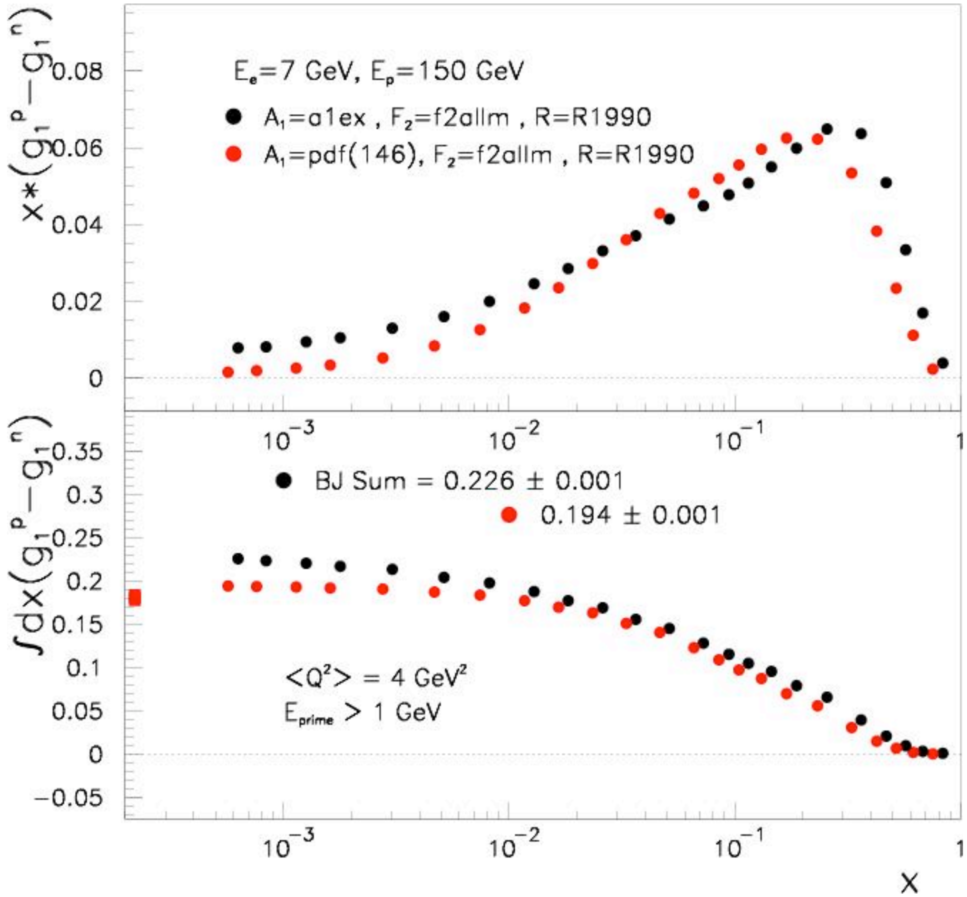
target-mass corrections

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

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

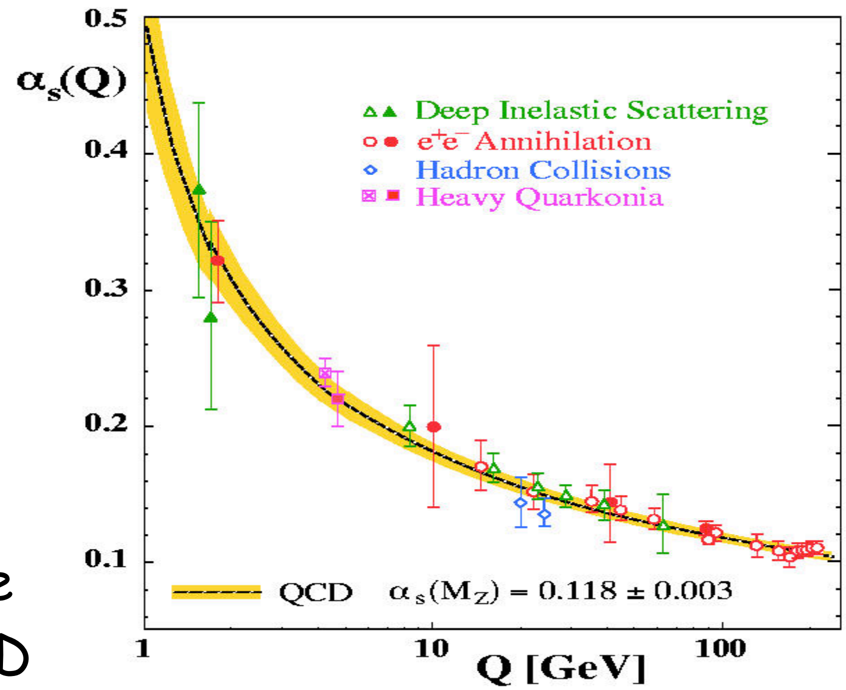
- **Precision QCD. Currently tested at ~10%. Can it be tested at ~1 or 2% ?**

Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = 1/6\, g_A [1+O(\alpha_s)]$



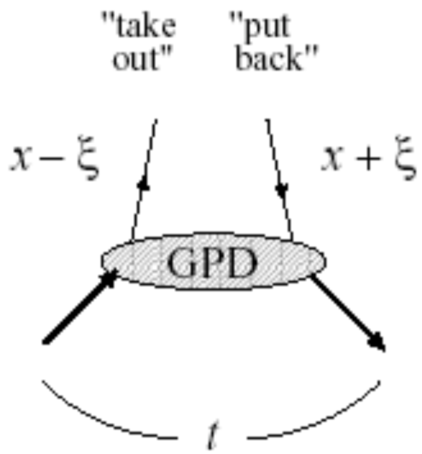
Needs:
O(1%) Ion Polarimetry!!!

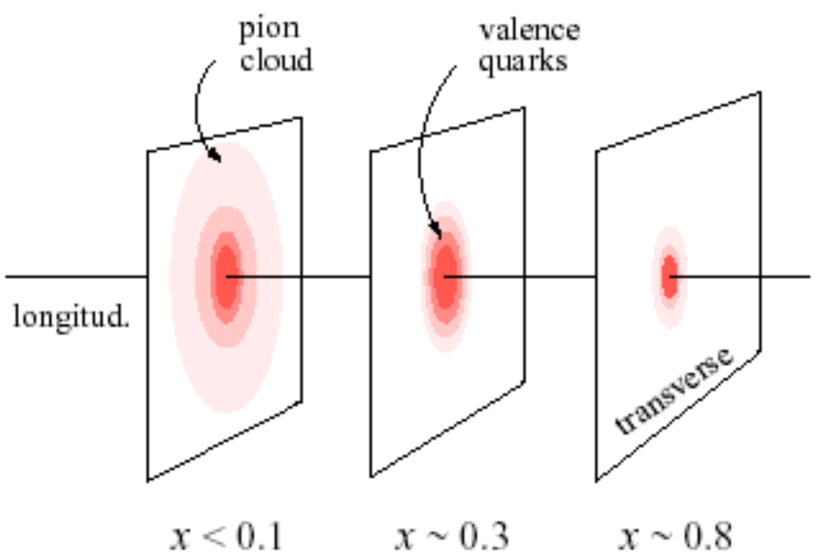
determination of $\alpha_s(Q^2)$



- 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

GPDs and nucleon structure





- Unify concepts of parton density and elastic form factor

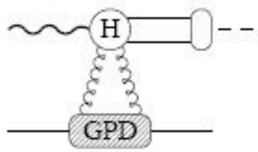
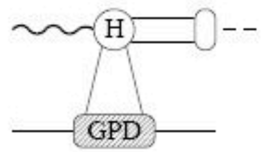
- Describe correlation of longitudinal momentum and transverse position of quarks/gluons

  → 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

Exclusive Processes: Collider Energies

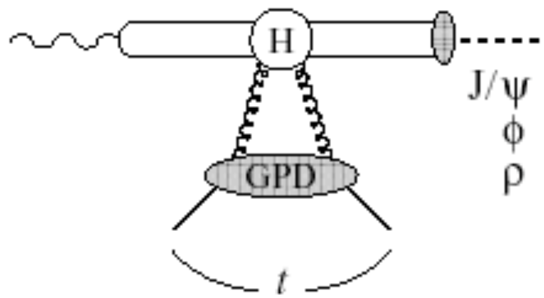
	"diffractive" (vacuum exchange)	"non-diffractive" (quantum number exchange)
Channel	$\gamma p,\ \ \rho^0 p,\ \ J/\psi\, p, \ldots$	$\pi^+ p,\ \ \pi^0 p,\ \ K\Lambda,\ \ \rho^+ n, \ldots$
GPDs	 gluon	 non-singlet quark
Cross section	rises with energy	drops with energy
Interest	gluon imaging of nucleon	spin/flavor structure of quark GPDs
	"one channel"	"many channels"

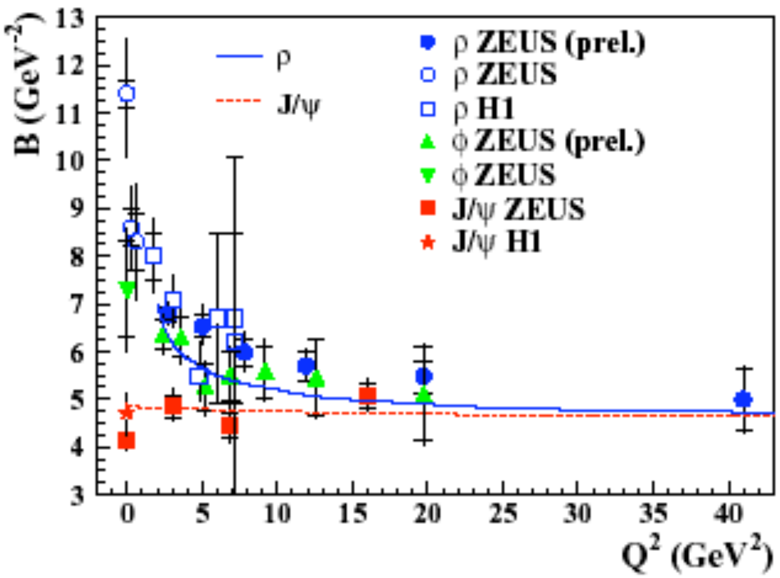
Exclusive Processes: EIC Potential and Simulations

- Diffractive channels
  - Data/experience from HERA: γp (DVCS), $\rho^0 p$, ϕp, $J/\psi\, p$
  - DVCS simulations [A. Sandacz 06/07; cf. GPD/EIC White Paper]
  - Certainly feasible even with modest luminosity (10^{33}cm$^{-2}s^{-1}$)
    Discussion about "quantitative" issues

- Non-diffractive channels
  - New territory for collider!
  - Much more demanding in luminosity
  - Physics interest closely related to JLab 6 + 12 GeV program:
    Quark spin/flavor distributions, nucleon/meson structure
  - Feasibility study of $\pi^+ n$, $\pi^0 p$, $K\Lambda$
    [A. Bruell, T. Horn, C. Weiss, V. Guzey, in progress]

Diffractive channels: HERA results





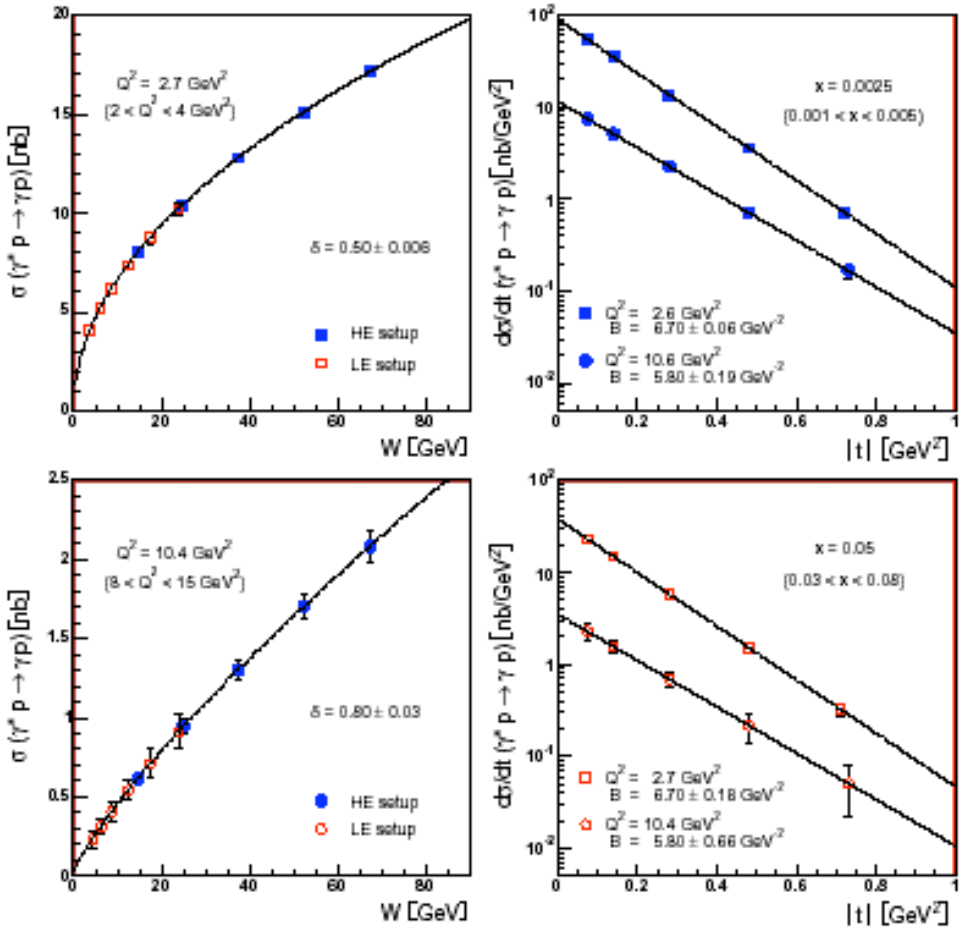
[Levy; Frankfurt, Strikman, CW 05]

- 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!

Diffractive channels: EIC projections



- Aim: Transverse gluon/singlet quark imaging of nucleon over wide range $10^{-3} < x < 10^{-1}$

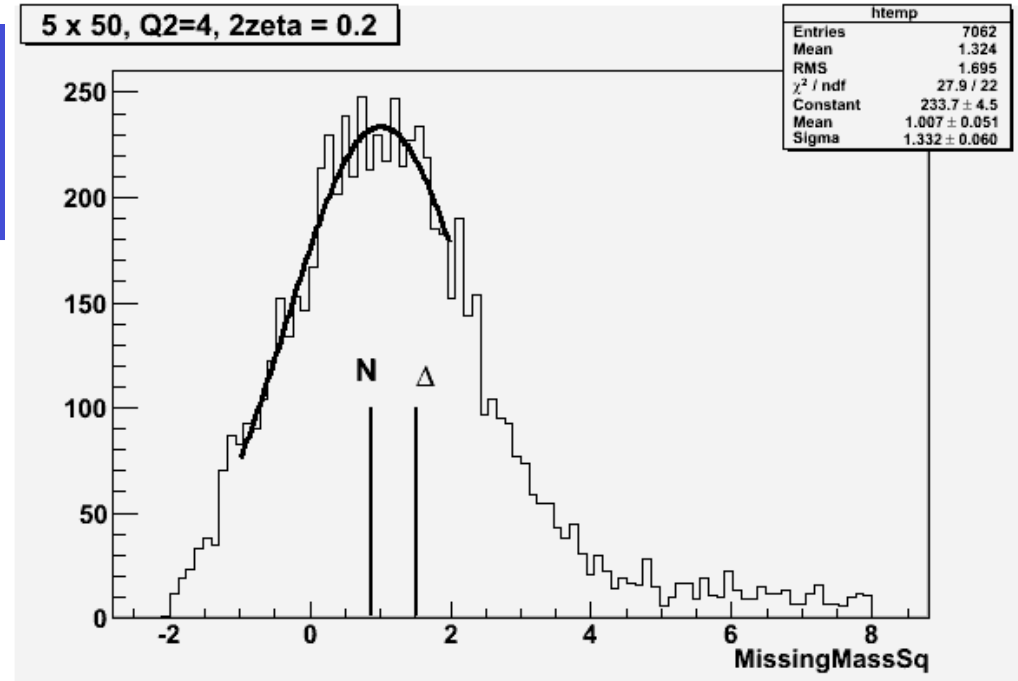
- Requirements:
  - $Q^2 \sim 10$–$20\ \text{GeV}^2$: Factorization
  - Wide Q^2–range: Leading/higher twist, QCD evolution
  - Wide W–range: x–dependence, overlap with fixed–target
  - Luminosity: Differential measurements in W, Q^2, t

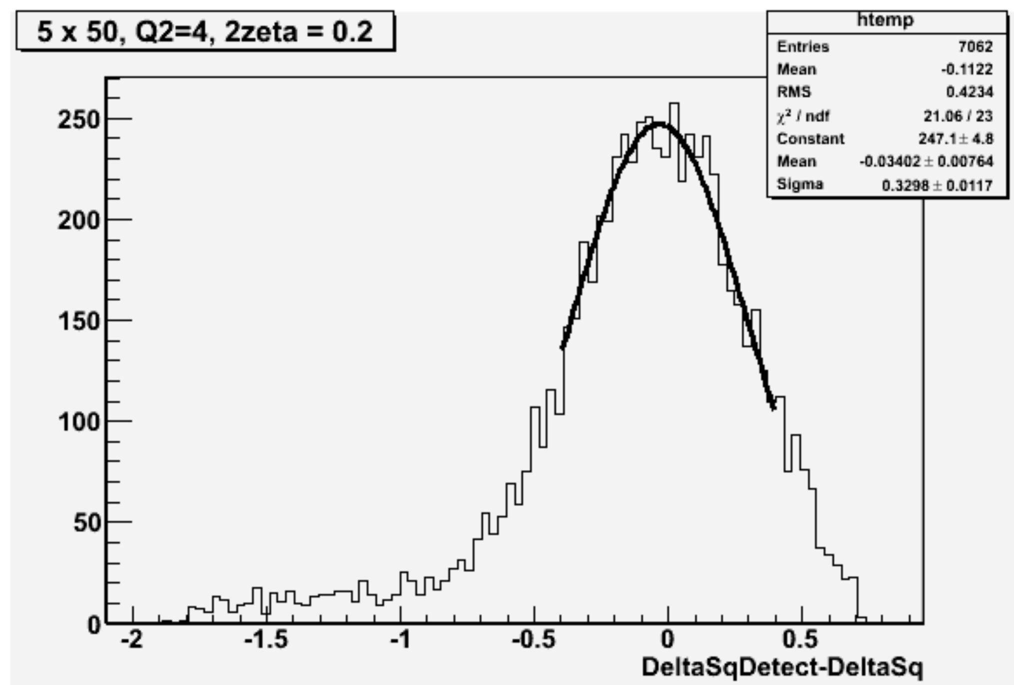
[DVCS with eRHIC HE/LE, $530/180\,\text{pb}^{-1}$
A. Sandacz, GPD White Paper (2007)]

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

5 GeV ⊗ 50 GeV/c (e⁻ ⊗ P)

- Q^2=4 GeV^2
- 2ζ= 0.2
- **P' tagging required**
  - Exclusivity
  - Δ^2 Resolution
    - $\sigma(\Delta^2) \approx 0.3 GeV^2$ without tagging
    - Transverse Imaging





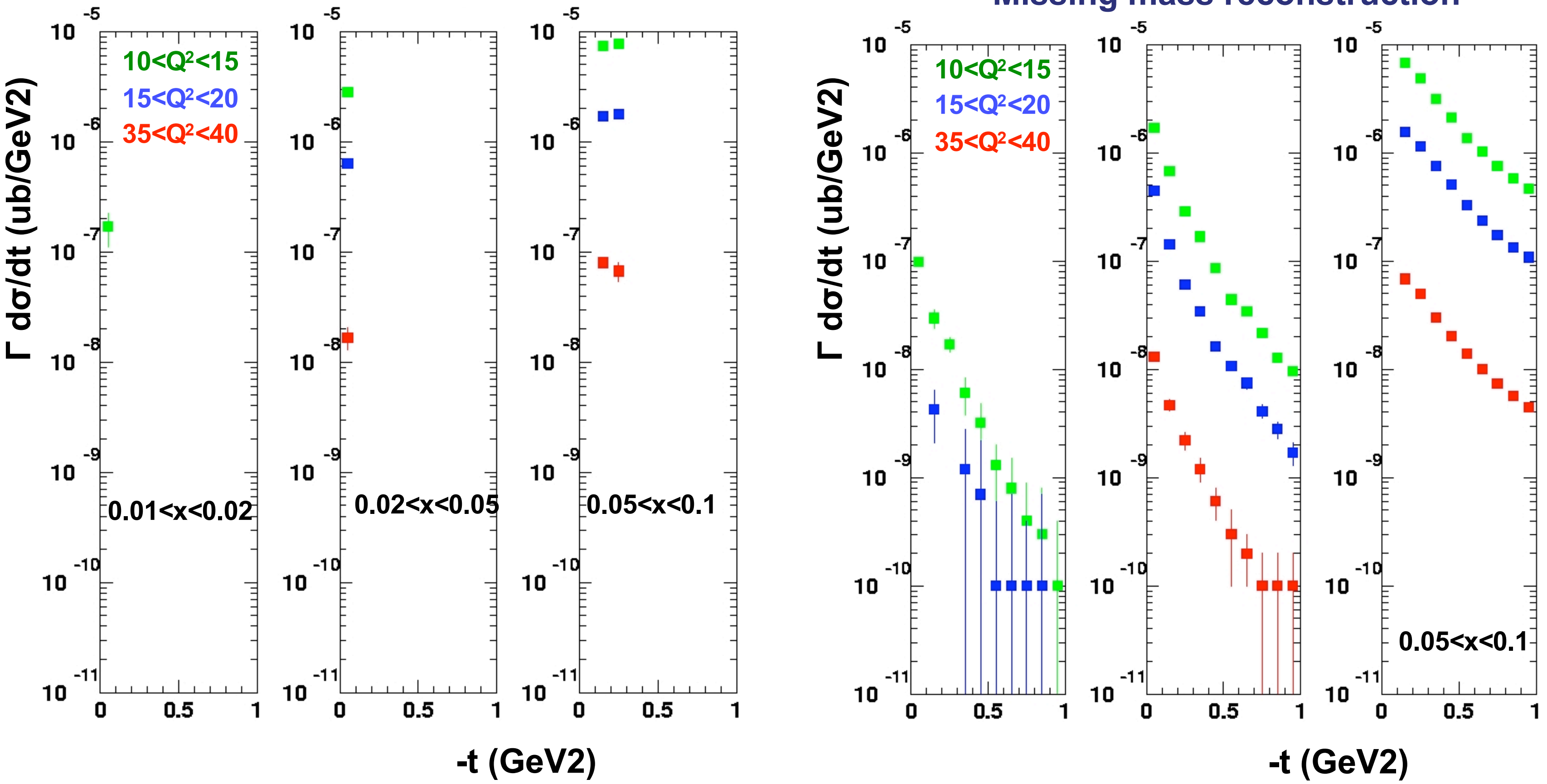
Exclusive charged pion production

E_p=50 GeV → ← E_e=5 GeV

Assume: 100 days,
Luminosity=10E34

Detect the neutron

Missing mass reconstruction

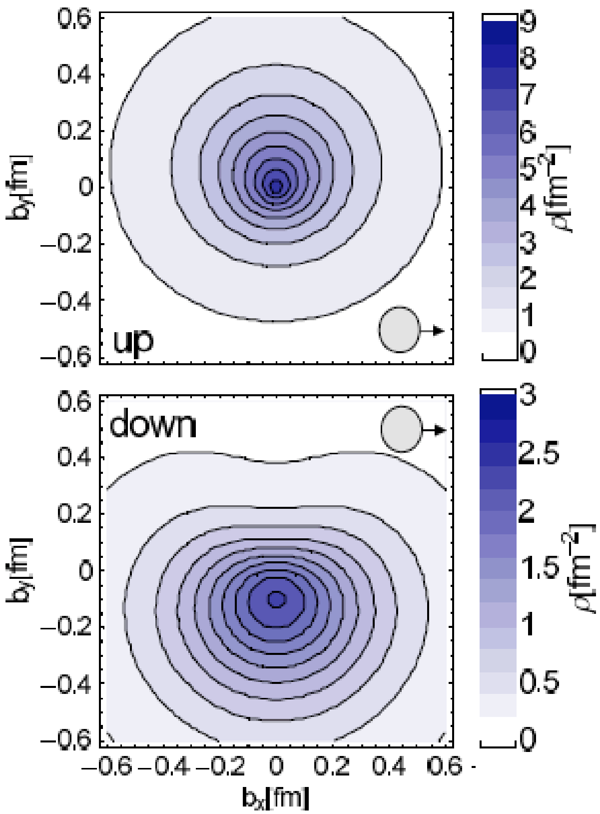


- Neutron acceptance limits the t-coverage
- The missing mass method gives full t-coverage for x<0.2

Assume
dp/p=1% (p_π<5
GeV)

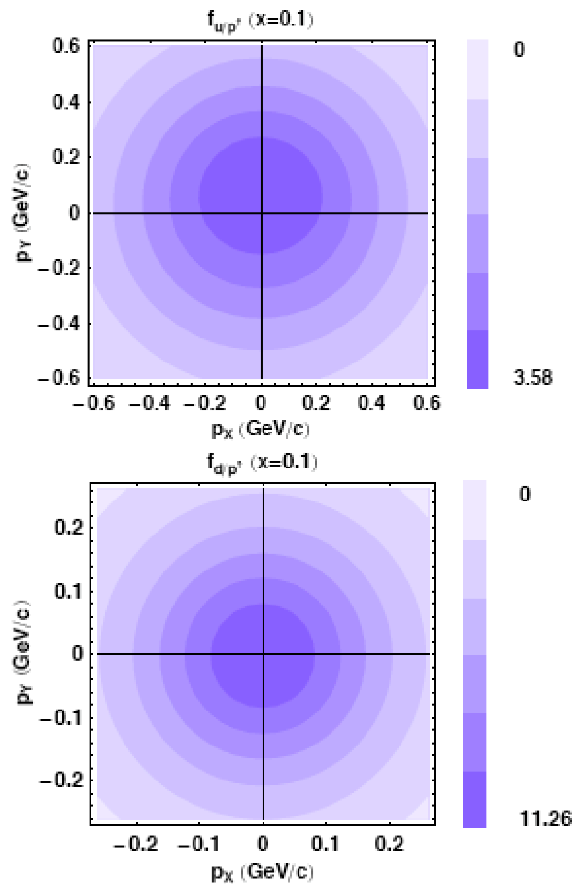
New dimensions

Transverse position



QCDSF/UKQCD, PRL 98 (07)

Transverse momentum



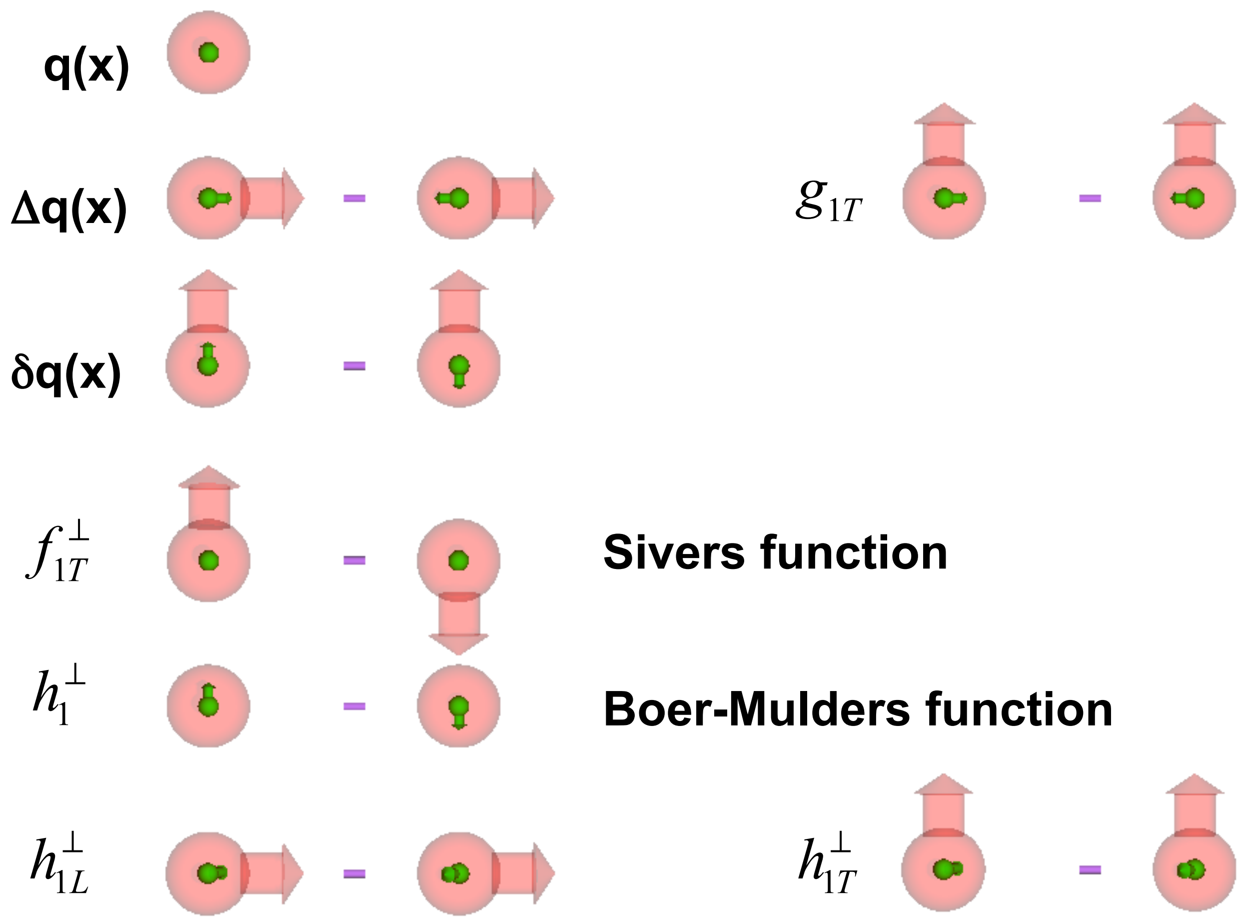
A.B., F. Conti, M. Radici, in preparation

Transversity and friends

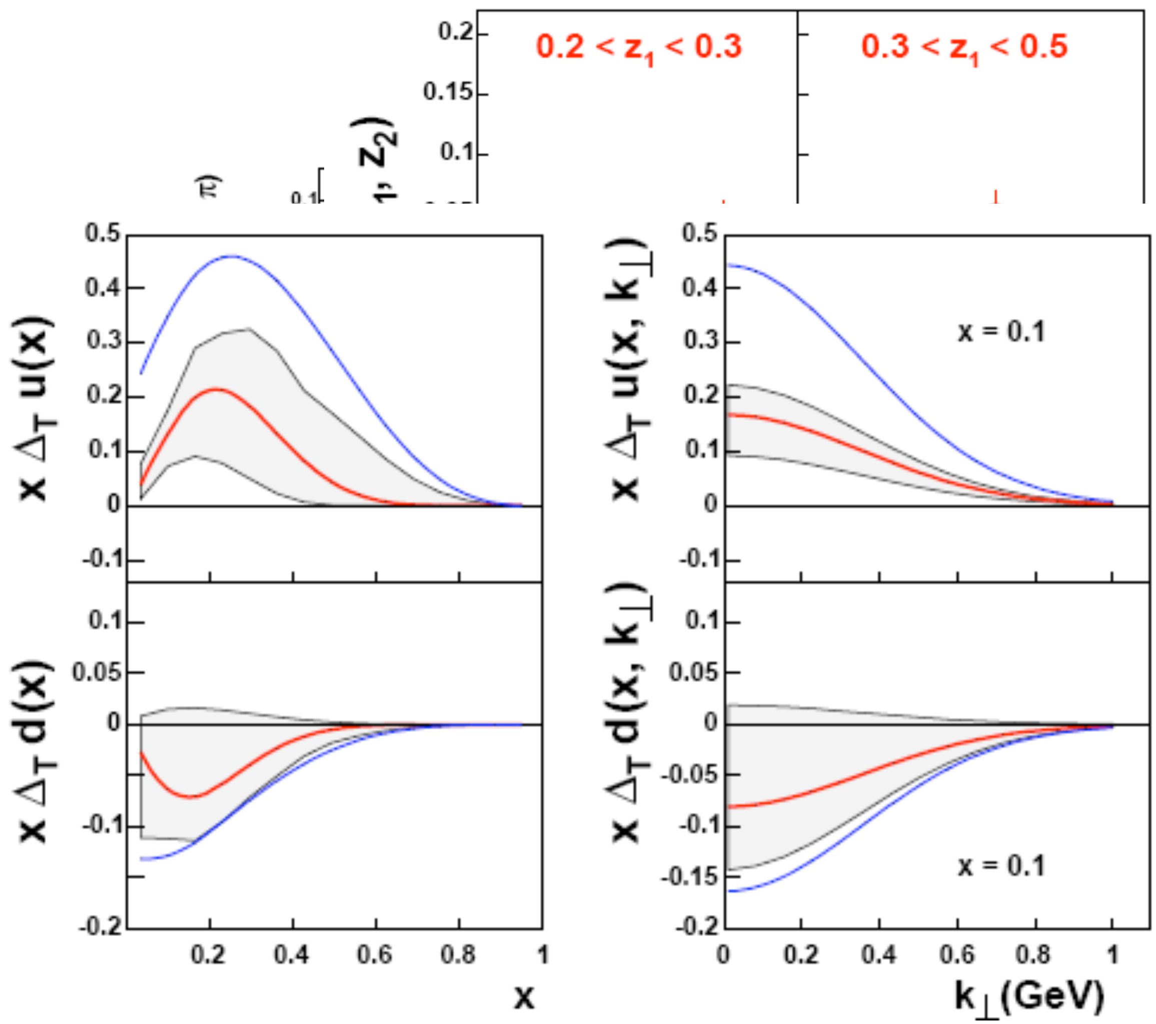
Unpol. DF

Helicity

Transversity



First successful attempt at a global analysis for the transverse SIDIS and the BELLE Collins data



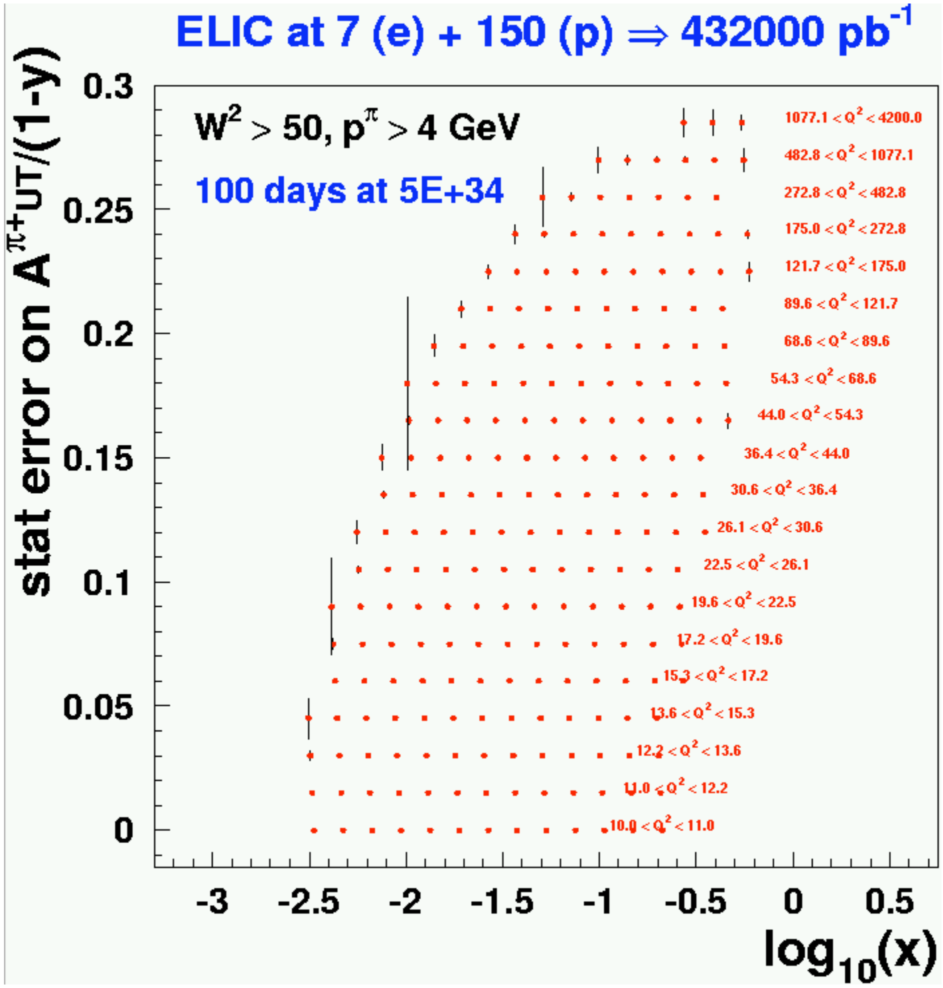
- HERMES A_{UT} p data
- COMPASS A_{UT} d data
- Belle $e^+ e^-$ Collins data
- Kretzer FF

➔ First extraction of transversity (up to a sign)

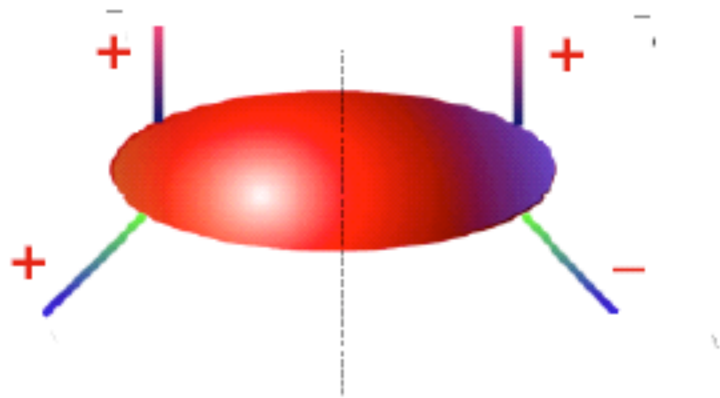
Anselmino et al: hep-ex 0701006

What can be expected at EIC?

- Larger x range measured b y existing experiments
  - →COMPASS ends at ~ 0.01, go lower by almost one order of magnitude, but asymmetries become small
- Have some overlap at intermediate x to test evolution of Collins function and higher twist but at higher Q^2

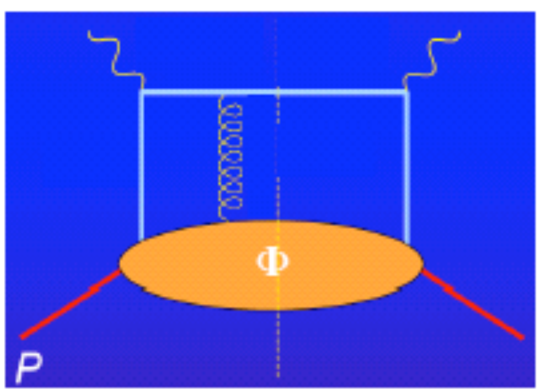


What's the physics of the Sivers functions ?



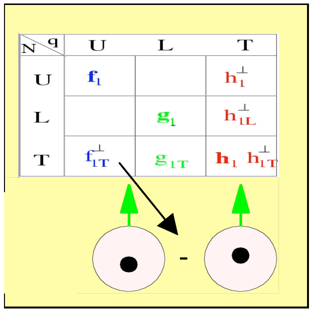
Probes overlap of proton wave fcts. with $J_z = \pm 1/2$

- → 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 !

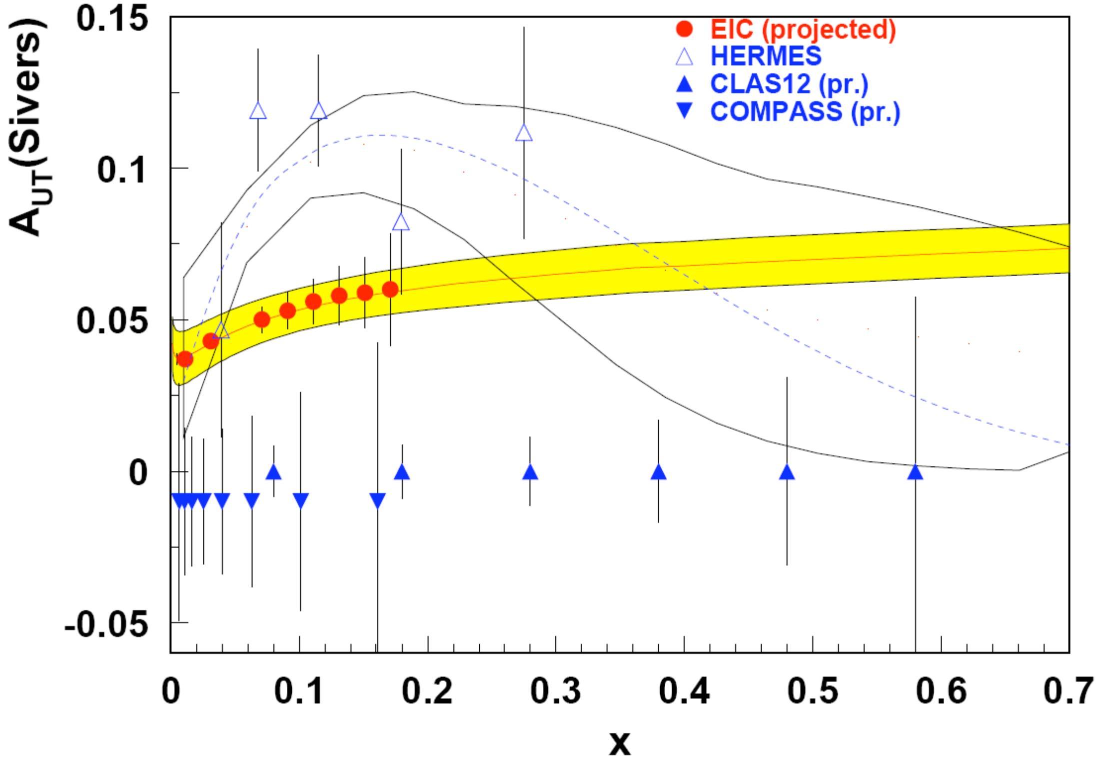


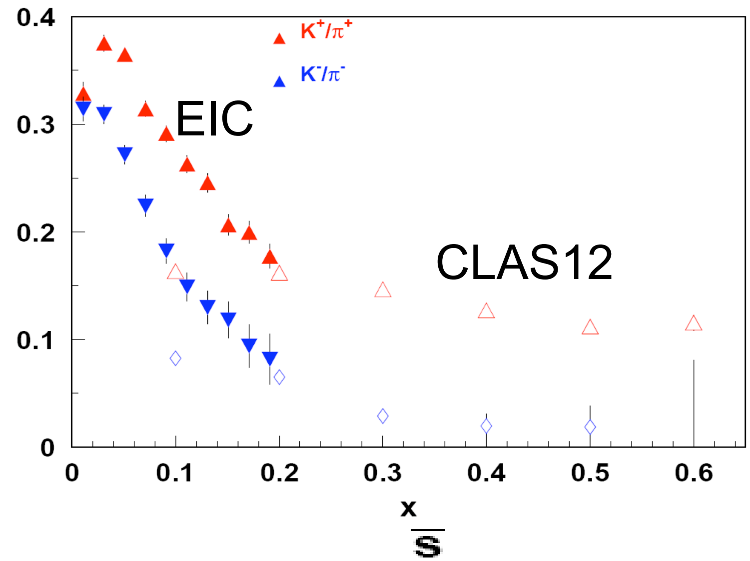
Sivers effect: Kaon electroproduction

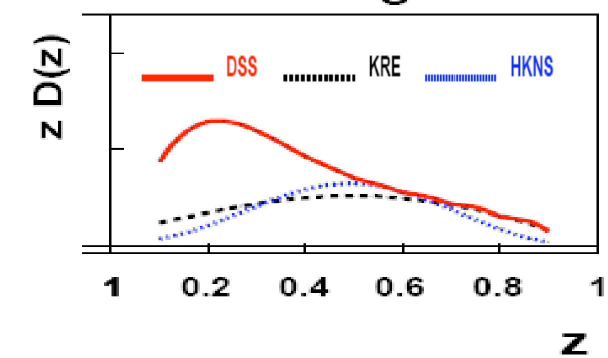
$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

$K^+ \sim u\bar{s}$ $\qquad K^- \sim s\bar{u}$

ep→e' K$^+$+X



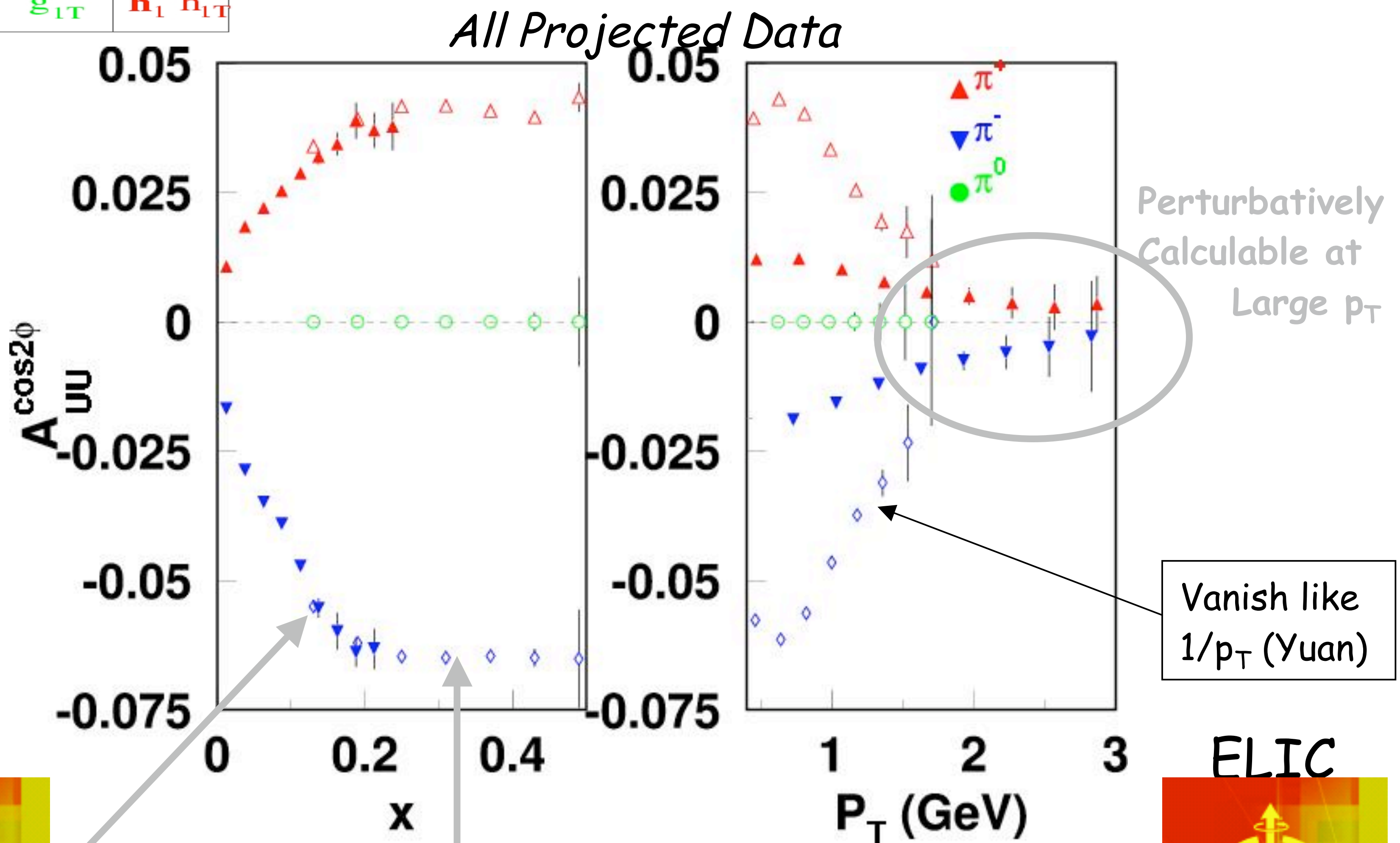




- The low x of EIC makes it ideal place to study the Sivers asymmetry in Kaon production (in particular K-).
- Combination with CLAS12 data will provide almost complete coverage in x

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Correlation between Transverse Spin and Momentum of Quarks in Unpolarized Target



ELIC

Gluon Saturation at EIC ?

Gluon distribution $G(x,Q^2)$

- What's the issue ?
- What can we measure at EIC ?
  - Extract from scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - $F_L \sim \alpha_s\, G(x,Q^2)$
- Other Methods:
  - 2+1 jet rates (needs jet algorithm and modeling of hadronization for inelastic hadron final states)
  - inelastic vector meson production (e.g. J/ψ)
  - diffractive vector meson production - very sensitive to $G(x,Q^2)$

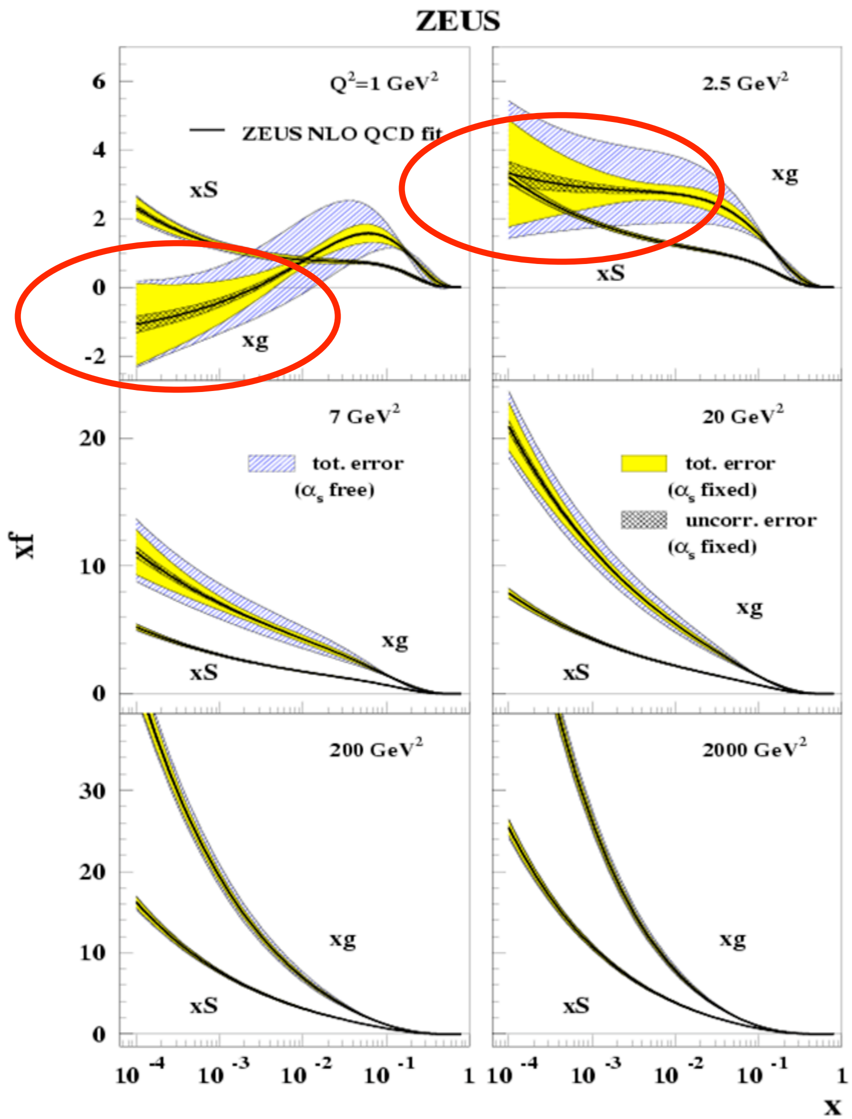
$$\left.\frac{d\sigma}{dt}\right|_{t=0} (\tilde{a}^*A \rightarrow VA) \propto \alpha_S^2 [G_A(x,Q^2)]^2$$

The Issue With Our Current Understanding

Established Model:

Linear DGLAP evolution scheme

- Weird behavior of xG and F_L from HERA at small x and Q^2
  - Could signal saturation, higher twist effects, need for more/better data?
- Unexpectedly large diffractive cross-section



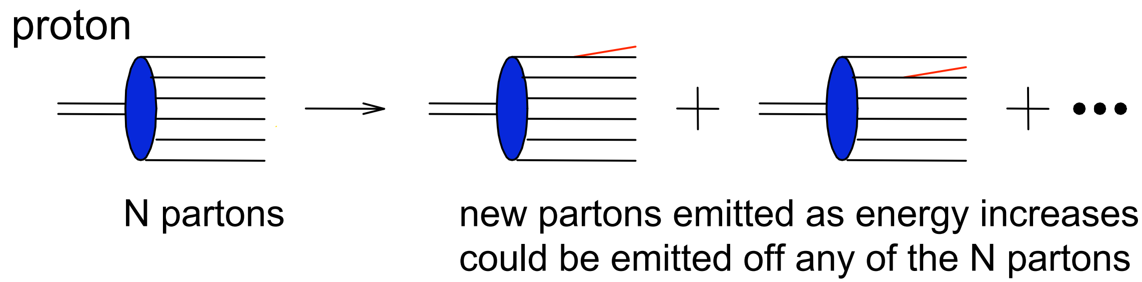
more severe:

Linear Evolution has a built in high energy "catastrophe"

- xG rapid rise for decreasing x and violation of (Froissart) unitary bound
- ⇒ **must** saturate
  - What's the underlying dynamics?

Non-Linear QCD - Saturation

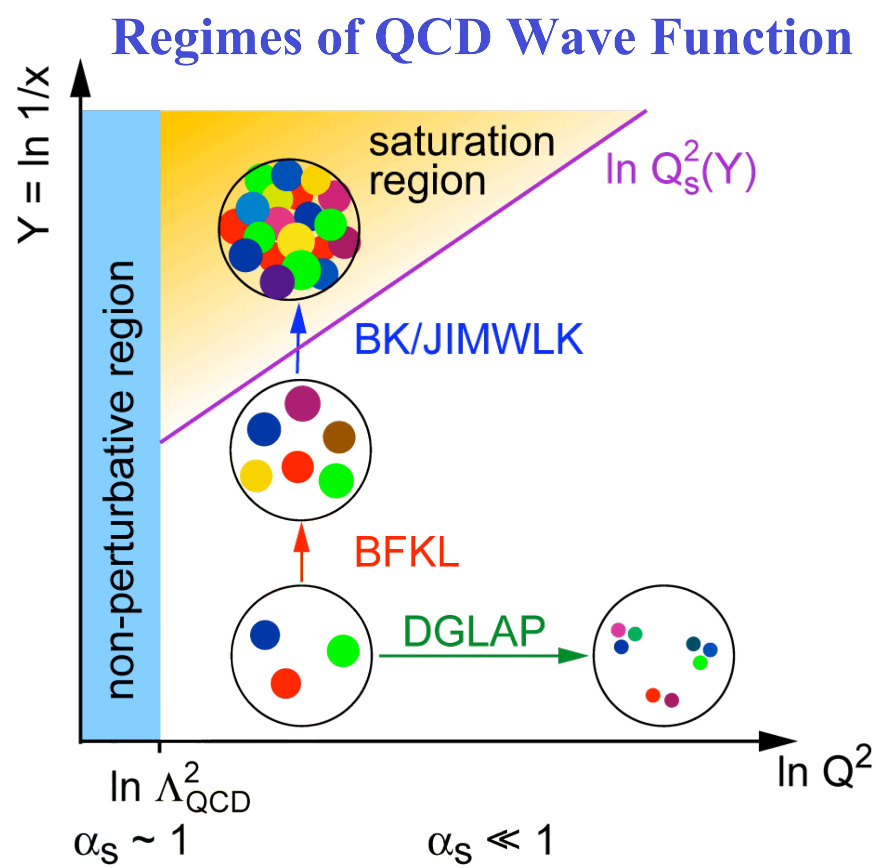
- BFKL Evolution in x
  - linear
  - explosion of color field?



- New: BK/JIMWLK

  based models
  - introduce *non-linear* effects

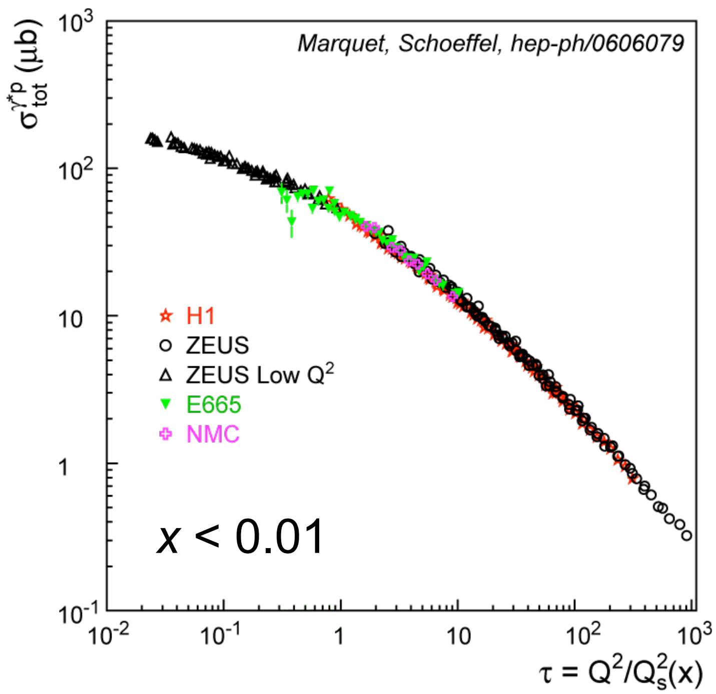
  ⇒ saturation
  - characterized by a scale $Q_s(x,A)$
  - grows with decreasing x and increasing A
  - arises naturally in the Color Glass Condensate (CGC) framework

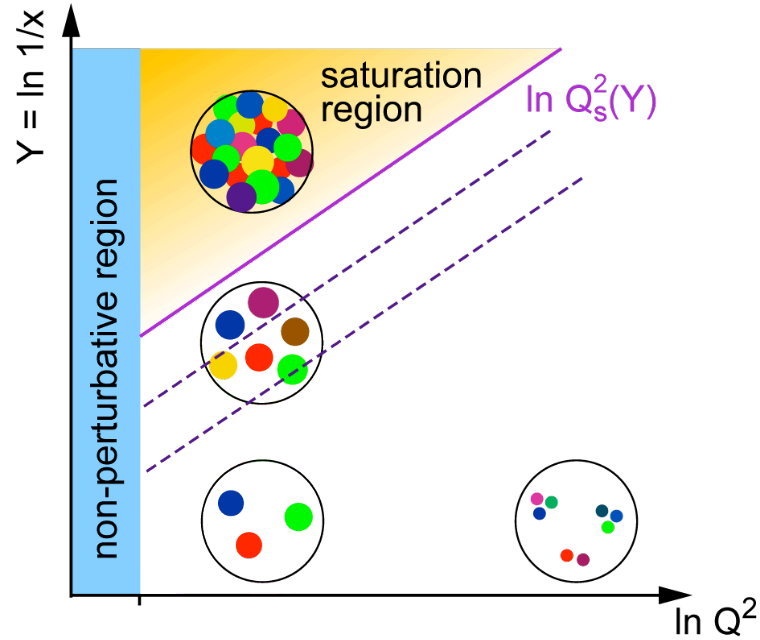


Universality & Geometric Scaling

Crucial consequence of non-linear evolution towards saturation:

- Physics *invariant* along trajectories parallel to saturation regime (lines of constant gluon occupancy)
- Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately





⇐ Geometric Scaling

- Consequence of saturation which manifests itself up to $k_T > Q_s$
- This functional form is independent of whether Q_S is that of a hadron or nucleus.

All Depends on the Oomph

Nuclear Oomph Factor: $(Q_s^A)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{1/3}$

Enhancement of Q_S with A

⇒ non-linear QCD regime reached at significantly lower energy in e+*A* than in *e+p*

$$
\begin{aligned}
s_{Hera} &\approx (330\ \mathrm{GeV})^2 \\
s_{EIC} &\approx (63\ \mathrm{GeV})^2 \\
\frac{s_{EIC}}{s_{Hera}} &\approx \frac{1}{27}
\end{aligned}
$$

Instead of extending *x, Q* reach we increase Q_s

$Q^2 \sim sx$: EIC factor 27 behind (10+100 GeV)

$$
\begin{aligned}
Q_s^2(Hera) &= Q_s^2(EIC) \rightarrow Q_0^2\ x_{Hera}^{-1/3} = c\ Q_0^2\ A^{1/3}\ x_{EIC}^{-1/3} \\
x_{EIC} &= x_{Hera} \cdot c^3 A \\
c^3 A &= 0.5^3 \cdot 197 \approx 25
\end{aligned}
$$

State-of-the-Art Oomph ?

The e+A program lives and dies with the enhancement of Q_s^A over Q_s^p

This factor is huge (500)

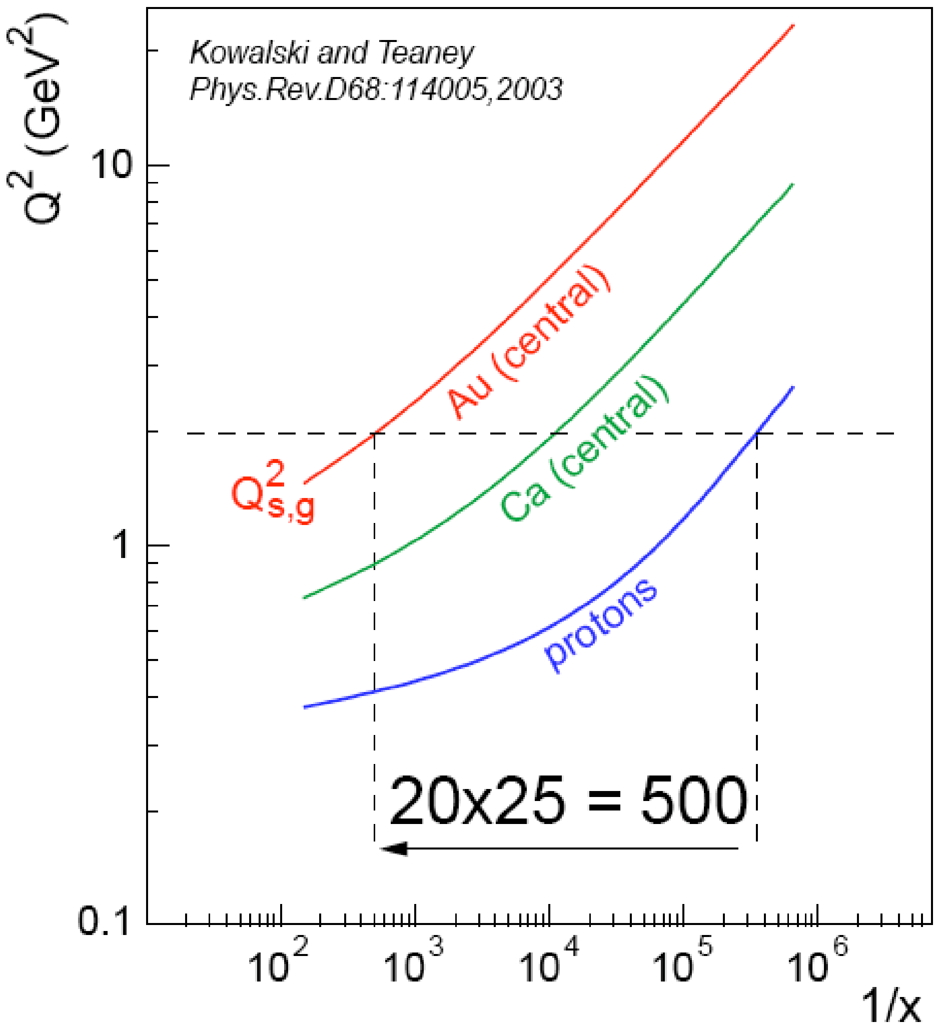
but

it's a model calculation!

Assuming it's correct we "reach" further compared to HERA by 500/27 = 18

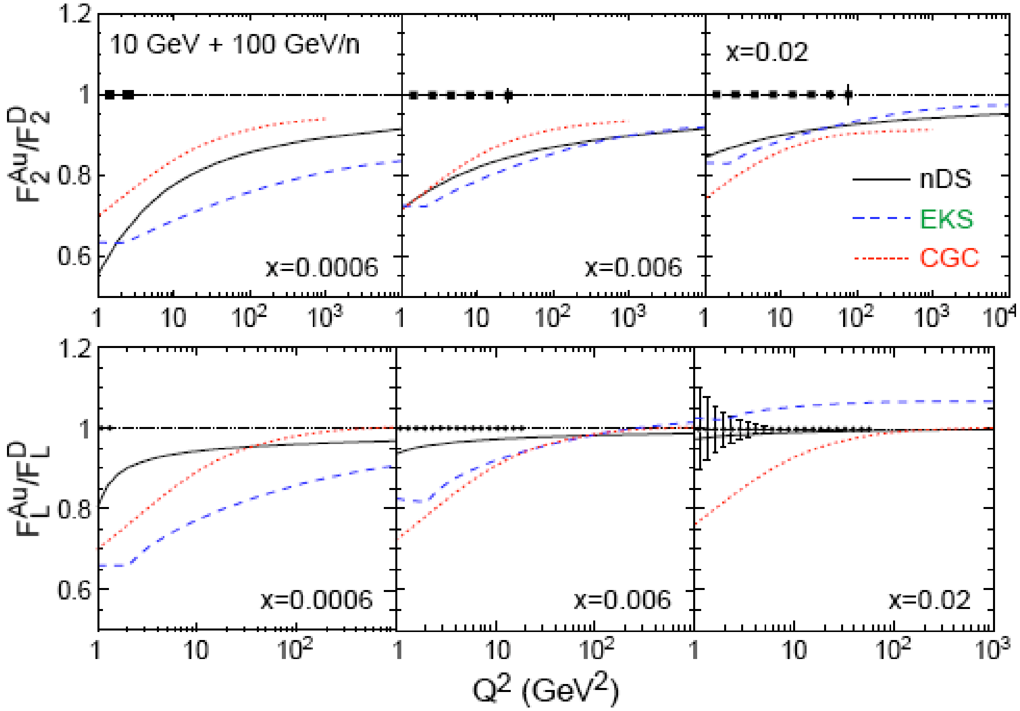
(where we see no striking saturation effects)

Here: protons for $b=b_{med}$

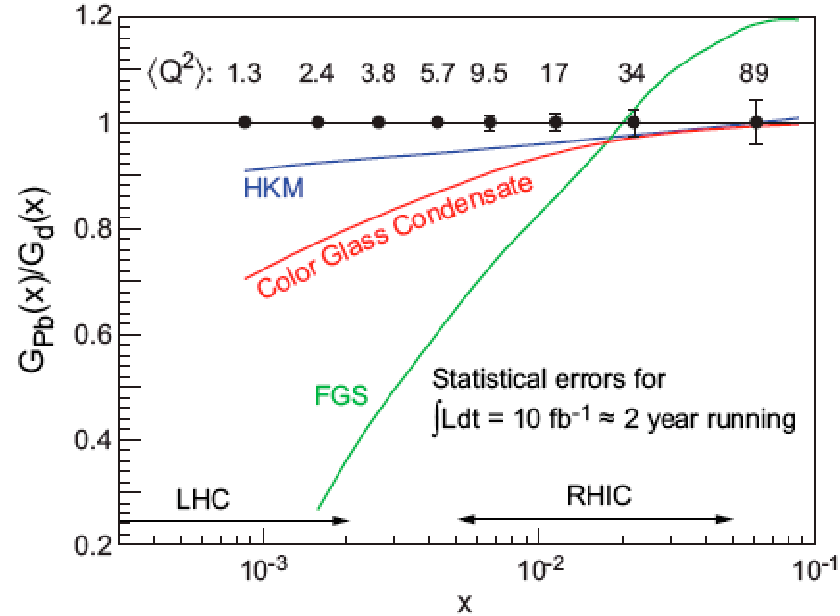


G(x,Q²) and Luminosity

Simulations to demonstrate the quality of EIC measurements



Folded with EIC acceptance



$F_L \sim \alpha_s\, G(x,Q^2)$ requires √s scan, $Q^2/xs = y$

Assume:

$L = 3.8\ 10^{33}\ cm^{-2}\ s^{-1}$ (100x Hera)

T = 10 weeks

duty cycle: 50%

L ~ 1/A (approx)

$\int Ldt = 11\ fb^{-1}$

Plots above:

$\int \mathcal{L}dt$ = 4/A fb^{-1} (10+100) GeV

= 4/A fb^{-1} (10+50) GeV

= 2/A fb^{-1} (5+50) GeV

statistical error only

Summary

EIC is the ideal machine to provide the final answers on the structure of the proton, especially in the region where sea quarks and gluons dominate

It will allow to :

- measure precisely the gluon distribution at low x and moderate Q2
- 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 phyiscs of saturation in the nucleus