Science Overview I: (Polarized) e-p Collisions

Nuclear Science Goals: How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

→ Explore the structure of the nucleon

(it's what we are made of)

Rolf Ent (JLab) for the EIC Collaboration
EICAC Meeting
SURA Headquarters, Washington D.C.
February 16, 2009

EIC science has evolved from new insights and technical accomplishments over the last decade

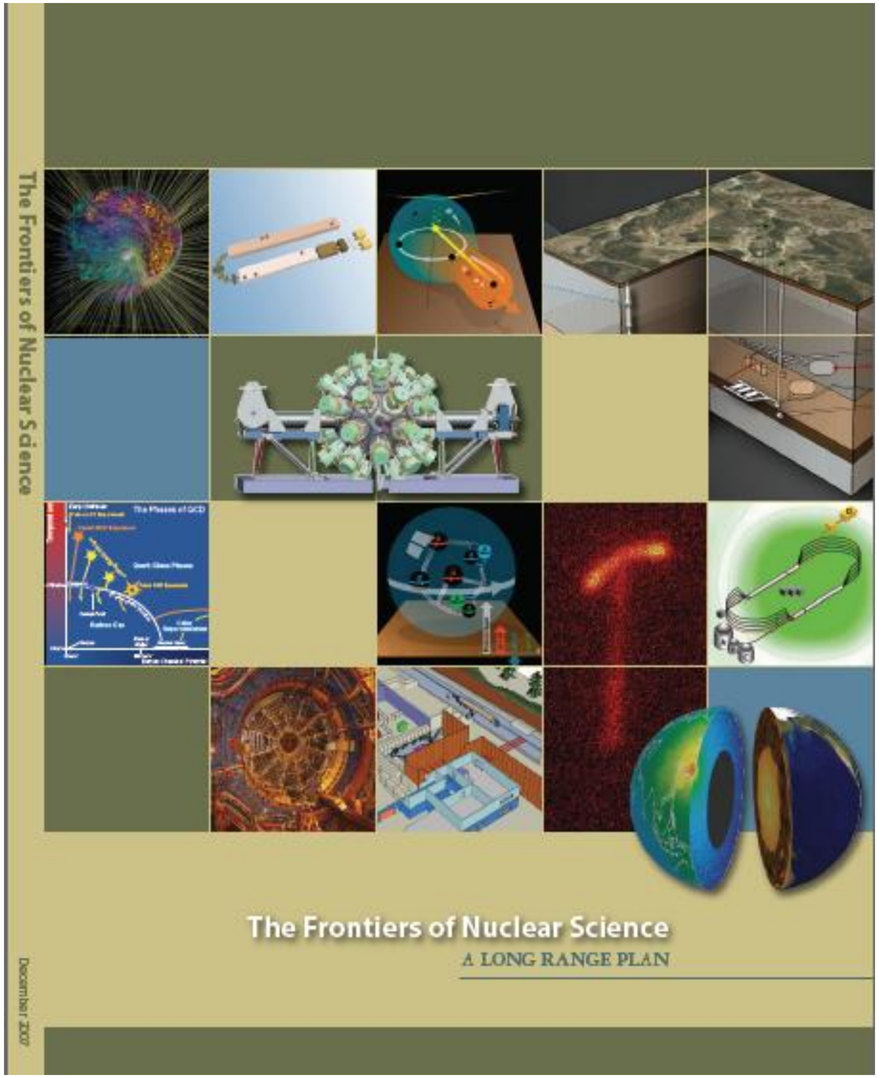
- ~1996 development of Generalized Parton Distributions
- ~1999 high-power energy recovery linac technology
- ~2000 universal properties of strongly interacting glue
- ~2000 emergence of transverse-spin phenomenon
- ~2001 world's first high energy polarized proton collider
- ~2003 tantalizing hints of saturation
- ~2006 electron cooling for high-energy beams

Still many ongoing developments: constraints on gluon polarization, 1st tests of crab cavities, development of semi-inclusive DIS framework at NLO, 2nd round of deep exclusive measurements, Lattice QCD progress, etc., etc.

NSAC 2007 Long Range Plan

"An **Electron-Ion Collider (EIC)** with polarized beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton."



(Polarized) e-p Collisions Science Goal:

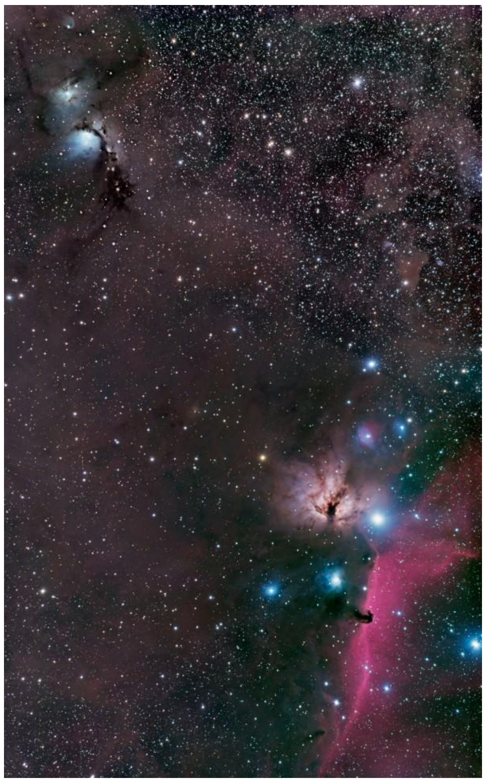
Precisely image the quarks and gluons in the nucleon

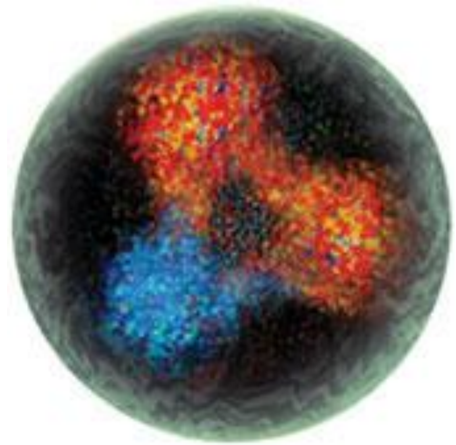
- How do the gluons and quarks contribute to the spin structure of the nucleon?
- What is the spatial distribution of the gluons and quarks in the nucleon?
- How do hadronic final-states form in QCD?

Transformational or incremental?

Nuclear Science Goals: How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

A large scale view of the universe:
Astronomy picture of the day,
Feb. 11, 2009. Orion's Belt.





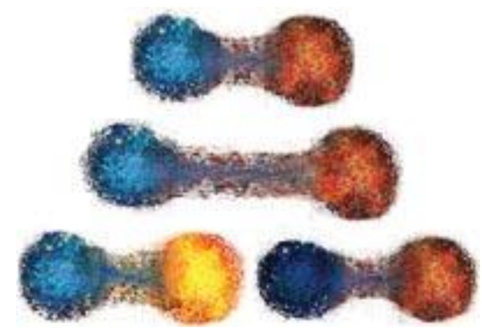
small scale view of the universe:
Cartoon of a nucleon…

But, some recent progress in transverse imaging and QCD visualizations from Lattice QCD.

The root of Modern Physics:

$$E = Mc^2$$

But, we only know how this actually works in cartoon form …



- What is the spatial distribution of the gluons and quarks in the nucleon?
- How do hadronic final-states form in QCD?

Nuclear Science Goals: How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

- How do the gluons and quarks contribute to the spin structure of the nucleon?

The Spin of the Proton

Otto Stern

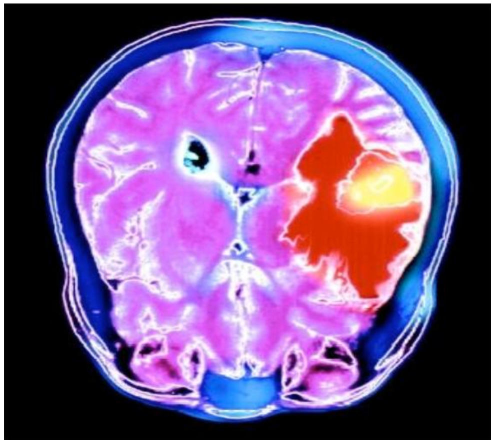
Nobel Prize, 1943: "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

μ_p = 2.5 nuclear magnetons, ± 10% (1933)

Proton spins are used to image the structure and function of the human body using the technique of *magnetic resonance imaging*.

Paul C. Lauterbur

Sir Peter Mansfield



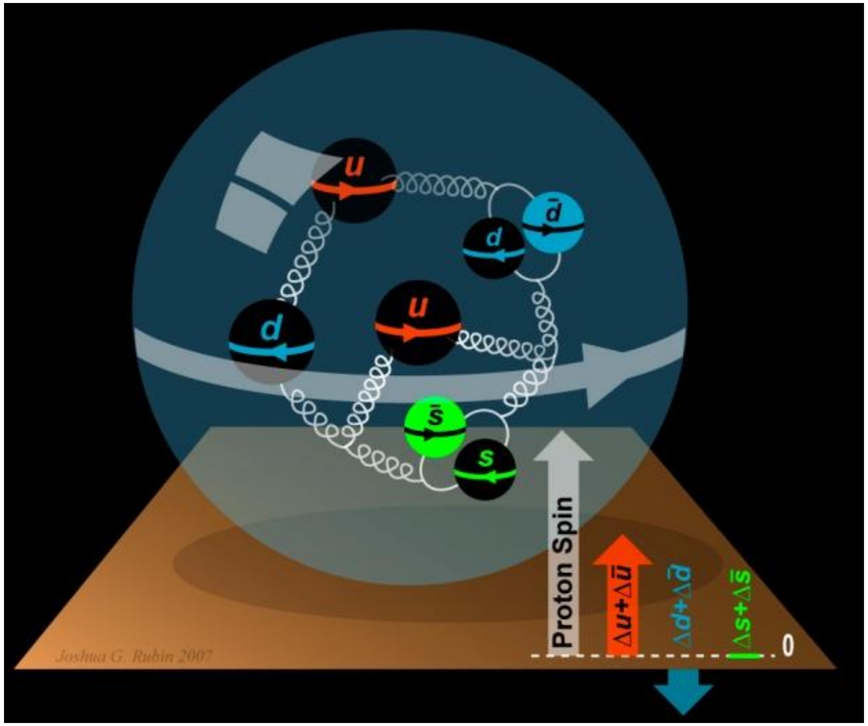
Nobel Prize, 2003: "for their discoveries concerning magnetic resonance imaging"

But where does the spin of the proton originate? (let alone other hadrons…)

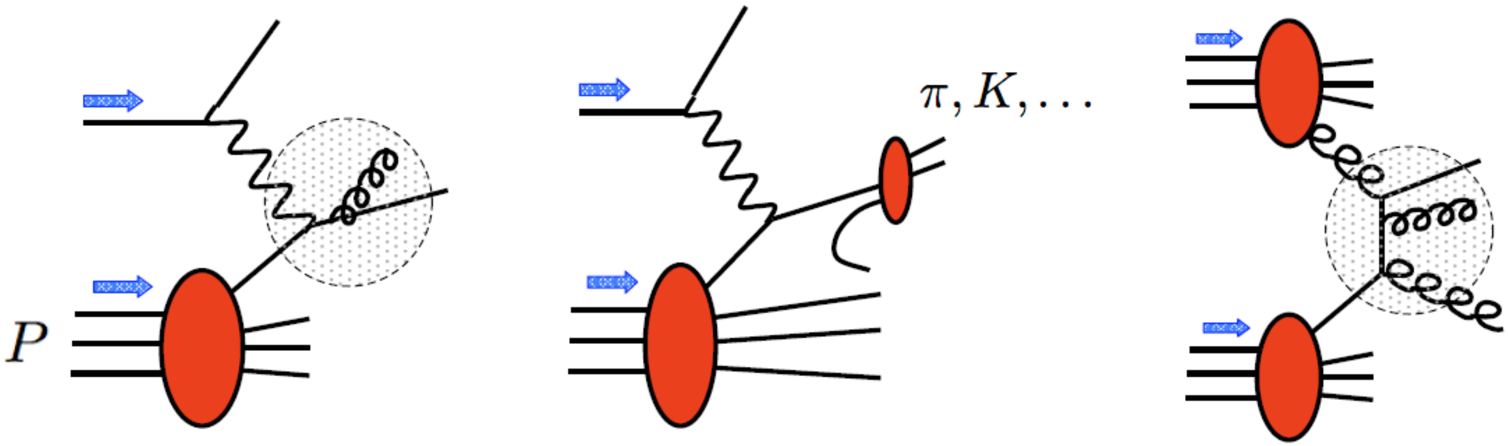
The Standard Model tells us that spin arises from the spins and orbital angular momentum of the quarks and gluons:

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

- Experiment: $\Delta\Sigma \approx 0.3$
- Gluons contribute to ≈ half of the mass and momentum of the proton, but…
- … recent results indicate that their contribution to the proton spin is small: $\Delta G < 0.1$?
- … and recent LQCD tells us that $L_u + L_d$ is small?? *(but…)*

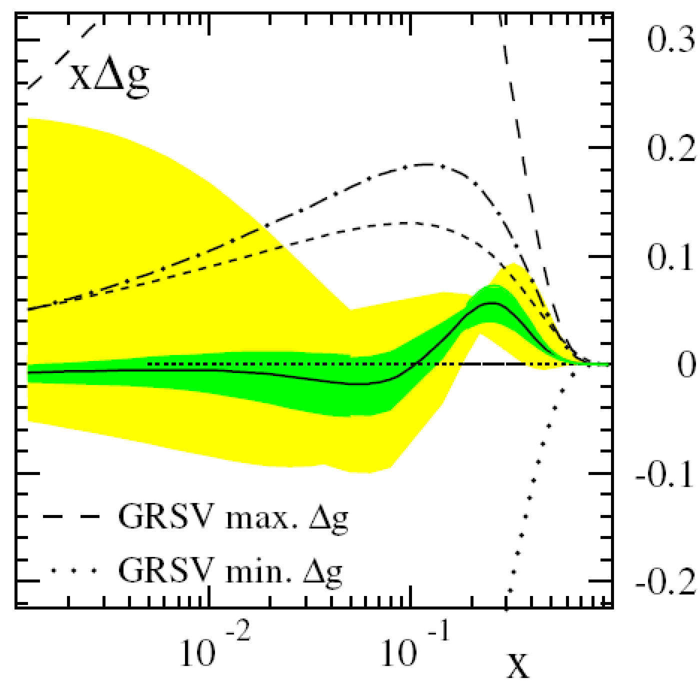


Where does the spin of the proton originate?



Input from DIS, SIDIS, pp (RHIC) and Global Fits…

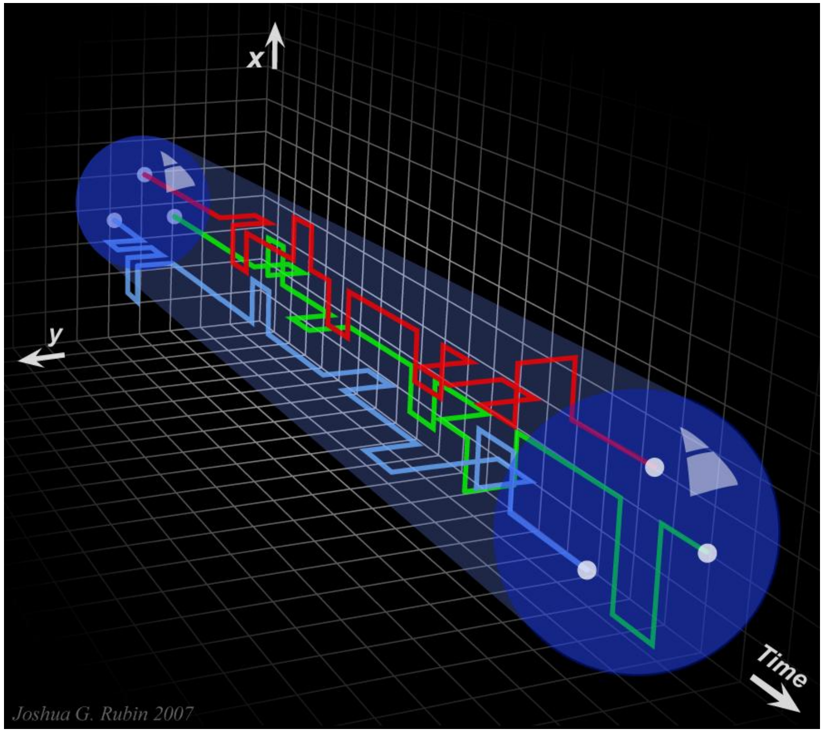
De Florian, Sassot, Stratmann and Vogelsang, Phys. Rev. Lett. 101, 072001 (2008)



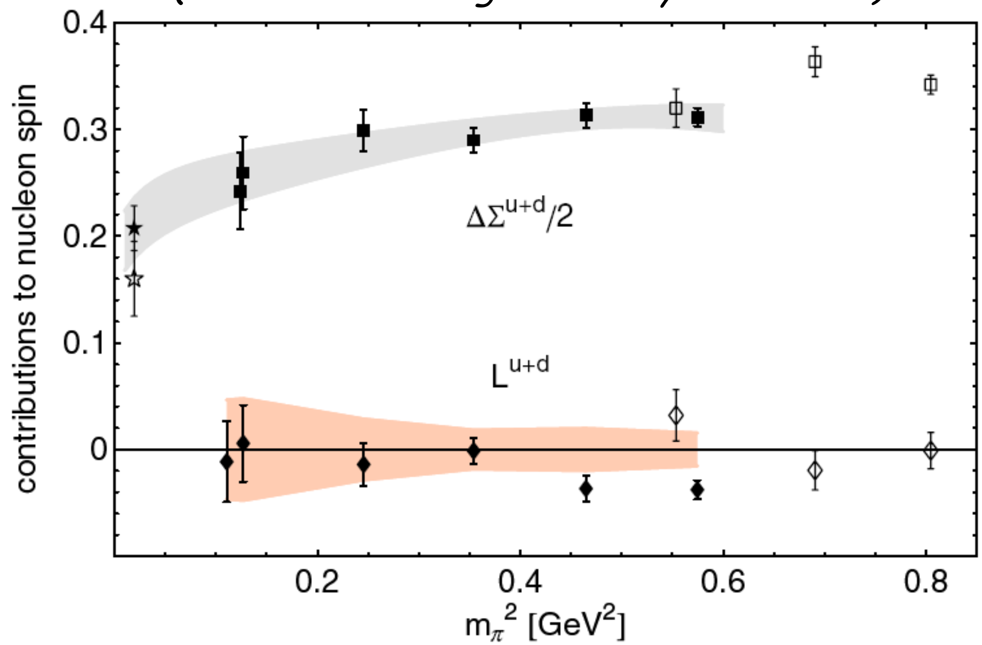
$\Delta G < 0.1$?

(constrained in narrow region of x only)

Where does the spin of the proton originate?



(disconnected diagrams not yet included)



LHPC Collaboration,
Phys. Rev. D77, 094502 (2008)

… and input from Lattice QCD on GPD moments (also from deep exclusive scattering)

L_u and L_d separately quite substantial (~0.15), but cancel

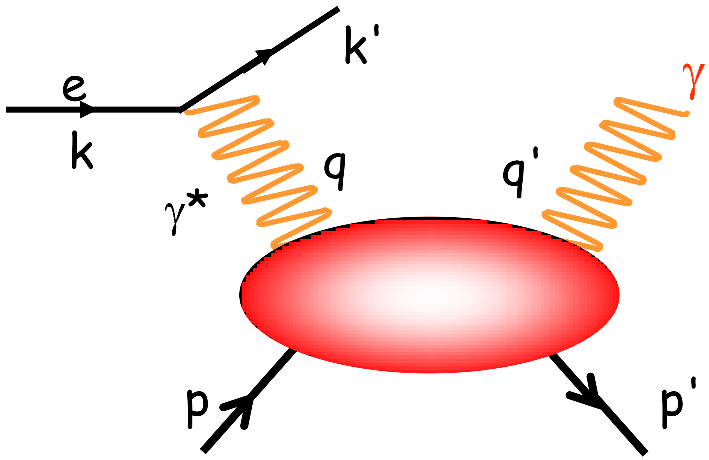
Where does the spin of the proton originate?

Generalized Parton Distributions provide access to total quark contribution to proton angular momentum in (deep) exclusive processes: e + N → e′ + N + X

$$\tfrac{1}{2} = J_q + J_g = \tfrac{1}{2}\Delta\Sigma + L_q + J_g$$

H(x,ξ,t), E(x,ξ,t), . .

"Generalized Parton Distributions"
Accessible through deep exclusive reactions (and Lattice QCD)



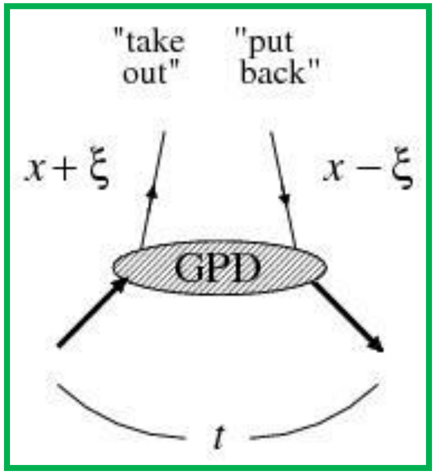
Quark angular momentum (Ji's sum rule)

$$J_q = \frac{1}{2} - J_g = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H_q(x,\xi,0) + E_q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

What's the use of GPDs?

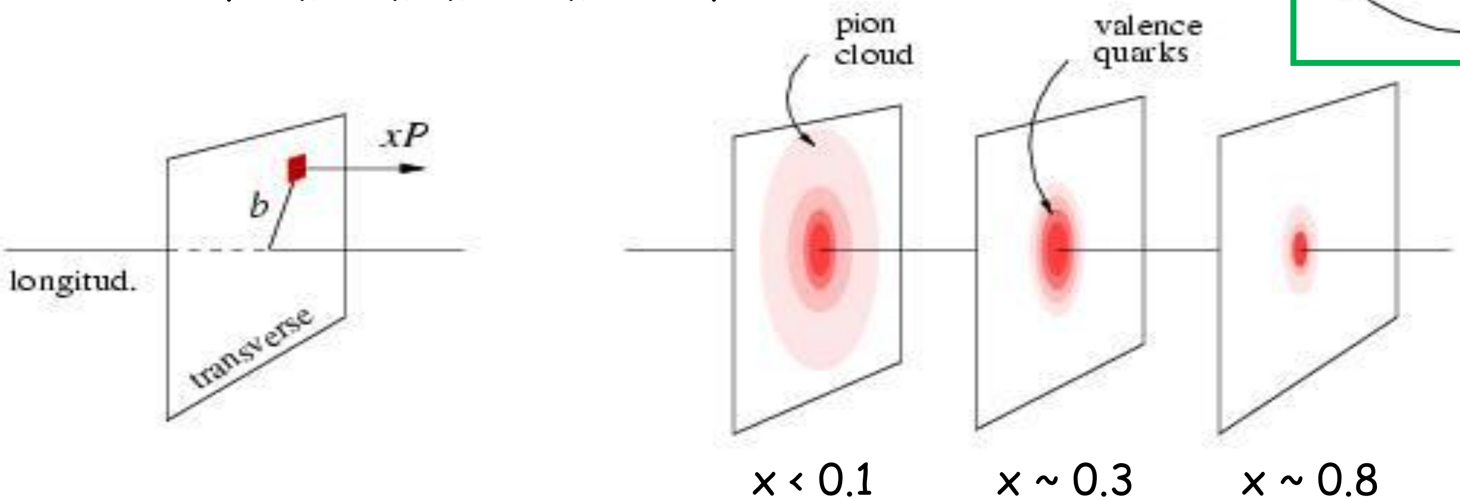
1. Allows for a unified description of form factors and parton distributions



2. Describe correlations of quarks/gluons

3. Allows for Transverse Imaging

Fourier transform in momentum transfer

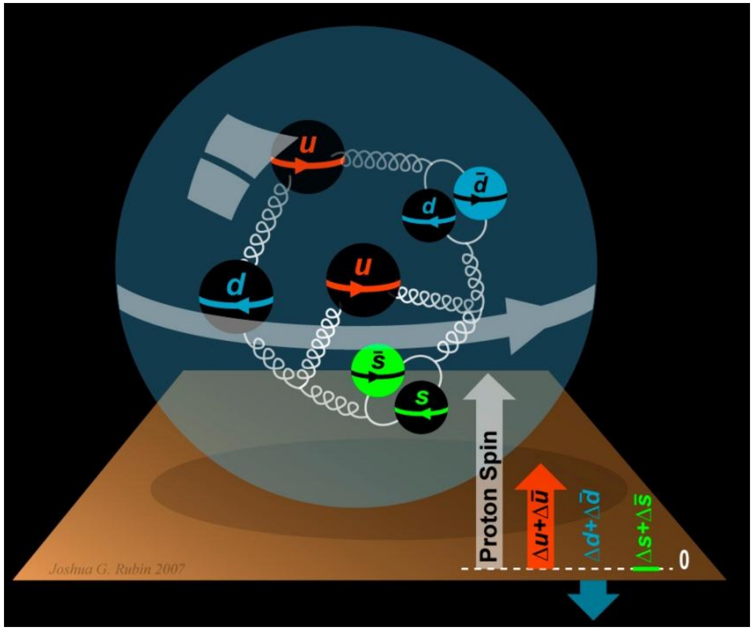


gives transverse spatial distribution of quark (parton) with momentum fraction x

3. Allows access to quark angular momentum (in model-dependent way)

Explore the structure of the nucleon

Examples of EIC science simulations



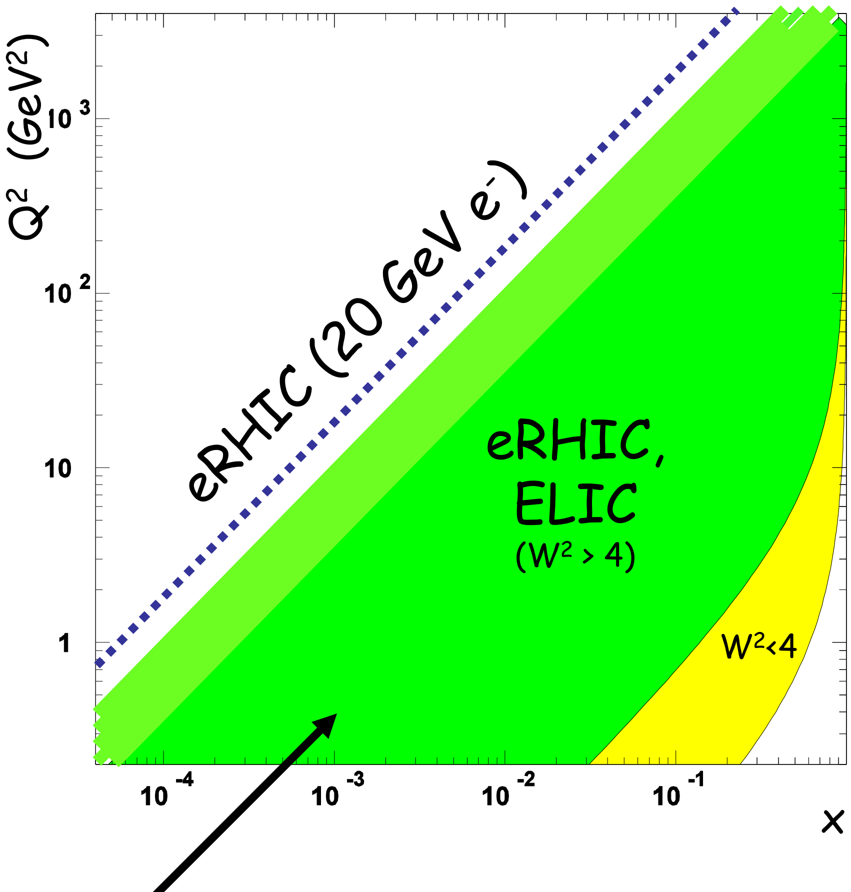
- Parton distribution functions
- Longitudinal and transverse spin distribution functions
- Generalized parton distributions
- Unintegrated parton distribution functions

Will emphasize proton, but neutron results equally important:

- spectator tagging in D(e,e'p)X ideal for collider
- plans to use both polarized ^{2}H and ^{3}He beams

Luminosity Considerations for EIC

eRHIC: x = 10^{-4} @ $Q^2 = 1$
ELIC : x = 10^{-4} @ $Q^2 = 1$
12 GeV: x = 4.5×10^{-2} @ $Q^2 = 1$



Include low-Q^2 region

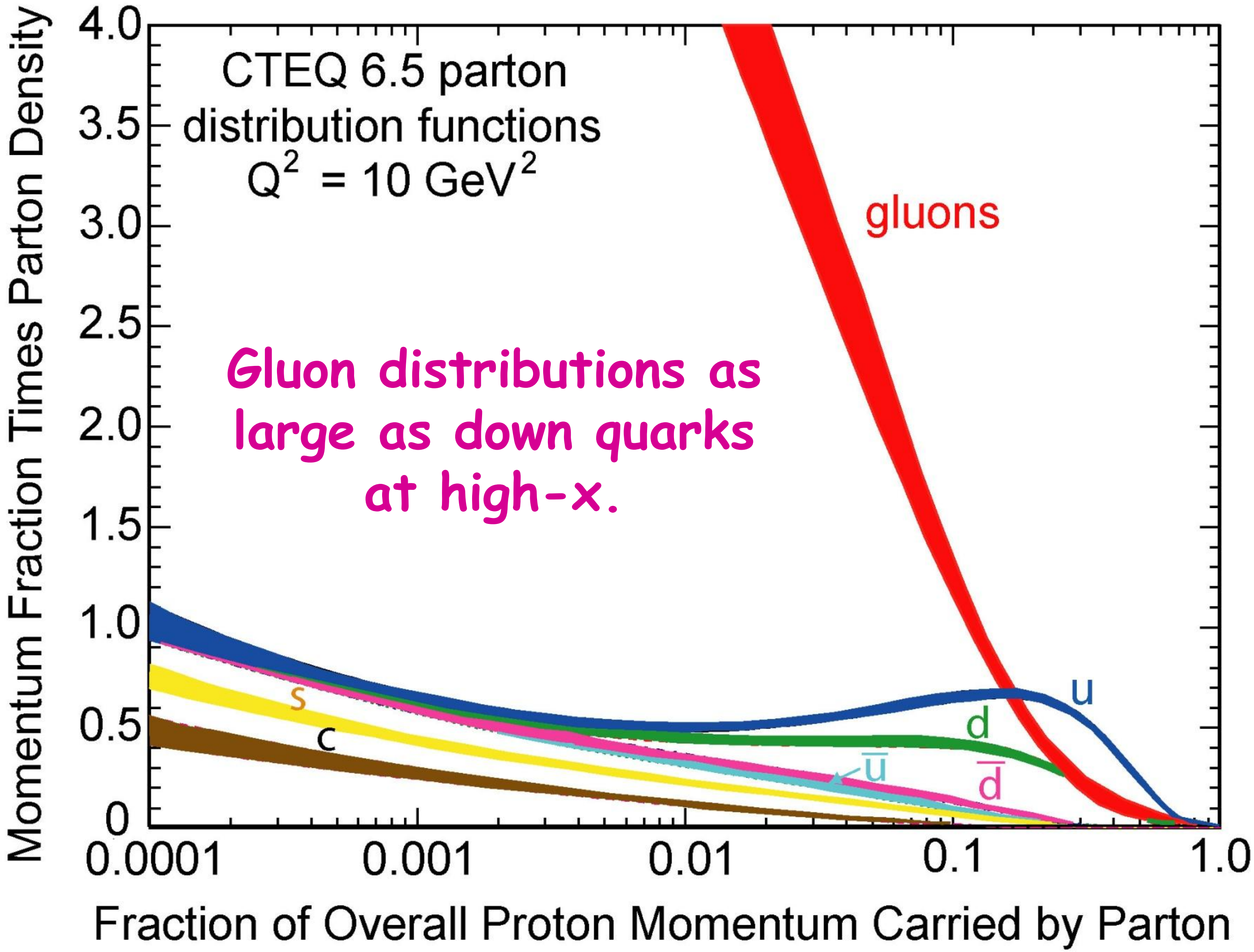
- Luminosity of 1×10^{33} cm^{-2} sec^{-1}
  - One day → 50 events/pb
  - Supports Precision Experiments

Lower value of x scales as s^{-1}

- DIS Limit for $Q^2 > 1$ GeV^2 implies x down to 1.0 times 10^{-4}
  - Significant results for 200 events/pb for inclusive scattering
- If $Q^2 > 10$ GeV^2 required for Deep Exclusive Processes can reach x down to 1.0 times 10^{-3}
  - Typical cross sections factor 100-1,000 smaller than inclusive scattering
  - Significant results for 20,000-200,000 events/pb → high luminosity essential

ELIC-staged: s = 600 → x = 1.7×10^{-3}@Q^2=1

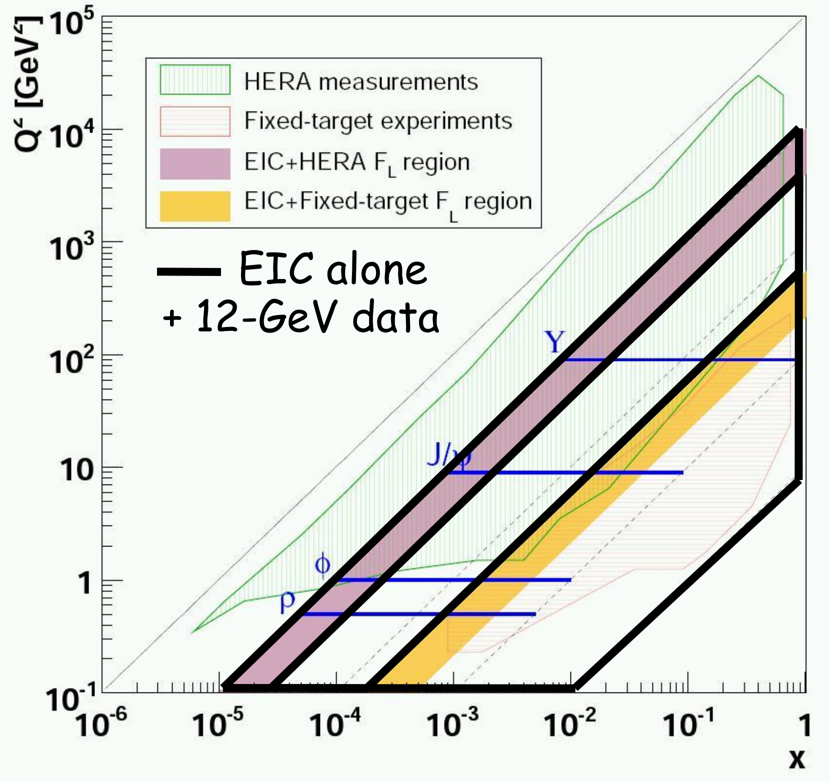
CTEQ Example at Scale Q^2 = 10 GeV^2



F_L at EIC: Measuring the Glue Directly

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

- Experimentally can be determined directly IF VARIABLE ENERGIES!
- Highly sensitive to effects of gluon

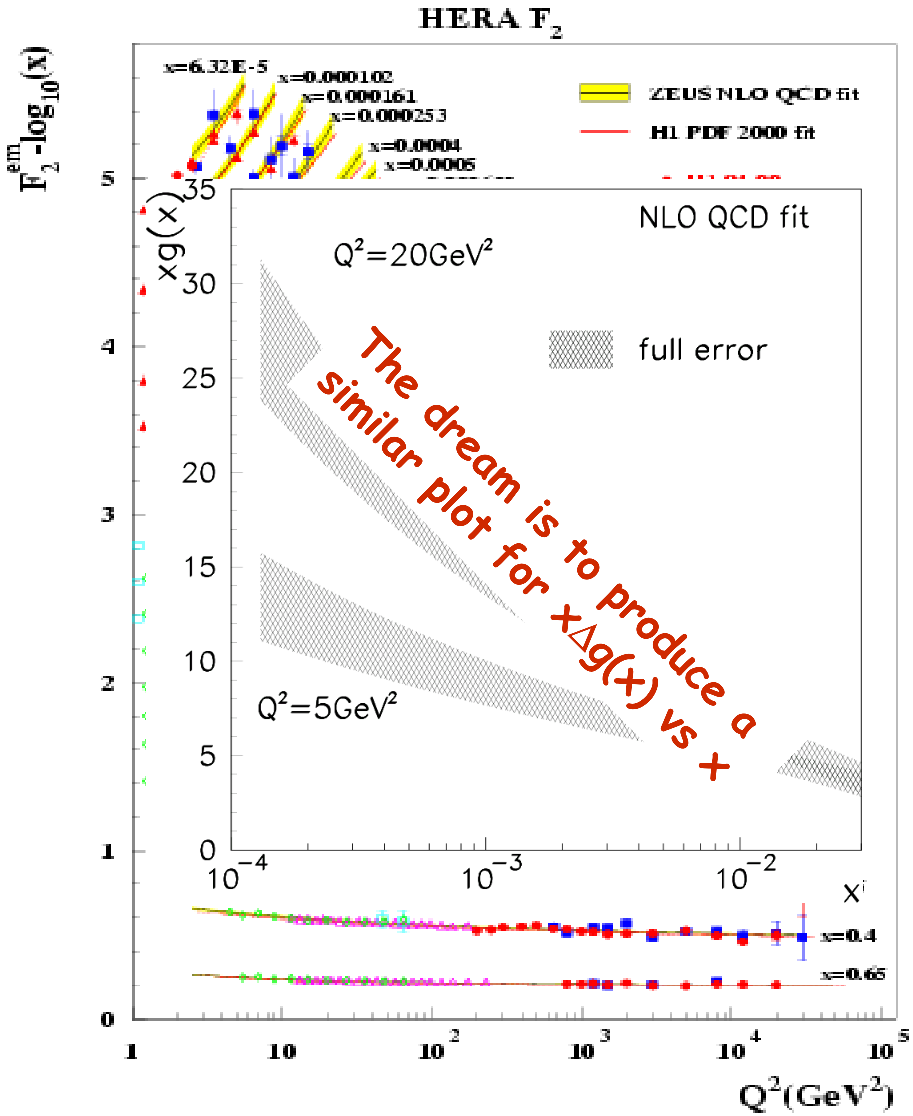


How to measure Gluon distribution $G(x,Q^2)$:

- Scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
- $F_L \sim \alpha_s\, G(x,Q^2)$
- inelastic vector meson production (e.g. J/ψ)
- diffractive vector meson production $\sim [G(x,Q^2)]^2$

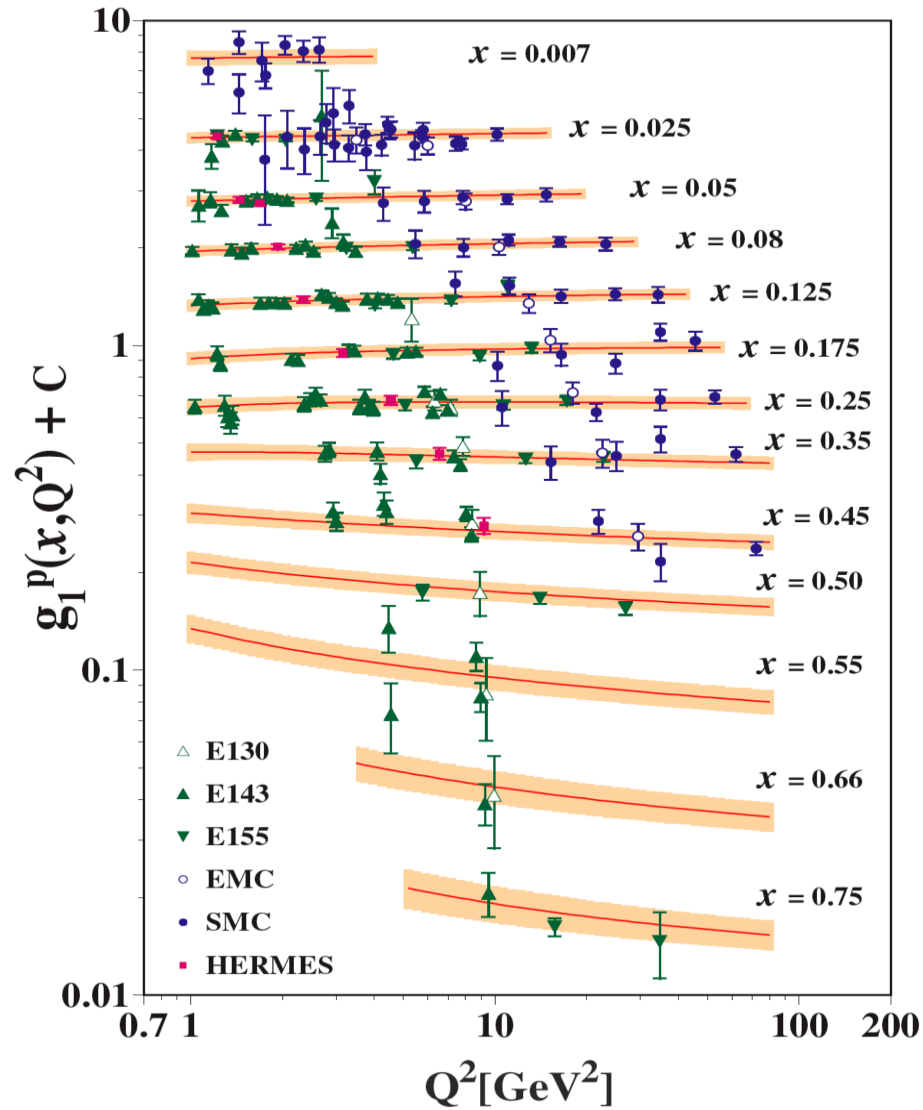
$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

World Data on F_2^p



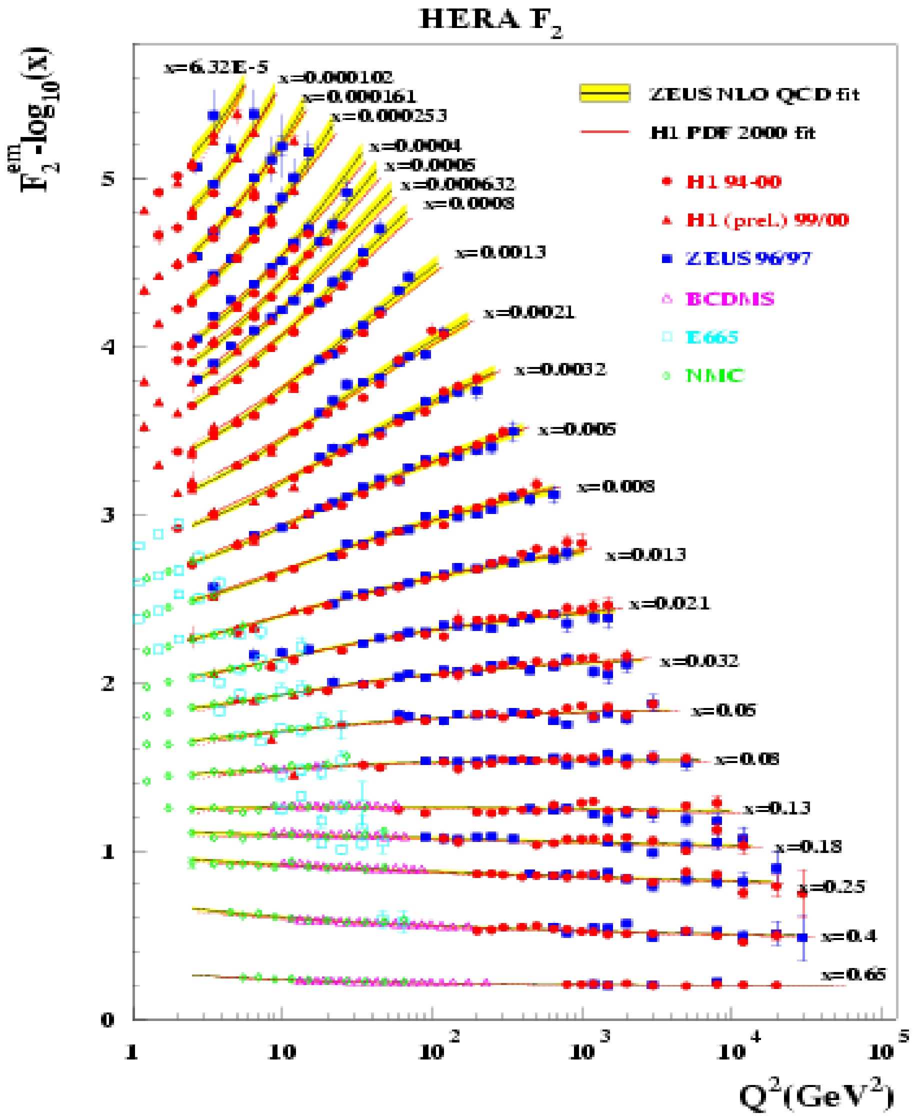
→ 50% of momentum carried by gluons

World Data on g_1^p



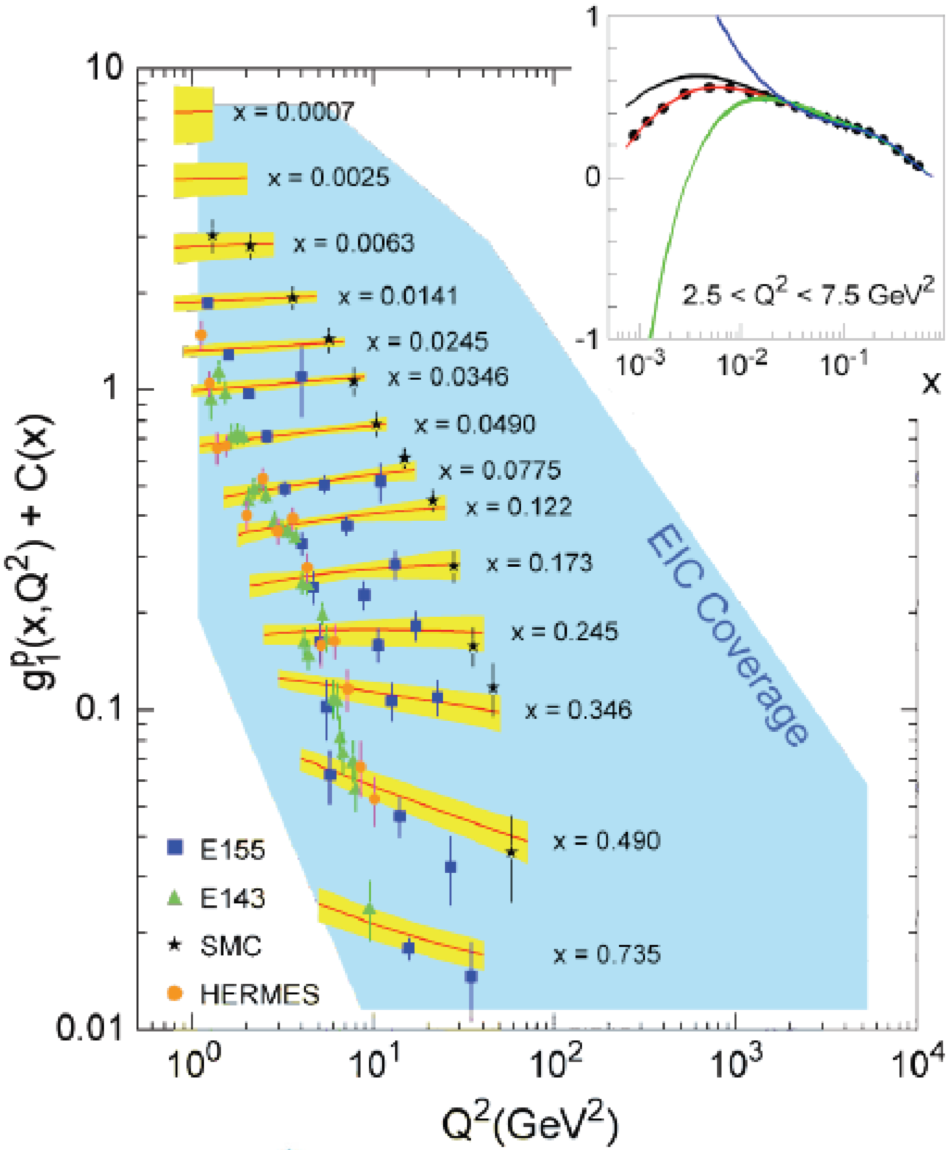
→ 30% of proton spin carried by quark spin

World Data on F_2^p



→ 50% of momentum carried by gluons

World Data on g_1^p



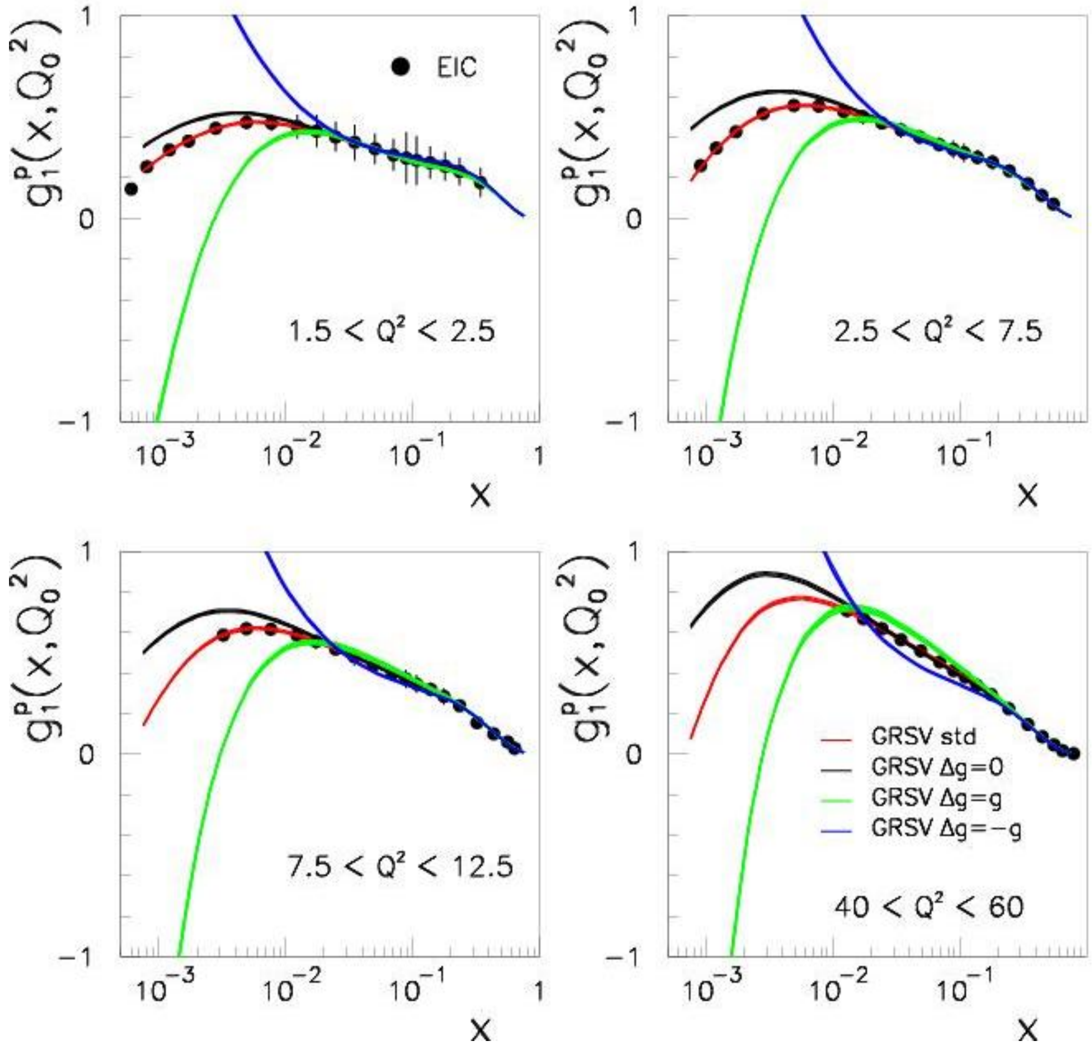
An EIC makes it possible!

The Gluon Contribution to the Proton Spin

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

(Antje Bruell, Abhay Deshpande)

at small x



Superb sensitivity to Δg at small x!

The Gluon Contribution to the Proton Spin

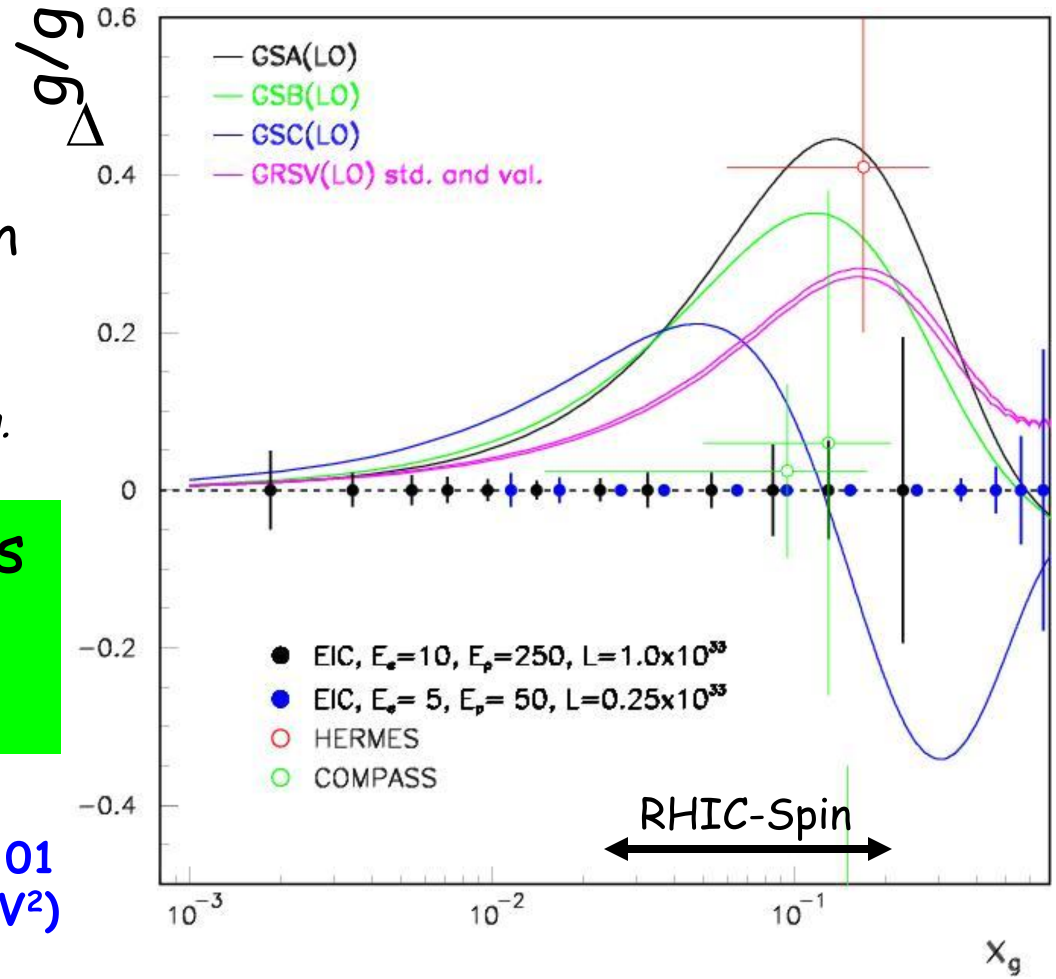
Projected data on $\Delta g/g$ with an EIC, via $\gamma + p \rightarrow D^0 + X$

$\hookrightarrow K^- + \pi^+$

assuming vertex separation of 100 μm.

Advantage: measurements directly at fixed $Q^2 \sim 10$ GeV^2 scale!

- Uncertainties in $x\Delta g$ smaller than 0.01
- Measure 90% of ΔG (@ $Q^2 = 10$ GeV^2)

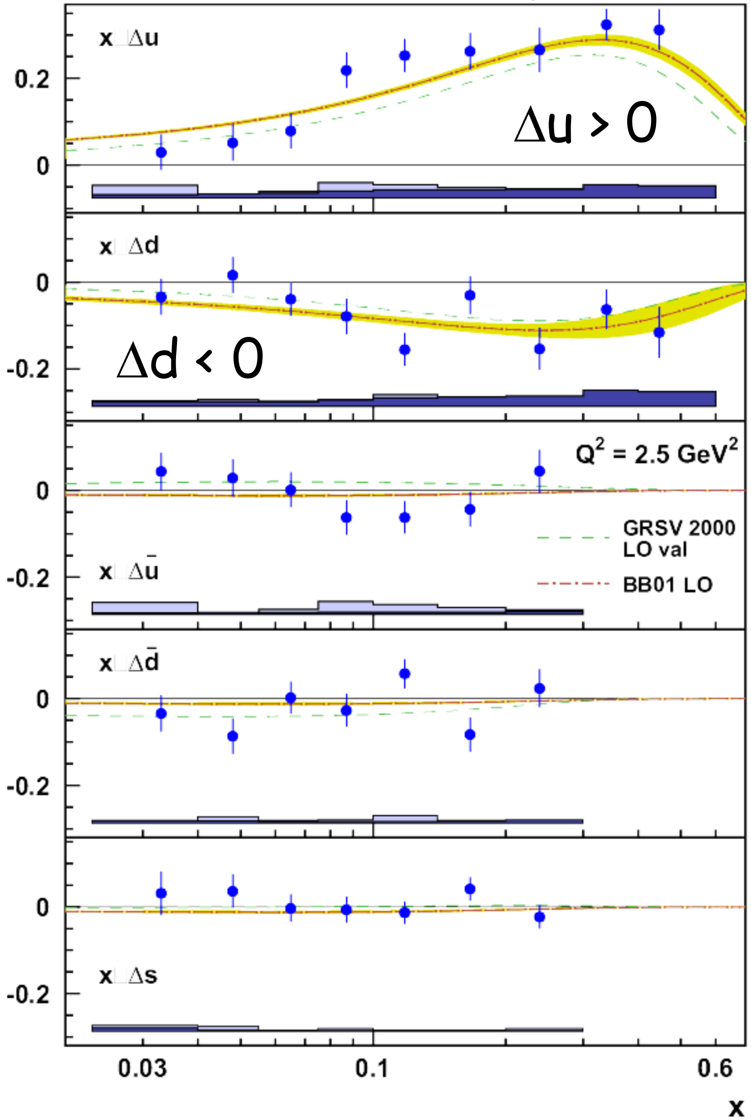


Access to $\Delta g/g$ is also possible from the g_1^p measurements through the QCD evolution, and from di-jet measurements.

Flavor Decomposition @ EIC

❖ quark polarization $\Delta q(x)$

→ first 5-flavor separation



100 days at 10^{33}

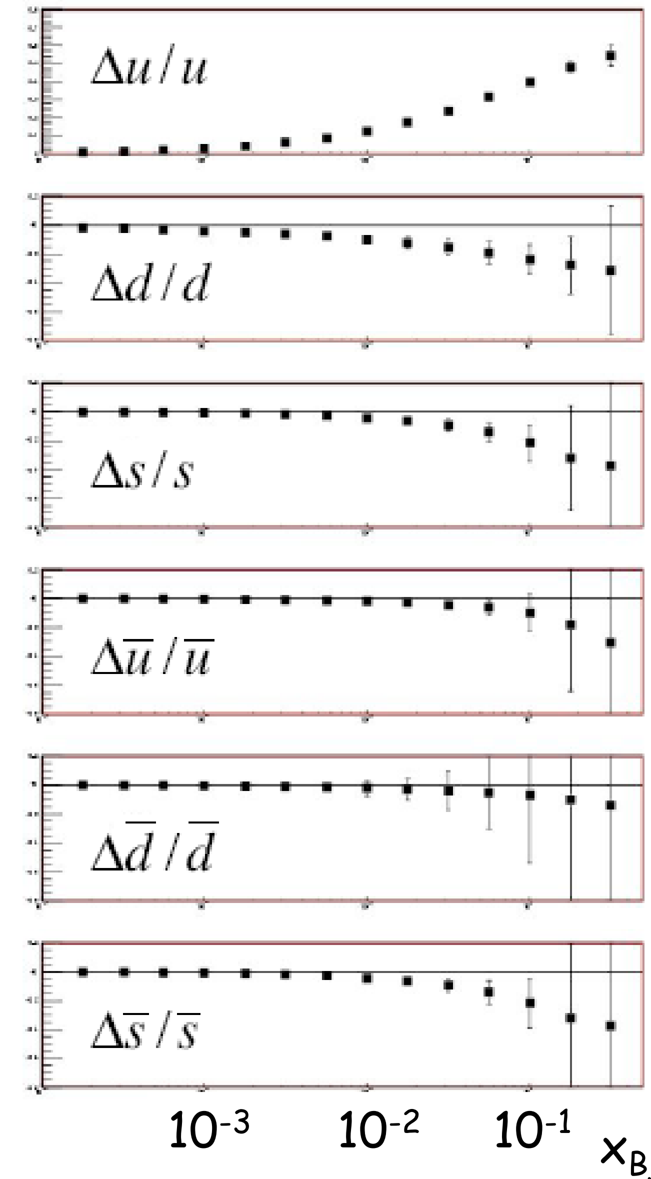
Lower $x \sim 1/s$

5 on 50 → $s = 1000$

10 on 250 → $s = 10000$

(Ed Kinney, Joe Seele)

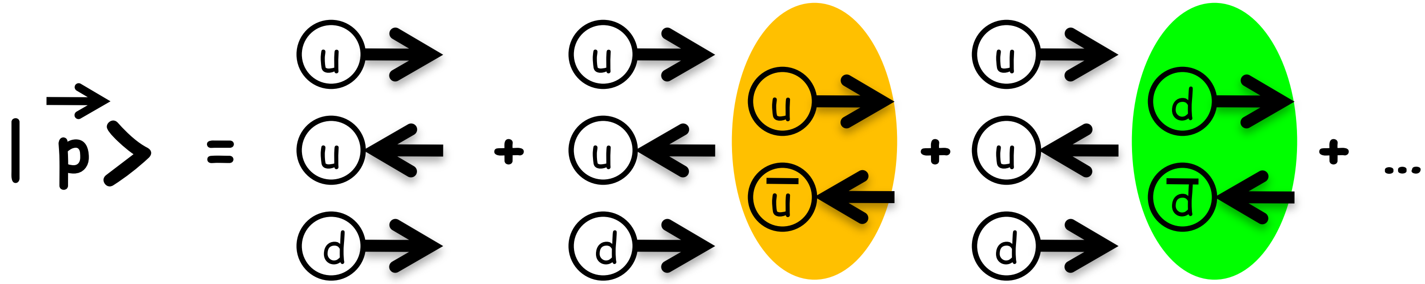
10 on 250 EIC projected data



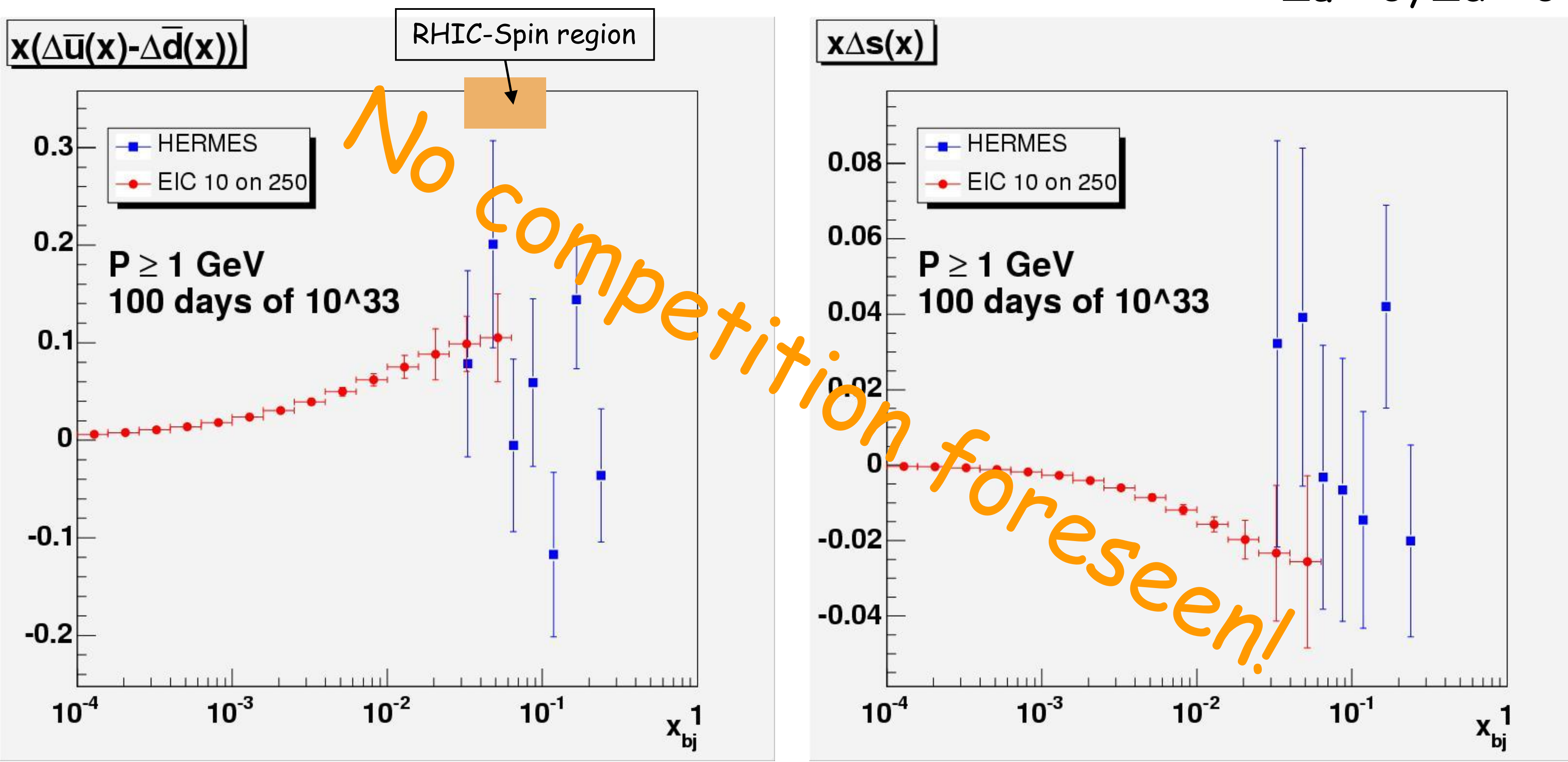
Polarized pdfs also constrained through Electroweak DIS!

Precisely image the sea quarks

Spin-Flavor Decomposition of the Light Quark Sea



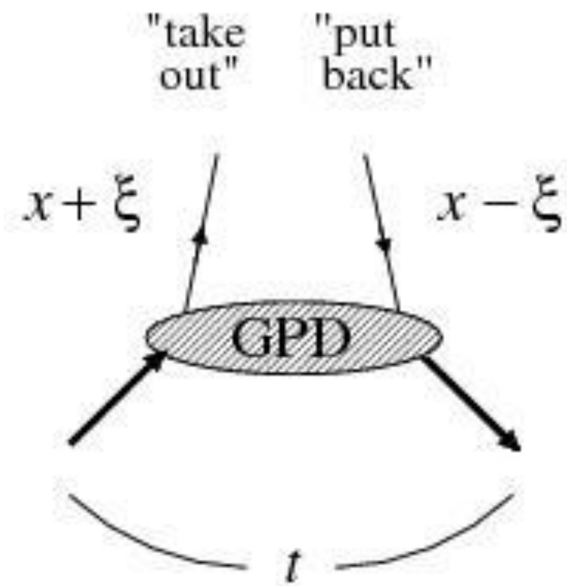
Many models predict
$\Delta\bar{u} > 0, \Delta\bar{d} < 0$



GPDs and Transverse Imaging

Deep exclusive measurements in ep/eA with an EIC:

diffractive:	transverse gluon imaging	J/ψ, ρ^o, γ (DVCS)
non-diffractive:	quark spin/flavor structure	π, K, ρ^+, …



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

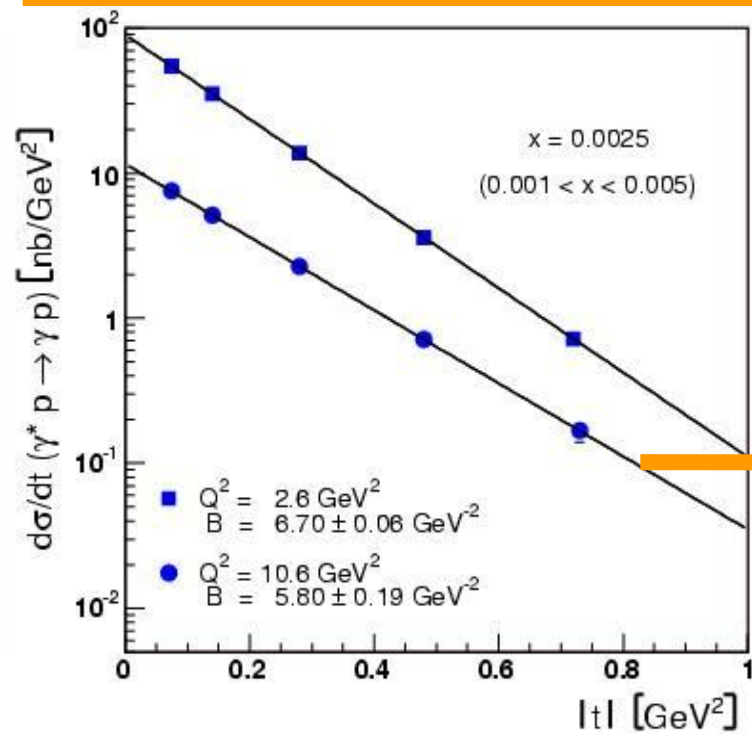
Transverse quark/**gluon** imaging of nucleon ("tomography")

GPDs and Transverse Gluon Imaging

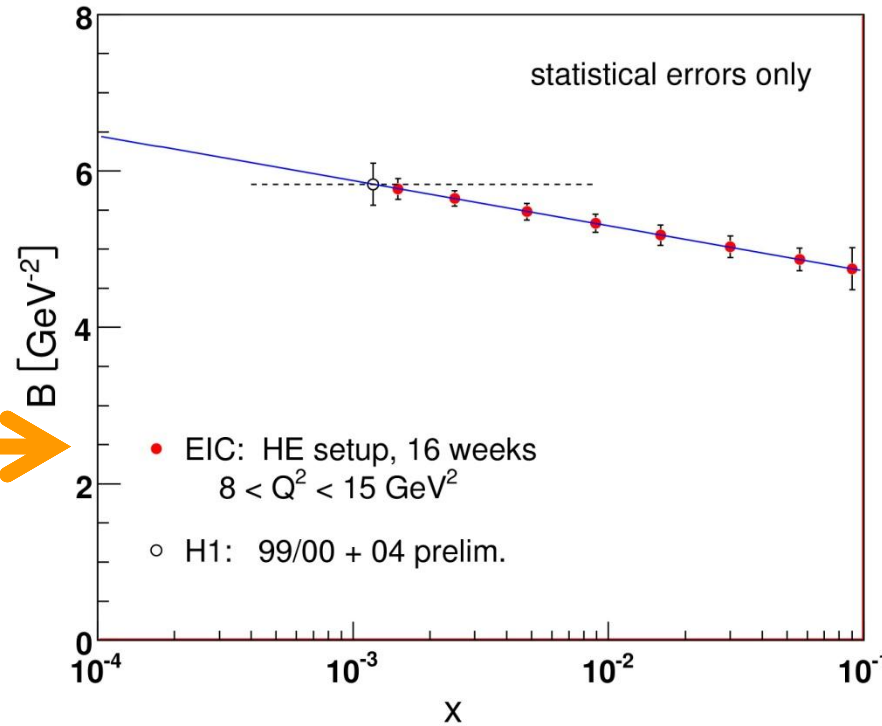
Goal: Transverse gluon imaging of nucleon over wide range of x: $0.001 < x < 0.1$

Requires:
- $Q^2 \sim 10\text{-}20\ GeV^2$ to facilitate interpretation
- Wide Q^2, W^2 (x) range
- Sufficient luminosity to do differential measurements in Q^2, W^2, t

$Q^2 = 10\ GeV^2$ projected data



EIC enables gluon imaging!



(Andrzej Sandacz)

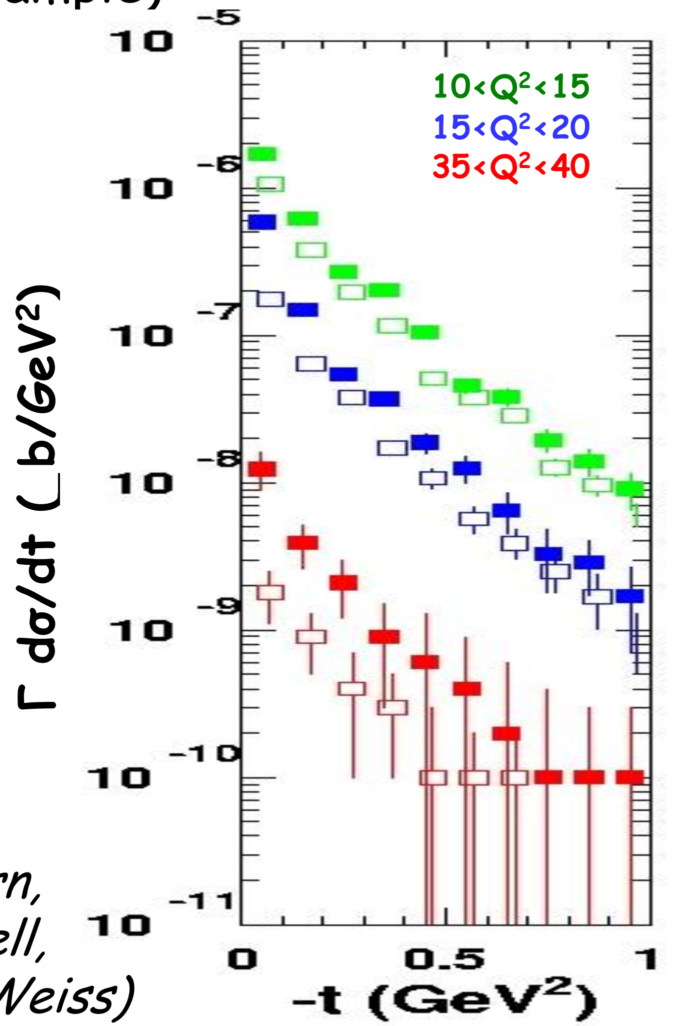
Simultaneous data at other Q^2-values

Extend to Quark Imaging: Non-Diffractive Channels

- New territory for collider!
- Much more demanding in luminosity (see example)
- Physics closely related to JLab 6/12 GeV
  - quark spin/flavor separations
  - nucleon/meson structure

Simulation for charged π^+ production, assuming 100 days at a luminosity of 10^{34}, with 5 on 50 GeV (s = 1000)

- Ch. Weiss: Regge model
- T. Horn: π^+ empirical parameterization



(Tanja Horn, Antje Bruell, Christian Weiss)

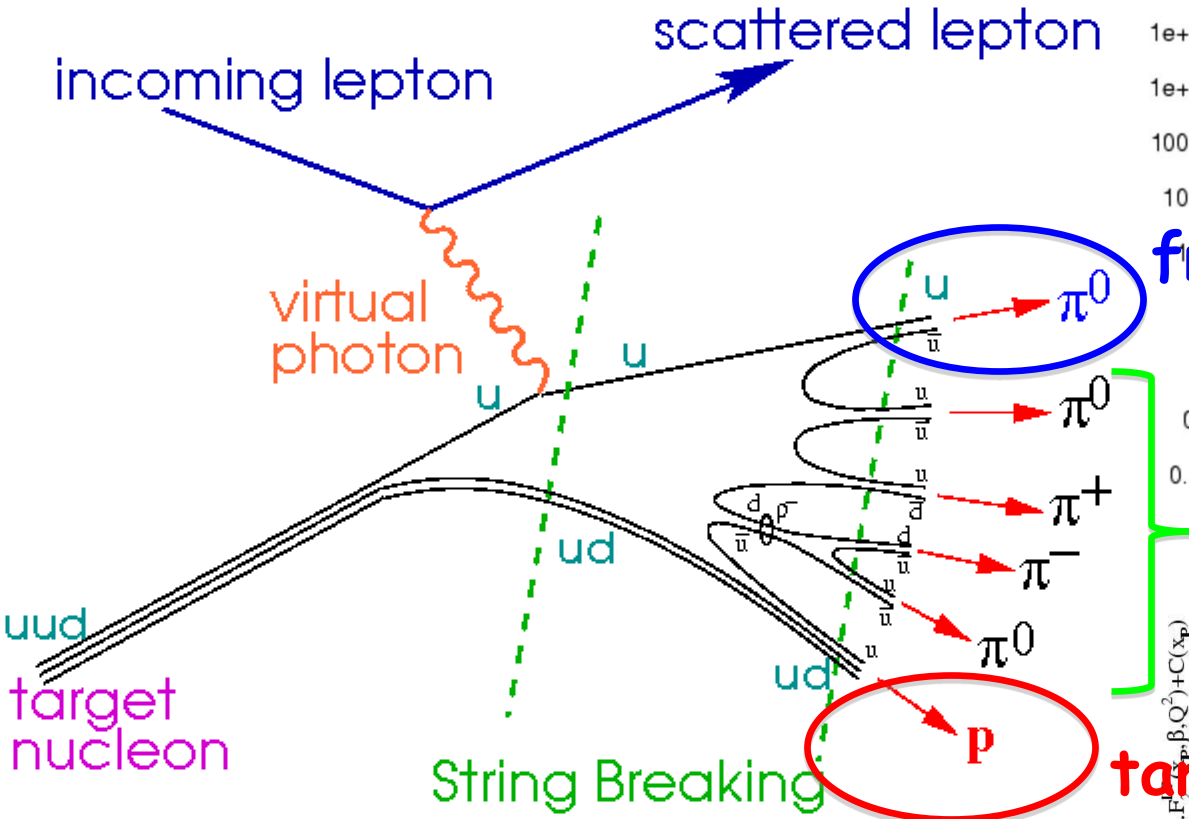
Pushes for lower and more symmetric energies (to obtain sufficient ΔM_x)

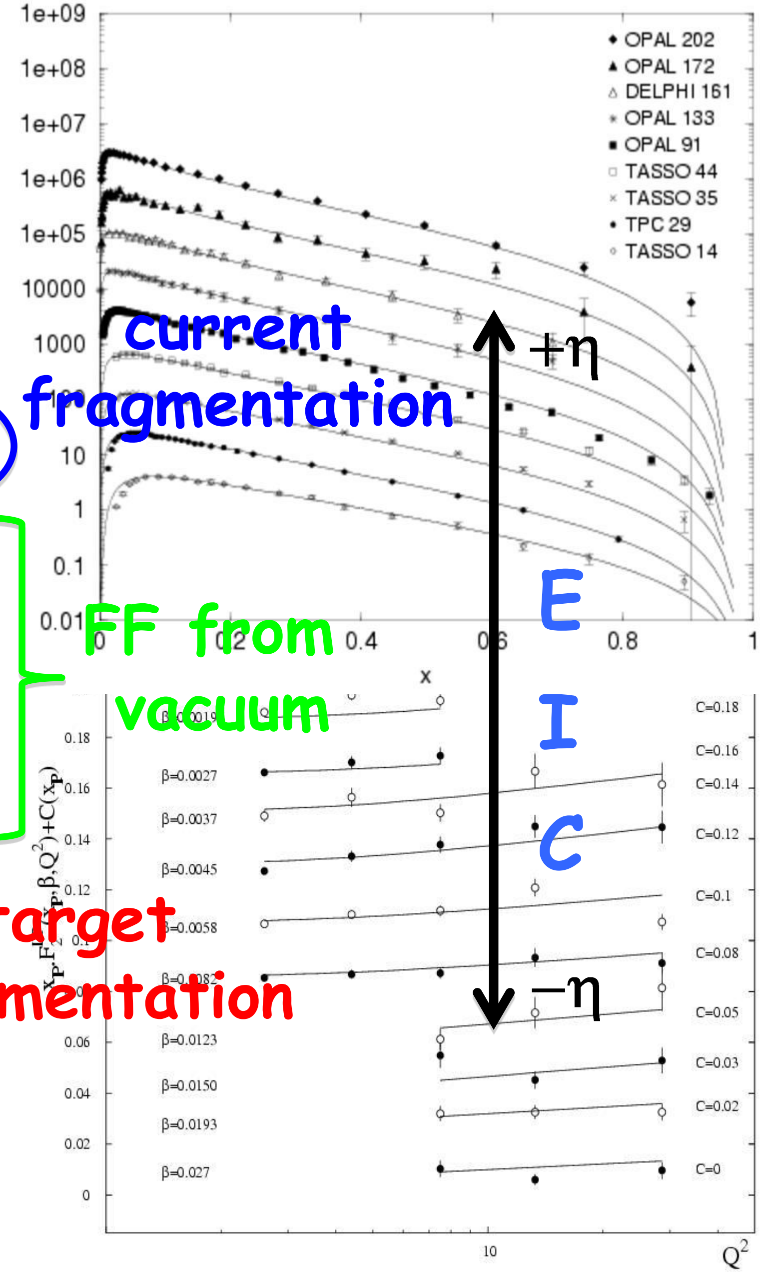
(polarized) e-p at medium energies

- Exclusive processes and GPDs
  - Deeply-Virtual Meson Production: spin/flavor/spatial quark structure ($Q^2 \sim 10$ GeV^2)
  - DVCS: helicity GPDs, spatial quark and gluon imaging
- Charm as direct probe of gluons
  - J/ψ, exclusive: spatial distribution of gluons
  - D Λ_c, open charm (including quasi-real D^0 photoproduction for ΔG)
- Semi-inclusive DIS
  - Flavor decomposition: $q \leftrightarrow \bar{q}$, $u \leftrightarrow d$, strangeness s, $\bar{s}$
  - TMDs: spin-orbit interactions from azimuthal asymmetries, p_T dependence
  - Target fragmentation and fracture functions
- Inclusive DIS
  - ΔG and $\Delta q+\Delta\bar{q}$ from global fits (+ RHIC-spin, COMPASS, JLab 12 GeV)
  - Neutron structure from spectator tagging in D(e,e'p)X

The Future of Fragmentation

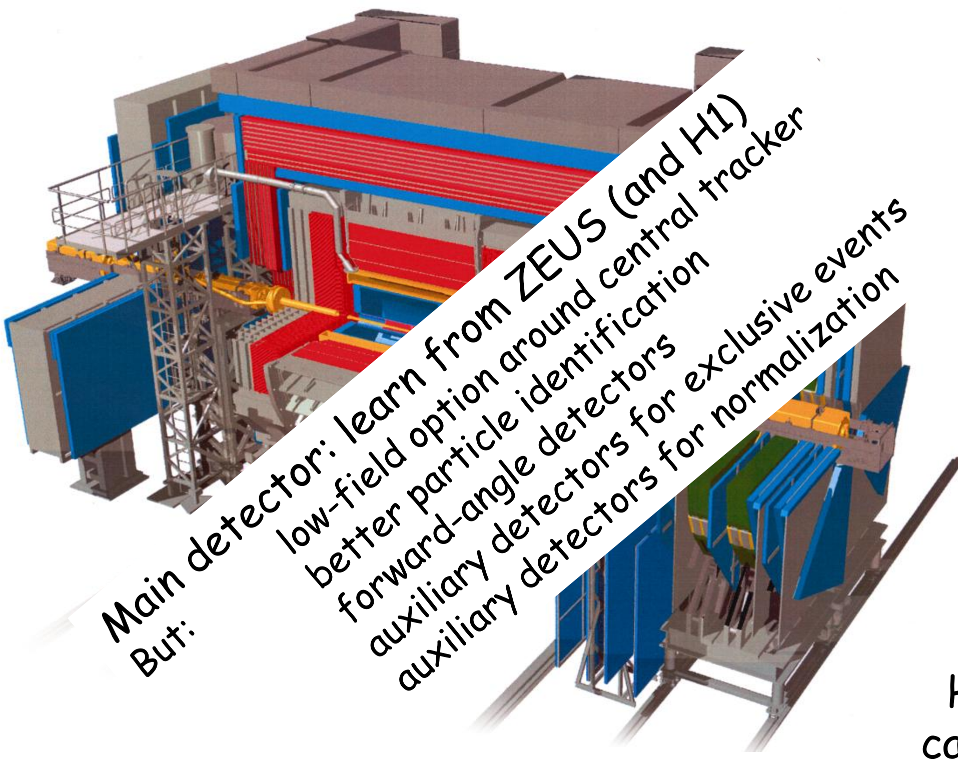
- un-integrated:

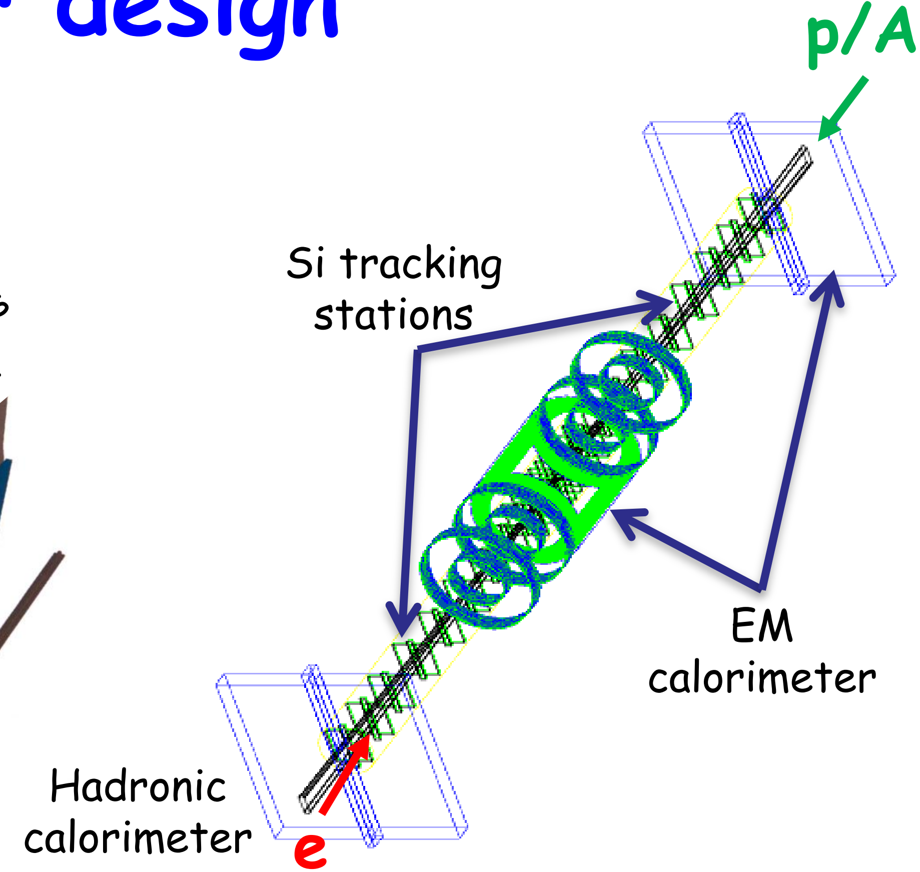




Can we understand the physical mechanism of fragmentation and how do we calculate it quantitatively?

Detector design

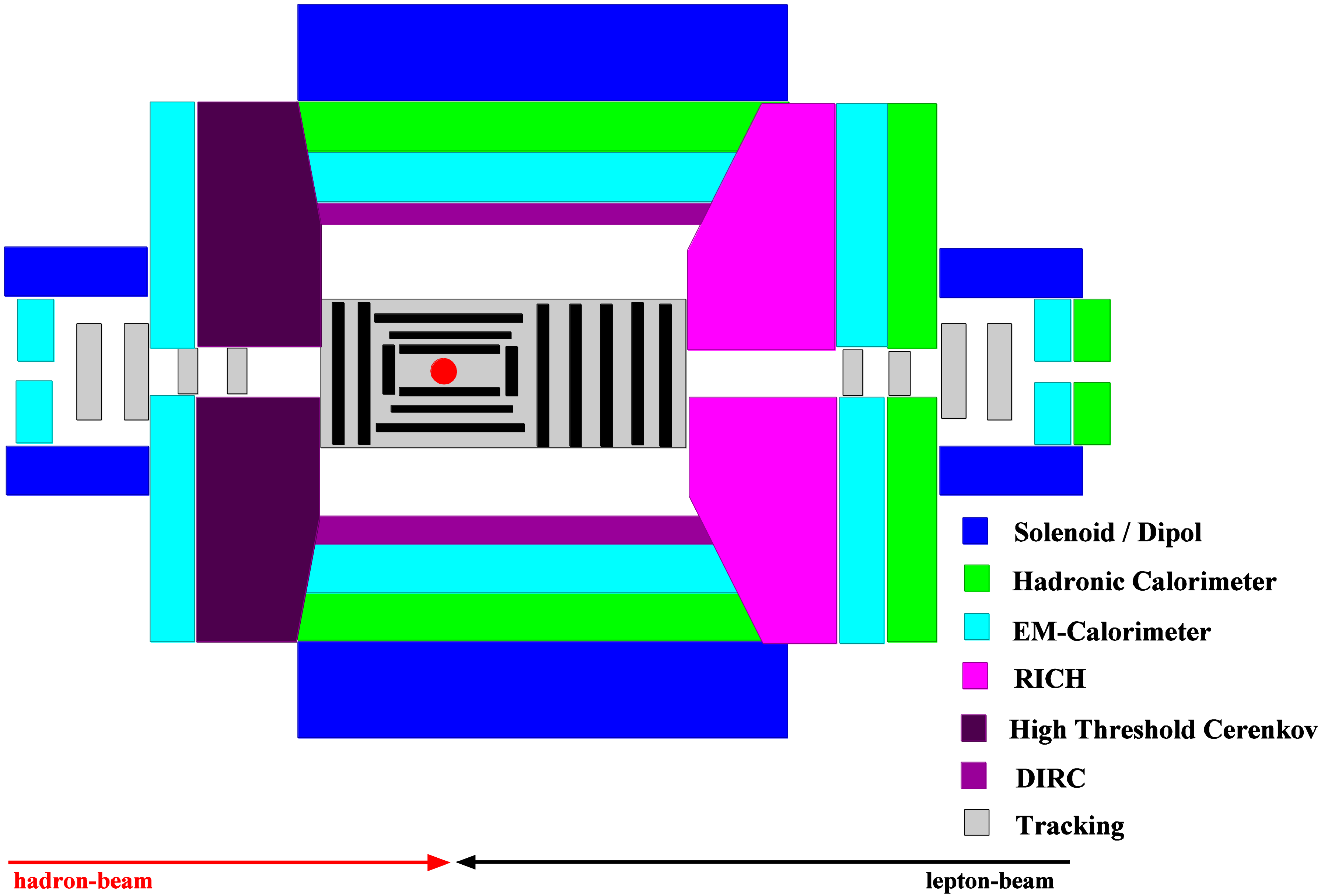




Main detector:
Emphasize high-luminosity
full physics program

Alternate detector:
Emphasize low-x, low-Q^2
diffractive physics
("HERA-III design",
MPI-Munchen)

Present Main Detector cartoon



Detector R&D

(Detector R&D is same for full EIC and staged options)

General R&D items:

1. Particle Id. Detectors
   a. Study alternate (cheaper) materials than quartz for DIRC, allowing for momenta > 3 GeV
   b. Develop a TRD that allows for e/h separation at ~1 GeV
2. Photon Detection
   a. Develop cost-effective photon detection replacing PMTs like big area SiPMTs
      - Compact and work in magnetic field w.o. shielding
      - Perfect single photon resolution (for DIRC/RICH)
3. Small angle particle tracking
   a. Radiation hard (diamond?) electron detectors
   b. High-efficiency neutron detectors
4. High precision electron and ion beam polarimetry

EIC@JLab specific R&D related to 500 MHz operation

(more detailed recipe next slide)

Detector R&D

(Detector R&D is same for full EIC and staged options)

EIC@JLab specific R&D related to 500 MHz operation: Detector Signal Capture and Trigger System

1. High-Speed Flash ADCs

a. JLAB design operates at 4 ns sampling (250MHz) which is adequate for many detector signal shapes
b. Commercial ADC chips are available at 2 ns (500MHz) and 1 ns (1GHz) sampling
c. Engineering design will be needed to solve cooling issues and board layout challenges
d. Continue R&D efforts with latest FPGA technology → 500 MHz clocking exists now on some devices
e. Continue R&D efforts to use industry standards: (VXS, or new VPX) for extremely high speed serial transmission for Level 1 trigger decisions and global timing synchronization

2. Multi-crate DAQ with L1 trigger rates > 150KHz

a. JLAB *prototype* multi-crate system achieves 165KHz at 80MB/s
b. Explore the use of high speed serial links as data transfer paths rather than VME backplane method
c. Continue R&D of Crate Trigger Processor algorithms and Global Trigger hardware designs

3. EIC Readout/DAQ Electronics (in int'l collab.)

a. R&D for new vertex detector readout chips: Most designs are for much longer bunch crossing time
b. FPGA design/simulation and firmware code sharing
c. Detector data rate simulation including trigger rate studies to improve trigger system design

Summary

The last decade or so has seen tremendous progress in our understanding of the partonic sub-structure of nucleons and nuclei based upon:

- The US nuclear physics flagship facilities: RHIC and CEBAF
- The surprises found at HERA (H1, ZEUS, HERMES)
- The development of a theory framework allowing for a revolution in our understanding of the inside of hadrons …
  QCD Factorization, Lattice QCD, Saturation

This has led to **new frontiers of nuclear science**:

- the possibility to truly **explore the nucleon**
- a new QCD regime of **strong color fields**

The EIC presents a **unique opportunity to maintain US and BNL&JLab leadership** in high energy nuclear physics and precision QCD physics

Energy Considerations for EIC

Facility	energies	CM energy [GeV]	(Peak) Luminosity	x_{min} @ $Q^2 = 1$	x_{min} @ $Q^2 = 10$
12 GeV	Fixed target	5	3×10^{38}	4×10^{-2}	4×10^{-1}
eRHIC	10 x 250	100	2.6×10^{33}	1×10^{-4}	1×10^{-3}
eRHIC (staged)	4 x 250	65	9.3×10^{32}	2.5×10^{-4}	2.5×10^{-3}
ELIC	10 X 250	100	3.0×10^{34}	1×10^{-4}	1×10^{-3}
ELIC (staged)	5 x 30	25	4.4×10^{33}	1.7×10^{-3}	1.7×10^{-2}

$Q^2 = 1$ gives DIS range in x, $Q^2 = 10$ gives lever arm in Q^2

Proposed EIC recommendation for the Galveston meeting

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:

- Explore the new QCD frontier: strong color fields in nuclei;
- Precisely image the sea-quarks and gluons to determine the spin, flavor and spatial structure of the nucleon.

This goal requires that R&D resources be allocated for expeditious development of collider and detector design.

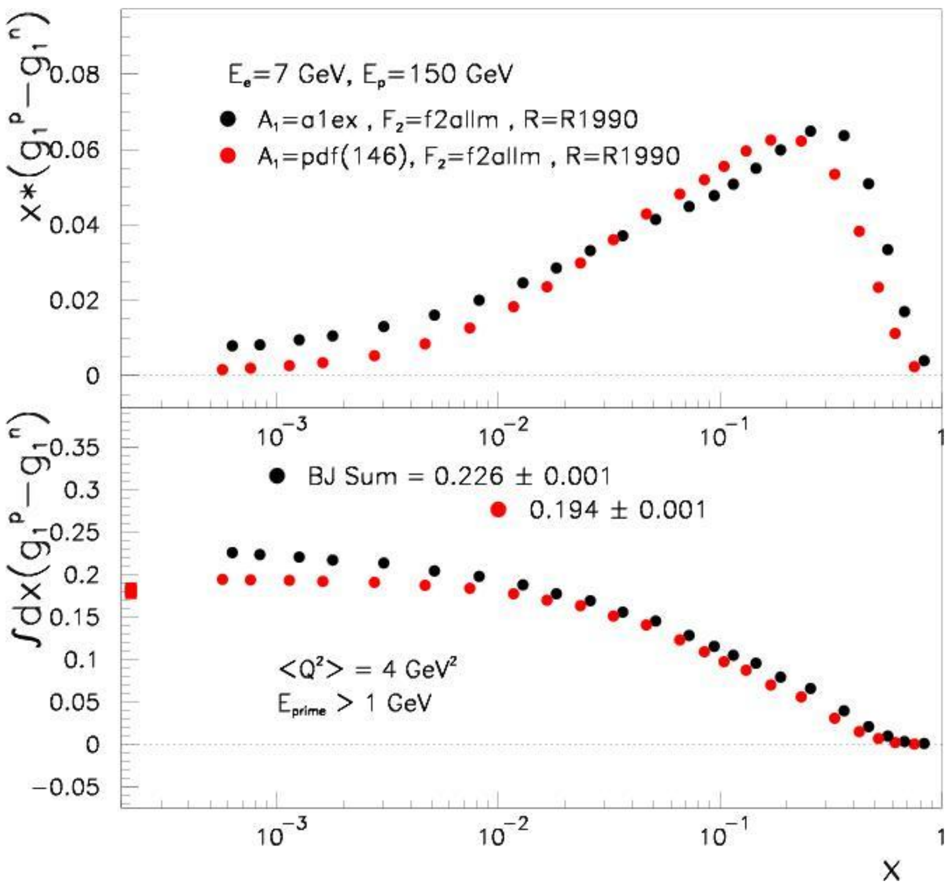
Galveston estimate: $4M/year for accelerator R&D,
$2M/year for detector R&D

(Five years each)

The Bjorken Sum Rule

$$\int_0^1 \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] dx = \frac{1}{6}\left[\frac{g_A}{g_V}\right]_{n\to p}\left[1-\frac{\alpha_s(Q^2)}{\pi}+\mathcal{O}(\alpha_s^2)\right]+\mathcal{O}\left(\frac{1}{Q^2}\right)$$

Precision QCD test, at present measured at 10-15% level



s = 4200

- **Aim to measure with 1-2% absolute uncertainty with EIC.**
- Severe demand on proton and ^3He or ^2H beam polarimetry (or in-situ calibration reaction).
- Lattice can give confidence in small-x extrapolations.
- 1-2% statistical precision at fixed Q^2 needs high luminosity.
- Could potentially give the best determination of α_s!

Parity-Violating g_5 Structure Function

$$A^W = \frac{d\sigma^W_{\uparrow\downarrow} - d\sigma^W_{\uparrow\uparrow}}{d\sigma^W_{\uparrow\downarrow} + d\sigma^W_{\uparrow\uparrow}} = \frac{(+/-)bg_1^W + ag_5^W}{aF_1^W (+/-)bF_3^W} \approx \frac{g_5^W}{F_1^W}$$

$$g_5^{W+} = \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}$$

$$g_5^{W-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}$$

To date unmeasured due to lack of high Q^2 polarized e-p possibility.

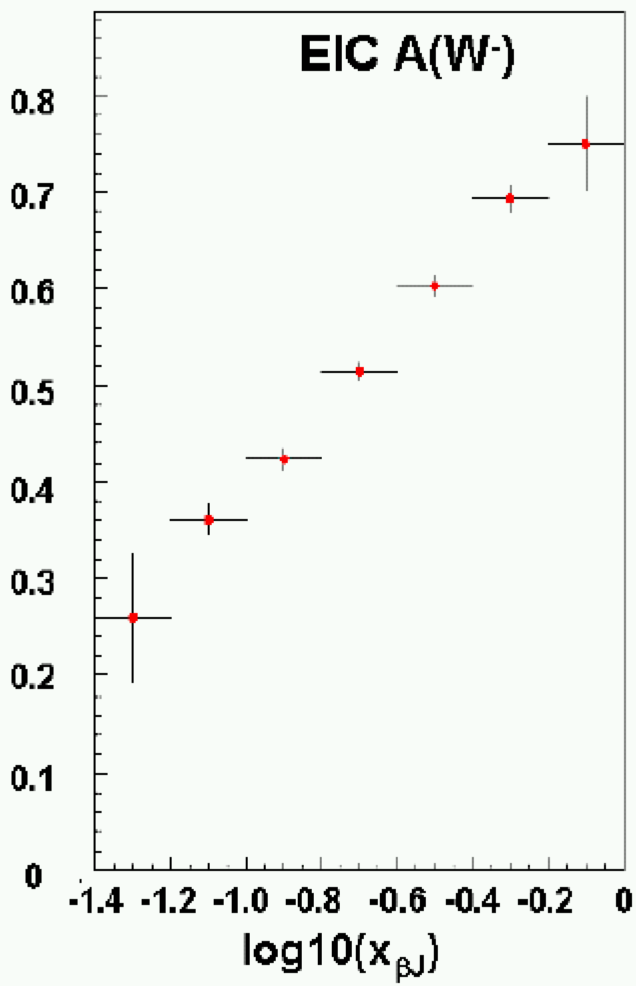
From 2002 White Paper (Contreras et al).

Assumptions:

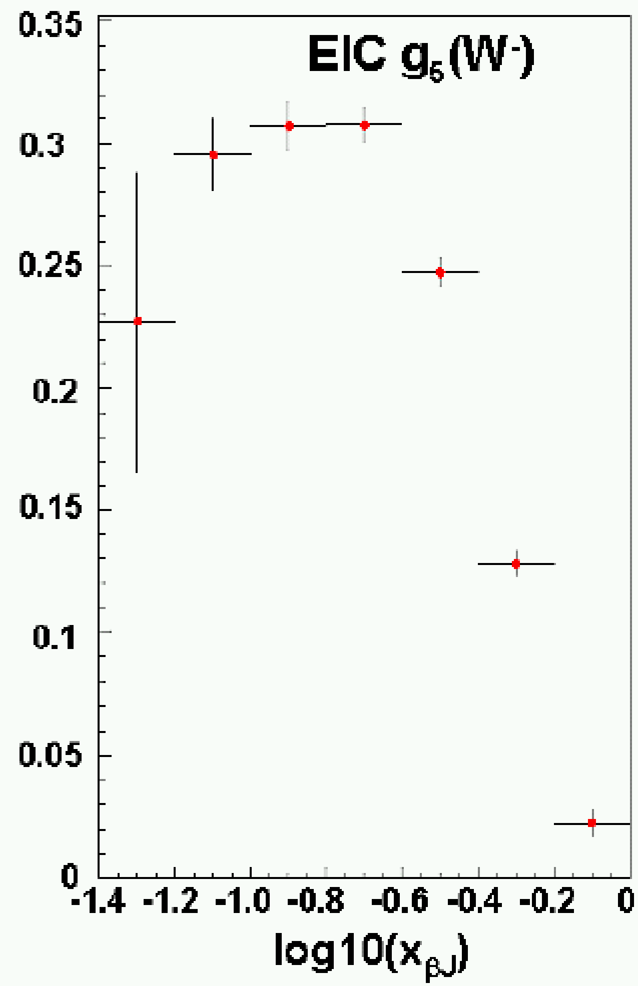
1) $Q^2 > 225\ GeV^2$
2) One month at luminosity of 10^{33}

Requires positron beam

Projected $A(W^-)$

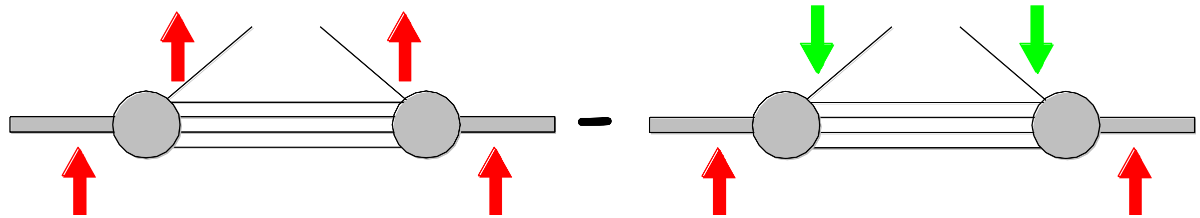


Assuming xF_3 will be known



New Spin Structure Function: Transversity

$\delta q(x) \sim$ (in transverse basis)



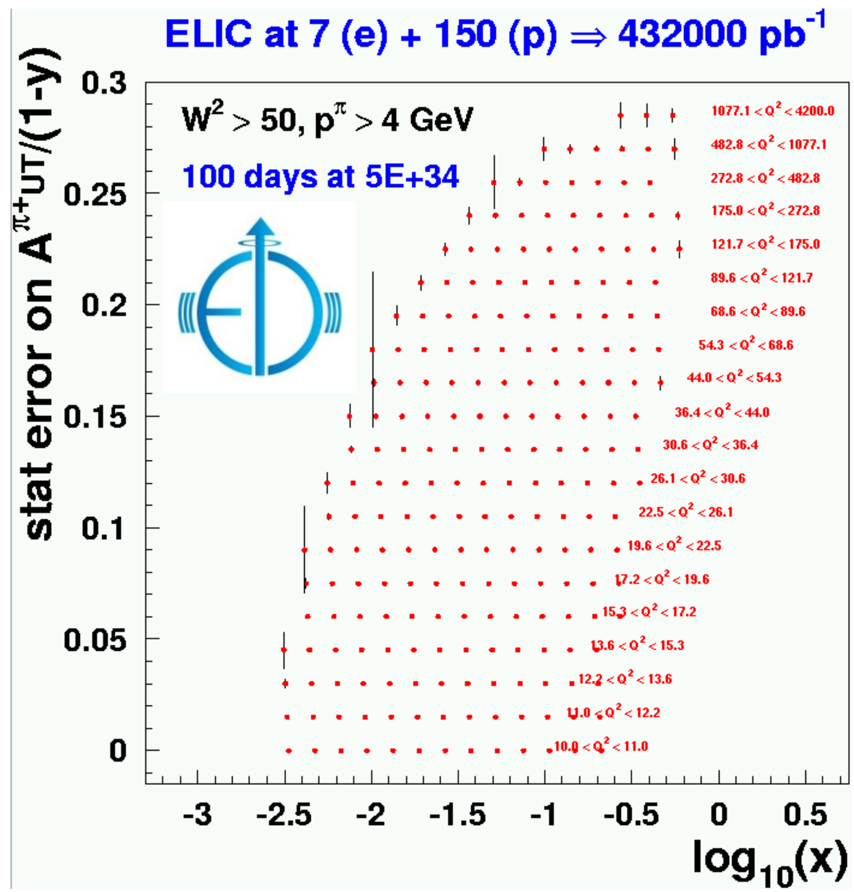
- Nucleon's transverse spin content → "tensor charge"
- No transversity of Gluons in Nucleon → "all-valence object"
- Chiral Odd → only measurable in semi-inclusive DIS

→ first glimpses from HERMES

→ COMPASS 1st results: ~0 @ low x

→ valence region only?

→ Future: Flavor decomposition (started by Anselmino et al.)



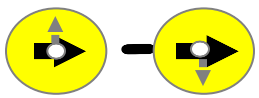
Need (high) transverse ion polarization

(Naomi Makins, Ralf Seidl)

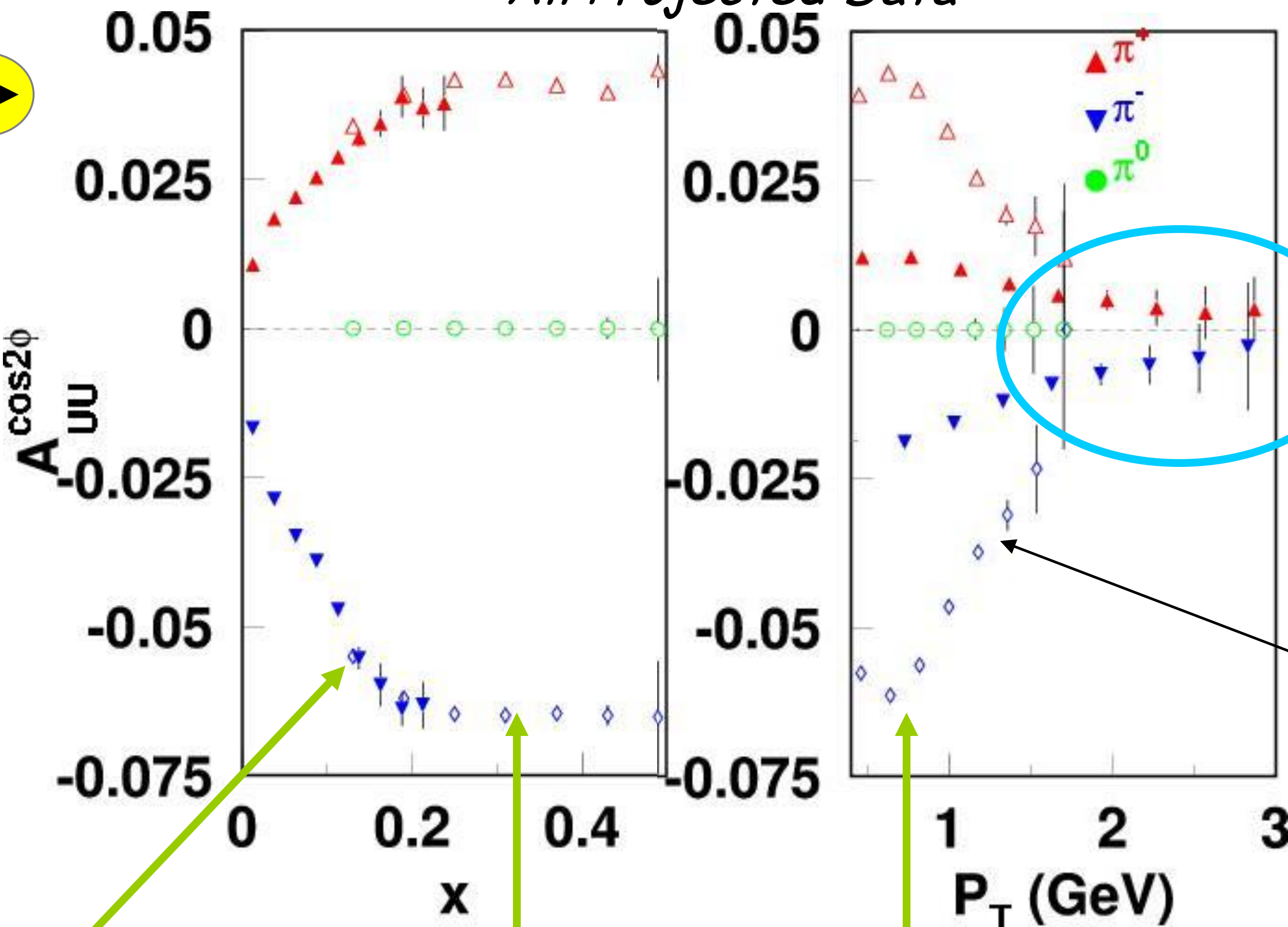
Correlation between Transverse Spin and Momentum of Quarks in Unpolarized Target

(Harut Avakian, Antje Bruell)

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 $h_{1T}^{\perp}$



All Projected Data



Perturbatively Calculable at Large p_T

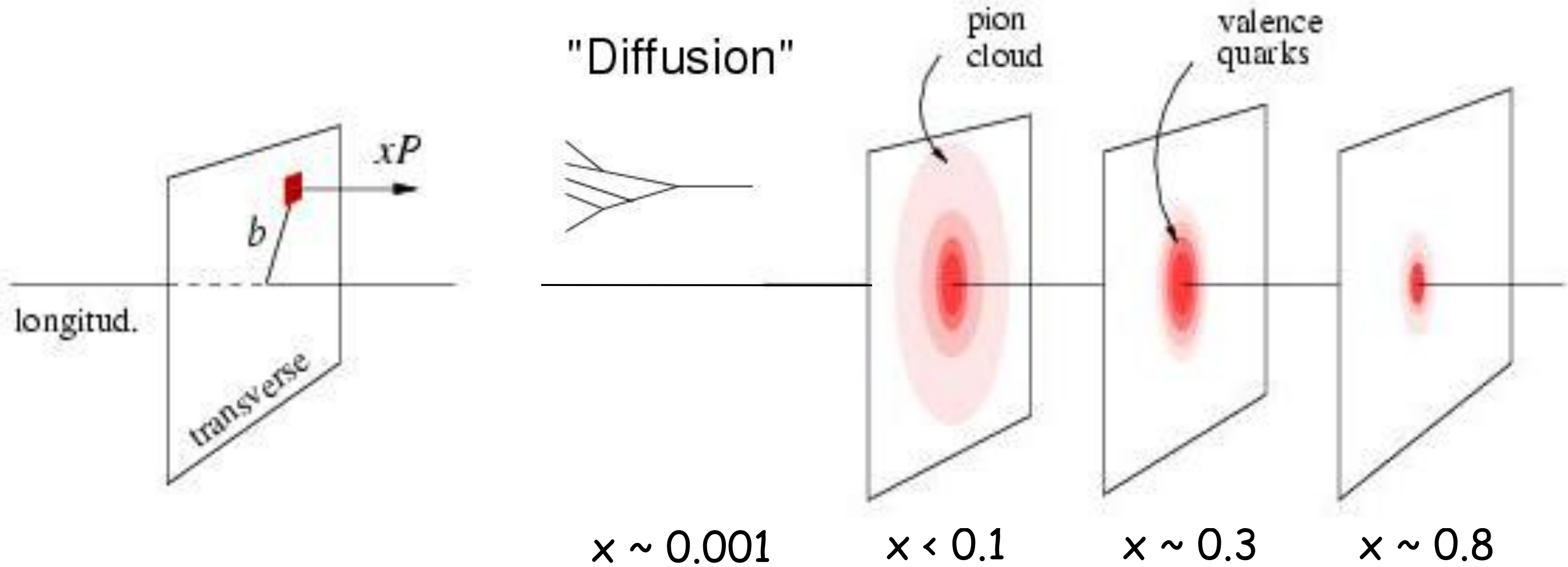
Vanish like $1/p_T$ (Yuan)

Jefferson Lab 12

Exploring the Nature of Matter

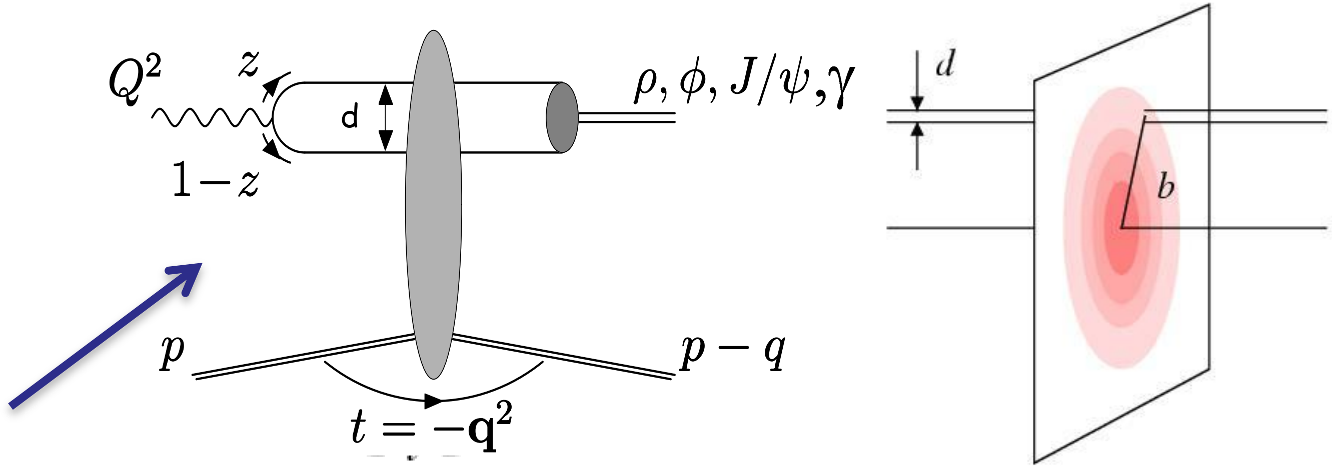
GPDs and Transverse Gluon Imaging

Fourier transform in momentum transfer

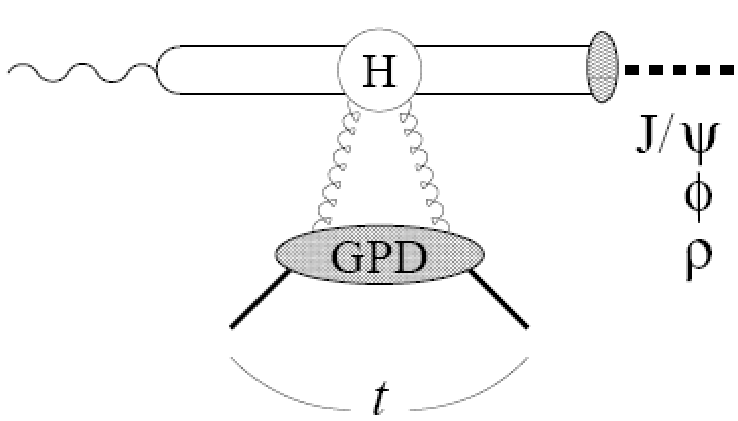


gives transverse size of quark (parton) with longitud. momentum fraction x

EIC:
1) x < 0.1: gluons!
2) ξ ~ 0 → the "take out" and "put back" gluons act coherently.

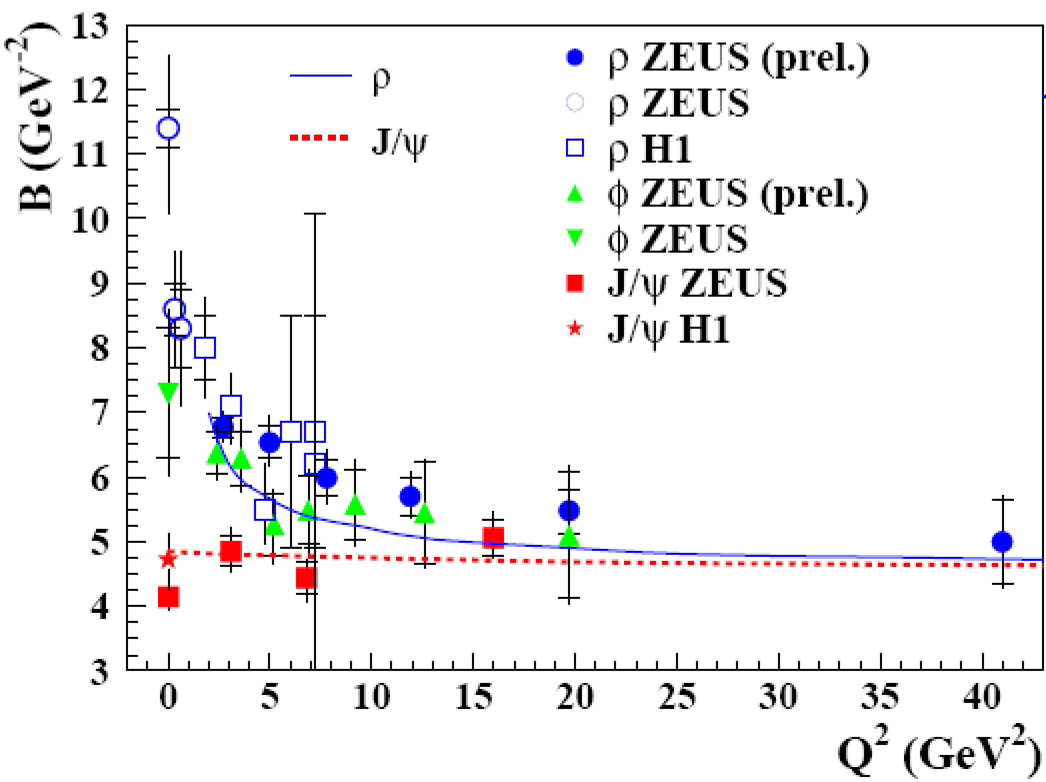


GPDs and Transverse Gluon Imaging



Two-gluon exchange dominant for J/ψ, φ, ρ production at large energies → **sensitive to gluon distribution squared!**

LO factorization ~ color dipole picture → access to gluon spatial distribution in nuclei: see eA!



← Fit with $d\sigma/dt = e^{-Bt}$

Measurements at DESY of diffractive channels (J/ψ, φ, ρ, γ) confirmed the applicability of QCD factorization:

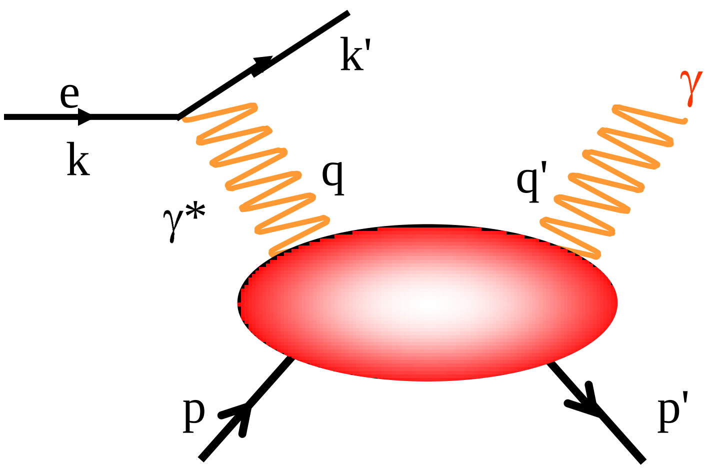
- t-slopes universal at high Q^2
- flavor relations φ:ρ

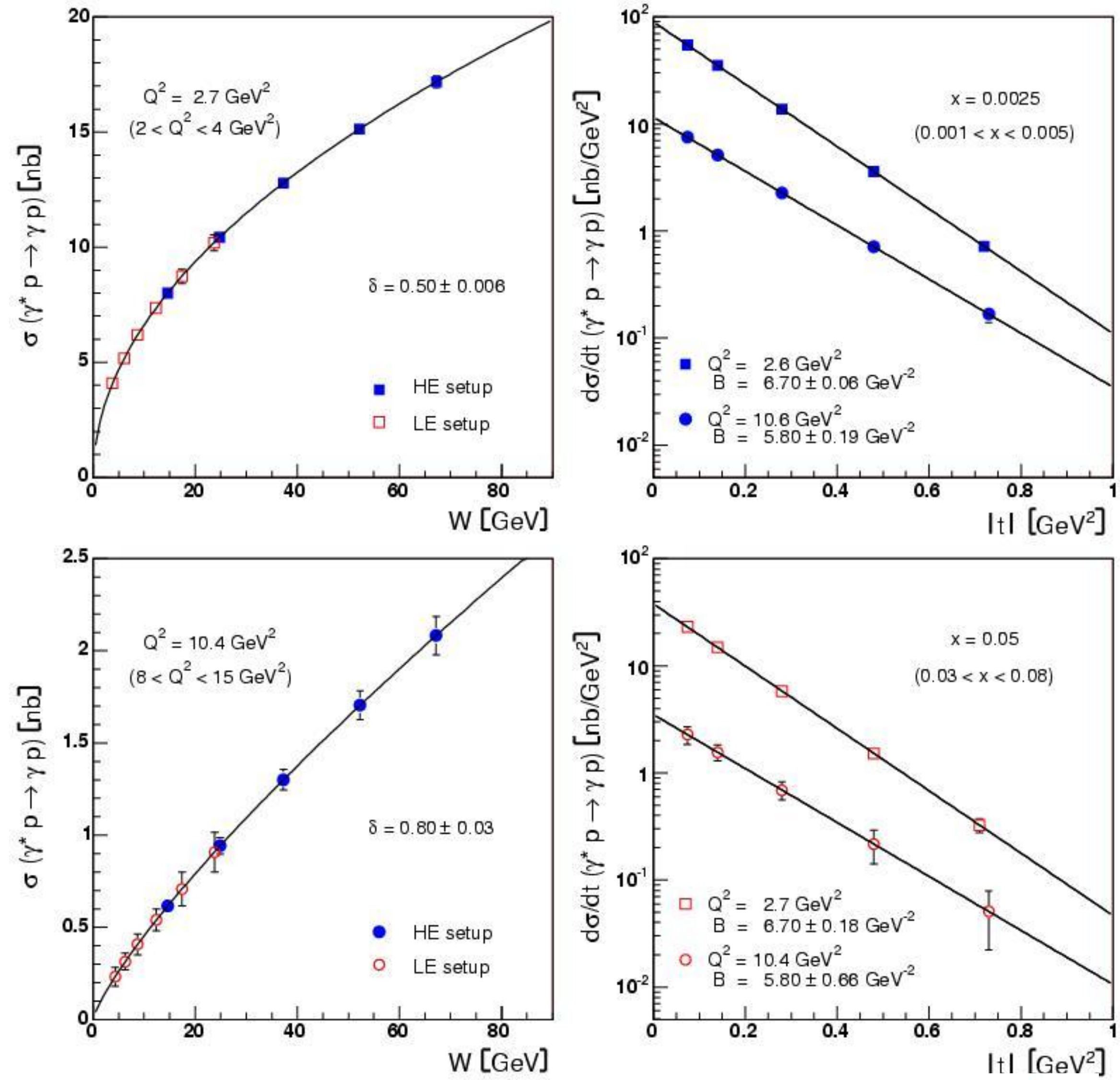
Unique access to transverse gluon imaging at EIC!

GPDs and Transverse Gluon Imaging

A Major new direction in Nuclear Science aimed at the 3-D mapping of the quark structure of the nucleon.

Simplest process:
Deep-Virtual Compton Scattering

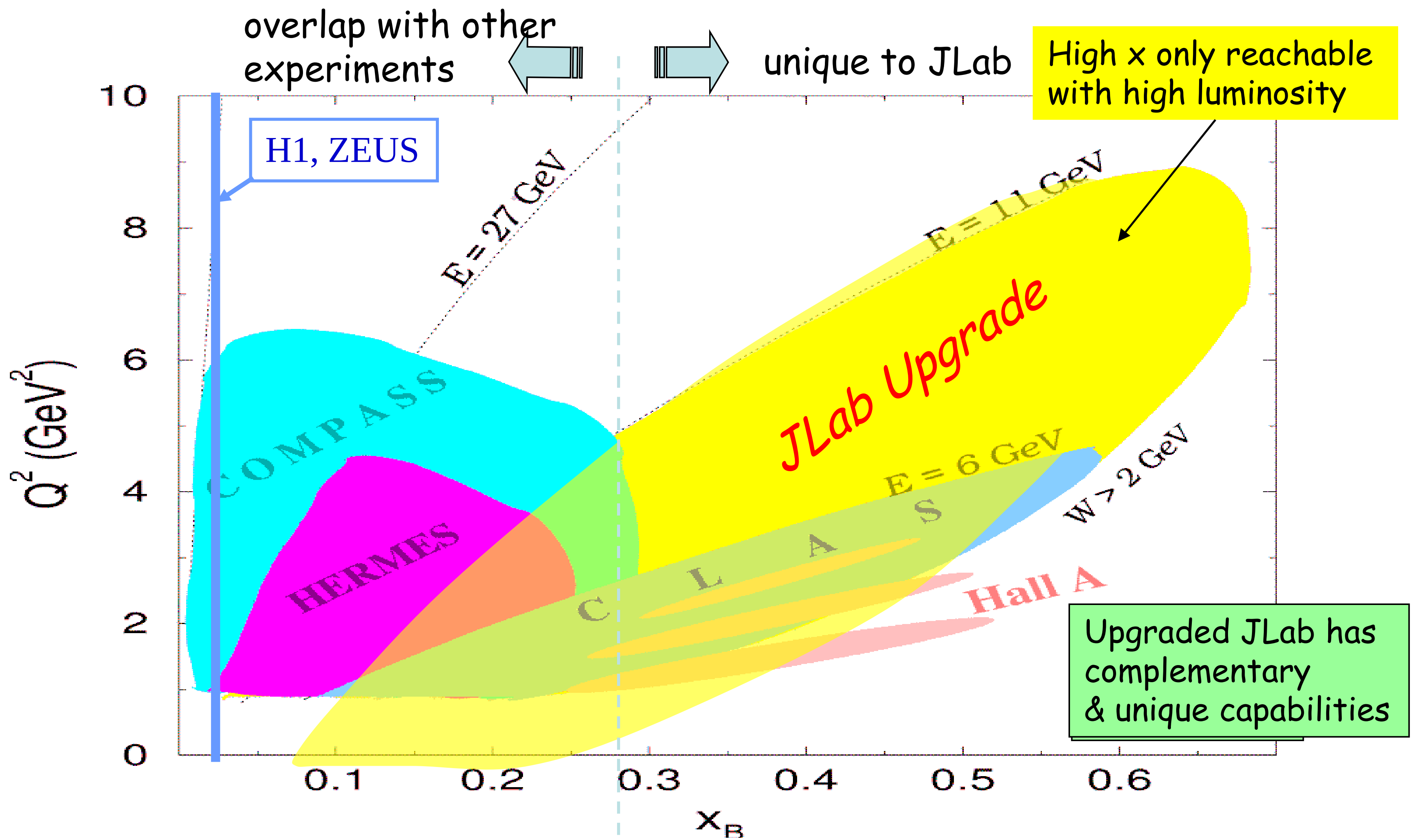




At small x (large W):
$\sigma \sim G(x,Q^2)^2$

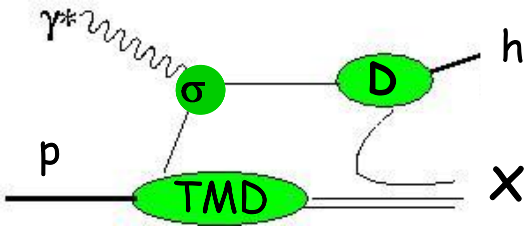
Simultaneous measurements over large range in x, Q^2, t at EIC!

Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade

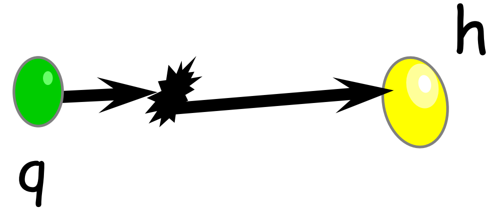


The Future of Fragmentation

Current Fragmentation

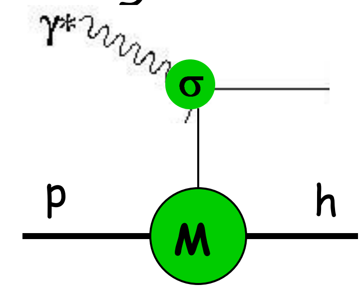


$$d\sigma^h \sim \Sigma_q\, f^q(x)\, \sigma\, D_f^{\,h}(z)$$

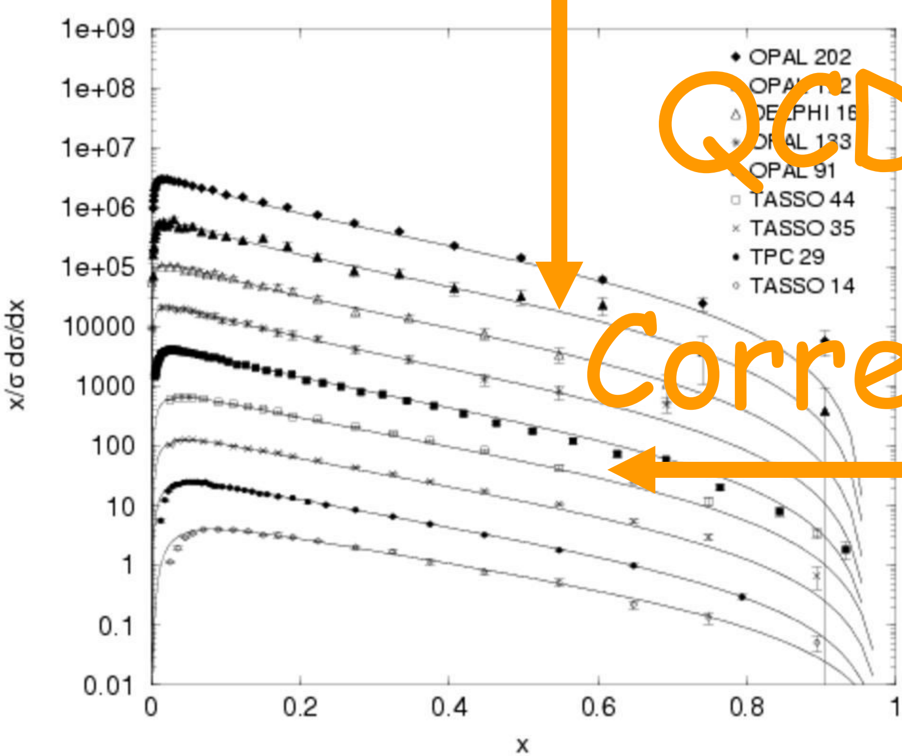


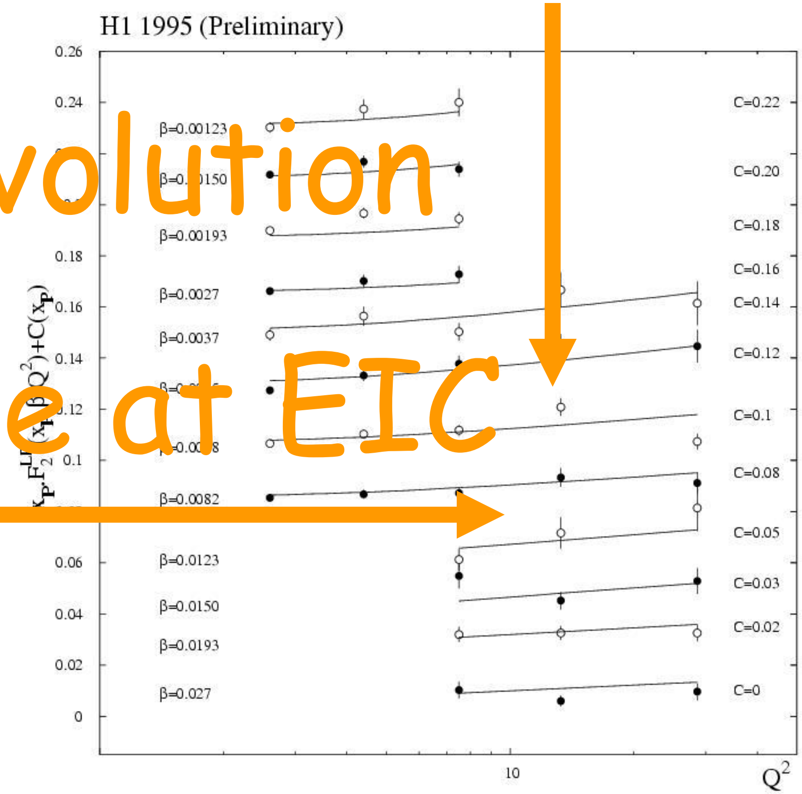
Can we understand the physical mechanism of fragmentation and how do we calculate it quantitatively?

Target Fragmentation



$$d\sigma^h \sim \Sigma_q\, \sigma\, M_{h/p}^{\,q}(x,z)$$



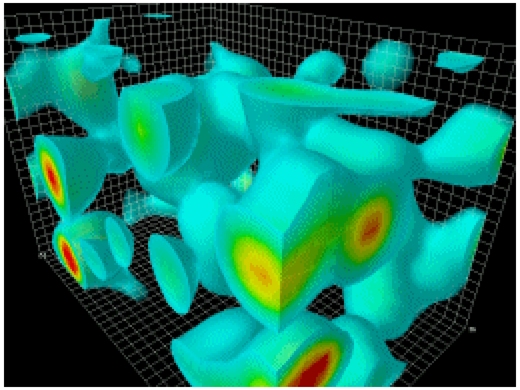


QCD Evolution

Correlate at EIC

Gluons dominate QCD

- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei
- Gluons dominate the structure of the QCD vacuum



- Facts:
  - The essential features of QCD (e.g. asymptotic freedom, chiral symmetry breaking, and color confinement) are all driven by the gluons!
  - Unique aspect of QCD is the self interaction of the gluons
  - 98% of mass of the visible universe arises from glue
  - Half of the nucleon momentum is carried by gluons

NSAC LRP December 2007: Overarching QCD Questions

- What are the phases of strongly interacting matter and what roles do they play in the cosmos?

- **What is the internal landscape of the nucleons?**

- What does QCD predict for the properties of strongly interacting matter?

- **What governs the transition of quarks and gluons into pions and nucleons?**

- **What is the role of gluons and gluon self-interactions in nucleons and nuclei?**

- What determines the key features of QCD, and what is their relation to the quantum nature of gravity and spacetime?