Overview of Science Goals, "Golden Measurements" and Implications for the Energy and Luminosity Reach of the EIC

- Introduction and Motivation
- The Golden Measurements
  - ➡ Nucleon Quark-Gluon Structure
  - ➡ Gluons in the Nucleus and Gluon Compression
- The non-Golden supporting cast
- Summary?

Acknowledgements and Disclaimer

Thanks to many members of the EIC Collaboration for allowing me to present their work and my apologies for not making this talk available in time for their (or anyone's!) comment.

For more detailed and complete documentation, see the EIC Collaboration website:

http://web.mit.edu/eicc/

The opinions expressed in this presentation are my own, and in no way should be construed as representing those of the EIC Collaboration

"Golden Measurements" Should ...

- Be exciting, interesting central pillars of the EIC program of
  - ➡ Overwhelming interest to the QCD community
  - ➡ Strong interest to the nuclear/particle community
  - ➡ Reasonable interest to the general scientific community
  - ➡ "Excitable" interest to the general public
- Explain parameters choices/needs for the EIC
- Not promise too much (watch out for windows and access!)
- Real measurement programs for an EIC are broad in nature; we are not searching for the Higgs. Compare with other appropriate great broad programs, such as those of Brahe and Moseley, perhaps even the human genome projects, for example...

Why study the Hydrogen atom?

- 1885 Balmer determines formula for hydrogen spectral lines
- 1887 Rydberg generalizes formula with wavenumbers to explain extended set of spectral lines
- 1908 Ritz develops universal formula for spectral lines in terms of frequency differences
- 1910-20's - Quantum mechanics developed to explain these empirical results
- Higher resolution study of the hydrogen spectrum continues - just doing more of the same??? Looking at small uninteresting 1% effects??? Testing the "standard model" ?
- 1947 - Lamb shift discovered, leads to birth of relativistic quantum electrodynamics

Where are we in the study of QCD?

- 1960's Explanation of particle zoo with 8-fold way (SU(3) Flavor)
- 1970's QCD with color SU(3) developed BEFORE observation of partons in DIS, asymptotic freedom understood
- 1980's DESY sees 3-jet events and gluons, surprises in spin structure and nuclear EMC effect
- 1990's - HERA ep collider observes rapidity gaps, spin "puzzle" established, lattice efforts begin, DVCS and exclusive reactions, azimuthal distributions and the re-establishment of TMDs
- 2000's - High precision empirical measurements of unpolarized valence quark pdfs down to low x, EM elastic form factors to high Q^2, first direct gluon polarization results, the discovery of the quark-gluon plasma, collective flow, the "ridge", shock waves, jet quenching...
- 2010's - High precision exclusive and semi-inclusive studies at mid-x, gluon polarization at lower x, sea quark distributions at high x from DY and Ws, energy scan of HI collisions at BNL, HI collisions at LHC, glueballs and hybrids, ...

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We are amidst an explosion of new information!!!

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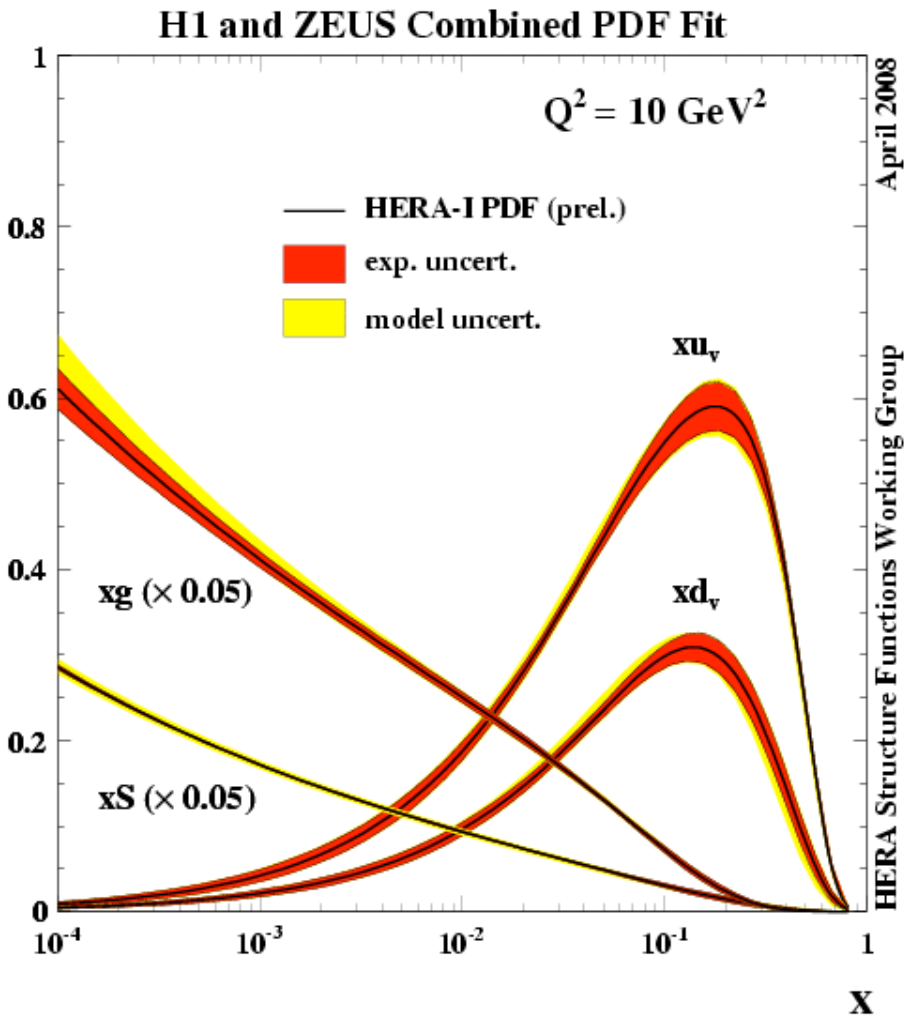

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- "Polarized" inclusive and semi-inclusive DIS have determined the helicity dependent quark distributions over much more modest range, similar to the pre-HERA era for unpolarized distributions

  ➡ Only a collider will allow us to make a similar broad advance in our empirical study; history suggests extrapolation to low x is unreliable

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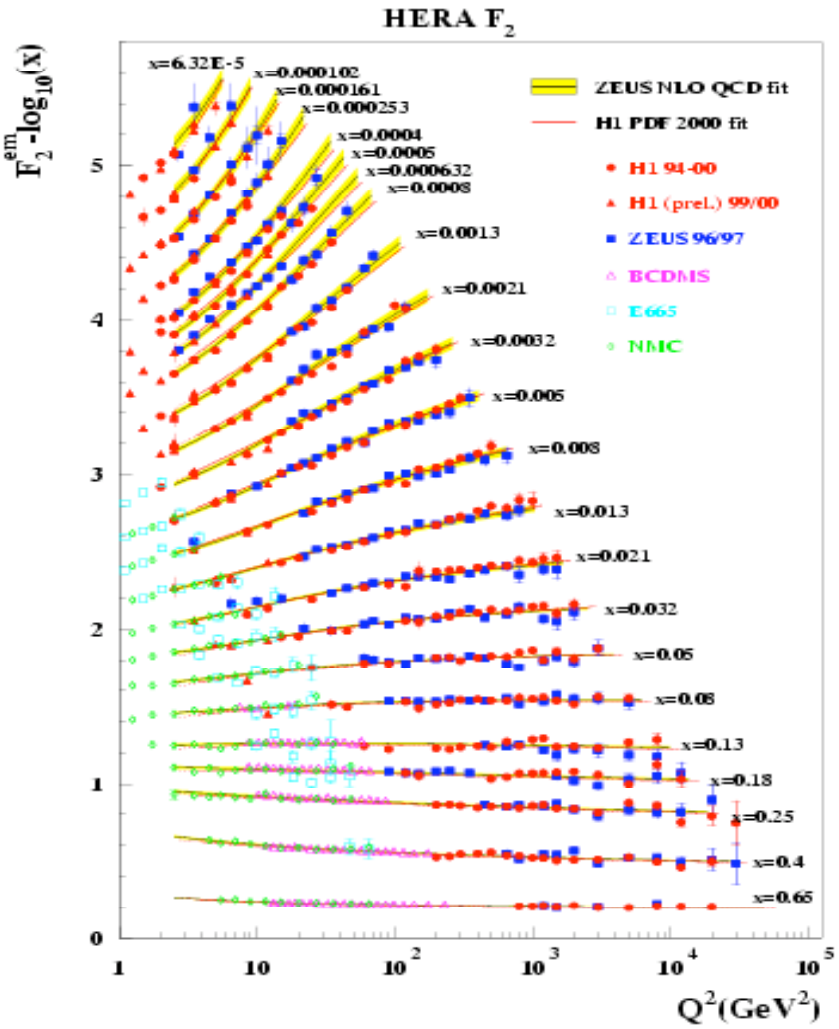

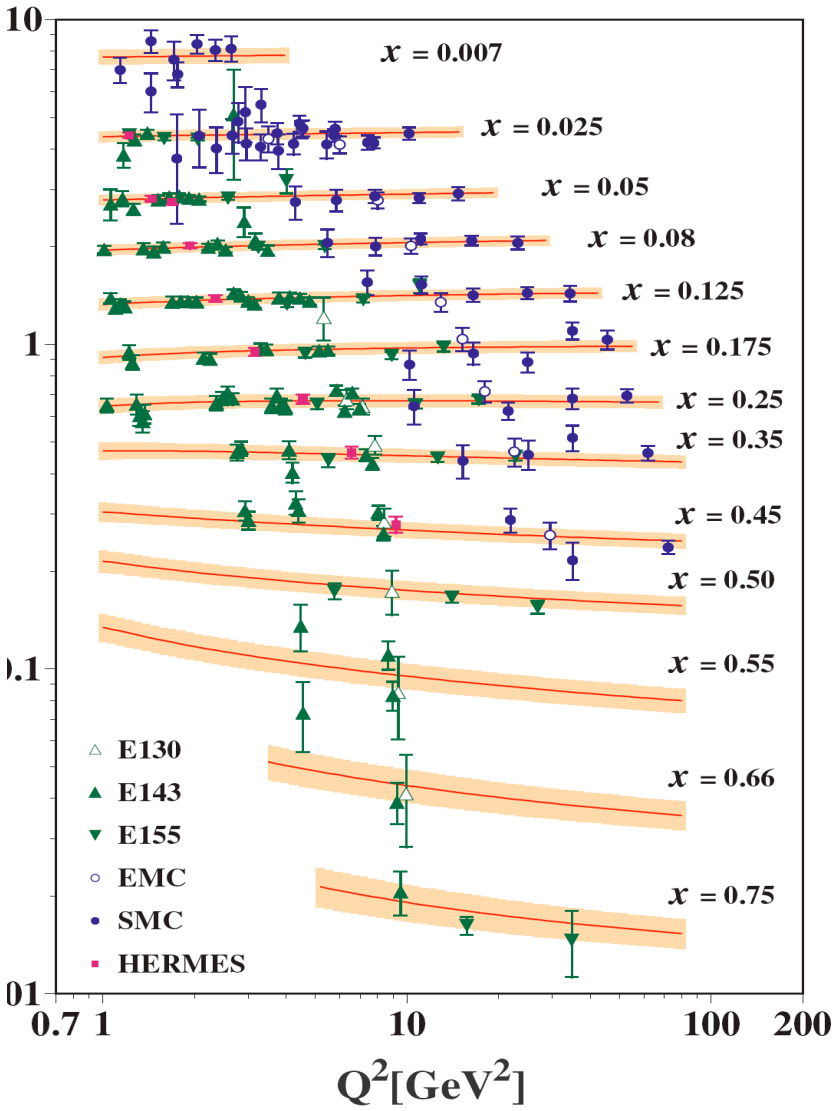

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- We are very much still at the empirical stage of understanding the proton!

Why continue to study the spin structure?

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- Where is the nucleon spin?

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- Tantalizing hints are appearing that the sea spin structure is really an interesting, non-trivial, aspect of the nucleon spin structure, especially now that we have measurements from the RHIC spin program:

  ➡ Most recent fits to world data prefer a node in the polarized strange quark and gluon distributions at intermediate *x*

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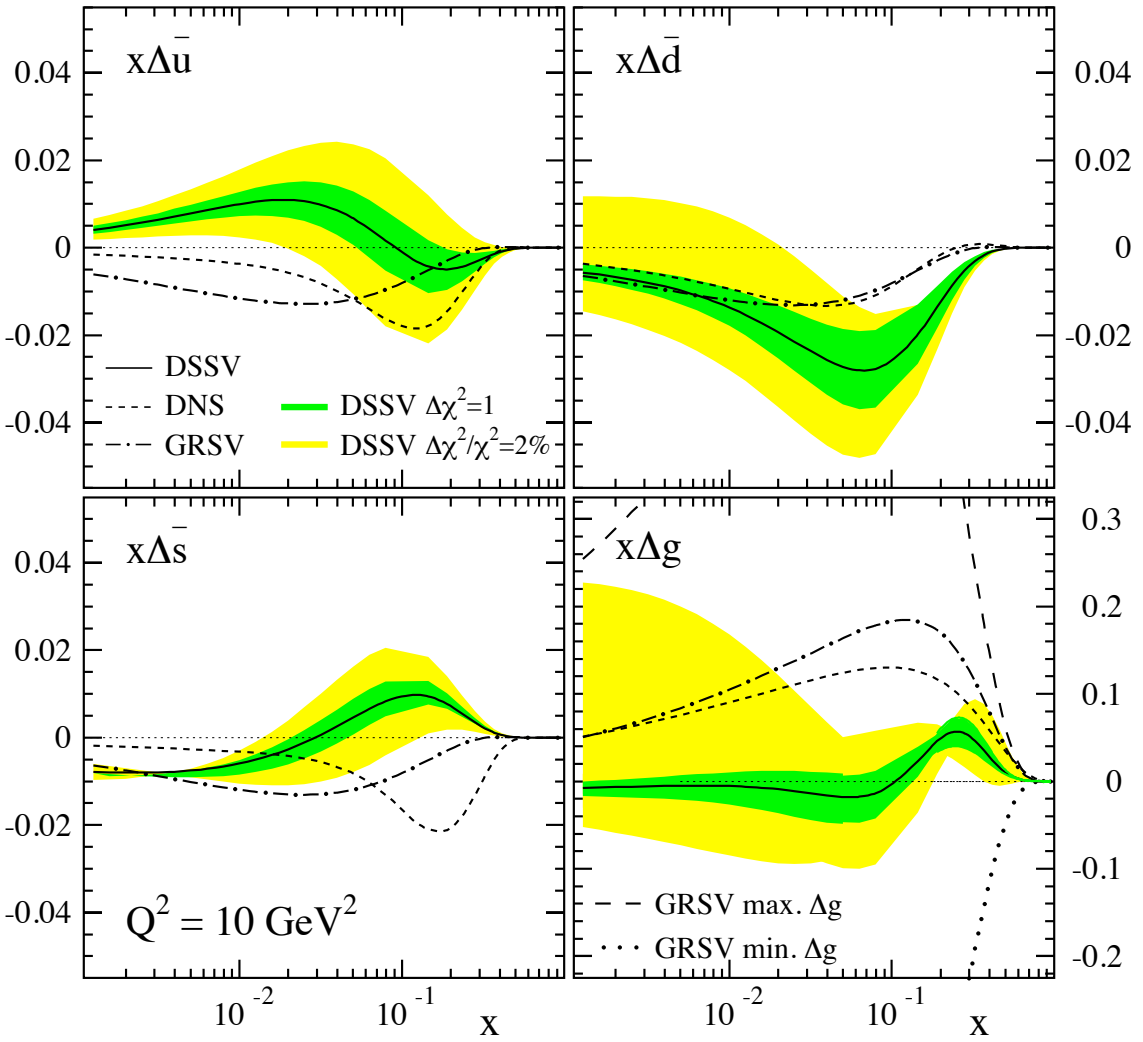

DeFlorian, Sassot, Stratmann, Vogelsang, PRL101 (2008) 072001

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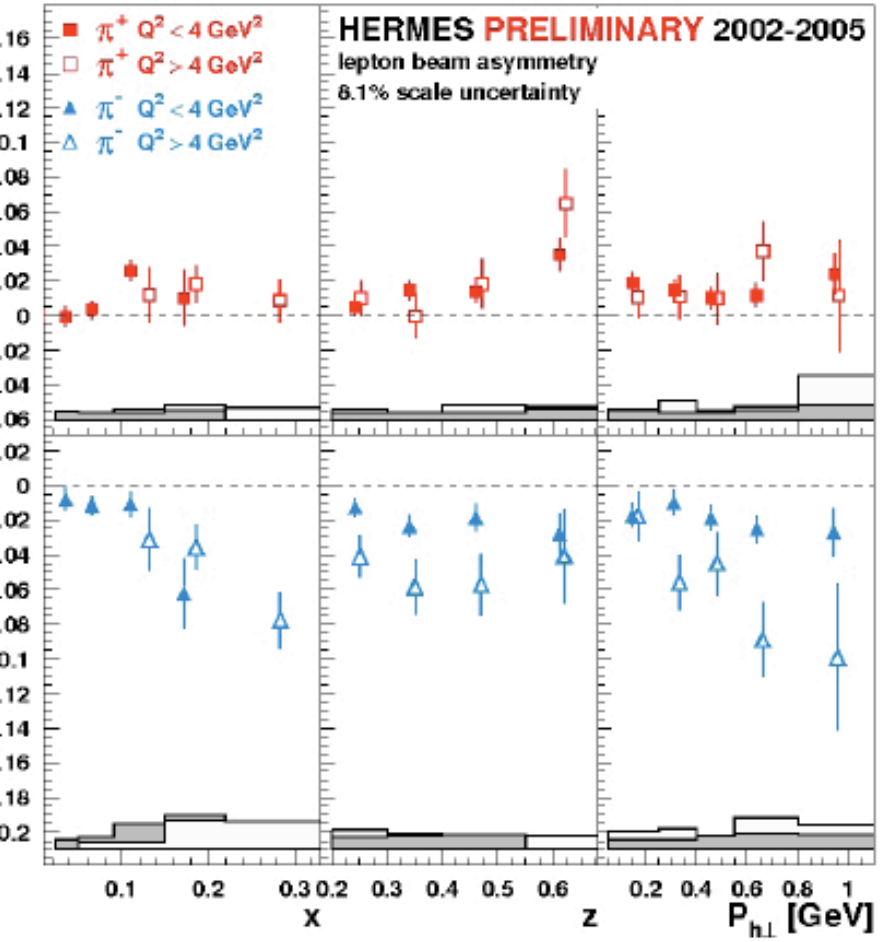
Why continue to study the spin structure?

Collins



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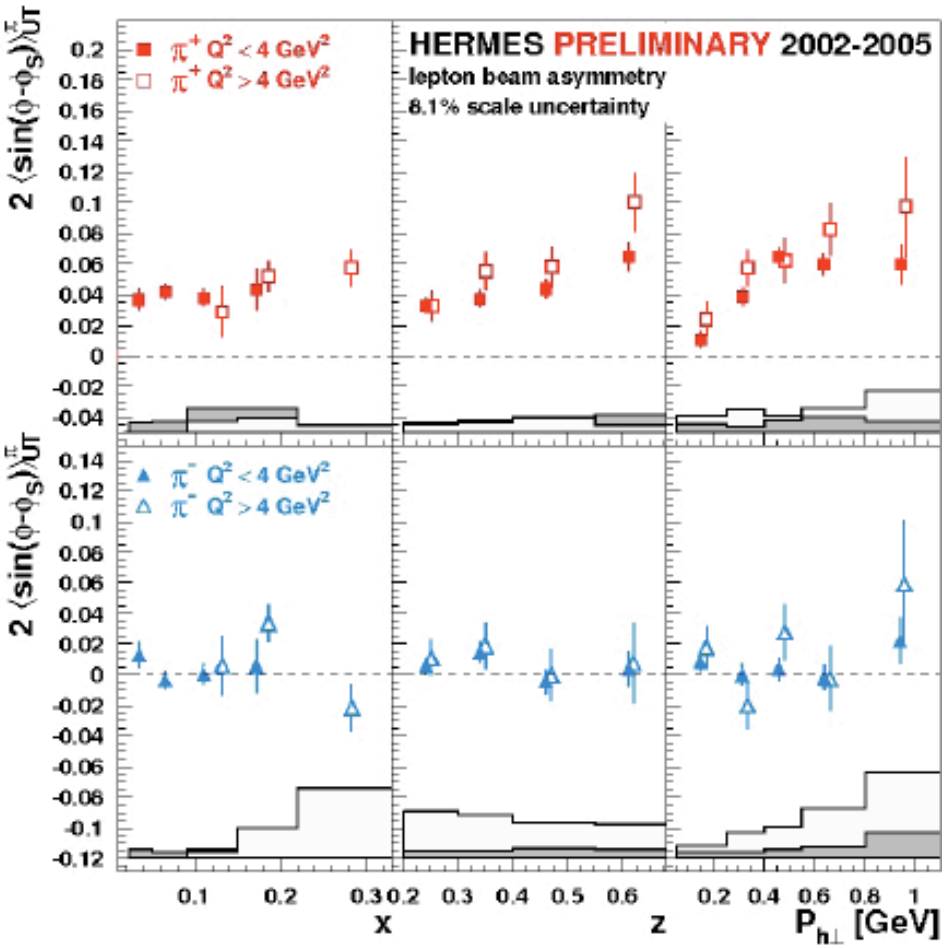

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- Exciting new results from transversely polarized targets have generated intense theoretical development of transverse momentum dependent distributions; These provide a framework to explore the effects of orbital motion in the nucleon. Both experiment and theory are in their infancy.
- Exclusive reactions bring us to a yet another 3D view of the nucleon structure, again a new “angle” to understand the quark-gluon dynamics

Nucleon Quark-Gluon Structure

We are "made of" glue and energy, not quarks!

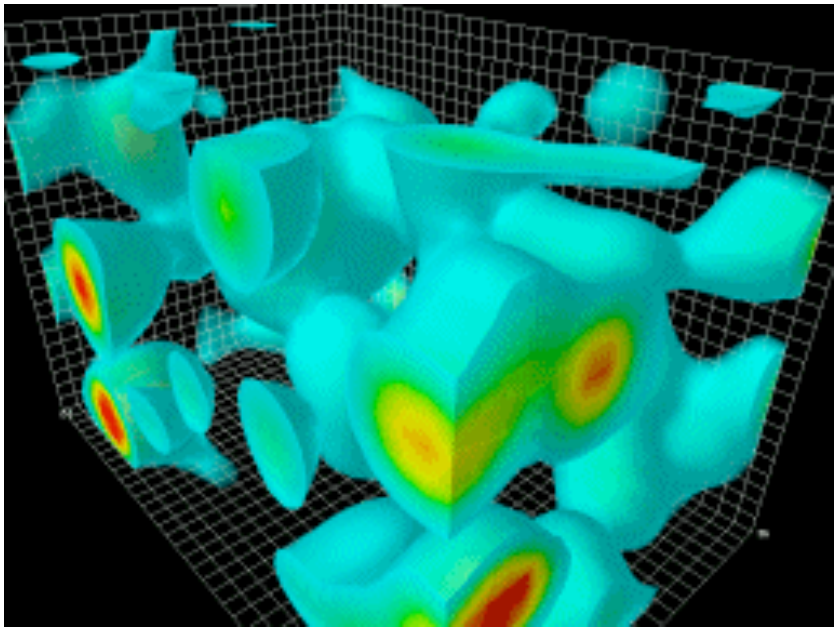
- Precision measurement of Δg to low x
  - ➡ Inclusive measurement of g_1 to low x and broad Q^2
  - ➡ Open charm electroproduction
- Precision measurement of polarized quark sea distributions
  - ➡ Semi-inclusive DIS to low x
- "3D" structure of nucleon *
  - ➡ Exclusive deep inelastic amplitudes over broad kinematics
  - ➡ Azimuthal distributions over broad kinematics for TMDs

Making sense of the empirical knowledge

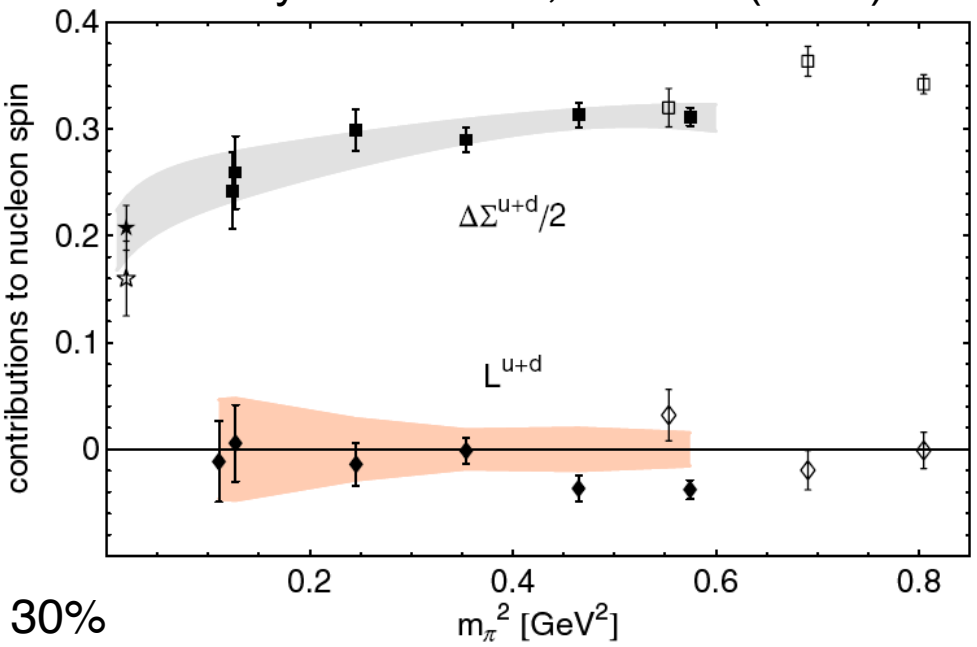
- Lattice QCD must start to organize all of our information

  ➡ We are not there yet! But we're getting close...

- Quantitative understanding of the QCD vacuum, flux tubes, pion clouds, constituent quarks,...



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



L^u and L^d cancel; quark spins 30%

(disconnected diagrams not yet included)

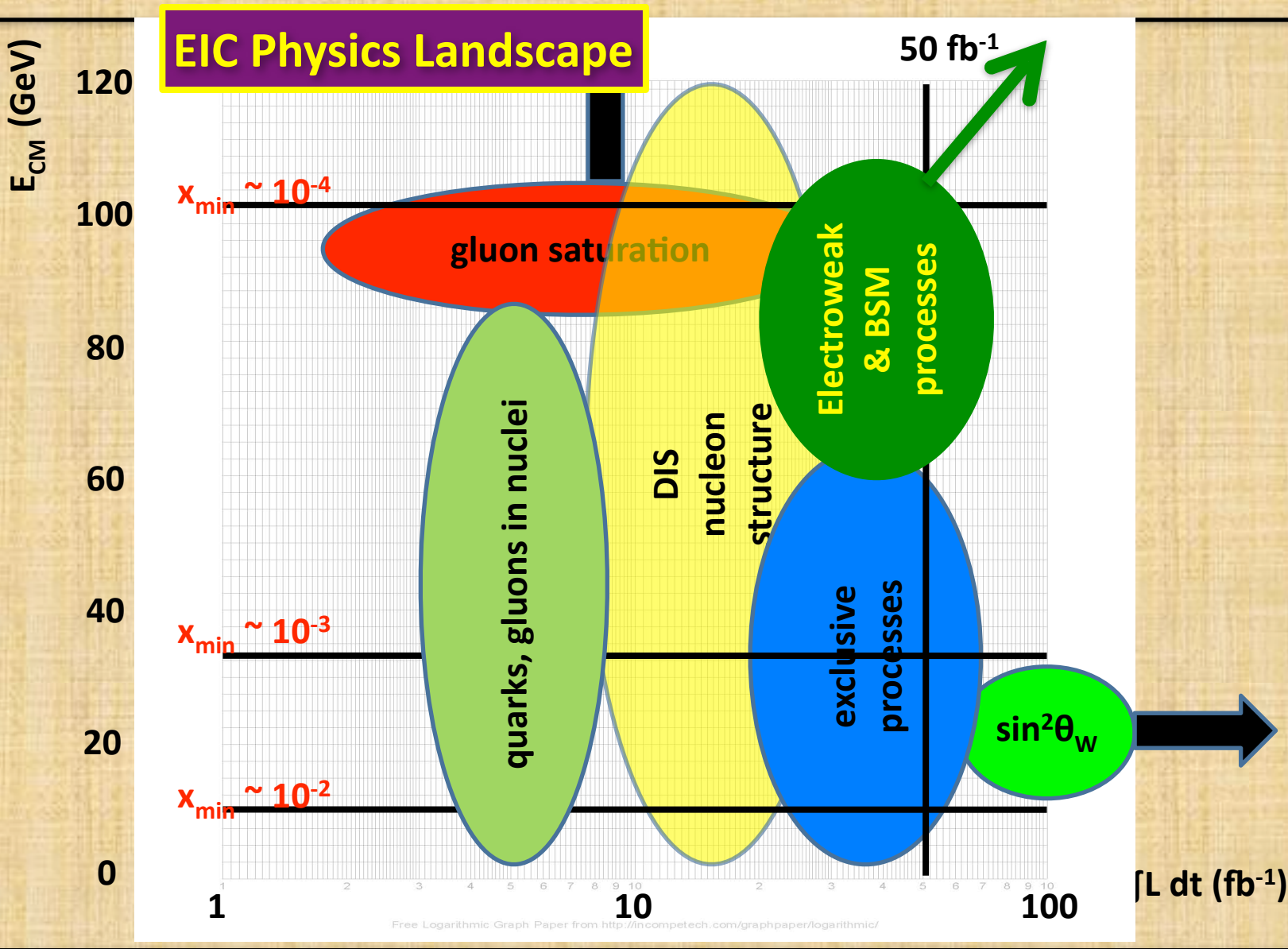
Gluons in the Nucleus and Gluon Compression

We are "made of" glue and energy, not quarks!

- Measurement of gluon distribution in the nucleus
  - ➡ Inclusive measurements of F_2, F_L from nucleon and nucleus
  - ➡ Measurements of "2+1" jets
  - ➡ Exclusive amplitudes for GPDs *
- Can the glue be compressed into condensation???
  - ➡ Diffractive measurements using hadronic photons (J/Ψ, ρ, ϕ)

Science Matrix Proposal 1

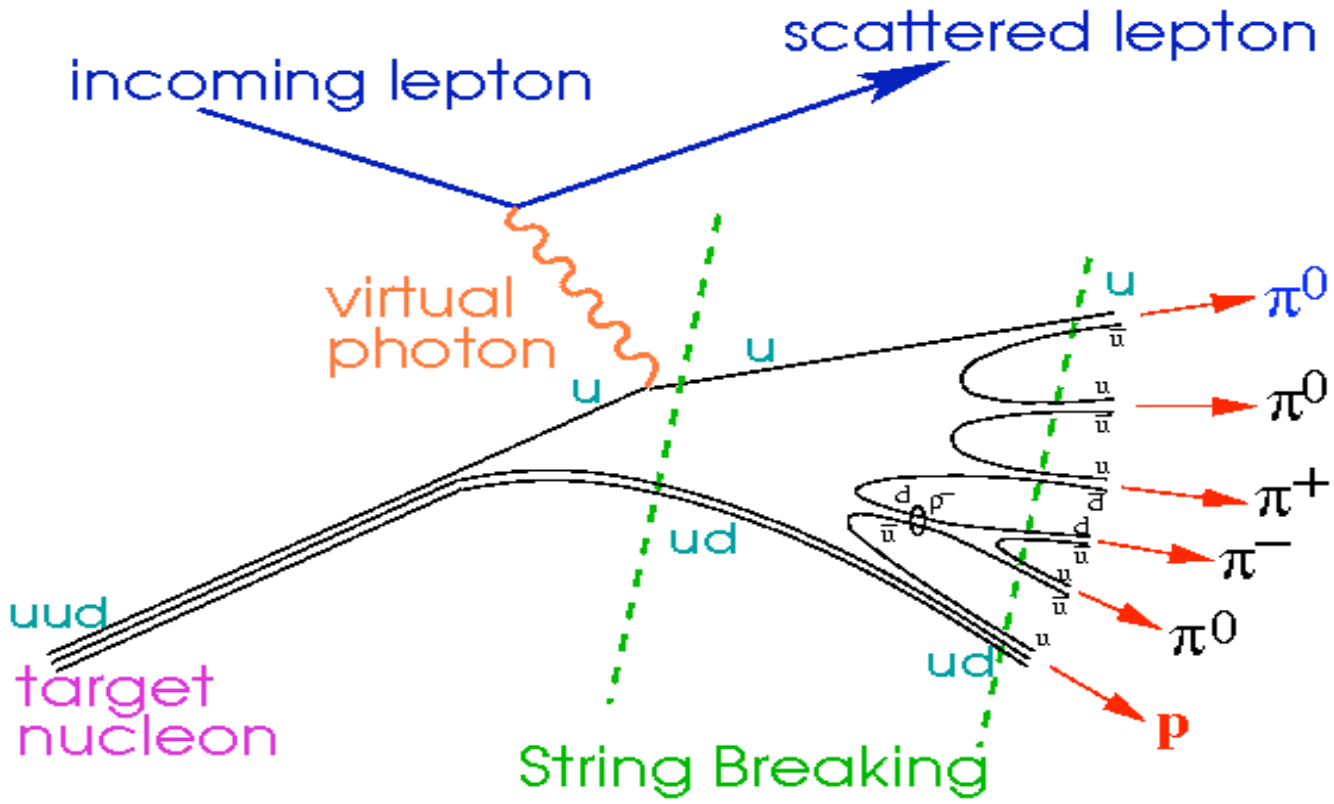
Deshpande



Some “Non-golden” Supporting Cast

- Precision ep and eA hadronization Studies (not just from EIC)
- Diffractive J/Ψ scattering from nuclei: the nuclear elastic form factor
- Testing SIDIS-derived results with EW processes
- Exploring new physics above the 10 TeV scale (complements LHC)

Understanding Fragmentation



Understanding Fragmentation

- New data from BaBar, Belle, JLab, HERMES, and COMPASS provides us the opportunity to make major advances in our detailed phenomenology of fragmentation.
  - ➡ We must explore the "forbidden" issues of isospin symmetry breaking, differences between e+e- and DIS, etc
  - ➡ We must learn how to handle transverse momentum dependence in fragmentation
  - ➡ Hadronization studies have shown that multidimensional measurements in kinematic variables such as z and p_T are essential
- At the EIC, we need to capture as much of the final state as we can

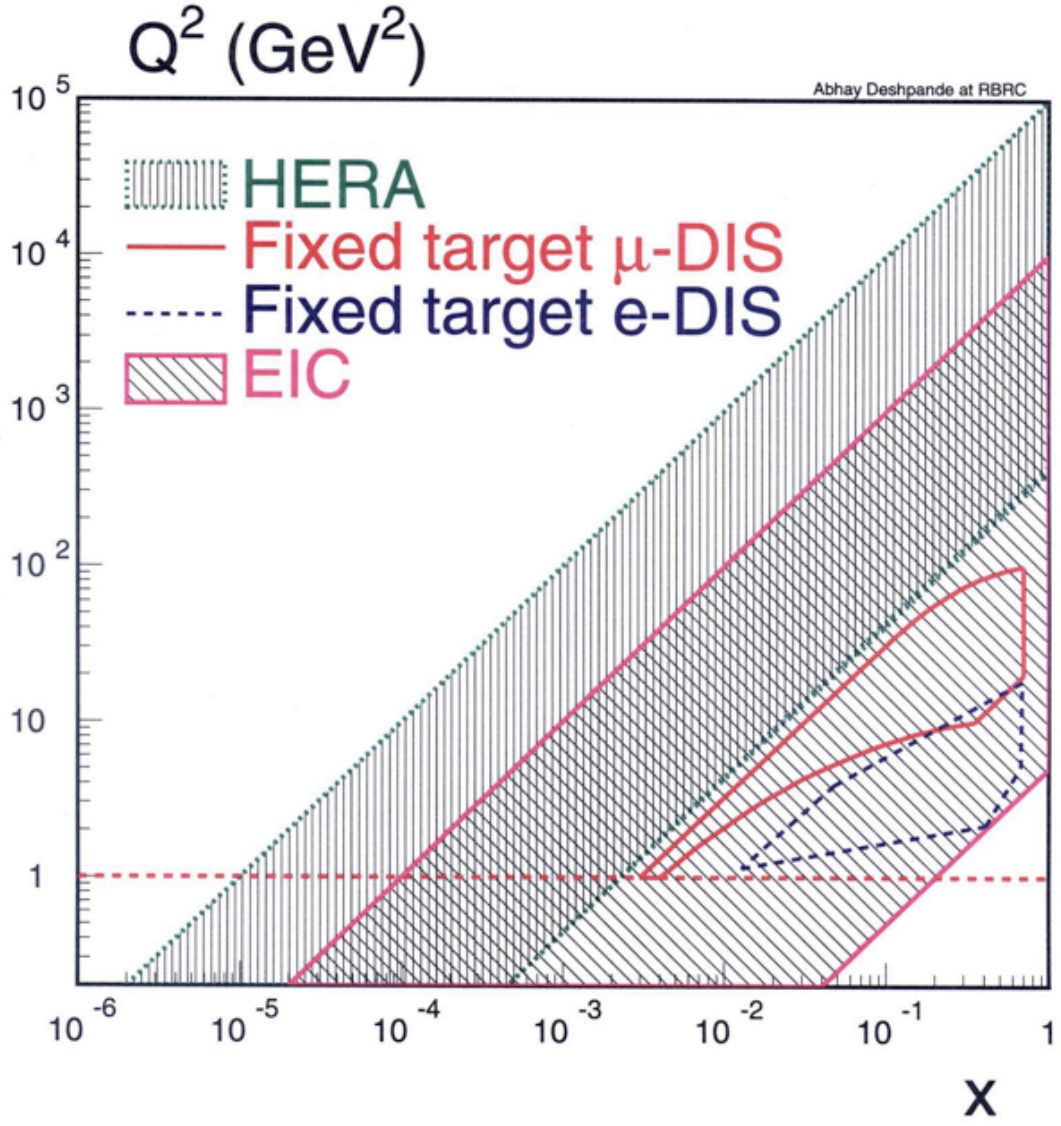
Summary?

- Nucleon quark gluon structure: Precision and range to break through to a new understanding the gluonic field in the nucleon? How is 1/2 encoded in such a complicated object?
- Spatial distributions and transverse motion: so new that we are still sorting out how to understand them. Are they intrinsic to our understanding of QCD states?
- Gluon compression: How do self-attracting fields behave? Can we provide data to bring new understanding? What if it's beyond the edge of our energy limit?

Backup Slides

- Projections

EIC Kinematic Range



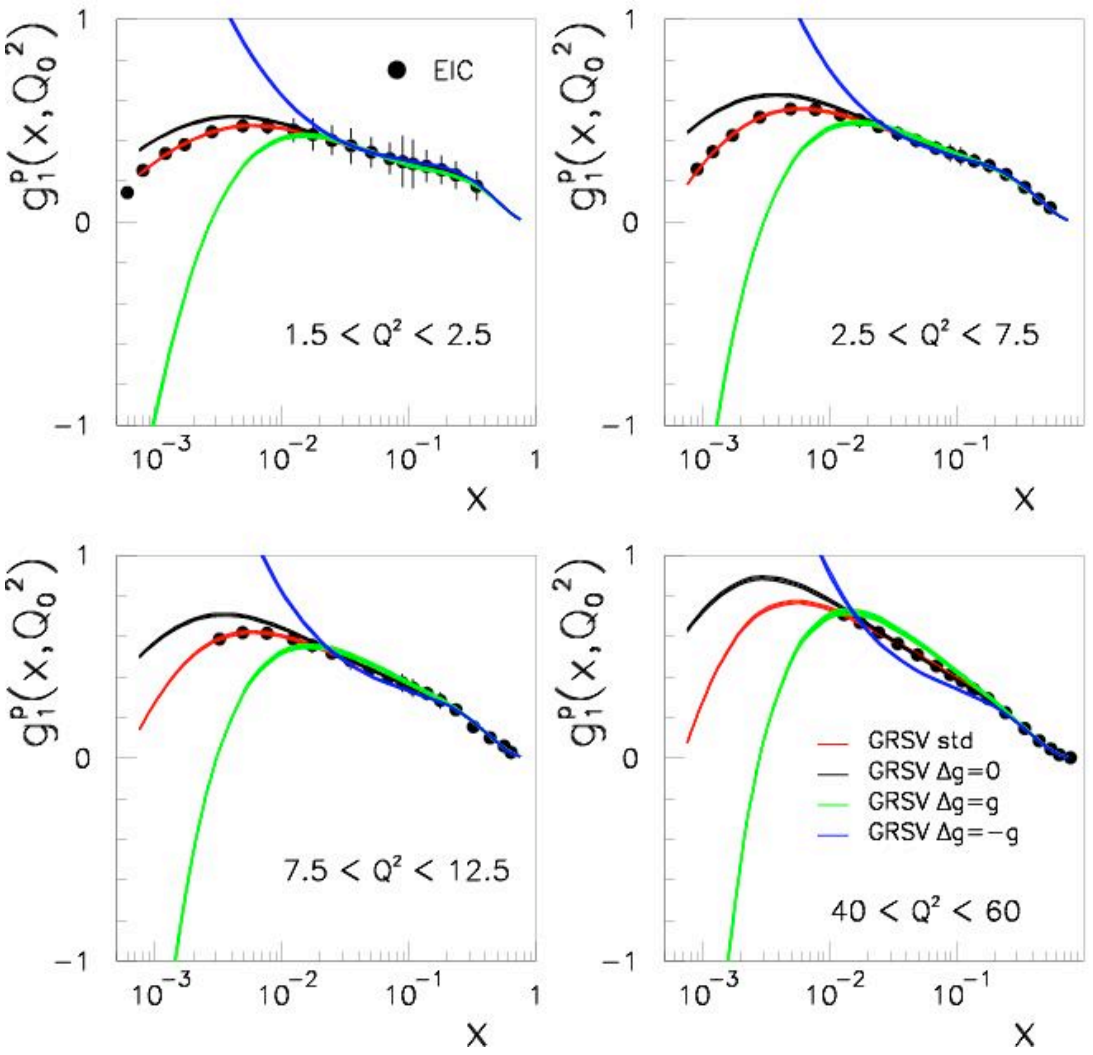
New kinematic region

- **E_e = 10 GeV (~4-20 GeV variable)**
- **E_p = 250 GeV (~50-250 GeV)**
- **E_A= 100 GeV /A**
- **Sqrt[S_{ep}] = 30-100 GeV**
- **Kinematic reach of EIC:**
  - **X = 10^{-4} --> 0.7 ($Q^2 > 1$ GeV^2)**
  - **Q_2 = 0 --> 10^4 GeV^2**
- **Polarization of e,p and light ion beams at least ~ 70% or better**
- **Heavy ions of ALL species**
- **Machine Luminosities envisioned**
  - **L(ep) ~$10^{33\text{-}34}$ cm^{-2} s^{-1}**
- **Integrated Luminosity goal:**
  - **50-500 fb^{-1} in 10 years**

The Gluon Contribution to the Proton Spin
Inclusive g_1 Measurements

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

- Projections for 7 GeV e- on 150 GeV p
- Excellent sensitivity to $\Delta g(x)$ at small *x*



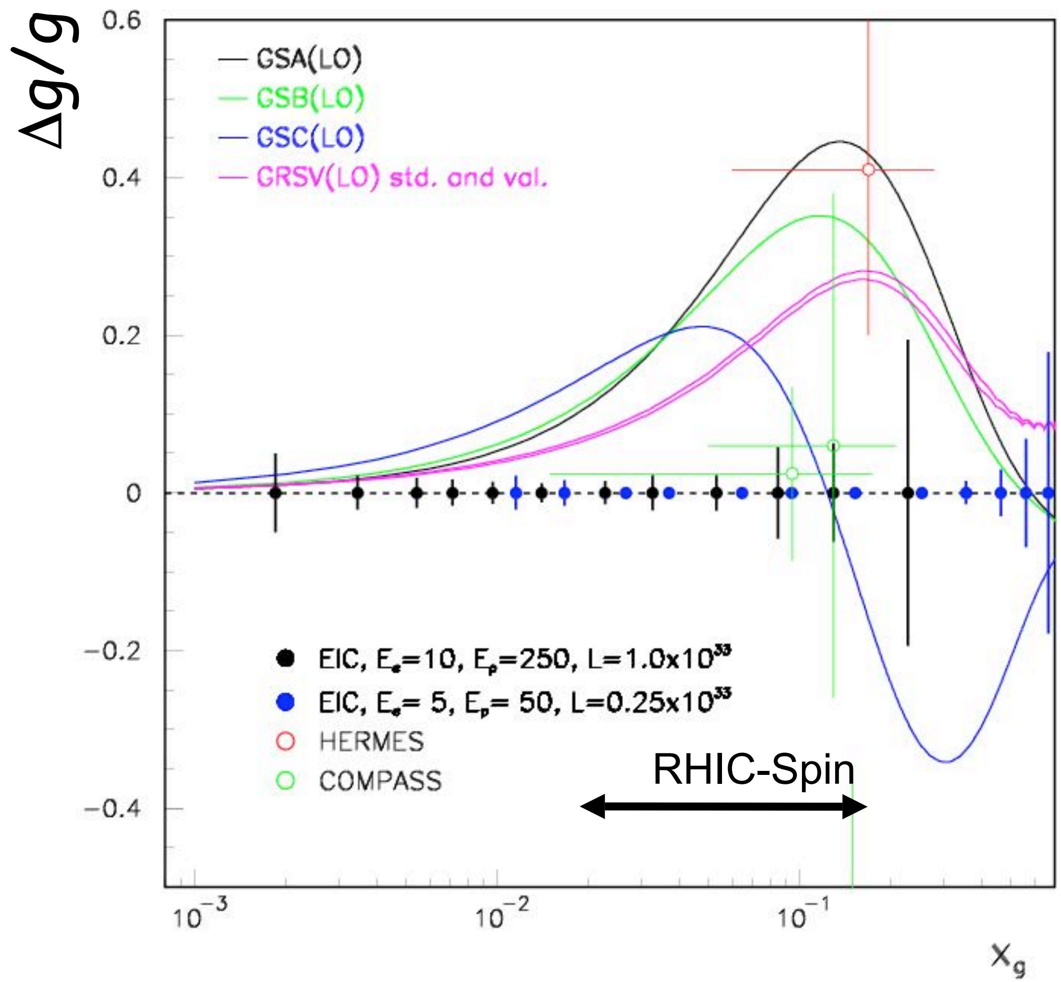
Antje Bruell, Abhay Deshpande

The Gluon Contribution to the Proton Spin
Open Charm SIDIS Measurements

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

$\quad\quad\quad\quad \mapsto K^- + \pi^+$

assuming vertex separation of 100 μm.

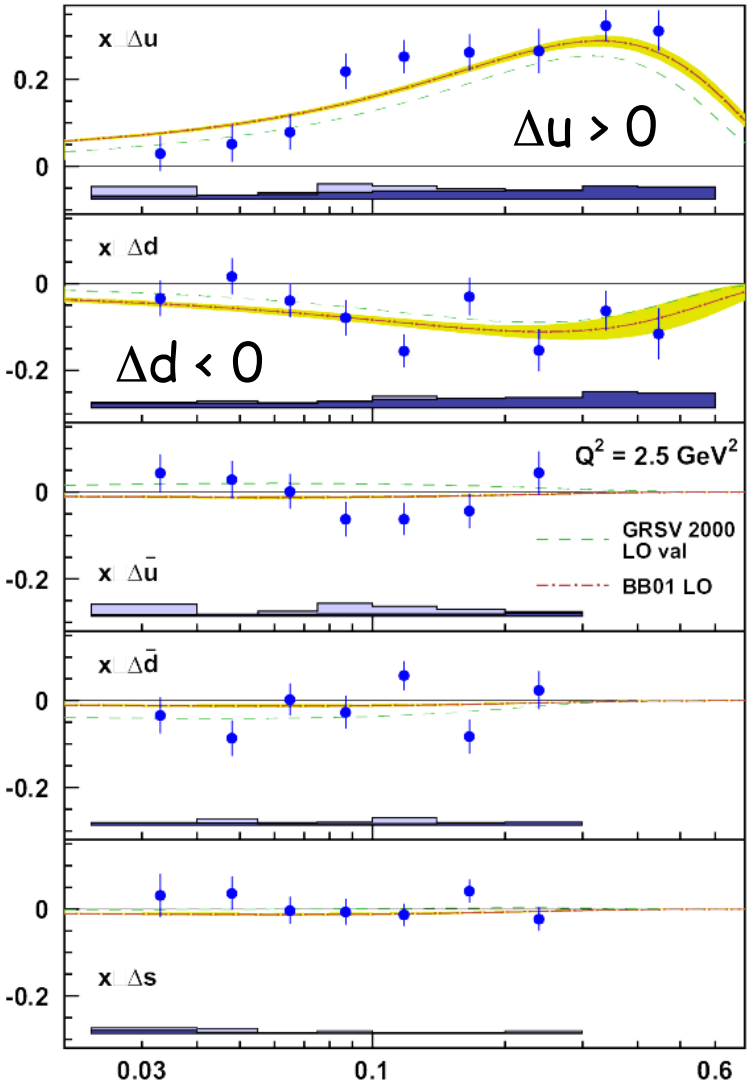


- Uncertainties in $x\,\Delta g$ smaller than 0.01
- Measure 90% of ΔG at $Q^2 = 10\ \mathrm{GeV}^2$

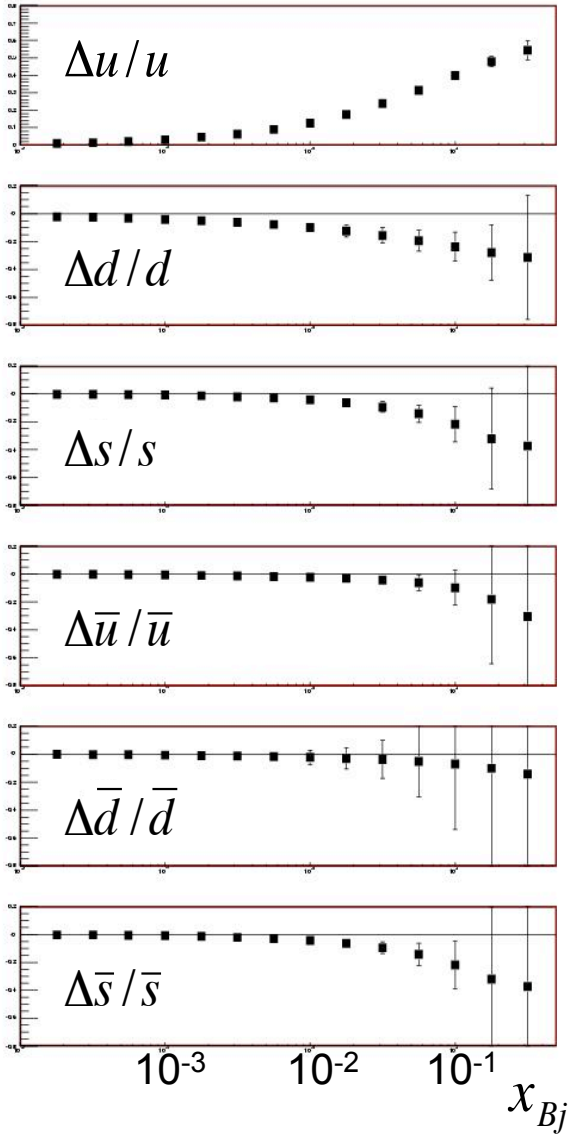
Antje Bruell

Spin-flavor Decomposition of the quark PDFs

HERMES SIDIS Results

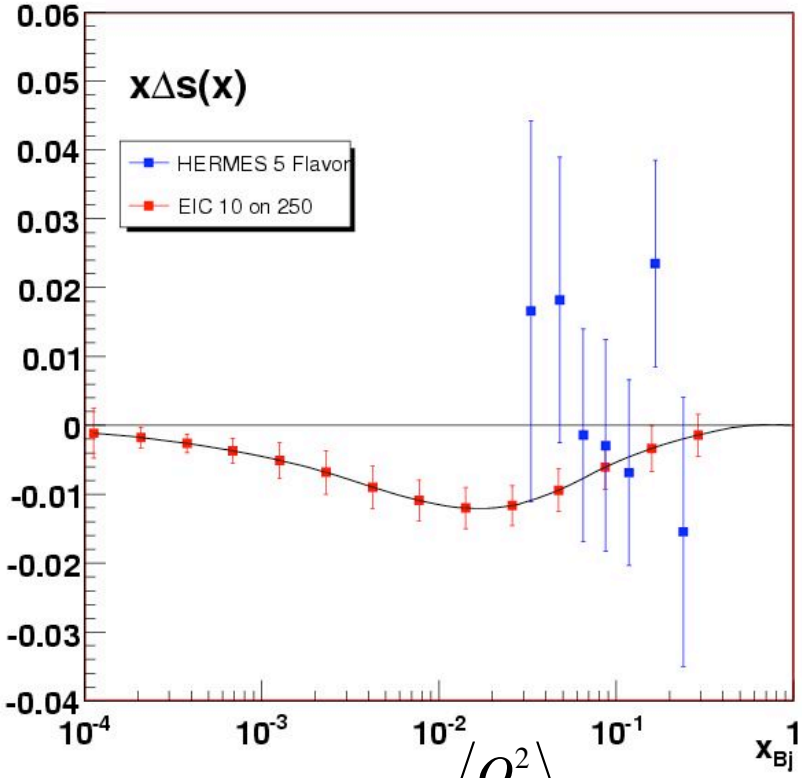


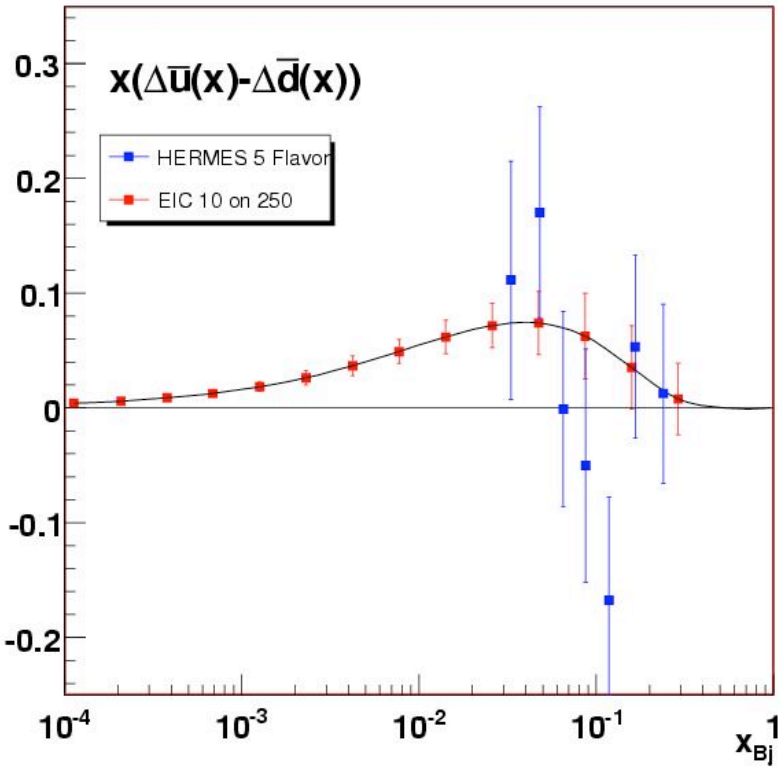
Projections for 9 fb^{-1} for 10 GeV on 250 GeV

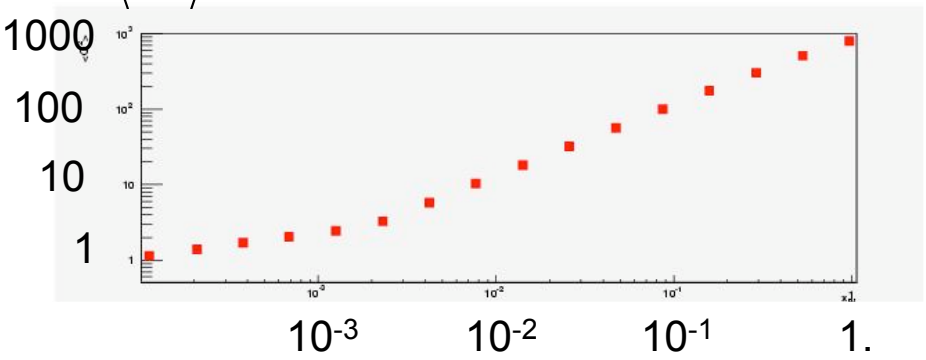


Joe Seele, ERK

Polarized Light and Strange Sea Distributions







Curves are GRSV parameterizations

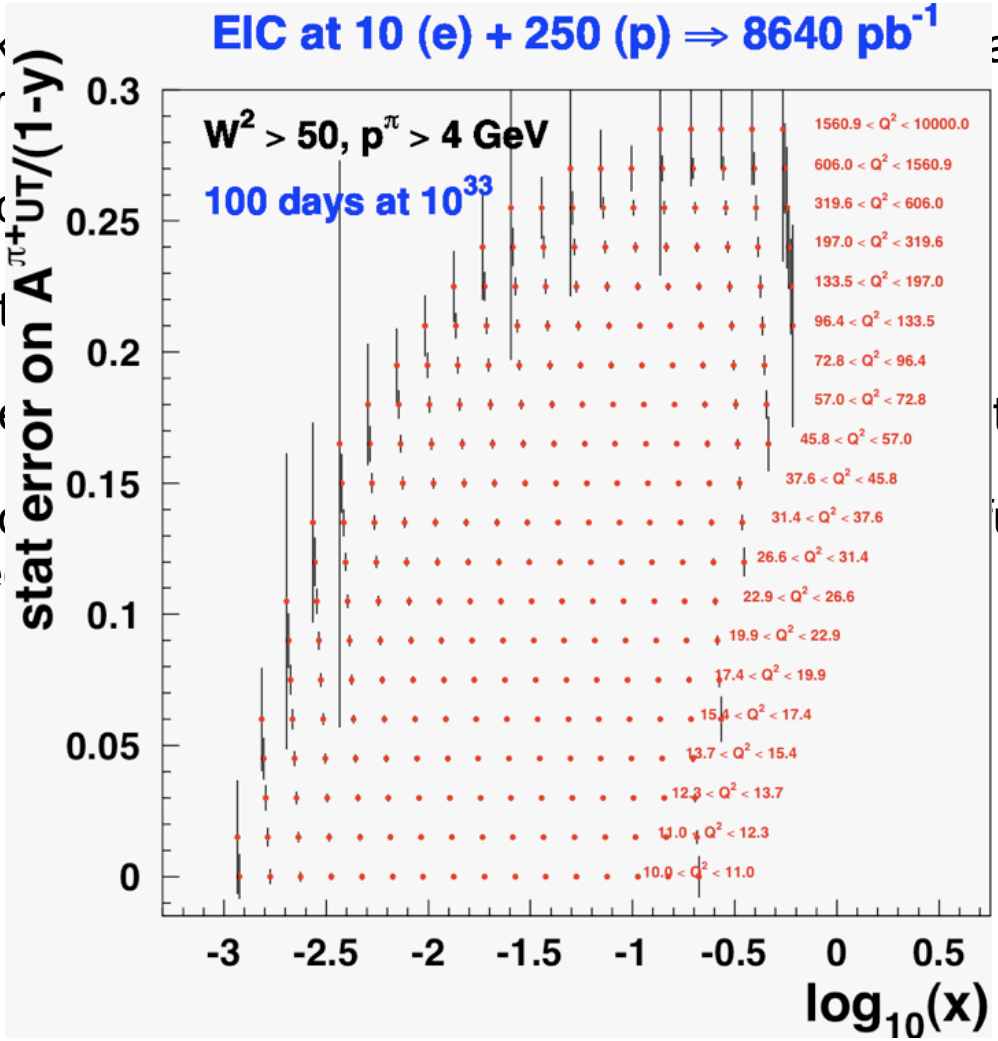
Transverse Momentum Dependent Distributions

- A breathtaking new field that has just truly opened in the last 5 years; everyone is still learning!
- Critical piece for understanding effects of orbital motion
- EIC data at collider energies would be unique
- Measurement relies on ability to extract azimuthal distributions

  ➡ Detector angular coverage/systematics must be carefully planned

Transverse Momentum Dependent Distributions

- A breathtak… ast 5 years; ever…
- Critical piec…
- EIC data at…
- Measureme… tions
  - ➡ Detecto… ully planne…



Naomi Makins

Nuclear Gluonic Measurements

Measurements & Techniques

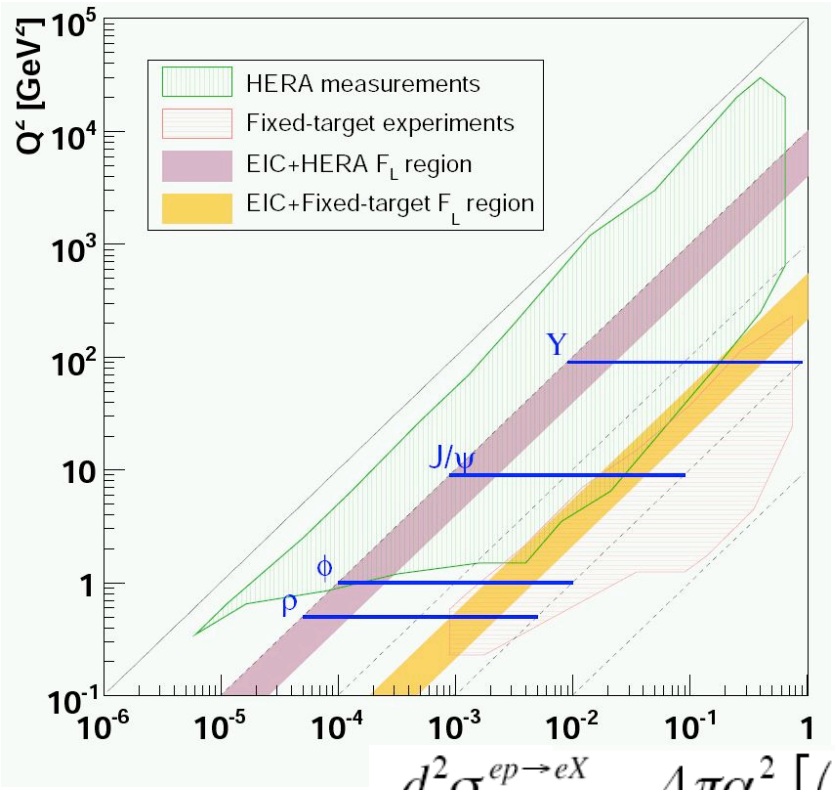
- Gluon Distribution $G(x,Q^2)$
  - Scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - $F_L \sim xG(x,Q^2)$
  - 2+1 jet rates
  - Diffractive vector meson production $([xG(x,Q^2)]^2)$
- Space-Time Distribution
  - Exclusive diffractive VM production (J/ψ, ϕ, ρ)
  - Deep Virtual Compton Scattering (nGPDs)
  - Structure functions for various mass numbers A and its impact parameter dependence

Ongoing studies On To-Do List

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 WITH VARIABLE ENERGIES!
- Highly sensitive to effects of gluon



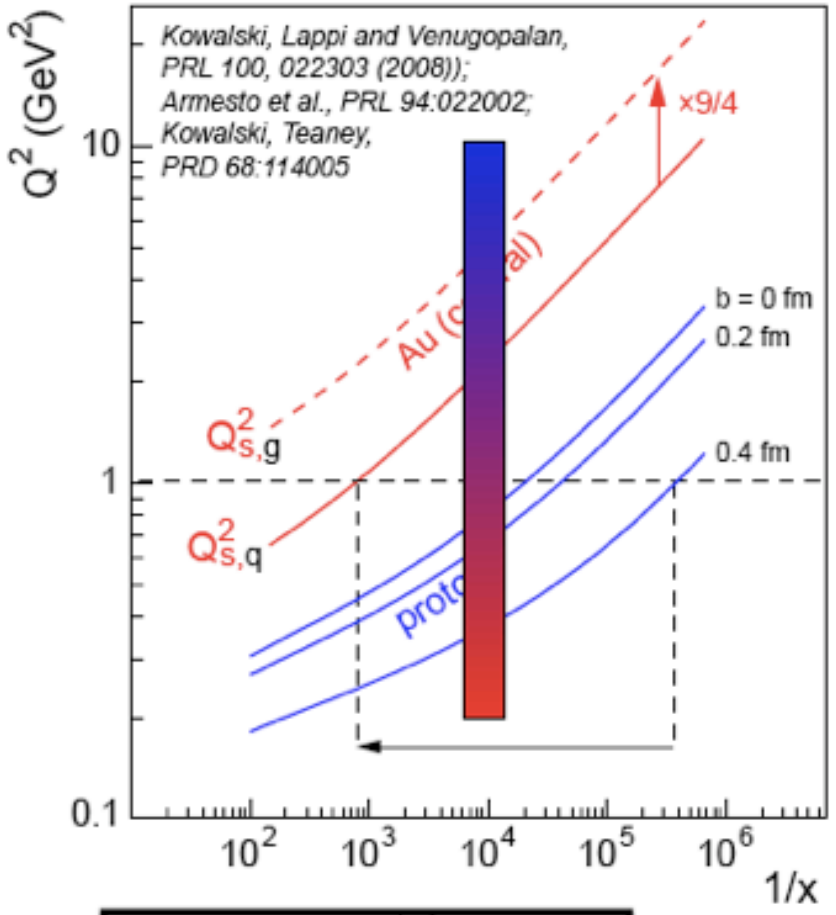
How to measure Gluon distribution $G(x,Q^2)$:

- 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 ~ $[G(x,Q^2)]^2$

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

Saturation & Kinematic Range

Ullrich



$E_e + E_A$ (GeV)	$\sqrt{s}$ (GeV)
4+100	40
10+100	63
20+100	89
30+100	110

Nuclear Enhancement of Q_s

$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

~6 for Au/U ⇒ at fix Q^2 translates into huge increase in x (~500)

pp, pA, AA: $Q_{s,g}$
DIS (ep, eA): $Q_{s,q}$

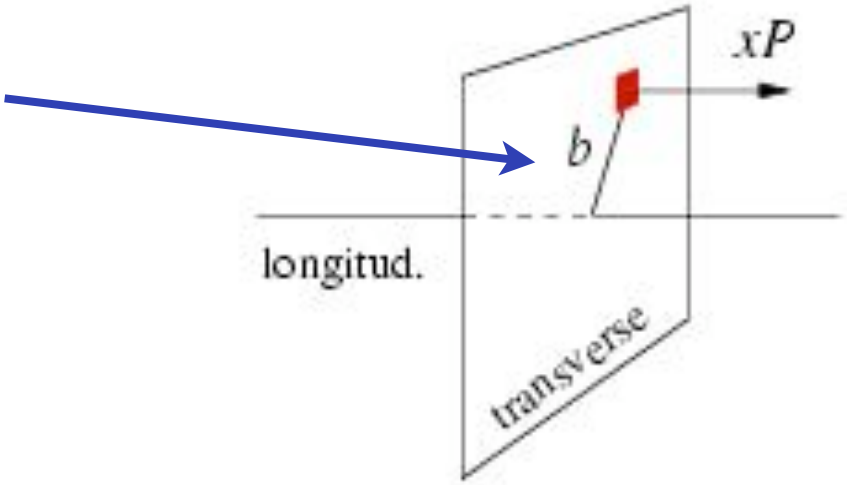
x, Q^2 kinematics:

$x = 10^{-3}$: $Q^2 = 0.2 \ldots 10$ GeV^2
$\sqrt{s} = 14 \ldots 100$ GeV

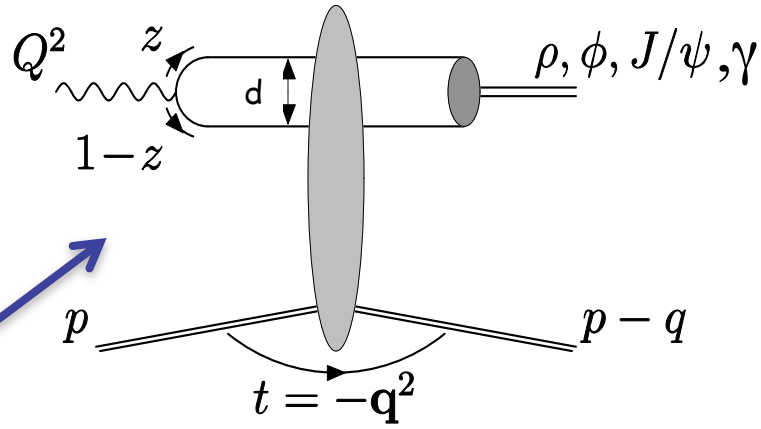
$x = 10^{-4}$: $Q^2 = 0.2 \ldots 10$ GeV^2
$\sqrt{s} = 45 \ldots 316$ GeV

Generalized Parton Distributions: Transverse Imaging of the Nucleon

- GPDs encode transverse size of quark (parton) with longitudinal momentum fraction *x*
- Fourier transform in momentum transfer



- EIC at High Energy:
  - ★ x< 0.1: Gluons!
  - ★ ξ ~ 0 : Gluon exchange is coherent



GPDs at High Energy: Transverse Gluon Imaging

Goal: Transverse gluon imaging of nucleon over wide range of x: 0.001 < x < 0.1
Requires: - Q^2 ~ 10-20 GeV^2 to facilitate interpretation
- Wide Q^2, W^2 (x) range
- Sufficient luminosity to do differential measurements in Q^2, W^2, t

Andrzej Sandacz

Q^2 = 10 GeV^2 projected data

Simultaneous data at other Q^2-values

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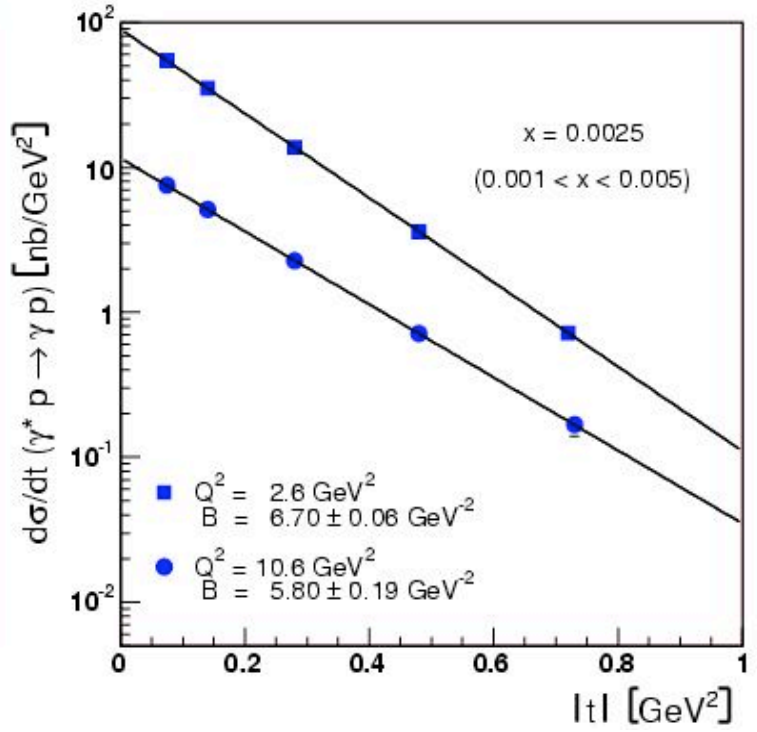

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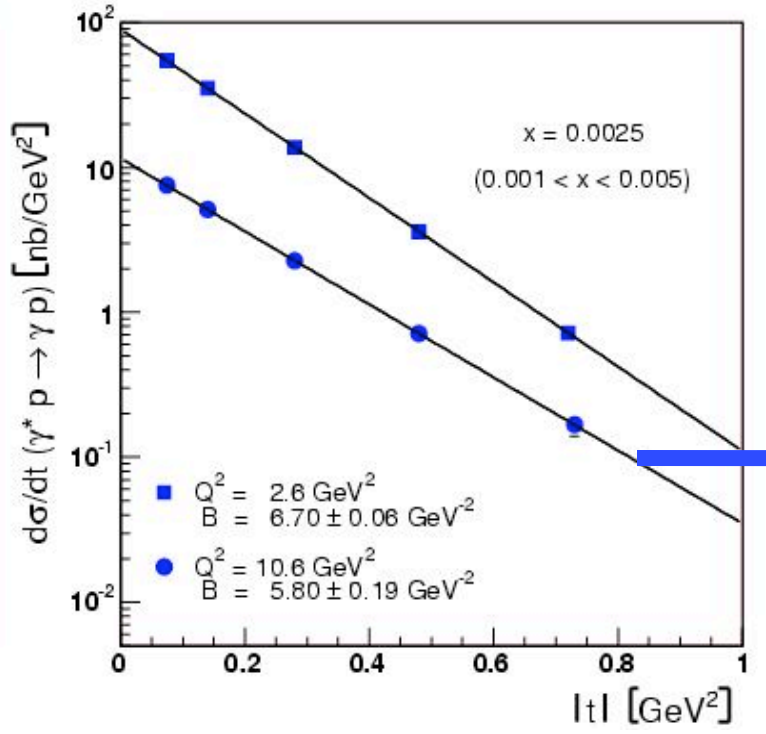

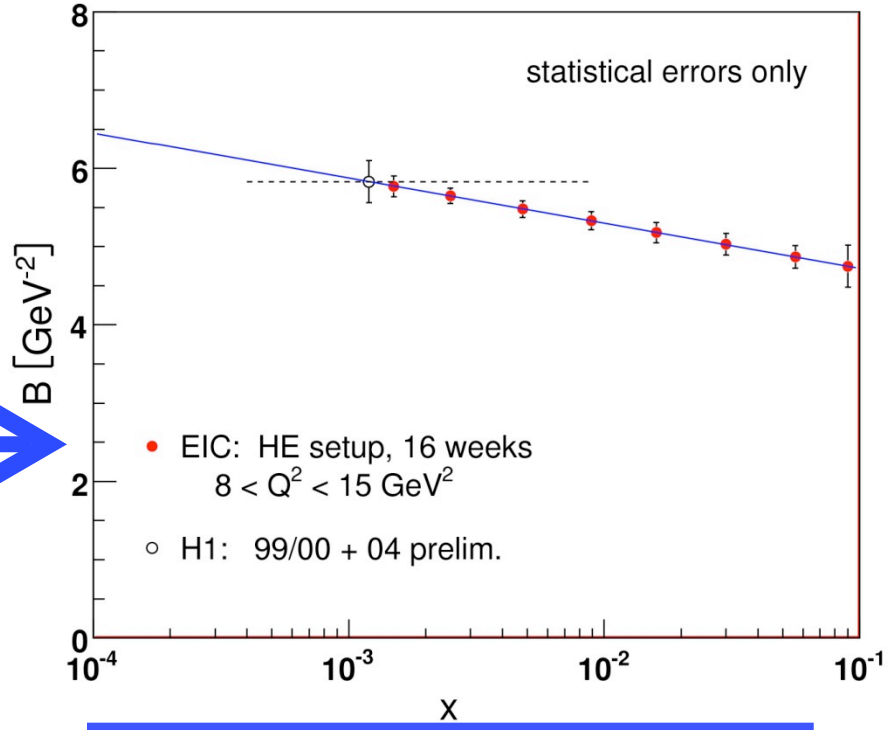

Q^2 = 10 GeV^2 projected data

Andrzej Sandacz

Simultaneous data at other Q^2-values

Nucleon Helicity Structure

- *Strange sea polarization a wide-open question*
  - I am a traditionalist.... I am distrustful of semi-inclusive measurements when high precision is needed
  - We need to get away from $SU(3)_f$
  - Phase I EIC might already contribute at $x \sim 0.01$
    - *another personal bias: I don't trust existing results below $x \sim 0.1$*

Kumar

From target-flip parity-violating asymmetry:

	y-independent	y-dependent
^1H	$\frac{2\Delta u^- + \Delta d^- + \Delta s^-}{4u^+ + d^+ + s^+}$	$\frac{\Delta u^+ + \Delta d^+ + \Delta s^+}{4u^+ + d^+ + s^+}$
^2H	$\frac{3\Delta u^- + 3\Delta d^- + 2\Delta s^-}{u^+ + d^+ + s^+}$	$\frac{\Delta u^+ + \Delta d^+ + \Delta s^+}{u^+ + d^+ + s^+}$

Why study the spin structure?

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- Higher and higher resolution in a single view will generally not be sufficient to understand the dynamics!