e-p Physics at an Electron-Ion Collider

E.R. Kinney, University of Colorado

- Introduction and Motivation
- Physics Projections
  - ➡ Inclusive spin structure at low x_{Bj}
  - ➡ Gluonic spin structure via charm production
  - ➡ Spin-flavor decomposition with Semi-inclusive DIS
  - ➡ Transverse momentum-dependent distributions
  - ➡ Fragmentation studies
- Outlook

Acknowledgements and Disclaimer

Thanks to members of the EIC Collaboration for allowing me to present their work and especially to Rolf Ent for the use of material from some of his presentations.

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

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

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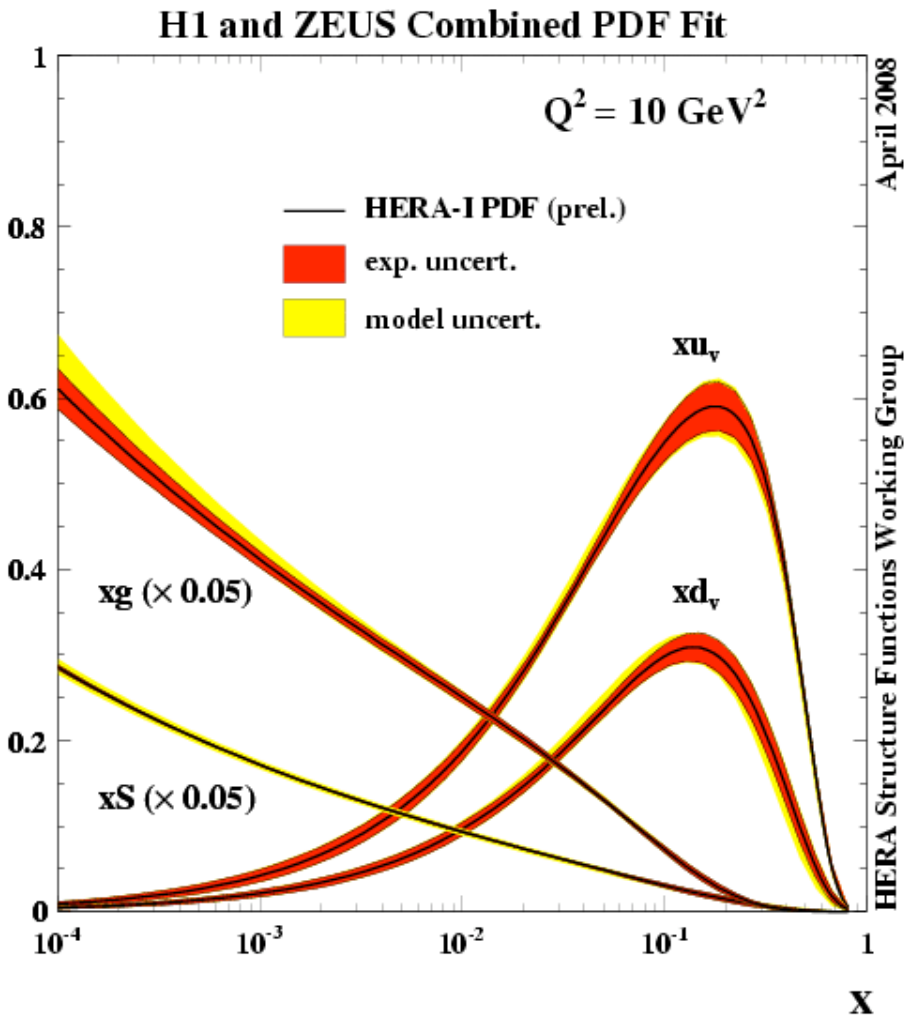

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- "Polarized" inclusive and semi-inclusive DIS have determined the helicity dependent quark distributions over much more modest range, similar to the pre-HERA era for unpolarized distributions

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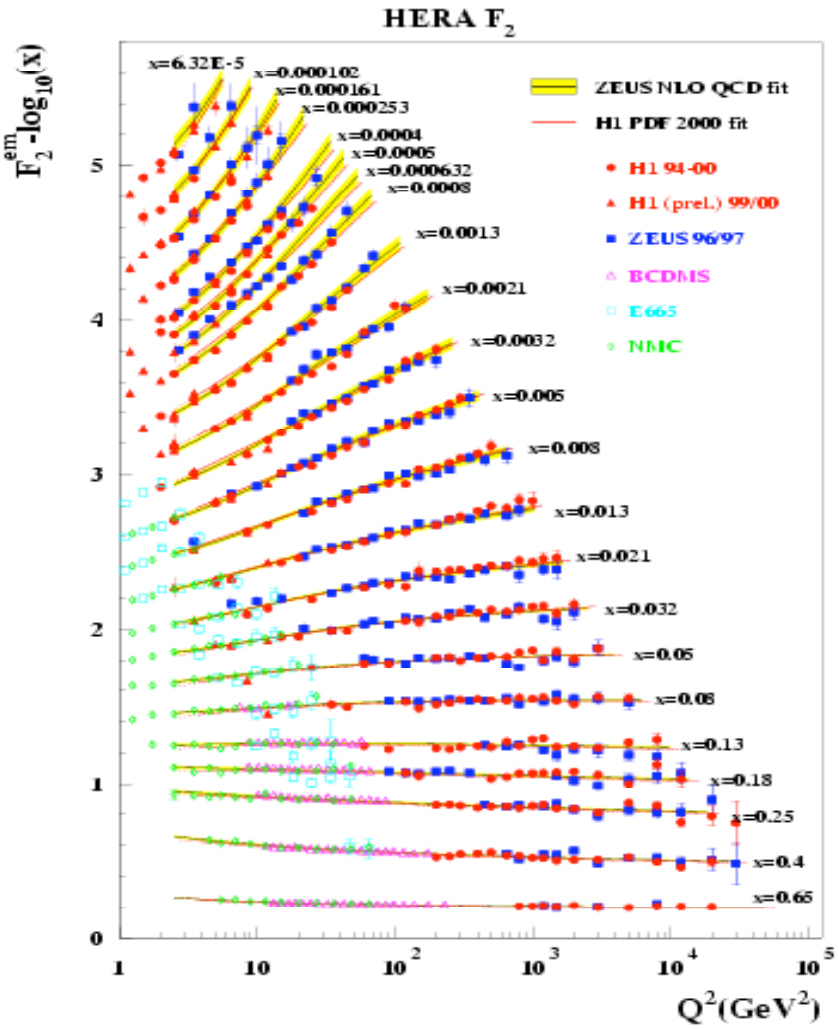

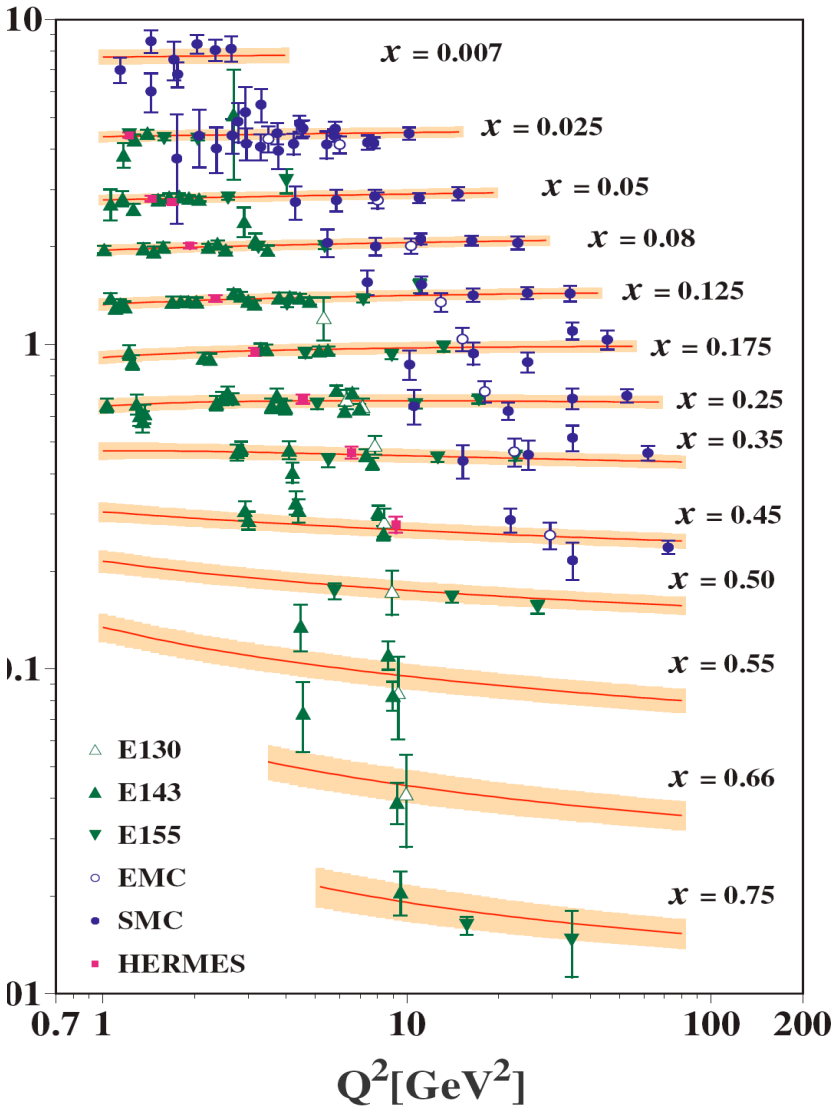

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- We are very much still at the empirical stage of understanding the proton!

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!

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- Where is the nucleon spin?
- 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*

Why continue to study the spin structure?

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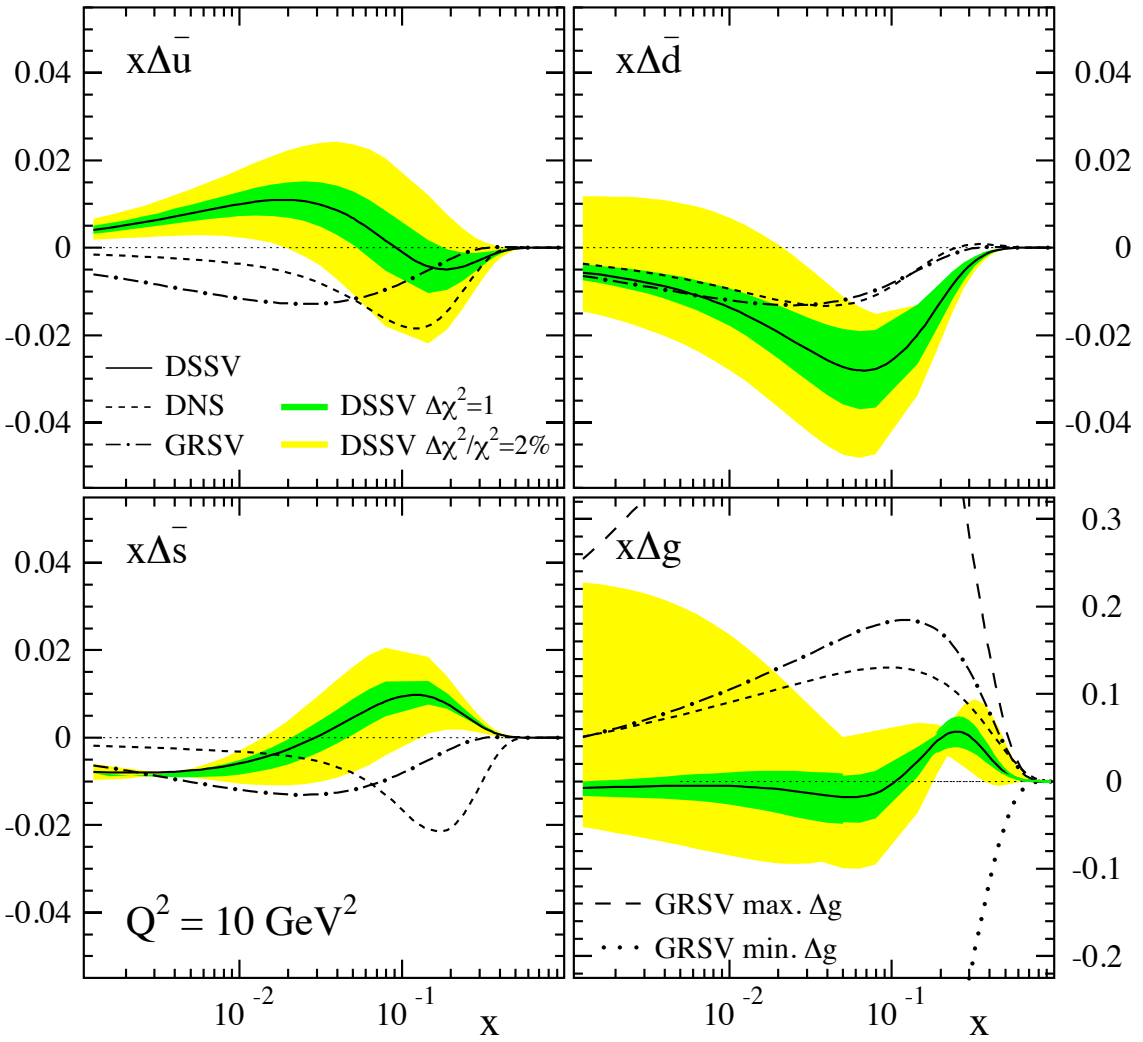

DeFlorian, Sassot, Stratmann, Vogelsang, PRL101 (2008) 072001

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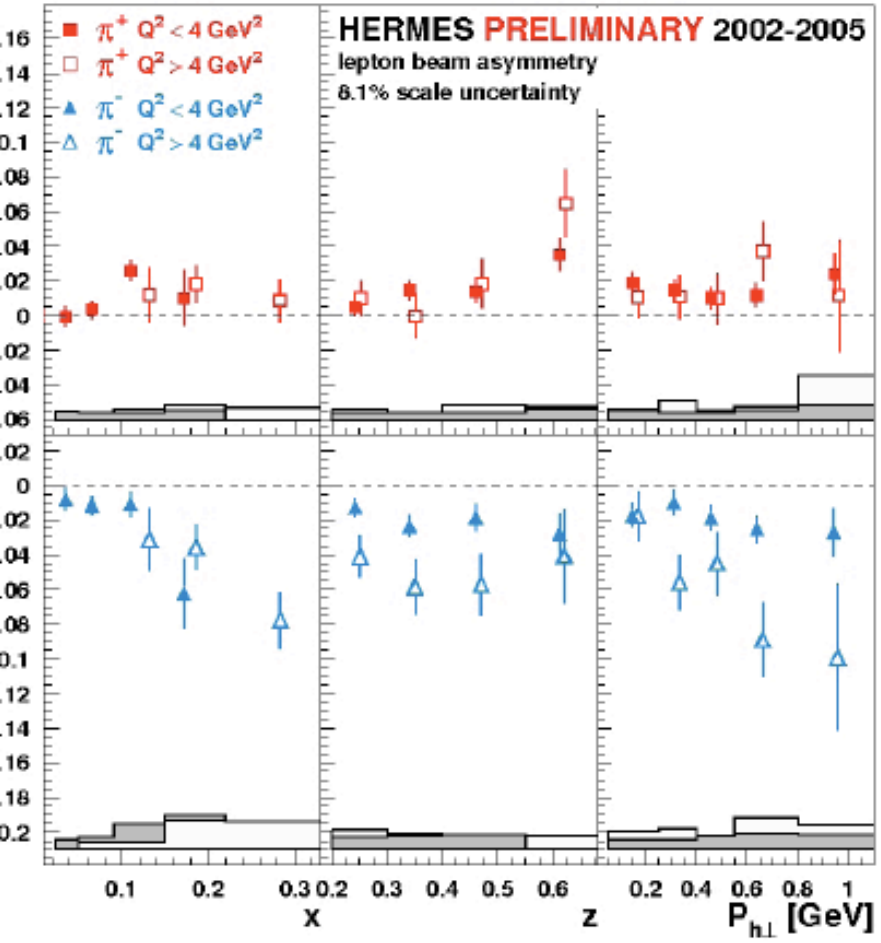

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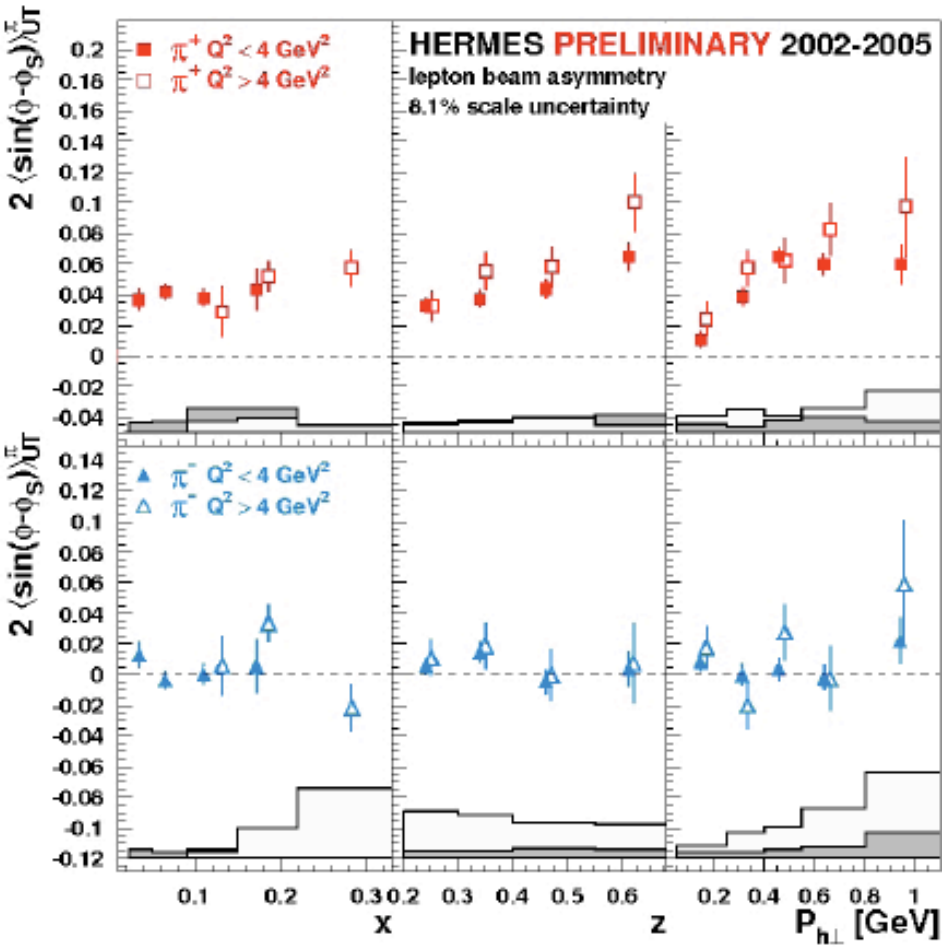

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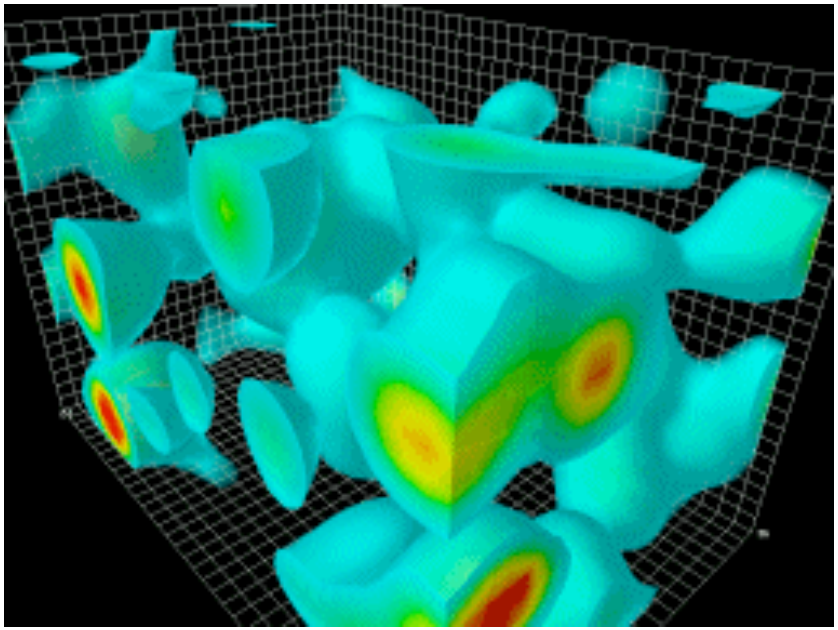
- Exclusive reactions bring us to a yet another 3D view of the nucleon structure, again a new “angle” to understand the quark-gluon dynamics

Making sense of the empirical knowledge

- Lattice QCD must start to organize all of our information

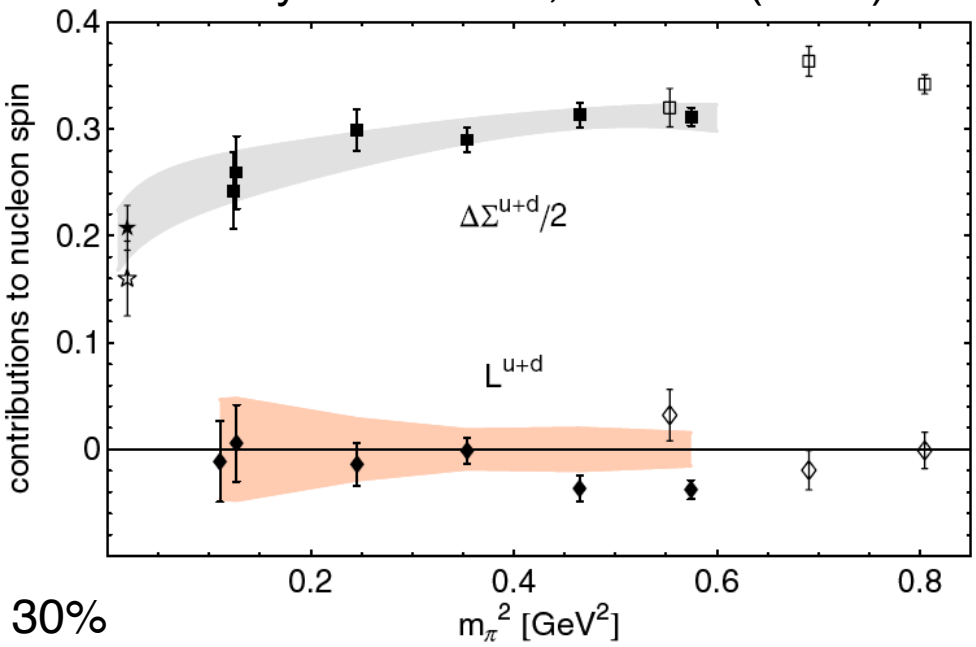
  ➡ We are not there yet! But we're getting close...

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



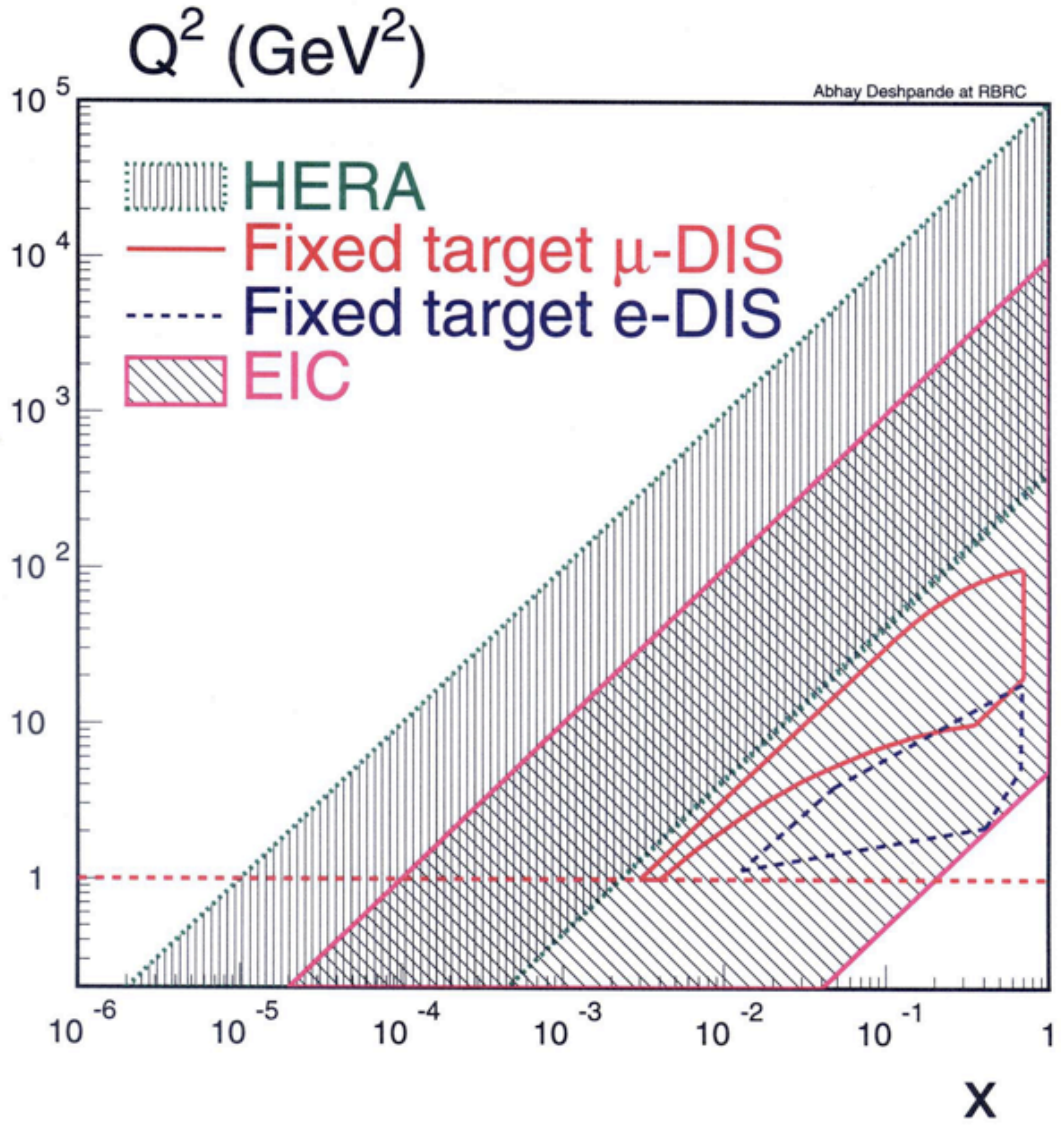
L^u and L^d cancel; quark spins 30%

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



(disconnected diagrams not yet included)

EIC Kinematic Range



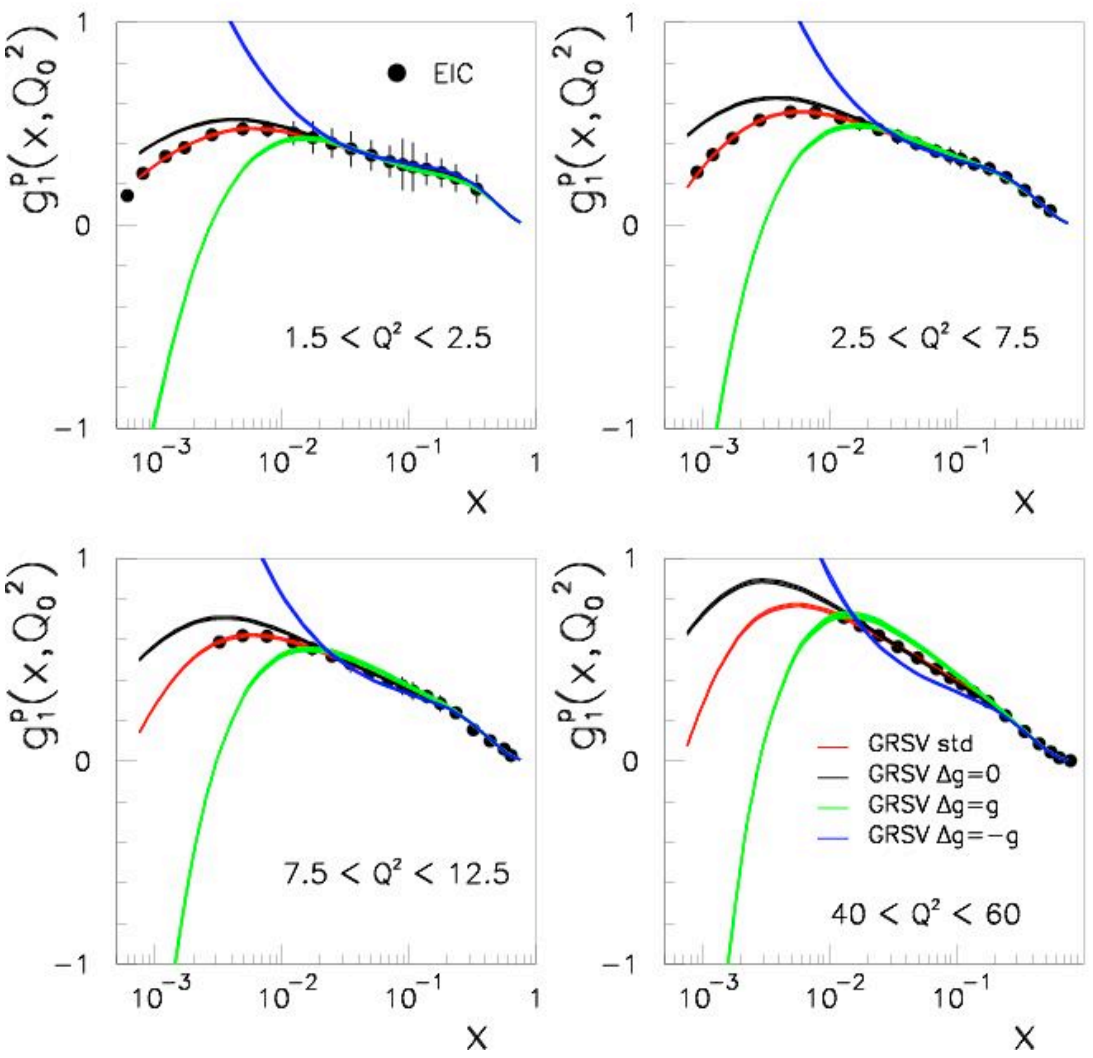
New kinematic region

- **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*

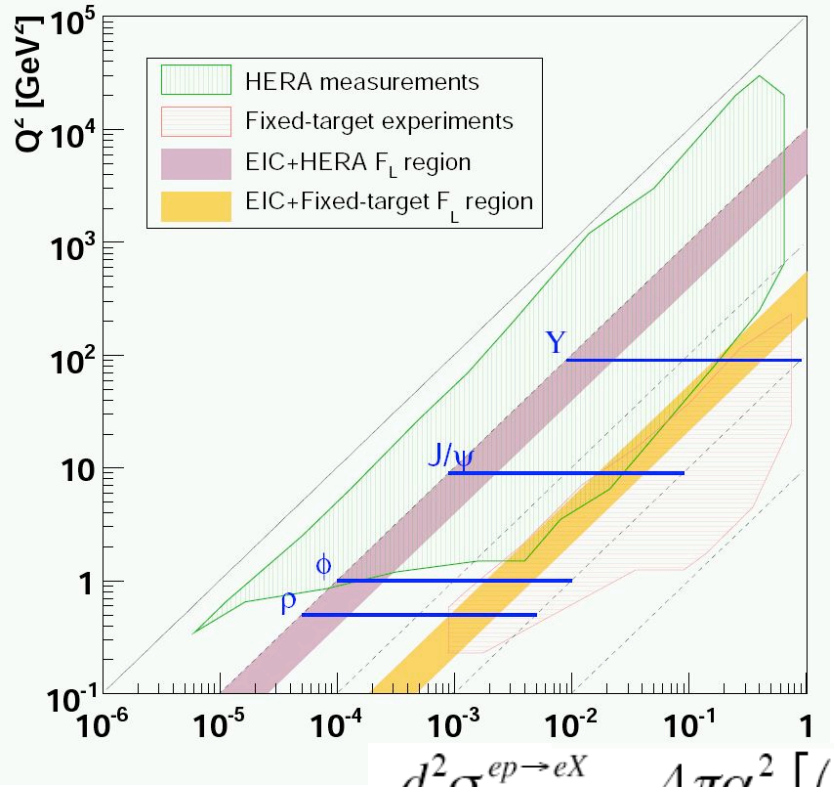


Antje Bruell, Abhay Deshpande

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

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

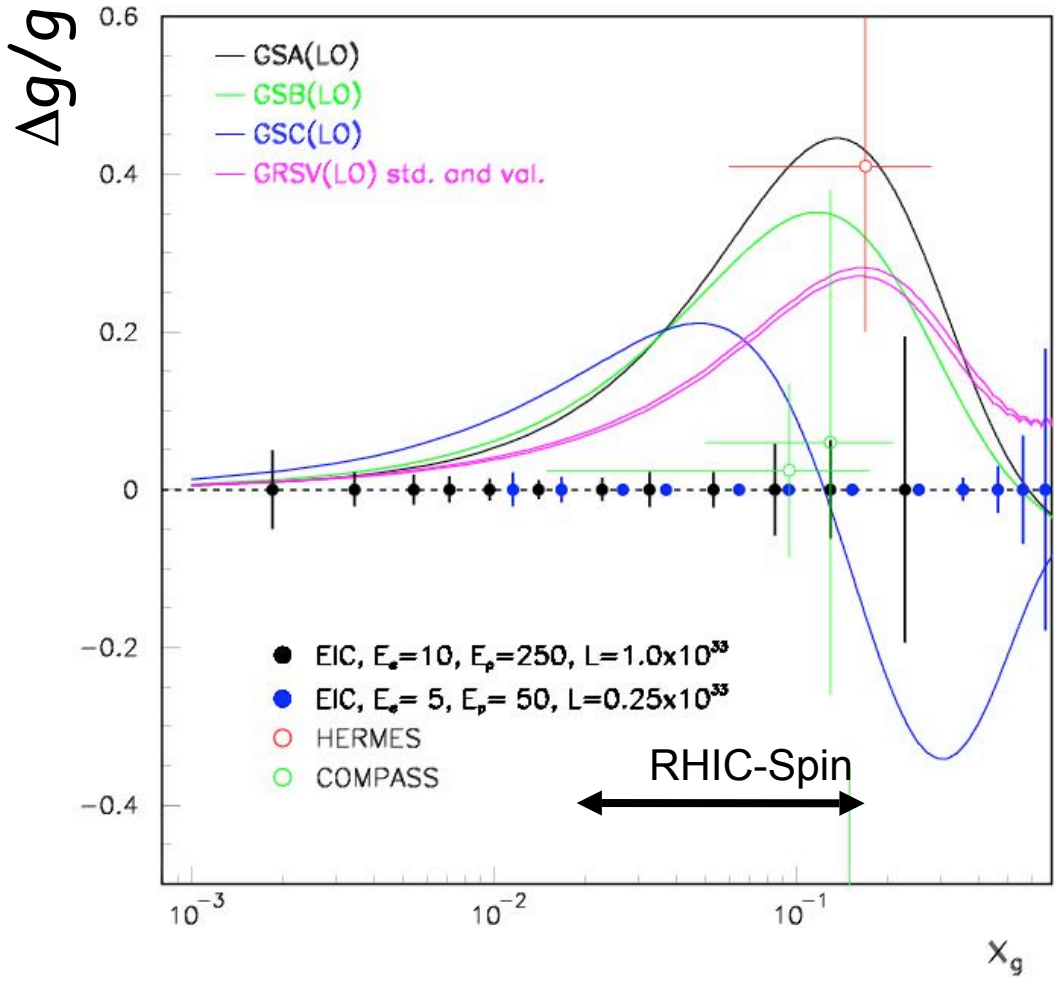
The Gluon Contribution to the Proton Spin
Open Charm SIDIS Measurements

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

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

assuming vertex separation of 100 μm.

- Uncertainties in x Δg smaller than 0.01
- Measure 90% of ΔG at $Q^2 = 10\ GeV^2$



Antje Bruell

The Gluon Contribution to the Proton Spin
Open Charm SIDIS Measurements

Projected c
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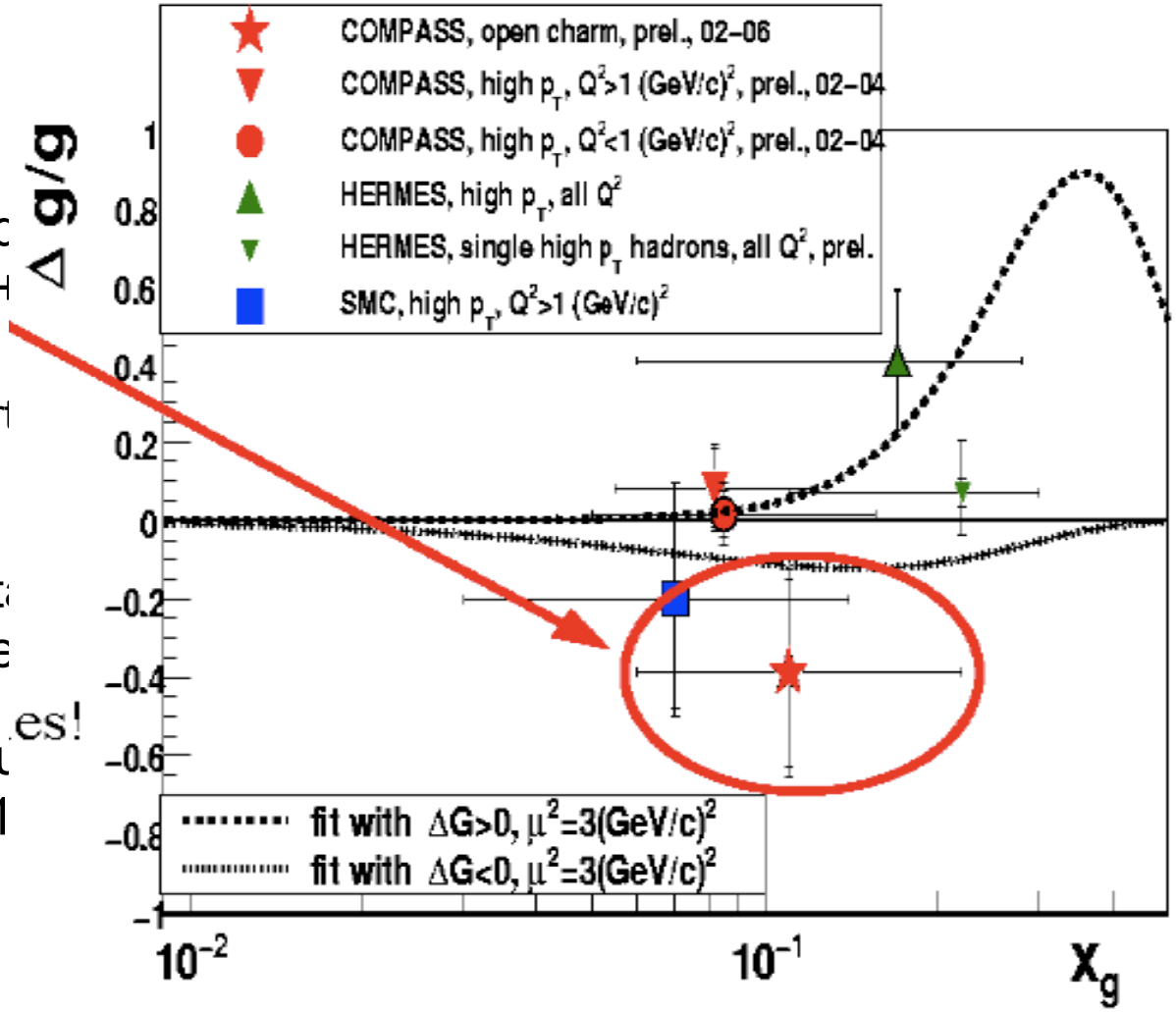
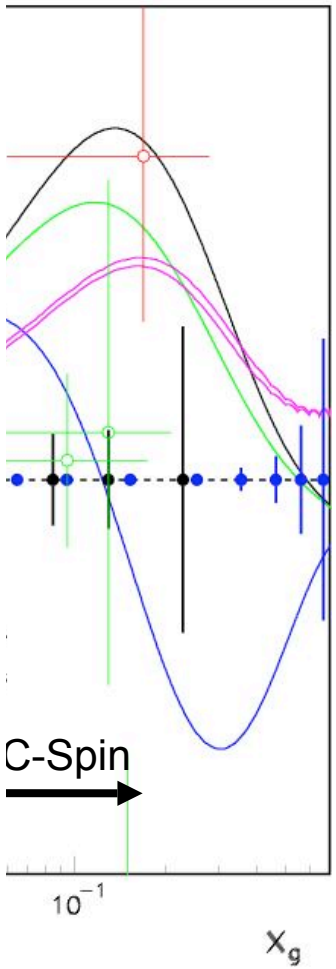
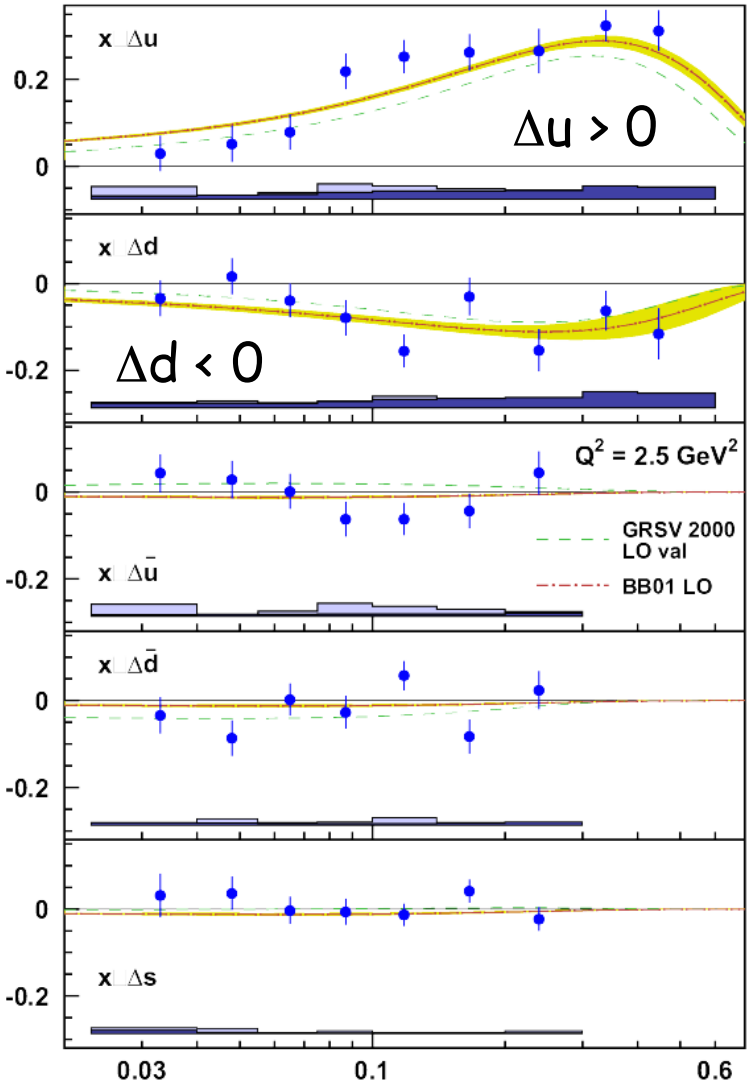




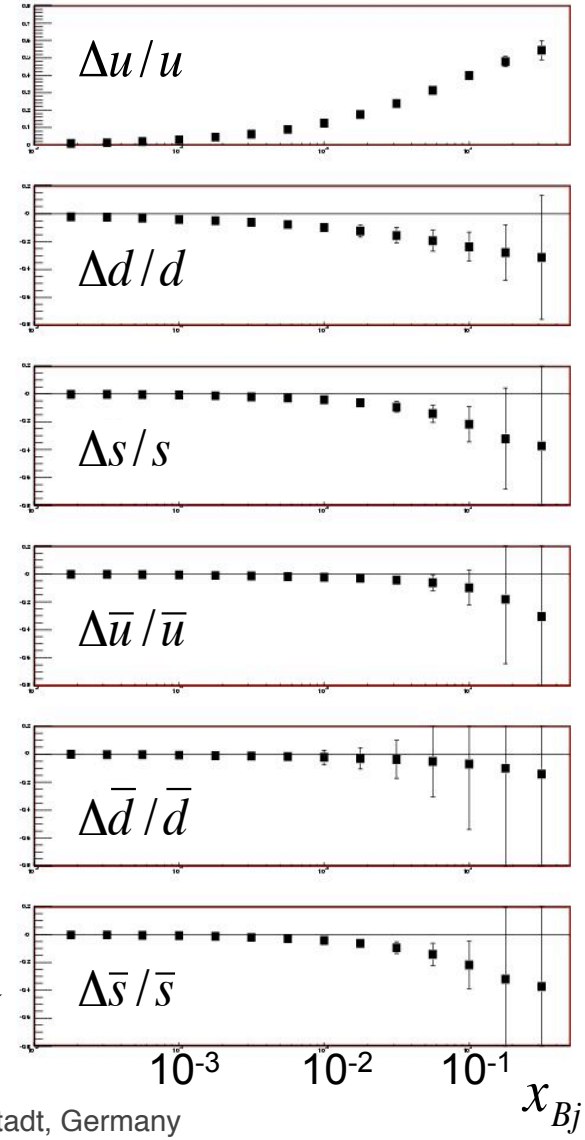
Antje Bruell

Spin-flavor Decomposition of the quark PDFs

HERMES SIDIS Results

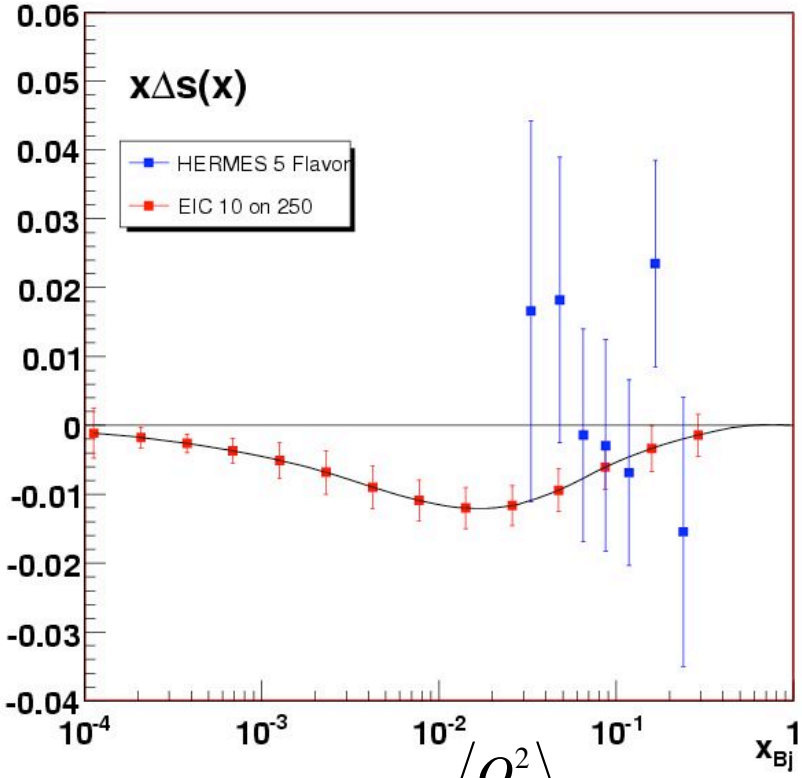


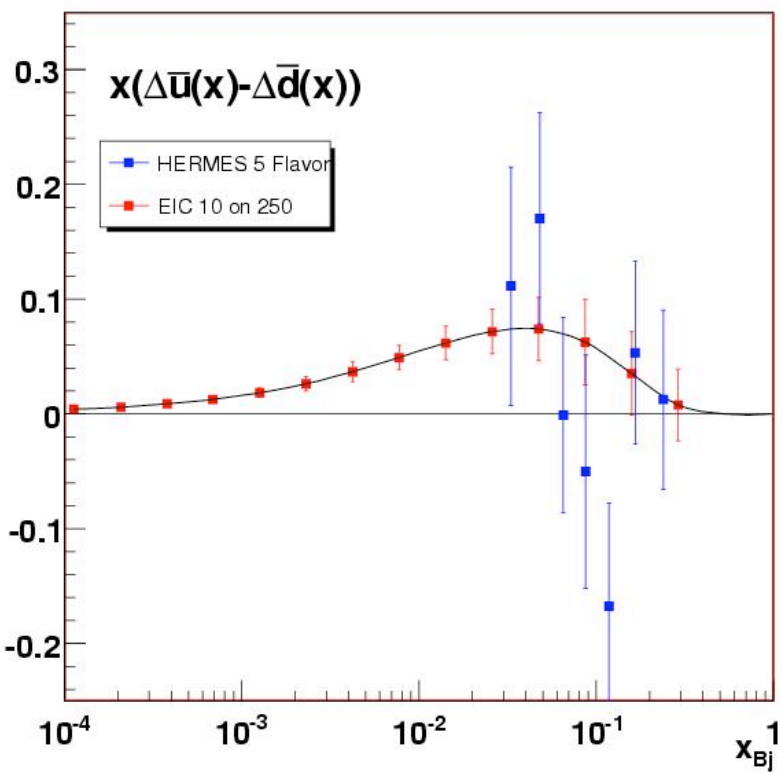
Projections for 9 fb^{-1} for 10 GeV on 250 GeV

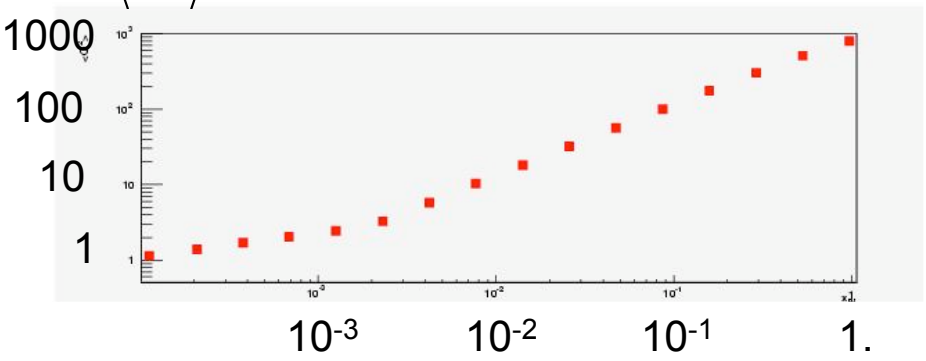


Joe Seele, ERK

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…
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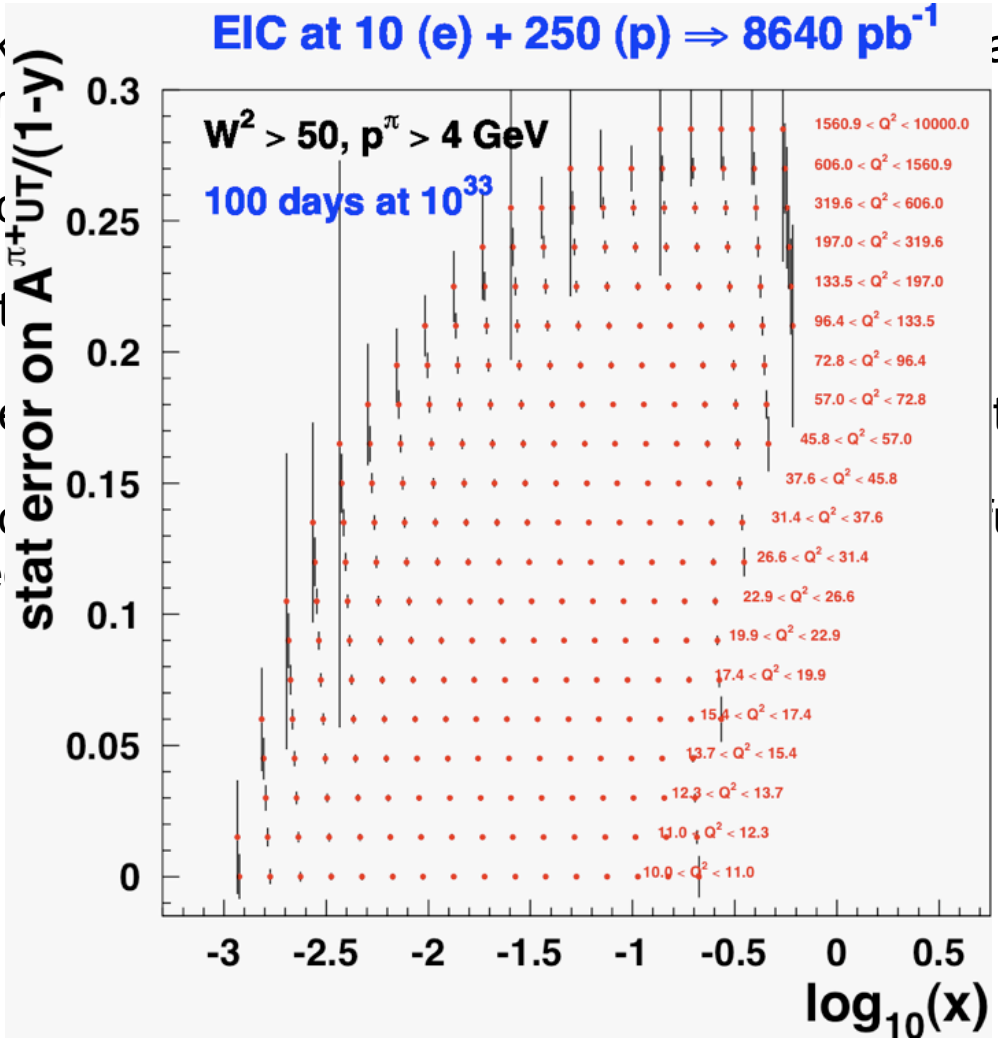
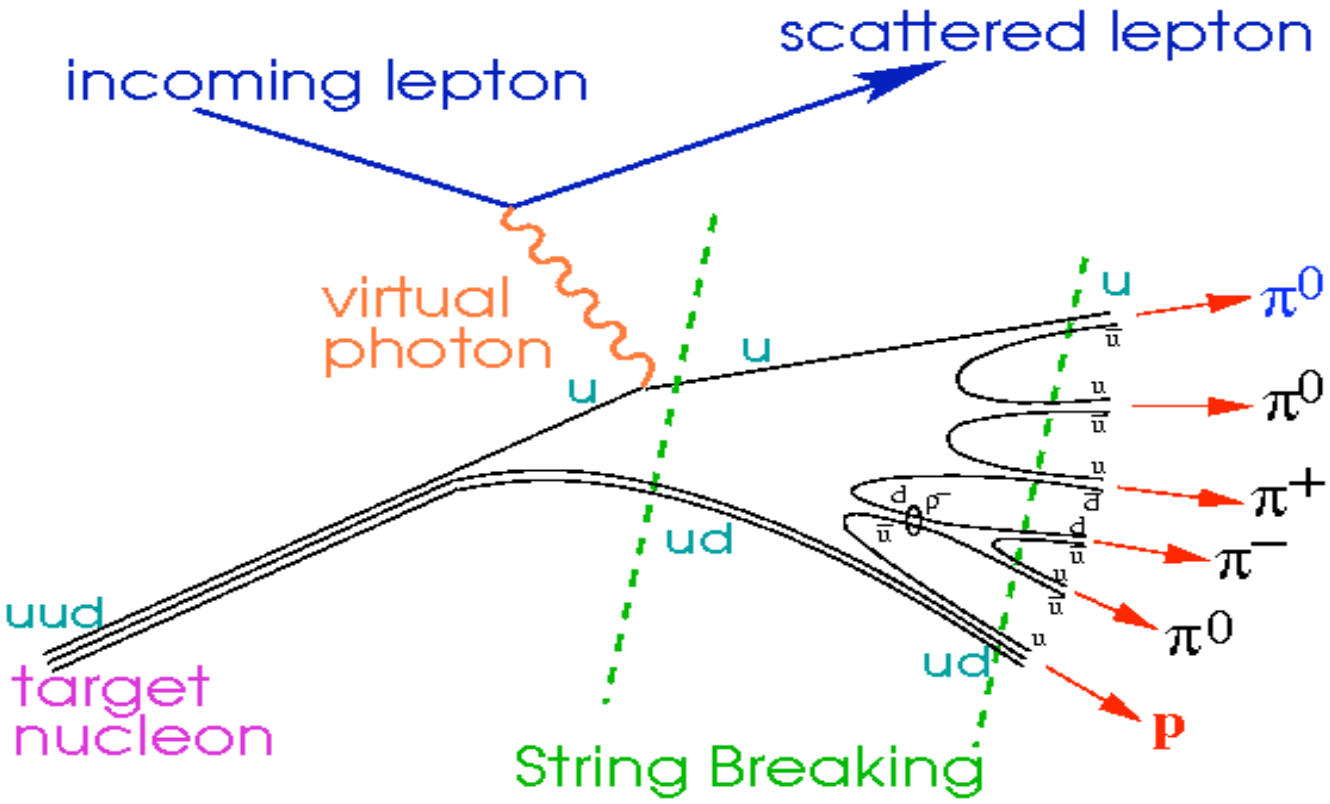


Naomi Makins

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

And much more!

- Measurements I haven't mentioned:
  - ➡ Forward measurements
  - ➡ Exclusive reactions! Deeply virtual compton scattering and meson production
    - ✓ A primary focus of lower energy "staged" scenarios, requires high luminosity
  - ➡ "Tagged" structure function measurements from DIS on n in deuteron
  - ➡ Inclusive measurements of g_5 constrain Δq's
  - ➡ Possible electroweak measurements (e.g. lepton flavor violation)

Outlook

- US Nuclear Science Advisory Committee (NSAC) endorses continued development of case for EIC and funding for R&D in its most recent long range planning exercise
- Strong suite of measurements has been developed to aggressively explore “the fine structure” of the proton
- Nearly ready with, e.g. Lattice QCD, to move beyond phenomenology to physical understanding of the nucleon
- Both BNL(eRHIC) and JLab(ELIC) are pursuing realizations to carry out this physics, both with staged approaches. A major issue will be the inevitable cost vs performance comparison.
- Target date for project “approval” for construction is NSAC Long Range Plan for 2012
  - ➡ Requires a compelling physics case consistent with detector, IR, and machine design, with well articulated cost description
  - ➡ Staging options should be well-developed and the path to the full EIC understood and well defined

Backup Slides

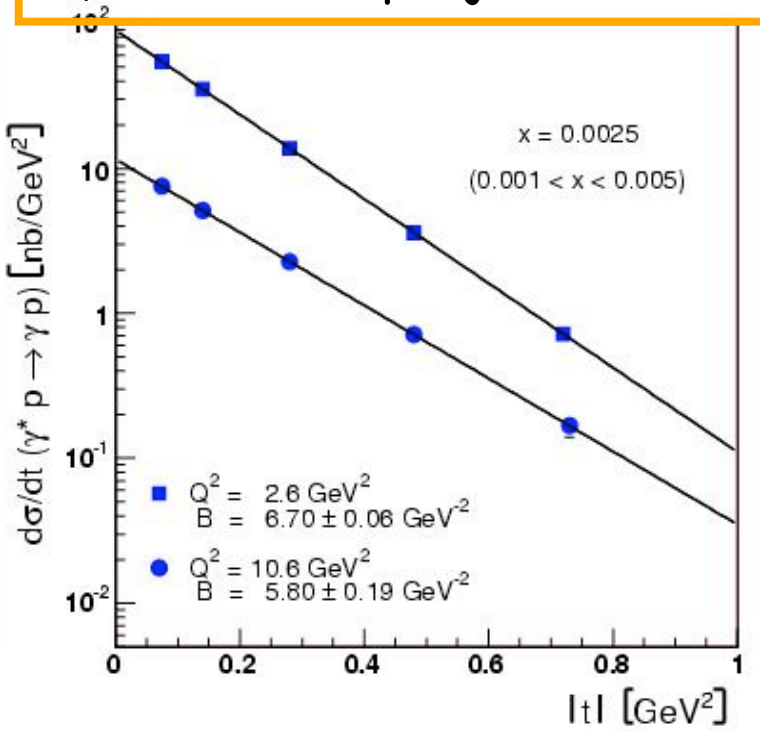
GPDs and Transverse Gluon Imaging

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



(Andrzej Sandacz)

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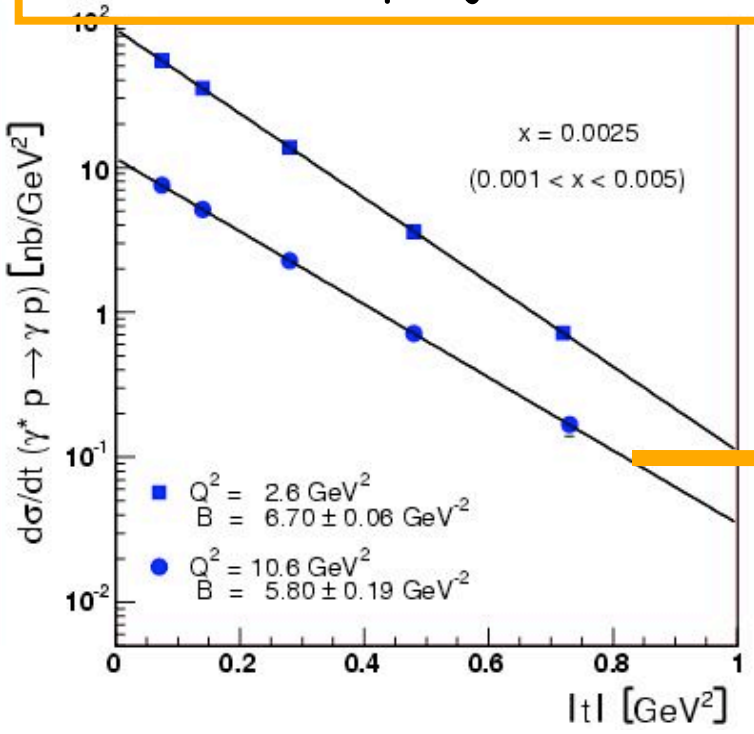

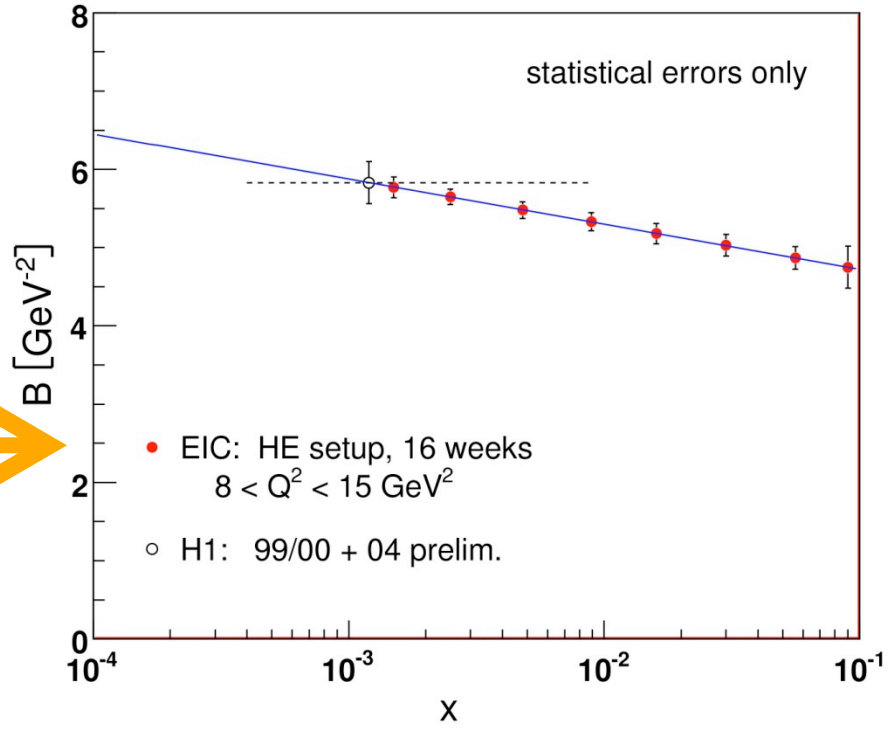

(Andrzej Sandacz)

GPDs and Transverse Gluon Imaging

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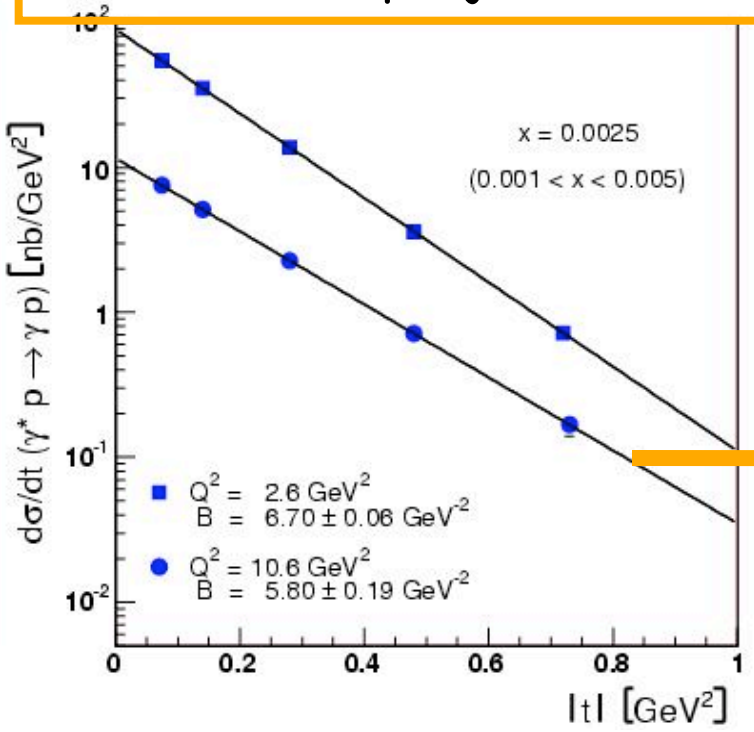
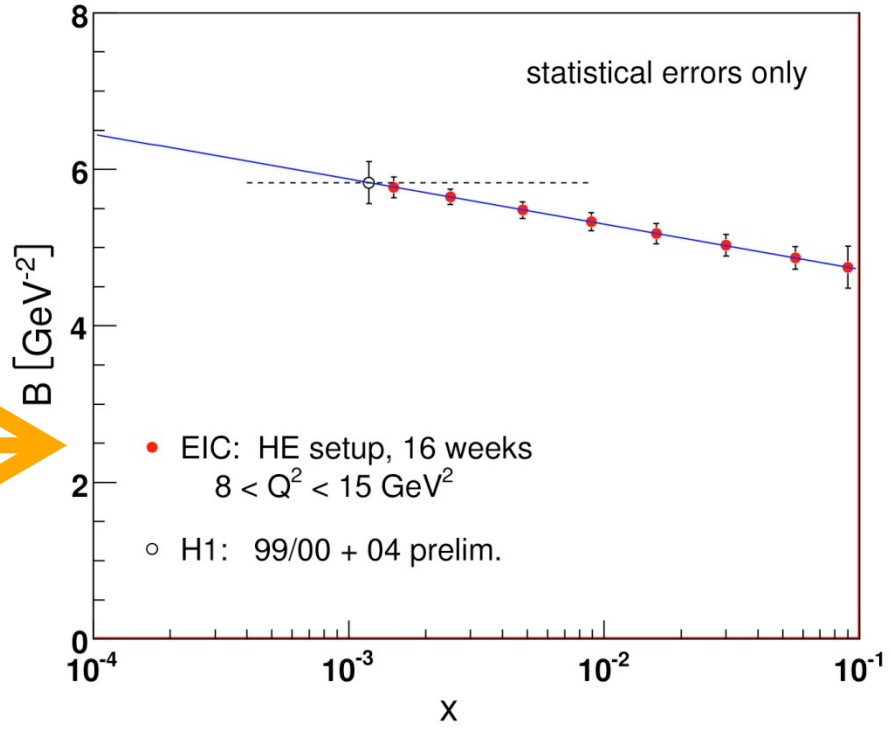
Q^2 = 10 GeV^2 projected data



EIC enables gluon imaging!



(Andrzej Sandacz)

Simultaneous data at other Q^2-values