Central Questions in Nucleon Structure

Werner Vogelsang

BNL Nuclear Theory

Presented

by

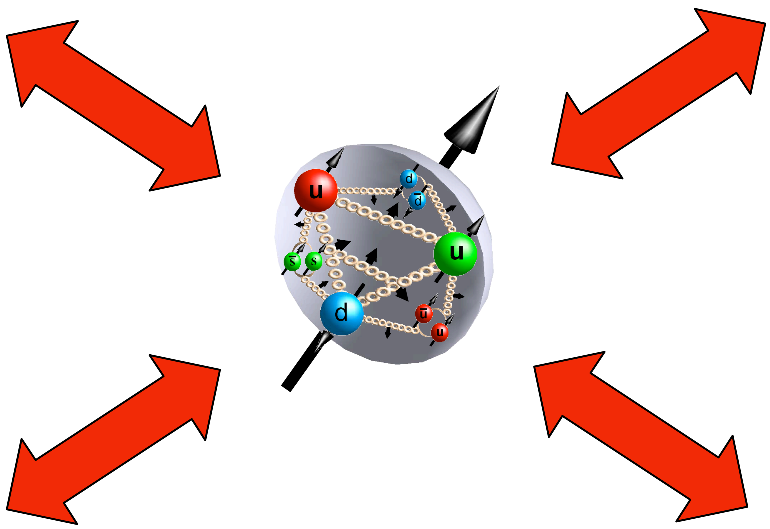
Abhay Deshpande

at the EIC meeting (MIT), April 6, 2007

Exploring the nucleon:
Of fundamental importance in science

Know what we are made of !

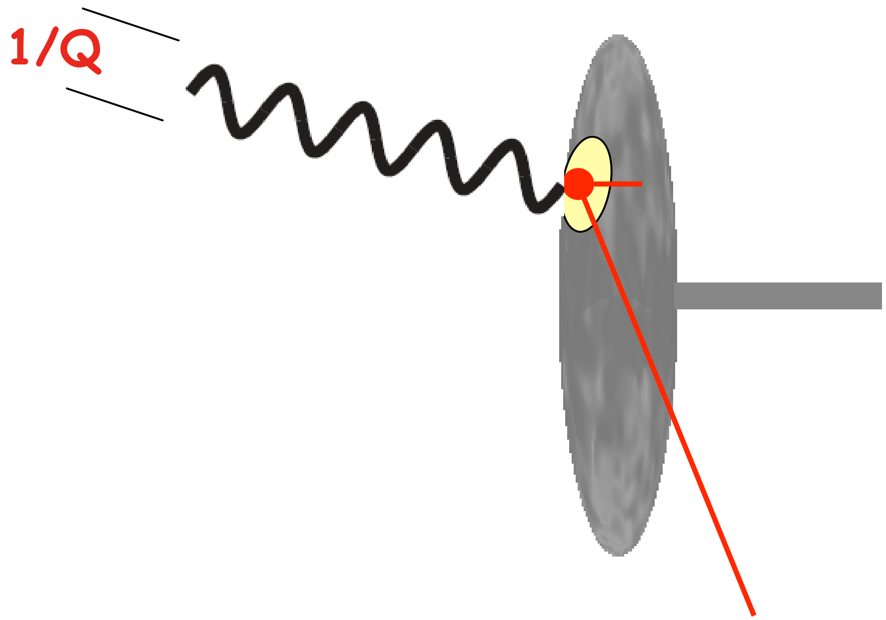
Test our ability to *use* QCD:
Asymptotic Freedom, Factorization



Explore and Understand QCD:
Lattice, Models

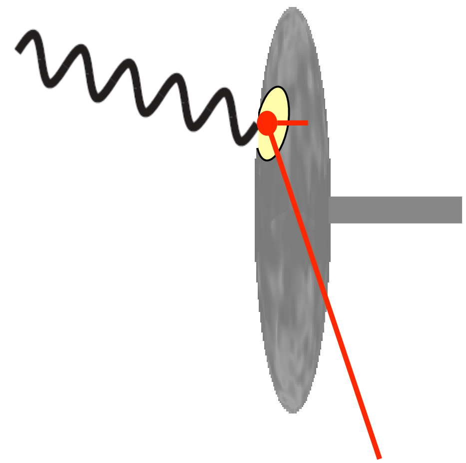
Nucleon as tool for discovery:
RHIC Heavy Ions, LHC
Tevatron High-E_T jets
NuTeV anomaly, …

- We can probe the quark-gluon structure of the Nucleon in short-distance processes:

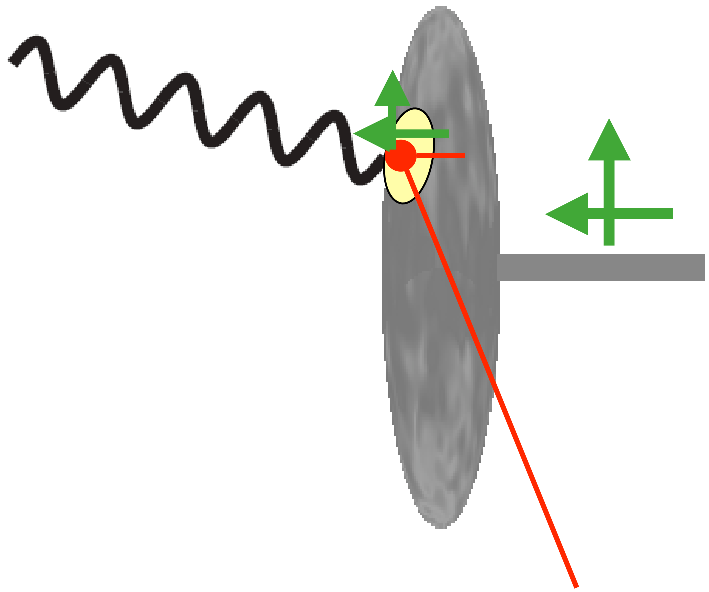


- Diverse probes: DIS, DVCS, Drell-Yan, pp→jetX, …

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 ← vs. ↑ make ?
  What novel features arise ?
- How are quarks and gluons correlated ?

These are central questions of the field.

The challenge is: Map out the Nucleon

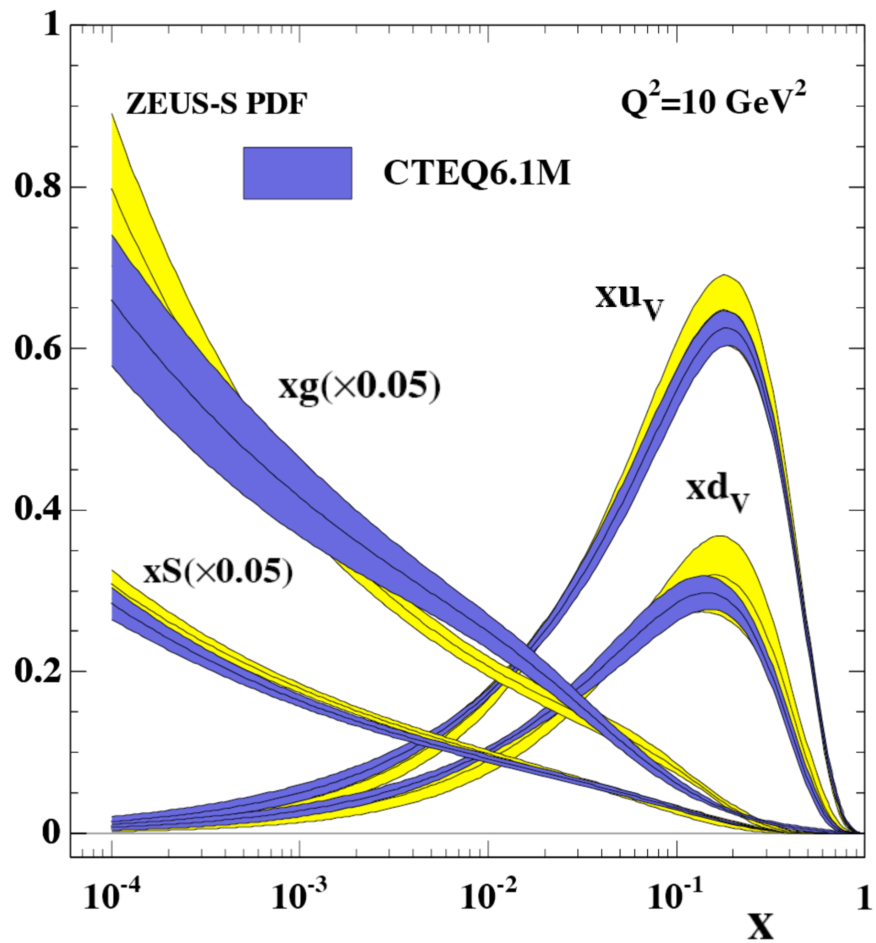
Its complete spin, flavor, gluon landscape

- We have a pretty good picture of some aspects
- We are learning about others
- We are still in the dark in many cases

We'll have a good chance to get all the answers with present and next-generation facilities !

Momentum distributions of quarks and gluons

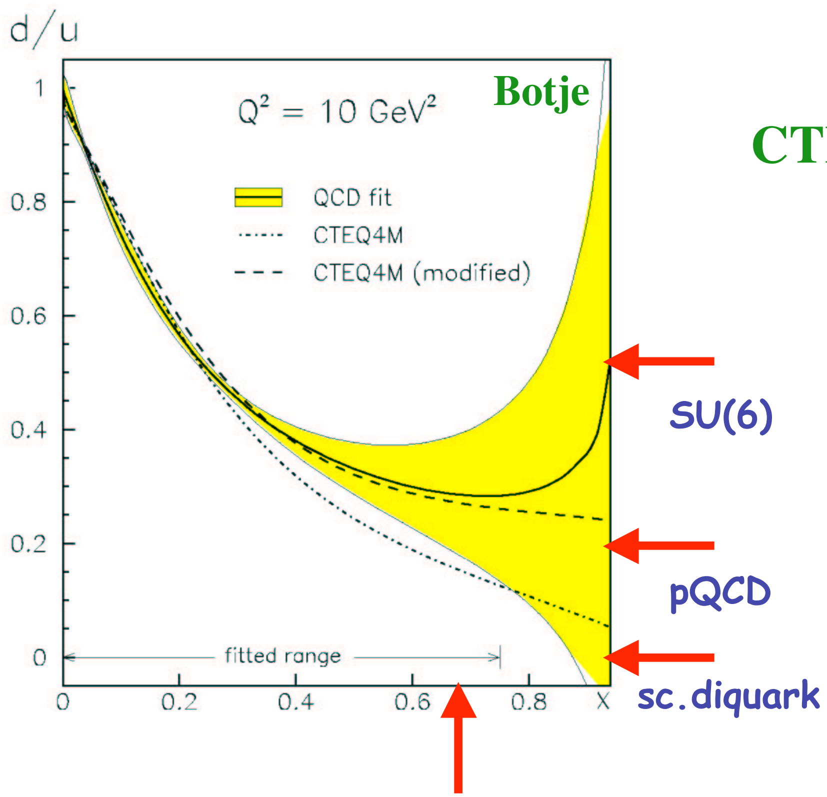
- An important part of our picture of the nucleon:
  Gluons rule at small-x !

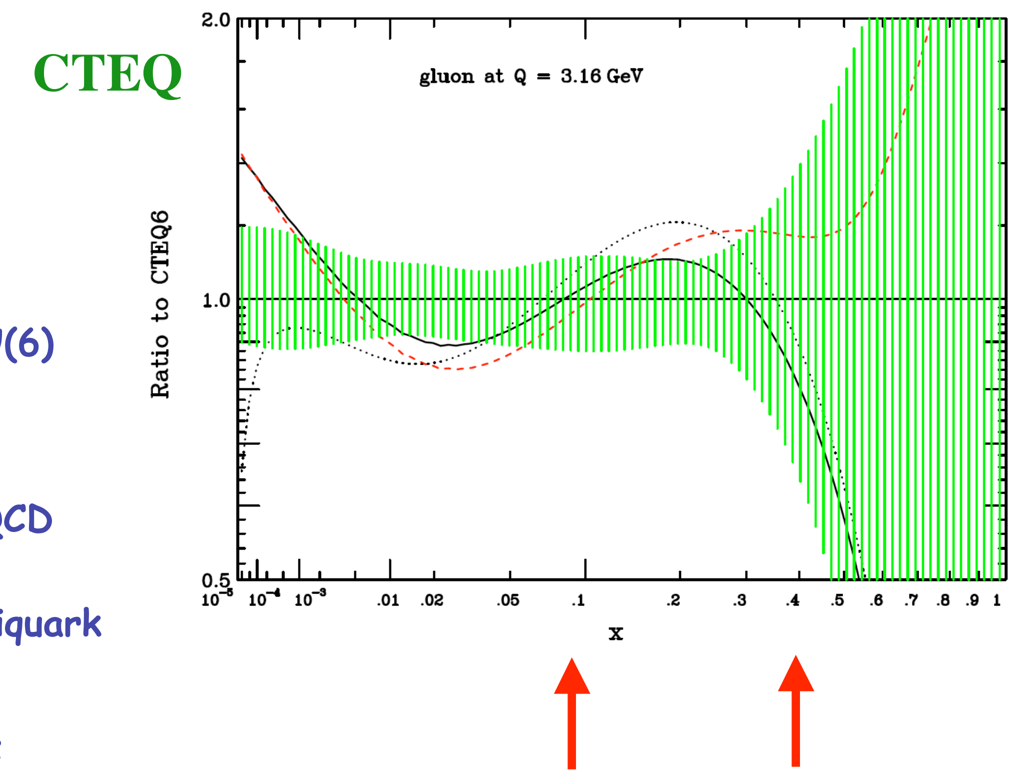


- We know a lot, but …

- **but … some aspects little understood, for example:**

sea quarks and gluon at high-x, valence at very-high-x

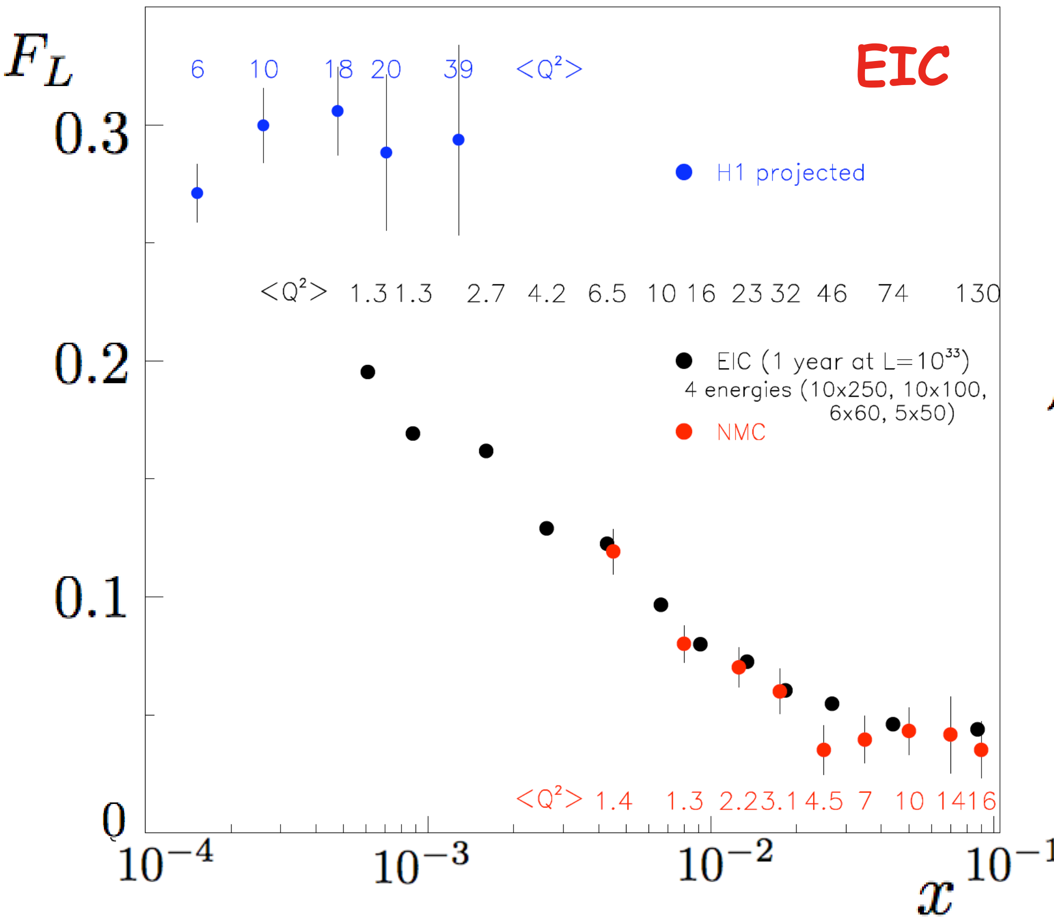




Testing ground for models of
Proton wave function
Measure at Jlab-12 GeV
sea: DY

Not an academic problem: LHC
Measure at HERA, EIC

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

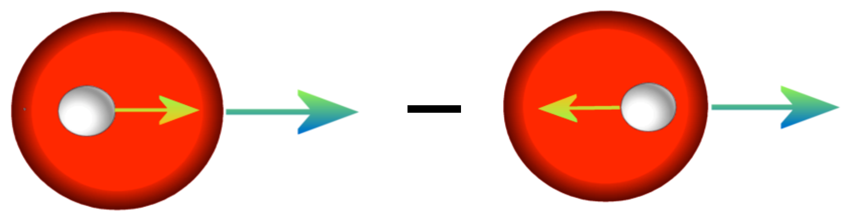


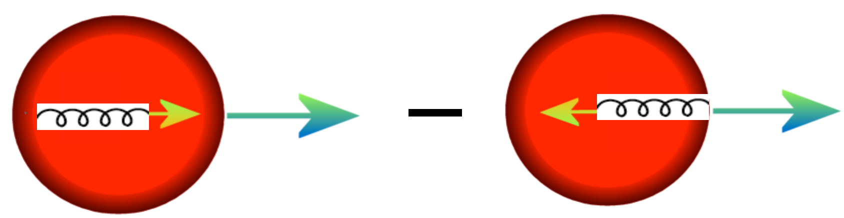
A. Bruell, R. Ent

$$\mathcal{L} = 5\,\mathrm{fb}^{-1}$$

One observable among many: $dF_2/d\mathrm{Log}(Q^2)$, $ep \rightarrow$ jet+jet+X, charm, …

Helicity structure of the Nucleon

$\Delta q(x) =$ 

$\Delta g(x) =$ 

A major motivation : Explore the proton spin !

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

q+$\bar{q}$ spin contribution

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

Gluon spin contribution

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

Orbital ang. momenta

"Quotable" properties of the proton

- Rests on a number of things:
  - small-x extrapolation of structure function
  - at small-x, typically Q^2 small as well. Higher twists?

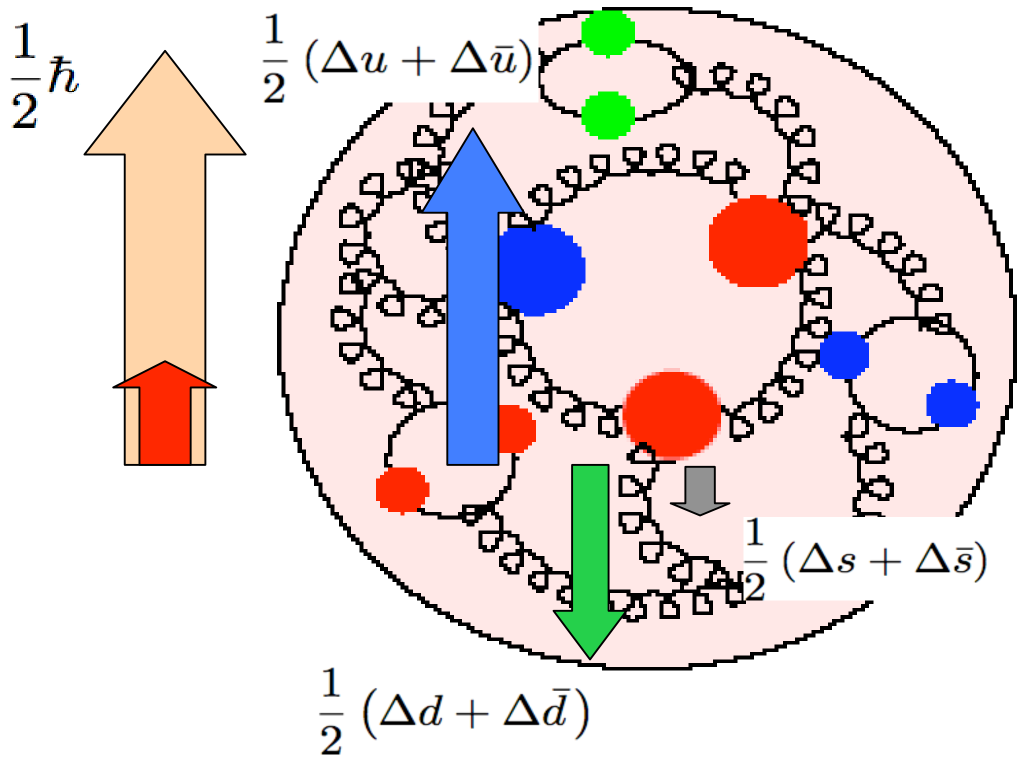
To really nail it down, need measurements at lower x.
And: at current x, but higher Q^2 → EIC

  - use of SU(3) symmetry:

$$\int_0^1 dx\, g_1 = \frac{1}{9}\Delta\Sigma + \frac{1}{12}\underbrace{\left[\Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d}\right]}_{g_A \,=\, 1.257 \pm \ldots} + \frac{1}{36}\underbrace{\left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2(\Delta s + \Delta\bar{s})\right]}_{3F - D \,=\, 0.575 \pm 0.05}$$

Bjorken

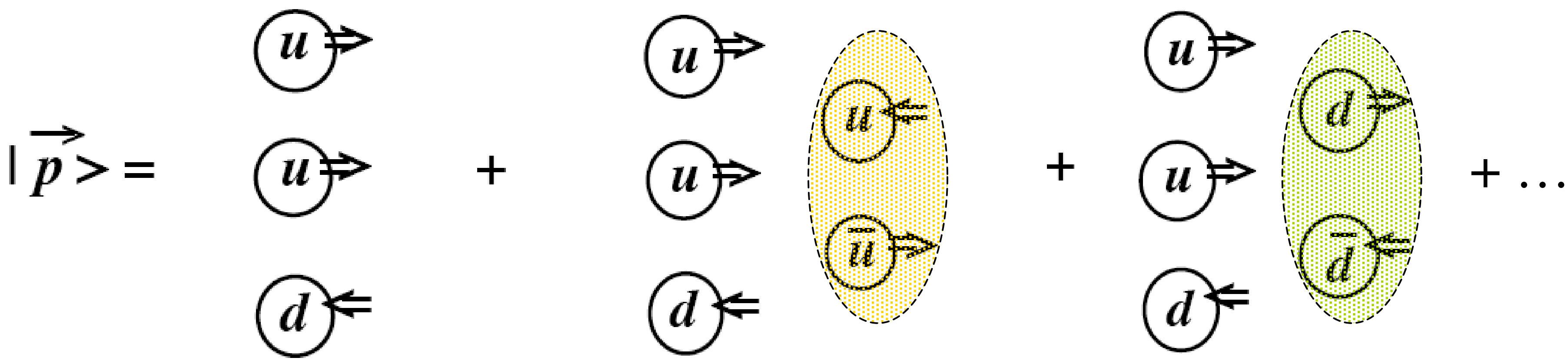
- if all true, current picture is:



- is it correct ?

- would like to know more: $\Delta \bar{u}$ vs. $\Delta \bar{d}$ vs. $\Delta \bar{s}$ etc.

- **Important applications for models :**



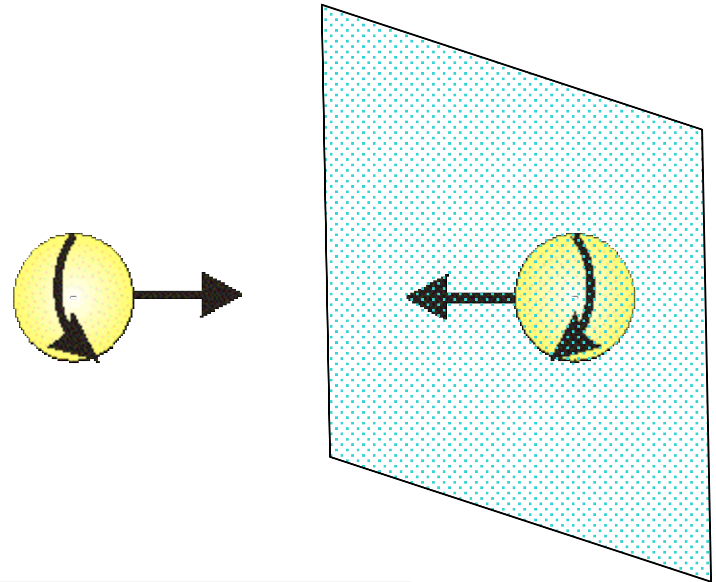
Many models predict $\Delta\bar{u} > 0 \quad \Delta\bar{d} < 0$

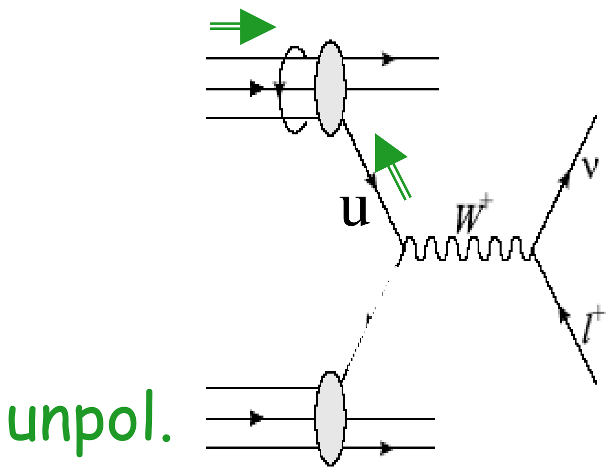
Thomas,Signal,Cao; Holtmann,Speth,Fässler; Diakonov,Polyakov,Weiss;
Glück,Reya; Schäfer,Fries; Kumano; Wakamatsu; ...

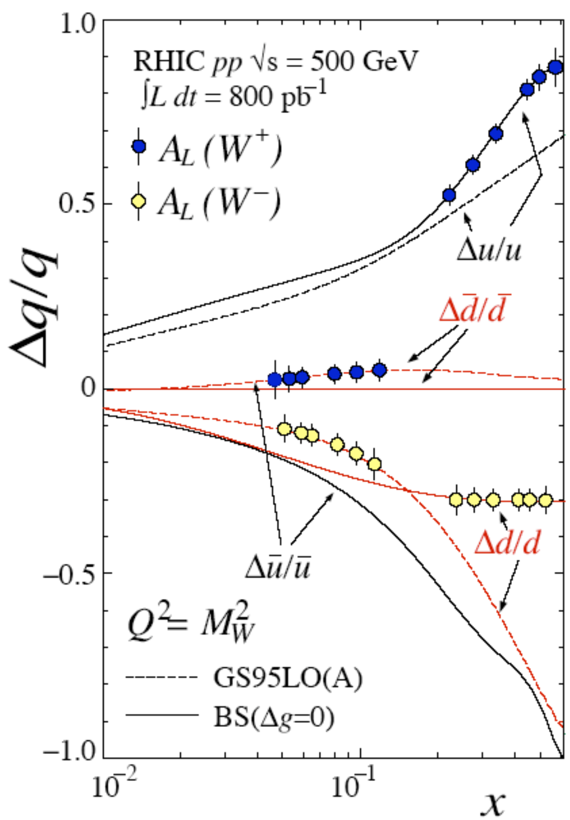
Various avenues for addressing these questions

At RHIC:

$$A_L^{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

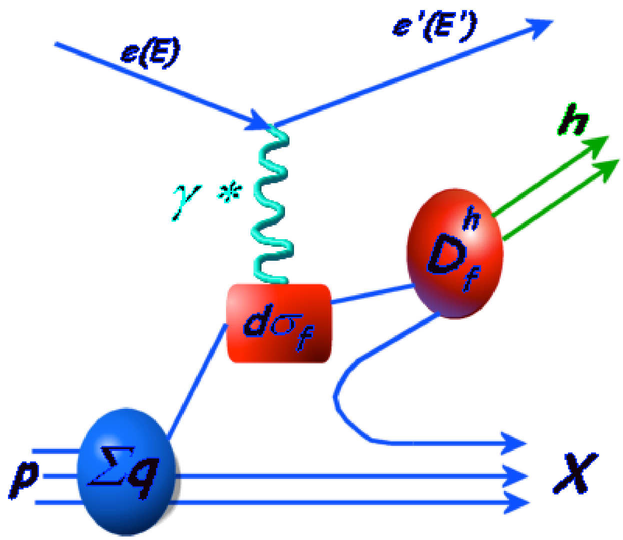




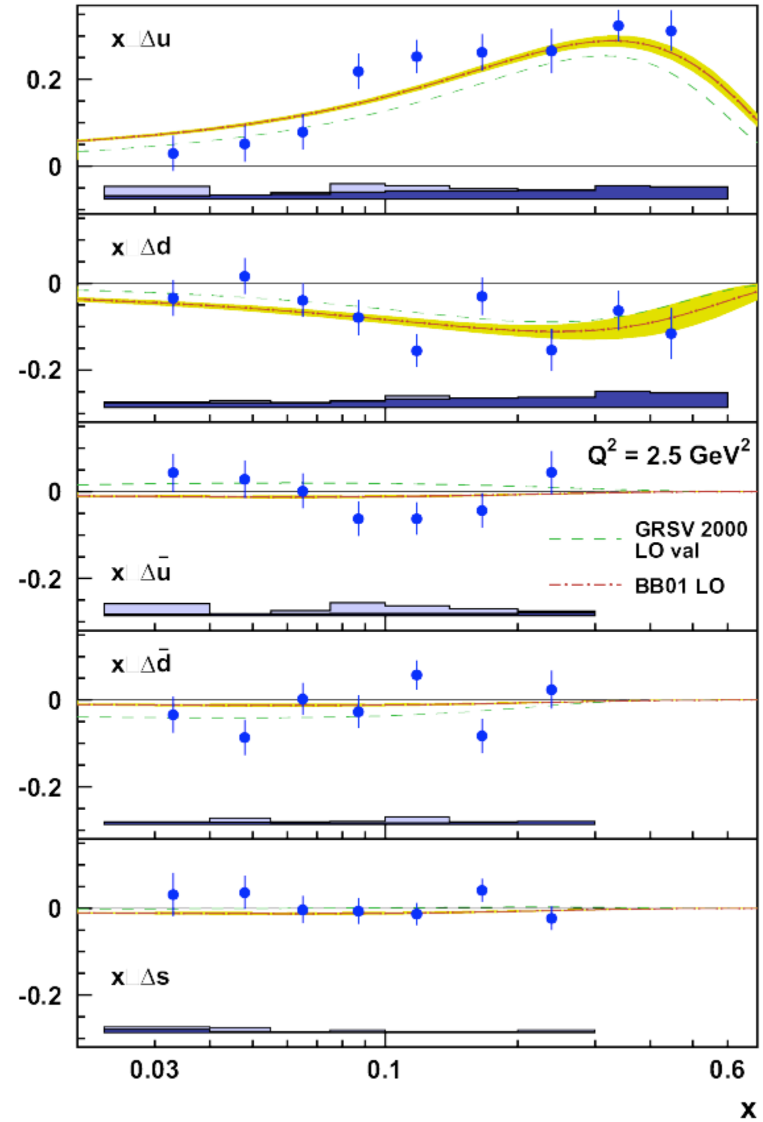


- W+charm at RHIC-II

In lepton scattering : "SIDIS"

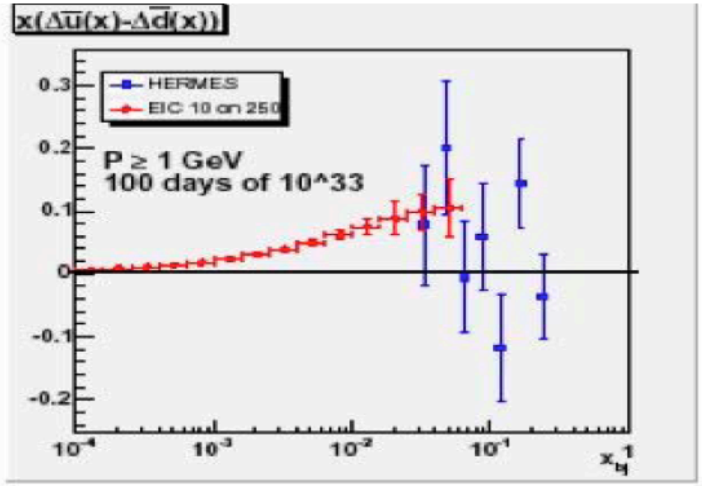


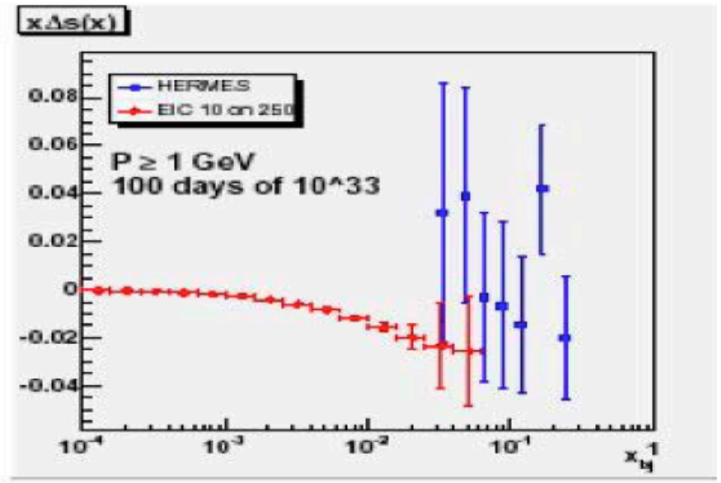
HERMES



- Major topic at Jlab-12 GeV

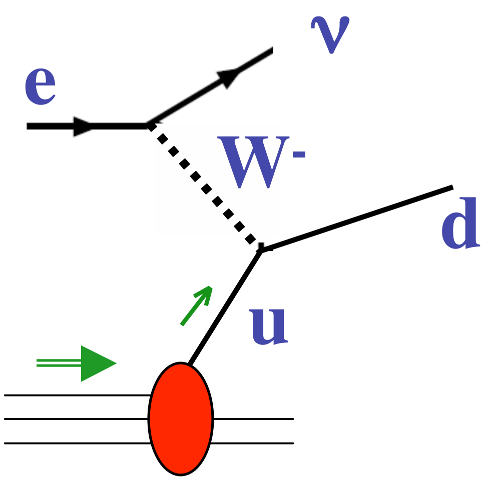
EIC:

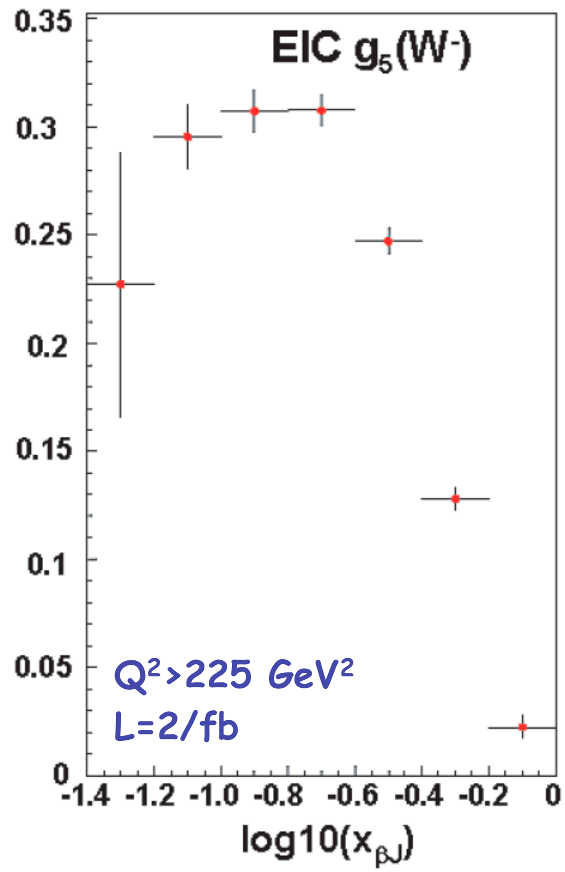




J. Seele

- also, at EIC:





$$g_5 \propto \Delta u - \Delta\bar{d} - \Delta\bar{s}$$

- get $\sin^2(\Theta_W)$?

- **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 $\sim \langle \bar{q}\tilde{F}q \rangle$

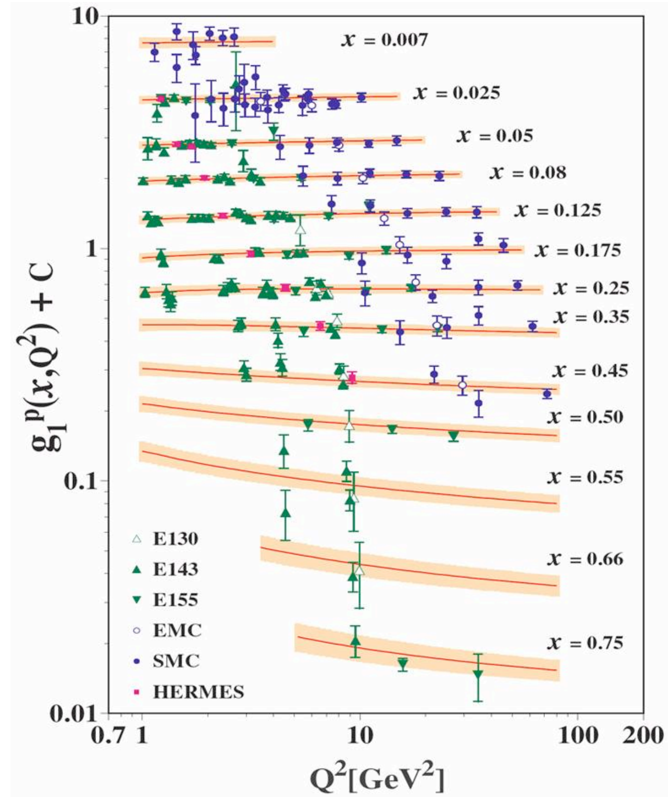
- **Precision QCD. Currently tested at ~10%.**
  Can it be tested at ~1 or 2% ?

See Antje Bruell's talk next

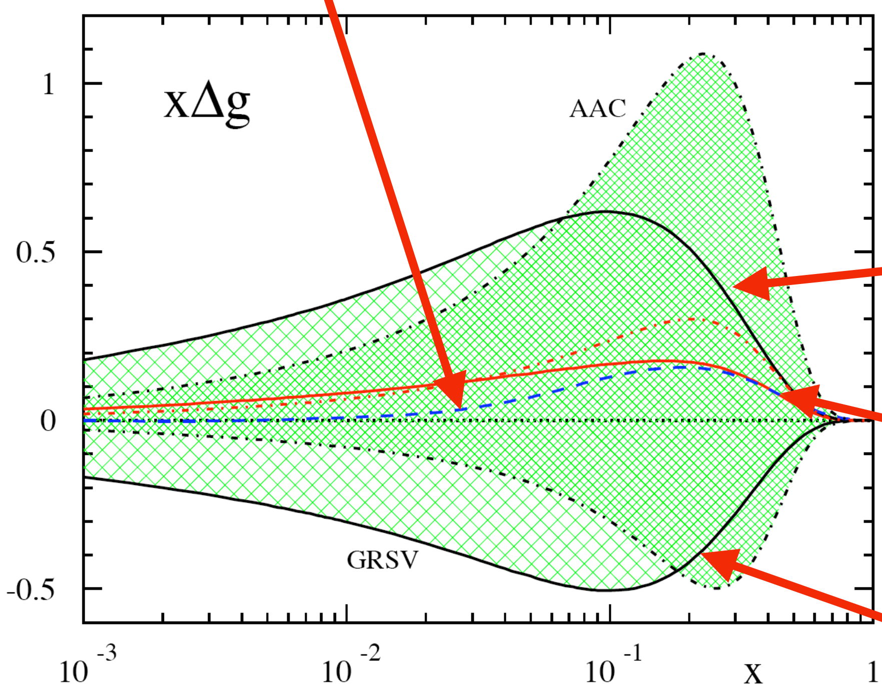
The gluon spin distribution Δg

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 $\Delta G \approx 0.3$



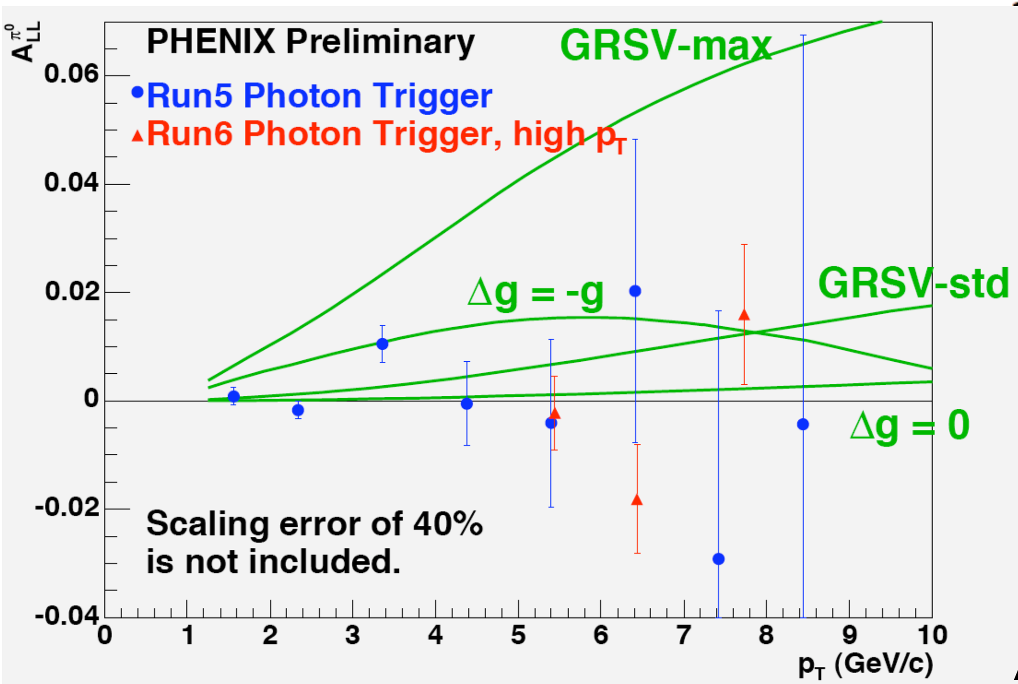
$\Delta G \approx 1.8 \; (@\,1\mathrm{GeV}^2)$

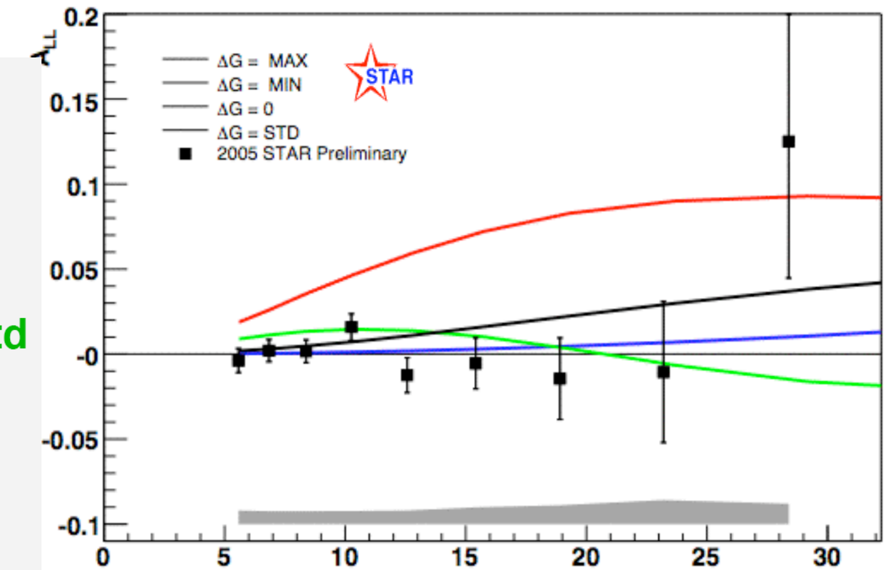
"axial anomaly" Altarelli et al.

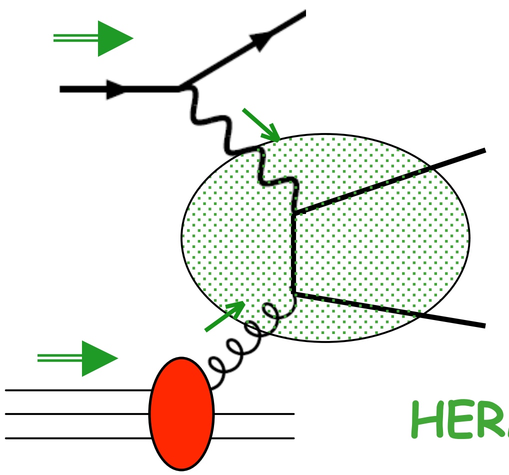
$\Delta G \approx 0.4$

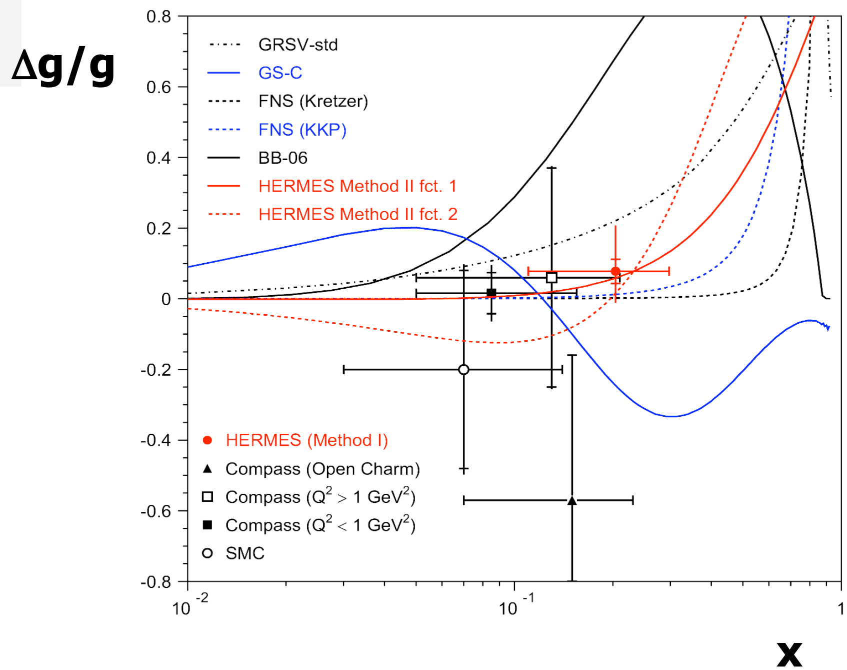
$\Delta G \approx -1.7$

- **NOW:**

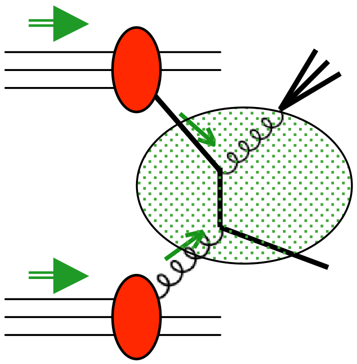

PHENIX Preliminary
•Run5 Photon Trigger
▴Run6 Photon Trigger, high p_T
GRSV-max
$\Delta g = -g$
GRSV-std
$\Delta g = 0$
Scaling error of 40%
is not included.
$A_{LL}^{\pi^0}$
p_T (GeV/c)


ΔG = MAX
ΔG = MIN
ΔG = 0
ΔG = STD
2005 STAR Preliminary
STAR
A_{LL}


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

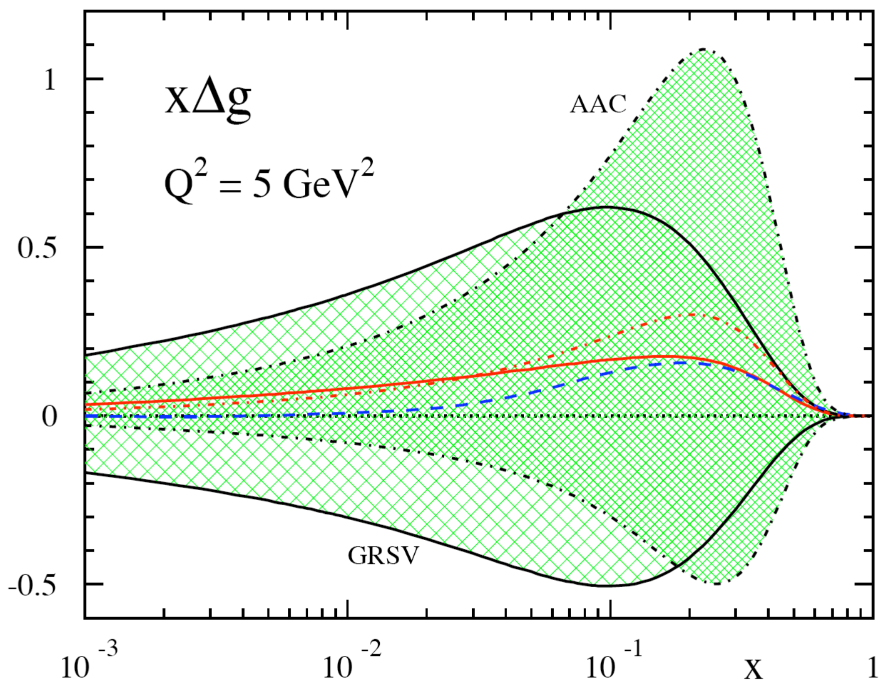

Δg/g
GRSV-std
GS-C
FNS (Kretzer)
FNS (KKP)
BB-06
HERMES Method II fct. 1
HERMES Method II fct. 2
HERMES (Method I)
Compass (Open Charm)
Compass ($Q^2 > 1$ GeV^2)
Compass ($Q^2 < 1$ GeV^2)
SMC
x

Challenge will be to really *extract* Δg and its integral:



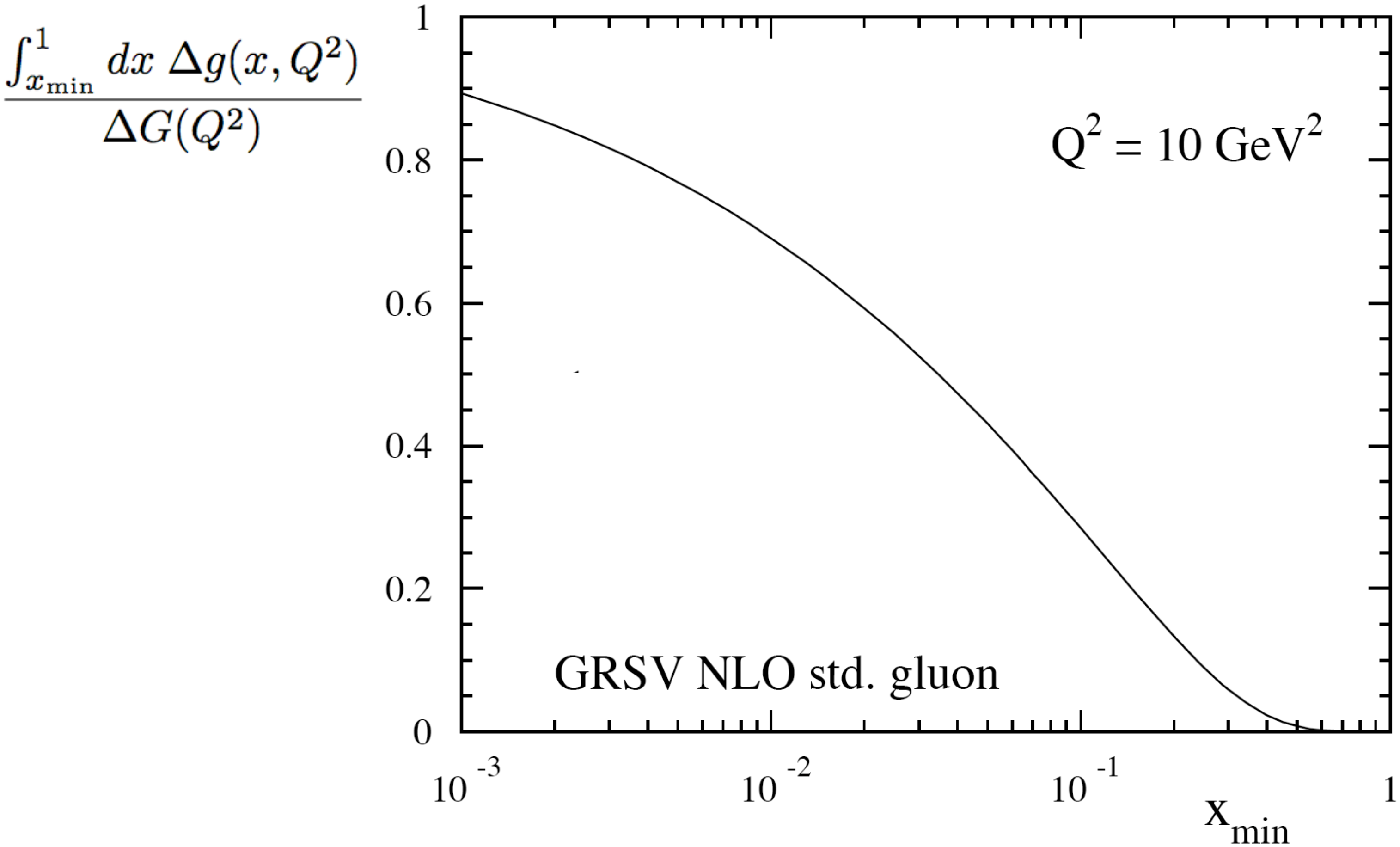
$$\Delta\sigma = \sum_q \int dx_g \int dx_q \, \Delta g(x_g, p_T) \, \Delta q(x_q, p_T) \, \Delta\hat{\sigma}^{qg}(x_g, x_q, p_T, \alpha_s(p_T)) + \ldots$$

→ Need "Global analysis"

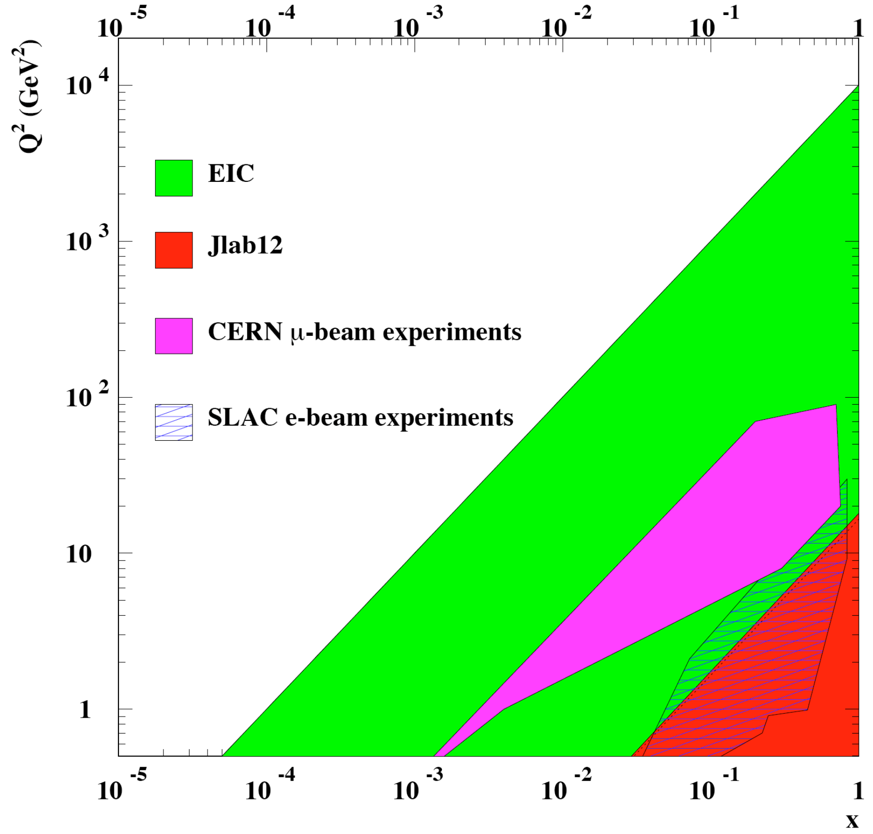


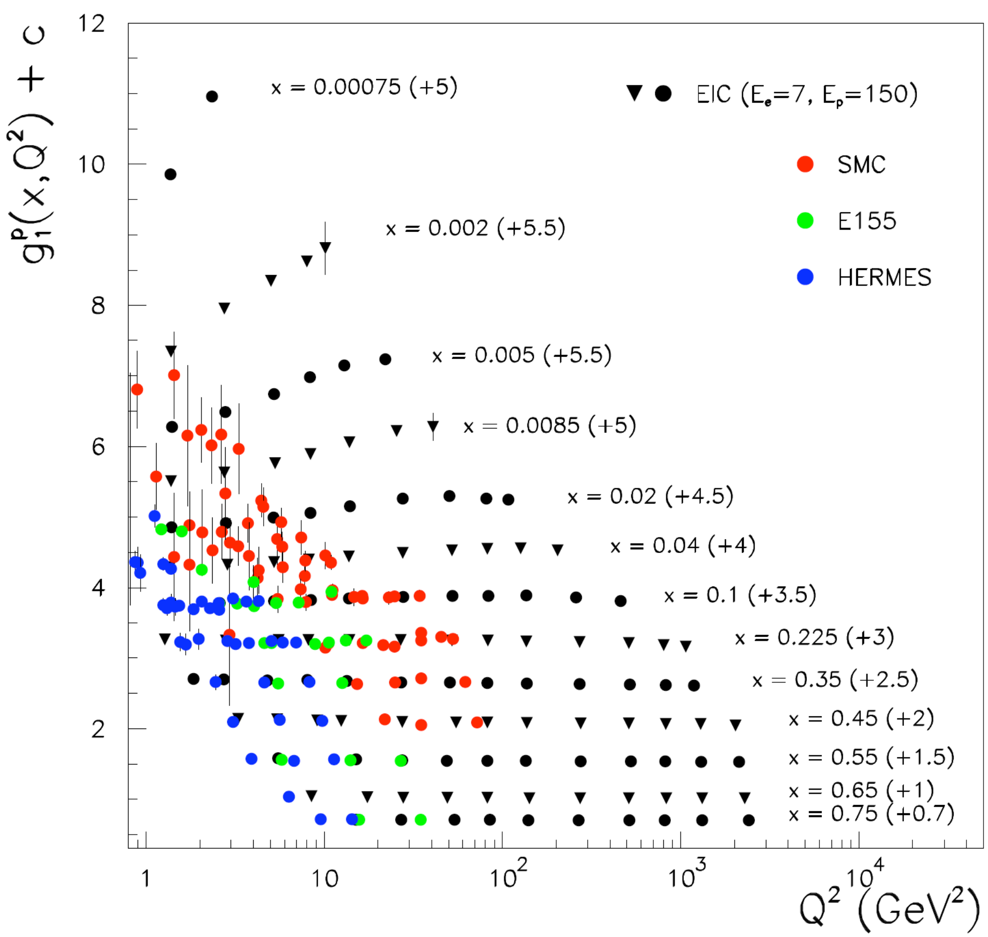
~ RHIC 200 GeV midrap. data

Eventually, for integral will likely need additional information, in particular from smaller x



- RHIC at 500 GeV, and with jet+jet, gamma+jet at forward kinematics
- An Electron-Ion Collider !

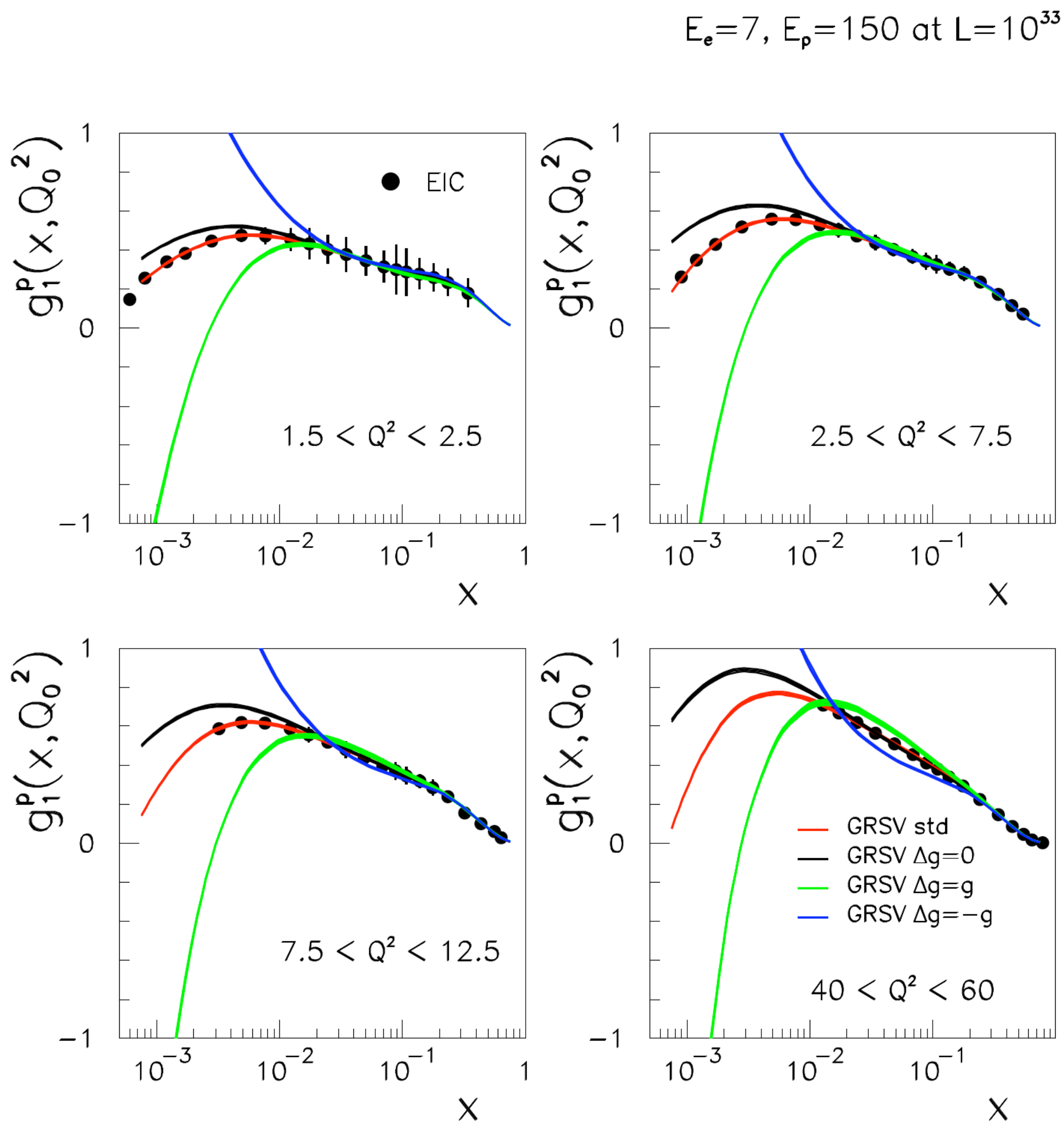




A. Bruell, R. Ent

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

at small x

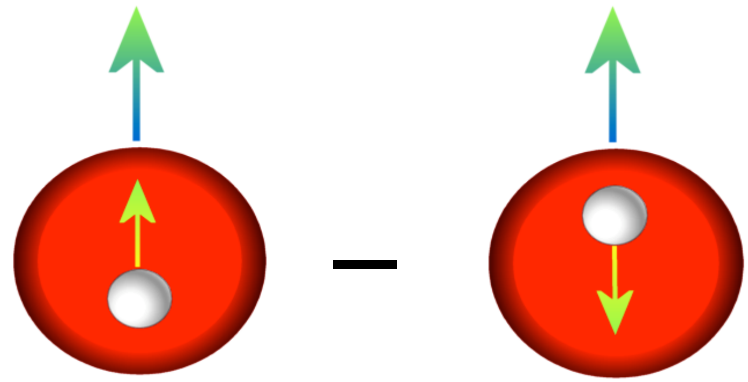


A. Bruell, R. Ent

What's the structure of a
Transversely polarized Nucleon ?

Transversity:

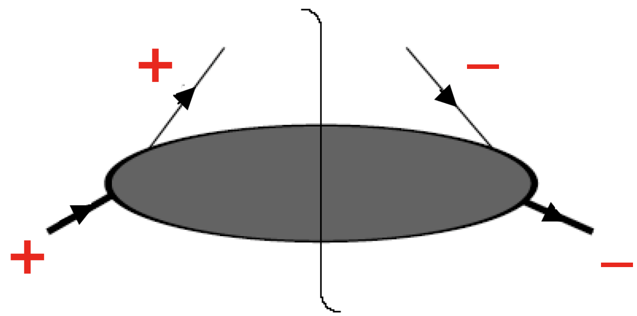
$$\delta q(x) =$$



Ralston, Soper; Jaffe, Ji; ...

- in helicity basis:

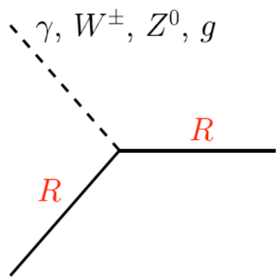
$$\delta q(x) \sim$$

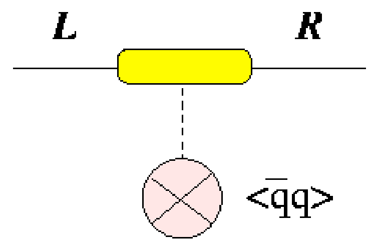


Helicity-flip !

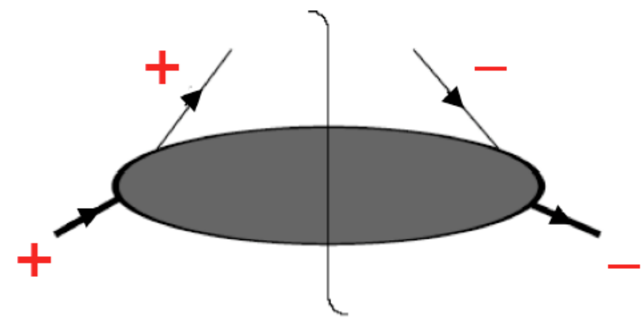
- **the physics involved:**

  - ∗ “odd chirality” → helicity-flip, χSB





  - ∗ no mixing with gluons



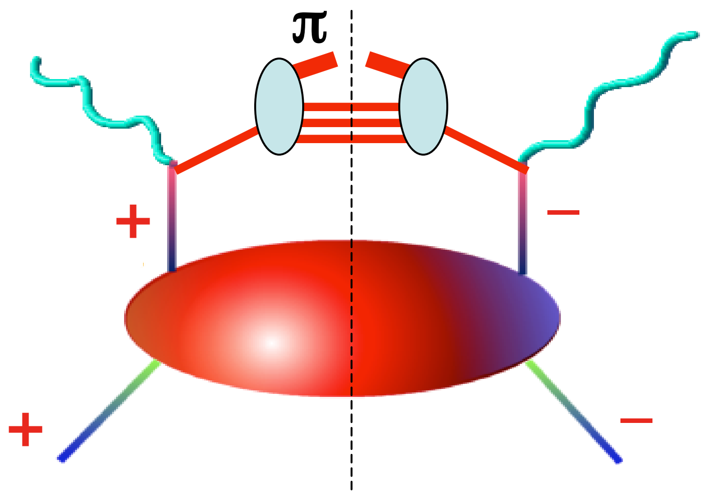
  - ∗ tensor charge

$$\langle \mathbf{P} \,|\, \bar{\mathbf{q}}\, \mathbf{i}\, \sigma^{\mu\nu}\, \gamma^{\mathbf{5}}\, \mathbf{q} \,|\, \mathbf{P} \rangle = \int_{\mathbf{0}}^{\mathbf{1}} \mathbf{dx}\, [\, \delta\mathbf{q}(\mathbf{x}) - \delta\bar{\mathbf{q}}(\mathbf{x})\,]$$

  - ∗ difference to helicity probes relativistic / dynamical effects

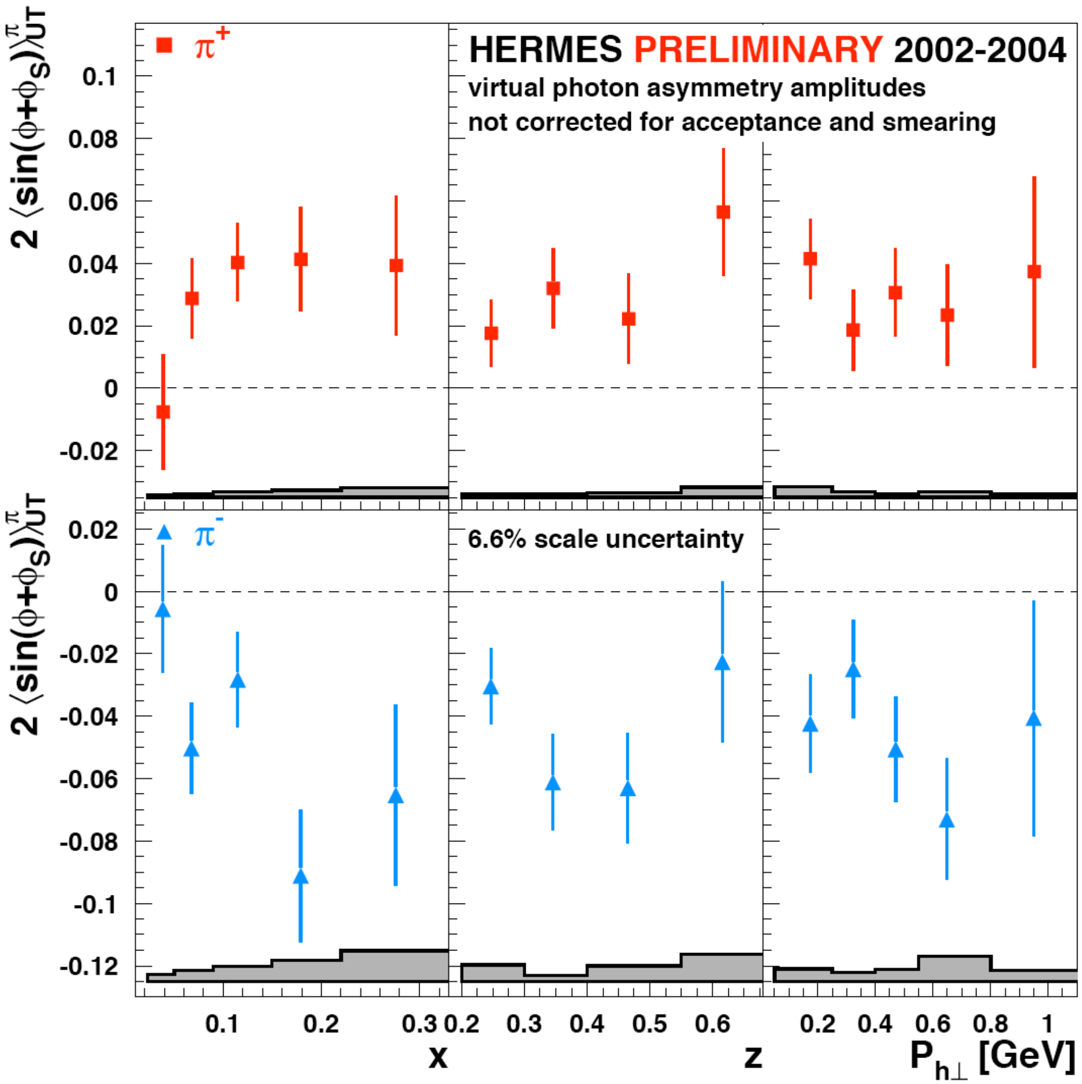
• **Opportunities for measurement ?**

∗ not in inclusive DIS, but:



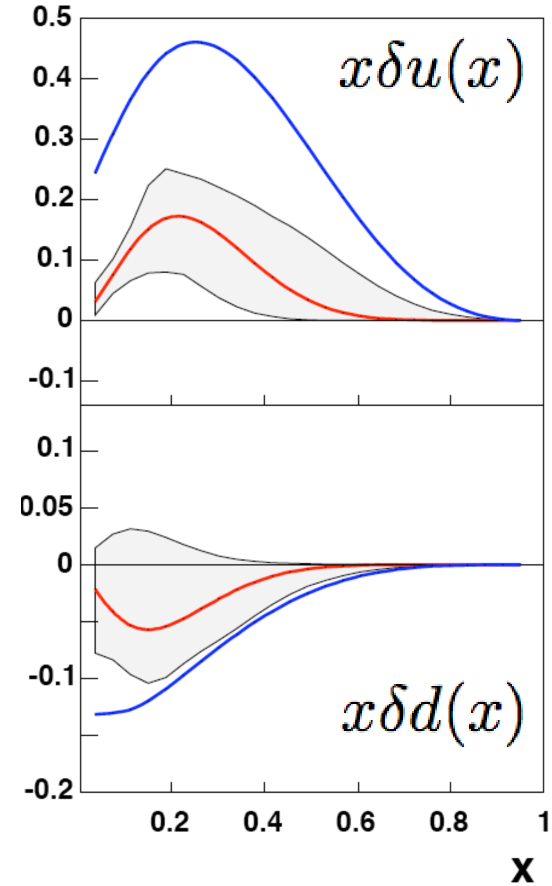
"**Collins** effect"
→ **azimuthal asym.**

∗ this effect actually appears to be there : HERMES



→ First glimpse of Transversity !

(Anselmino et al.)

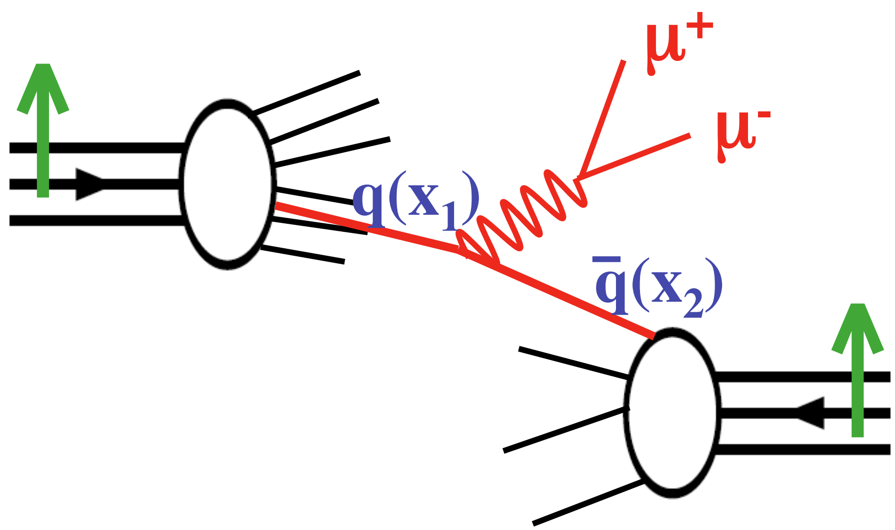


(up to sign)

- information on Collins fragm. fct. has become available from **BELLE** in $e^+e^- \rightarrow \pi\pi X$

The future of transversity:

- SIDIS at COMPASS, Jlab-12 GeV
- Collins-type asymmetries at RHIC
- Drell-Yan:

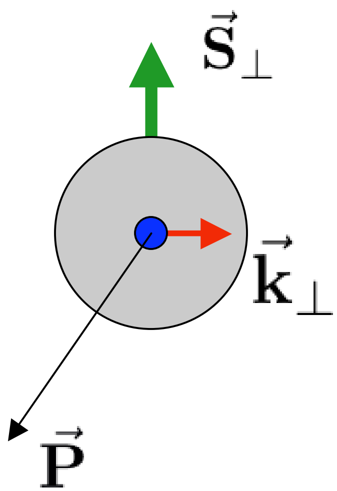


RHIC / RHIC-II

GSI, J-PARC

- azimuthal asymmetries in SIDIS at EIC

Transverse spin offers further new insights into Nucleon structure.



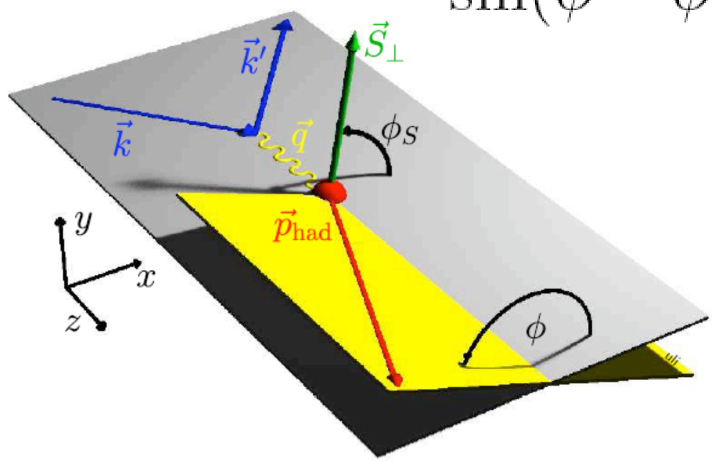
correlation $\sim \vec{S}_T \cdot \left(\vec{P} \times \vec{k}_T\right)$

Sivers

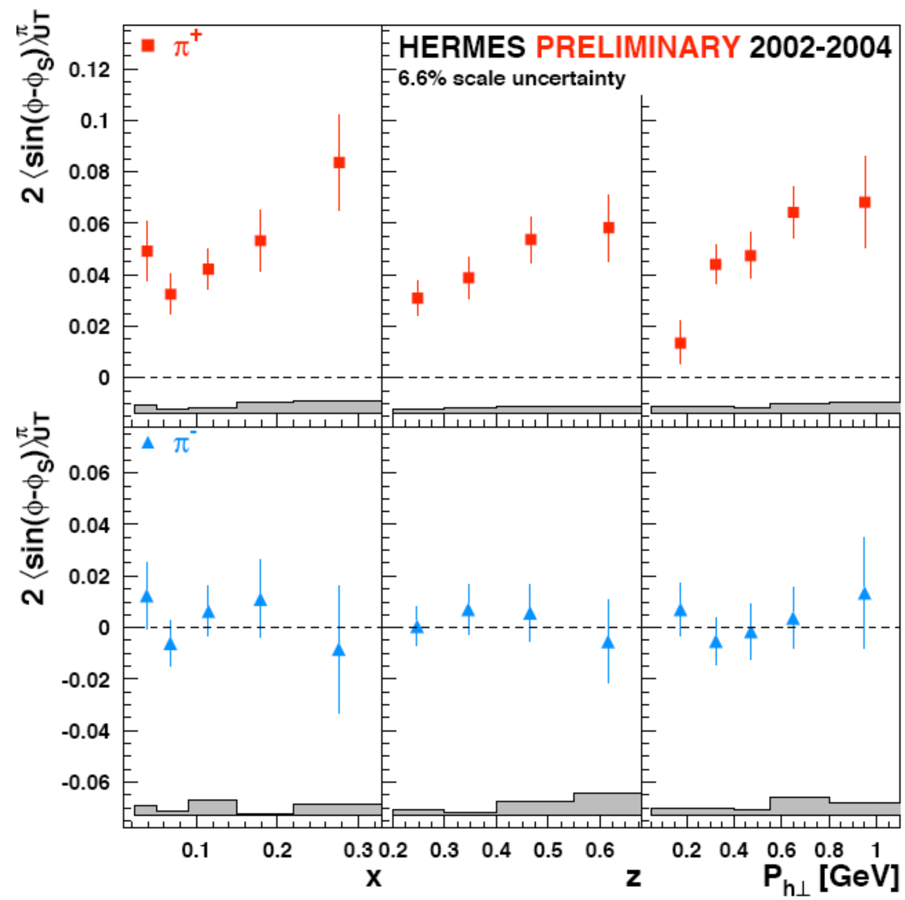
Where would this show up ?

$\mathbf{e\,p^{\uparrow} \rightarrow e\,\pi\,X}$

$$\sin(\phi - \phi_S)\ \sum_q e_q^2\ f_{1T}^{\perp,q}(x)\ D_q(z)$$

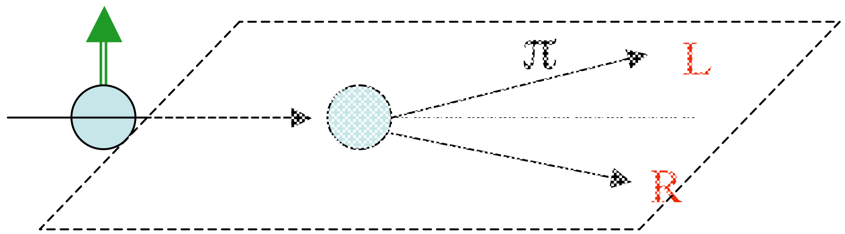


SMC, HERMES,
COMPASS, CLAS

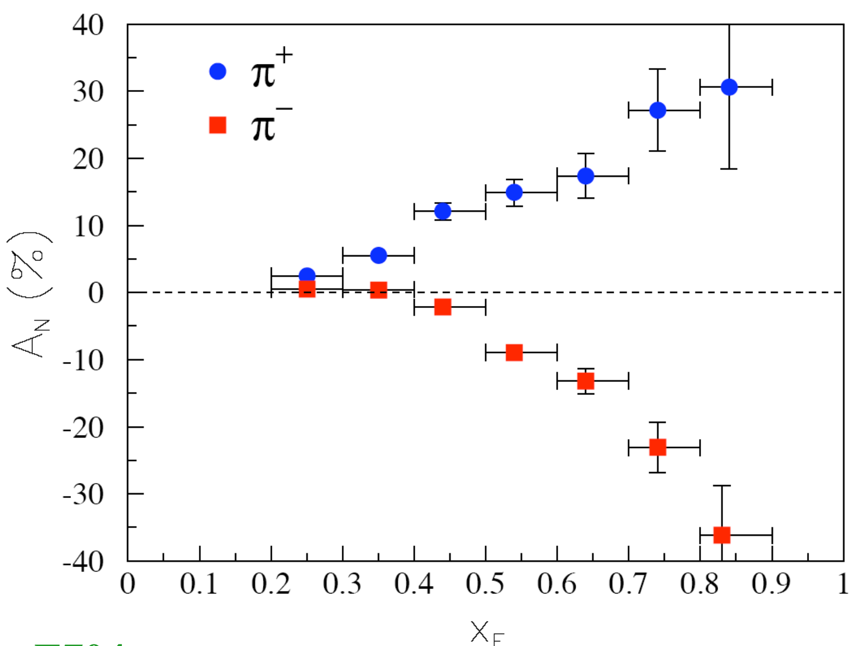


Seen !

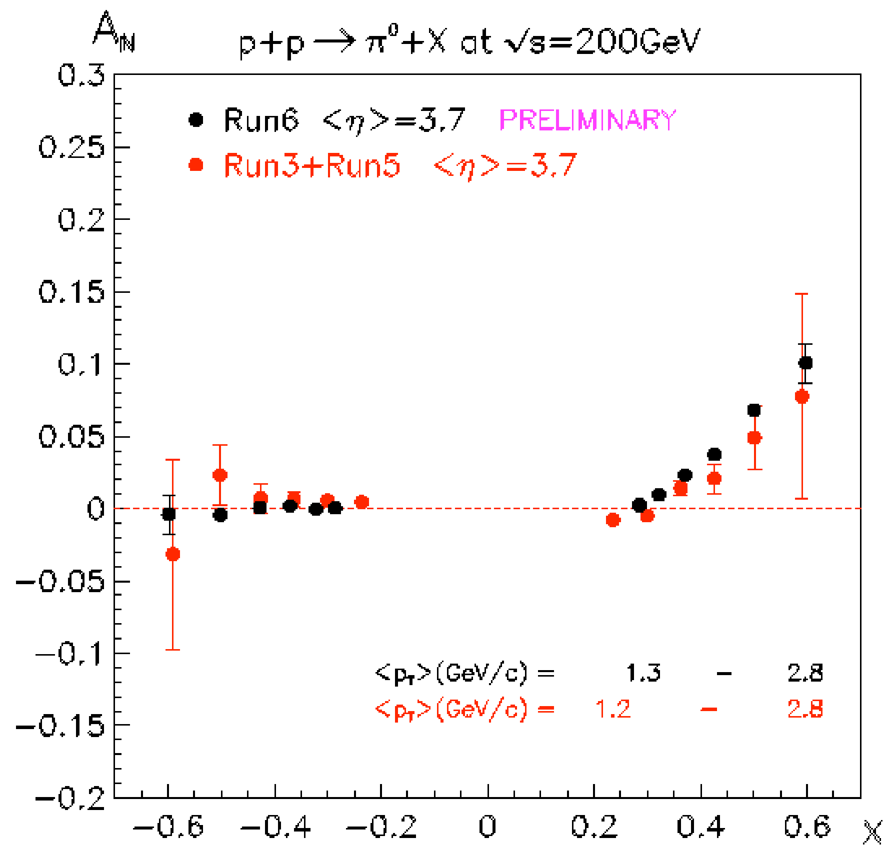
In pp scattering: involved (in disguised form) in large “left-right” asymmetries



$$A_N = \frac{L - R}{L + R}$$

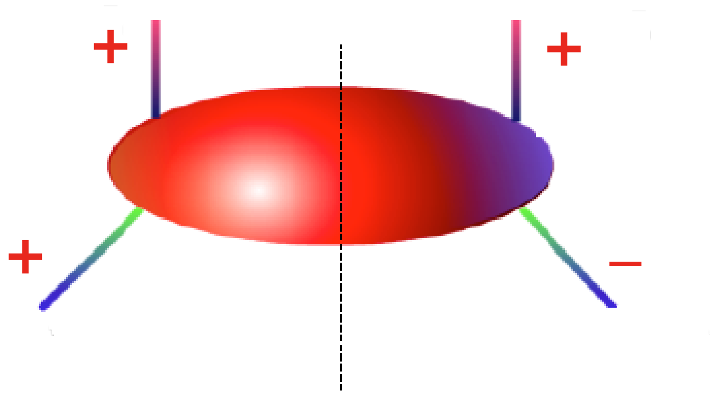


E704



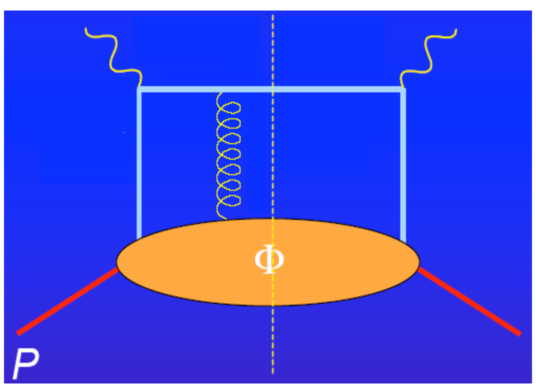
STAR (BRAHMS, too)

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



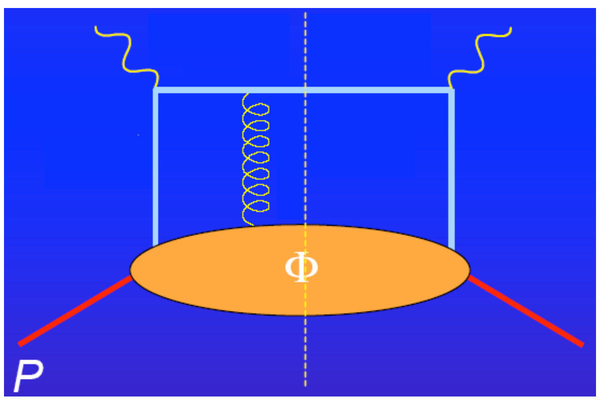
Brodsky, Hwang, Schmidt; Collins;
Belitsky, Ji, Yuan;
Boer, Mulders, Pijlman

Attractive !

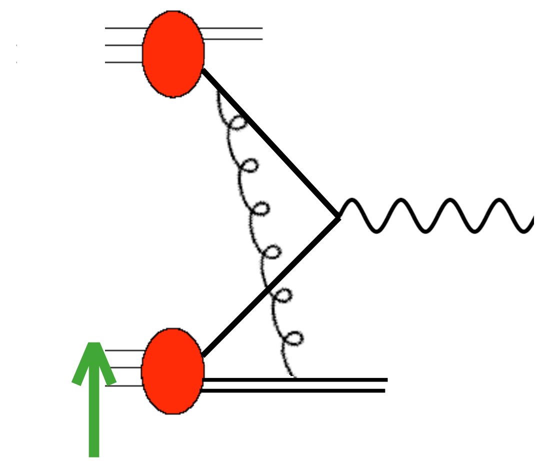
- profound physics implication:

  → 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

Many avenues for important measurements:

- Drell-Yan — RHIC / RHIC-II; GSI, J-PARC

- correlations in $pp \rightarrow jet + jet\ X$ at RHIC (now data!)

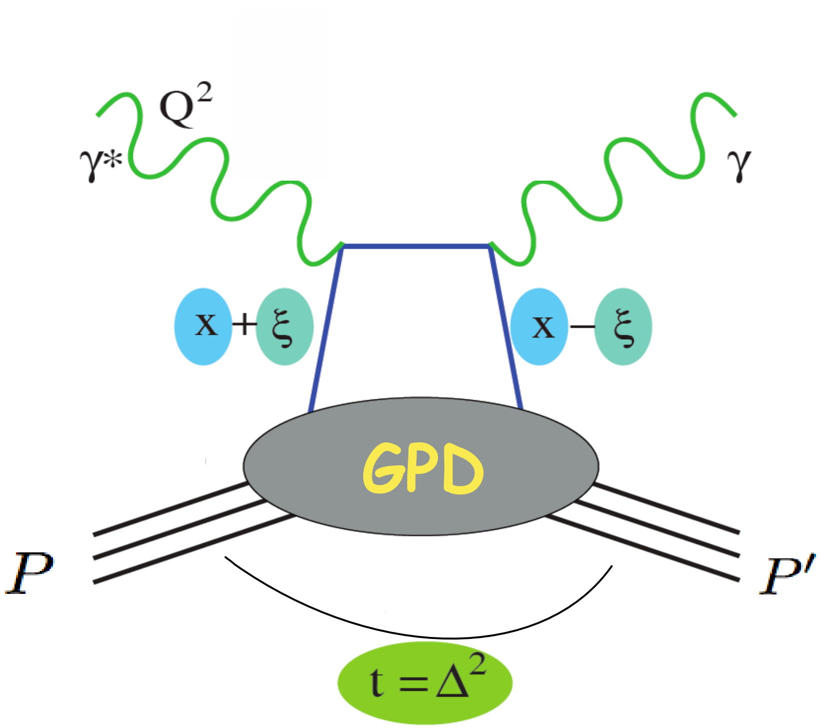
- detailed studies of azimuthal asymmetries in SIDIS at EIC at high Q^2

What's the spatial structure of the Nucleon ?

Over the last decade, theory has understood that parton distributions and form factors are special cases of a much more powerful representation of nucleon structure:

"Generalized Parton Distributions"

Müller, Robaschik; Ji; Radyushkin



- x: average quark momentum fracⁿ
- ξ: "skewing parameter" = $x_1 - x_2$
- t: 4-momentum transfer²

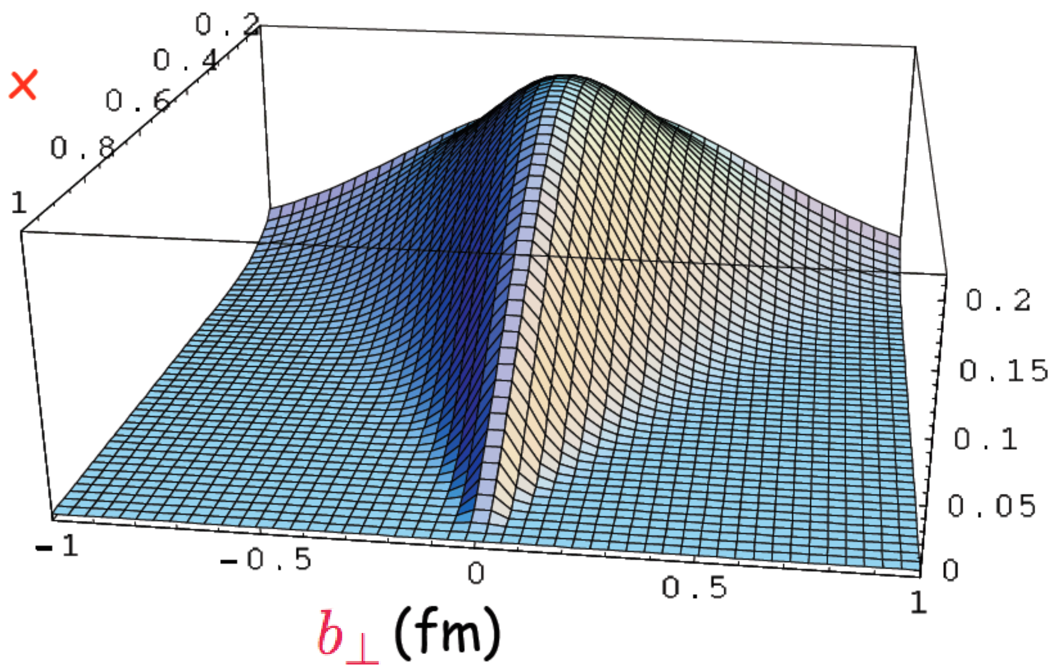
What we dream of:

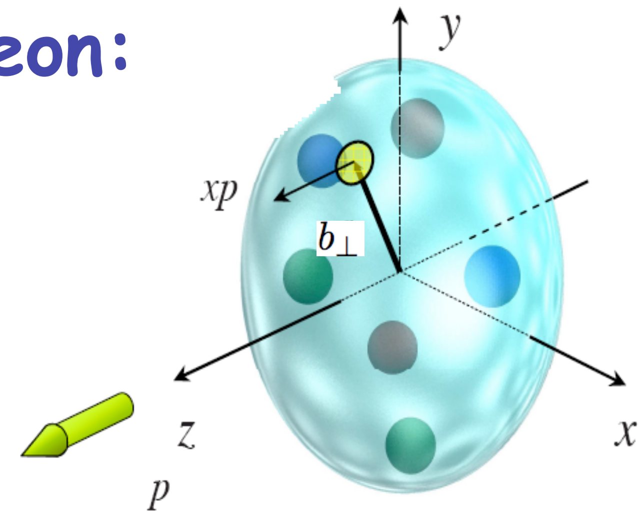
Burkardt; Ji

Tomographic images of the nucleon:

$$\int d^2\mathbf{\Delta}_\perp \, \mathrm{e}^{-i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp} \, H_q(x,\xi=0,-\mathbf{\Delta}_\perp^2)$$

$$= \; q(x,b_\perp)$$





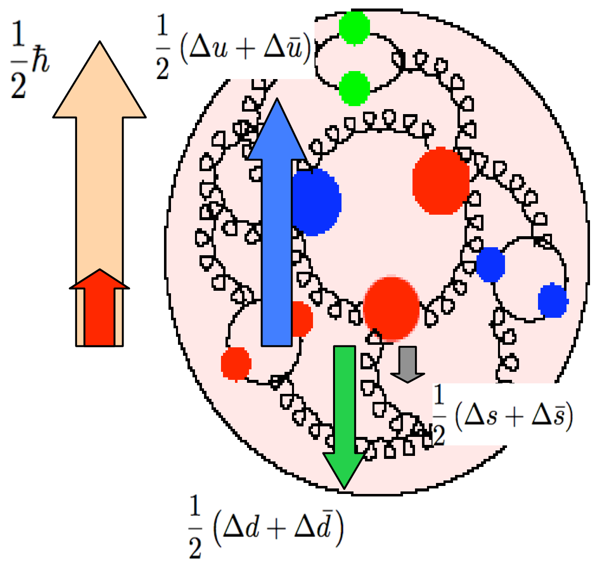
At EIC: spatial distribution of sea and glue

- Quantify orbital motion of partons in nucleon

$$J_q = \frac{1}{2} \lim_{t\to 0} \int dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)]$$

Ji

$$= \frac{1}{2}\Delta q + L_q$$



+ L + glue

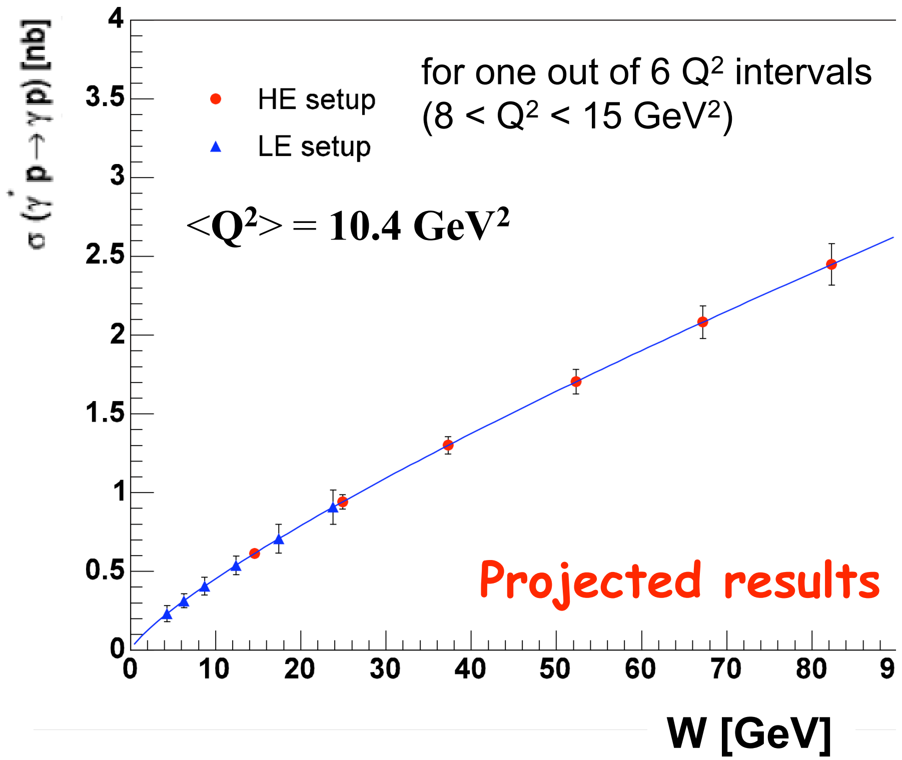
GPDs have potential to take our picture of the nucleon to a new level.

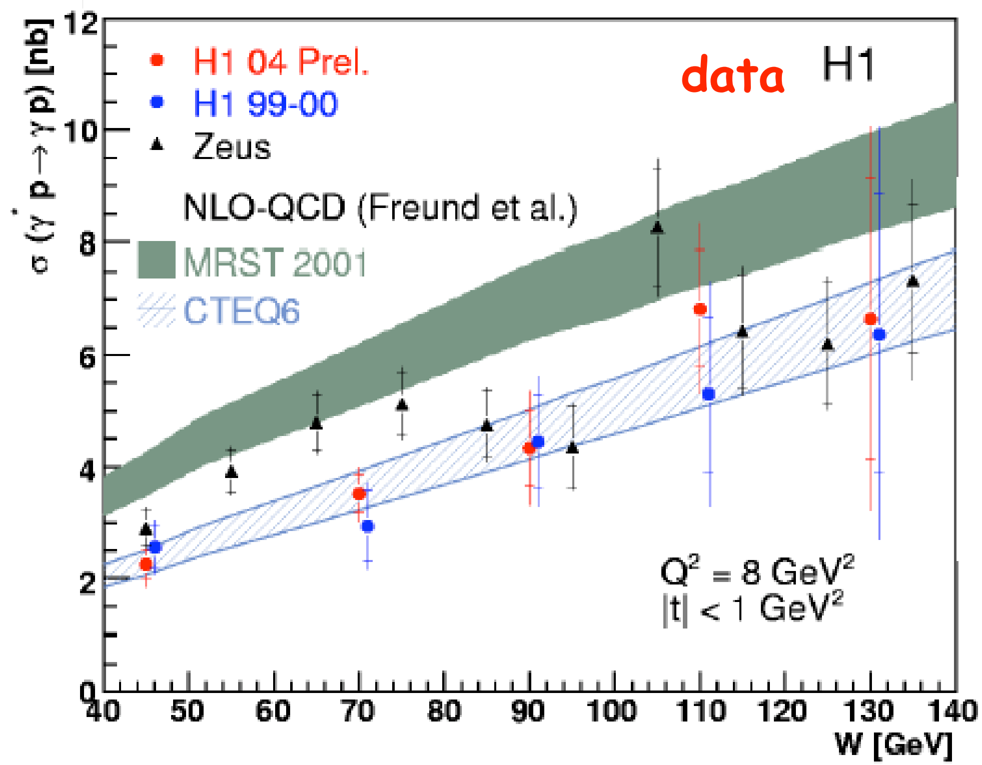
HE setup: $e^{+/-}$ (10 GeV) + p (250 GeV) L = $4.4 \cdot 10^{32}$ $cm^{-2}s^{-1}$ 38 pb^{-1}/day

LE setup: $e^{+/-}$ (5 GeV) + p (50 GeV) L = $1.5 \cdot 10^{32}$ $cm^{-2}s^{-1}$ 13 pb^{-1}/day

Sandacz

Precision of DVCS unpolarized cross sections



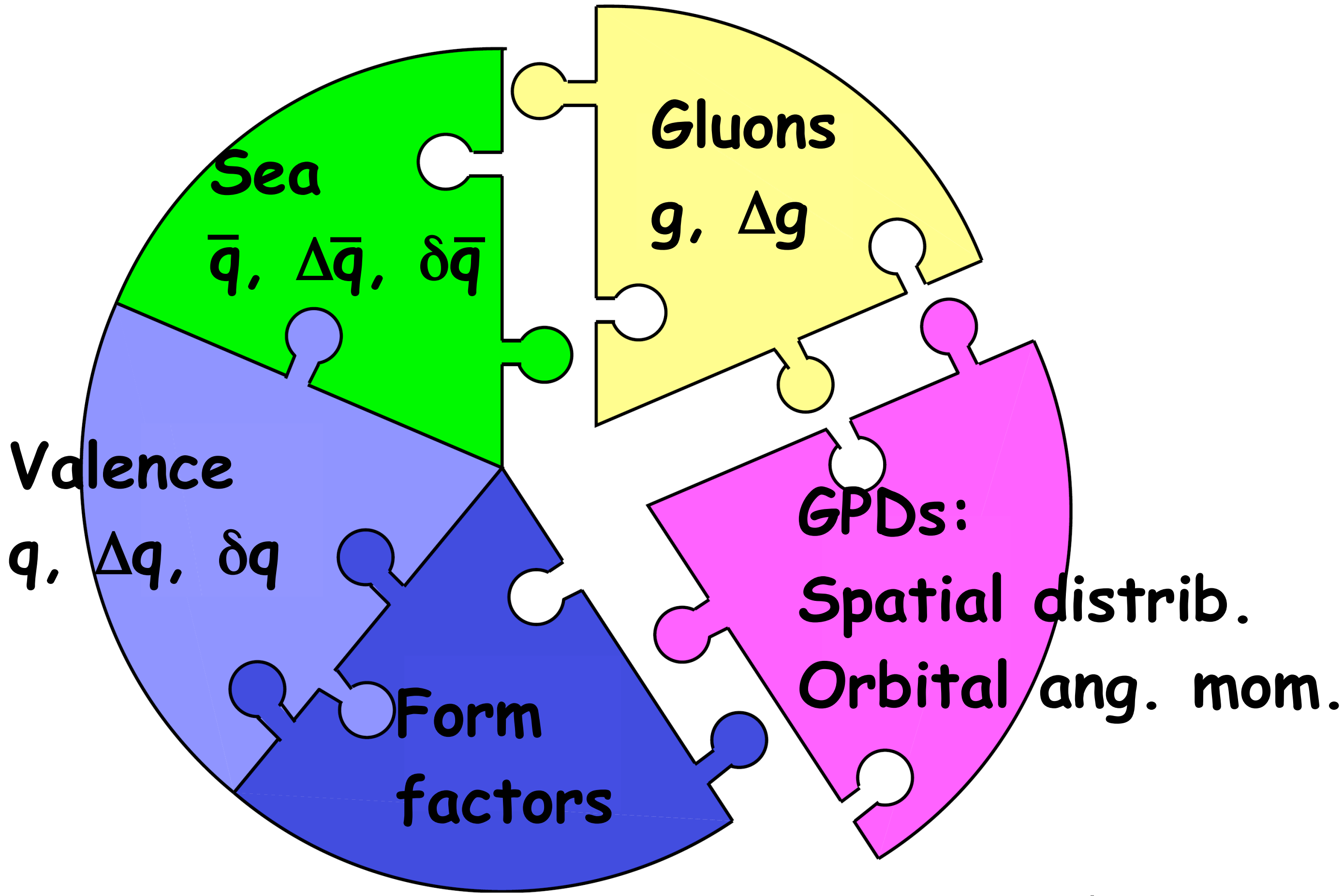


- also: gluon imaging with exclusive J/Ψ

Frankfurt, Strikman, Weiss

The challenge is: Map out the Nucleon

Its complete spin, flavor, gluon landscape



We'll have a good chance to get all the answers with present and next-generation facilities !

http://www.bnl.gov/eic

All NSAC 2007 White/Position Papers Associated with EIC

EIC White Paper (Draft April 4)
eA Position Paper (Final)
GPD White Paper, Summary of GPD WS at Maryland (January 2007)
eRHIC Accelerator Position Paper (BNL) (Final)
eLIC ZDR Version (January, 2007)