Central Questions in Nucleon Structure

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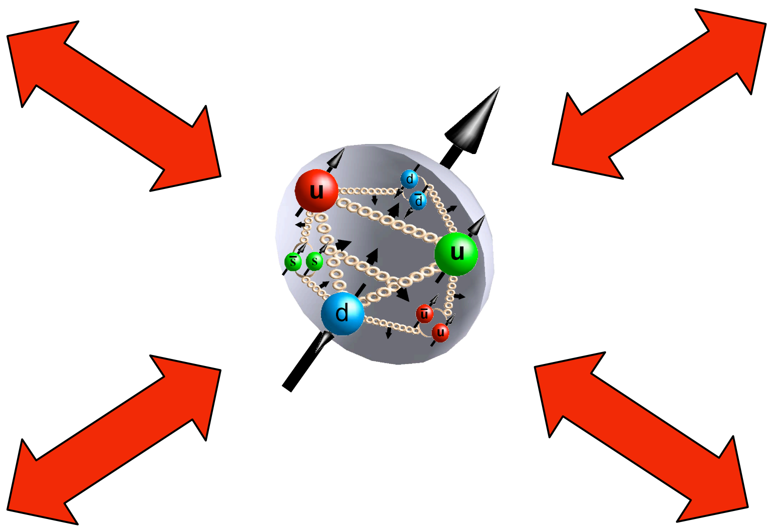
BNL Nuclear Theory

QCD and Hadron Physics Town Meeting, 01/13/2007

Exploring the nucleon:
Of fundamental importance in science

Know what we
are made of !

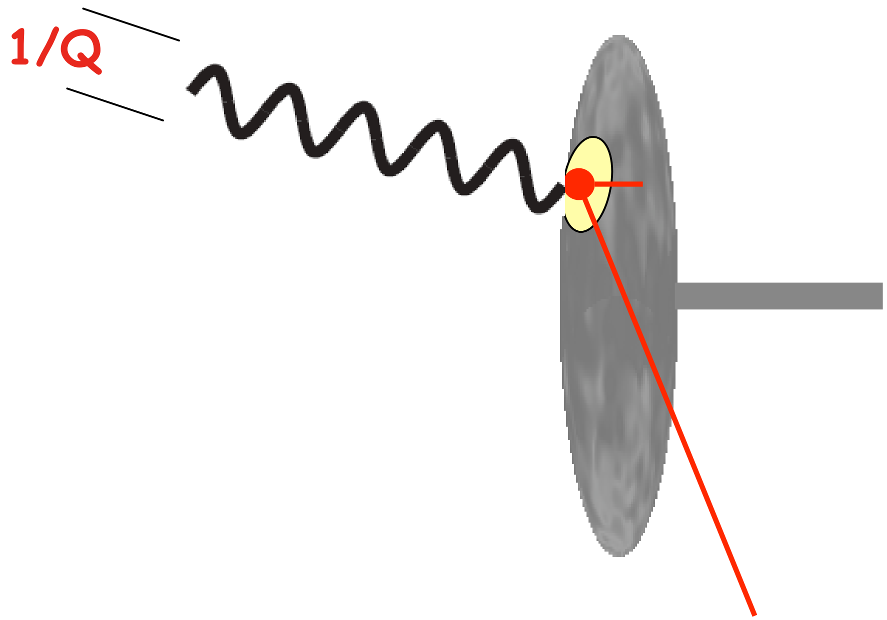
Test our ability
to *use* QCD:
Asymptotic Freedom,
Factorization



Explore and
Understand QCD:
Lattice, Models

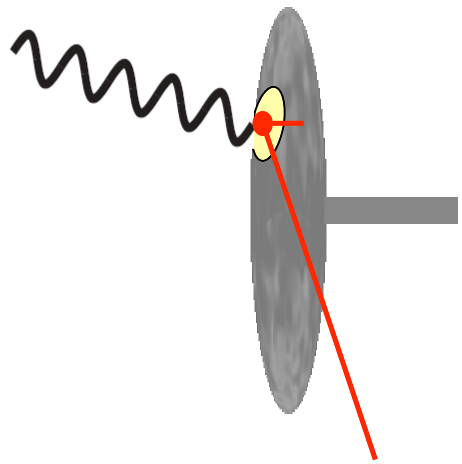
Nucleon as tool for
discovery:
RHIC Heavy Ions, LHC
Tevatron High-E_T jets
NuTeV anomaly, …

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

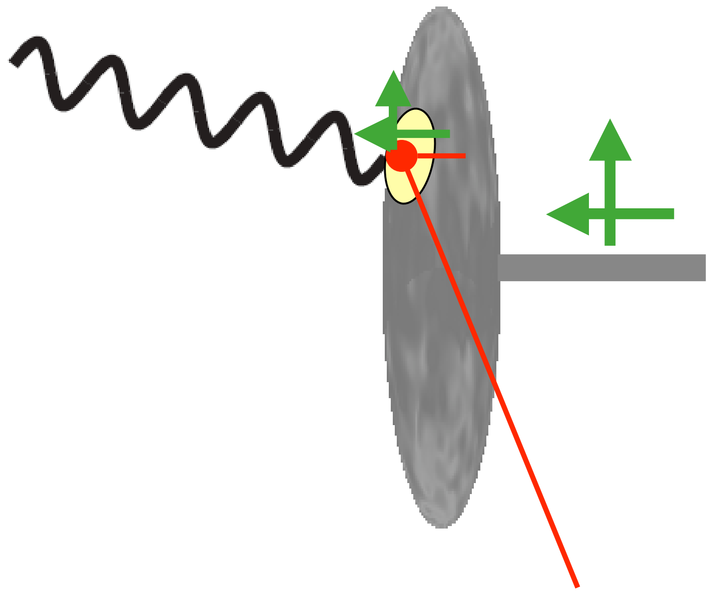


- Diverse probes: DIS, DVCS, Drell-Yan, pp→jetX, …

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 $\leftarrow$ vs. $\uparrow$ 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

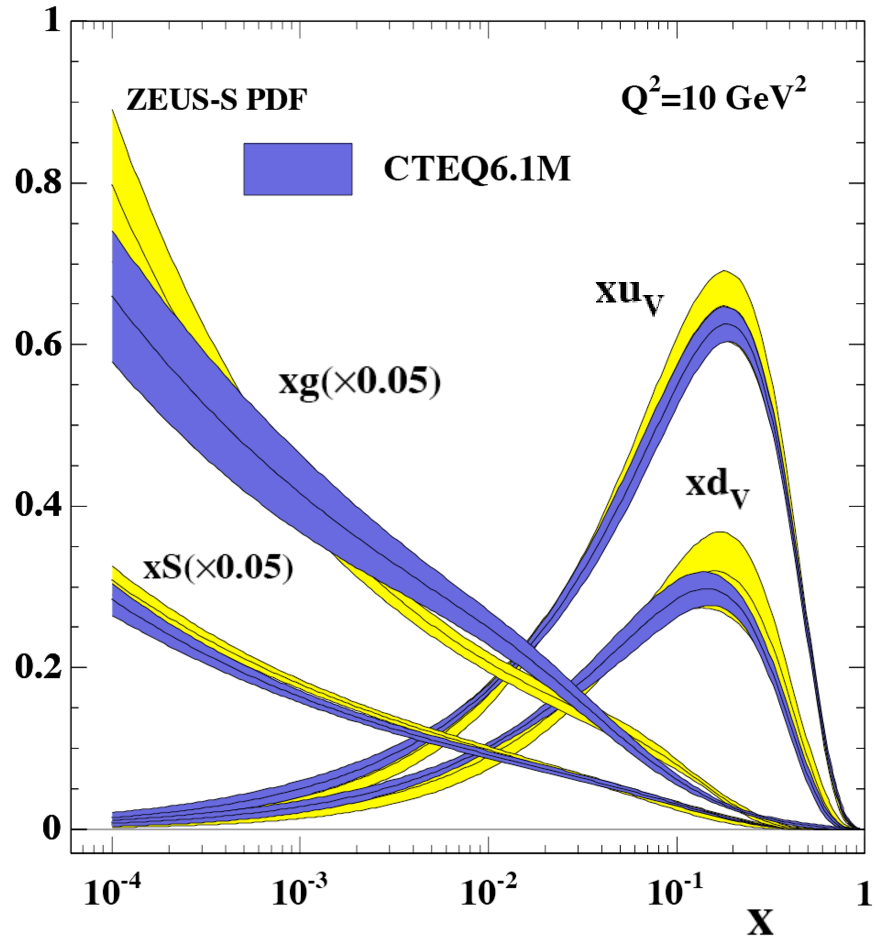
Its complete spin, flavor, gluon landscape

- 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

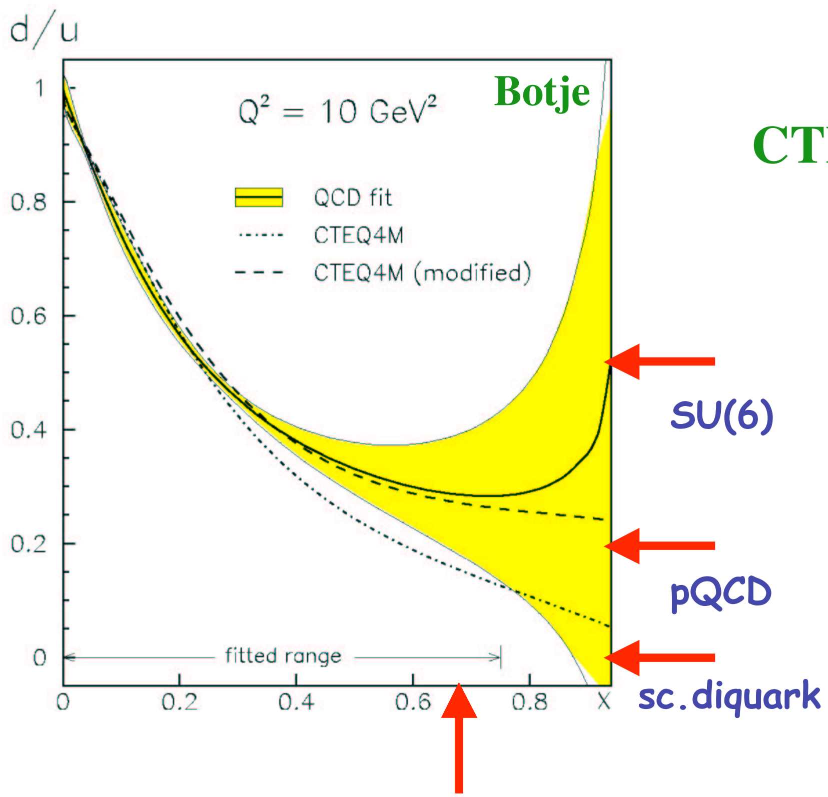
- An important part of our picture of the nucleon:
  Gluons rule at small-x !

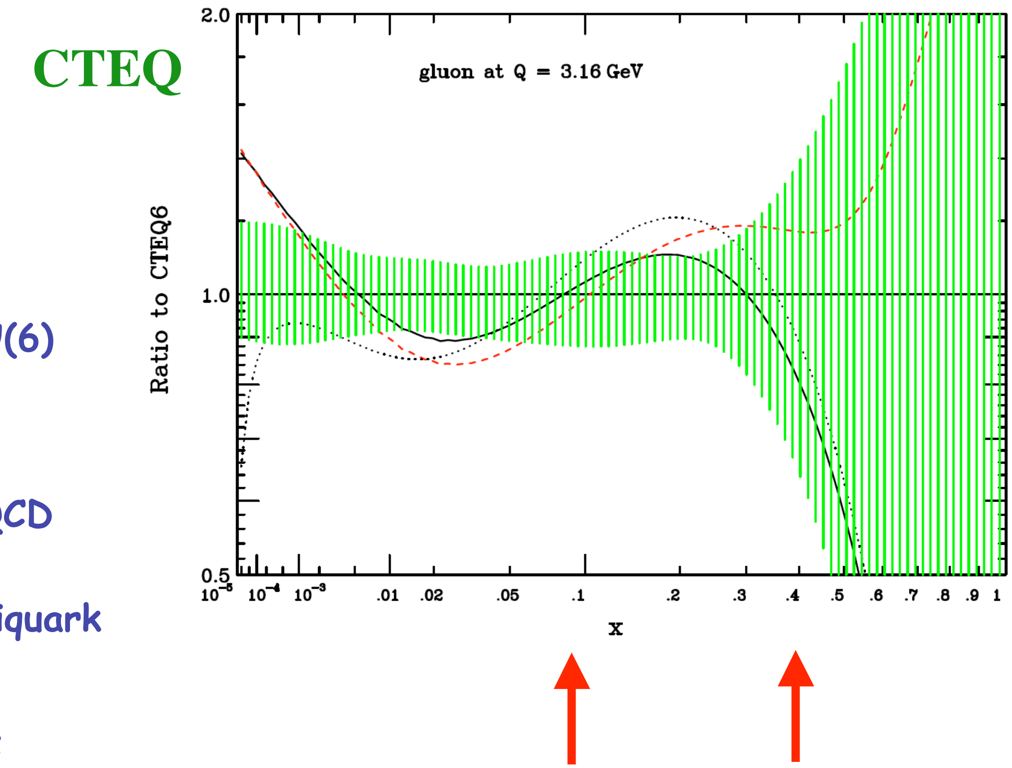


- We know a lot, but …

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

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

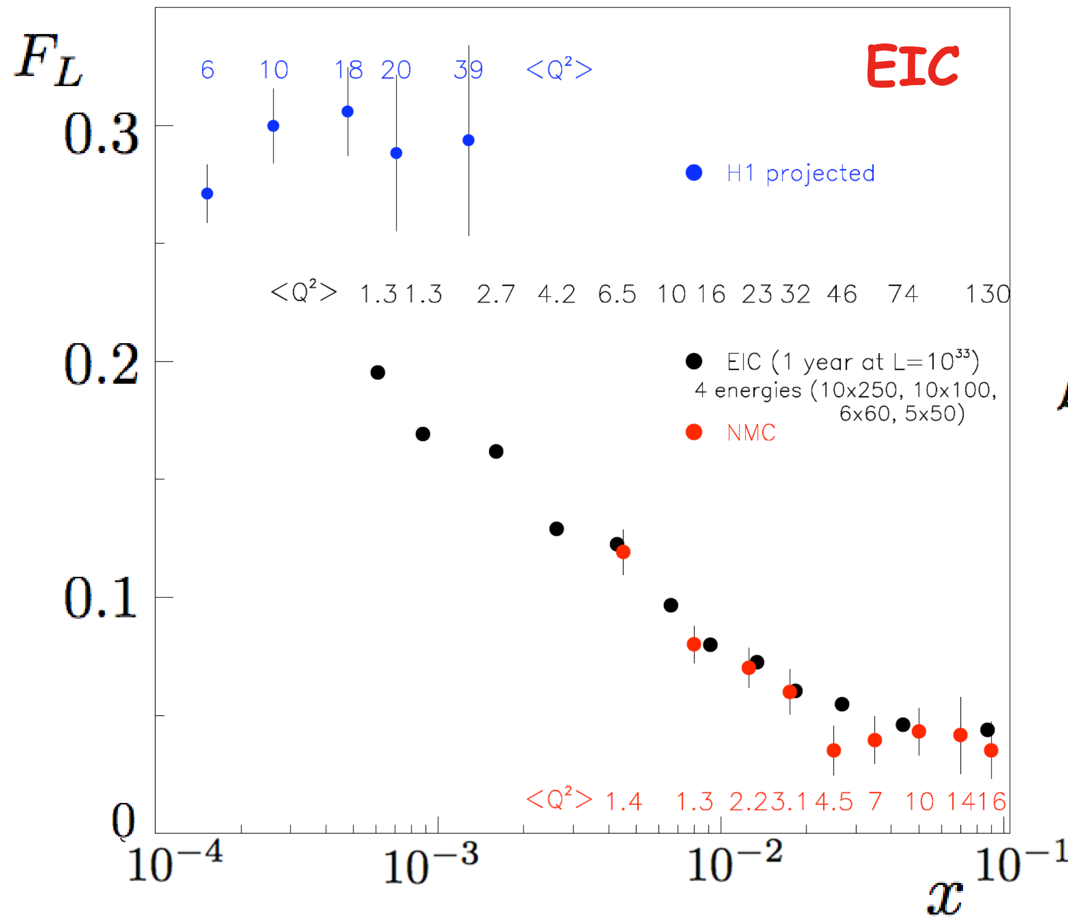




Testing ground for models of
Proton wave function
Measure at Jlab-12 GeV
sea: DY

Not an academic problem: LHC
Measure at HERA, EIC

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



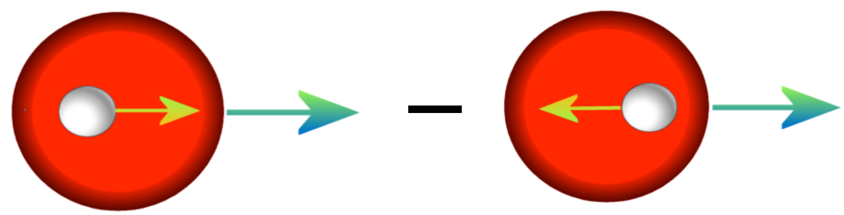
A. Bruell, R. Ent

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

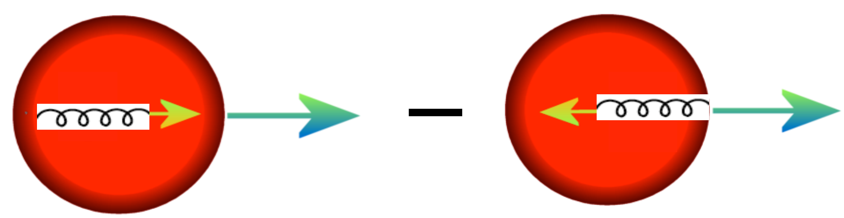
One observable among many: $dF_2/d\mathrm{Log}(Q^2)$, $ep \to$ jet+jet+X, charm, …

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+$\bar{\text{q}}$ spin contribution

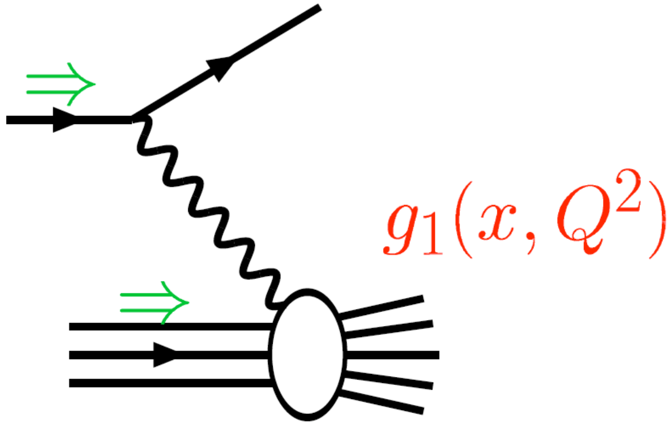
Gluon spin contribution

Orbital ang. momenta

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

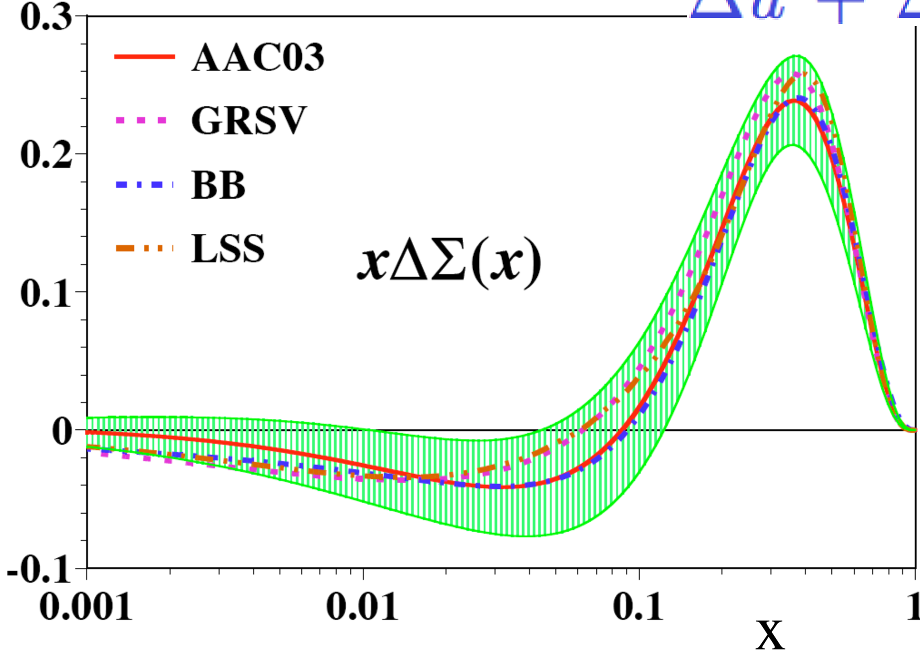
$$\int_0^1 dx\,\Delta g(x)$$

"Quotable" properties of the proton



EMC, SMC, E142-155, HERMES

$$\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}$$



Hirai, Kumano, Saito

q and $\bar{q}$ spins carry

$\sim 25\%$ of proton spin

How sure are we?

And, what are the details?

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

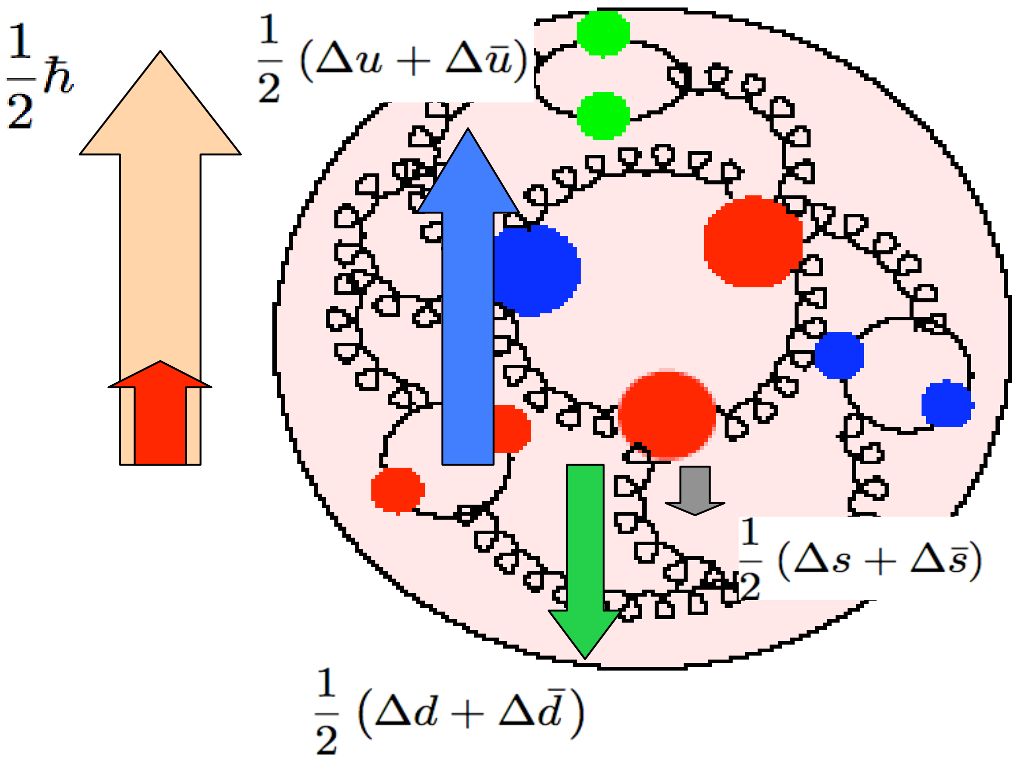
To really nail it down, need measurements at lower x.
And: at current x, but higher Q^2 $\rightarrow$ EIC

  - 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

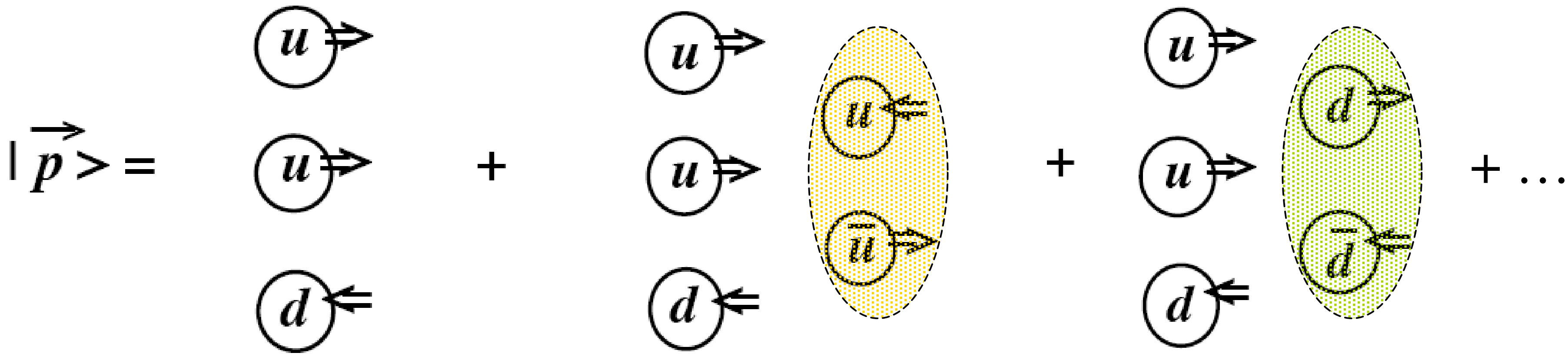
- if all true, current picture is:



- is it correct ?

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

- **Important applications for models :**



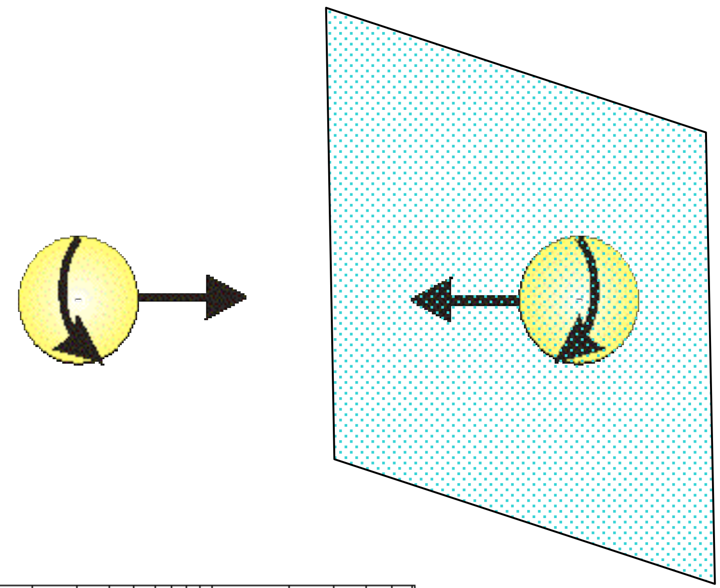
Many models predict $\Delta\bar{u} > 0 \quad \Delta\bar{d} < 0$

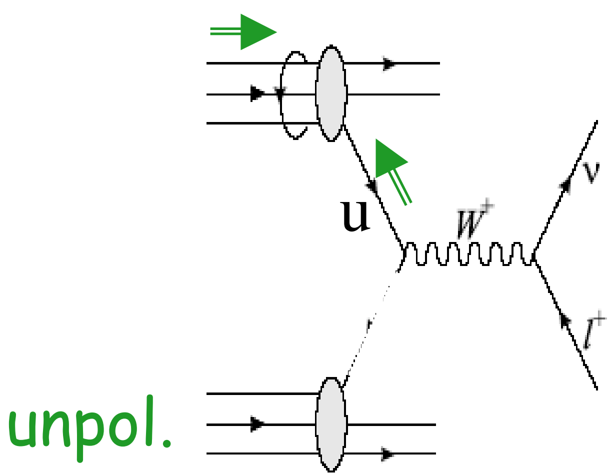
Thomas, Signal, Cao; Holtmann, Speth, Fässler; Diakonov, Polyakov, Weiss; Glück, Reya; Schäfer, Fries; Kumano; Wakamatsu; ...

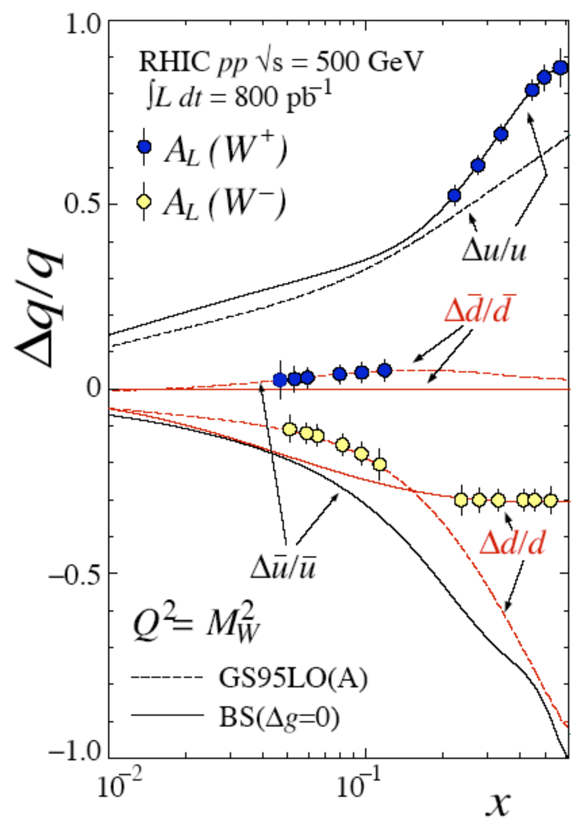
Various avenues for addressing these questions

At RHIC:

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



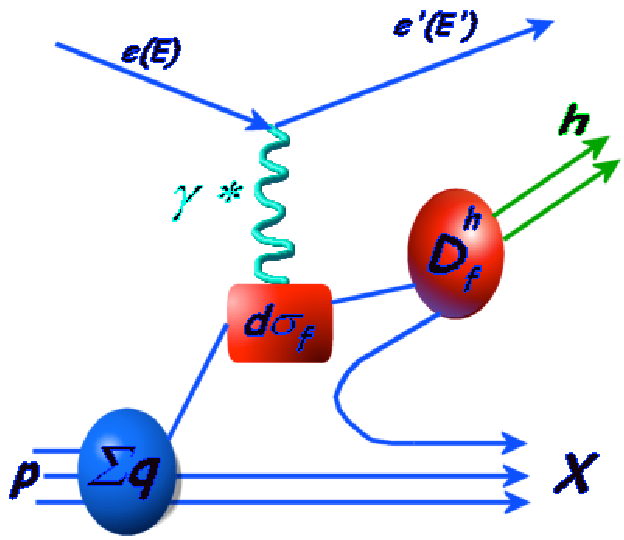


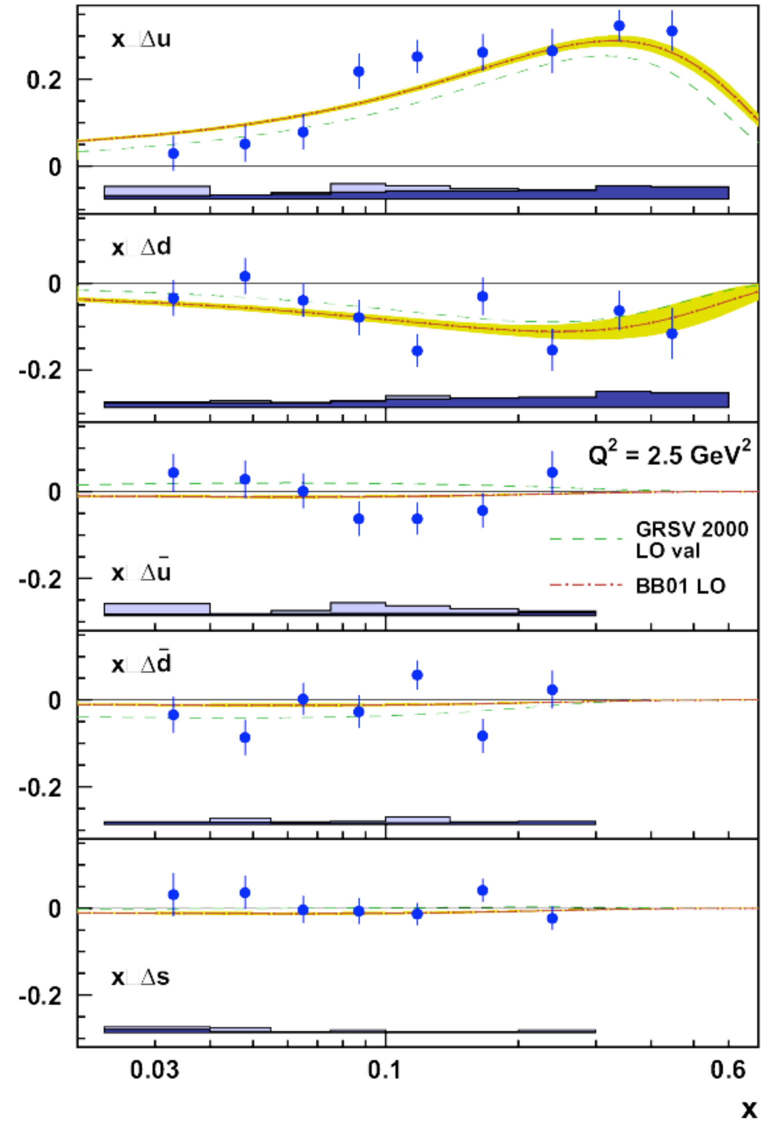


- W+charm at RHIC-II

In lepton scattering : "SIDIS"

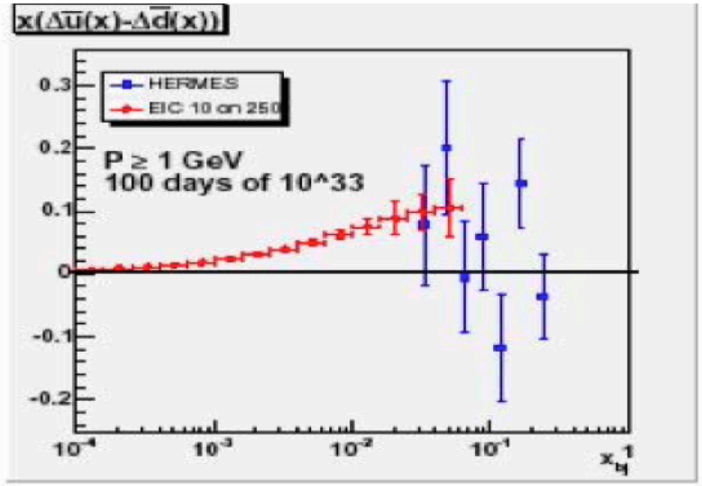
HERMES

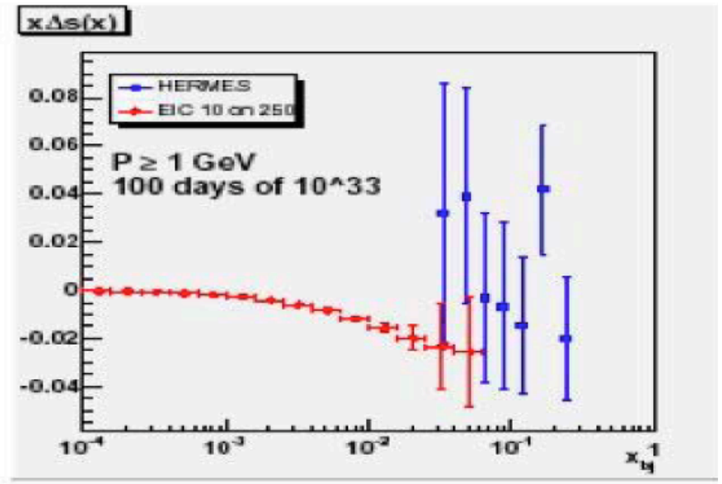




- Major topic at Jlab-12 GeV

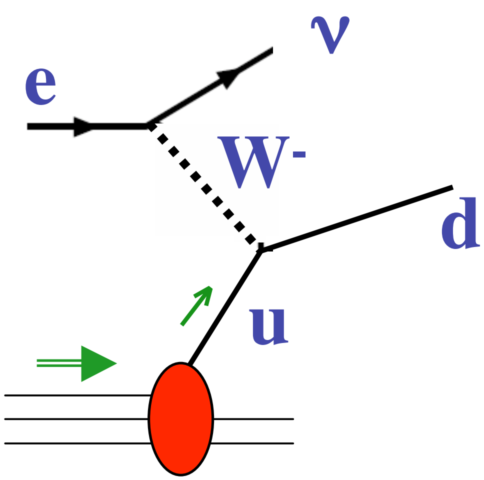
EIC:

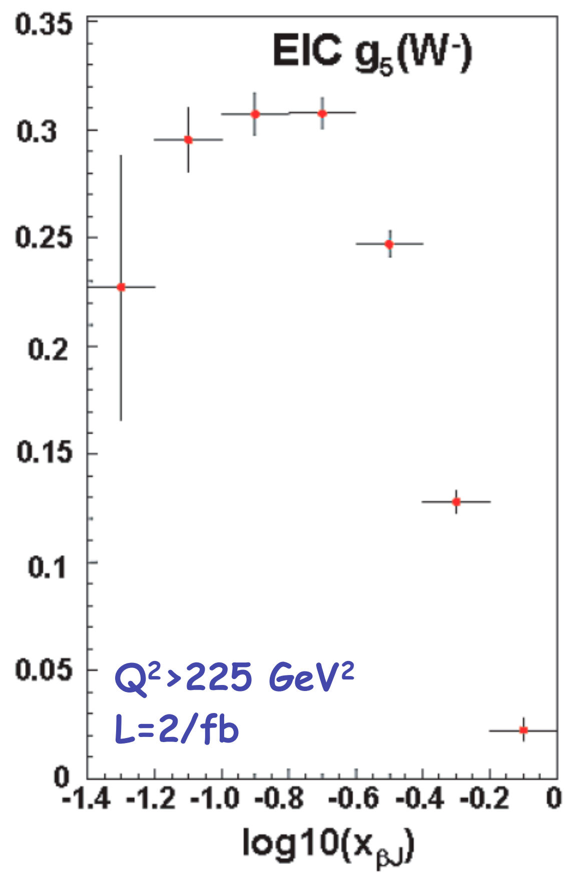




J. Seele

- 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

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

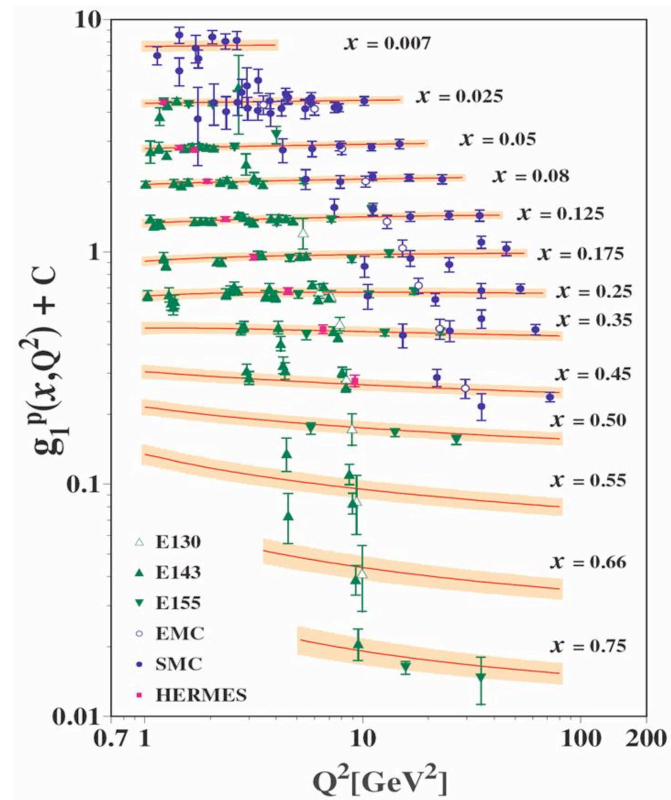
Twist-4 matrix elements $\sim \langle \bar{q}\tilde{F}q \rangle$

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

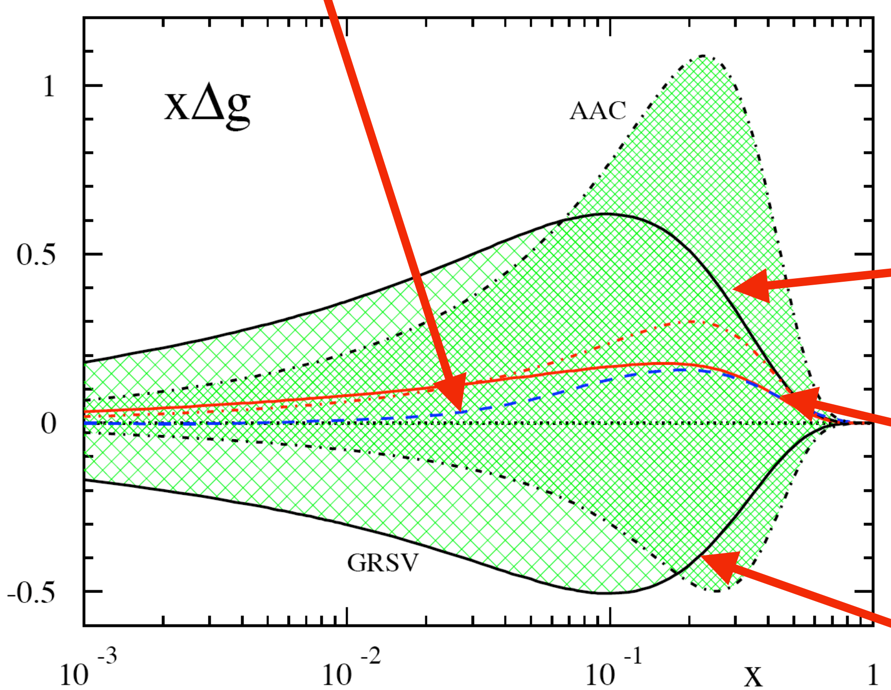
The gluon spin distribution Δg

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 $\Delta G \approx 0.3$



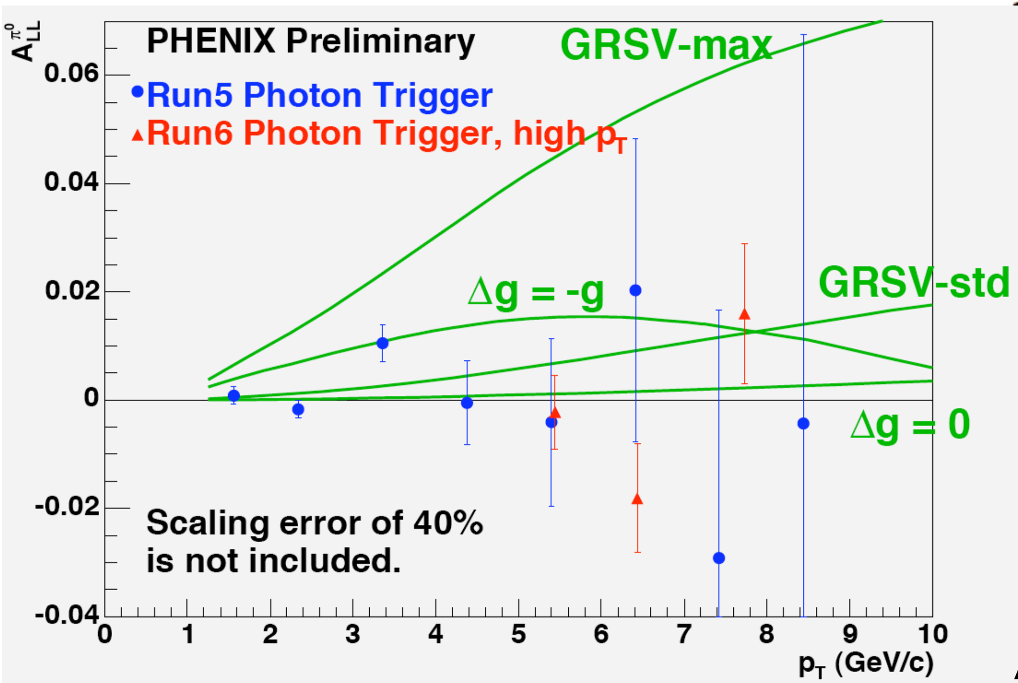
$\Delta G \approx 1.8 \; (@\,1\mathrm{GeV}^2)$

"axial anomaly" Altarelli et al.

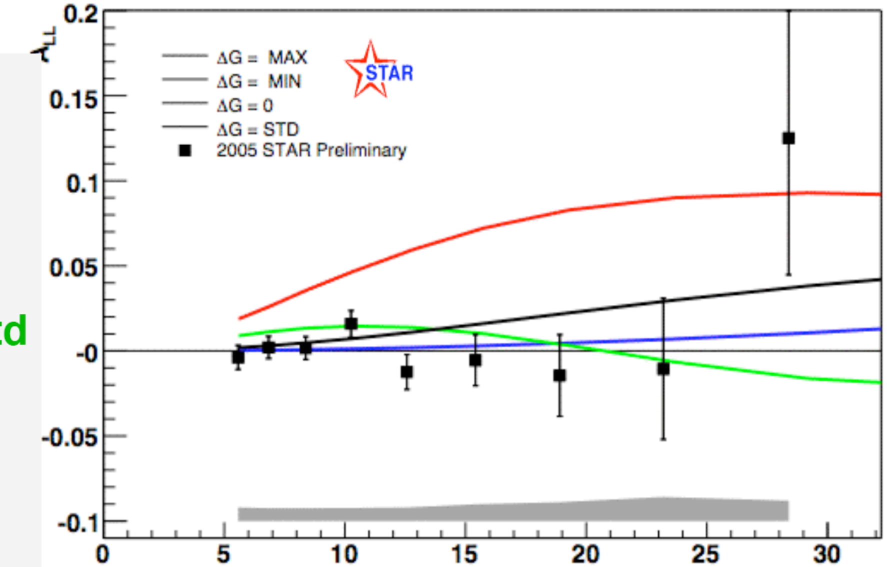
$\Delta G \approx 0.4$

$\Delta G \approx -1.7$

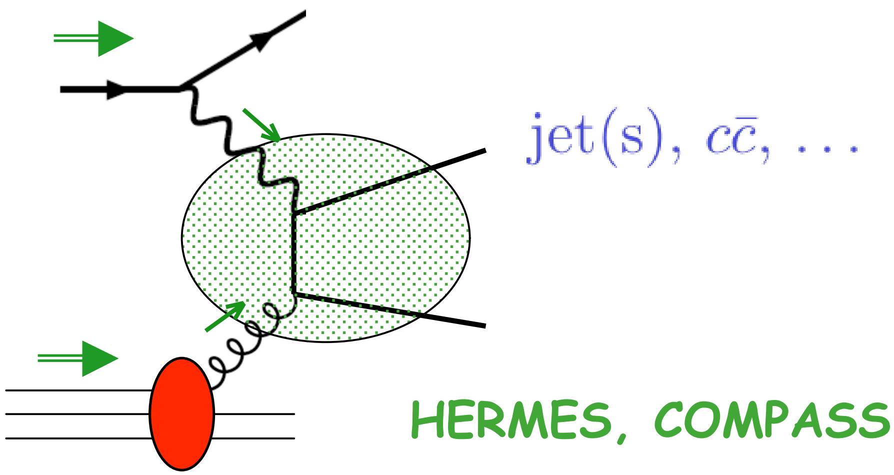
- **NOW:**



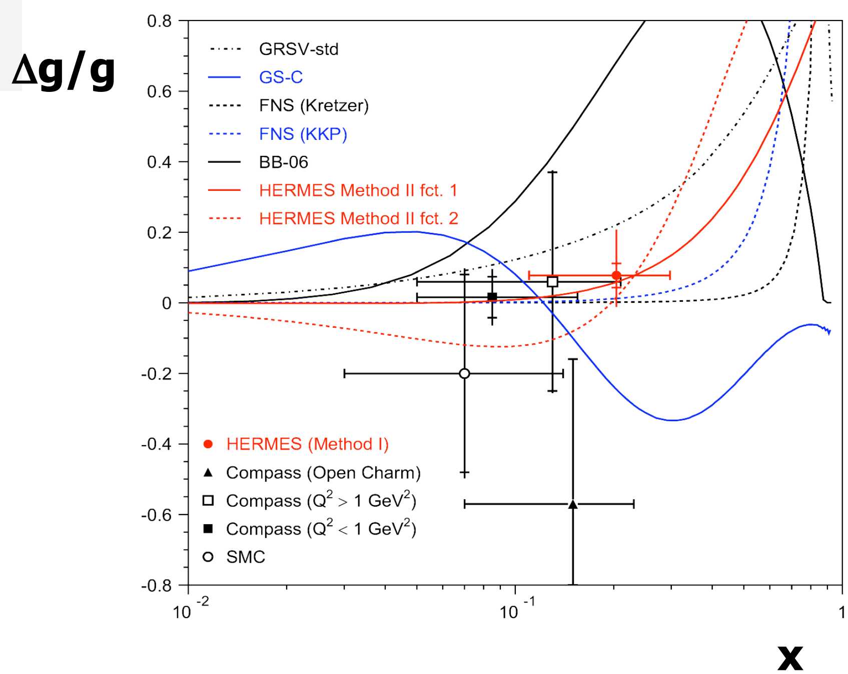
PHENIX Preliminary
GRSV-max
•Run5 Photon Trigger
▲Run6 Photon Trigger, high p_T
$\Delta g = -g$
GRSV-std
$\Delta g = 0$
Scaling error of 40%
is not included.
$A_{LL}^{\pi^0}$
p_T (GeV/c)



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

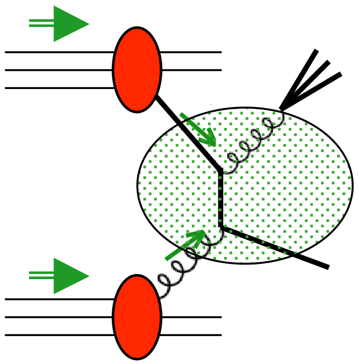


jet(s), $c\bar{c}$, ...
HERMES, COMPASS



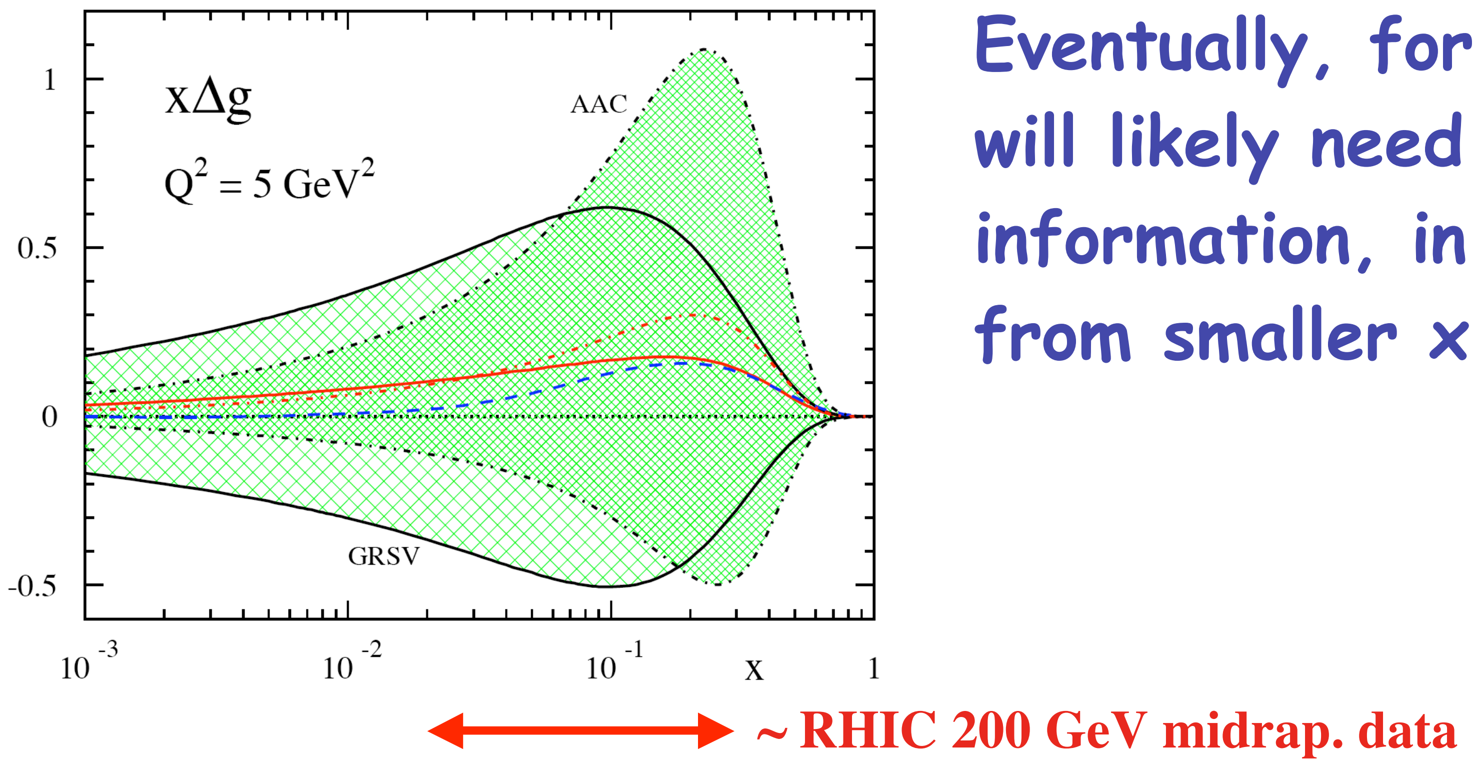
Δg/g
GRSV-std
GS-C
FNS (Kretzer)
FNS (KKP)
BB-06
HERMES Method II fct. 1
HERMES Method II fct. 2
HERMES (Method I)
Compass (Open Charm)
Compass ($Q^2 > 1$ GeV^2)
Compass ($Q^2 < 1$ GeV^2)
SMC
x

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

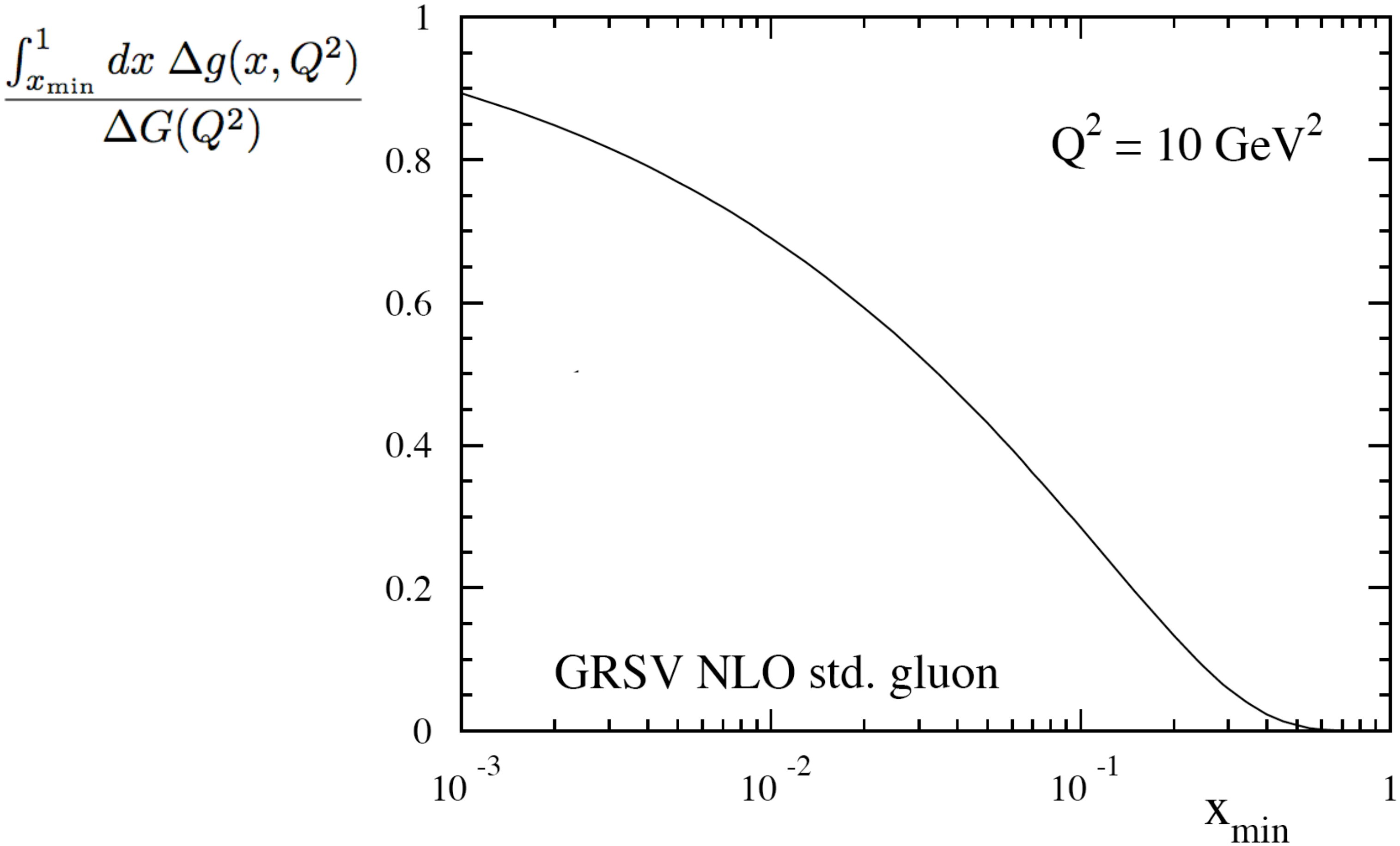


$$\Delta\sigma = \sum_q \int dx_g \int dx_q \, \Delta g(x_g, p_T) \, \Delta q(x_q, p_T) \, \Delta\hat{\sigma}^{qg}(x_g, x_q, p_T, \alpha_s(p_T)) + \ldots$$

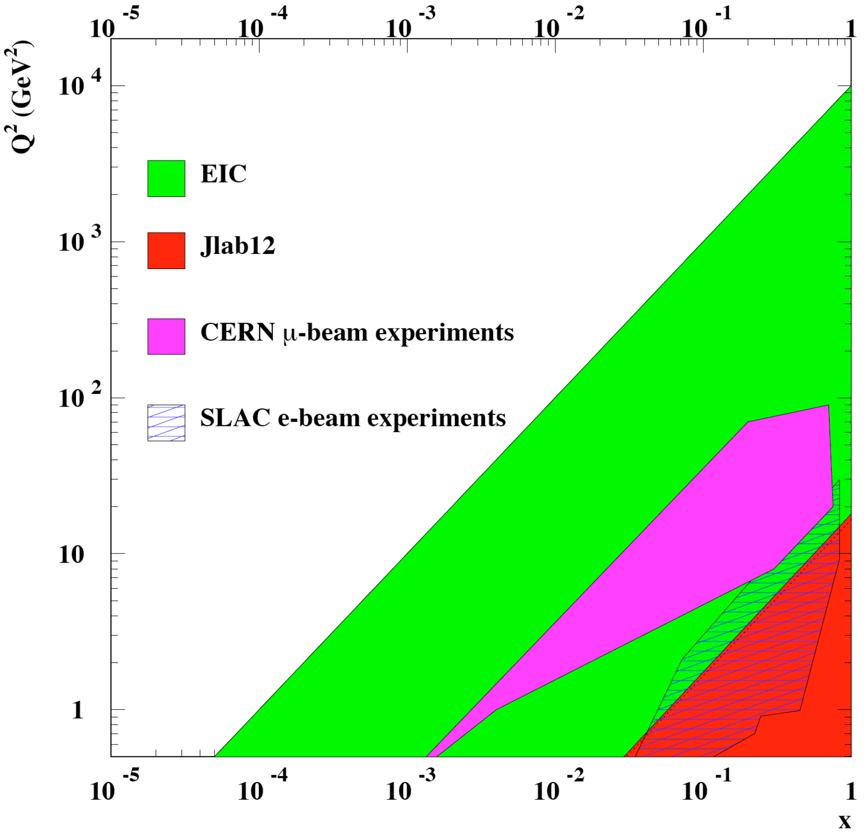
→ Need "Global analysis"

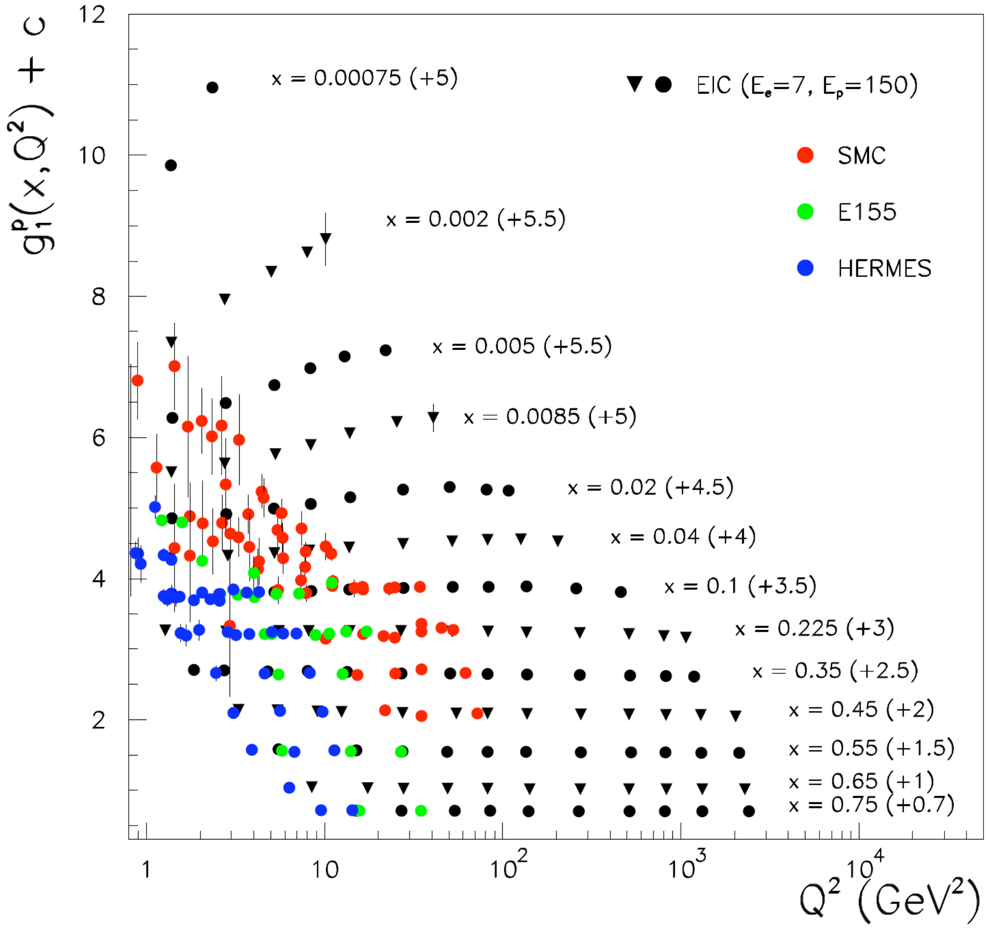


Eventually, for integral will likely need additional information, in particular from smaller x



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

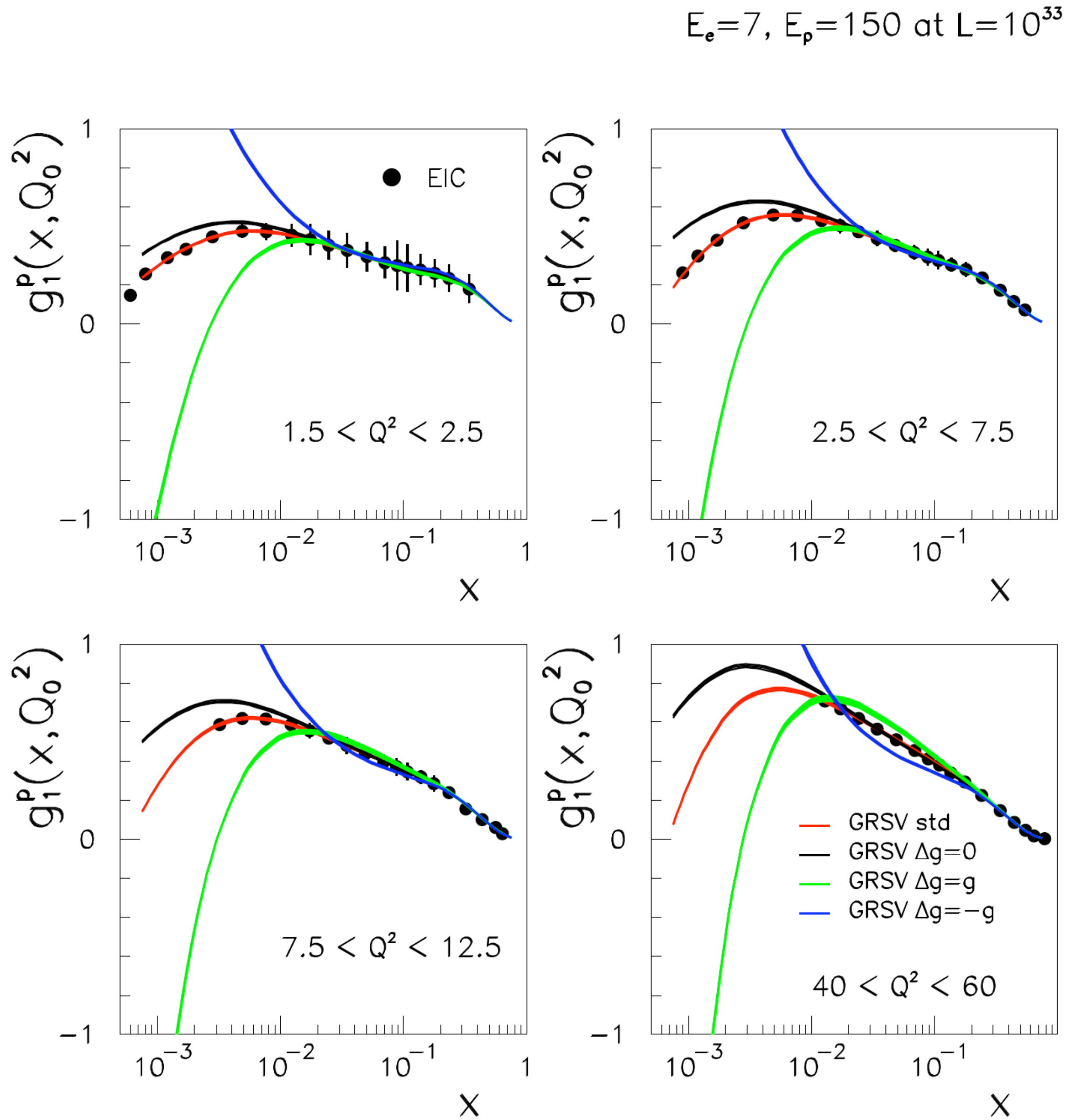




A. Bruell, R. Ent

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

at small x



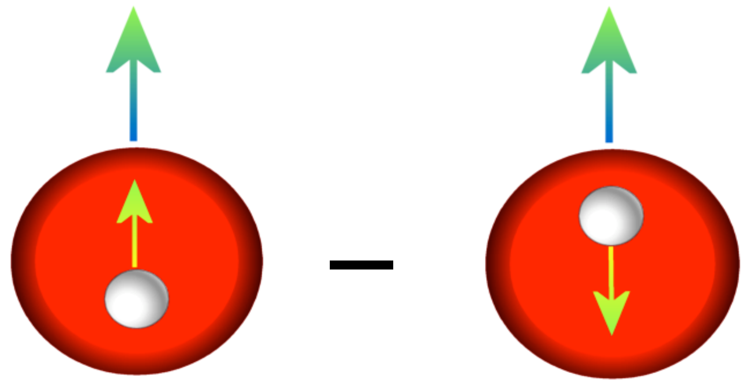
A. Bruell, R. Ent

What's the structure of a

Transversely polarized Nucleon ?

Transversity:

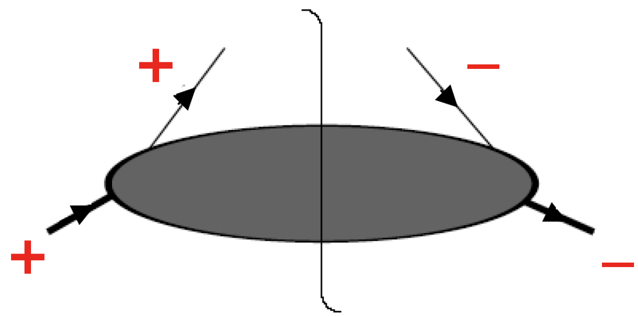
$$\delta q(x) \;=$$



Ralston, Soper; Jaffe, Ji; ...

- in helicity basis:

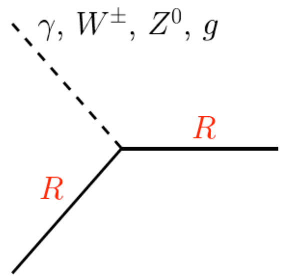
$$\delta q(x) \;\sim$$

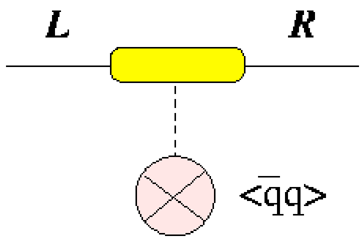


Helicity-flip !

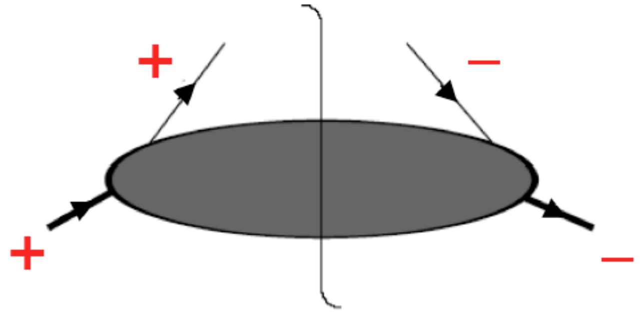
- **the physics involved:**

  - $*$ “odd chirality” $\rightarrow$ helicity-flip, χSB





  - $*$ no mixing with gluons



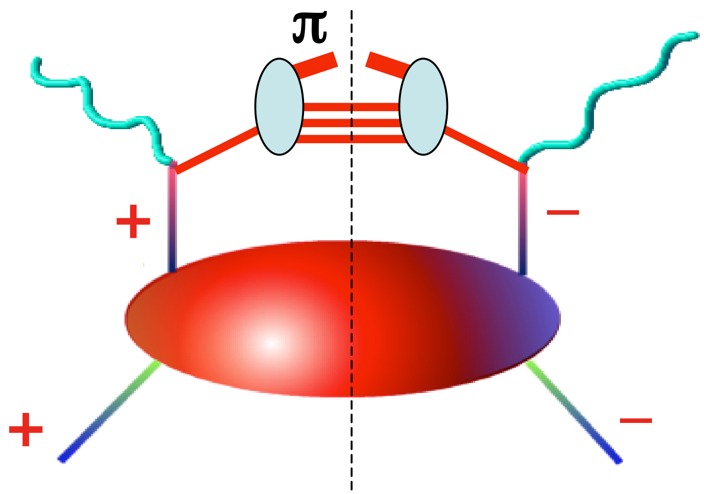
  - $*$ tensor charge

$$\langle\, \mathbf{P} \,|\, \bar{\mathbf{q}}\, \mathbf{i}\, \sigma^{\mu\nu}\, \gamma^5\, \mathbf{q} \,|\, \mathbf{P} \,\rangle \;=\; \int_0^1 \mathbf{dx}\, [\, \delta\mathbf{q}(\mathbf{x}) \;-\; \delta\bar{\mathbf{q}}(\mathbf{x}) \,]$$

  - $*$ difference to helicity probes relativistic / dynamical effects

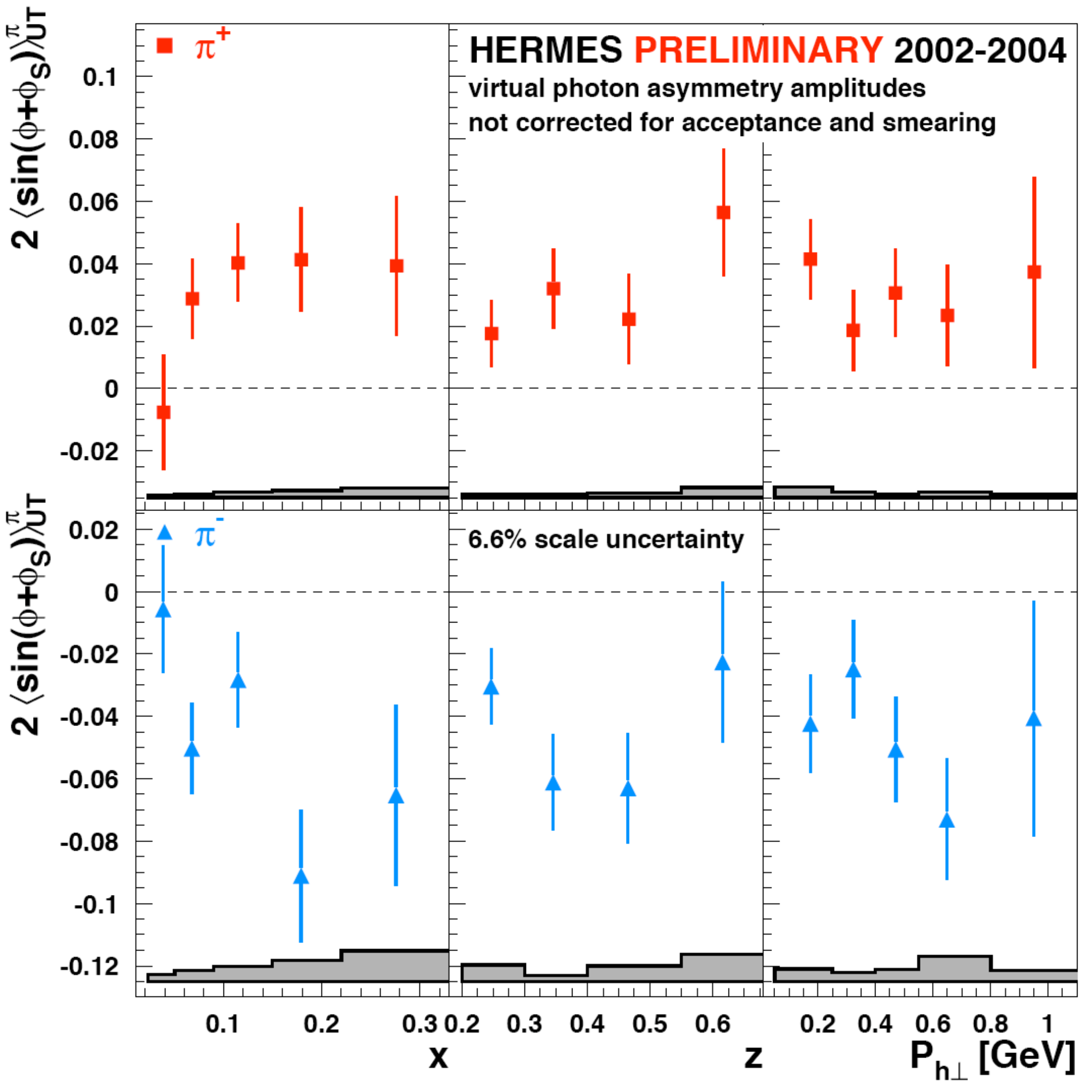
- **Opportunities for measurement ?**

  ∗ not in inclusive DIS, but:



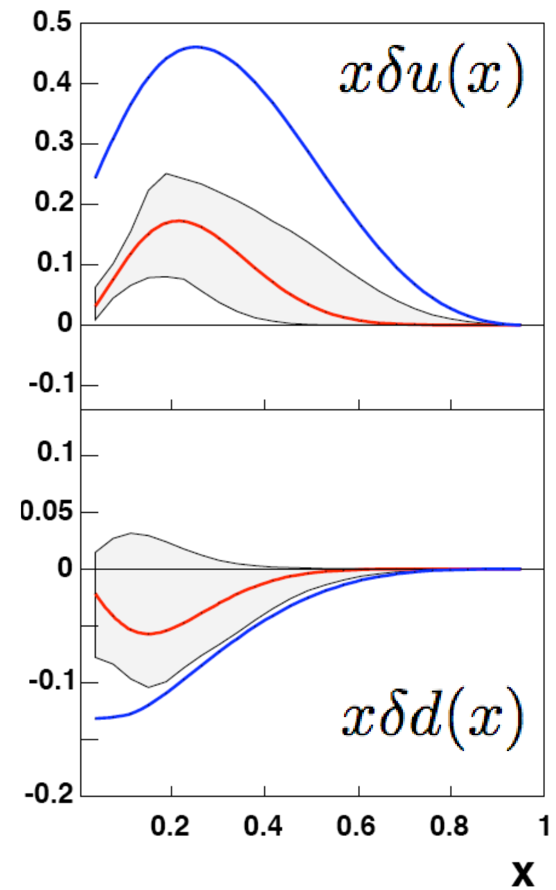
"**Collins** effect"
→ **azimuthal asym.**

∗ this effect actually appears to be there : HERMES



→ First glimpse of Transversity !

(Anselmino et al.)

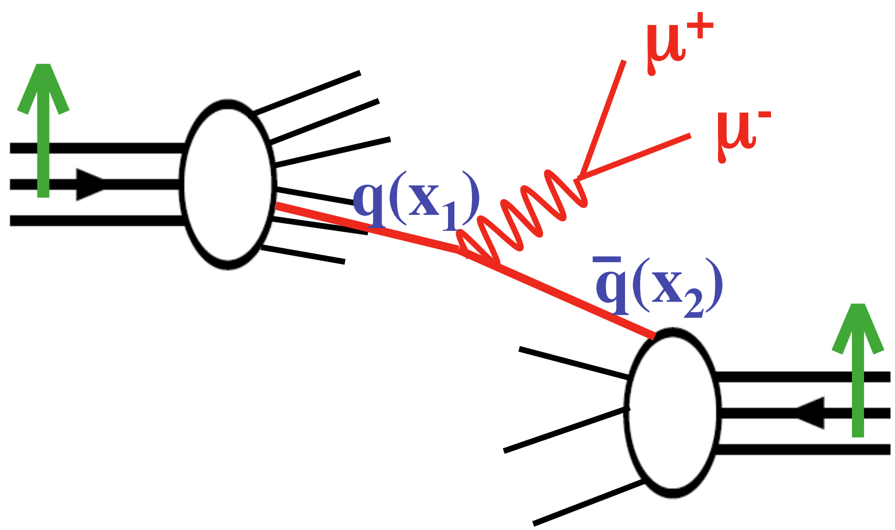


(up to sign)

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

The future :

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

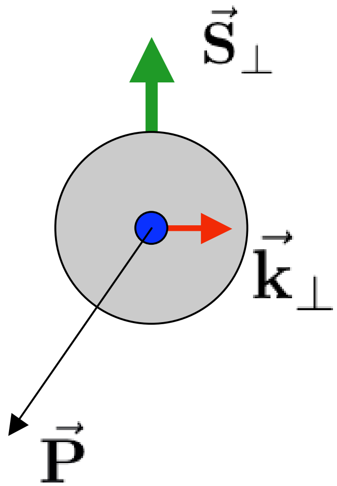


RHIC / RHIC-II

GSI, J-PARC

- azimuthal asymmetries in SIDIS at EIC

Transverse spin offers further new insights into Nucleon structure.



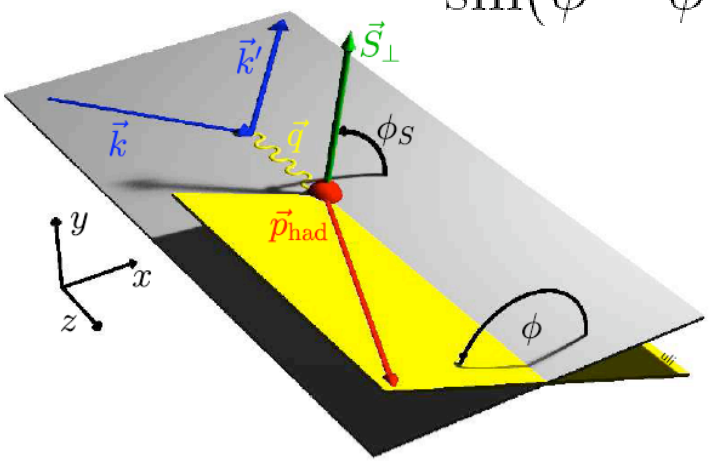
correlation $\sim \vec{S}_T \cdot \left(\vec{P} \times \vec{k}_T \right)$

Sivers

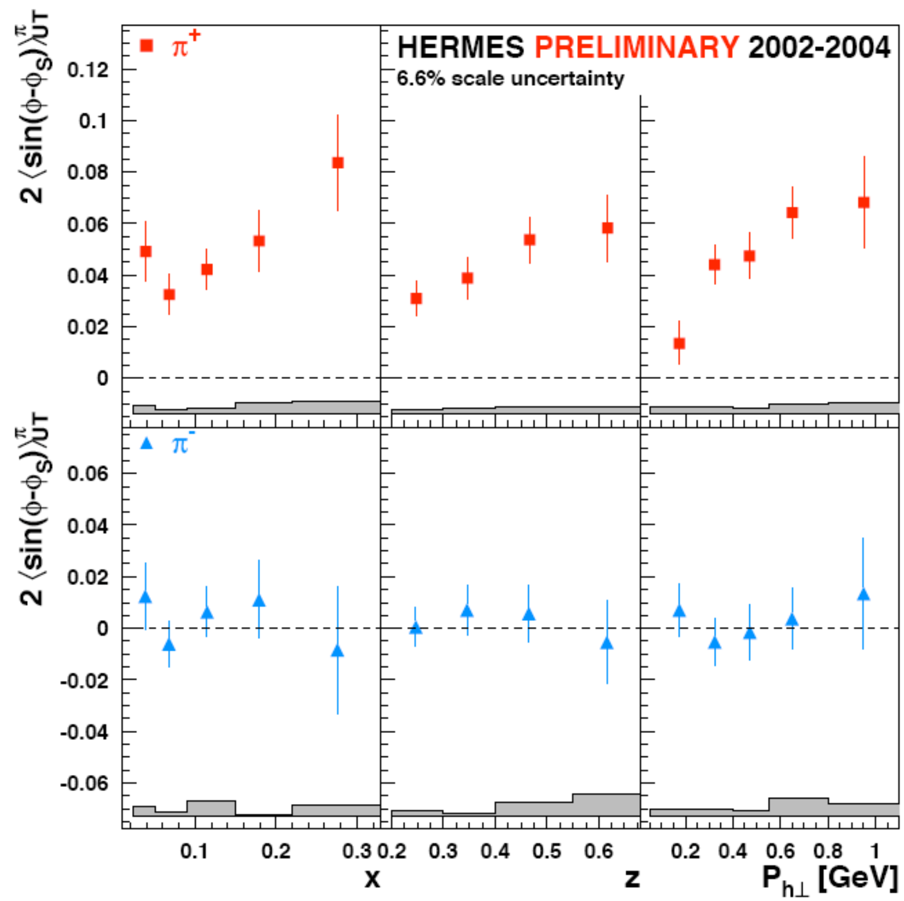
Where would this show up ?

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

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

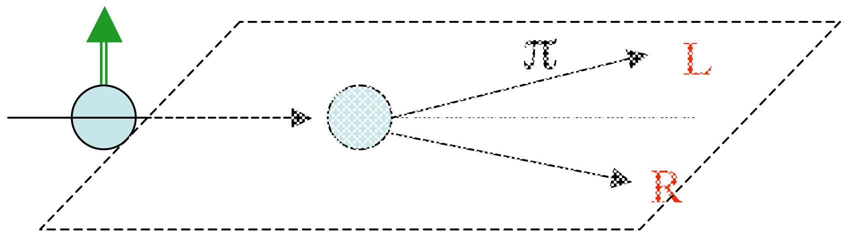


SMC, **HERMES,**
COMPASS, CLAS

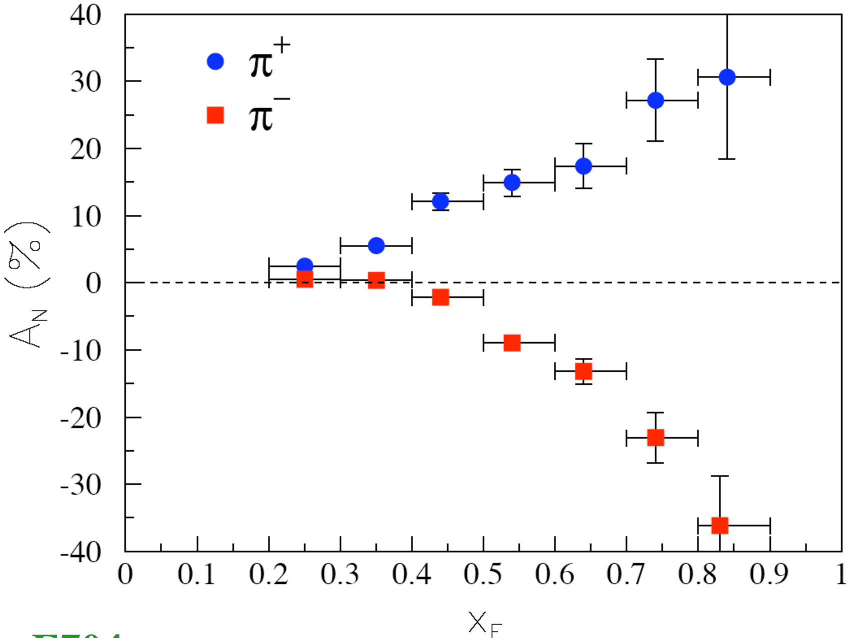


Seen !

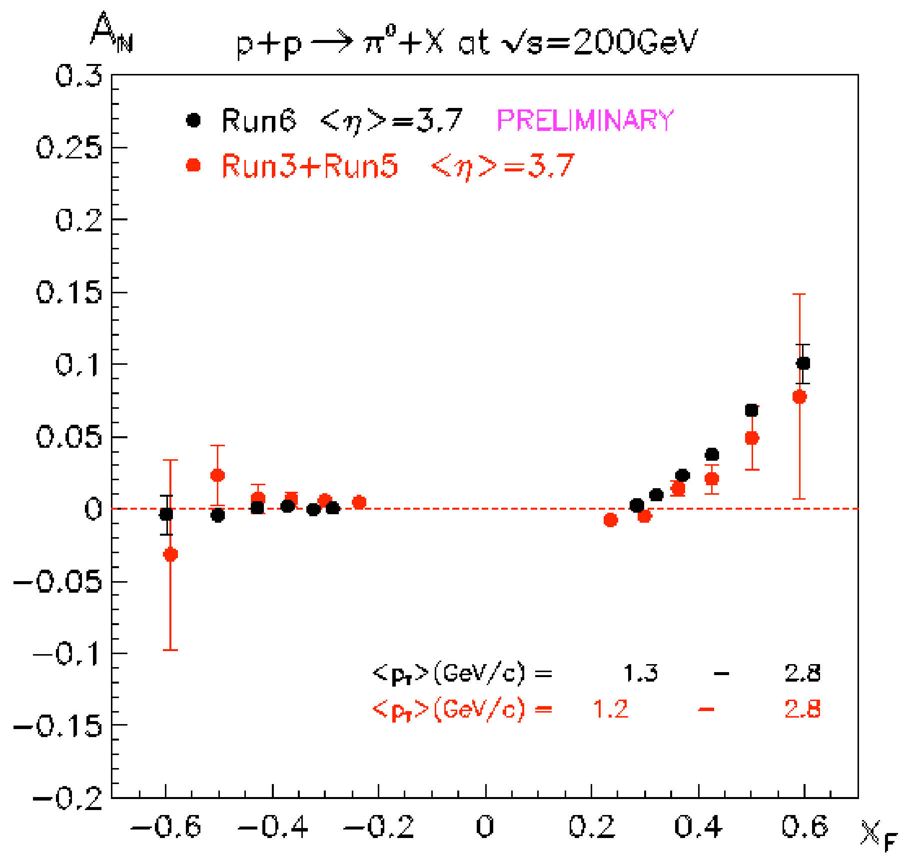
In pp scattering: involved (in disguised form) in large "left-right" asymmetries



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

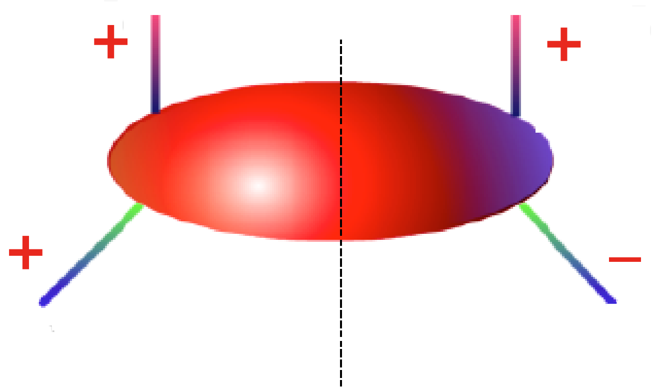


E704



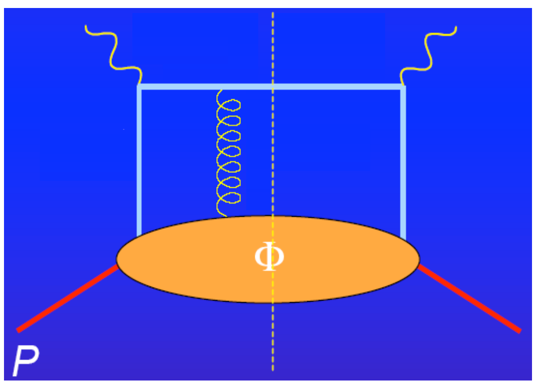
STAR (BRAHMS, too)

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

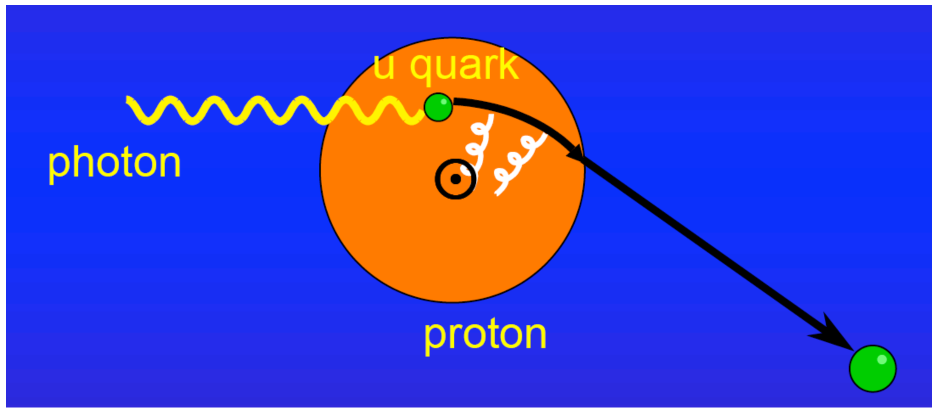


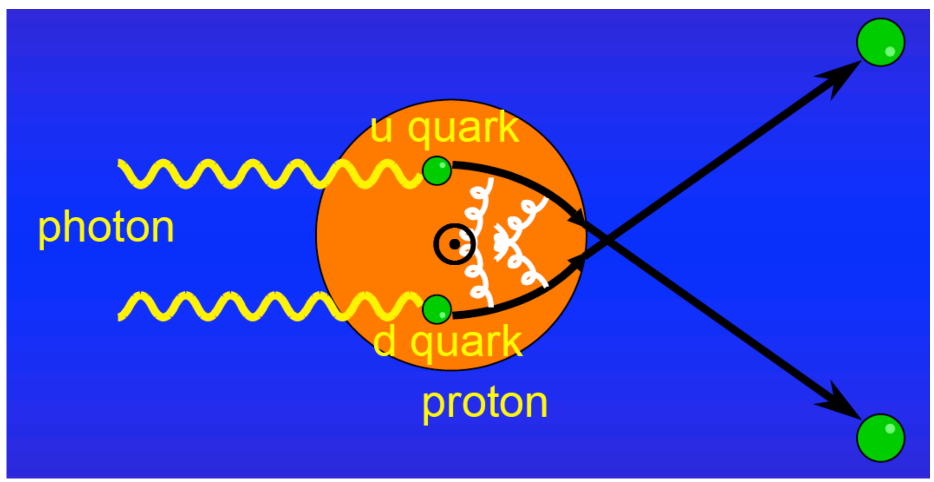
Brodsky, Hwang, Schmidt; Collins;
Belitsky, Ji, Yuan;
Boer, Mulders, Pijlman

Attractive !

- **intuitive (model-based) picture :**

Burkardt

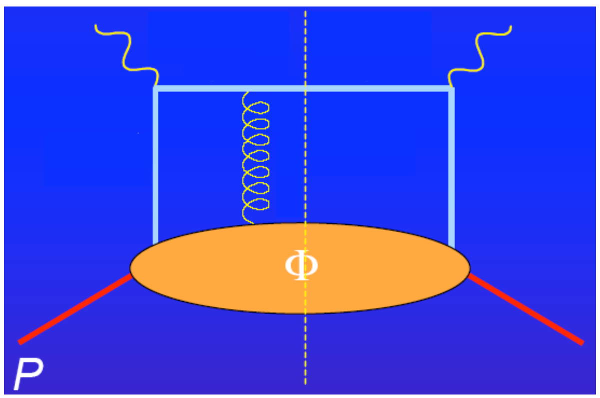


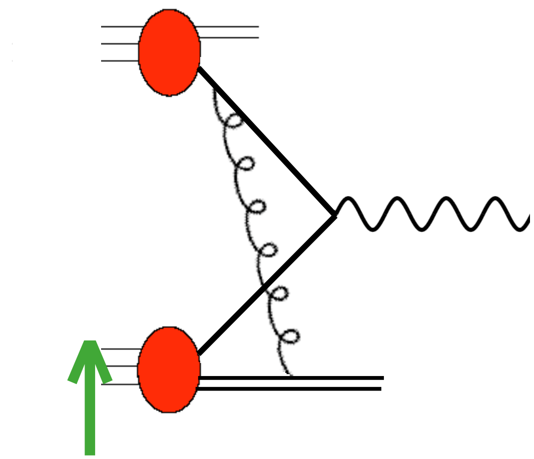


- profound physics implication:

  → process-dependence of Sivers functions

DIS: "attractive" DY: "repulsive"





$$\mathrm{Sivers}|_{\mathrm{DIS}} = -\mathrm{Sivers}|_{\mathrm{DY}}$$

- 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 $pp \to jet+jet\ X$ at RHIC (now data!)

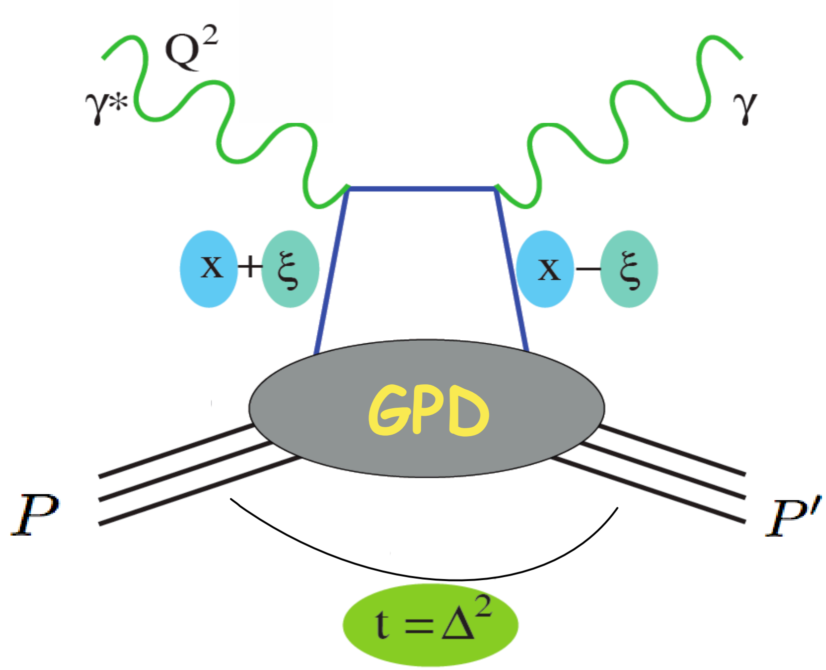
- detailed studies of azimuthal asymmetries in SIDIS at EIC at high Q^2

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 frac^n
- ξ: "skewing parameter" $= x_1 - x_2$
- t: 4-momentum transfer^2

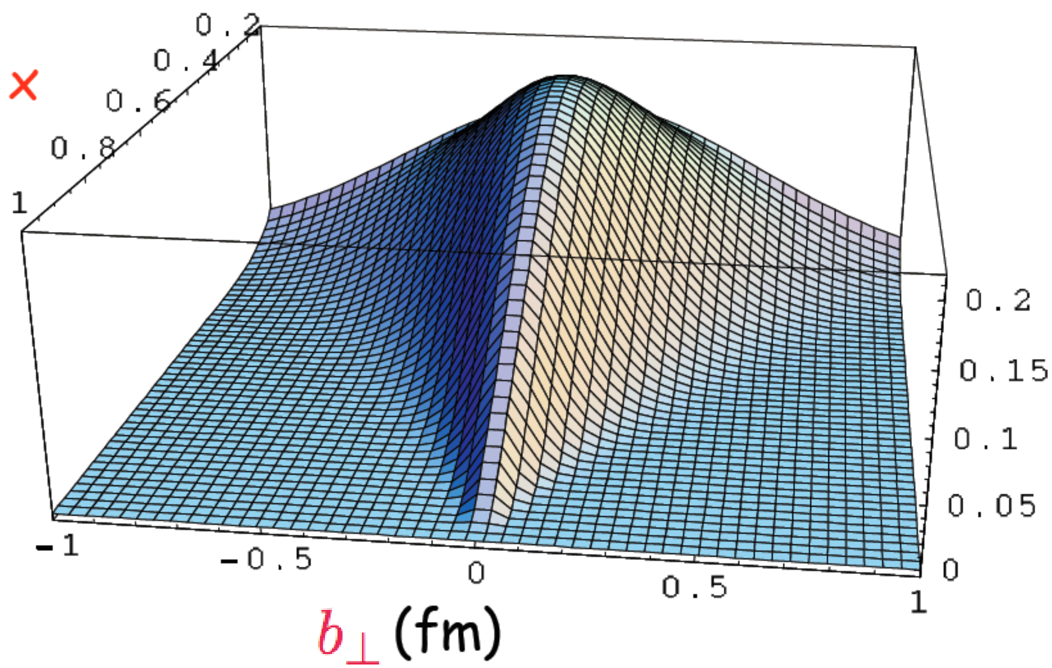
What we dream of:

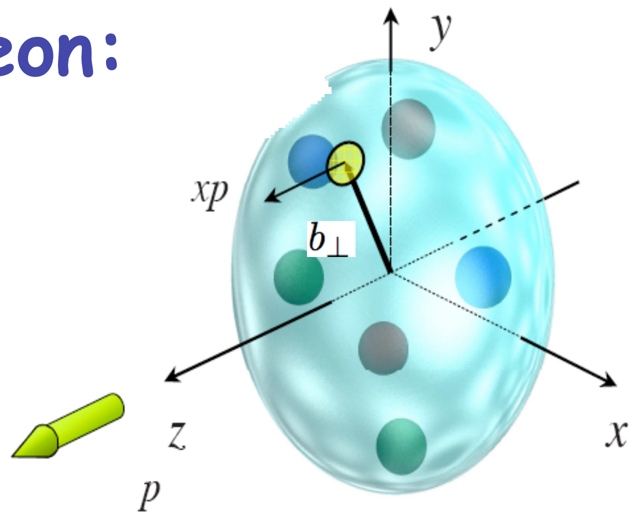
Burkardt; Ji

Tomographic images of the nucleon:

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

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



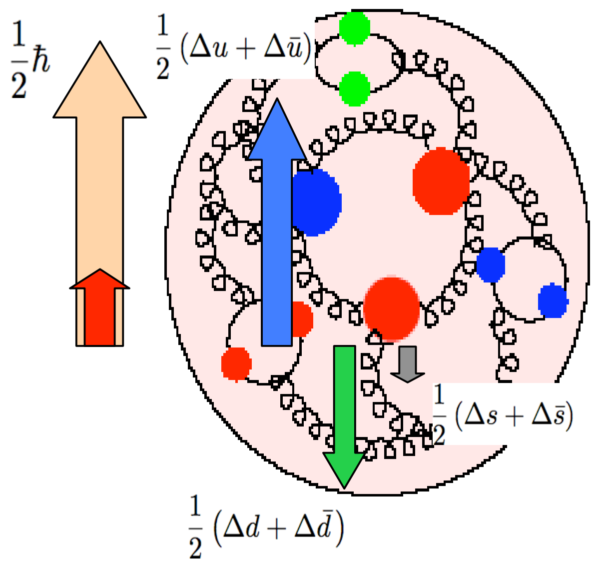


At EIC: spatial distribution of sea and glue

- 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

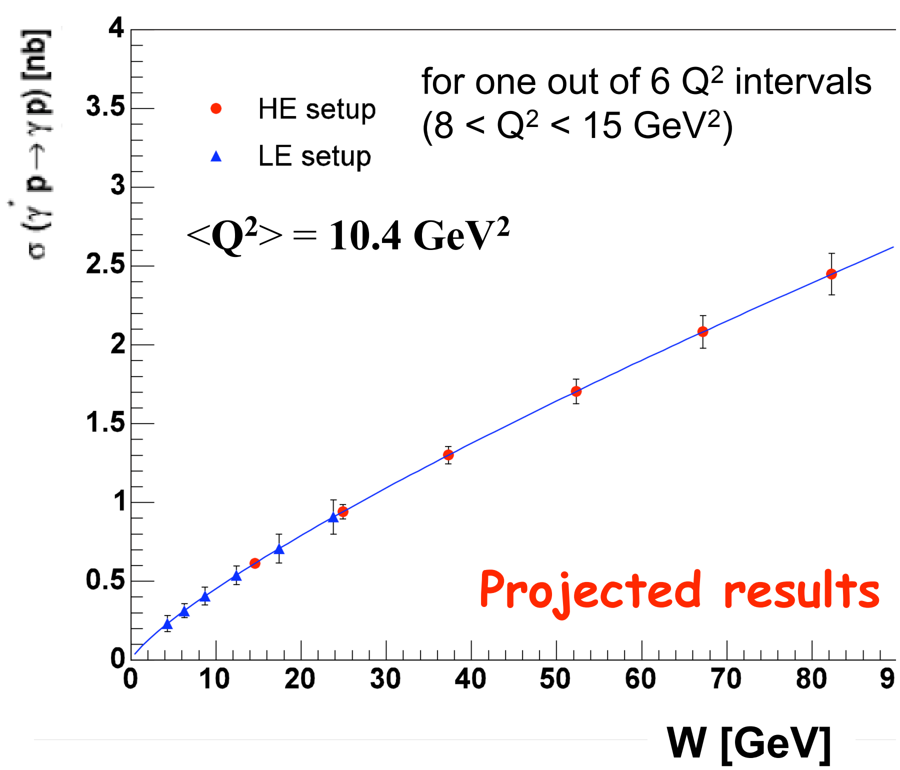
GPDs have potential to take our picture of the nucleon to a new level.

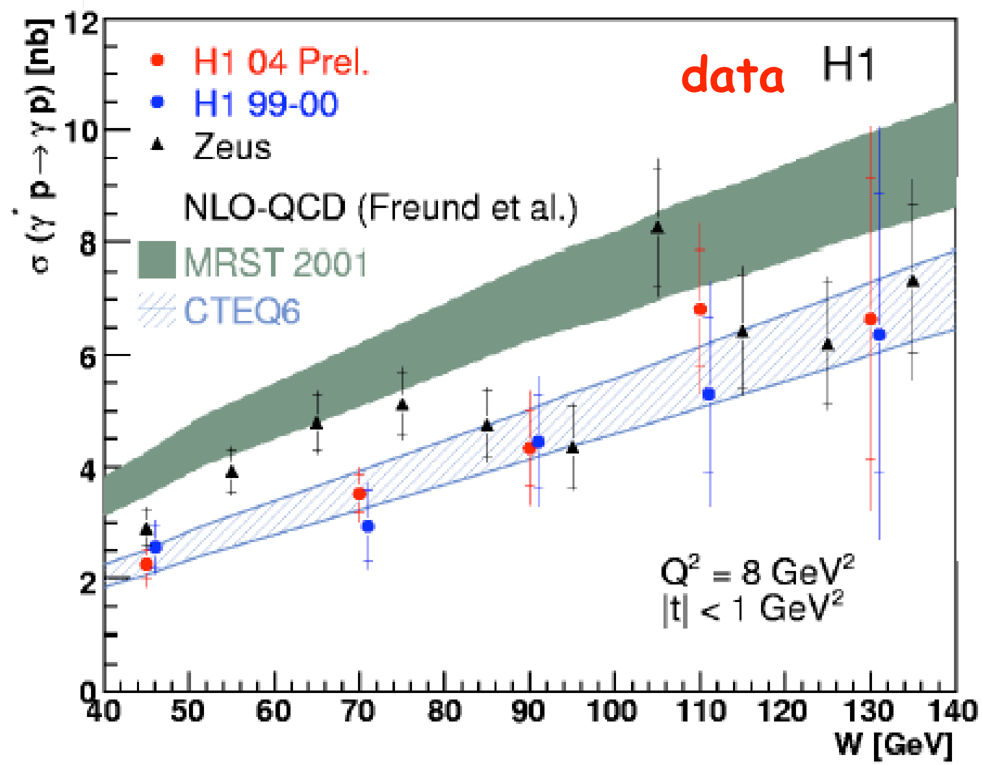
HE setup: $e^{+/-}$ (10 GeV) + p (250 GeV) L = $4.4 \cdot 10^{32}$ cm^{-2}s^{-1} 38 pb^{-1}/day

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



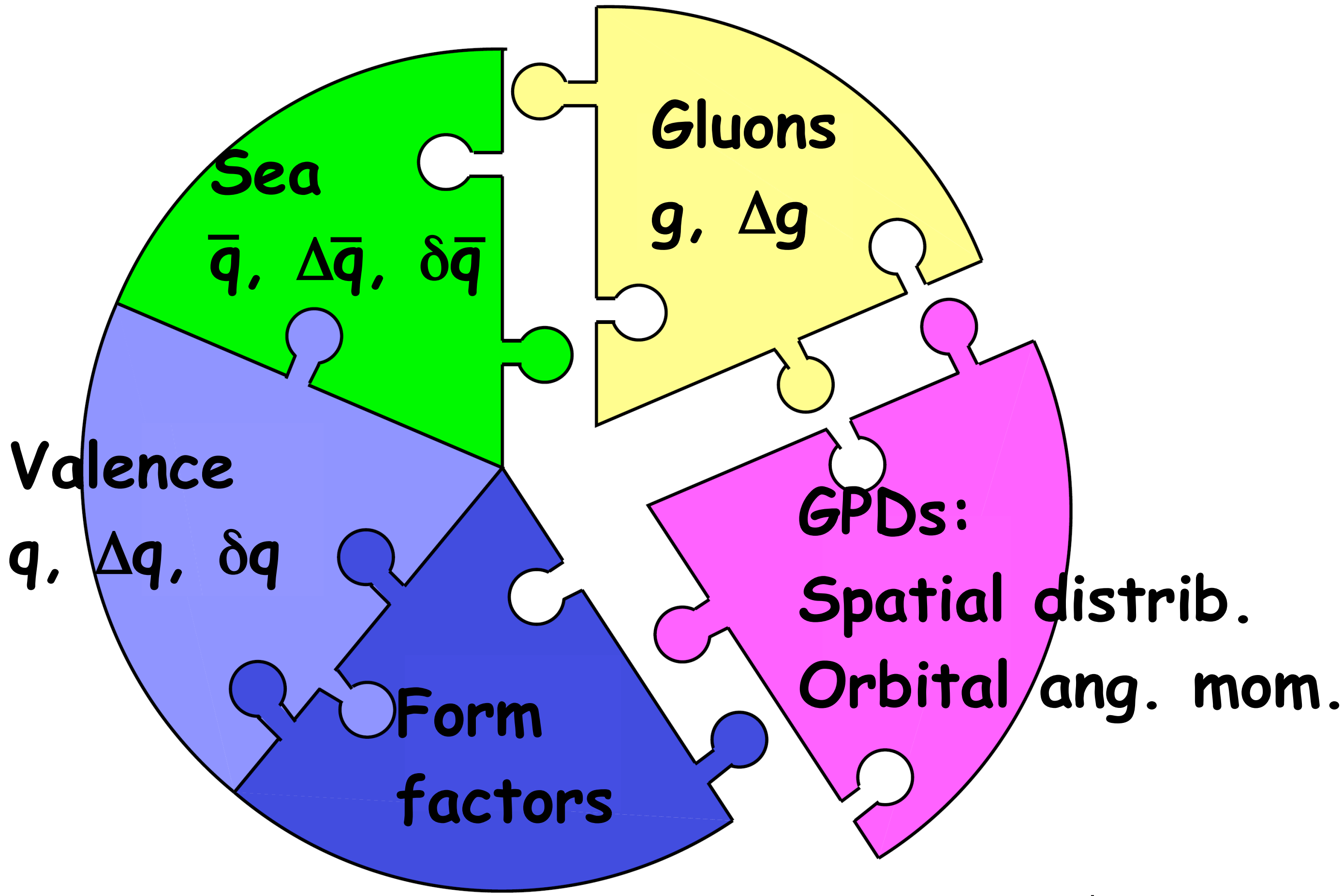


- also: gluon imaging with exclusive J/Ψ

Frankfurt, Strikman, Weiss

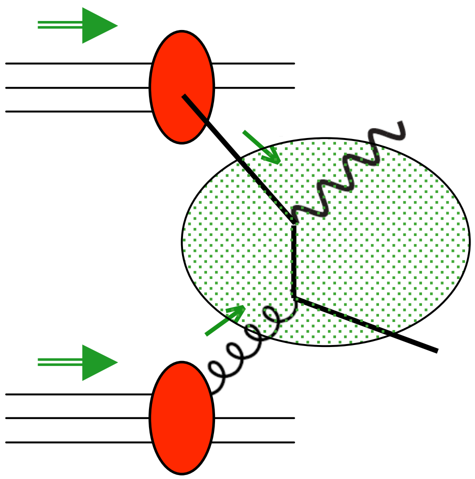
The challenge is: Map out the Nucleon

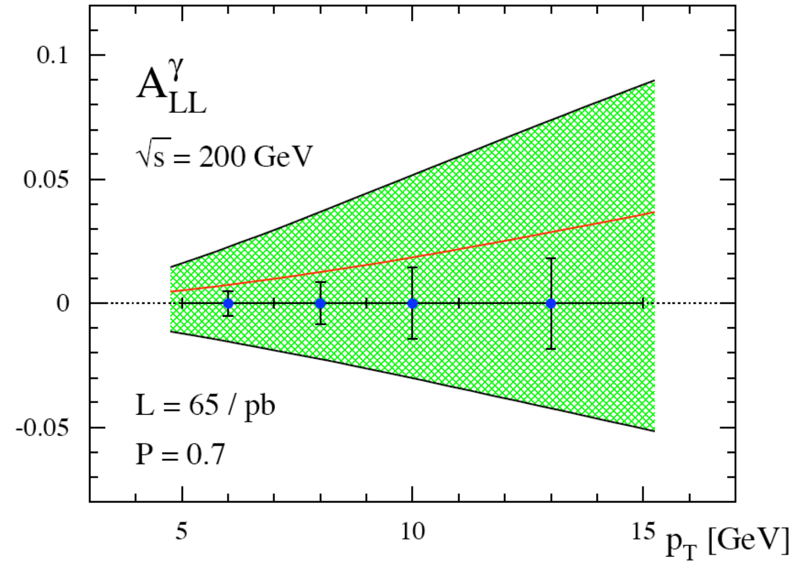
Its complete spin, flavor, gluon landscape



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

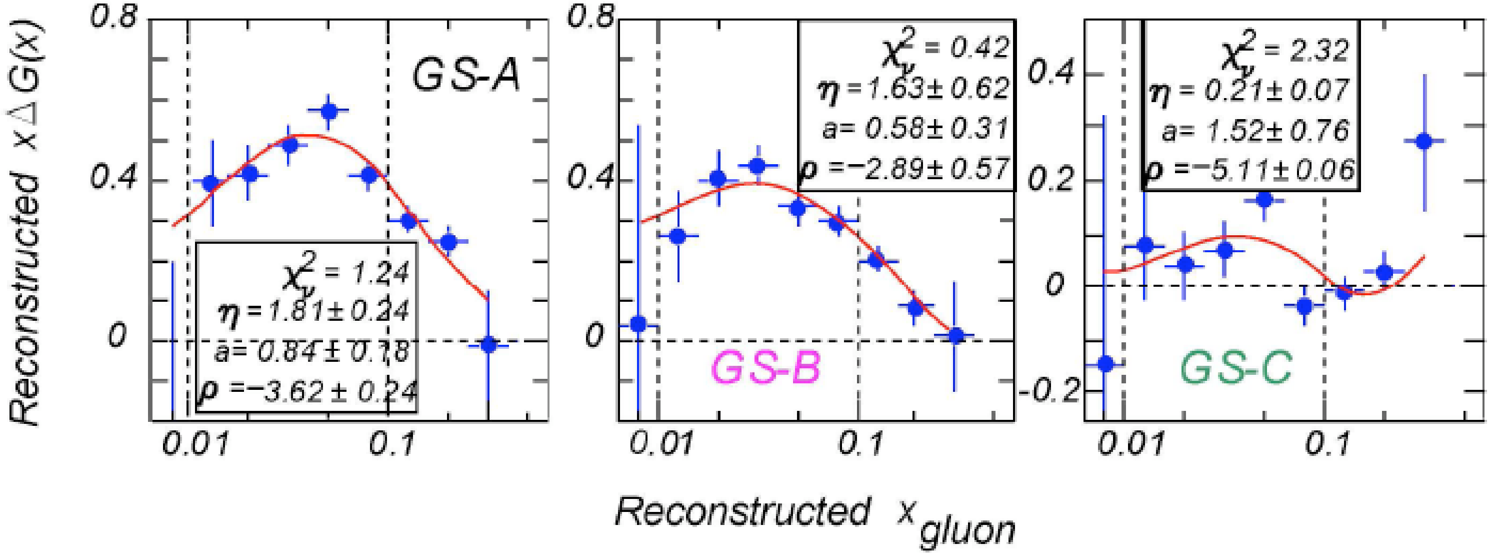
- **a little further into the future: prompt photons**



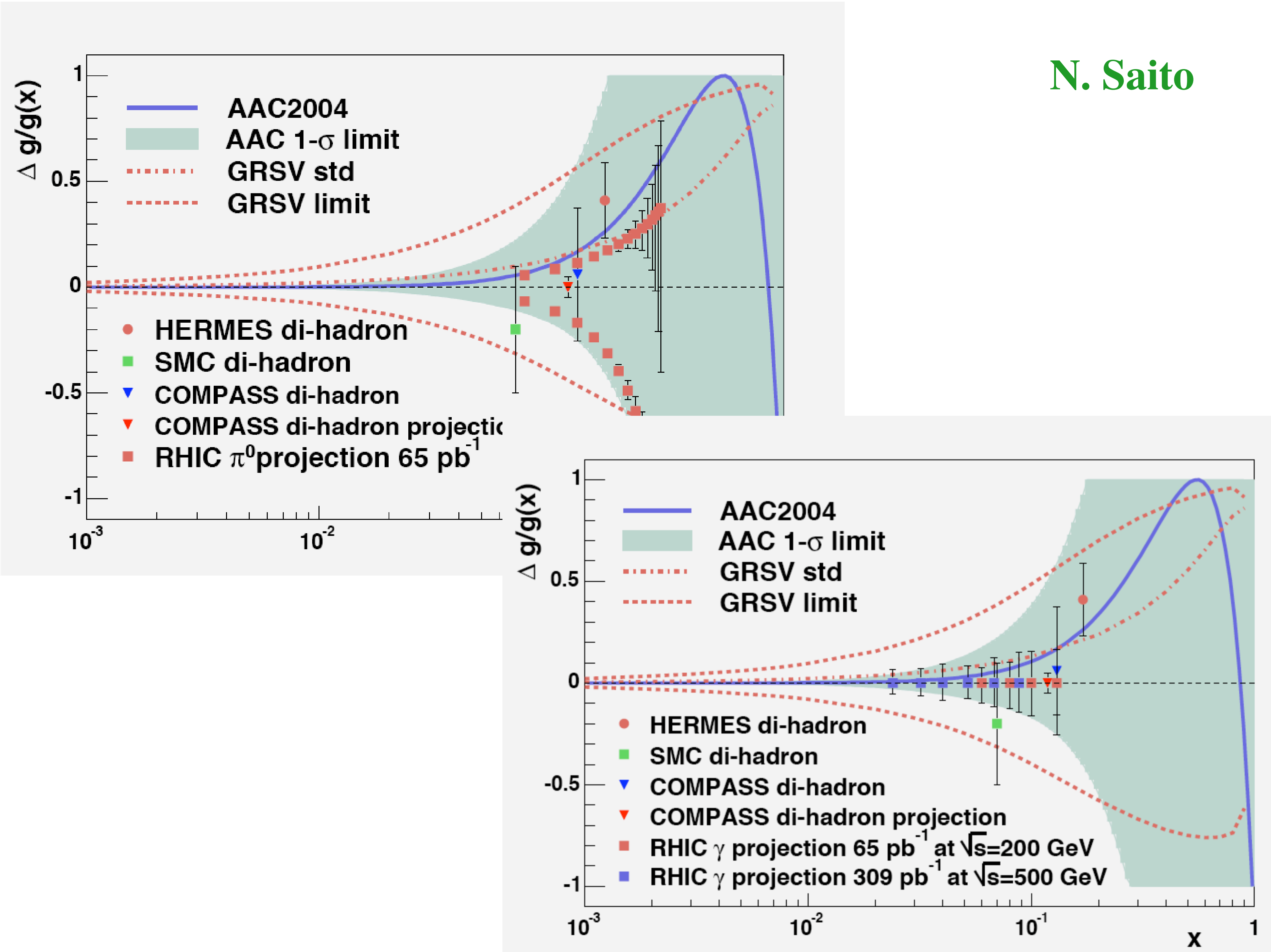


$\vec{p} + \vec{p} \rightarrow \gamma + jet + X$ *with STAR + EEMC at*

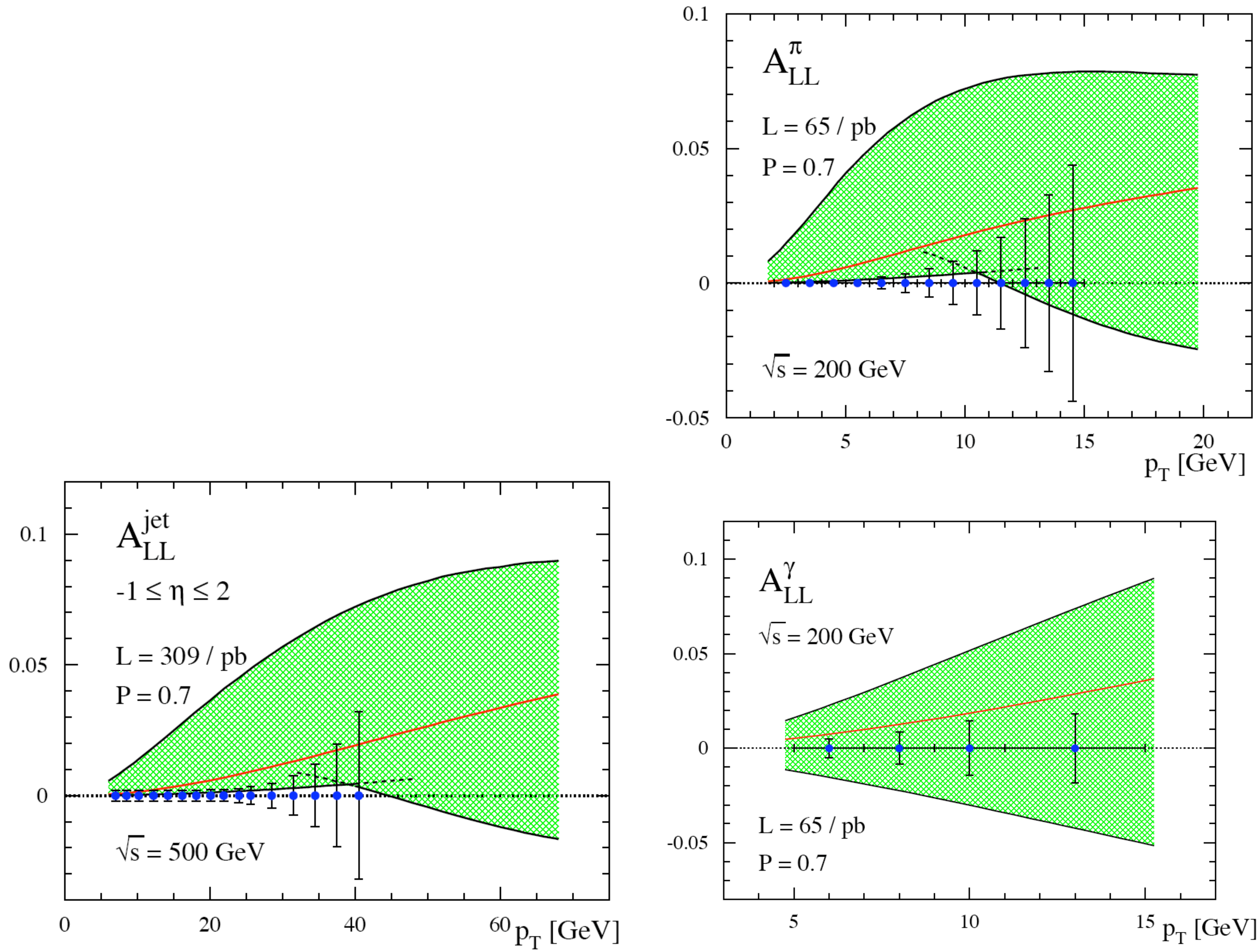
$\sqrt{s} = 200$ *GeV* $(320\ pb^{-1}) + \sqrt{s} = 500$ *GeV* $(800\ pb^{-1})$



N. Saito



Δ g/g(x)
AAC2004
AAC 1-σ limit
GRSV std
GRSV limit
HERMES di-hadron
SMC di-hadron
COMPASS di-hadron
COMPASS di-hadron projectic
RHIC π0projection 65 pb-1
1
0.5
0
-0.5
-1
10-3
10-2
Δ g/g(x)
AAC2004
AAC 1-σ limit
GRSV std
GRSV limit
HERMES di-hadron
SMC di-hadron
COMPASS di-hadron
COMPASS di-hadron projection
RHIC γ projection 65 pb-1 at √s=200 GeV
RHIC γ projection 309 pb-1 at √s=500 GeV
1
0.5
0
-0.5
-1
10-3
10-2
10-1
1
x

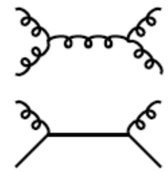
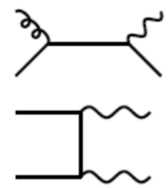
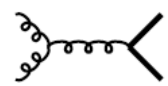
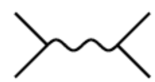
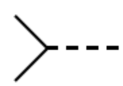


A_{LL}^{π}
L = 65 / pb
P = 0.7
$\sqrt{s}$ = 200 GeV
0.1
0.05
0
-0.05
0
5
10
15
20
p_T [GeV]
A_{LL}^{jet}
$-1 \leq \eta \leq 2$
L = 309 / pb
P = 0.7
$\sqrt{s}$ = 500 GeV
0.1
0.05
0
0
20
40
60
p_T [GeV]
A_{LL}^{γ}
$\sqrt{s}$ = 200 GeV
L = 65 / pb
P = 0.7
0.1
0.05
0
-0.05
5
10
15
p_T [GeV]

RHIC offers great possibilities to probe Δg :

Δg

$\Delta\bar{q}$

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \mathrm{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$ [77]	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80]	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$ [78]	$\vec{q}\vec{\bar{q}} \to Z^0$, $\vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm$, $q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

Jäger,Schäfer, Stratmann,WV

Jäger,Stratmann,WV; Signer et al.

Gordon,WV; Contogouris et al.; Gordon, Coriano

Stratmann, Bojak

Weber; Gehrmann; Kamal

NLO corrections known in all cases.