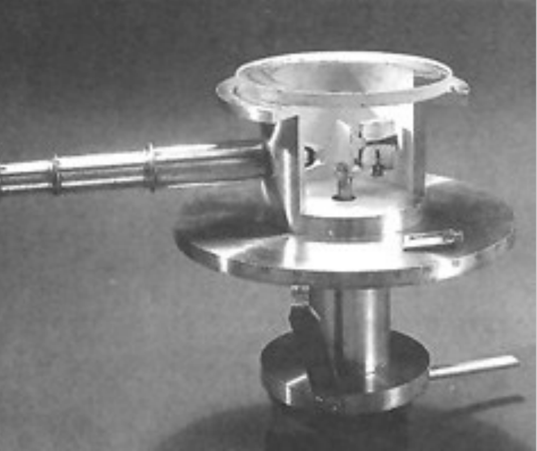
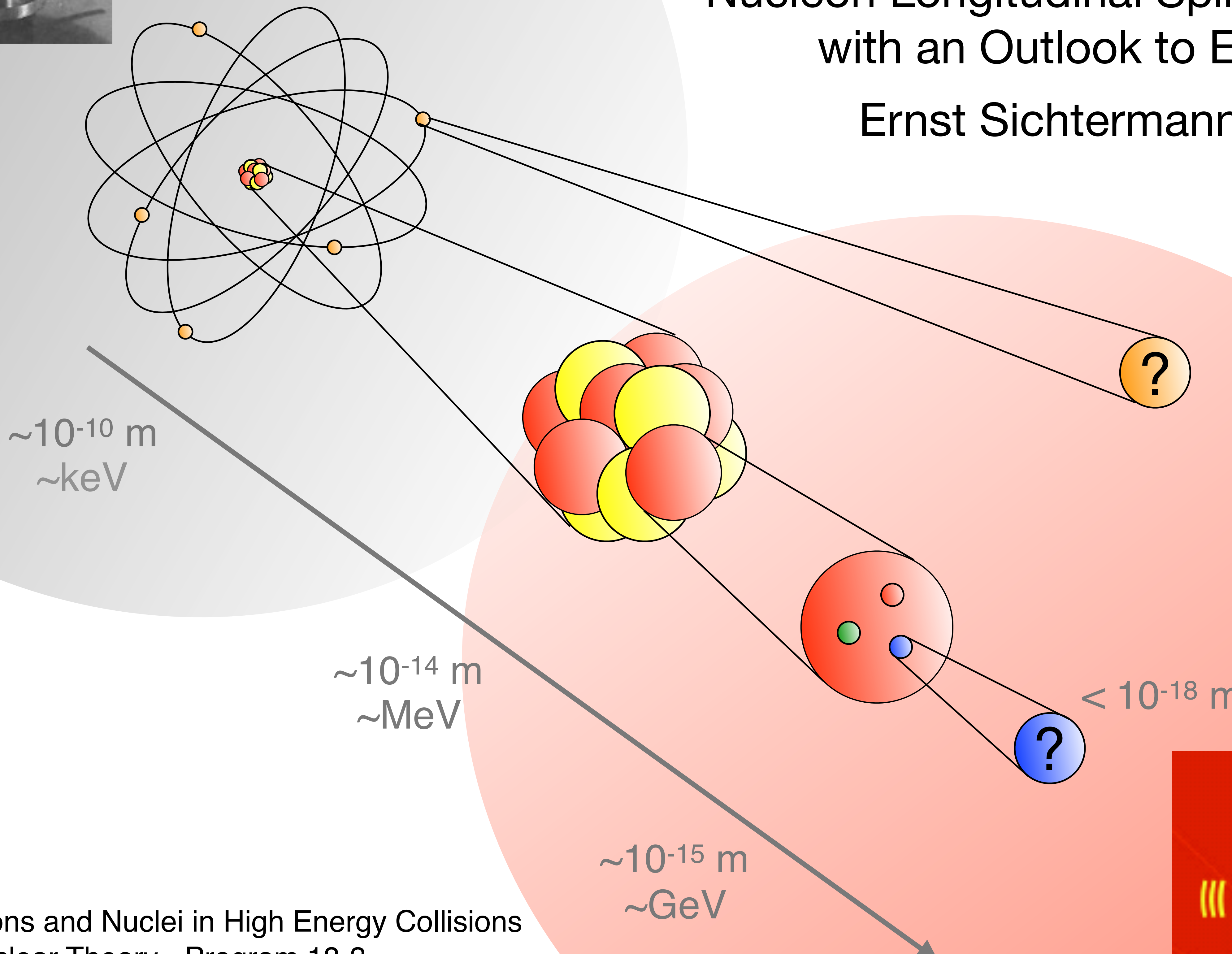


Nucleon Longitudinal Spin Status with an Outlook to EIC

Ernst Sichtermann

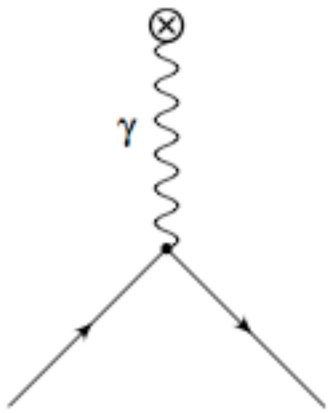


Probing Nucleons and Nuclei in High Energy Collisions
Institute for Nuclear Theory - Program 18-3
Seattle, WA - October 23, 2018

Proton Magnetic Moment - circa 1935

- The magnetic moment $\vec{\mu}$ of a particle is related to its spin $\vec{S}$ according to:

$$\vec{\mu} = g \frac{e}{2mc} \vec{S}$$



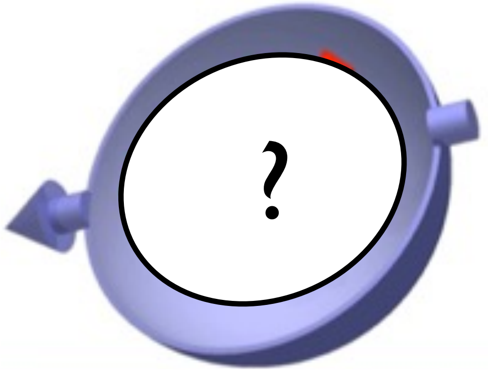
$$g = 2 + \mathcal{O}(\alpha_{\mathrm{e}})$$

for Dirac particles

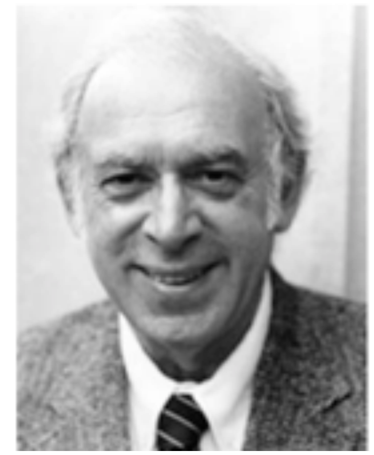
- 1933 - Frisch and Stern:

$$\vec{\mu}_p = 5.8 \frac{e}{2mc} \vec{S}_p$$ - *Proton has (spin-)substructure*

But, what is it?



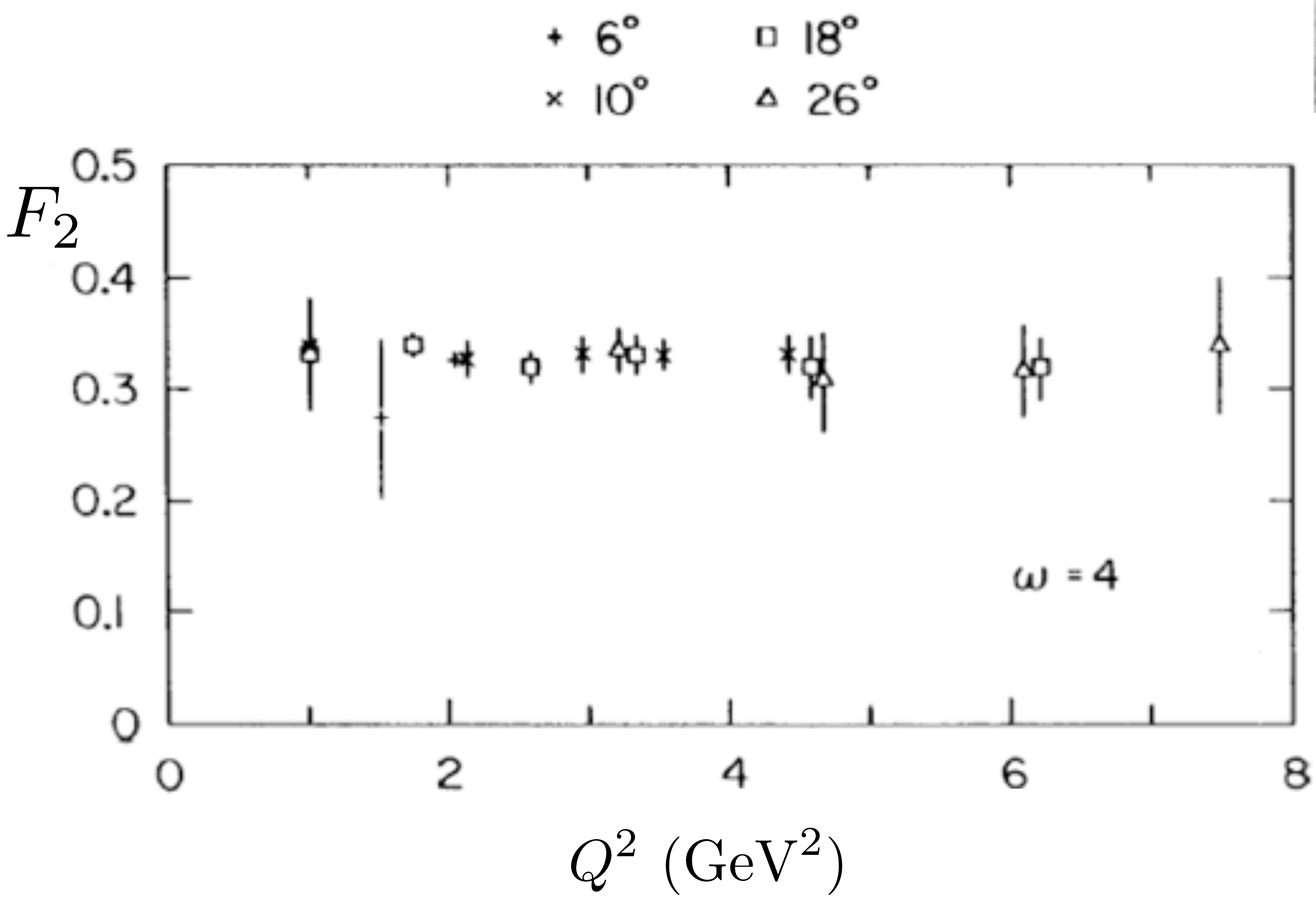
Deep-Inelastic Electron Scattering


J.T. Friedman

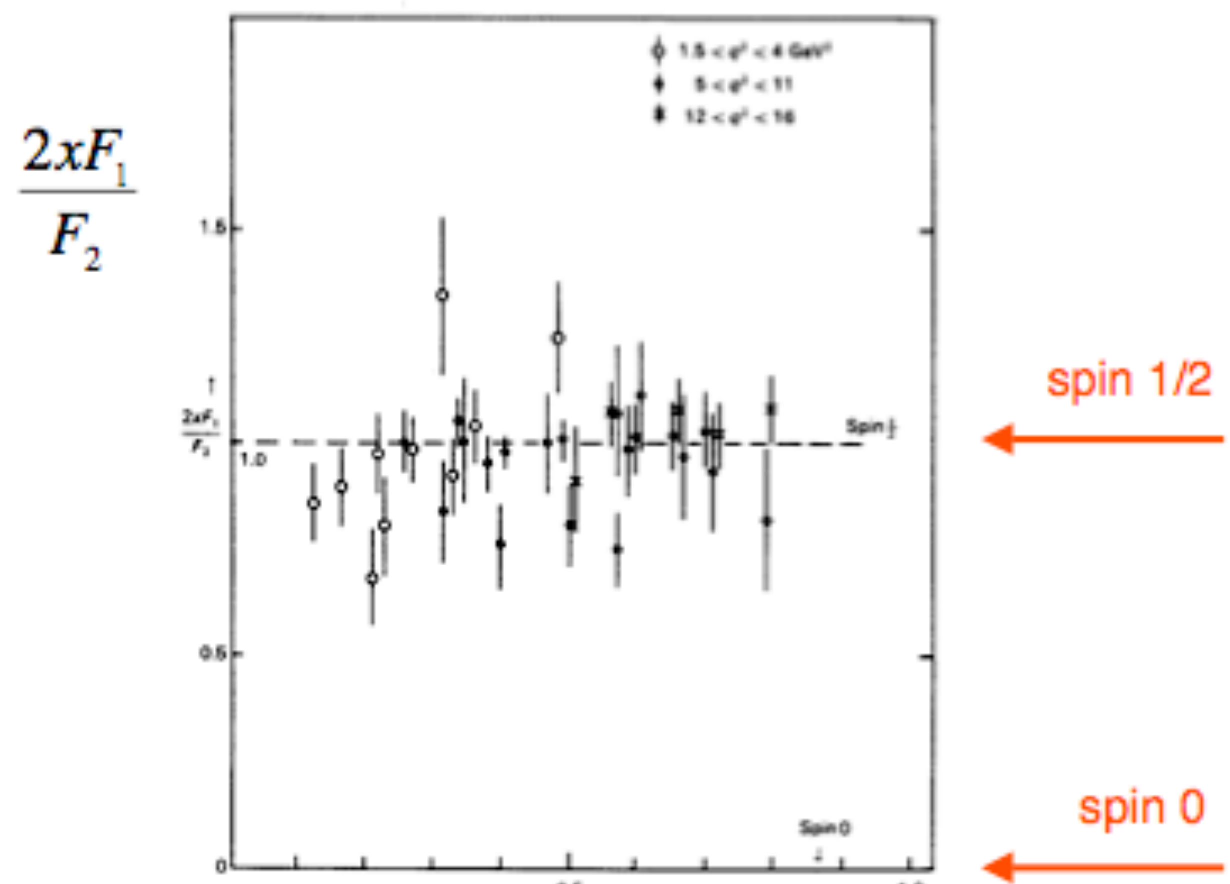

R. Taylor
Nobel Prize 1990


H.W. Kendall

Bjorken scaling:



Callan-Gross relation:



Point particles cannot be further resolved; their measurement does not depend on wavelength, hence Q^2,

Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.

Proton Structure

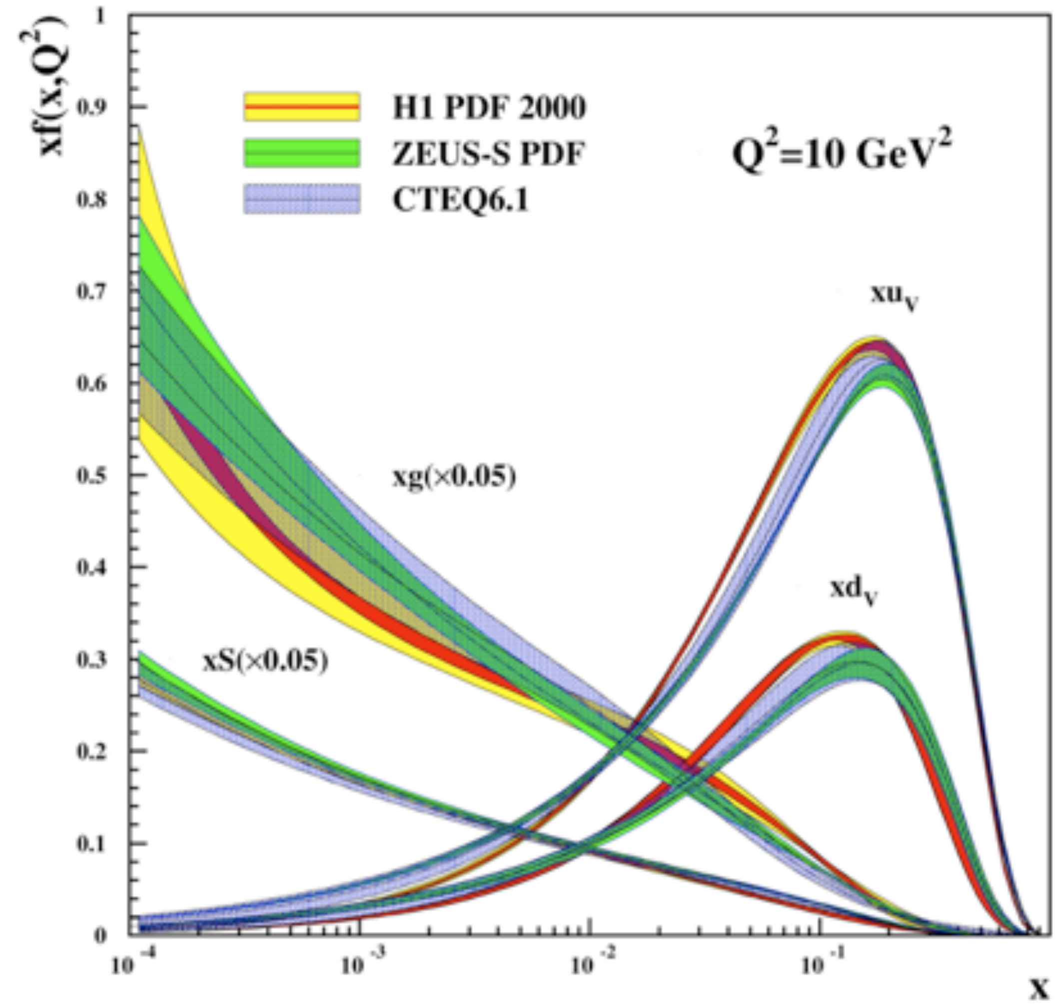
- Development of the (initial) quark-parton model,

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 q(x)$$

$$F_2(x) = x\sum_q e_q^2 q(x)$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x) \qquad +\mathcal{O}(\alpha_s)$$

$$h_1(x) = \frac{1}{2}\sum_q e_q^2 \delta q(x)$$



improved by perturbative QCD radiation.

- Gluons *dominate*; responsible for ~98% of observed mass, carry ~50% of the proton momentum, *role(s) in nucleon spin?*

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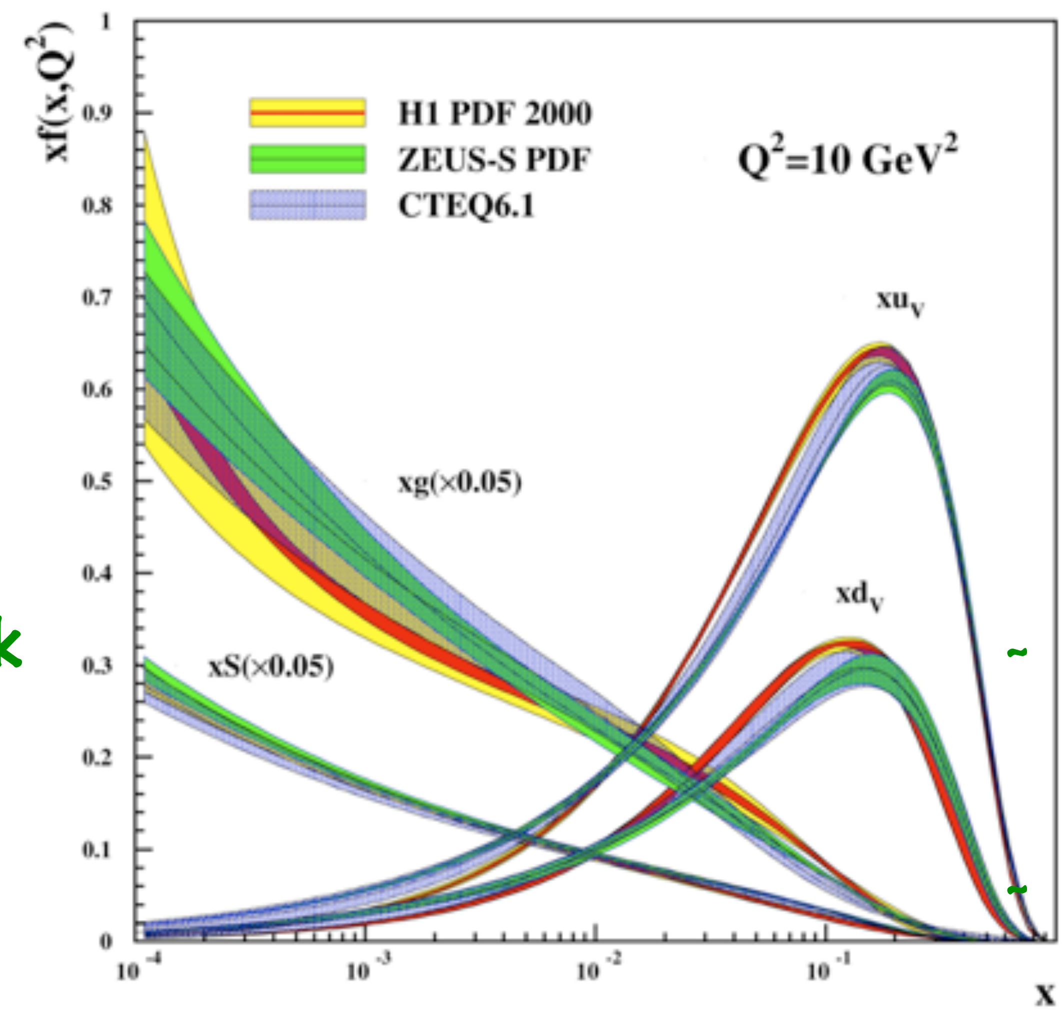
$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x)$$ much of this talk

$$h_1(x) = \frac{1}{2}\sum_q e_q^2 \delta q(x)$$ c.f. Marco's talk



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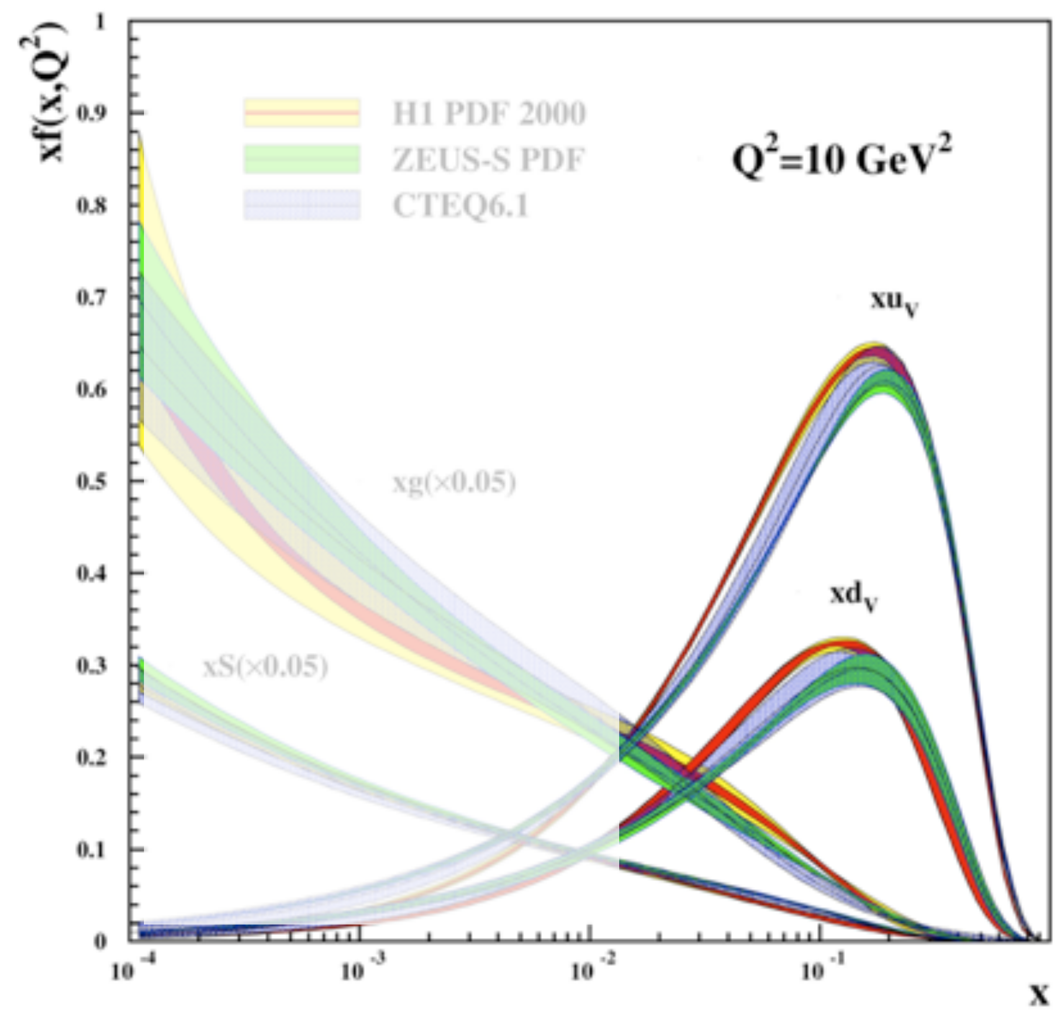


- Naively,

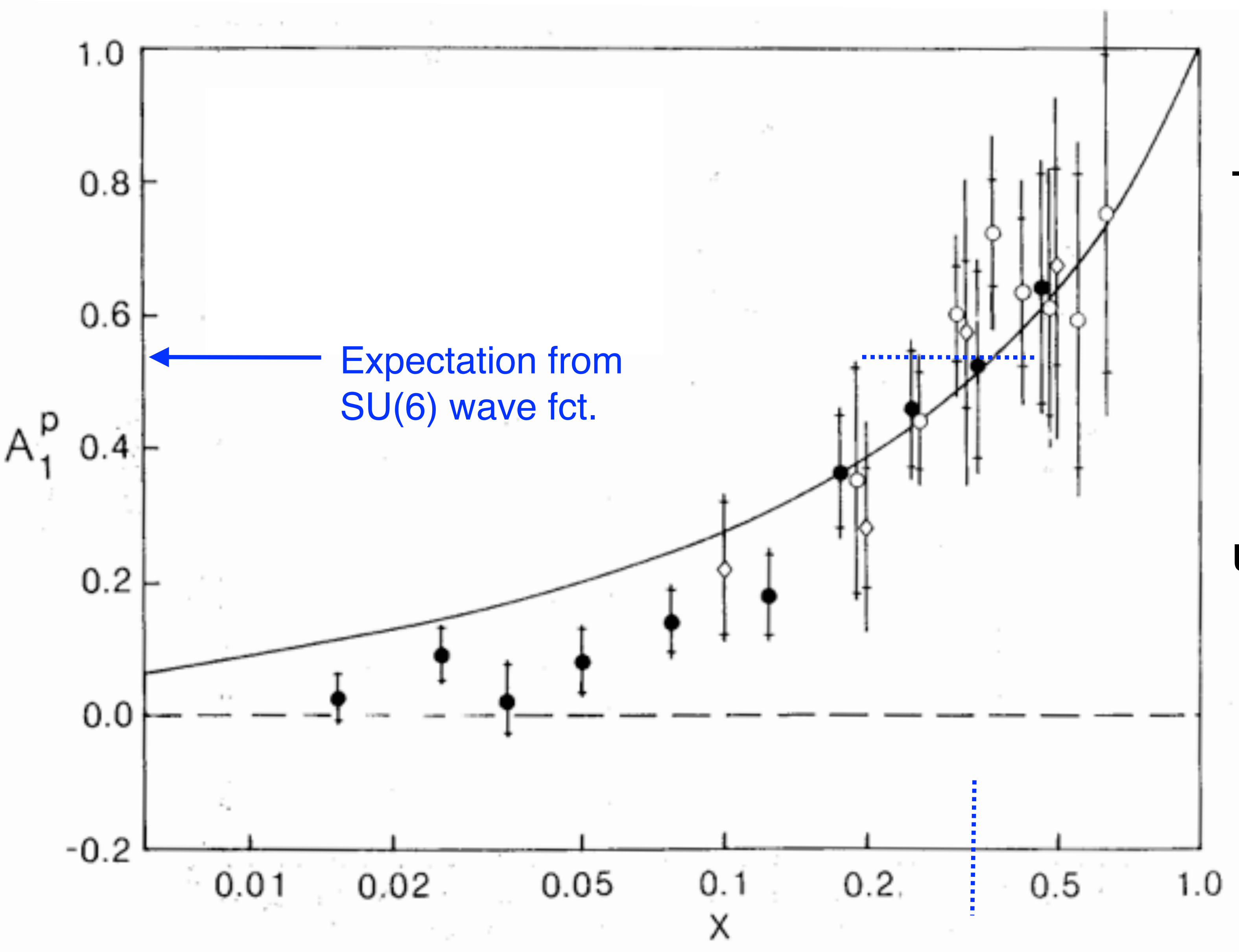
$$g_{\text{proton}}(\text{QPM}) \simeq 5.6 \quad \surd$$

and perhaps even more naive,

$$A_1^{\text{p}}(x) \equiv \frac{g_1(x)}{F_1(x)} \simeq \frac{5}{8}$$

Proton spin

Early measurements:



The spin asymmetry,

$$A_1^{\mathrm{p}} \simeq \frac{\Delta\sigma}{\sigma} \simeq \frac{\sum e_q^2 (q^\uparrow - q^\downarrow)}{\sum e_q^2 (q^\uparrow + q^\downarrow)}$$

undershoots expectation.

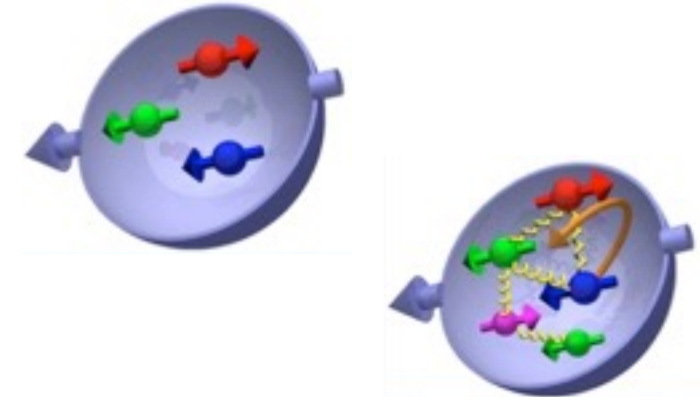
European Muon Collaboration (1989)

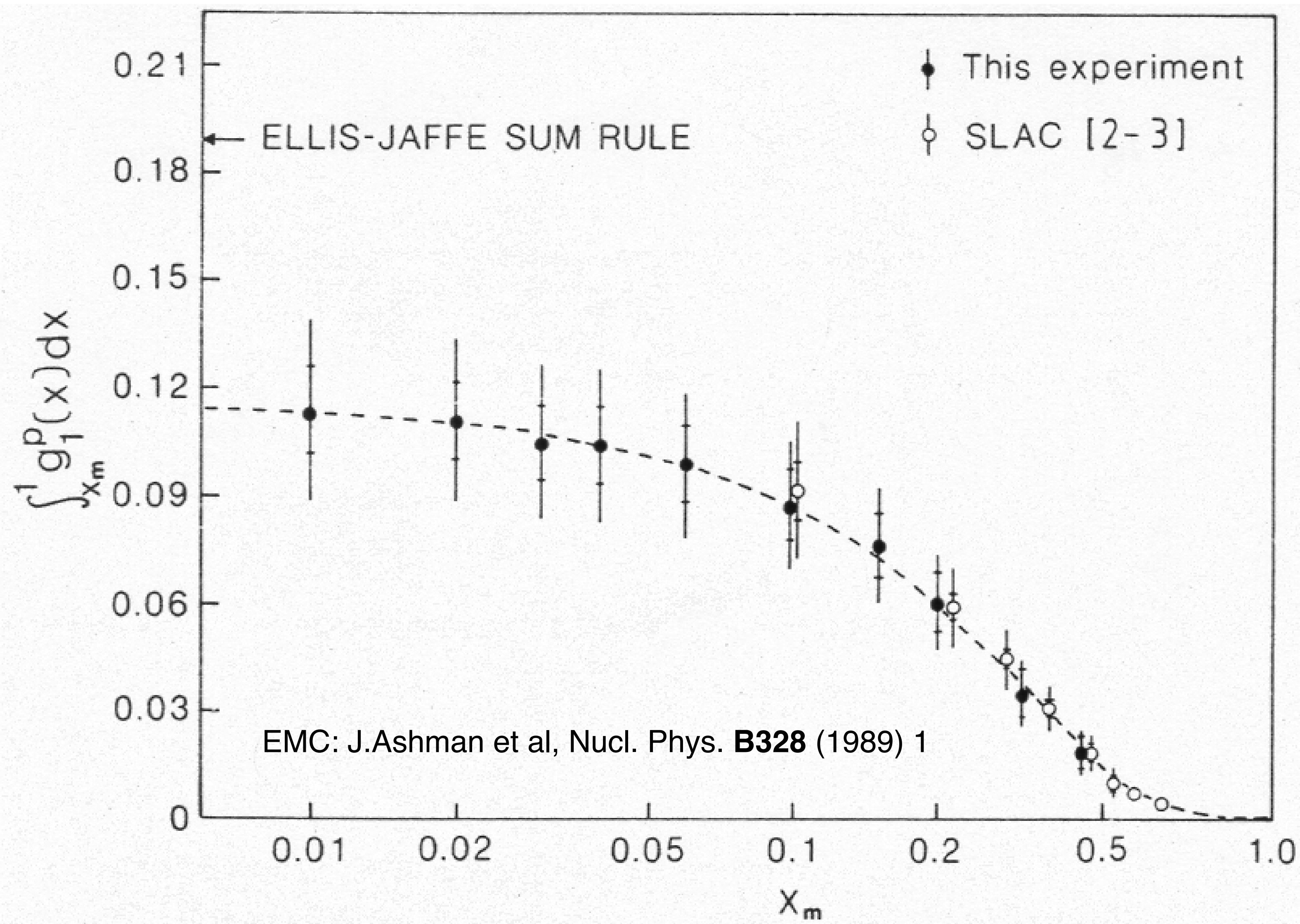
Naively,

$$A_1^{\mathrm{p}}(x) \equiv \frac{g_1(x)}{F_1(x)} \simeq \frac{5}{8}$$

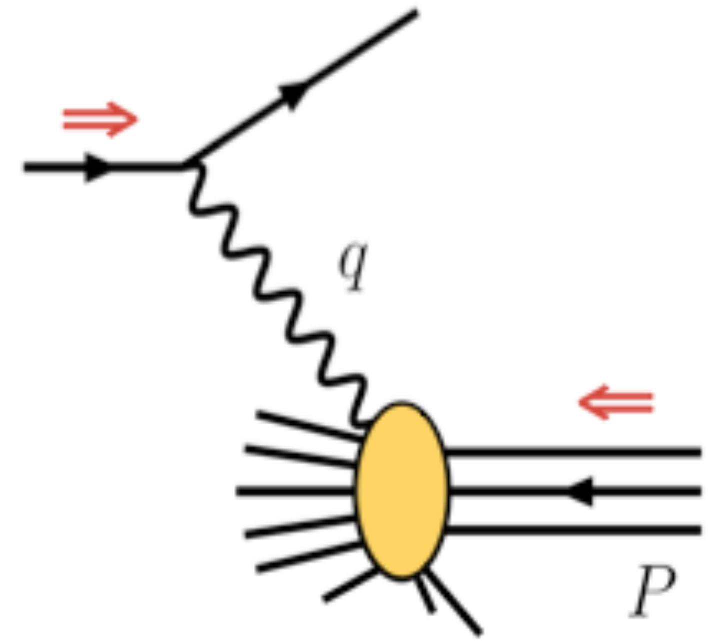
Better, relate $\int g_1(x)\mathrm{d}x$ to the couplings in weak n and Σ^- decays.

Proton spin



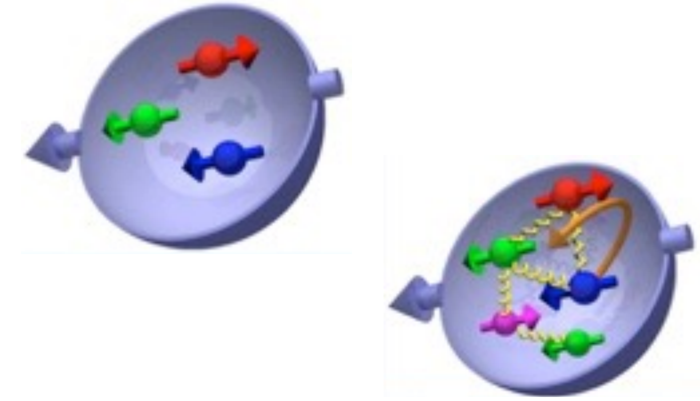


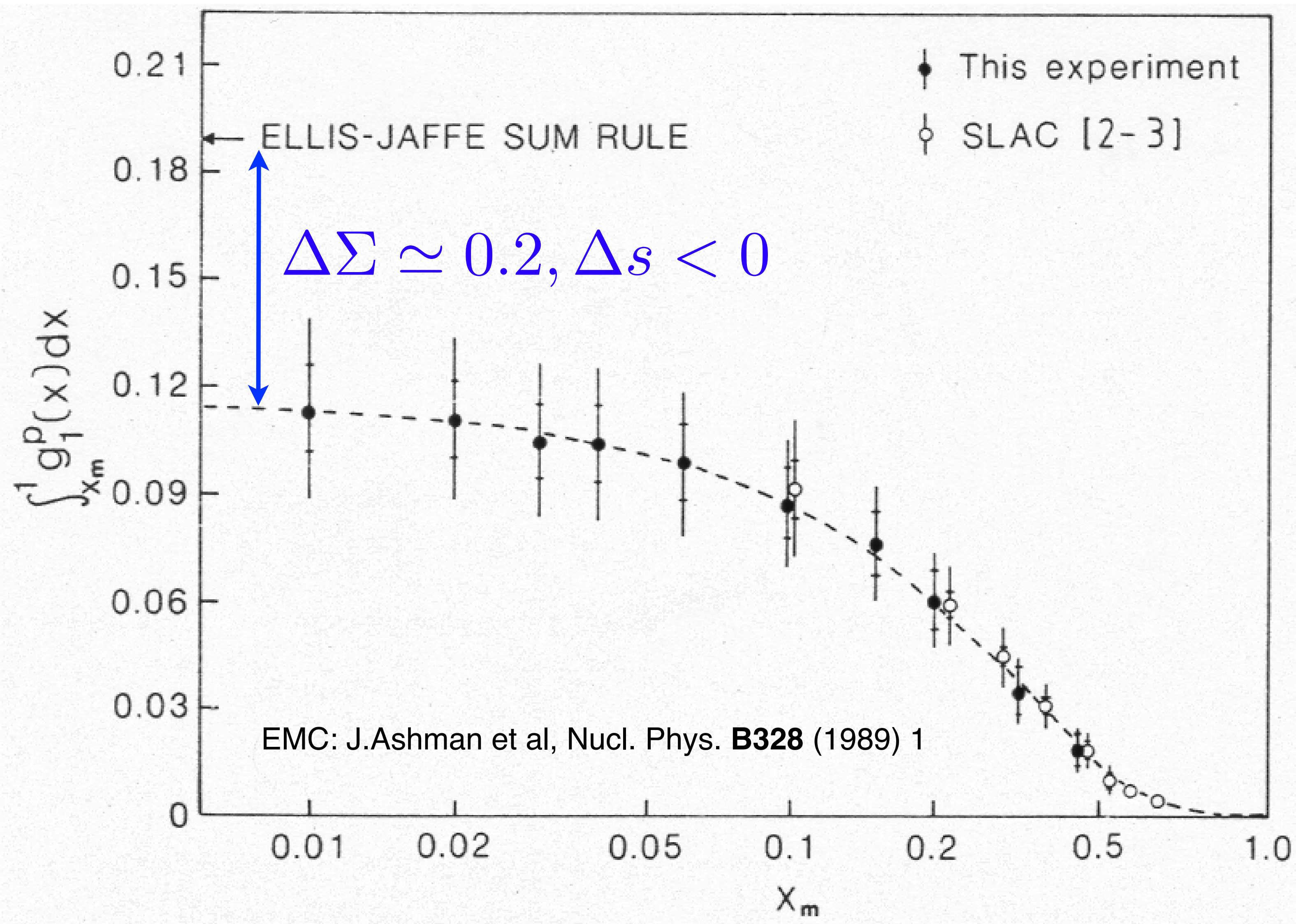
EMC: J.Ashman et al, Nucl. Phys. **B328** (1989) 1



$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x,Q^2)}$$

Proton spin





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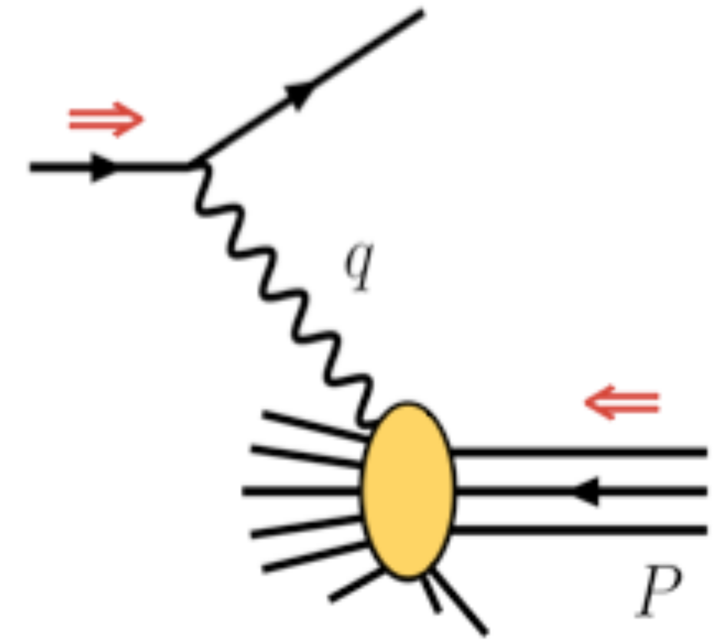
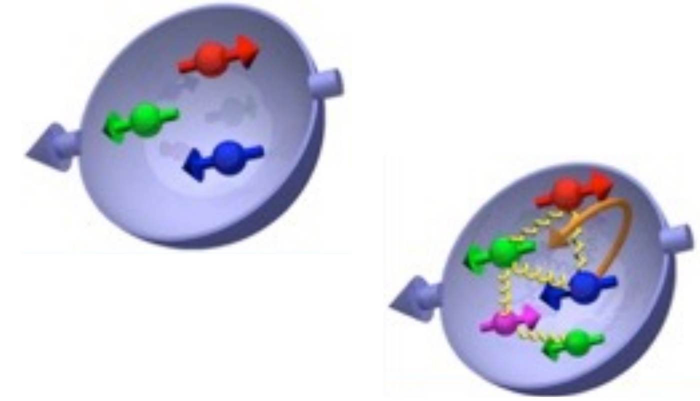


$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x, Q^2)}$$

“ The sum of quark and anti-quark spins contribute little to the proton spin, and strange quarks are negatively polarized. ”

Proton spin



For the proton,

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x = \int_0^1 \left(\frac{1}{2}\sum e_q^2 \Delta q(x)\right)\mathrm{d}x = \frac{1}{2}\left(\frac{4}{9}\Delta_1 u + \frac{1}{9}\Delta_1 d + \frac{1}{9}\Delta_1 s\right)$$

$$= \frac{1}{12}\left(\Delta_1 u - \Delta_1 d\right) + \frac{1}{36}\left(\Delta_1 u + \Delta_1 d - 2\Delta_1 s\right) + \frac{1}{9}\left(\Delta_1 u + \Delta_1 d + \Delta_1 s\right)$$

Unique to DIS, $\Delta\Sigma$

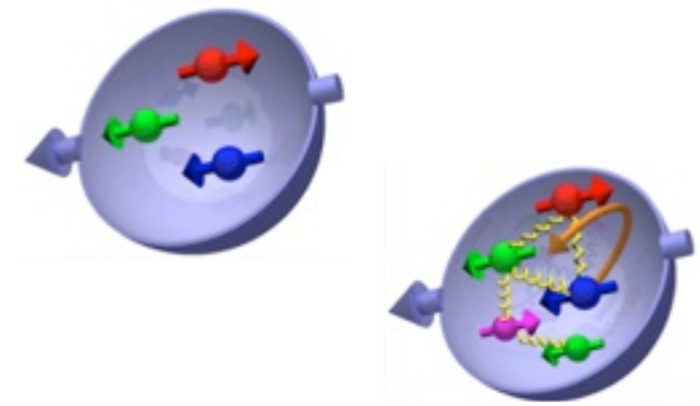
Known from weak neutron to proton decay, combined with weak Σ to neutron decay

Known from weak neutron to proton decay

which becomes a prediction if $\Delta_1 s = 0$

No (reliable) substitute for energy; $x \propto 1/\sqrt{s}$

Proton spin



For the proton,

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$$= \frac{1}{12}(\Delta_1 u - \Delta_1 d) + \frac{1}{36}\underbrace{(\Delta_1 u + \Delta_1 d - 2\Delta_1 s)}_{a_8 \;=\; 3F-D \;=\; 0.59\pm 0.03} + \frac{1}{9}(\Delta_1 u + \Delta_1 d + \Delta_1 s)$$

✓ < 10%

Known from weak neutron to proton decay, combined with weak ∑ to neutron decay

Unique to DIS, ΔΣ

Since,

$$\left.\frac{\partial \Gamma_1}{\partial a_8}\right|_{\mathrm{Ellis-Jaffe}} \simeq \frac{5}{36}$$

$$\left.\frac{\partial \Gamma_1}{\partial a_8}\right|_{\mathrm{experiment}} \simeq 0$$

} one *can* recover the E-J expectation with a *sizable* shift of $a_8 = 3F - D,\ a_8 \simeq 0.2 \pm 0.1$

Proton spin - SU(3)

Such a *sizable* shift, however, is hard to support from (new) data:

Table 1. Present world HSD rate and angular-correlation data [14]. Numerical values marked g_1/f_1 are as extracted from angular and spin correlations.

Decay $A \to B\ell\nu$	Rate$(10^6\,\mathrm{s}^{-1})$ $\ell = e^{\pm}$	Rate$(10^6\,\mathrm{s}^{-1})$ $\ell = \mu^-$	g_1/f_1 $\ell = e^-$	g_1/f_1 SU(3)	
$n \to p$	1.1291 ± 0.0010		1.2670 ± 0.0030	$F + D$	Close & Roberts
$\Lambda^0 \to p$	3.161 ± 0.058	0.60 ± 0.13	0.718 ± 0.015	$F + \frac{1}{3}D$	Close & Roberts
$\Sigma^- \to n$	6.88 ± 0.23	3.04 ± 0.27	-0.340 ± 0.017	$F - D$	Close & Roberts
$\Sigma^- \to \Lambda^0$	0.387 ± 0.018			$-\sqrt{\frac{2}{3}}\,D^{\dagger}$	
$\Sigma^+ \to \Lambda^0$	0.250 ± 0.063			$-\sqrt{\frac{2}{3}}\,D^{\dagger}$	
$\Xi^- \to \Lambda^0$	3.35 ± 0.37	2.1 ± 2.1	0.25 ± 0.05	$F - \frac{1}{3}D$	
$\Xi^- \to \Sigma^0$	0.53 ± 0.10			$F + D$	
$\Xi^0 \to \Sigma^+$	0.876 ± 0.071	0.012 ± 0.007 *	1.32 ± 0.21	$F + D$	KTeV

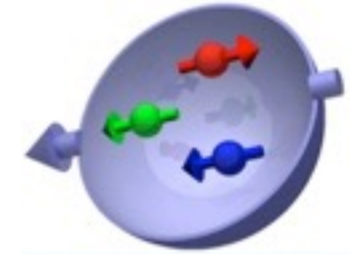
* KTeV data [5]—not included in the fits presented here.

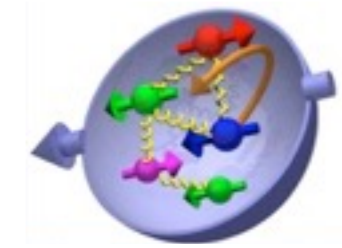
† The absolute expression for g_1 is given, not g_1/f_1 (as $f_1 = 0$).

P. Ratcliffe, Czech J. Phys. 54, A21 (2004).

Smaller shifts have been reported, e.g. by Ehrnsperger (1995), Song (1997), Flores-Mendieta (1998), Yamanashi (2007), Sasaki (2009), …

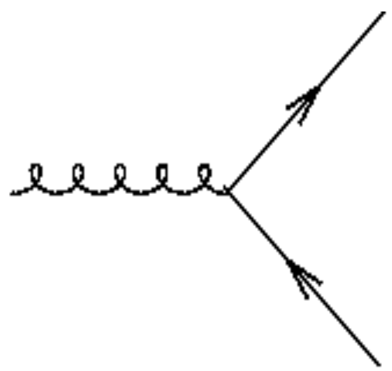
Proton spin





Numerous follow-up questions and experiment programs,

Among the early attempts at a resolution,



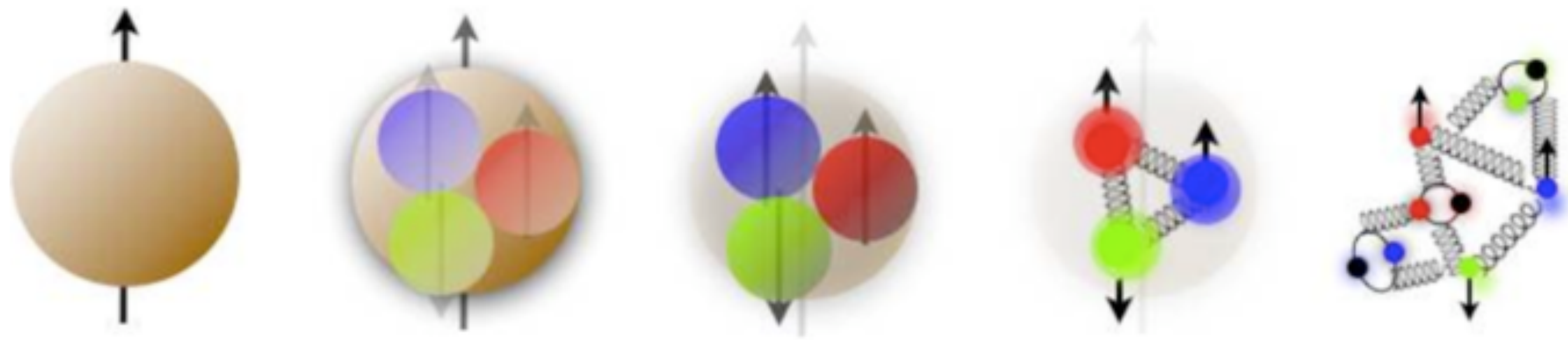
with the gluons *polarized*.

G. Altarelli and G.G. Ross Phys. Lett. **B212** (1998) 391

Note: this attempt requires *very* large polarization,
factors larger than the nucleon spin itself, and
by inference, *huge* compensating *orbital momenta.*
Quite the proton, a ground-state object and all.

Other attempts include e.g extrapolation over unmeasured low-x.

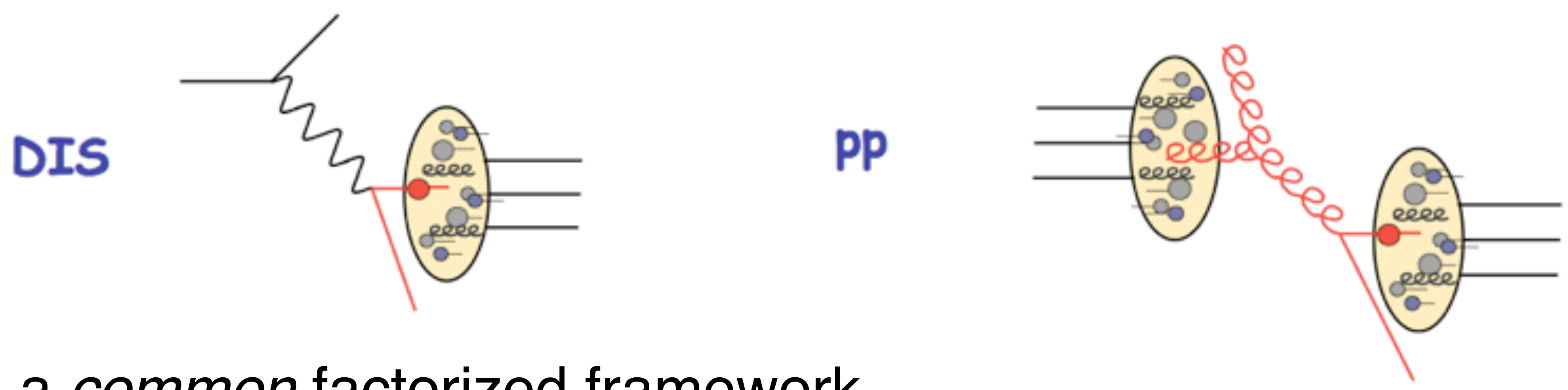
Renewed Interest in Nucleon Spin



What is the nucleon spin decomposition?

What is the role of spin in QCD?

Complementary ways to address several of the open questions,



within a *common* factorized framework.

Nucleon Spin - A World-Wide Quest

SLAC

E142, E143, E154, E155

CERN

EMC, SMC, COMPASS

DESY

HERMES

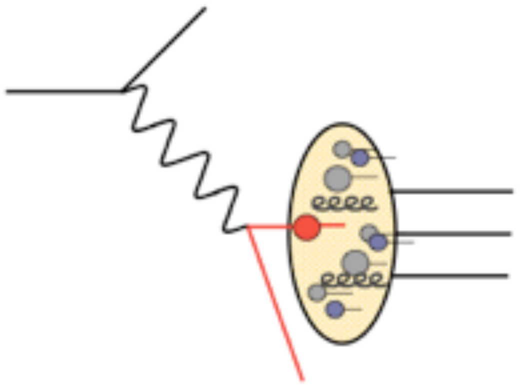
JLab

Hall A, CLAS

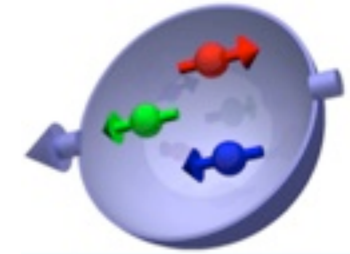
BNL

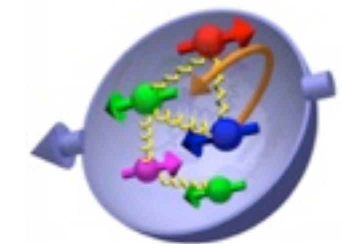
PHENIX, STAR

DIS



DIS - Nucleon spin





For the proton,

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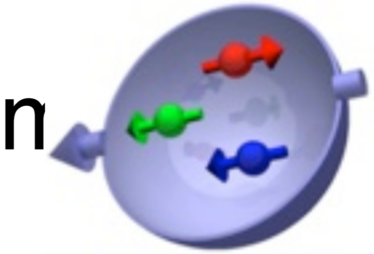
$$+ \mathcal{O}(\alpha_s) \text{ now well known } + \mathcal{O}(1/Q^2)$$

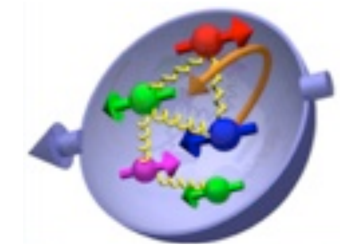
✓ < 10%

Similar can be done for the neutron,

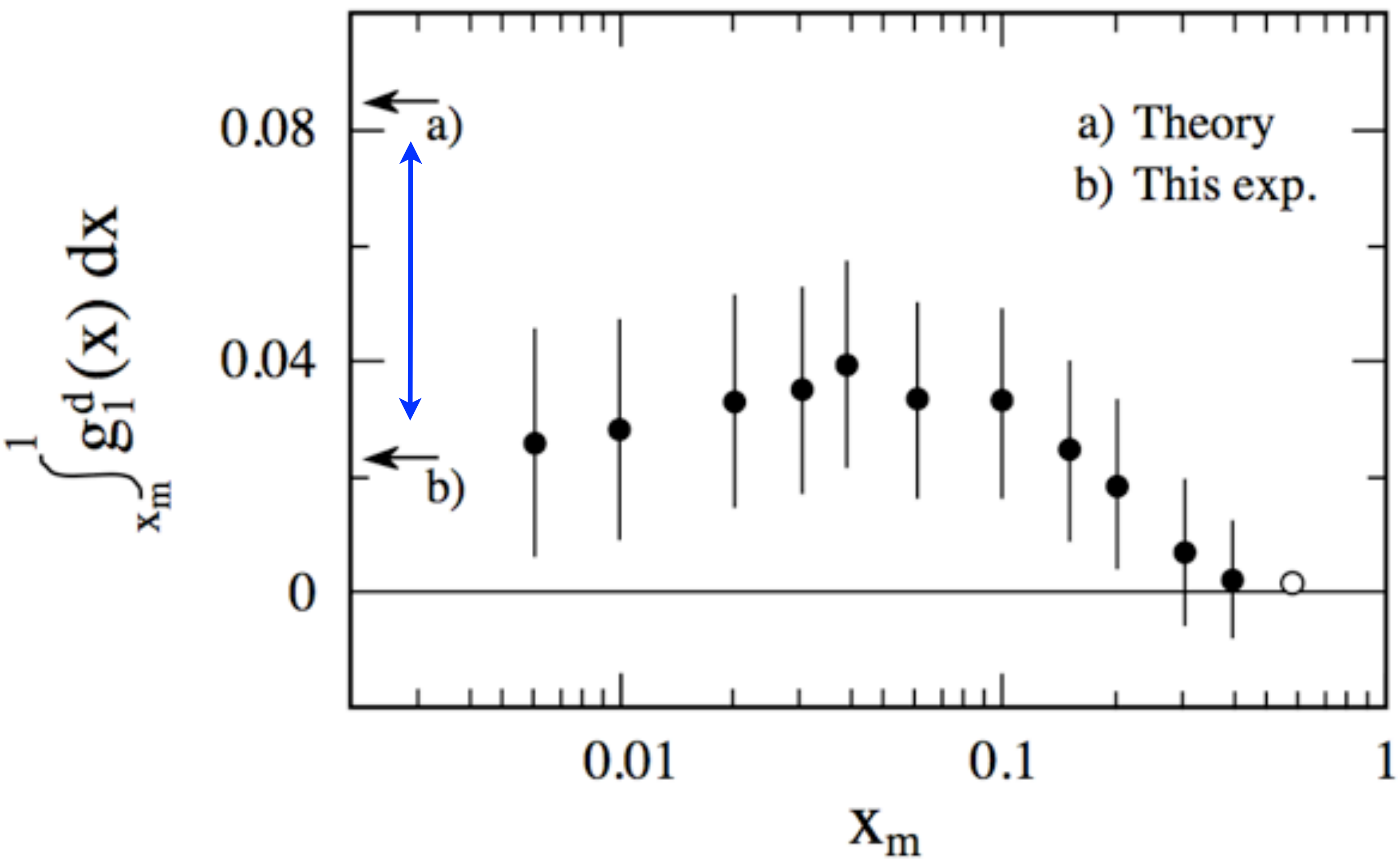
experimentally via the deuteron or ^{3}He,

Nucleon Spin - Bjorken Sum





$$\int_{0.006}^{0.6} g_1^d(x)dx = 0.024 \pm 0.020_{\rm stat} \pm 0.014_{\rm sys}$$



SMC: B.Adeva et al, Phys. Lett. B302, 533 (1993)

$$\Gamma_1^p = 0.126 \pm 0.010_{\rm stat} \pm 0.015_{\rm sys} \quad \text{(EMC)}$$

$$\Gamma_1^n = -0.08 \pm 0.04_{\rm stat} \pm 0.04_{\rm sys}$$

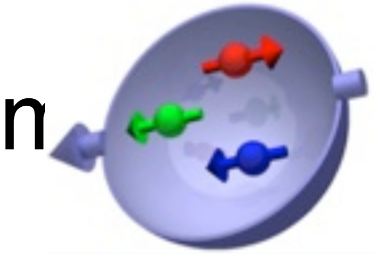
$$\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05_{\rm stat} \pm 0.04_{\rm sys}$$

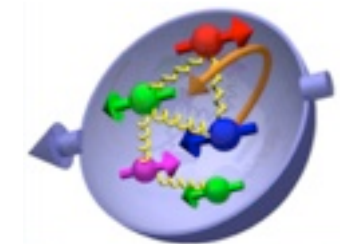
$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right|\left[1 - \frac{\alpha_s}{\pi} + \ldots\right]$$

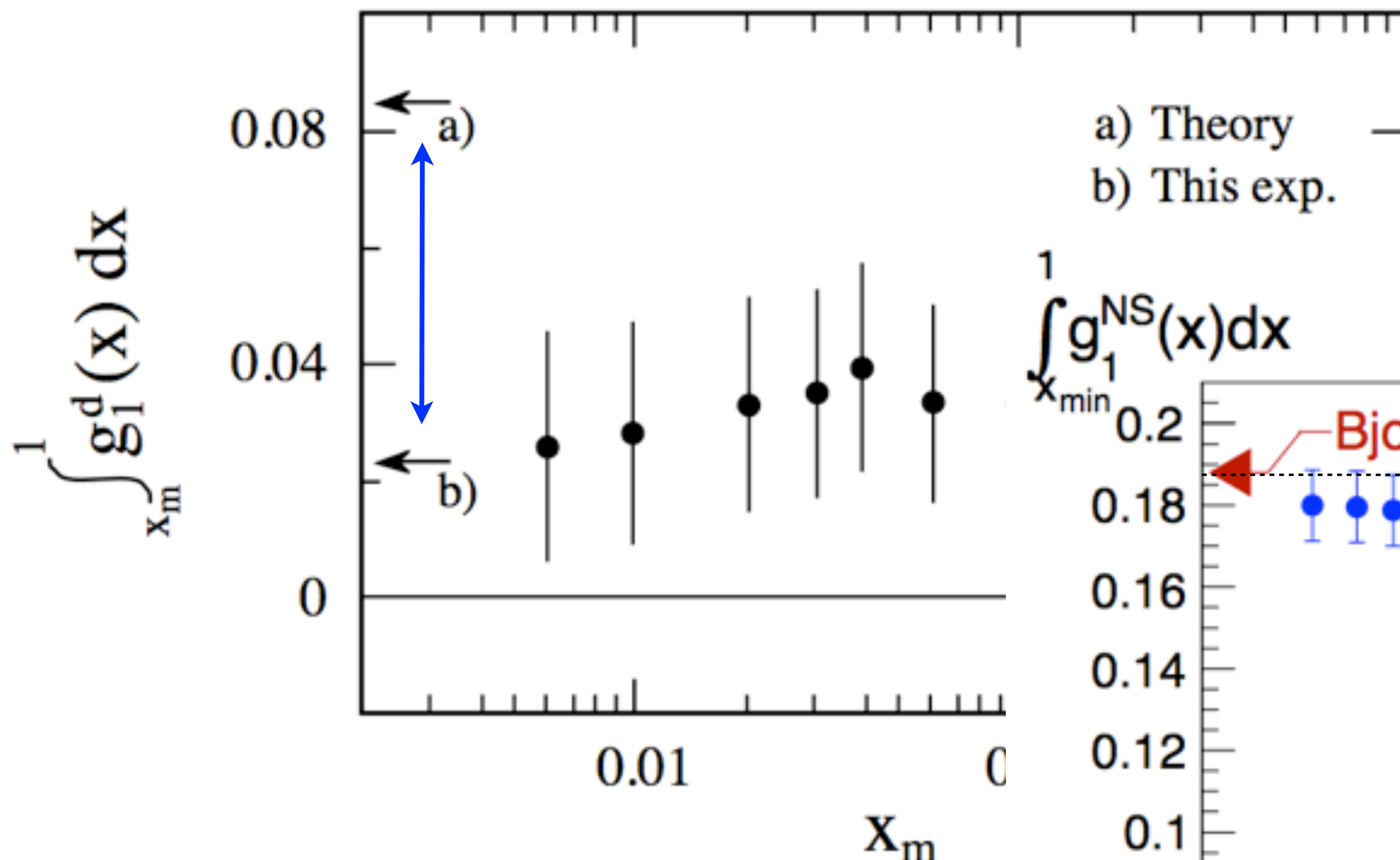
$$= 0.191 \pm 0.002 + \mathcal{O}(\alpha_s^2)$$

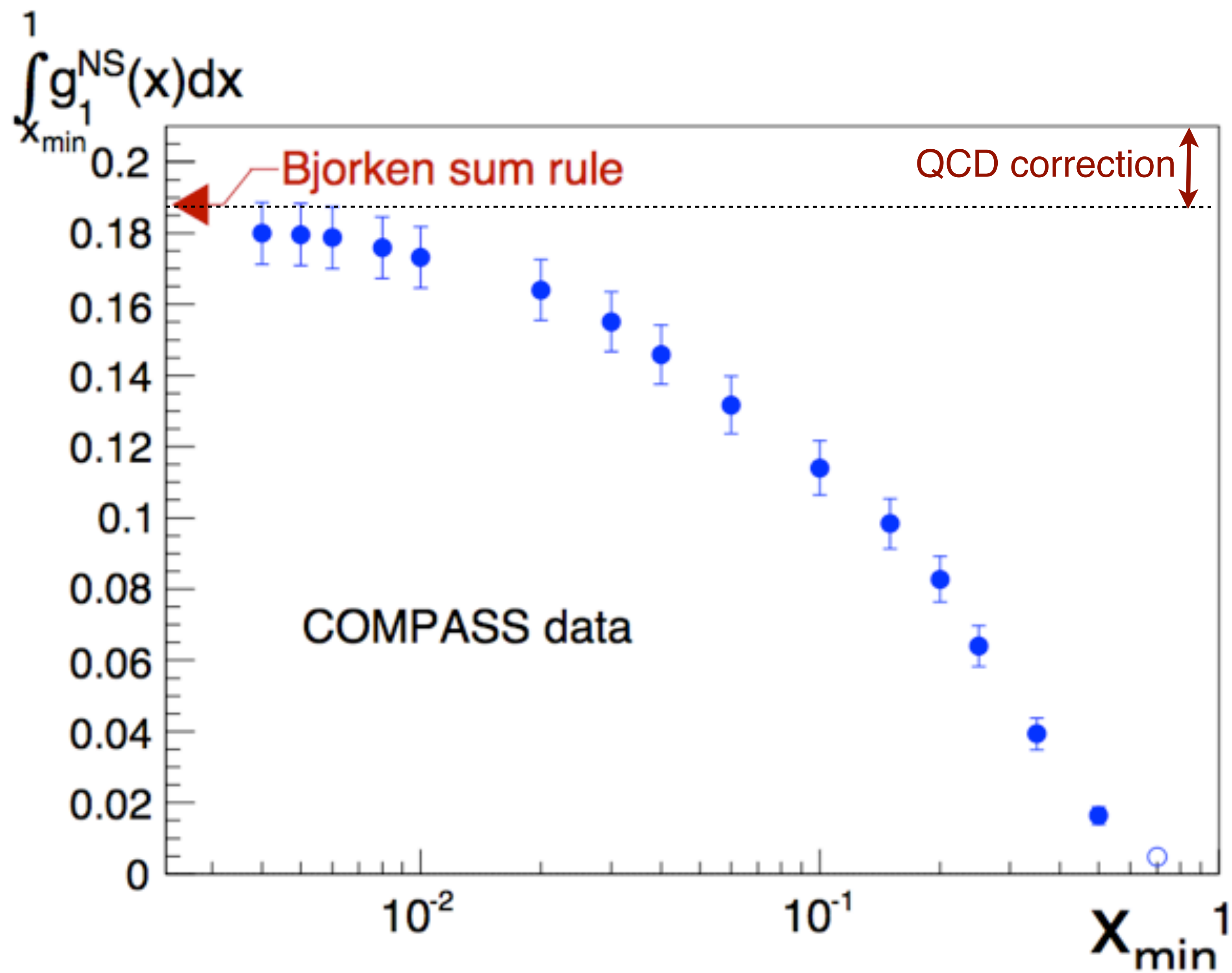
✓ 25%

Nucleon Spin - Bjorken Sum





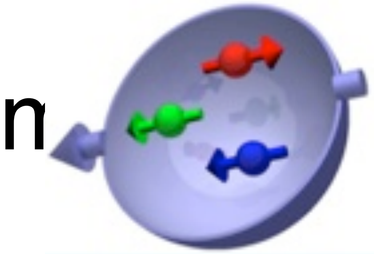


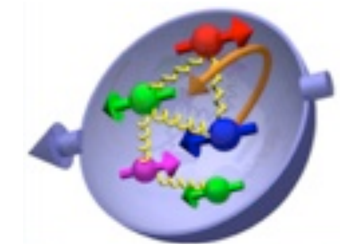


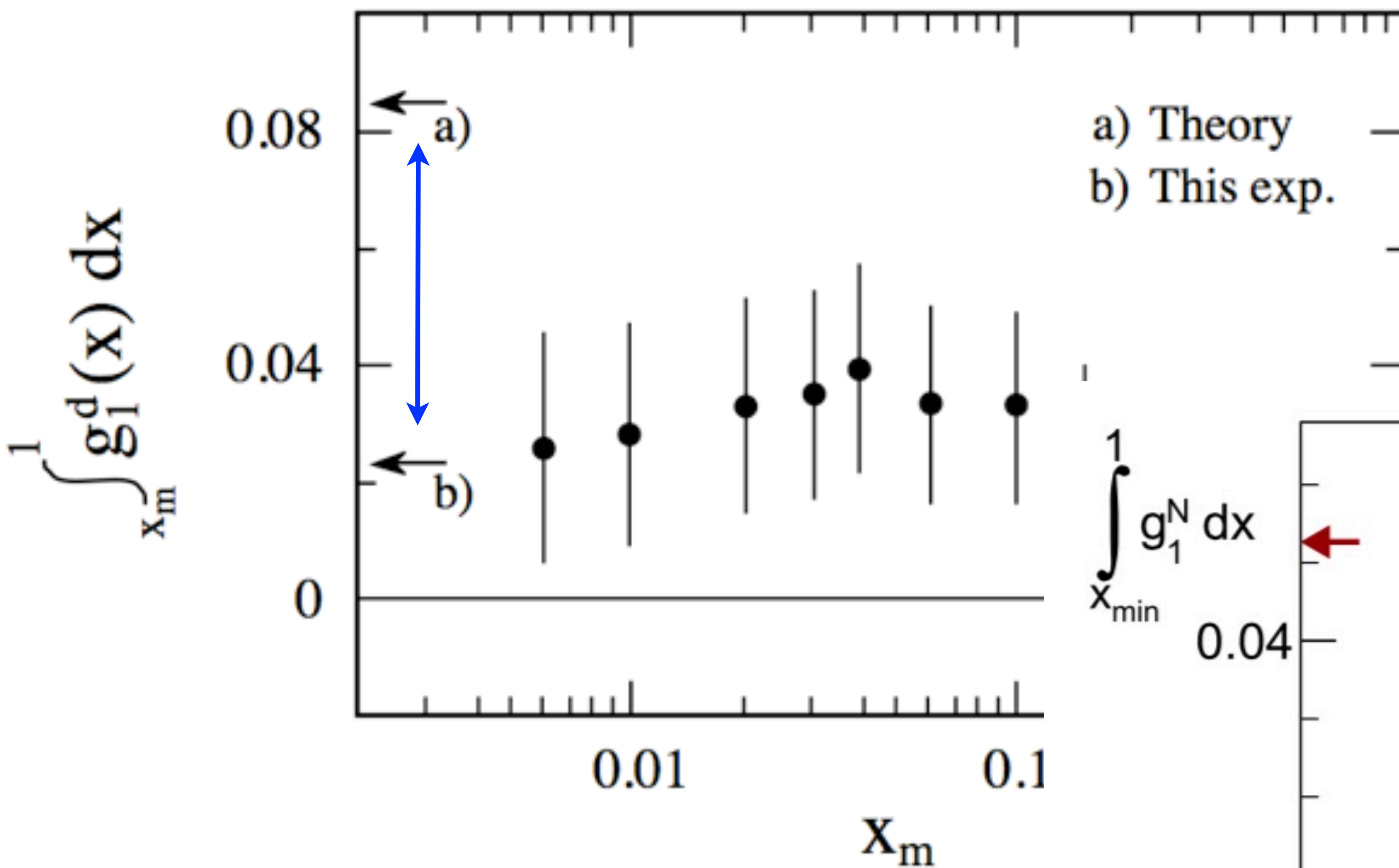
COMPASS: M.G. Alekseev et al, Phys. Lett. B690, 466 (2010)

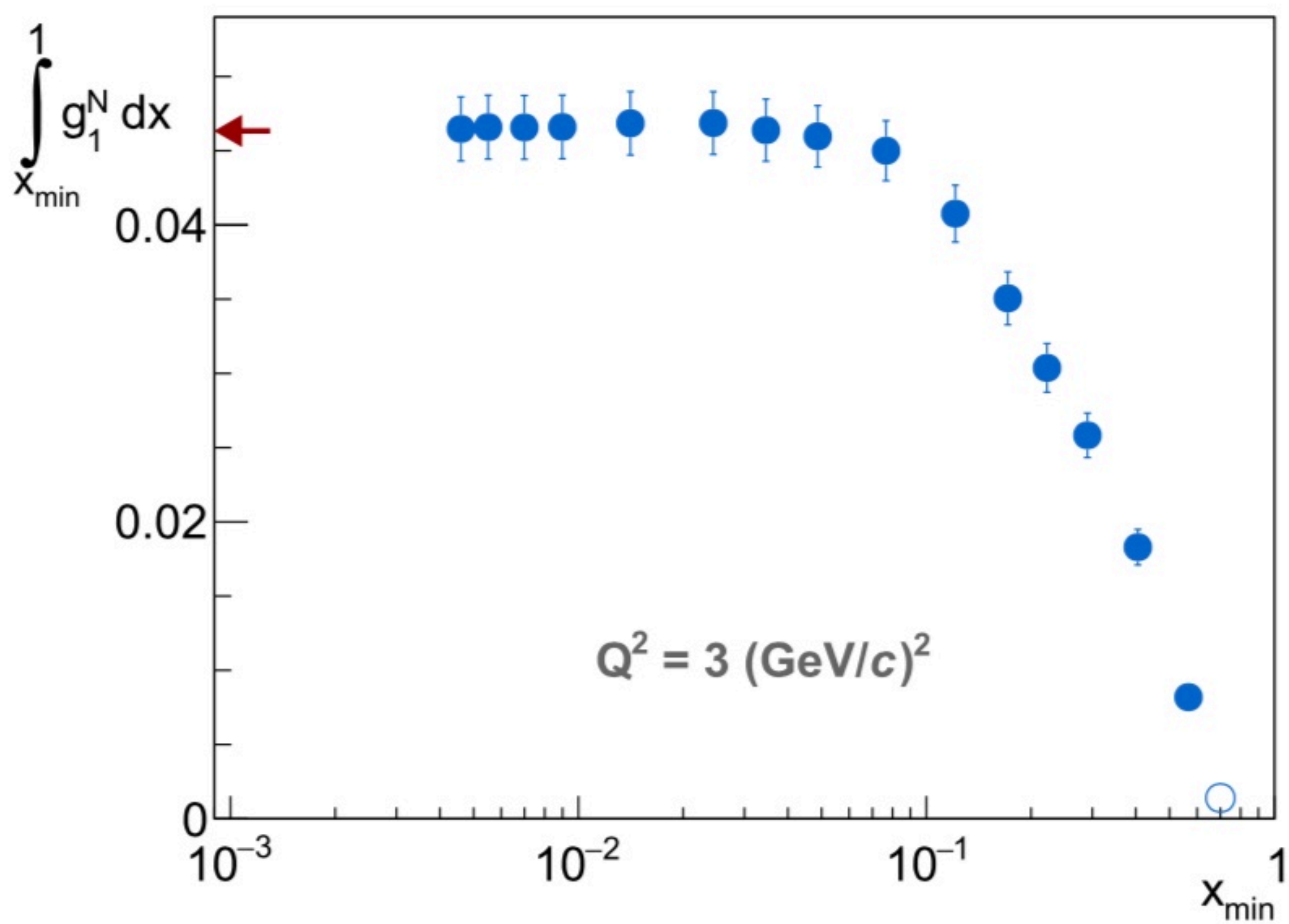
Nucleon Spin - Bjorken Sum

✓ < 10%









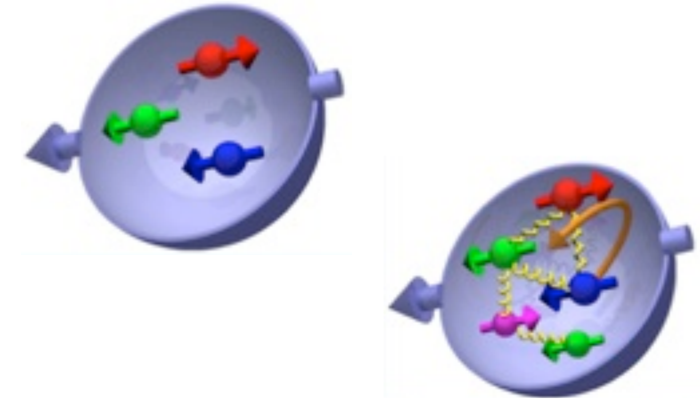
$$\Gamma_1^{NS} = 0.192 \pm 0.007_{stat} \pm 0.015_{syst}$$

$$|g_A/g_V| = 1.29 \pm 0.05_{stat} \pm 0.10_{syst}$$

COMPASS PLB 769 (2017) 34

Nucleon spin - $\Delta\Sigma$

$$\underbrace{\Delta_1 u + \Delta_1 d - 2\Delta_1 s}_{a_8 \;=\; 3F-D \;=\; 0.59\pm0.03}$$



Known from weak neutron to proton decay,
combined with weak ∑ to neutron decay

Table 1. Present world HSD rate and angular-correlation data [14]. Numerical values marked g_1/f_1 are as extracted from angular and spin correlations.

Decay	Rate($10^6\,\mathrm{s}^{-1}$)		g_1/f_1	g_1/f_1	
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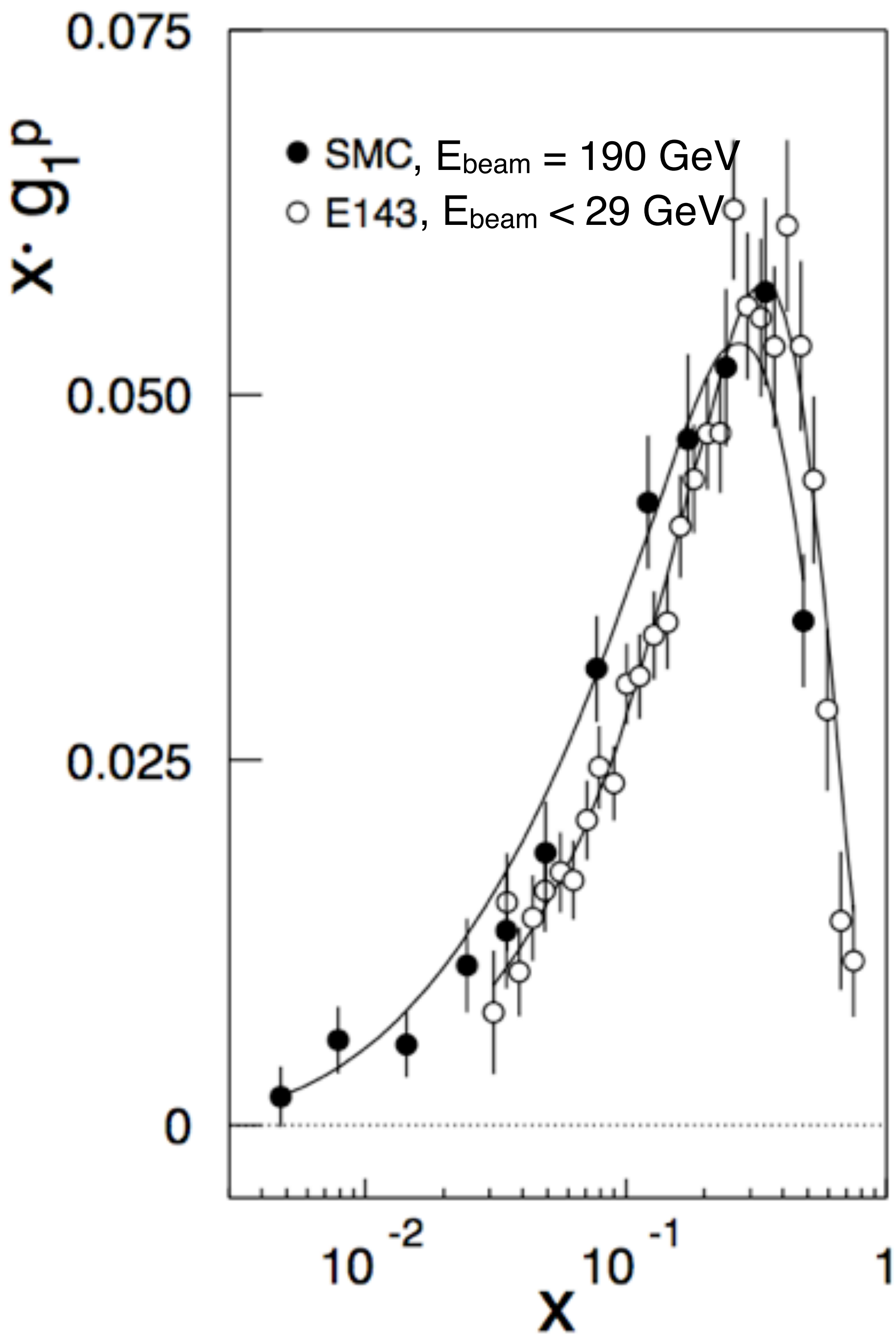
* KTeV data [5]—not included in the fits presented here.
† The absolute expression for g_1 is given, not g_1/f_1 (as $f_1 = 0$).

$$a_0(Q^2 = 3\,(\mathrm{GeV}/c)^2) = 0.32 \pm 0.02_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}} \pm 0.05_{\mathrm{evol}}\,.$$

COMPASS PLB 769 (2017) 34

Nucleon Spin - Scaling Violations, Global Analyses



Provide sensitivity to $\Delta G(x, Q^2)$

Closely related also to extrapolations over unmeasured small-*x*,

$$g_1(x, Q^2) \;\propto\; \exp\sqrt{\ln\frac{1}{x}\,\ln\ln\frac{Q^2}{\Lambda^2}},$$

as $x \to 0, \quad Q^2 \to \infty,$

R.D. Ball et al, Nucl. Phys. B444, 287 (1995),
B449, 680 (1995)

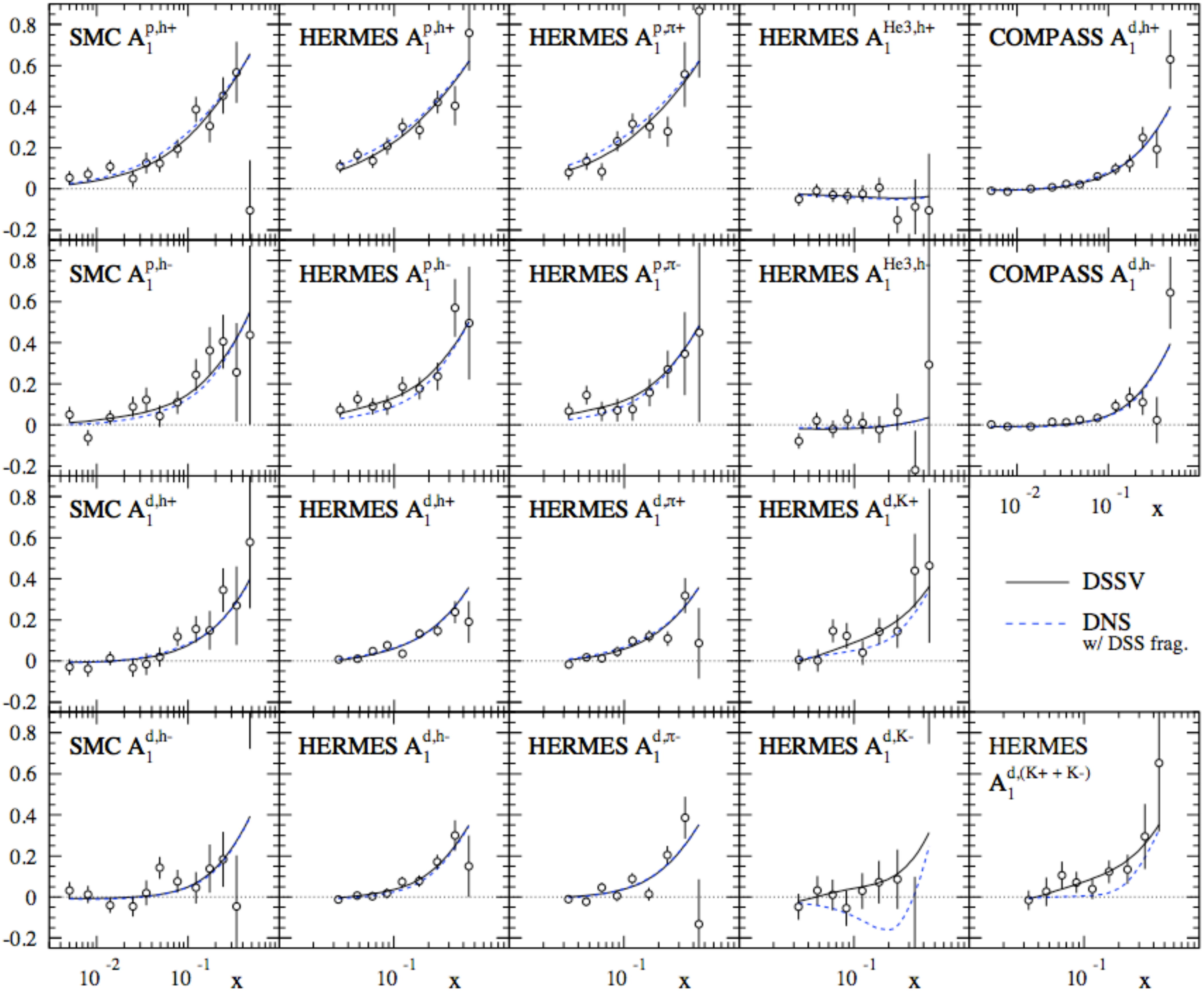
Start of polarized pQCD analyses.

More recent work at NLO:

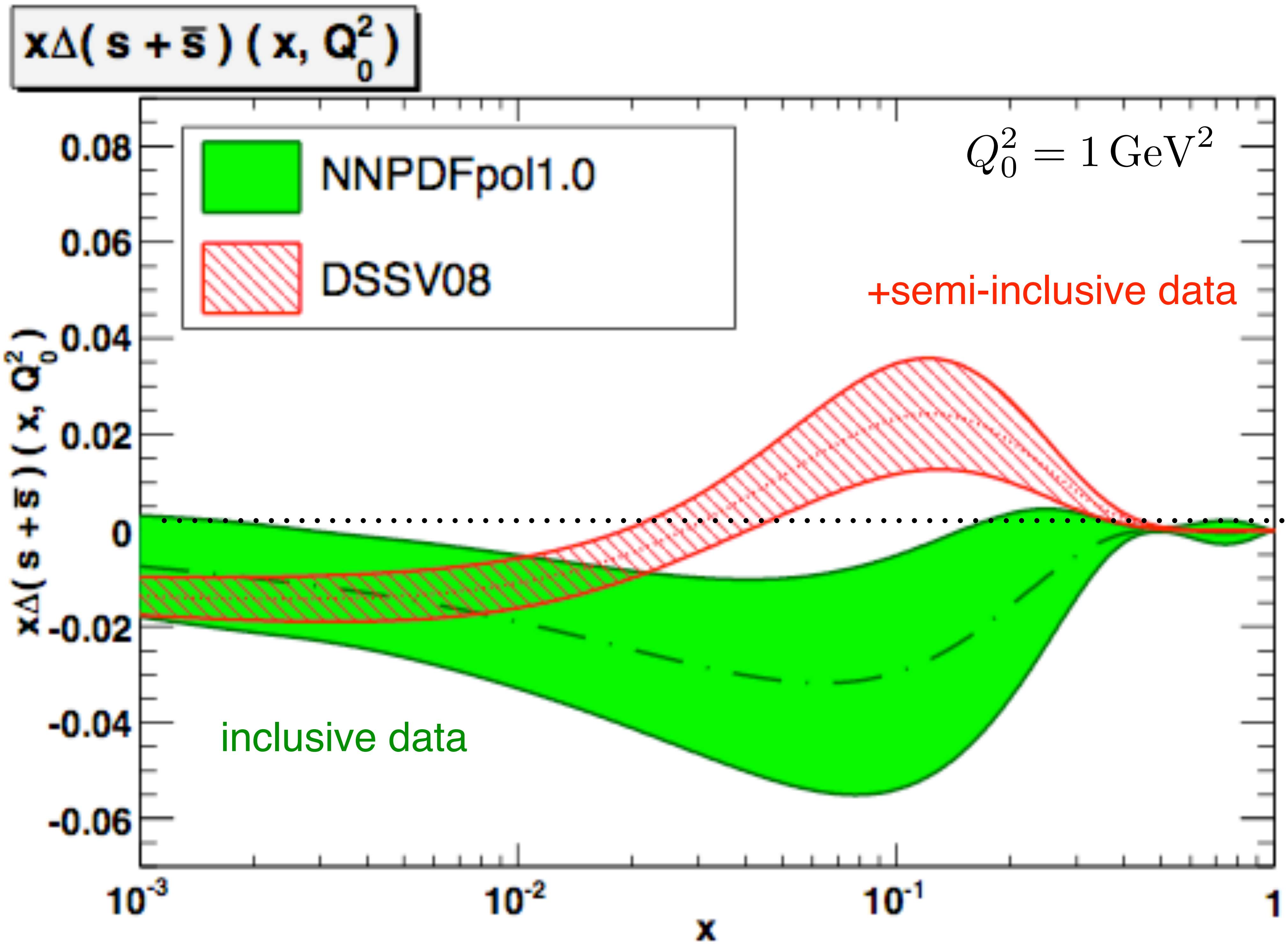
NNPDF: Ball et al,
initially inclusive DIS data only,
Nucl. Phys. B874, 36 (2013)

DSSV: De Florian et al,
inclusive DIS, SIDIS, RHIC
ArXiv 1304.0079 (2013)

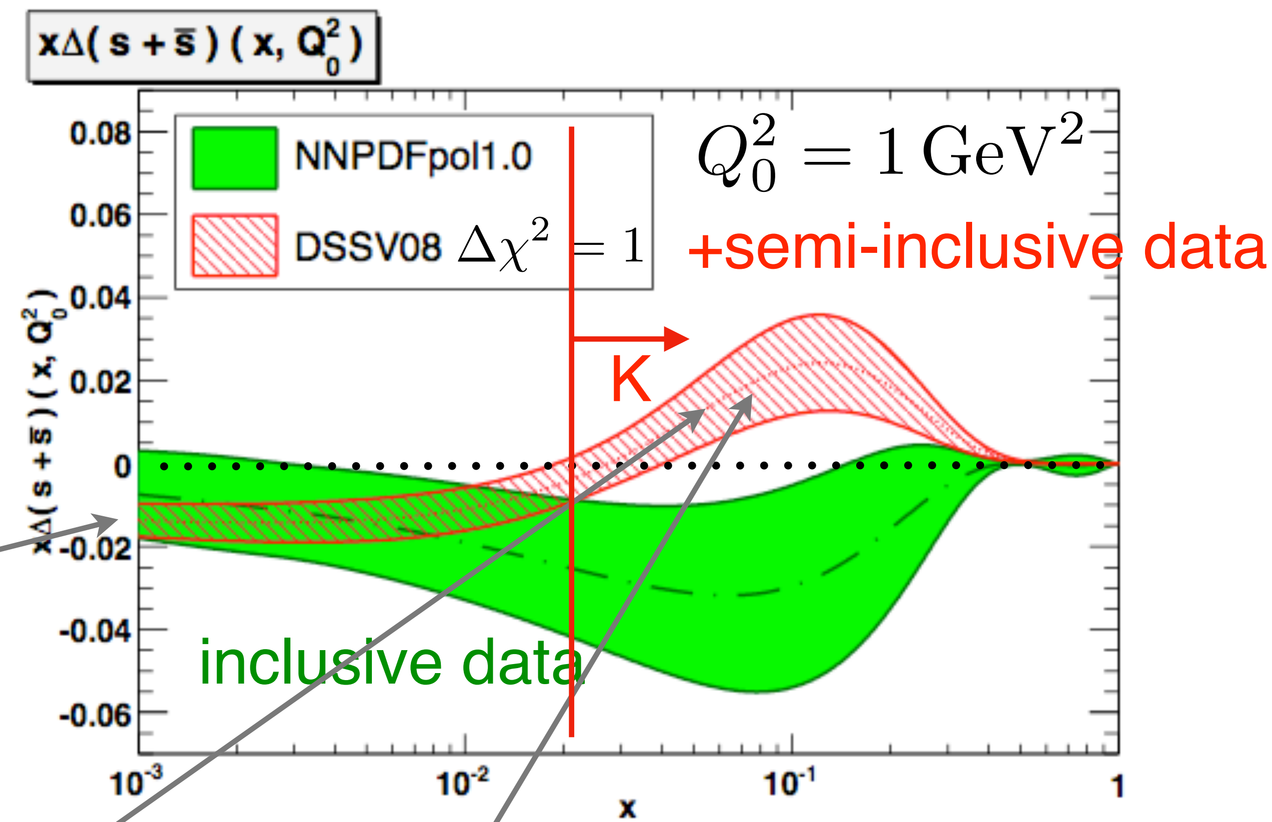
SIDIS - Quark Flavor Structure



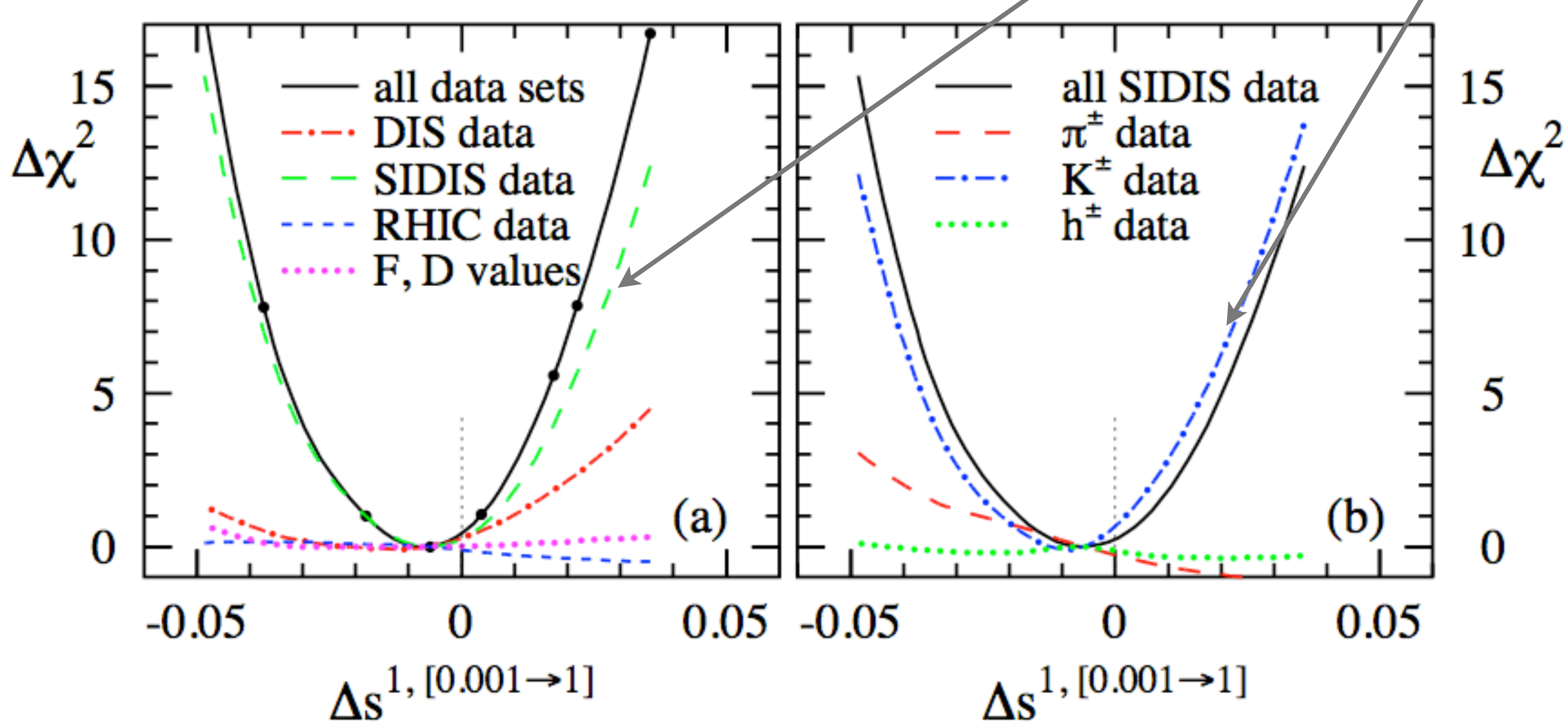
Nucleon spin - strange quark polarization, Δs



Nucleon spin - strange quark polarization, Δs



F, D constraints

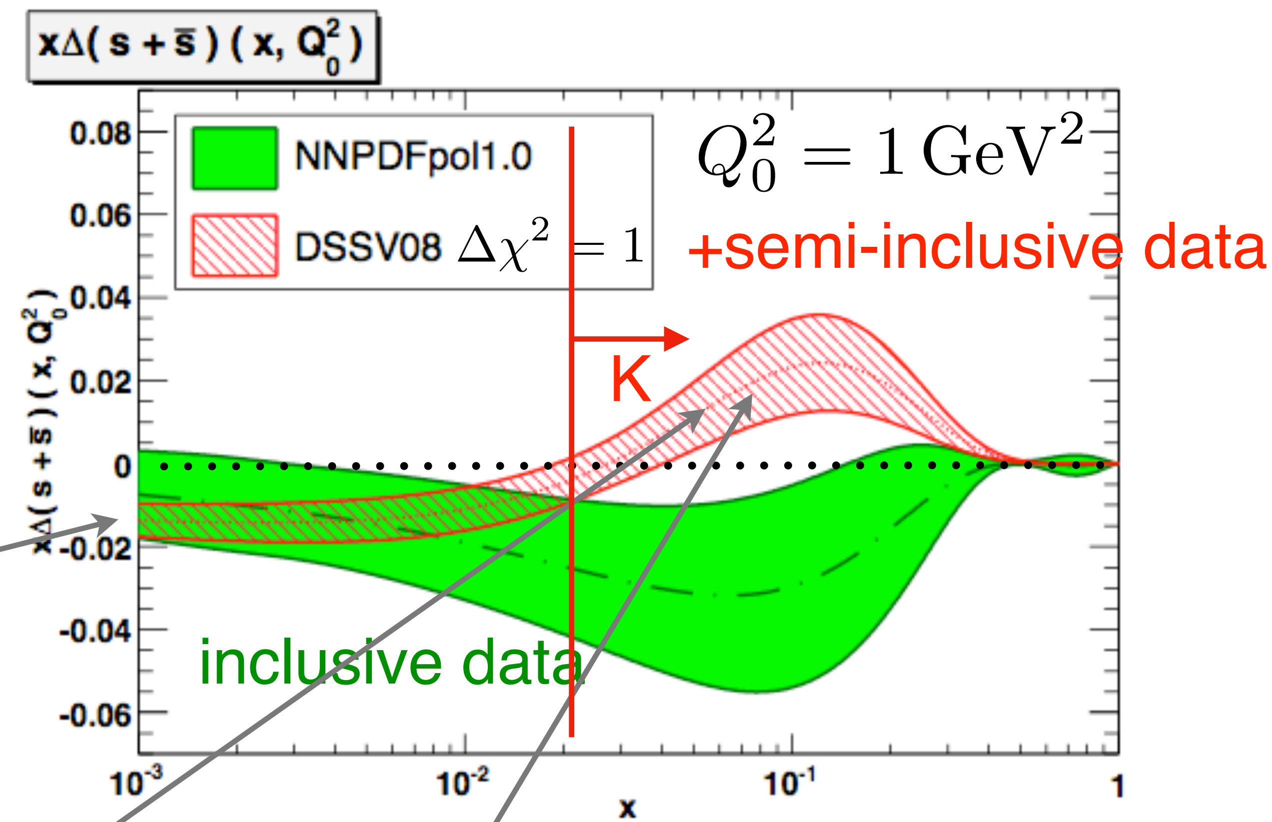


DSSV: De Florian et al
PRD 80, 034030 (2009).

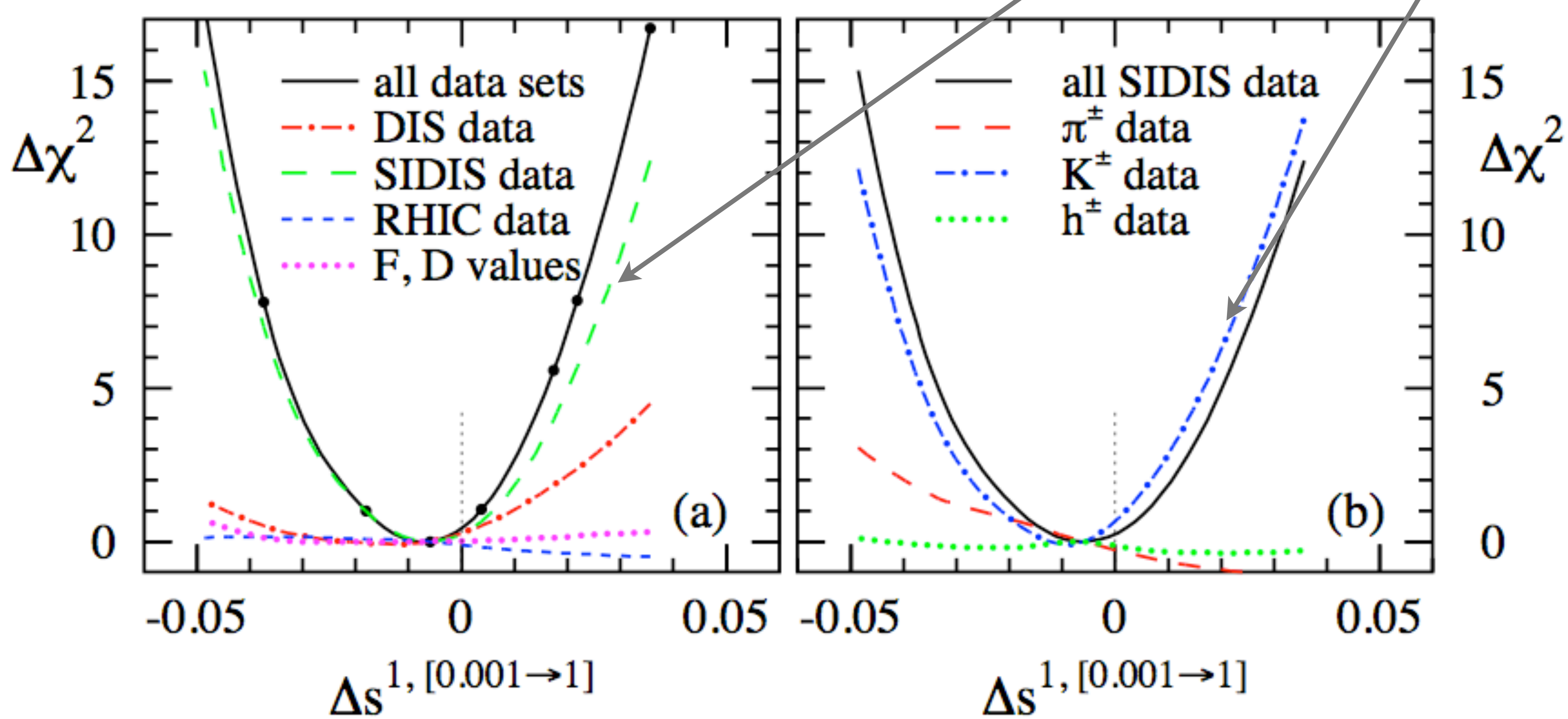
Nucleon spin - strange quark polarization, Δs

SIDIS relies on FF,
in particular to Kaon FF,
no "tension" in DSSV though,
Larger F, D uncertainty in NNPDF
Lattice indicative of small net Δs

Clear role for a future EIC



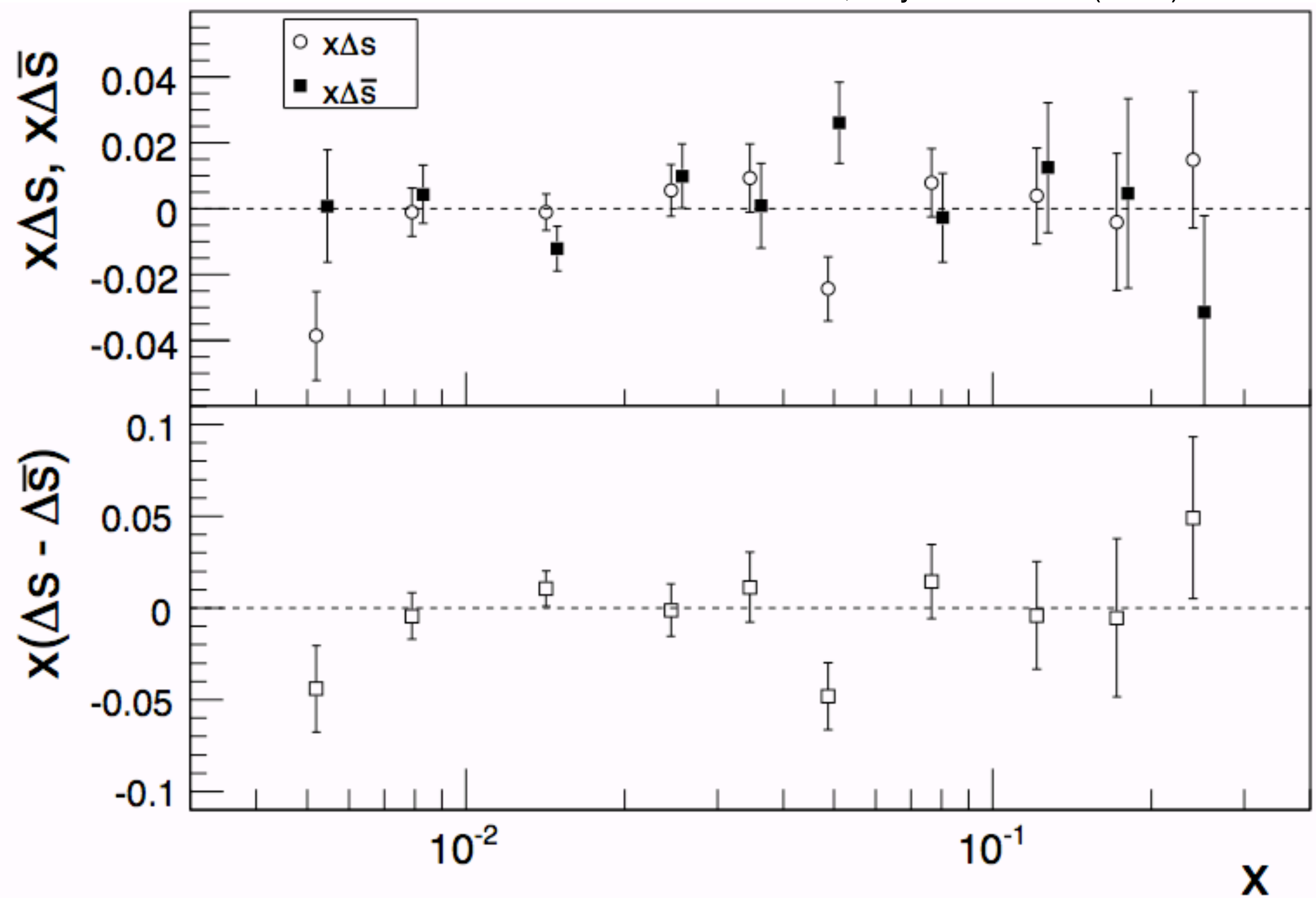
F, D constraints



DSSV: De Florian et al
PRD 80, 034030 (2009).

Nucleon spin - COMPASS L.O. Δs

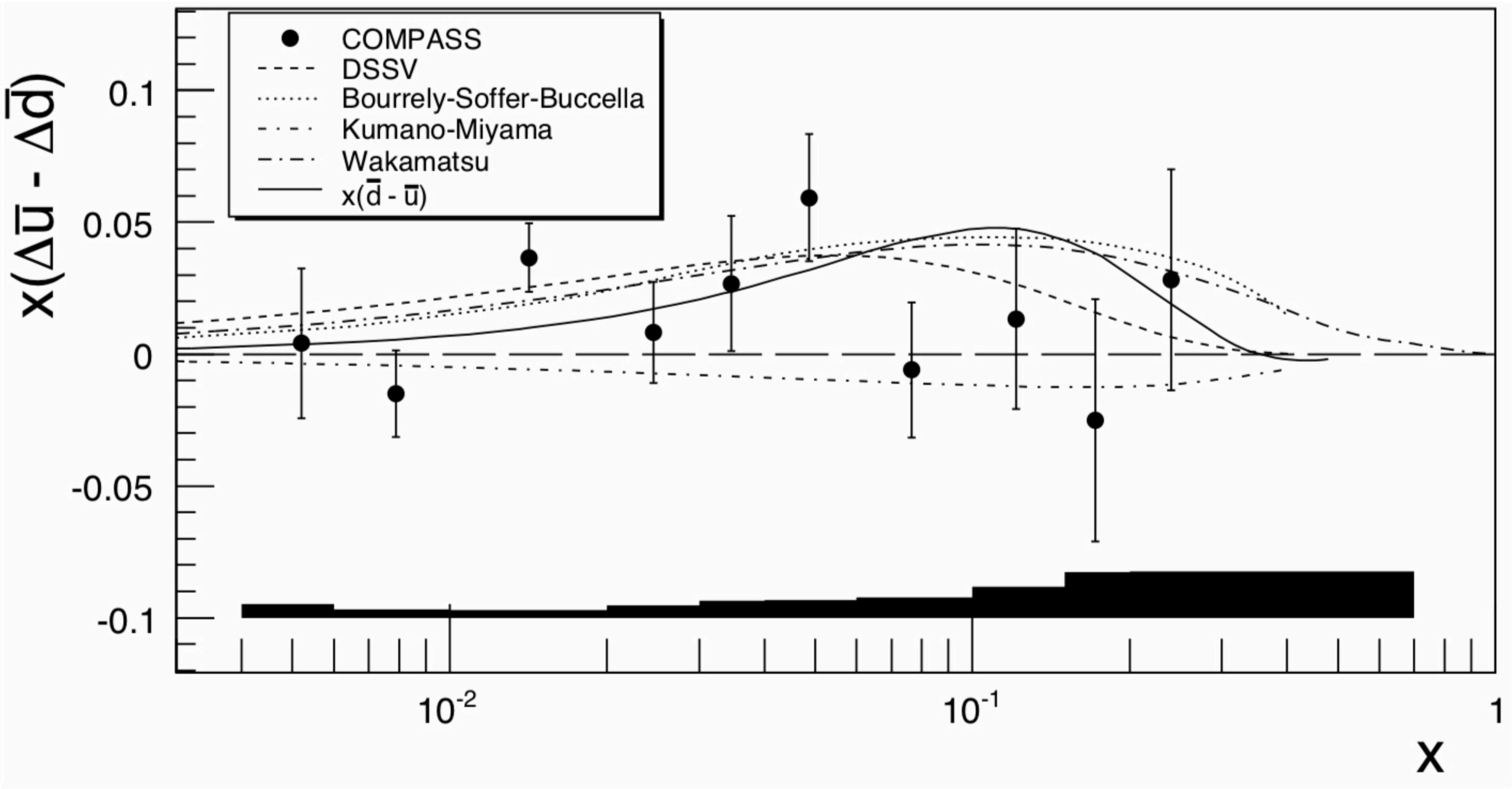
M.G. Alekseev, Phys.Lett. B693 (2010) 227-235



No evidence for negative net strange quark polarization,
not from $(K^+ + K^-)$ asymmetries of D either,
Renewed interest in FF, in-situ multiplicities, etc.

Nucleon spin - COMPASS L.O. $\Delta\bar{u} - \Delta\bar{d}$

M.G. Alekseev, Phys.Lett. B693 (2010) 227-235

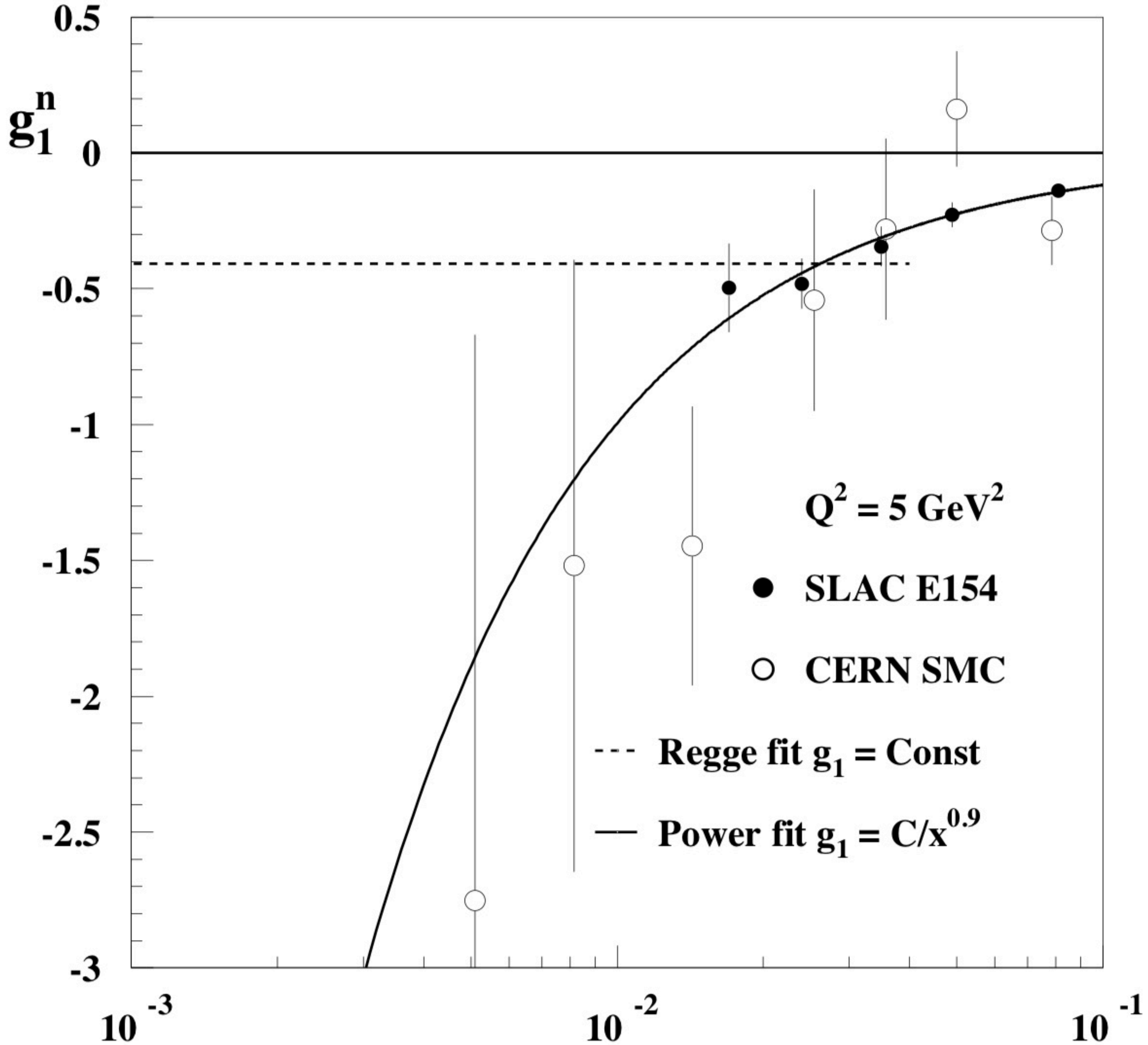


Well known flavor asymmetry in unpolarized sea,

COMPASS: $\Delta\bar{u} - \Delta\bar{d}$, is slightly positive, about 1.5 standard deviations from zero

Nucleon Spin - Scaling Violations, small-x

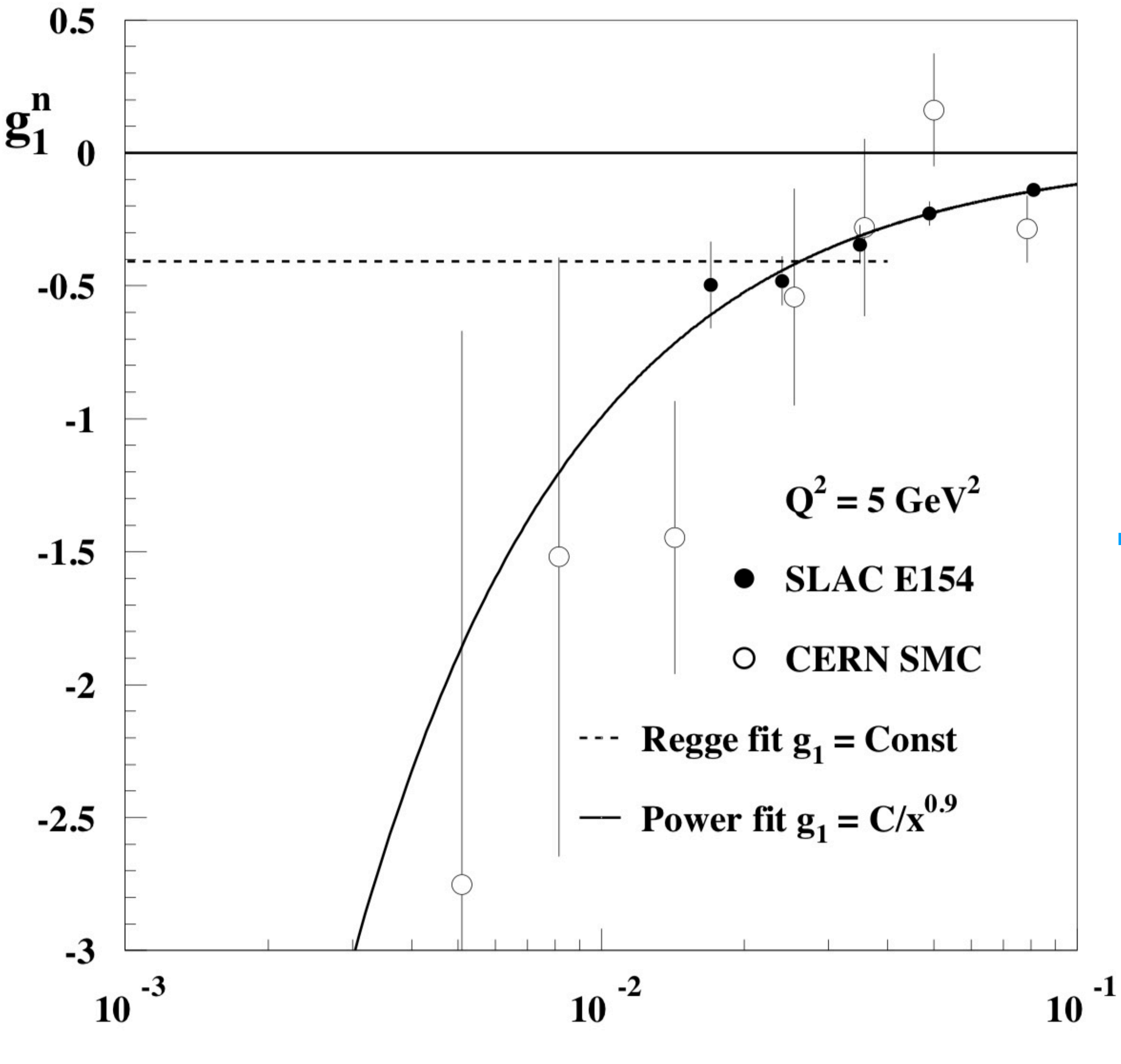
K. Abe, Phys. Rev. Lett. 79 (1997) 26



COMPASS has improved small-x uncertainties by a factor,
Nevertheless, the field has a ways to go...

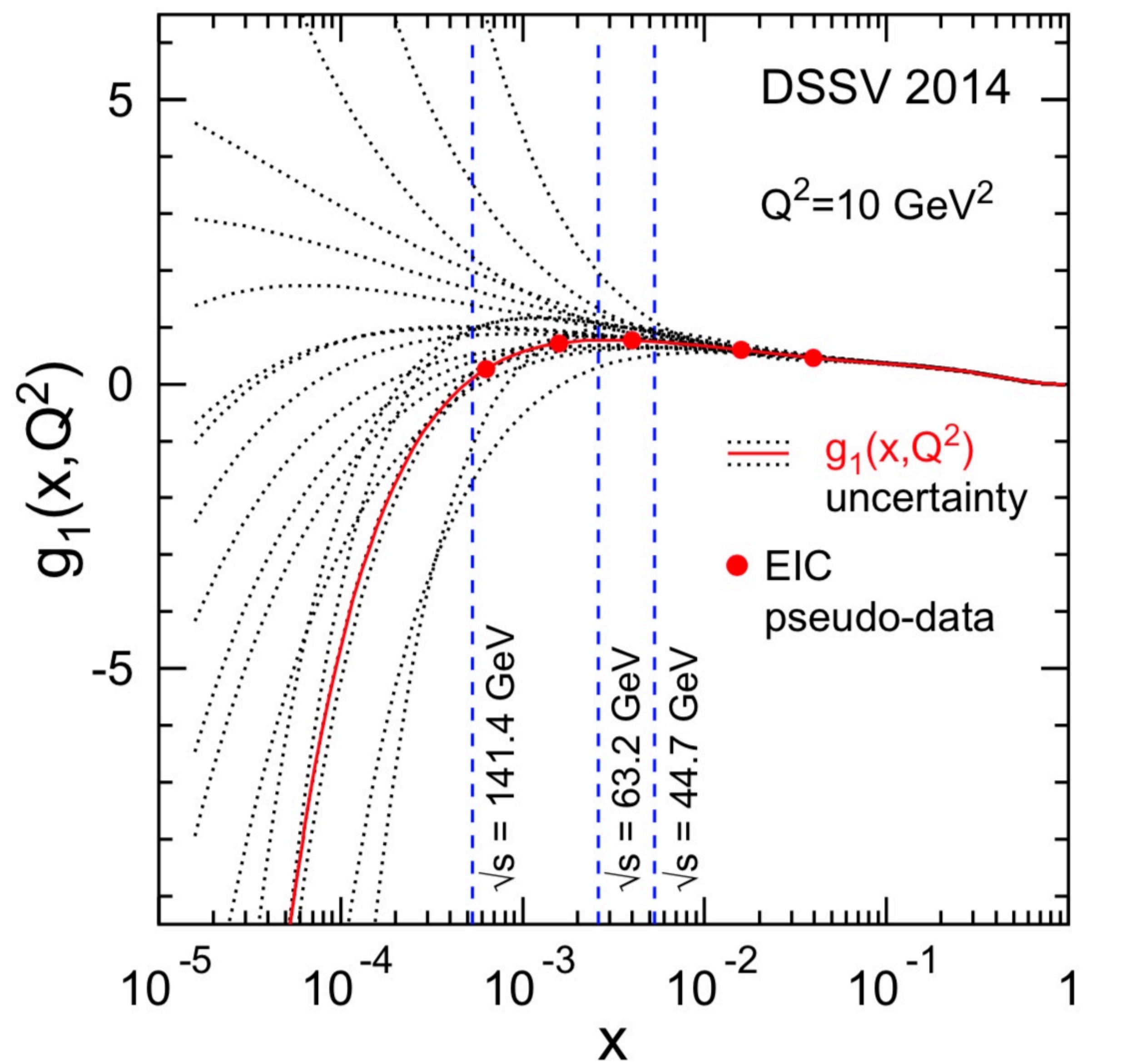
Nucleon Spin - Scaling Violations, small-*x*

K. Abe, Phys. Rev. Lett. 79 (1997) 26



neutron

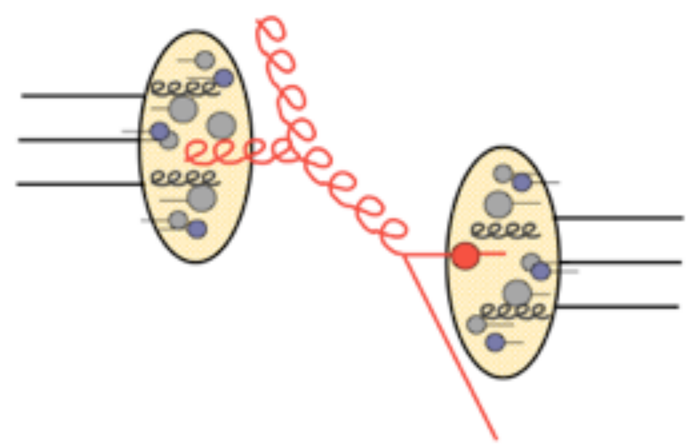
E.C. Aschenauer, ArXiv:1708.01527



proton

Clear role and impact for a future EIC

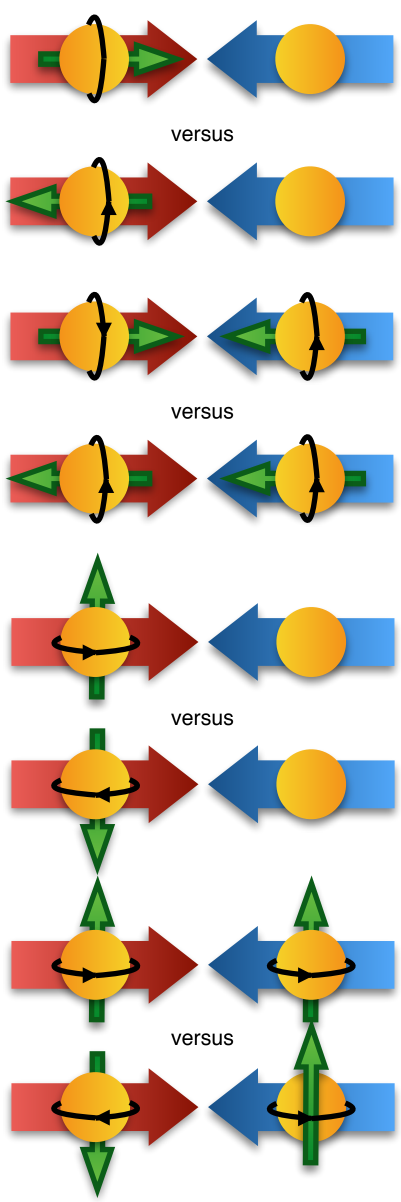
pp

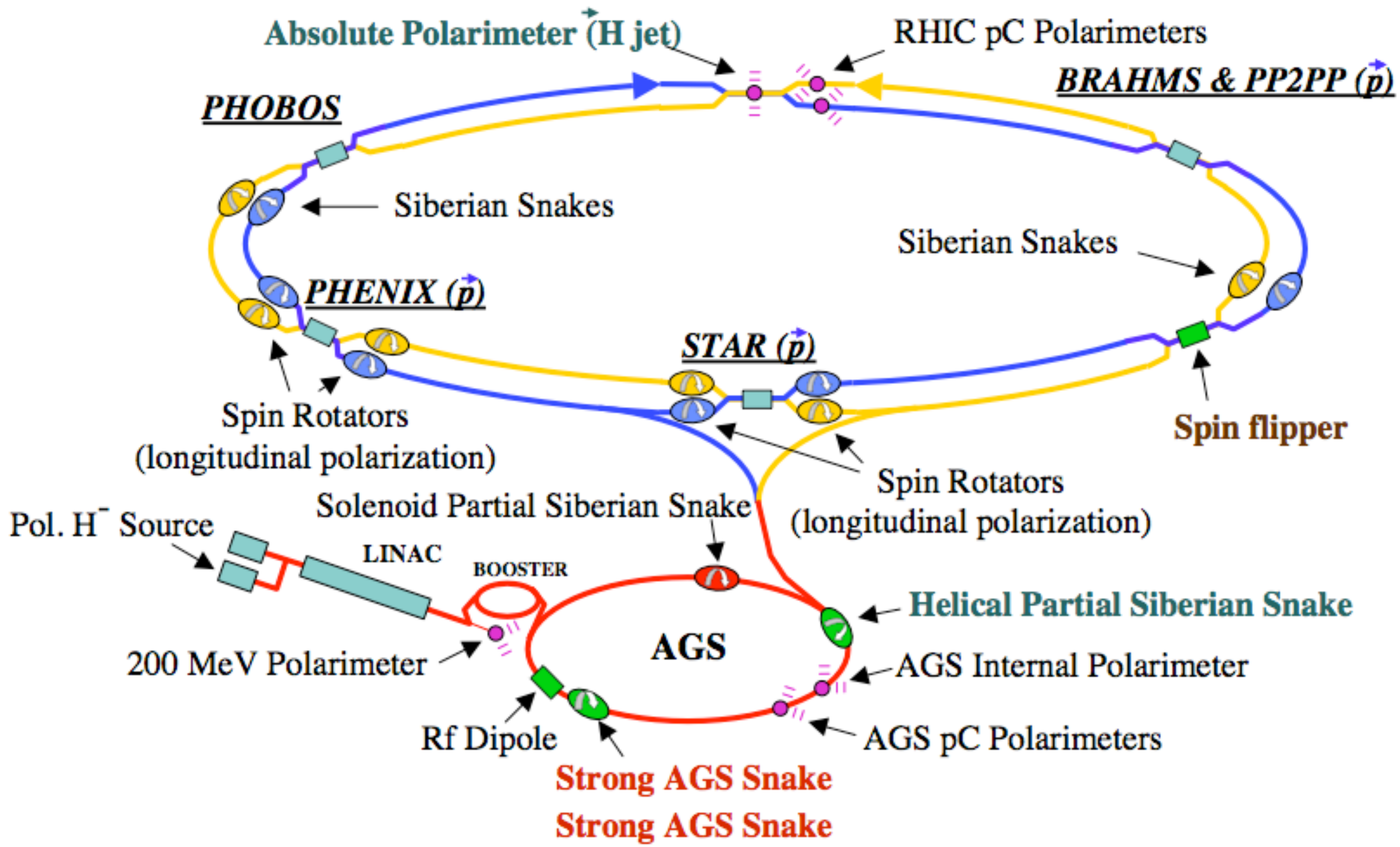


RHIC - Polarized Proton-Proton Collider

Unique opportunities to study nucleon spin properties and spin in QCD,

$\sqrt{s}$ = 62, 200, and 500 GeV



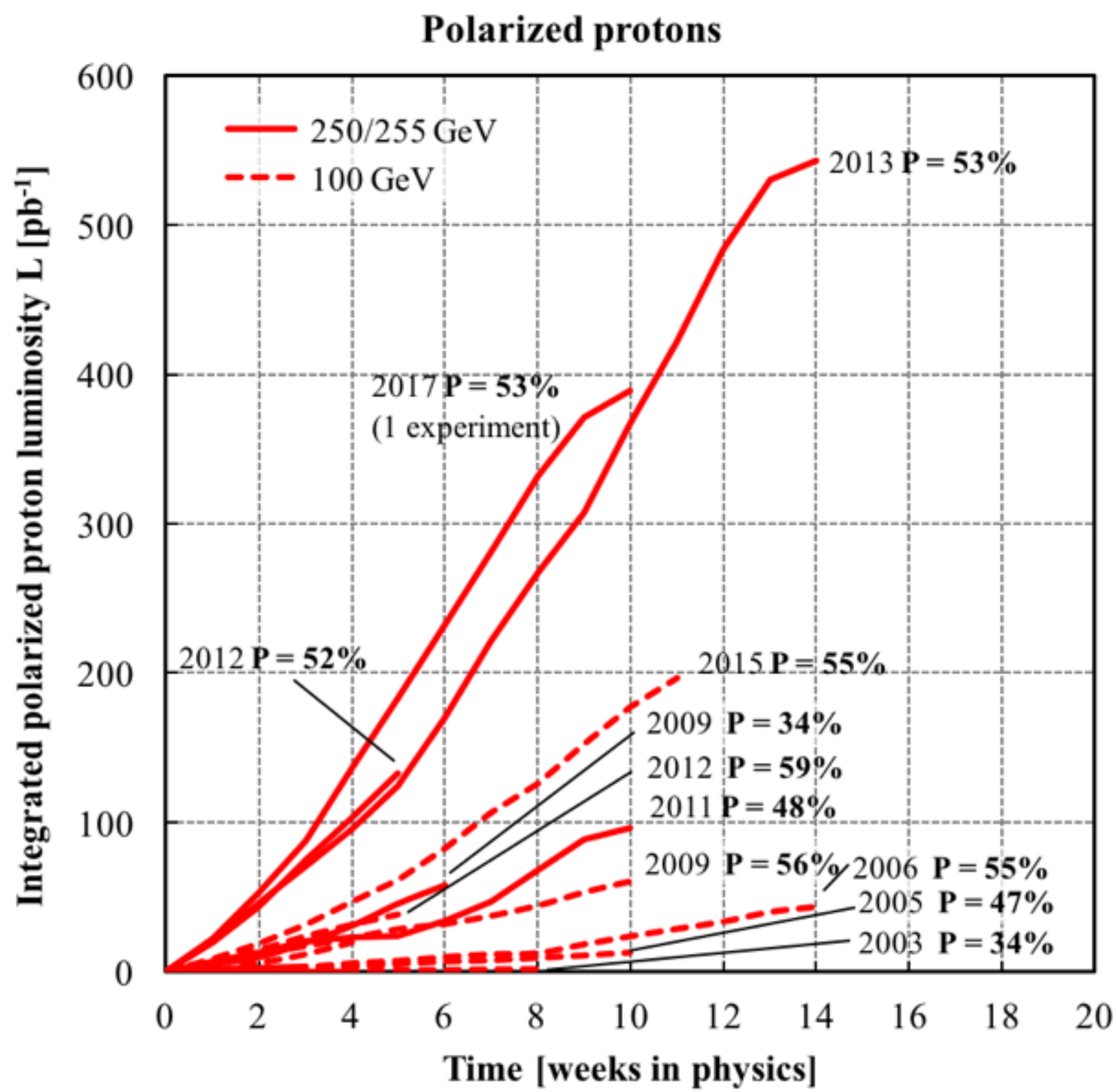


at hard (perturbative) scales with good systematic controls, e.g. from the ~100ns succession of beam bunches with alternating beam spin configurations.

RHIC - Polarized Proton-Proton Collider

Unique opportunities to study nucleon spin properties and spin in QCD,

Longitudinal data	**STAR**
√s = **200 GeV**	
2005	
2006	35 pb^{-1}
2009	
2015	50 pb^{-1}
√s = **500 GeV**	
2009	
2011	
2012	350 pb^{-1}
2013	
Transverse data	
√s = **200 GeV**	
2006	
2008	38 pb^{-1}
2012	
2015	50 pb^{-1}
√s = **500 GeV**	
2011	25 pb^{-1}
2017	350 pb^{-1}



50-60% polarization

Gluon Polarization at RHIC

Measurement: $$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \stackrel{?}{=} \sum_{f=q,g} \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \otimes (\text{fragmentation functions})$$

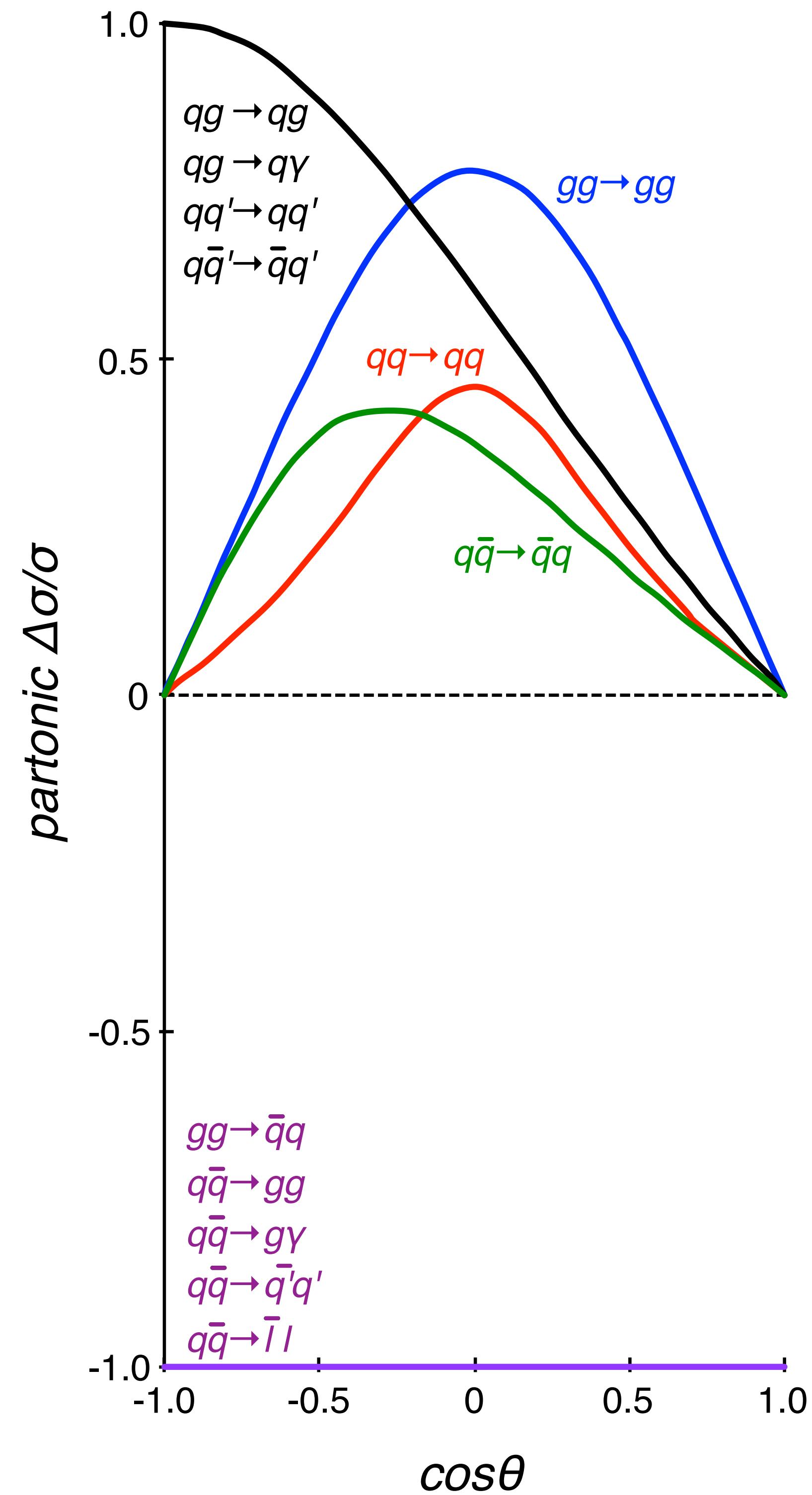
- Detect and reconstruct particle, jet,
- Extract beam-spin dependent yields,
- Measure relative luminosity, beam polarization
- Evaluate double beam-helicity asymmetry

Advantages:

- High yields of neutral pions, jets at RHIC,
- Relatively straightforward triggering,
- Understood reconstruction techniques,
- Sizable partonic asymmetries

Disadvantages:

- Contributions from several sub-processes,
- Wide x_g range sampled for each fixed p_T
- x_g, $x_q \sim p_T/\sqrt{s} \cdot \exp(-\eta)$



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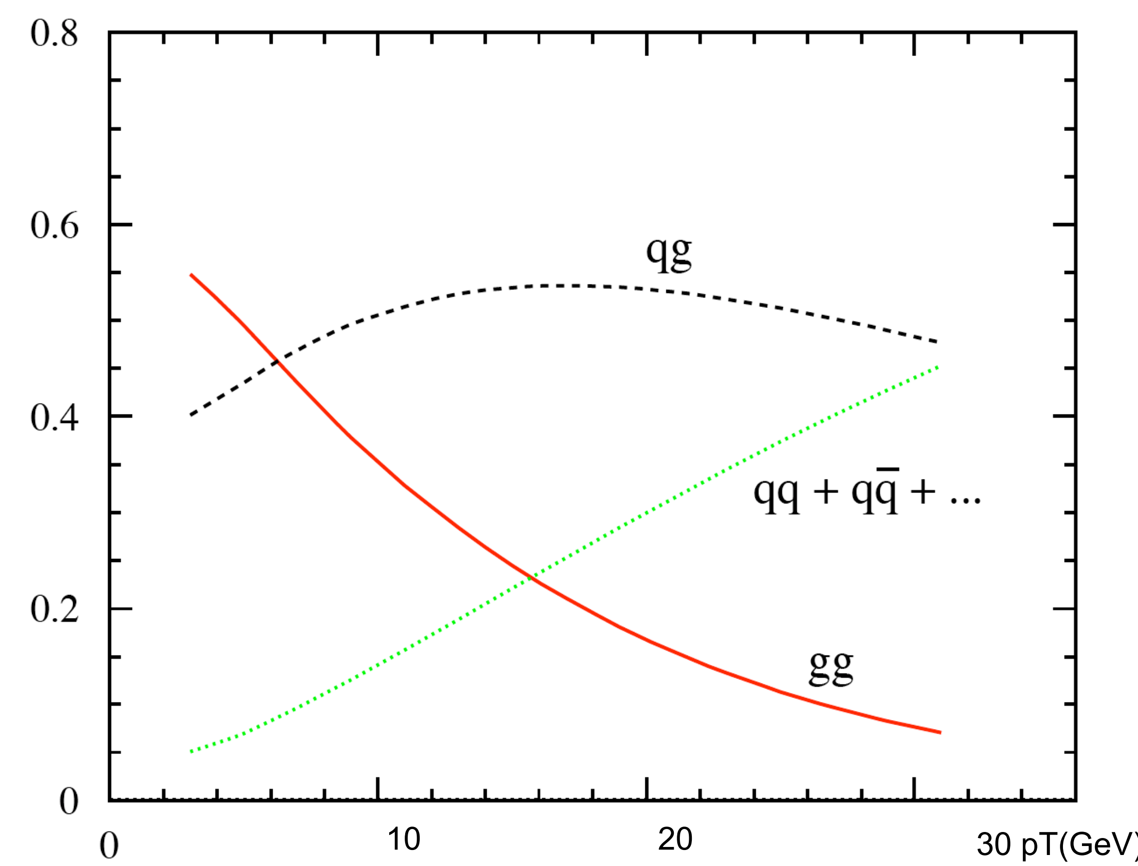

Disadvantages:

- Contributions from several sub-processes,
- Wide x_g range sampled for each fixed p_T
- x_g, x_q ~ $p_T/\sqrt{s} \cdot \exp(-\eta)$

gluon-gluon and quark-*gluon* scattering contributions dominate.

Gluon Polarization at RHIC

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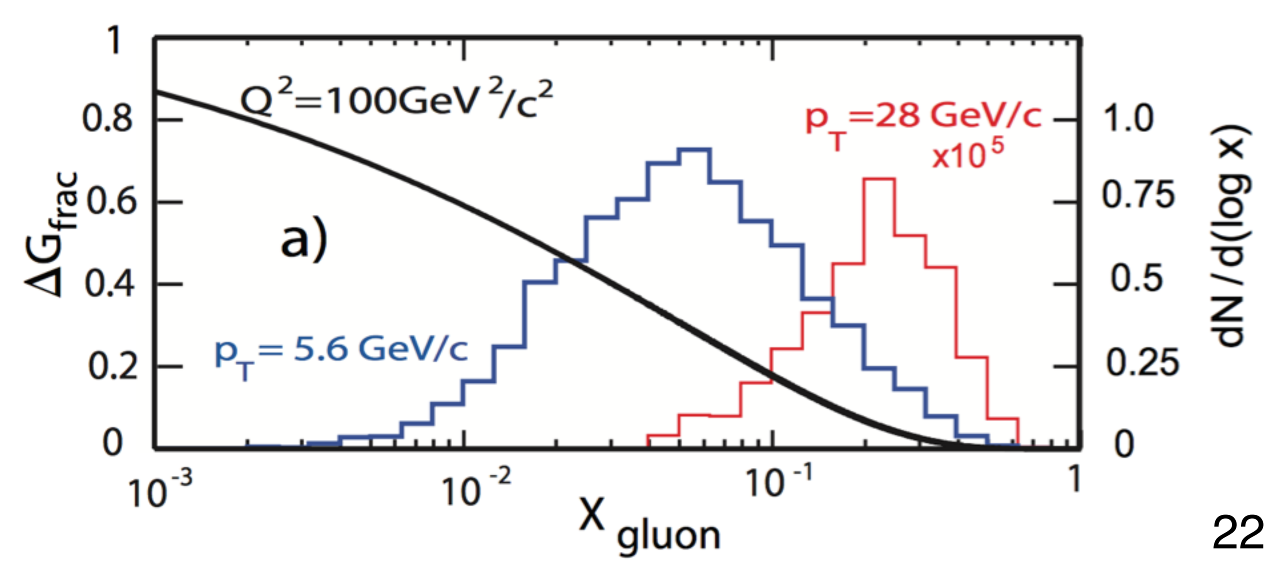

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- Extract beam-spin dependent yields,
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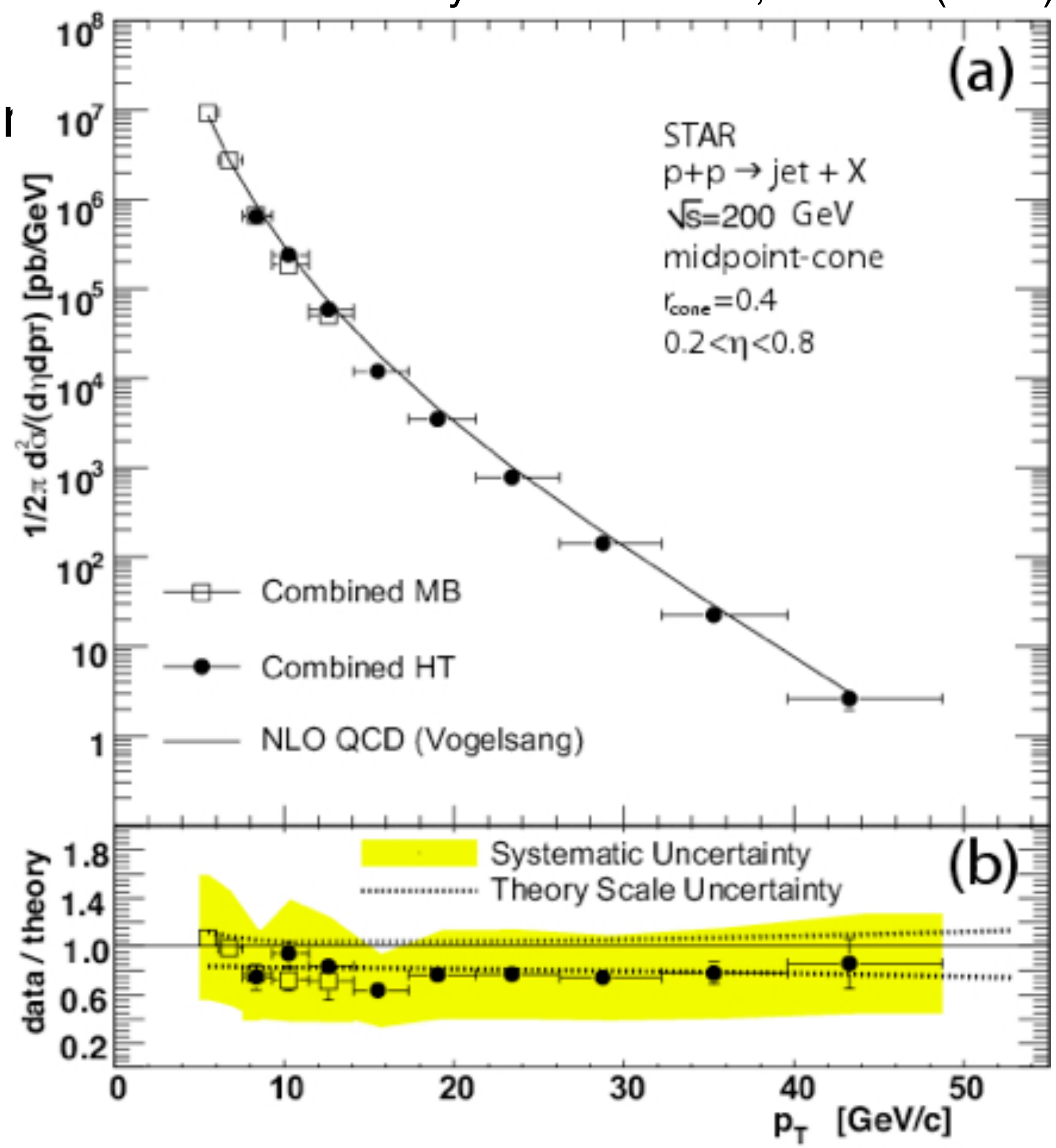
Phys. Rev. Lett. 97, 252001 (2006)



NLO pQCD agrees well with the "numerator"

Advantages:

- High yields of neutral pions, jets at RHIC,
- Relatively straightforward triggering,
- Relatively simple reconstruction,
- Sizable partonic asymmetries

Disadvantages:

- Contributions from several sub-processes,
- Wide x_g range sampled for each fixed p_T
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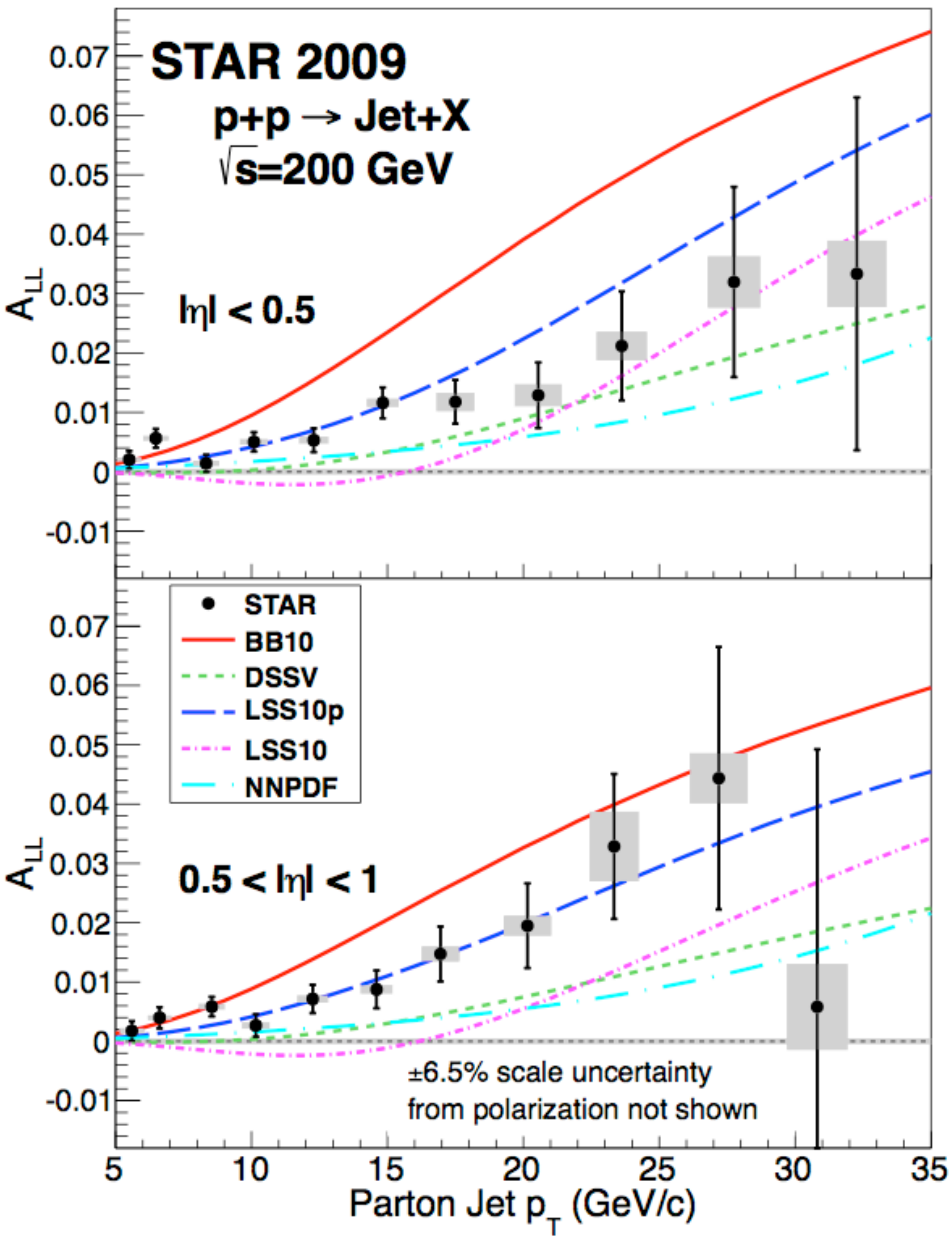
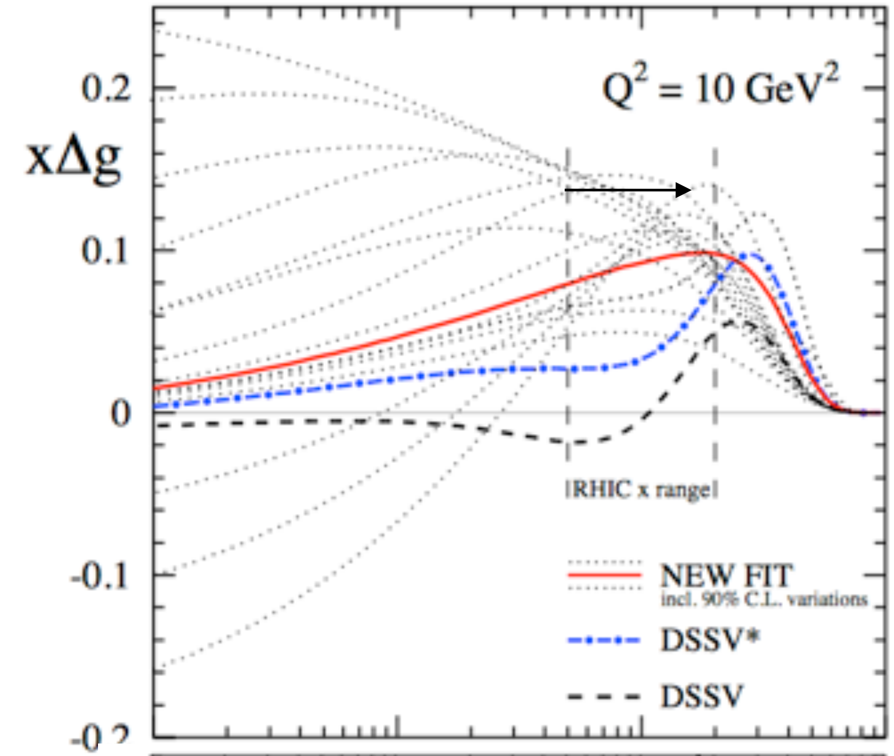
ΔG

Gluon Polarization from RHIC

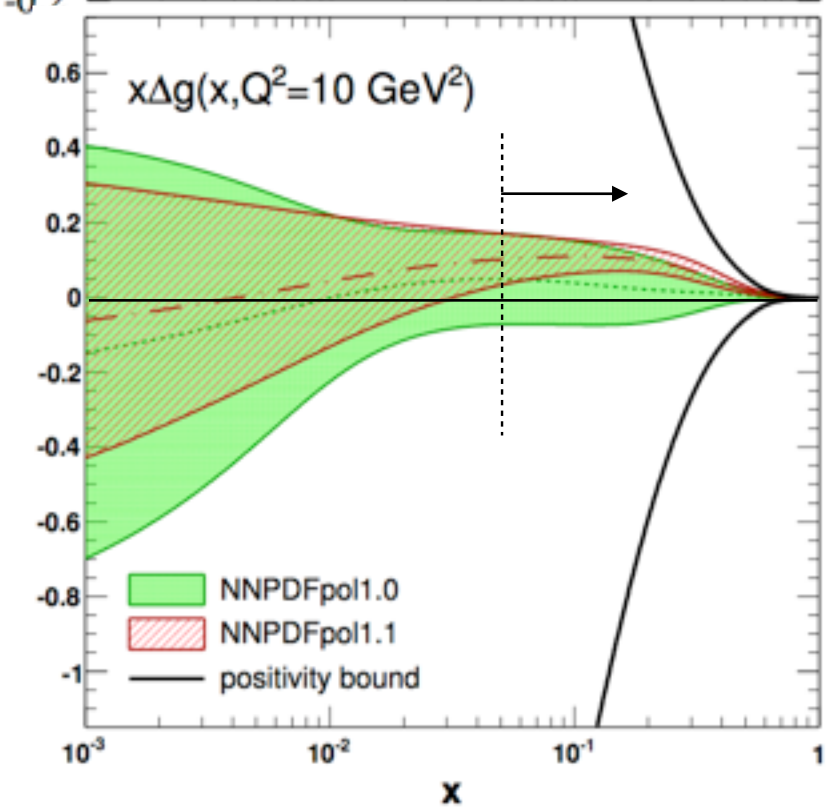
Phys.Rev.Lett 115 (2015) 092002





0.20 ± 0.07

DSSV, PRL 113, 012001(2014)



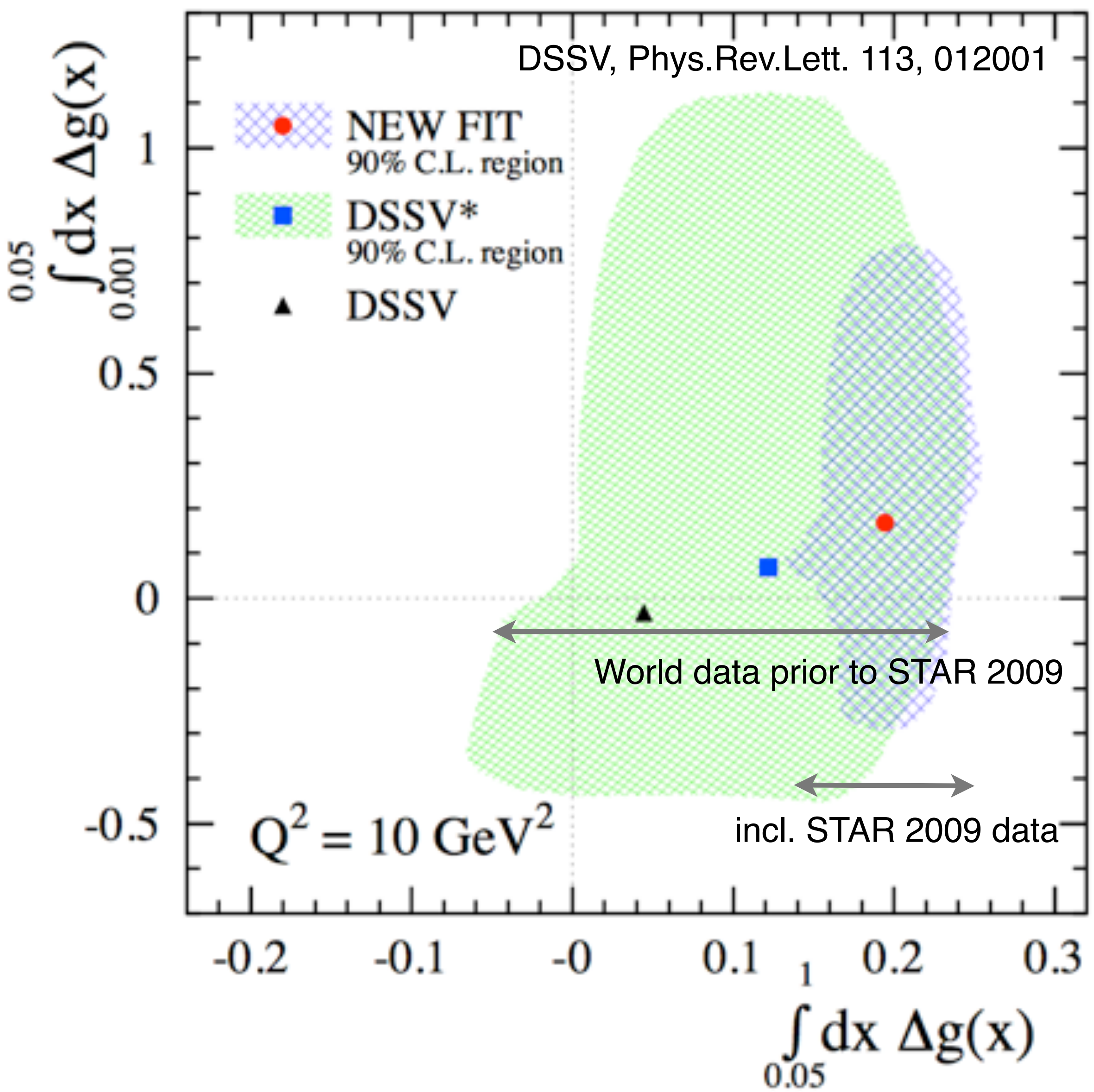
0.21 ± 0.10

NNPDF, Nucl. Phys. B 887, 276 (2014)

Gluon polarization is positive in the region of the data; ~0.2 ħ

Gluon Polarization

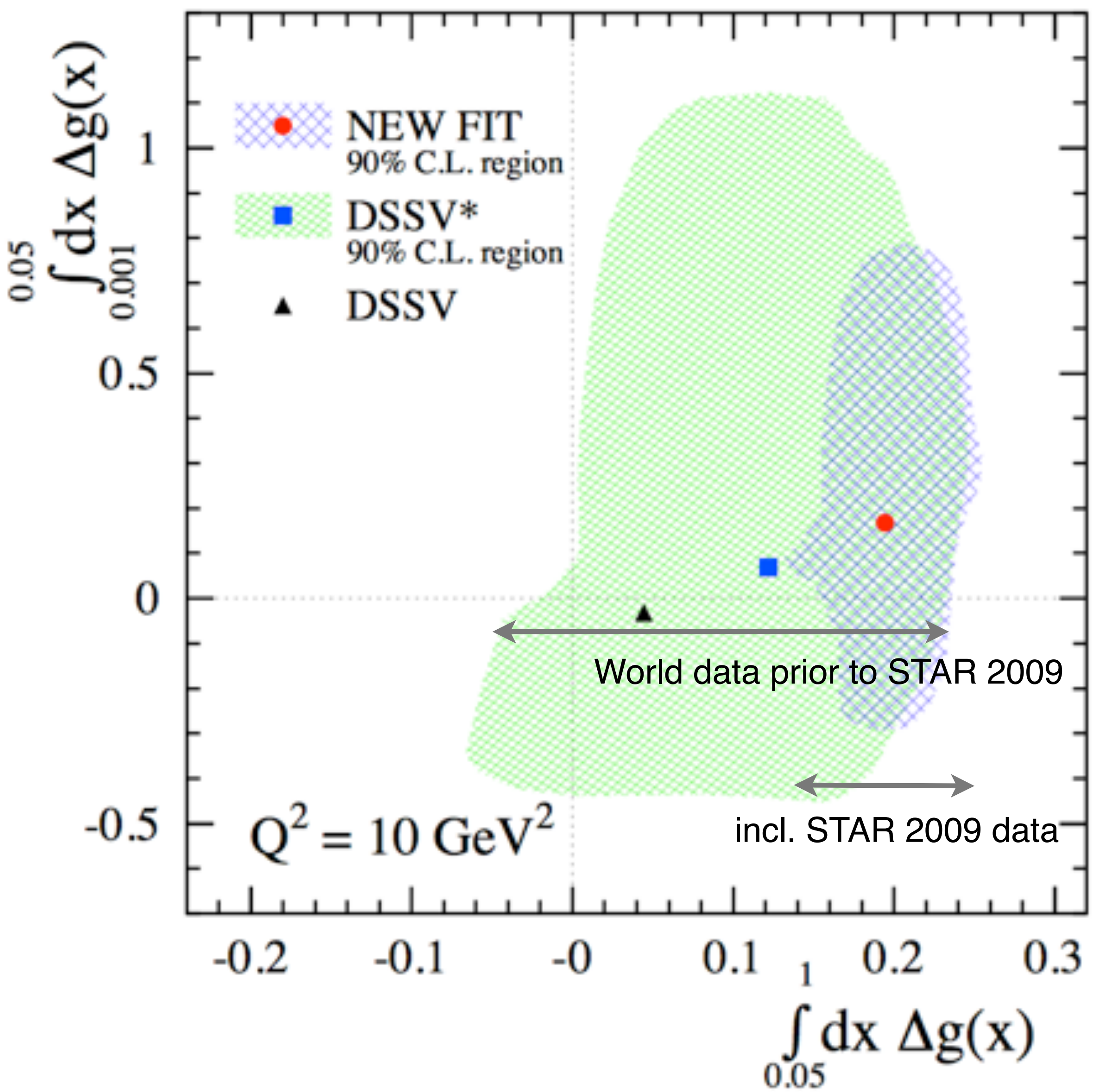
Evidence for positive gluon polarization



Easy to "hide" 1 h in the unmeasured region

Gluon Polarization

DSSV, Phys.Rev.Lett. 113, 012001



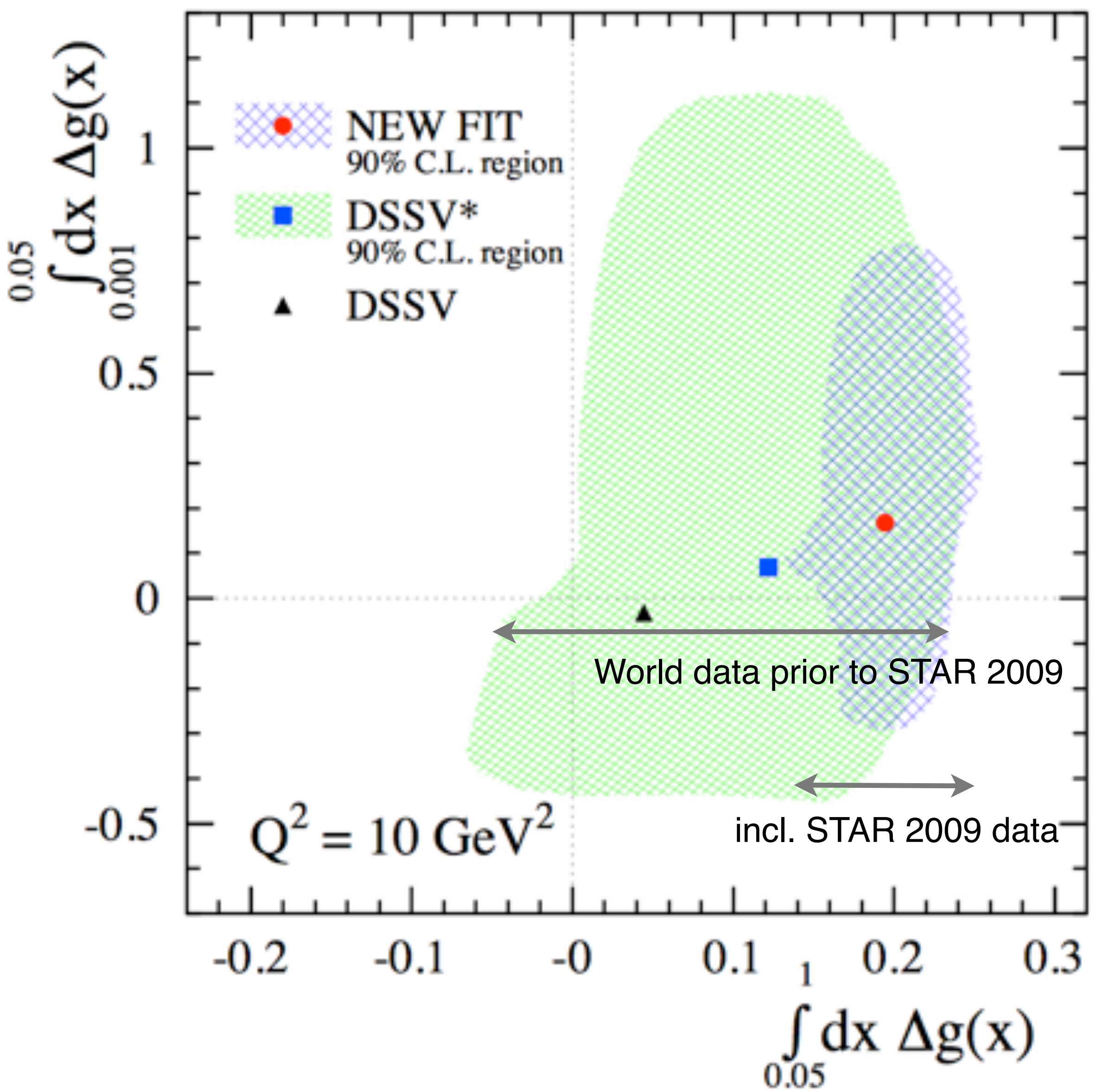
Extend sensitivity to *smaller* x_g

$\sqrt{s}$ = 500 GeV data, $x_g \sim 1/\sqrt{s}$,

forward rapidity, $x_g \sim \exp(-\eta)$,

Gluon Polarization

DSSV, Phys.Rev.Lett. 113, 012001



Extend sensitivity to *smaller* x_g

$\sqrt{s}$ = 500 GeV data, $x_g \sim 1/\sqrt{s}$,

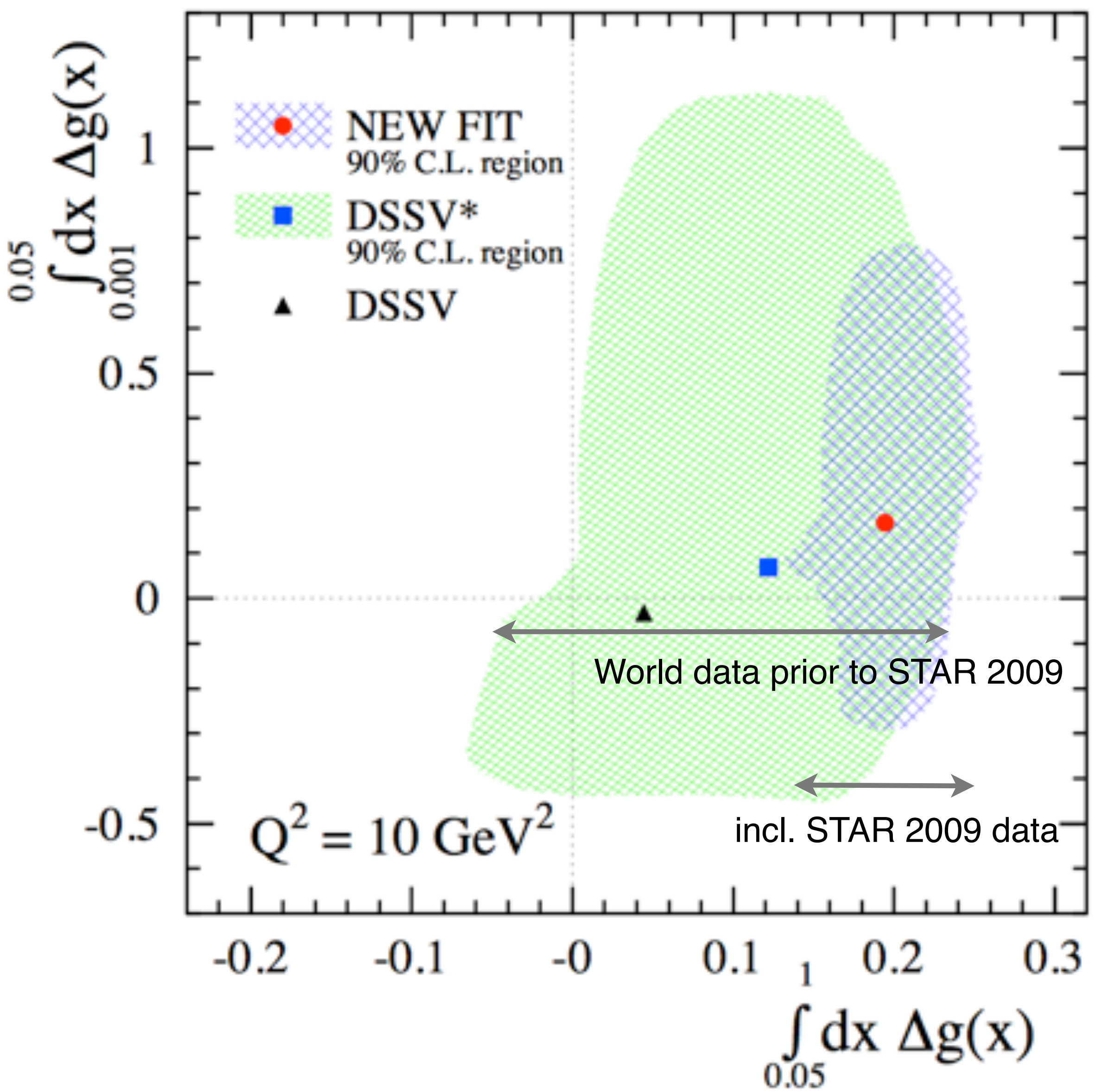
forward rapidity, $x_g \sim \exp(-\eta)$,

Further *precision* from jet and neutral pion probes, and from *complementary* probes

Gain insight in x_g dependence.

Gluon Polarization

DSSV, Phys.Rev.Lett. 113, 012001



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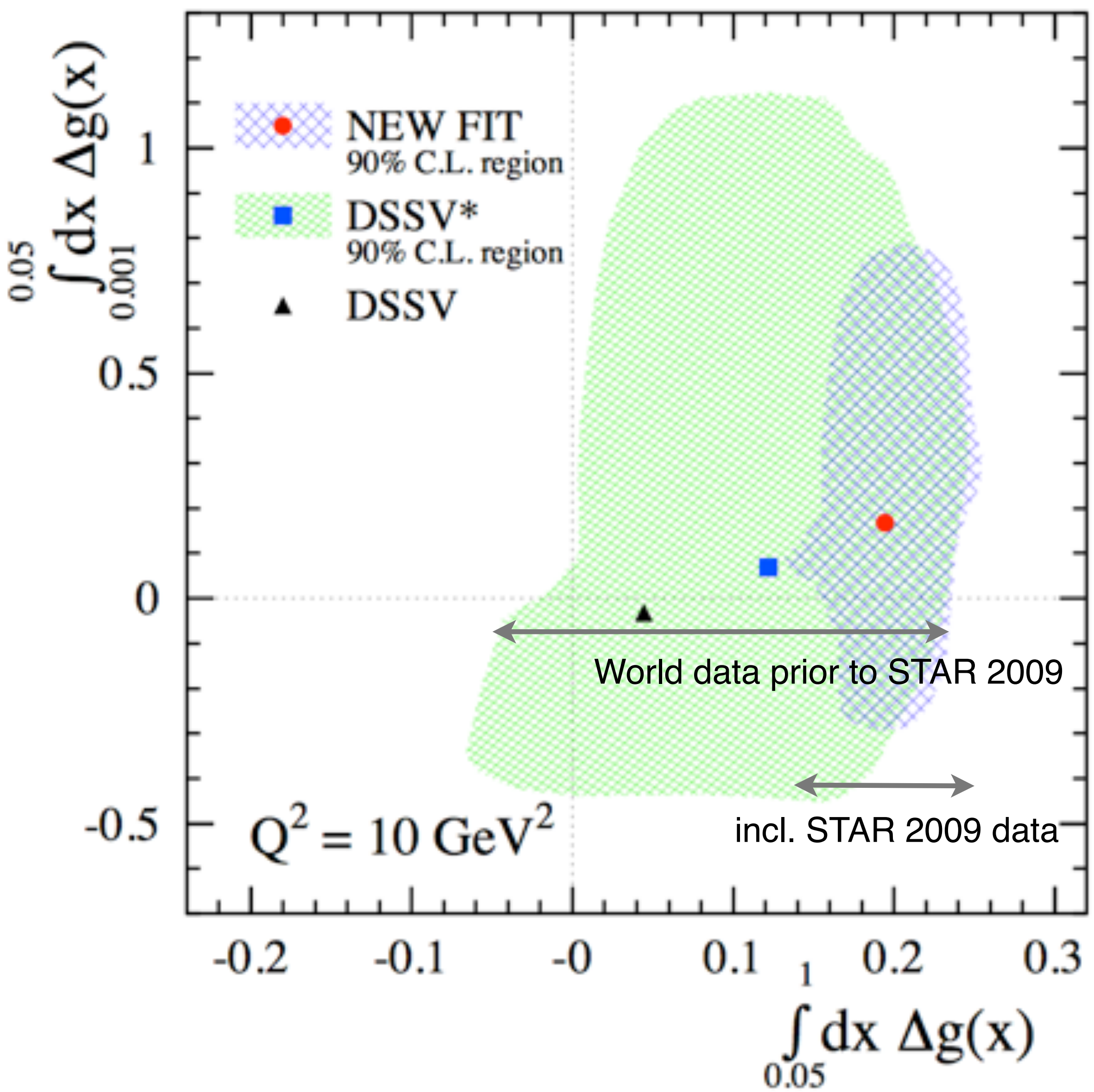
DSSV, Phys.Rev.Lett. 113, 012001



Extend sensitivity to *smaller* x_g

$\sqrt{s}$ = 500 GeV data, $x_g \sim 1/\sqrt{s}$,

forward rapidity, $x_g \sim \exp(-\eta)$,

RHIC continues to make progress and impact,
see also Elke's talk yesterday,

Clear role for a future EIC

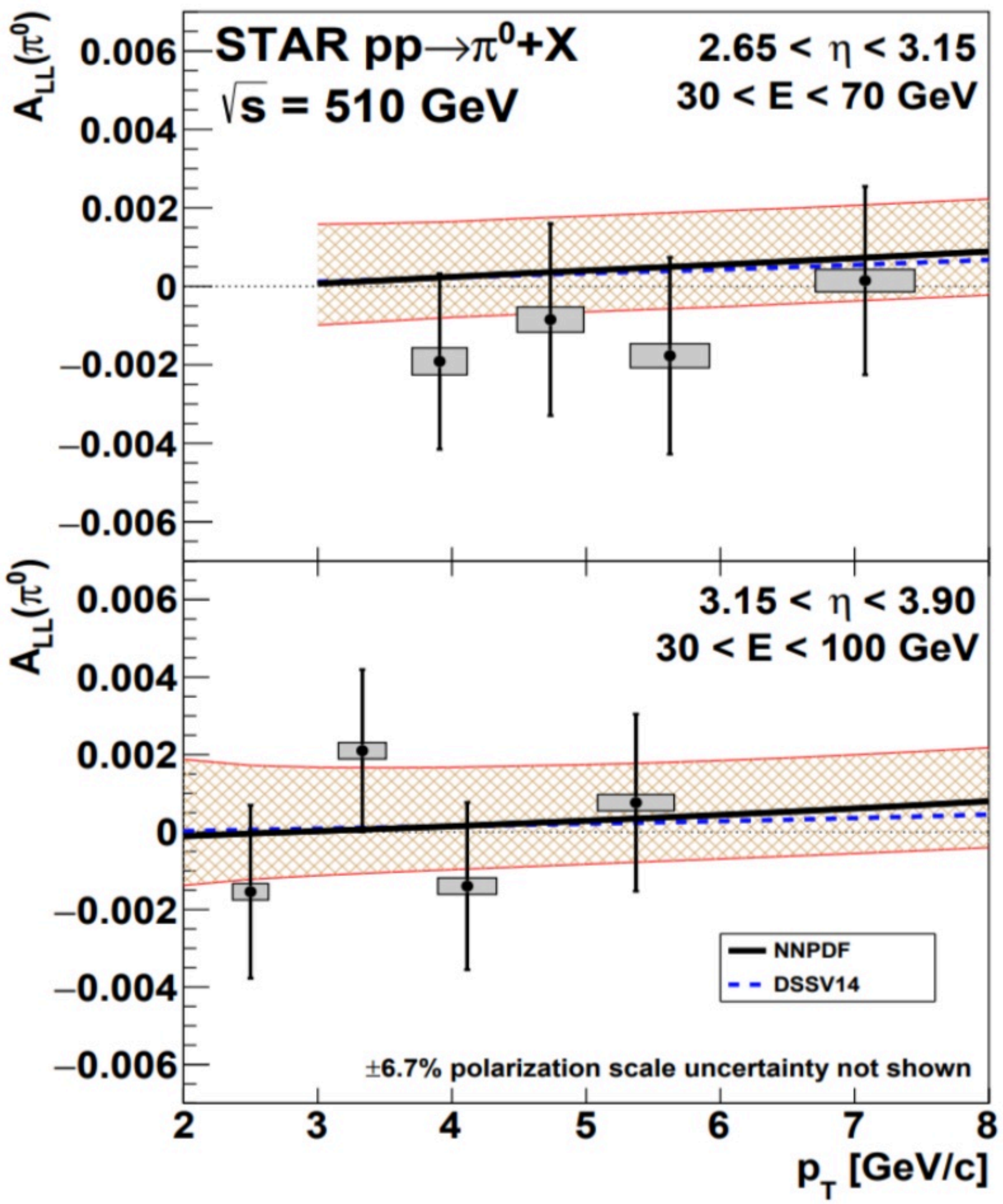
Further *precision* from jet and neutral pion probes, and from *complementary* probes

Gain insight in x_g dependence.

Gluon Polarization

An early glimpse in the forward acceptance region:

arXiv: 1805.09745, PRD 98, 032013 (2018)



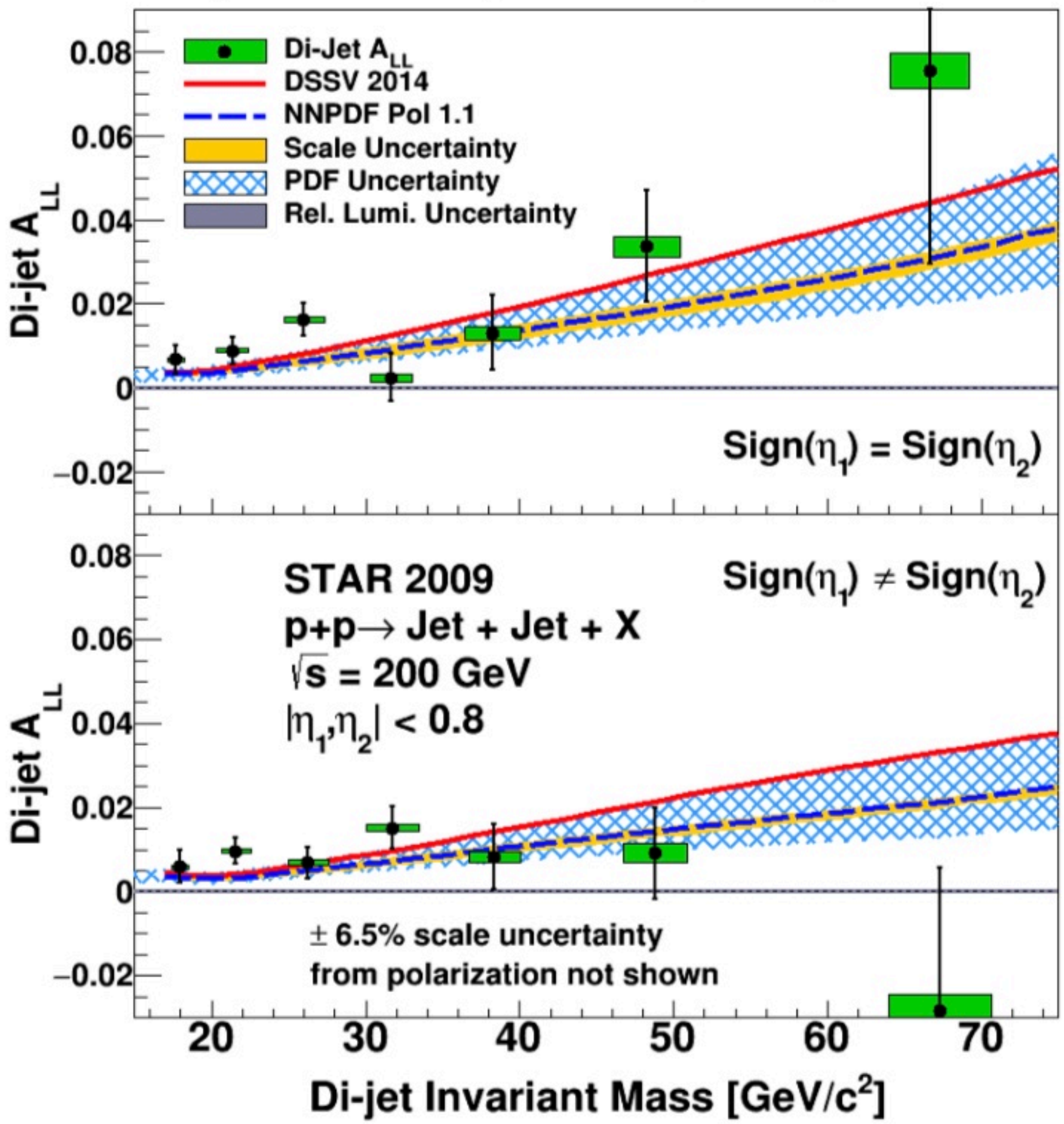
- Results are given for transverse momenta in the range $2 < p_T < 10$ GeV/c within two regions of pseudorapidity that span $2.65 < \eta < 3.9$
- These results are sensitive to the polarized gluon parton distribution function, $\Delta g(x)$, down to the region of parton momentum fraction $x \sim 0.001$
- These results will provide the first direct experimental constraints in $x << 0.01$

Correlation measurements will access larger (average) partonic asymmetries.

Gluon Polarization

Mid-central di-jet asymmetries:

Phys. Rev. D 95, 071103 (2017)

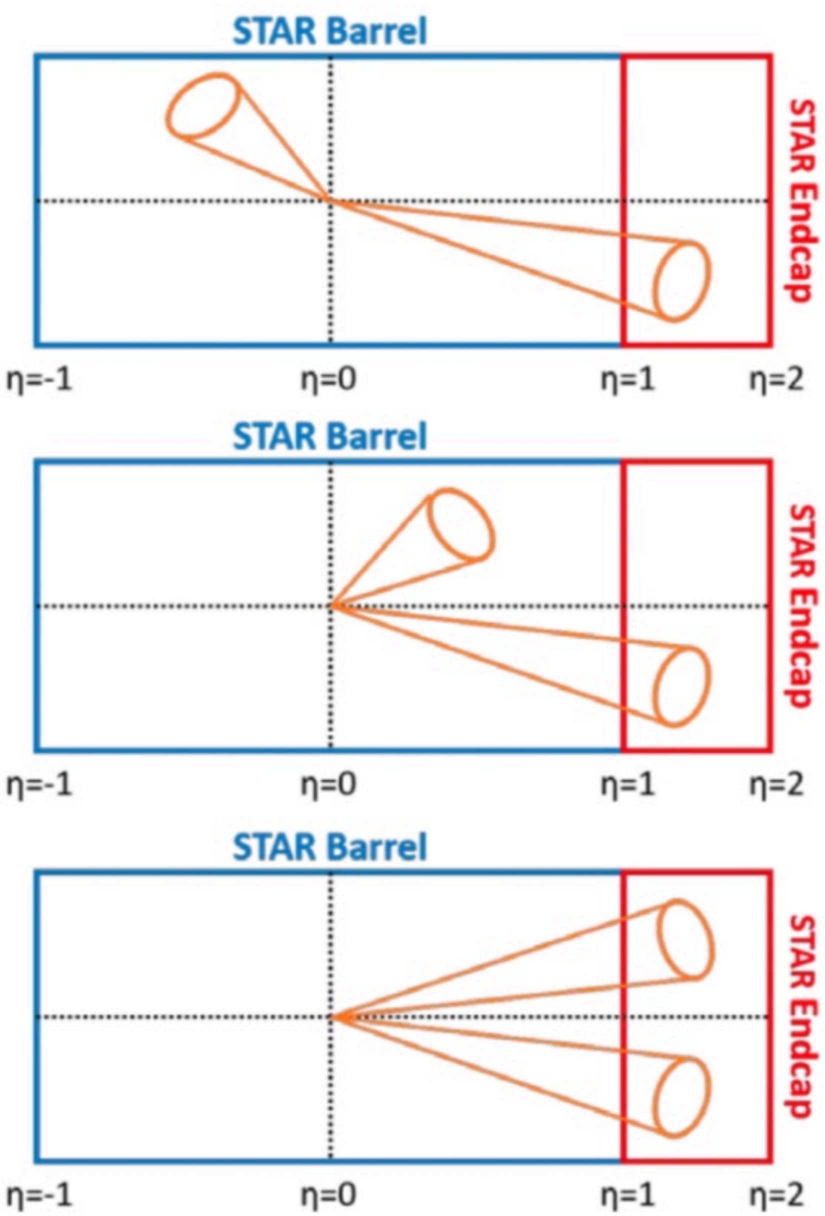


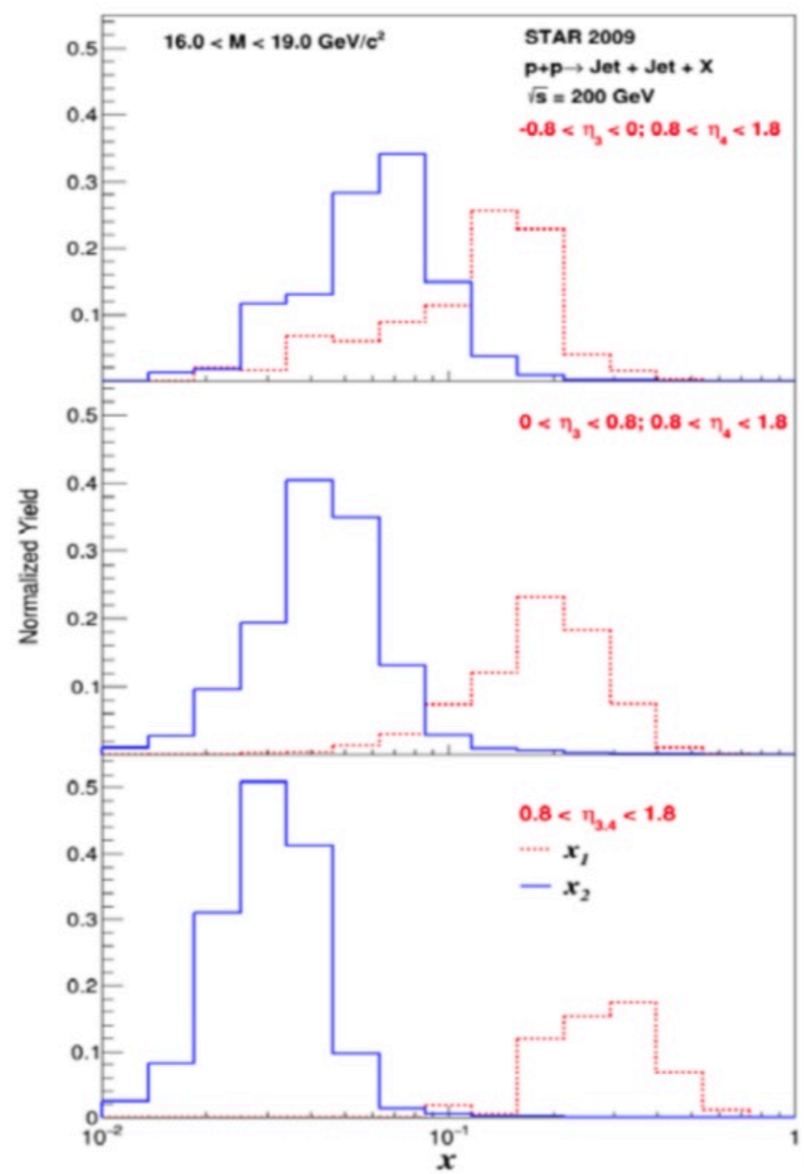
Towards sensitivity to Bjorken-x.

Preliminary results at 500 GeV have come out as well, paper in preparation

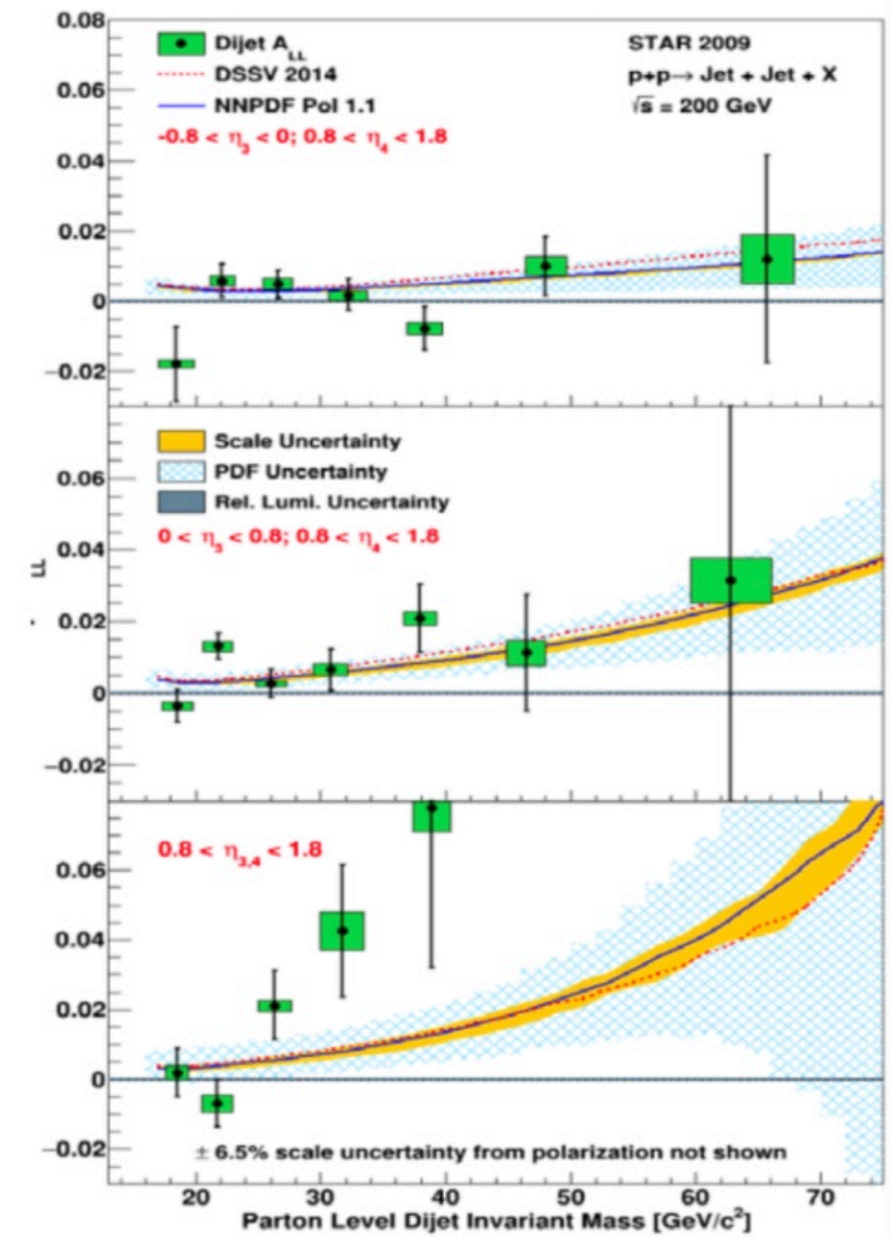
Gluon Polarization

di-jet asymmetries in a more forward region:



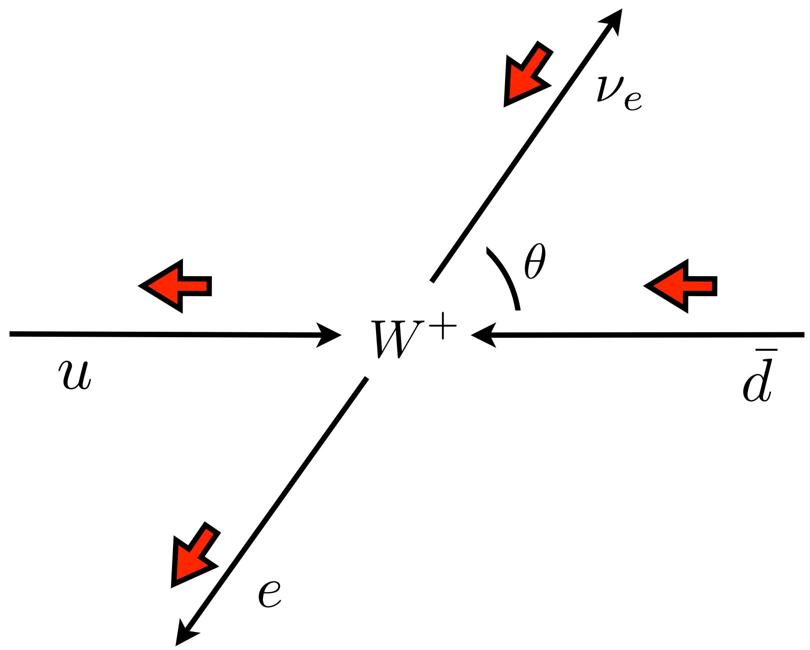


PRD 98 (2018) 032011



Impact clearly exists; quantifying it will require renewed global analysis (and/or reweighting)

Quark Polarization at RHIC



$\sqrt{s}$ = 500 GeV above W production threshold,

Experiment Signature:
large p_T lepton, missing E_T

Experiment Challenges:
charge-ID at large |rapidity|
electron/hadron discrimination
luminosity hungry

Free of fragmentation (!)

$$\Delta\sigma^{\text{Born}}(\vec{p}p \to W^+ \to e^+\nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2$$

Spin Measurements:

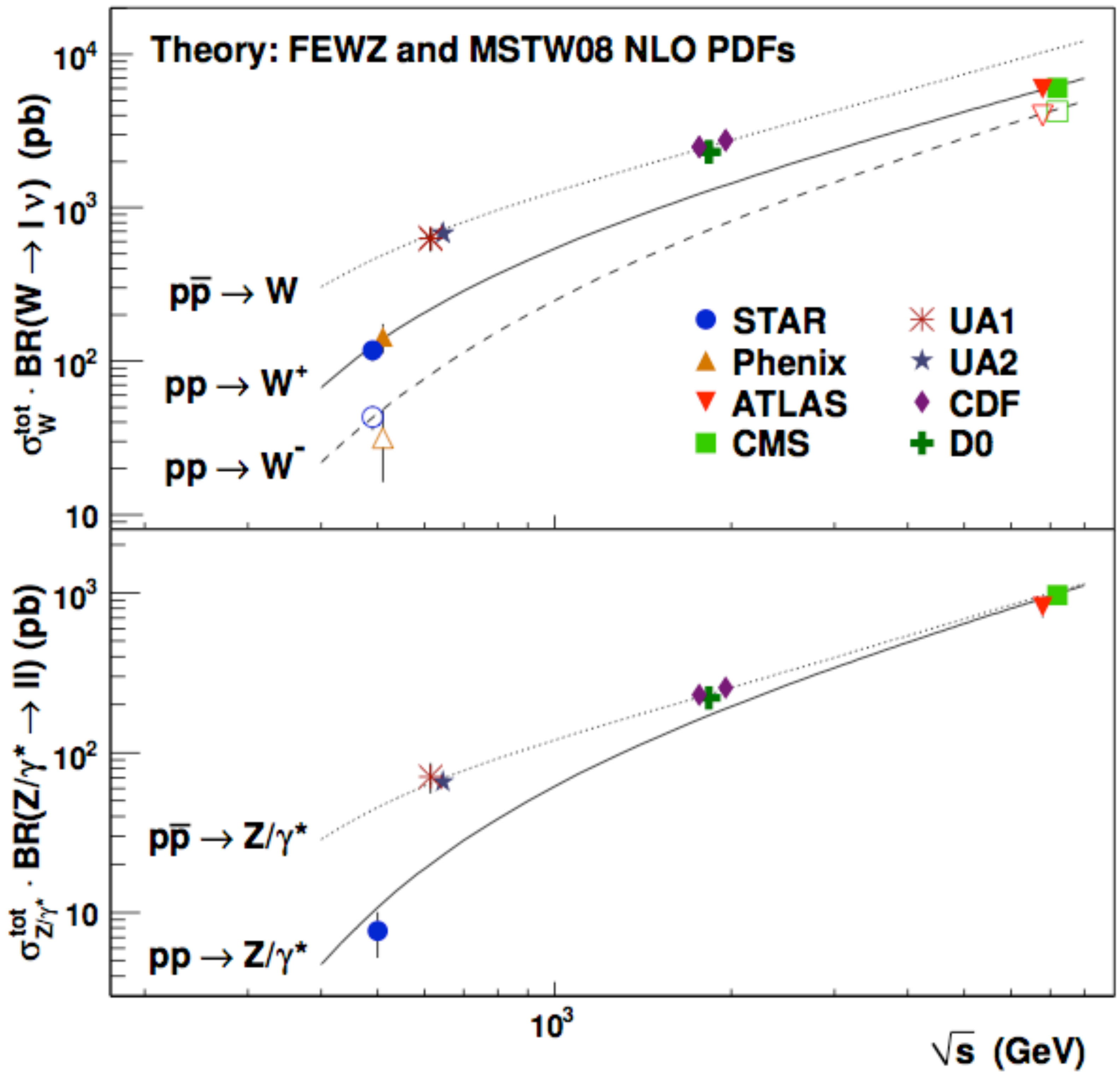
$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

LO expressions to illustrate overall behavior,

$$A_L(W^-) = \begin{cases} -\dfrac{\Delta d(x_a)}{d(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \to 1 \end{cases}$$

NLO known and used in extracting pPDFs.

W and *Z* Production Cross Sections



PHENIX: first W^+ and W^- production cross sections in proton-proton collisions, Phys.Rev.Lett. **106** (2011) 062001,

STAR: Initial NC cross section at RHIC, confirmation of PHENIX CC cross section measurements, Phys. Rev. **D85** (2012).

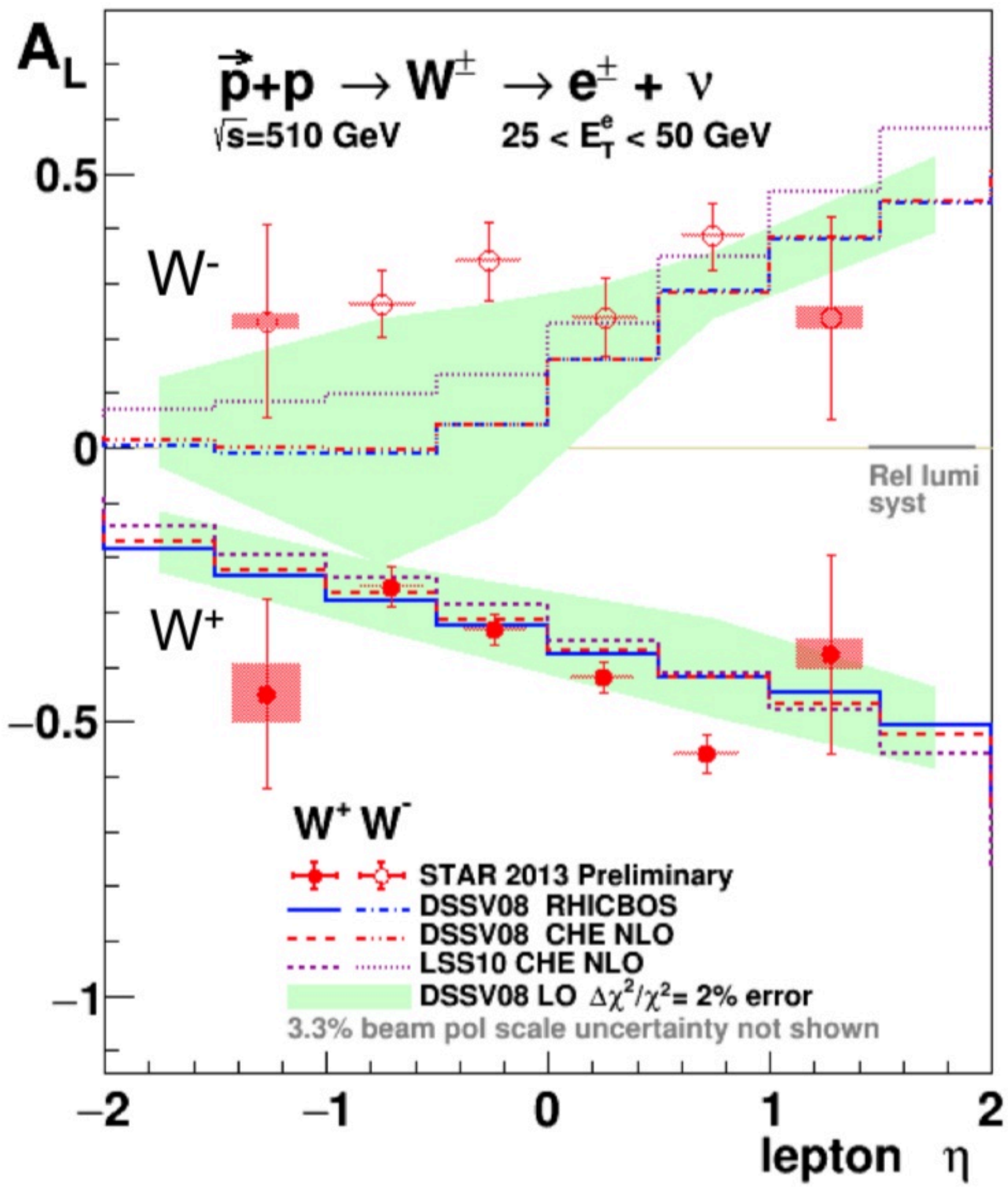
Data are well-described by NLO pQCD theory (FEWZ + MSTW08),

Necessary condition to interpret asymmetry measurements,

Future ratio measurements may provide insights in unpolarized light quark distributions

The "numerator" is again well-described; differential c.s. ratios complementary to E866, ...

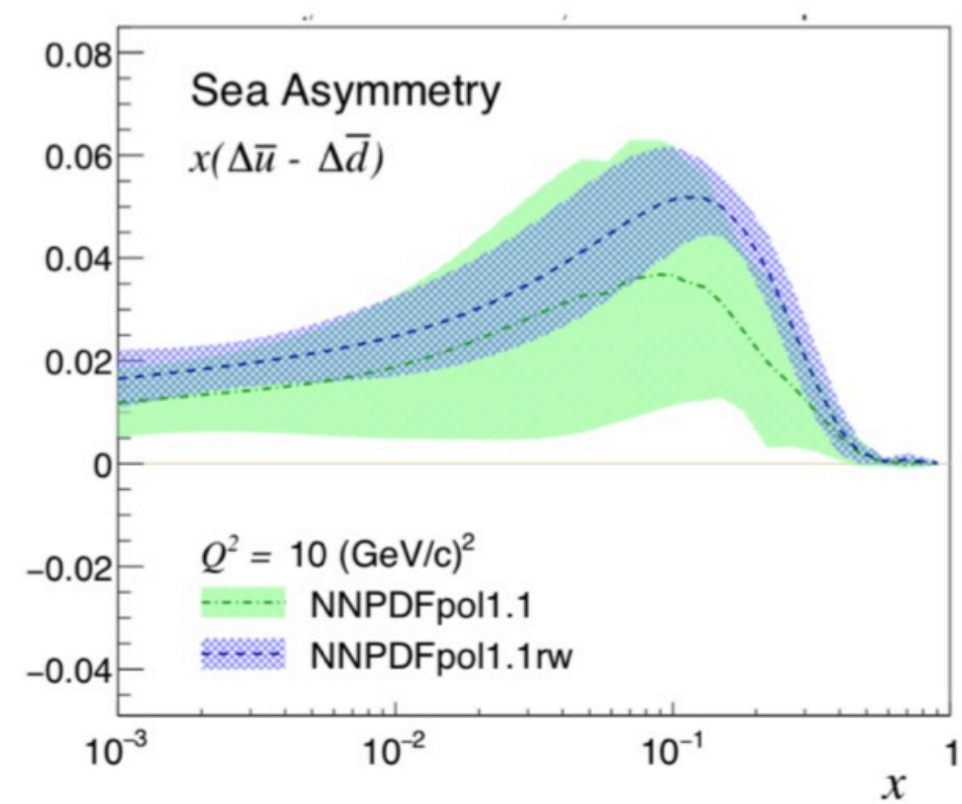
Quark Polarization at RHIC



See e.g. J. Zhang, INPC
Q.H. Xu, DIS

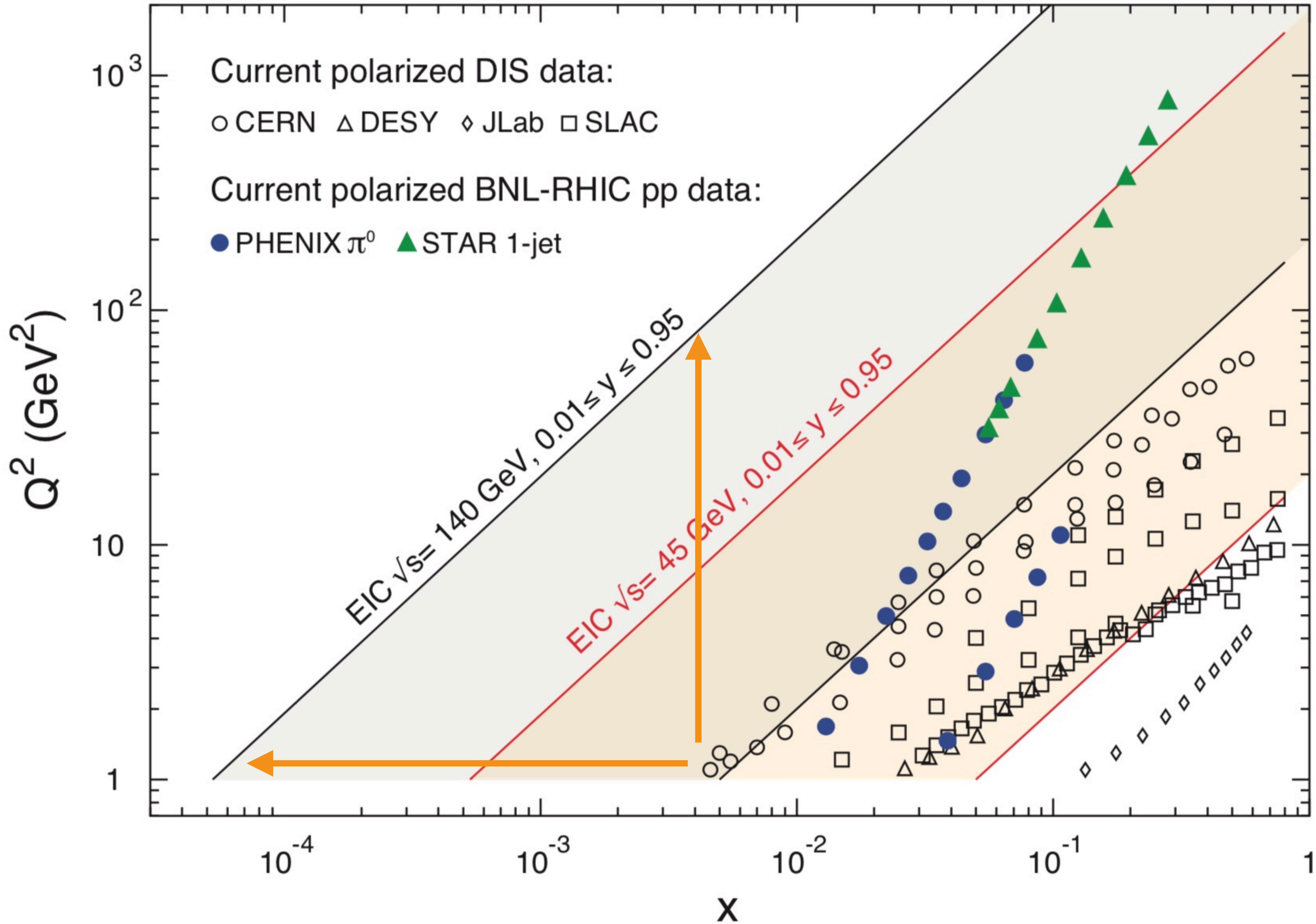
- Further confirmed the polarized sea asymmetry:

$$\Delta\bar{u} > \Delta\bar{d}$$



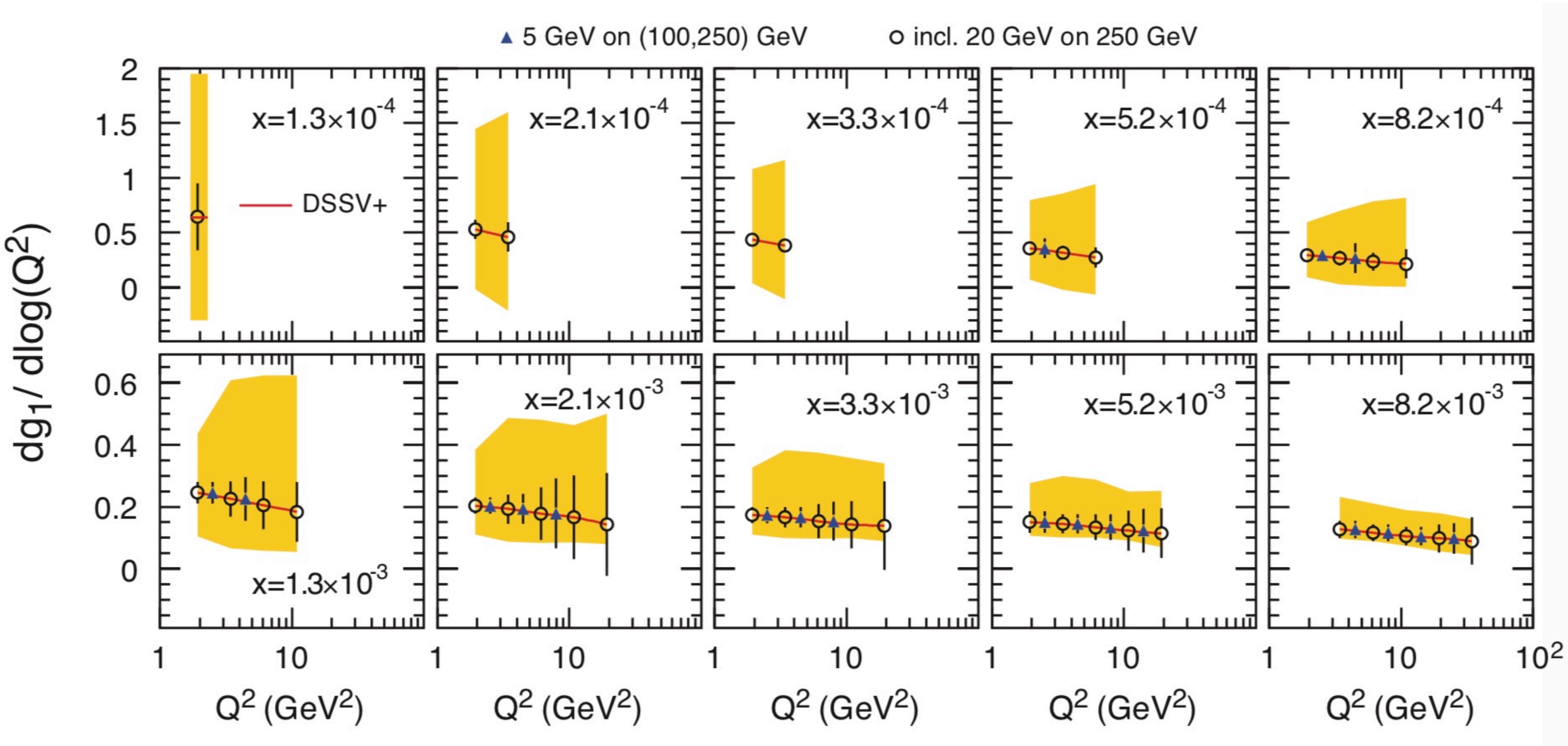
The light quark-sea is polarized and exhibits a flavor asymmetry.

Outlook to EIC



Two orders in x and Q^2 compared to existing data; few, if any, alternatives.

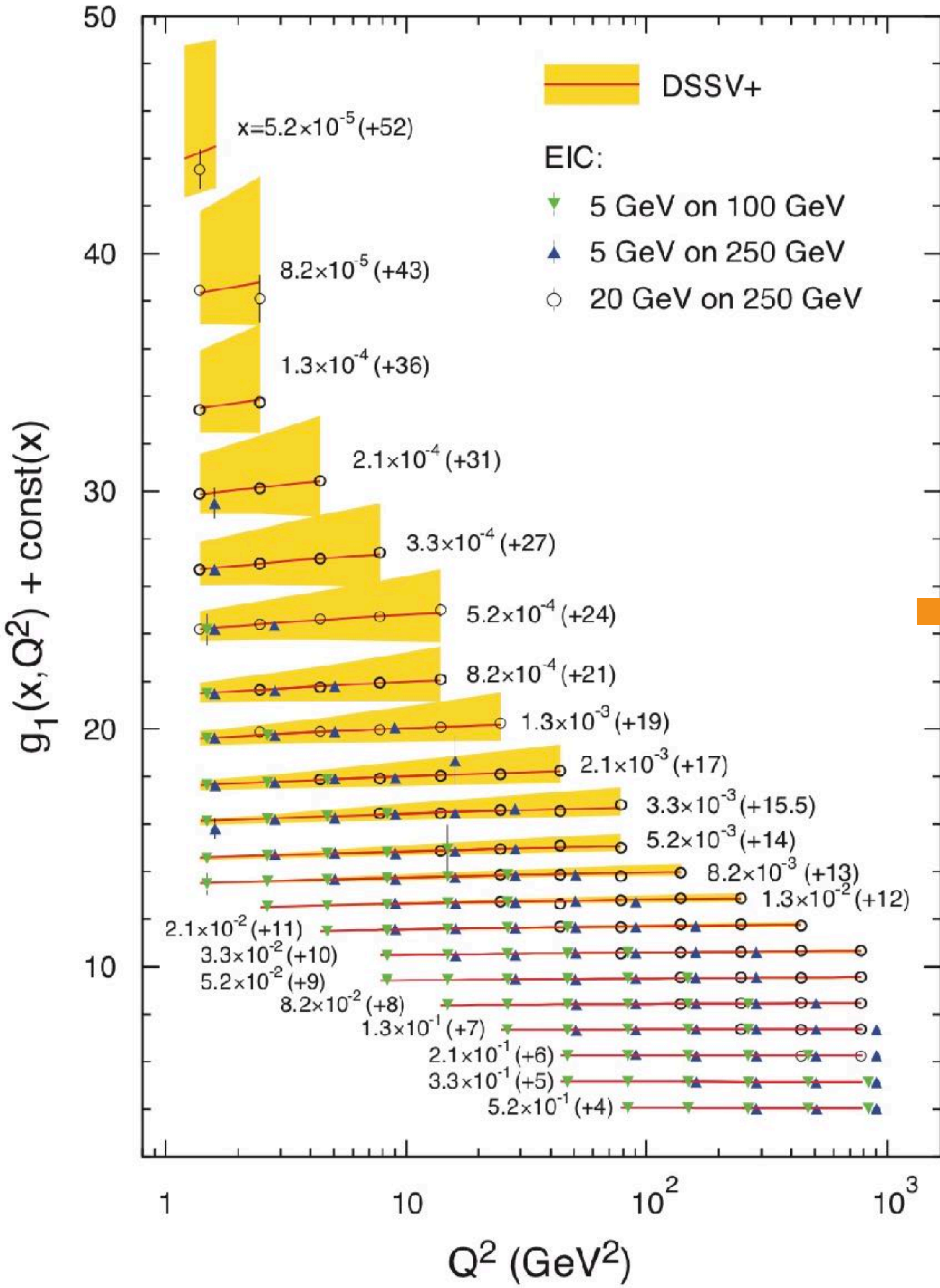
Outlook to EIC

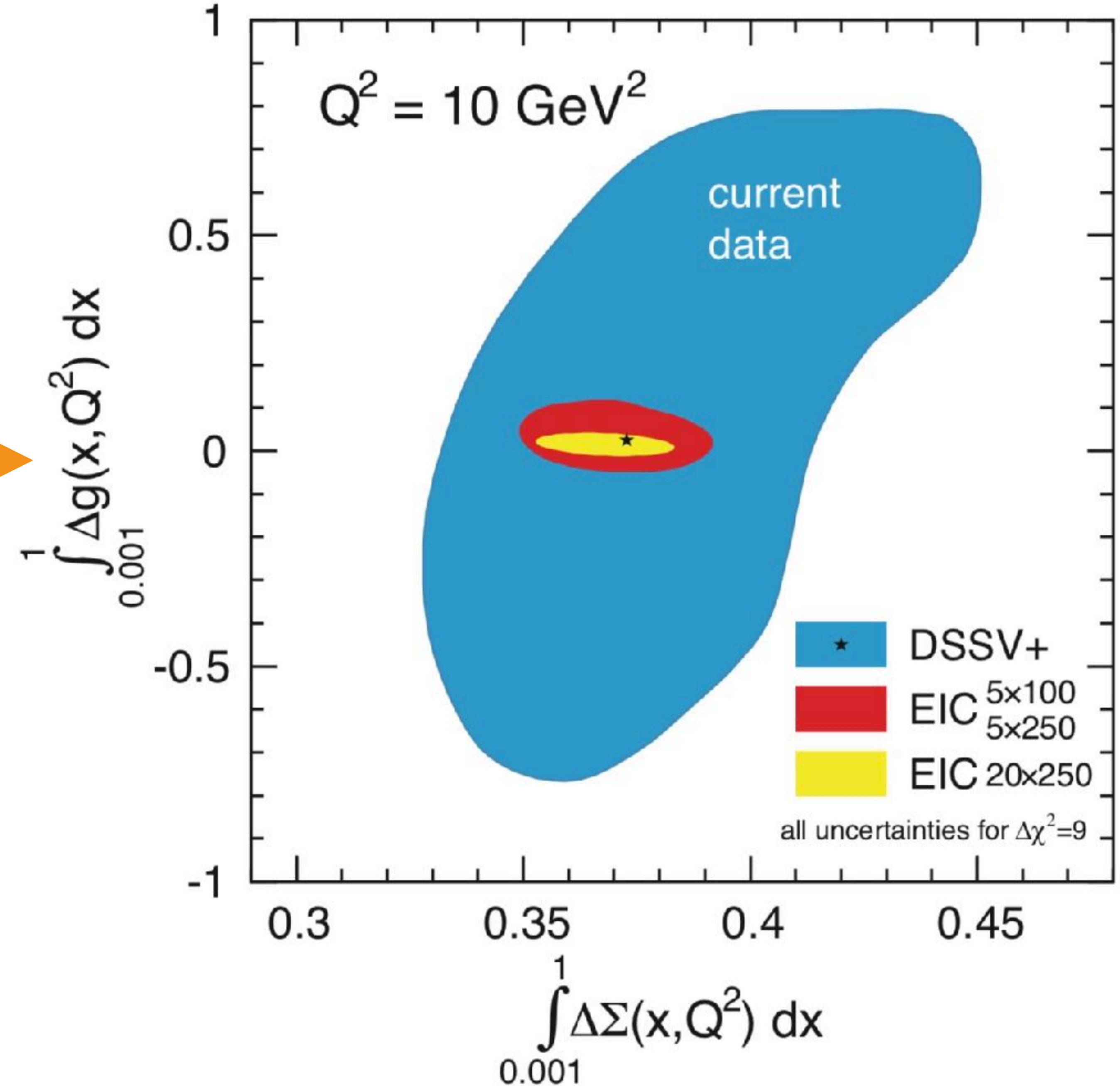


Direct sensitivity to scale-dependence, and hence gluon polarization, at least to $x \sim 10^{-3}$

Simultaneous access also to a host of complementary channels,
e.g. open charm production.

Outlook to EIC

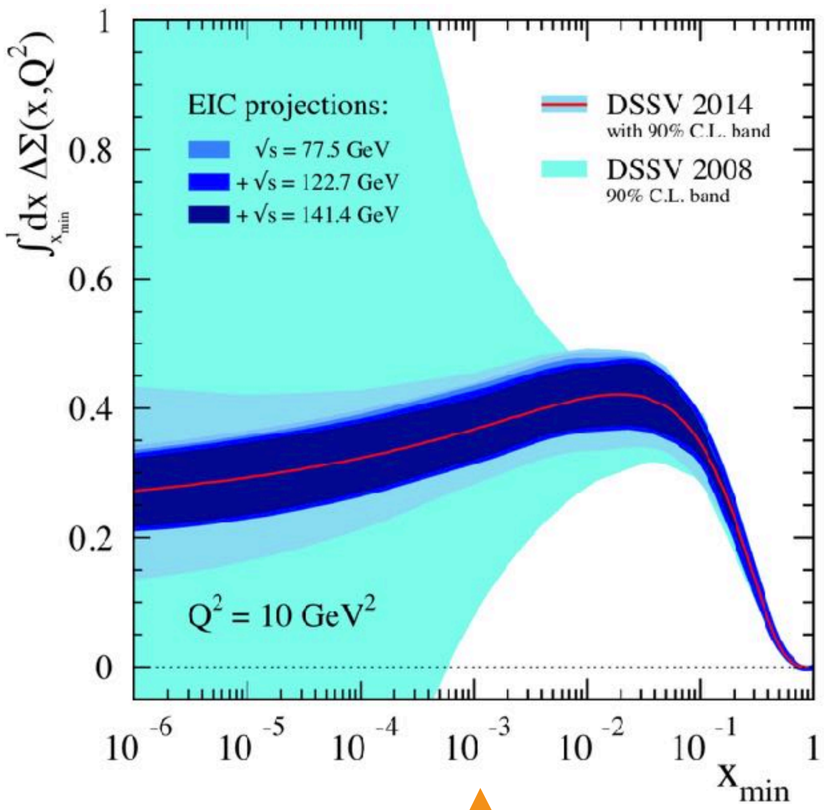




Conclusive insights in quark and gluon helicity from inclusive measurements, and orbital momentum by subtraction (!)

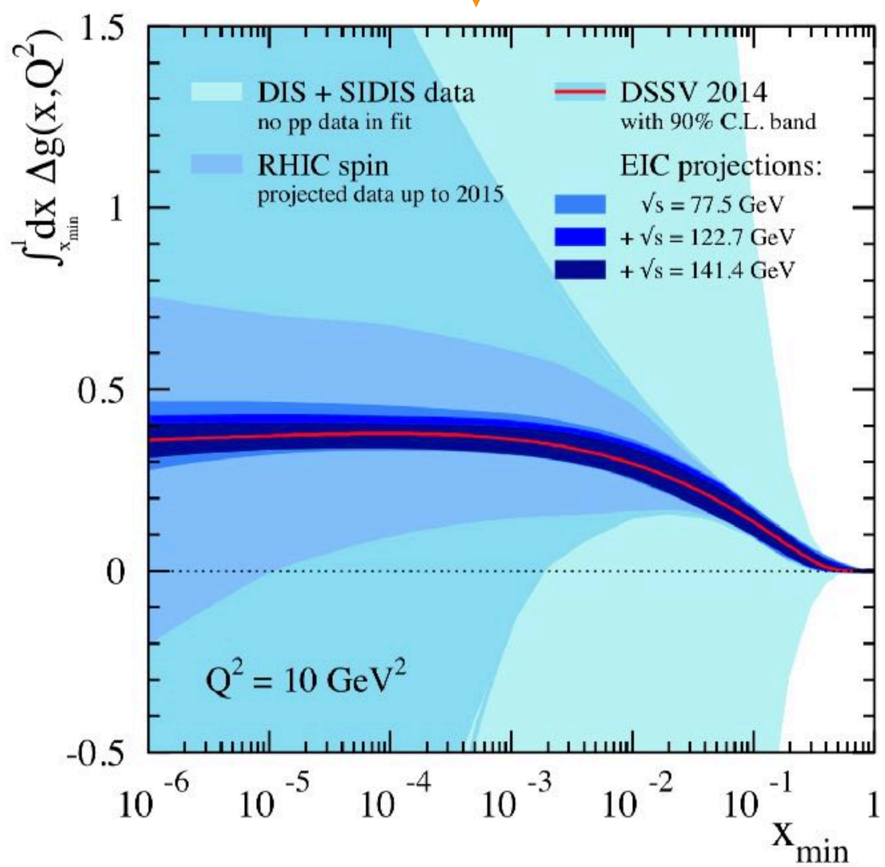
Outlook to EIC

A more up-to-date view; E. Aschenauer et al.
PRD 92 (2015) 094030

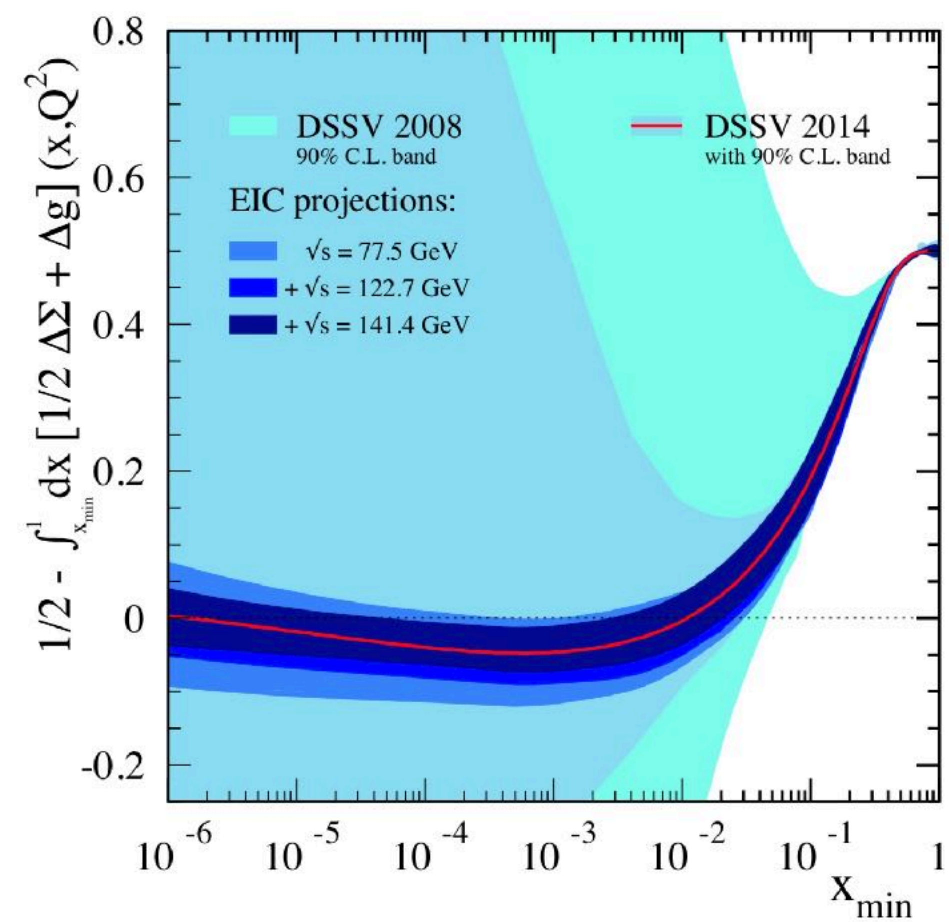


(anti-)quark helicity

gluon helicity



"orbital momenta"

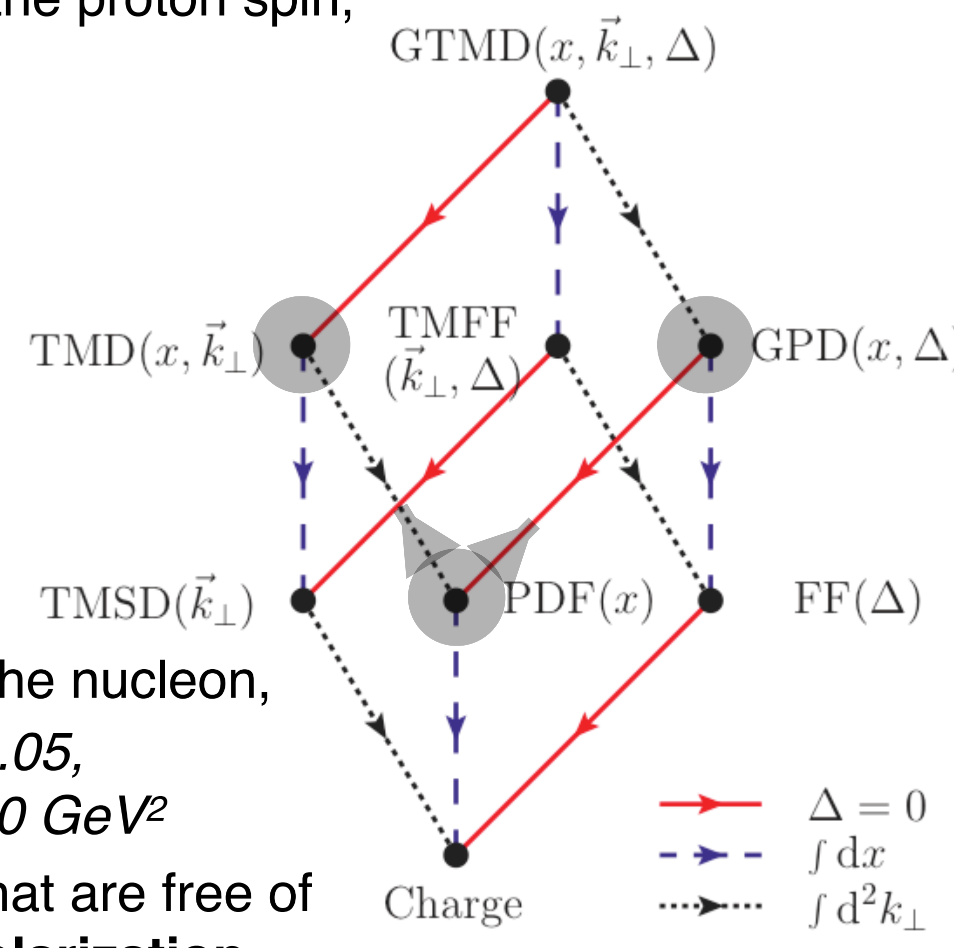


Clearly requires EIC

We are still far from fundamental knowledge and understanding of nucleon spin

DIS data:

- small-x measurements provided the impetus for renewed study of the proton spin,
- data on proton and neutron targets over a wide x-range,
  confirming the Bjorken Sum rule,
  decent insight in the sum of quark and anti-quark spins,
- initial sensitivities to scale dependence,
- best (lack of) insight in strangeness,
- going beyond collinear distributions,



Lorce, Pasquini.

RHIC spin program:

- has achieved the most sensitive insights in **gluon polarization** in the nucleon,
  gluons are positively polarized for momentum fractions x > 0.05,
  at the level of 0.2 h for Q^2 = 10 GeV^2
- has provided evidence, with measurements at the W-mass scale that are free of fragmentation uncertainties, of non-perturbative **sea-quark polarization**,
- (quite promising TMD measurements; a talk by itself)

Lattice QCD:

- considerable progress, *also* on *x*-dependence,
- combination with data in the foreseeable future ?

EIC and theory will be essential to solve the "spin puzzle."