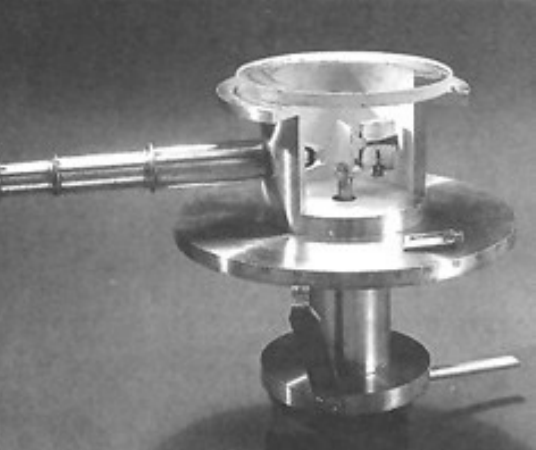
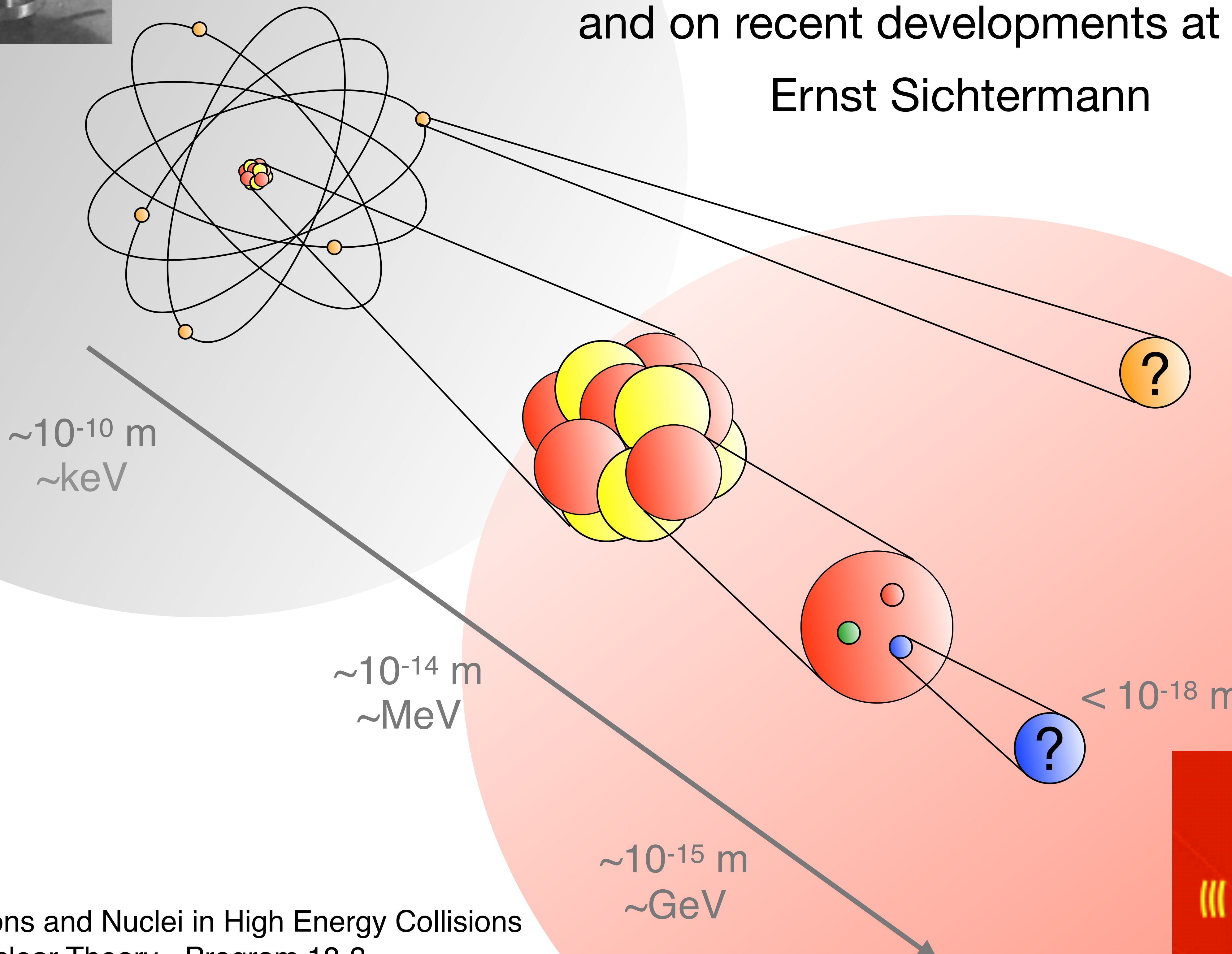


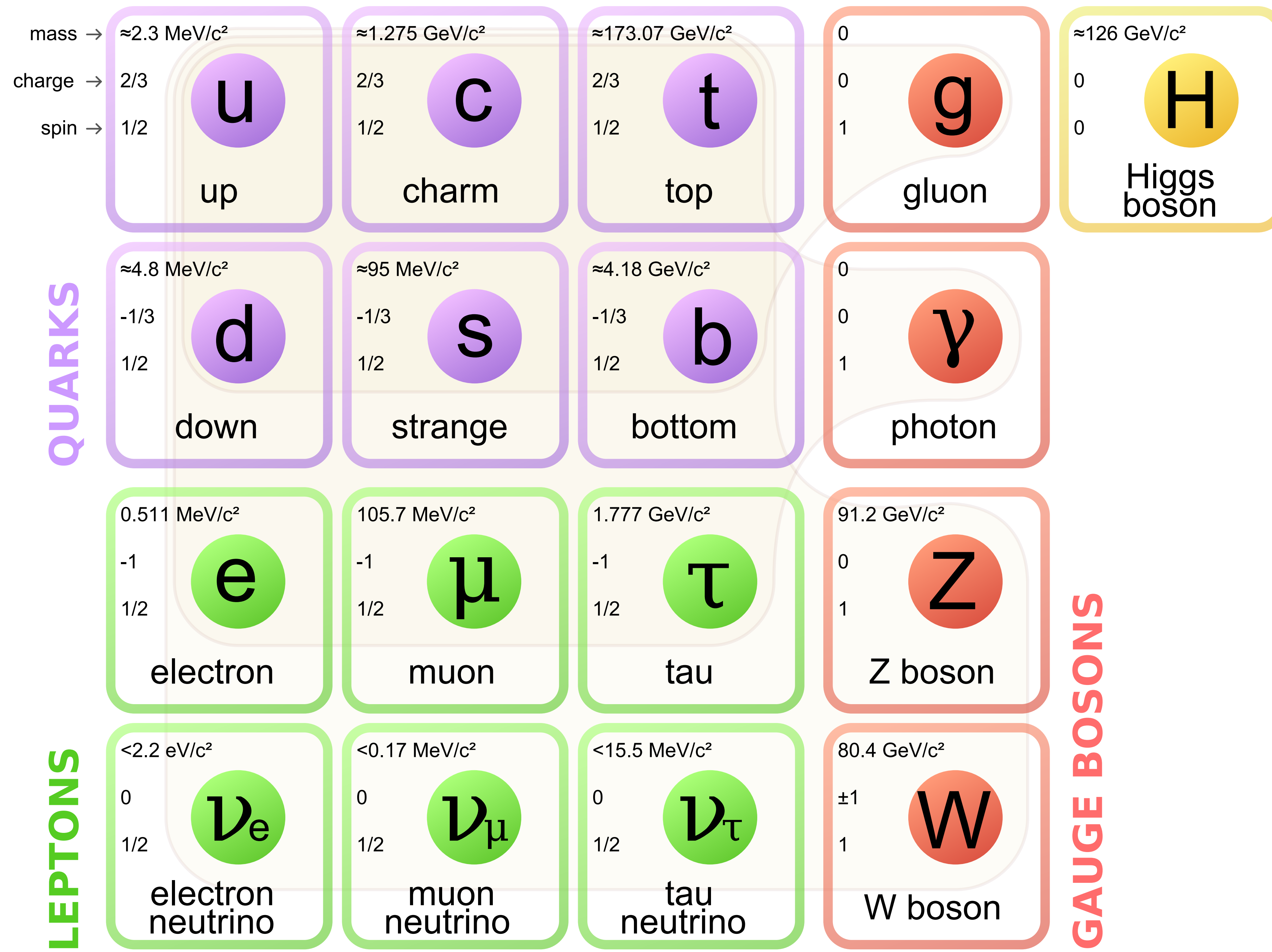
A few comments on the spin decomposition, and on recent developments at RHIC

Ernst Sichtermann



Probing Nucleons and Nuclei in High Energy Collisions
Institute for Nuclear Theory - Program 18-3
Seattle, WA - October 17, 2018

What *is* a proton, neutron, nucleus anyway?



The proton is 2 up quarks and 1 down quark, …

Really? "Just open many textbooks…"

What *is* a proton, neutron, nucleus?

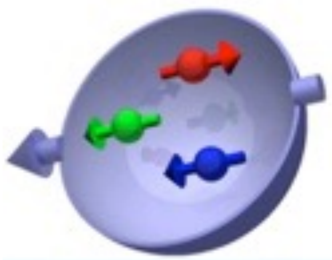
A high-energy view: *an unseparated, broadband beam of quarks, anti-quarks, and gauge bosons (primarily gluons), and perhaps other constituents, yet unknown.*

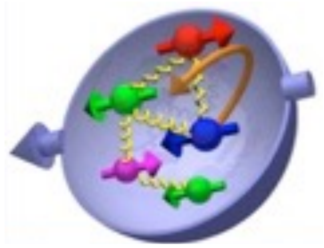
40 years of an amazingly robust idealization:
Renormalization group-improved Parton Model

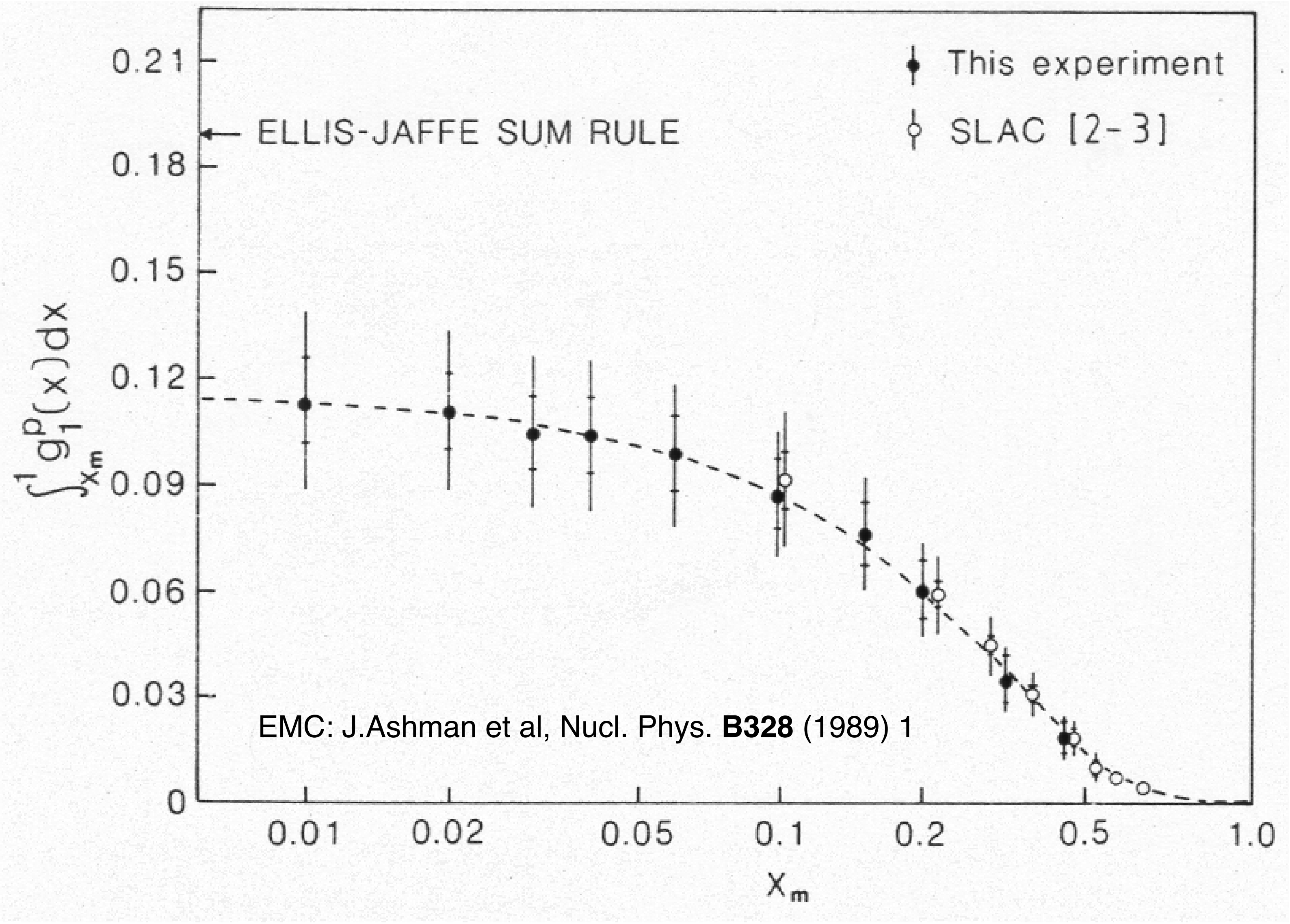
Factorization theorem(s) + one-dimensional parton distributions,
no correlations among the partons

Really? ***More than a few of our high-energy observations are actually different***
Essential to separate intrinsic structure from interaction dynamics,
push the envelope beyond the theoretically established,
obtain <u>meaningful accuracy</u>.

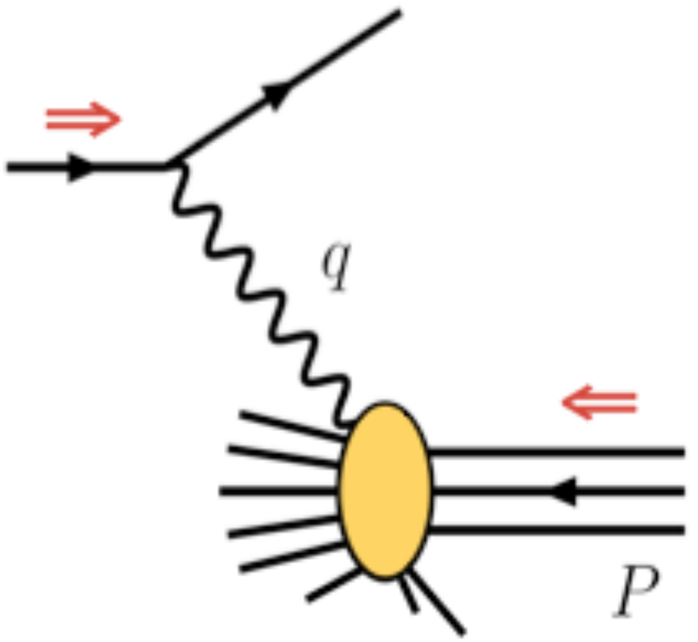
Really? - Proton spin





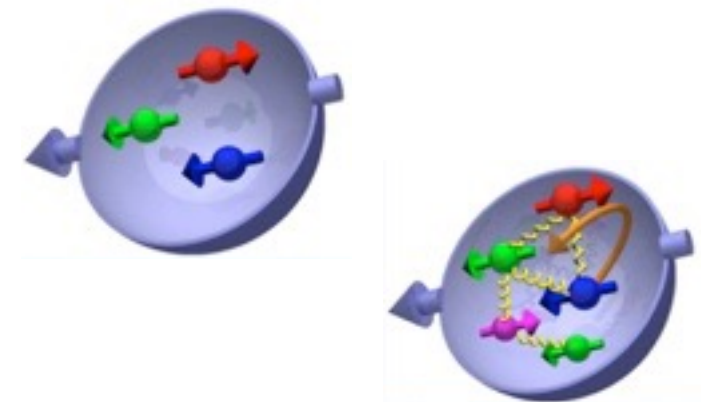


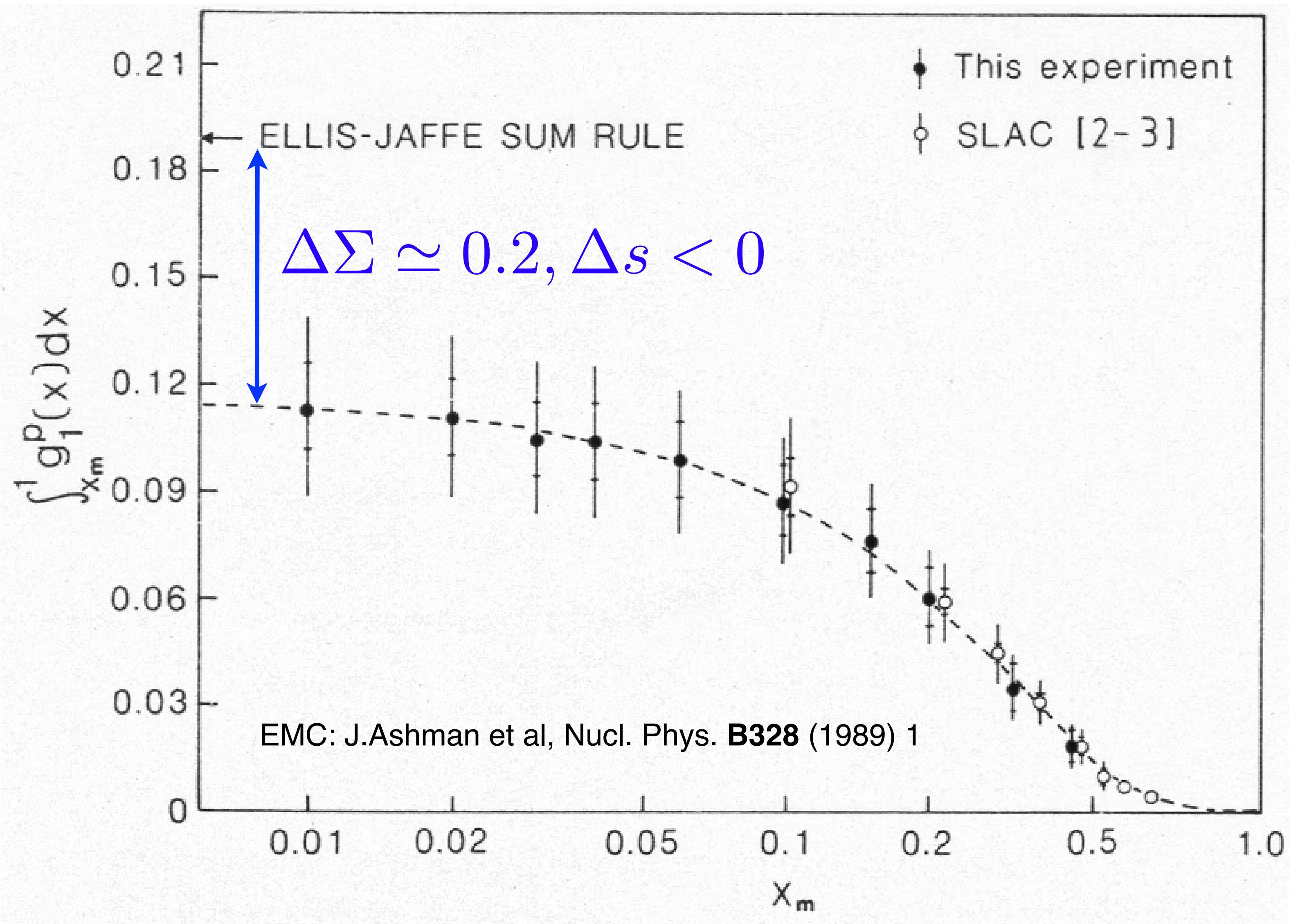
EMC: J.Ashman et al, Nucl. Phys. **B328** (1989) 1

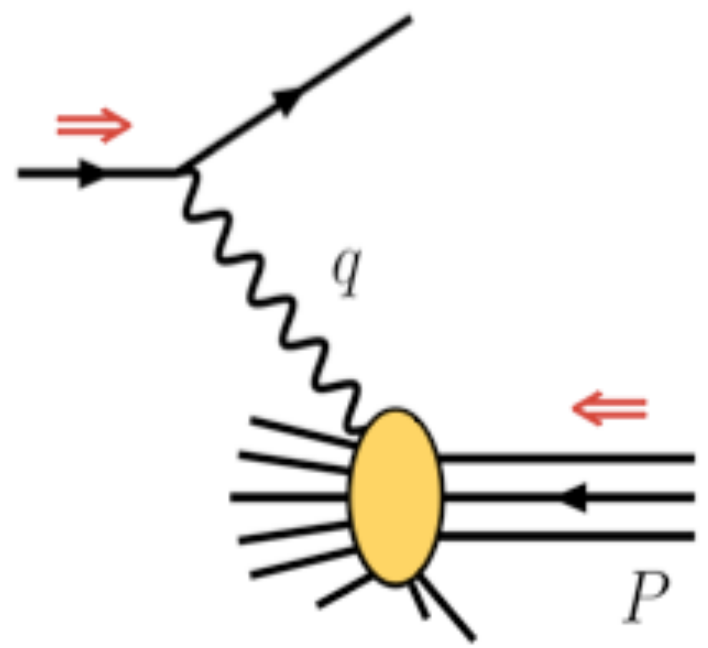


$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x,Q^2)}$$

Really? - Proton spin



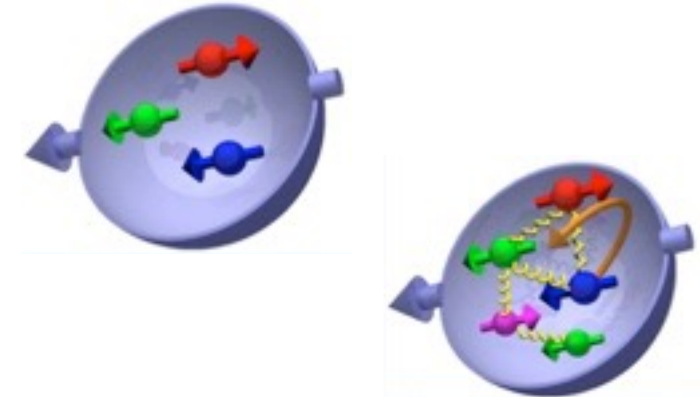




$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x, Q^2)}$$

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

Really? - Proton spin



For the proton,

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

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

Unique to DIS, $\Delta\Sigma$

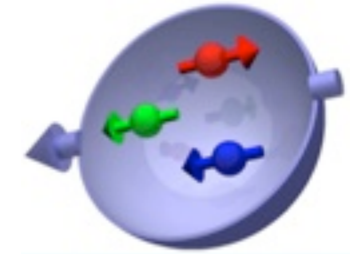
Known from weak neutron to proton decay, combined with weak Σ to neutron decay

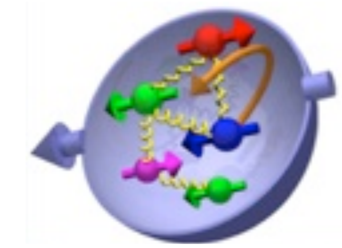
Known from weak neutron to proton decay

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

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

Really? - Proton spin





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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

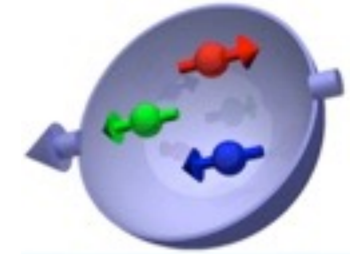
Since,

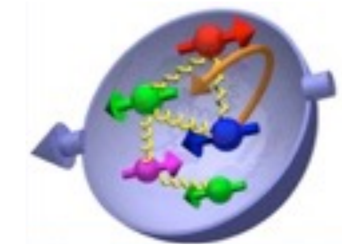
$$\left.\frac{\partial \Gamma_1}{\partial a_8}\right|_{\mathrm{Ellis-Jaffe}} \simeq \frac{5}{36}$$

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

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

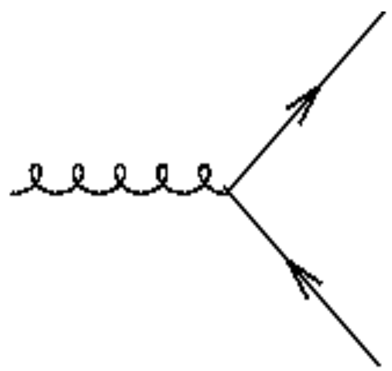
Really? - Proton spin





Numerous follow-up questions and experiment programs,

Among the early attempts at a resolution,



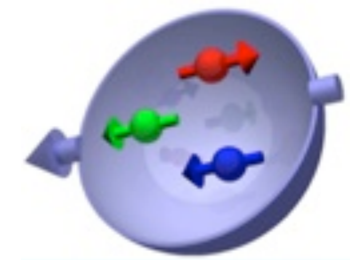
with the gluons *polarized*.

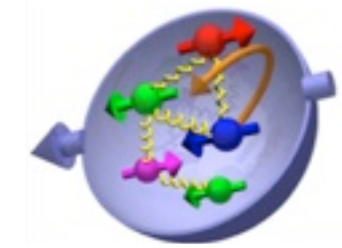
G. Altarelli and G.G. Ross Phys. Lett. **B212** (1998) 391

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*.

DIS - Proton spin





For the proton,

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

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

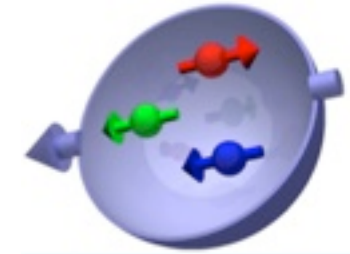
$$+\ \mathcal{O}(\alpha_s)\ \text{now well known}\ +\ \mathcal{O}(1/Q^2)$$

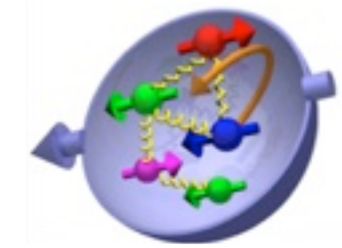
✓ < 10%

Similar can be done for the neutron,

experimentally via the deuteron or ^{3}He,

DIS - Proton spin





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↑ ✓

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

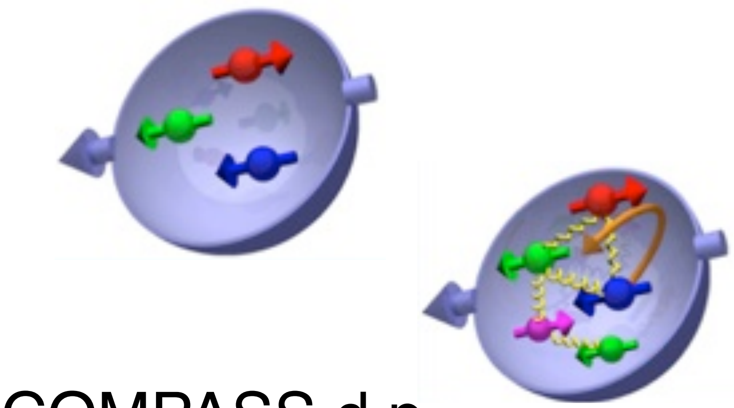
Similar can be done for the neutron,

experimentally via the deuteron or ^{3}He,

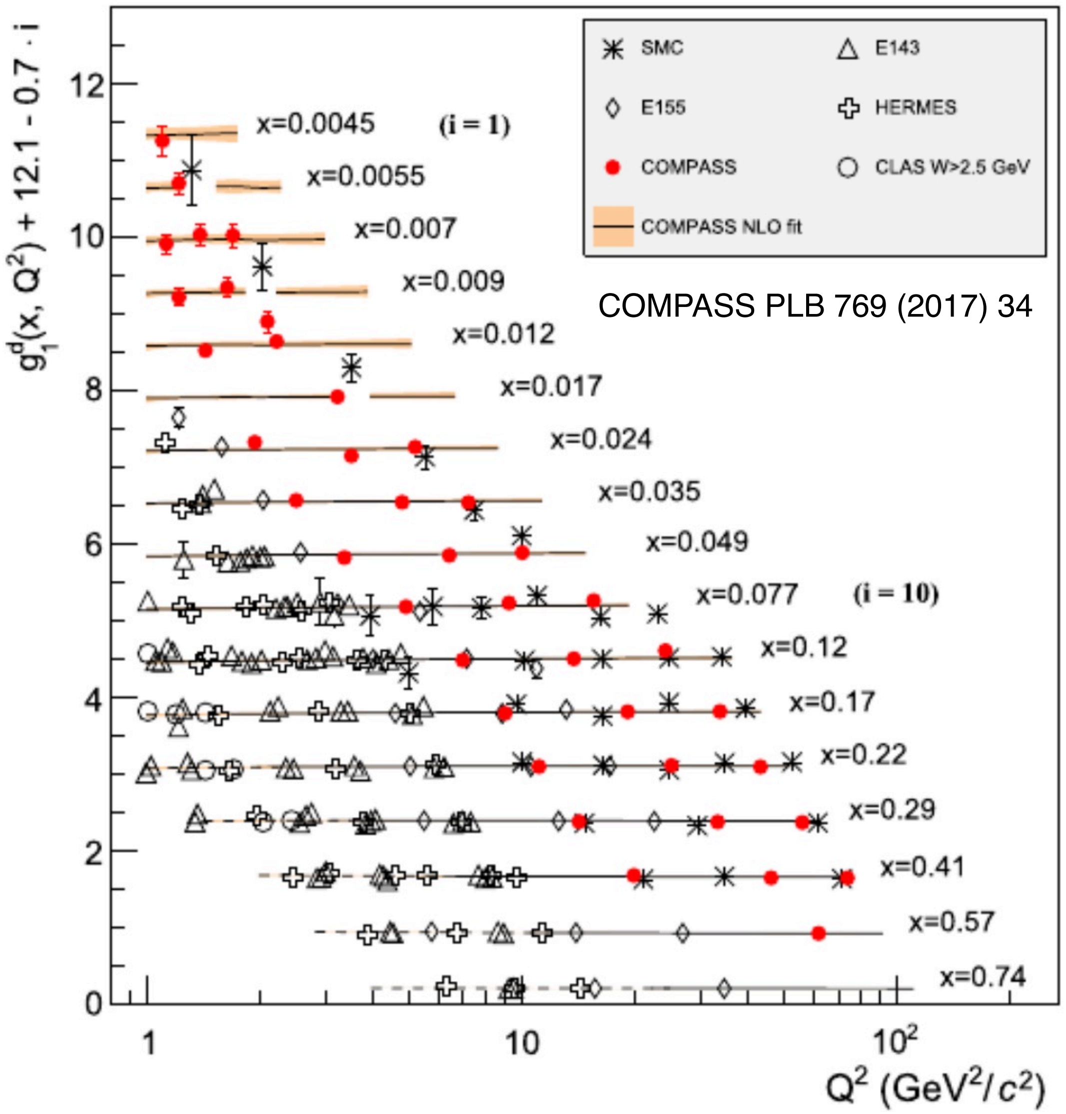
Note, experimental precisions can straightforwardly be matched as can the (low) energies in fixed-target experiments.

Not so at a collider and looking ahead to EIC we should revisit the handling of nuclear effects.

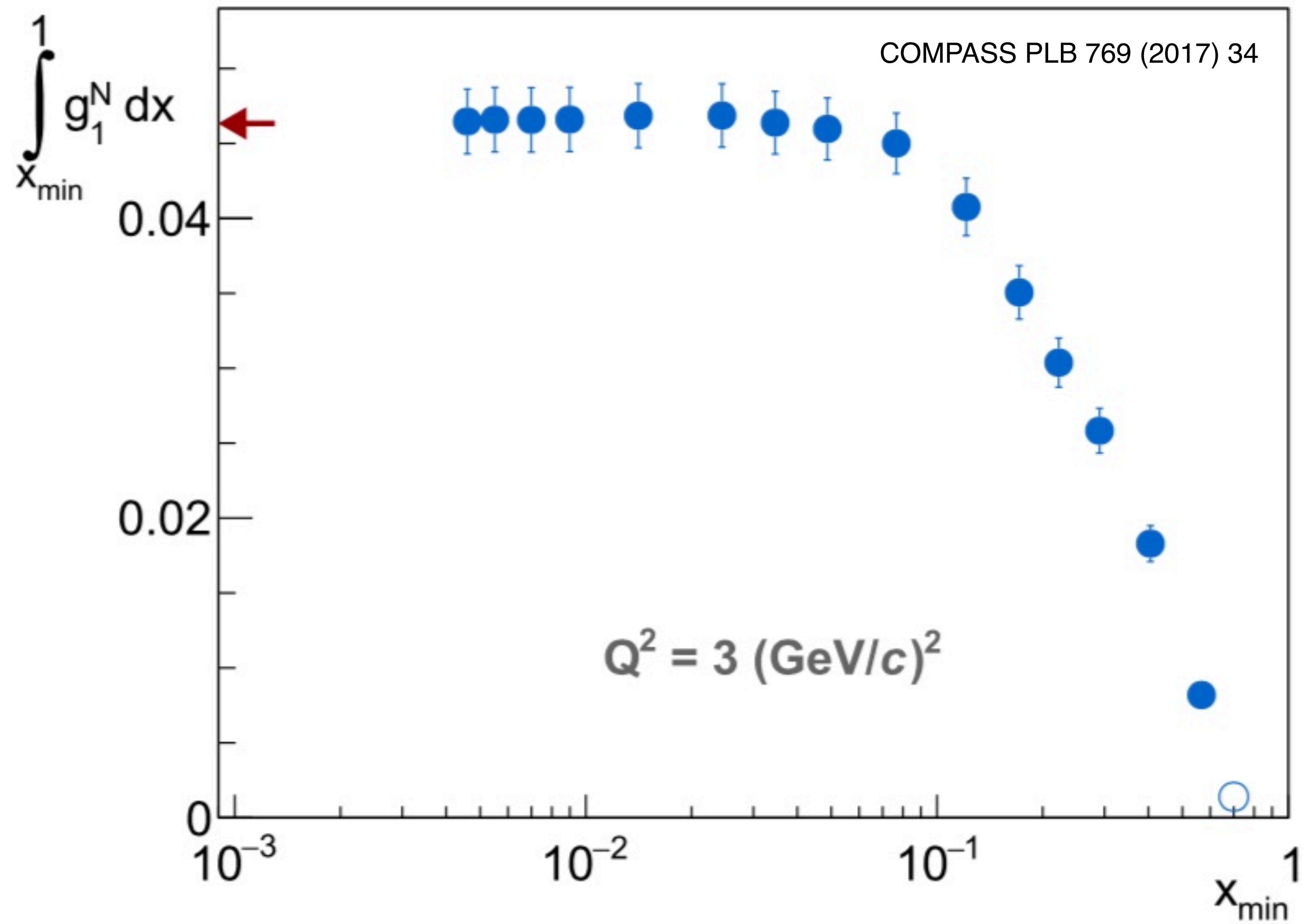
DIS - Neutron spin



World deuteron data, $+\mathcal{O}(\alpha_s)$



Neutron, from COMPASS d,p



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

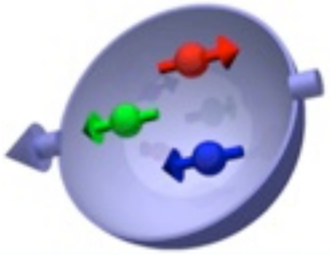
$$|g_A/g_V| = 1.29 \pm 0.05_{stat} \pm 0.10_{syst}$$

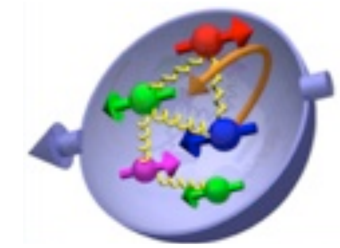
✓ < 10%

COMPASS PLB 769 (2017) 34

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

DIS - spin decomposition





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

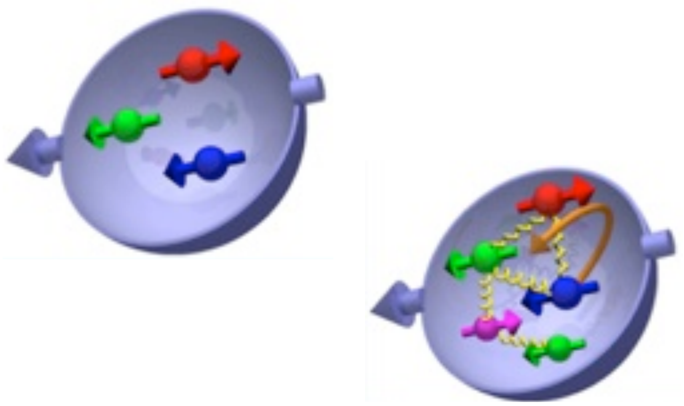
Channel	$f_1^{SU(3)}$	$\lvert f_1 V_{us}\rvert$	$(g_1/f_1)^{SU(3)}$	$(g_1/f_1)^{\text{exp}}$
$n \to p$	1	n/a	$F+D$	1.2670(30)
$\Lambda \to p$	$-\sqrt{3/2}$	0.2221(33)	$F+D/3$	0.718(15)
$\Sigma^- \to n$	-1	0.2274(49)	$F-D$	$-0.340(17)$
$\Xi^- \to \Lambda$	$\sqrt{3/2}$	0.2367(97)	$F-D/3$	0.25(5)
$\Xi^- \to \Sigma^0$	$\sqrt{1/2}$	n/a	$F+D$	n/a
$\Xi^0 \to \Sigma^+$	1	0.216(33)	$F+D$	1.32(22)

A 1+1-experiment determination, more or less, with little hope of materially better data,

SU(3) breaking often largely ignored so far,

Renewed opportunity for lattice-QCD?

DIS - spin decomposition



$\Delta\Sigma$

Channel	$f_1^{SU(3)}$	$\lvert f_1 V_{us} \rvert$	$(g_1/f_1)^{SU(3)}$	$(g_1/f_1)^{\mathrm{exp}}$
$n \to p$	1	n/a	$F+D$	$1.2670(30)$
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$\Xi^- \to \Sigma^0$	$\sqrt{1/2}$	n/a	$F+D$	n/a
$\Xi^0 \to \Sigma^+$	1	$0.216(33)$	$F+D$	$1.32(22)$

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

COMPASS PLB 769 (2017) 34

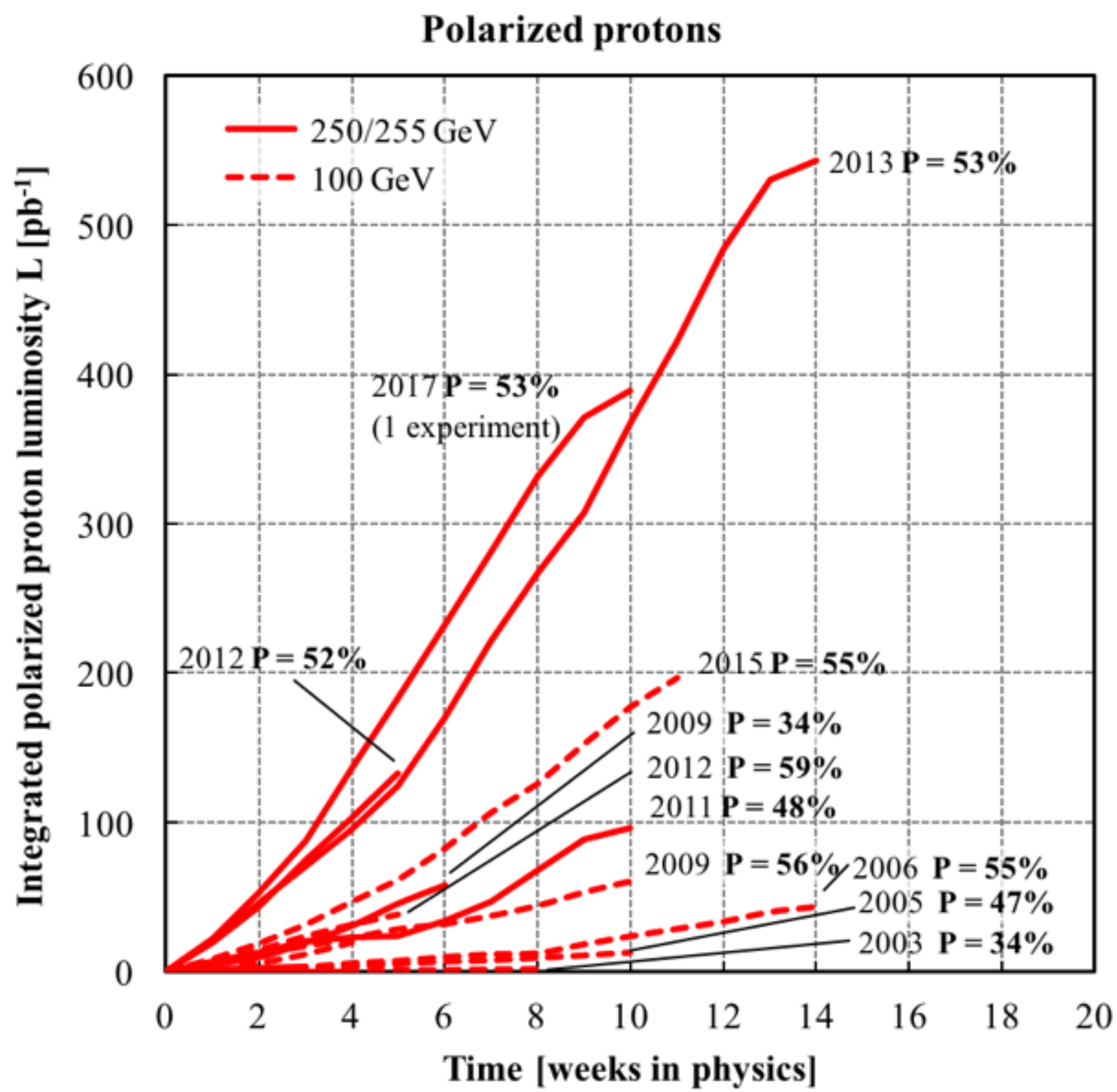
Note, *semi*-inclusive DIS data truly drive the DIS flavor decomposition.

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}

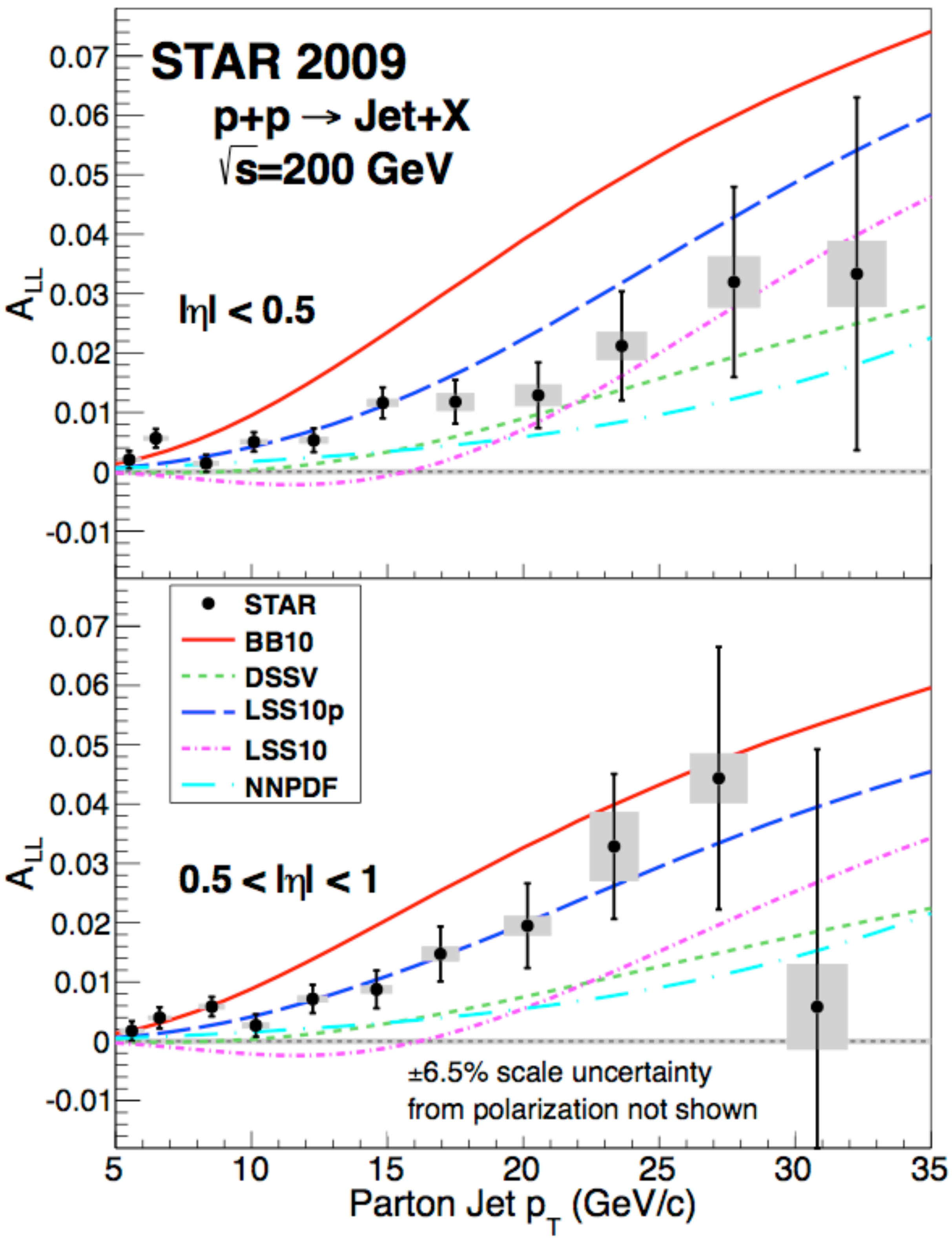


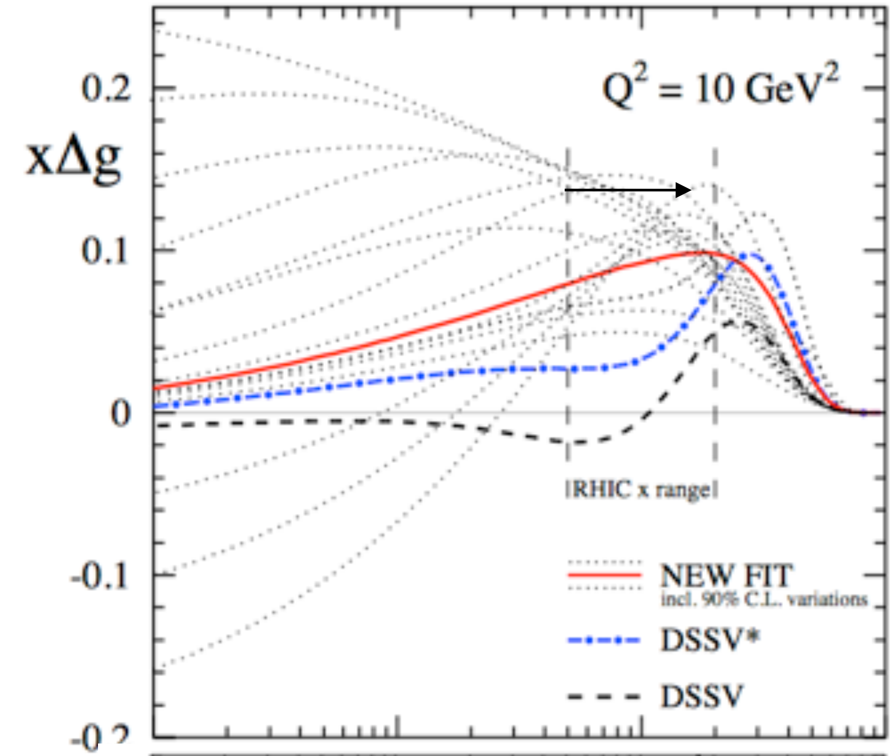
50-60% polarization

ΔG

Gluon Polarization from RHIC

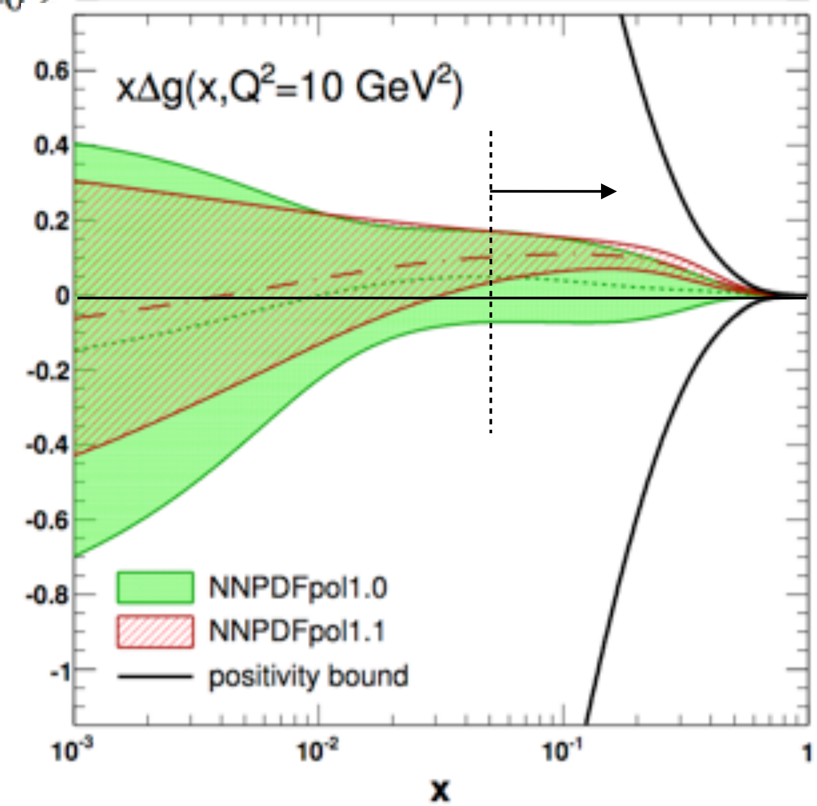
Phys.Rev.Lett 115 (2015) 092002





0.20 ± 0.07

DSSV, PRL 113, 012001(2014)



0.21 ± 0.10

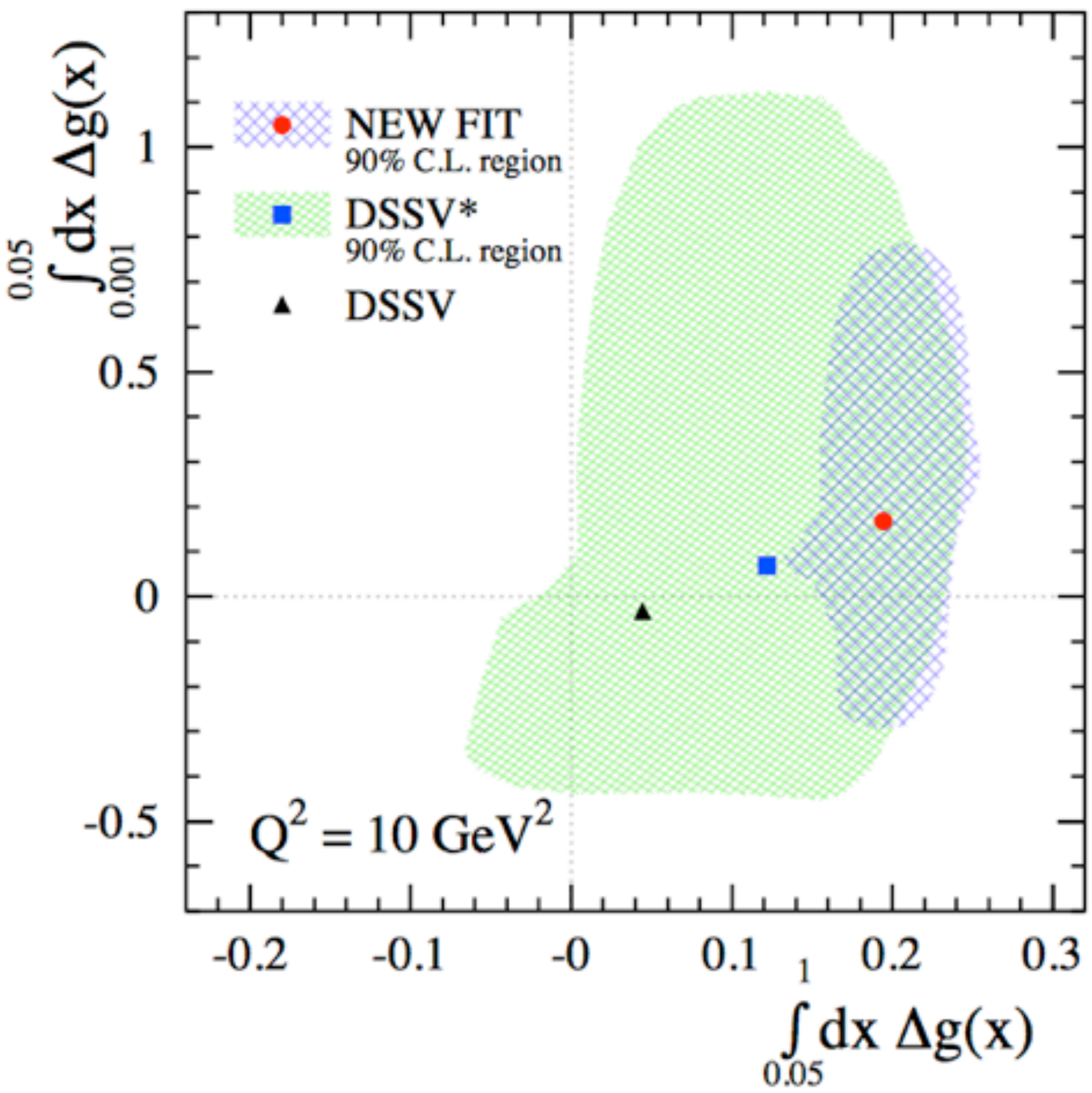
NNPDF, Nucl. Phys. B 887, 276 (2014)

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

Gluon Polarization

Some properties of the DSSV polarized gluon:

DSSV, PRL 113, 012001(2014)

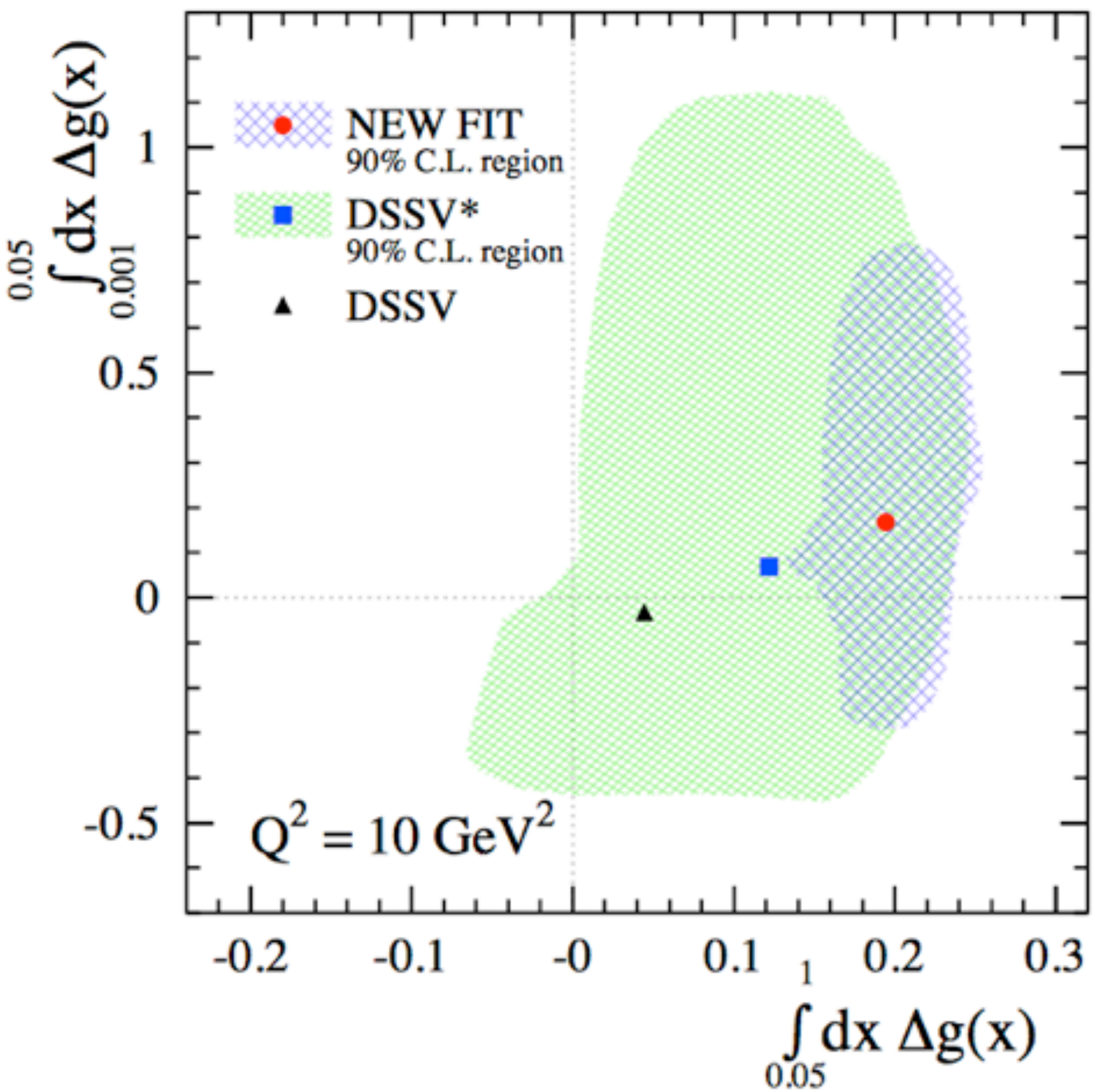


Easy to "hide" 1 ħ in the unmeasured region

Gluon Polarization

Some properties of the DSSV polarized gluon:

DSSV, PRL 113, 012001(2014)



Strong impetus for

better precision, via renewed measurement

sensitivity to underlying kinematics, via
correlation (di-jet) measurement

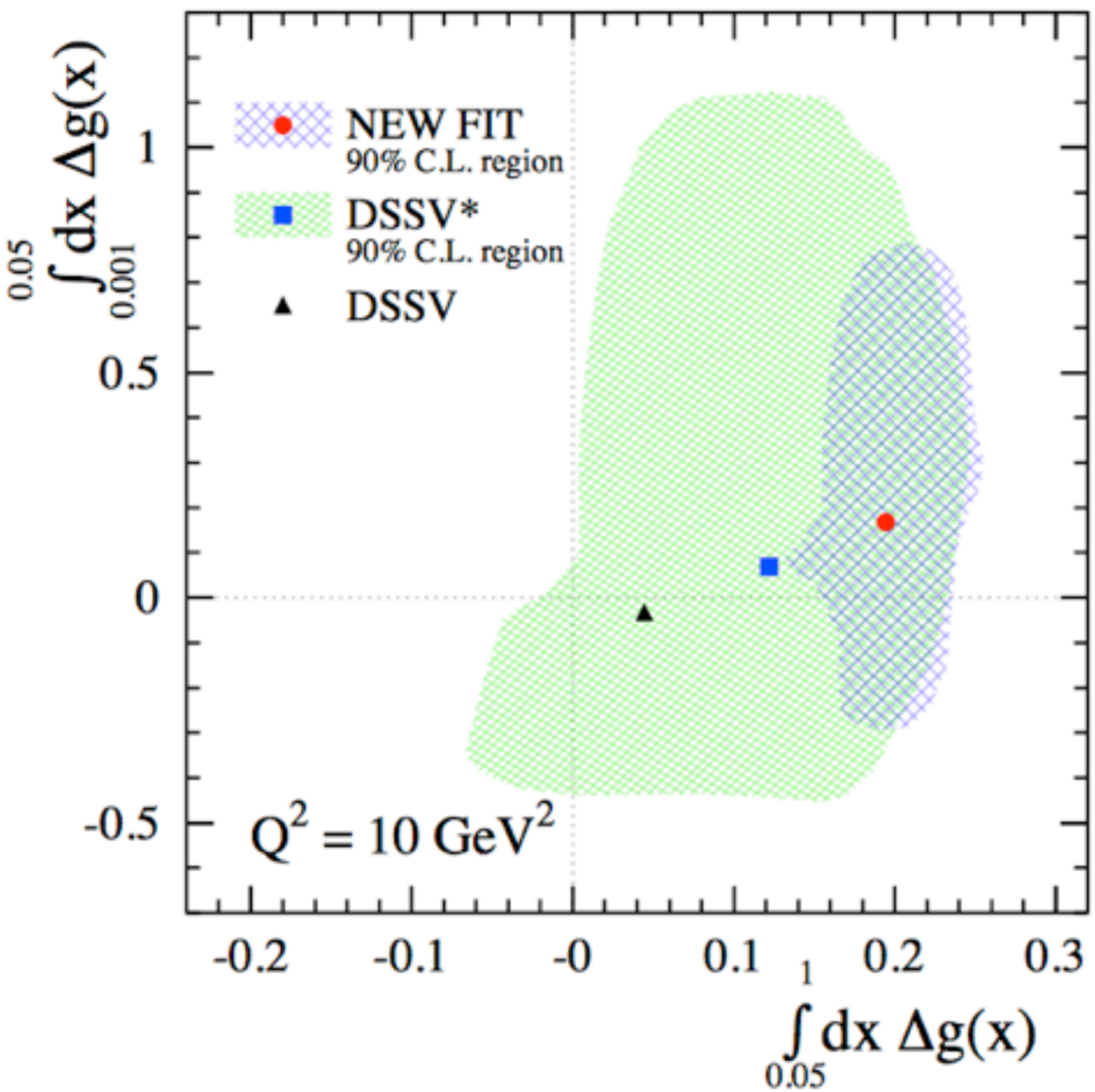
sensitivity to smaller *x*, via
500 GeV data,
forward acceptance

Easy to "hide" 1 ℏ in the unmeasured region

Gluon Polarization

Some properties of the DSSV polarized gluon:

DSSV, PRL 113, 012001(2014)



The good news,

STAR is releasing (has released) a *wealth* of data addressing each of these aspects,

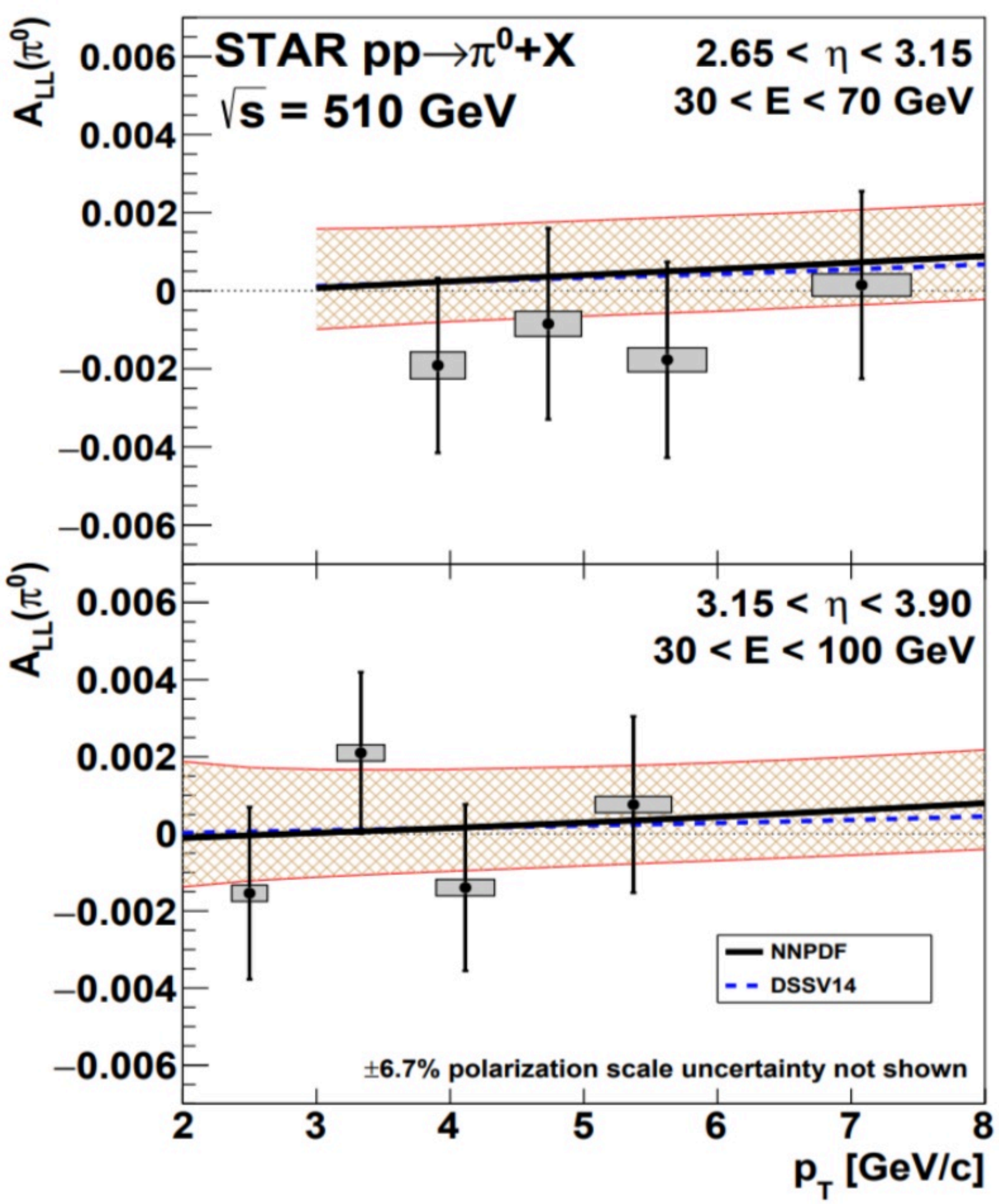
has a science-driven plan for forward instrument upgrades (a talk in itself; truth in advertisement plan $\neq$ approval, at least not as of today).

Easy to "hide" 1 $\hbar$ in the unmeasured region

Gluon Polarization

An early glimpse in the forward acceptance region:

arXiv: 1805.09745, PRD 98, 032013 (2018)

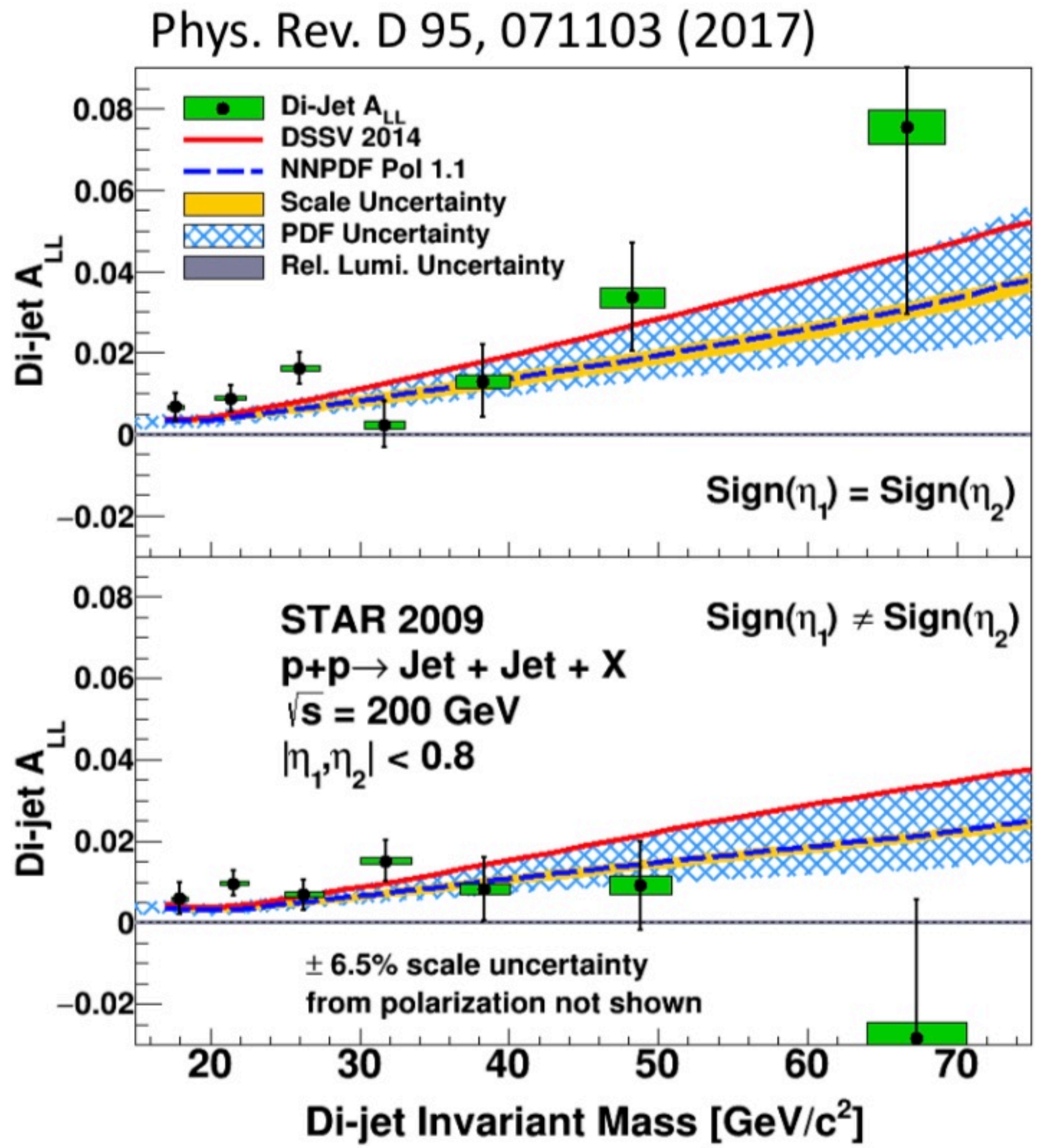


- Results are given for transverse momenta in the range $2 < p_T < 10$ GeV/c within two regions of pseudorapidity that span $2.65 < \eta < 3.9$
- These results are sensitive to the polarized gluon parton distribution function, $\Delta g(x)$, down to the region of parton momentum fraction $x \sim 0.001$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

Correlation measurements will access larger (average) partonic asymmetries.

Gluon Polarization

Mid-central di-jet asymmetries:



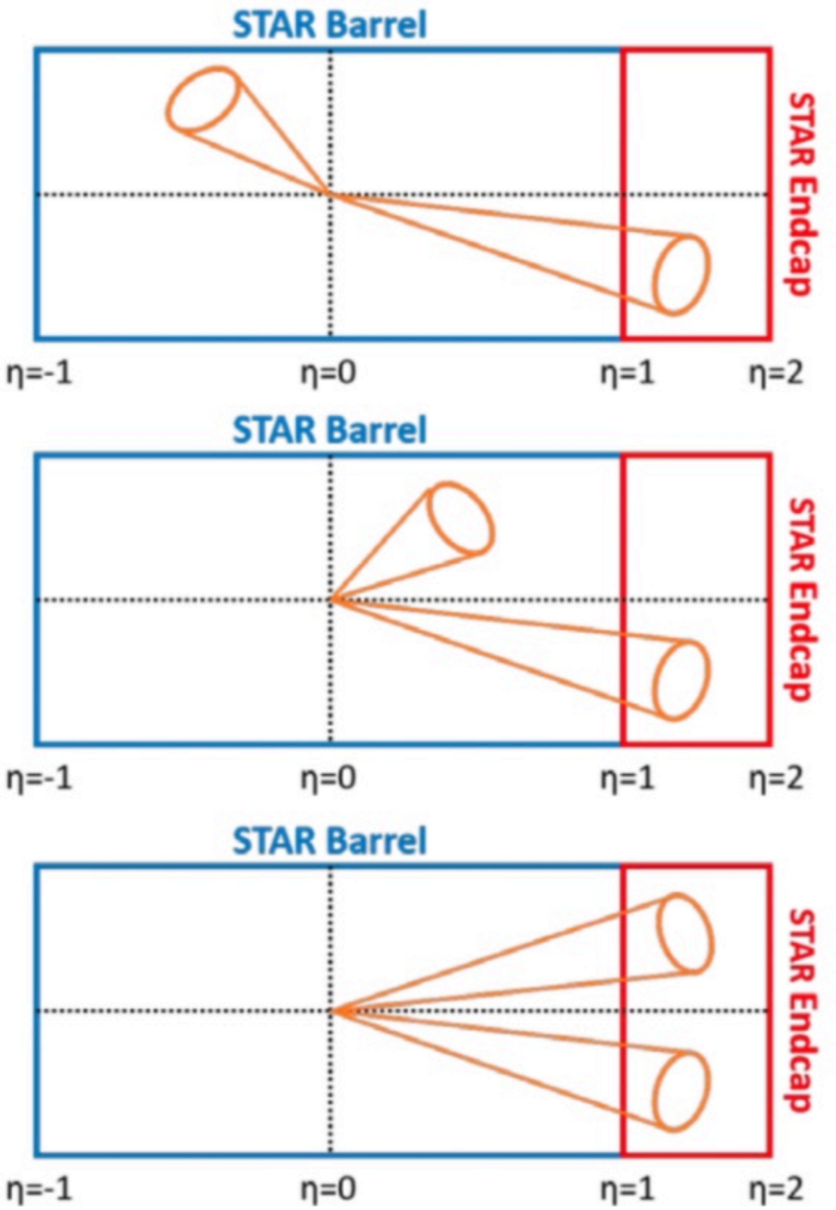
Towards sensitivity to Bjorken-x.

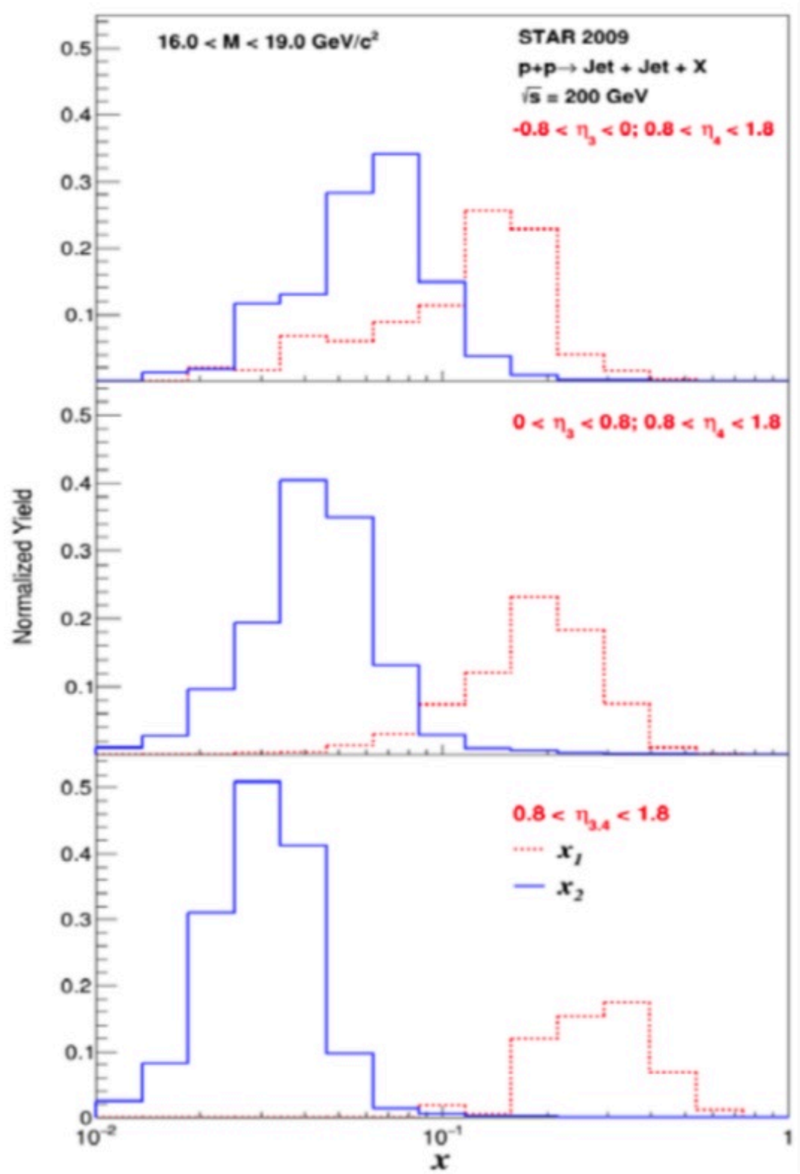
Preliminary results at 500 GeV have come out as well, paper in preparation

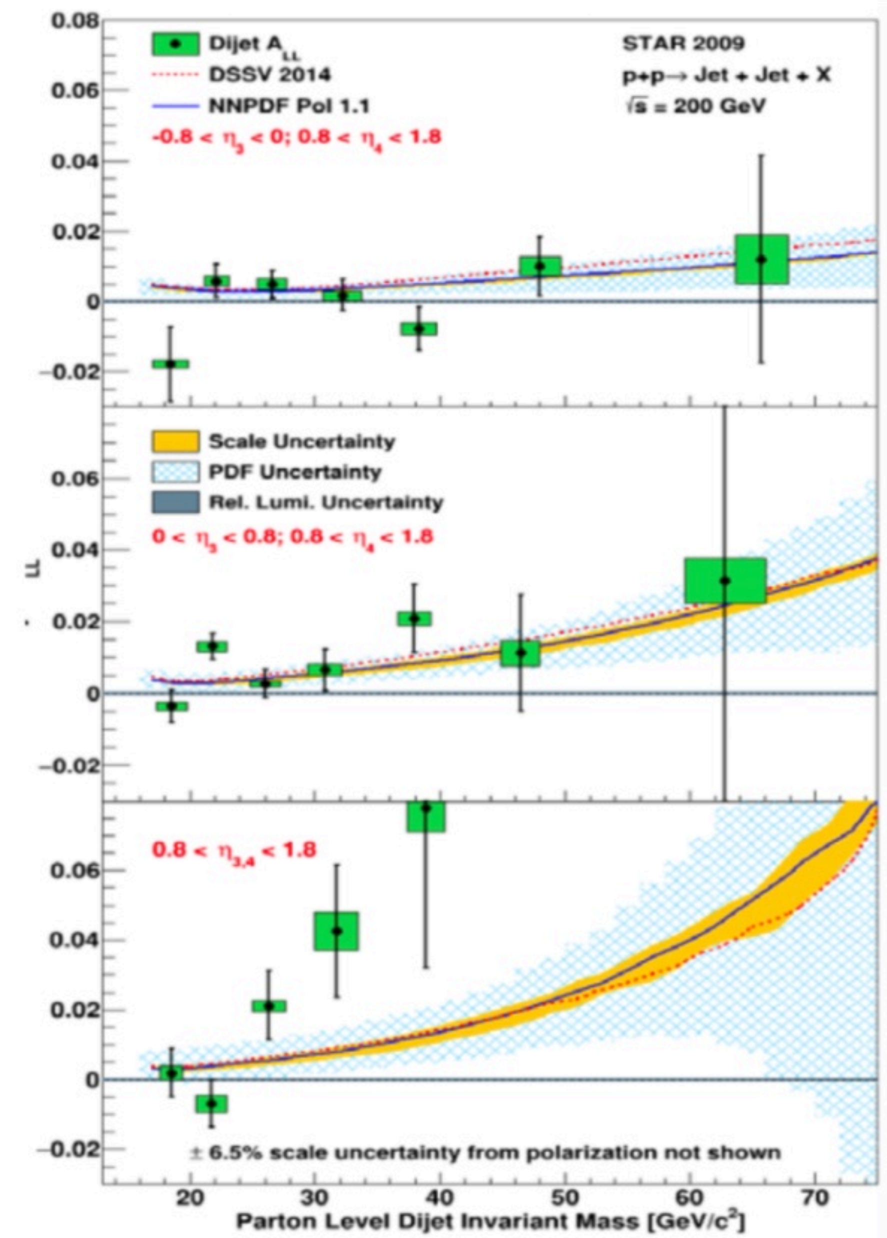
Gluon Polarization

di-jet asymmetries in a more forward region:

PRD 98 (2018) 032011

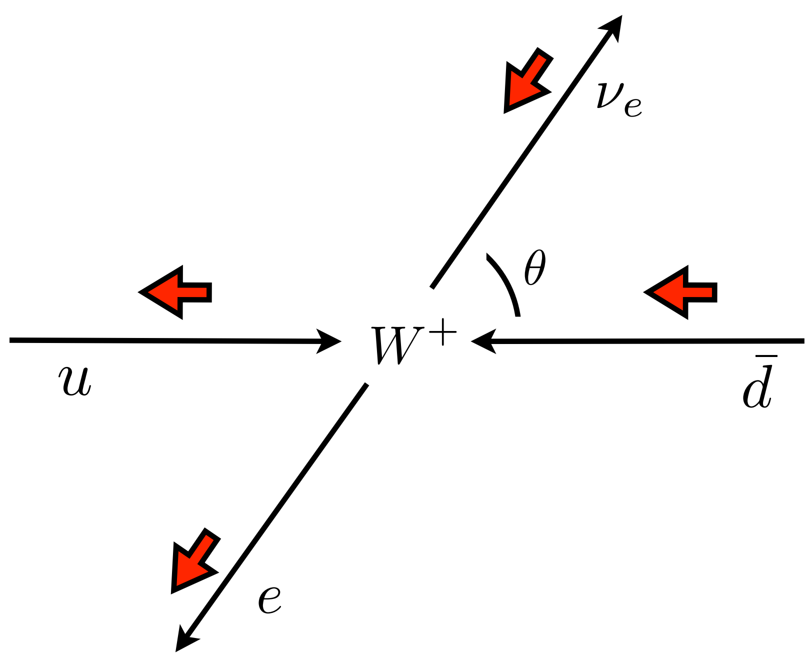






Impact clearly exists; quantifying it will require renewed global analysis (and/or reweighting)

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 Irapidityl
electron/hadron discrimination
luminosity hungry

Free of fragmentation (!)

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

Spin Measurements:

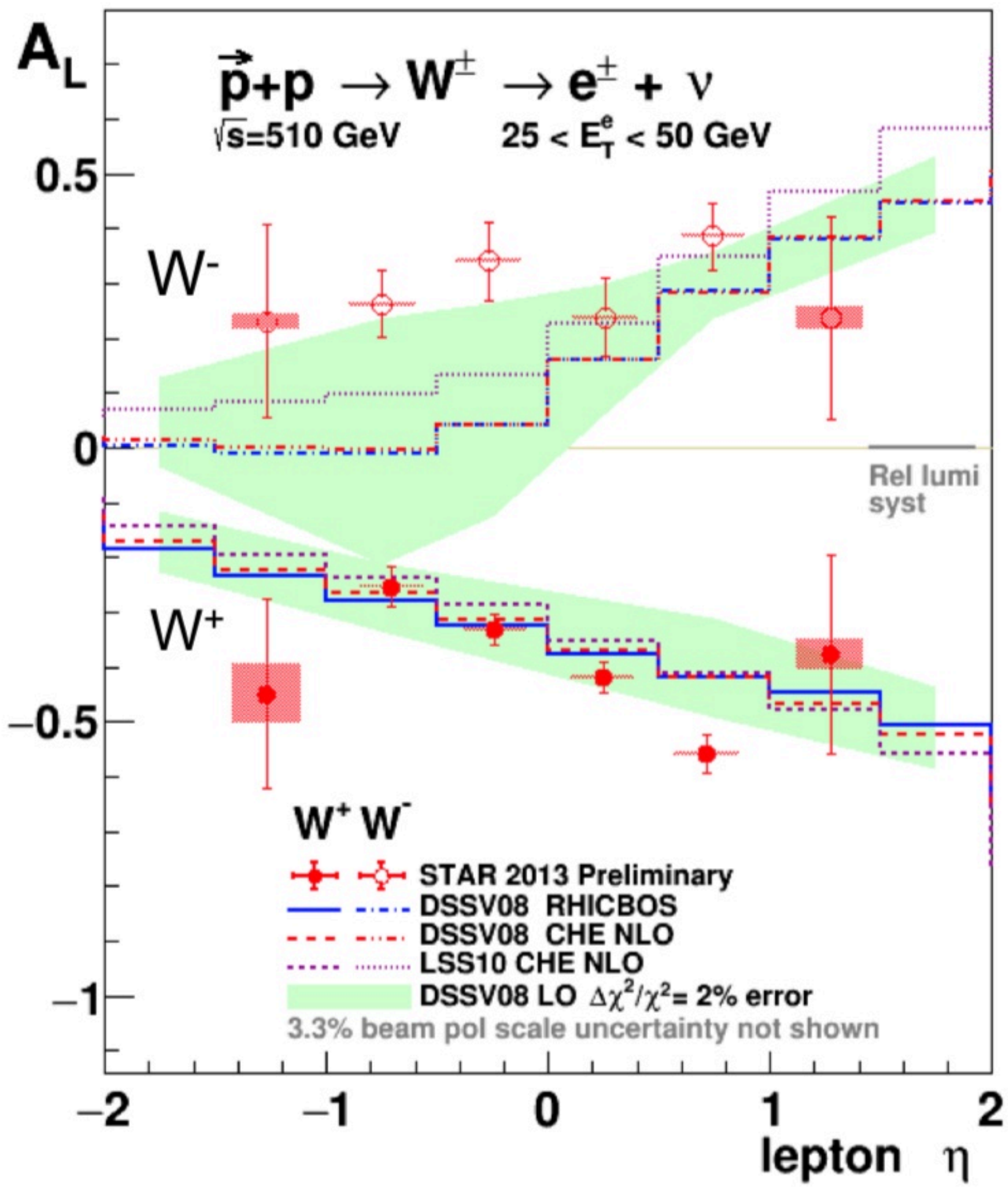
$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

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.

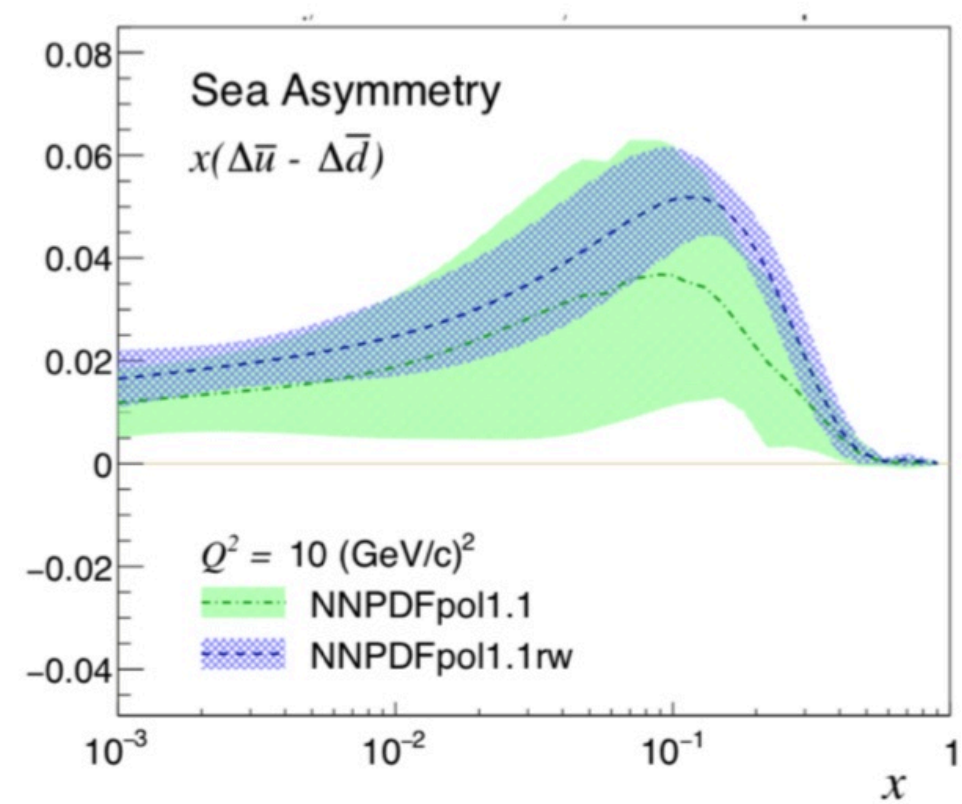
Quark Polarization at RHIC



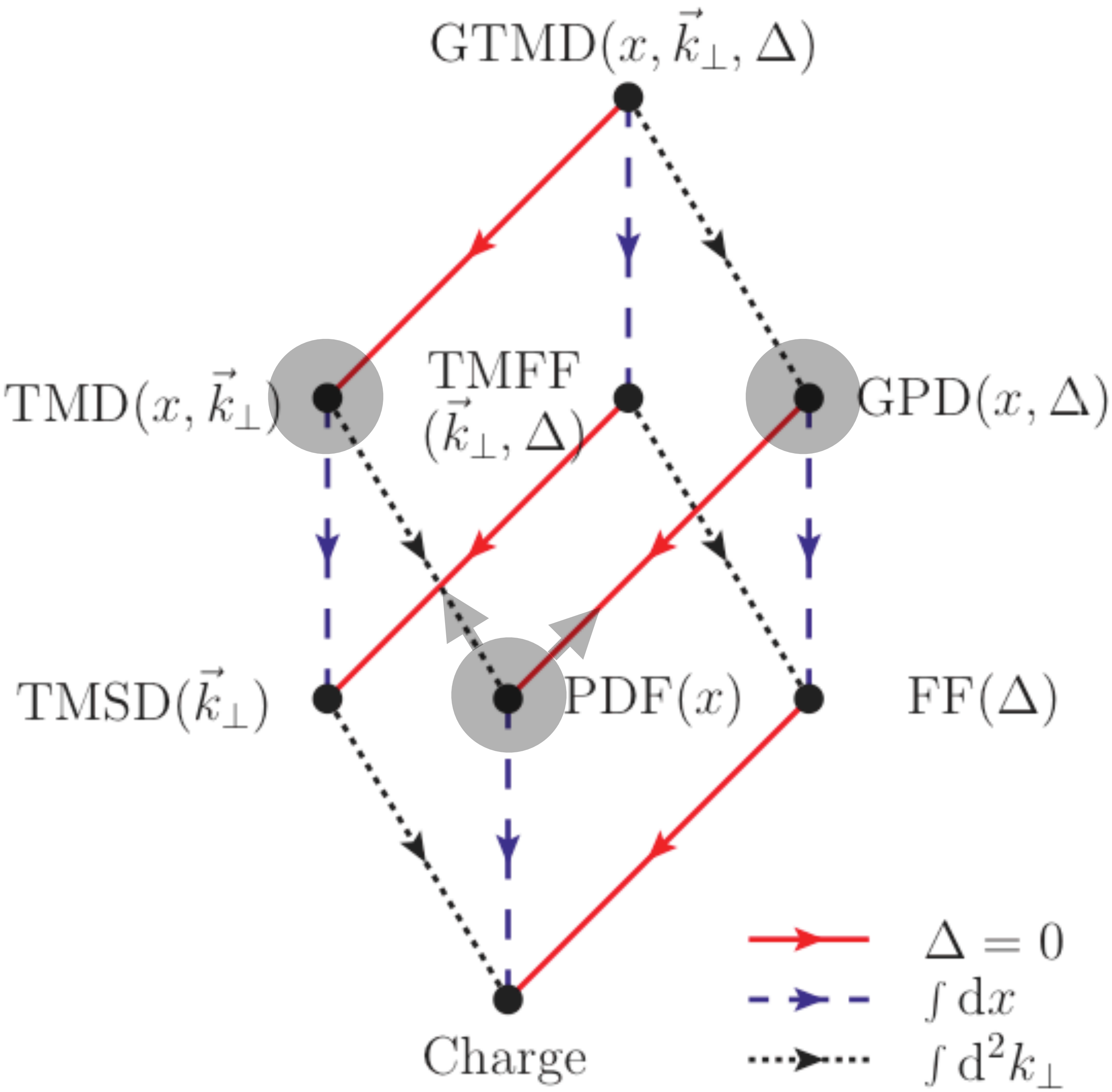
See e.g. J. Zhang, INPC
Q.H. Xu, DIS

- Further confirmed the polarized sea asymmetry:

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



Beyond Quark and Gluon Spins



Lorce, Pasquini, Vanderhaeghen

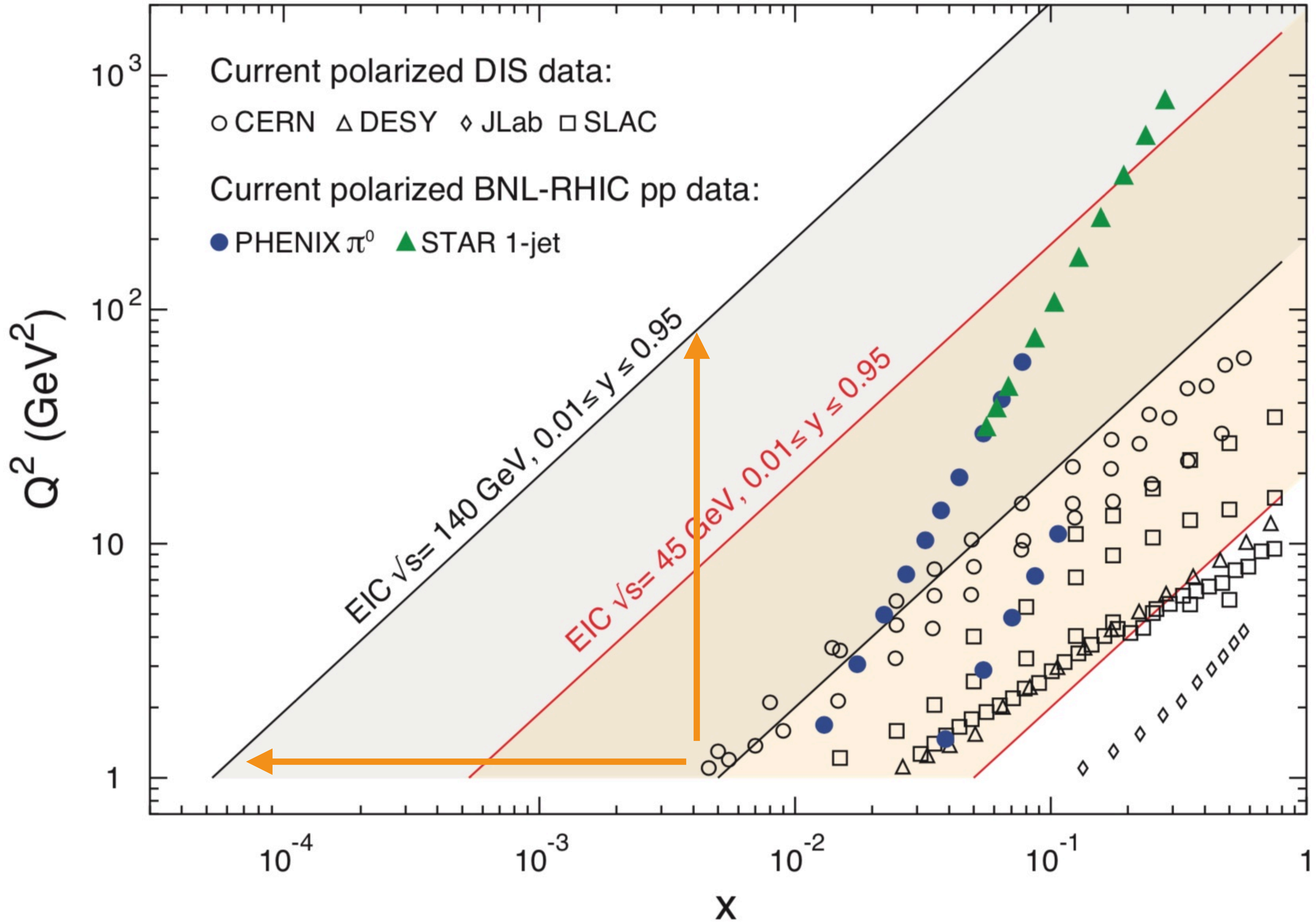
Theory may be ahead of experiment, although many questions remain,

Beautiful initial (DVCS) measurements from HERMES and JLab,

IMHO, very far from reliable insights on angular momentum parts in the (Ji) spin-decomposition,

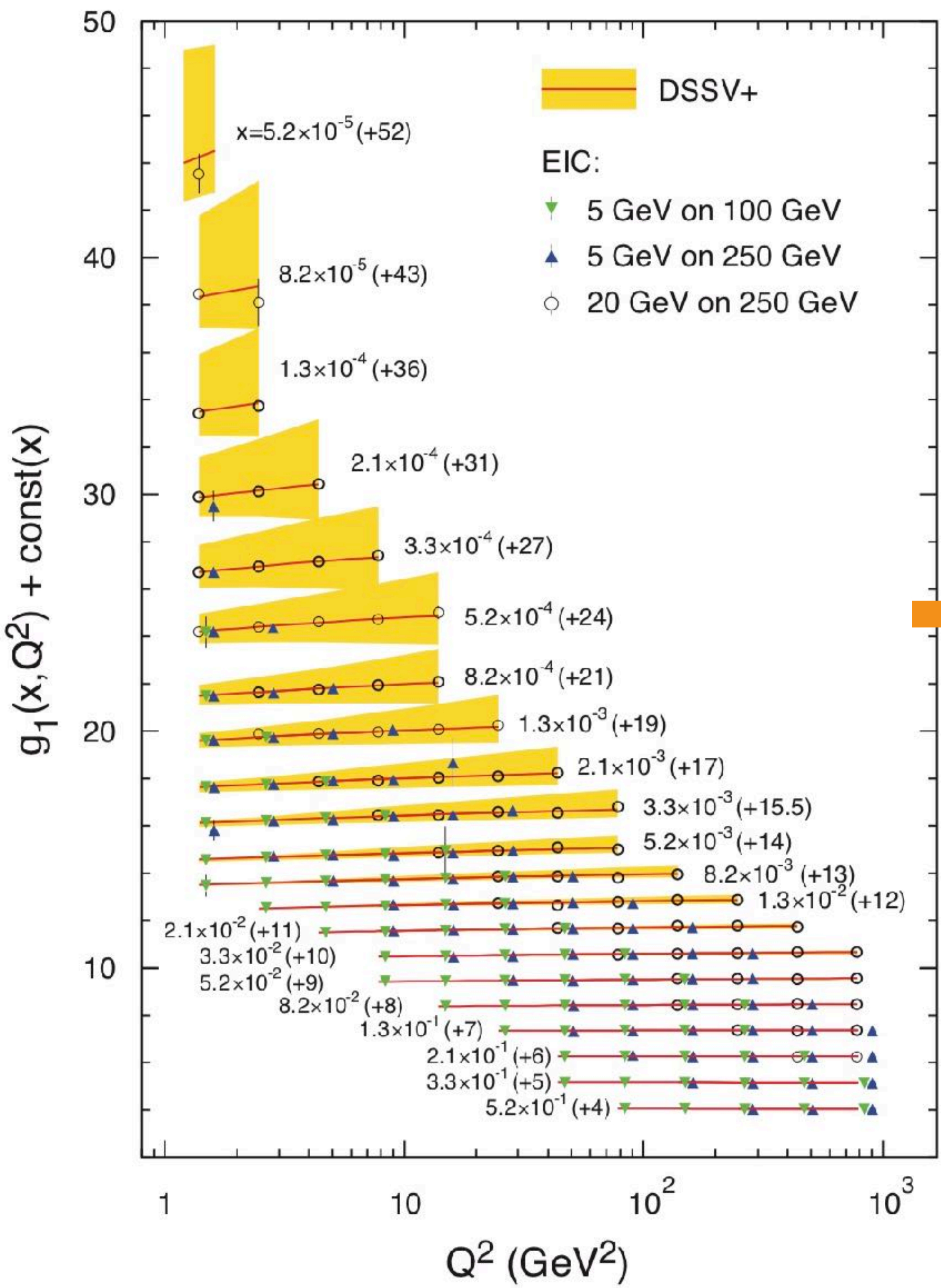
Looking Ahead

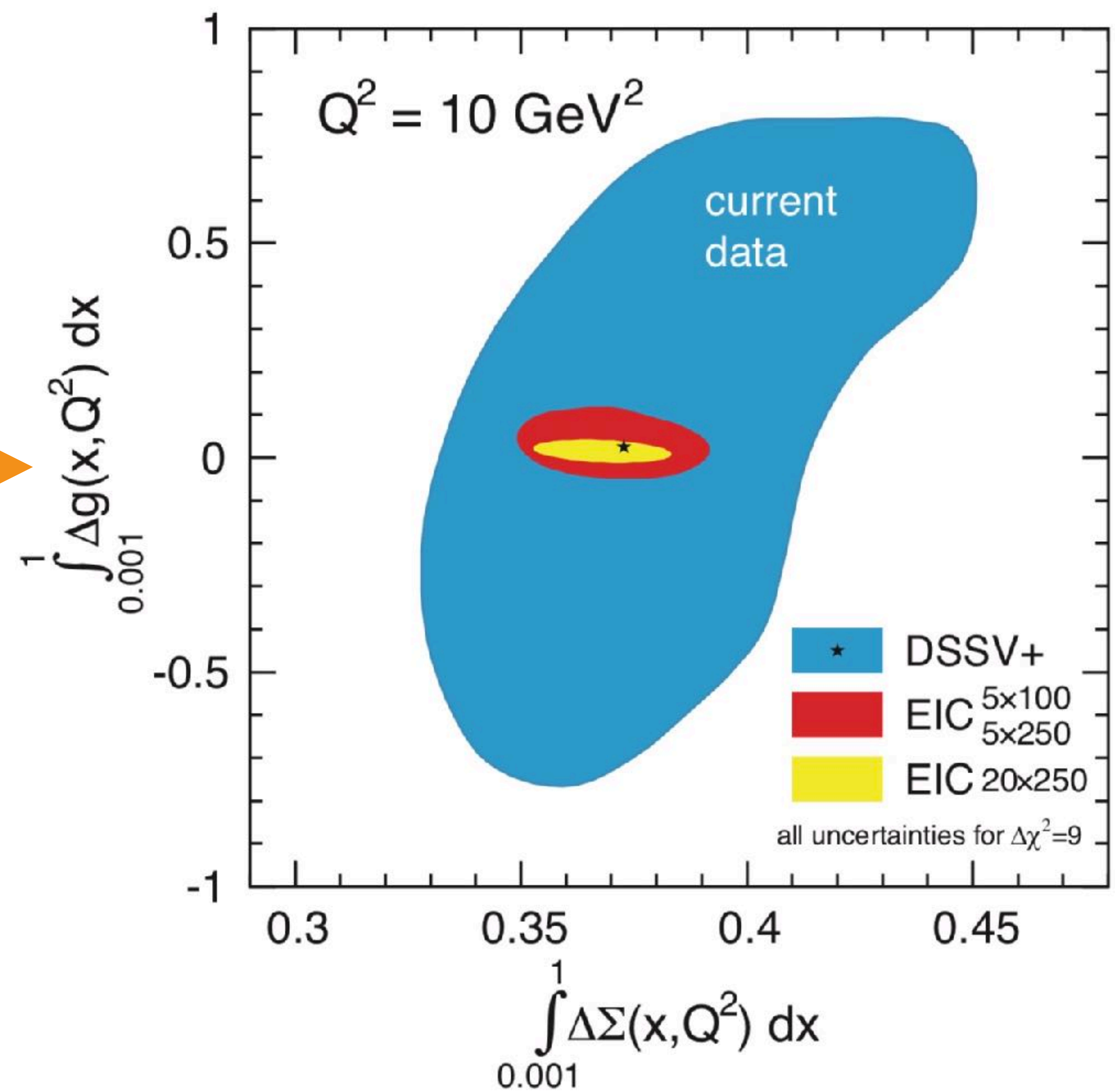
U.S.-based EIC - Proton Spin



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

U.S.-based EIC - Proton Spin





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

Also experimentally, we are still very far from a reliable decomposition of the proton spin

DIS data:

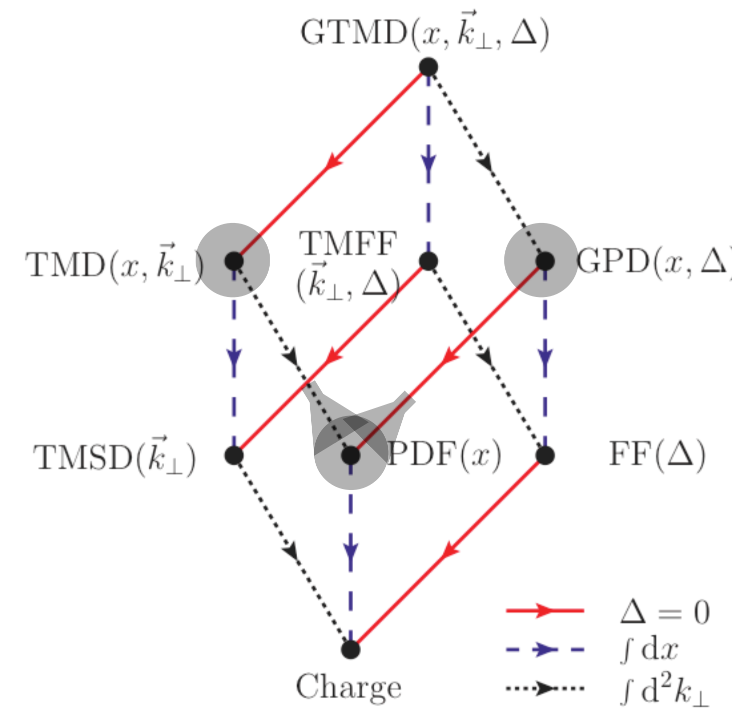
- small-x measurements provided the impetus for renewed study of the proton spin,

- 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,

- start of DVCS measurements with sensitivity to orbital momentum



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; again a talk by itself)

EIC + theory will be essential to arrive the spin decomposition (or at least a partial one).