Sea Quark and Gluon Spin

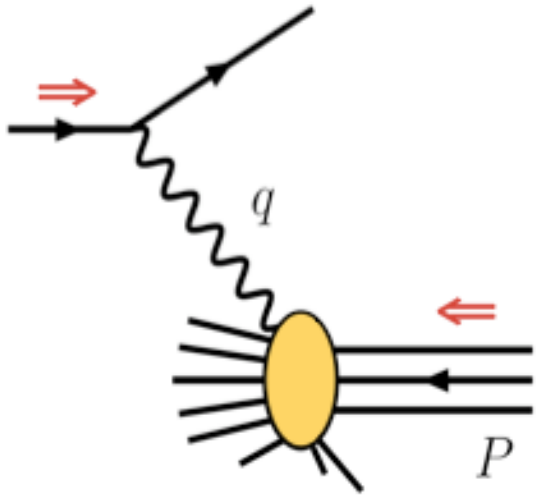
DIS, SIDIS, pp, $W^{+,-}$

Ernst Sichtermann
Lawrence Berkeley National Laboratory

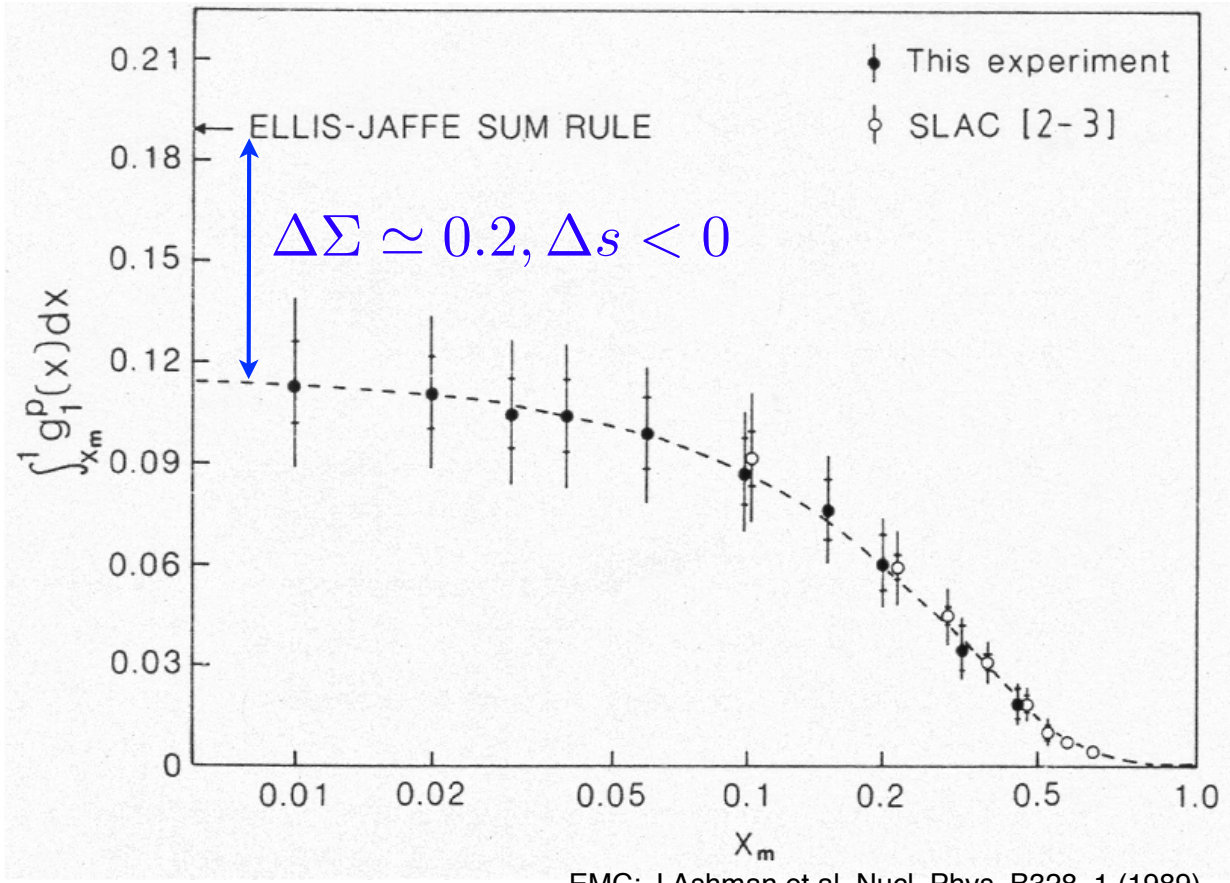
QCD Frontier 2013
October 21, 2013

Polarized Deep-Inelastic Scattering - circa 1985

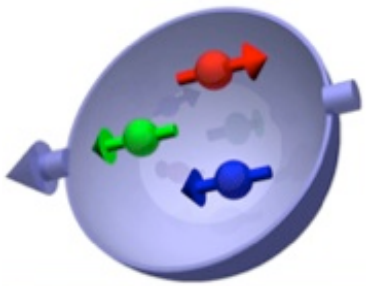
European Muon Collaboration:



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



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



Do the quark spins carry the proton spin?

For the proton,

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

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

Known from weak neutron to proton decay

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

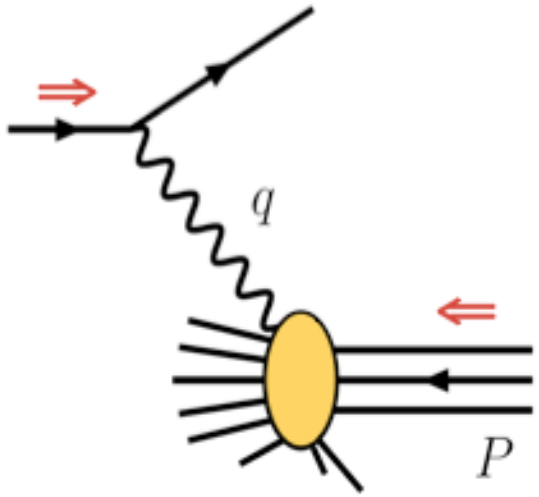
Unique to DIS, Δ∑

up to (known) QCD corrections in $\alpha_s(Q^2)$.

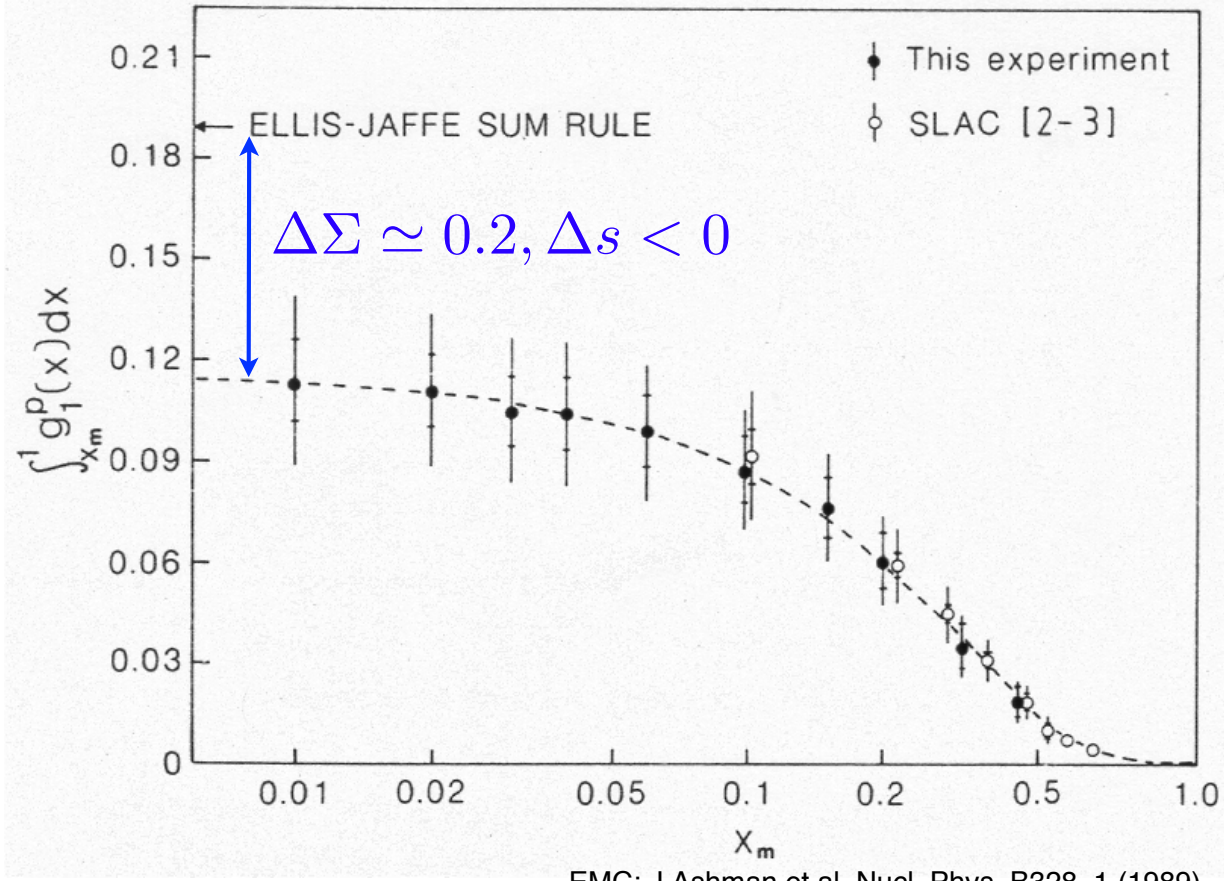
This becomes a prediction if $\Delta_1 s = 0$.

Polarized Deep-Inelastic Scattering - circa 1985

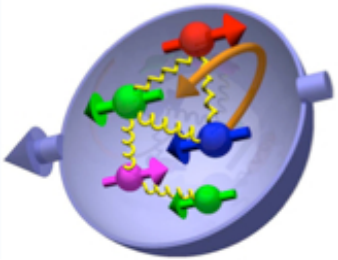
European Muon Collaboration:



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

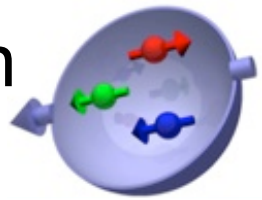


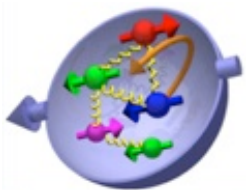
EMC: J.Ashman et al, Nucl. Phys. B328, 1 (1989)



The sum of Quark Spins contribute little to the proton spin, Strange quarks are negatively polarized, $\Delta s < 0$

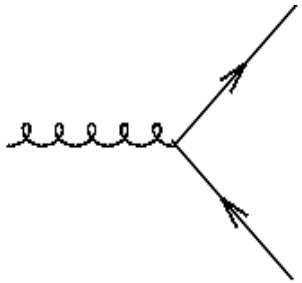
Renewed Interest in Nucleon Spin





Numerous follow-up questions and experiment programs,

Among the early attempts at a resolution,



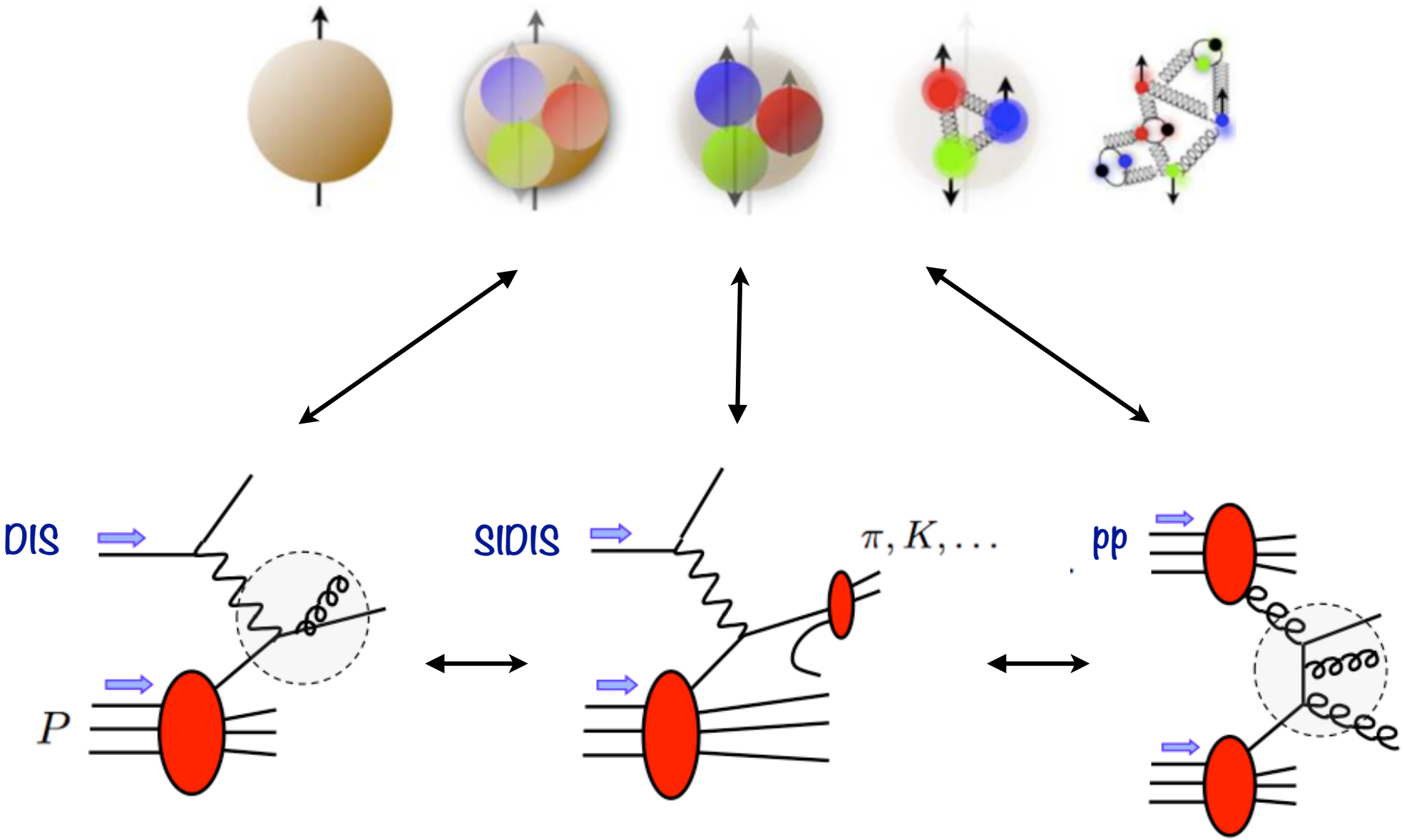
with the gluons *polarized*, $a_0 = \Delta\Sigma - \frac{3}{2}\frac{\alpha_s}{\pi}\Delta G$

G. Altarelli and G.G. Ross Phys. Lett. **B212** (1988) 391

Note: this attempt requires *very* significant polarization,
factors larger than the nucleon spin itself, and
by inference, *huge* compensating orbital momenta.

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

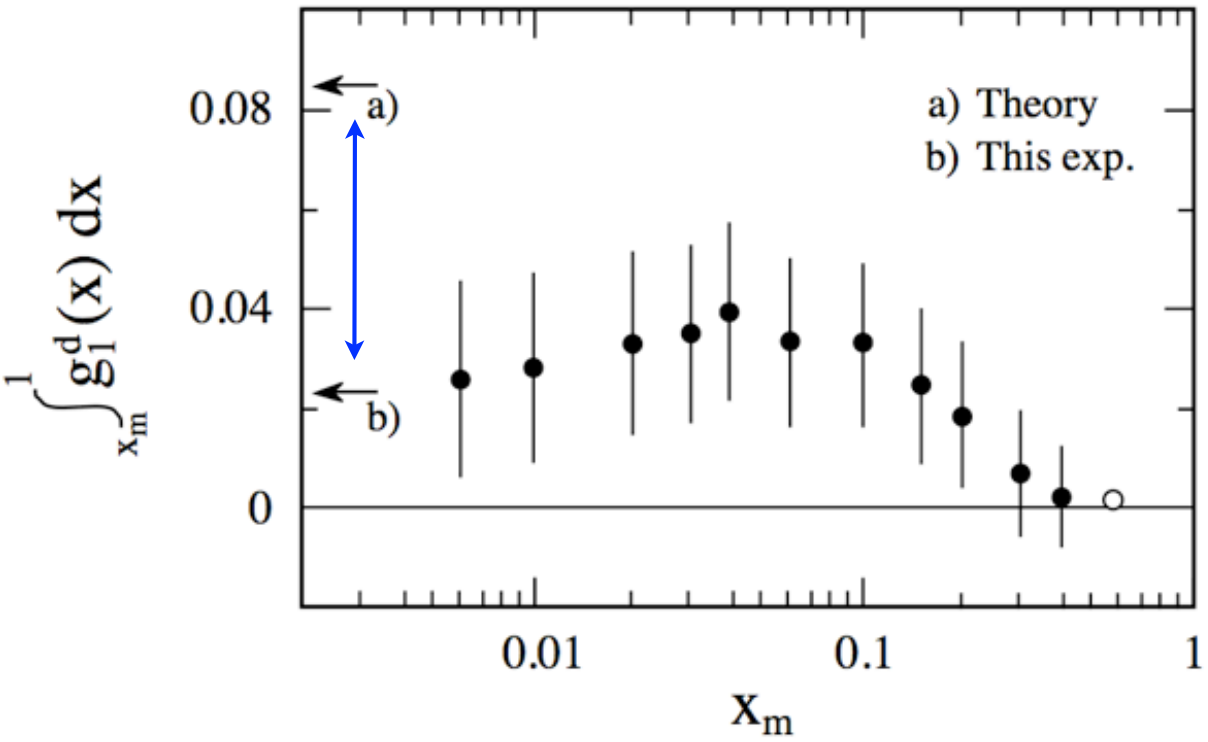
Renewed Interest in Nucleon Spin



and hopefully soon also polarized Drell-Yan - COMPASS, FNAL E1027, ... (c.f. Y. Goto's talk)

Renewed Interest in Nucleon Spin - Bjorken Sum Rule

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



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

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

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

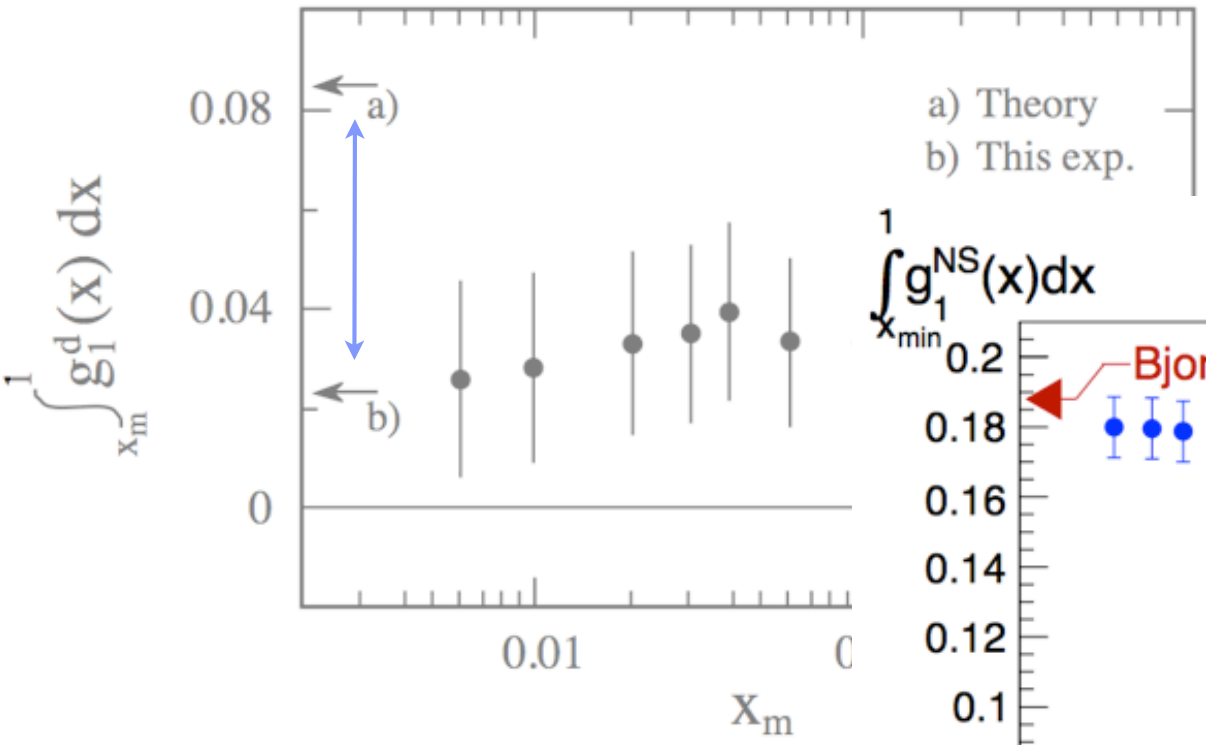
$$\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05_{\rm stat} \pm 0.04_{\rm sys}$$

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right|\left[1 - \frac{\alpha_s}{\pi} + \ldots\right] \quad \checkmark \text{ 25\%}$$

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

Renewed Interest in Nucleon Spin - Bjorken Sum Rule

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

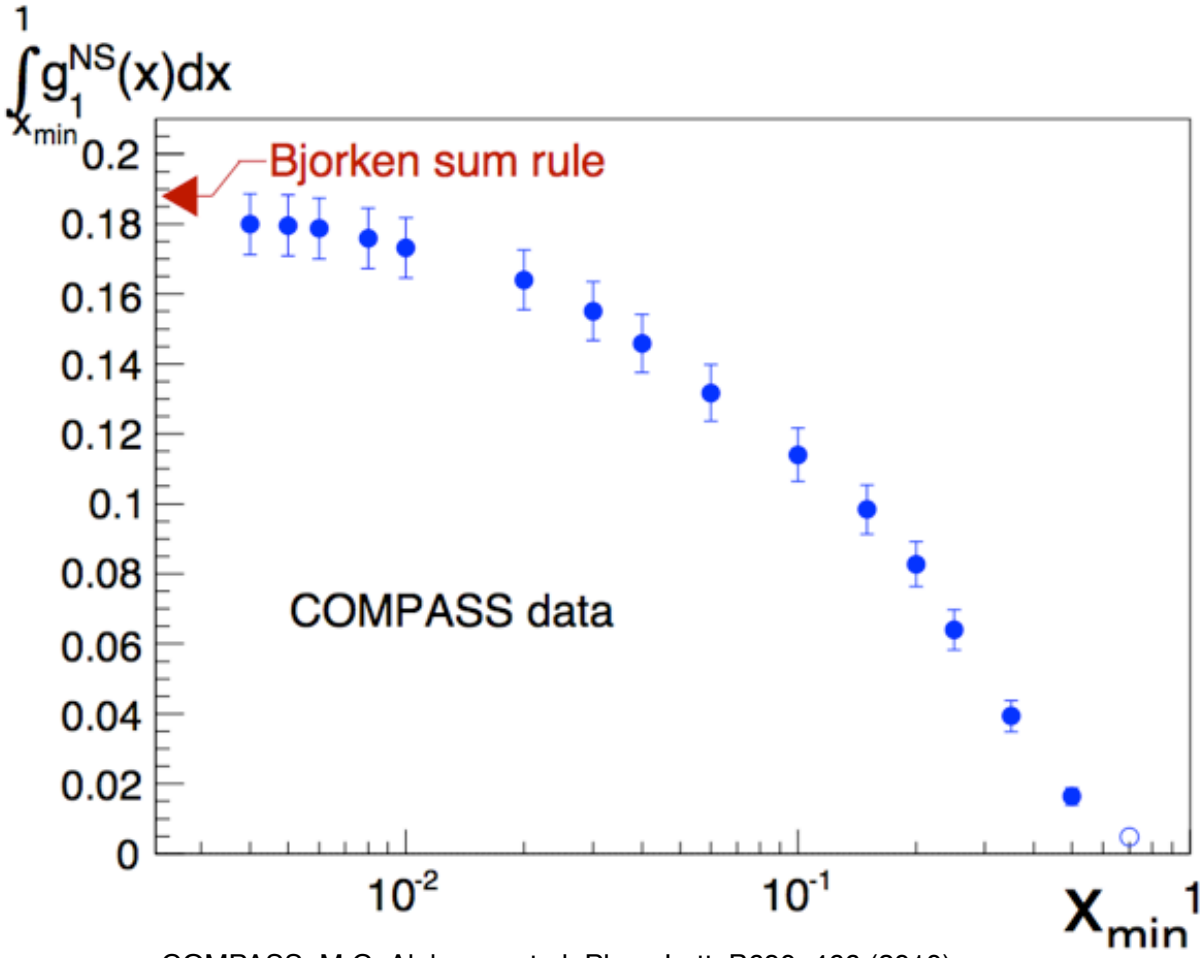


$$\Gamma_1^p = 0.126 \pm 0.010_{\text{stat}} \pm 0.015_{\text{sys}} \quad \text{(EMC)}$$

$$\Gamma_1^p - \Gamma_1^n = 0.190 \pm 0.009 \pm 0.015 \quad (Q^2 = 3\,\text{GeV}^2)$$

$$\Gamma_1^p - \Gamma_1^n = 0.188 \pm 0.002$$

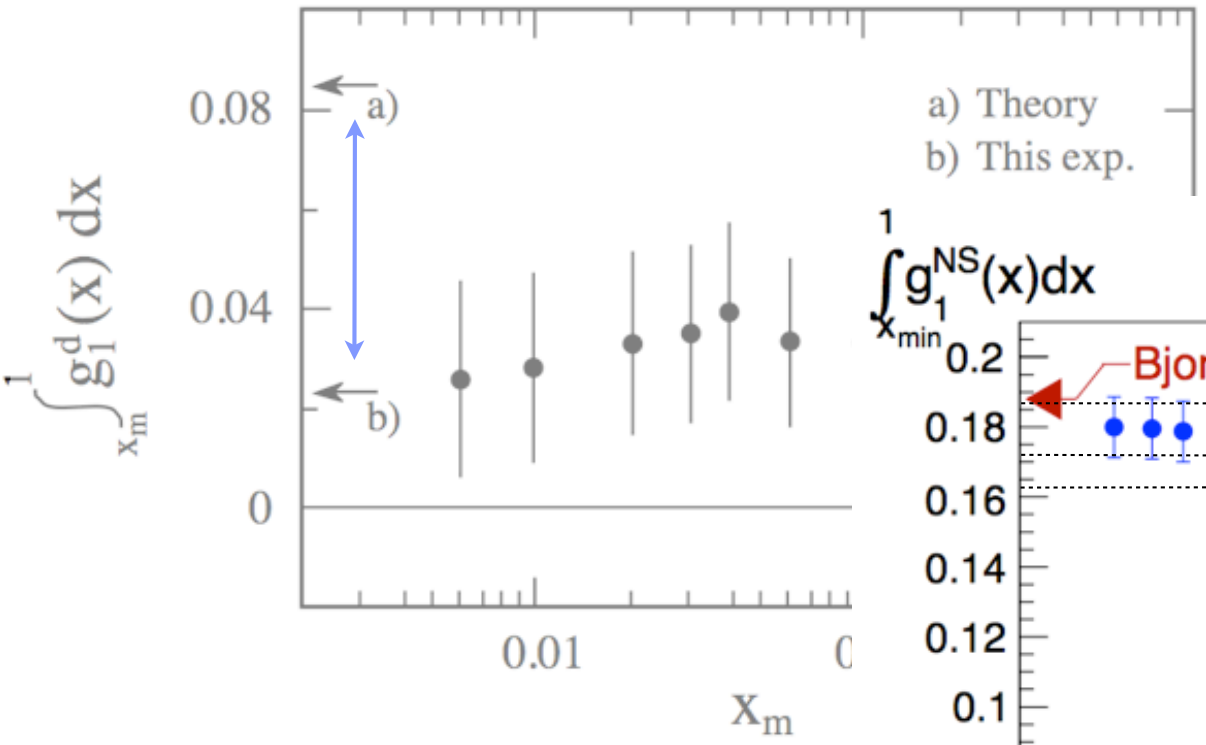
✓ 9%



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

Renewed Interest in Nucleon Spin - Bjorken Sum Rule

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

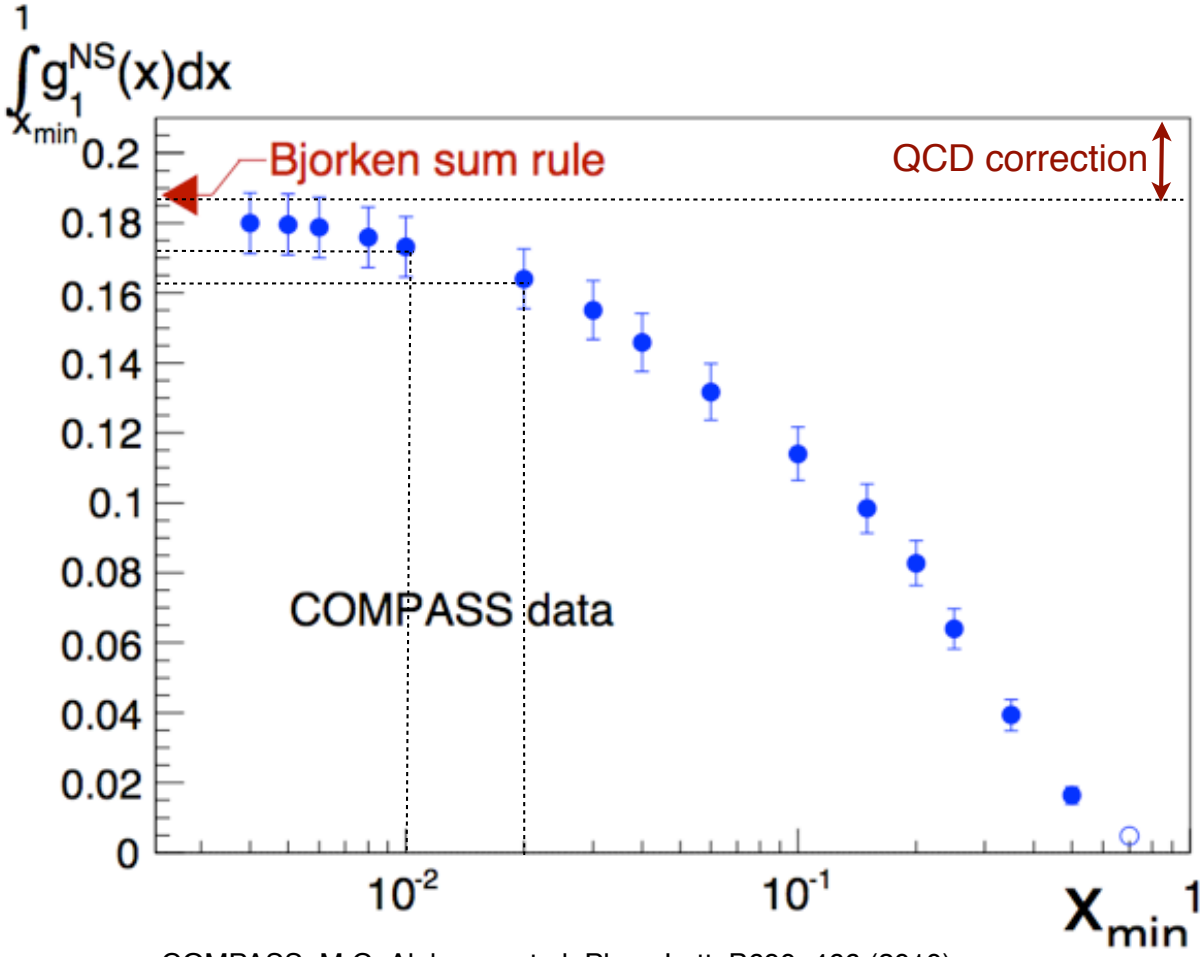


$$\Gamma_1^p = 0.126 \pm 0.010_{\text{stat}} \pm 0.015_{\text{sys}} \quad \text{(EMC)}$$

$$\Gamma_1^p - \Gamma_1^n = 0.190 \pm 0.009 \pm 0.015 \quad (Q^2 = 3\,\text{GeV}^2)$$

$$\Gamma_1^p - \Gamma_1^n = 0.188 \pm 0.002$$

✓ 9%



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

Renewed Interest in Nucleon Spin - SU(3)

For the proton,

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

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

✓ 9%

Known from weak neutron to proton decay, combined with weak Σ 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 $a_8 = 3F - D,\ a_8 \simeq 0.2 \pm 0.1$

Renewed Interest in Nucleon 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	Rate($10^6\,s^{-1}$)				g_1/f_1		g_1/f_1	
$A \to B\ell\nu$	$\ell = e^{\pm}$		$\ell = \mu^-$		$\ell = e^-$		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					$-\sqrt{\frac{2}{3}}\,D$ †	
$\Sigma^+ \to \Lambda^0$	0.250	± 0.063					$-\sqrt{\frac{2}{3}}\,D$ †	
$\Xi^- \to \Lambda^0$	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

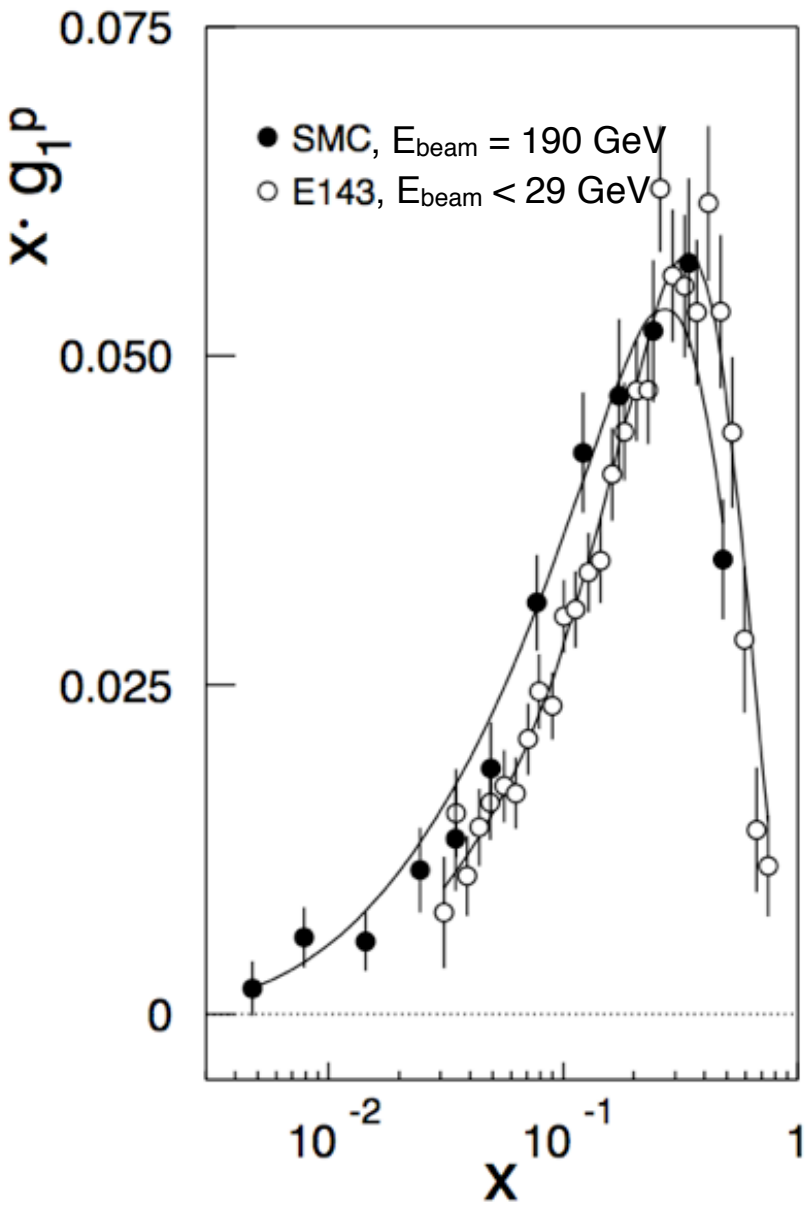
* KTeV data [5]—not included in the fits presented here.

† 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), ...

Renewed Interest in Nucleon Spin - Scaling Violations



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

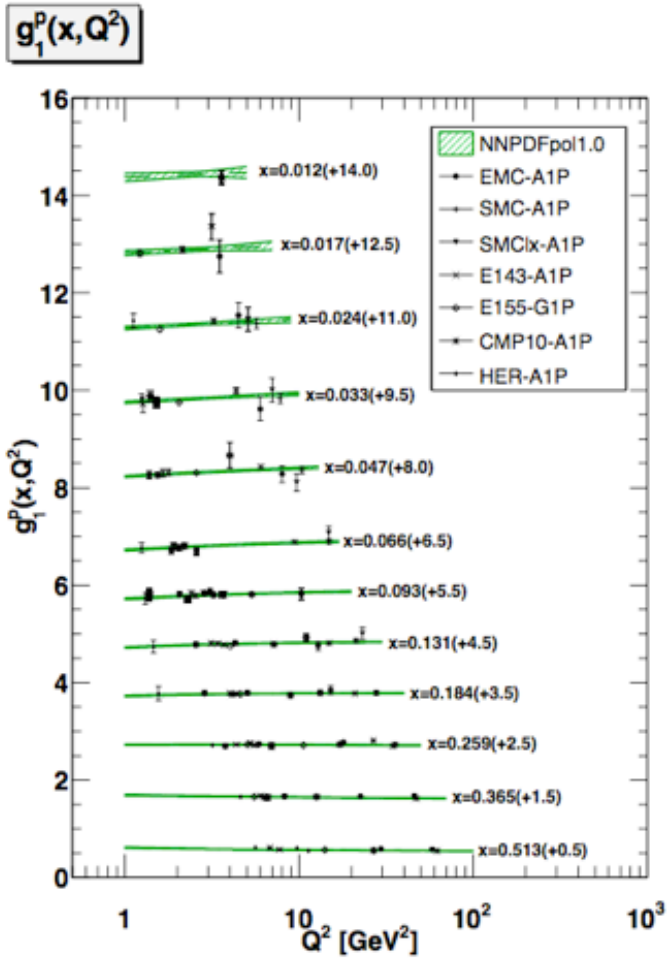
R.D. Ball et al, Nucl. Phys. B444, 287 (1995), B449, 680 (1995)

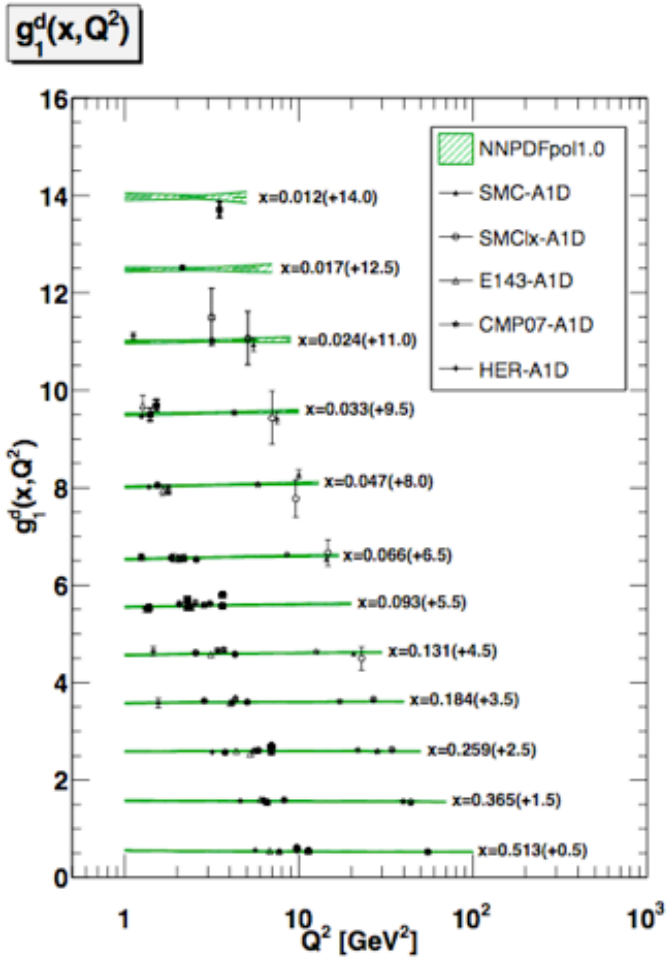
Start of polarized pQCD analyses. Recent work at NLO:

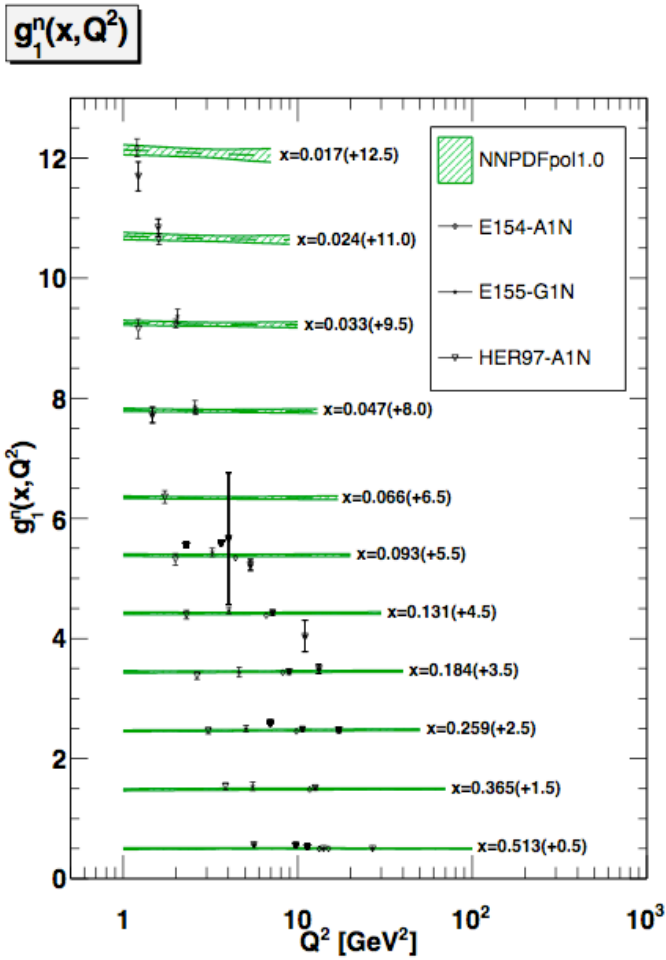
NNPDF: Ball et al,
inclusive DIS data only,
Nucl. Phys. B874, 36 (2013)

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

NNPDF: Polarized Inclusive DIS data





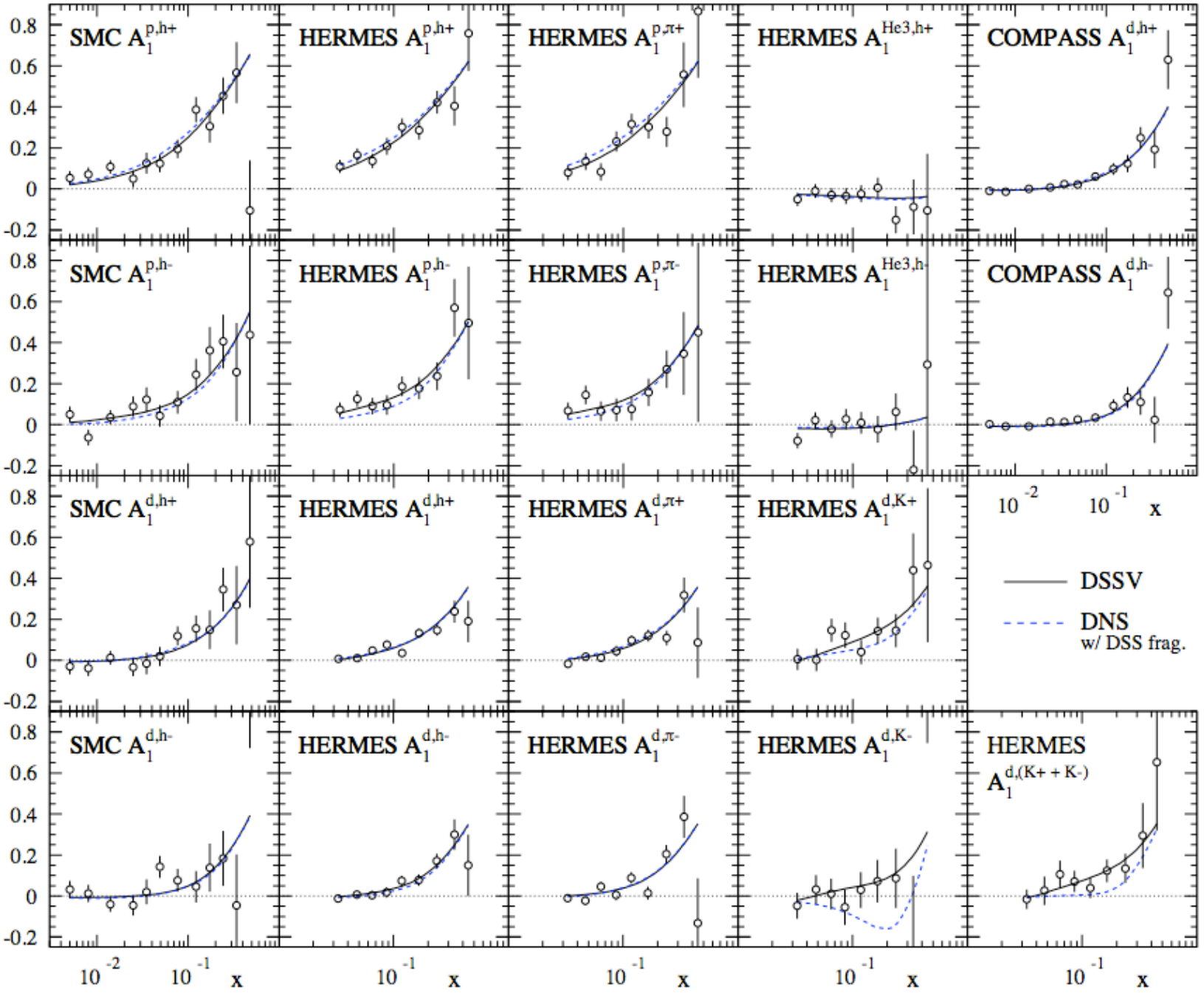


NNPDF: inclusive data only (so far, but note the new work in ArXiv:1307.0146)

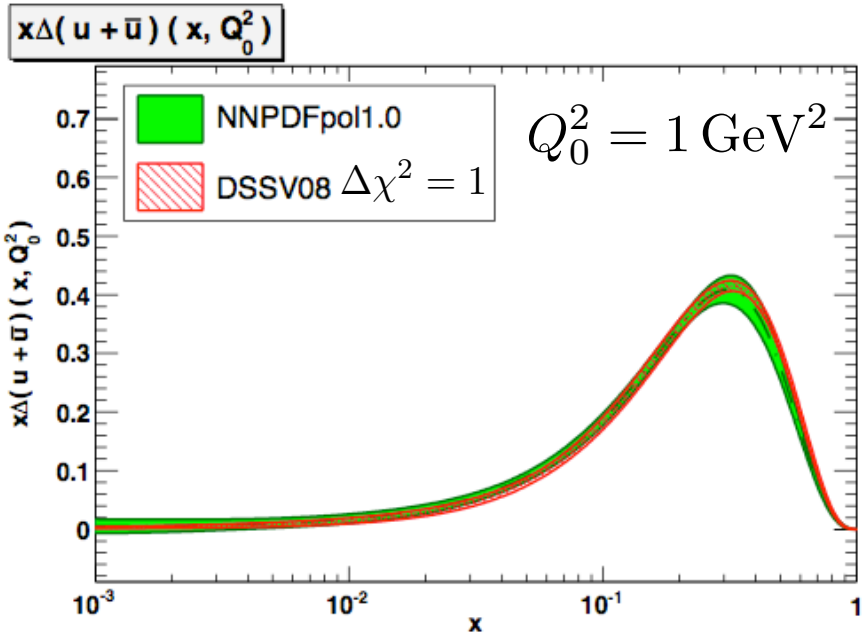
$Q^2 > 1$ GeV^2

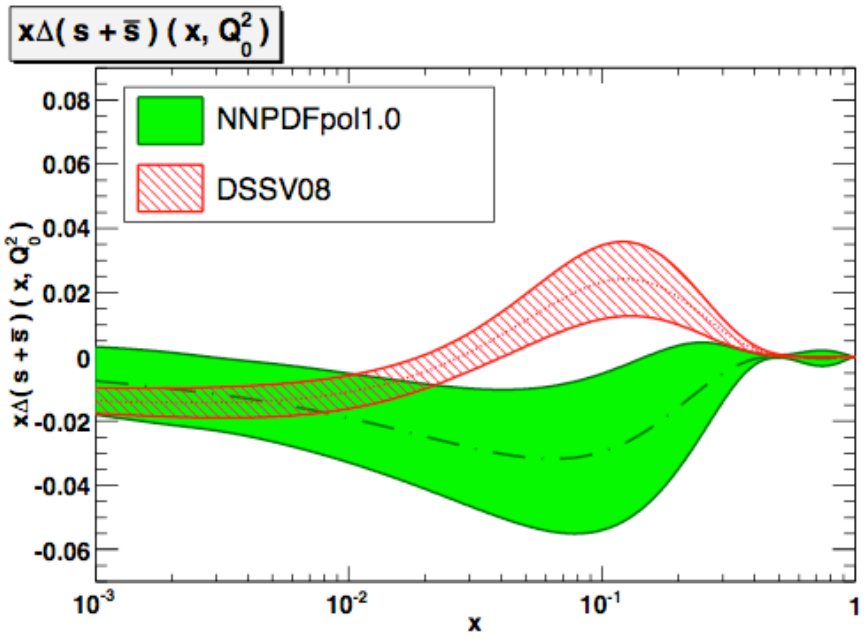
$W^2 > 6.25$ GeV^2 (cuts all JLab data)

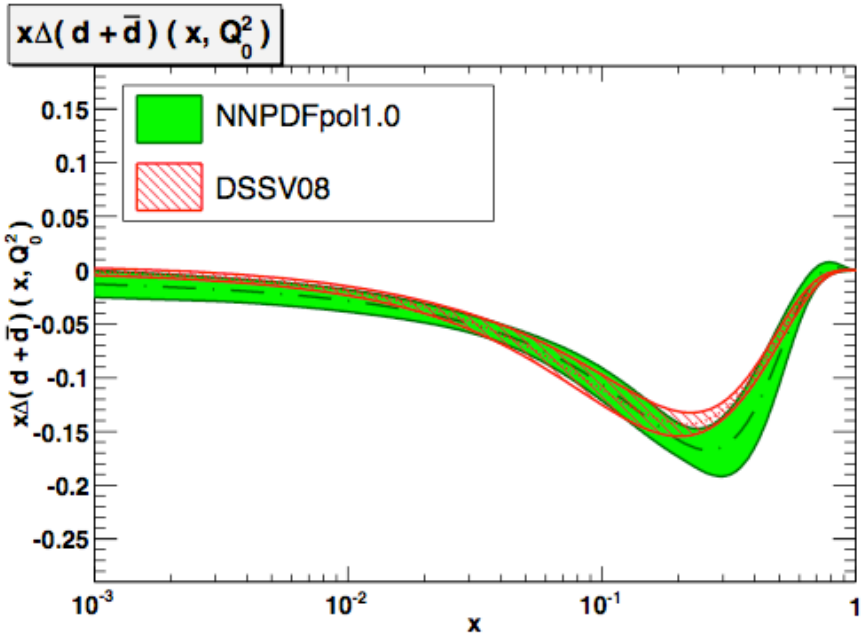
DSSV: Polarized Semi-Inclusive DIS data

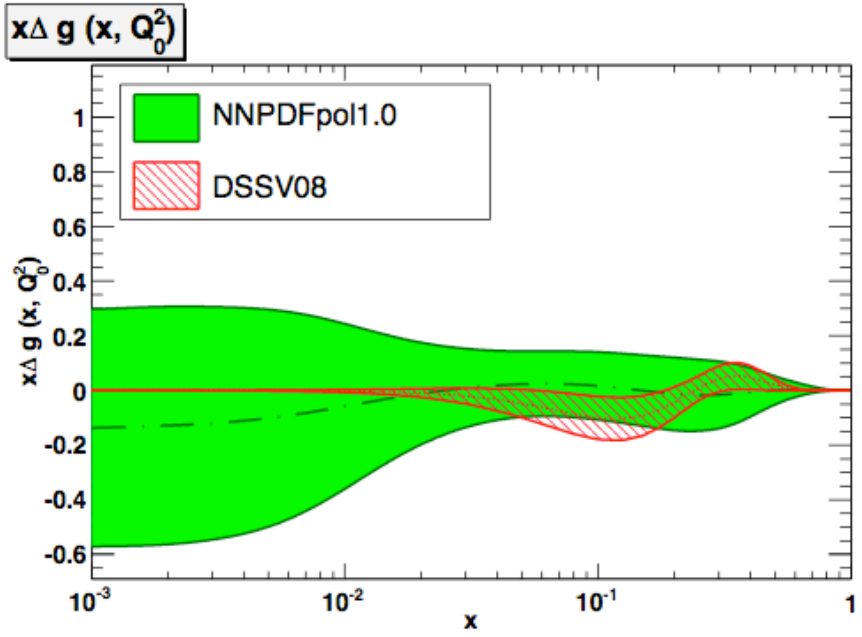


NNPDF, DSSV: Emerging Nucleon Spin Structure





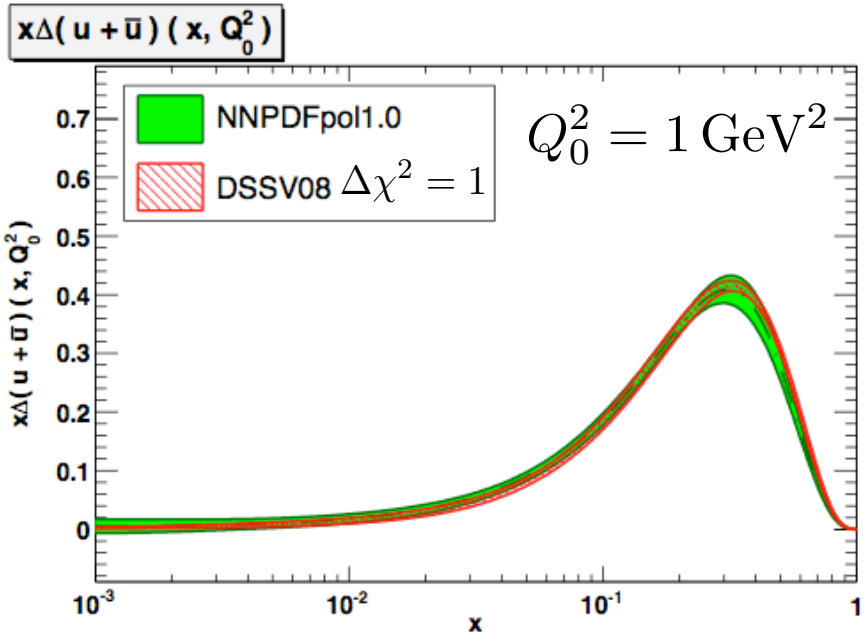


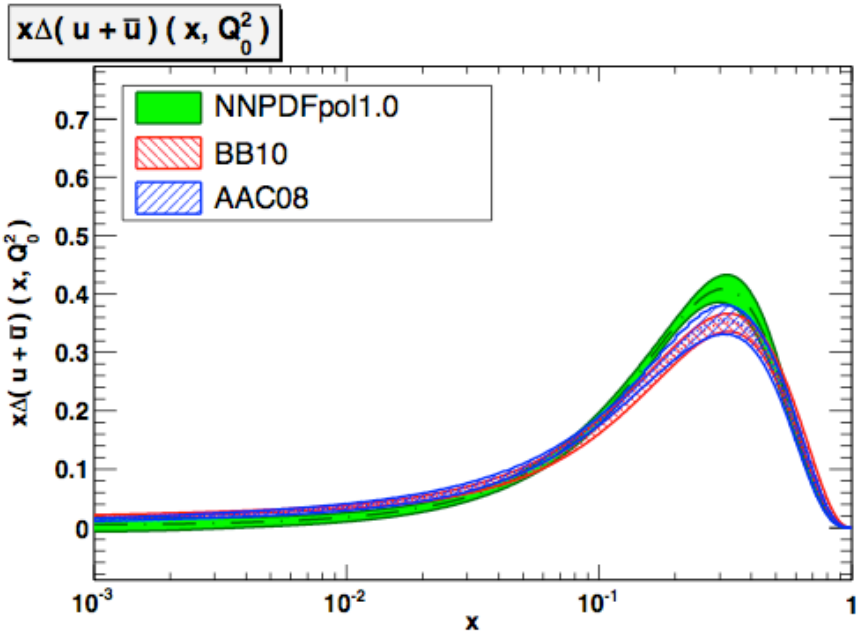


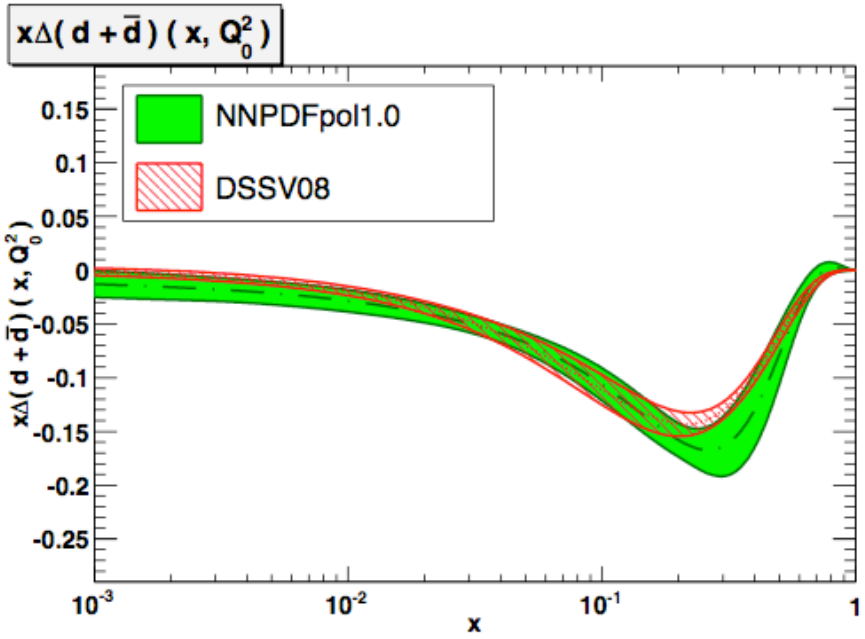
up and down well constrained

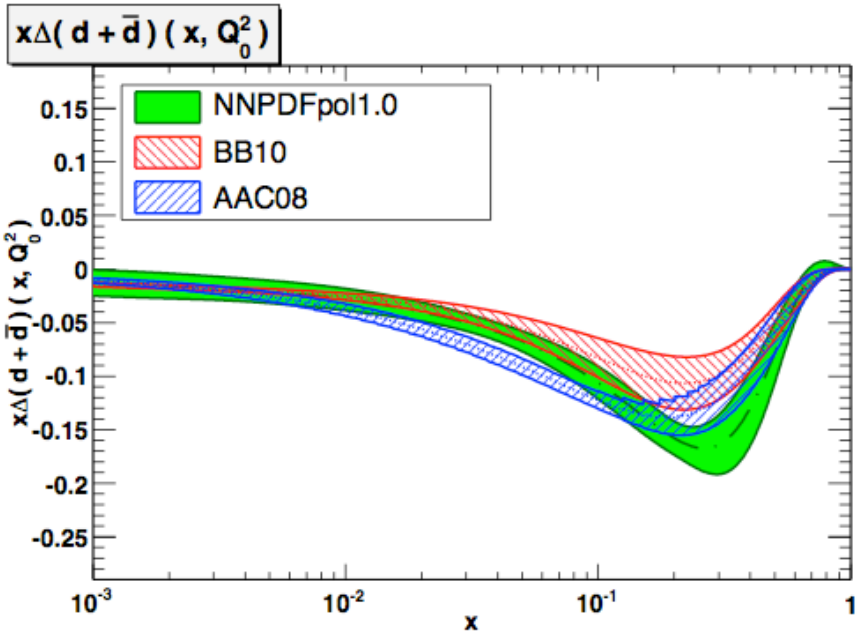
strange and glue less so

NNPDF, DSSV: Emerging Nucleon Spin Structure







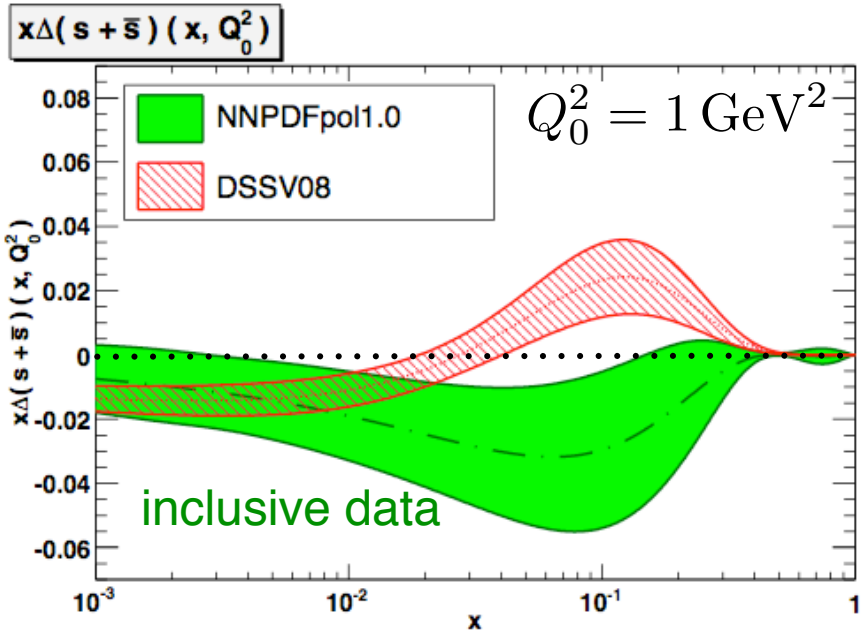


up and down well constrained

AAC, BB agreement slightly worse

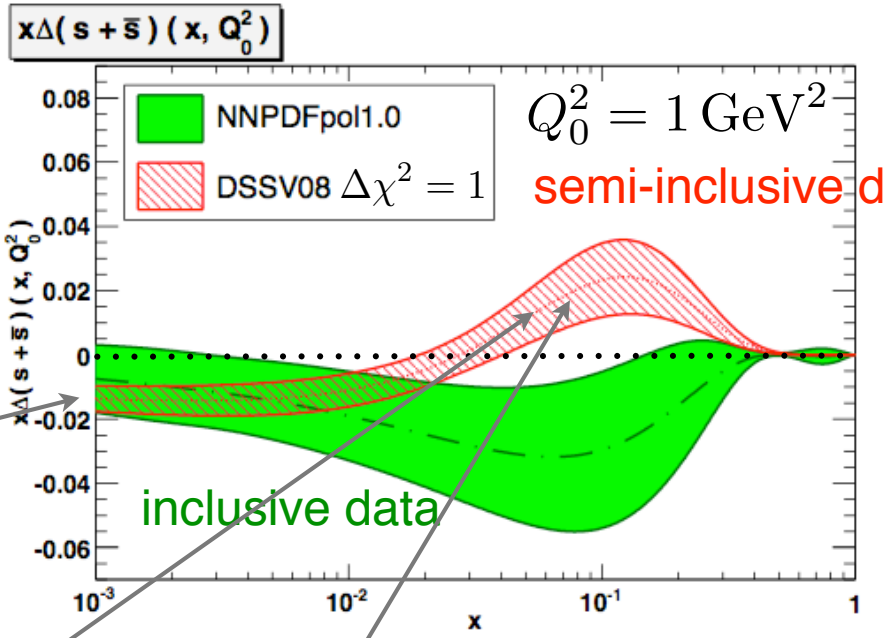
NNPDF, DSSV: Emerging Nucleon Spin Structure

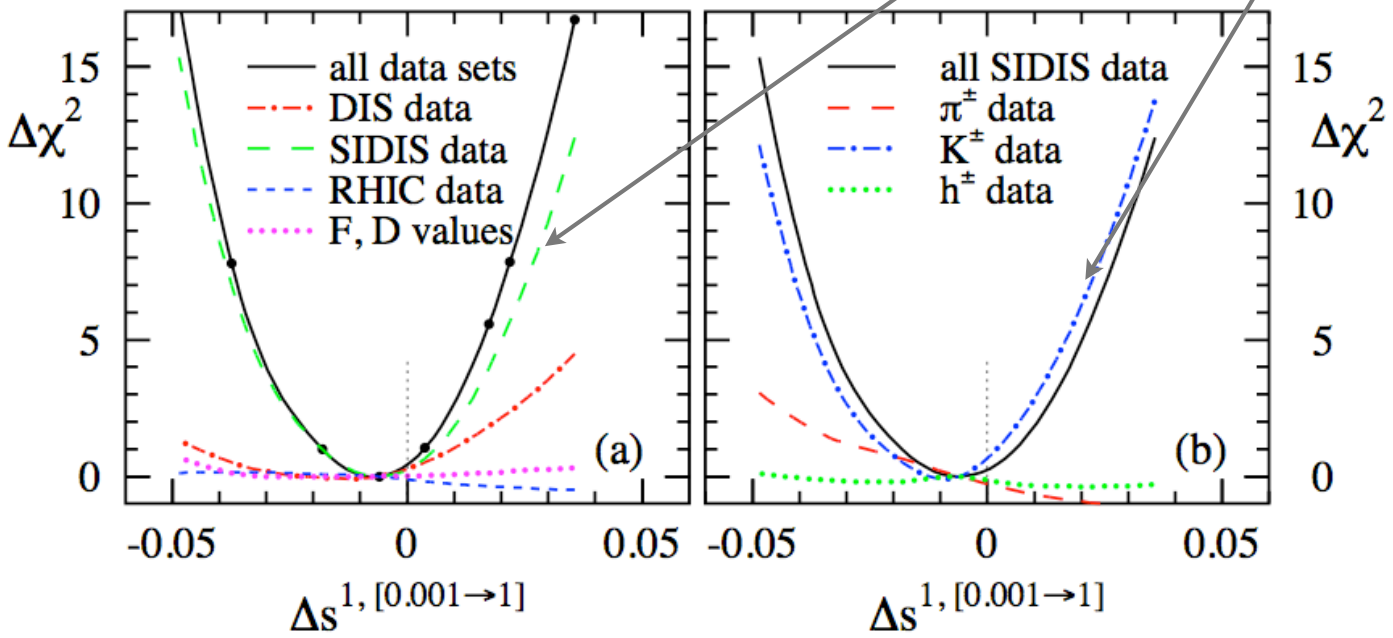
Strange quark polarization:



NNPDF, DSSV: Emerging Nucleon Spin Structure

Strange quark polarization:



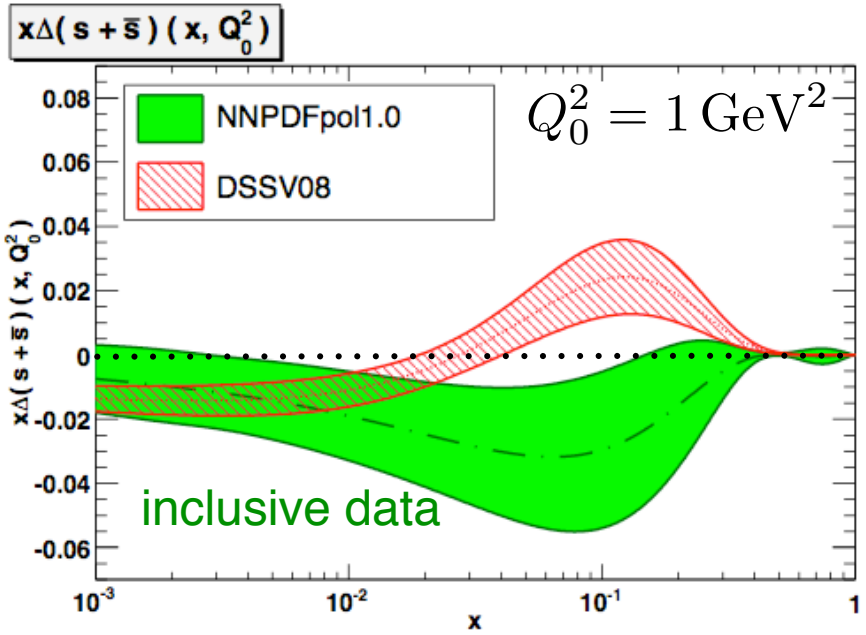


DSSV: De Florian et al
PRD 80, 034030 (2009).

NNPDF, DSSV: Emerging Nucleon Spin Structure

Strange quark polarization:

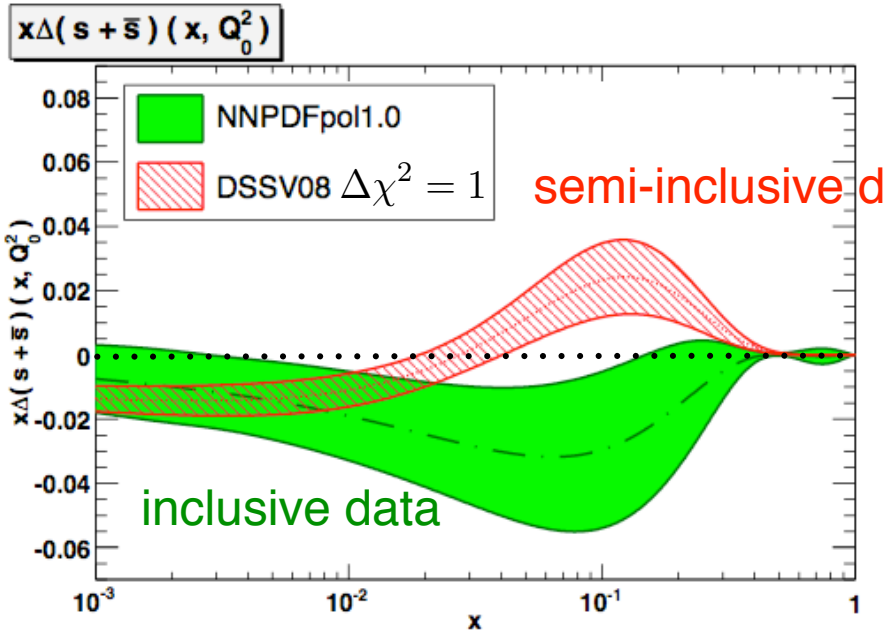
SIDIS relies on FF,
in particular to Kaon FF,
no "tension" in DSSV though,
Larger F, D uncertainty in NNPDF
Unpolarized strange quark distributions
Lattice indicative of small net Δs



NNPDF, DSSV: Emerging Nucleon Spin Structure

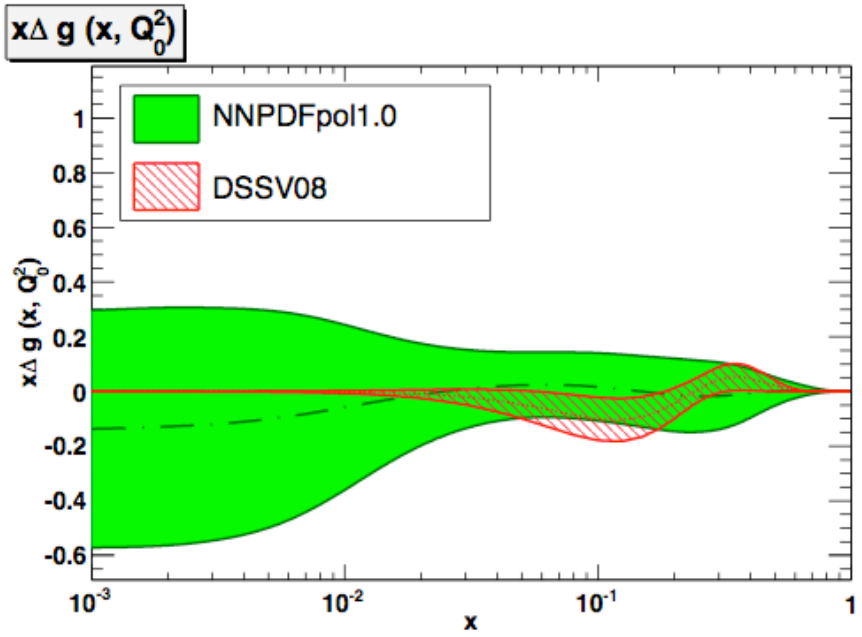
Strange quark polarization:

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



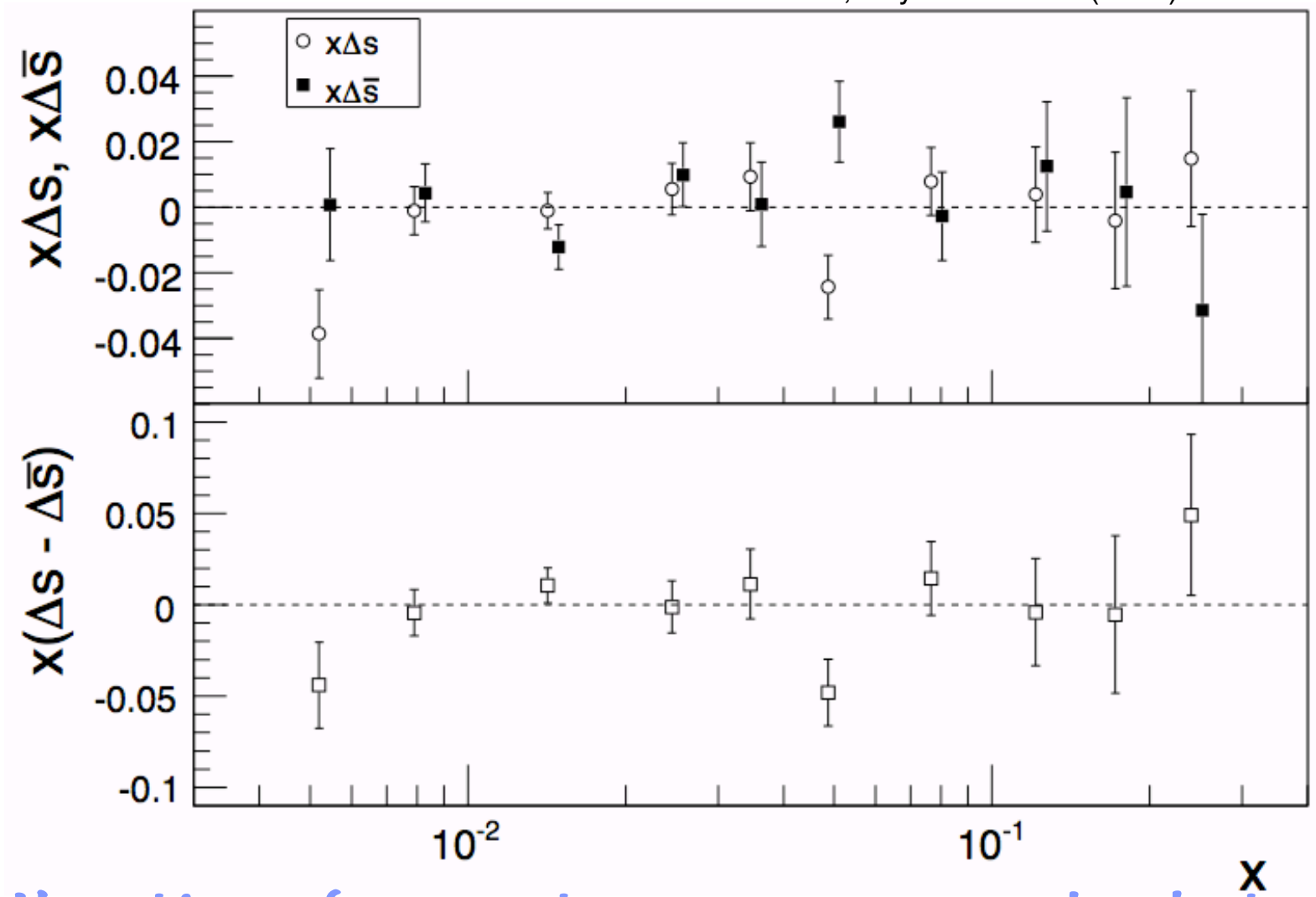
Gluon polarization:

Role of RHIC



HERMES, COMPASS L.O. Quark Spin Distributions

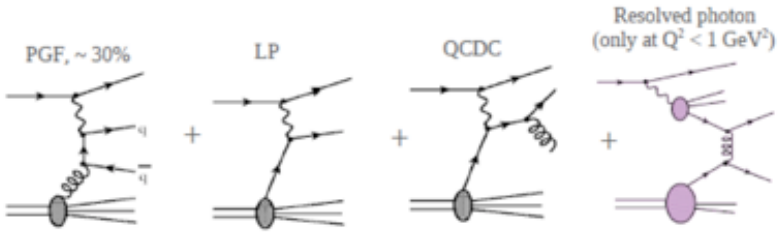
M.G. Alekseev, Phys.Lett. B693 (2010) 227-235

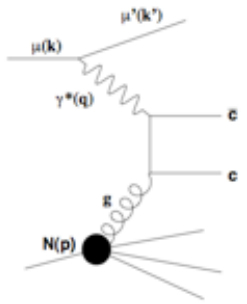


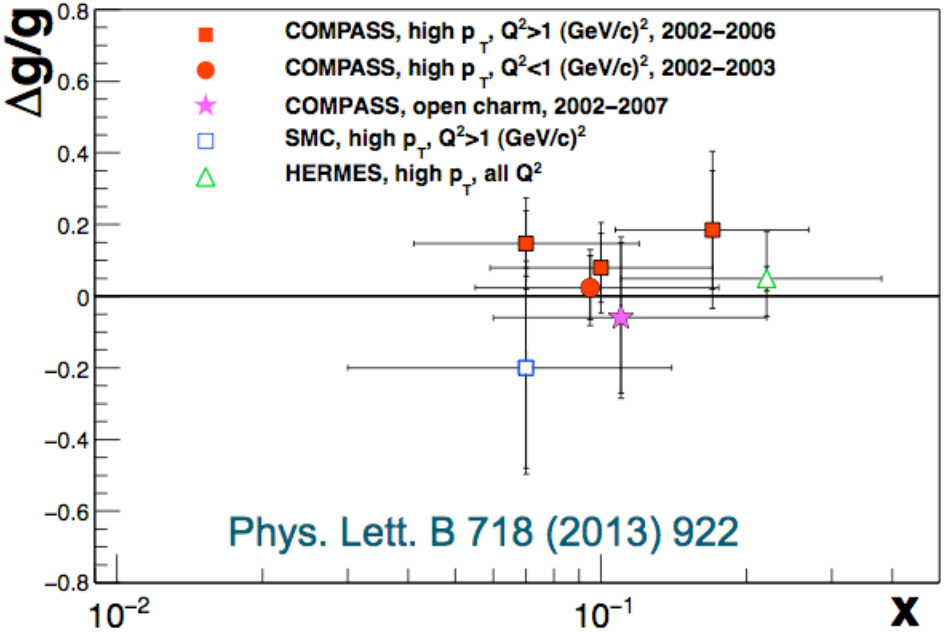
No evidence for negative net strange quark polarization,
not from $(K^+ + K^-)$ asymmetries of D either,

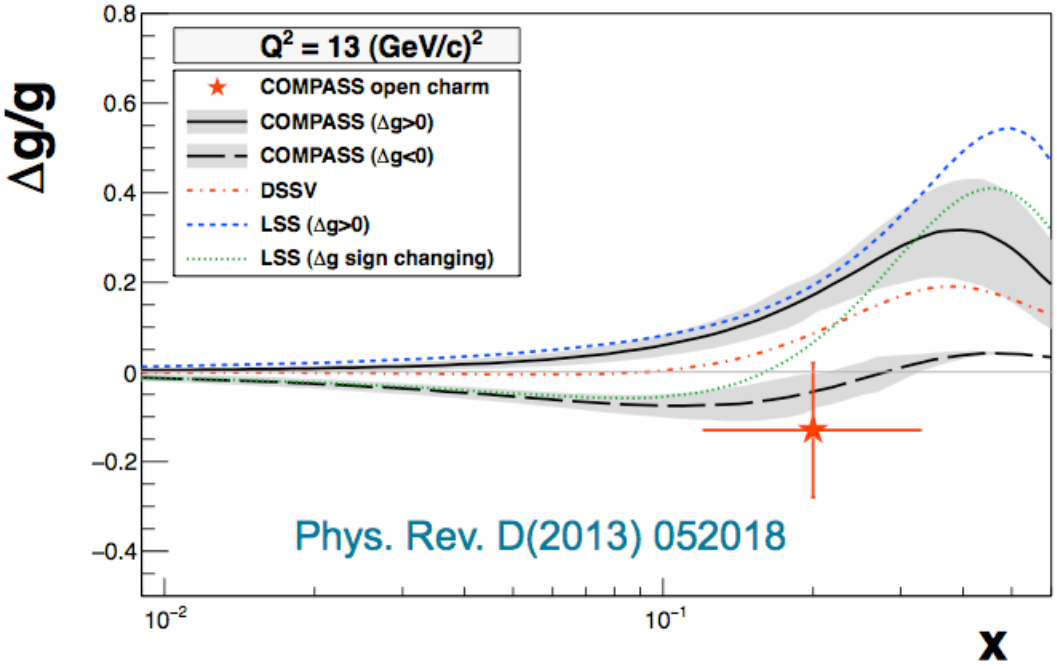
Renewed interest in FF, in-situ multiplicities, etc.

HERMES, COMPASS - Gluon Polarization (direct)



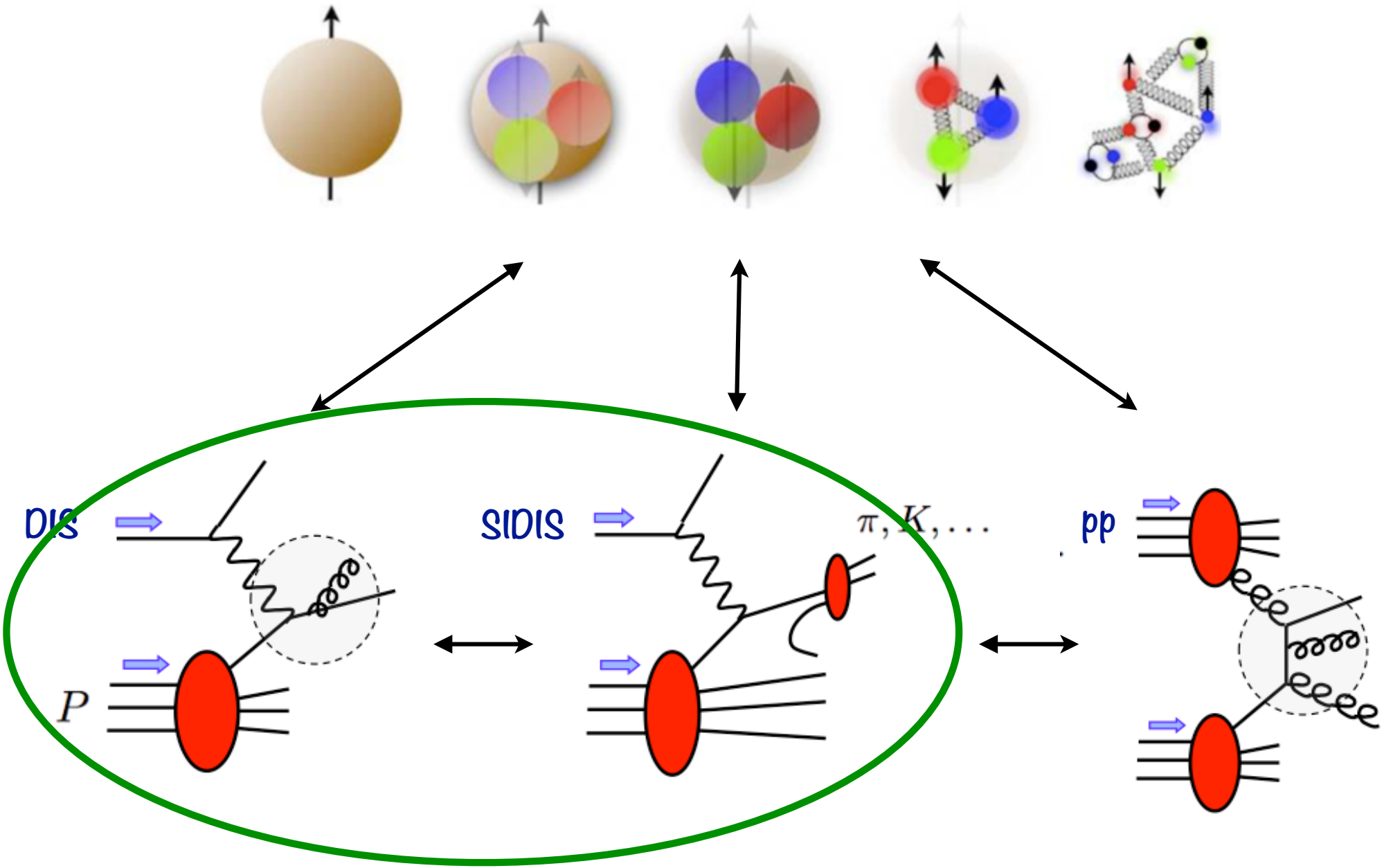




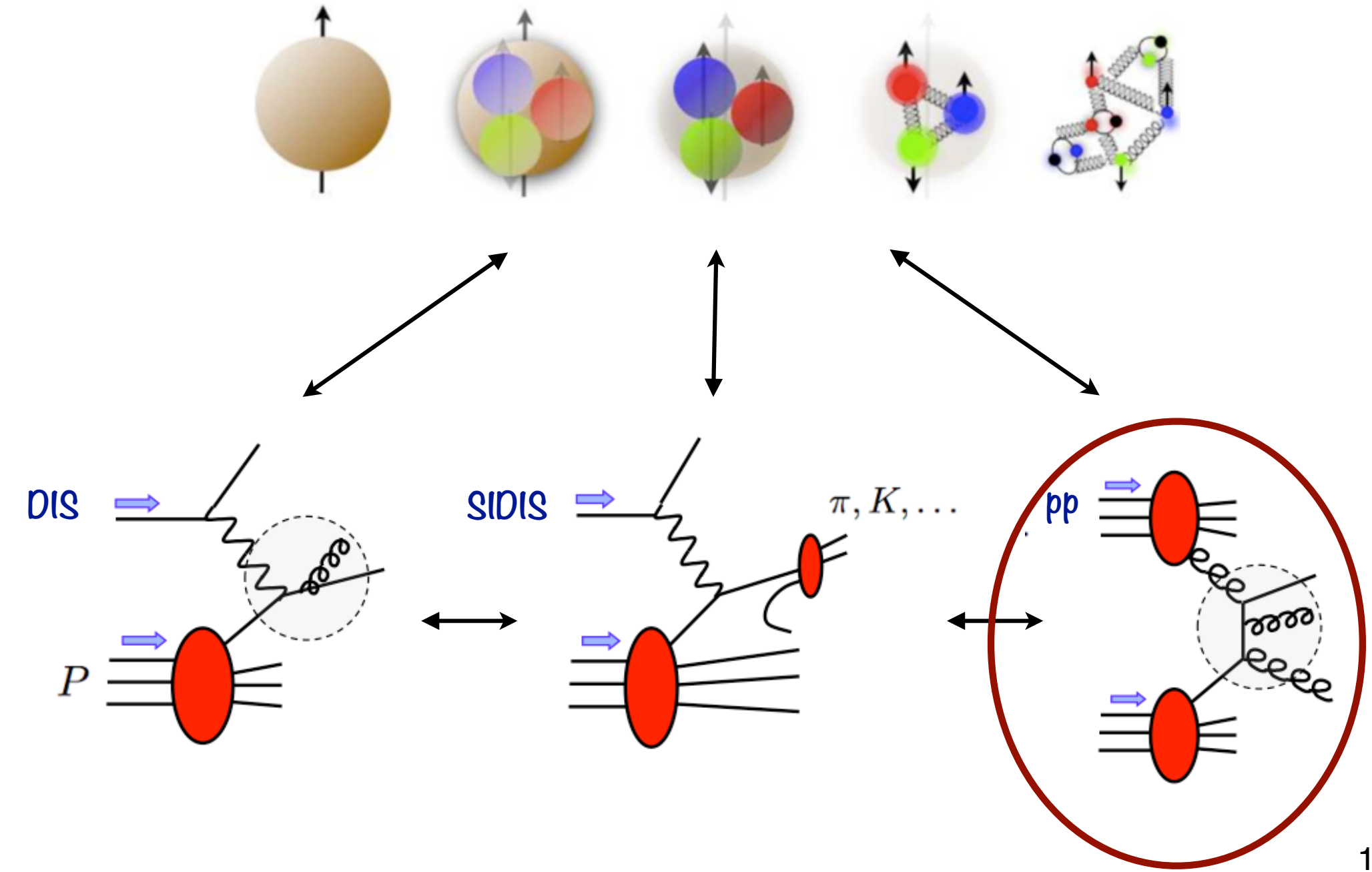


Hard...

Synergies and Novel Approaches: Nucleon Structure



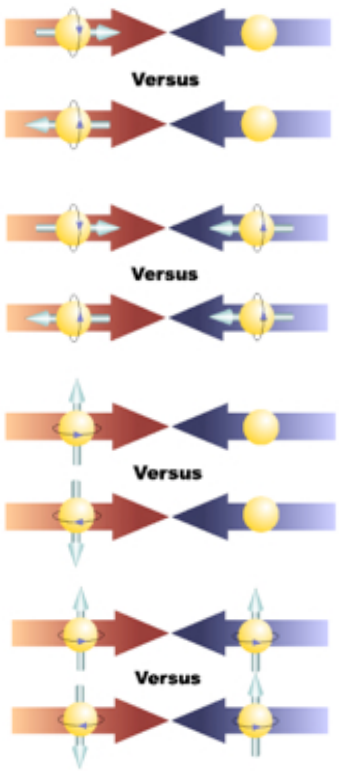
Synergies and Novel Approaches: Nucleon Structure

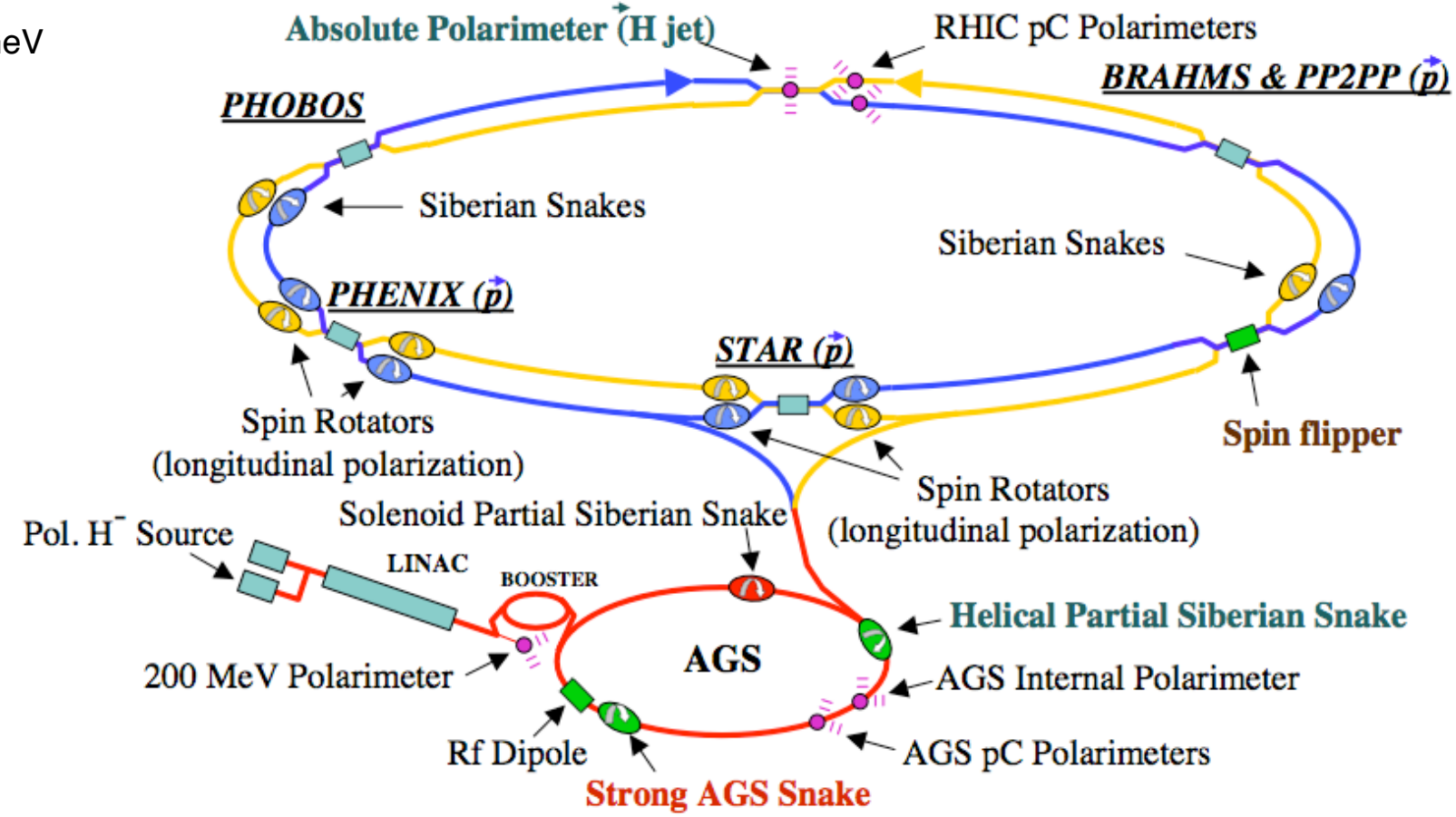


RHIC - Polarized Proton-Proton Collider

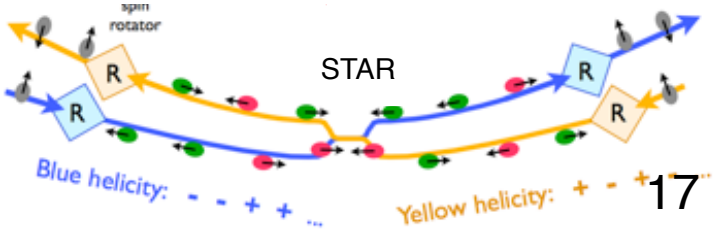
Unique opportunities to study spin in QCD:

√s = 62, 200, and 500 GeV





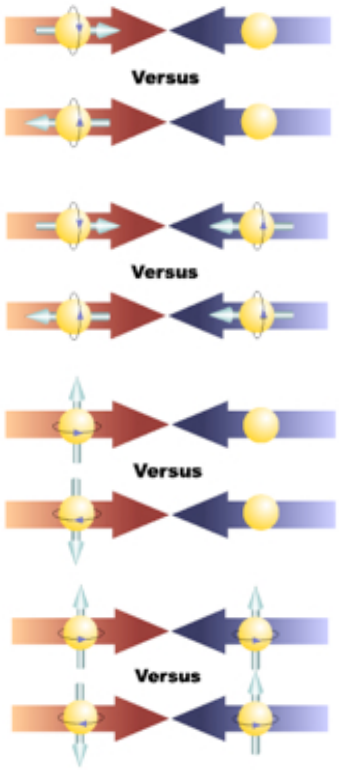
at hard (perturbative) scales with good systematic controls, e.g. bunch pattern:



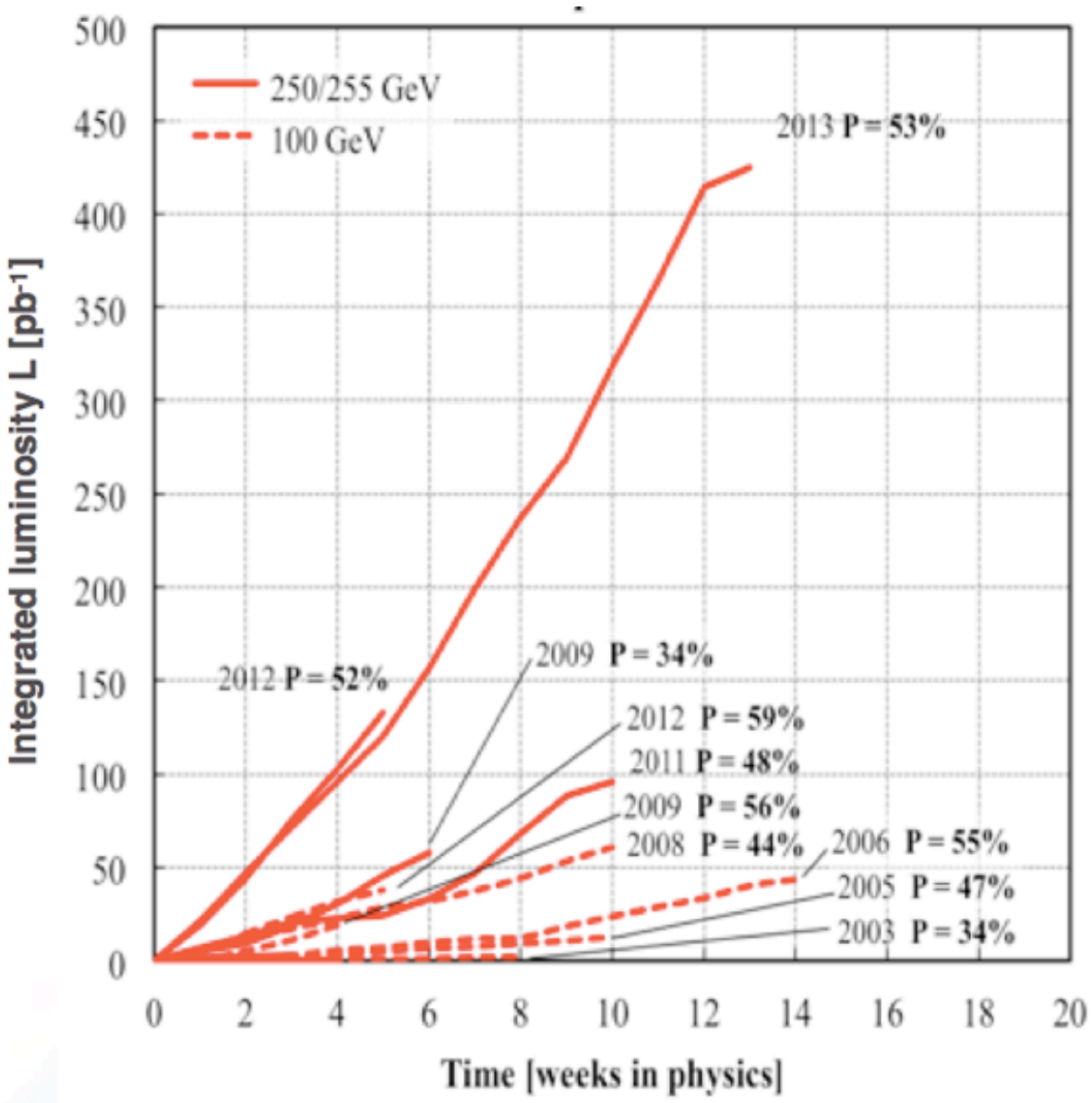
RHIC - Polarized Proton-Proton Collider

Unique opportunities to study spin in QCD:

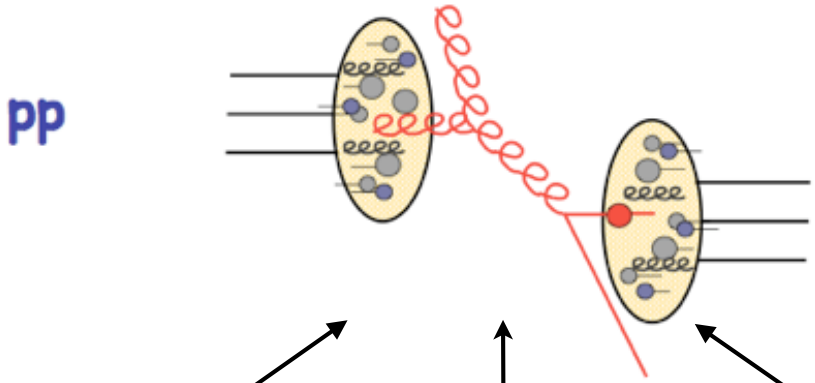
√s = 62, 200, and 500 GeV

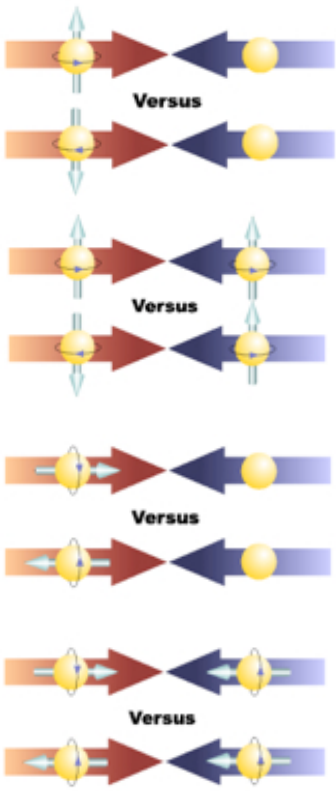


courtesy RHIC-CAD



Spin Measurements at RHIC





$q, \bar{q}, g, \Delta q, \Delta\bar{q}, \Delta g$ $\quad \hat{\sigma}, \Delta\hat{\sigma}$ $\quad q, \bar{q}, g, \Delta q, \Delta\bar{q}, \Delta g \leftrightarrow$

√s = 62 - 500 GeV

Theory: perturbative QCD evaluations, typically at next-to-leading order,

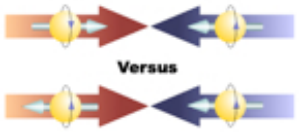
Experiment: observe cross sections (asymmetries) of (hadronized) final states,
test applicability of theoretical framework,
extend measurements to correlated and selective final states.

Combination: insight in $q, \bar{q}, g, \Delta q, \Delta\bar{q}, \Delta g$

Complementary insights from measurements of A_{LL}, A_L, A_N, D_{LL}, inclusive probes, correlations ...

Gluon Polarization

Measure double longitudinal spin asymmetries and establish that the factorized framework applies,



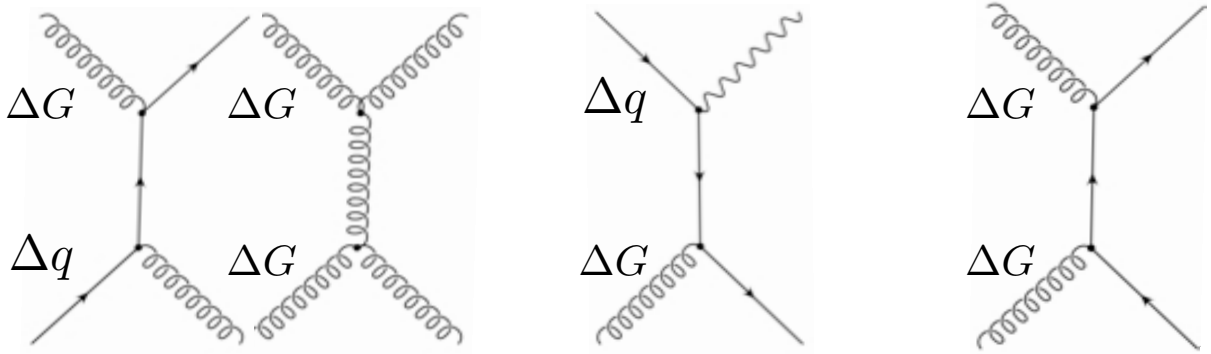
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \stackrel{?}{=} \sum_{f=q,g} \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \otimes (\text{fragmentation functions})$$

Start with abundantly produced jets or pions at mid-rapidity, where the partonic asymmetries are sizable,

Gluon-gluon scattering contribution dominates up to jet pT ~ 8 GeV, where quark-gluon scattering takes over,

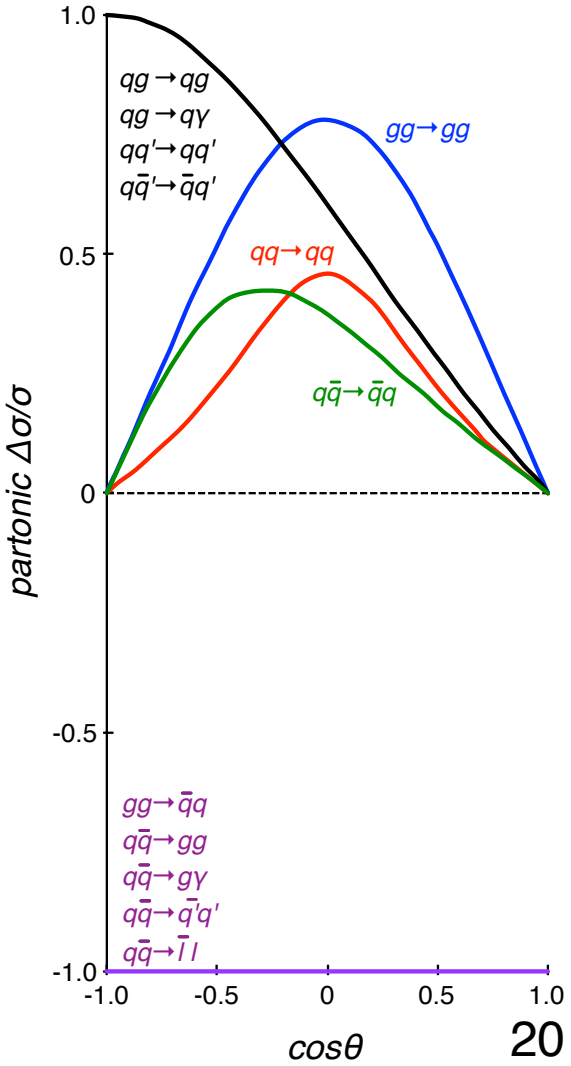
Path: precision, coverage, sensitivity to initial kinematics, and selective probes.

$\vec{p} + \vec{p} \to \text{jet(s)} + X$ $\quad$ $\vec{p} + \vec{p} \to \gamma + \text{jet}$ $\quad$ $\vec{p} + \vec{p} \to c\bar{c}, b\bar{b} + X$



$$\mathcal{L} \simeq 3 - 8 \cdot 10^2\,\text{pb}^{-1}, \quad P = 0.4 - 0.7, \quad \sqrt{s} = 200 - 500\,\text{GeV}$$

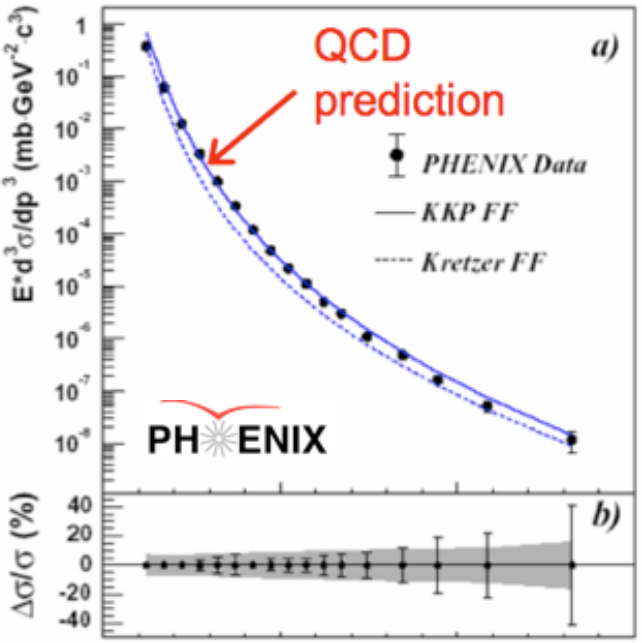
time



RHIC - Inclusive Cross Sections

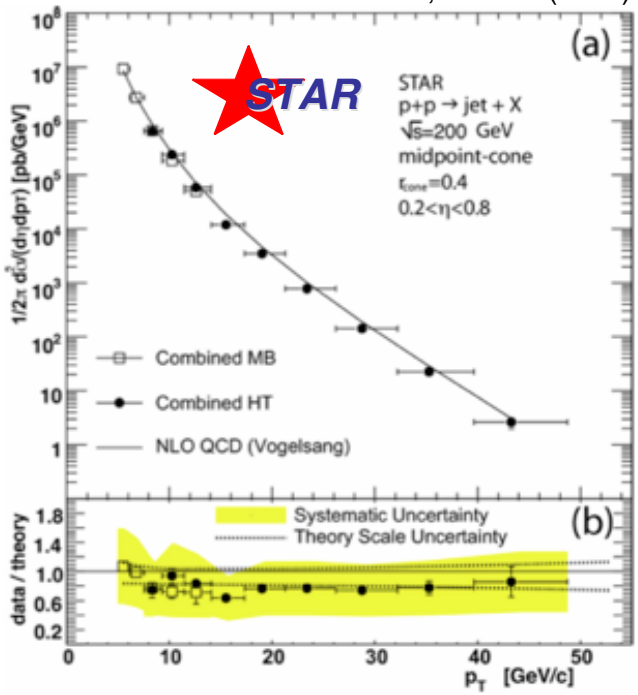
pions

PRL 91, 241803 (2003)



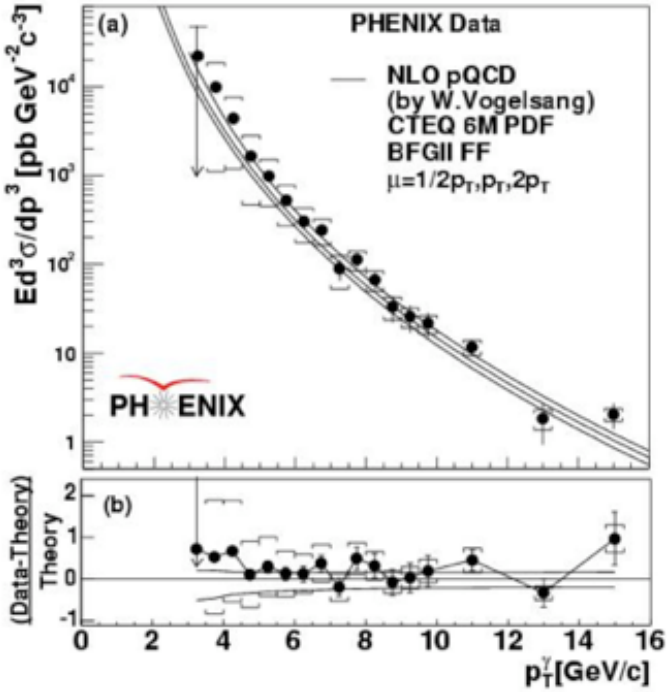
jets

PRL 97, 252001 (2006)

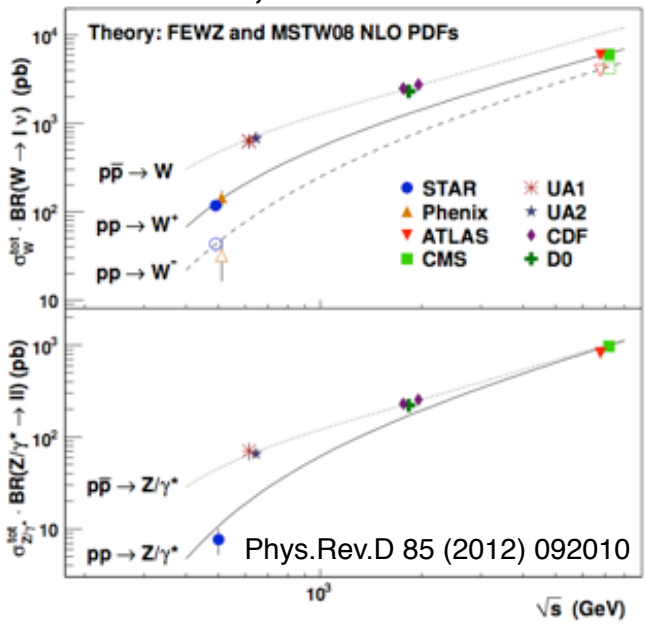


photons

PRL 98, 012002 (2007)



W, Z bosons



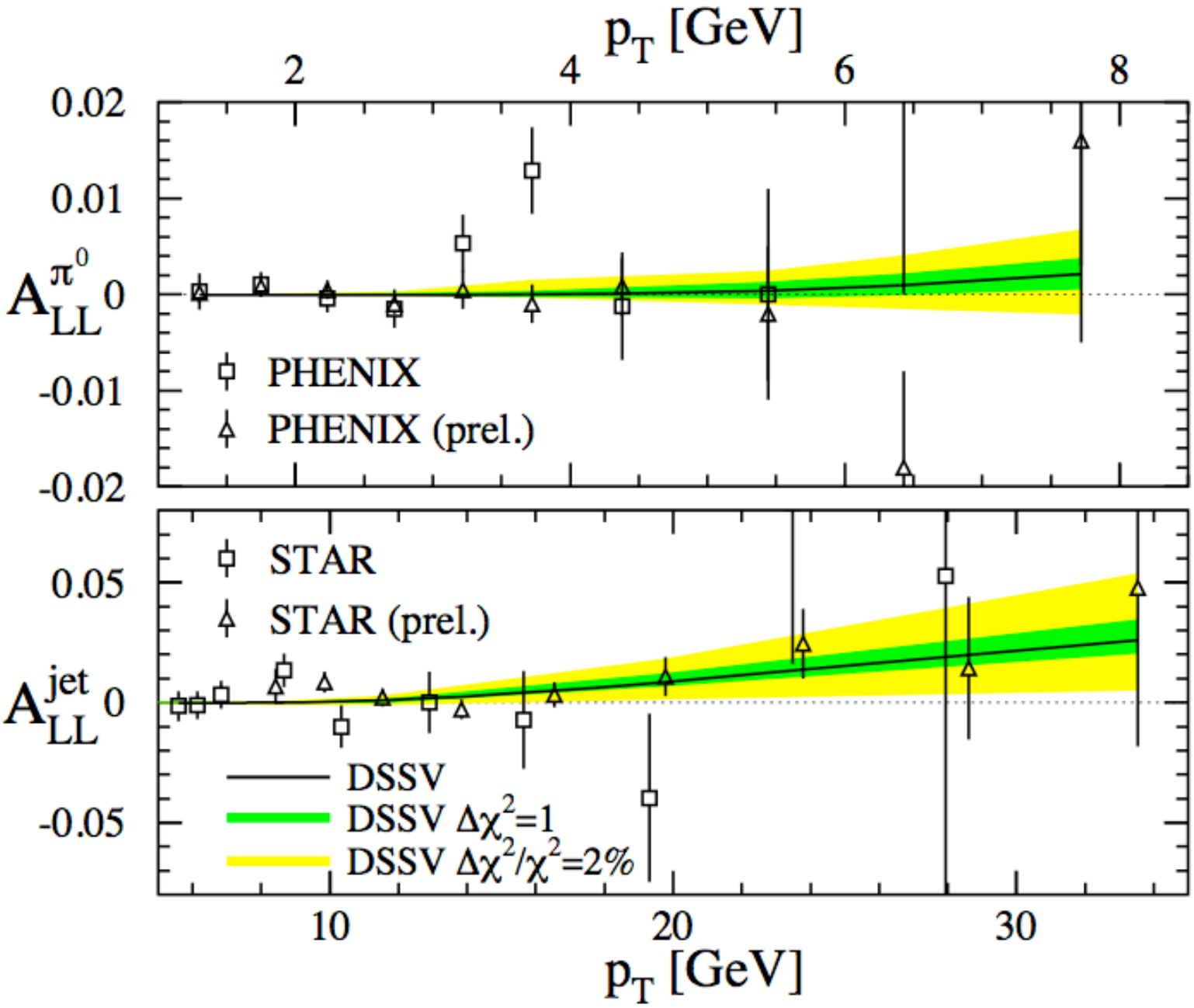
Phys.Rev.D 85 (2012) 092010

Good agreement between data and theory (pQCD @NLO) for mid-rapidity pions, jets, photons, W and Z bosons;

⟶ interpretable measurements.

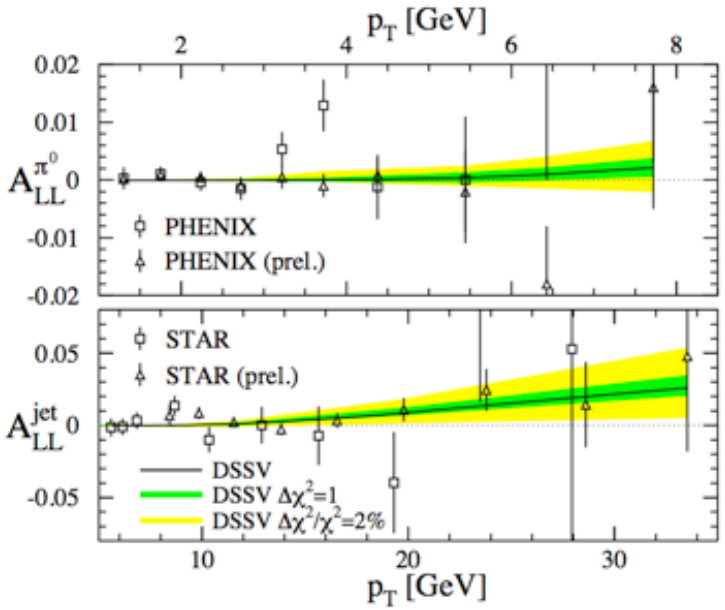
Other examples exist, more to come!

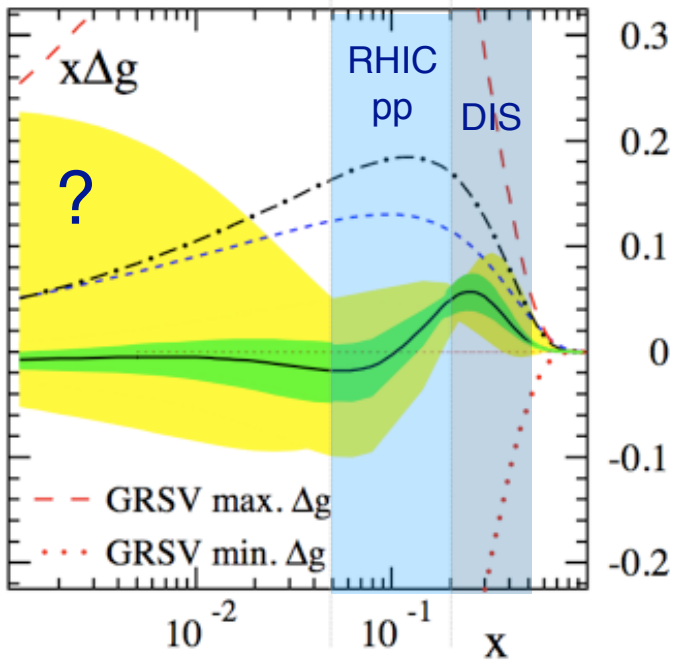
Gluon Polarization - RHIC Data from 2005, 2006



D. de Florian et al, Phys.Rev.Lett. 101:072001(2008)

RHIC 2005, 2006 Data - Significant Constraints

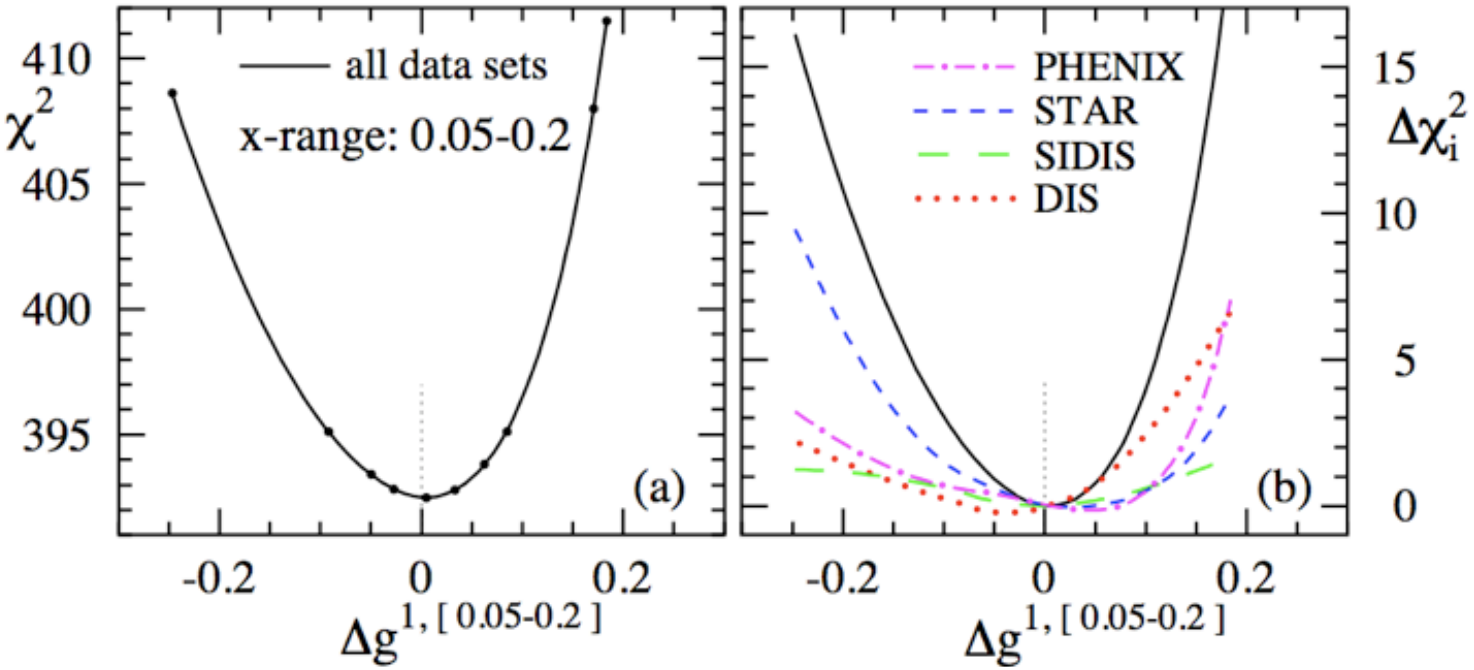




D. de Florian et al,
Phys.Rev.Lett. 101:072001(2008)
Phys. Rev. D 80:034030 (2009),

"State-of-the-art": only polarized analysis that incorporates DIS, SIDIS, and RHIC data,

Not all data though, missing are
- DIS hadron pairs and open charm,
- PHENIX 62 GeV, charged pions,
- STAR neutral and charged pions,



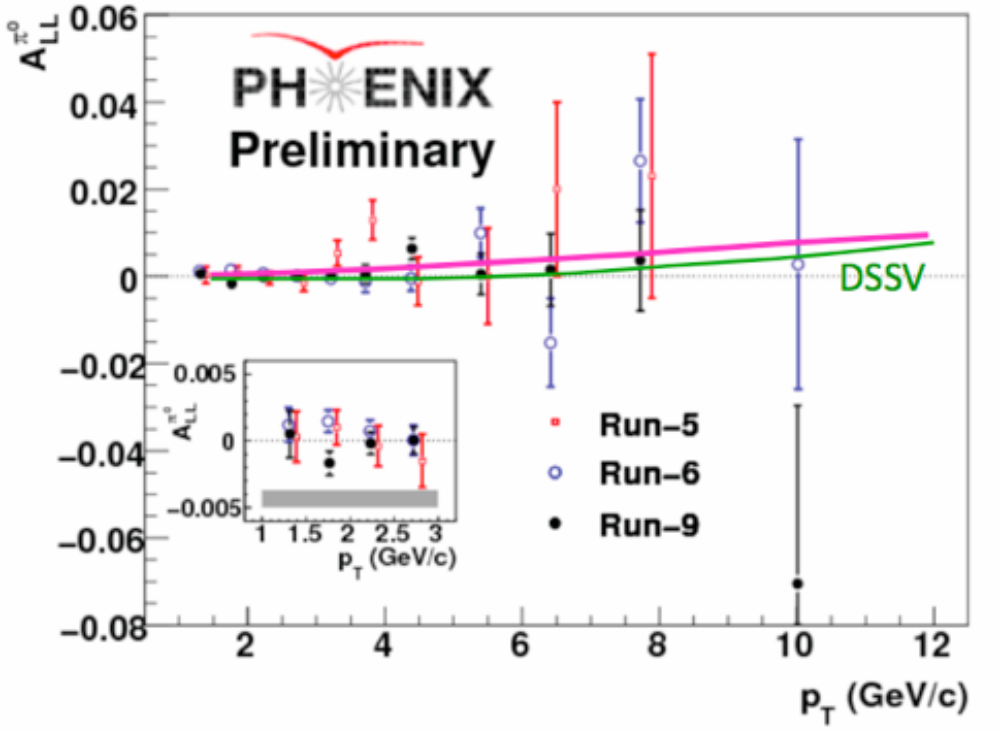
Significant constraints from RHIC,

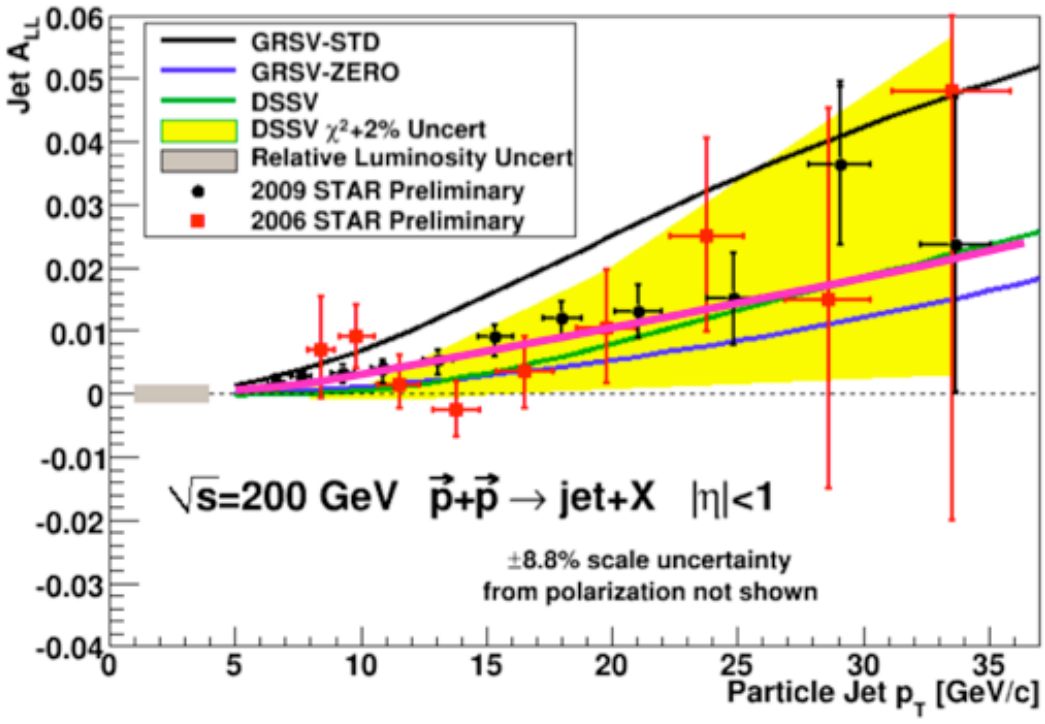
Small gluon spin contribution to proton spin from $0.05 < x_g < 0.2$, possibly because of a node,

Note that the node, if any, is opposite to the GS-C node,

Extrapolations to small x_g are... *extrapolations*!

RHIC 2009 Data - Precision





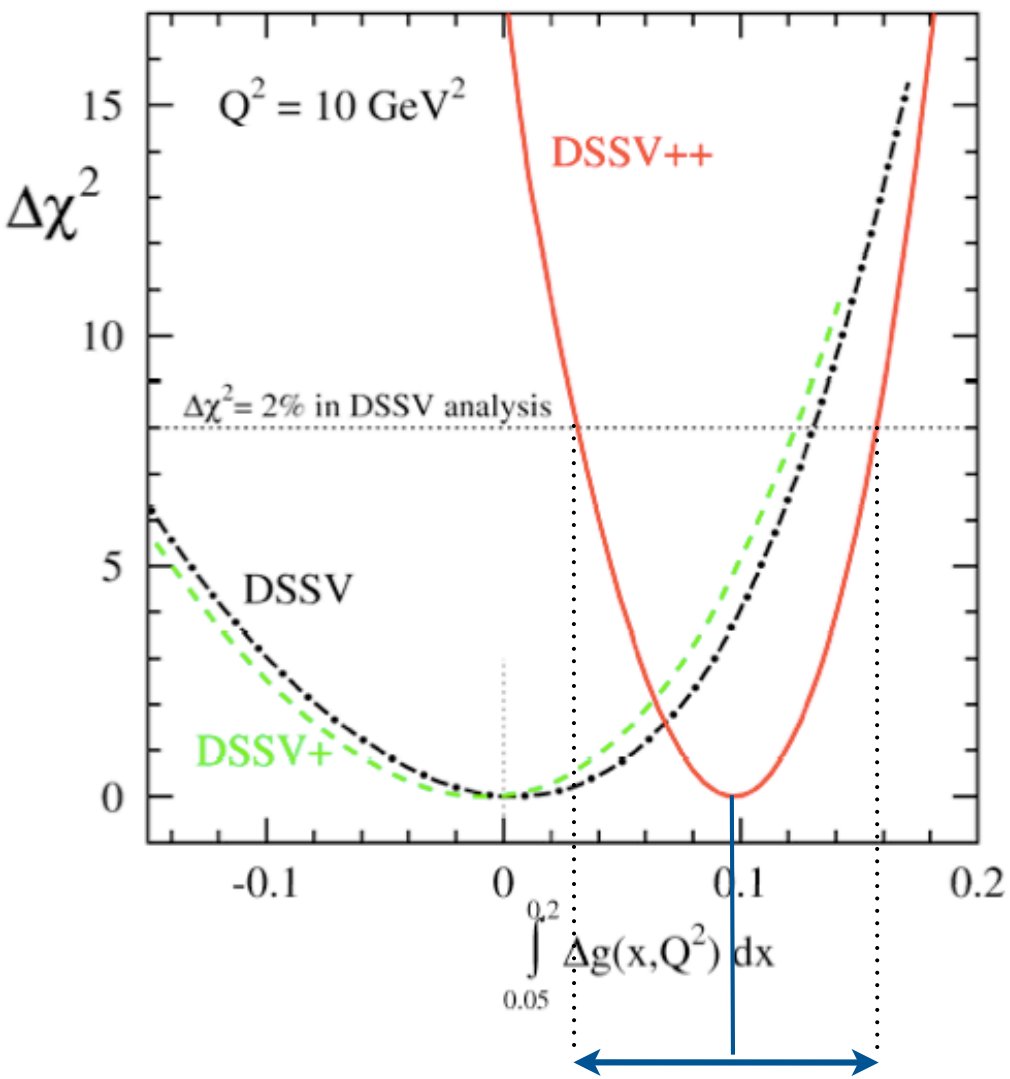
D. de Florian et al, arXiv 1112.0904

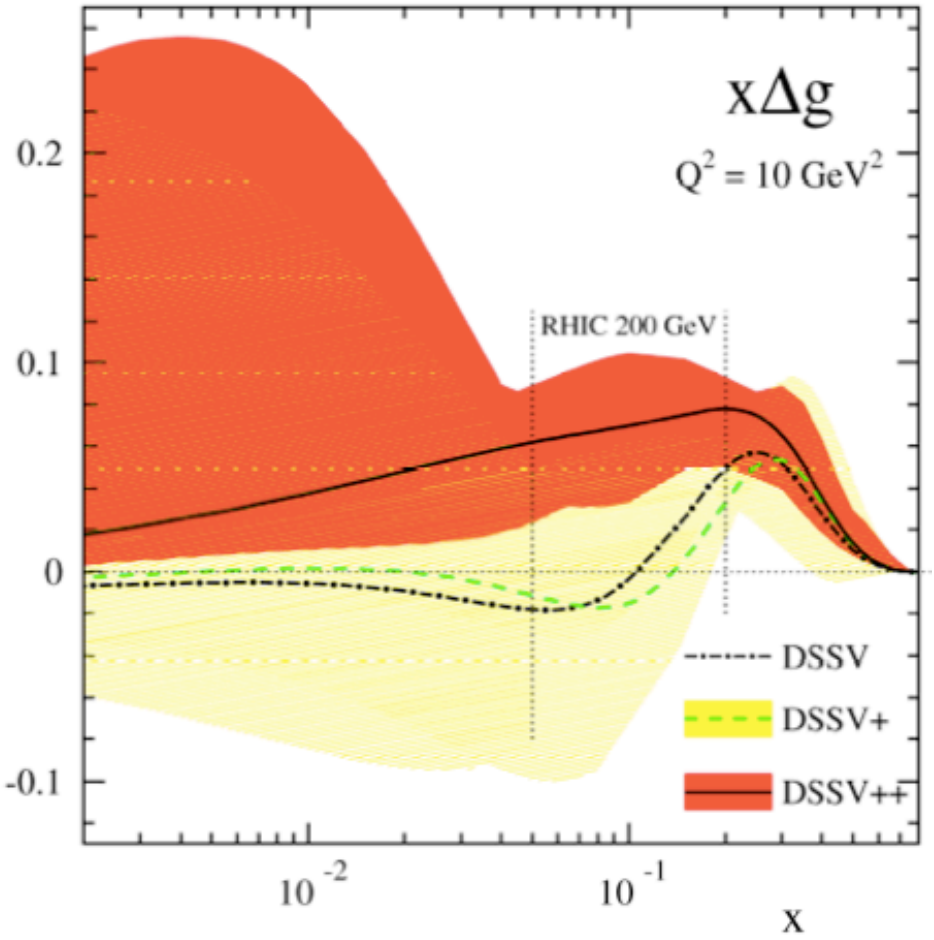
Three to four-fold increase in precision over 2005, 2006 data,

Data are systematically above the DSSV central value and below the GRSV-STD values,

Direct indication of non-zero gluon polarization in the nucleon in the RHIC kinematic range.

RHIC 2009 Data - Impact

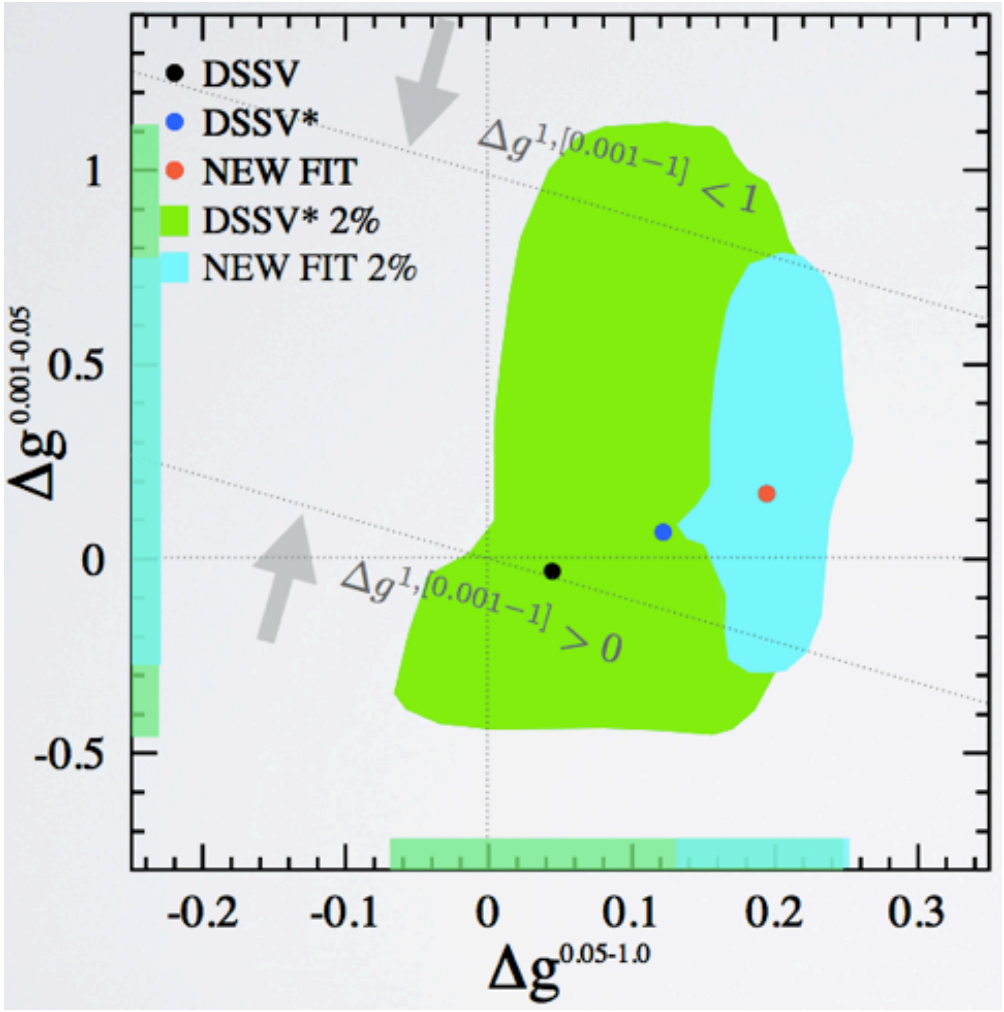




M. Stratmann et al, arXiv:1304.0079

Similar to net quark polarization.

RHIC prospects for ΔG



R. Sassot, 2013 Spin Summer Program

Further precision,

~Direct sensitivity to *x* with:

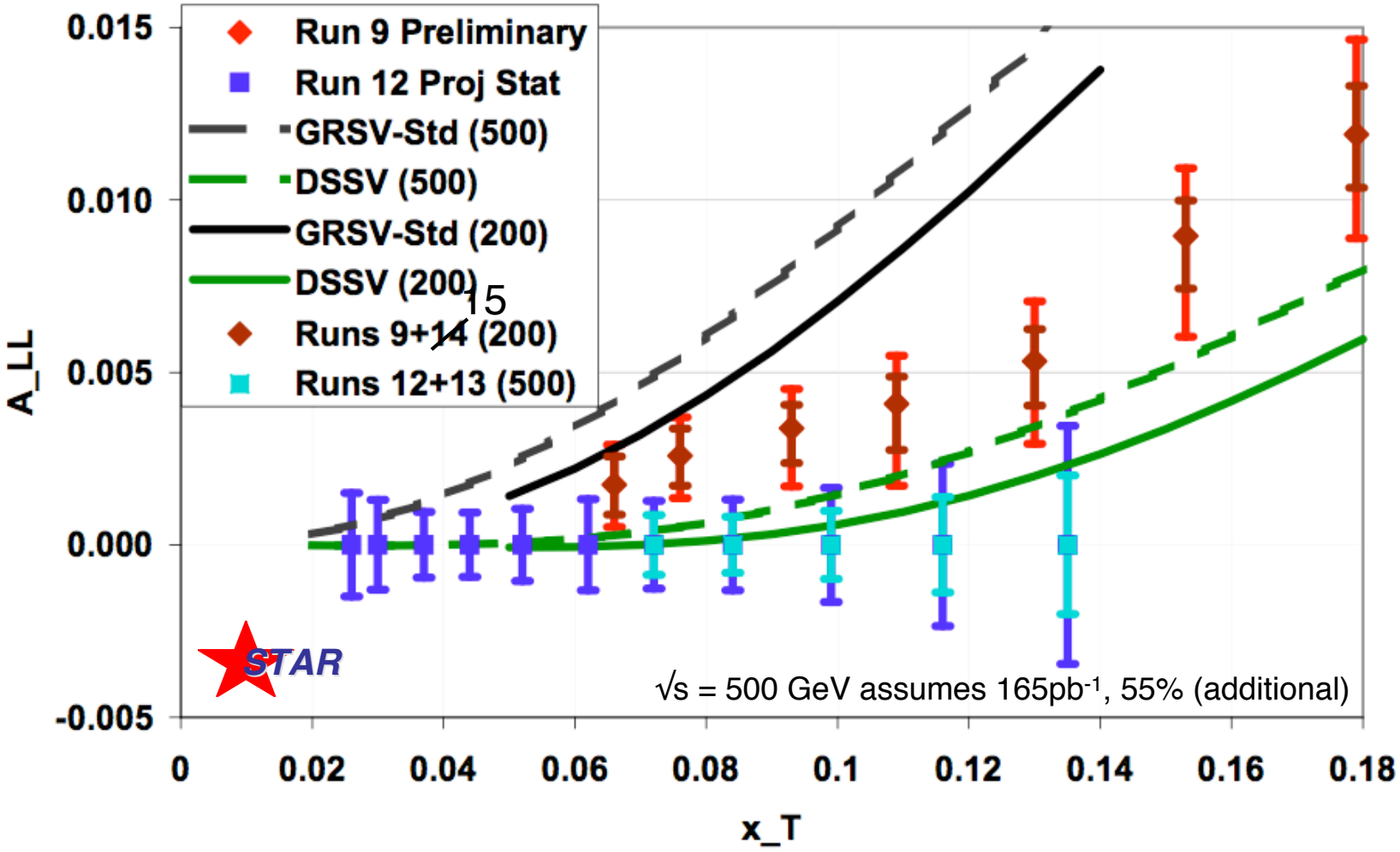
correlation measurements,

Sensitivity to smaller *x*:

√s = 500 GeV,

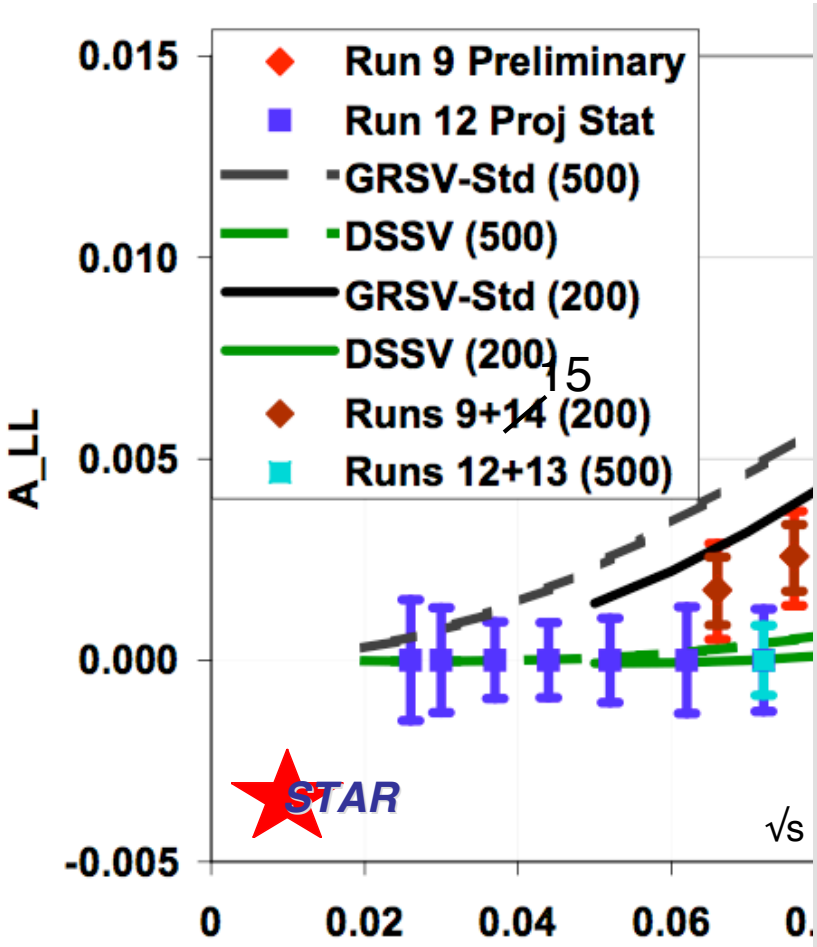
forward instrumentation.

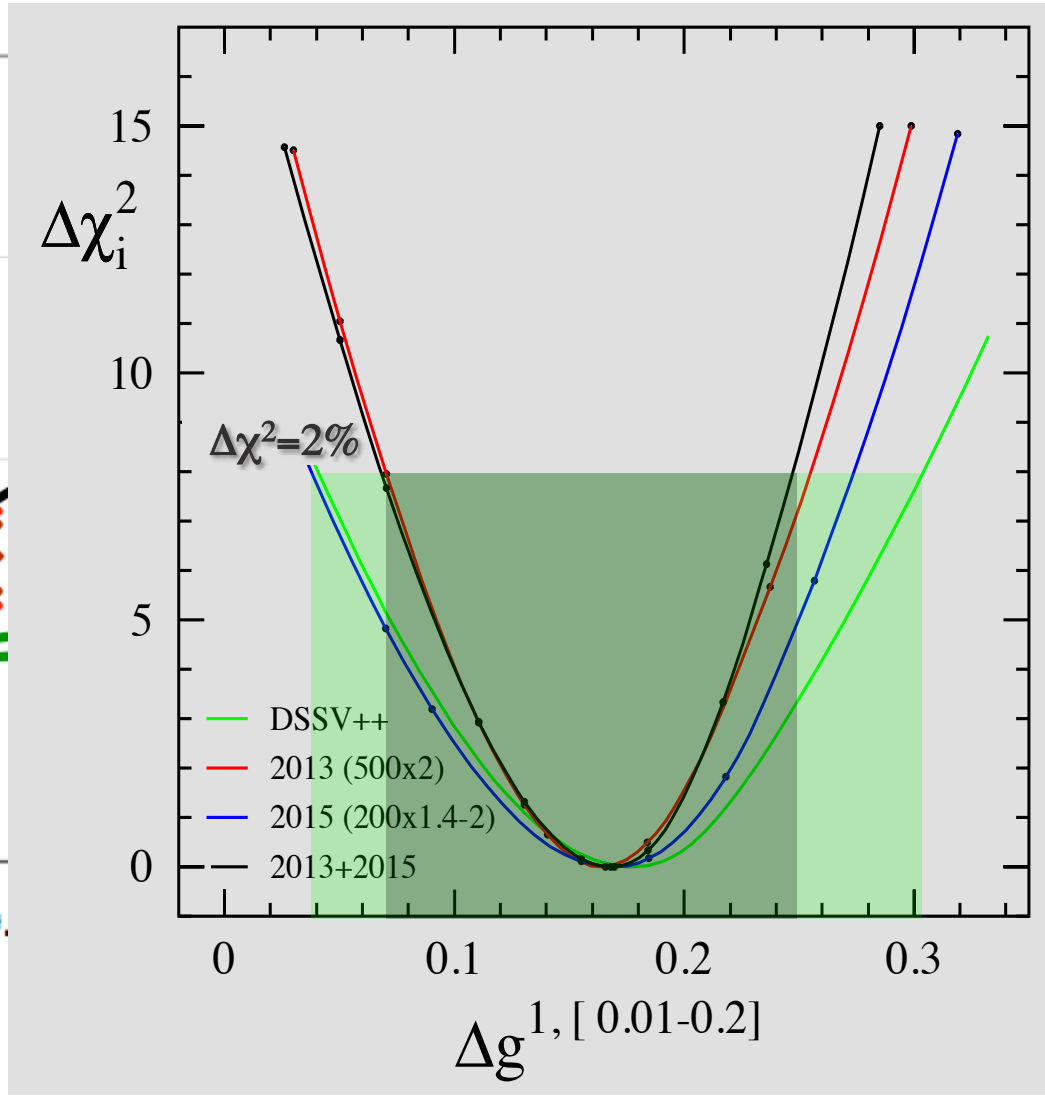
RHIC prospects for ΔG



√s = 500 GeV probes ~2.5 times smaller x_g than √s = 200 GeV,
Systematics... relative luminosity, trigger bias
Evolution-like analyses not likely in the cards.

RHIC prospects for ΔG



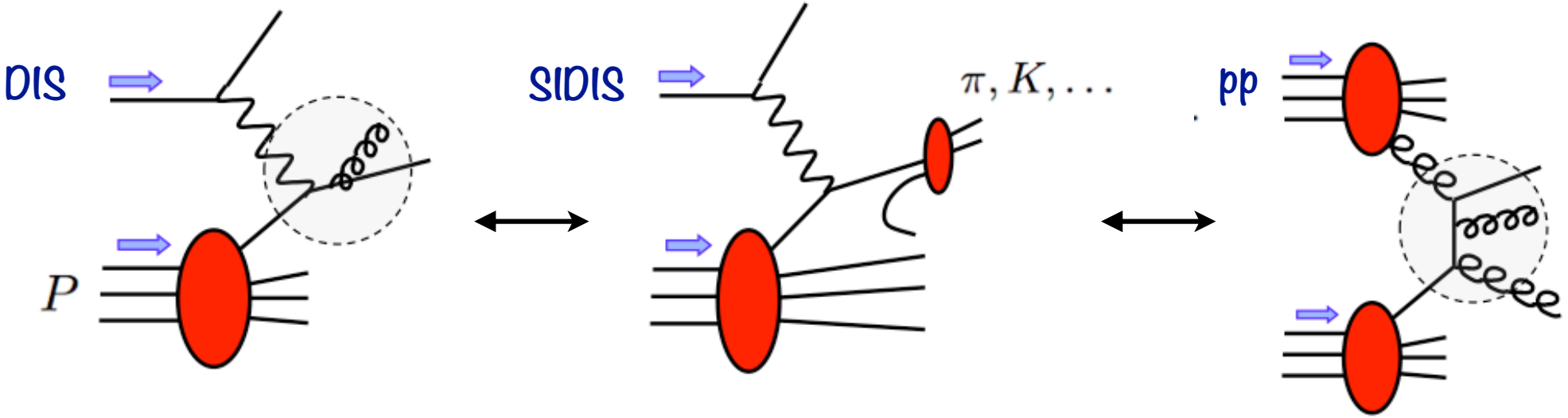


√s = 500 GeV probes ~2.5 times smaller x_g than √s = 200 GeV,

Systematics... relative luminosity, trigger bias

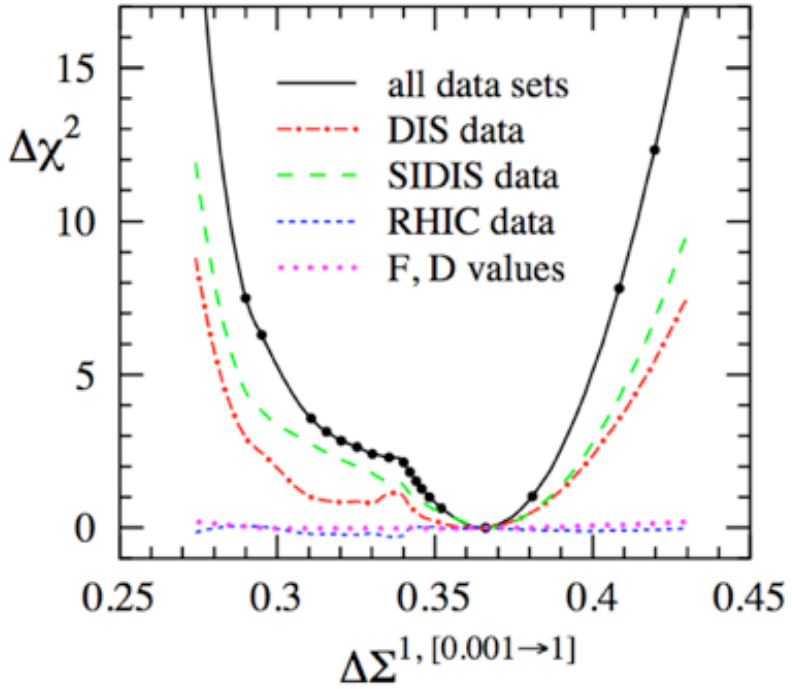
Evolution-like analyses not likely in the cards.

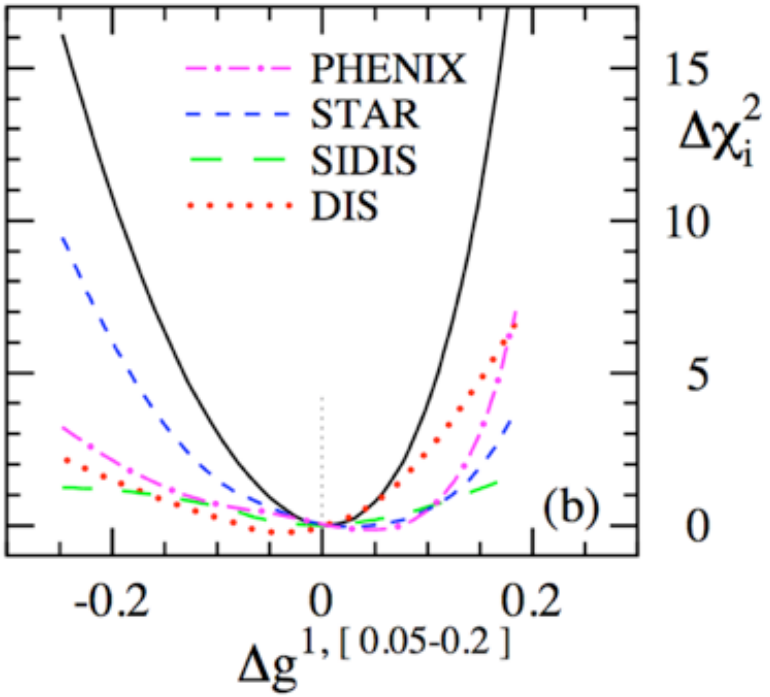
Nucleon Spin

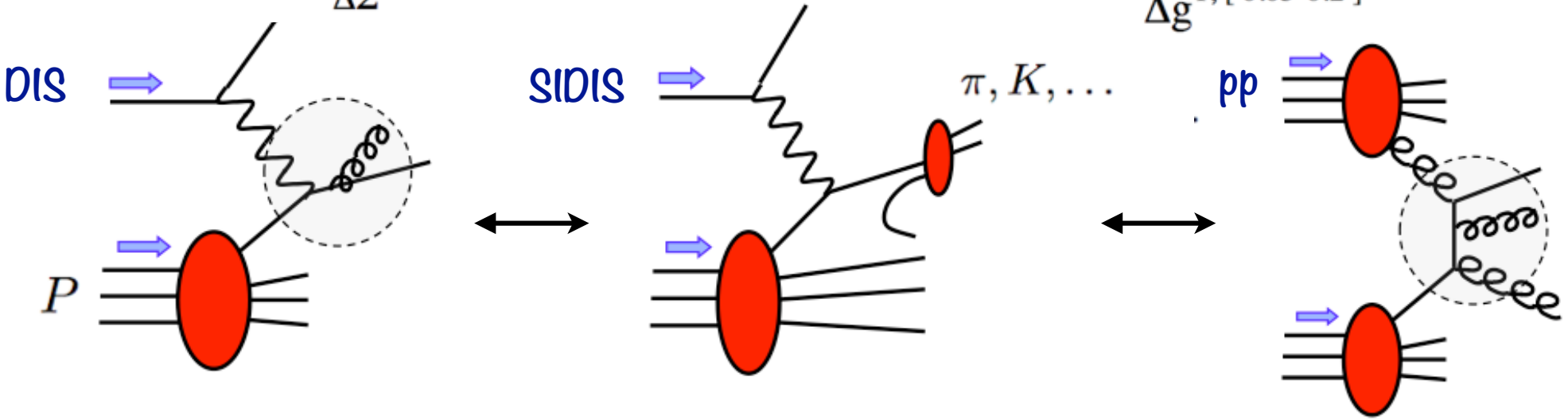


All we know about (anti-)quark polarization ⟷ gluon polarization

Nucleon Spin

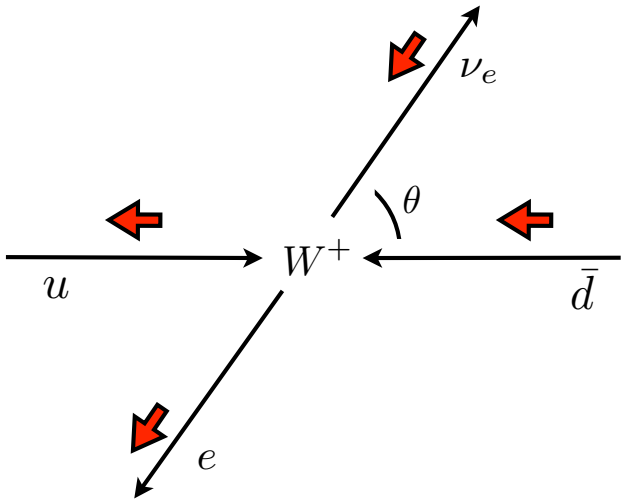






All we know about (anti-)quark polarization ⟷ gluon polarization

Quark Polarization at √s = 500 GeV



√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!

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

Spin Measurements:

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

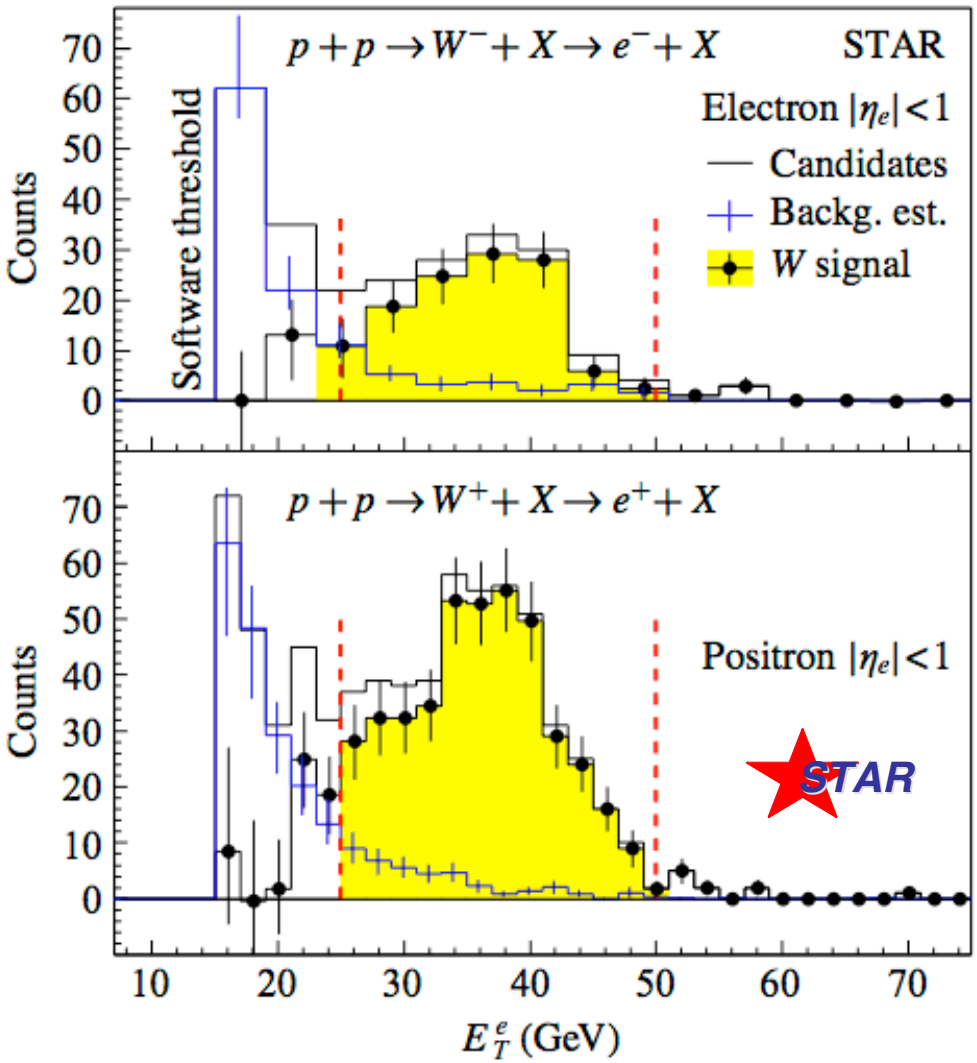
$$A_L(W^-) = \begin{cases} -\dfrac{\Delta d(x_a)}{d(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \to 1 \end{cases}$$

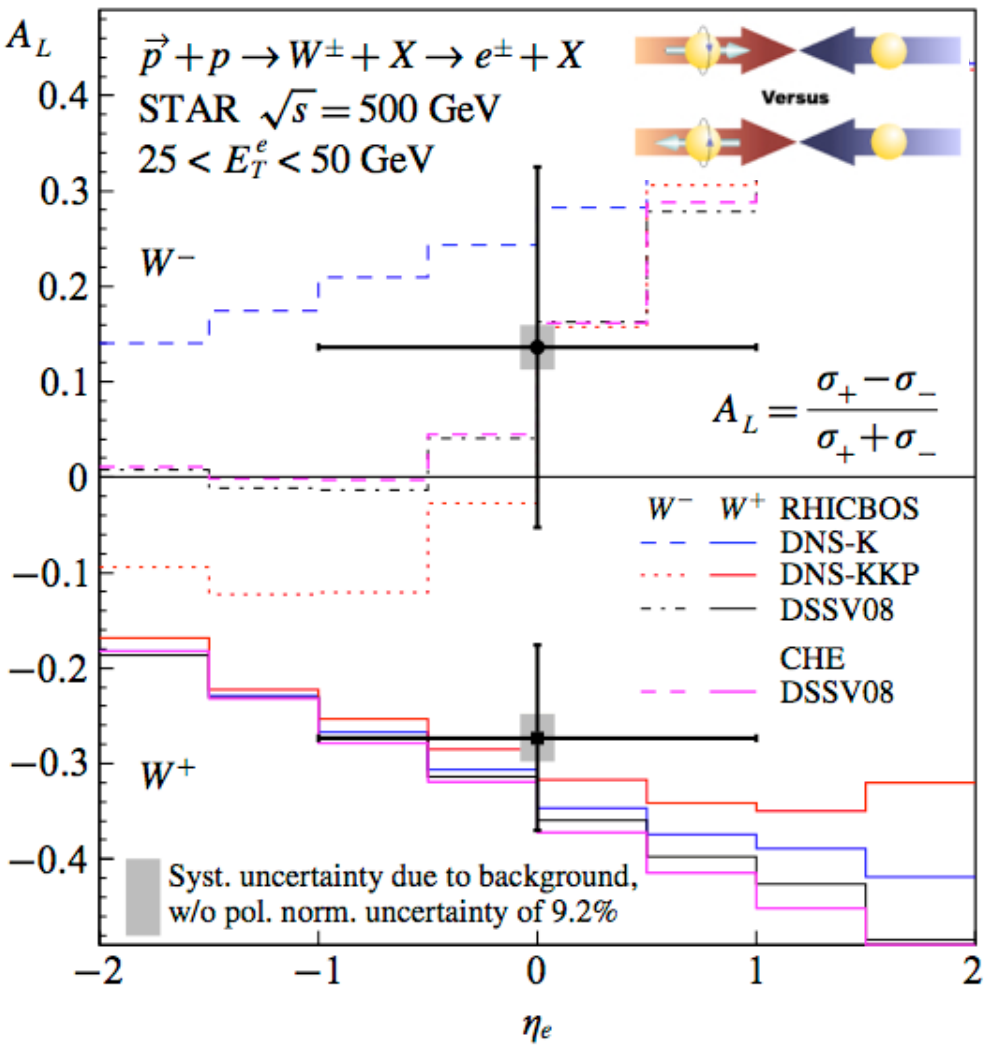
Initial mid-rapidity data in 2009,

Tour-de-force for both experiments at RHIC.

See talk by J. Stevens.

Quark Polarization - leptonic W decay

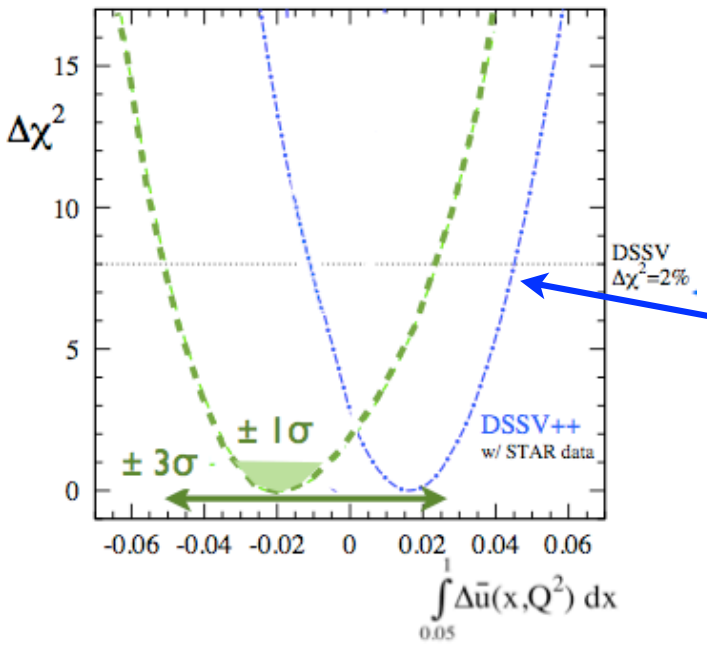


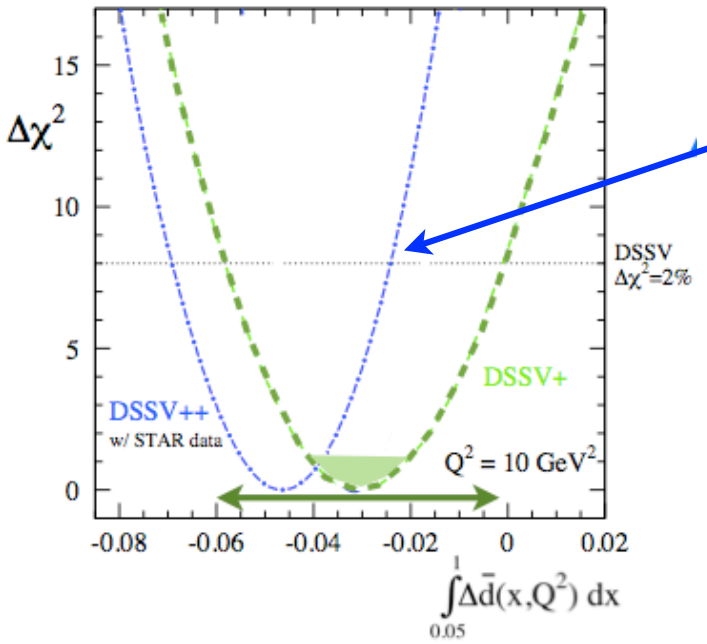


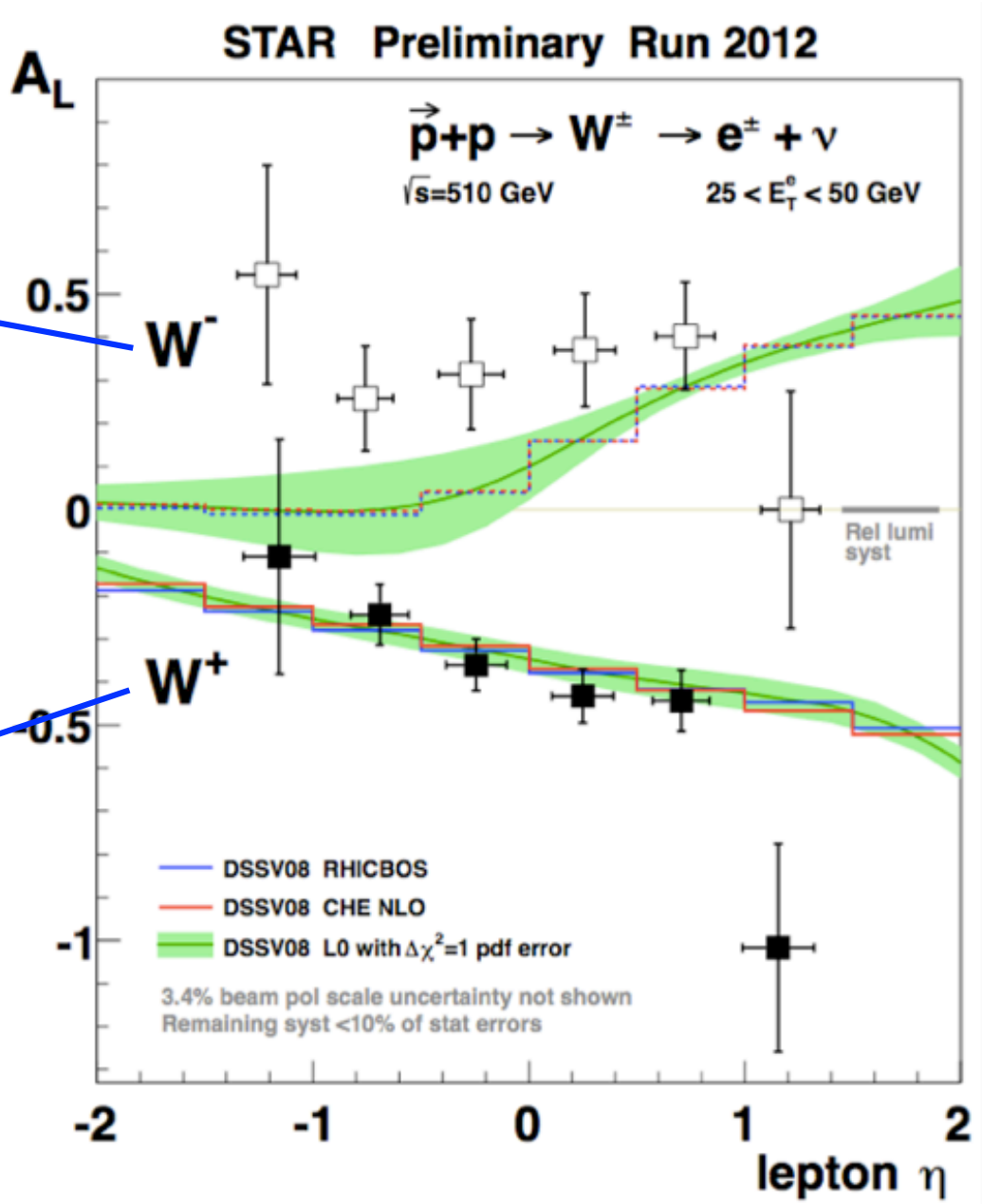
Mid-rapidity yields agree with expectations, 139 W^- and 462 W^+ candidate events in 12 pb^{-1}
First asymmetries consistent with expectations based on quark polarizations.

M.M. Agarwal et al, Phys.Rev.Lett.106:062002,2011

Quark Polarization - Impact

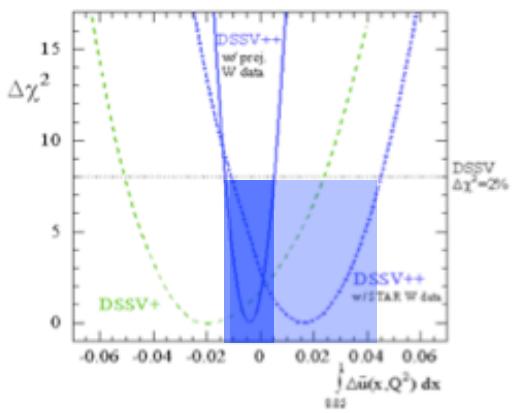


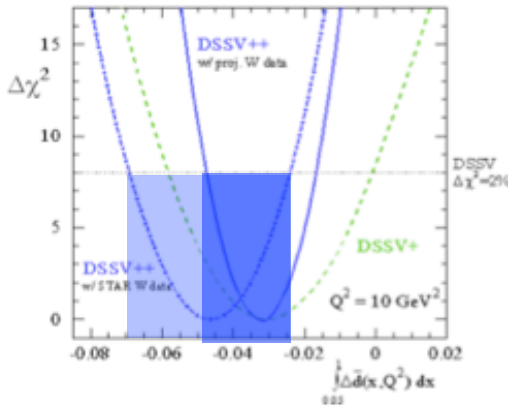


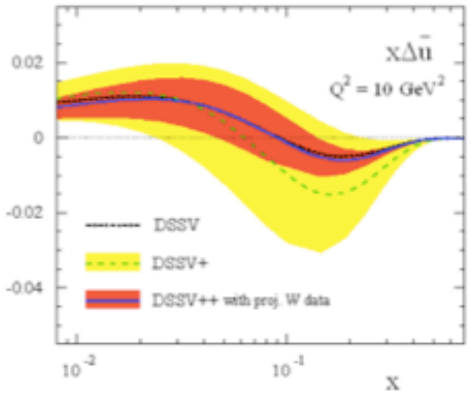


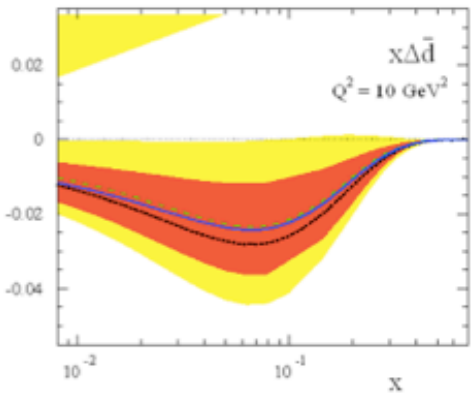
Quark Polarization - Next steps

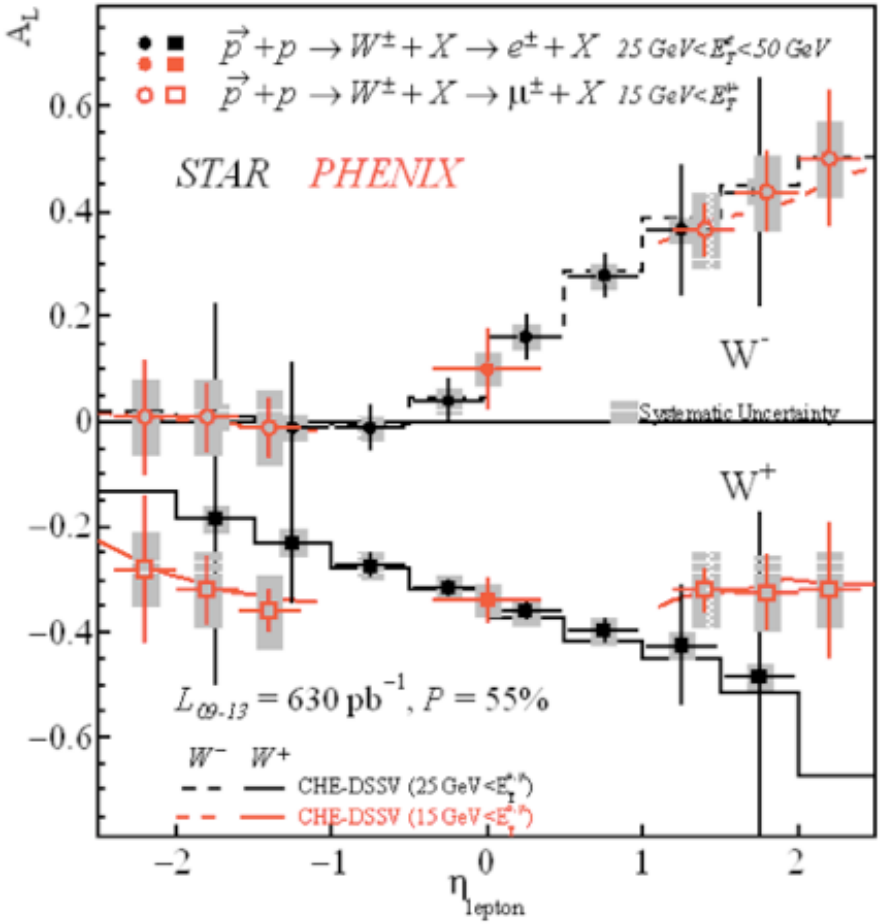
Anticipate 2-3 times better precision from 2013 data.











Quark Polarization - Strange Quarks at RHIC?

Hadronic W decay

Charm associated W production

Hyperon spin transfer?

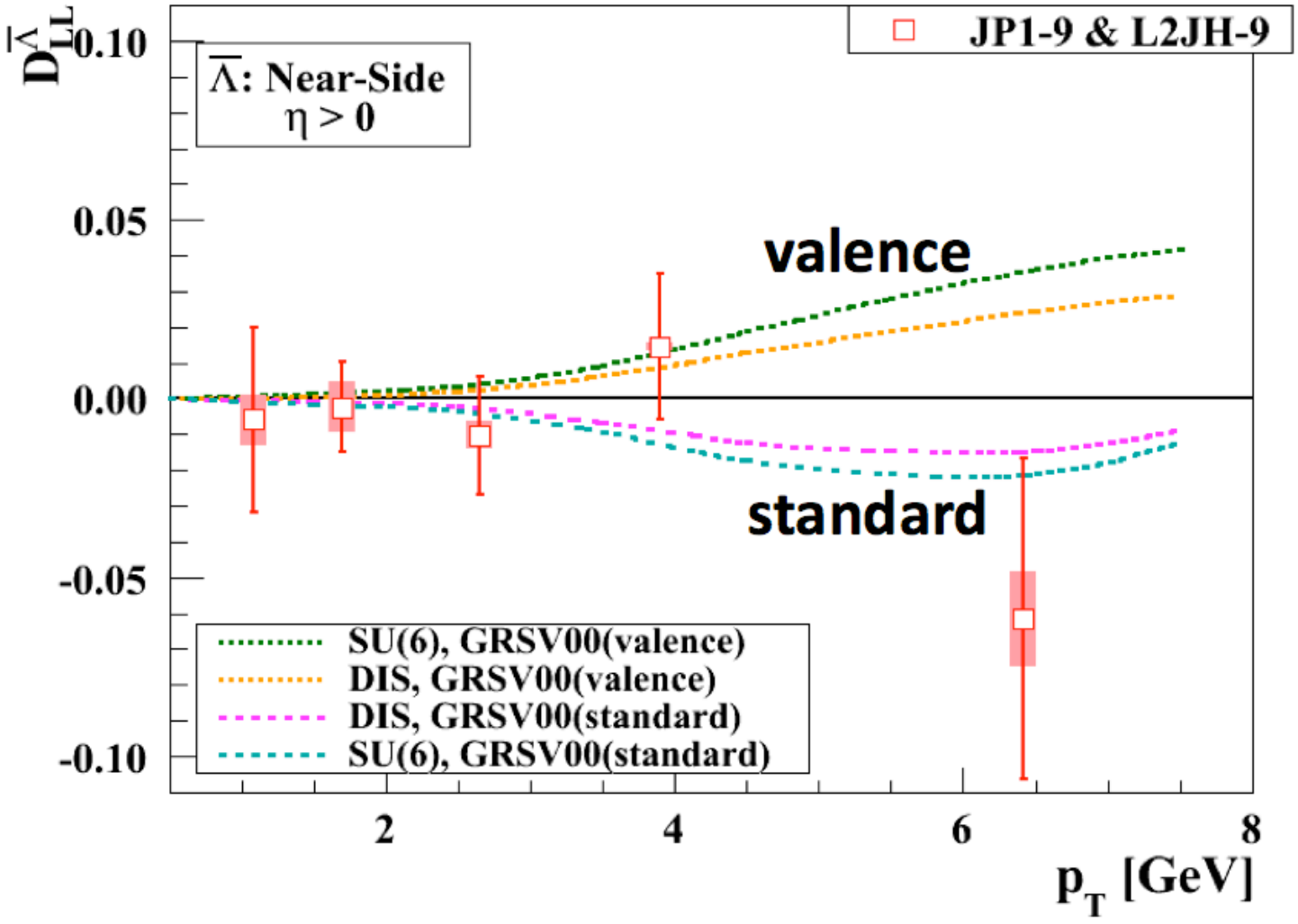
need to tag charm,

luminosity...

at best model dependent

Hyperon Spin Transfer - Status

Ramon Cendejas (UCLA/LBNL), PhD Thesis 2012



Hard...

Closing Remarks

Quark Polarization - precise insight in net polarization of light (anti-)quarks from DIS,
sensitive and fragmentation-free constraints from RHIC W-data,
with more to come

look forward to precision high-*x* data from 12 GeV JLab,

look forward to EIC to address the strange quark conundrum.

Gluon Polarization - *very* significant constraints from inclusive pions and jets at RHIC,

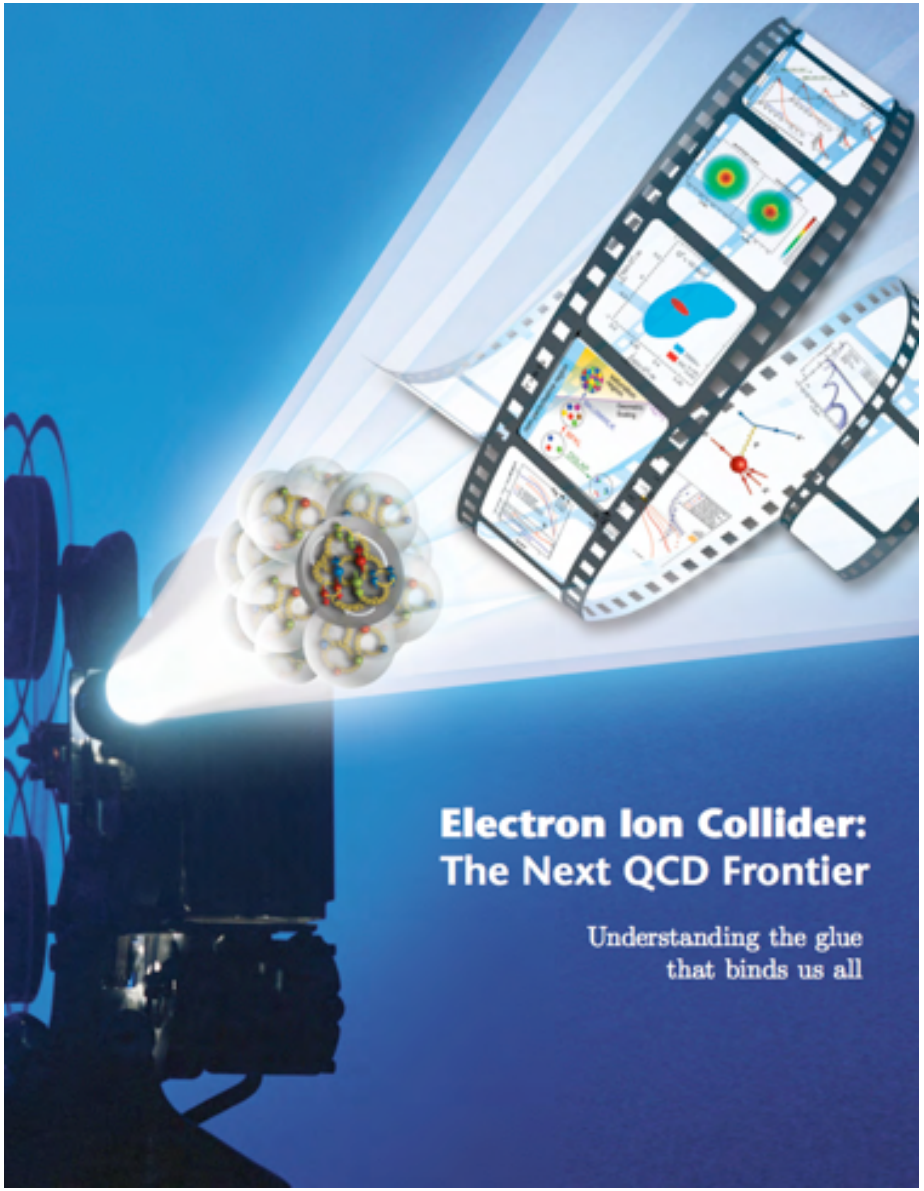
clear evidence for non-zero polarization for $x_{gluon} \sim 0.05 - 0.2$
at the level of ~0.1 at 10 GeV^2

near-term prospects at RHIC for (di-)jets, new forward instruments

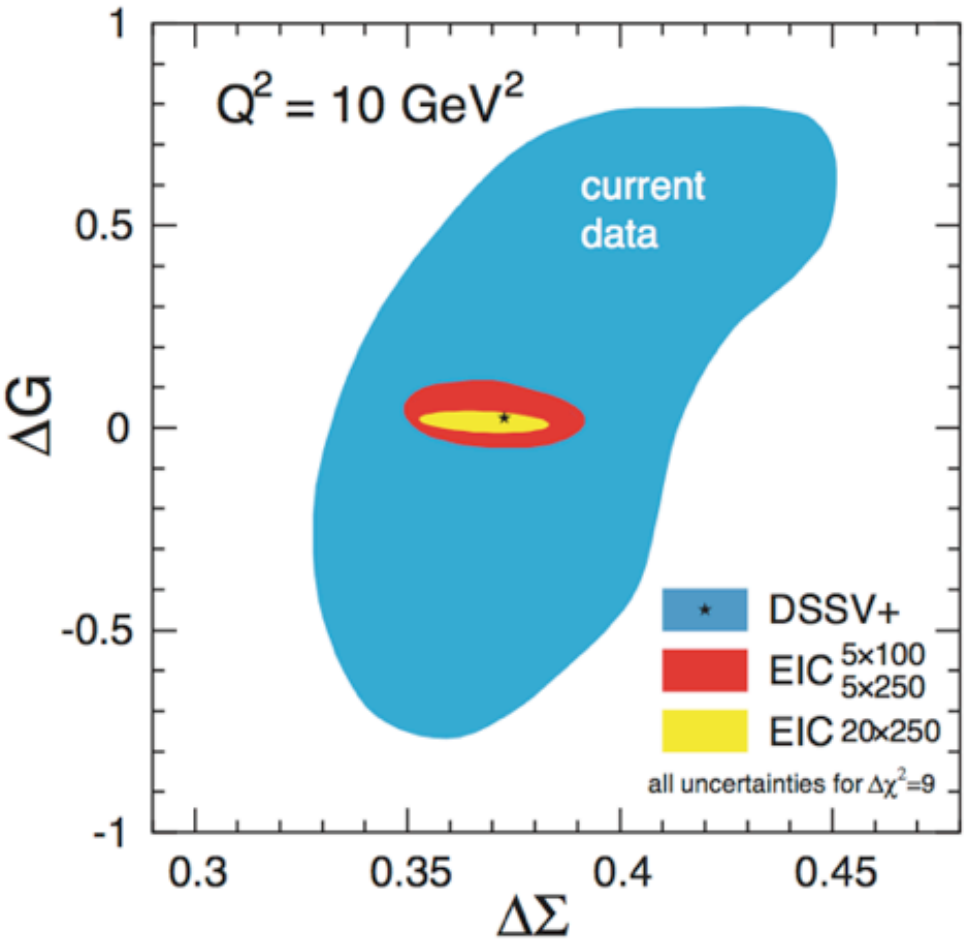
"demands" second-generation measurements at an EIC.

EIC - Science Case

ArXiv:1212.17010



One of the science highlights:



definitive insight in nucleon spin.

Talks by T. Hemmick, T. Ullrich, ...