QCD in Collisions with Polarized Beams

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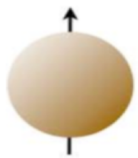
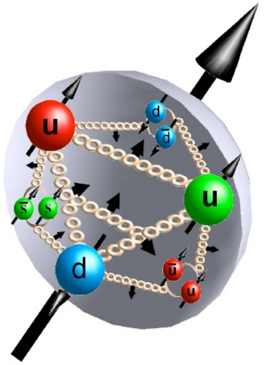
Annual Hua-Da School on QCD: EIC physics
China Central Normal University (CCNU), Wuhan, China, May 23 – June 3, 2016

Summary of lecture five

- **Key for a good proton spin decomposition – sum rule:**



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



  - ✧ Every term can be related to a physical observable with controllable approximation – "independently measurable"

    DIS scheme is ok for F2, but, less effective for other observables

    Additional symmetry constraints, leading to "better" decomposition?

  - ✧ Natural physical interpretation for each term – "hadron structure"

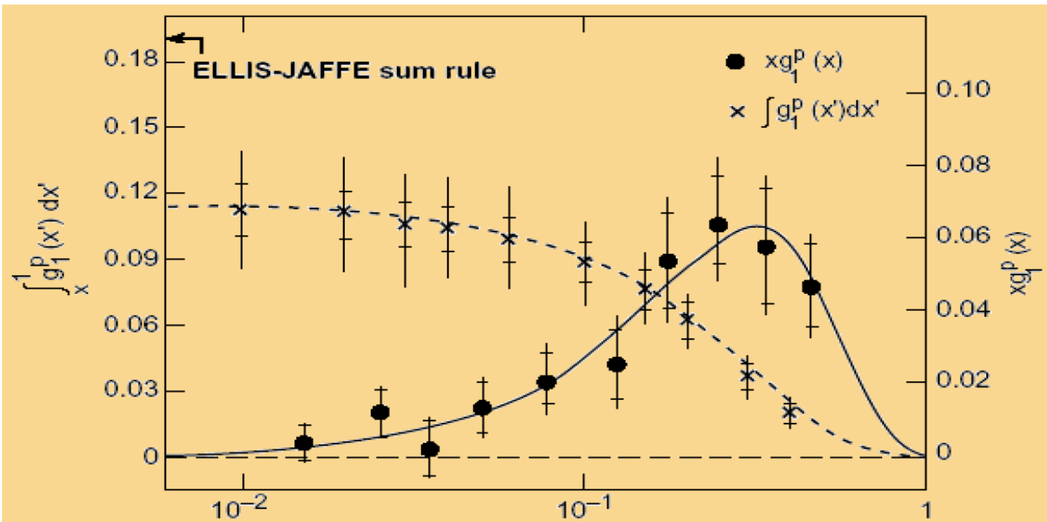
  - ✧ Hopefully, calculable in lattice QCD – "numbers w/o distributions"

- **Since the "spin crisis" in the 80th, we have learned a lot about proton spin – likely, we will need for orbital contribution**

Thank you!

Proton "spin crisis" – excited the field

- ❑ **EMC (European Muon Collaboration '87) – "the Plot":**



$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x) + \Delta\bar{q}(x)\right] + \mathcal{O}(\alpha_s) + \mathcal{O}\left(1/Q\right)$$

✧ **Combined with earlier SLAC data:** $\int_0^1 g_1^p(x)dx = 0.126 \pm 0.018$

✧ **Combined with:** $g_A^3 = \Delta u - \Delta d$ **and** $g_A^8 = \Delta u + \Delta d - 2\Delta s$

from low energy neutron & hyperon β decay

➡ $$\Delta\Sigma = \sum_q \left[\Delta q + \Delta\bar{q}\right] = 0.12 \pm 0.17$$

- ❑ **"Spin crisis" or puzzle:**

✧ **Strange sea polarization is sizable & negative**

✧ **Very little of the proton spin is carried by quarks**

➡ ***New era of spin physics***

Proton spin decomposition

- ❑ **The "big" question:**

  If there are infinite possibilities, why bother and what do we learn?

- ❑ **The "origin" of the difficulty/confusion:**

  QCD is a gauge theory: a pure quark field in one gauge is a superposition of quarks and gluons in another gauge

- ❑ **The fact:**

  None of the items in all spin decompositions are direct physical observables, unlike cross sections, asymmetries, …

- ❑ **Ambiguity in interpretation – two old examples:**

  ✧ **Factorization scheme:**

$$F_2(x,Q^2) = \sum_{q,\bar{q}} C_q^{\rm DIS}(x,Q^2/\mu^2) \otimes q^{\rm DIS}(x,\mu^2)$$

No glue contribution to F_2?

  ✧ **Anomaly contribution to longitudinal polarization:**

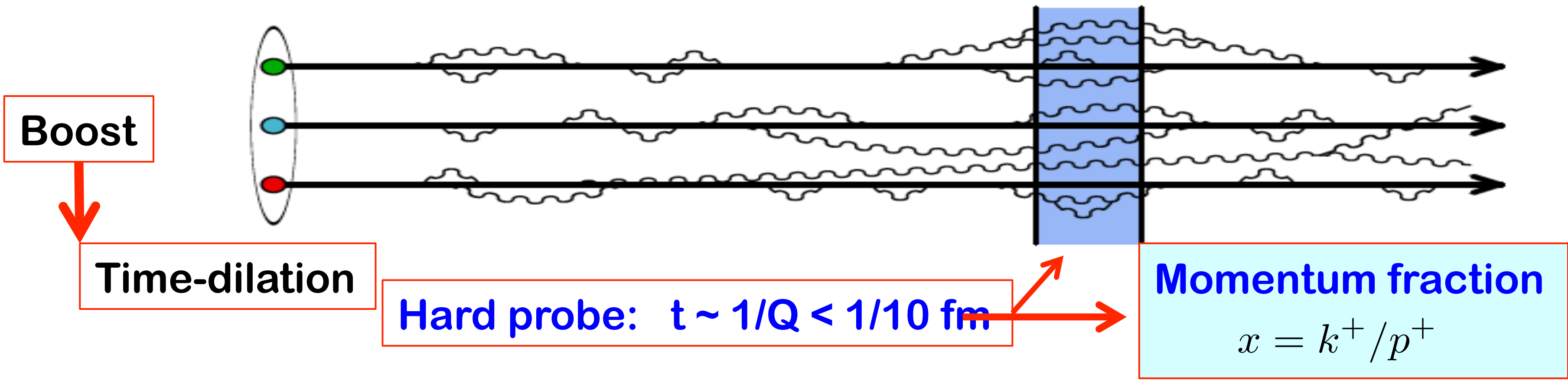
$$g_1(x,Q^2) = \sum_{q,\bar{q}} \widetilde{C}_q^{\rm ANO} \otimes \Delta q^{\rm ANO} + \widetilde{C}_g^{\rm ANO} \otimes \Delta G^{\rm ANO}$$

$$\Rightarrow \quad \Delta\Sigma \longrightarrow \Delta\Sigma^{\rm ANO} - \frac{n_f \alpha_s}{2\pi} \Delta G^{\rm ANO}$$

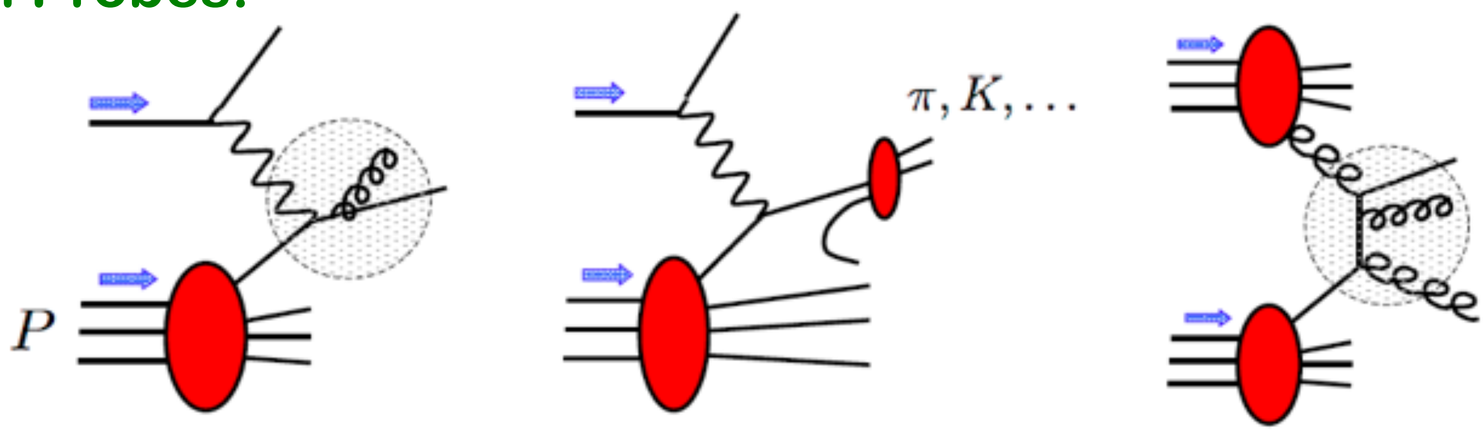
Larger quark helicity?

Probes and facilities

❑ High energy scattering – to see quarks and gluons:



❑ Spin Probes:



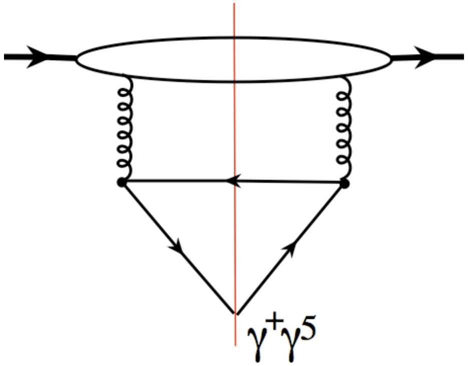
DIS **SIDIS** **Hadron-hadron**

HEMES, COMPASS, JLab, Future EIC, … RHIC, FermiLab, JPAC, …

Earlier "solution" to the "crisis"

- **Large ΔG to cancel the "true" Δq:**

$$\Delta q = \int_0^1 dx \Delta q(x) = \langle P, s_{\parallel} | \overline{\psi}_q(0) \gamma^+ \gamma_5 \psi_q(0) | P, s_{\parallel} \rangle$$



$$\Rightarrow \quad \Delta\Sigma \rightarrow \Delta\Sigma - \frac{n_f \alpha_s(Q^2)}{2\pi} \Delta G(Q^2)$$

- **What value of ΔG is needed?**

$$\Delta G(Q^2) \sim 2$$ **at Q ~ 1 GeV**

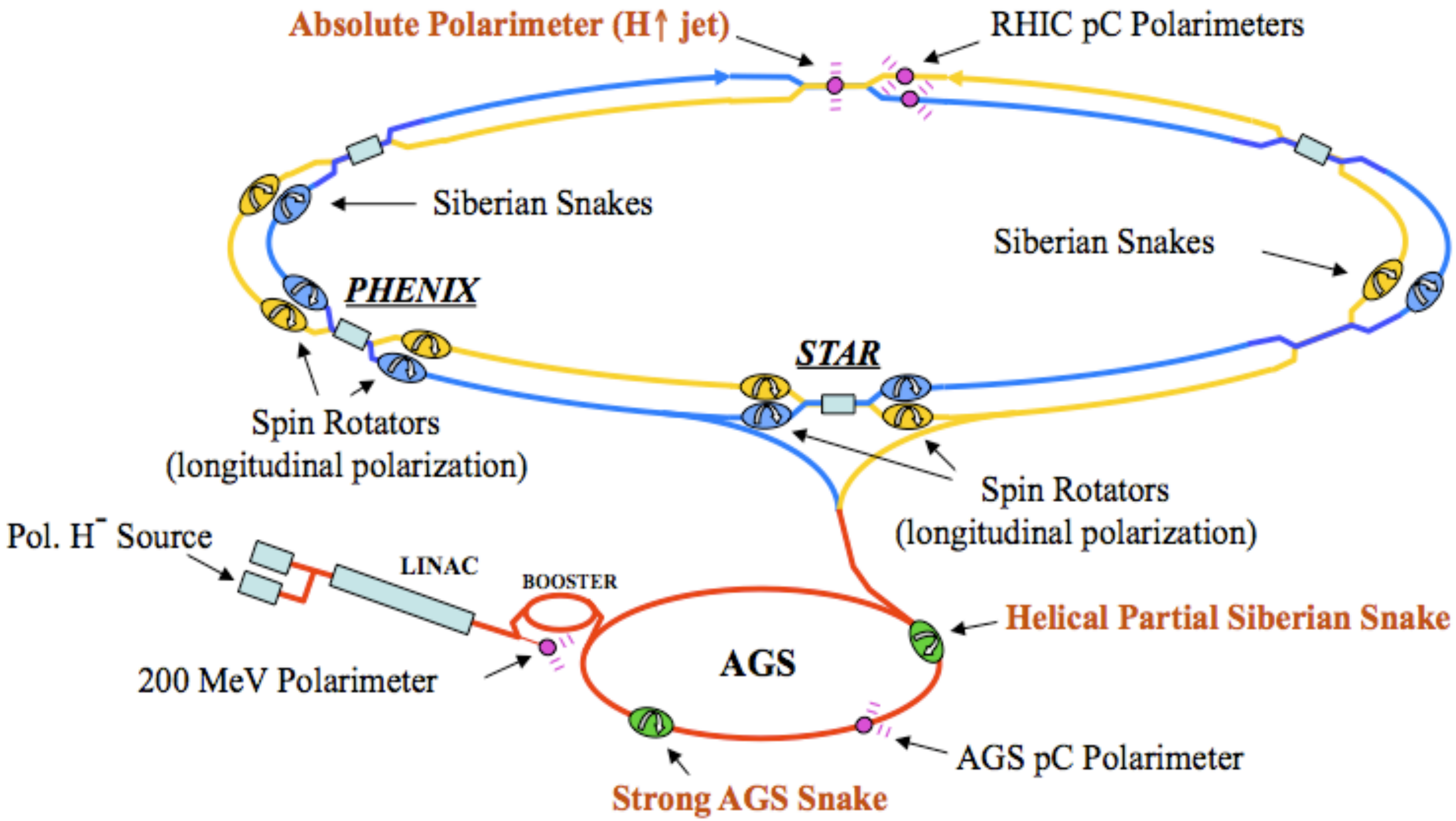
- **Question: How to measure ΔG independently?**

  - ✧ **Precision inclusive DIS**
  - ✧ **Jets in SIDIS**
  - ✧ **Hadronic collisions – RHIC spin, …**

Lead to the first goal of RHIC spin program

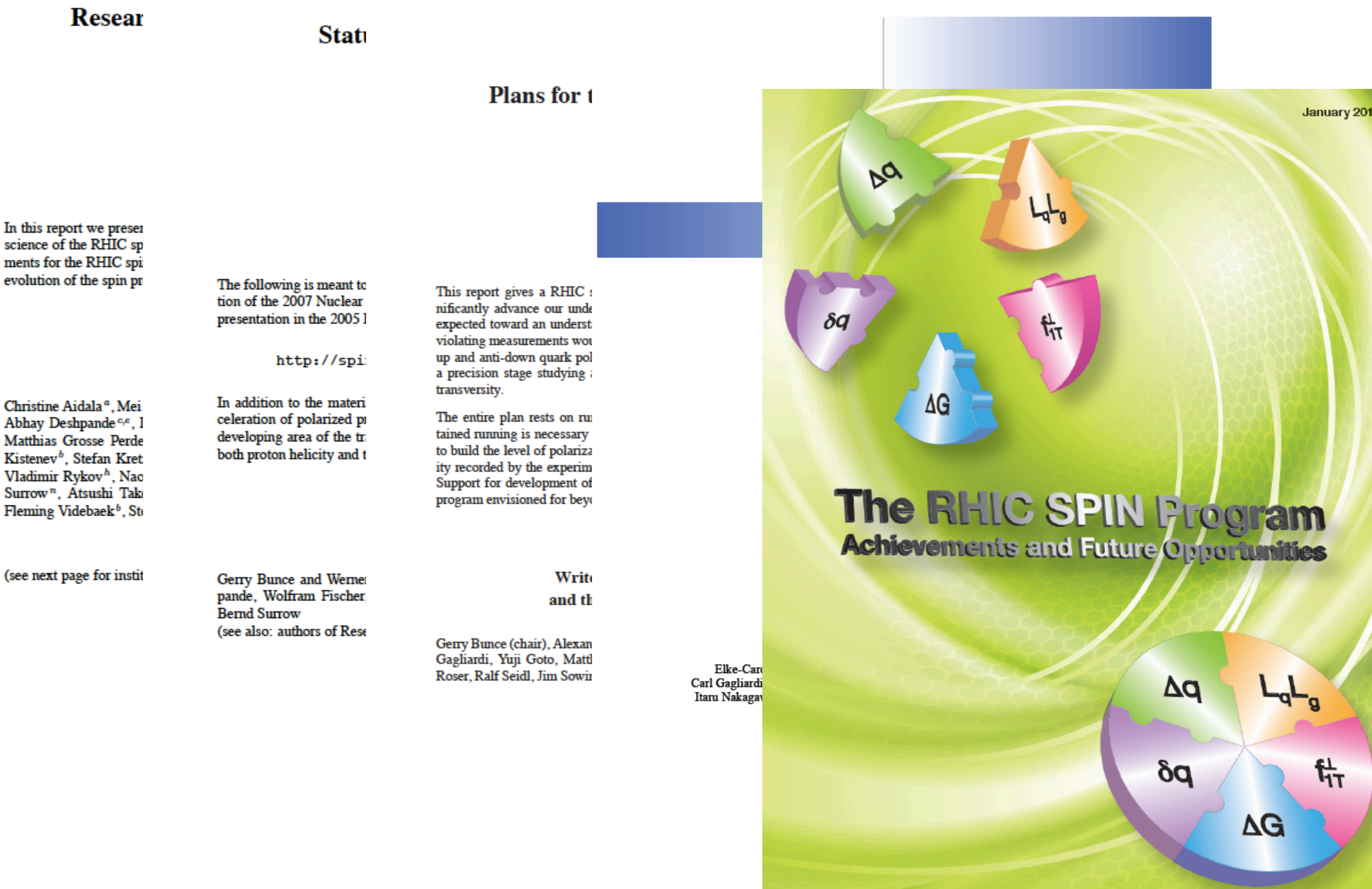
RHIC spin program

- The machine:



Collider of two 100 GeV (250 GeV) polarized proton beams

RHIC spin program



Goals of RHIC spin program

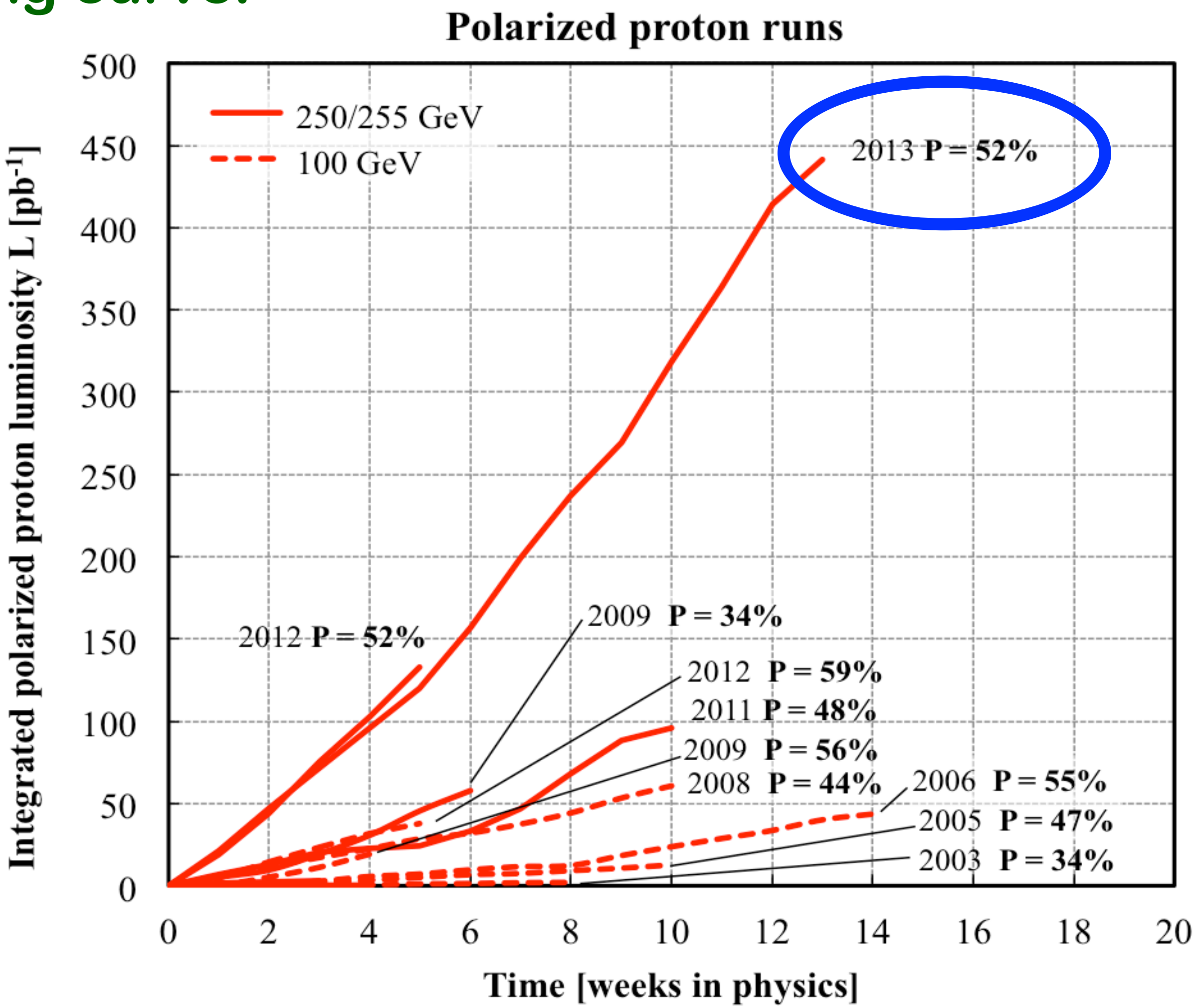
- Determination of polarized gluon distribution (ΔG) over a large range of momentum fraction x, using multiple probes

- Determination of flavor identified quark and anti-quark polarization using parity violating production of $W^{\pm}$

- Transverse spin phenomena in QCD:
  transversity (δq), parton orbital angular momentum (L_q), and etc.

What has RHIC delivered?

- ❑ Learning curve:



- ❑ Maturity and discovery:

What a year of 2013!

RHIC Measurements on ΔG

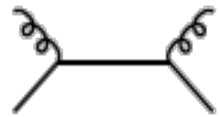
- Physical channels sensitive to ΔG:

$\vec{p} + \vec{p} \to \pi + X$

$\vec{p} + \vec{p} \to \text{jet} + X$

$\vec{g}\vec{g} \to gg$

$\vec{q}\vec{g} \to qg$



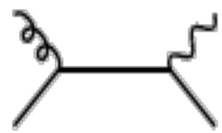
Pion or jet production

high rates

$\vec{p} + \vec{p} \to \gamma + X$

$\vec{p} + \vec{p} \to \gamma + \text{jet} + X$

$\vec{q}\vec{g} \to \gamma q$



Direct photon production

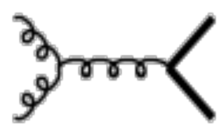
low rates

$\vec{p} + \vec{p} \to D + X$

$\vec{p} + \vec{p} \to B + X$

$\vec{g}\vec{g} \to c\bar{c}$

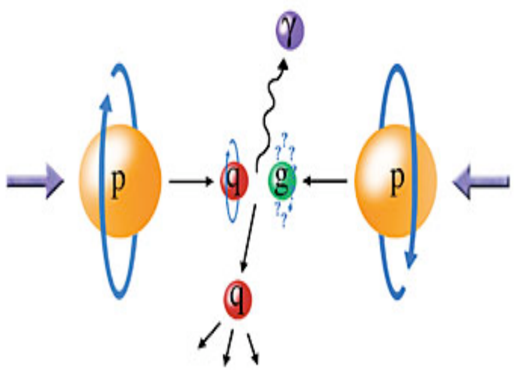
$\vec{g}\vec{g} \to b\bar{b}$



Heavy-flavour production

separated vertex detection required

- Collinear QCD factorization:

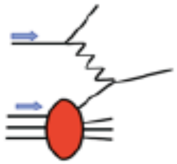
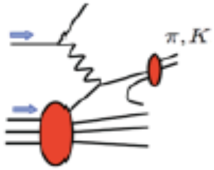
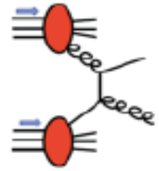


Experiments measure cross sections,
And asymmetries, not helicity distributions!

QCD global analyses to extract the best helicity districutions at NLO, to calculate helicity contribution to proton spin

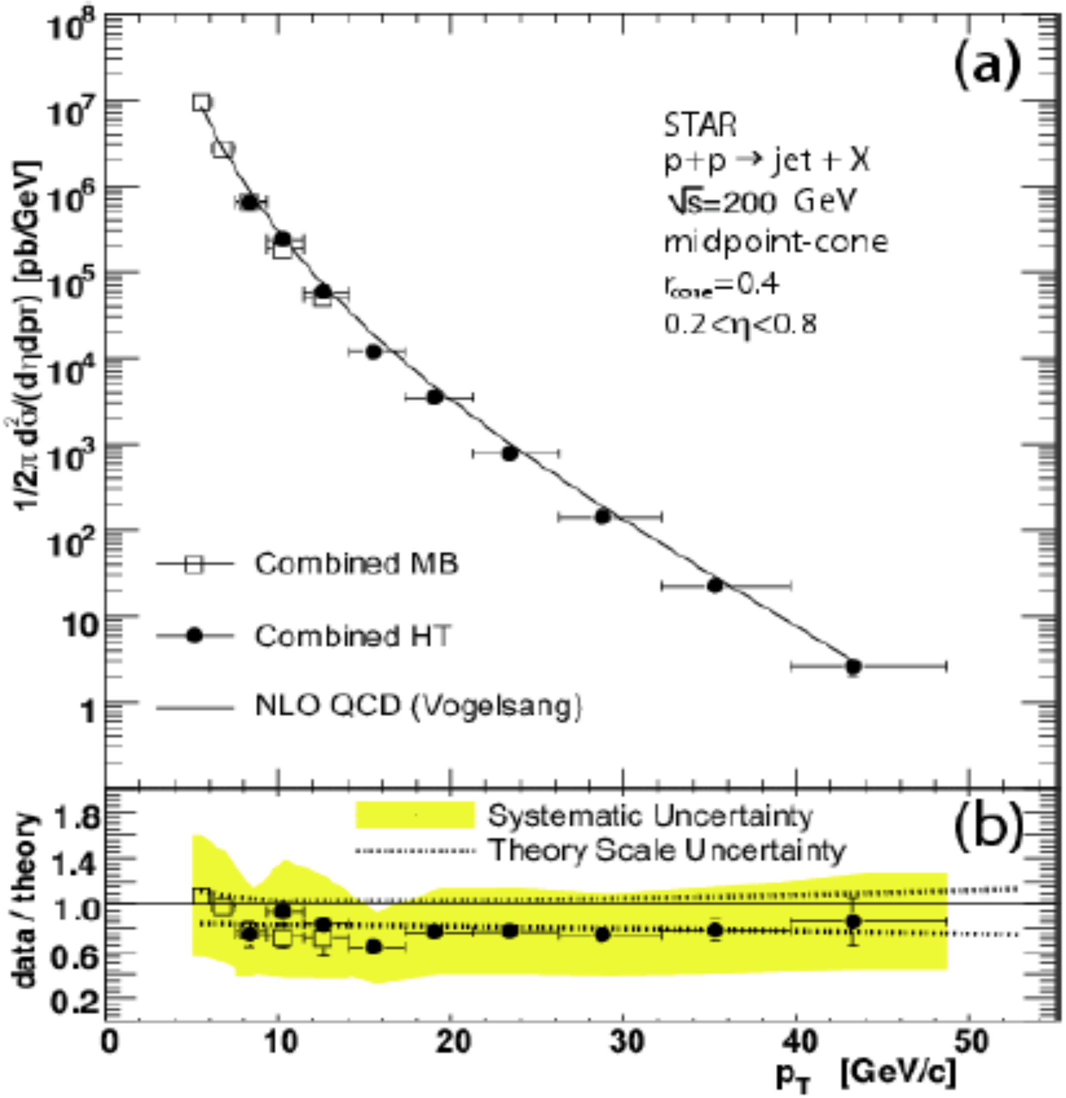
Global fits for helicity PDFs @ NLO

Stratmann's talk
@BNL Users

				uncertainties	last update
NNPDF Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo	✓	✗	✗	100 replicas stat. approach	1303.7236
DSSV de Florian, Sassot, MS, Vogelsang	✓	✓	✓	L.M. $\Delta\chi^2 = 8$ (1) (Hessian $\Delta\chi^2 = 1$)	0904.3821 [DSSV+/++: 1112.0904 1304.0079]
LSS Leader, Sidorov, Stamenov	✓	✓	✗	Hessian $\Delta\chi^2 = 1$	1010.0574
BB Blumlein, Bottcher	✓	✗	✗	Hessian $\Delta\chi^2 = 1$	1010.3113
⋮		⋮			⋮
GRSV Gluck, Reya, MS, Vogelsang	✓	✗	✗	✗	1st NLO analysis 9508347
JAM PoS DIS2013 (2013) 208	✓	✗	✗	TMC, HT, …	Accardi's talk on Tue

Inclusive jet at 200 GeV

- **STAR:**

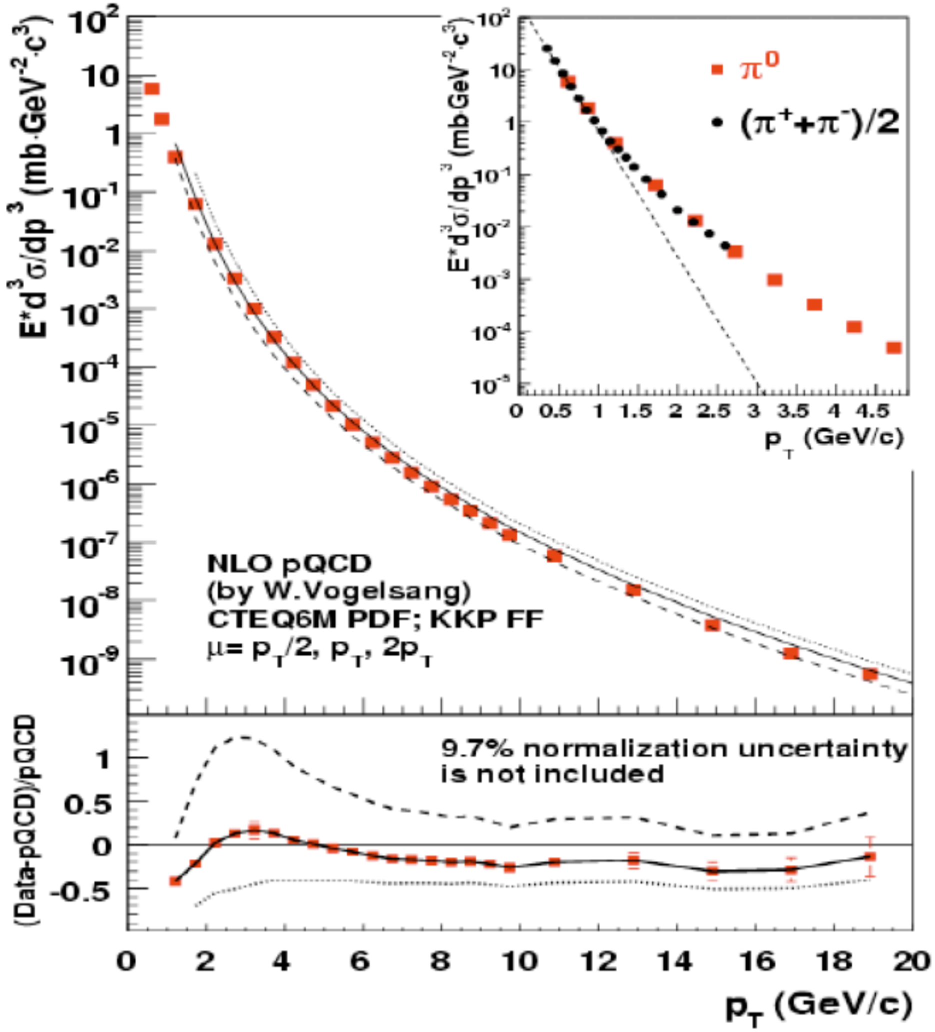


PRL97, 252001 (2006)

QCD factorization/calculation works at RHIC energies!

Inclusive single hadron at 200 GeV

- PHENIX:



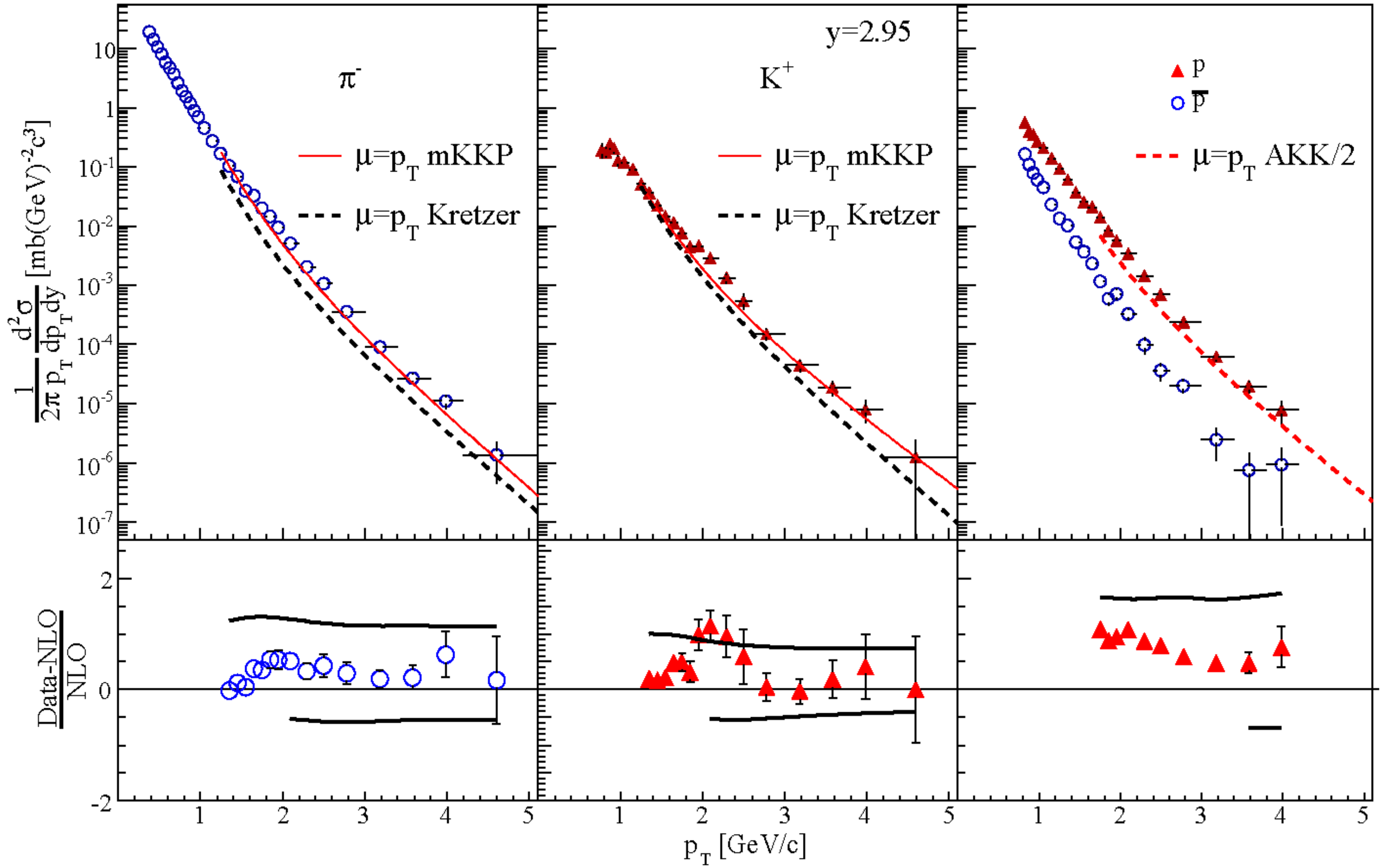
PRD76, 051106 (2007)

QCD factorization/calculation works at RHIC energies!

Extend x coverage and particle type

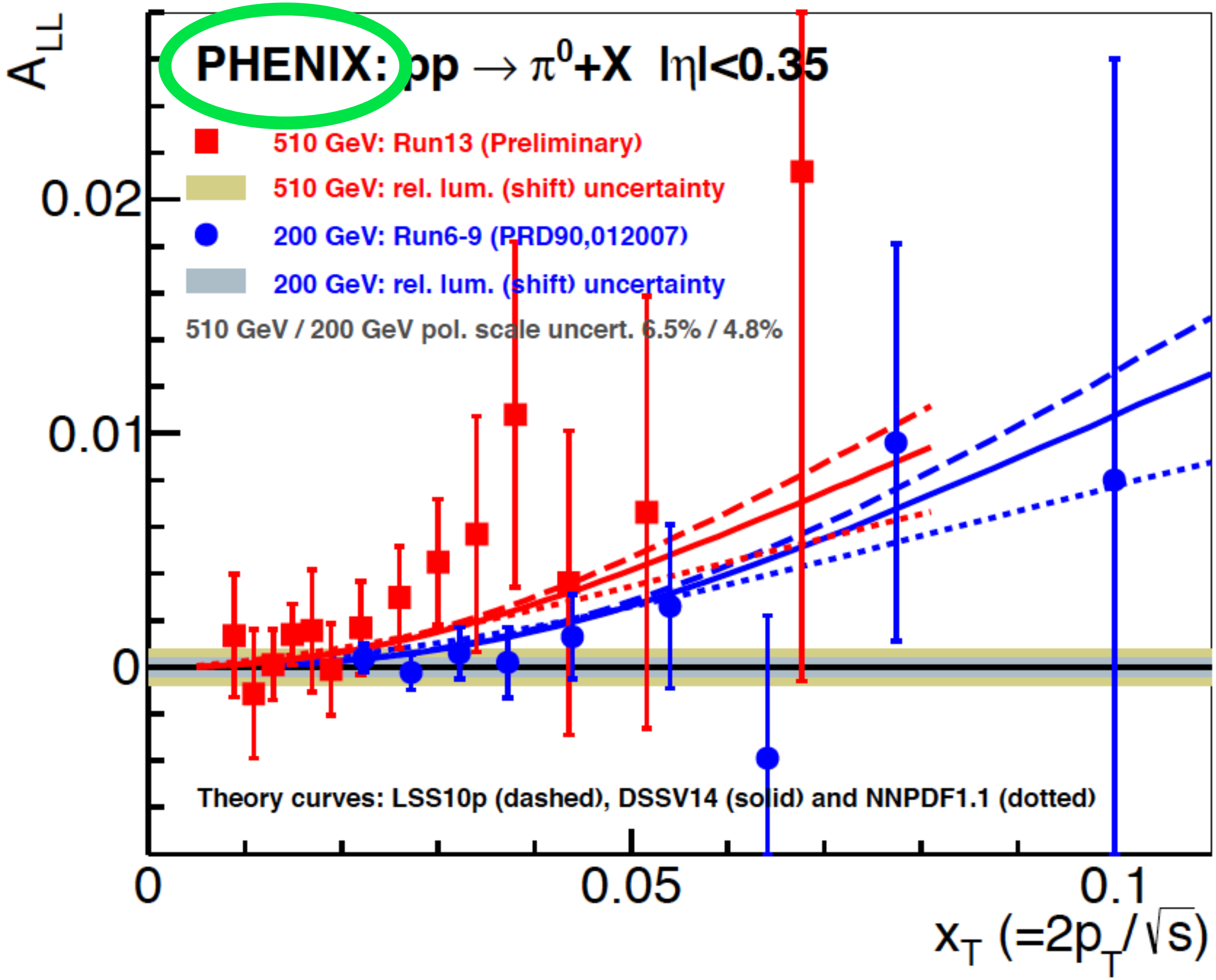
- BRAHMS: Large rapidity p,K,p cross sections for p+p, √s=200 GeV

PRL98, 252001 (2007)

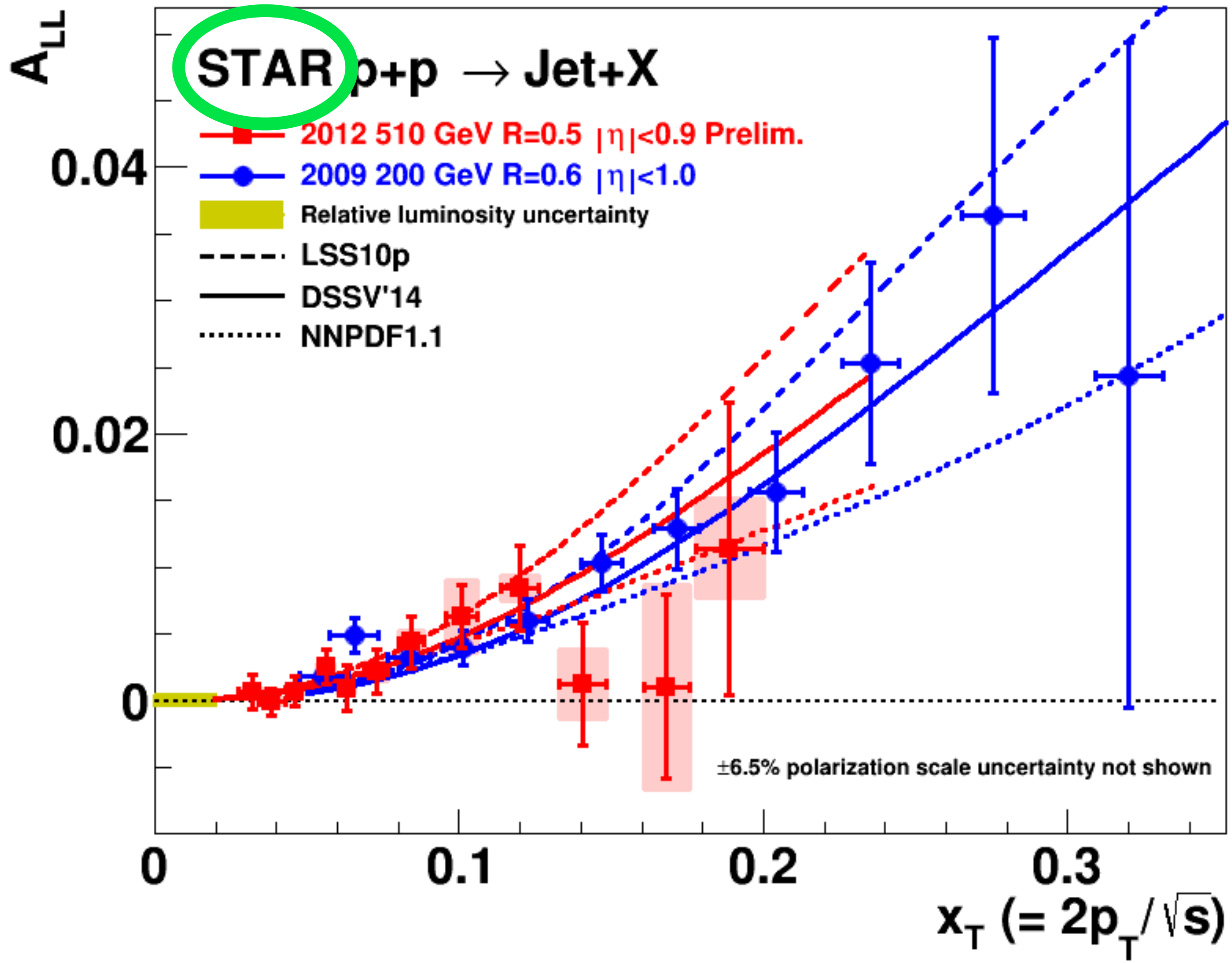


QCD factorization/calculation works at RHIC energies!

RHIC Measurements on ΔG

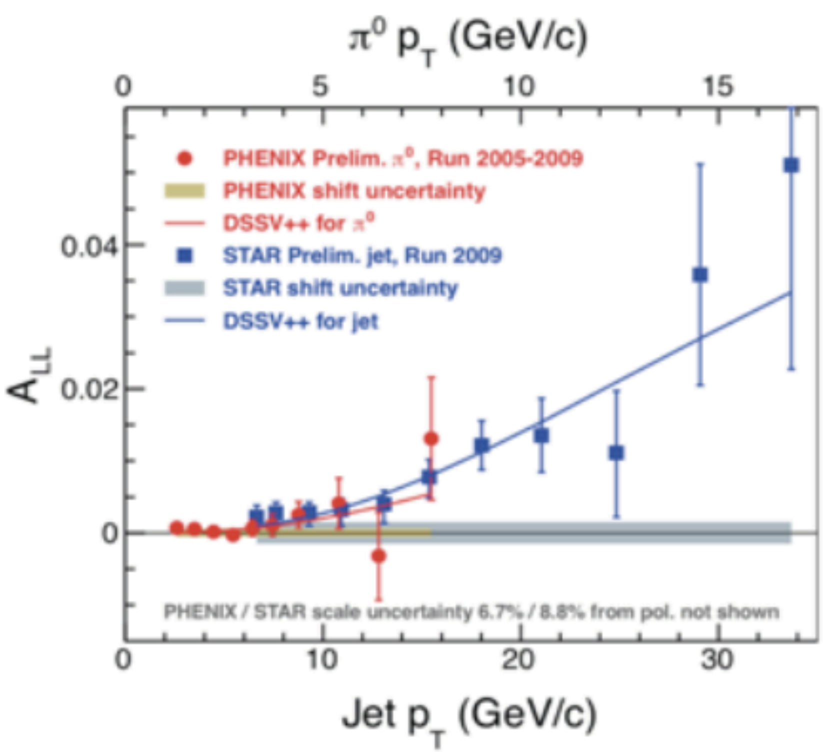


RHIC Measurements on ΔG

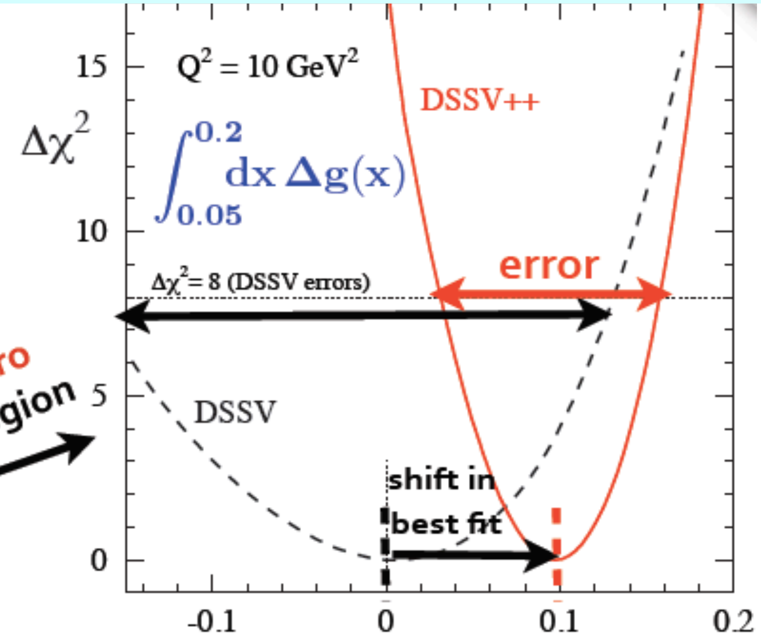


Impact of RHIC measurements

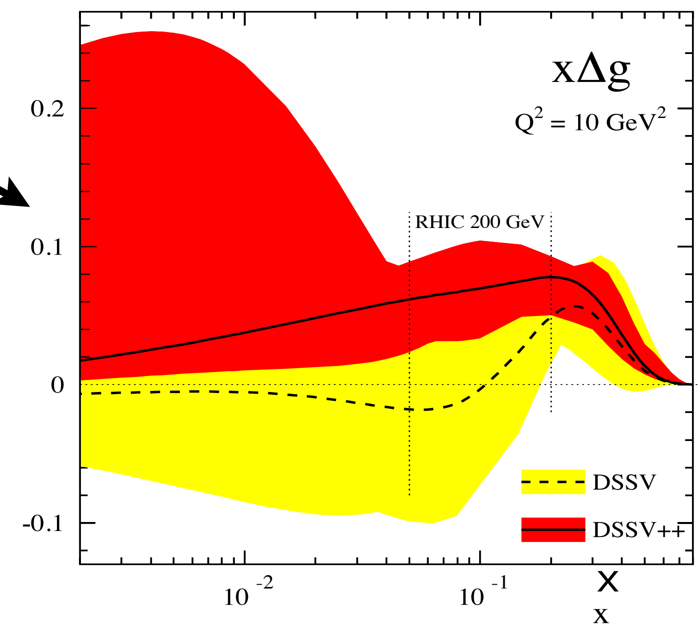
new RHIC data included in DSSV++



lead to non-zero Δg in RHIC x-region



positive Δg in RHIC x-region

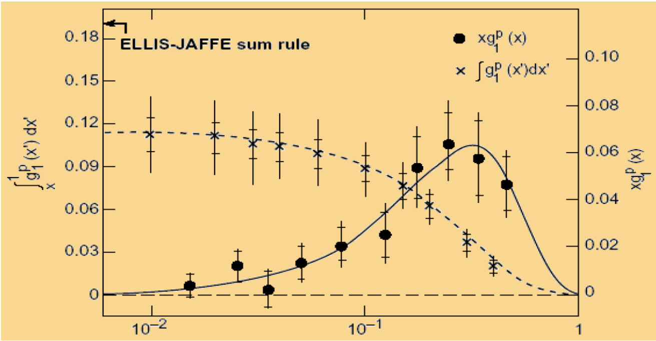


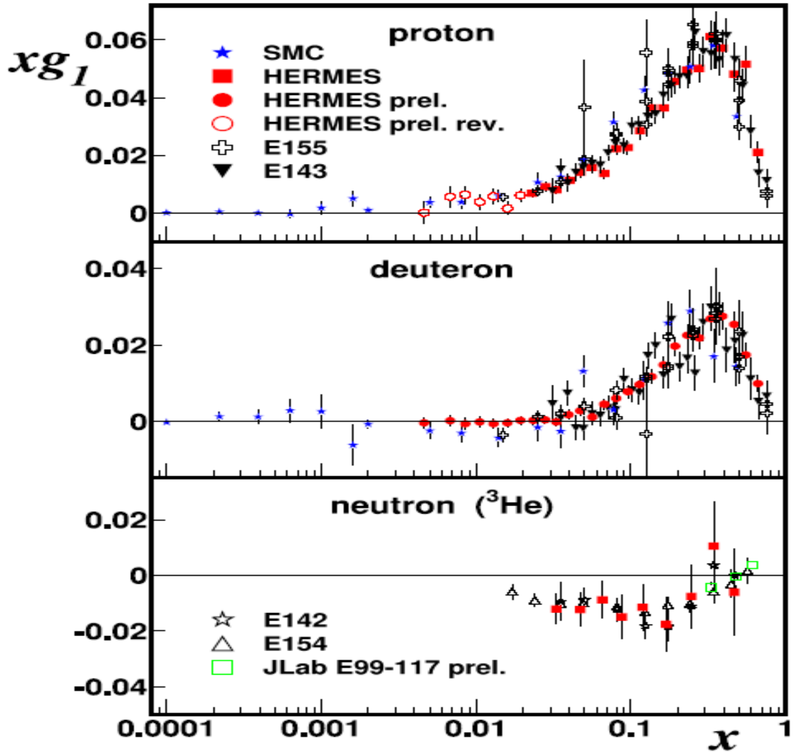
$$\int_{0.05}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2) = 0.1^{+0.06}_{-0.07}$$

fully compatible with old DSSV error estimate

Inclusive DIS data

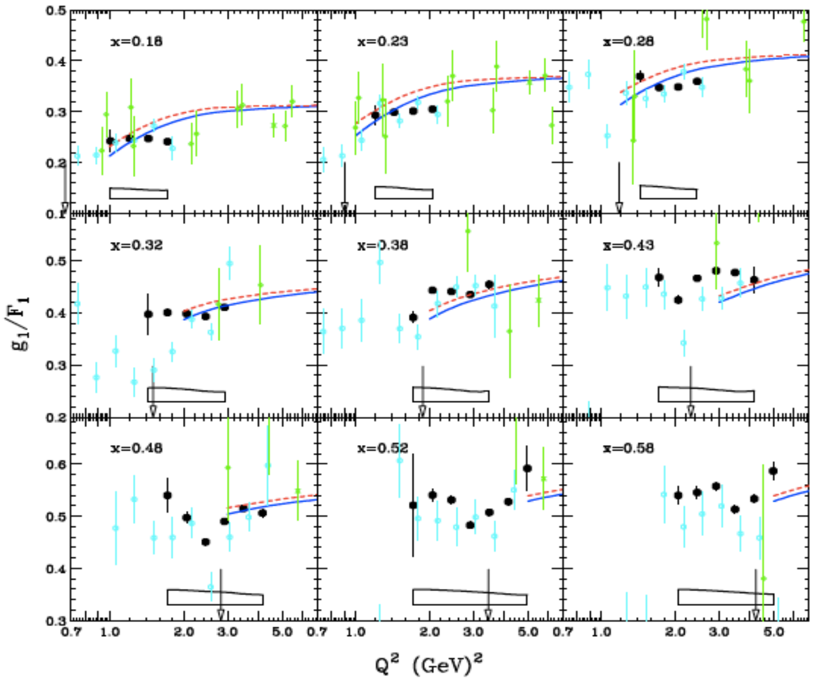
- ❑ The "Plot" is greatly improved:



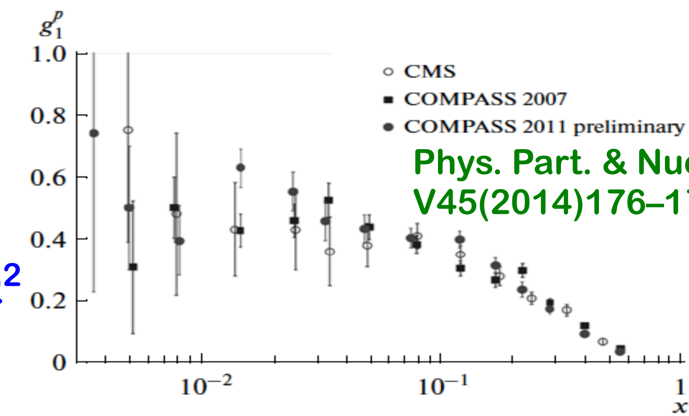


JLab/CLAS

arXiv:1404.6231



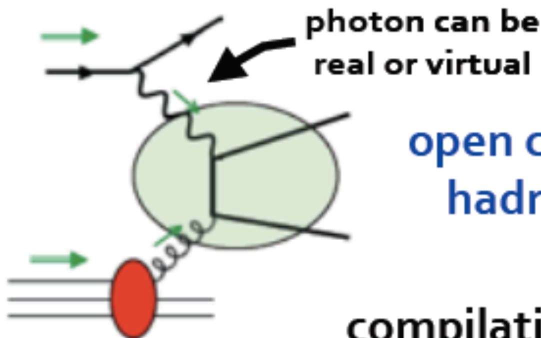
Lower Q^2 HT's



Phys. Part. & Nucl, V45(2014)176–178

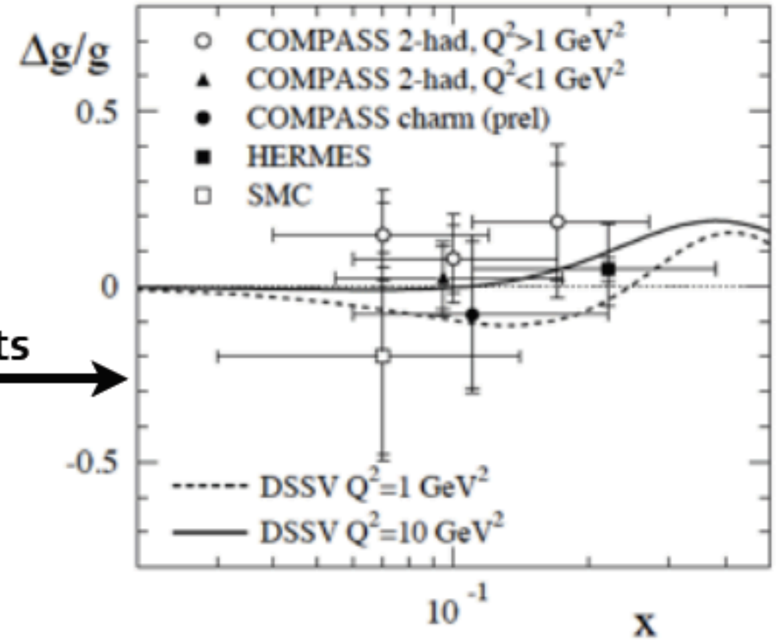
Role of DIS measurements

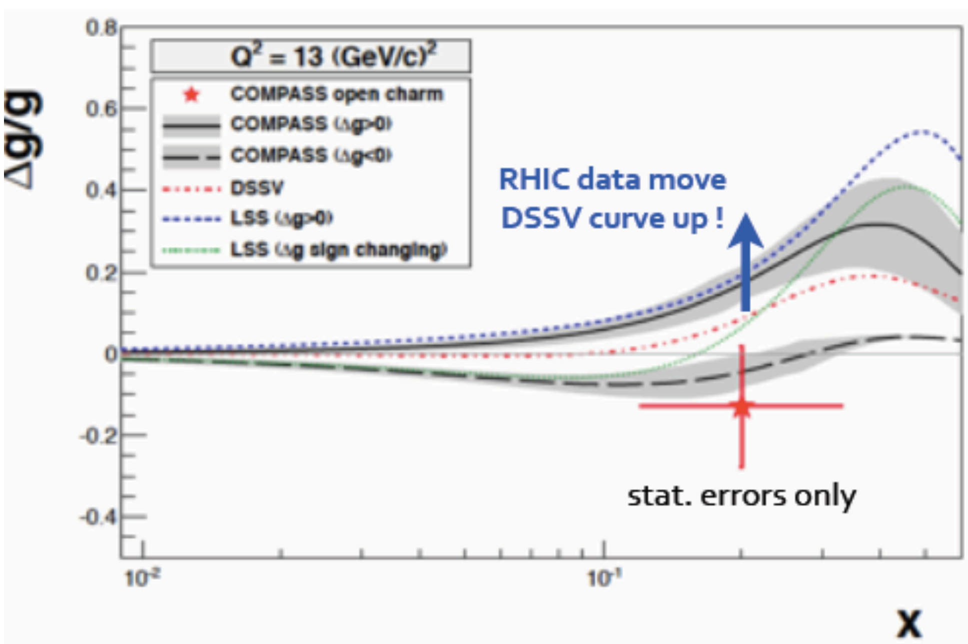
idea: processes with (dominant) contributions from γg-fusion



open charm
hadrons

compilation of existing results





new result

1211.6849

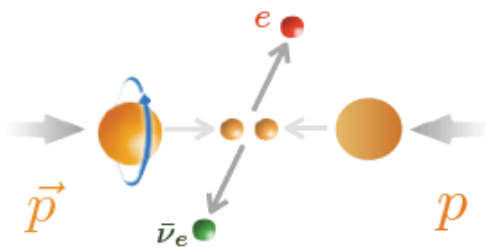
$$\langle \frac{\Delta g}{g} \rangle = -0.13 \pm 0.15 \pm 0.15$$

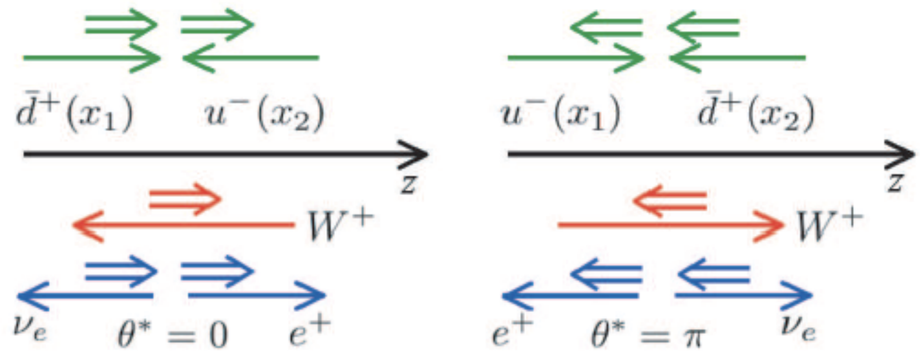
$$\langle x \rangle = 0.2 \quad \langle \mu^2 \rangle = 13\,\mathrm{GeV}^2$$

from some "hybrid MC/NLO" extraction

Determination of Δq and $\Delta \bar{q}$

- ❑ **W's are left-handed:**





- ❑ **Flavor separation:**

Lowest order:

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta \bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

Forward W⁺ (backward e⁺):

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)}{u(x_1)} < 0$$

Backward W⁺ (forward e⁺):

$$A_L^{W^+} \approx -\frac{\Delta \bar{d}(x_2)}{\bar{d}(x_2)} < 0$$

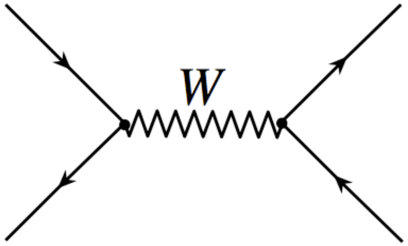
- ❑ **Complications:**

High order, W's p_T-distribution at low p_T

High order effect

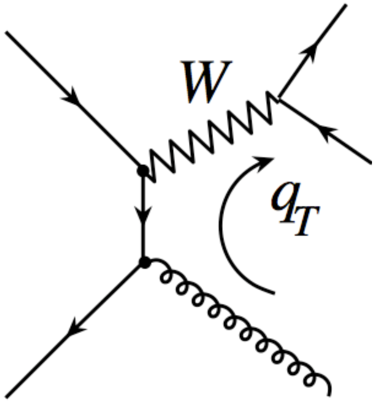
❑ Fixed order pQCD calculation:

LO:



$$\propto \delta^2(q_T)$$

NLO:

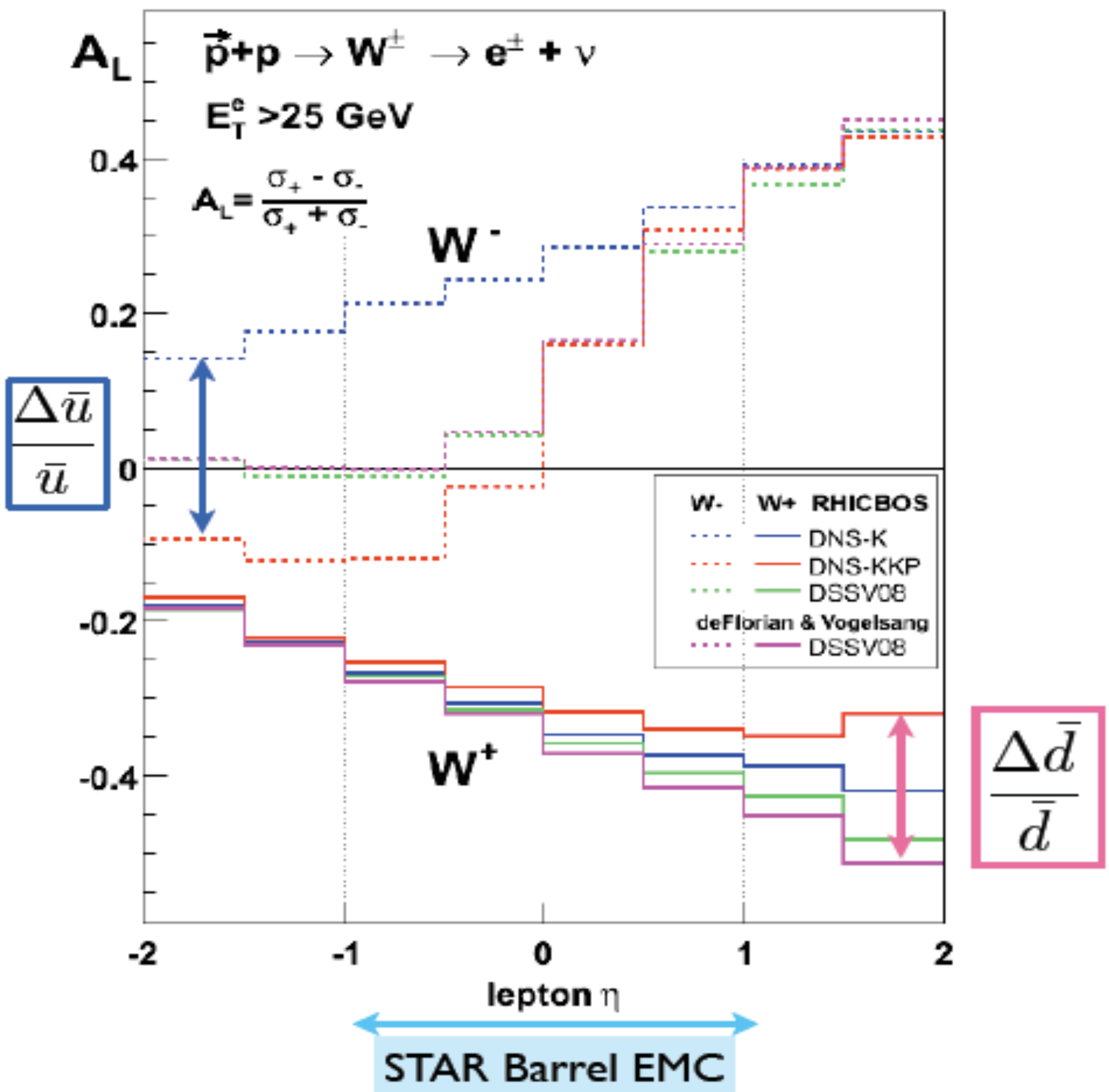


$$\propto \frac{1}{q_T^2} \quad \Rightarrow \infty \quad \text{as} \quad q_T^2 \to 0$$

❑ All order resummation is needed at low p_T:

CSS formalism – implemented in RHICBOS

Predicted W asymmetry

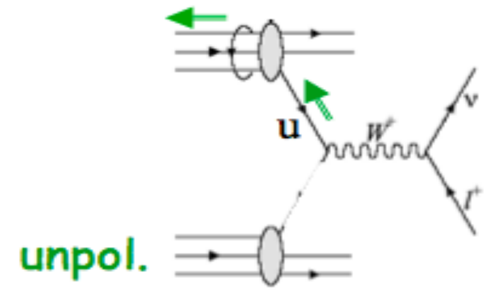


Sea quark polarization – RHIC W program

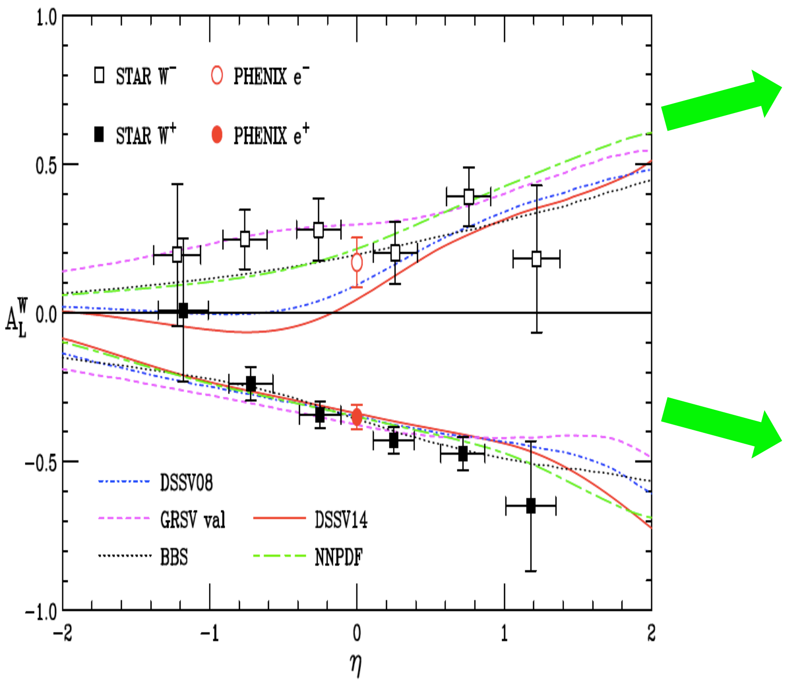
❑ Single longitudinal spin asymmetries:

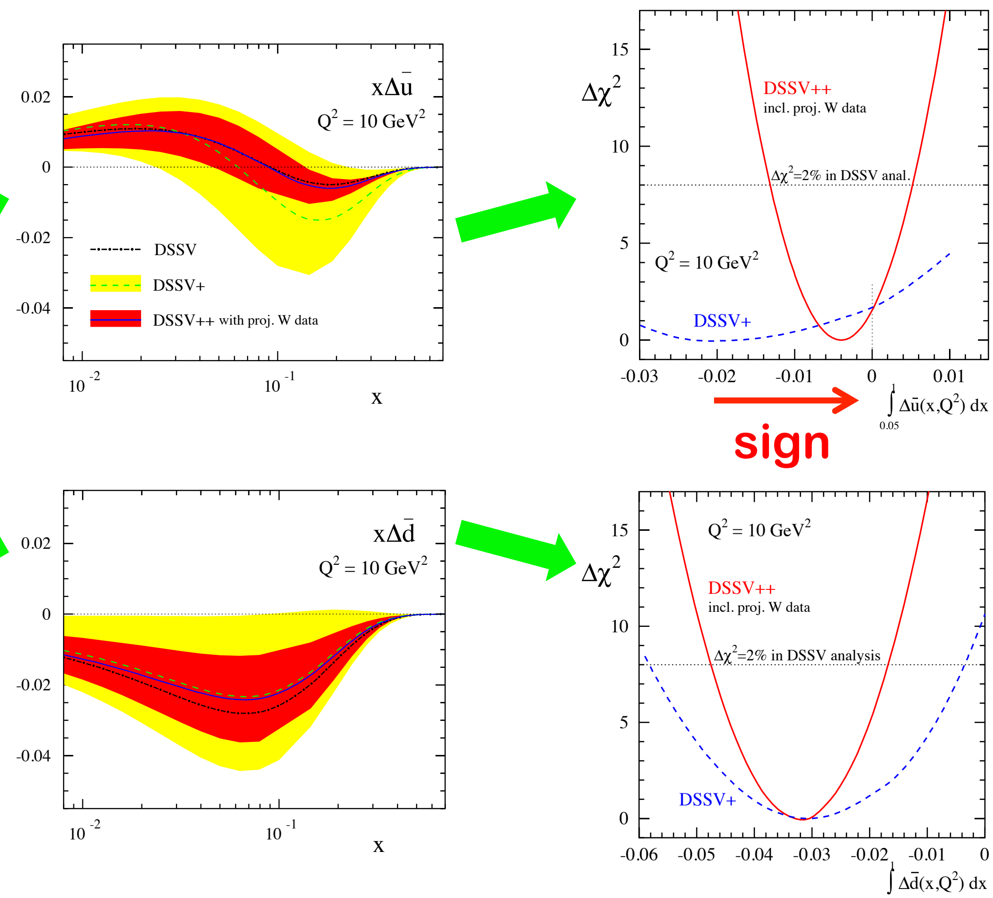
$$A_L = \frac{[\sigma(+) - \sigma(-)]}{[\sigma(+) + \sigma(-)]} \quad \text{for } \sigma(s)$$

Parity violating weak interaction

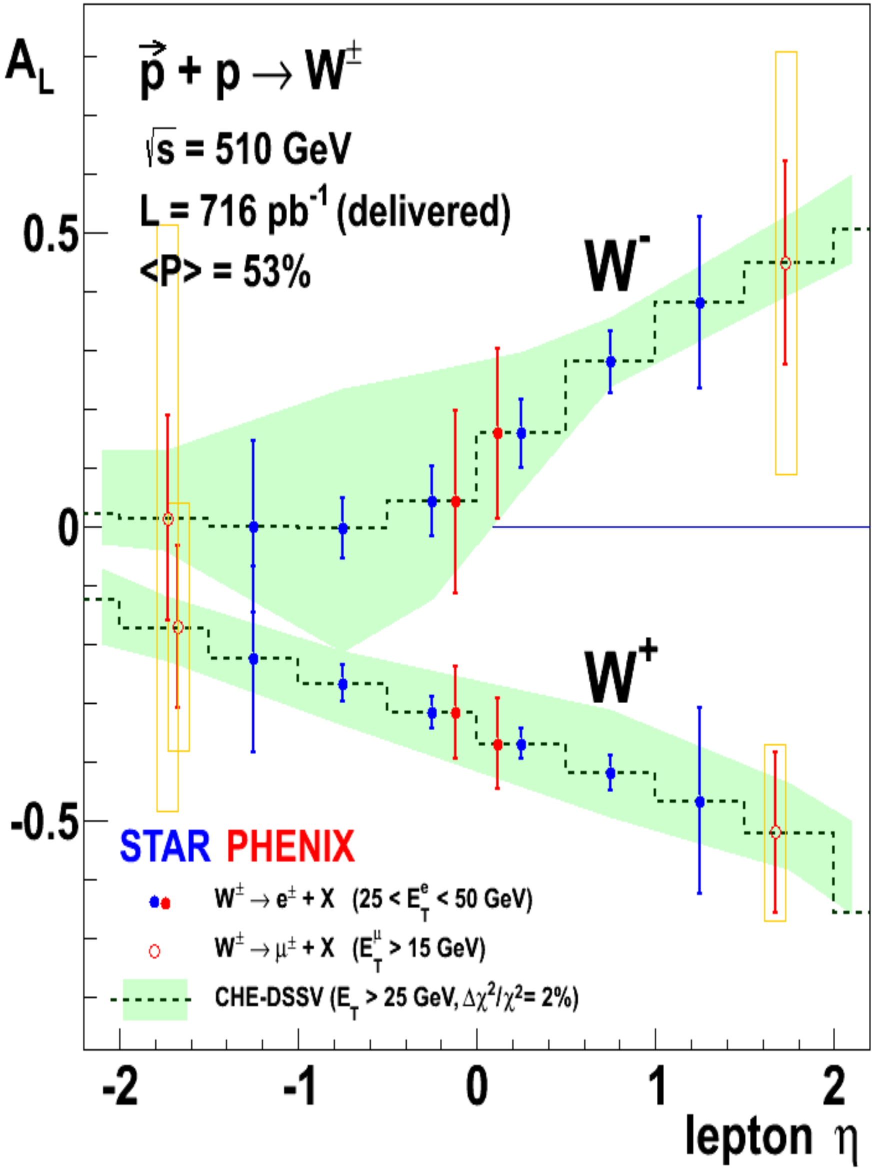


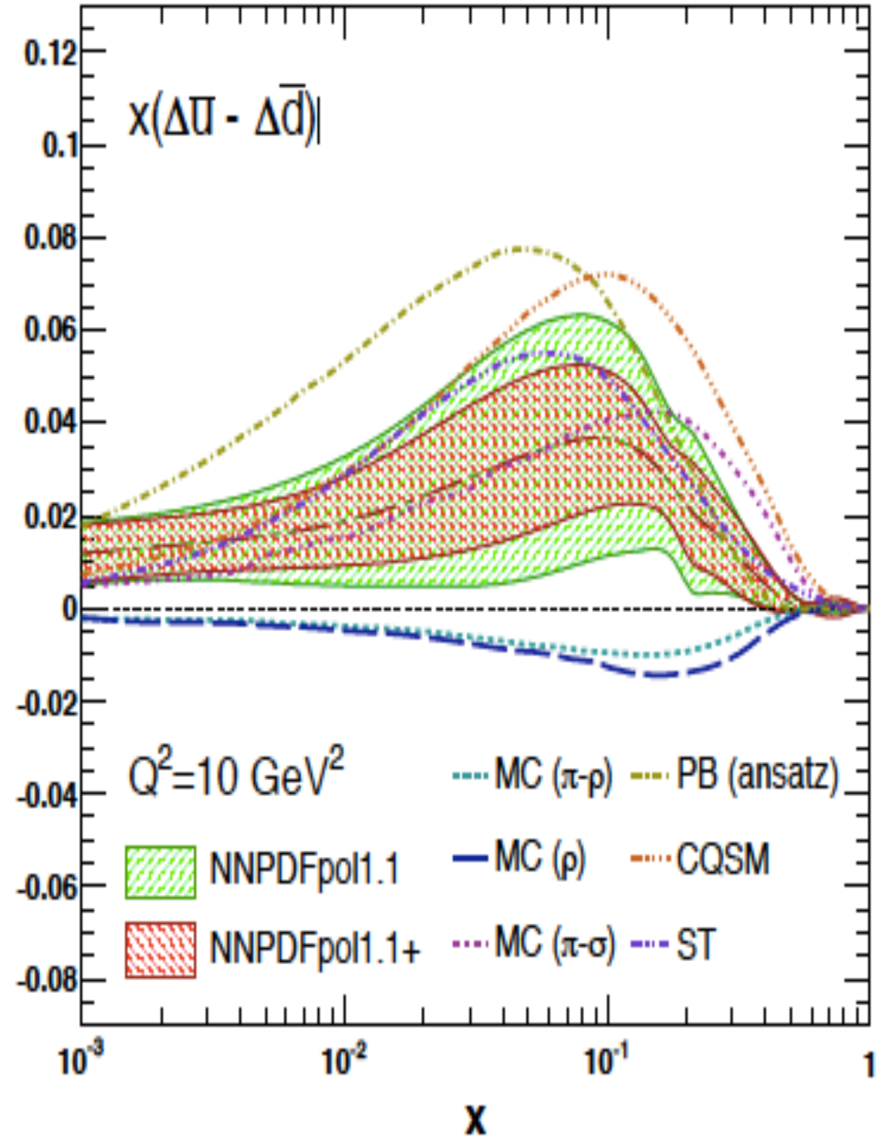
❑ From 2013 RHIC data:





Projected future W asymmetries



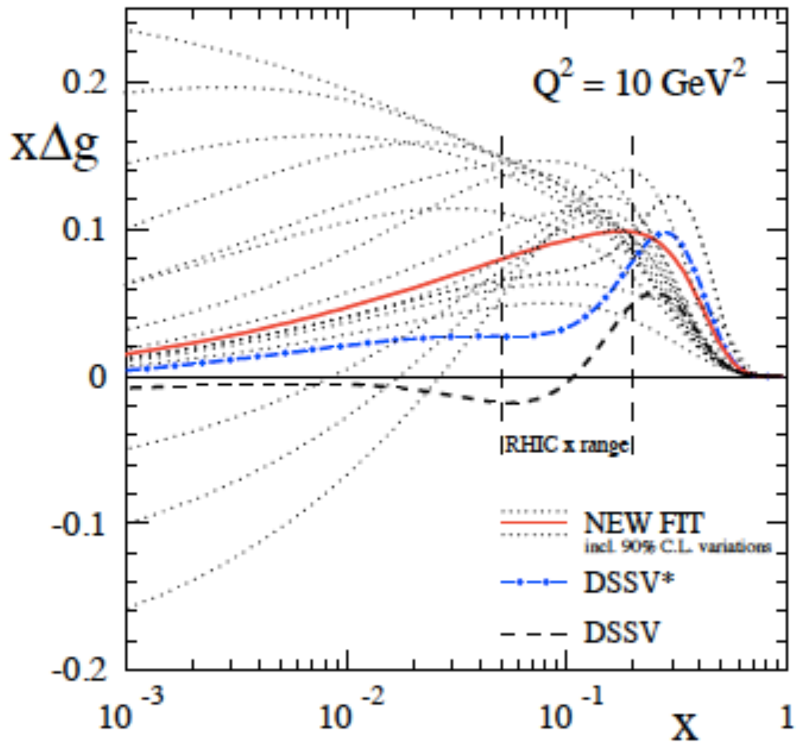


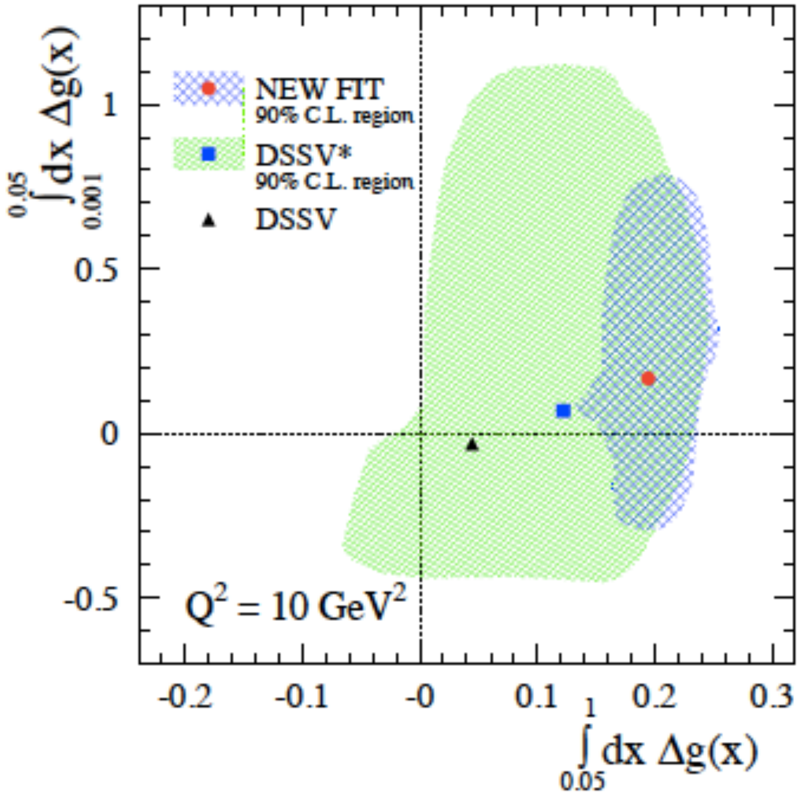
Global QCD analysis of helicity PDFs

D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRL 113 (2014) 012001

results featured in Sci. Am., Phys. World, ...

❑ Impact on gluon helicity:





- ✧ Red line is the new fit
- ✧ Dotted lines = other fits with 90% C.L.

- ✧ 90% C.L. areas
- ✧ Leads ΔG to a positive #

Hadron structure at large x

- ❑ **Testing ground for hadron structure at x → 1:**

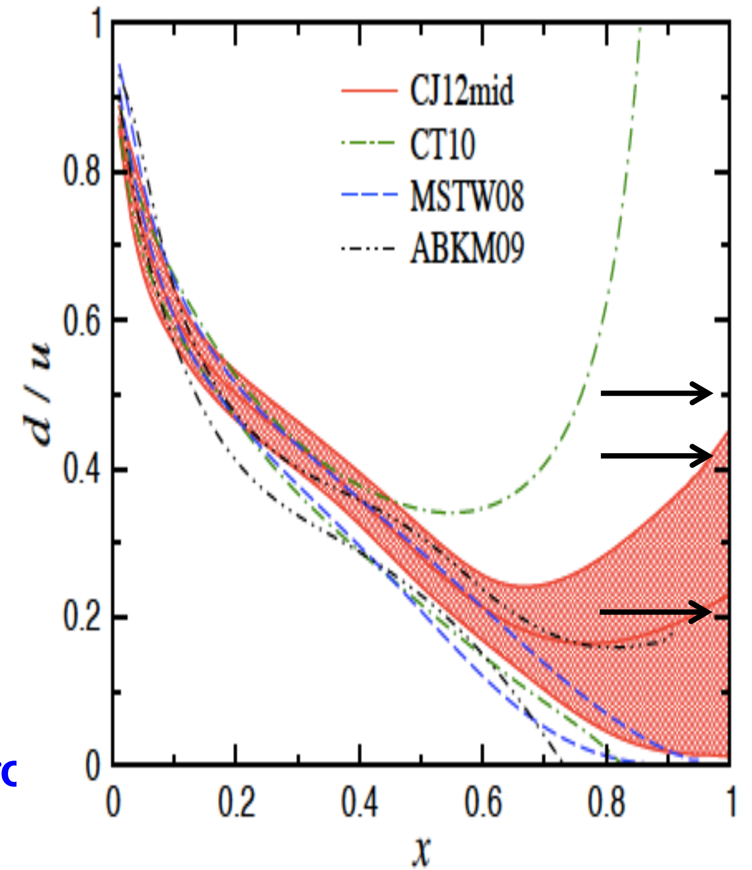
✧ $d/u \rightarrow 1/2$ — **SU(6) Spin-flavor symmetry**

✧ $d/u \rightarrow 0$ — **Scalar diquark dominance**

✧ $d/u \rightarrow 1/5$ — **pQCD power counting**

✧ $d/u \rightarrow \frac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2}$ — **Local quark-hadrc duality**

$\approx\ 0.42$



Hadron structure at large x

- Testing ground for hadron structure at **x → 1**:

$\diamond \; d/u \to 1/2$ — **SU(6) Spin-flavor symmetry** — $\diamond \; \Delta u/u \to 2/3$, $\Delta d/d \to -1/3$

$\diamond \; d/u \to 0$ — **Scalar diquark dominance** — $\diamond \; \Delta u/u \to 1$, $\Delta d/d \to -1/3$

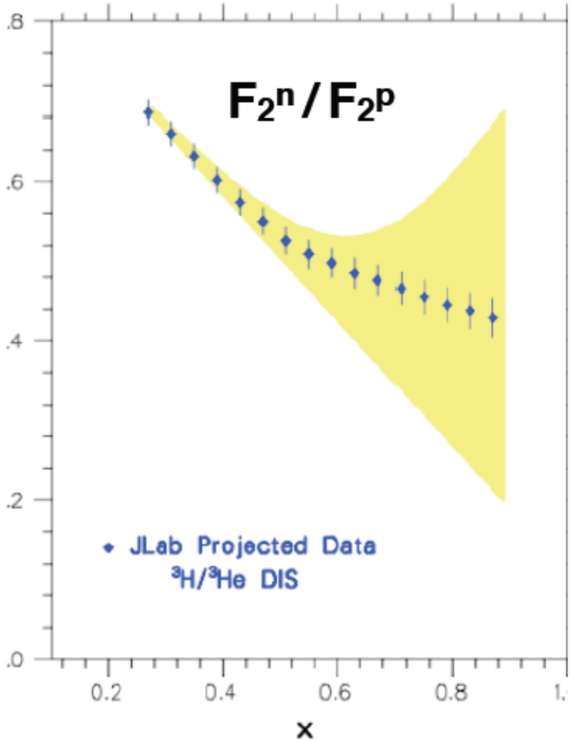
$\diamond \; d/u \to 1/5$ — **pQCD power counting** — $\diamond \; \Delta u/u \to 1$, $\Delta d/d \to 1$

$\diamond \; d/u \to \dfrac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$ — **Local quark-hadron duality** — $\diamond \; \Delta u/u \to 1$, $\Delta d/d \to 1$

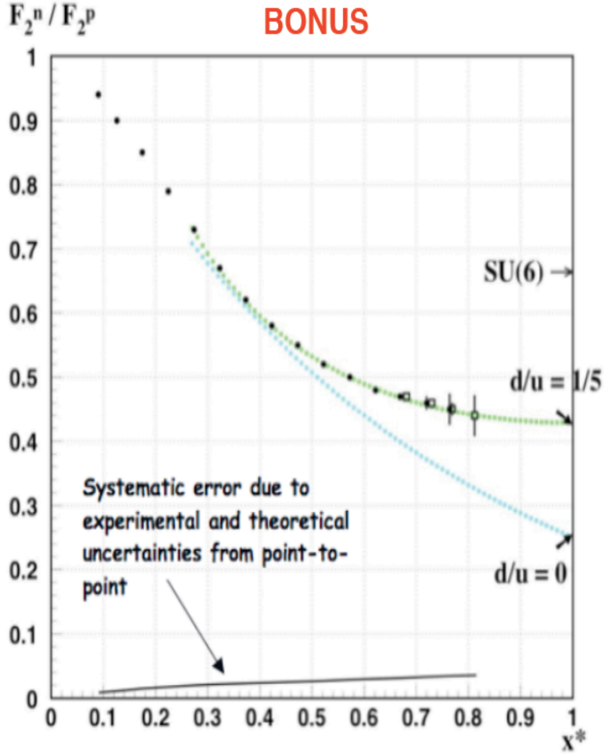
Future large-x experiments – JLab12

❑ **NSAC milestone HP14 (2018):**

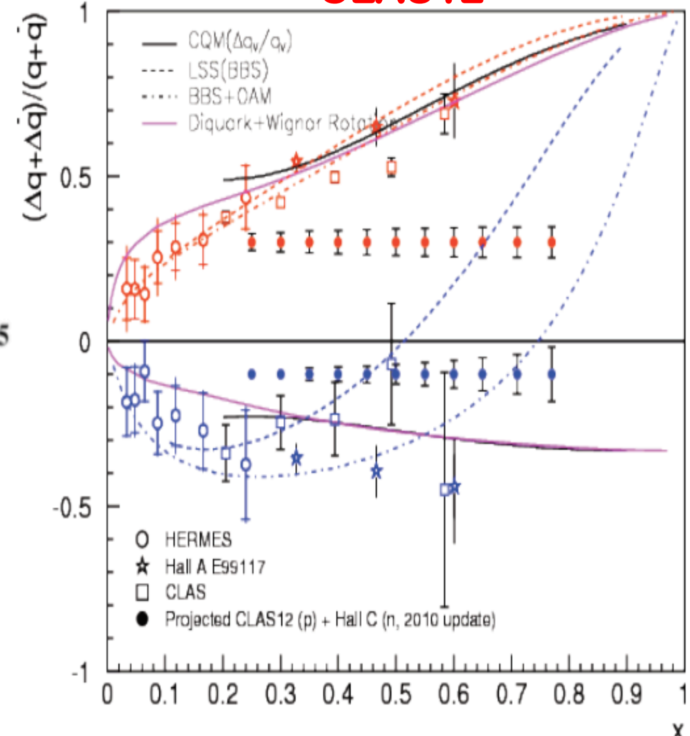
MARATHON



BONUS



CLAS12



Plus many more JLab experiments:

E12-06-110 (Hall C on ^3He), E12-06-122 (Hall A on ^3He),

E12-06-109 (CLAS on NH_3, ND_3), …

and Fermilab E906, …

Future improvement to ΔG

- NNLO? Probably not yet

- Key: Extrapolation to low x and high x

  ✧ Large x: total contribution might be small due to the steep falling phase space

  ✧ Small x: larger phase space for shower and smaller Q for a fixed collision energy $\Rightarrow \text{Large } \langle k_T^2 \rangle, \quad \ln(s/Q^2) \sim \ln(1/x)$

- Collinear factorization does not work when $Q \sim Q_s(x) \sim \langle k_T \rangle$

$$G(x) = G^+(x) + G^-(x) \propto \frac{1}{x^{1+\alpha}}$$

at small x

$$\Delta G(x) = G^+(x) - G^-(x)$$

Could be proportional to $\frac{1}{x^\alpha}$

Not positive definite!

- Current understanding of ΔG :

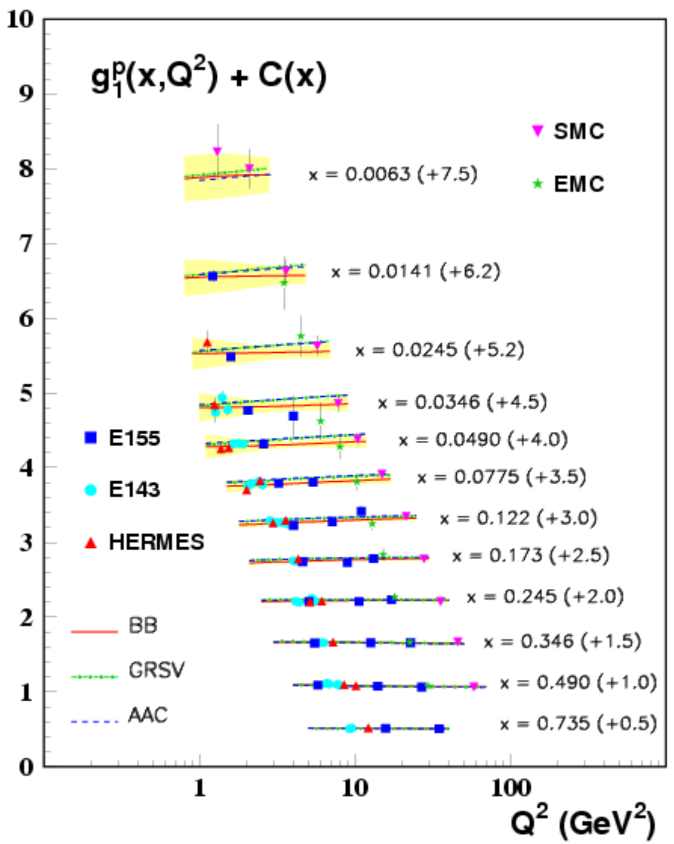
  ΔG ~ 2 is unlikely, but, ΔG ~ ¼ or ½ (¼) is still possible

  It is the G(x), not $\int$ dx G(x), that is more sensitive to QCD dynamics!

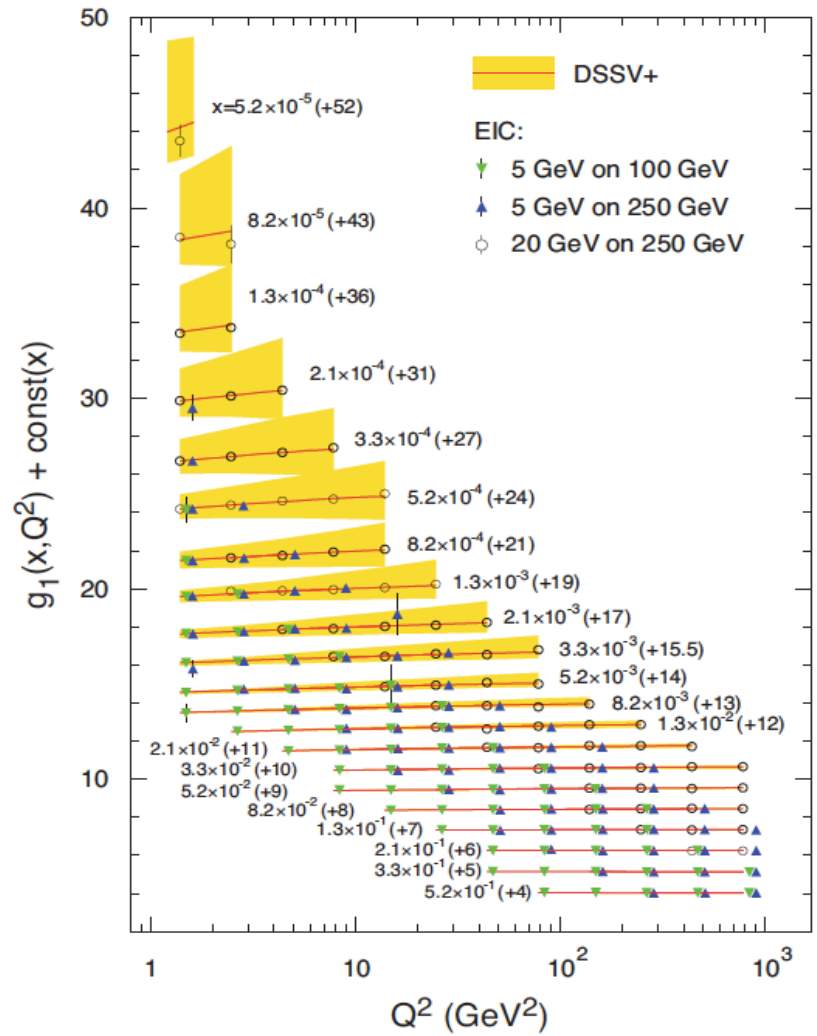
  Future EIC – Q^2 evolution

The Future: Challenges & opportunities

❑ The power & precision of EIC:



at EIC



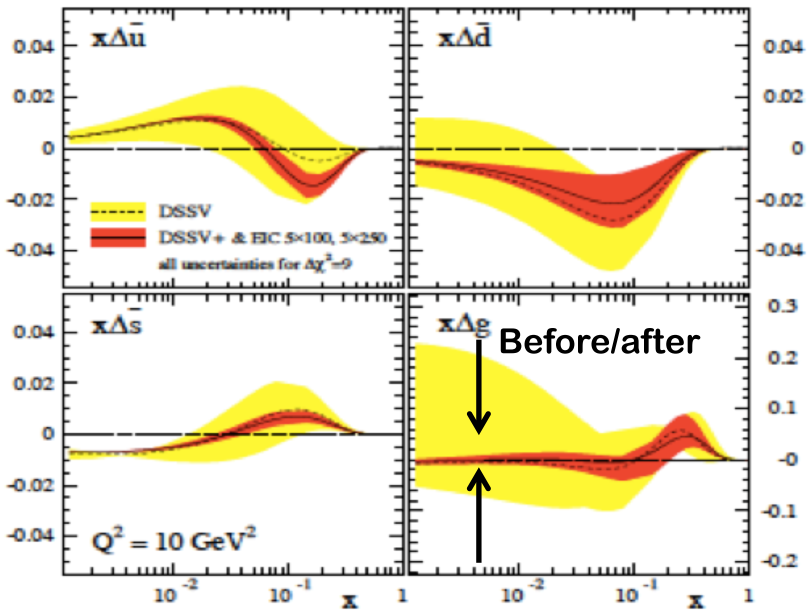
❑ Reach out the glue:

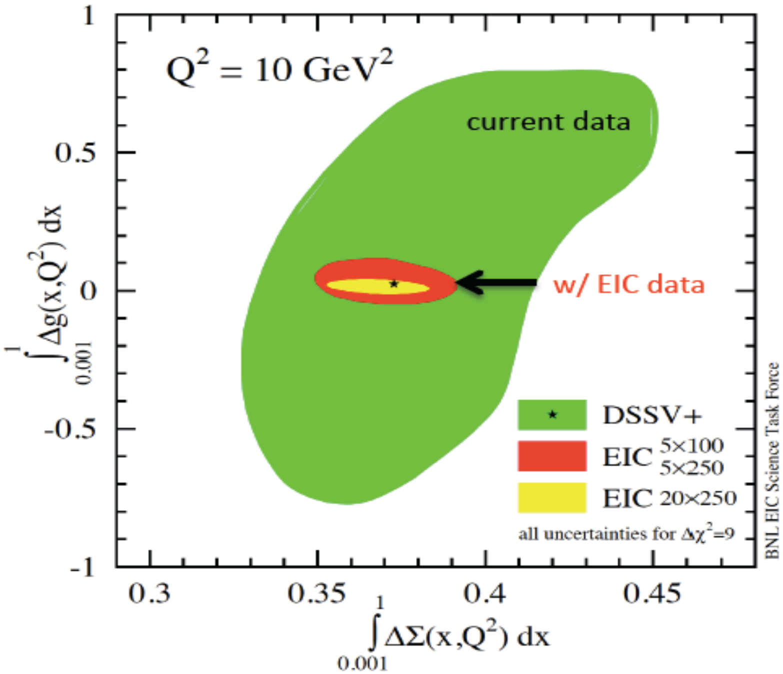
$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

The Future: Challenges & opportunities

- ❑ **One-year of running at EIC:**

Wider Q^2 and x range including low x at EIC!





No other machine in the world can achieve this!

- ❑ **Ultimate solution to the proton spin puzzle:**
  - ✧ ***Precision measurement of $\Delta g(x)$ – extend to smaller x regime***
  - ✧ ***Orbital angular momentum contribution – measurement of GPDs!***

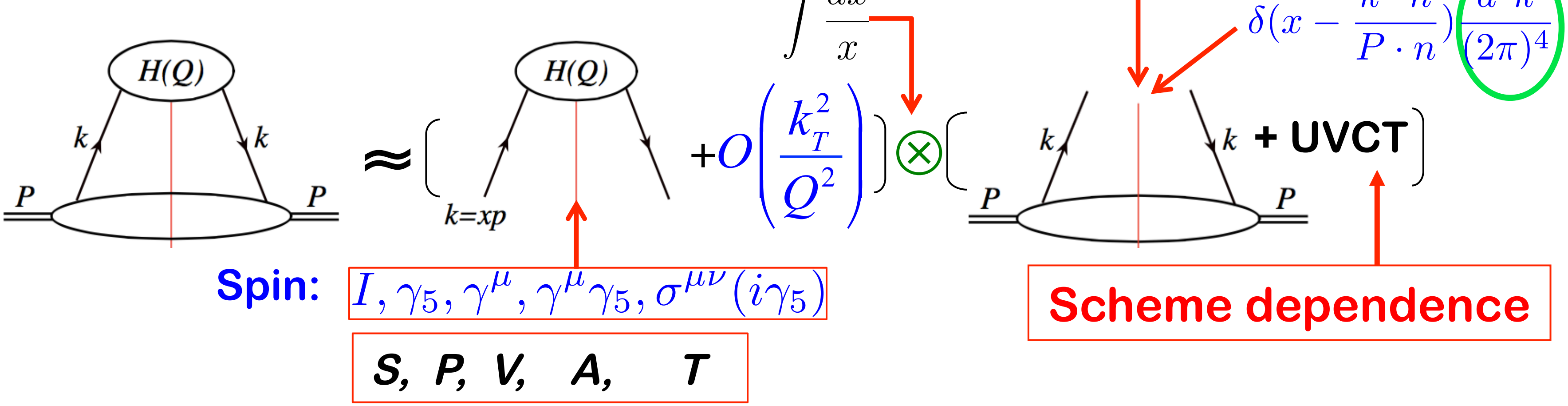
Recall: the other leading power distribution

❑ Collinear approximation:

– **quark:**

S, P, V, A, T

$I, \gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu}(i\gamma_5)$



❑ Leading power hard parts in *p*:

$$\frac{1}{2}\gamma\cdot p(V),\ \frac{1}{2}\gamma_5\gamma\cdot p(A),\ \frac{1}{2}\gamma\cdot p\gamma_\perp^\alpha\gamma_5(T) \longleftrightarrow$$ **4 – spin states of the "quark-pair"**

Non-flip, longitudinally flip, transversely flip

❑ Leading power distributions:

$$\frac{\gamma\cdot n}{2p\cdot n}(V),\ \frac{\gamma_5\gamma\cdot n}{2p\cdot n}(A),\ \frac{\gamma\cdot n\gamma_\perp^\alpha\gamma_5}{2p\cdot n}(T) \longleftrightarrow q(x,Q),\ \Delta q(x,Q),\ h_1(x,Q)$$

Unpolarized PDF, Helicity/Polarized PDF, Transversity distribution

Transversity Distributions

❑ Transversity:

Jaffe and Ji, 1991

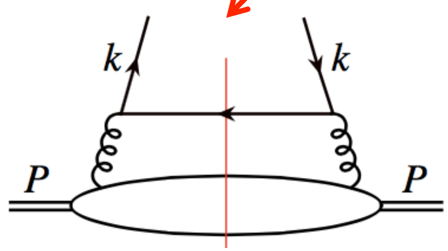
$$h_1(x) = \frac{1}{\sqrt{2}p^+}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle PS_\perp|\psi_+^\dagger(0)\gamma_\perp\gamma_5\psi_+(\lambda n)|PS_\perp\rangle$$ **+ UVCT**

with $\psi_\pm = P_\pm\psi$ and $P_\pm = \frac{1}{2}\gamma^\mp\gamma^\pm$

❑ Unique for the quarks:

No mixing with gluons!

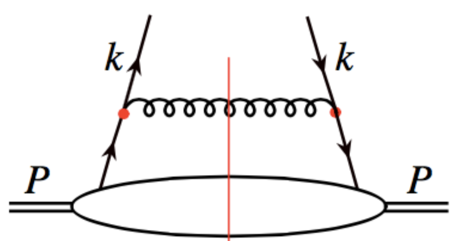
$\gamma\cdot n\gamma_\perp\gamma_5$ ← Even # of γ 's



= 0

No mixing with PDFs, helicity distributions

❑ Perturbatively UV and CO divergent:



+ wave function renormalization

$$\Delta_T P_{qq}^{(0)}(x) = C_F\left[\frac{2x}{(1-x)_+}+\frac{3}{2}\delta(1-x)\right]$$

→ "DGLAP" evolution kernels

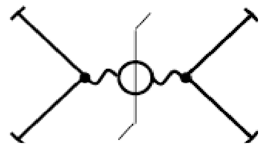
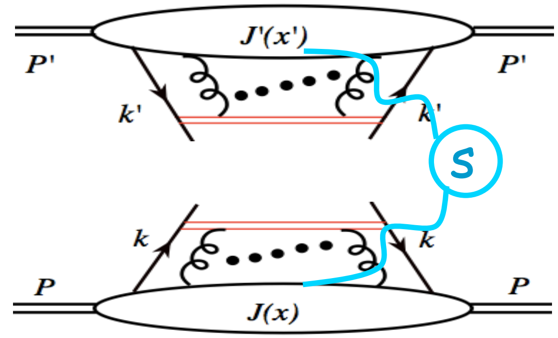
NLO - Vogelsang, 1998

Connection to physical observables

- **Need two-chiral odd distributions – two hadrons:**

Soper, Ralston, 1978
Jaffe, Ji, 1991, 1992

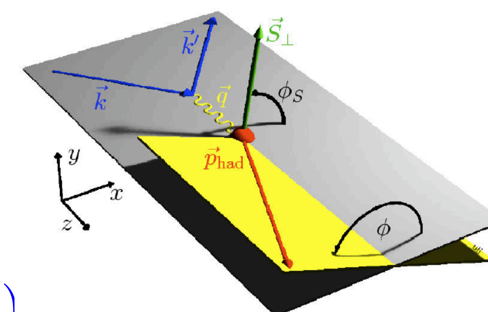
– **Drell-Yan:**

$\sigma_{\text{tot}}^{\text{DY}} \sim$  $\otimes$ 

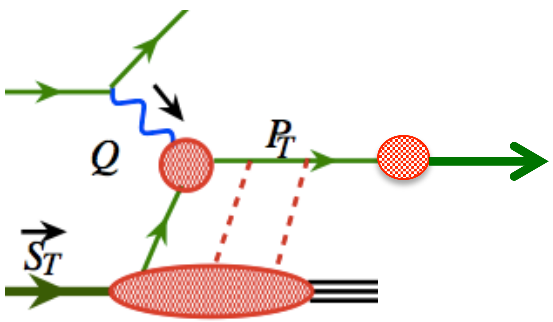
$+\, O\left(\dfrac{1}{QR}\right)$

$$\sim \; h_1(x) \otimes h_1(x')$$

Predictive power: Universal Transversity



– **SIDIS:**



$$\sim \; h_1(x) \otimes D_{\text{Collins}}(z)$$

$$\sim \; A_T^{\sin(\phi+\phi_s)}$$

- **Caution:**

Transversity extracted depends on the "scheme" or UVCT

Cross section is always positive!

Like PDFs (helicity distributions), transversity does not have to be positive

Soffer's inequality

- Relation between quark distributions:

$$h_1(x) \leq \frac{1}{2}\left[q(x) + \Delta q(x)\right] = q^+(x)$$

Derived by using the positivity constraint of
quark + nucleon -> quark + nucleon
forward scattering helicity amplitudes

Cautions:

- Quark field of the Transversity distribution is NOT on-shell
- Quark + nucleon -> quark + nucleon
  forward scattering amplitude is perturbatively divergent

- Testing vs using as a constraint:

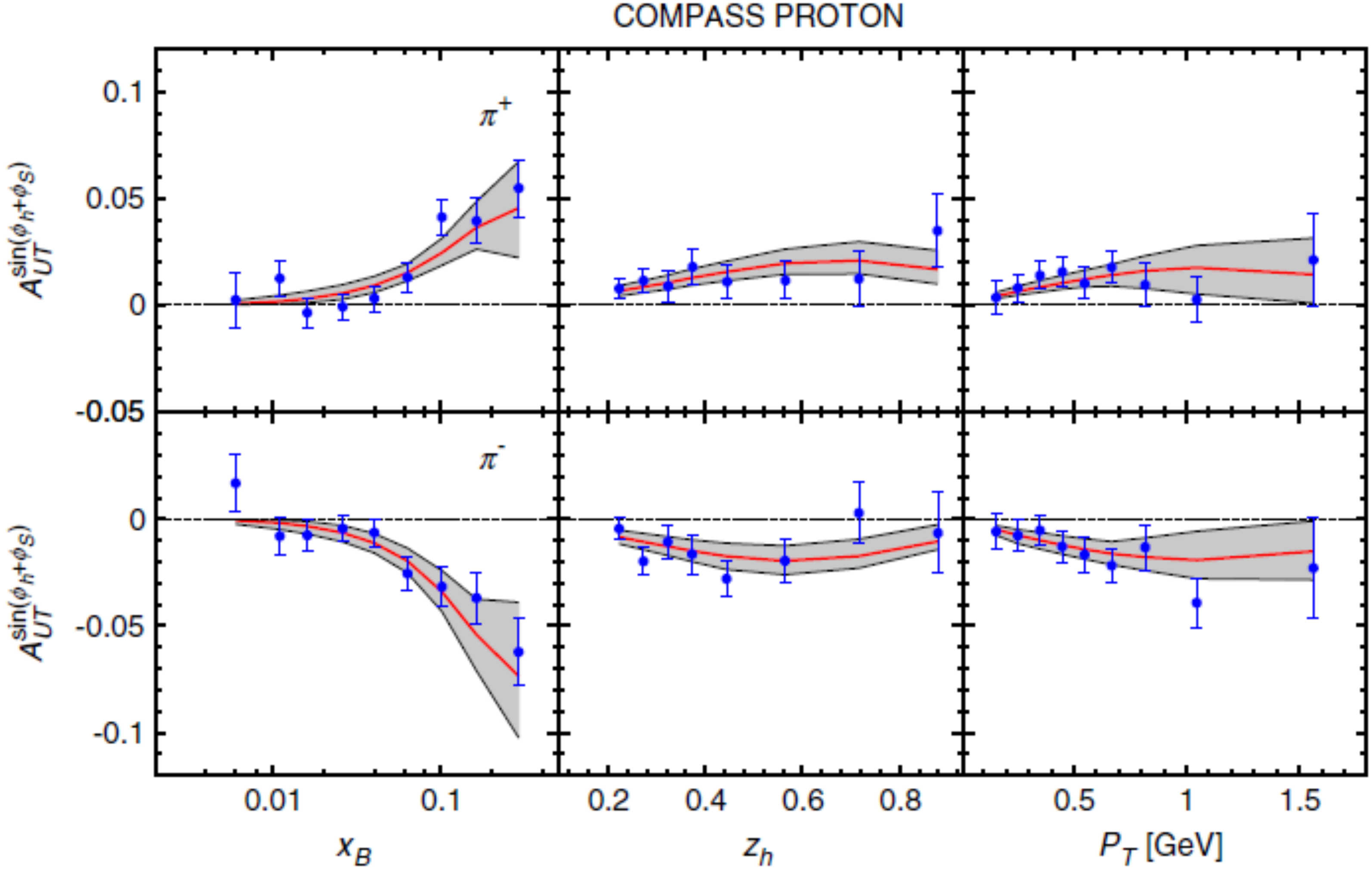
It is important to test this inequality, rather than using it as a constraint for fitting the transversity

Perturbatively calculated evolution kernels seem to be consistent with the inequality – the scale dependence

Extraction of Transversity

❑ **SIDIS – mixed with Collins function:**

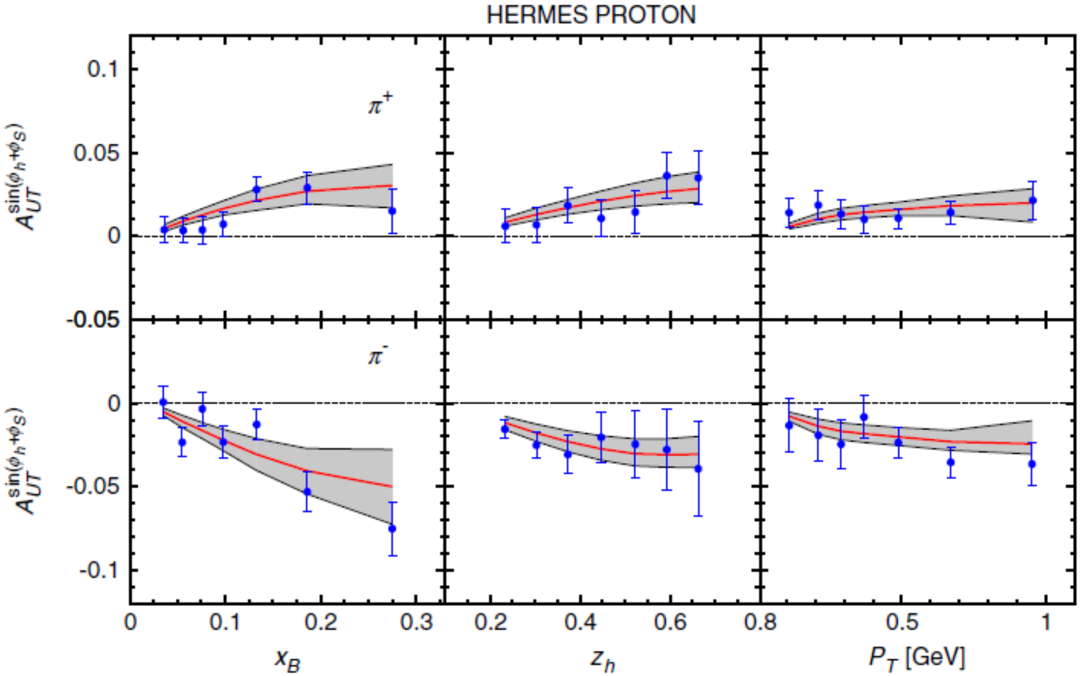
Anselmino et al., PRD 87, 094019 (2013)



Extraction of Transversity

- **SIDIS – mixed with Collins function:**

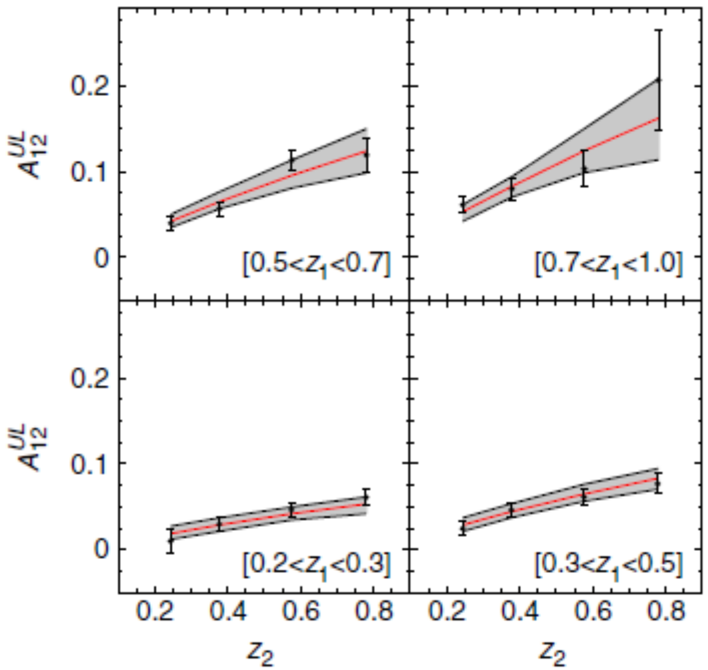
Anselmino et al.,
PRD 87, 094019 (2013)



HERMES (eP)

- **e+e- – Collins functions:**

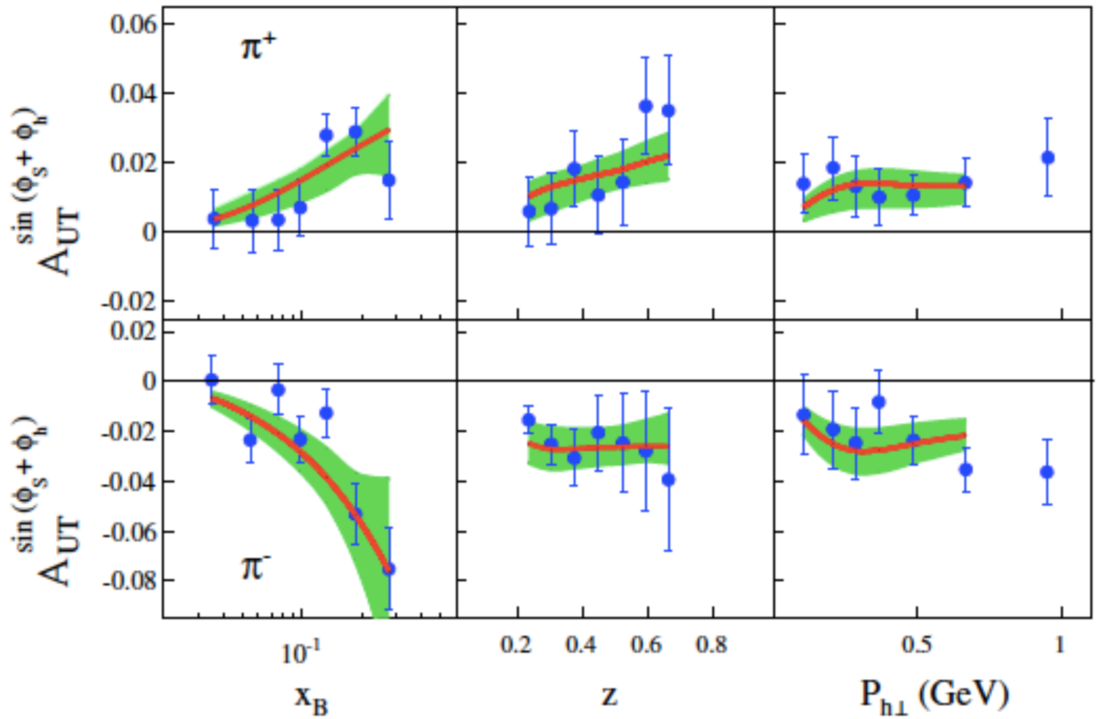
Belle (e+e-)



Extraction of Transversity

Kang et al, PRD, 2016

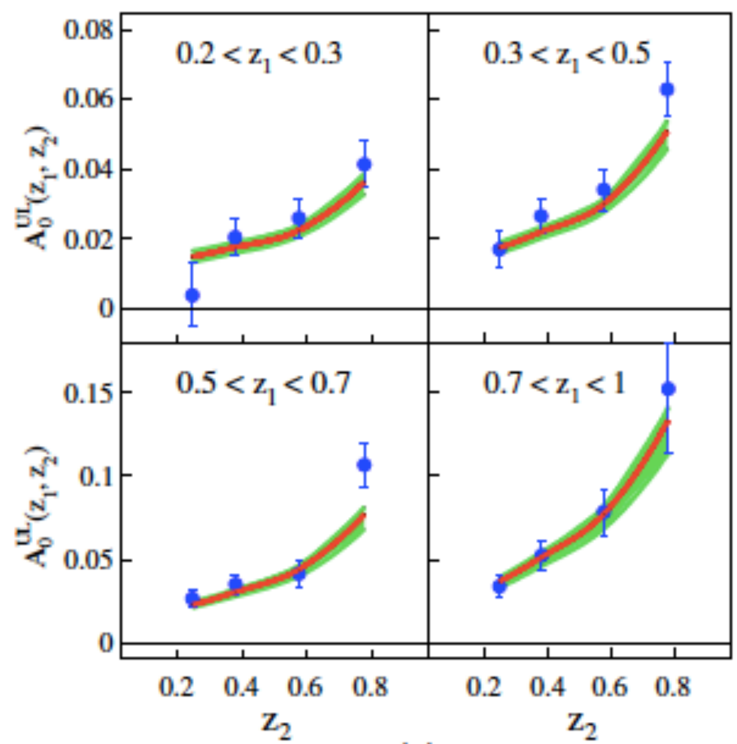
- SIDIS – mixed with Collins function:



HERMES (eP)

- e+e- – Collins functions:

Belle (e+e-)

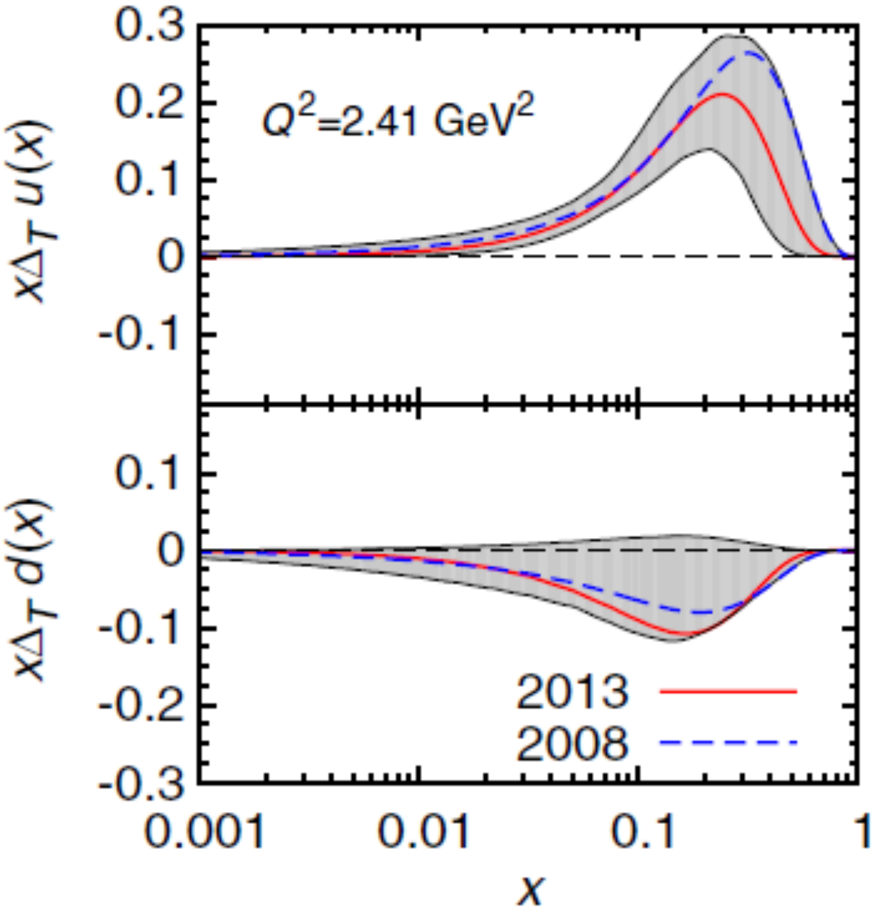


Extraction of Transversity

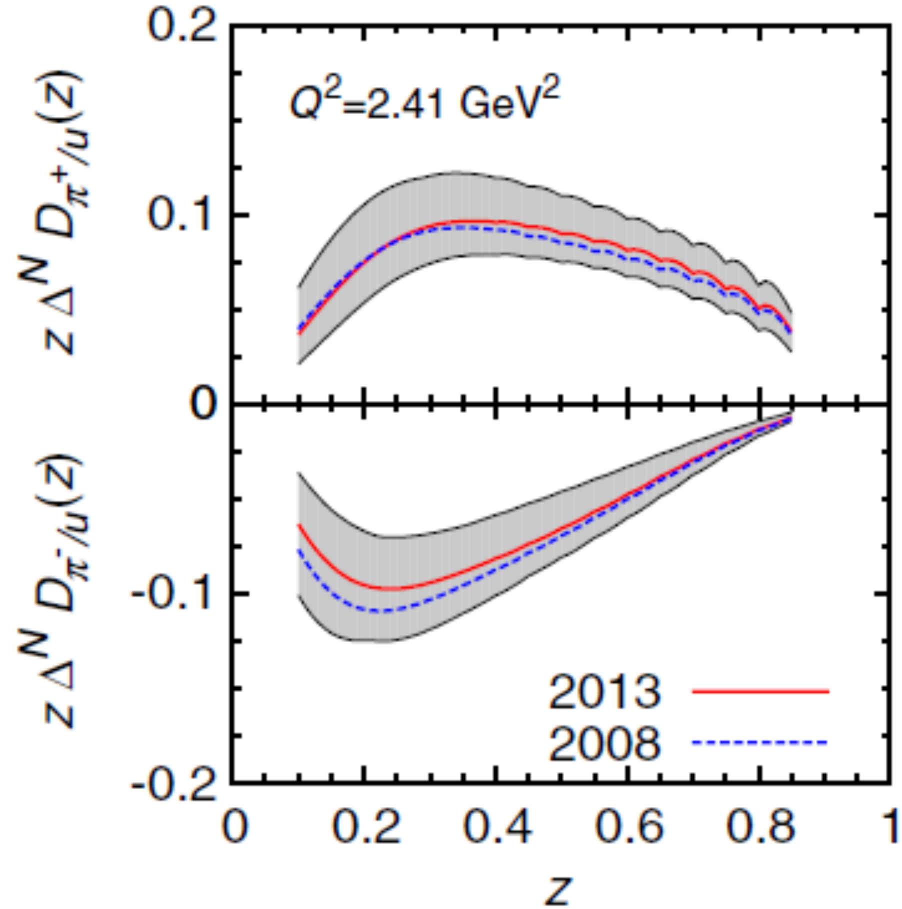
Anselmino et al., PRD 87, 094019 (2013)

- Transversity and Collins function:

Transversity



Collins function

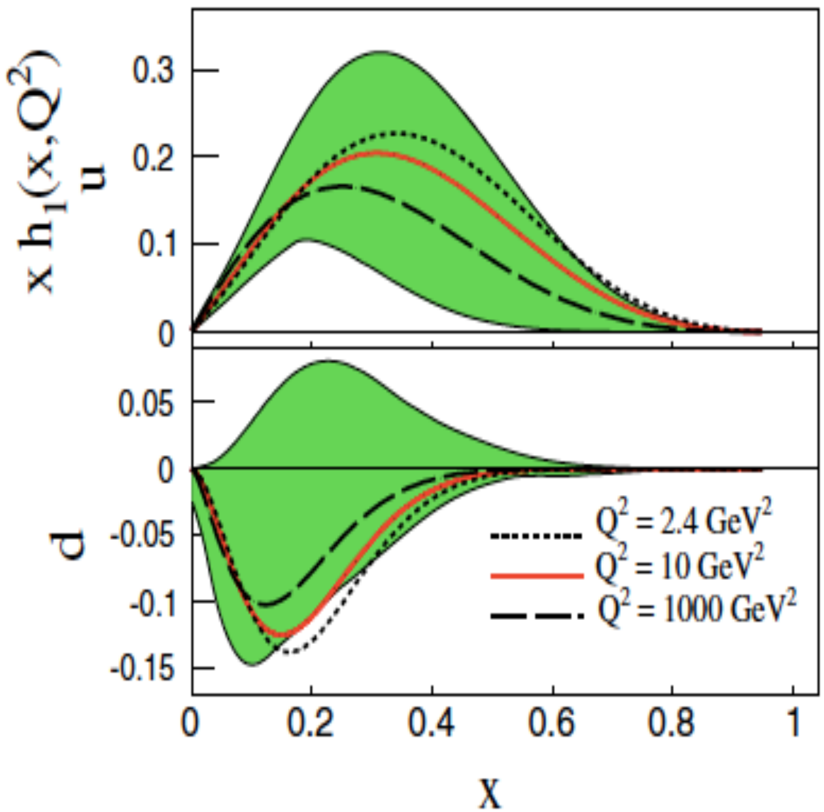


Extraction of Transversity

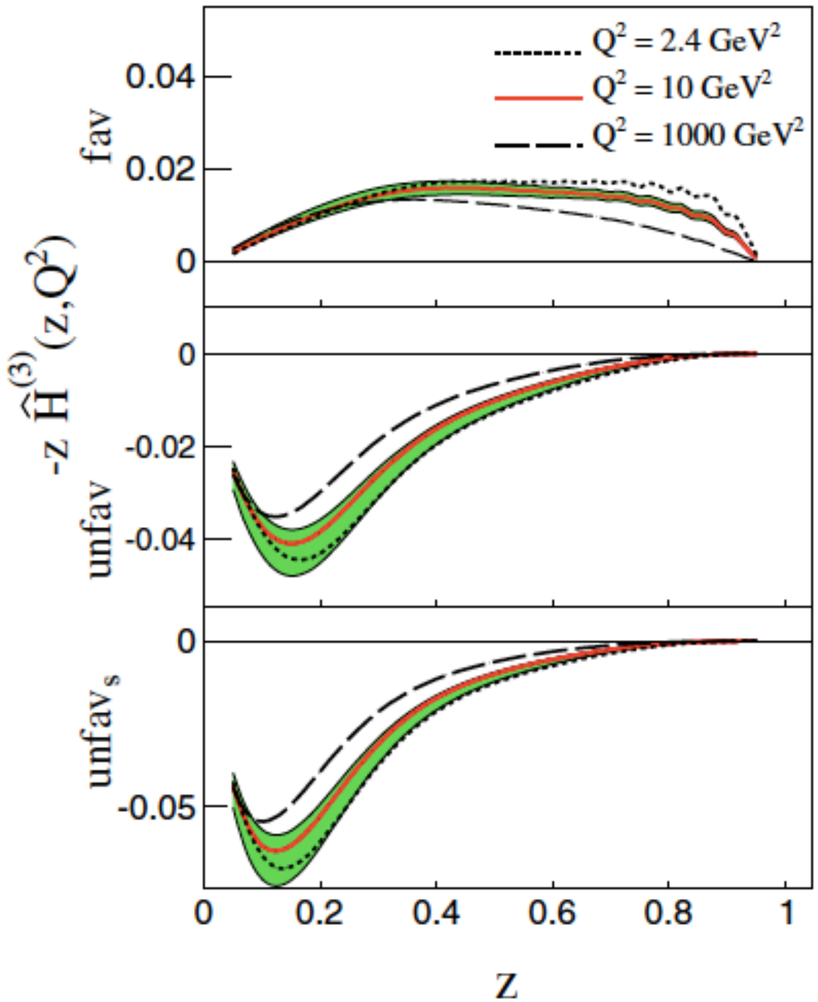
Kang et al, PRD, 2016

❑ Transversity and Collins function:

Transversity



Collins function

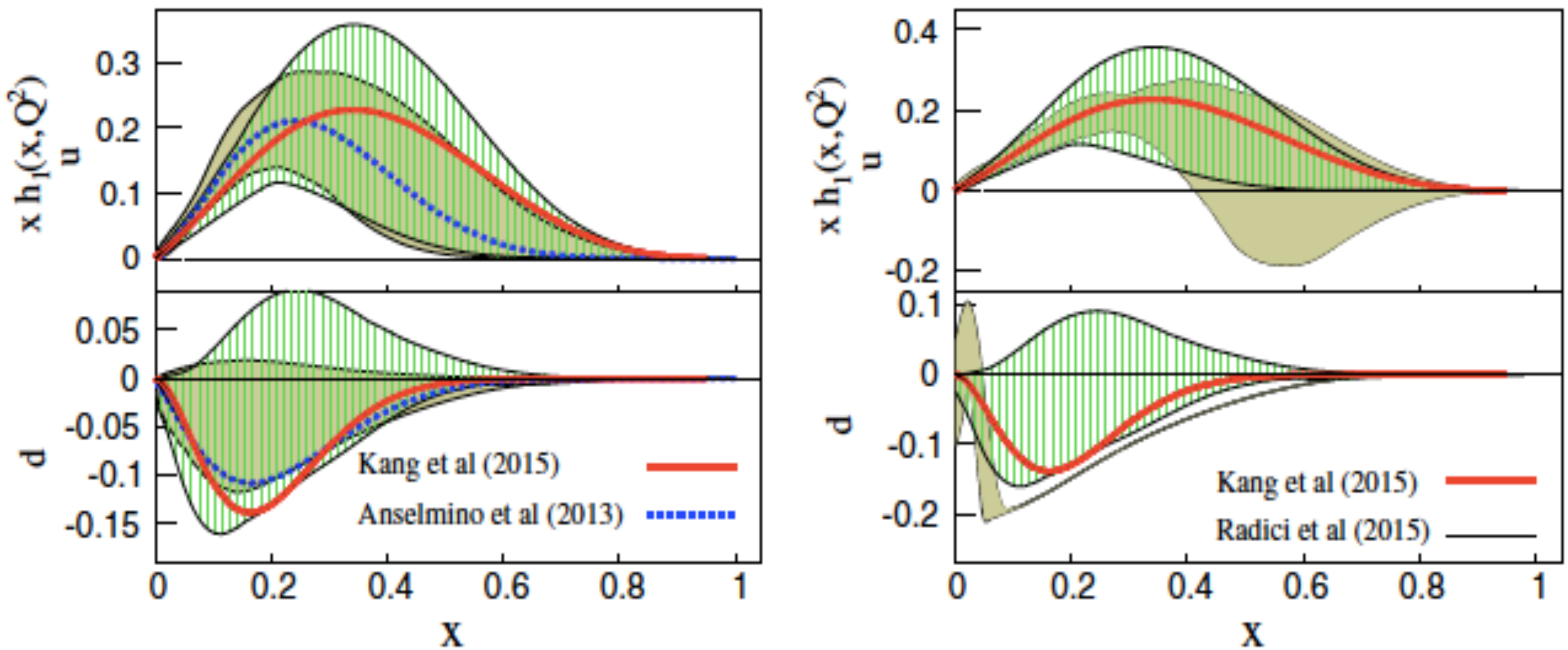


Extraction of Transversity

- Transversity comparison:

Anselmino et al.,
PRD 87, 094019 (2013)

Kang et al, PRD, 2016



✧ Consistent in overall shape and sign, but, different in details

✧ Large uncertainties!

- Future:

JLab12, Compass, EIC; Transverse polarized Drell-Yan?

Tensor charge

- Definition:

$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

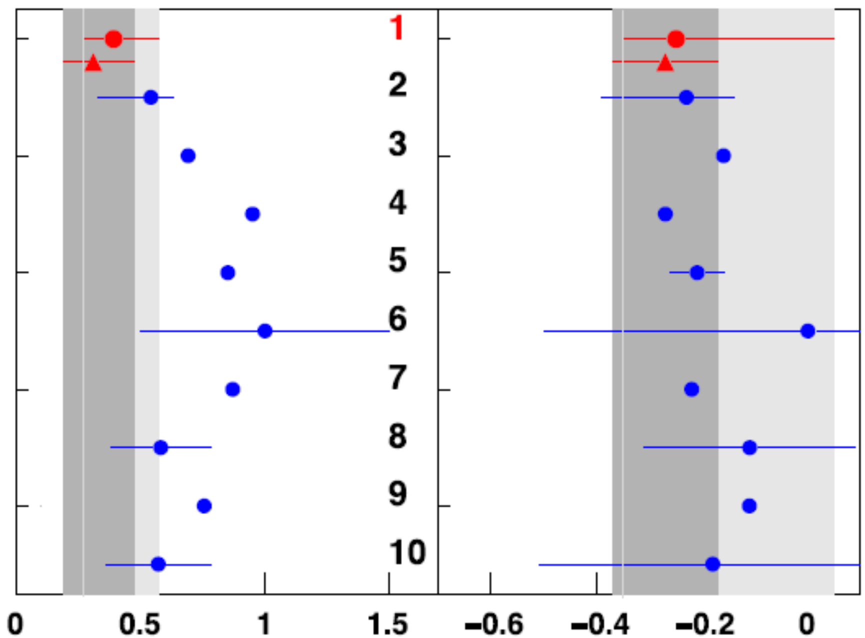
Moment – matrix elements of local operators
– fundamental QCD quantity – calculable on lattice or using models

- Extraction:

Anselmino et al.,
PRD 87, 094019 (2013)

● $\delta u = 0.39^{+0.18}_{-0.12}$ ● $\delta d = -0.25^{+0.30}_{-0.10}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$ ▲ $\delta d = -0.27^{+0.10}_{-0.10}$



✧ Extracted from global fits

by using two different parameterizations for Collins FF)

✧ Predictions from various models (including LQCD)

✧ Tensor charges are expected to be smaller than axial charge

$$\Delta u = 0.787 \quad \Delta d = -0.319$$

Tensor charge

- **Definition:** $$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

  Moment – matrix elements of local operators
  – fundamental QCD quantity – calculable on lattice or using models

- **Extraction from global fits :**

$$\delta q^{[x_{\min}, x_{\max}]}(Q^2) \equiv \int_{x_{\min}}^{x_{\max}} dx h_1^q(x, Q^2)$$

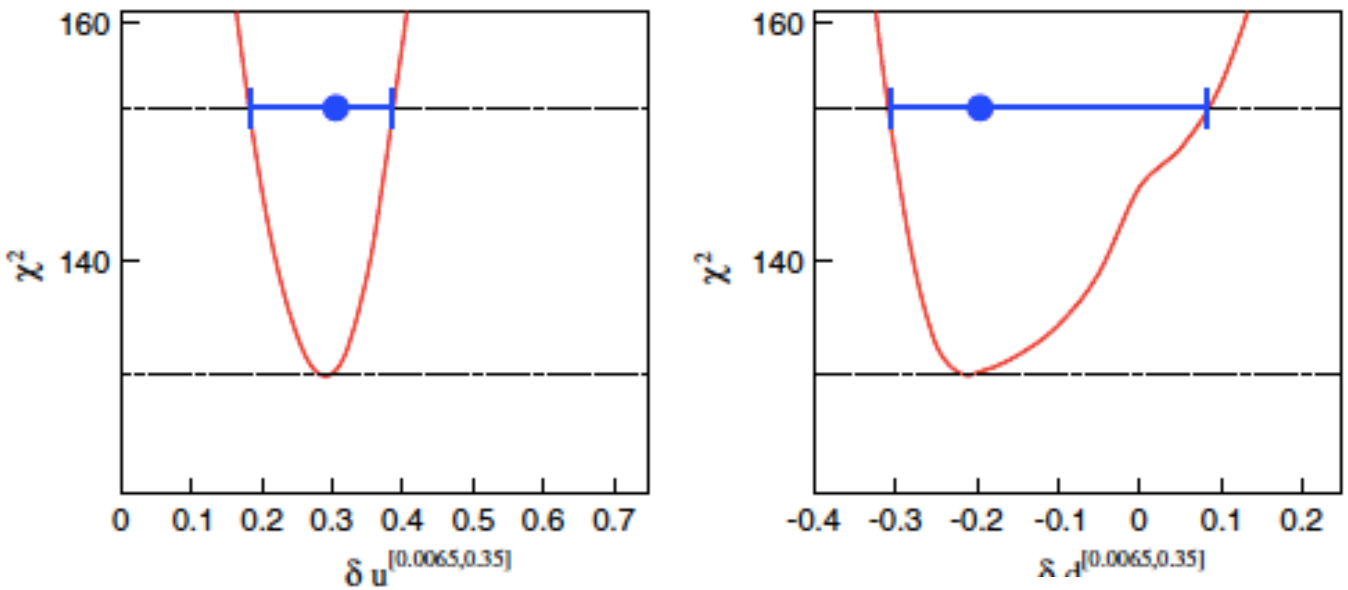
$$\delta u^{[0.0065, 0.35]} = +0.30^{+0.08}_{-0.12}$$

$$\delta d^{[0.0065, 0.35]} = -0.20^{+0.28}_{-0.11}$$

Kang et al, PRD, 2016

$Q^2 = 10 \text{ GeV}^2$

90% C.L.



$\Delta u = 0.787 \quad \Delta d = -0.319$

Summary of lecture six

- With the existing data from lepton-hadron and hadron-hadron collisions with polarized beams, we have a good idea on the quark/gluon helicity contribution to proton's spin

- Transversity and tensor charge are fundamental QCD quantities!

- But, EIC is a ultimate QCD machine, and absolutely needed:
  1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
  2) to search for hints and clues of color confinement, and
  3) to measure the color fluctuation and color neutralization

In particular, EIC can determine the helicity contribution to proton's spin, and to answer the question if there is a need for orbital contribution

Thanks!

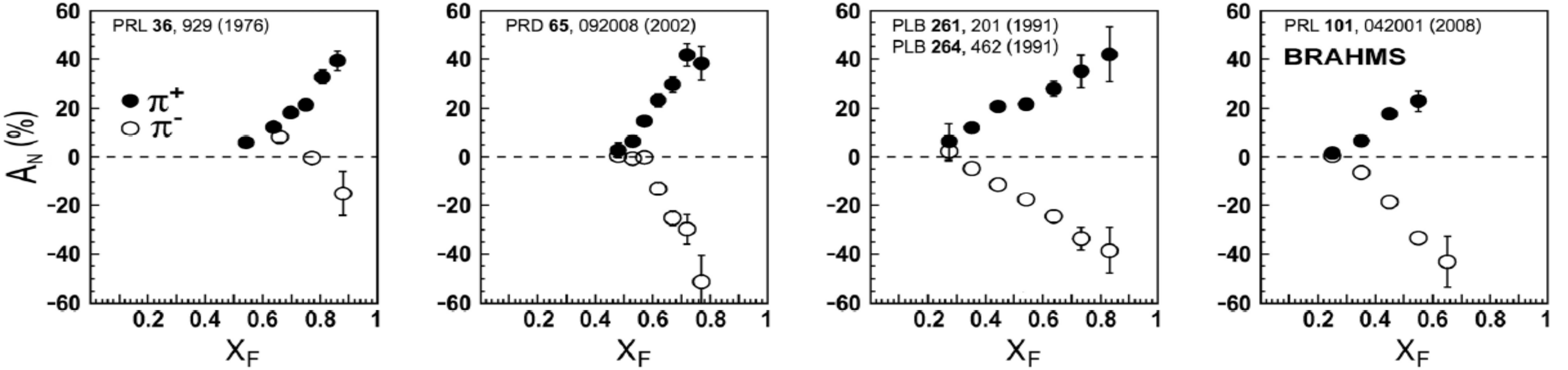
Backup slides

QCD and hadrons

Single transverse-spin asymmetry

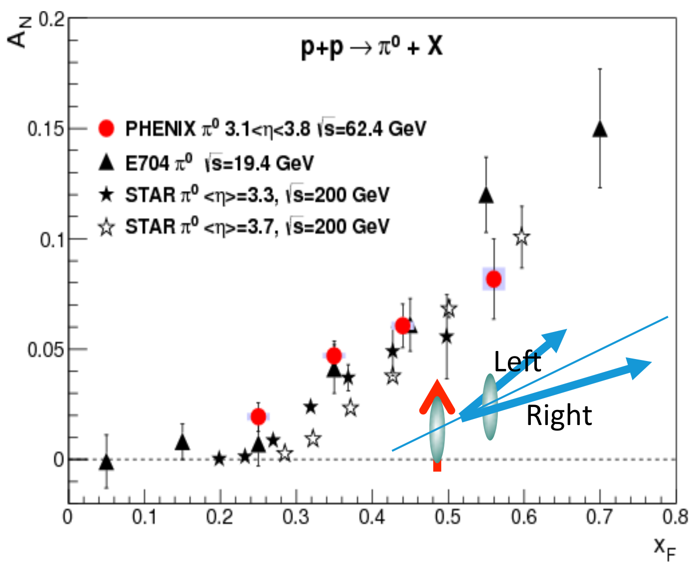
- A_N - consistently observed for over 35 years (~ 0 in parton model)!

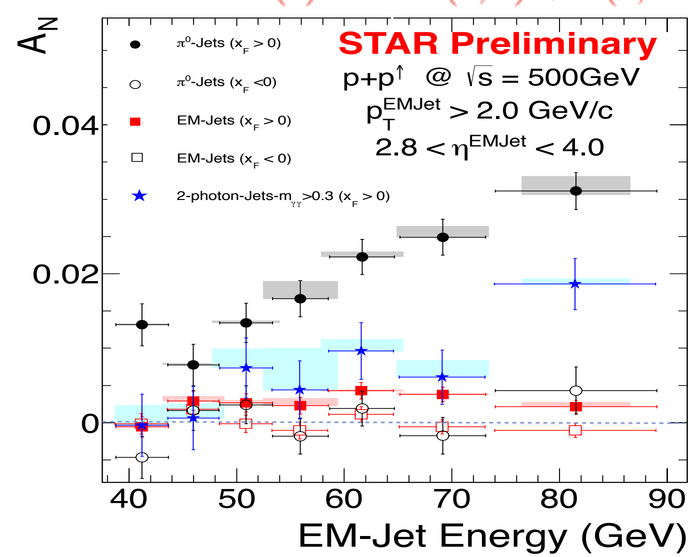
ANL – 4.9 GeV | BNL – 6.6 GeV | FNAL – 20 GeV | BNL – 62.4 GeV



- Survived the highest RHIC energy:

$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$



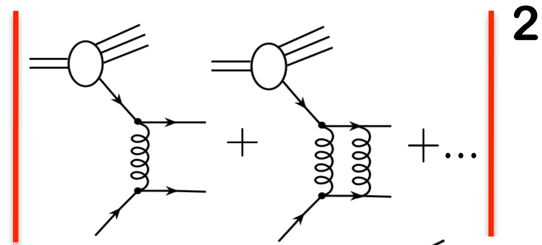


Do we understand it?

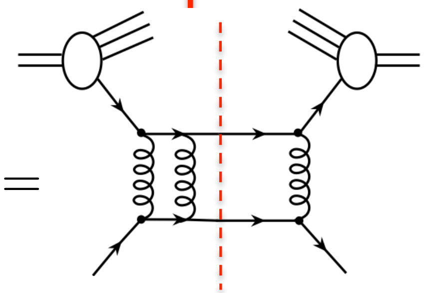
Kane, Pumplin, Repko, PRL, 1978

❑ Early attempt:

Cross section: $\sigma_{AB}(p_T, \vec{s}) \propto$



Asymmetry: $\sigma_{AB}(p_T, \vec{s}) - \sigma_{AB}(p_T, -\vec{s}) =$



$\propto \alpha_s \frac{m_q}{p_T}$

Too small to explain available data!

❑ What do we need?

$$A_N \propto i\vec{s}_p \cdot (\vec{p}_h \times \vec{p}_T) \Rightarrow i\epsilon^{\mu\nu\alpha\beta} p_{h\mu} s_\nu p_\alpha p'_{h\beta}$$

Need a phase, a spin flip, enough vectors

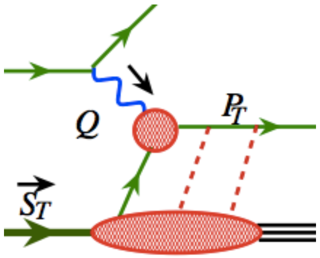
❑ Vanish without parton's transverse motion:

➡ **A direct probe for parton's transverse motion,**

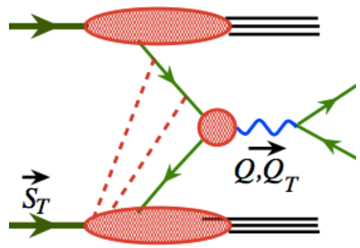
Spin-orbital correlation, QCD quantum interference

Current understanding of SSAs

- Two scales observables – $Q_1 >> Q_2 \sim \Lambda_{QCD}$:



SIDIS: $Q>>P_T$

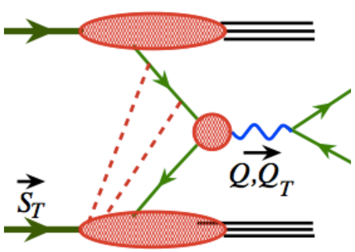


DY: $Q>>Q_T$

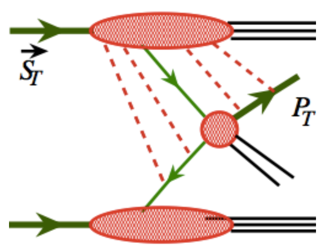
TMD factorization
TMD distributions

Direct information on parton k_T

- One scale observables – $Q >> \Lambda_{QCD}$:



DY: $Q \sim Q_T$

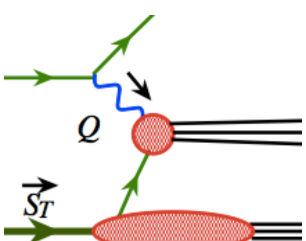


Jet, Particle: P_T

Collinear factorization
Twist-3 distributions

Information on moments of parton k_T

- Symmetry plays important role:



Inclusive DIS
Single scale
Q

Parity
Time-reversal

$A_N = 0$