30 Years Spin Physics in 30 minutes Past, Present and Future

at a "logarithmic" scale

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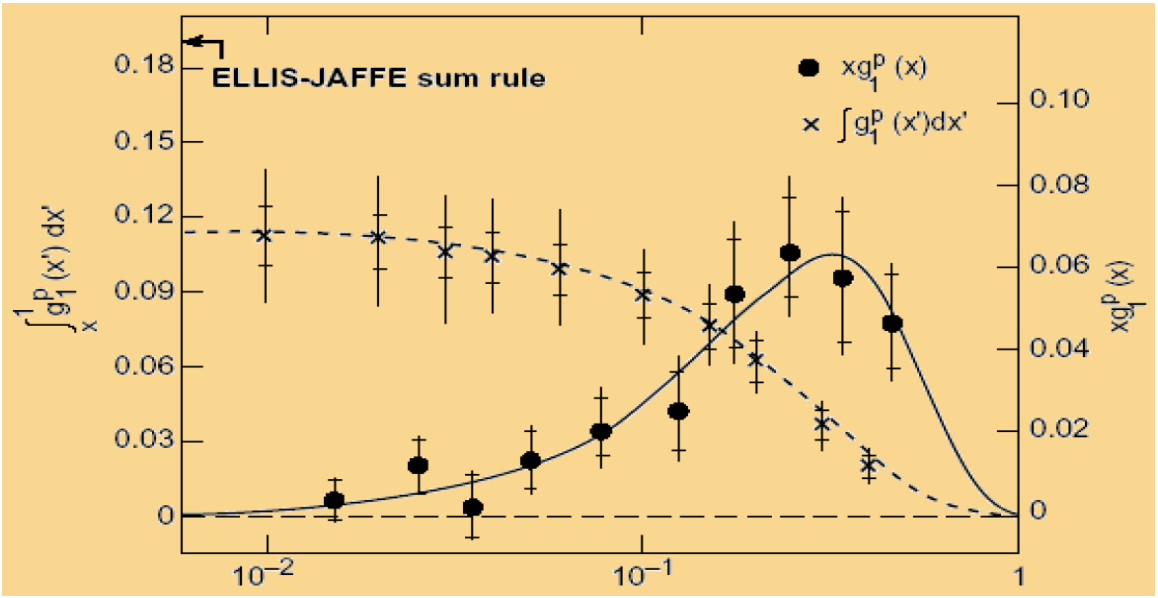
Brookhaven National Laboratory

XXII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2014)

University of Warsaw, Poland, April 28 – May 2, 2014

The Past

- 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

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

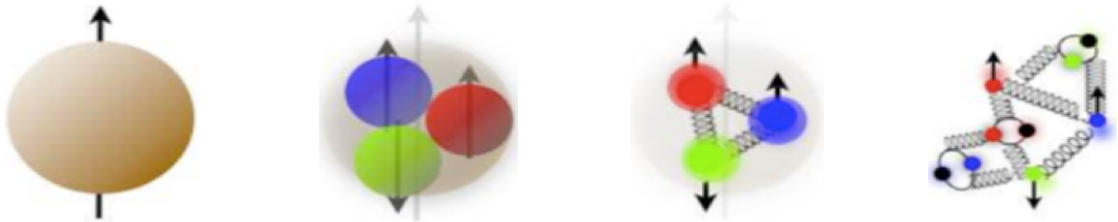
- "Spin crisis" or puzzle:
  - Strange sea polarization is sizable & negative
  - Very little of the proton spin is carried by quarks

New era of spin physics

Questions driving the spin physics

- How do quarks/gluons + their dynamics make up the proton spin?

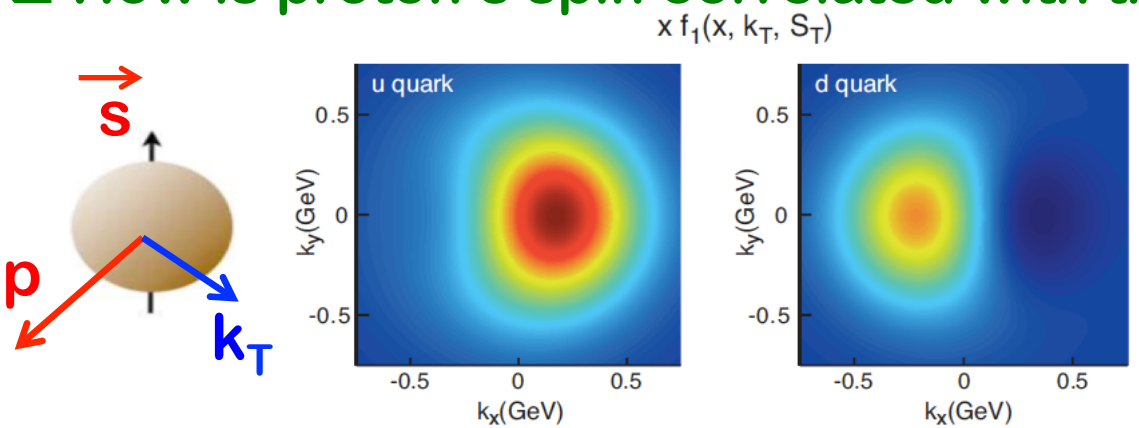
$$S(\mu) = \frac{1}{2}$$



$$\mu \Rightarrow \infty$$

Helicity distributions + orbital contribution

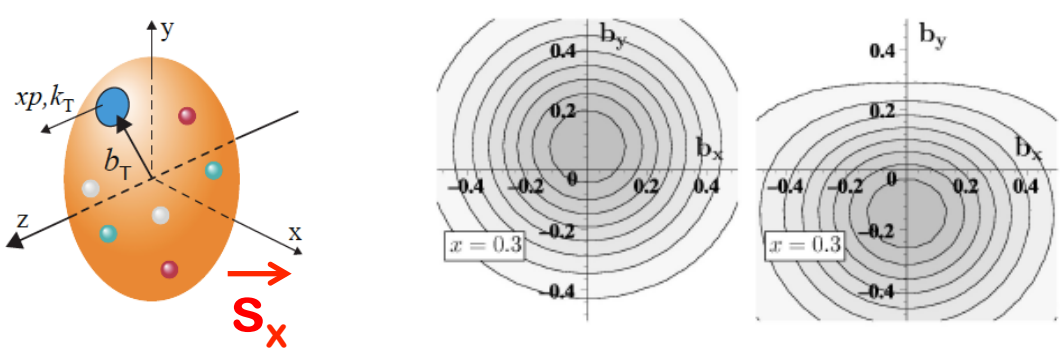
- How is proton's spin correlated with the motion of quarks/gluons?



Deformation of parton's *confined motion* when hadron is polarized?

TMDs!

- How does proton's spin influence the spatial distribution of partons?



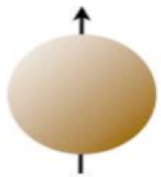
Deformation of parton's *spatial distribution* when hadron is polarized?

GPDs!

The Present: Proton Spin

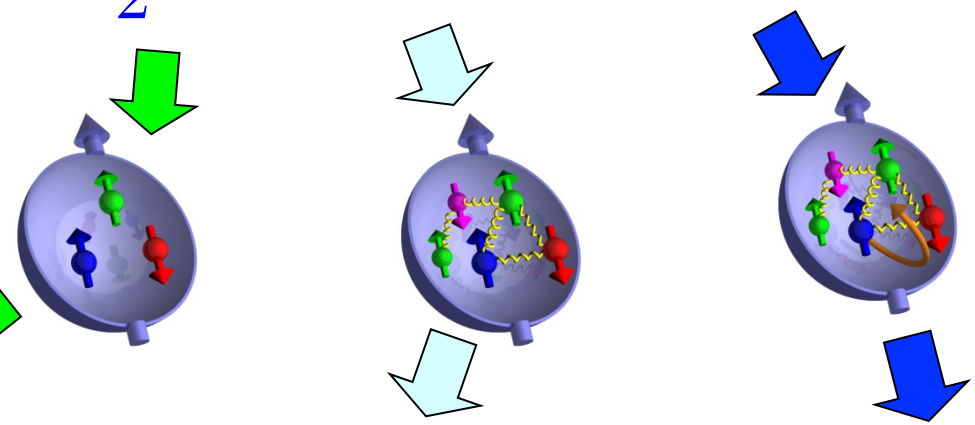
- **The sum rule:** $$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$
  - Infinite possibilities of decompositions – connection to observables?
  - Intrinsic properties + dynamical motion and interactions
- **An incomplete story:**

Jaffe-Manohar, 90
Ji, 96, …



Proton Spin

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



Quark helicity
Best known

$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$
$$\sim 30\%$$

Gluon helicity
Start to know

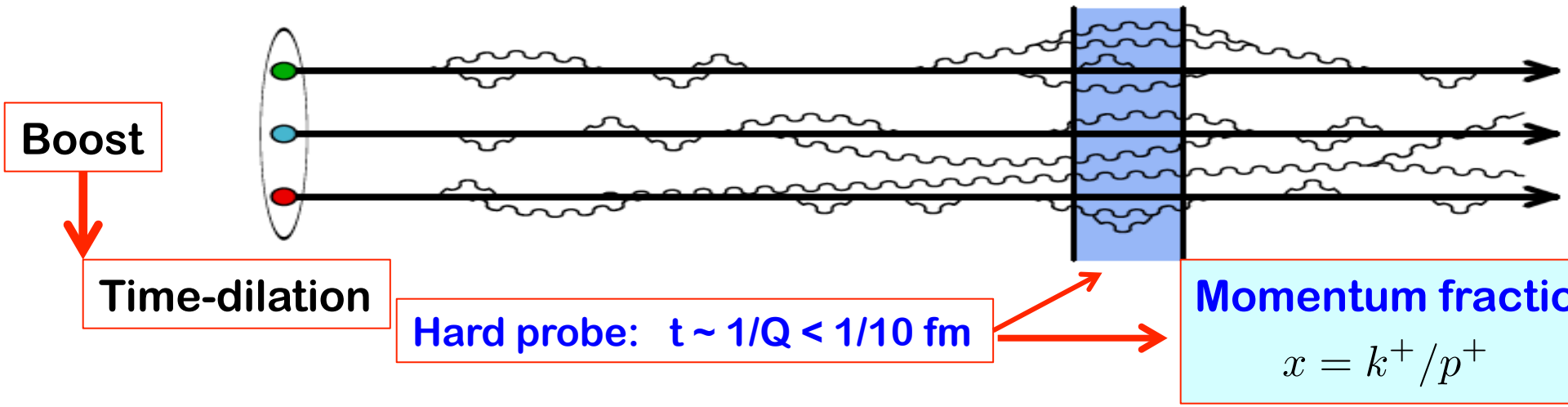
$$\Delta G = \int dx \Delta g(x)$$
$$\sim 20\%(\text{STAR Data})$$

Orbital Angular Momentum of quarks and gluons
Little known

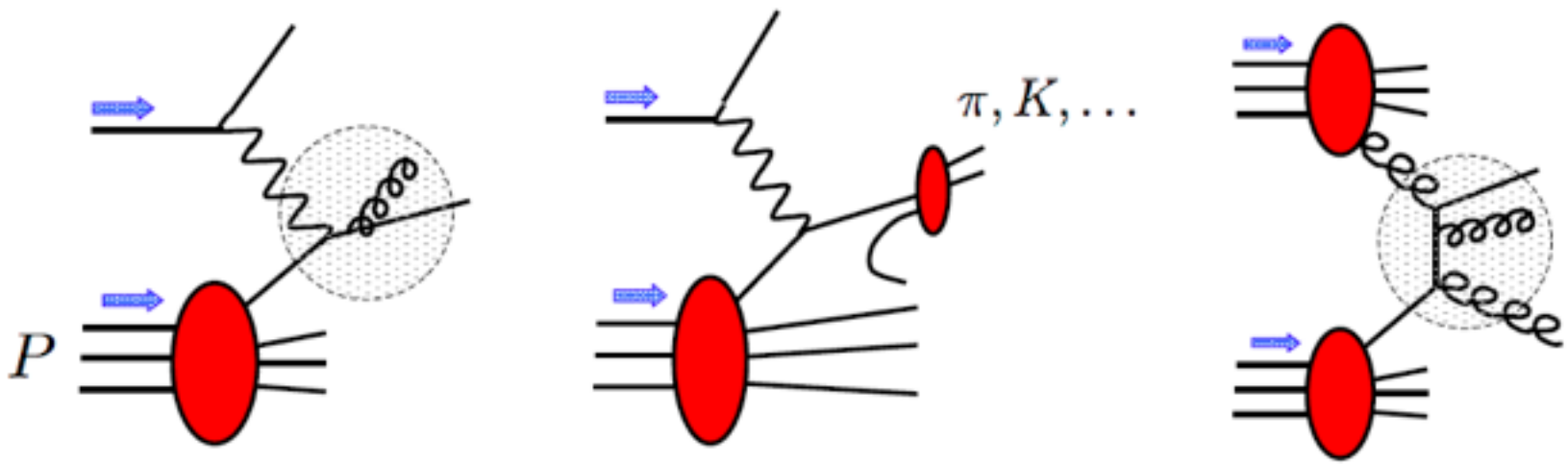
Net effect of partons' transverse motion?

Probes and facilities

- High energy scattering – to see quarks and gluons:



- Spin Probes:

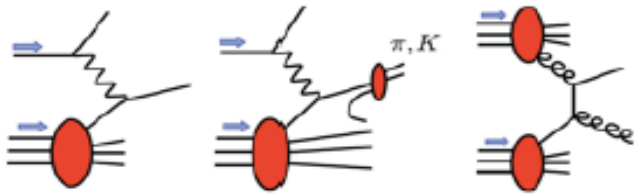


DIS SIDIS Hadron-hadron

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

Global fits for helicity PDFs @ NLO

Stratmann's talk
@BNL Users

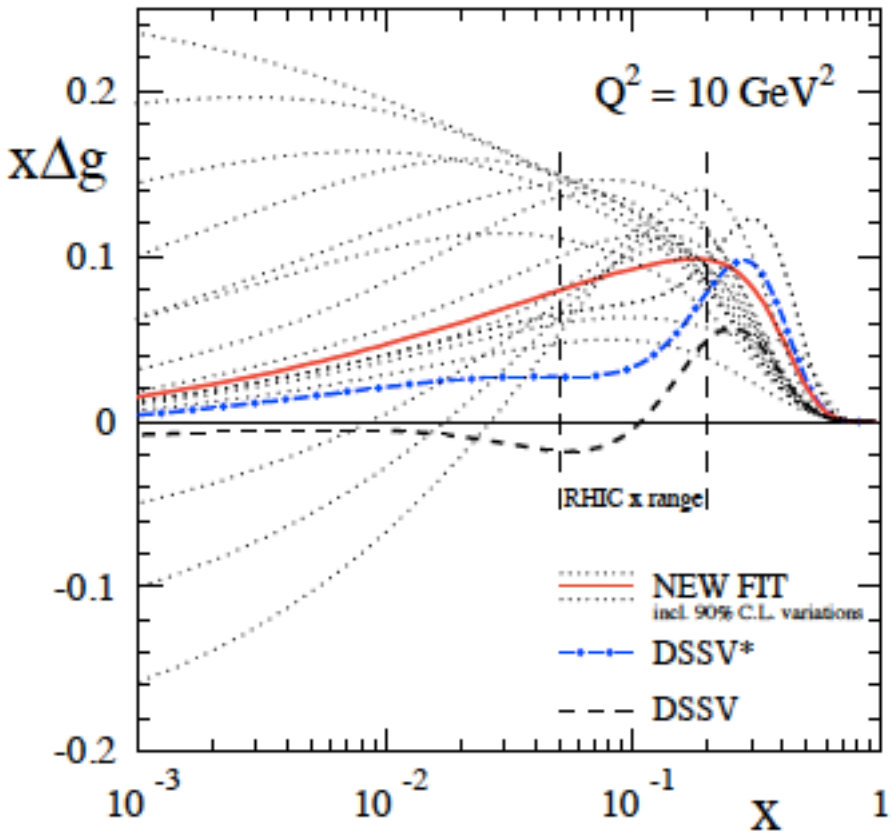


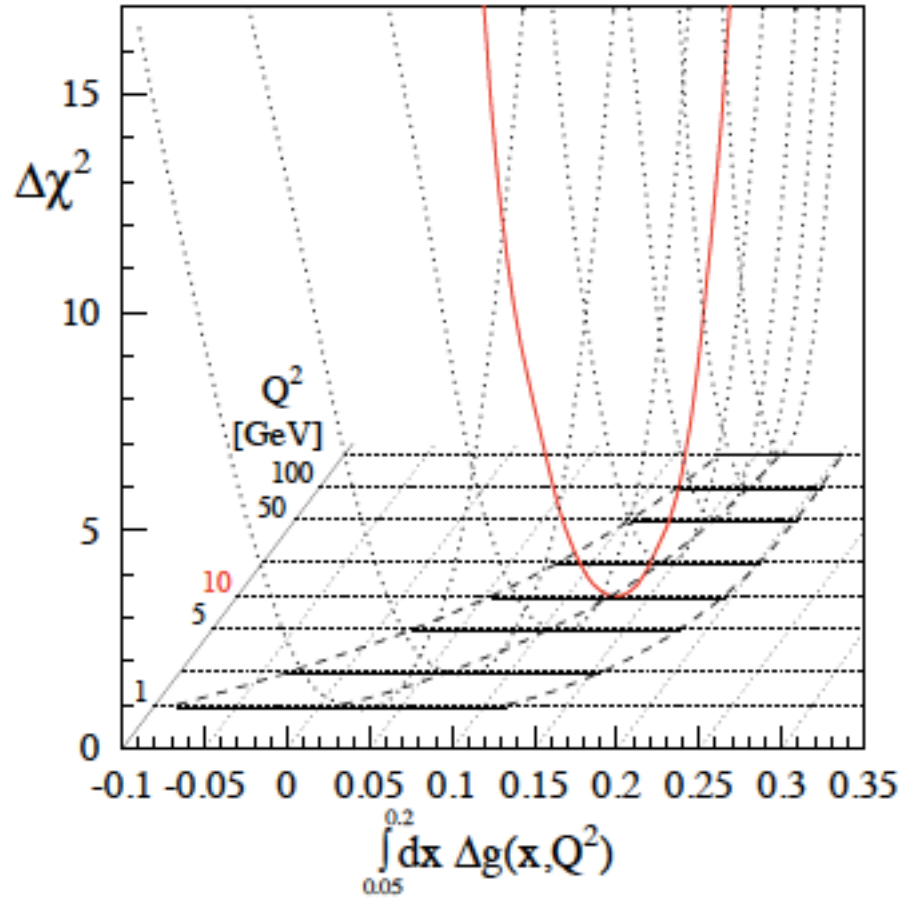
				uncertainties	last update
NNPDF Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo	✓	✗	✗	100 replicas stat. approach	1303.7236
DSSV de Florian, Sassot, MS, Vogelsang	✓	✓	✓	L.M. $\Delta\chi^2 = 8$ (1) (Hessian $\Delta\chi^2 = 1$)	0904.3821 [DSSV+/++: 1112.0904 1304.0079]
LSS Leader, Sidorov, Stamenov	✓	✓	✗	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

Highlights from new DSSV fits

de Florian, et al. 1404.4293

- Gluon polarization with new RHIC 2009 data:





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

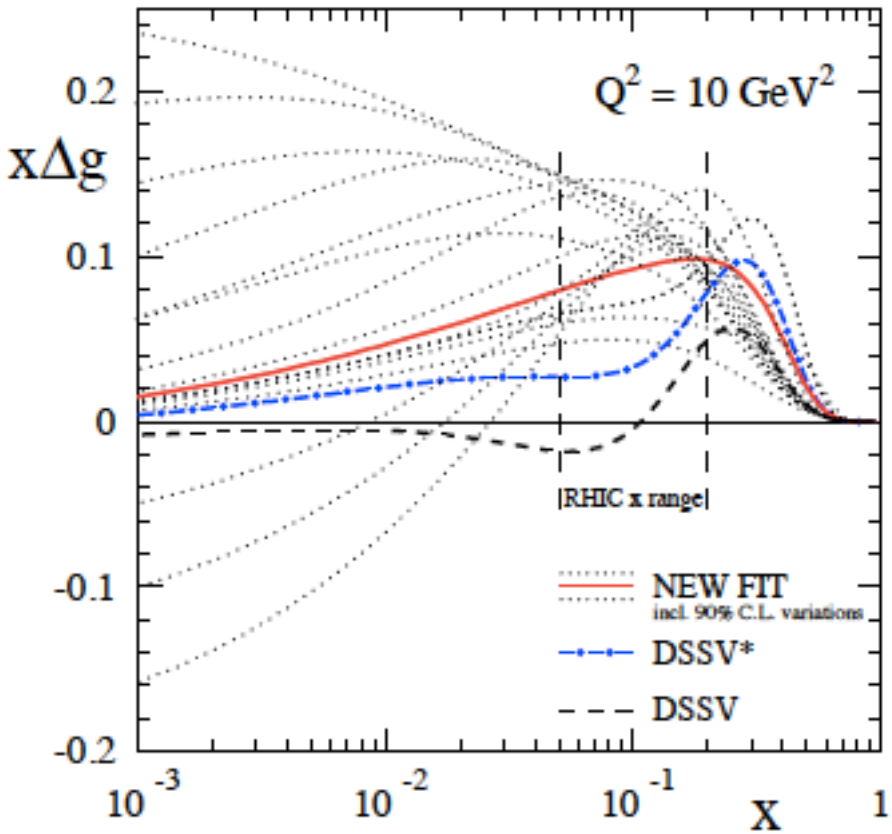
- ✧ Δg - moment from RHIC data
- ✧ Increase with Q^2
  Dashed lines – 90% C.L.

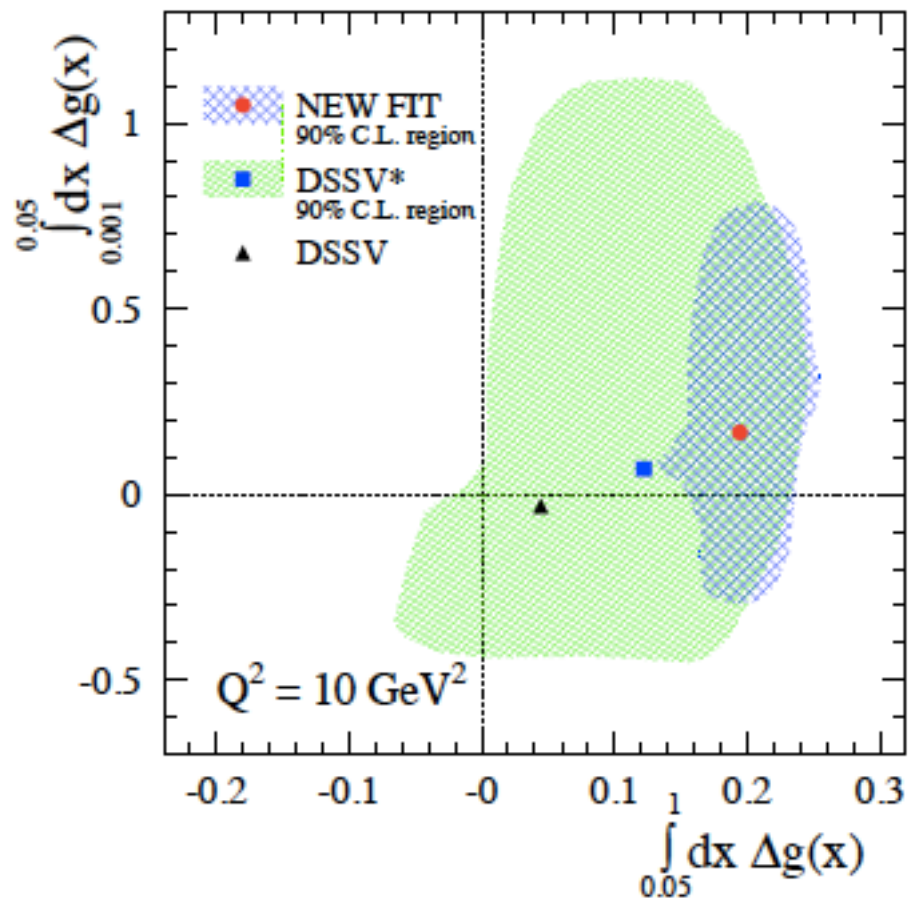
- Δg from COMPASS DIS data – talk by Stolarski, M.

Highlights from new DSSV fits

de Florian, et al. 1404.4293

❑ Gluon polarization with new RHIC 2009 data:





✧ Red line is the new fit

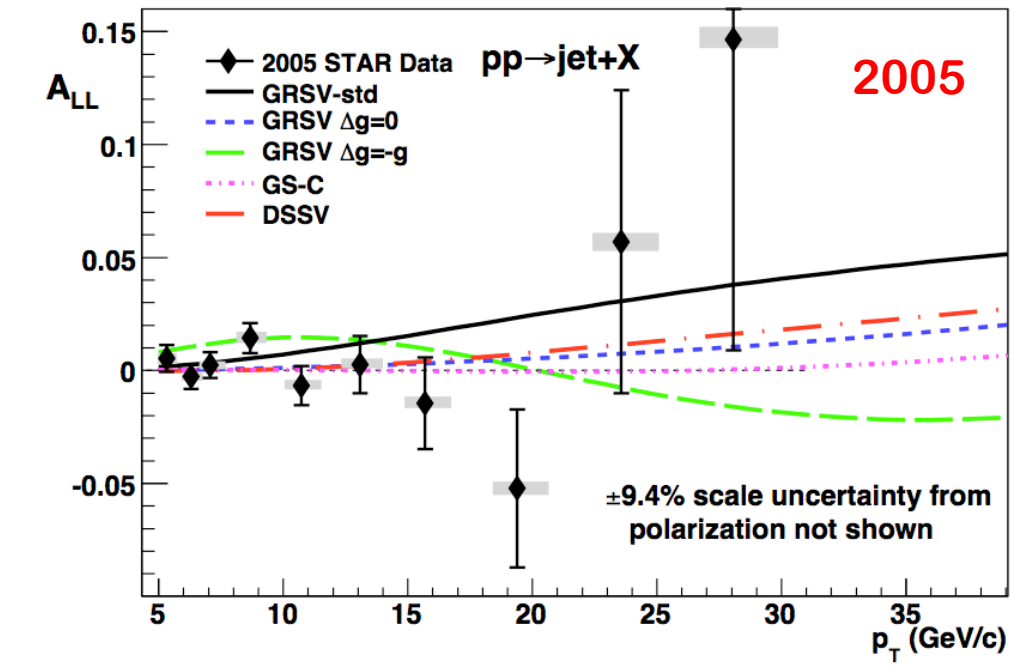
✧ Dotted lines
= Alternative fits with 90% C.L.

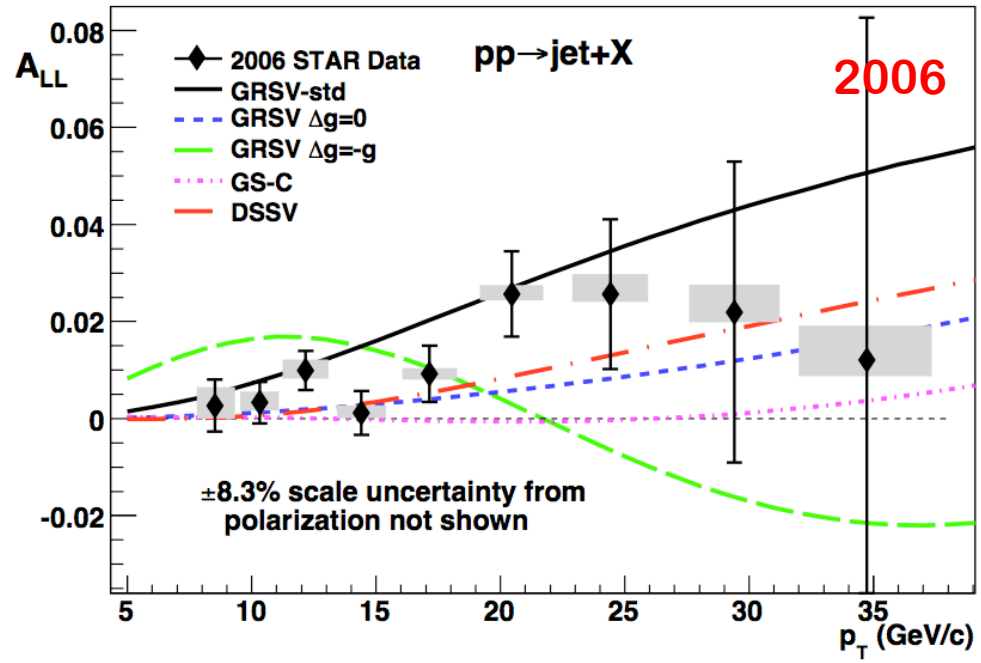
✧ 90% C.L. areas for truncated moments from
$0.001 < x < 0.05$, $0.05 < x < 1$

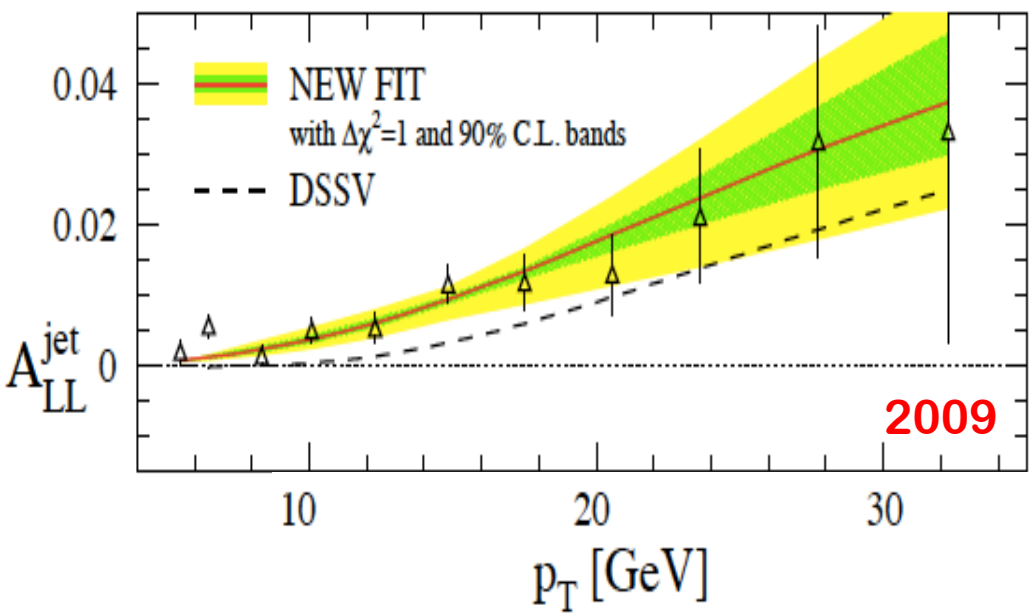
✧ Leads Δg to to a positive #

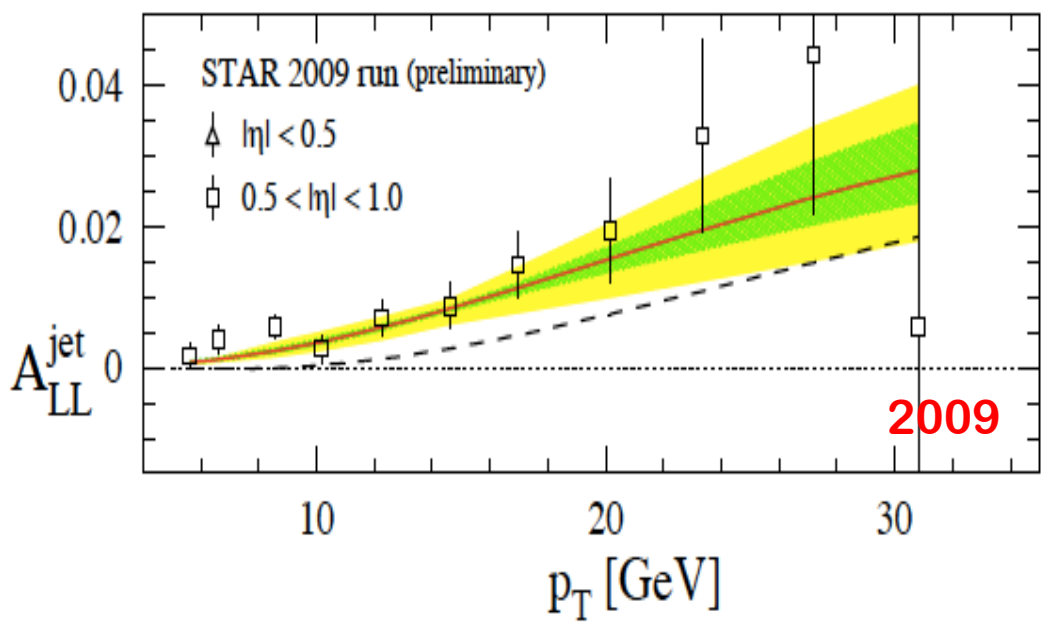
STAR data

Talk by Stevens, J.



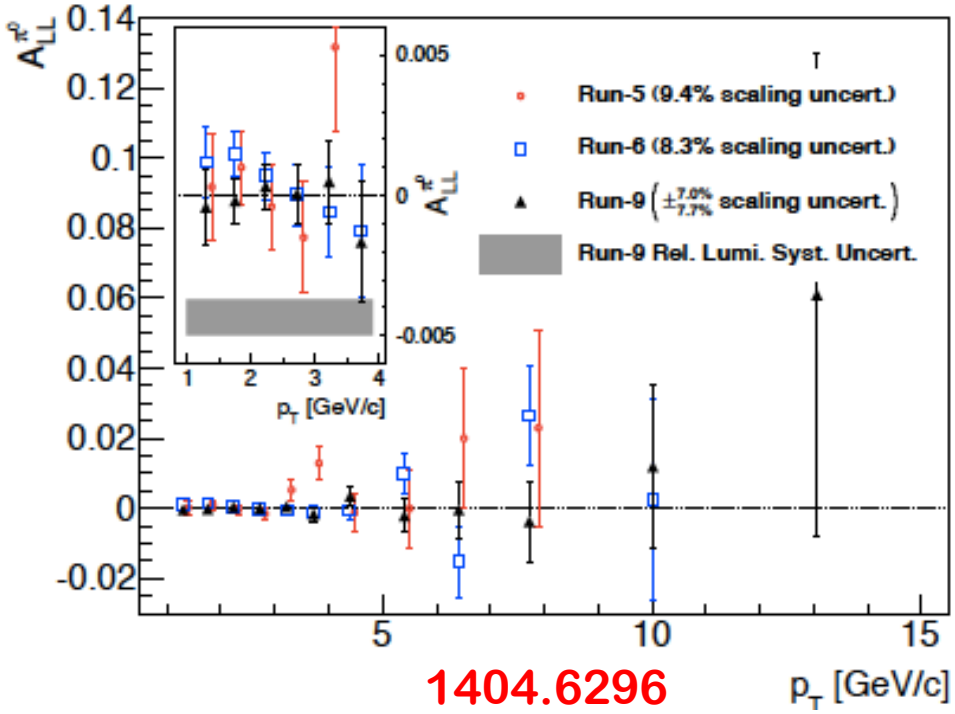




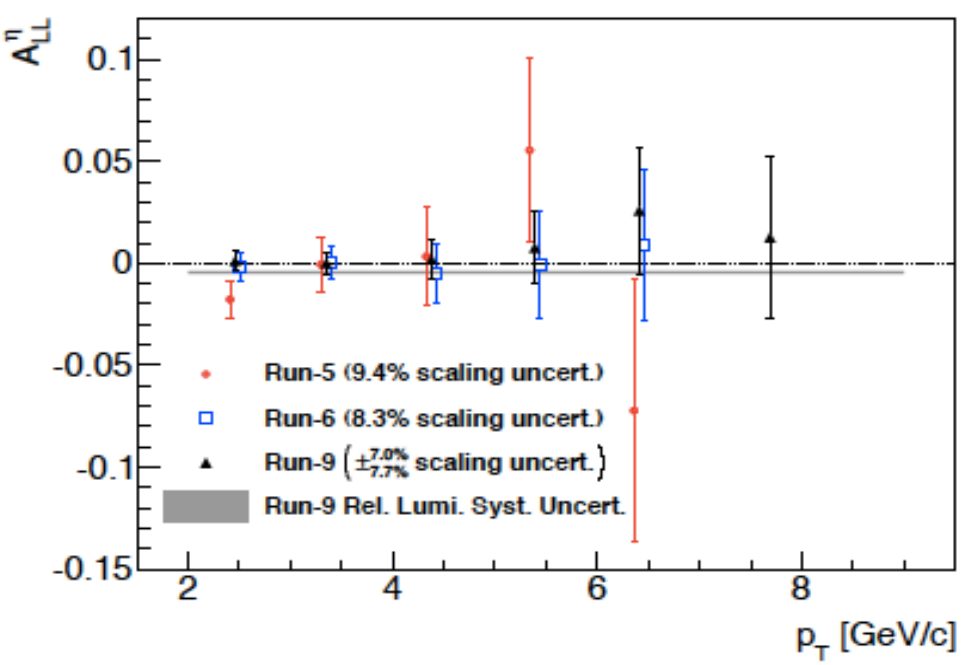


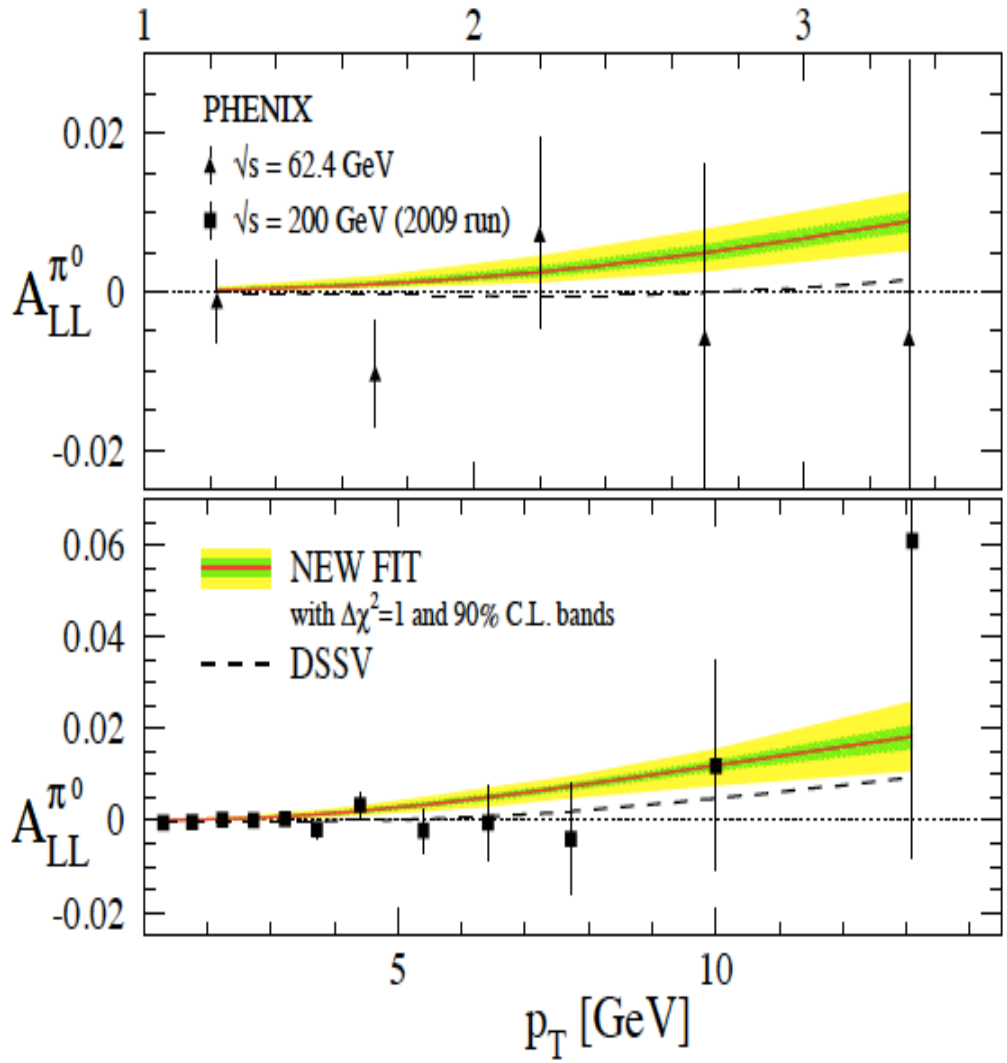
PHENIX data

Talk by Nakagawa, I.



1404.6296





Also di-jets – STAR
Di-hadrons - PHENIX

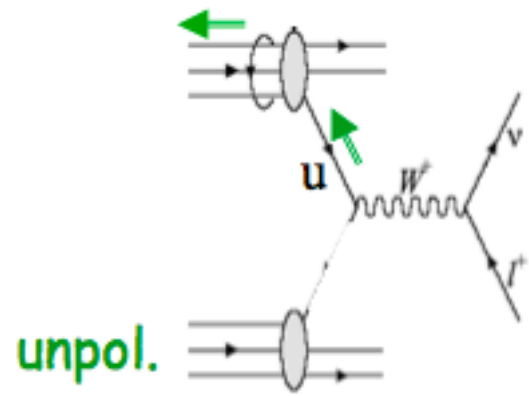
Quark Polarization – RHIC W program

Talks by Gal, Seidl, …

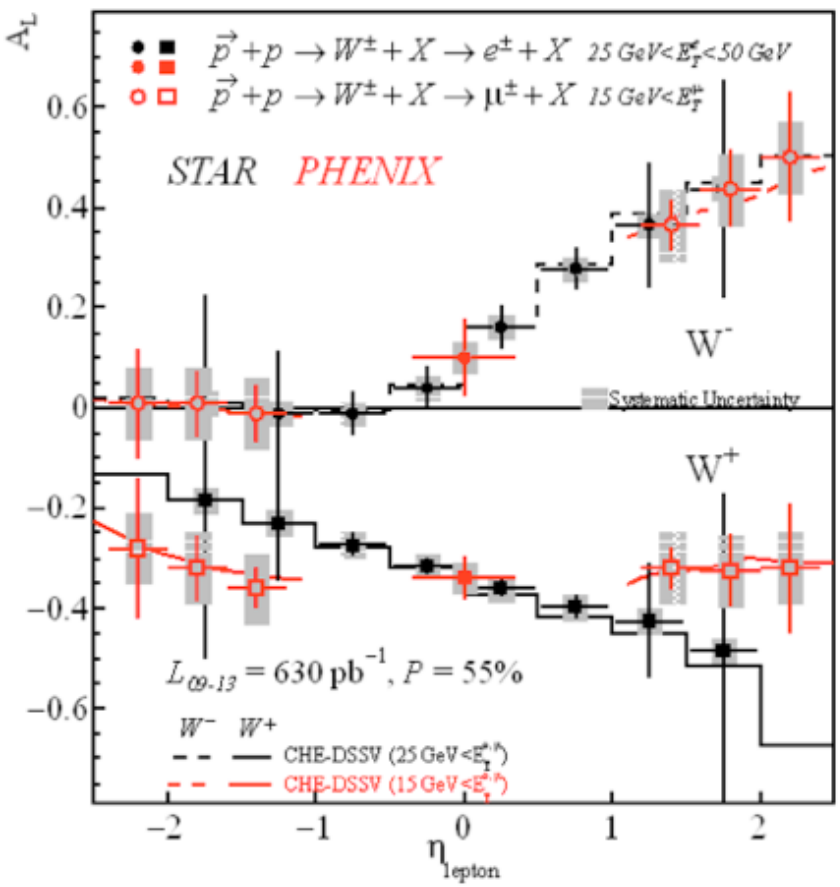
- **Single longitudinal spin asymmetries:**

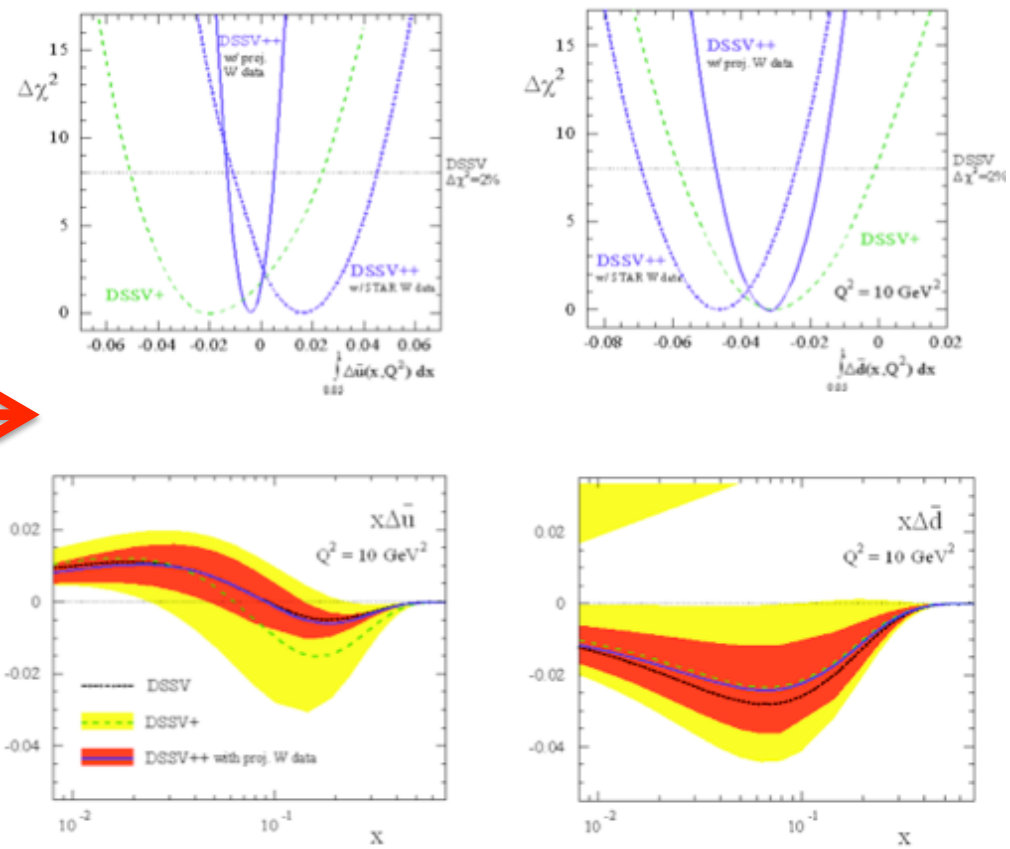
$$A_L = \frac{[\sigma(+) - \sigma(-)]}{[\sigma(+) + \sigma(-)]} \quad \text{for } \sigma(s)$$

Parity violating weak interaction



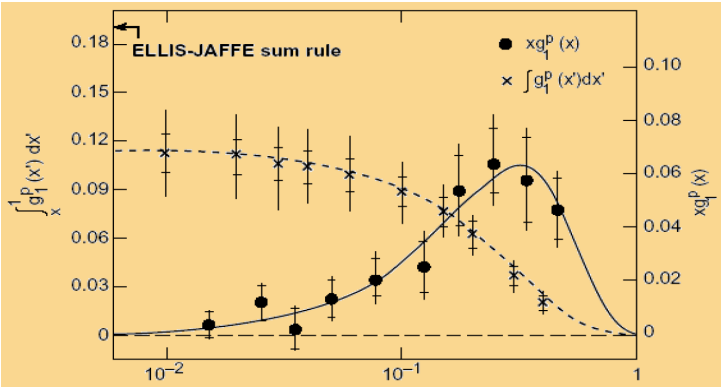
- **From 2013 RHIC data:**

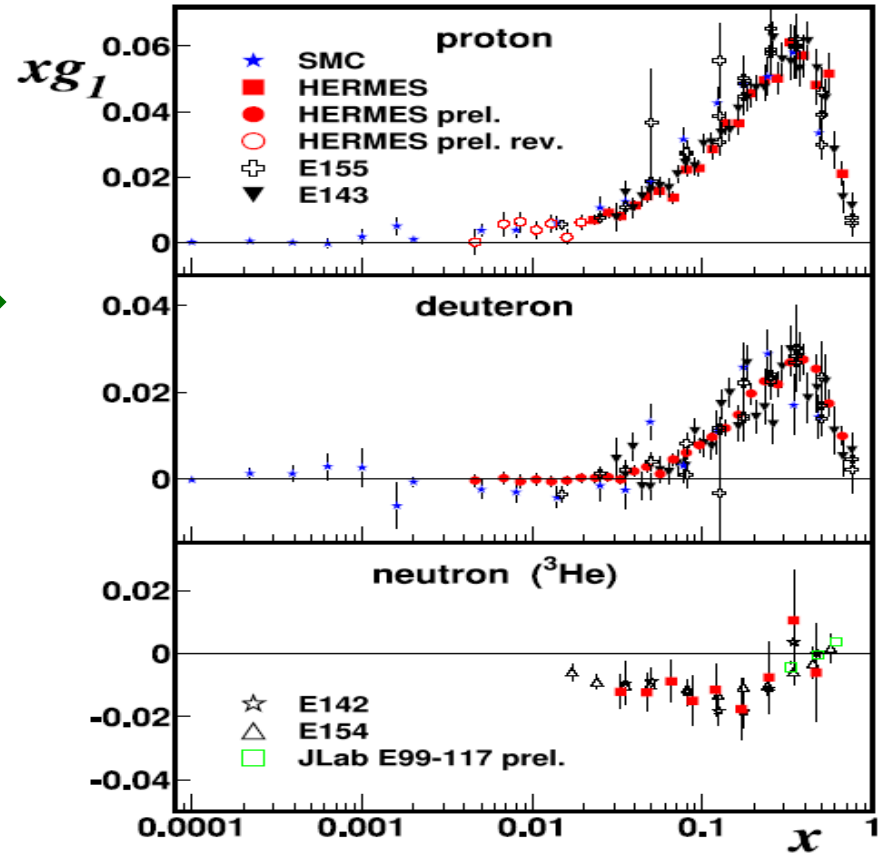




Inclusive DIS

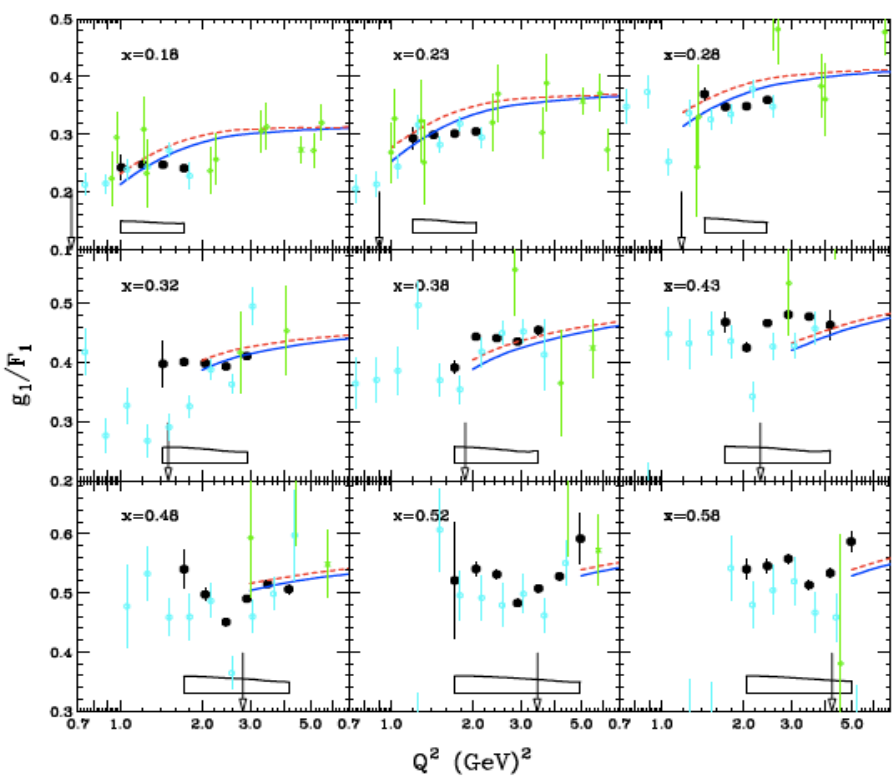
- The "Plot" is greatly improved:



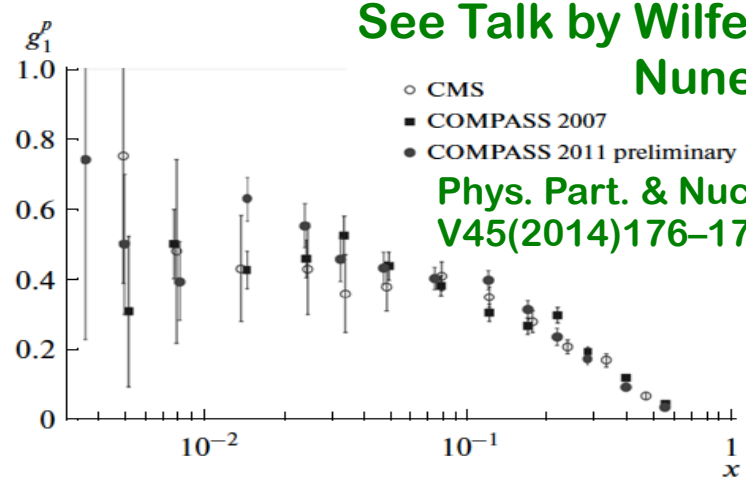


JLab/CLAS

arXiv:1404.6231



Lower Q^2 HT's



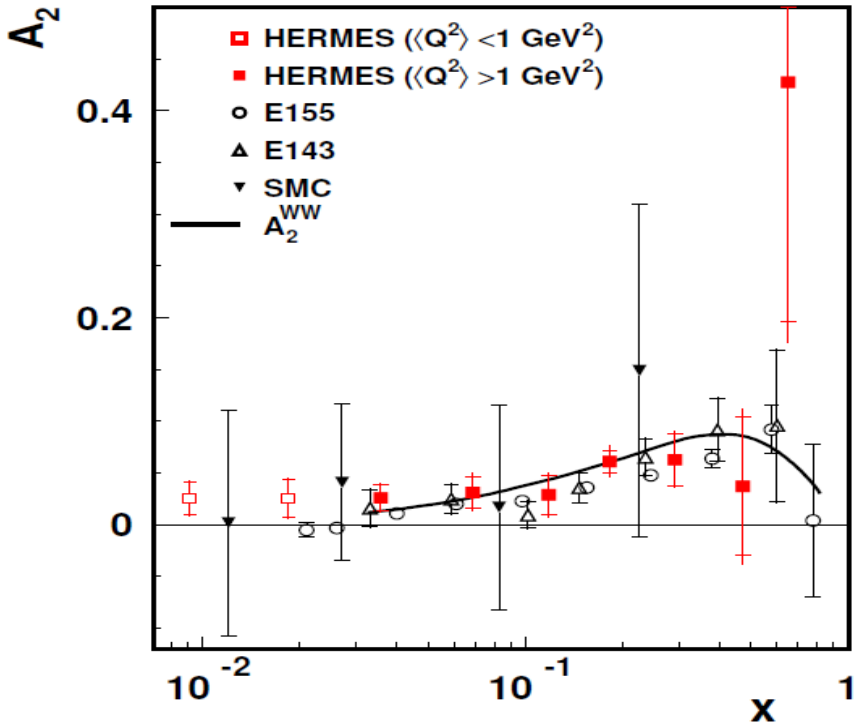
See Talk by Wilfert Nunes

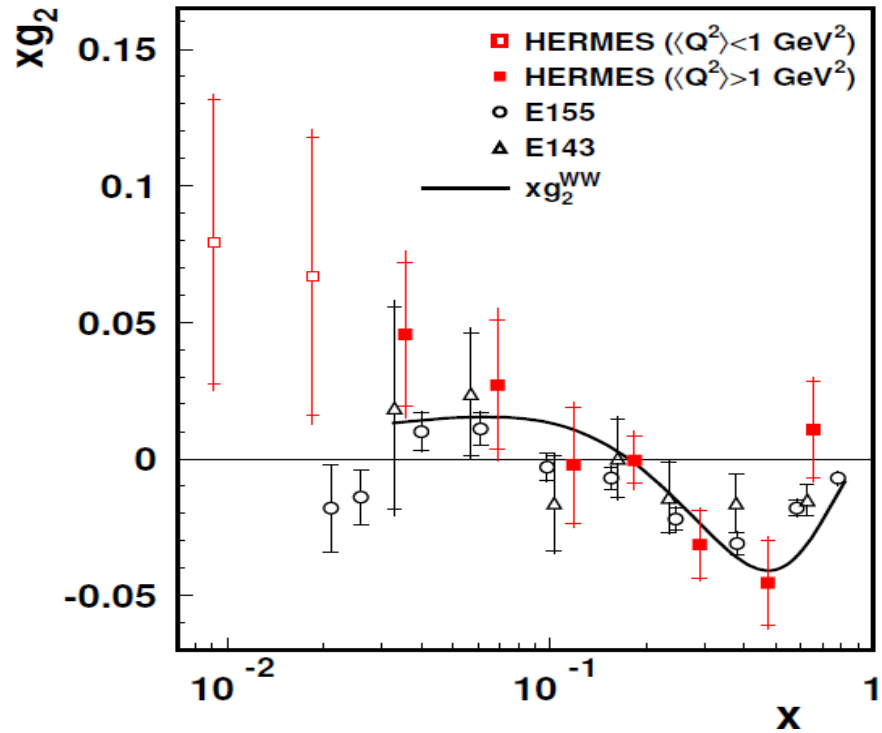
Phys. Part. & Nucl, V45(2014)176–178

Inclusive DIS

Van Hulse, Pan Pacific Spin '13

❑ g_2 - go beyond g_1^p:





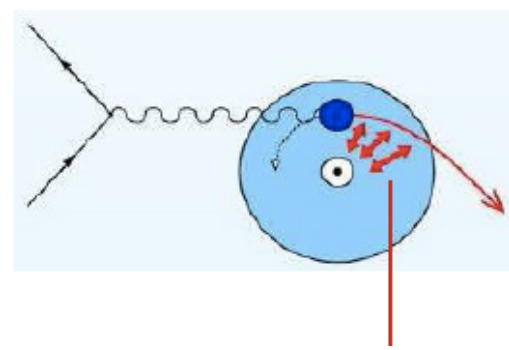
❑ Physics behind g_2 :

$$\bar{g}_2(x,Q^2) = g_2(x,Q^2) - g_2^{\mathrm{WW}}(x,Q^2),$$

$$g_2^{\mathrm{WW}}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)dy/y,$$

$$d_2 = 3\int_0^1 dx x^2 \bar{g}_2(x) = \int_0^1 dx x^2 \left[3g_2(x) + 2g_1(x)\right]$$

M. Burkardt



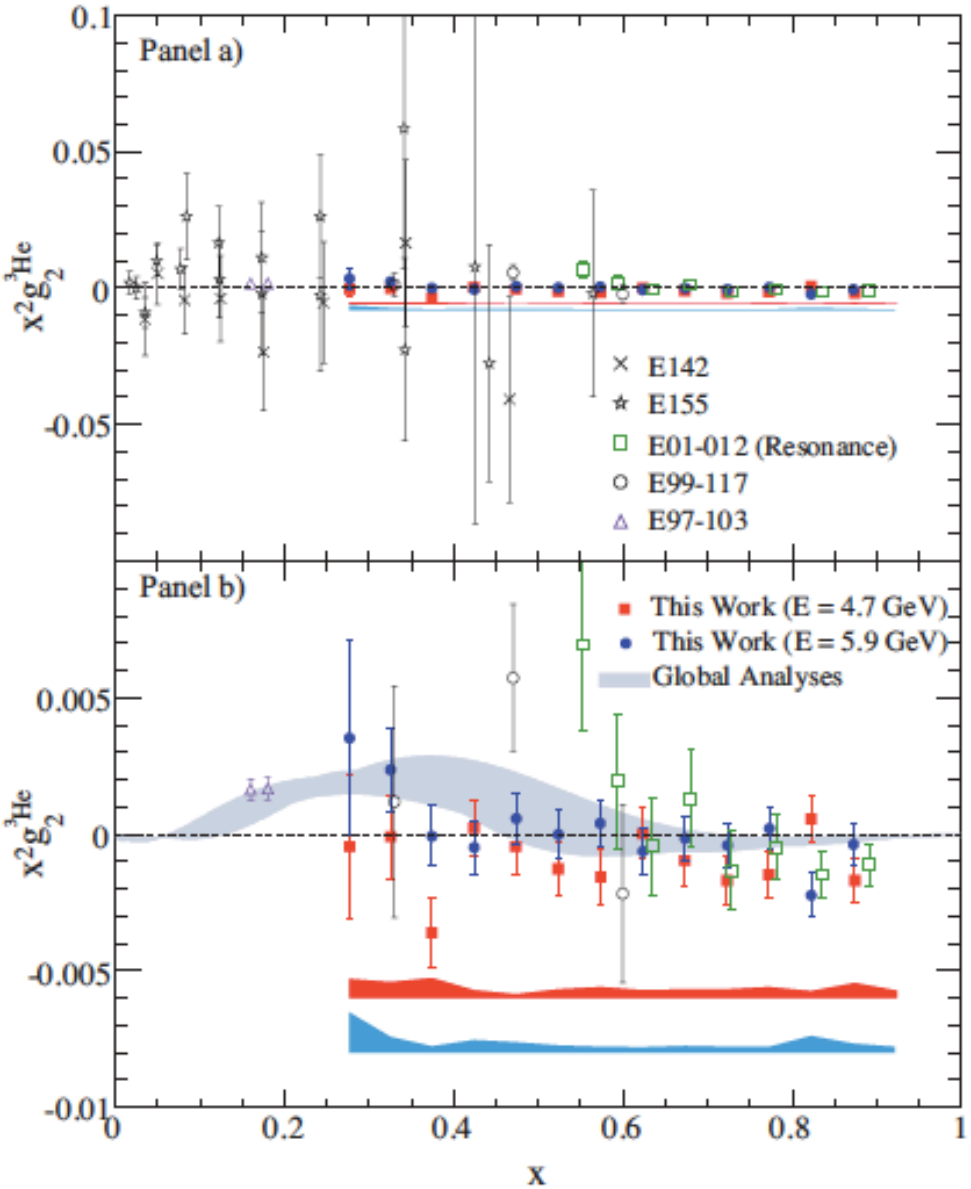
force on struck quark at t=0

$\propto -d_2$

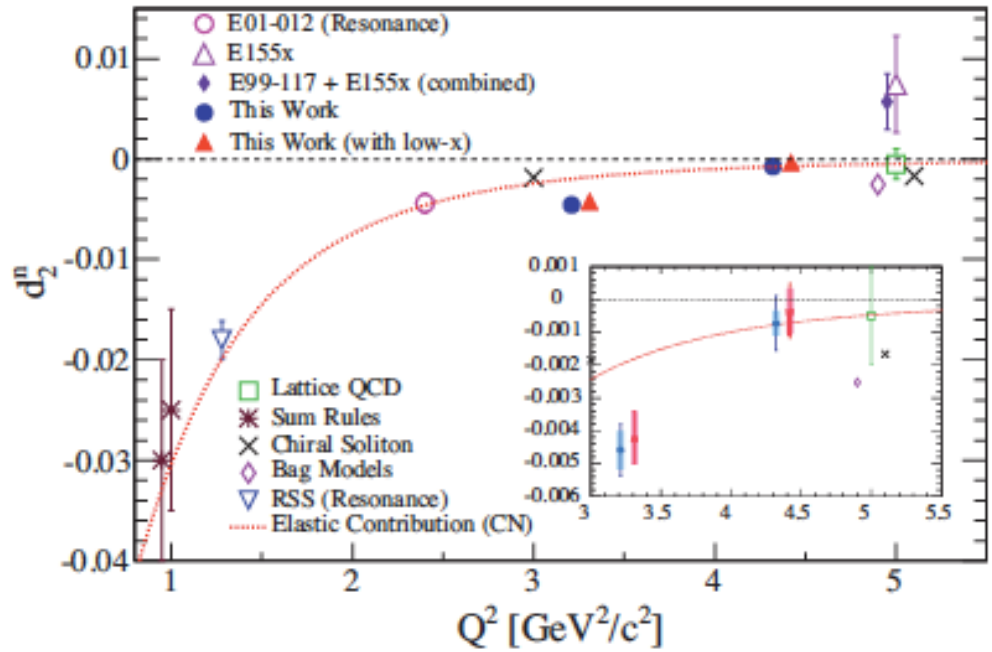
Inclusive DIS

arXiv:1404.4003

❑ Jlab/Hall A - precision d_2^n on ^{3}He:



$$d_2 = 3\int_0^1 dx x^2 \bar{g}_2(x) = \int_0^1 dx x^2 \left[3g_2(x) + 2g_1(x)\right]$$



Color electric/magnetic force: Burkardt

$$F_E = -\frac{M^2}{4}\chi_E = -\frac{M^2}{4}\left[\frac{2}{3}(2d_2 + f_2)\right]$$

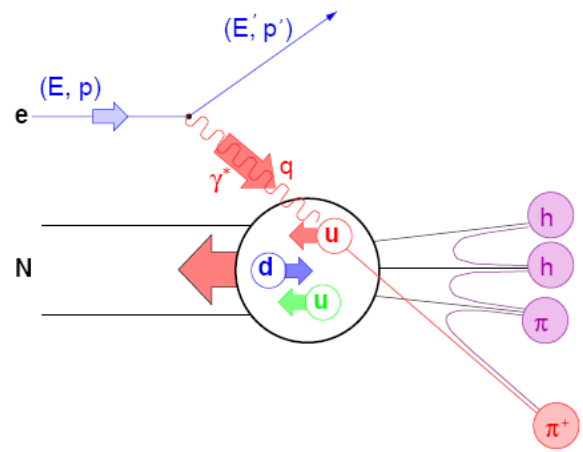
$$F_B = -\frac{M^2}{2}\chi_B = -\frac{M^2}{2}\left[\frac{1}{3}(4d_2 - f_2)\right]$$

Claim: $f_2^n \gg d_2^n$ → $F_E \sim -F_B$

The Future: Challenges & opportunities

- Quark polarization – better determined:
  - Quark polarization at x → 1 – challenges
- Sea quark polarization – not well-determined:
  - SIDIS @ EIC

    A sizable contribution to the proton spin
    (~ 6%, current global fittings)



- Gluon polarization – need small-x region:
  - Inclusive DIS + SIDIS @ EIC

    Current small-x technique for unpolarized gluon
    Need to develop new technique to treat polarized small-x glue

- Lattice QCD to calculate PDFs, not the moments:
  - Quasi-PDFs ~ two-parton correlators along z-axis ≠ PDFs

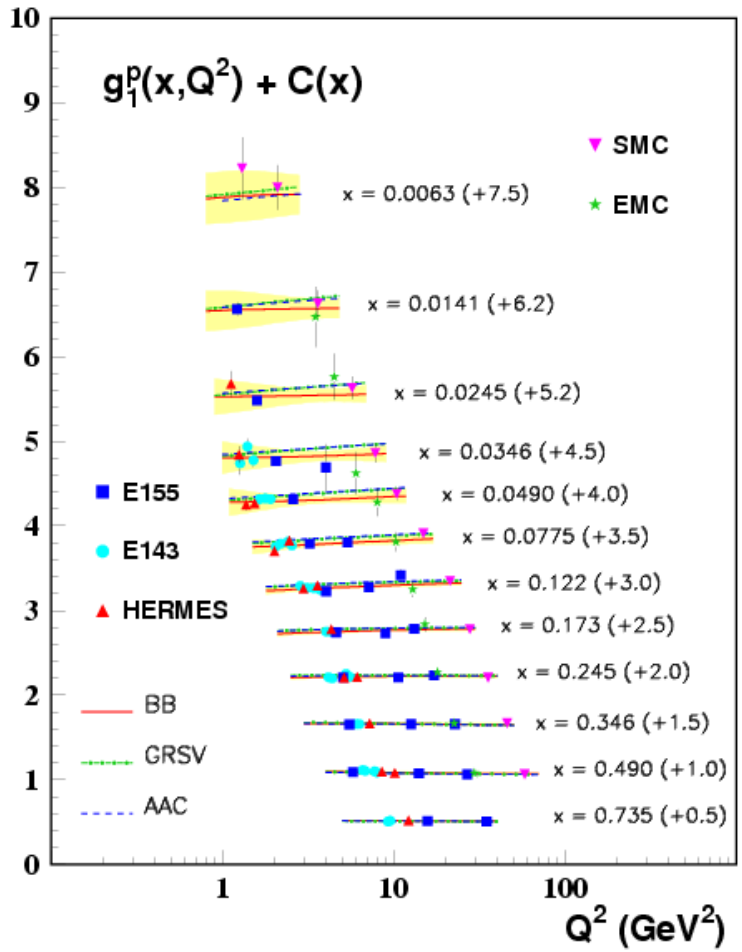
    → Normal PDFs as $P_z \to \infty$ — *X.D. Ji, H. Lin, …*

    → Factorized to Normal PDFs at a finite P_z — *Y.-Q. Ma, J.W. Qiu*

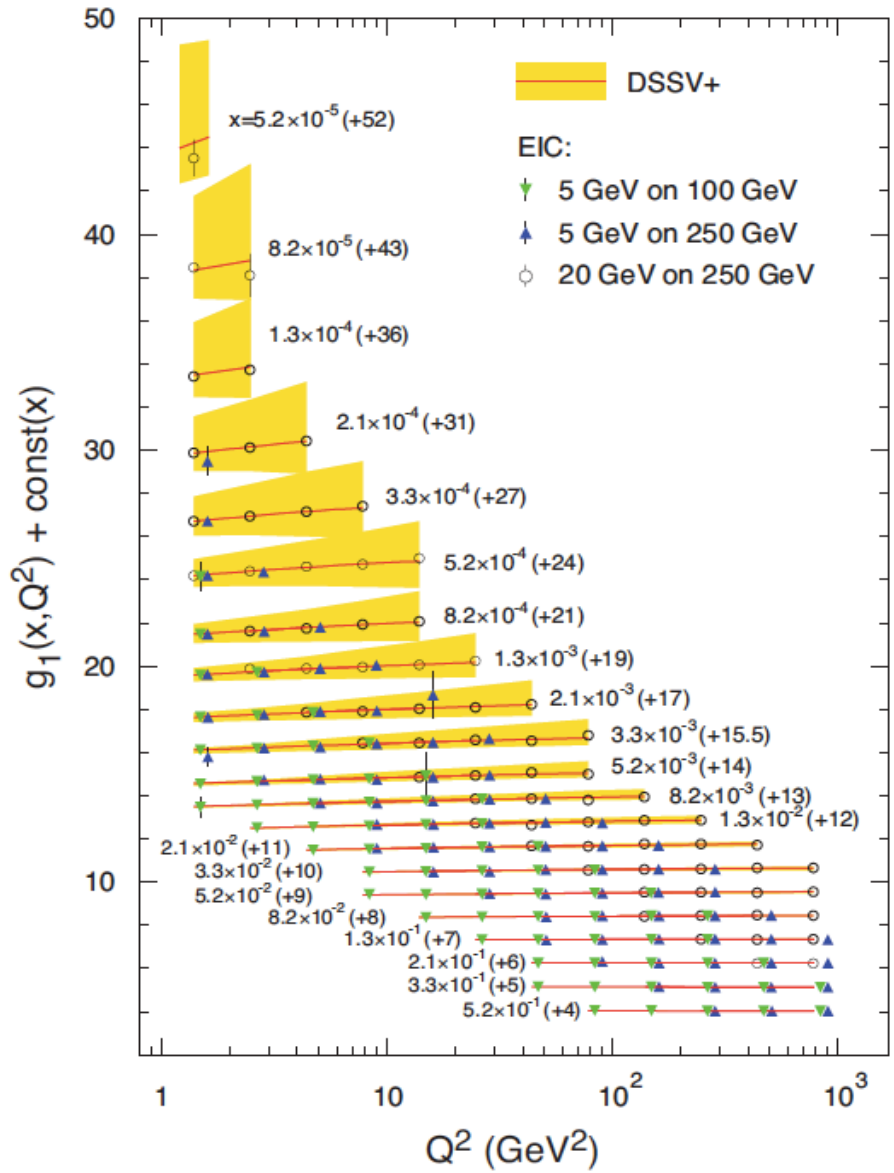
    Global analysis of lattice "data" for PDFs

The Future: Challenges & opportunities

- The power & precision of EIC:



at EIC



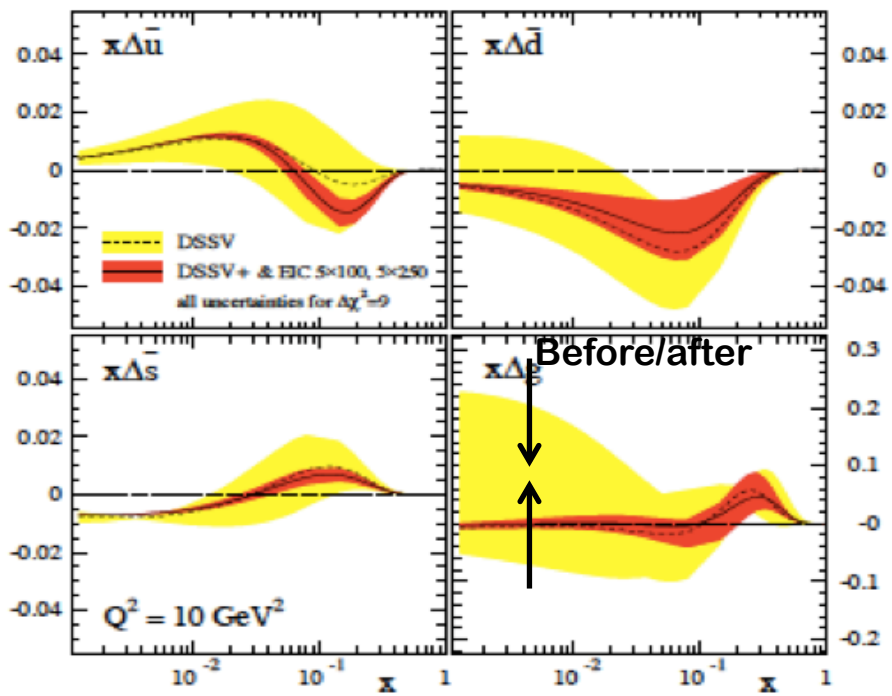
- Reach out the glue:

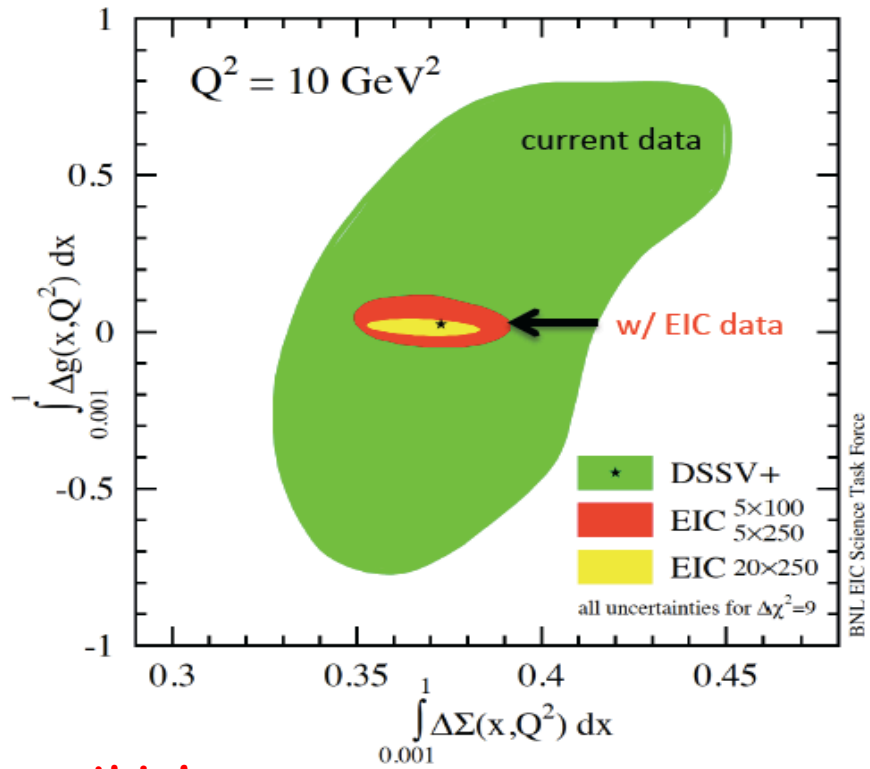
$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

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!***

Additional talks in parallel sessions

❑ Tuesday – WG6:

Measurements of parity violating spin asymmetries of the W boson (to e) at mid-rapidity with the PHENIX Detector at RHIC *Mr. Ciprian GAL*

PHENIX W to mu measurements in polarized proton-proton collisions *Dr. Ralf SEIDL*

Hermes reevaluation of the Parton Distribution of Strange Quarks in the Nucleon *F. GIORDANO*

First results on A_1 and g_1^p at low x and low Q^2 from COMPASS *Ana Sofia NUNES*

Single hadron double longitudinal spin asymmetries at $p_T < 1$ GeV/c measured at COMPASS *Maxime LEVILLAIN*

Unbiased helicity-dependent parton distributions with polarized collider data *Emanuele Roberto NOCERA*

❑ Wednesday – WG7:

eRHIC: An Electron-Ion Collider at BNL *Elke-caroline Aschenauer*

Physics opportunities at th MEIC at JLab *Pawel Nadel-Turonski*

❑ Thursday – WG6:

The g_2 Spin Structure Function *Ms. Melissa CUMMINGS*

Hunting for orbital angular momentum

Talk by Lorce, C.

❑ Orbital angular momentum:

$$L_q \equiv J_q - \frac{1}{2}\Delta\Sigma$$

Ji '96

$$J_q = \int_0^1 x\,(H_q + E_q)\,dx$$

= Hadronic matrix element of local operator

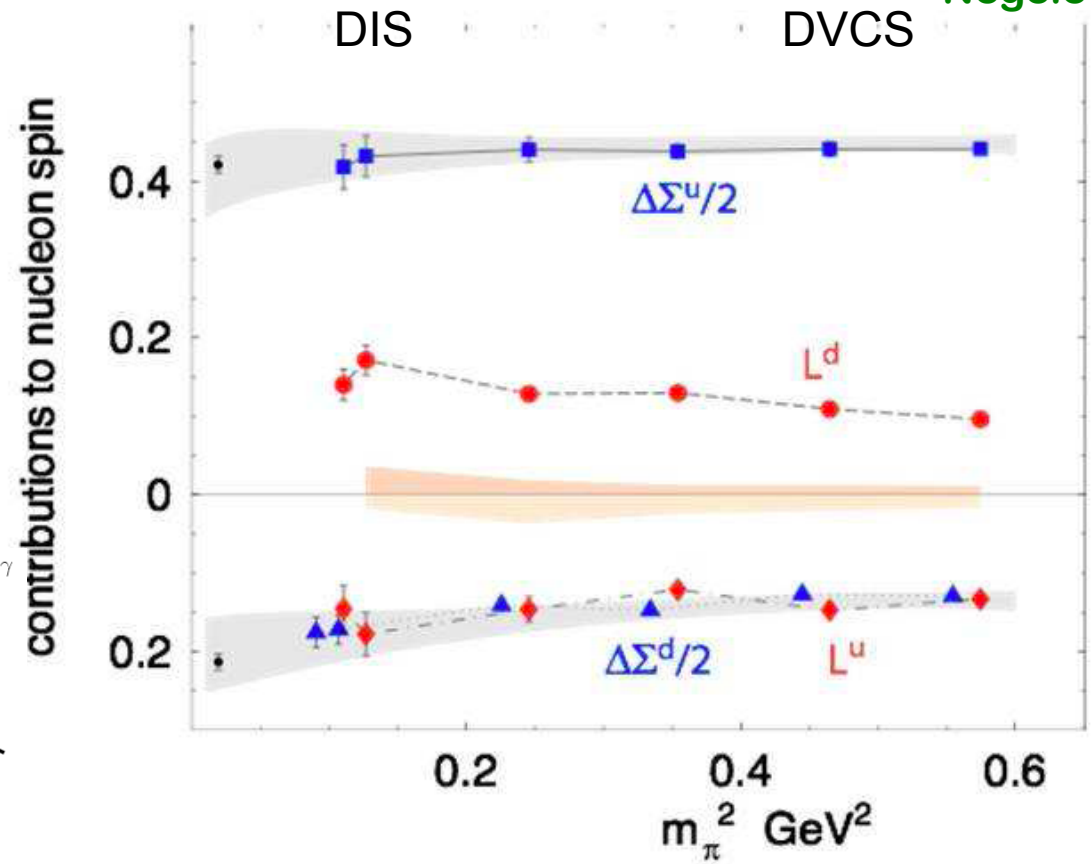
Calculable in Lattice QCD!

Experimental Extraction of GPDs

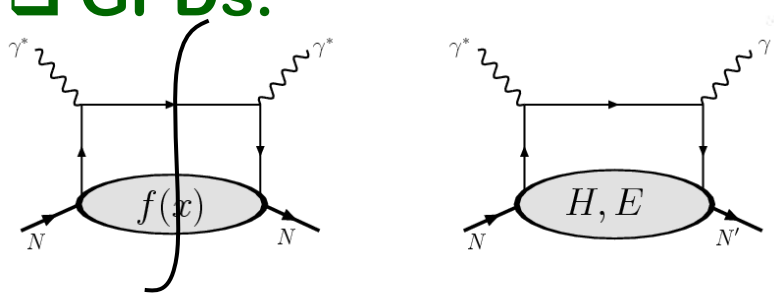
Both L_u amd L_d large

But, $L_u + L_d \sim 0$

Negele et al



❑ GPDs:



PDFs, TMDs

GPDs, GTMDs

The present: GPDs

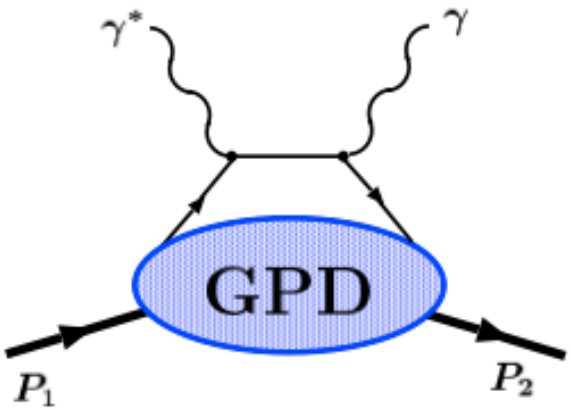
Mueller et al., 94;
Ji, 96;
Radyushkin, 96

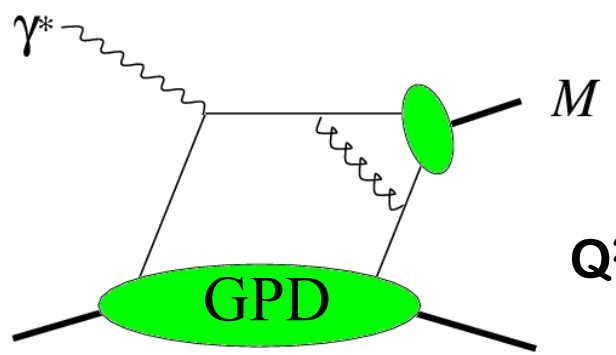
❑ Experimental access to GPDs:

✧ Diffractive exclusive processes – high luminosity:

DVCS: Deeply virtual Compton Scattering
DVEM: Deeply virtual exclusive meson production

✧ No factorization for hadronic processes – EIC is ideal:





Require

$Q^2 >> (-t), \Lambda^2_{QCD}, M^2$

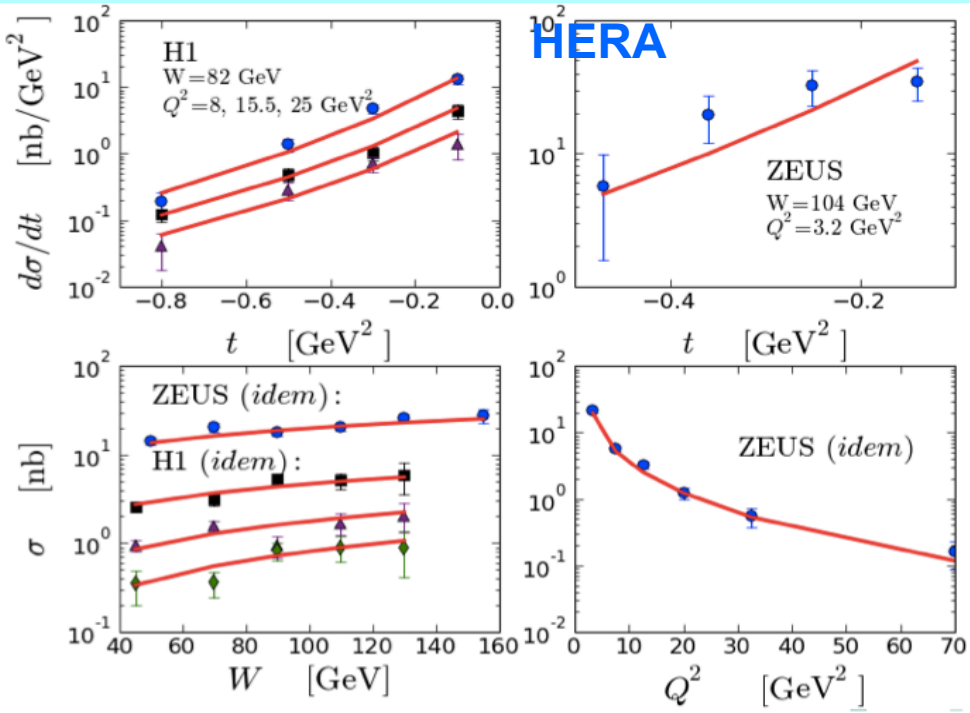
❑ Much more complicated – (x, ξ, t) variables:

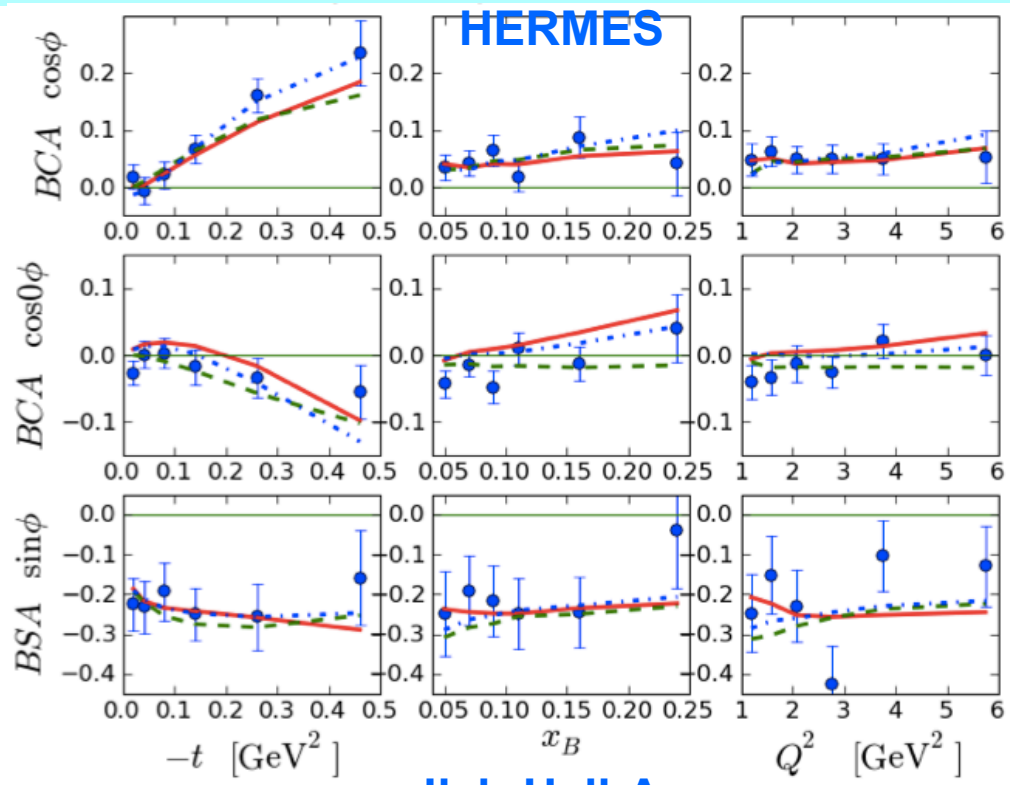
Challenge to derive GPDs from data

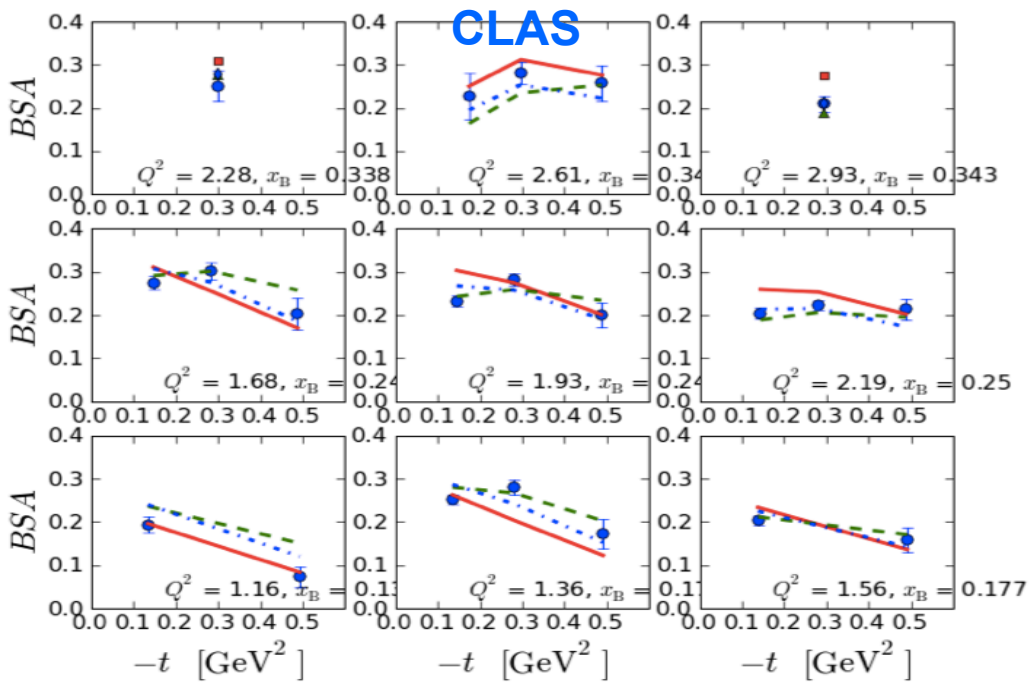
❑ Great experimental effort:

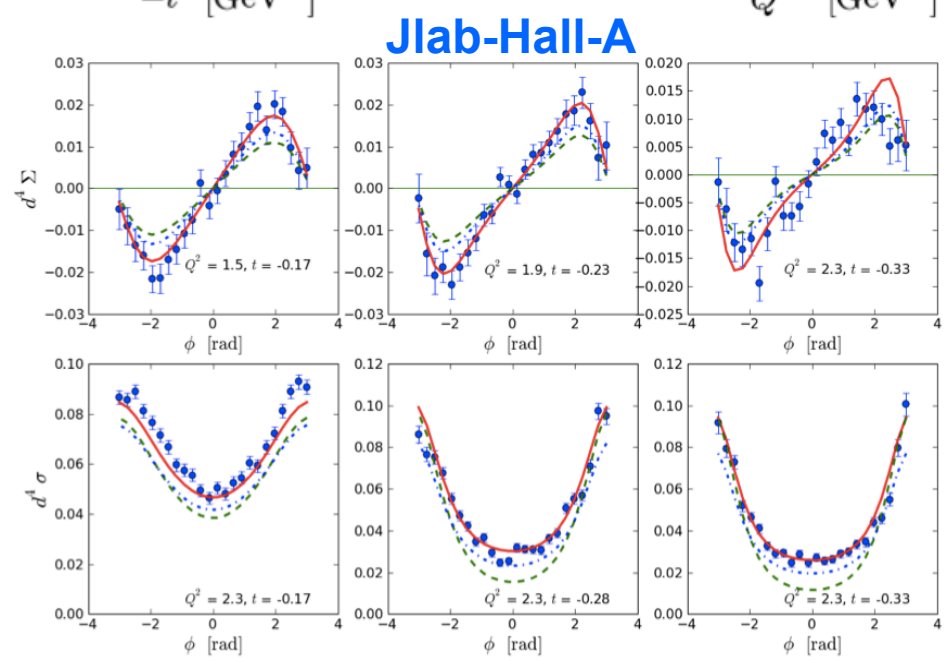
HERA, HERMES, COMPASS, JLab → JLab12, COMPASS-II, EIC

The present: GPDs



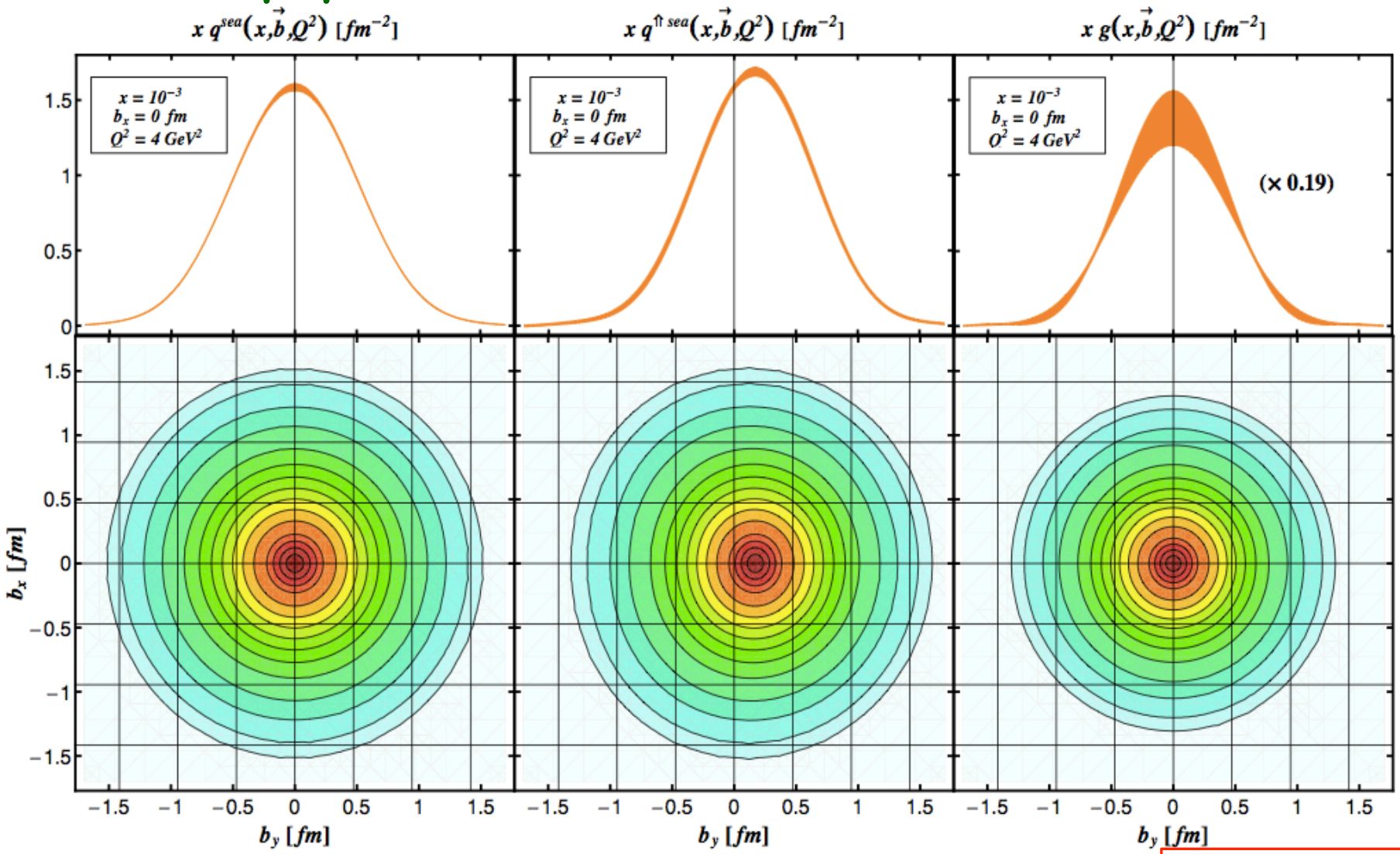






The Future: Spatial Imaging

- **EIC Whitepaper:**



$$q(x,|\vec{b}|,Q^2) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0(|\vec{b}|\sqrt{|t|})\, H(x,\xi=0,t,Q^2)$$

Quark radius?
Sea radius?
Gluon radius?

Additional talks in parallel sessions

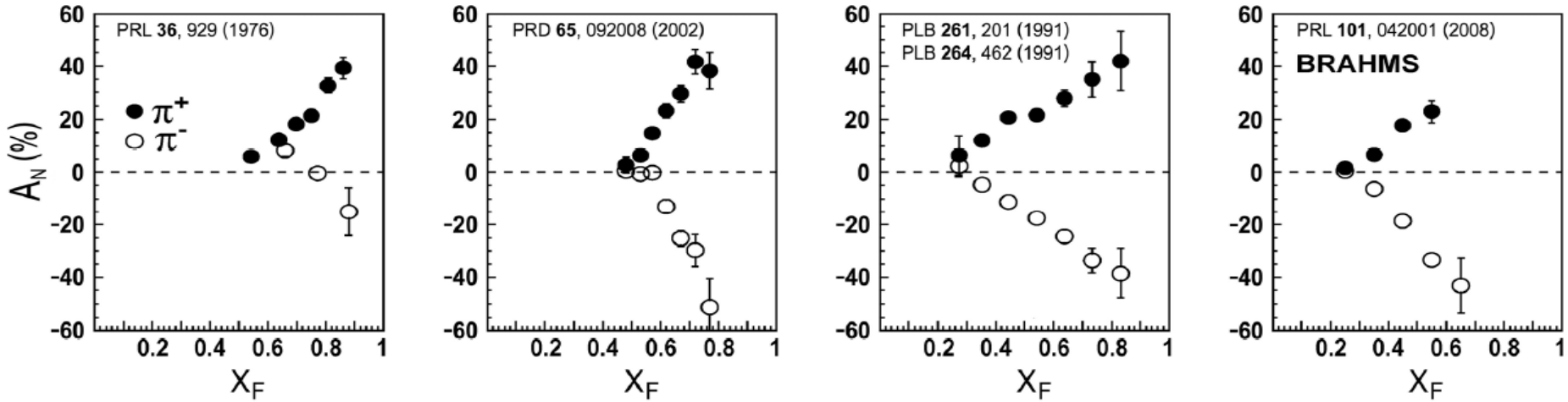
❑ Thursday – WG6:

Deeply Virtual Compton Scattering to the twist-four accuracy: Impact of finite-t and target mass corrections	*Vladimir BRAUN*
Crossed channel analysis of quark and gluon Generalized parton distributions with helicity flip	*Dr. Kirill SEMENOV-TIAN-SHANSKY*
A classification of chiral-odd pion generalized parton distributions beyond leading twist	*Samuel WALLON*
Transverse densities in the nucleon's chiral periphery	*Carlos GRANADOS*
DVCS measurements at HERMES	*Klaus RITH*
Single and double polarization asymmetries from deeply virtual exclusive π^0 electroproduction	*Andrey KIM*
JLab/Hall A Deeply Virtual Compton Scattering results	*Franck SABATIÉ*
Exclusive meson production at COMPASS	*Pawel SZNAJDER*

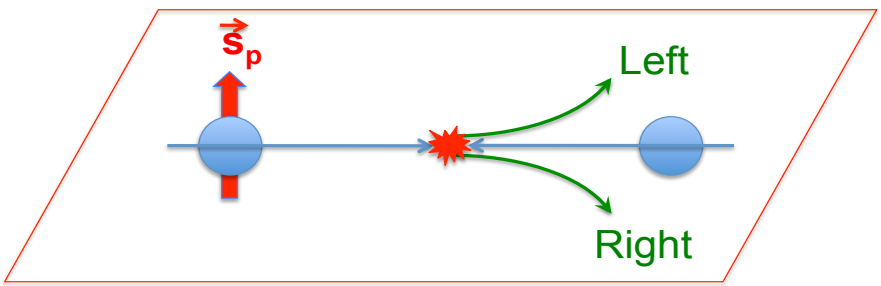
The Present: TMDs

- A_N - consistently observed for over 35 years!

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



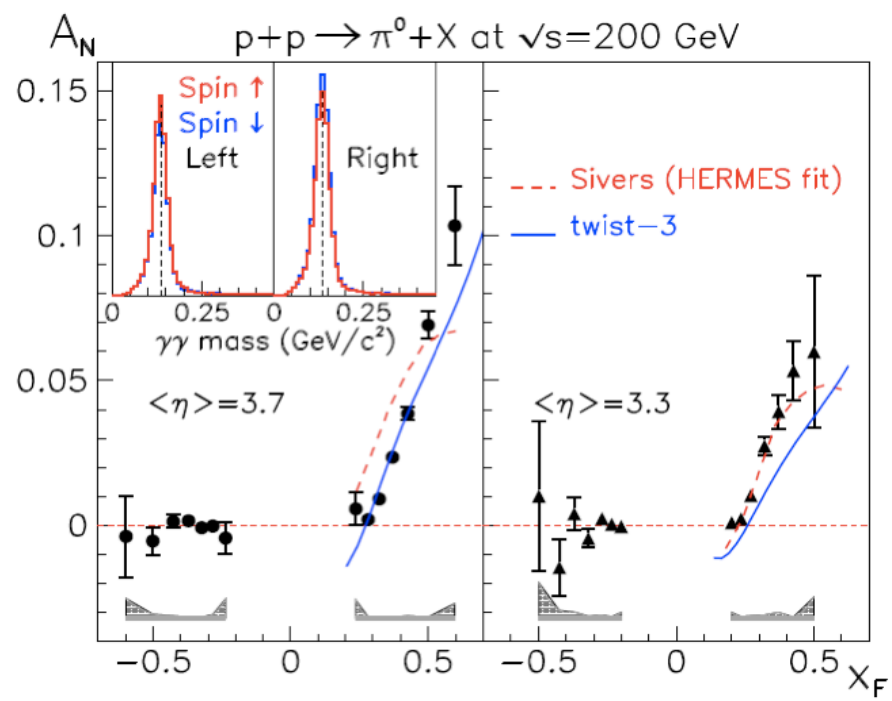
- Definition:



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

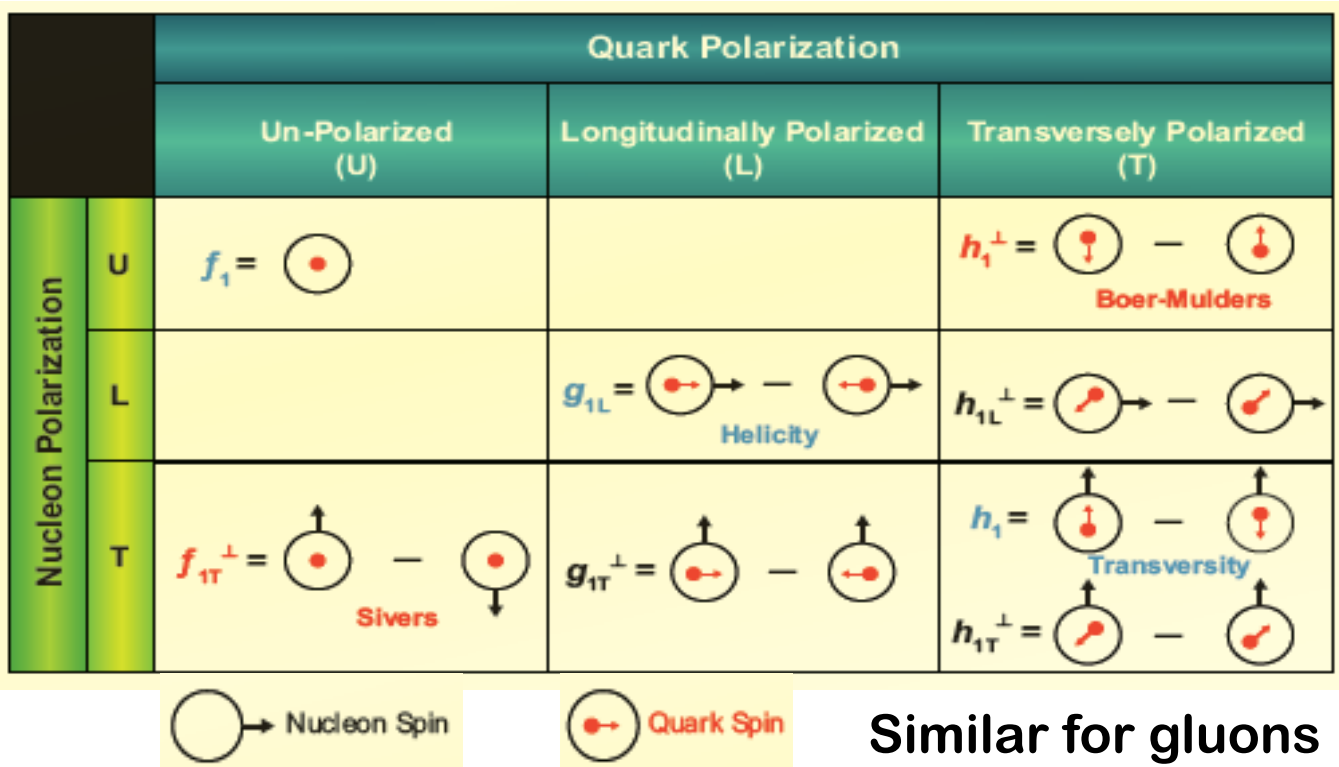
Vanish if active parton has no kT!!!

BNL – 200 GeV

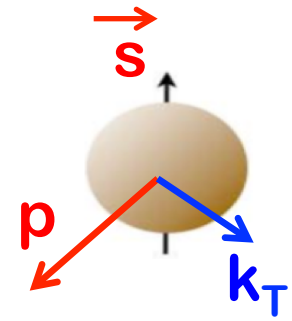


The Present: TMDs

❑ Power of spin – many more correlations:



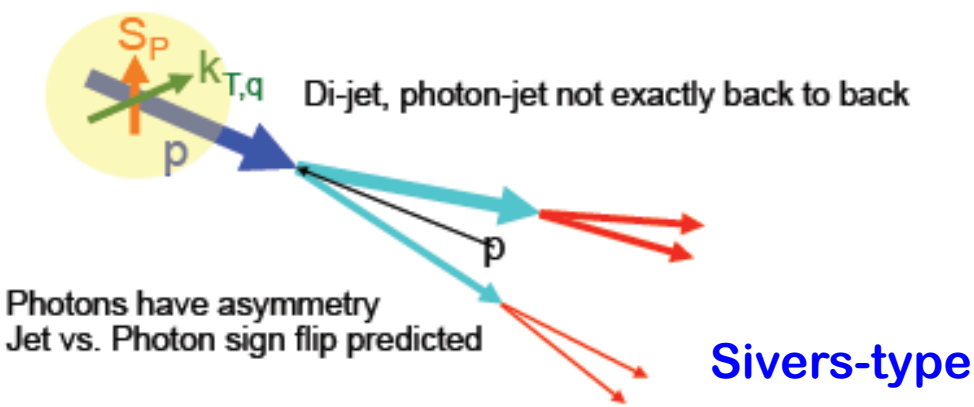
Similar for gluons



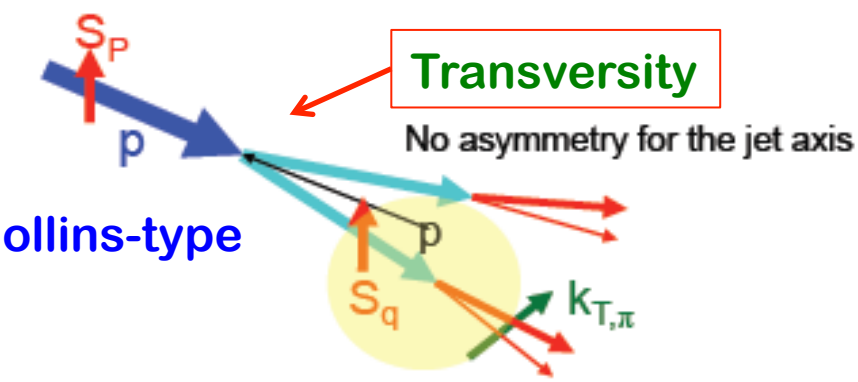
Require two Physical scales

More than one TMD contribute to the same observable!

❑ A_N – single hadron production:



Sivers-type

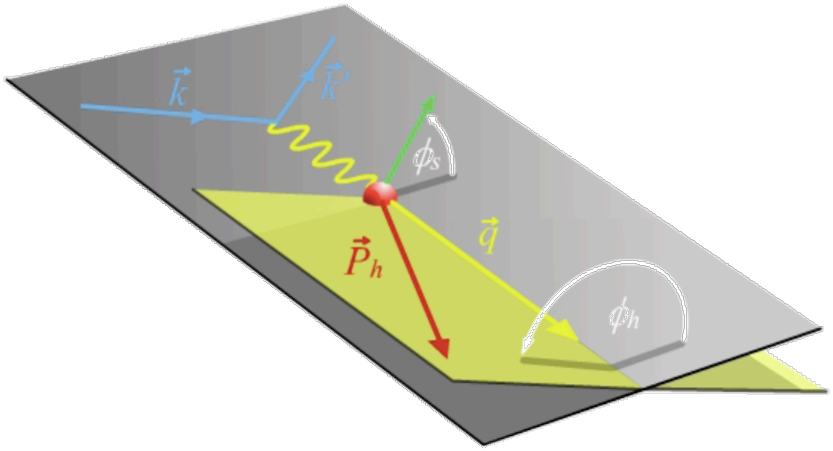


Collins-type

SIDIS – best place to measure TMDs

❑ Naturally two scales and two planes:

- ✧ high Q – localized probe
  To "see" quarks and gluons
- ✧ Low p_T – sensitive to confining scale
  To "see" their confined motion
- ✧ *Theory – QCD TMD factorization*



❑ Separation of TMDs:

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

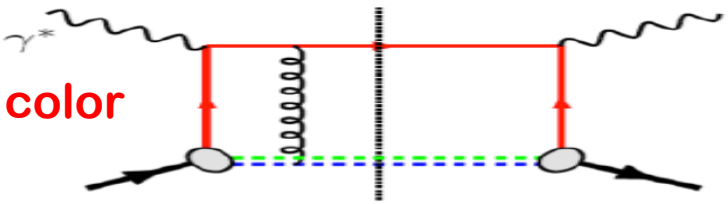
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

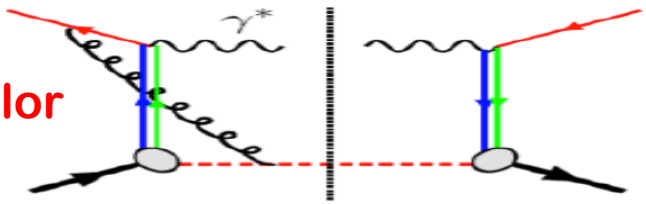
Collins frag. Func.
from e^+e^- collisions

❑ Critical test – sign change of Sivers function – color flow!

Same color

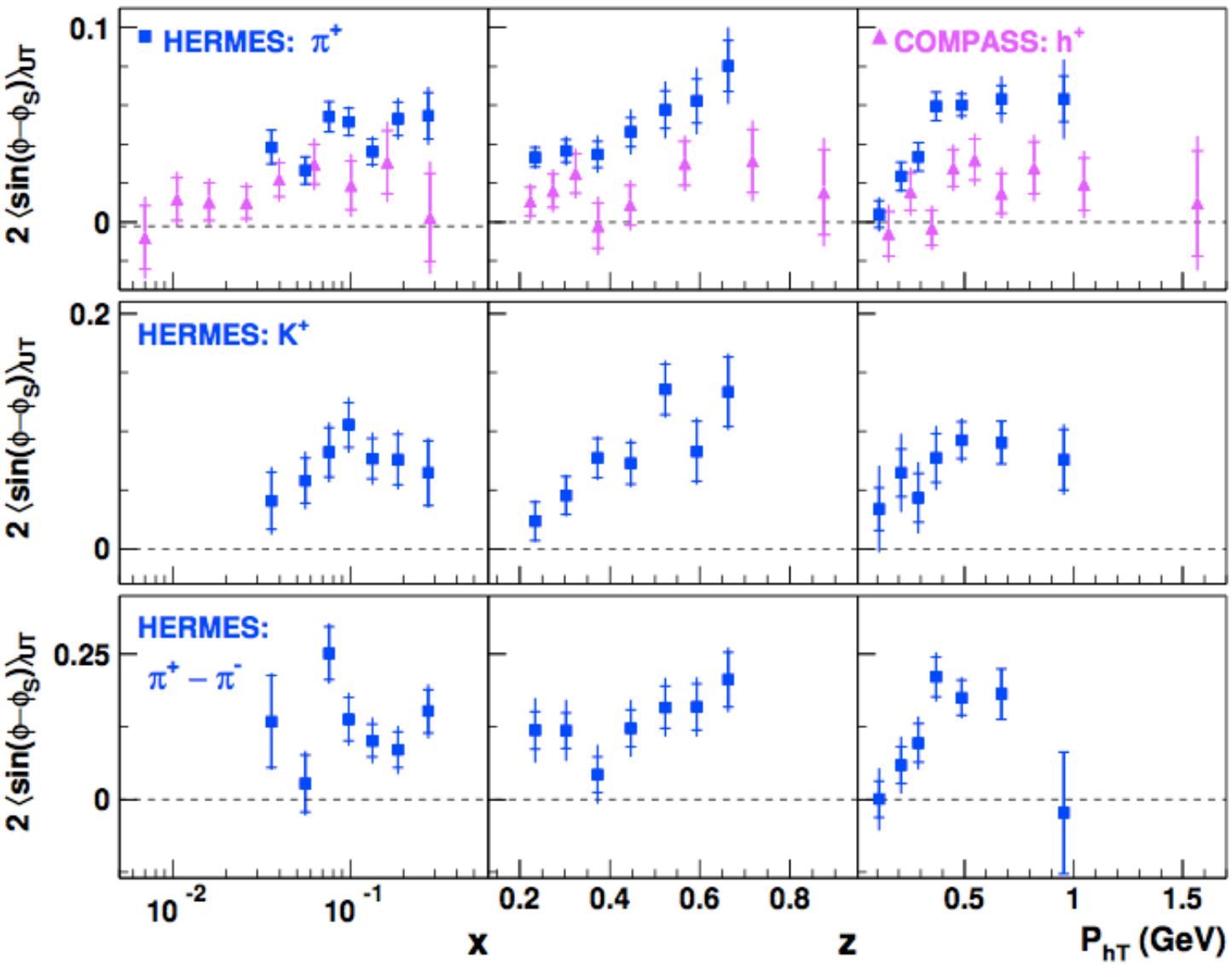


Anti-color



Sivers asymmetries from SIDIS

- From SIDIS (HERMES and COMPASS) – low Q:



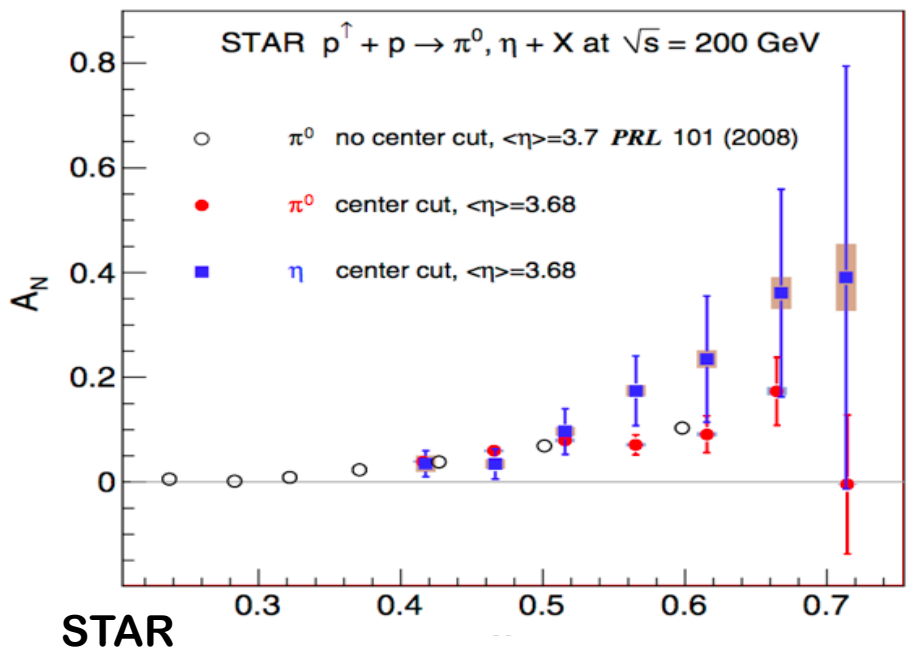
Non-zero Sivers effects Observed in SIDIS!

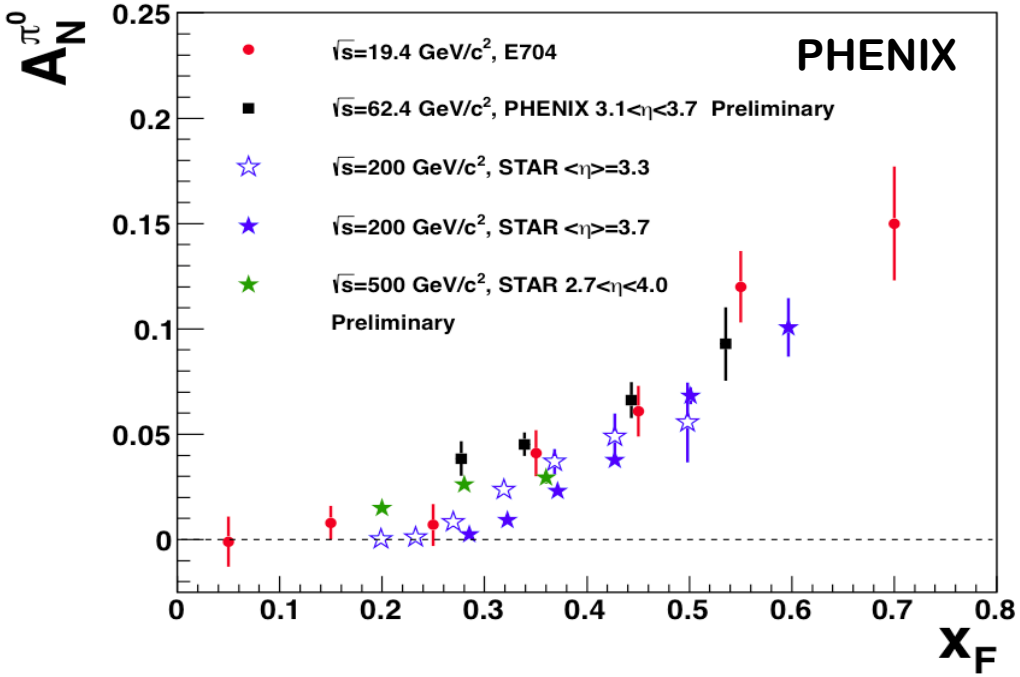
Visible Q^2 dependence

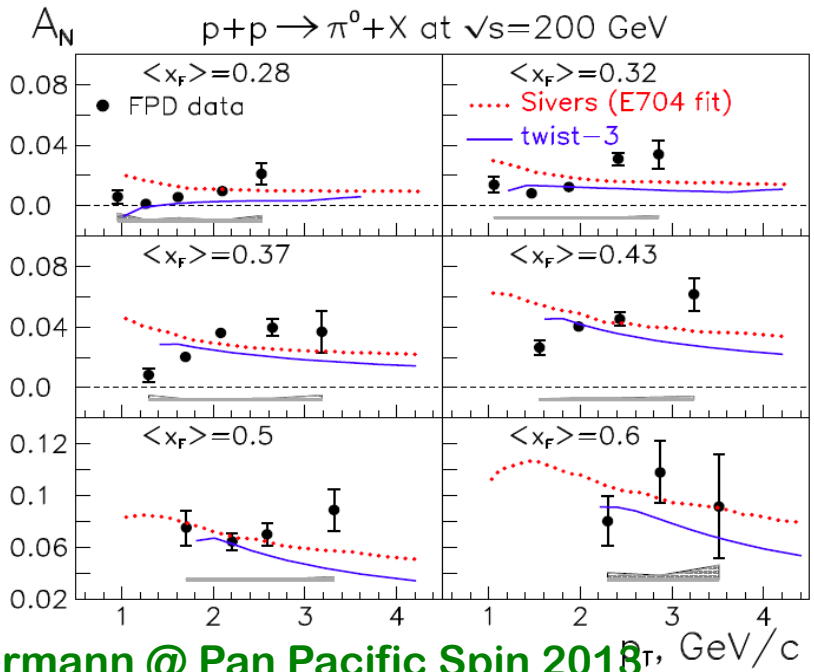
Major theory Development In last year

A_N from RHIC

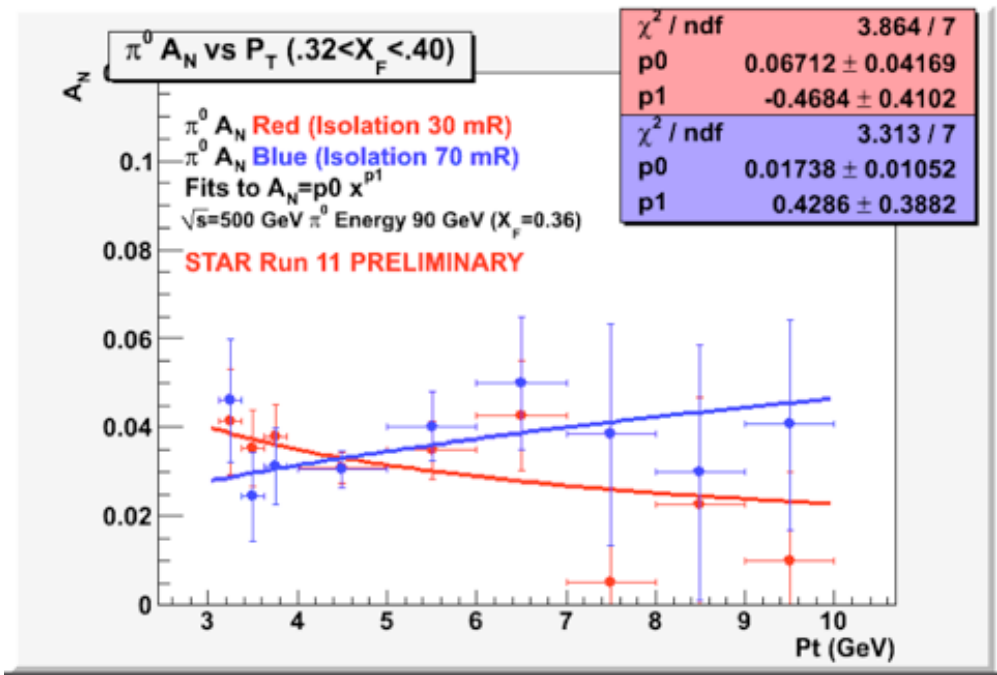
Jiang @ Pan Pacific Spin 2013







Sichtermann @ Pan Pacific Spin 2013



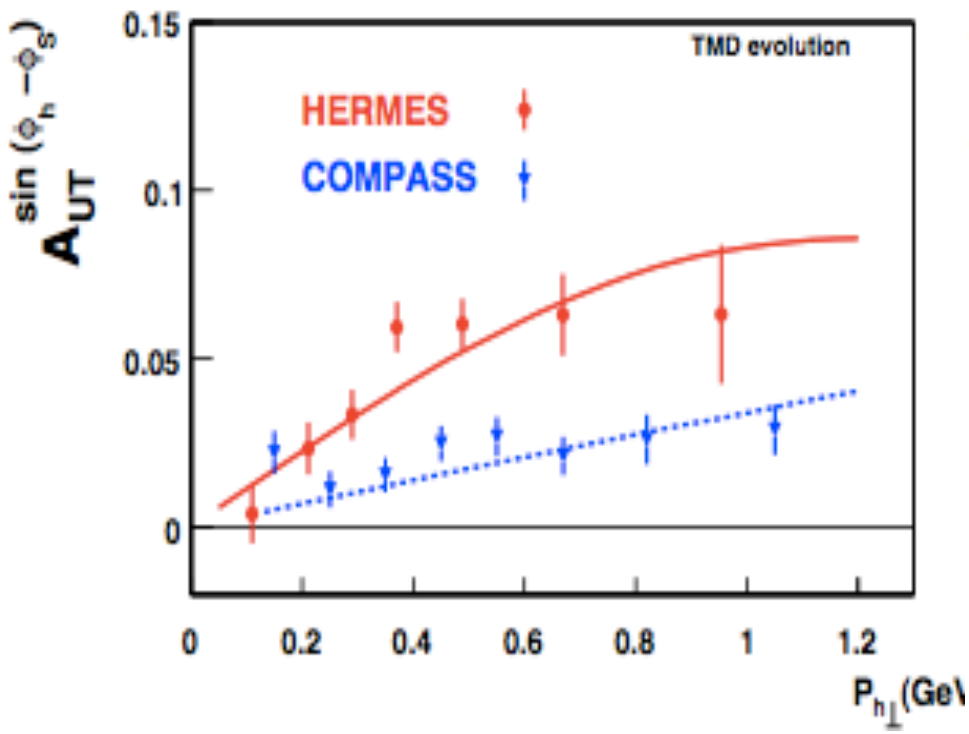
Evolution of Sivers function

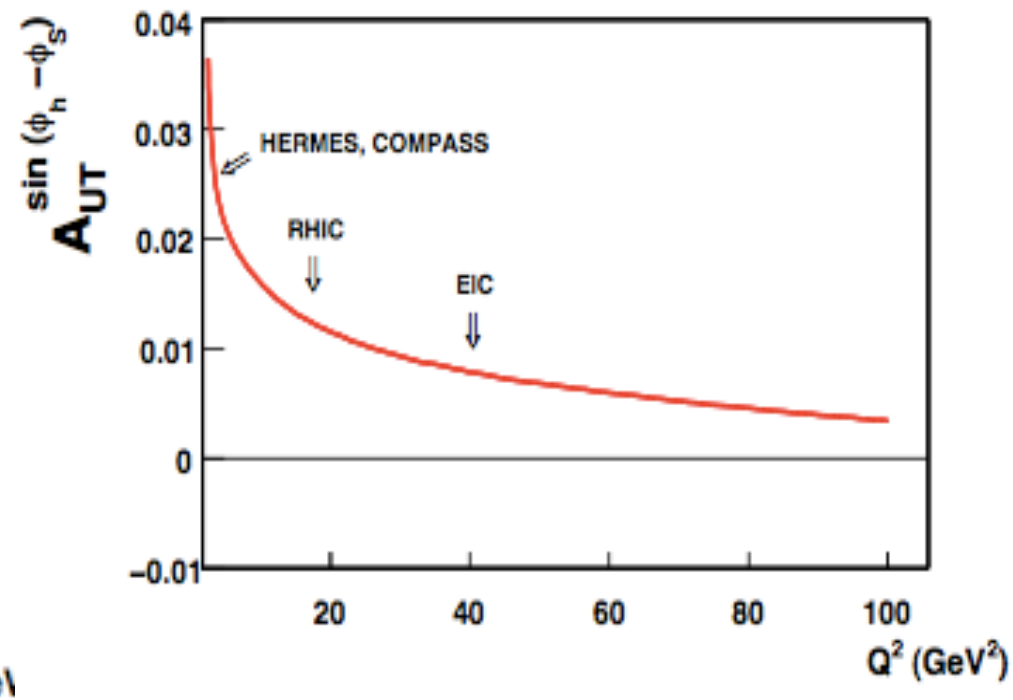
Aybat, Rogers, 2012

❑ SSAs – Sivers function:

Collins-Soper-Sterman (CSS) resummation approach

$$F(x,b;Q) = F(x,c/b_*)\exp\left\{-\int_{c/b_*}^{Q}\frac{d\mu}{\mu}\left(A\ln\frac{Q^2}{\mu^2}+B\right)\right\}\exp\left\{-b^2\left[g_1^{pdf}+\frac{g_2}{2}\ln(Q/Q_0)\right]\right\}$$

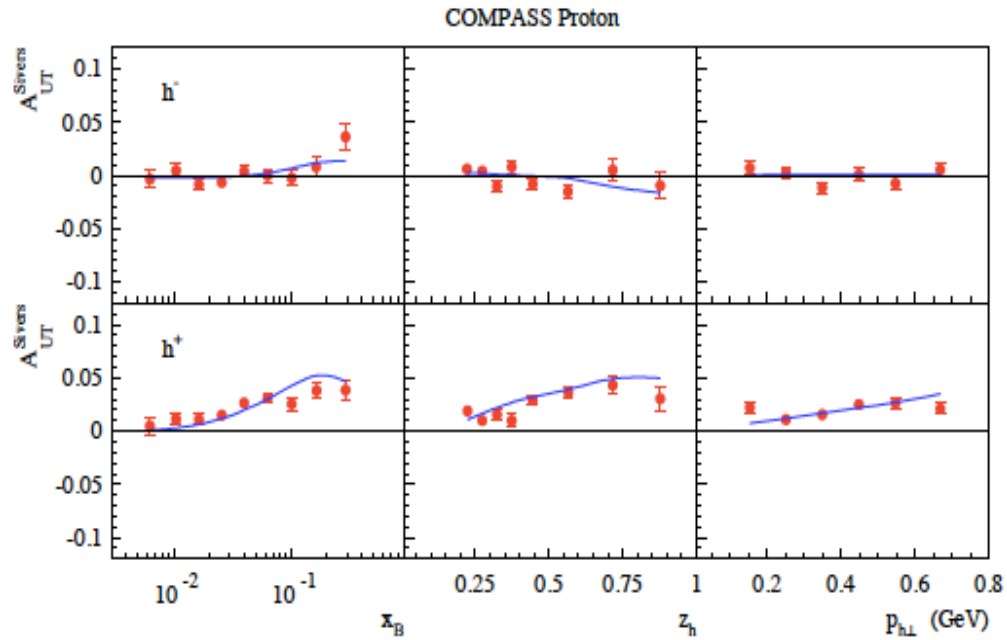


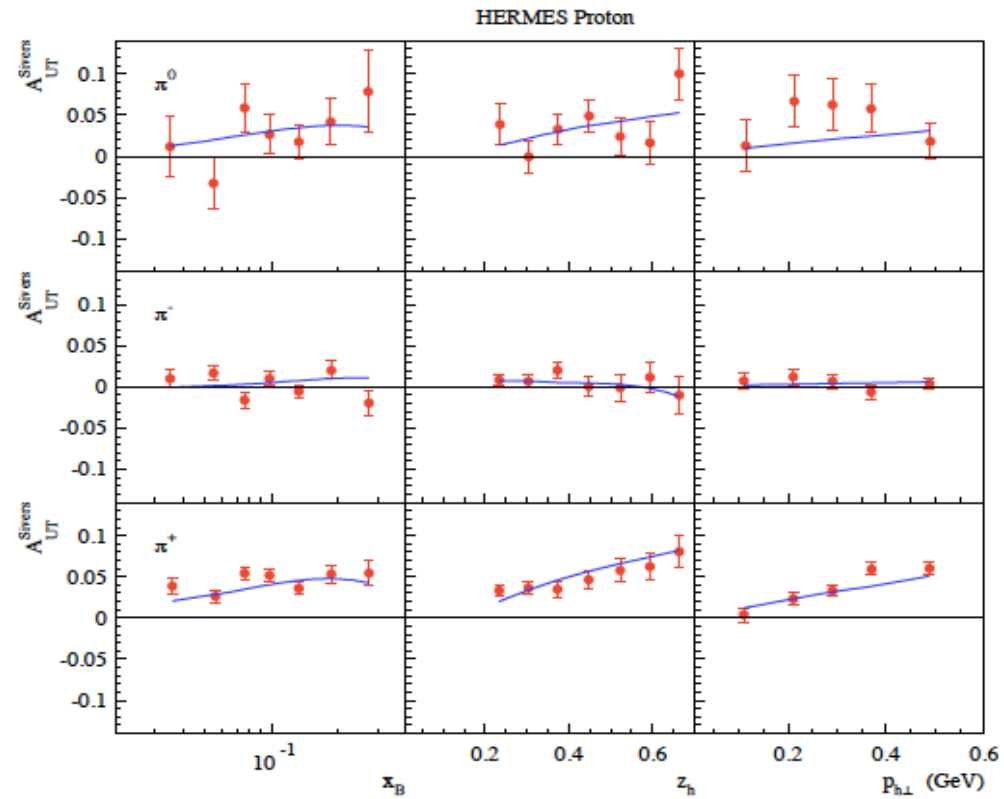


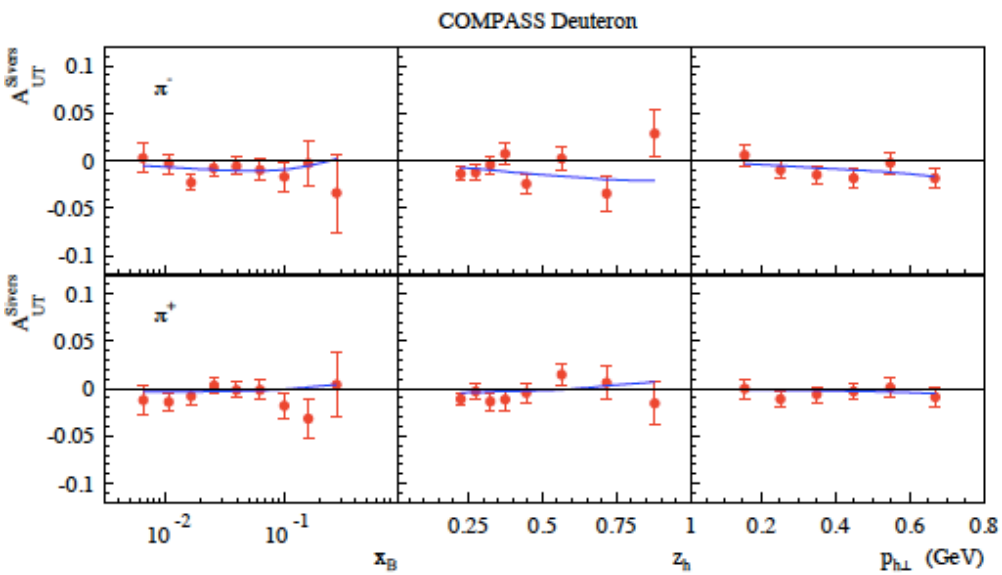
Q^2 dependence – effectiveness of the probe?

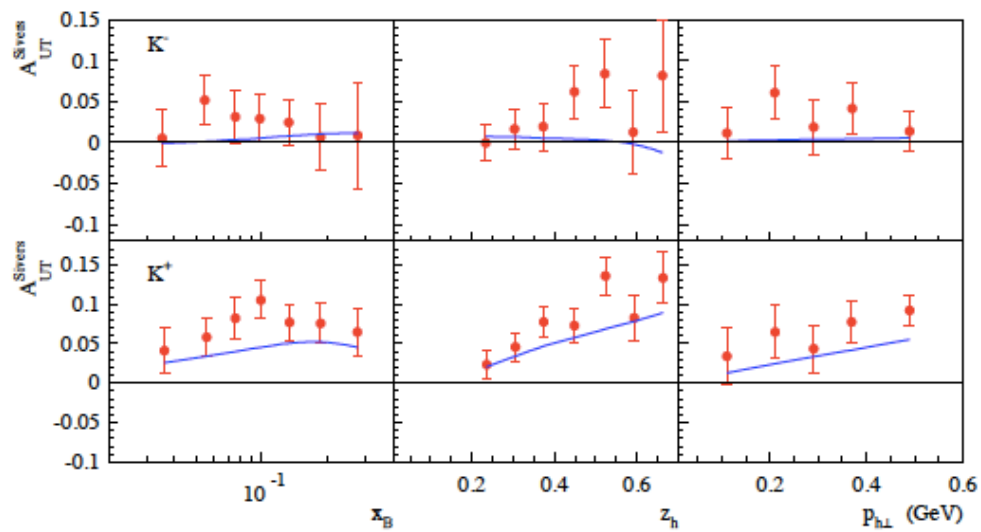
Global fit to Sivers function

Kang, INT 14







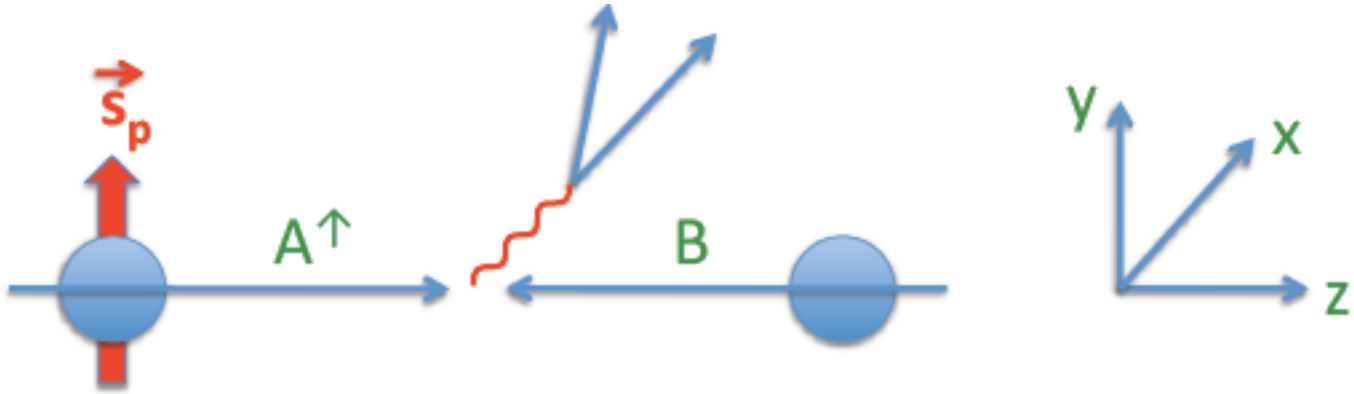


Future: opportunities with Drell-Yan A_N

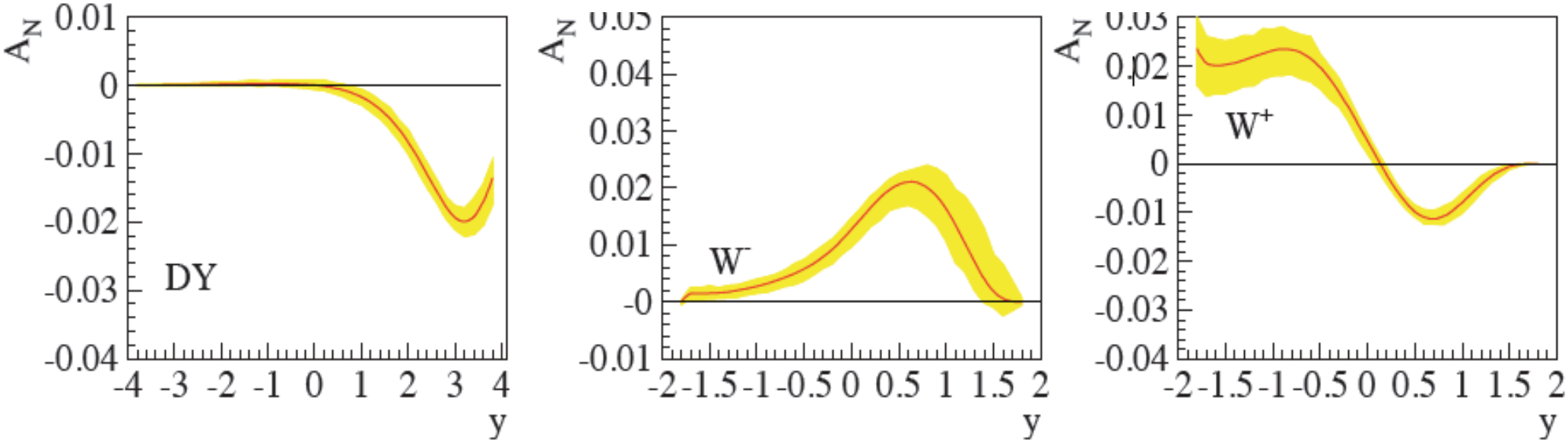
Kang, INT-14

Kang-Xiao-Yuan, PRL. 2011

❑ Drell-Yan, W @ RHIC :



Test the sign change



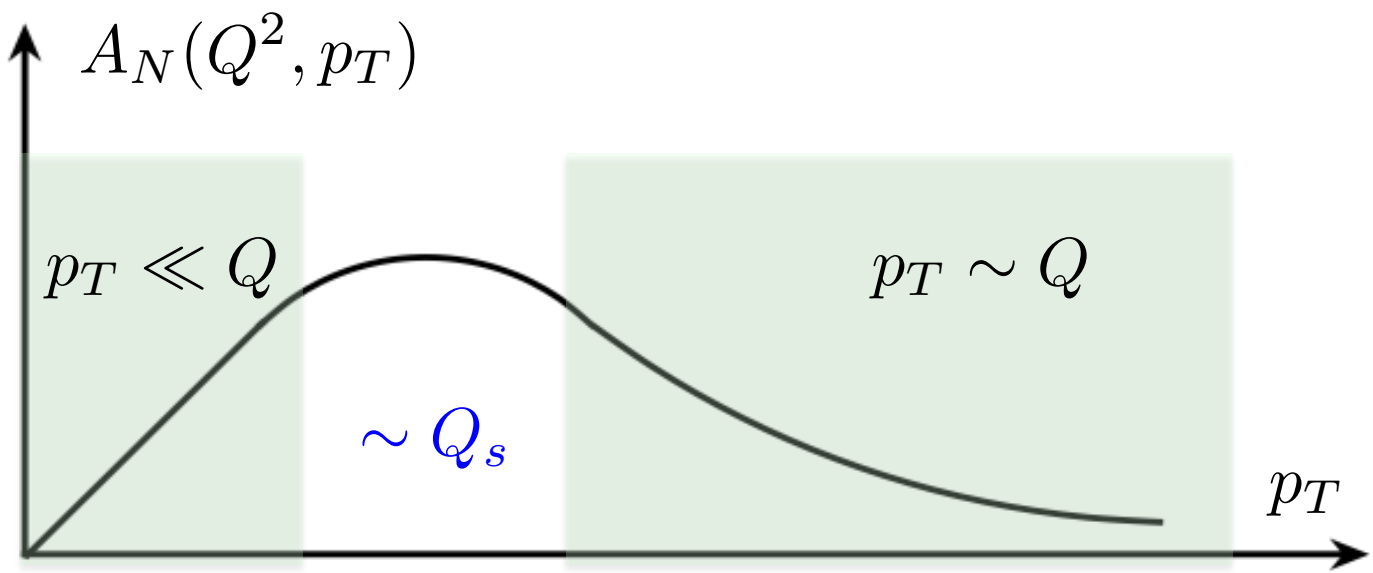
Caution:

- ✧ Uncertainty in non-perturbative input at high b
- ✧ Different treatment to extrapolate to large b

❑ Also opportunities at COMPASS-II

Transition from low p_T to high p_T

- Two-scale becomes one-scale:



TMD Collinear Factorization

- TMD factorization to collinear factorization:

Ji,Qiu,Vogelsang,Yuan,
Koike, Vogelsang, Yuan

Two factorization are consistent in the overlap region: $\Lambda_{\rm QCD} \ll p_T \ll Q$

A_N finite – requires correlation of multiple collinear partons

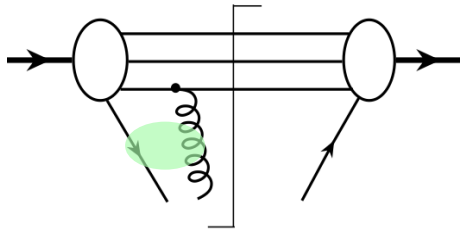
New opportunities!

Twist-3 correlation functions

- **Twist-3 polarized correlation functions:**

Efremov, Teryaev, 1982, …
Qiu, Sterman, 1991, …

$T^{(3)}(x, x, S_\perp) \propto$

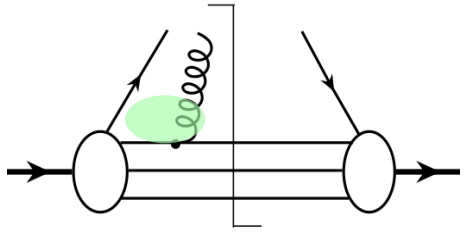


Moment of Sivers function

- **Twist-3 unpolarized correlation functions:**

Kanazawa, Koike 2000, …

$T^{(3\sigma)}(x', x') \propto$

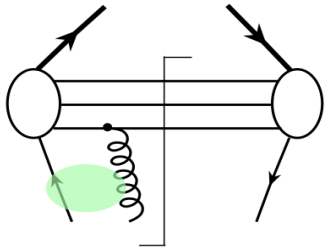


Moment of Boer-Mulders function

- **Twist-3 fragmentation functions:**

Kang, Yuan, Zhou, 2010

$D^{(3)}(z, z) \propto$



Moment of Collins function?

All these correlation functions have No probability interpretation!

Quantum interference between a single and a composite state

Additional talks in parallel sessions

❑ Tuesday – WG6:

Phenomenological aspects of evolution in transverse momentum dependent PDF's and fragmentation — *Prof. Ignazio SCIMEMI*

COMPASS results on the transverse spin asymmetry in identified dihadron production in SIDIS — *Christopher BRAUN*

HERMES results on transverse target single-spin asymmetries in inclusive electroproduction of charged pions and kaons — *Klaus RITH*

Transverse-spin gluon distribution function — *Kazuhiro TANAKA*

❑ Wednesday – WG6:

A_N in inclusive lepton-proton collisions — *Dr. Umberto D'ALESIO*

Measurement of the Transverse Single-Spin Asymmetries for pi^{0) and Jet-like Events at Forward Rapidities at STAR in p+p Collisions at sqrt{s} = 500 GeV — *Dr. Mriganka Mouli MONDAL*

Results on Transverse Spin Asymmetries in Polarized Proton - Proton Elastic Scattering at sqrt(s) = 200 GeV — *Wlodek GURYN*

Gluon TMDs and Higgs boson production — *Marc SCHLEGEL*

+ talks on unpolarized TMDs — *Mr. Andrea SIGNORI, J. Osvaldo GONZALEZ H.*

Summary

- After 40 years, we have learned a lot of QCD dynamics, but, only at very short-distance - less than 0.1 fm, and limited information on non-perturbative parton structure

- Understanding proton spin could provide the first complete example to describe the fundamental properties of hadrons at various distance scale

- Transverse spin opens a new domain to test QCD dynamics and new observables for extracting partonic structure beyond PDFs

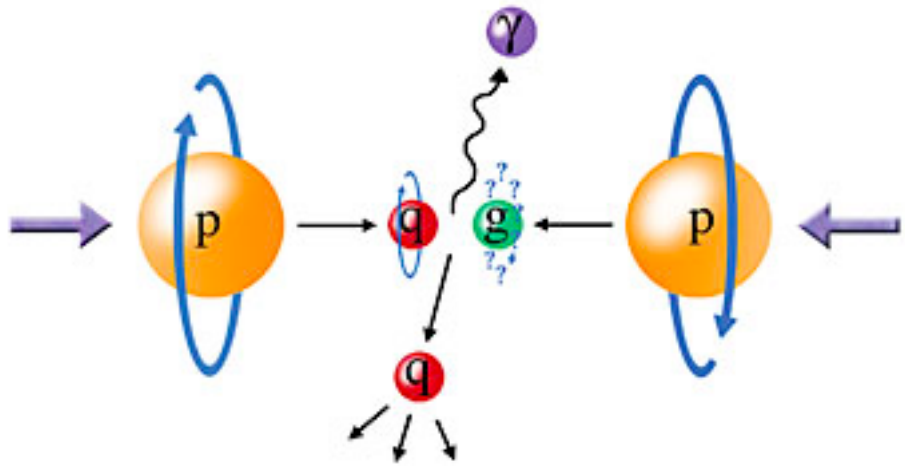
- From GPDs and TMDs, we could derive a comprehensive 3D ``view'' of hadron's quark and gluon structure
  – new frontier of QCD

Thank you!

Backup slices

QCD global analysis

- **QCD factorization + DGALP evolution:**



+ DIS + SIDIS + …

$$\frac{d\Delta\sigma_{hh}}{dydp_T^2} = \sum_{ij} \Delta f_{i/h}(x) \otimes \Delta f_{j/h}(x') \otimes \frac{d\Delta\hat{\sigma}_{ij}}{dydp_T^2} + \mathcal{O}\left(\frac{1}{p_T^2}\right)$$

Better experimental Measurements

Improved theoretical calculations, resummations

Extract helicity distributions with DGLAP evolution

$$\frac{\partial \Delta f_{i/h}(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} \sum_{ij} \mathcal{P}_{i/j}(x/x',\alpha_s) \otimes \Delta f_{j/h}(x,\mu^2)$$

Determination of ΔG

❑ Double longitudinal spin asymmetries:

$$A_{LL} = \frac{[\sigma(+,+) - \sigma(+,-)] - [\sigma(-,+) - \sigma(-,-)]}{[\sigma(+,+) + \sigma(+,-)] + [\sigma(-,+) + \sigma(-,-)]} \quad \text{for } \sigma(s_1, s_2)$$

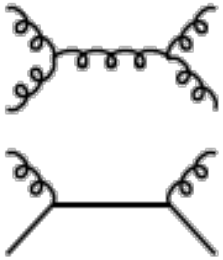
❑ Physical channels sensitive to ΔG:

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

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

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

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



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

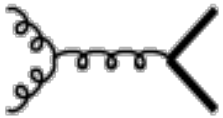
low rates

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

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

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

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



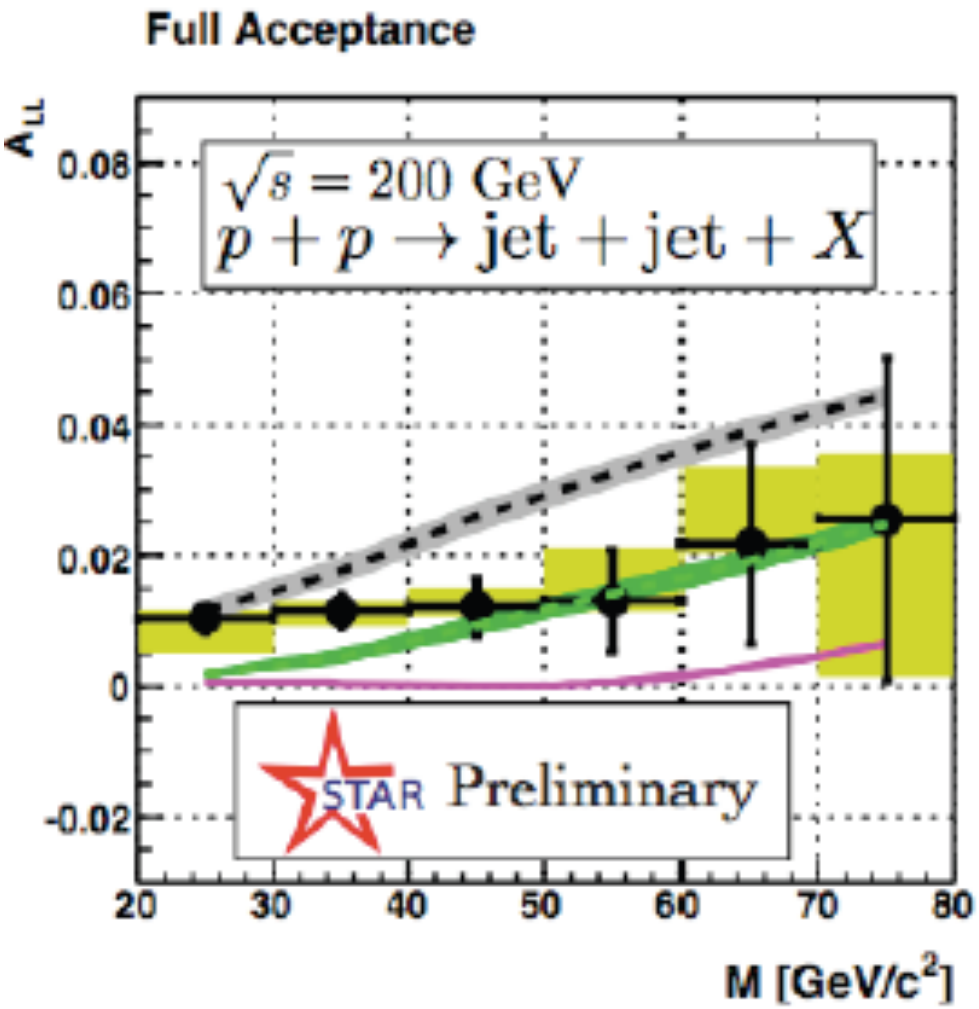
Heavy-flavour production

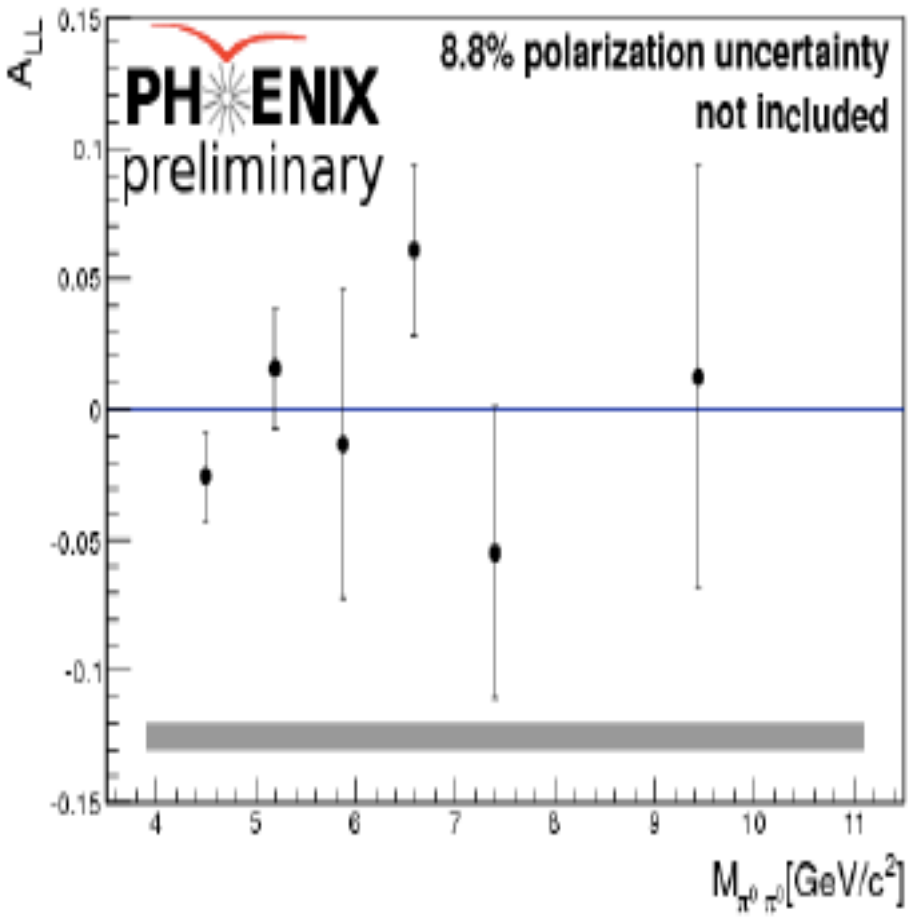
separated vertex detection required

Future data can further help!

Di-jets + Di-hadrons

- Proof of principle from 2009 data:





Sichtermann, E.

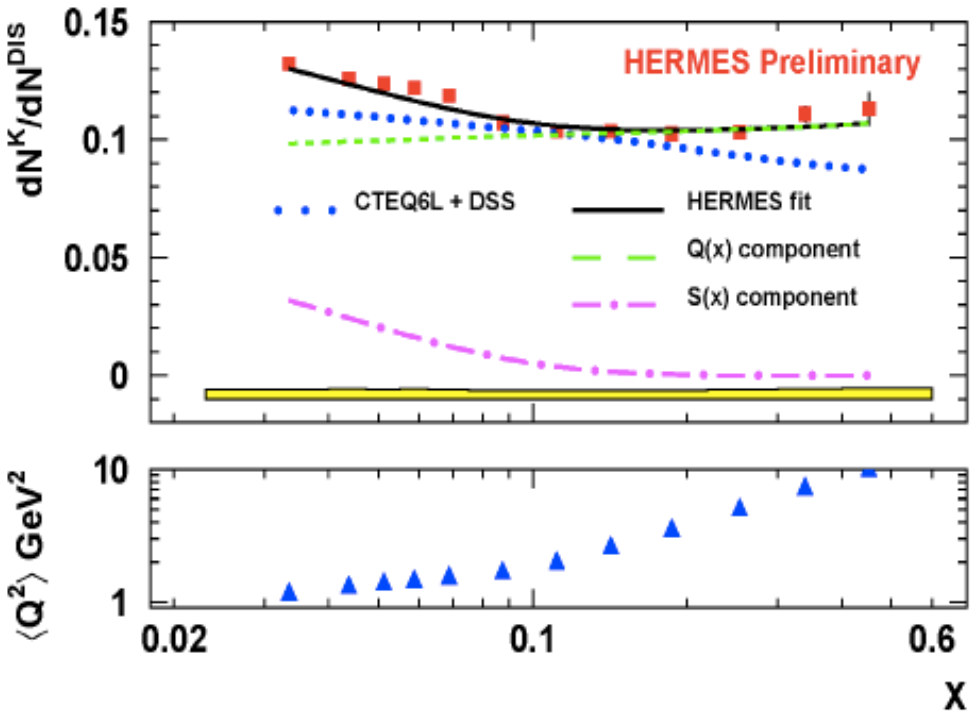
Manion, A.

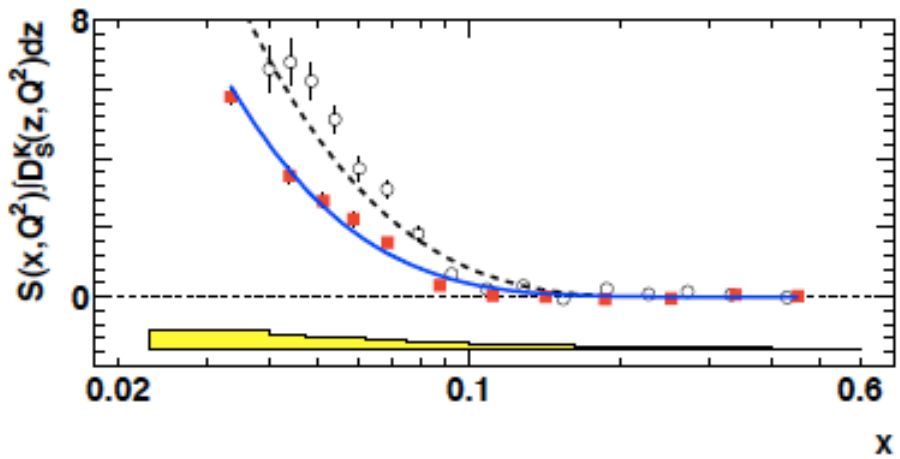
@ Pan Pacific Spin 2013

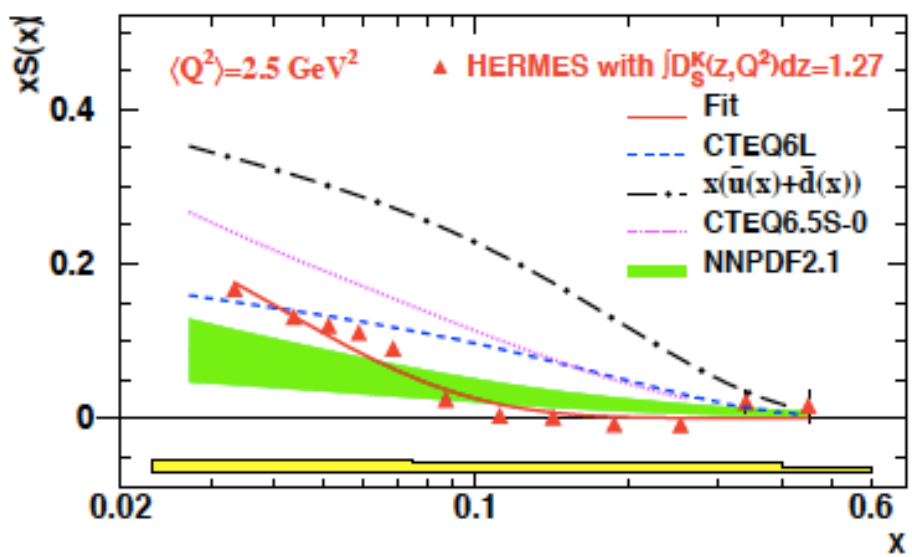
Re-evaluation of strange quark distributions

arXiv:1312.7028

❑ HERMES:

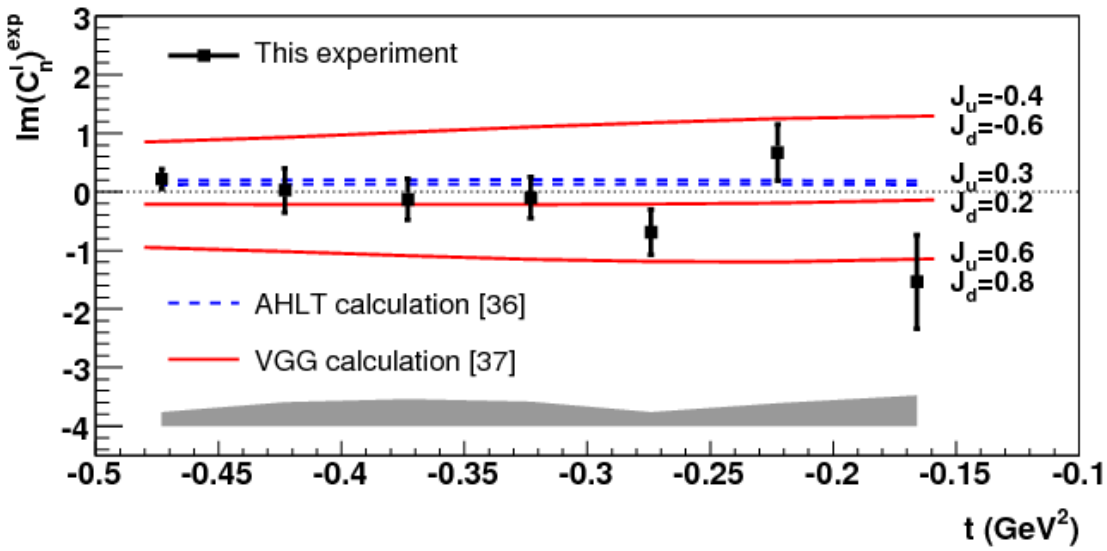


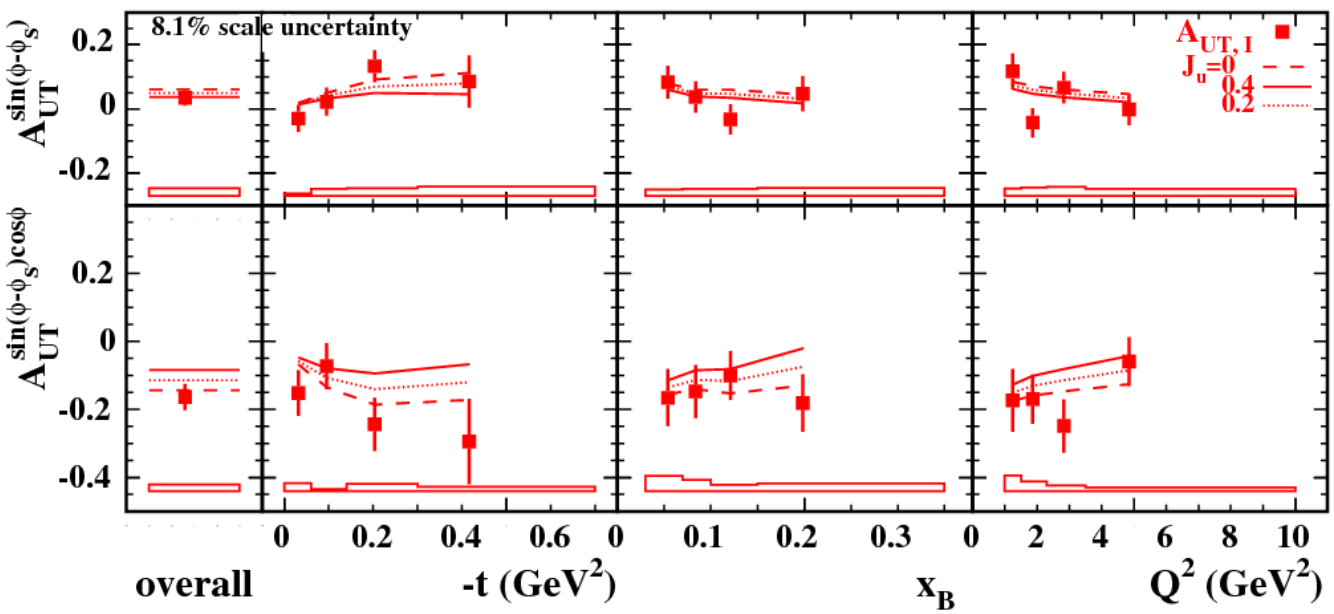




DVCS with transversely polarized targets

❑ HERMES & JLab:

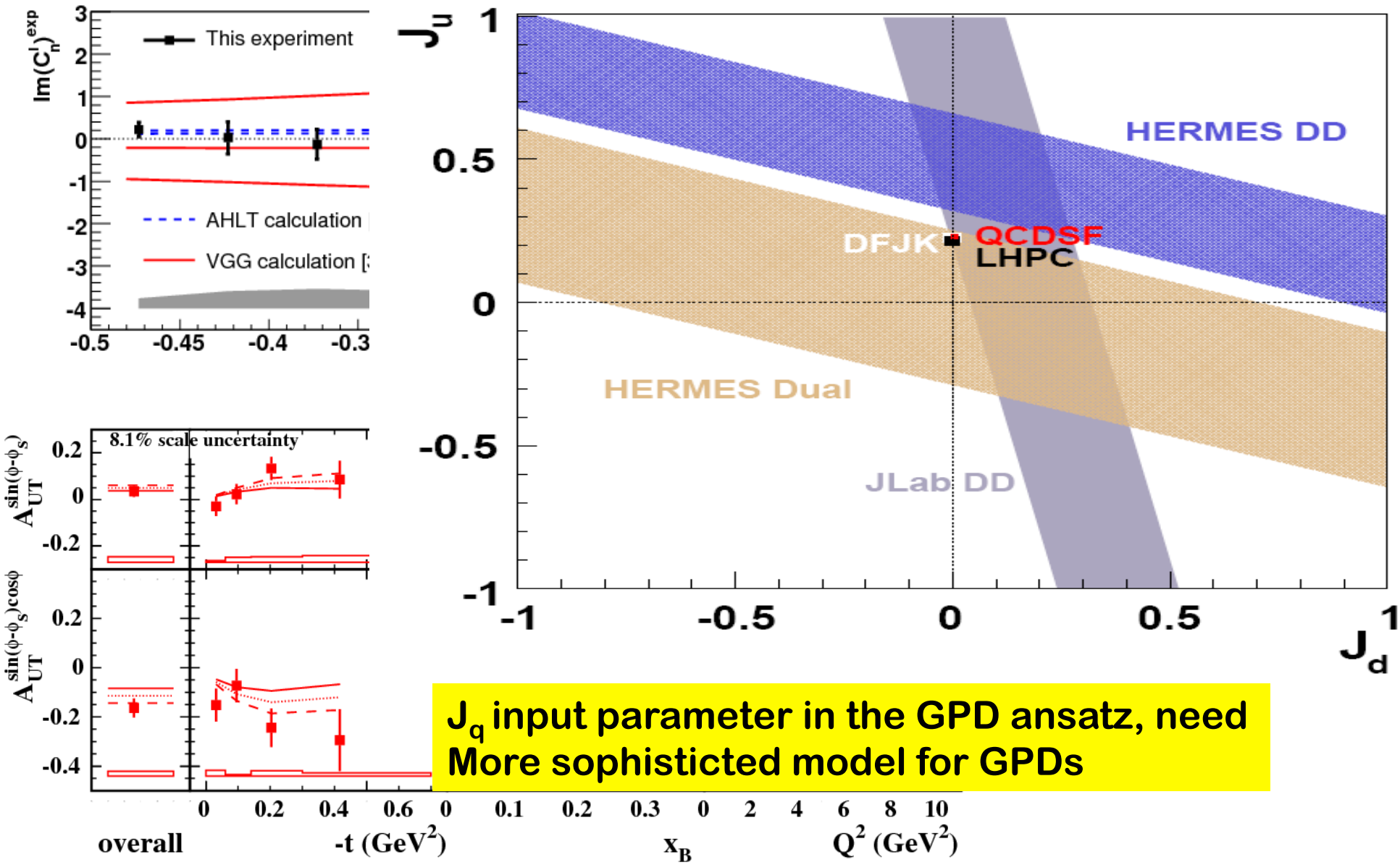




Jlab Hall A, 0709.0450; HERMES, 0802.2499

DVCS with transversely polarized targets

❑ HERMES & JLab:



J_q input parameter in the GPD ansatz, need More sophisticted model for GPDs

Jlab Hall A, 0709.0450; HERMES, 0802.2499