# Overview of Spin Structure at Large $x$

Elena Long

HiX2014

Laboratori Nazionali di Frascati

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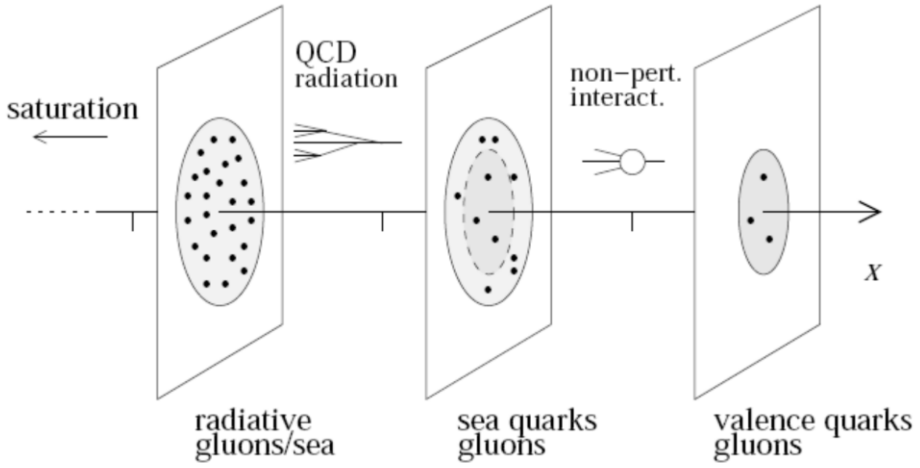
# Picture of the Nucleon

Understanding spin structure allows us to access information regarding the structure of nucleons

A 3D picture of nucleons would give insights on the dynamics of how quarks and gluons form the nucleons

We can begin to access this information through spin observables



# Wigner Distribution

The Wigner Distribution would give 3D distributions of partons, including how they move and are located inside a nucleon

$$W(\boldsymbol{p},\boldsymbol{r}) = \int d^3\eta e^{i\boldsymbol{p}\eta} \psi^*(\boldsymbol{r} + \frac{\eta}{2})\psi(\boldsymbol{r} - \frac{\eta}{2})$$

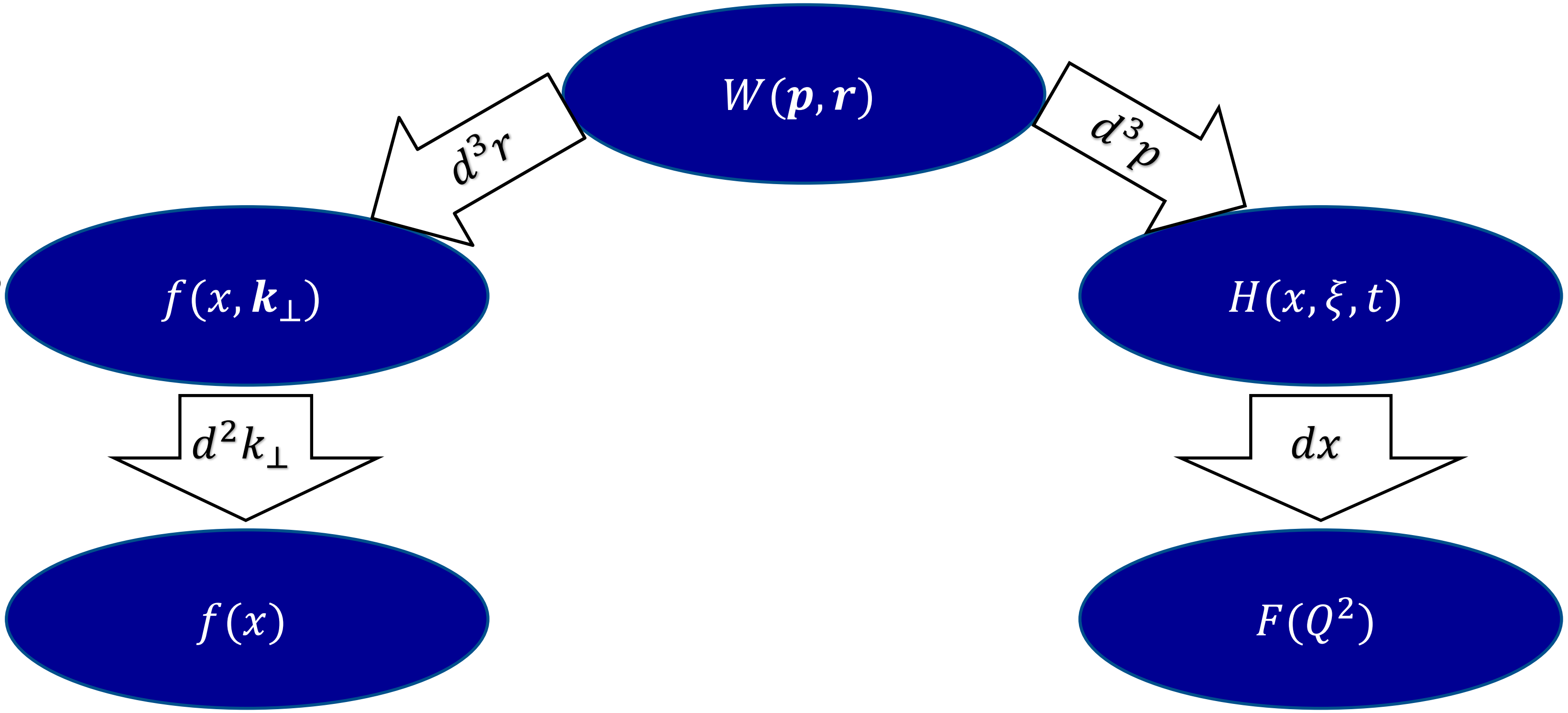
But it requires simultaneous measurement of the position and momenta

$$\Delta p \Delta r \geq \hbar/2$$

# Wigner Distribution

Transverse Momentum Distributions

Generalized Parton Distributions




Patron Distribution Functions

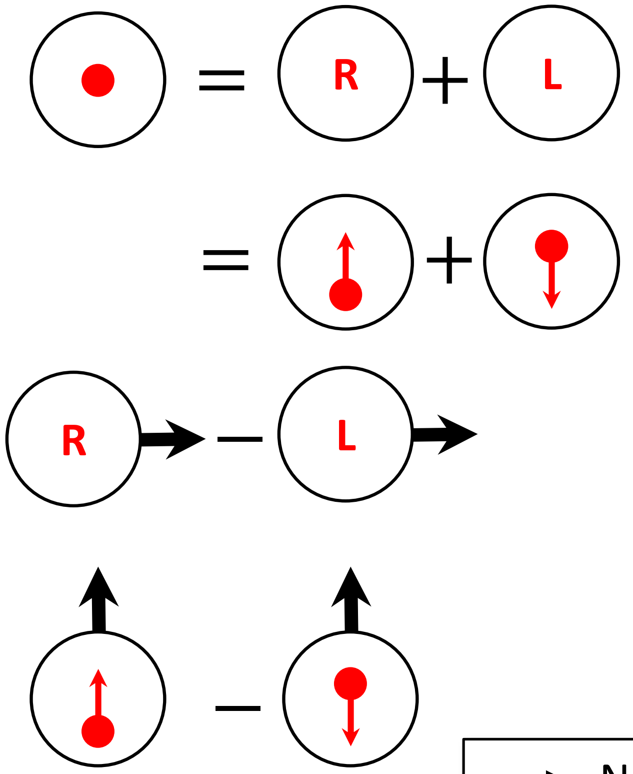
Form Factors

# Parton Distribution Functions (PDFs)

Unpolarized $f_1(x) =$

Helicity $g_1(x) =$

Transversity $h_1(x) =$




* See previous talk, next 2 talks and Monday morning session

# Transverse Momentum Distributions (TMDs)

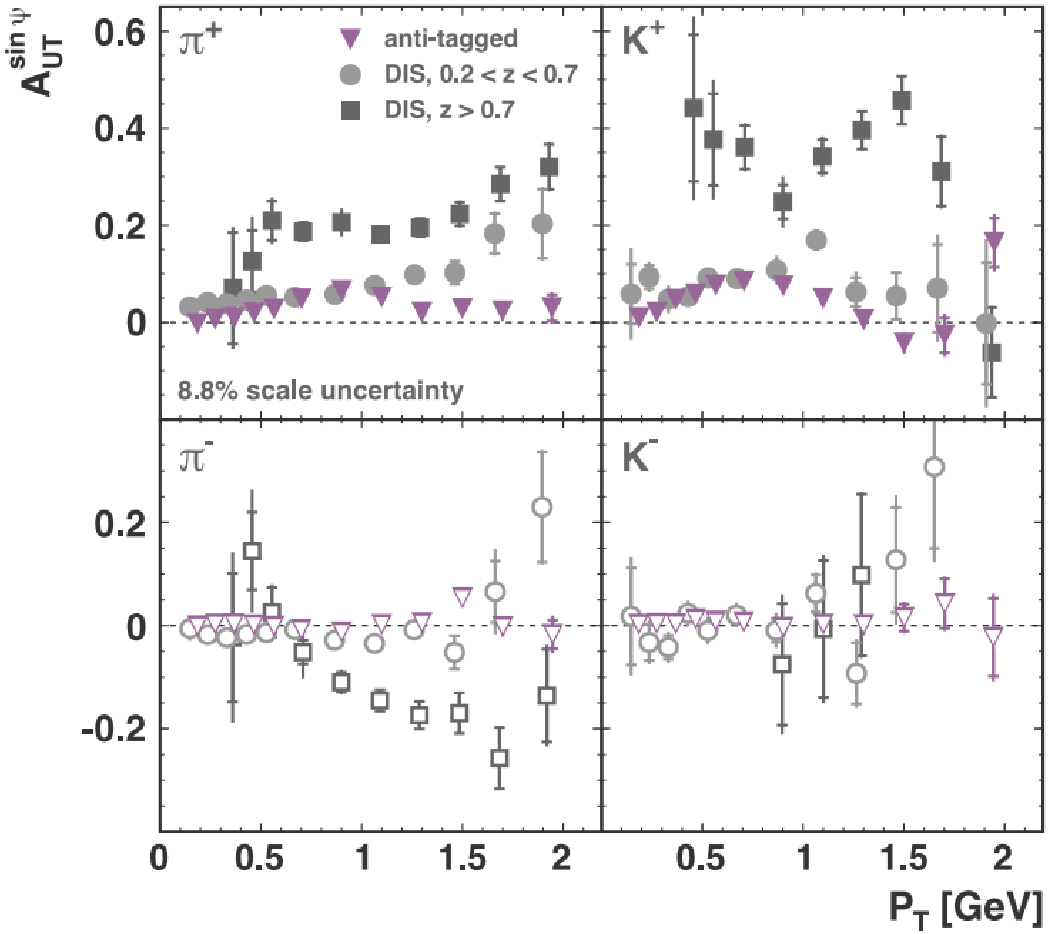
| N \ q | Unpolarized (U) | Longitudinally Polarized (L) | Transversely Polarized (T) |
|---|---|---|---|
| **U** | $f_1(x) =$ | | $h_1^{\perp}(x) =$ − <br> Boer-Mulders |
| **L** | | $g_1(x) =$ − <br> Helicity | $h_{1L}^{\perp}(x) =$ − <br> Worm Gear |
| **T** | $f_{1T}^{\perp}(x) =$ − <br> Sivers | $g_{1T}(x) =$ − <br> Worm Gear | $h_1(x) =$ − <br> Transversity <br> $h_{1T}^{\perp}(x) =$ − <br> Pretzelosity |

→ Nucleon Spin
→ Quark Spin

* See TMD Sessions, Tuesday and Thursday Afternoon

# Transverse Asymmetries @ HERMES

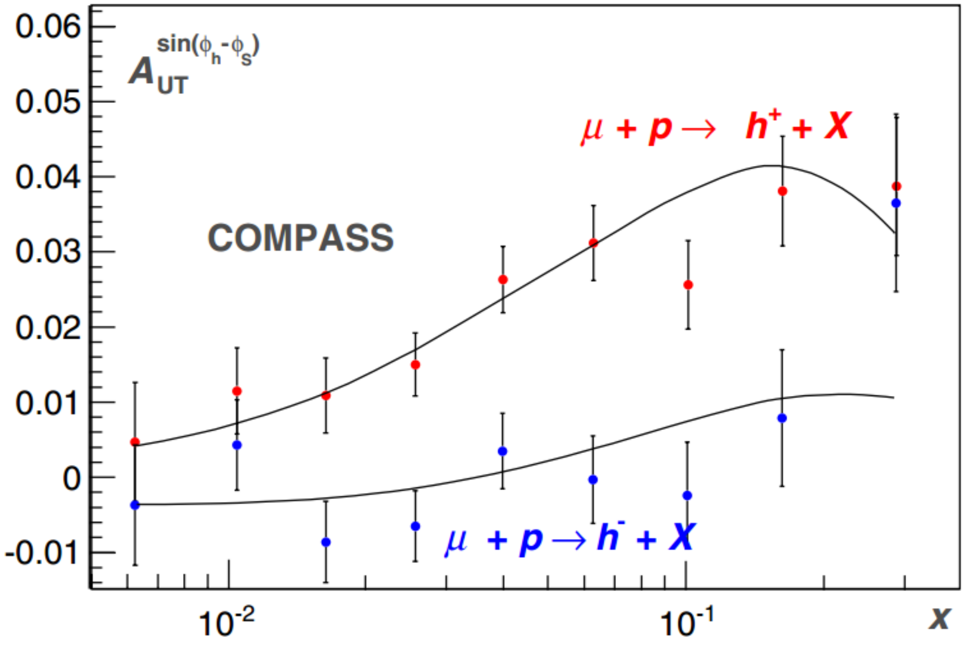
- Inclusive electroproduction of pions and kaons from transversely polarized protons
- $P_T$ dependence primarily caused by the Sivers effect
- Very large asymmetries measured with high *z*
  - Exclusive processes can contribute & effects from fragmentation of the struck quark dominate
- Data can lead to better understanding of spin-orbit effects of partons in the nucleon

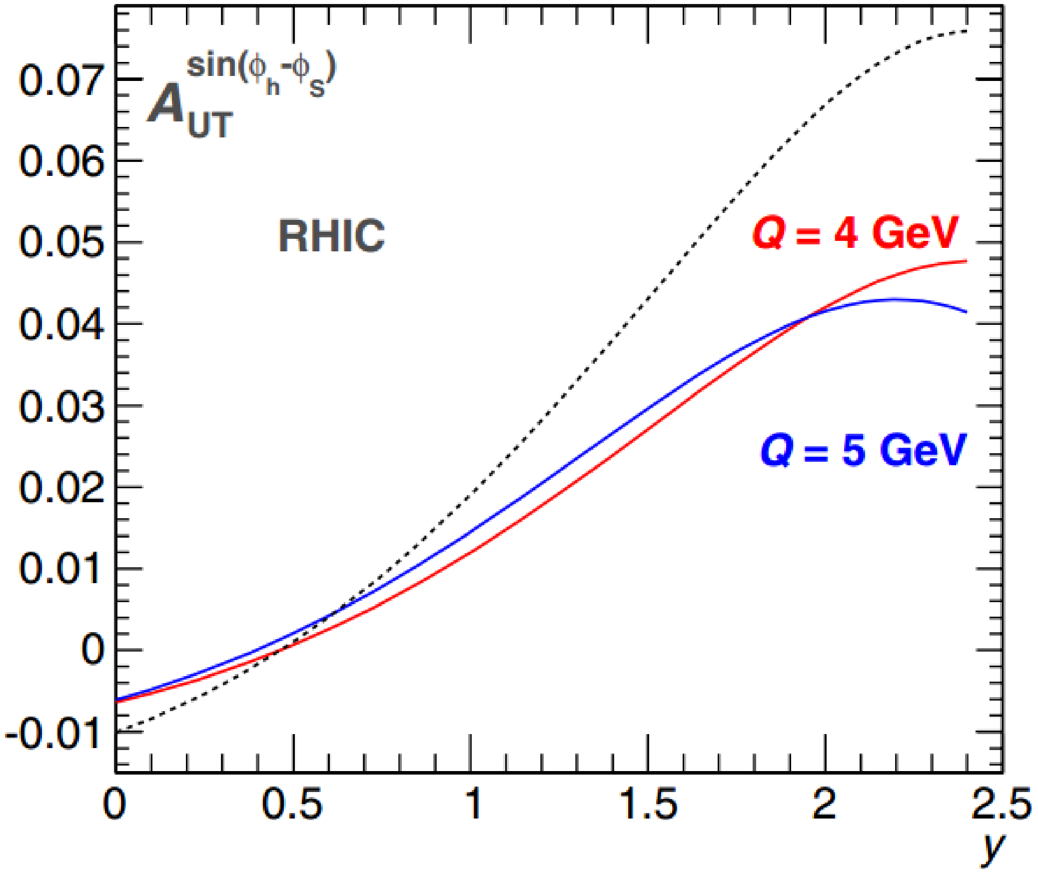



A. Airapetian et al., Phys. Lett. B **728**, 183 (2014)

# Transverse Asymmetries – Theory & Predictions

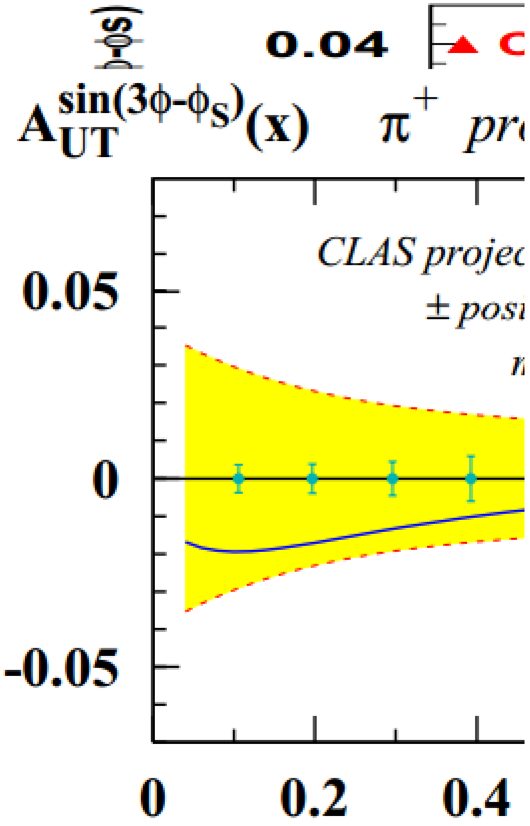
- Recent Sivers theoretical fits for SIDIS and Drell-Yan
- Include Q2 evolutions
- Predictions for upcoming experiments

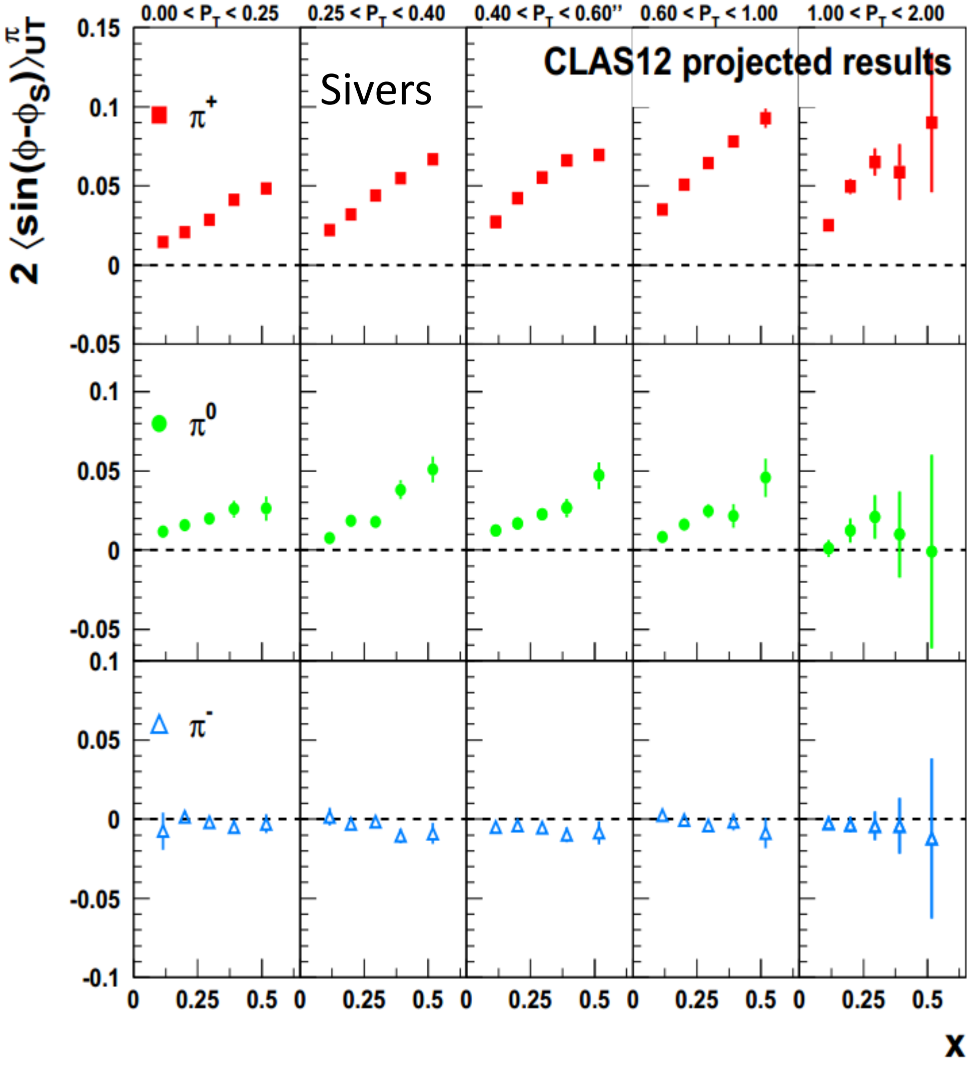


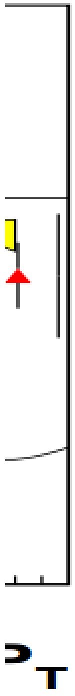



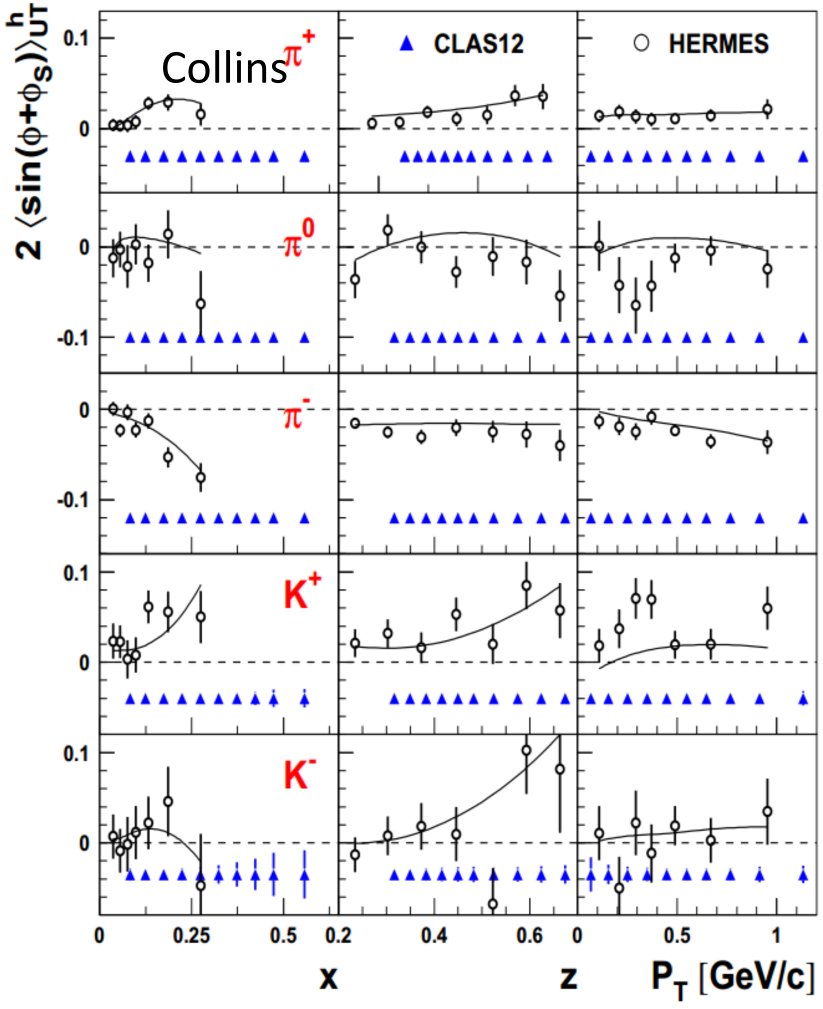

P. Sun, F. Yuan, Phys. Rev. D **88**, 034016 (2013)

# Future “High Impact” Transverse SIDIS @ JLab12



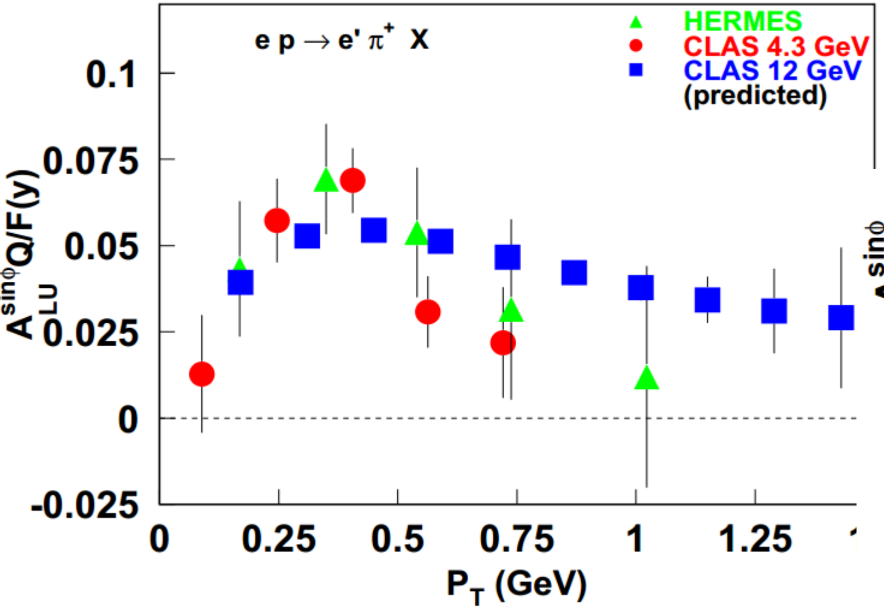



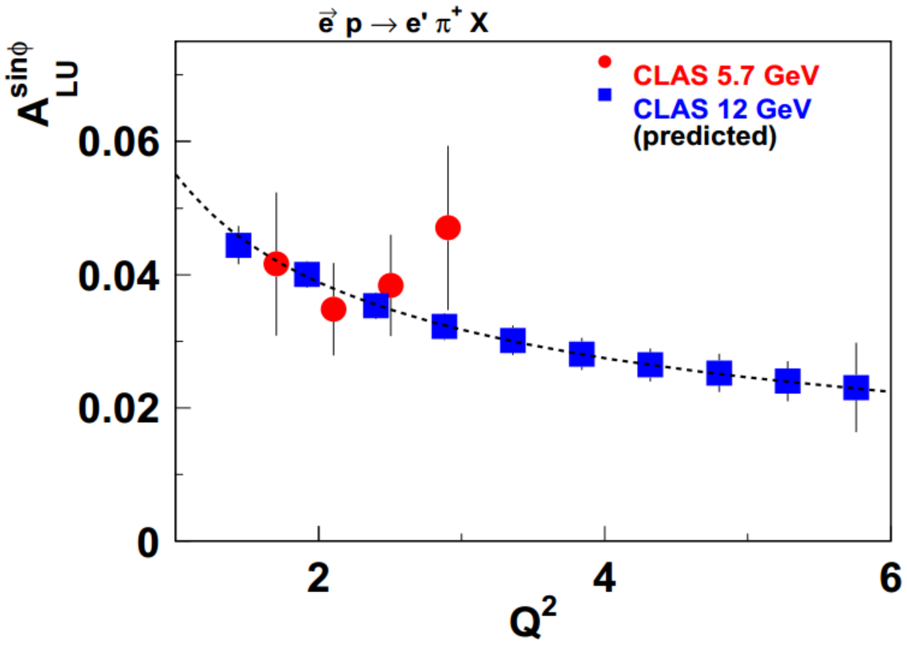



M. Contalbrigo *et al.*, JLab E12-11-111

* See TMD Sessions, Tuesday and Thursday Afternoon

# Future "High Impact" Boer-Mulders @ JLab12 CLAS12



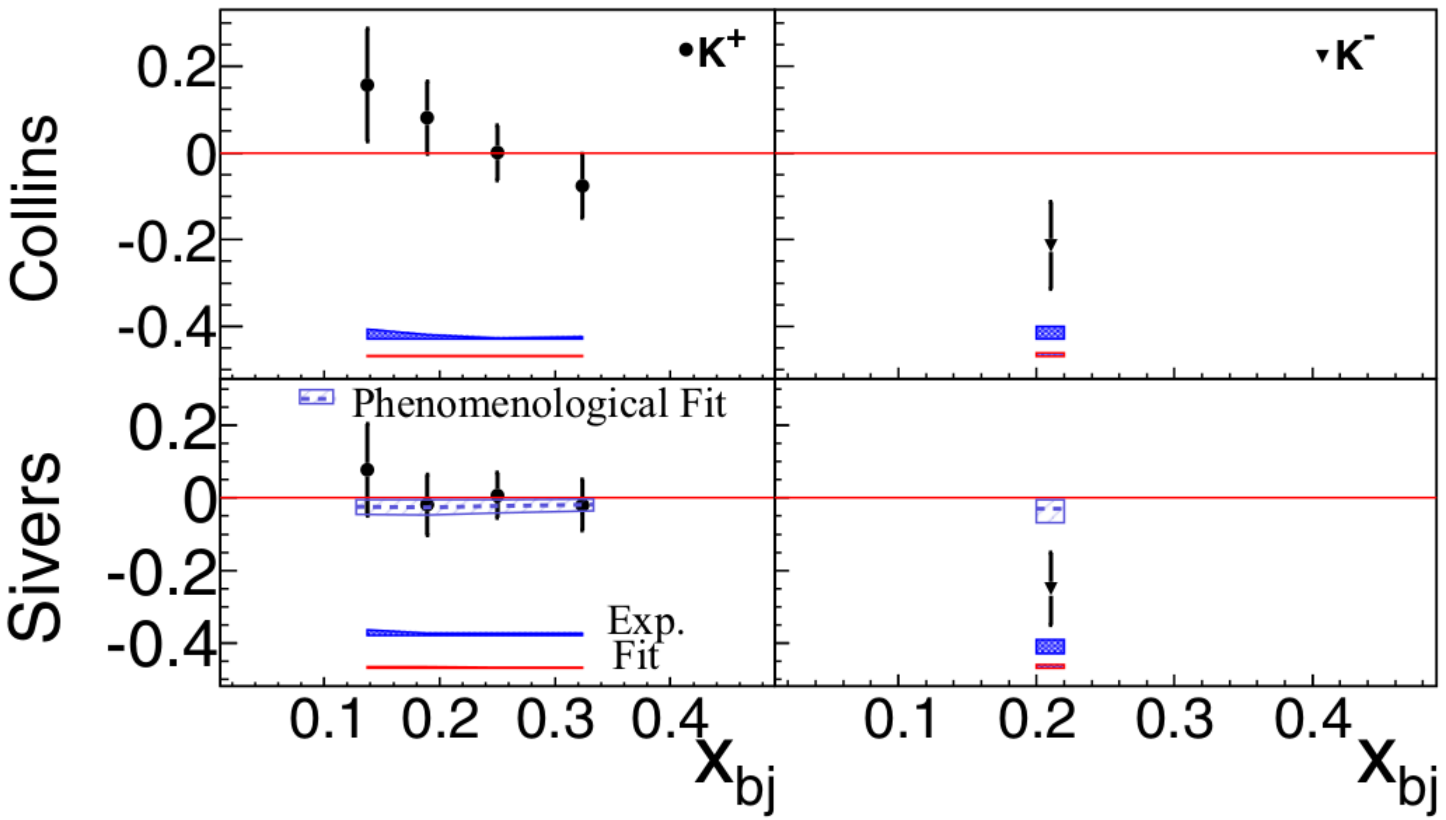




- Classified "High impact" by JLab PAC41
- Polarized electron beam on unpolarized target
- Azimuthal asymmetries provide access to Buer-Mulders function, $h_1^{\perp}(x)$
- Increase statistics by factor of ~100

H. Avakian *et al.*, JLab E12-06-112

* See TMD Sessions, Tuesday and Thursday Afternoon

# Transversity @ JLab

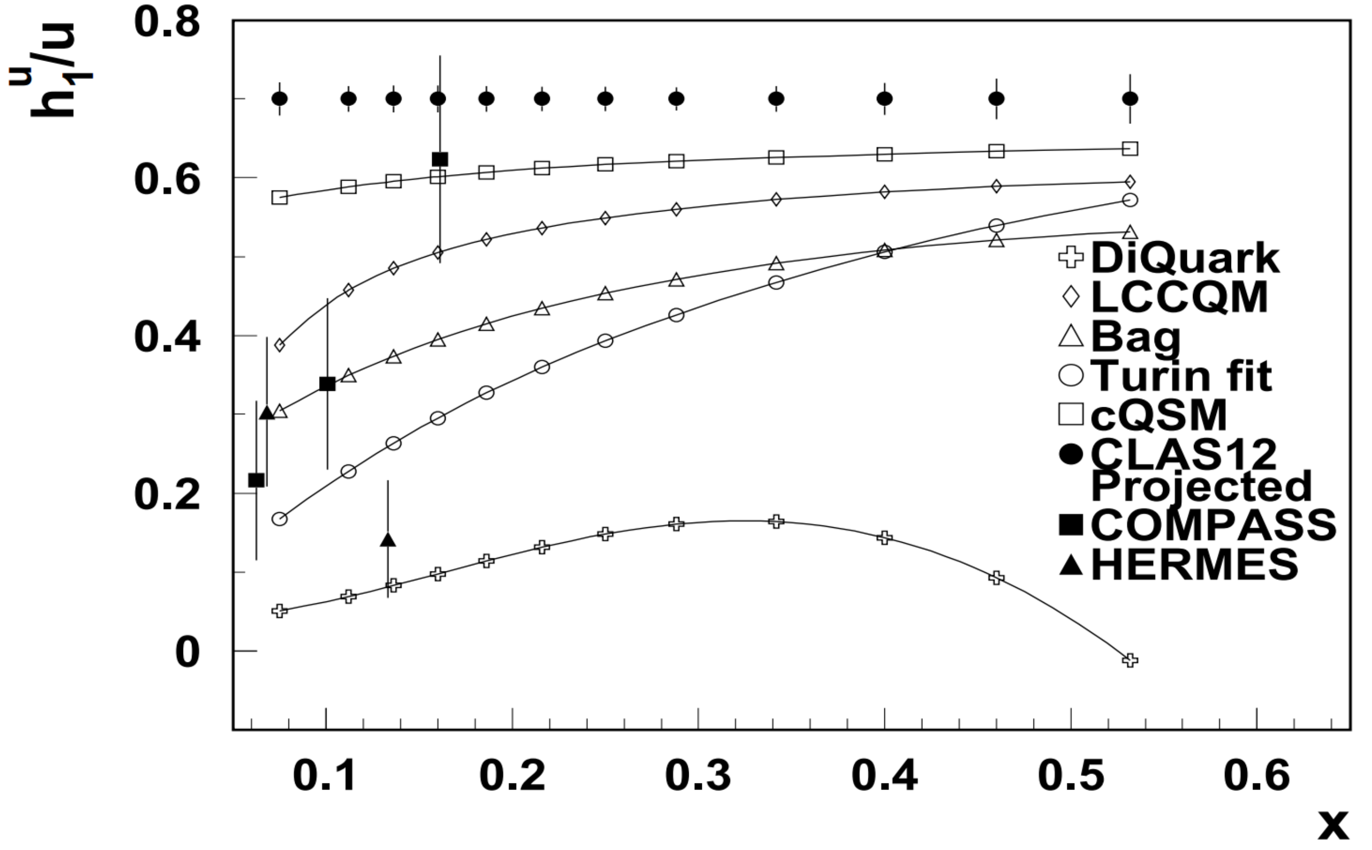



- K+ and K- production in SIDIS from transversely polarized 3He target
- Measured Collins and Sivers moments, related to nucleon transversity & Sivers distributions
- Collins & Sivers for $K^+$ ~0
- Collins & Sivers for $K^-$ negative, differ from prediction at $2\sigma$ level

Y.X. Zhao et al., Phys. Rev. C **90**, 055201 (2014)

* See TMD Sessions, Tuesday and Thursday Afternoon

# Future "High Impact" Transversity @ JLab12 CLAS12




- SIDIS Di-hadron production from transversely polarized HD-Ice target
- To measure transversity distribution, $h_1(x)$
- Classified "High impact" by JLab PAC41

H. Avakian *et al.*, JLab E12-12-009

* See TMD Sessions, Tuesday and Thursday Afternoon

# Generalized Parton Distributions (GPDs)

GPDs give insight into nucleon spin crisis

- Quark OAM?
- Gluon polarization?
- Gluon OAM?

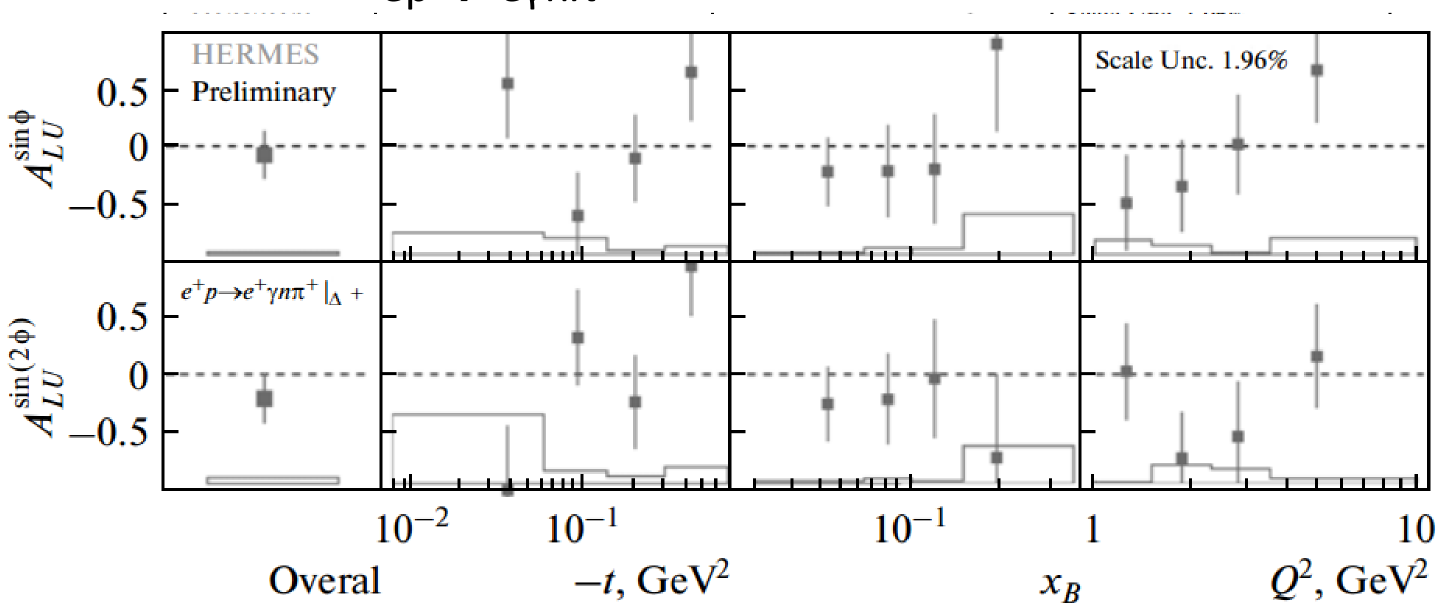
$$H, E, \widetilde{H}, \tilde{E}, H_T, E_T, \widetilde{H_T}, \widetilde{E_T}$$

Measured through Deeply Virtual Compton Scattering (DVCS) and Meson Production (DVMP)

- "DVCS is the cleanest 'golden' channel to study GPDs" –JLab Pac41

# DVCS @ Hermes

ep → eγnπ⁺

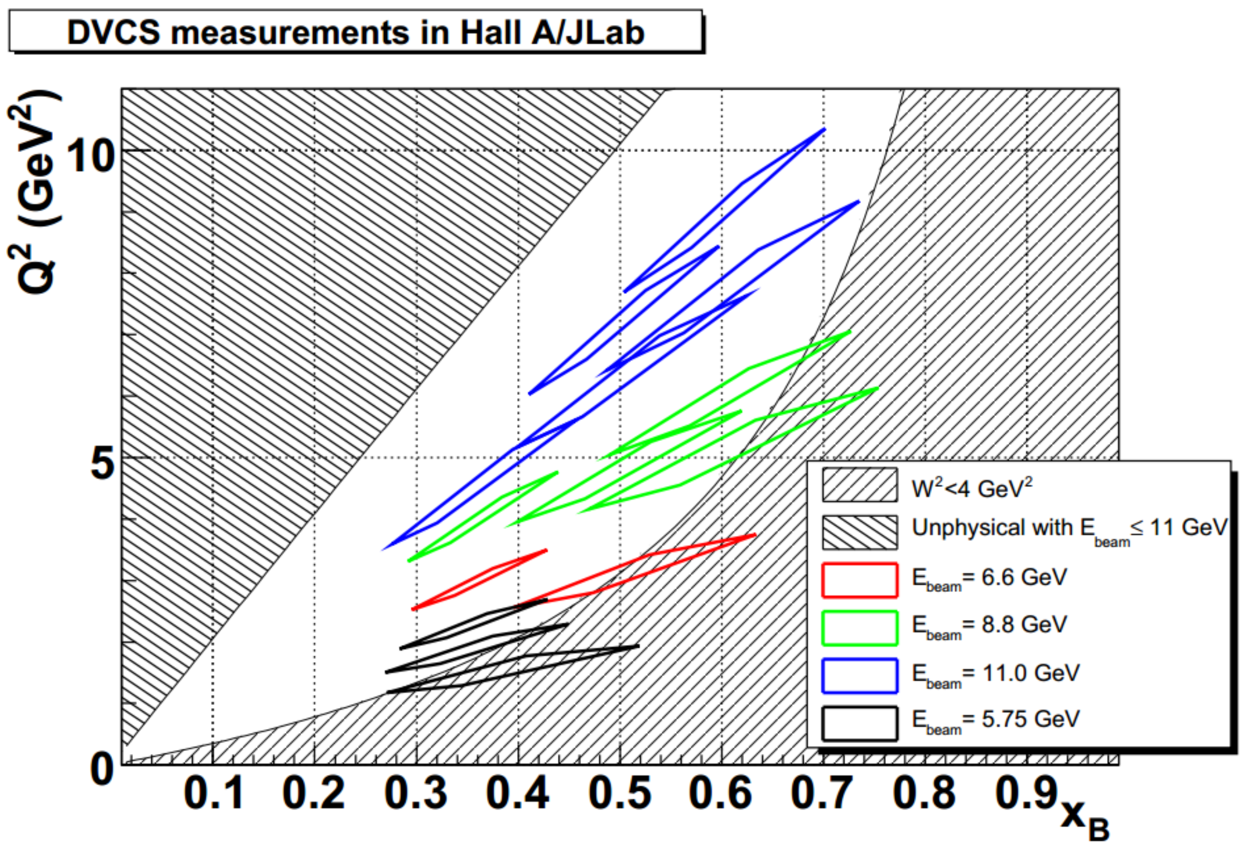



S. Yaschenko, Phys. Part. Nucl. **45**, 173 (2014)

- DVCS results still in analysis
- Longitudinally polarized electron beam on unpolarized hydrogen target
- Data from recoil detector added in last 2 years of HERA running
- Beam-helicity asymmetry amplitudes provide constraints to GPD models and fits

* See TMD Sessions, Tuesday and Thursday Afternoon

# “High Impact” DVCS @ JLab12 Hall A

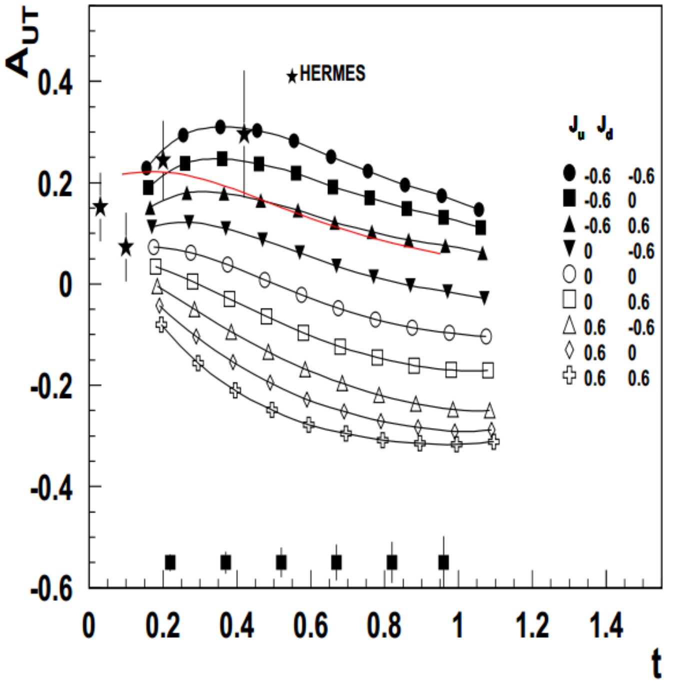


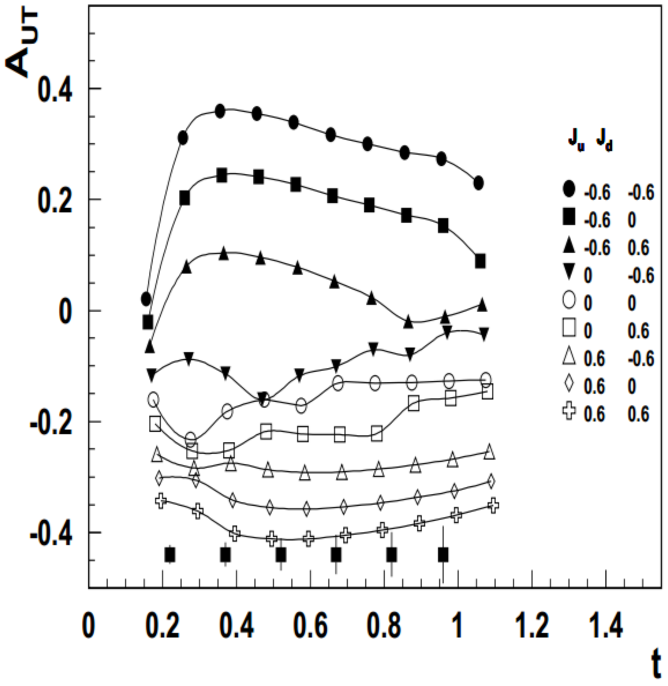

A. Camsonne, et al, JLab E12-06-114

- Classified “Major high-impact highlight” by JLab PAC41
- Longitudinally polarized electron beam on unpolarized hydrogen target
- Precision test of scaling through measurement of DVCS absolute cross section
- Just starting to run!

* See TMD Sessions, Tuesday and Thursday Afternoon

# Future “High Impact” DVCS @ JLab12 CLAS12




- Classified “Major highlight” by JLab PAC41
- Longitudinally polarized electron beam on transversely polarized HD-Ice target
- Provide access to elusive GPD $E$ and the u and d quark contributions to total OAM

A. Camsonne, et al, JLab E12-06-114

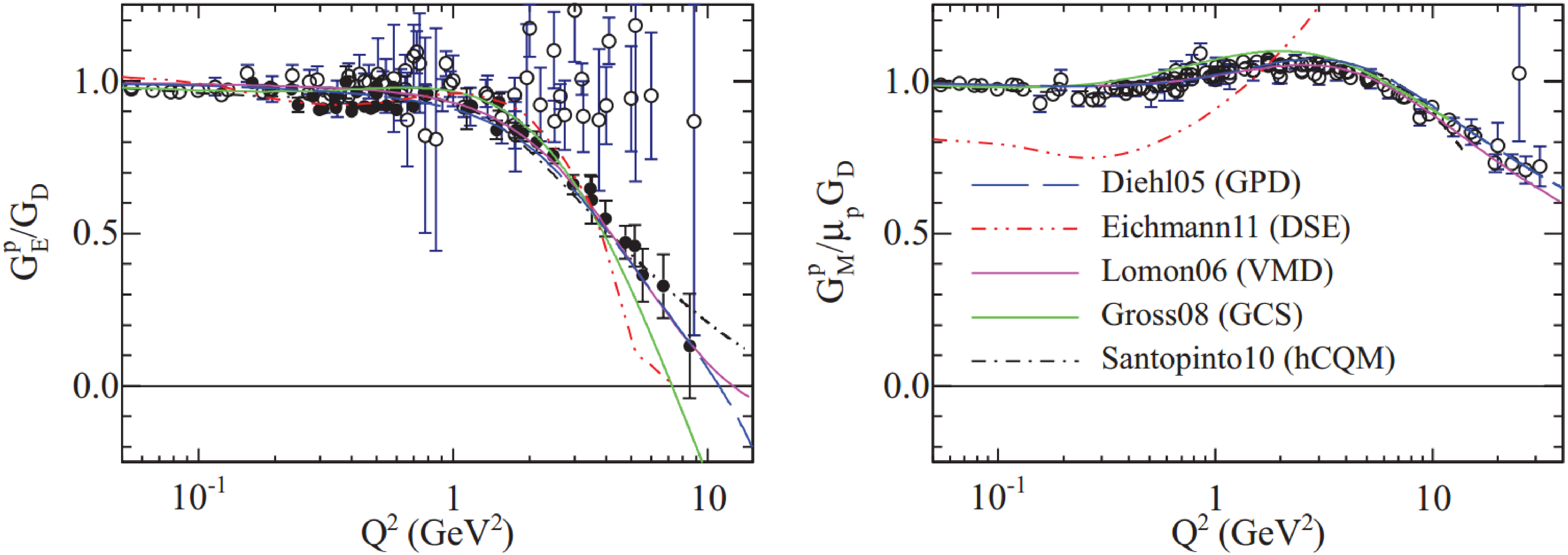
* See TMD Sessions, Tuesday and Thursday Afternoon

# EM Form Factors

Describe the electromagnetic structure of nucleons

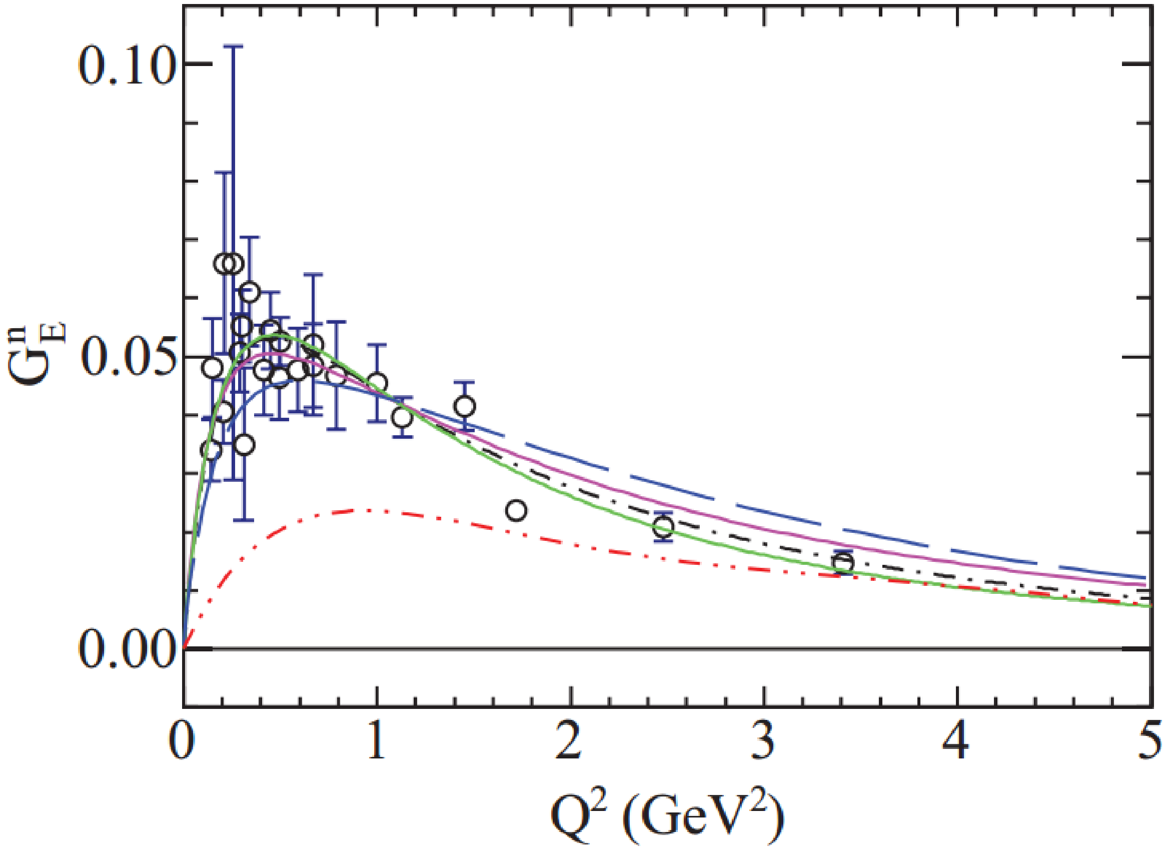
$$G_E, G_M$$

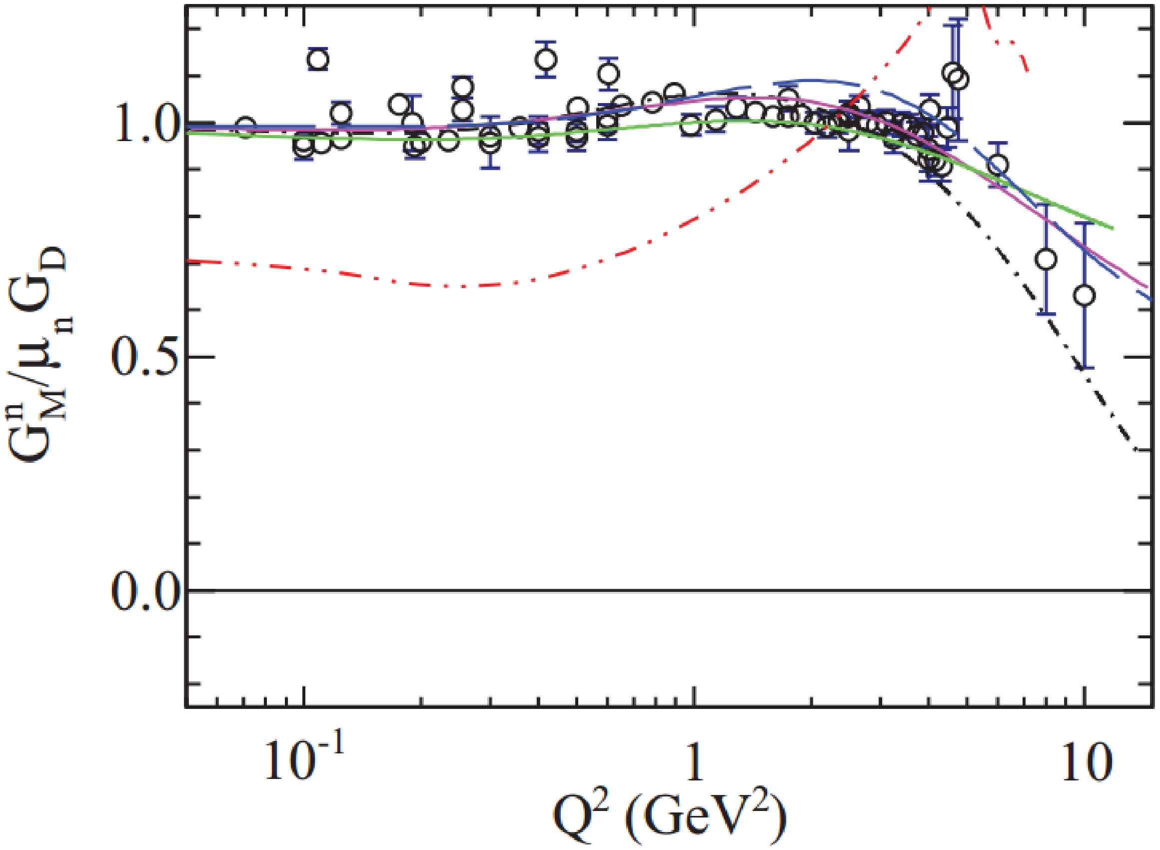
# Proton Form Factors – World Data




A. Puckett, et al, Phys. Rev. C **85**, 045203 (2012)

# Neutron Form Factors – World Data




A. Puckett, et al, Phys. Rev. C **85**, 045203 (2012)

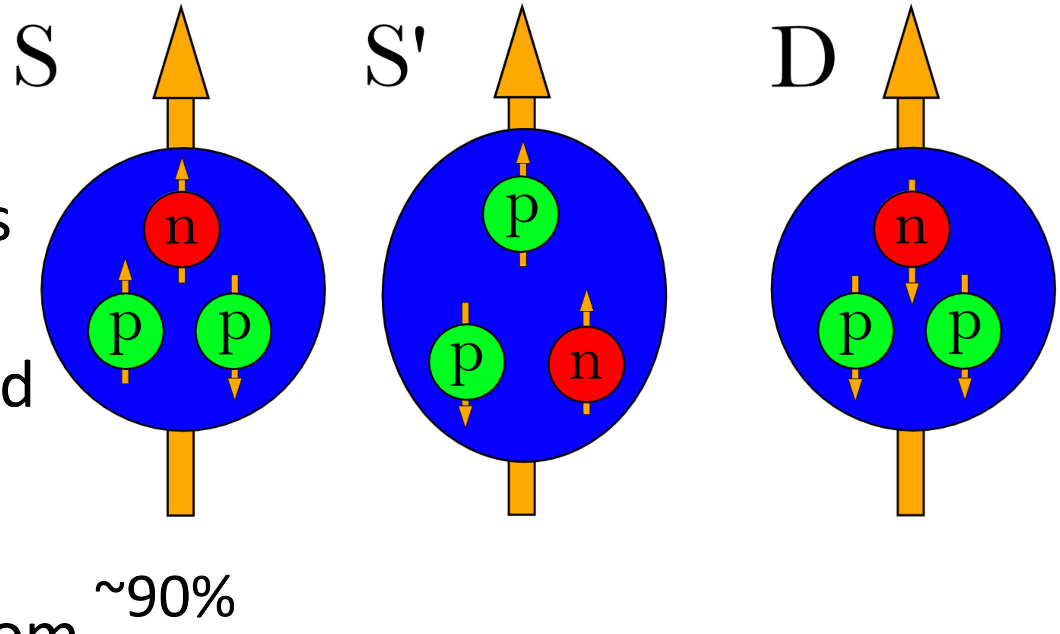
# Using $^3$He as a Free Neutron Target – Spin Asymmetries

- $^3$He often used as a free neutron target due to its unique spin properties

- Experimental uncertainties have matched or surpassed theoretical descriptions of the $^3$He nucleus

- Recent studies have been done to better understand the effects on a neutron inside of a $^3$He nucleus

- Necessary for extracting any neutron information from $^3$He

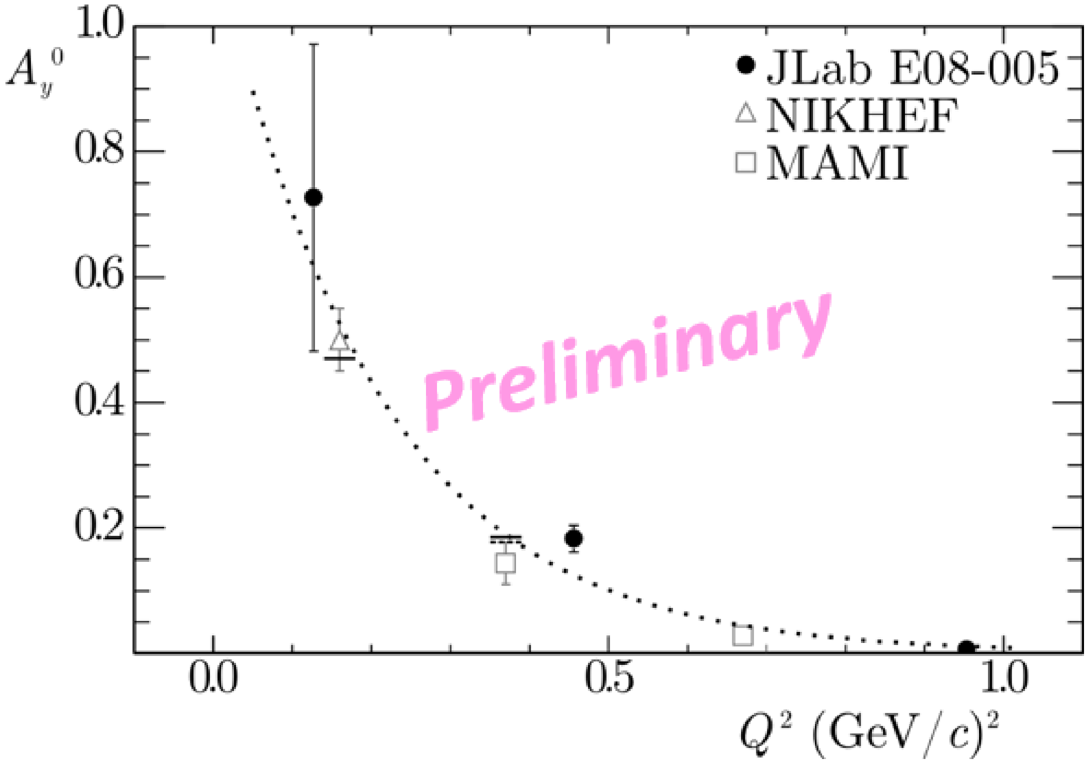


# $^3\vec{He}(\vec{e},e'n)$ SSA $A_y^0$

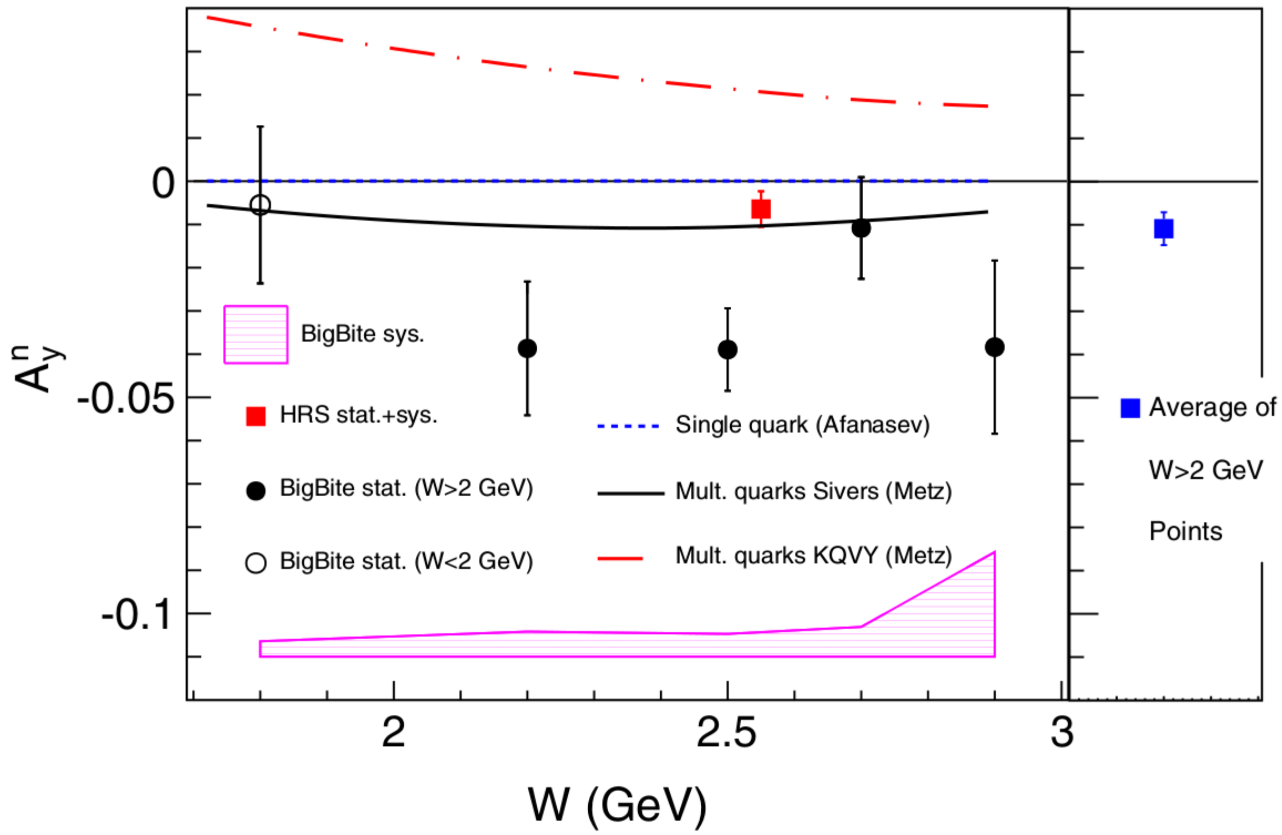
- Unpolarized beam on polarized target

- Probe of nucleonic effects of knocking out neutrons from $^3$He
  - Particular Final State Interactions and Meson Exchange Currents

- In PWIA, $A_y^0 = 0$
  - Any non-zero result indicates higher-order effects



# $^3$He(e,e')X SSA / 2-Photon Exchange

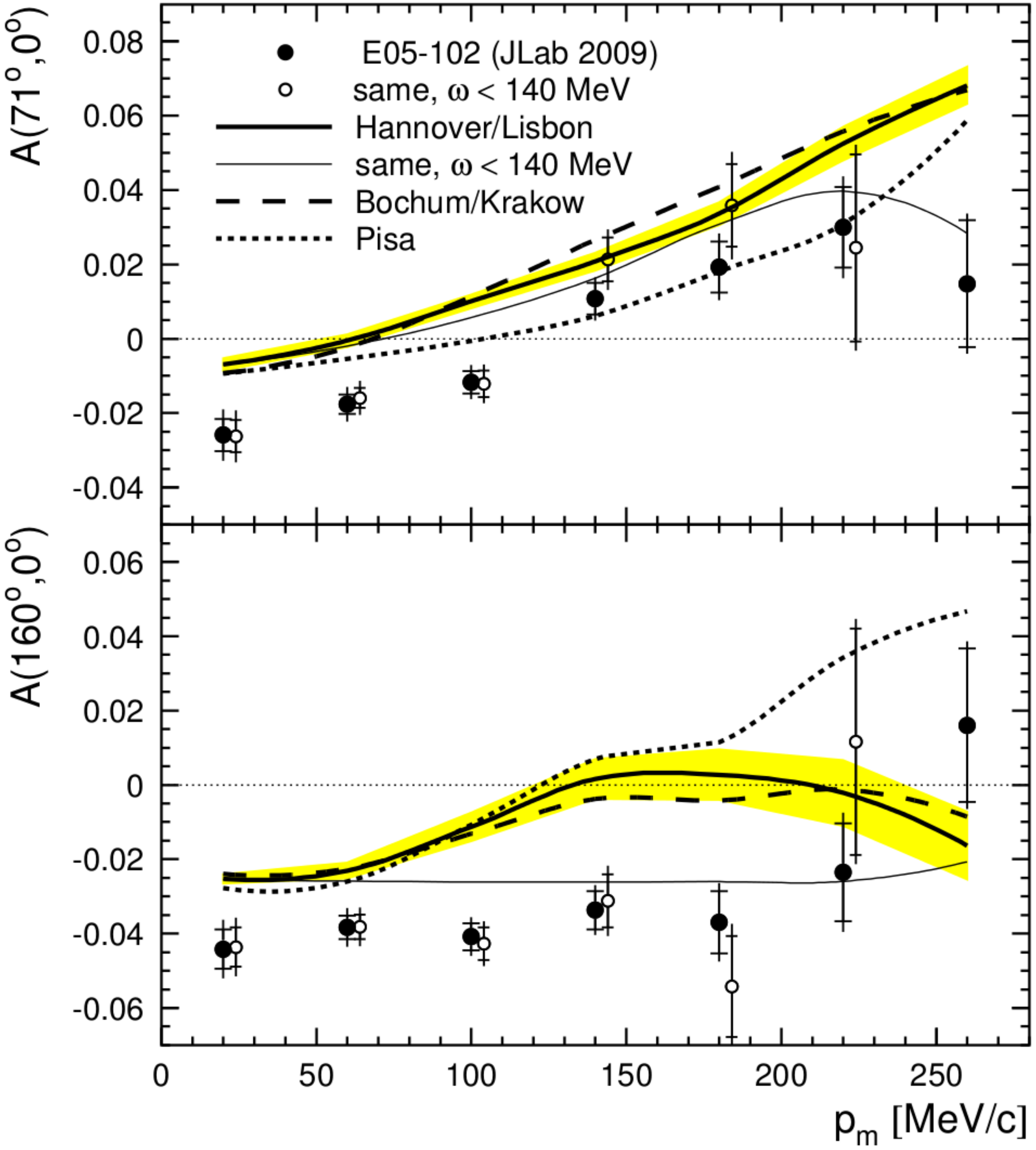



J. Katich et al., Phys. Rev. Lett. **113**, 022502 (2014)

- $0.16 < x < 0.65$
- First measurement of $A_y$ for neutron
- In Born approximation, $A_y^n = 0$
  - Unless 2-photon exchange effects included
- Non-zero negative value found, 2.8σ level
- Agrees with 2-photon-exchange using Sivers TMD input

# 3He(e,e'd) DSA

- $Q^2$=0.25 GeV$^2$, $p_{miss}$ < 270 MeV/*c*
- Systematic discrepancy with state-of-the-art 3-body Fadeev calculations
- First measurement of $^3$He(e,e'd)p DSA
- Sensitive to 3He ground-state wavefunction and 3-nucleon forces
- Extracted deuteron Pz and Pzz in $^3$He




M. Mihovilovic, G. Jin, E. Long, Y.W. Zhang, et al., arXiv:1409.2253

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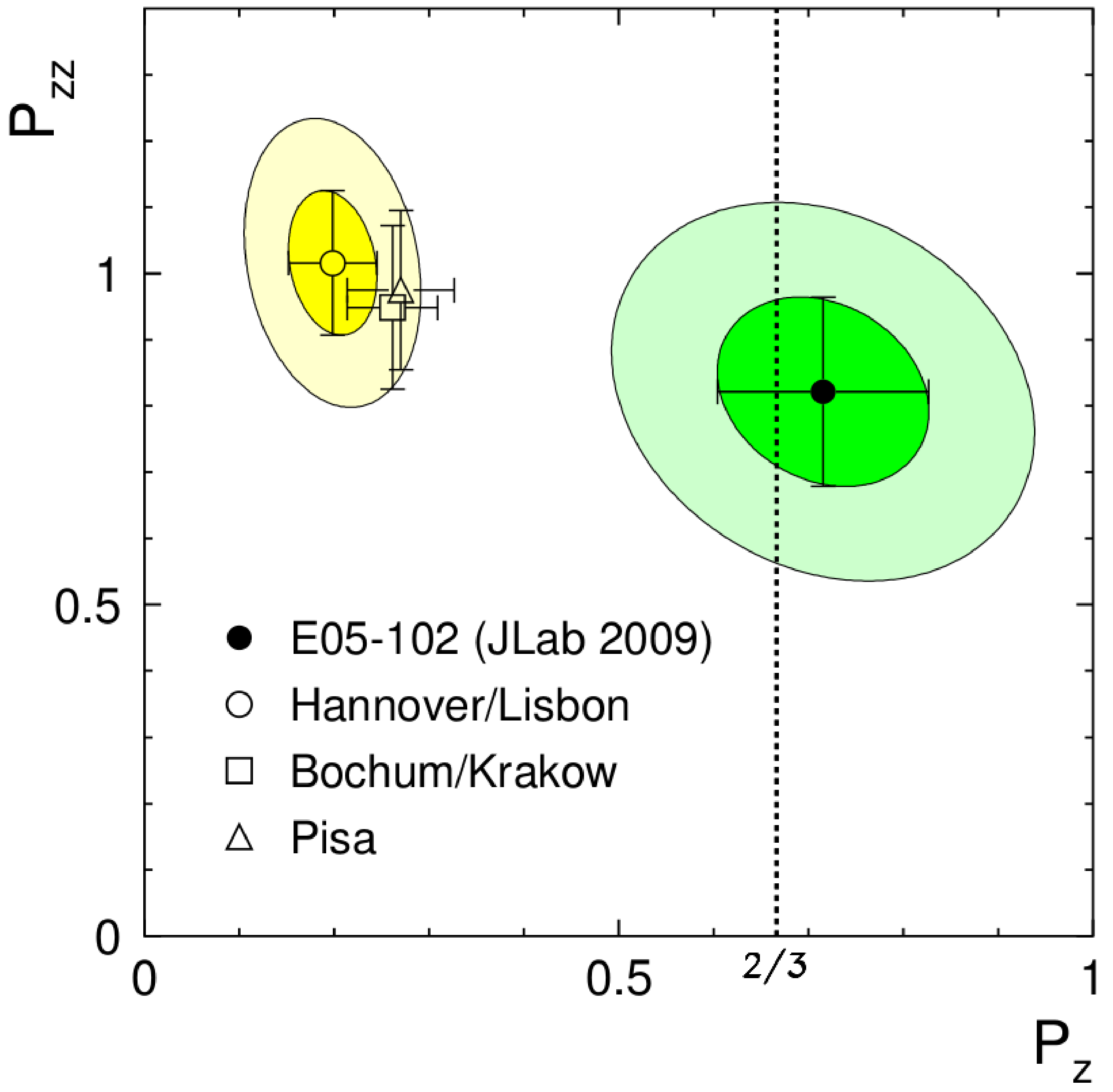


# Structure Functions

Describe the longitudinal momentum distribution of quarks and gluons

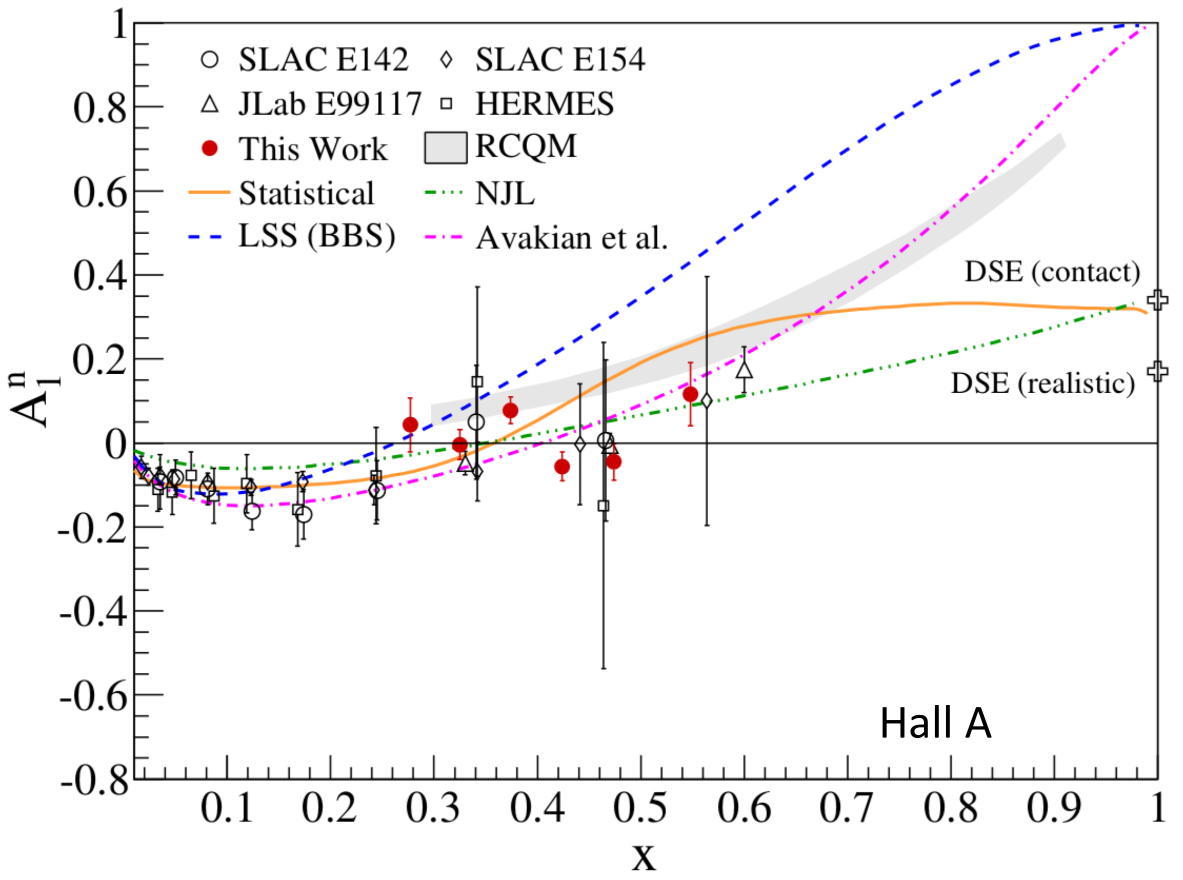
$$
\begin{aligned}
W_{\mu\nu} = & -\alpha F_1 + \beta F_2 \\
& + i\gamma g_1 + i\delta g_2 \\
& - \varepsilon b_1 + \zeta b_2 + \eta b_3 + \kappa b_4
\end{aligned}
$$

Scattering on Unpolarized Targets

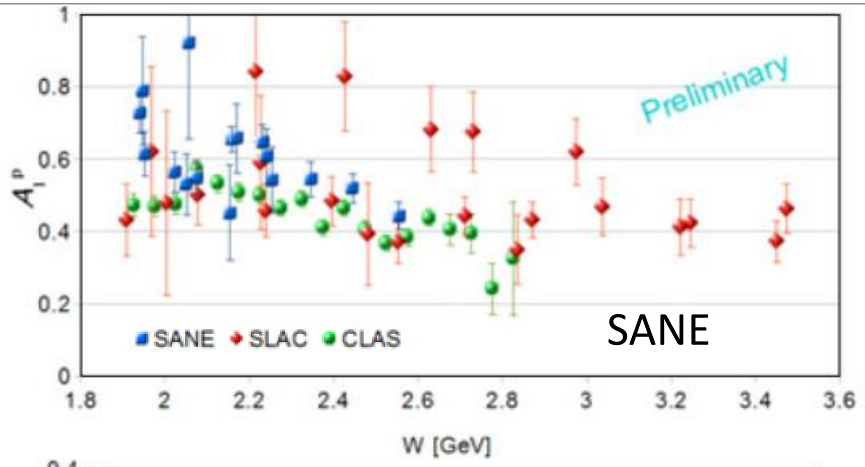
Scattering on Polarized Targets

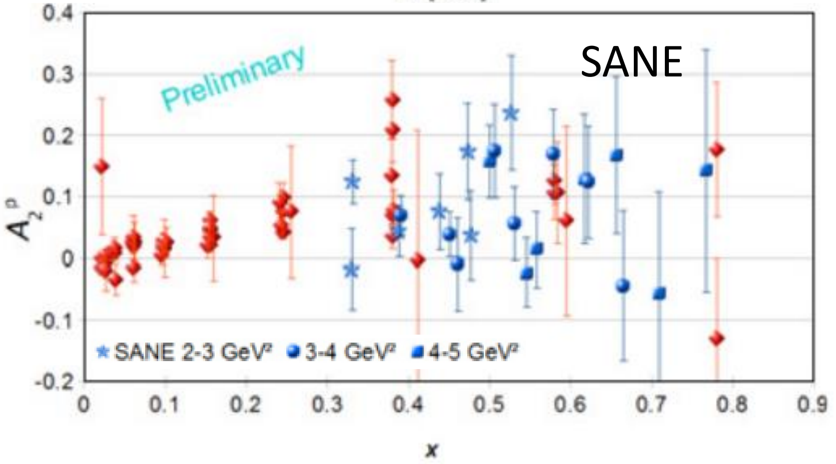
Scattering on Tensor-Polarized Targets (Save for later)

# $A_1^n, A_1^p, A_2^p$ Analysis @ JLab




D.S. Parno et al., arXiv:1406.1207




* See Mark Jones's Talk, Wed. 11am

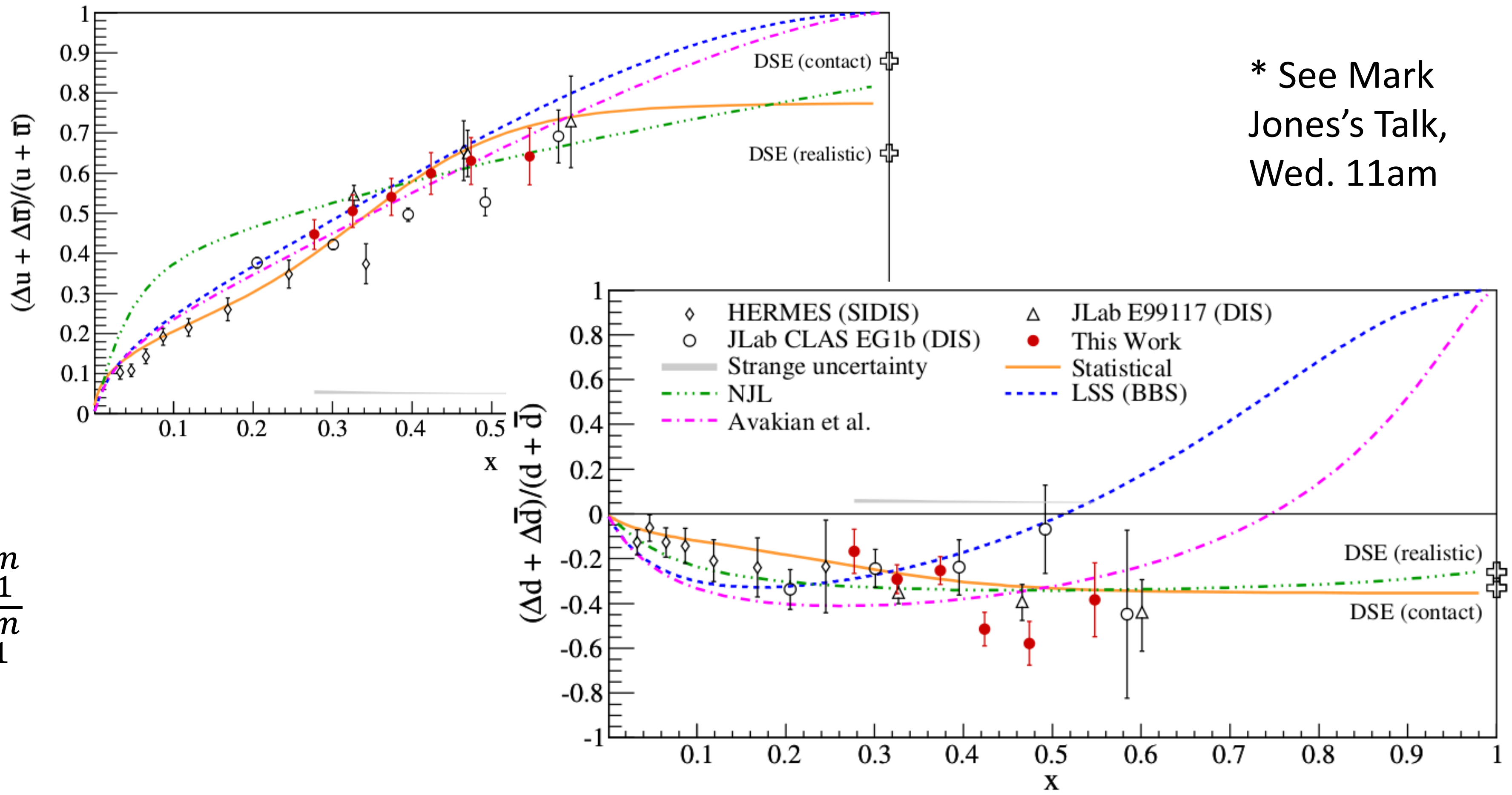
O.A. Rondon, EPJ WoC **73**, 02001 (2014)

# $A_1^n, g_1^n/F_1^n$ Results @ JLab Hall A

$$A_1 = \frac{[g_1 - \gamma^2 g_2]}{F_1}$$

$$\frac{\Delta u + \Delta\bar{u}}{u + \bar{u}} = \alpha(R)\frac{g_1^p}{F_1^p} - \beta(R)\frac{g_1^n}{F_1^n}$$

$$\frac{\Delta d + \Delta d}{d + \bar{d}} = -\beta(R)\frac{g_1^p}{F_1^p} + \alpha(R)\frac{g_1^n}{F_1^n}$$

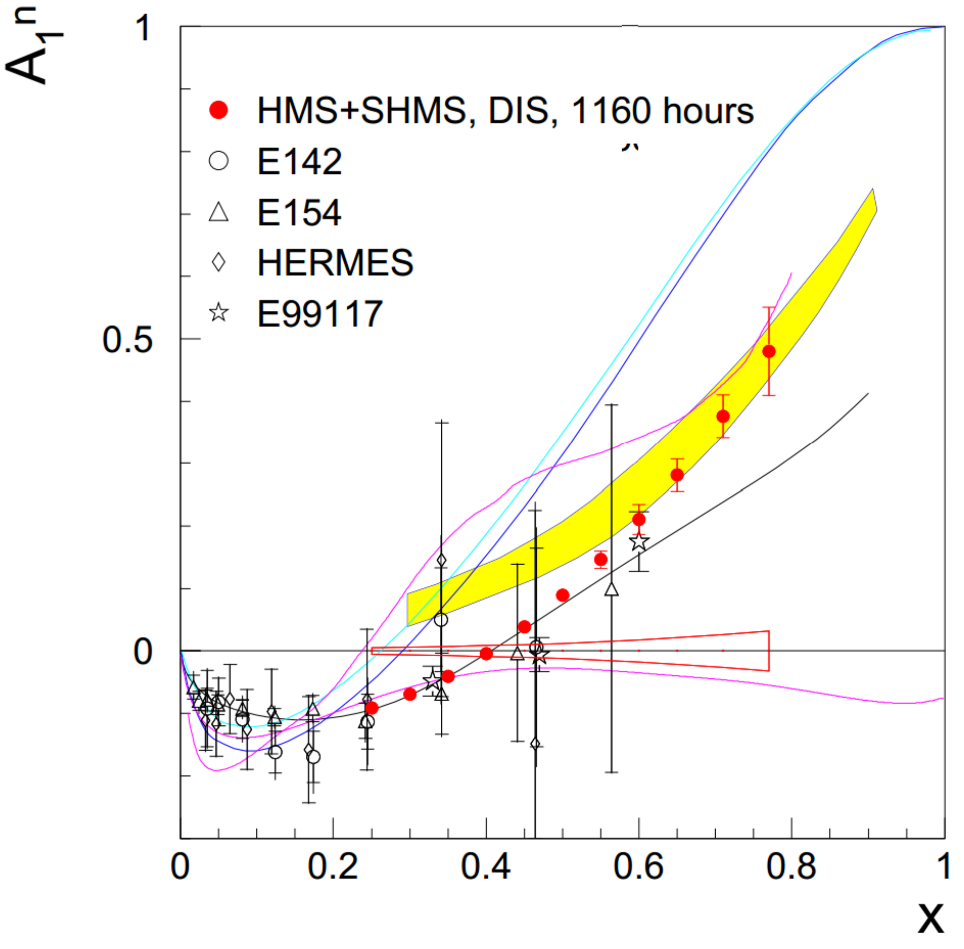



* See Mark Jones's Talk, Wed. 11am

D.S. Parno et al., arXiv:1406.1207

# Future "High Impact" $A_1^n$ @ JLab12 Hall C

- Identified as "High Impact" by JLab PAC41
- Polarized electron beam on polarized $^3$He target
- Extend Δq/q for u & d quarks up to large *x*

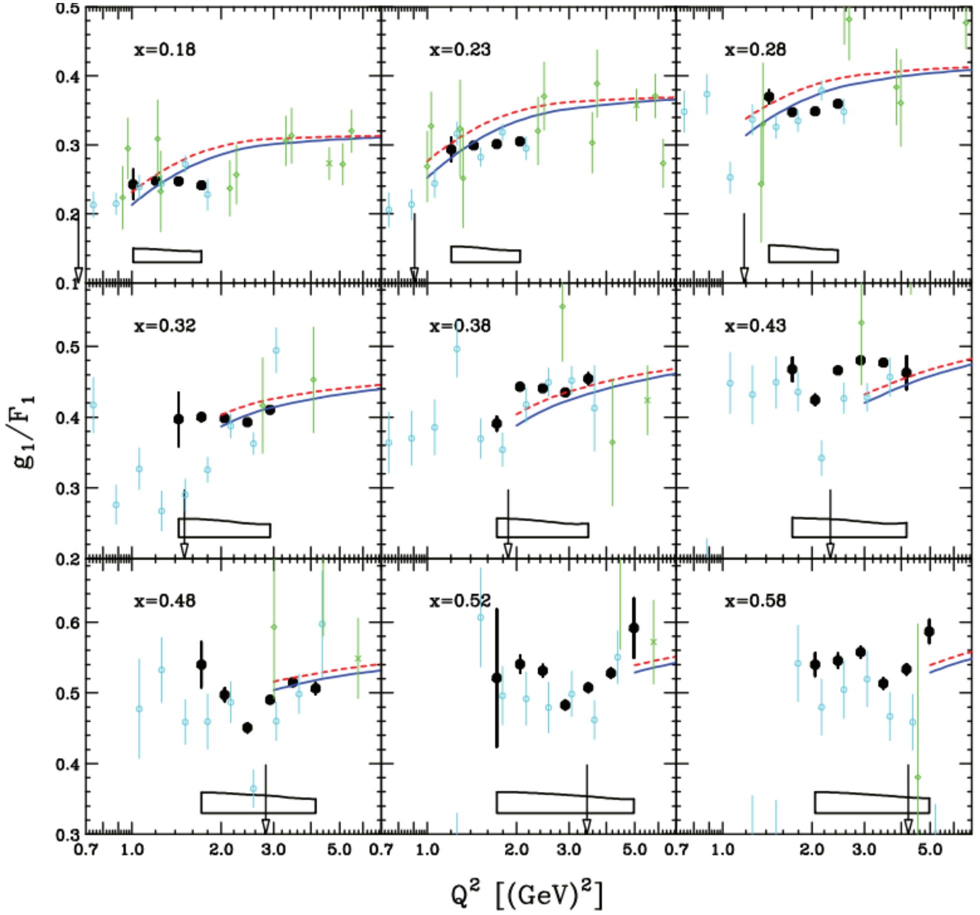



* See Mark Jones's Talk, Wed. 11am

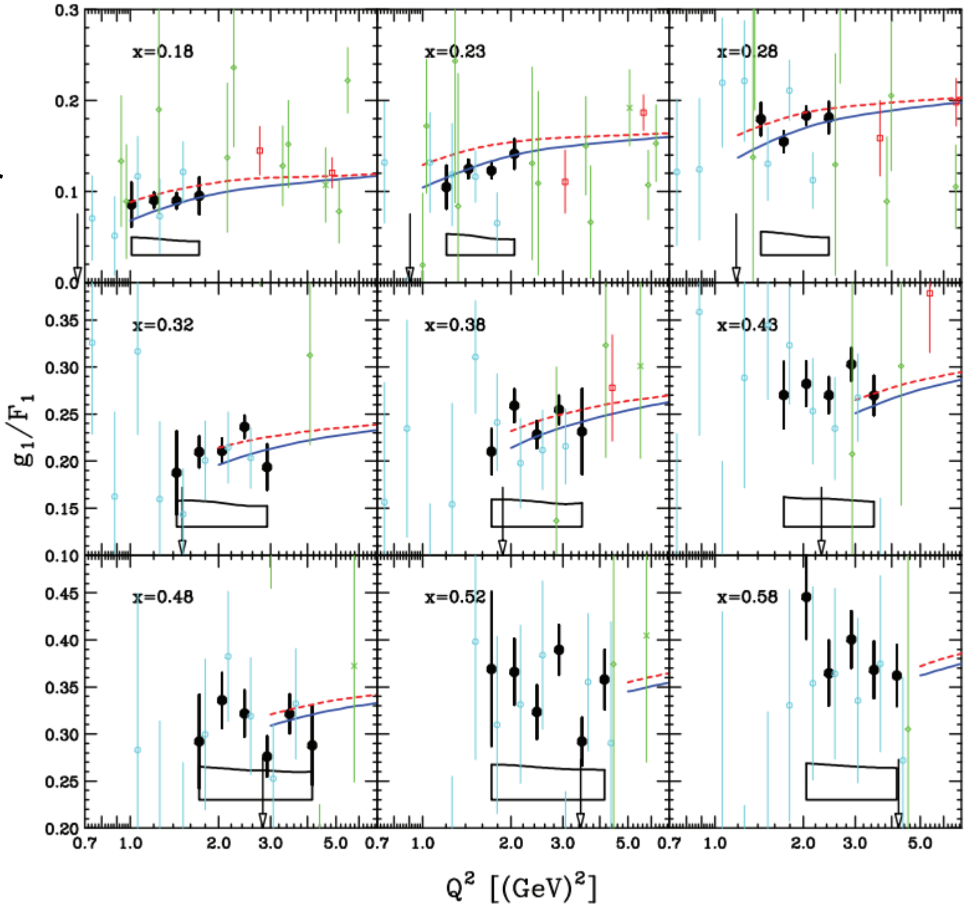
X. Zheng *et al.*, JLab E12-06-110

# $g_1/F_1$ Results @ JLab CLAS

Proton

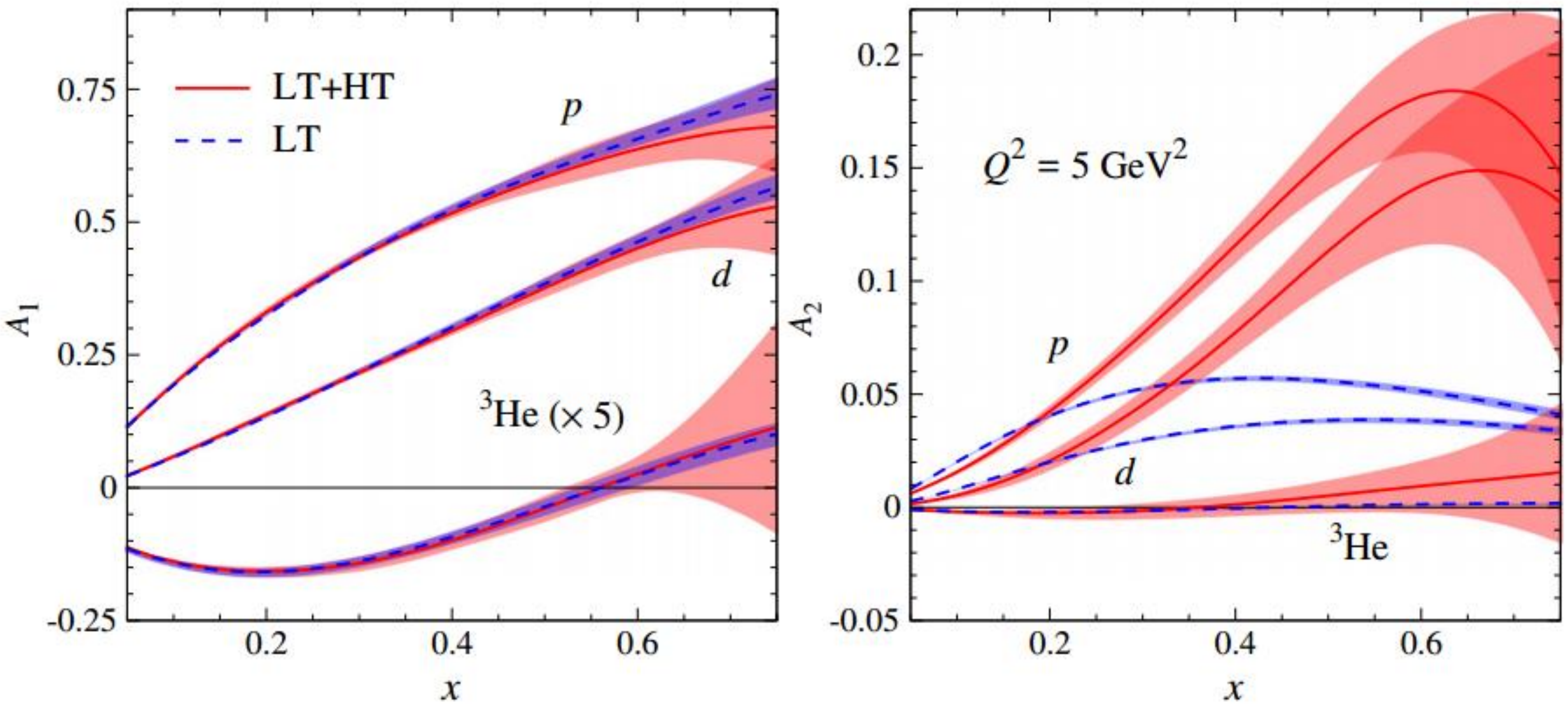



Deuteron




Y. Prok, *et al*, Phys. Rev. C **90**, 025212 (2014)

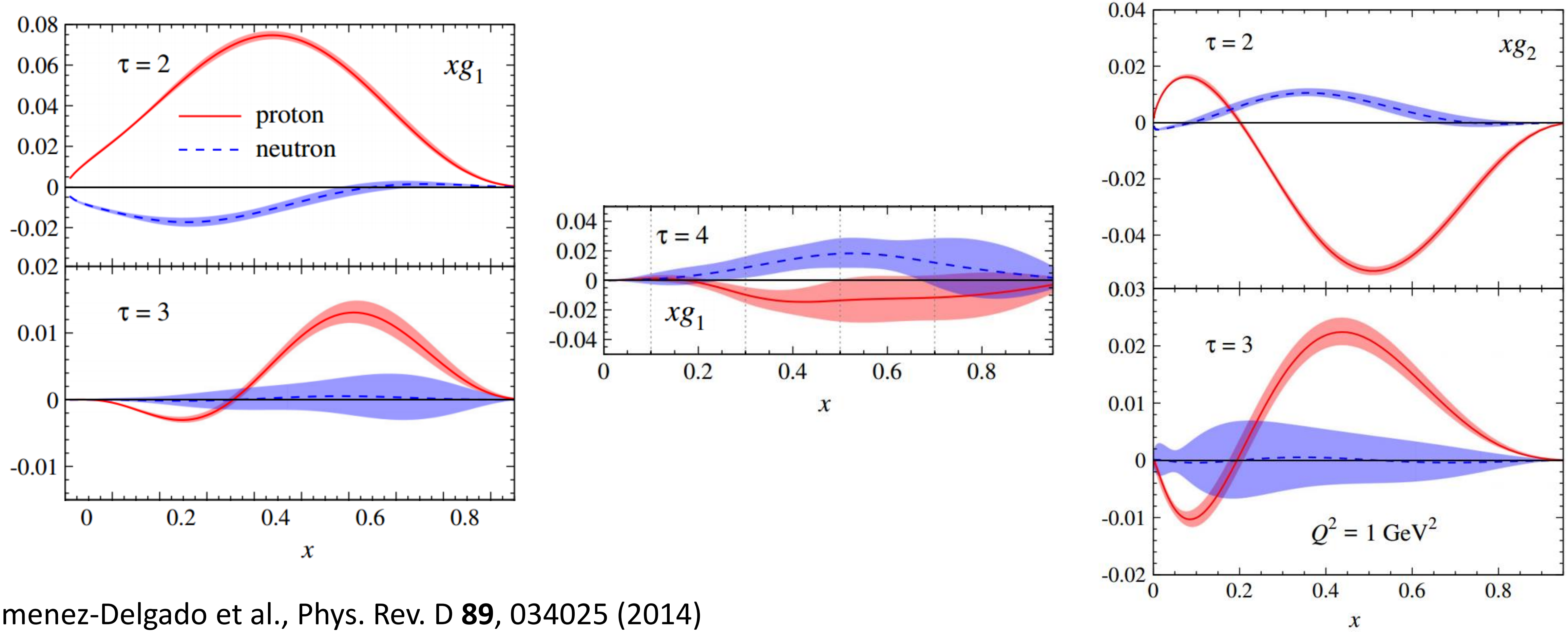
# Structure Functions from World Data Fits




| Experiment | Reference | Observable | Target | $N_{data}$ | $\chi^2(LT)/N_{data}$ | $\chi^2(JAM)/N_{data}$ |
|---|---|---|---|---|---|---|
| EMC | [1] | $A_1$ | $p$ | 10 | 0.42 | 0.39 |
| SMC | [30] | $A_1$ | $p$ | 12 | 0.36 | 0.36 |
| | [30] | $A_1$ | $d$ | 12 | 1.59 | 1.66 |
| | [31] | $A_1$ | $p$ | 8 | 1.37 | 1.35 |
| | [31] | $A_1$ | $d$ | 8 | 0.54 | 0.56 |
| COMPASS | [32] | $A_1$ | $p$ | 15 | 0.95 | 0.97 |
| | [33] | $A_1$ | $d$ | 15 | 0.57 | 0.51 |
| SLAC E80/E130 | [34] | $A_\parallel$ | $p$ | 23 | 0.52 | 0.54 |
| SLAC E142 | [35] | $A_1$ | $^3He$ | 8 | 0.58 | 0.70 |
| | [35] | $A_2$ | $^3He$ | 8 | 0.70 | 0.70 |
| SLAC E143 | [36] | $A_\parallel$ | $p$ | 85 | 0.85 | 0.81 |
| | [36] | $A_\perp$ | $p$ | 48 | 0.95 | 0.91 |
| | [36] | $A_\parallel$ | $d$ | 85 | 1.05 | 0.85 |
| | [36] | $A_\perp$ | $d$ | 48 | 0.92 | 0.91 |
| SLAC E154 | [37] | $A_\parallel$ | $^3He$ | 18 | 0.43 | 0.42 |
| | [37] | $A_\perp$ | $^3He$ | 18 | 1.00 | 1.00 |
| SLAC E155 | [38] | $A_\parallel$ | $p$ | 73 | 1.00 | 0.92 |
| | [38,39] | $A_\perp$ | $p$ | 66 | 1.00 | 0.96 |
| | [40] | $A_\parallel$ | $d$ | 73 | 0.98 | 0.97 |
| | [39,40] | $A_\perp$ | $d$ | 66 | 1.51 | 1.49 |
| SLAC E155x | [41] | $\tilde{A}_\perp$ | $p$ | 117 | 2.17 | 1.64 |
| | [41] | $\tilde{A}_\perp$ | $d$ | 117 | 0.90 | 0.84 |
| HERMES | [42] | $A_\parallel$ | $p$ | 37 | 0.38 | 0.39 |
| | [42] | $A_\parallel$ | $d$ | 37 | 0.86 | 0.85 |
| | [43] | $A_1$ | "$n$" | 9 | 0.29 | 0.30 |
| | [44] | $A_2$ | $p$ | 20 | 1.07 | 1.16 |
| JLab E99-117 | [45] | $A_\parallel$ | $^3He$ | 3 | 0.62 | 0.06 |
| | [45] | $A_\perp$ | $^3He$ | 3 | 1.08 | 0.87 |
| COMPASS | [49] | $\Delta g/g$ | $p$ | 1 | 5.27 | 2.71 |
| Total | | | | 1043 | 1.07 | 0.98 |
| JLab E97-103* | [46] | $A_\parallel$ | $^3He$ | 2 | ... | ... |
| | [46] | $A_\perp$ | $^3He$ | 2 | ... | ... |
| JLab EG1b* | [48] | $A_1$ | $p$ | 766 | ... | ... |
| (preliminary) | [48] | $A_1$ | $d$ | 767 | ... | ... |

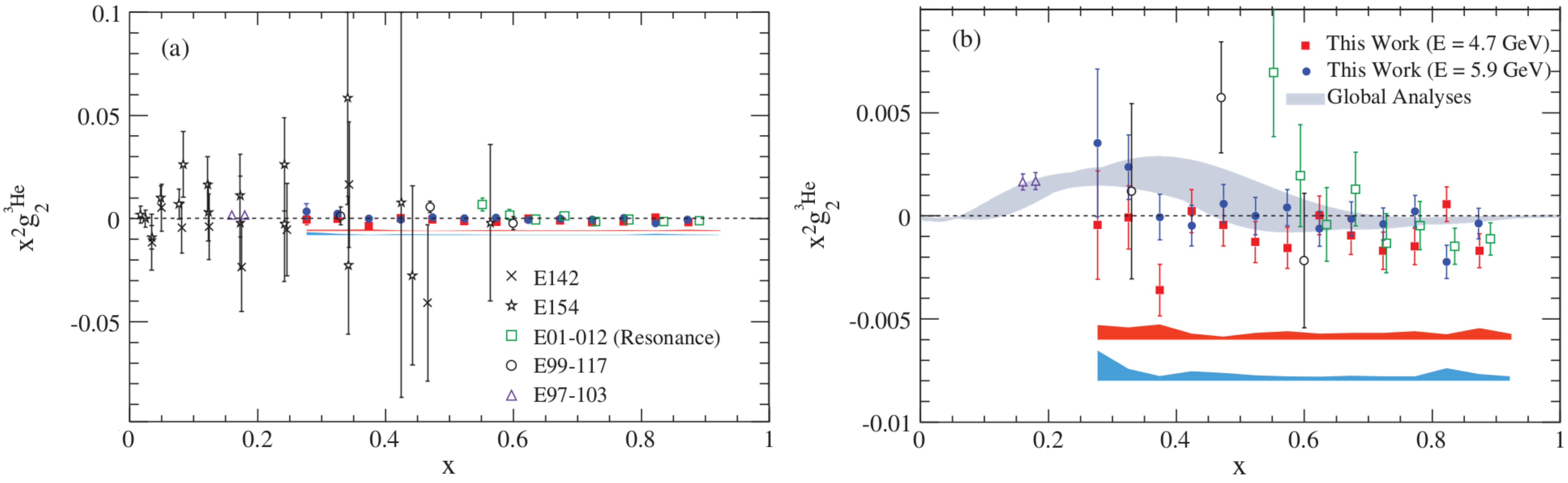
P. Jimenez-Delgado et al., Phys. Rev. D **89**, 034025 (2014)

# Structure Functions from World Data Fits



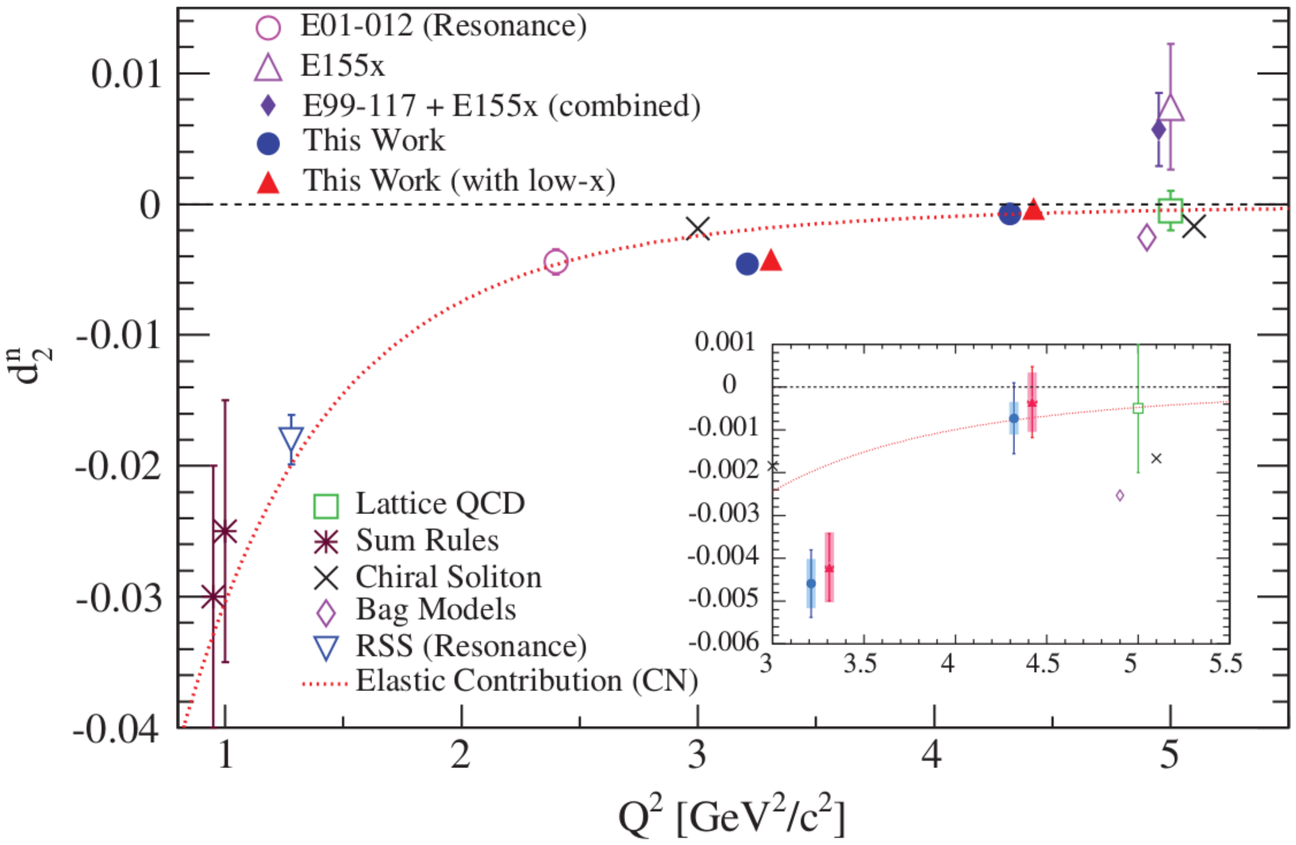

P. Jimenez-Delgado et al., Phys. Rev. D **89**, 034025 (2014)

# $g_2^{^3\mathrm{He}}$ from $d_2^n$ @ JLab




M. Posik et al., Phys. Rev. Lett. **113**, 022002 (2014)

# Twist-3 Matrix Element $d_2^n$ @ JLab




M. Posik et al., Phys. Rev. Lett. **113**, 022002 (2014)

- Long. polarized electrons on trans. & long. polarized 3He target

$$\bar{g}_2(x,Q^2) = g_2(x,Q^2) - g_2^{WW}(x,Q^2)$$
$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{g_1(y,Q^2)dy}{y}$$
$$d_2 = 3\int_0^1 dx x^2 \bar{g}_2(x)$$

- Agree with QCD, resolve previous data disagreement at Q2=5 GeV^2
- Neutron color E&M FF extracted, opposite sign ~30 MeV/fm
  - Probes confinement forces
- See Brad Sawatzky's talk, Wed. 12pm

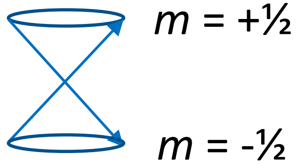
# Tensor Structure Functions

$$W_{\mu\nu} = -\alpha F_1 + \beta F_2$$ Scattering on Unpolarized Targets

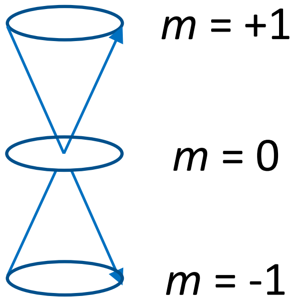
$$+i\gamma g_1 + i\delta g_2$$ Scattering on Vector Polarized Targets

$$-\varepsilon b_1 + \zeta b_2 + \eta b_3 + \kappa b_4$$ Scattering on Tensor-Polarized Targets

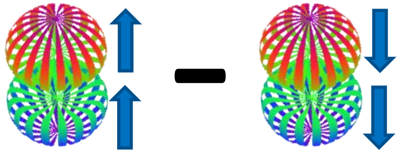
**Spin-½ System**



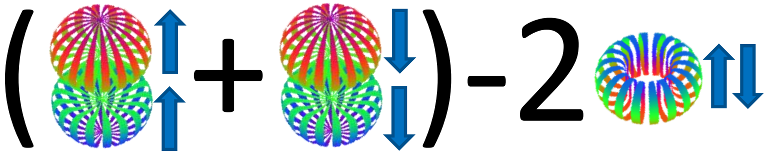

**Spin-1 System**




Vector $P_z = p_+ - p_-$



Tensor $P_{zz} = (p_+ + p_-) - 2p_0$




P Hoodbhoy *et al*, Nucl. Phys. **B312,** 571 (1989)

# Tensor Structure Function, $b_1$

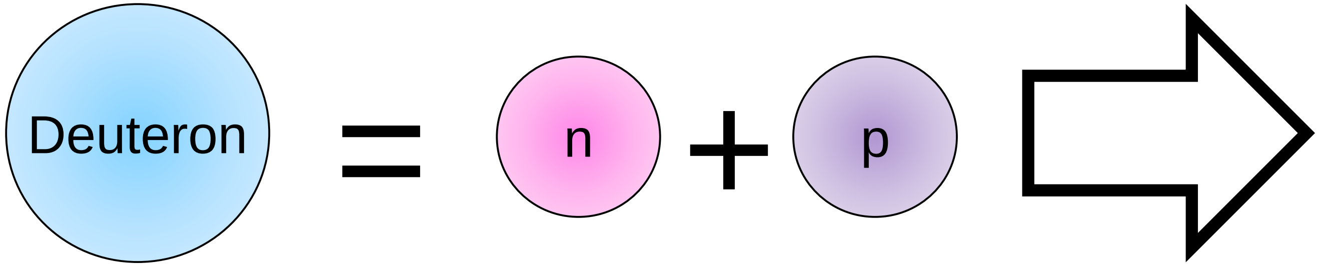
$b_1 \rightarrow$ Leading twist

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

$b_1$ is the measure of quark distributions when the nucleus is in a particular spin state

**<u>Looks at nuclear effects at the resolution of quarks!</u>**

If there are no nuclear effects, then $b_1$ vanishes.




$$b_1 = 0$$

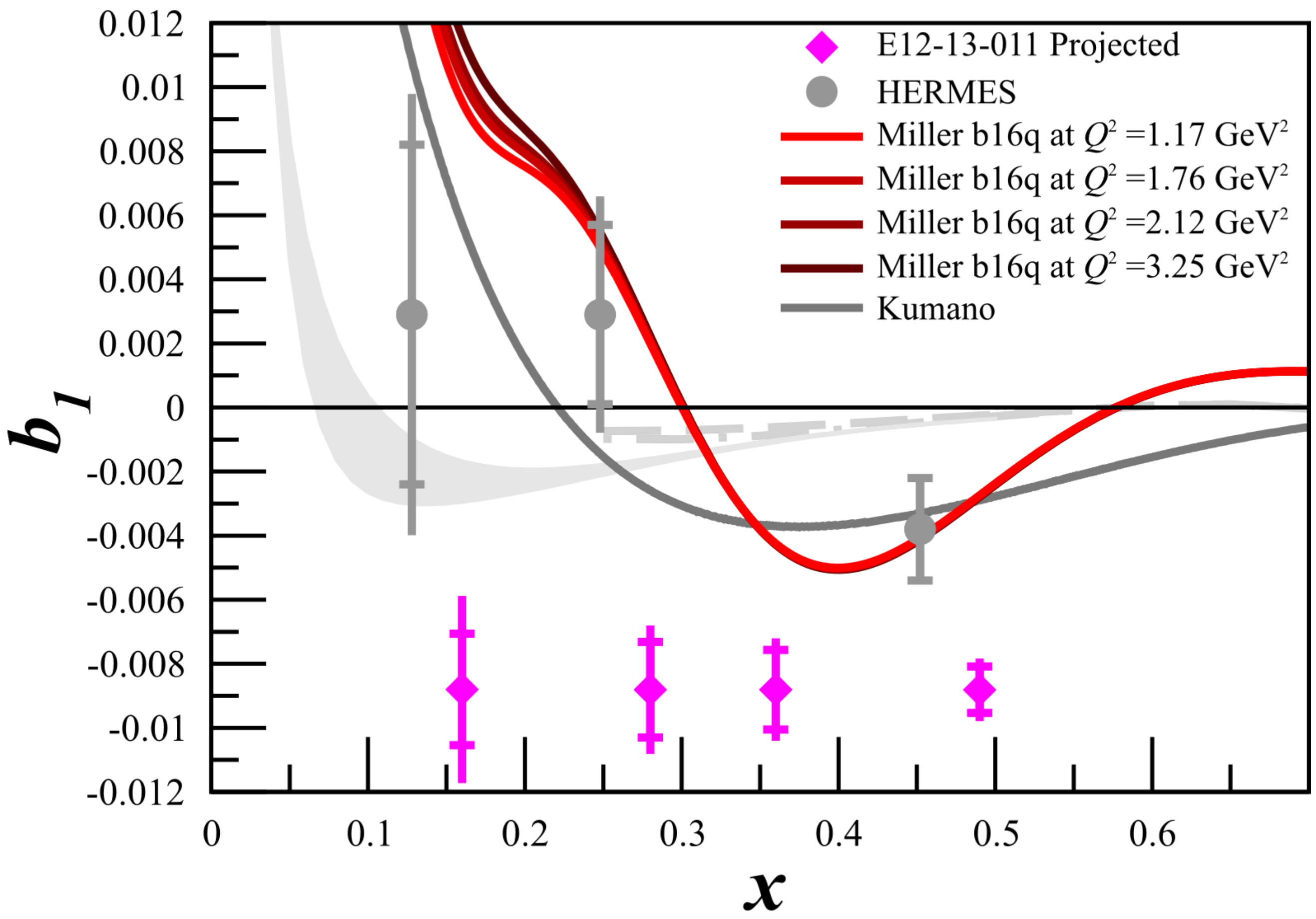
Even with D-state admixture, it's expected to be vanishingly small

Khan & Hoodbhoy, PRC 44 ,1219 (1991)
Umnikov, PLB 391, 177 (1997)

# Tensor Structure Function, $b_1$

All conventional **models predict small or vanishing values of $b_1$** in contrast with the HERMES data

Any measurement of a $b_1$<0 indicates exotic physics




K. Slifer *et al*, JLab E12-13-011

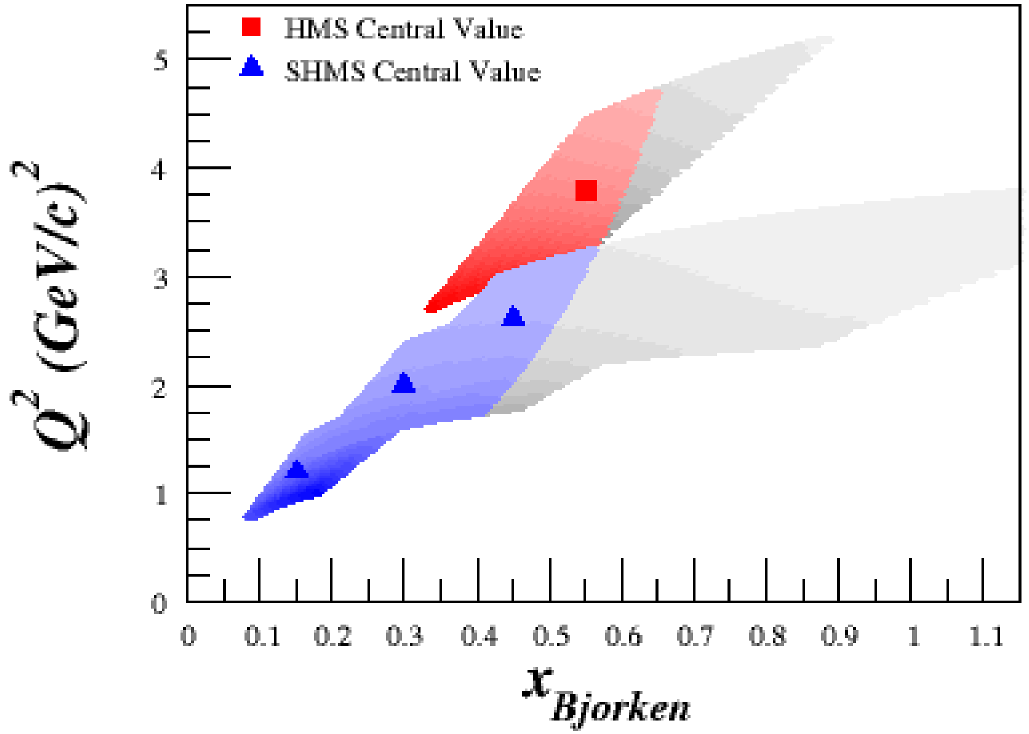
# Tensor Structure Function, $b_1$

Measured by ratio method

$$\frac{N_{Pol}}{N_u} - 1 = f\frac{1}{2}A_{zz}P_{zz}$$

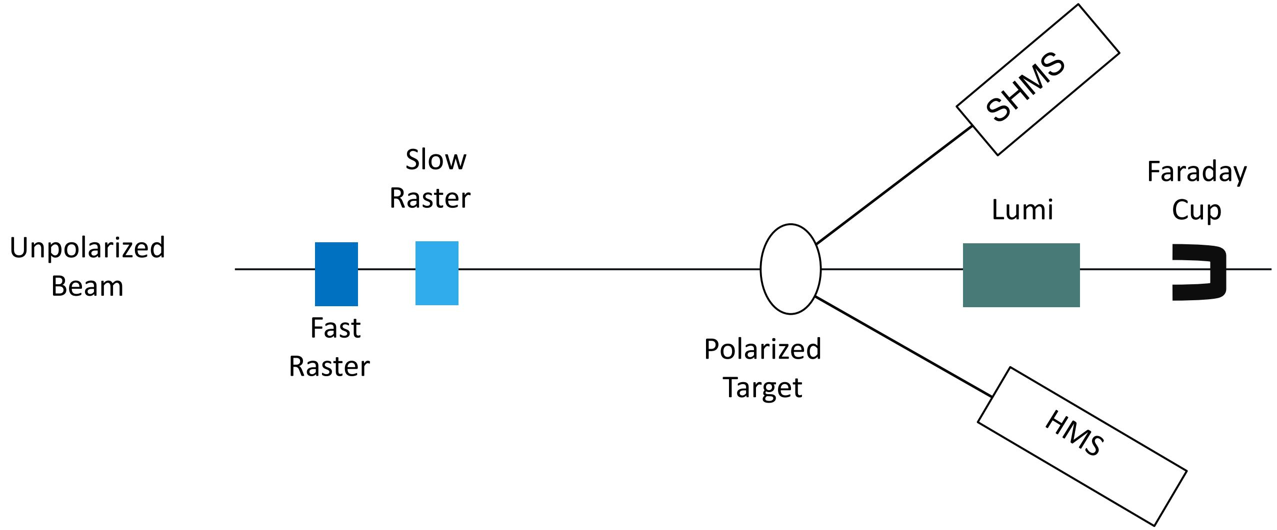
$$A_{zz} = \frac{2}{f \cdot P_{zz}}\left(\frac{N_{Pol}}{N_u} - 1\right)$$

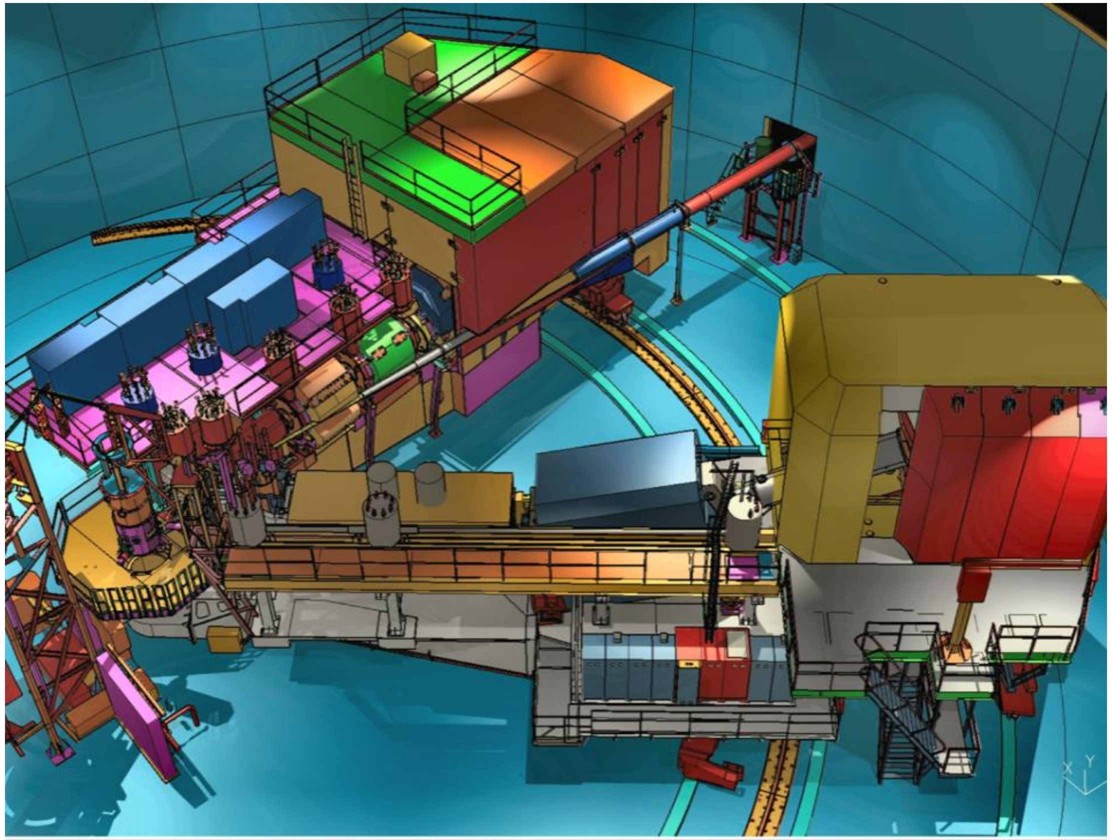
$$b_1 = -\frac{3F_1}{f \cdot P_{zz}}\left(\frac{N_{Pol}}{N_u} - 1\right)$$



# Tensor Structure Function, $b_1$

- Jefferson Lab's Hall C
- Unpolarized beam, tensor polarized target (longitudinal alignment)

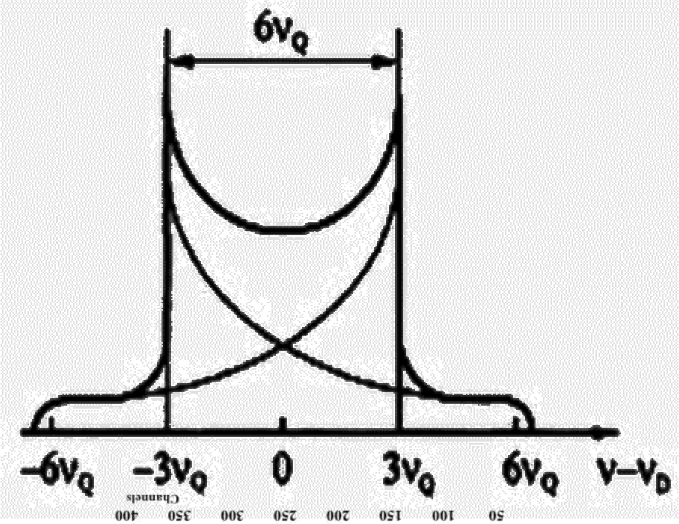


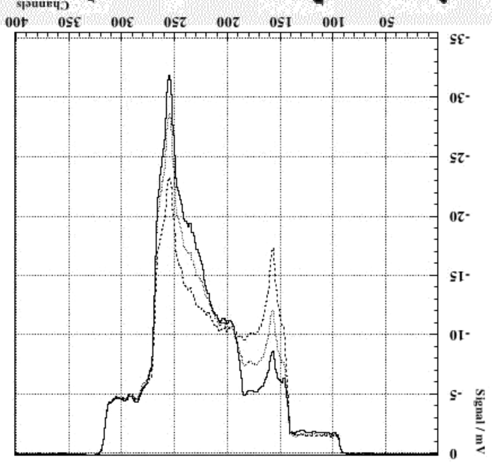



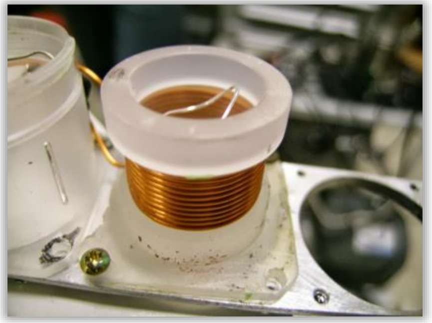
# Tensor Structure Function, $b_1$

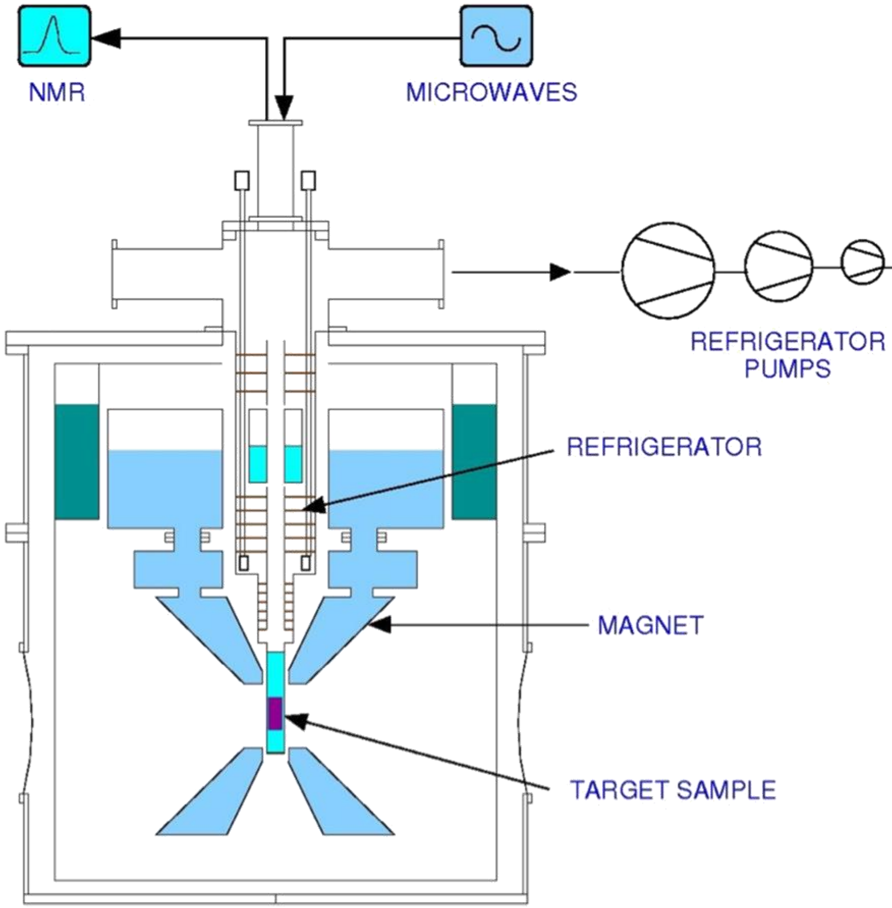
* See Dustin Keller's Talk, Wed. 12:30pm

- Dynamic Nuclear Polarization of $ND_3$
- $P_{zz} \sim 30\%$
- 5 Tesla at 1 K
- 3cm Target Length
- $p_f \sim 0.65$
- $f_{dil} \sim 0.27$



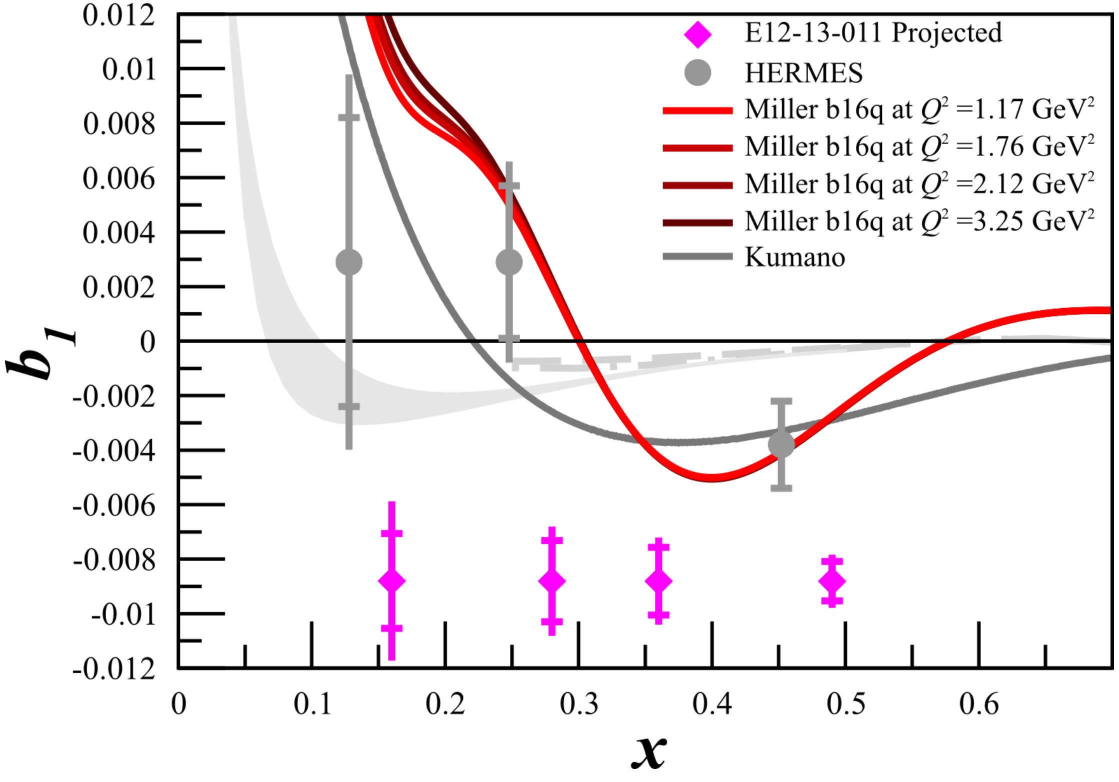




# Tensor Structure Function, $b_1$

Measuring $b_1$ will give insight into:

- Close-Kumano sum rule[1]
- 6-quark hidden color[2]
- OAM and spin crisis[3]
- Pionic effects[2,4]
- Polarized sea quarks[4]



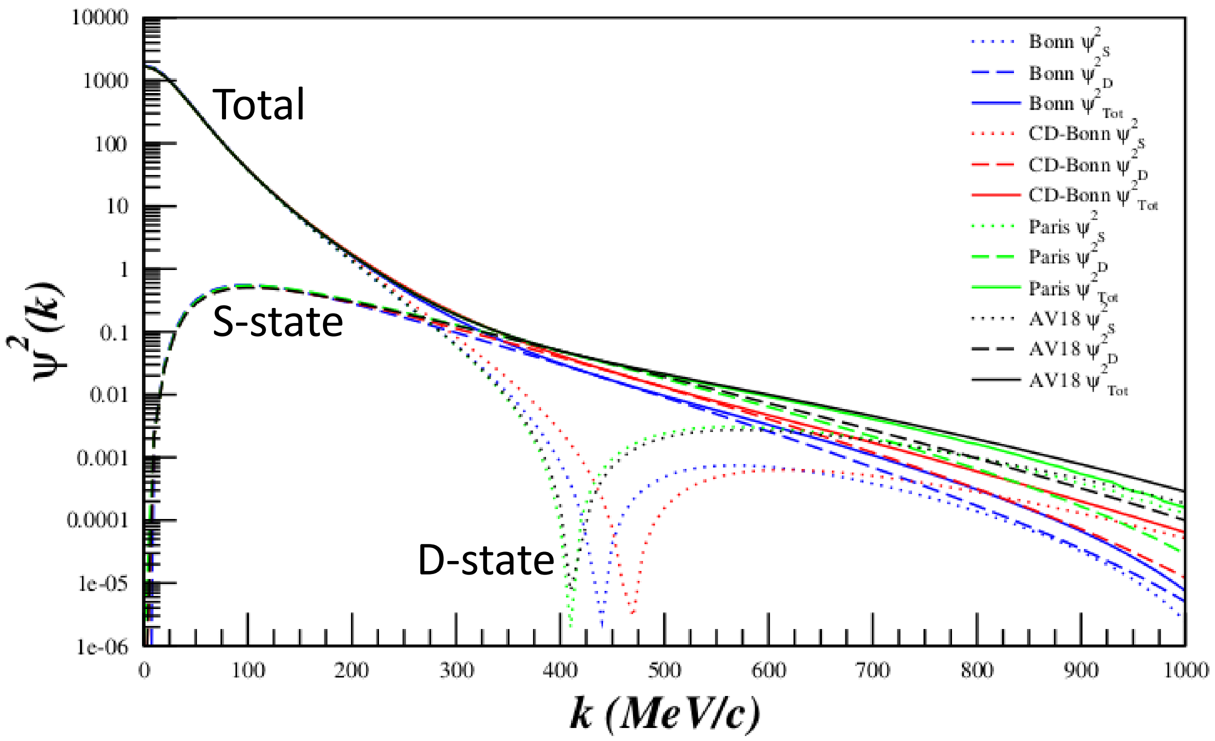

**Approved** JLab Experiment E12-13-011
Spokespersons: K. Slifer, E. Long, D. Keller, P. Solvignon, J.P. Chen, O.R. Aramayo, N. Kalantarians

[1] FE Close, S Kumano, Phys. Rev. **D42,** 2377 (1990)
[2] G Miller, Phys. Rev. **C89,** 045203 (2014)
[3] SK Taneja *et al*, Phys. Rev. **D86,** 036008 (2012)
[4] S Kumano, Phys. Rev. **D82,** 017501 (2010)

# High-x Tensor Structure

Repeat same experiment, only look at $A_{zz}$ in the quasi-elastic region

Can give insight to short range deuteron structure




$$A_{zz} = \frac{2}{f \cdot P_{zz}} \left( \frac{N_{Pol}}{N_u} - 1 \right)$$

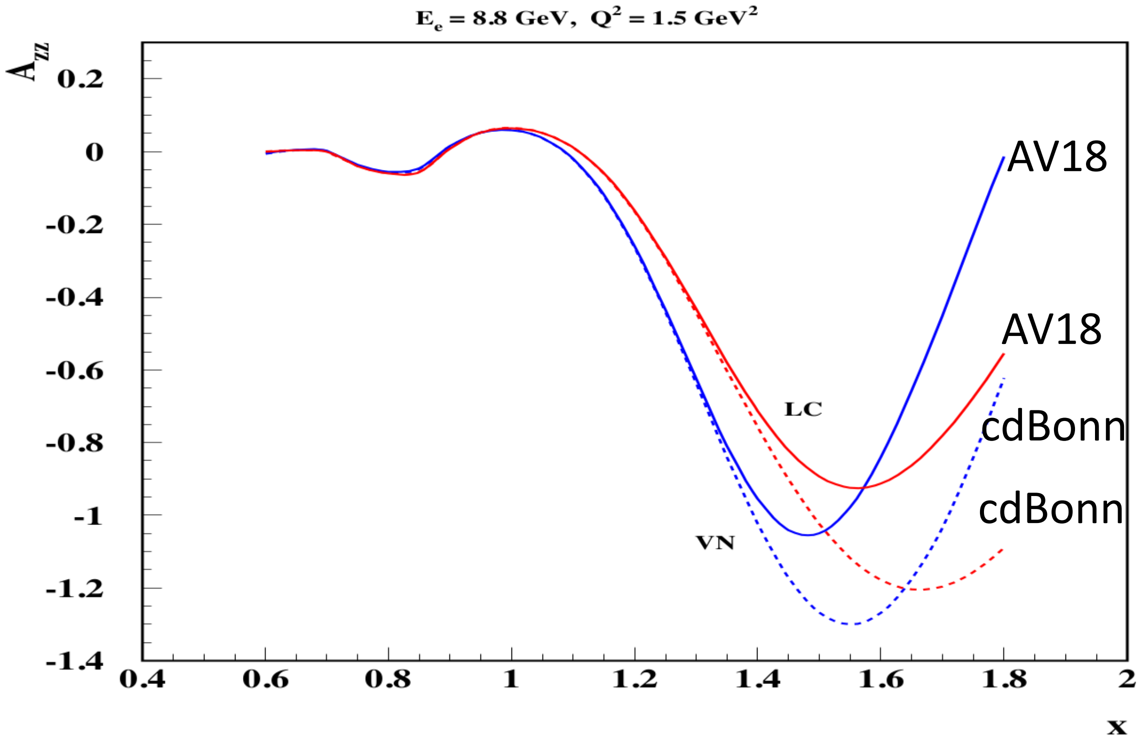
$$A_{zz} \propto \frac{\frac{1}{2} D^2 - SD}{S^2 + D^2}$$

L. Frankfurt, M. Strikman, Phys. Rept **160**, 235 (1988)

# High-*x* Tensor Structure

Repeat same experiment, only look at $A_{zz}$ in the quasi-elastic region

Can give insight to short range deuteron structure



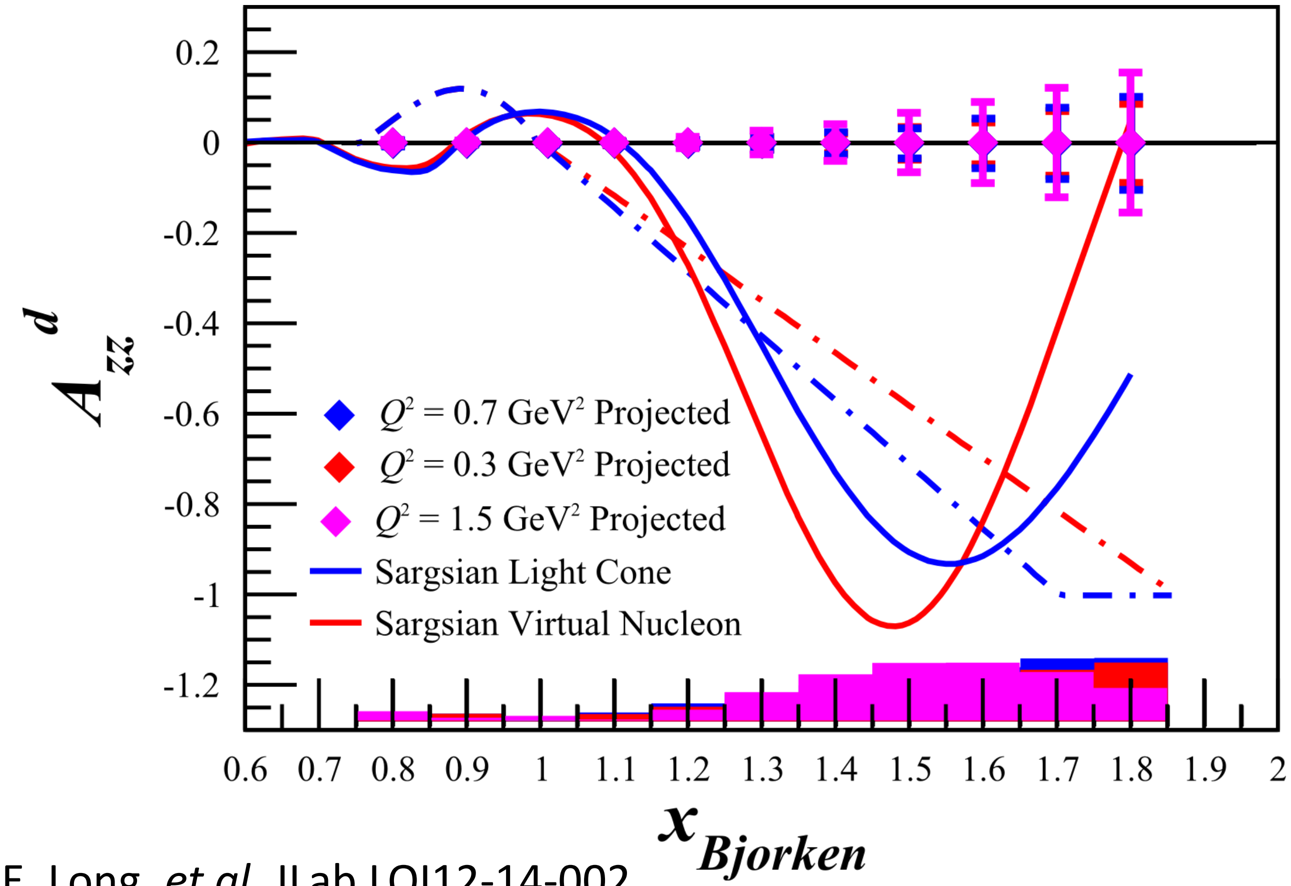

$$A_{zz} = \frac{2}{f \cdot P_{zz}} \left( \frac{N_{Pol}}{N_u} - 1 \right)$$

$$A_{zz} \propto \frac{\frac{1}{2} D^2 - SD}{S^2 + D^2}$$

Sargsian, Strikman, J. Phys.: Conf. Ser. **543**, 012099 (2014)

L. Frankfurt, M. Strikman, Phys. Rept **160**, 235 (1988)

# High-$x$ Tensor Structure



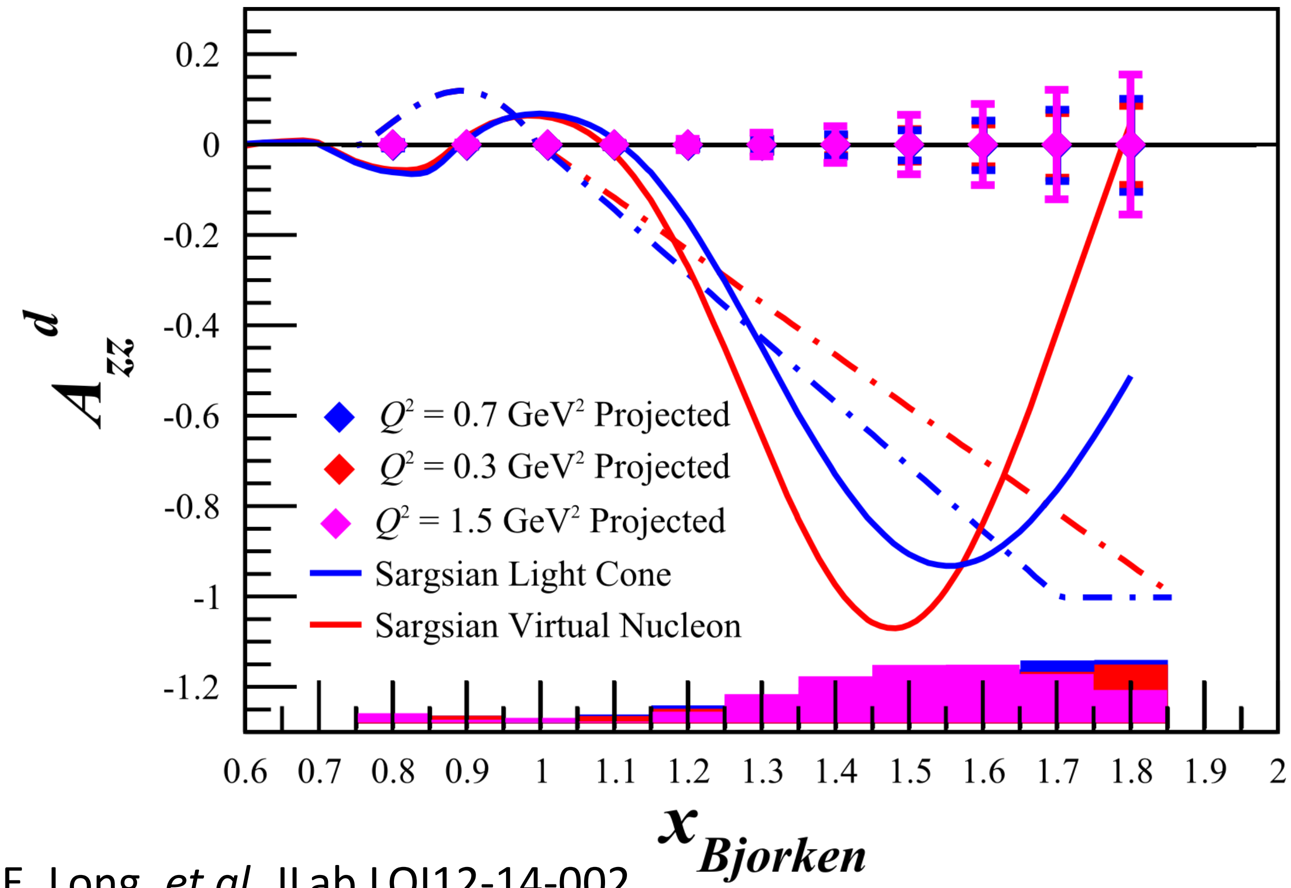

E. Long, *et al*, JLab LOI12-14-002

Measuring high-$x$ $A_{zz}$ will give insight into:

- SRCs & pn dominance[1]
- Differentiate light cone and VN models[2]
- Better understanding of s/d[3]
- Final state interaction models[4]


[1] J Arrington *et al*, Prog. Part. Nucl. Phys. **67,** 898 (2012)
[2] M. Sargsian, private communication
[3] L Frankfurt, M Strikman, Phys. Rept. **160,** 235
[4] W Cosyn, M Sargsian, arXiv:1407.1653

# High-x Tensor Structure




E. Long, *et al*, JLab LOI12-14-002

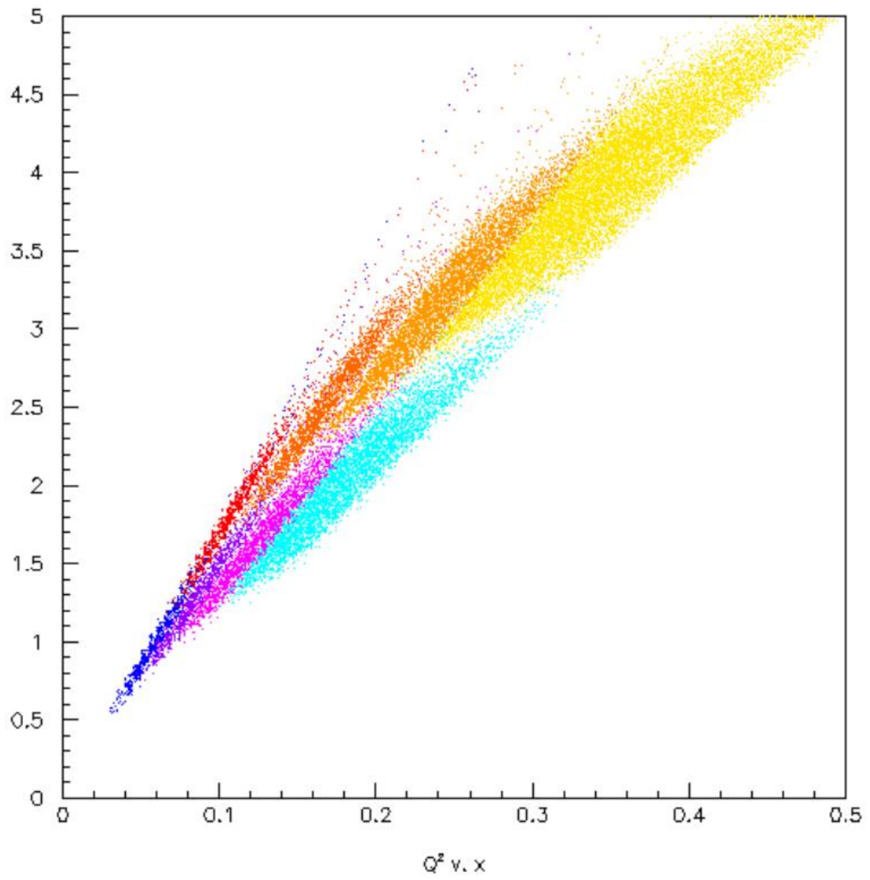
Encouraged for full submission by PAC42

**"The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range *pn* correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program."**

-JLab PAC42 Theory Advisory Committee

# Tensor Structure Function, $b_4$

- Hadronic double helicity flip structure function, $\Delta(x, Q^2) = b_4$
- Unpolarized electron beam on transversely-aligned tensor polarized target
- Insensitive to bound nucleons or pions
- Any non-zero value indicates exotic gluonic components
- Encouraged for full submission by PAC42




J. Maxwell, *et al*, JLab LOI-14-001

R Jaffe, A Manohar, Phys. Lett. **B223,** 218 (1989)

# Conclusion – Recent results are exciting and the future is promising!

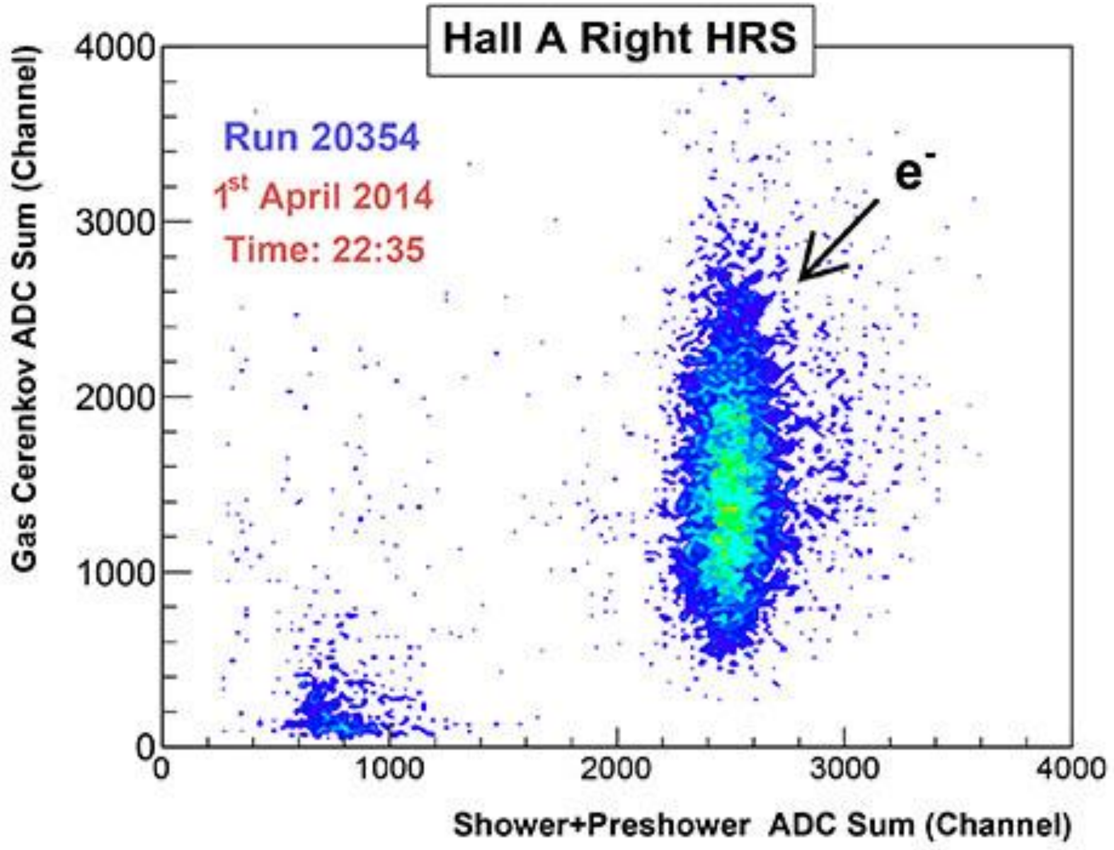
PDFs

TMDs

Structure Functions

Spin Asymmetries

DVCS at JLab12 just starting to turn on!



# Thank you