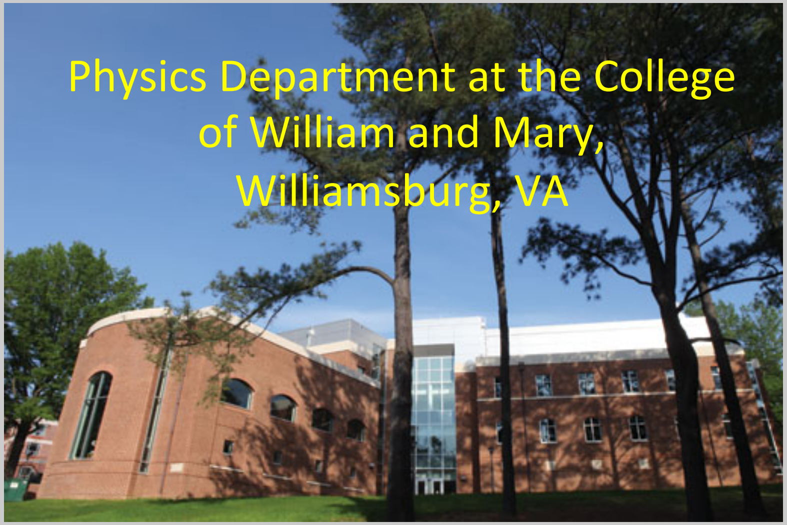
Measurement of Target Single-Spin Asymmetries using Polarized ^{3}He in Quasi-Elastic and DIS Scattering

Todd Averett, *College of William and Mary*
on behalf of the Jefferson Lab Hall A and Polarized ^{3}He collaborations

- Jefferson Lab Hall A
- ^{3}He(*e,e'*), target polarized *normal* to electron scattering plane
- Unpolarized e^- beam, *E*= *1-6* GeV



Two-photon Exchange

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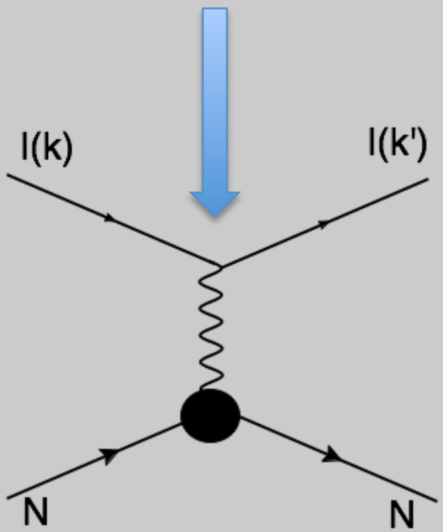
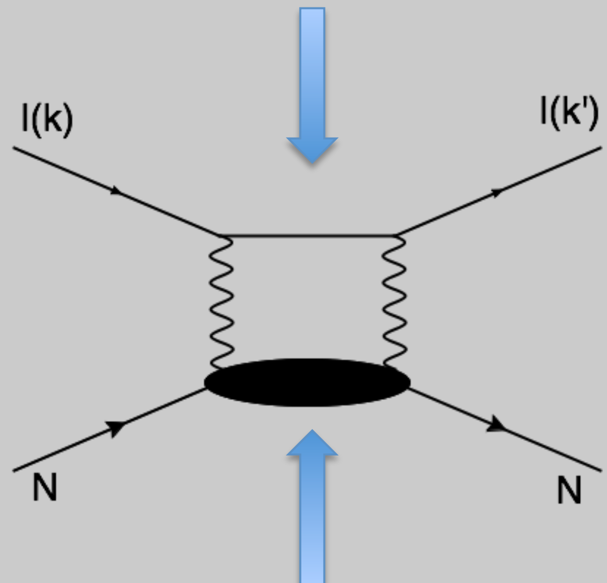
- One-photon exchange
- Typically dominates unpolarized polarized *N(e,e')* scattering.
- G_E, G_M, F_1, F_2, g_1, g_2, *SIDIS*

- Two-photon exchange
- Loop contains:
  entire elastic and inelastic nucleon response
- New tool to test nucleon models.





How do we observe this at <u>leading order</u>?

→ Target Single-spin Asymmetry, A_y

Elastic Form Factor Ratio, G_E^p/G_M^p vs. Q^2

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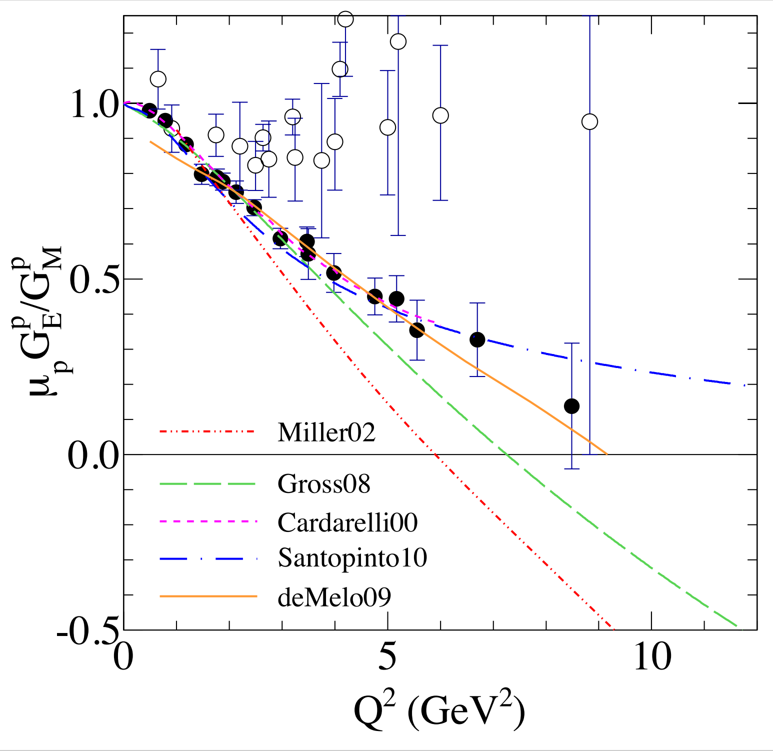


A. J. R. Puckett,
Phys. Rev. C85 (2012) 045203

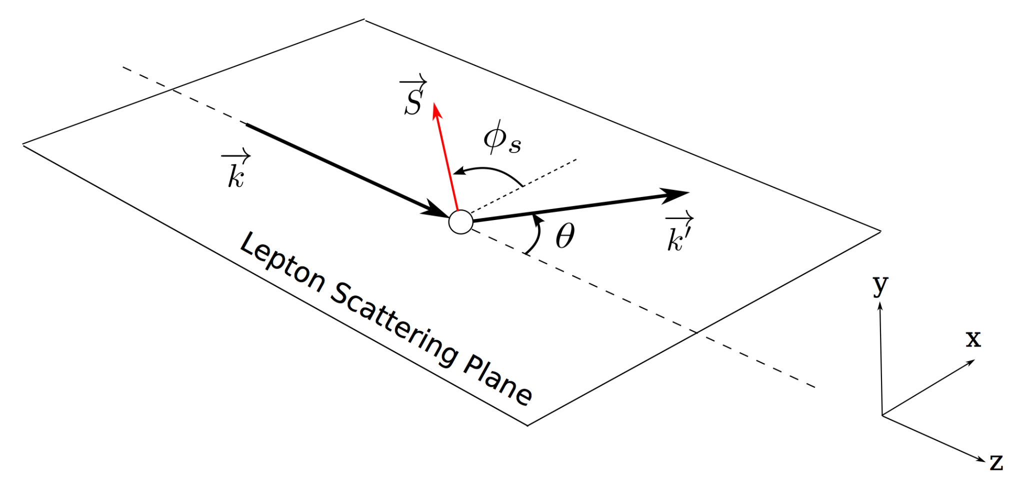
- Rosenbluth Separation vs. Recoil Polarimetry
- Inconsistency dramatically increases with Q^2
- Dominated by one-photon exchange
- Difference largely due to TPEX

$$\sigma_R = \underbrace{G_M^2 + \frac{\varepsilon}{\tau} G_E^2}_{\text{OPEX}} + \underbrace{2 G_M \mathcal{R}\left(\delta\tilde{G}_M + \varepsilon \frac{\nu}{M^2} \tilde{F}_3\right)}_{\text{TPEX}} + \underbrace{2\frac{\varepsilon}{\tau} G_E \mathcal{R}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right)}_{\text{TPEX}} + \mathcal{O}(e^4),$$

OPEX TPEX TPEX

- $^3\mathbf{He}^{\uparrow}(e,e')$ inclusive, unpolarized electron scattering

$$A_{UT} \propto \vec{S}\cdot(\vec{k}\times\vec{k}')$$



$$A_{UT}(\phi_S) = \frac{d\sigma(\phi_S) - d\sigma(\phi_S+\pi)}{d\sigma(\phi_S) + d\sigma(\phi_S+\pi)} = A_y \sin\phi_S$$

$$A_y \equiv \frac{d\sigma_{UT}}{d\sigma_{UU}}$$

- Measured when $\phi_S = \frac{\pi}{2}$

$$d\sigma_{UU} \propto \mathrm{Re}(\mathcal{M}_{1\gamma}\mathcal{M}^*_{1\gamma})$$

- Unpolarized cross-section dominated by 1-photon exchange,
  - $\mathcal{M}_{1\gamma}$ is real (time-reversal invariance)*

$$d\sigma_{UT} \propto \mathrm{Im}(\mathcal{M}_{1\gamma}\mathcal{M}^*_{2\gamma})$$

- Leading contribution to target SSA contains two-photon contribution
  - $\mathcal{M}_{2\gamma}$ is complex

*N. Christ and T. D. Lee, Phys. Rev. 143 (1966) 1310

Quasi-elastic Scattering

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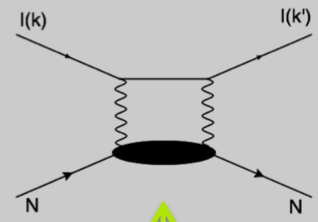
- When two photon exchange is included, we can write

$$A_y = \sqrt{\frac{2\,\varepsilon\,(1+\varepsilon)}{\tau}}\;\frac{1}{\sigma_R}\left\{-\,G_M\,\mathrm{Im}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + \;G_E\,\mathrm{Im}\left(\delta\tilde{G}_M + \left(\frac{2\varepsilon}{1+\varepsilon}\right)\frac{\nu}{M^2}\tilde{F}_3\right)\right\},$$

$\tau \equiv Q^2/4M^2,\ \nu = \frac{1}{4}(k_\mu + k'_\mu)(p^\mu + p'^\mu)$ $\varepsilon \equiv (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1}$



- The following contributions are <u>complex</u> and arise from two-photon exchange
- Exactly zero for one-photon exchange

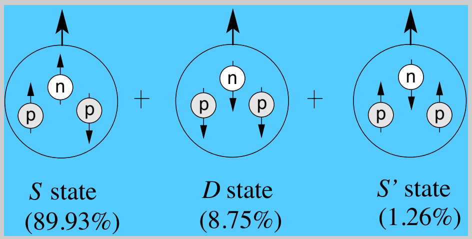
$$\delta\tilde{G}_E,\ \delta\tilde{G}_M \text{ and } \tilde{F}_3$$

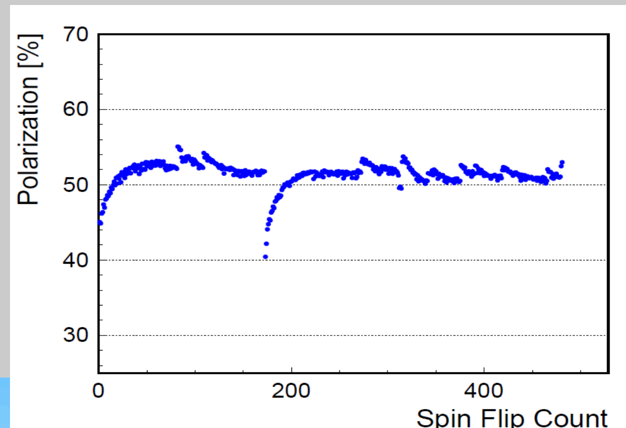
- Inelastic contribution <u>modeled</u> at large Q^2 assuming interaction with a single quark and <u>using weighted moments of GPDs</u> (parameterization).
- <u>Same model</u> used for estimating two-photon exchange contribution to the unpolarized cross-section (G_e^p/G_M^p vs. Q^2).
- Measurement of A_y provides independent constraint of GPDs.

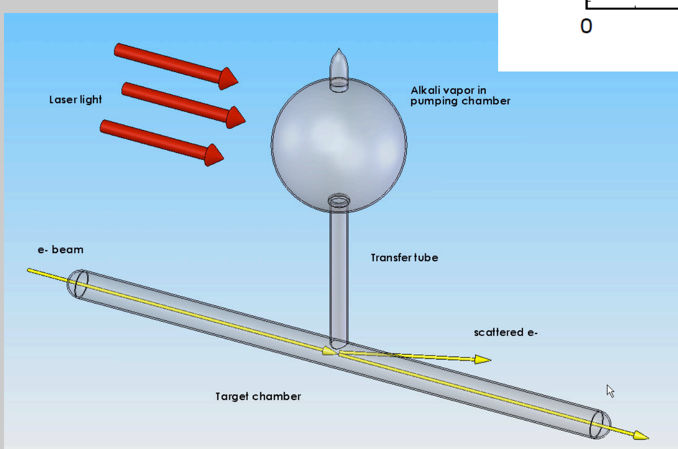
Y. Chen, A. Afanasev, S. Brodsky, C. Carlson and M. Vanderhaeghen, Phys. Rev. Lett. 93, 122301 (2004)

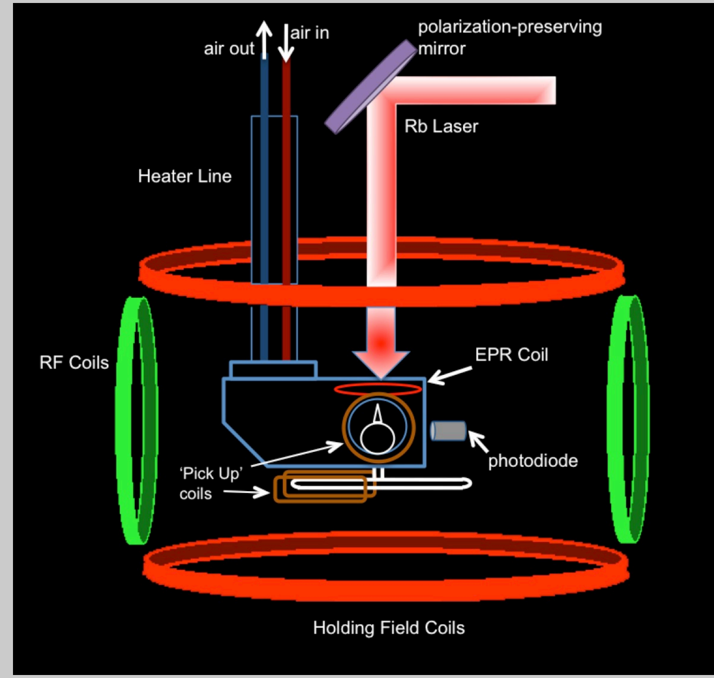
Polarized ^3He Target

- Alkali-hybrid Spin-exchange Optical Pumping
- Line narrowed lasers >100 Watts CW
- Effectively a polarized neutron target

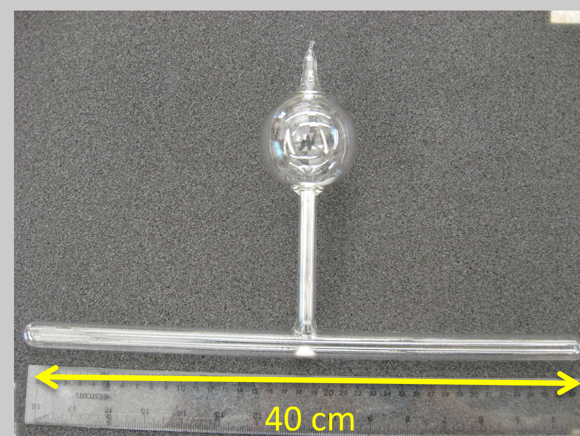








Typical glass target cell



Experimental Setup

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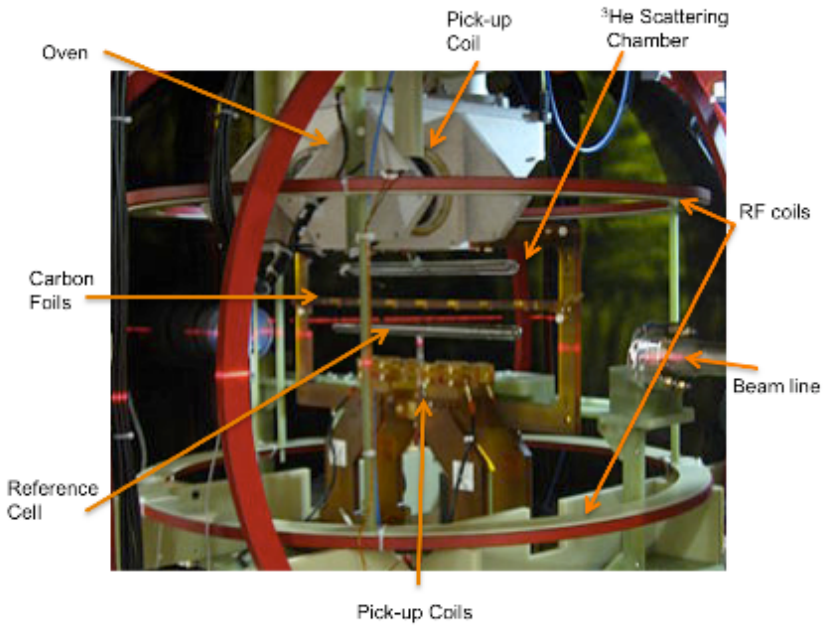
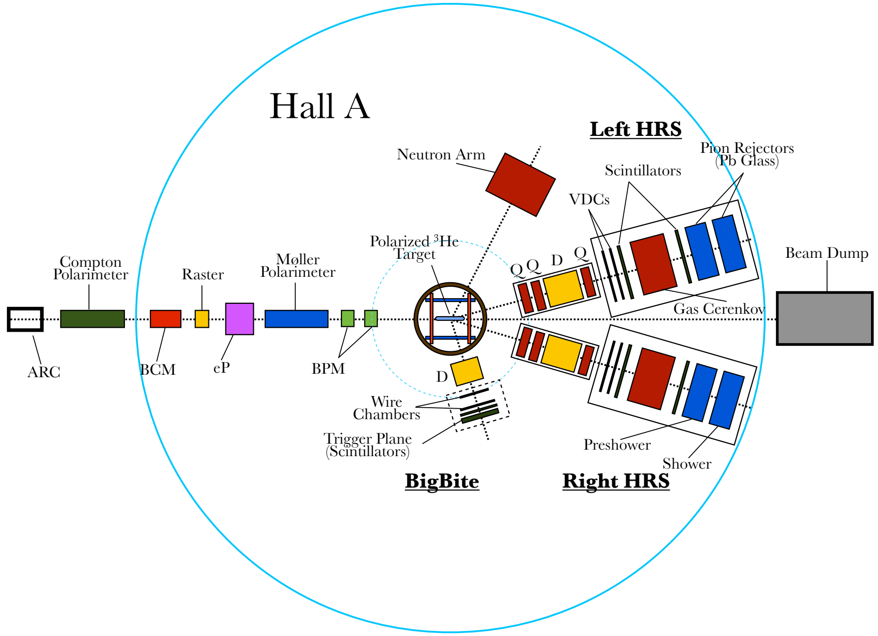


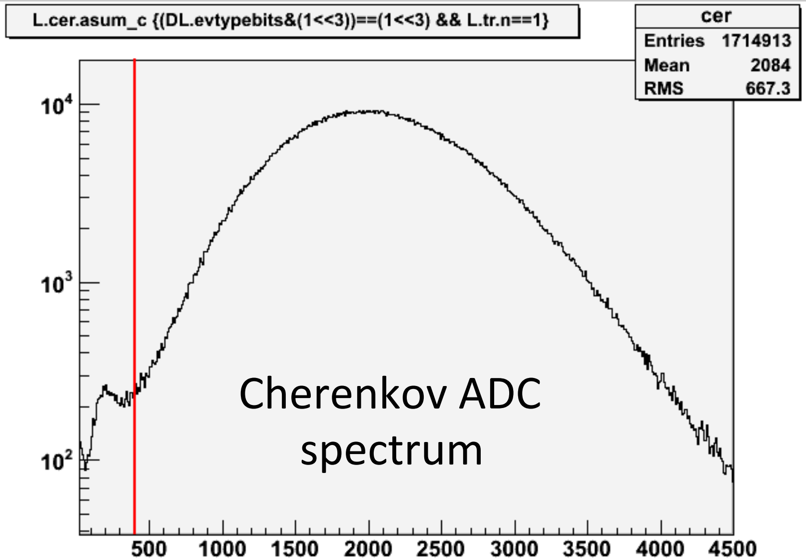


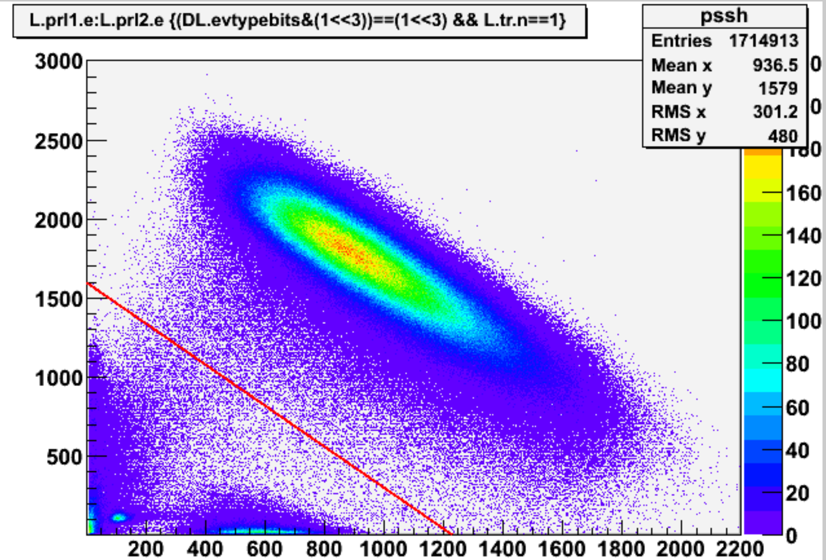
- Spin flip every 20 minutes using RF-sweep NMR
- Calibrate polarization with EPR
- Minimize false asymmetries
- Small polarization losses

Using LHRS and RHRS
in singles mode

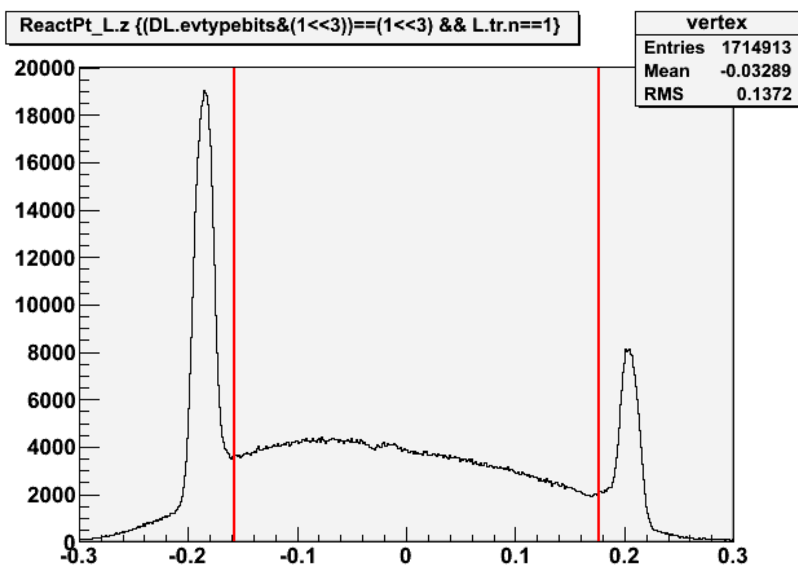
E (GeV)	$\langle E' \rangle$ (GeV)	$\langle \theta \rangle$ deg.	$\langle Q^2 \rangle$ (GeV^2)
1.245	1.167	17.0	0.127
2.425	2.170	17.0	0.460
3.605	3.070	17.0	0.967

Events Selection



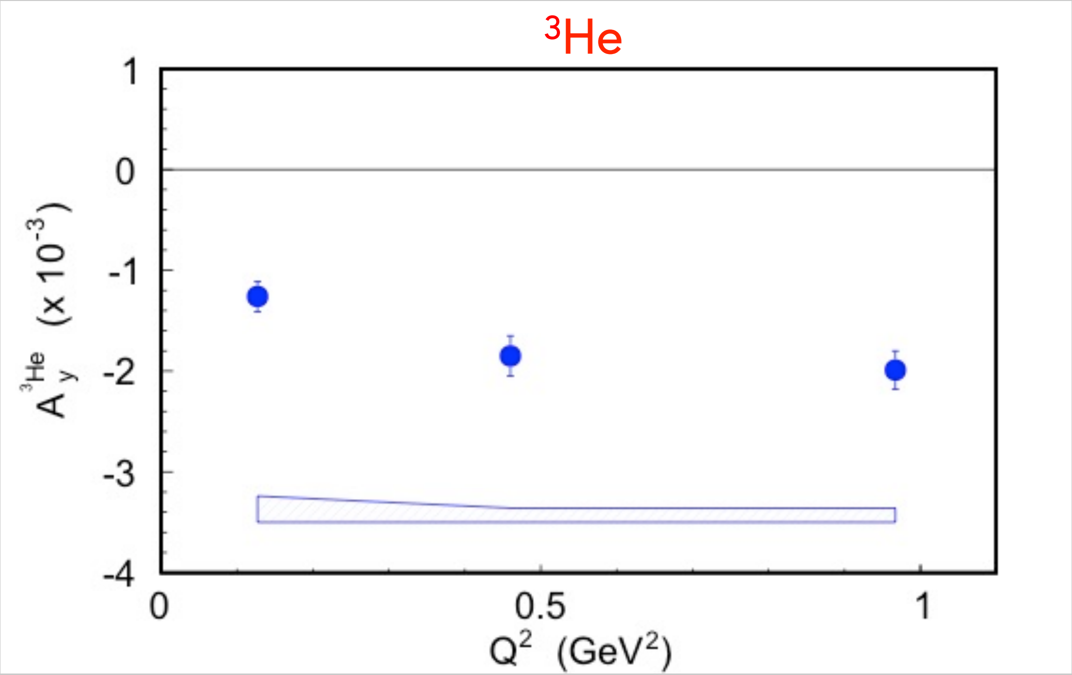


EM calorimeter ADC
Pre-shower vs. shower



Reconstructed interaction position in glass target cell

Quasi-elastic Results for ^{3}He

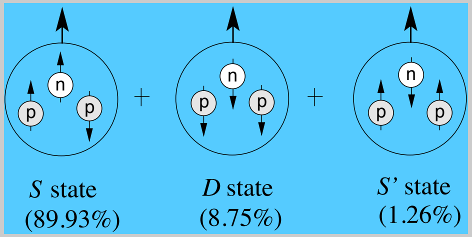


Smoking gun for large two-photon exchange contribution

- Large and negative at ~*9σ level (statistical)*
- Christ-Lee holds for (e,e') on ^{3}He: A_y=0 for OPEX
- No theory for A_y on ^{3}He — Theorists Please

Y. W. Zhang et al., Phys. Rev. Lett. 115 (2015) 172502

Neutron Extraction

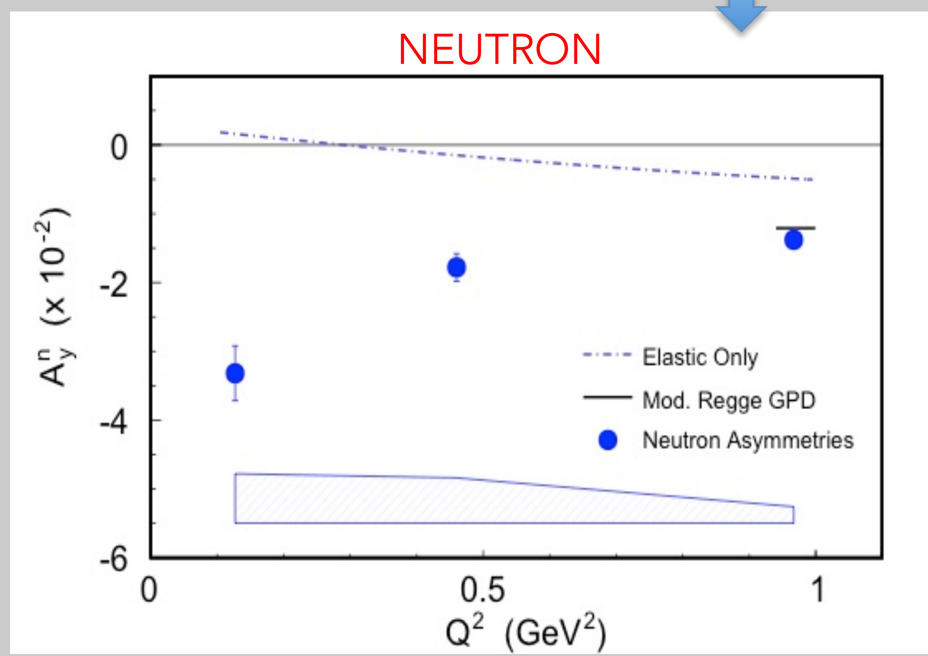


$$A_y^n = \frac{1}{(1-f_p)P_n}(A_y^{^3\mathrm{He}} - f_p P_p A_y^p)$$

$$f_p = (1-f_n) = 2\sigma_p/\sigma_{^3\mathrm{He}} = 2\sigma_p/(2\sigma_p + \sigma_n)$$

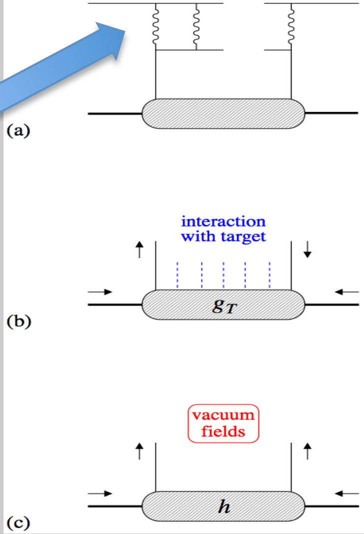
- Neutron Extraction
- $f_n = \sigma_n/\sigma_{3He}$ estimated using:
  - Kelly parameterizations of $G_E(Q^2)$ and $G_M(Q^2)$
    - $\sigma_{3He} = 2\sigma_p + \sigma_n$
  - Deltuva non-relativistic ^{3}He model using CD-Bonn + Δ potential for σ_{3He}

- Non-zero and negative at $4\text{-}9\ \sigma$ (stat + sys)
- Large inelastic contribution to intermediate state
- Consistent with GPD model at $Q^2 = 1$ GeV^2
- No theory for lower Q^2
  - Theorists PLEASE!!

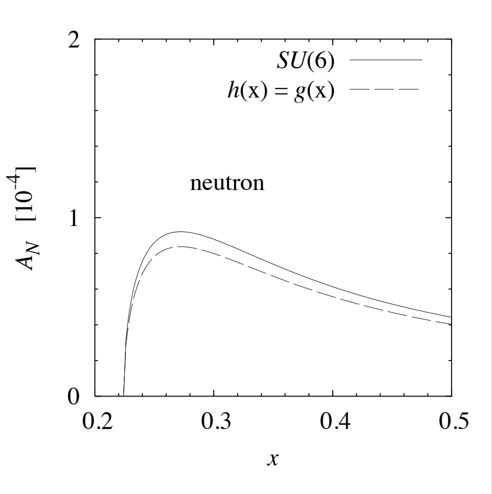


Two-photon Exchange in DIS

- Parton model descriptions:
- Photons coupling to the same quark.

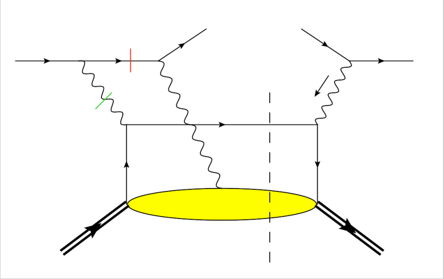


Predict:
$A_y \sim \alpha_{em} m_q/Q$
$\sim 10^{-4}$

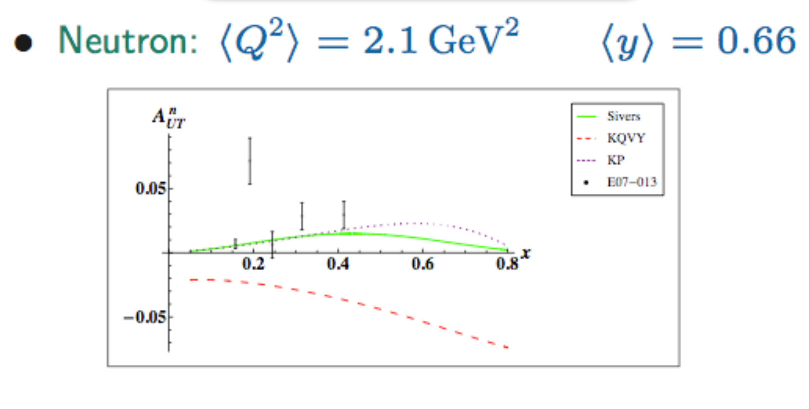


A. Afanasev, M. Strikman, C. Weiss
Phys. Rev. D77 (2008) 014028

- Photons coupling to different quarks.

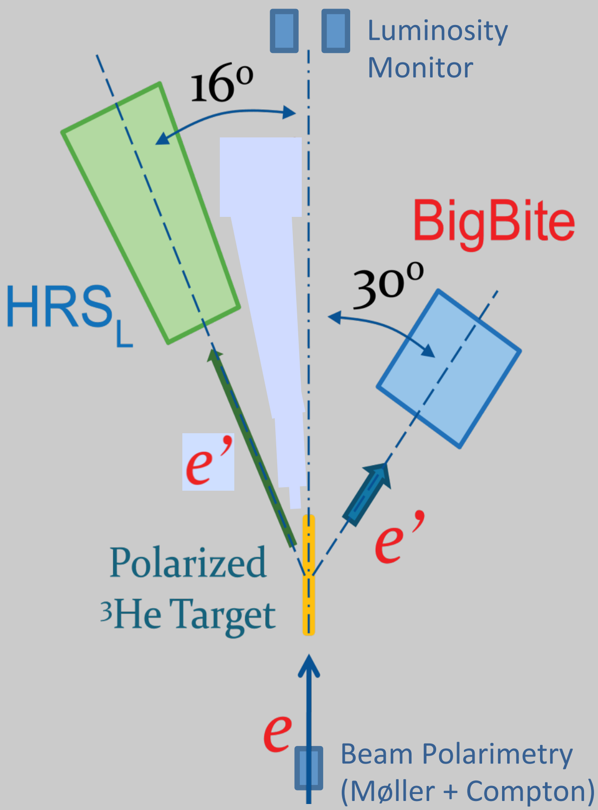


Predict:
$A_y \sim \pm 10^{-2}$
Sign Not Known



- <u>Unresolved problem</u>: Sign inconsistency using *q-g-q* correlator from SIDIS Sivers distribution vs. hadron-hadron collisions (KQVY).

A. Metz *et al.*, Phys. Rev. D86 (2012) 094039



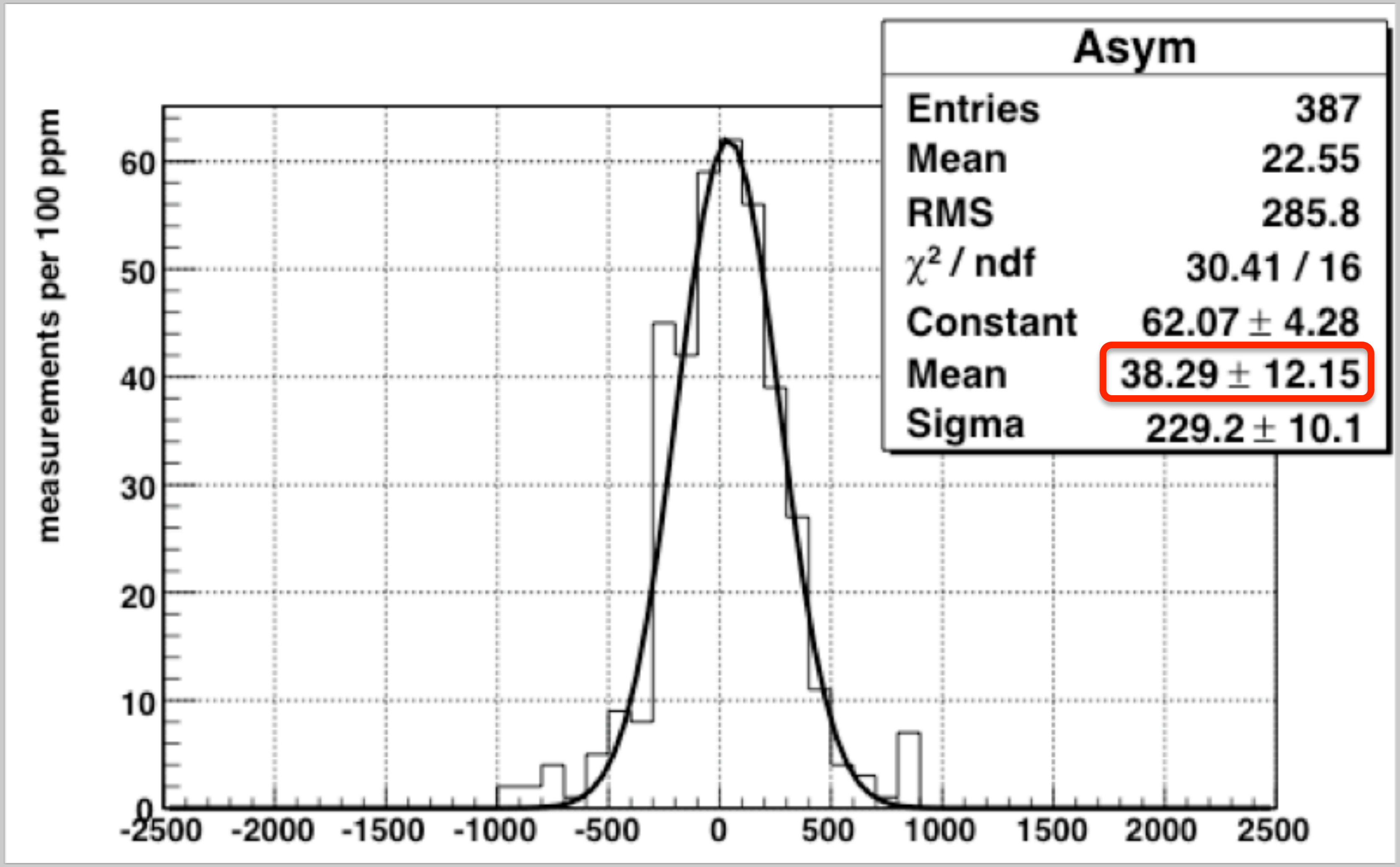
Measured ^{3}He(e,e') SSA using

Large Acceptance BigBite Spectrometer
and
Left High Resolution Spectrometer

Detector	W GeV	x	Q^2 GeV^2	$A_y^{^3\text{He}} \pm$ (stat) $\pm$ (sys) ($\times 10^{-3}$)	$A_y^n \pm$ (stat) $\pm$ (sys) ($\times 10^{-2}$)	Pair-produced background contamination (%)
BigBite	1.72	0.65	3.98	$-0.45 \pm 2.79 \pm 0.53$	$-0.50 \pm 1.85 \pm 0.60$	1.0 ± 0.8
BigBite	2.17	0.46	3.24	$-6.21 \pm 2.45 \pm 0.64$	$-3.78 \pm 1.49 \pm 0.50$	3.1 ± 1.1
BigBite	2.46	0.34	2.65	$-8.52 \pm 1.98 \pm 1.52$	$-4.10 \pm 0.95 \pm 0.80$	9.5 ± 2.0
BigBite	2.70	0.24	2.08	$-2.61 \pm 2.47 \pm 1.52$	$-1.21 \pm 1.18 \pm 0.71$	22.0 ± 4.5
BigBite	2.89	0.17	1.58	$-8.35 \pm 4.35 \pm 5.36$	$-3.80 \pm 2.00 \pm 2.43$	48 ± 10
LHRS	2.54	0.16	1.05	$-1.57 \pm 0.99 \pm 0.2$	$-0.64 \pm 0.41 \pm 0.09$	1.3 ± 0.05

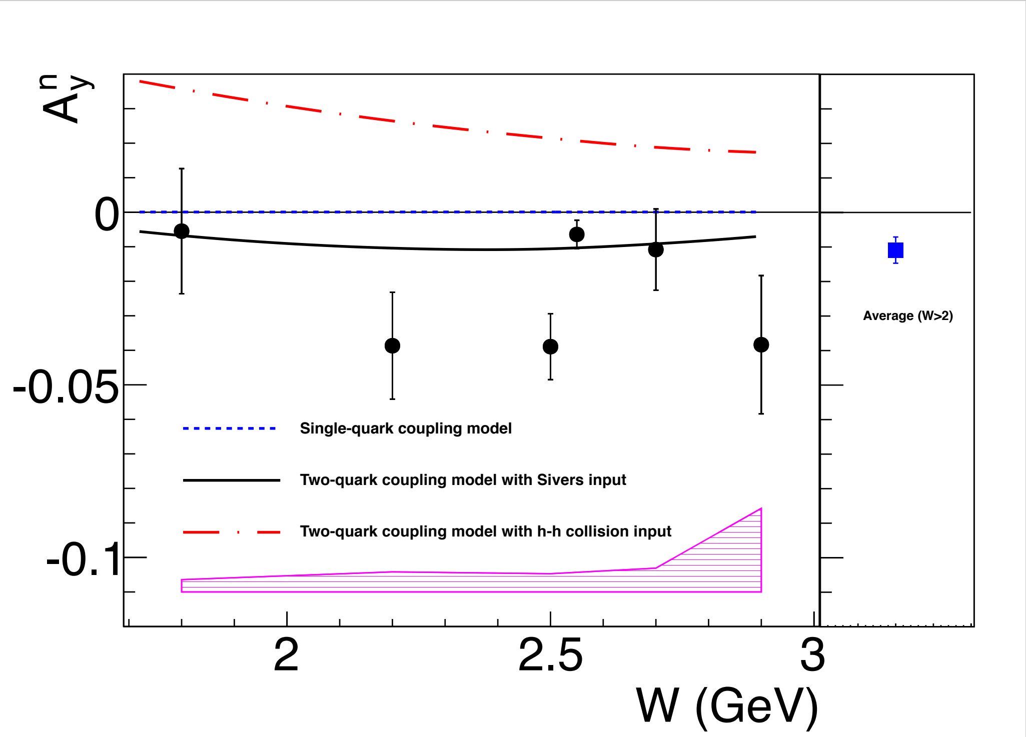
Luminosity Asymmetry

- Small Downstream Luminosity Asymmetry



ppm

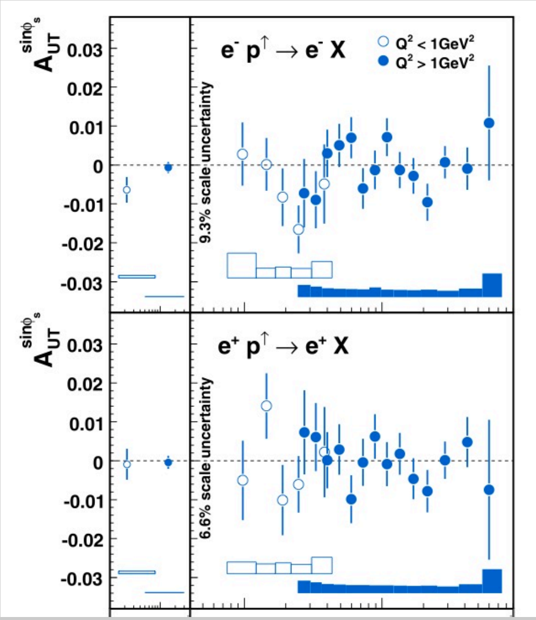
DIS Results



- Consistently negative and non-zero for *W>2* GeV
- Consistent with Metz *et al.* prediction using Sivers input for *q-g-q* correlator

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

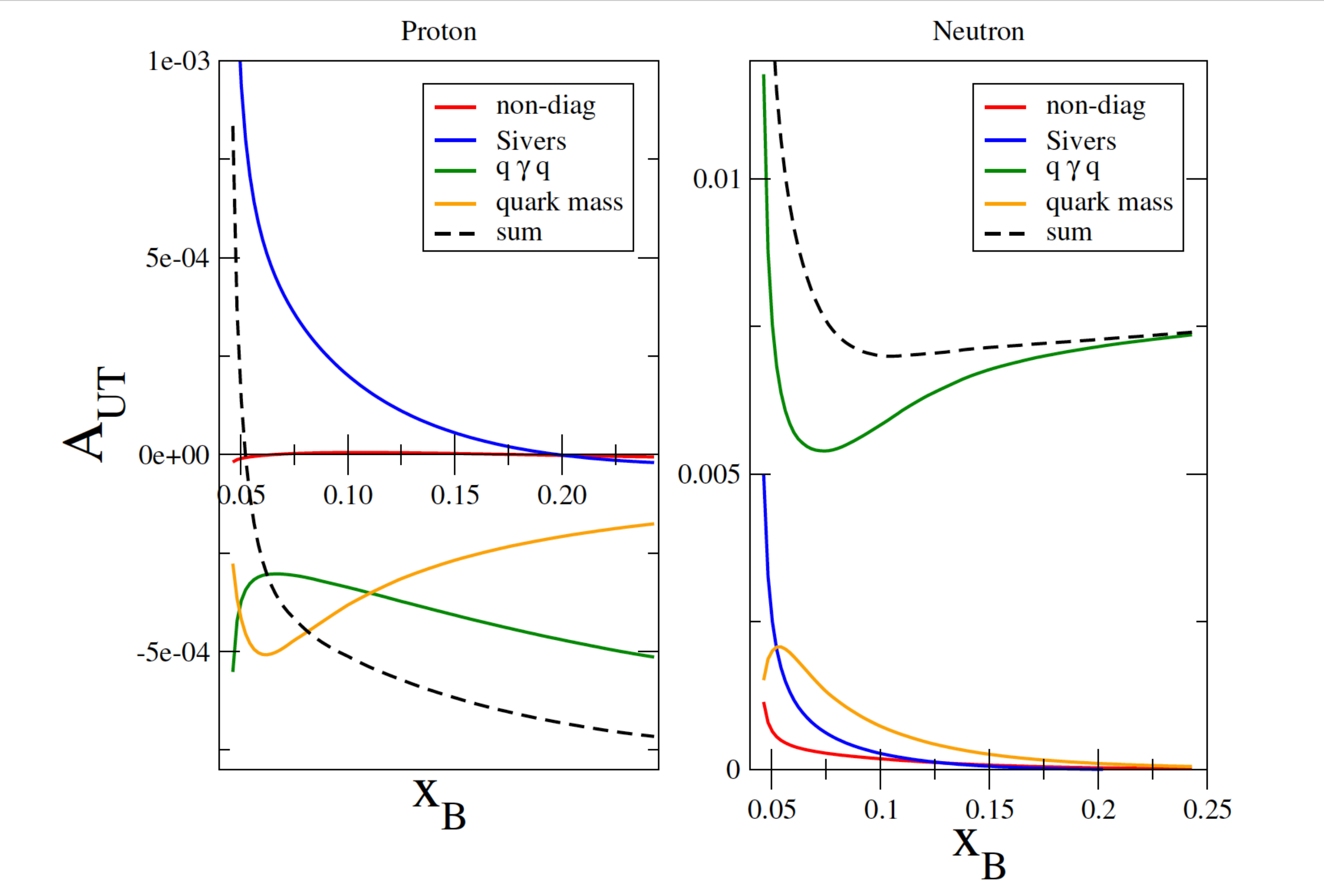
HERMES proton
Consistent with zero for $Q^2>1$ GeV^2



A. Airapetian *et al.*, Phys. Lett. B682, 351 (2010)

Future DIS Measurements

- Calculation by M. Schlegel includes interactions between one and multi-quarks.
- Proton asymmetry ~10^{-4} ; Neutron asymmetry ~10^{-2}
- Measure both targets with high precision vs. Q^2.

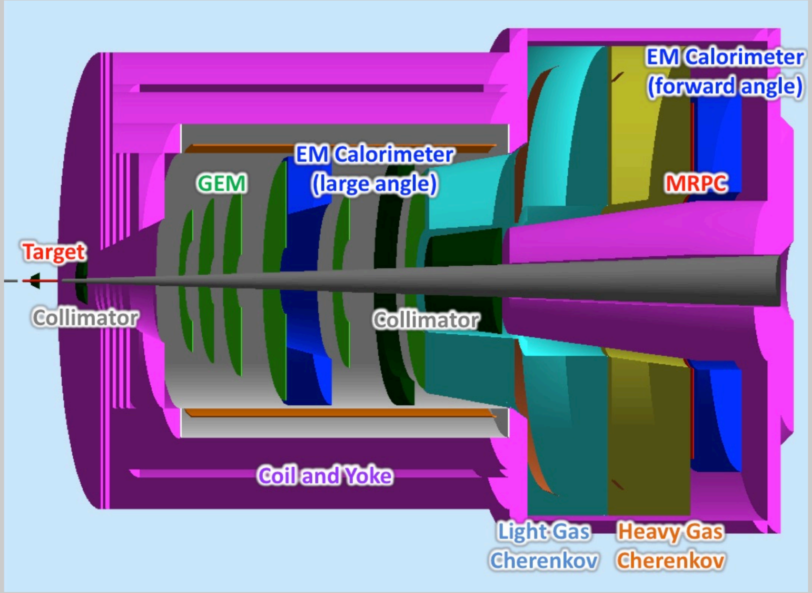


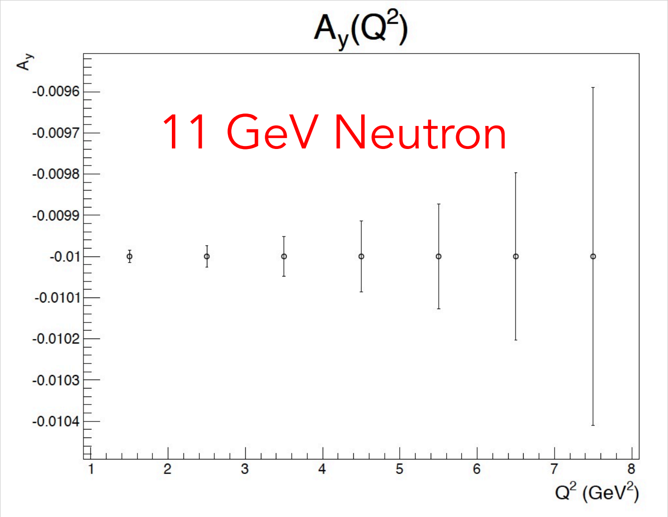
M. Schlegel, Phys. Rev. C70 (2004) 065207

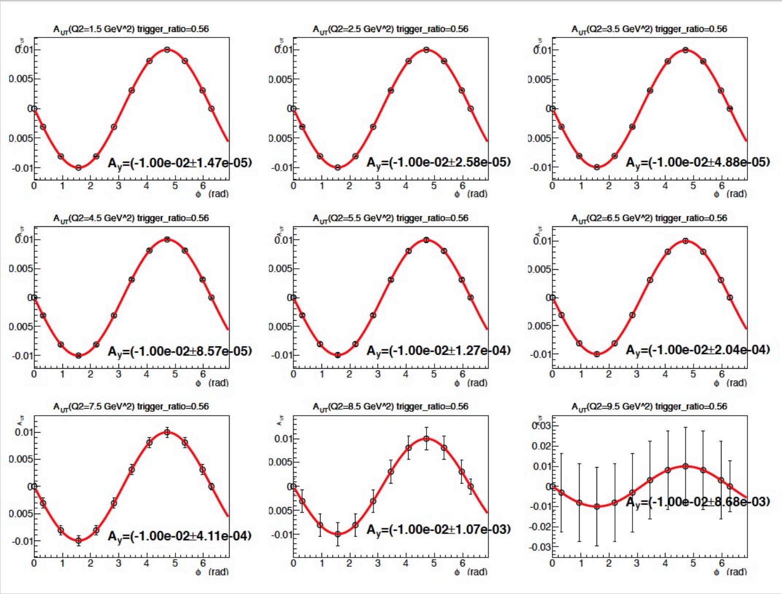
Future DIS Measurement

- SoLID spectrometer, 2 approved experiments
- $\Phi = 2\pi$ coverage
- E_{beam} = 8 and 11 GeV
- Transversely polarized <u>proton</u> and <u>neutron</u> (^{3}He) targets
- 7 bins in Q^2, 1 - 8 GeV^2

Expected statistical uncertainty
$2 \times 10^{-5} \rightarrow 4 \times 10^{-4}$







Quasi-elastic ^{3}He(*e*,*e'n*)

- Detect recoil neutron during QE scattering.
- Christ-Lee theorem doesn't apply for semi-inclusive scattering.
  - A_y can be non-zero for OPEX.
- However, PWIA predicts $A_y=0$.
- Sensitive to final state interactions/nuclear effects.
- Unpublished NIKHEF result showed A_y = *50%* at $Q^2=0.1$ GeV^2.
- Precise tool for studying details of ^{3}He wavefunction.

Preliminary Results

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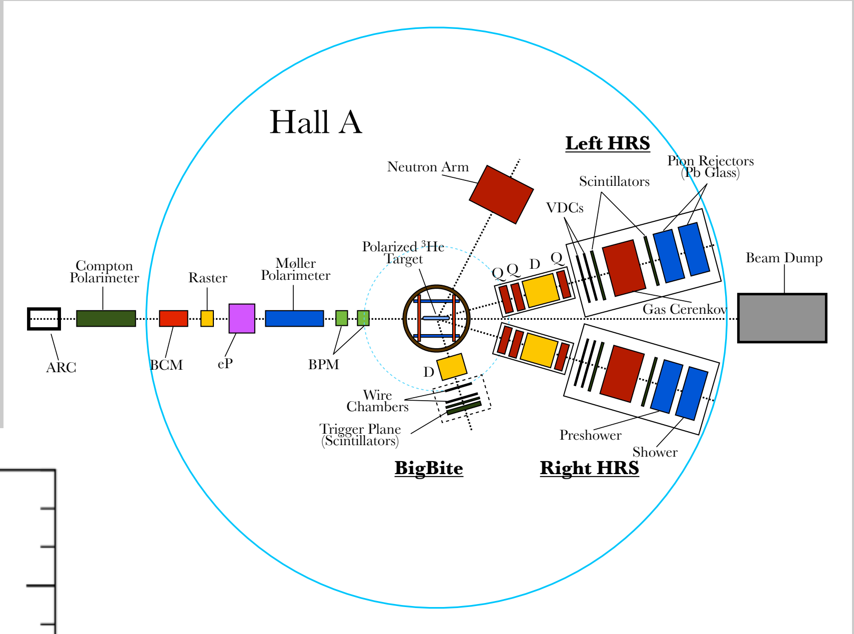
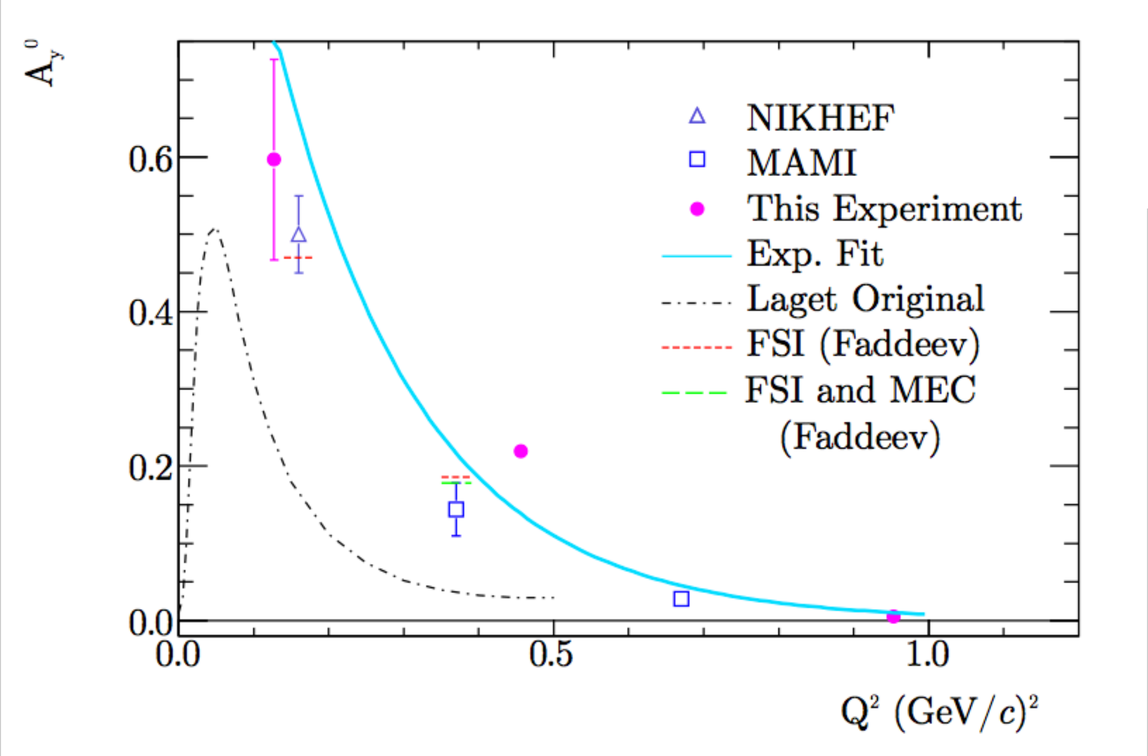
-- Detect recoil neutron using Hall A Neutron Detector (HAND)

-- A_y changes by <u>2 orders of magnitude</u> between $Q^2 = 0.1 - 1.0$ GeV^2.





- Data agree with Fadeev calculations with FSI and MEC.
  - J. Laget, Phys.Lett. B273, 367 (1991), H. R. Poolman, Ph.D. thesis, Vrije Universiteit, 1999

- Beautiful demonstration of transition from nuclear to nucleon degrees of freedom

Results and Figure from Elena Long, Ph.D. thesis, Kent State University (2012)

Summary

- First measurements of the inclusive target SSA using vertically polarized ^{3}He in QE, DIS scattering.

- Quasi-elastic: Large SSA observed at $Q^2 = 1$ GeV^2; Predicted by GPD moment model.
  - Remains large down to $Q^2 = 0.14$ GeV^2
  - TPEX important at low Q^2

- DIS: $\langle A_y \rangle = (-1.04 \pm 0.38) \times 10^{-2}$
  - Much larger than predicted by Afanasev *et al.*
  - Agreement with magnitude of Metz *et al.* prediction.
  - Sign agrees with Metz using Sivers SIDIS input; disagrees with sign using data from hadron-hadron collisions (KQVY).

- Precision DIS measurements of φ-dependence at high Q^2 possible with SOLID spectrometer at Jefferson Lab at 12 GeV.

- Precision results for SSA in ^{3}He$(e,e'n)$. Strong Q^2 dependence.
  - Sensitive to MEC and FSI in ^{3}He.

DIS Backgrounds

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- BigBite: Pair produced e^+/e^- pairs from π^o decay.
  - Measure using positive polarity
  - >50% contamination in lowest momentum bin
  - 1% in largest momentum bin
  - Largest systematic uncertainty

- BigBite: $\pi^{+/-}$ in $e^{+/-}$ spectrum. No Cherenkov detector. Relatively poor PID using only EM pre-shower and shower calorimeter.

- LHRS spectrometer, virtually background free.
  - Good PID
  - Highest momentum = negligible pair-electron contamination

Quasi-elastic Details

E (GeV)	$\langle E' \rangle$ (GeV)	$\langle \theta \rangle$ deg.	$\langle Q^2 \rangle$ (GeV^2)	$A_y^{^3\mathrm{He}}(\%)$	f_n (Kelly)	$A_y^n(\%)$ (Kelly)	f_n (Deltuva)	$A_y^n(\%)$ (Deltuva)
1.245	1.167	17.0	0.127	-0.126±0.015±0.027	0.050	-2.92±0.36±0.64	0.044	-3.32±0.40±0.72
2.425	2.170	17.0	0.460	-0.185±0.020±0.013	0.117	-1.78±0.26±0.16	0.104	-2.00±0.29±0.18
3.605	3.070	17.0	0.967	-0.199±0.019±0.013	0.159	-1.35±0.25±0.16	-	-