Two-Photon Exchange in DIS & SIDIS

Dave Gaskell, Tyler Hague, and **Michael Nycz**

Positron Working Group Workshop

March 25th 2025

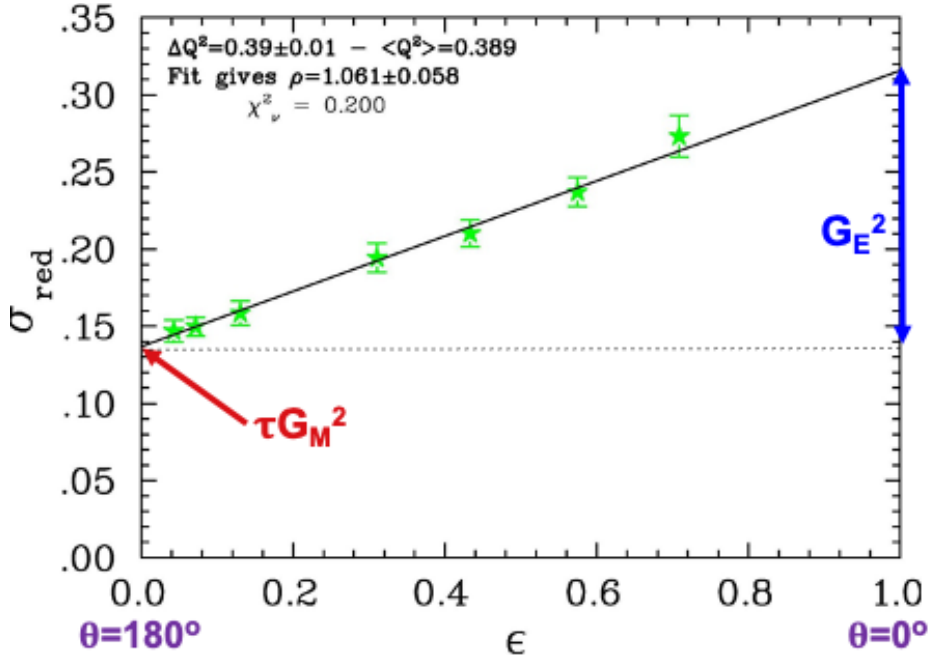
Outline

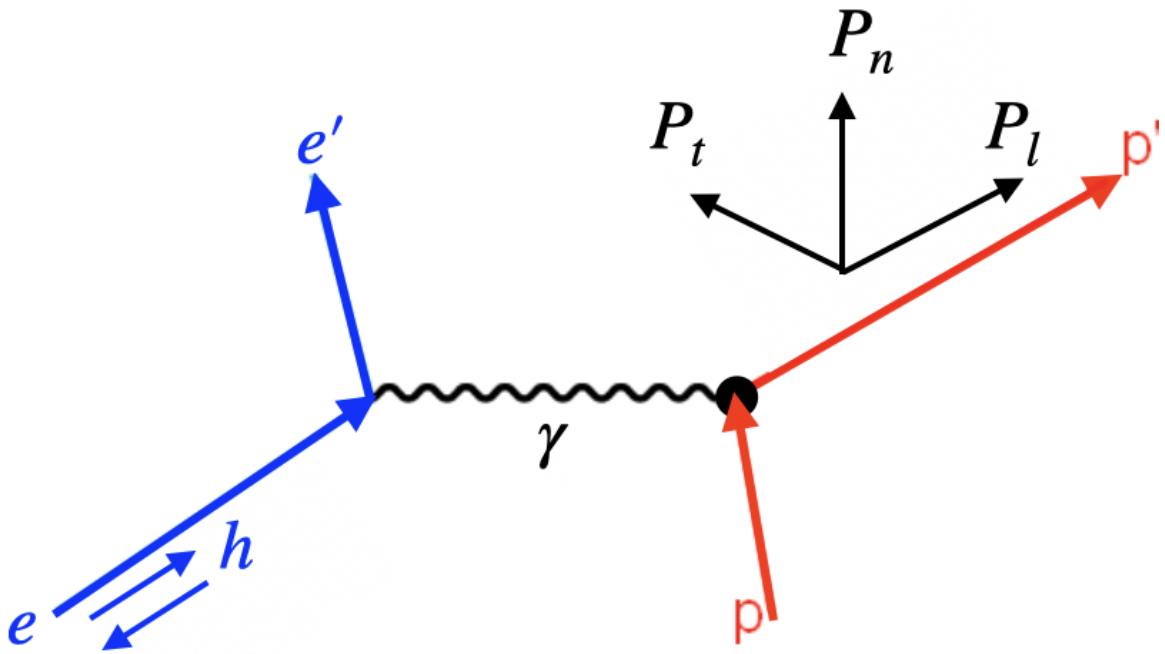
- Motivation I
  - Elastic Scattering
- Motivation II
  - Importance of studying TPE in Deep Inelastic Scattering & SIDIS
  - Summary of our current understanding of TPE in DIS & SIDIS
- Experimental Plan
  - Summary and Conclusion

G_E/G_M

$$\sigma_R = d\sigma/d\Omega[\varepsilon(1+\tau)/\sigma_{Mott}]$$
$$\sigma_R = \tau\, G_M^2(Q^2 + \varepsilon G_E^2)$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan\left({}^{\theta_e}/_{2}\right)$$





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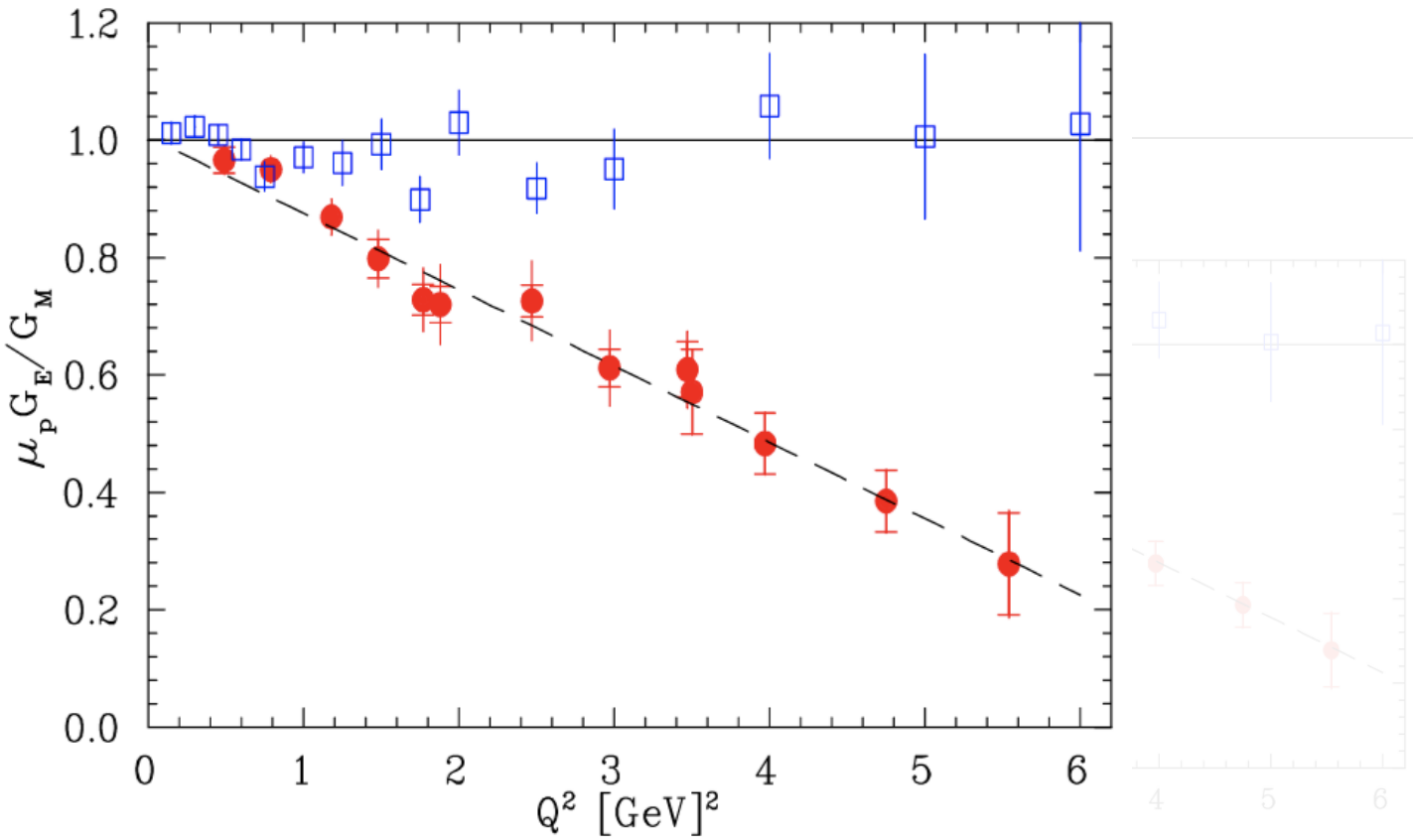
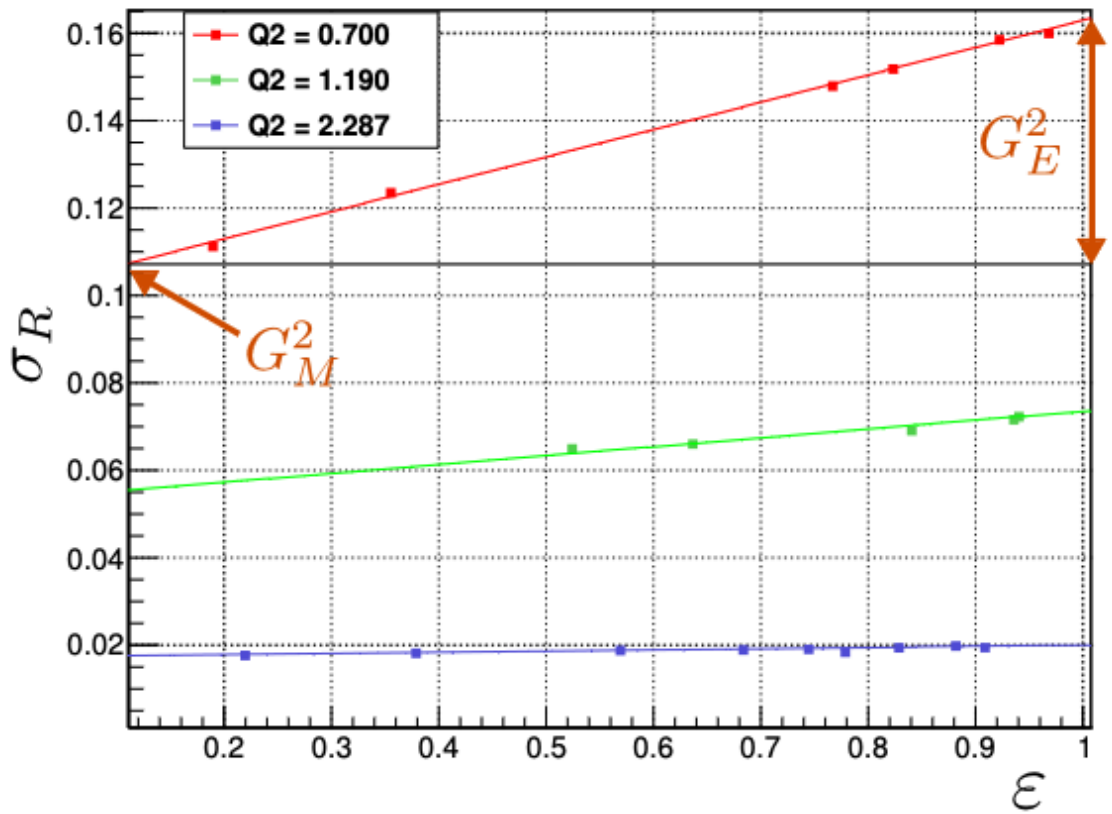


Two-Photon Exchange



Elastic Two-Photon Exchange Measurements

Cross section ratio: $\frac{e^+}{e^-}$

$$R \equiv \frac{\sigma^+}{\sigma^-} = \frac{|M_{1\gamma}+M_{2\gamma}|^2}{|M_{1\gamma}-M_{2\gamma}|^2} \rightarrow R_{2\gamma} = 1 - 2\delta_{2\gamma}$$

or

Comparison of Super-Rosenbluth e^+ & e^-measurements

Sensitive to the **Real** part of TPE

Beam- and Target- Normal SSA

$$A_n \propto 2Im\left(M_{1\gamma}M_{2\gamma}^*\right)$$

$$A_n = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Asymmetry is 0 at Born level (Single-Photon)
- No restrictions for multi-photon exchange (TPE)

Sensitive to the **Imaginary** part of TPE

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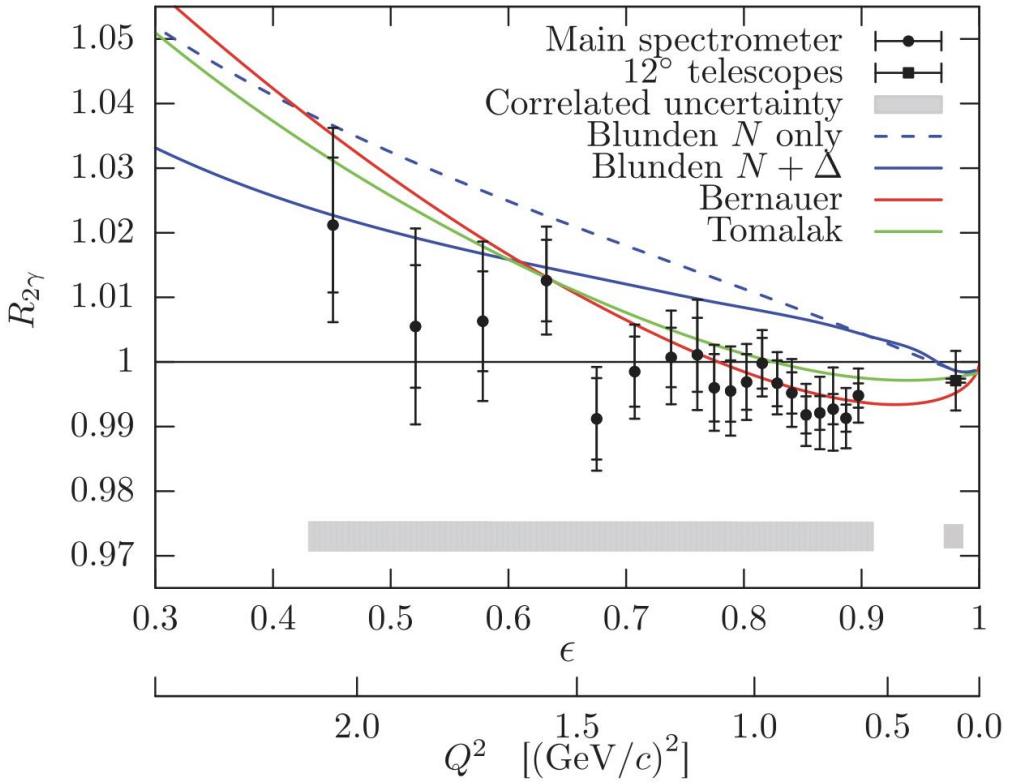
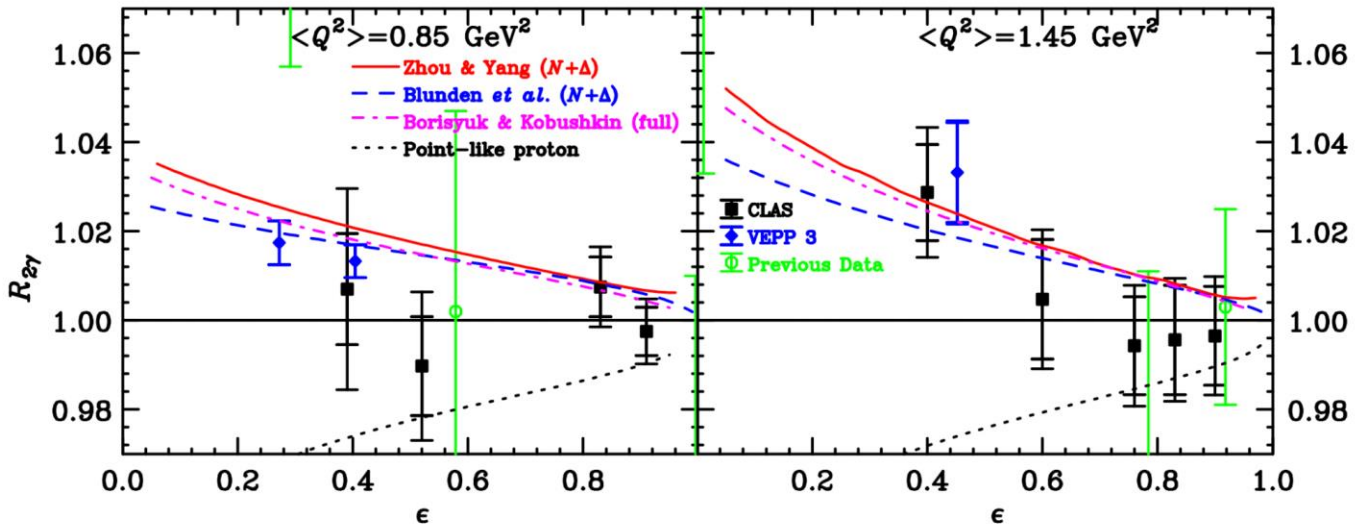


B. S. Henderson et al. (OLYMPUS Collaboration



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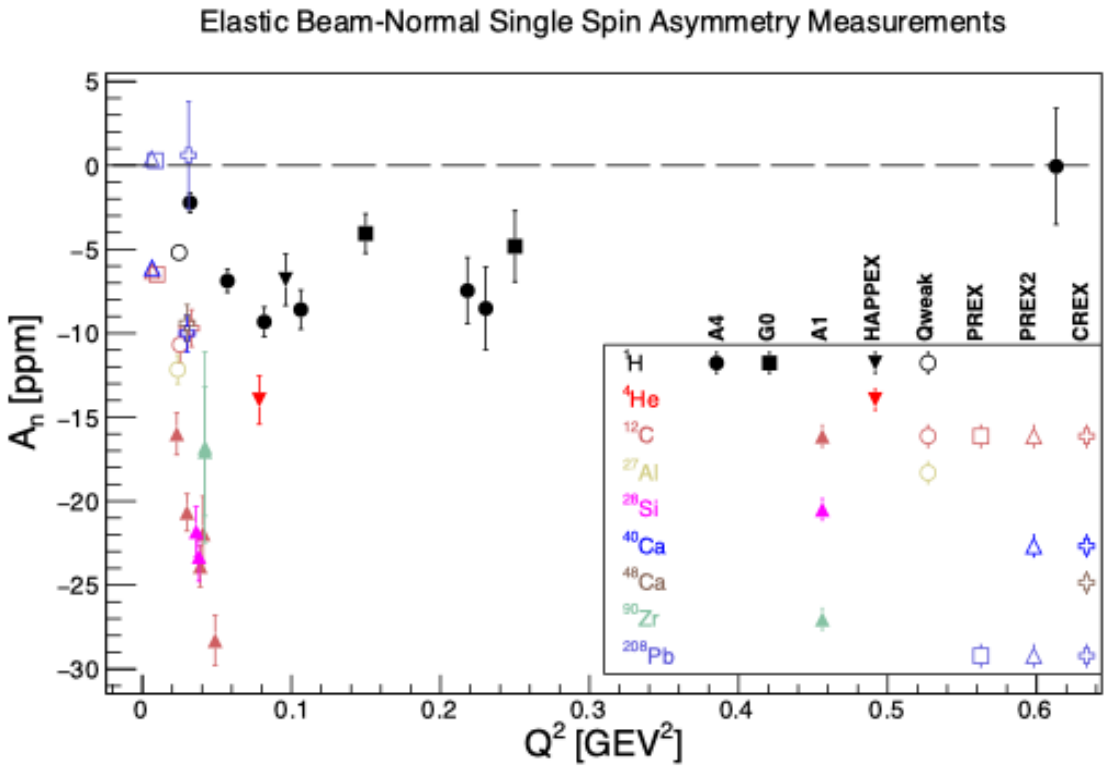
Elastic Two-Photon Exchange Measurements: BNSSA

- Large number of measurements for A_n
  - Non-zero asymmetry
  - Measured for range of light & heavy nuclei
- Measurements made in low Q^2 region
  - $Q^2 < 0.7$ GeV^2



Reproduced by Darren Upton

Summary from Elastic Scattering

- Large discrepancy between measurements of $\frac{G_E}{G_M}$
  - Discrepancy grows with Q^2
- Experimental
  - $\frac{e^+}{e^-}$ experiments – inconclusive
  - BNSSA – non-zero but cover a limited Q^2 range
- Theory
  - No consensus on size of the effect or the ε & Q^2 dependence

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Broad consensus: Two-Photon Exchange effects causing the discrepancy

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Would Two-Photon Exchange only be important for elastic scattering?

→ Broad consensus: Two-Photon Exchange effects causing the discrepancy

Two-Photon Exchange in DIS & SIDIS

- No corollary to polarization transfer in DIS or SIDIS
- $\frac{G_E}{G_M}$ highlights the importance of understanding TPE effects in DIS & SIDIS

Two-Photon Exchange in **DIS** & SIDIS

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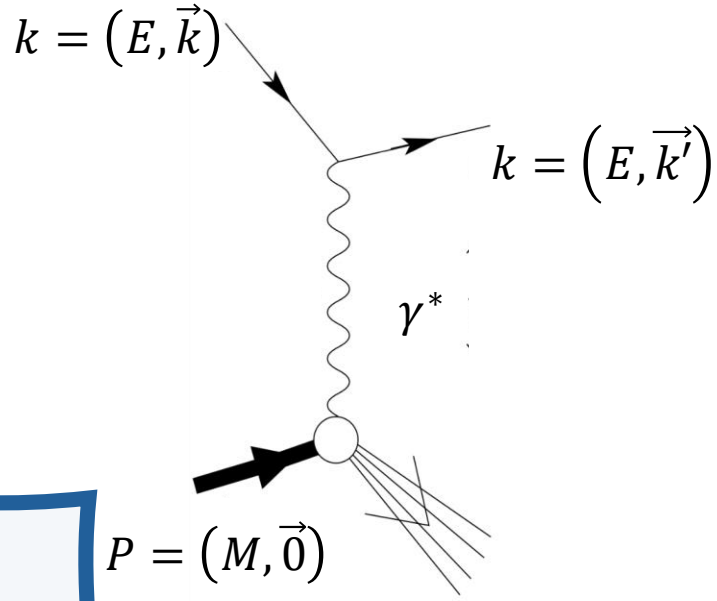
- $\frac{G_E}{G_M}$ highlights the importance of understanding TPE effects in DIS

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)}\left[\frac{F_2(\nu, Q^2)}{\nu}\cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(\nu, Q^2)}{M}\sin^2\left(\frac{\theta}{2}\right)\right]$$

$$\mathrm{R} = \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1}\left[1 + \frac{\nu^2}{Q^2}\right]$$



1. Cross section written in terms of F_2 & R
2. R is assumed to be the same for all nuclei
3. Allows to relate cross section ratio to structure function ratio
   a. EMC effect

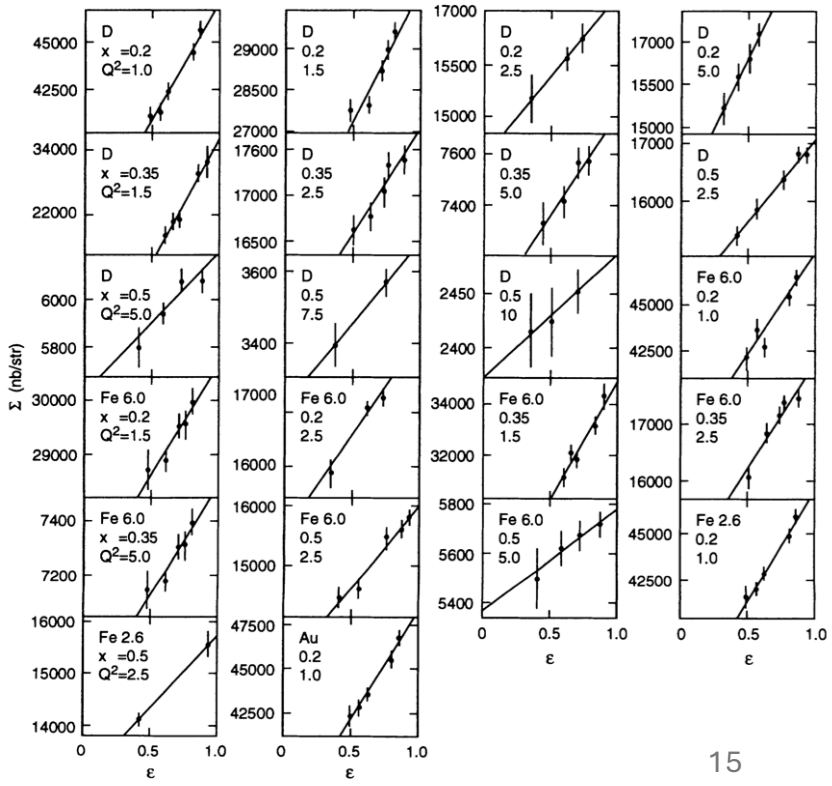
Two-Photon Exchange in **DIS** & SIDIS

- No corollary to polarization transfer in DIS or SIDIS
- $\frac{G_E}{G_M}$ highlights the importance of understanding TPE effects in DIS
  - Small effect can possibly have a large impact on
- Impact of TPE
  - L/T separations (Constant Q^2 and x bins)

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma[\sigma_T(x,Q^2) + \varepsilon\sigma_L(x,Q^2)]$$

$$\mathrm{R} = \frac{\sigma_L(x,Q^2)}{\sigma_T(x,Q^2)}$$

TPE effects
- ε dependent ?
- At large Q^2 ?



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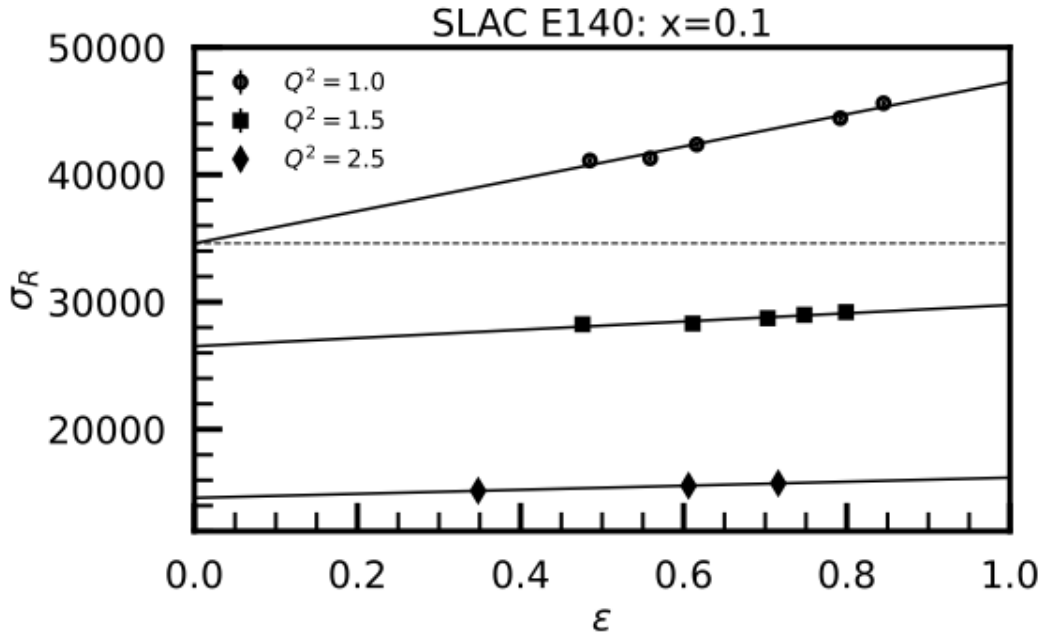

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Two-Photon Exchange in DIS & SIDIS

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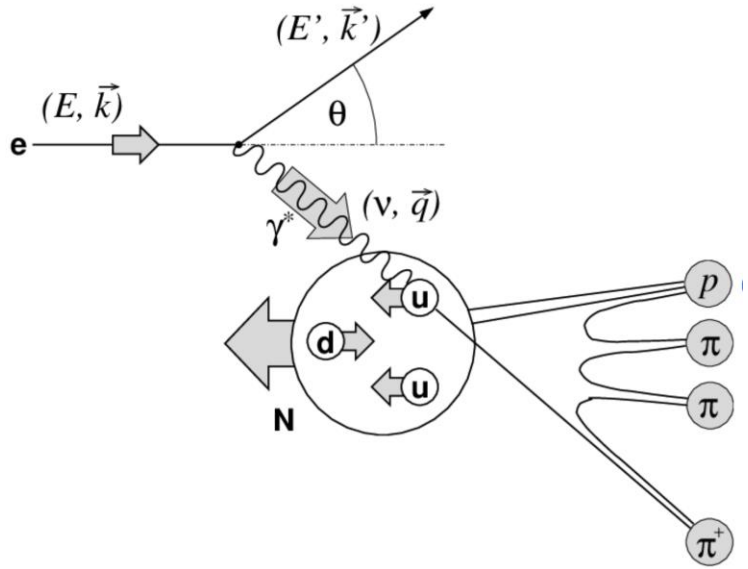
- Impact of TPE
  - L/T separations: Pion electroproduction cross section

$$\frac{d^2\sigma}{d\Omega_\pi dM_x} = \frac{d\sigma_T}{d\Omega_\pi dM_x} + \varepsilon \frac{d\sigma_L}{d\Omega_\pi dM_x} + \varepsilon \frac{d\sigma_{TT}}{d\Omega_\pi dM_x} \cos 2\varphi_{pq} + \sqrt{2\varepsilon(1+\varepsilon)} \frac{d\sigma_{LT}}{d\Omega_\pi dM_x} \cos\varphi_{pq}$$



$$x = \frac{Q^2}{2P\cdot q},\quad y = \frac{P\cdot q}{P\cdot l},\quad z = \frac{P\cdot P_h}{P\cdot q},\quad Q^2 = -q^2.$$

Two-Photon Exchange in DIS & **SIDIS**

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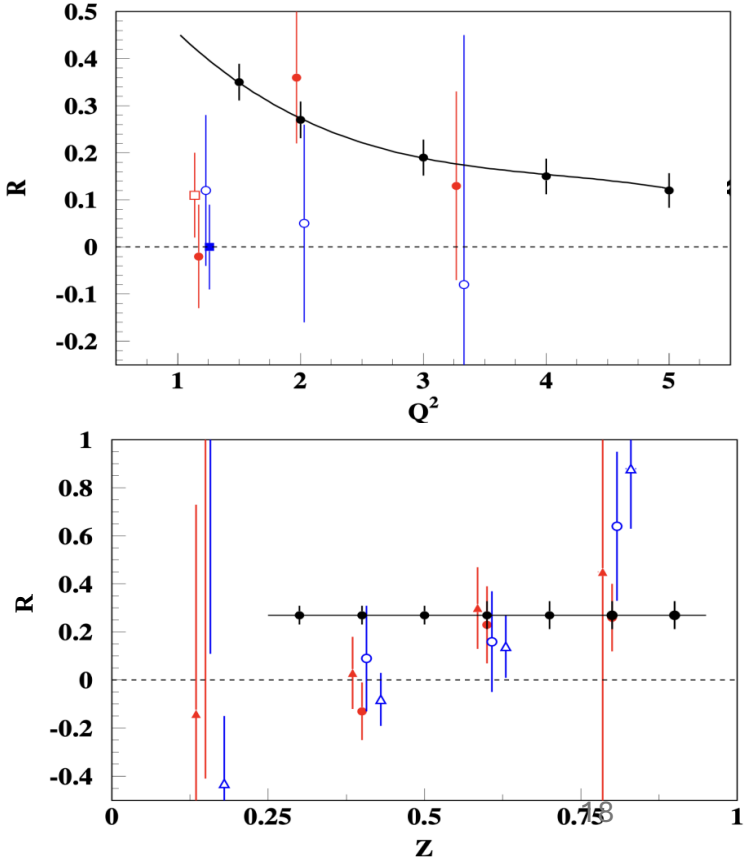
- R_{SIDIS} is assumed to be the same as R_{DIS} ($R_{SIDIS} = R_{DIS}$)
- Possible z & p_t-dependence of R_{SIDIS}?
- $R^{\pi^+}_{SIDIS} = R^{\pi^-}_{SIDIS}$?



Impact of TPE?

DIS Two-Photon Exchange Measurements

Ratio of $\frac{\nu W_2^+}{\nu W_2^-}$ in $\mu^-$and μ^+ scattering

Sensitive to the **Real** part of TPE

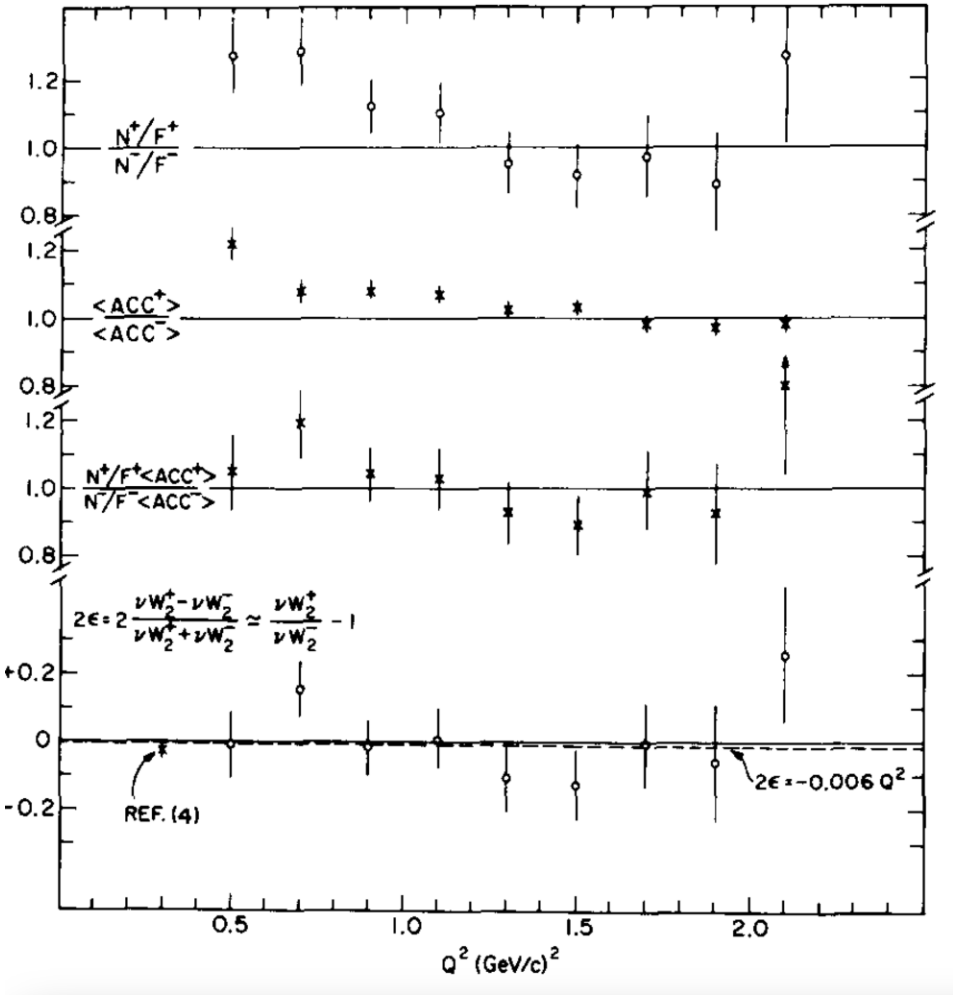
$A_n \propto 2Im\left(M_{1\gamma} M_{2\gamma}^*\right)$

Beam- and **Target**- Normal SSA

Sensitive to the **Imaginary** part of TPE

Measurements of TPE in DIS

- Brookhaven AGS
  - DIS μ^+ and μ^- scattering
  - Beryllium target
  - Q^2 range: 0.5 – 2.1 (GeV/c)^2
- Measured: νW_2^+, νW_2^- (Assumed R=0.18)
  - $\epsilon(Q^2, \nu) = (\nu W_2^+ - \nu W_2^-)/(\nu W_2^+ + \nu W_2^-)$
- Conclusion: at $\langle Q^2 \rangle = 1.09$ (GeV/c)^2
  - *"Contribution of two-photon exchange is less than 1.7% of the inelastic amplitude"*



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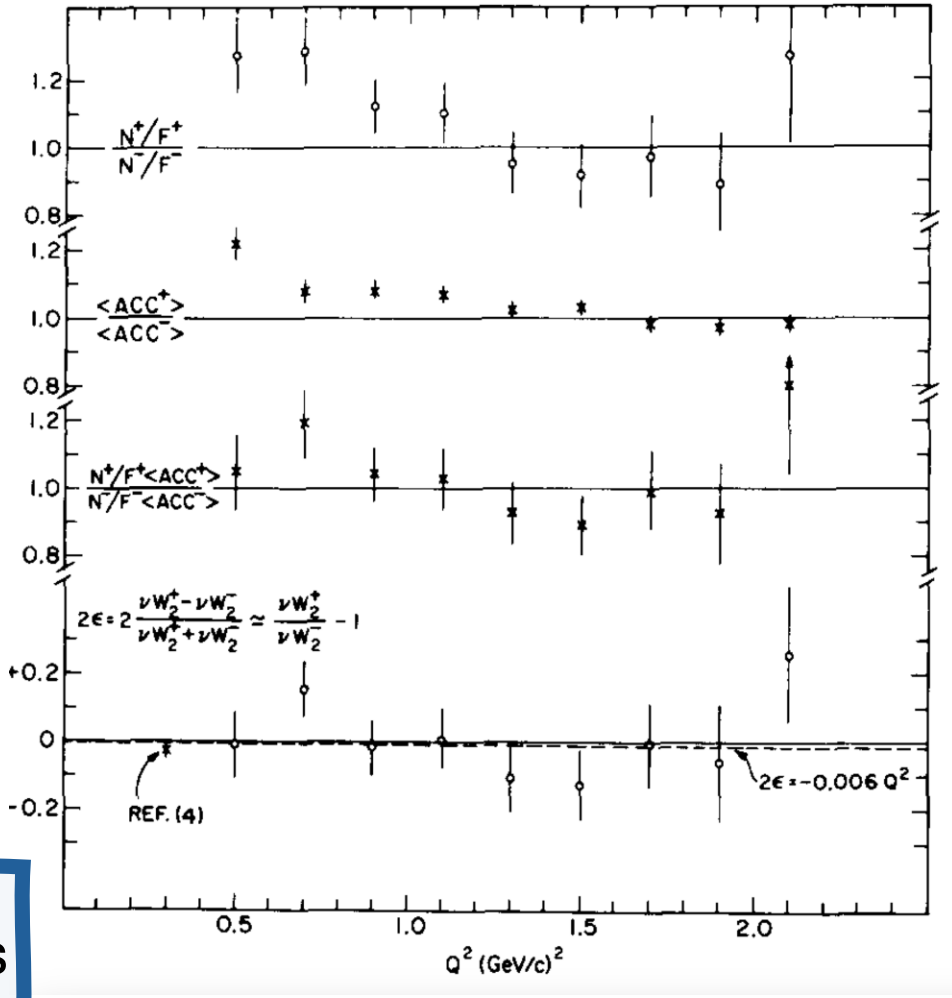

A 1.7 effect could have a large effect in LT separations

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Sensitive to the **Real** part of TPE

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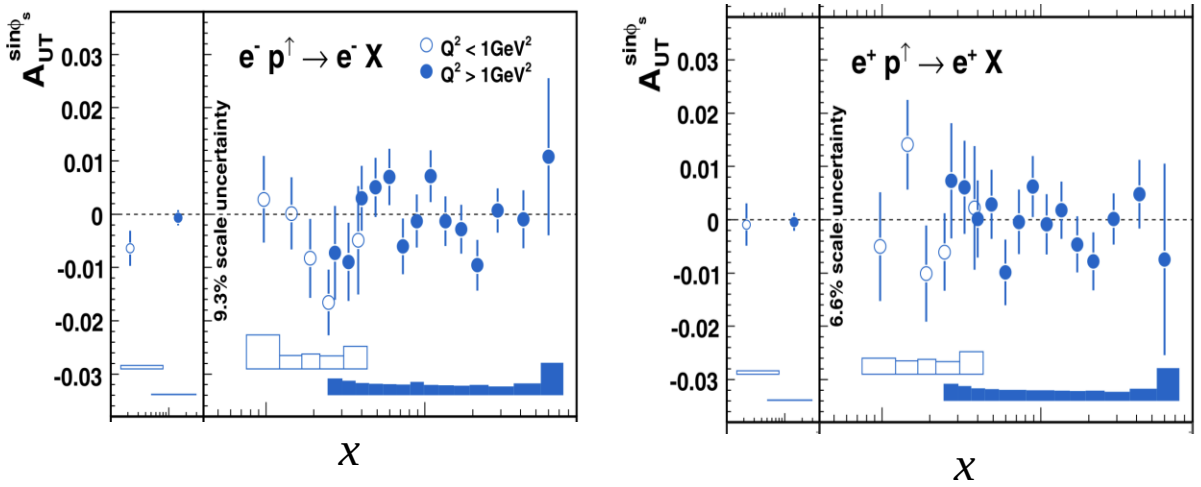
Beam- and **Target**- Normal SSA

Sensitive to the **Imaginary** part of TPE

Target-Normal Single Spin Asymmetry

Polarized proton target

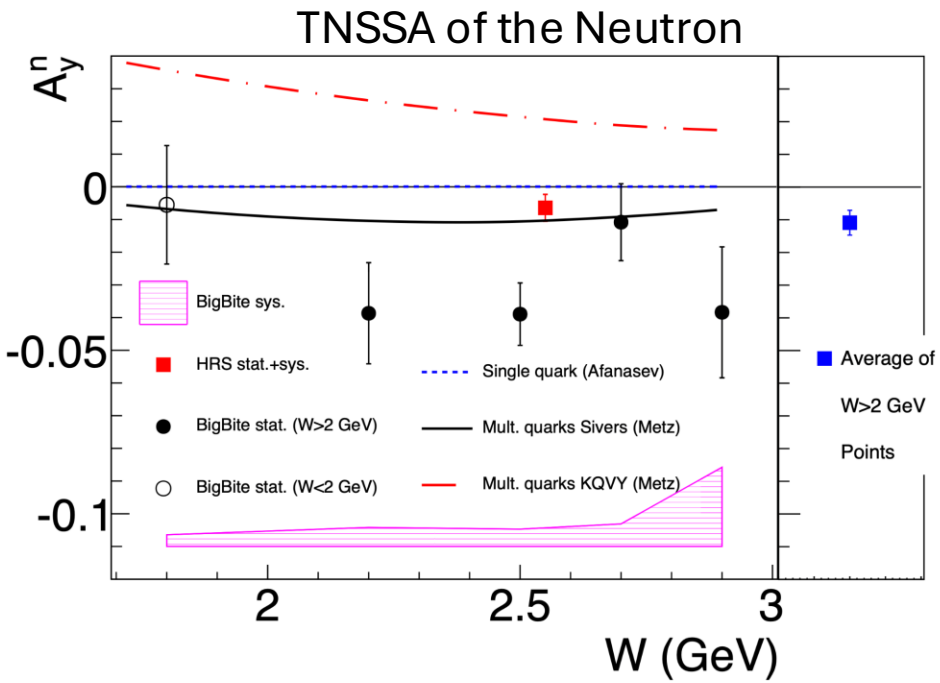
- Measured with both e^- & e^+



A. Airapetian et.al Phys. Lett. B (2010)

0.6 – 0.9 ± (1.50–3.97)× 10–3
(consistent with 0)

Polarized Helium-3



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

Ay = (-1.09 ±0.38) × 10–2
Non-zero: 2.89 σ

Target-Normal Single Spin Asymmetry

Polarized proton target

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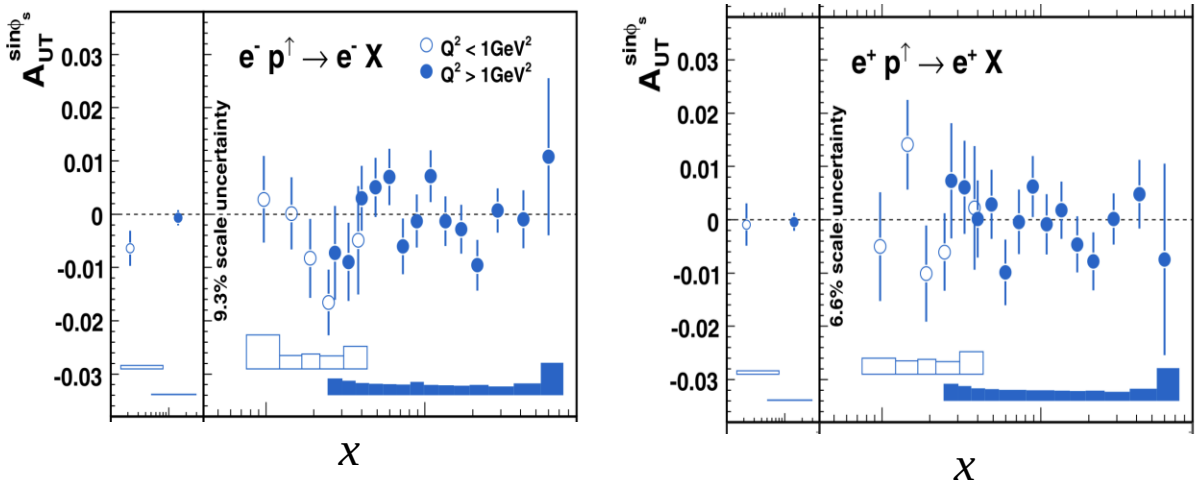

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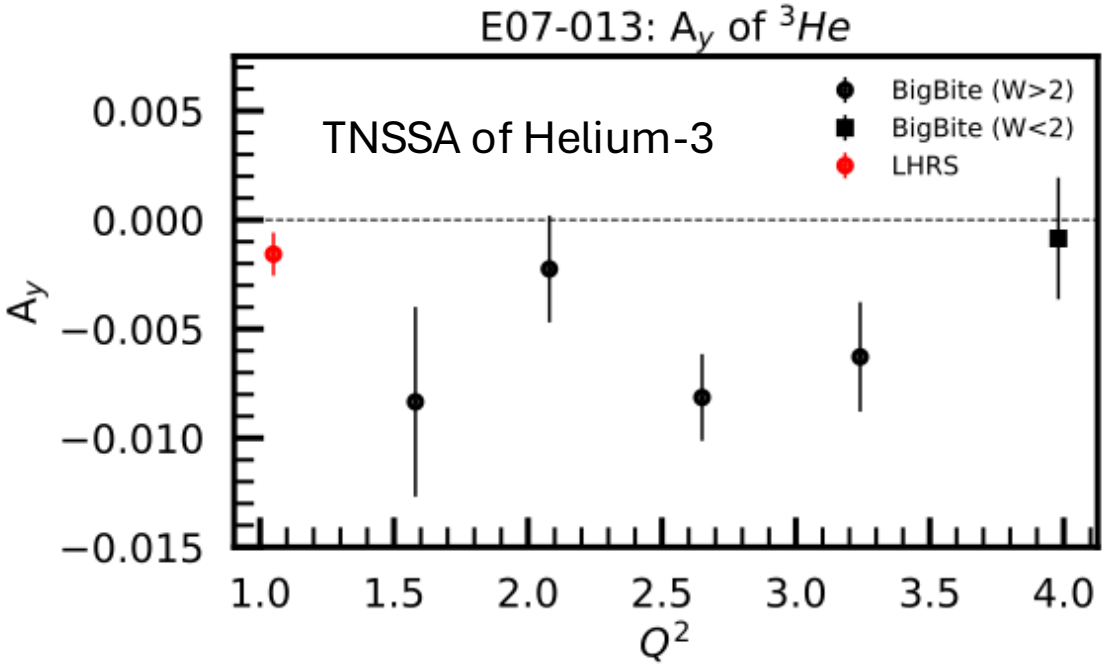
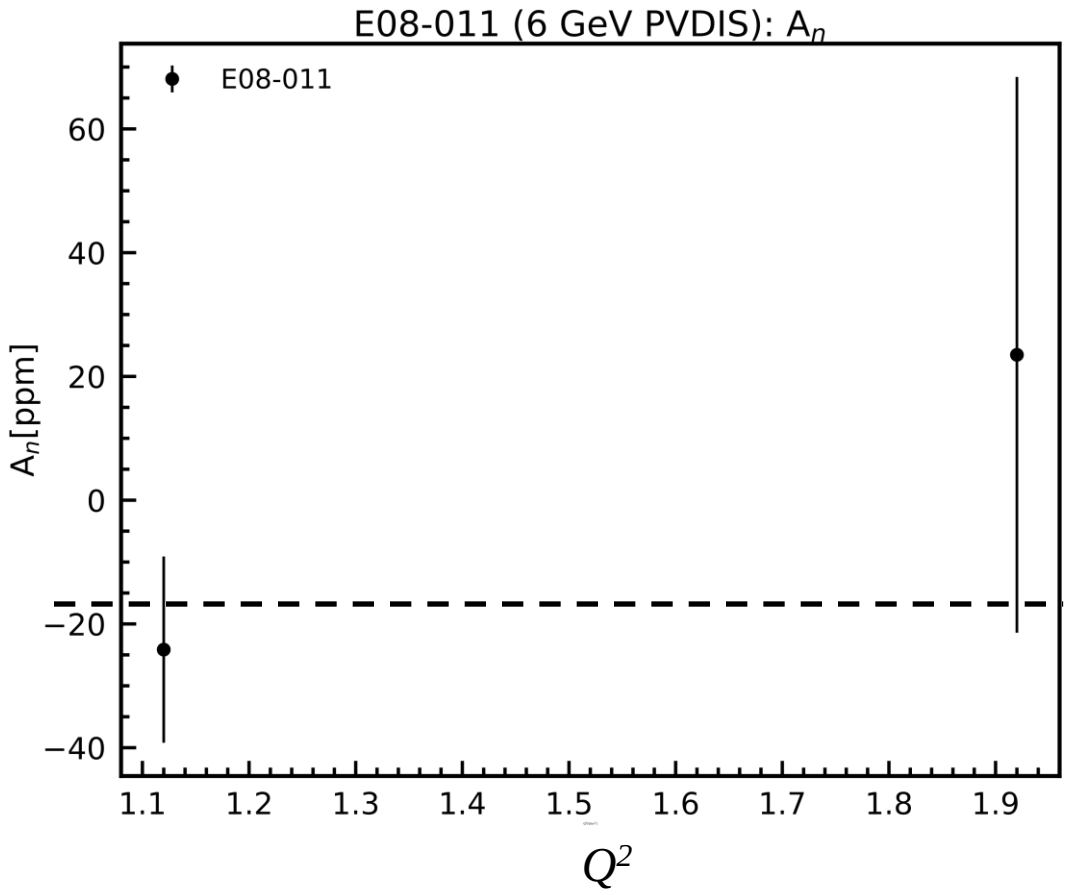


Reproduced from

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

Beam-Normal Single Spin Asymmetry

- E08-011
  - 6 GeV parity-violating asymmetry (PVDIS)
- Beam-Normal SSA potential background (dilution) to PVDIS asymmetry
- Large uncertainty



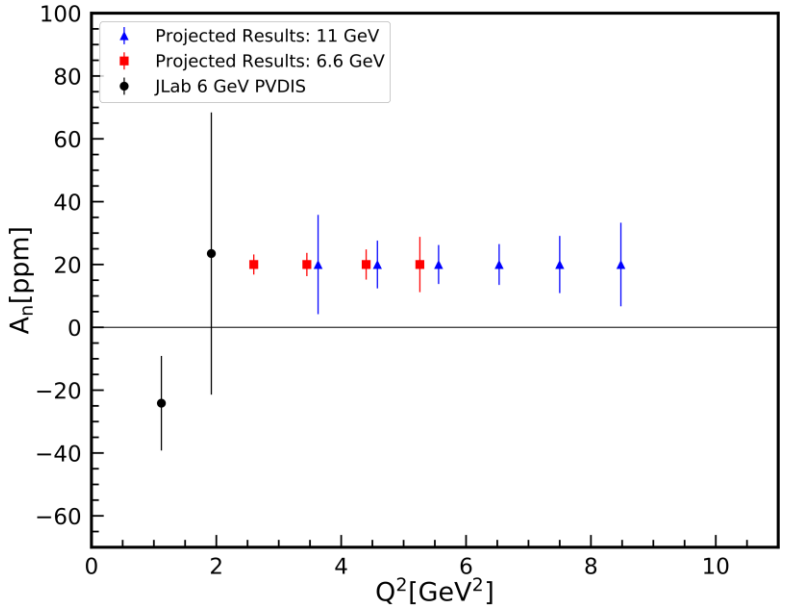
D. Wang et al., Phys. Rev. C 91 (2014)

Future Measurements

BNSSA with SoLID

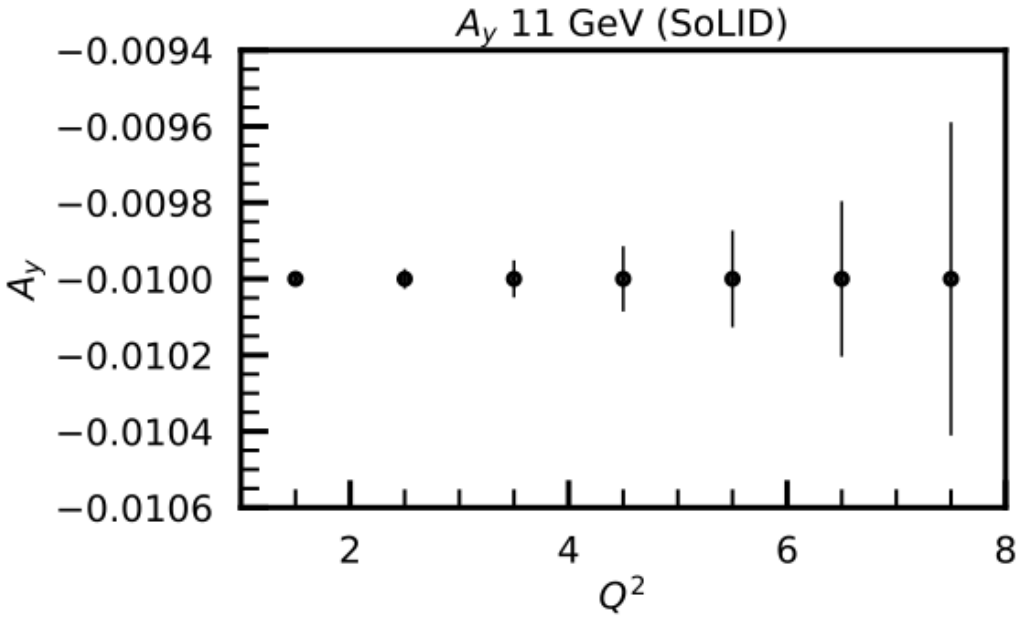
- Will combine each setting sepratley into single Q^2 bins

- $A_n = A_{measured} \pm$ **2.06 ppm** : 6.6 GeV
- $A_n = A_{measured} \pm$ **3.80 ppm** : 11 GeV



TNSSA with SoLID

1. NH_3 (polarized proton)
2. ^{3}He (polarized neutron)

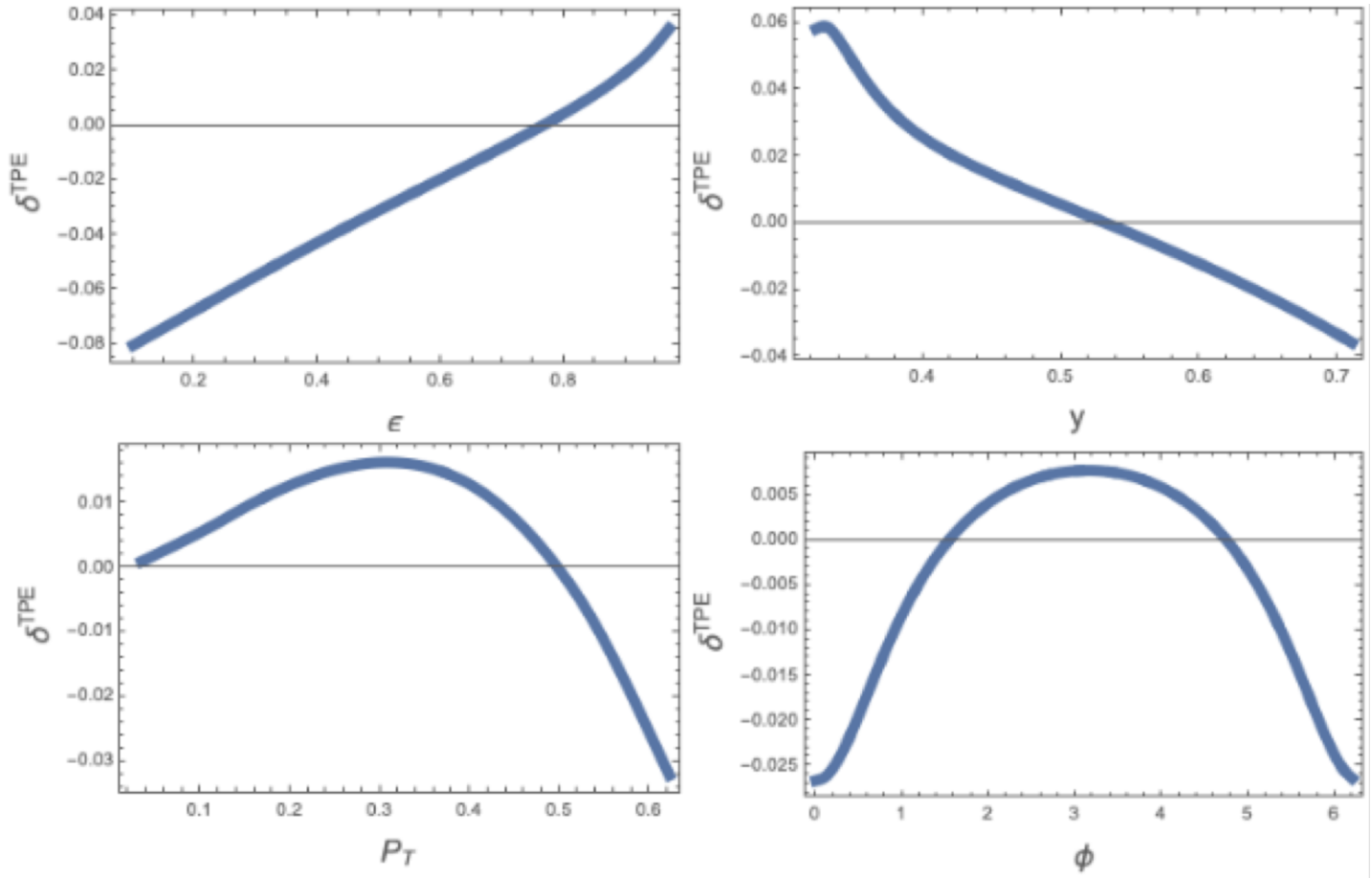


Two-Photon Exchange Measurements in SIDIS

Theoretical Predictions for TPE in SIDIS

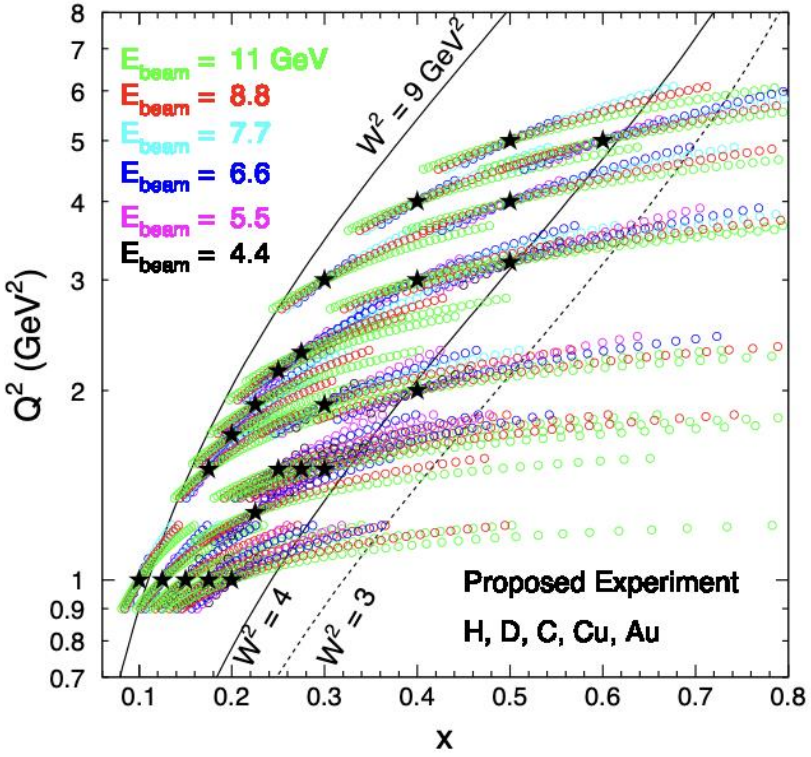
Andrei Afanasev & Stinson Lee

- E_{beam}=10.6 GeV
- Q^2 = 2.5 GeV^2
- y < 0.7
- X = 0.31
- Z = 0.5



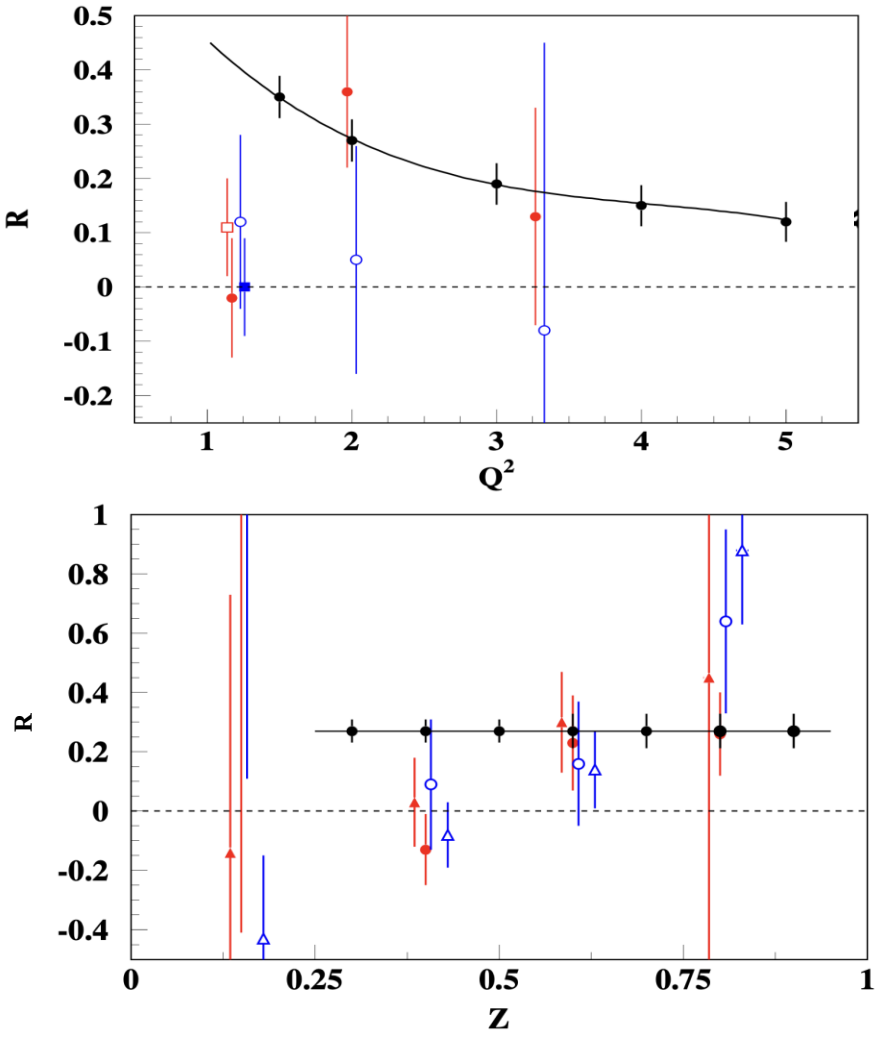
E12-14-002

- Precision Measurements and Studies of a Possible Nuclear Dependence of $\mathrm{R} = \frac{\sigma_L}{\sigma_T}$
  - Nuclear $\mathrm{R}_{\mathrm{DIS}}$
- Approved experiment / scheduled to begin FY 2026



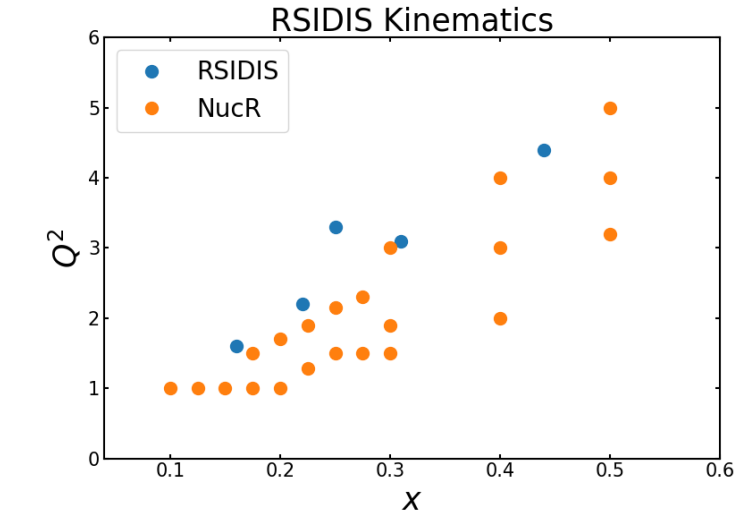
E12-06-104

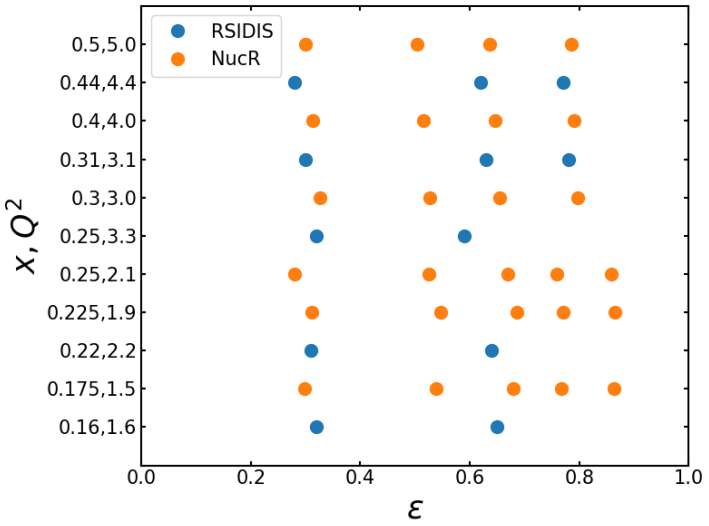
- Measurement of the Ratio $\mathrm{R} = \frac{\sigma_L}{\sigma_T}$ in Semi-Inclusive Deep-Inelastic Scattering
- Approved experiment / scheduled to begin FY 2025



Comparing Kinematics

- Can utilize kinematics from approved experiments E12-14-002 (R_{DIS}) & E12-06-104 (R_{SIDIS})
- Finalizing/optimizing in order to collect data for DIS & SIDIS concurrently
- Proposed positron experiment would leverage the synergy with the electron measurements





Plots courtesy of Tyler Hague

Summary and Outlook

- Limited experimental measurements in DIS
  - Non-zero A_y (TNSSA)
  - None in SIDIS
- Several approved DIS experiments to measure Beam- & Target-Normal SSA
- Approved experiments to measure R_{DIS} & R_{SIDIS}
  - Improve radiative corrections
  - Allow for more precise L/T separation
- Utilize kinematics of upcoming R_{DIS} and R_{SIDIS} experiments to design experiment
  - Maximize impact
  - Collect data at overlapping kinematics
- Theoretical predictions for SIDIS TPE (maybe DIS)
  - Andrei Afanasev
- Plan to submit proposal to measure TPE in both DIS & SIDIS in Hall C to PAC53