Constraining two-photon exchange with electrons through the target-normal SSA

Axel Schmidt

2025 Positron Working Group Meeting

March 26, 2025

This work is supported by the US DOE Office of Science, Office of Nuclear Physics, under contract no. DE-SC0016583.

Two-photon exchange in elastic scattering

- Need more data to constrain model-dependent calculations.
  - Ideally, many orthogonal constraints
  - Wide range of kinematics, particulary $Q^2 \sim 3$–5 GeV^2

Two-photon exchange in elastic scattering

- Need more data to constrain model-dependent calculations.
  - Ideally, many orthogonal constraints
  - Wide range of kinematics, particulary $Q^2 \sim 3$–5 GeV^2

- Polarization observables add information beyond $\sigma_{e^+p}/\sigma_{e^-p}$
  - Different combinations of TPE form factors

Two-photon exchange in elastic scattering

- Need more data to constrain model-dependent calculations.
  - Ideally, many orthogonal constraints
  - Wide range of kinematics, particulary $Q^2 \sim$ 3–5 GeV^2
- Polarization observables add information beyond $\sigma_{e^+p}/\sigma_{e^-p}$
  - Different combinations of TPE form factors
- We can already start without a positron beam.

Probes of two-photon exchange

1. Lepton charge asymmetry
   - Compare positrons and electrons
   - e.g., OLYMPUS, PR12+23-008, PR12+23-012, etc.

Probes of two-photon exchange

1. Lepton charge asymmetry
   - Compare positrons and electrons
   - e.g., OLYMPUS, PR12+23-008, PR12+23-012, etc.

2. Deviations in expected ϵ-dependence
   - Non-linearity of reduced cross sections
   - ϵ-dependence of polarization transfer
   - e.g., GEp-2γ, E12-24-010

Probes of two-photon exchange

1. Lepton charge asymmetry
   - Compare positrons and electrons
   - e.g., OLYMPUS, PR12+23-008, PR12+23-012, etc.

2. Deviations in expected ϵ-dependence
   - Non-linearity of reduced cross sections
   - ϵ-dependence of polarization transfer
   - e.g., GEp-2γ, E12-24-010

3. Normal single-spin asymmetries
   - Beam-normal: every PVES measurement ever
   - **Target-normal**

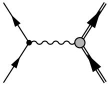
Normal single-spin asymmetries (SSAs)

- Beam-normal single-spin asymmetry, B_n
  - Transversely polarized beam, unpolarized target
  - Azimuthal asymmetry of scattered leptons
  - Electrons: widely measured (by-product of PV)
  - Positrons: not so feasible

- Target-normal single-spin asymmetry, A_n
  - Unpolarized polarized beam, transversely polarized target
  - Azimuthal asymmetry of scattered leptons
  - Electrons: very limited data
  - Positrons: distinguish TPE from T-violation

TPE can be characterized by higher-order form factors.

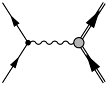
Formalism of Carlson, Vanderhaeghen, Annu. Rev. Nucl. Part. Sci., 2007



Form factors under one-photon exchange: $G_E(Q^2)$, $G_M(Q^2)$

TPE can be characterized by higher-order form factors.

Formalism of Carlson, Vanderhaeghen, Annu. Rev. Nucl. Part. Sci., 2007

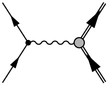


Form factors under one-photon exchange: $G_E(Q^2)$, $G_M(Q^2)$

Higher-order TPE Form Factors: $\delta\tilde{G}_E(Q^2,\nu)$, $\delta\tilde{G}_M(Q^2,\nu)$, $\tilde{F}_3(Q^2,\nu)$,

TPE can be characterized by higher-order form factors.

Formalism of Carlson, Vanderhaeghen, Annu. Rev. Nucl. Part. Sci., 2007



Form factors under one-photon exchange: $G_E(Q^2)$, $G_M(Q^2)$

Higher-order TPE Form Factors: $\delta\tilde{G}_E(Q^2,\nu)$, $\delta\tilde{G}_M(Q^2,\nu)$, $\tilde{F}_3(Q^2,\nu)$,

Suppressed by m_e: $\tilde{F}_4(Q^2,\nu)$, $\tilde{F}_5(Q^2,\nu)$

SSAs access the imaginary part of TPE.

$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 - 4G_M \mathrm{Re}\left(\delta\tilde{G}_M + \frac{\epsilon\nu}{M^2}\tilde{F}_3\right) - \frac{4\epsilon}{\tau}G_E \mathrm{Re}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + \mathcal{O}(\alpha^4)$$

Target-normal:

$$A_n = \frac{\sqrt{2\epsilon(1+\epsilon)}}{\sqrt{\tau}\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)} \times$$

$$\left[-G_M \mathrm{Im}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + G_E \mathrm{Im}\left(\delta\tilde{G}_M + \frac{2\epsilon\nu}{M^2(1+\epsilon)}\tilde{F}_3\right)\right] + \mathcal{O}(\alpha^4)$$

SSAs access the imaginary part of TPE.

$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 - 4G_M\mathrm{Re}\left(\delta\tilde{G}_M + \frac{\epsilon\nu}{M^2}\tilde{F}_3\right) - \frac{4\epsilon}{\tau}G_E\mathrm{Re}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + \mathcal{O}(\alpha^4)$$

Target-normal:

$$A_n = \frac{\sqrt{2\epsilon(1+\epsilon)}}{\sqrt{\tau}\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)} \times$$

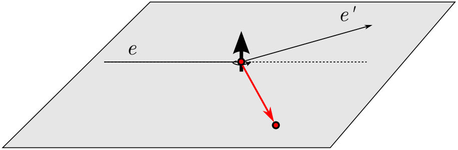
$$\left[-G_M\mathrm{Im}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + G_E\mathrm{Im}\left(\delta\tilde{G}_M + \frac{2\epsilon\nu}{M^2(1+\epsilon)}\tilde{F}_3\right)\right] + \mathcal{O}(\alpha^4)$$

Beam Normal:

$$B_n = \frac{4mM\sqrt{2\epsilon(1-\epsilon)(1+\tau)}}{Q^2\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)} \times$$

$$\left[-\tau G_M\mathrm{Im}\left(\tilde{F}_3 + \frac{\nu}{M^2(1+\tau)}\tilde{F}_5\right) - G_E\mathrm{Im}\left(\tilde{F}_4 + \frac{\nu}{M^2(1+\tau)}\tilde{F}_5\right)\right] + \mathcal{O}(\alpha^4)$$

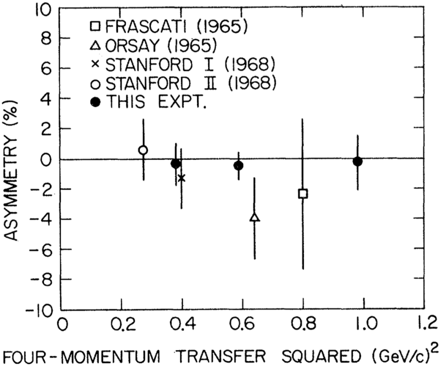
Target-normal SSAs are not suppressed by m_e but do require complex polarized target.



- $A_n \sim 10^{-3}$–10^{-2}
- Transverse holding field complicates beam steering
- Measurements in inelastic scattering from 1970s looked for evidence of T-violation
- Very limited elastic scattering data.

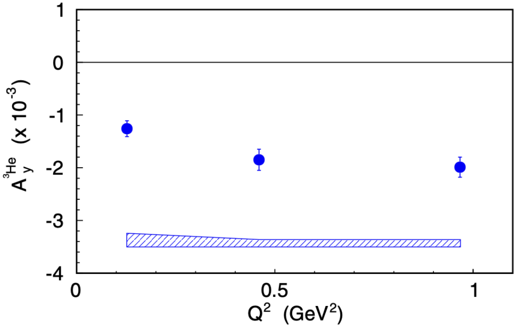
Previous measurements of (quasi-)elastic A_n

1. Frascati (1965)
2. Orsay (1965)
3. Stanford: T. Powell et al., PRL 24, 753 (1970)



Previous measurements of (quasi-)elastic A_n

1. Frascati (1965)
2. Orsay (1965)
3. Stanford: T. Powell et al., PRL 24, 753 (1970)
4. JLab (on ^{3}He): Y.W. Zhang et al., PRL 115, 172502 (2015), E. Long et al., PLB 797, 134875 (2019)



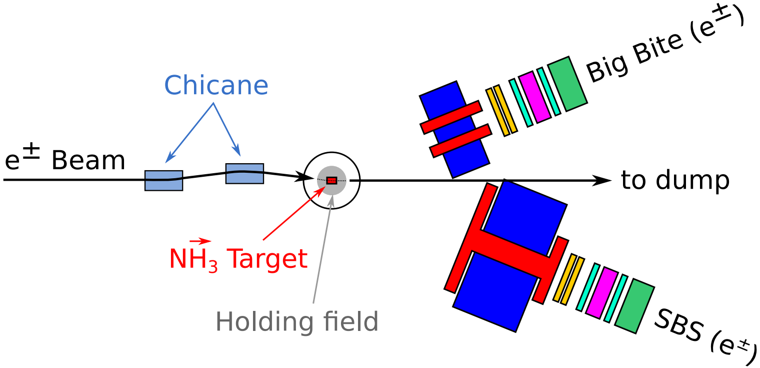
2021 Positron Working Group white paper: concept for A_n SSA with Super Big-Bite

G. N. Grauvogel, T. Kutz, A. Schmidt, EPJA 57:213 (2021)

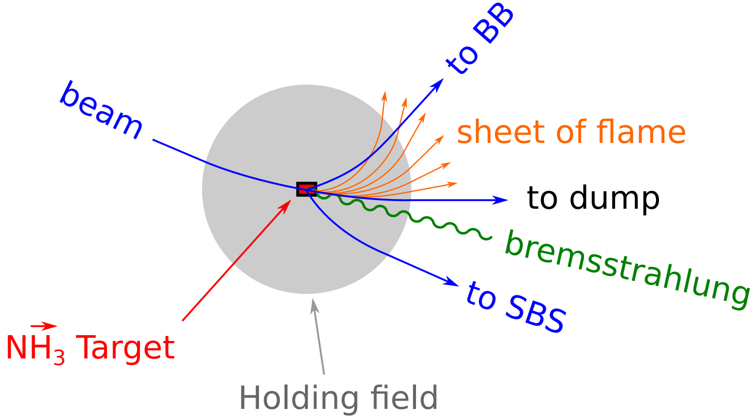
Gabe Grauvogel

Tyler Kutz

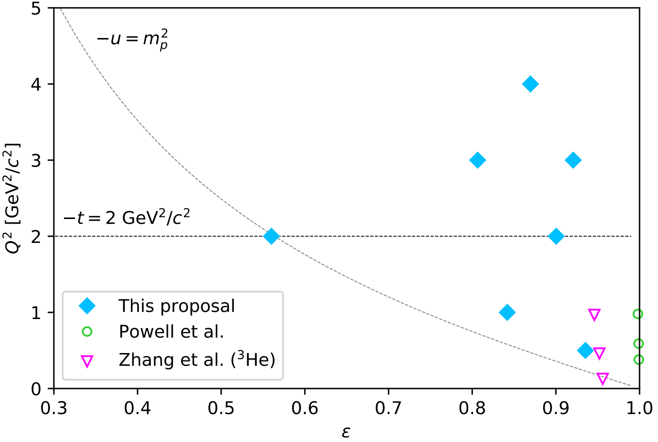
A transversely polarized proton target will require a strong holding field.



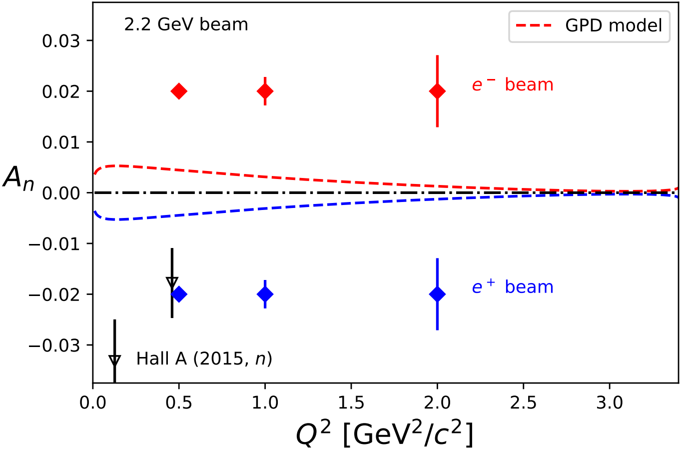
A transversely polarized proton target will require a strong holding field.



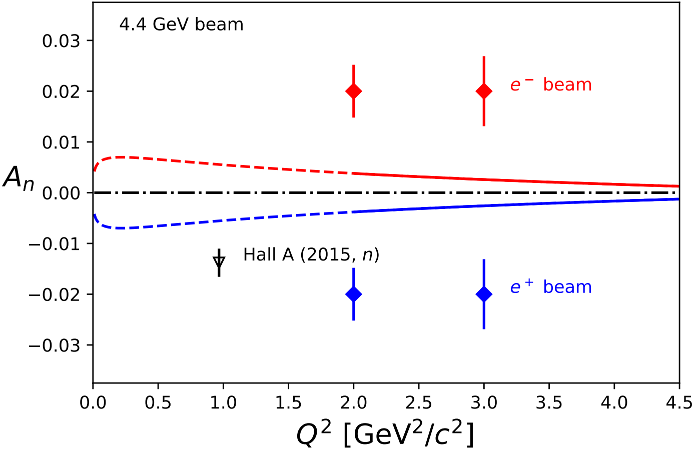
A 20-day measurement at JLab would cover new ground.



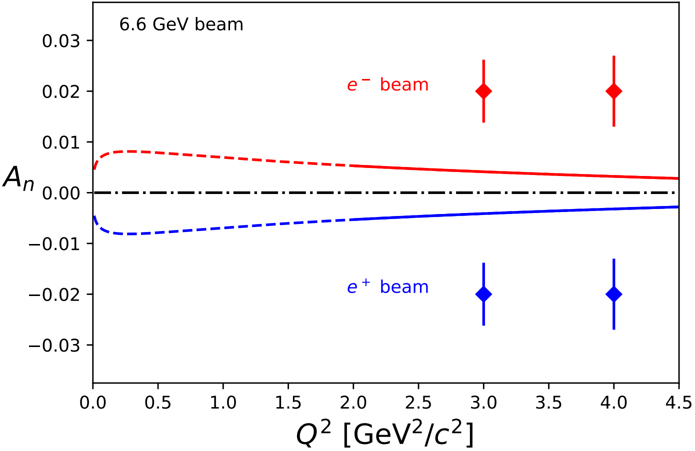
A 20-day measurement at JLab would cover new ground.



A 20-day measurement at JLab would cover new ground.



A 20-day measurement at JLab would cover new ground.



Draw-backs to the SBS concept

- We are not realistically going to move BB+SBS 7 times.
  - Each kinematic point required a move.

Draw-backs to the SBS concept

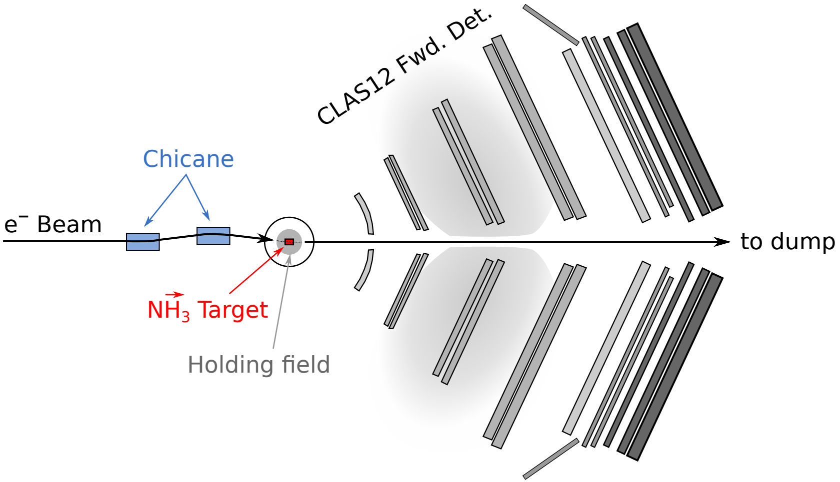
- We are not realistically going to move BB+SBS 7 times.
  - Each kinematic point required a move.

- We are demanding symmetric performance from BB and SBS
  - Two very different magnets.
  - Sheet of flame will dramatically impact one side

Draw-backs to the SBS concept

- We are not realistically going to move BB+SBS 7 times.
  - Each kinematic point required a move.
- We are demanding symmetric performance from BB and SBS
  - Two very different magnets.
  - Sheet of flame will dramatically impact one side
- We did not study background subtraction
  - Need to isolate elastic peak on QE background
  - Background contributes stat. uncertainty

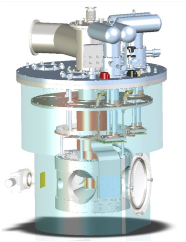
CLAS12 Run Group H plans to use a transverse target.

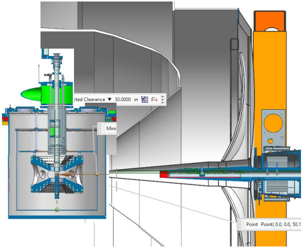


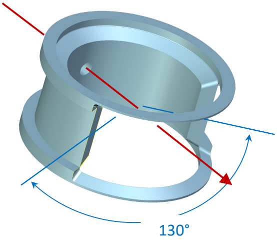
CLAS12 Run Group H plans to use a transverse target.

3 A-rated C2 proposals (110 PAC days)

- C12-11-111, M. Contalbrigo, “Transverse spin effects in SIDIS...”
- C12-12-009, H. Avakian, “...dihadron production in SIDIS...”
- C12-12-010, L. Elouadrhiri, “Deeply Virtual Compton Scattering...”

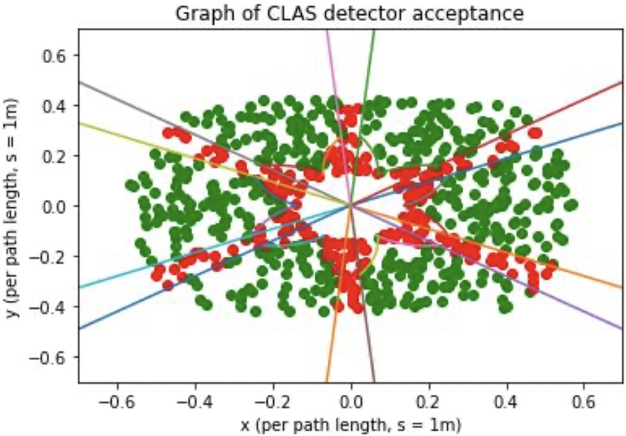




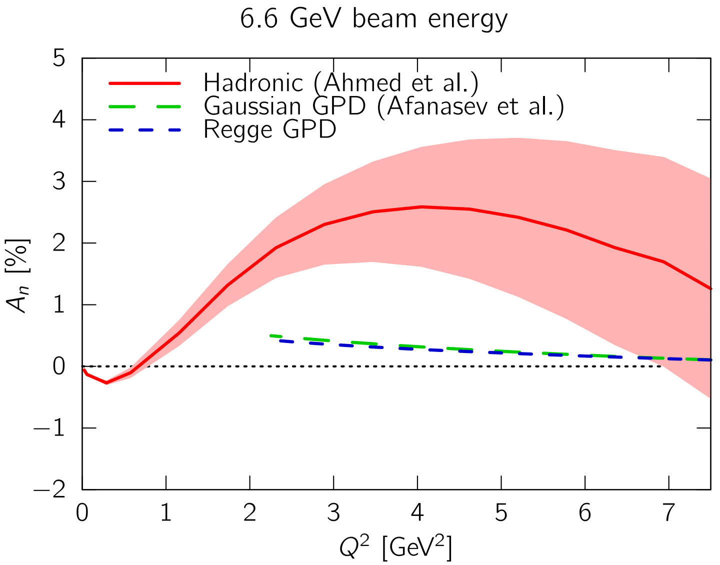


We are preparing an e^- LOI for upcoming PAC.

August Friebolin



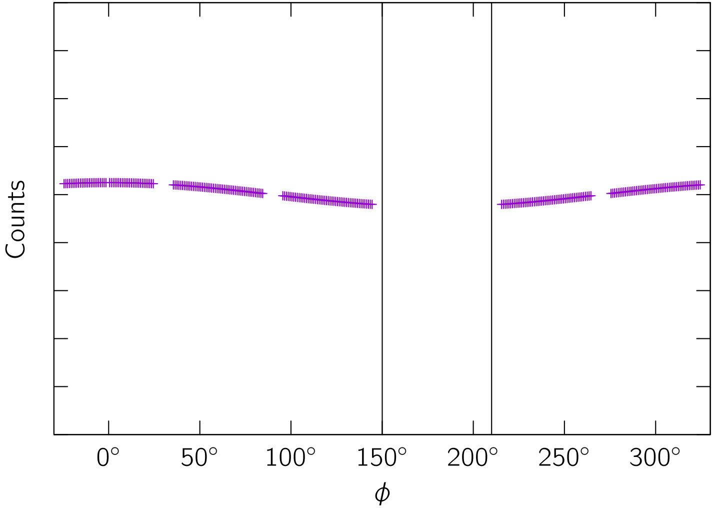
We need to aim for %-level uncertainty.



Challenges

- Beam energy
  - RG-H is being designed around 11 GeV running
  - Lower energies require larger chicanes
    - or reduced fields and lower target polarization
  - Harder to identify elastic events at high E
- Sheet of flame
  - One of the CLAS12 sectors will have to be disabled
  - Breaks left/right symmetry of the system
  - Impacts our ability to infer asymmetry

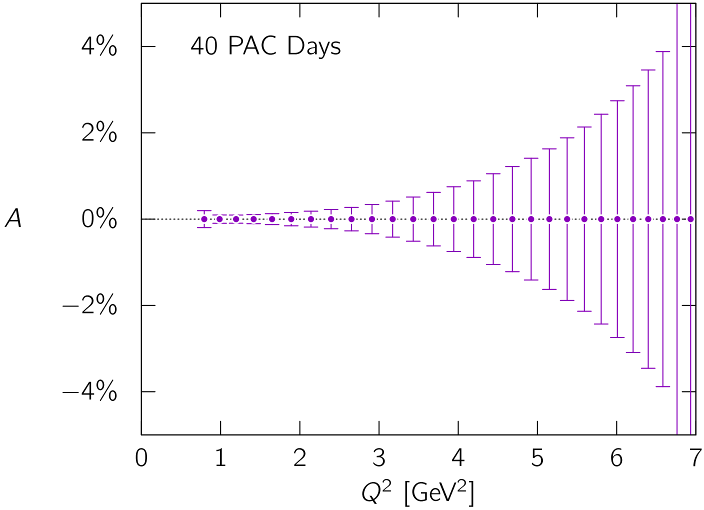
One of the most impactful CLAS sectors will need to be deactivated.



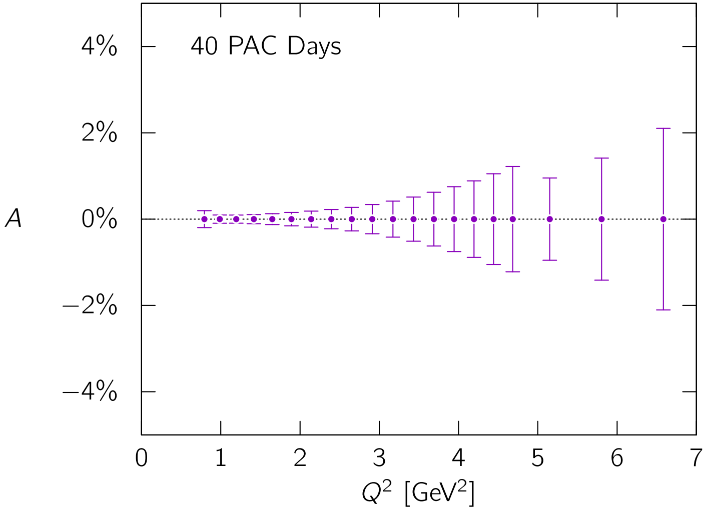
Our preliminary simulations

- Assume Rosenbluth cross section
- Modify momentum vectors due to target holding field
- Check target window aperture, CLAS12 fiducials
- Fit azimuthal distribution
    - Determine δA from covariance matrix

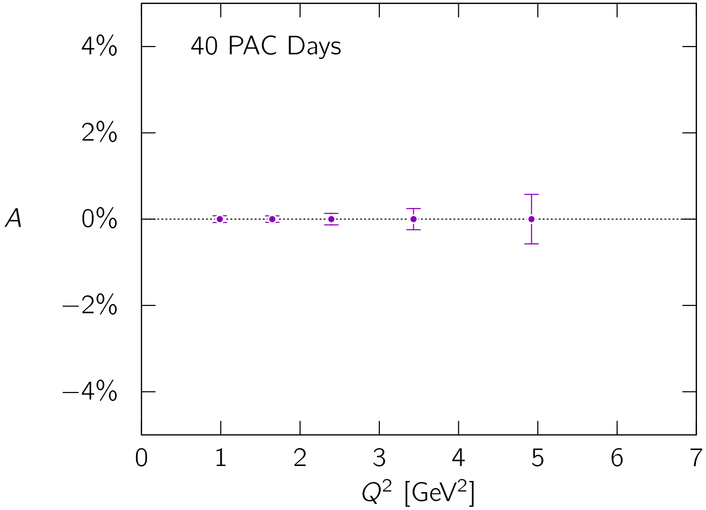
Projected Uncertainties with CLAS12



Projected Uncertainties with CLAS12

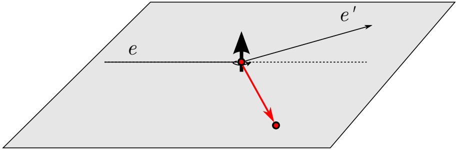


Projected Uncertainties with CLAS12



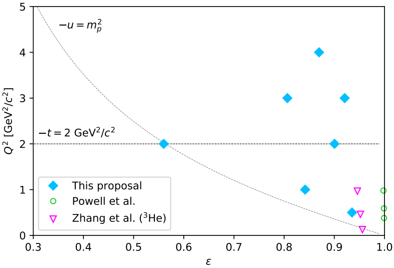
To Recap:

- Goal: add independent constraints on TPE



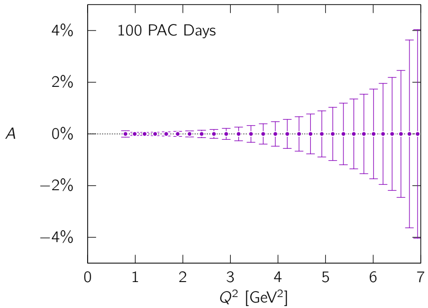
To Recap:

- Goal: add independent constraints on TPE
- Very little data on target normal SSA



To Recap:

- Goal: add independent constraints on TPE
- Very little data on target normal SSA
- Challenging but conceivable at RG-H



Conclusions

- Given a time demands, helpful to have other motivation for lower-energy running.
  - SSAs in other reactions, e.g., electroproduction
  - Combine with 11 GeV data, study ϵ-dependence
- Still some work to fully realize this concept
  - Uncertainty from isolating elastics from background
  - Dilution factor?
- Possible to look for elastic scattering at 11 GeV?

Back Up Slides

Polarization observables add info beyond what unpolarized scattering can access.

$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 - 4\,G_M \mathrm{Re}\left(\delta\tilde{G}_M + \frac{\epsilon\nu}{M^2}\tilde{F}_3\right) - \frac{4\epsilon}{\tau}G_E \mathrm{Re}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + \mathcal{O}(\alpha^4)$$

$$\frac{P_t}{P_l} = \sqrt{\frac{2\epsilon}{\tau(1+\epsilon)}}\frac{G_E}{G_M} \times [1 + \dots$$
$$+ \mathrm{Re}\left(\frac{\delta\tilde{G_M}}{G_M}\right) + \frac{1}{G_E}\mathrm{Re}\left(\delta\tilde{G_E} + \frac{\nu}{m^2}\tilde{F}_3\right) - \frac{2}{G_M}\mathrm{Re}\left(\delta\tilde{G_M} + \frac{\epsilon\nu}{(1+\epsilon)m^2}\tilde{F}_3\right)$$
$$+ \mathcal{O}(\alpha^4) + \dots]$$

Polarization observables add info beyond what unpolarized scattering can access.

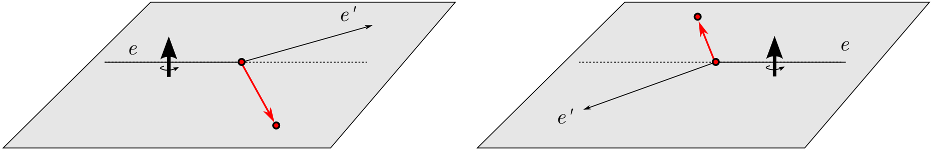
Target-normal:

$$A_n = \frac{\sqrt{2\epsilon(1+\epsilon)}}{\sqrt{\tau}\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)} \times$$
$$\left[-G_M \mathrm{Im}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + G_E \mathrm{Im}\left(\delta\tilde{G}_M + \frac{2\epsilon\nu}{M^2(1+\epsilon)}\tilde{F}_3\right)\right] + \mathcal{O}(\alpha^4)$$

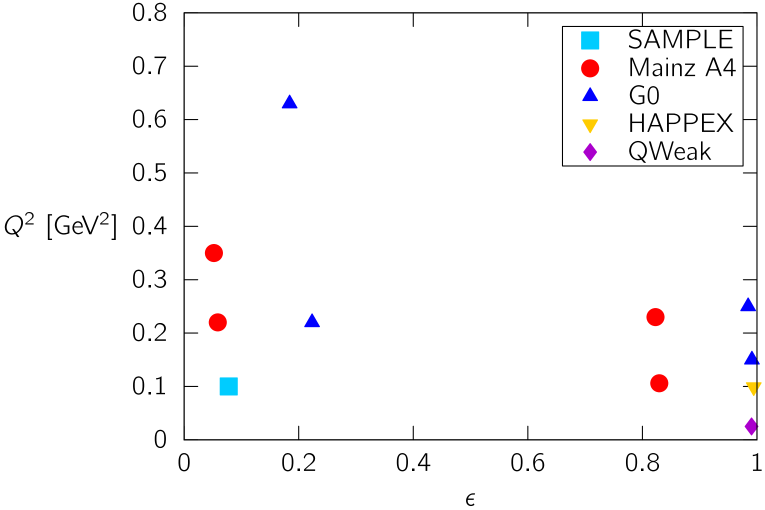
Beam Normal:

$$B_n = \frac{4mM\sqrt{2\epsilon(1-\epsilon)(1+\tau)}}{Q^2\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)} \times$$
$$\left[-\tau G_M \mathrm{Im}\left(\tilde{F}_3 + \frac{\nu}{M^2(1+\tau)}\tilde{F}_5\right) - G_E \mathrm{Im}\left(\tilde{F}_4 + \frac{\nu}{M^2(1+\tau)}\tilde{F}_5\right)\right] + \mathcal{O}(\alpha^4)$$

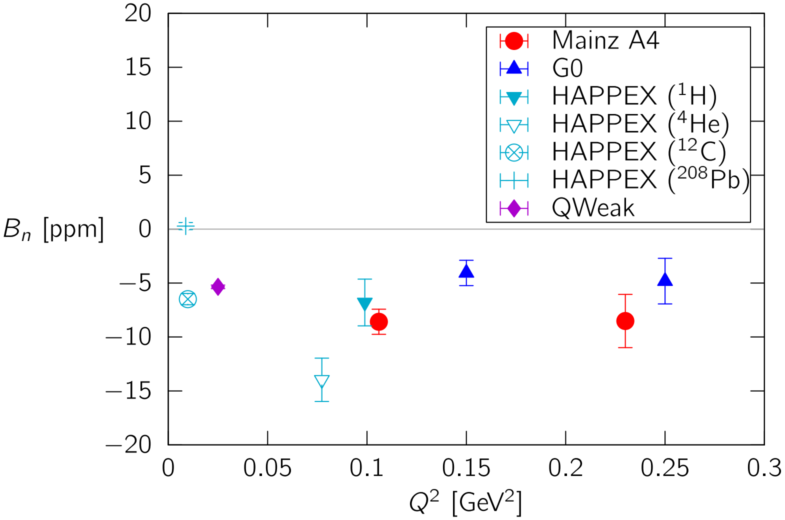
Transverse asymmetries do not violate parity.



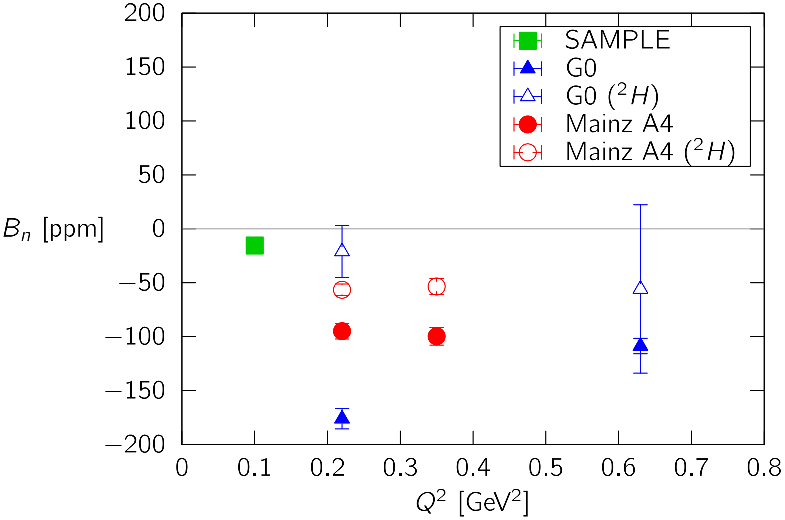
Beam-normal SSA is measured as a systematic in parity-violation experiments.



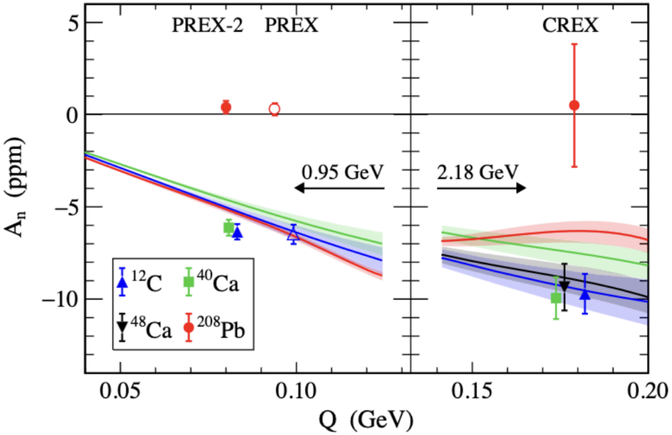
High-epsilon data



Low-epsilon data



Both PREX and CREX show that Pb is anomalous
compared to lighter nuclei.



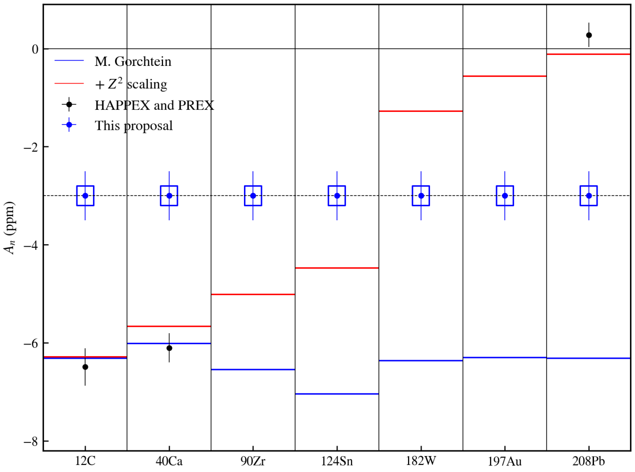
Jefferson Lab E12-24-007

Nuclear Dependence of Beam Normal Single Spin Asymmetry in Elastic Scattering from Nuclei

- Spokespersons: C. Gal, C. Ghosh, S. Park
- Approved for 9 days, 'A' rating
- Single arm measurement using Hall C SHMS using PV set-up

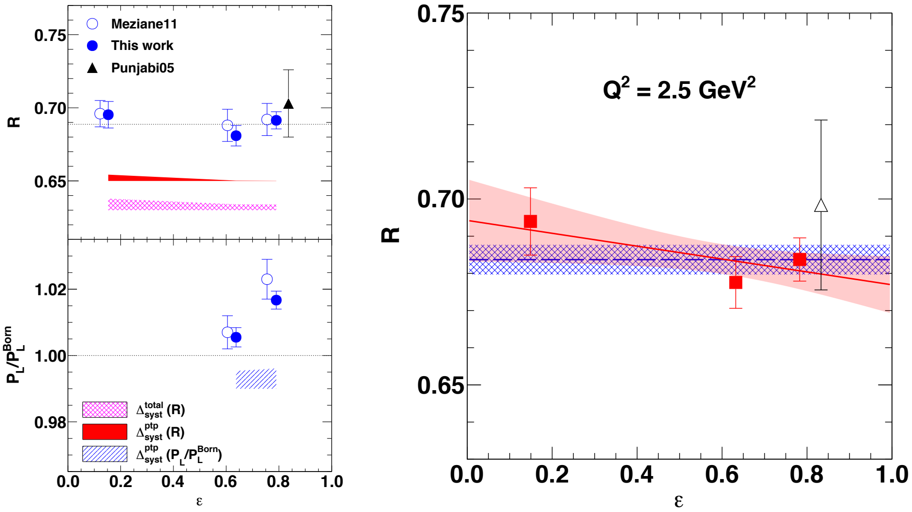
- Measurement of B_n over a wide range of nuclei:
  - ^{12}C, ^{40}Ca, ^{90}Zr, ^{124}Sn, ^{140}Ce, ^{142}Nd, ^{144}Sm, ^{182}W, ^{197}Au, ^{208}Pb, ^{232}Th

A scan accross nuclei can test for Z^2-dependence.



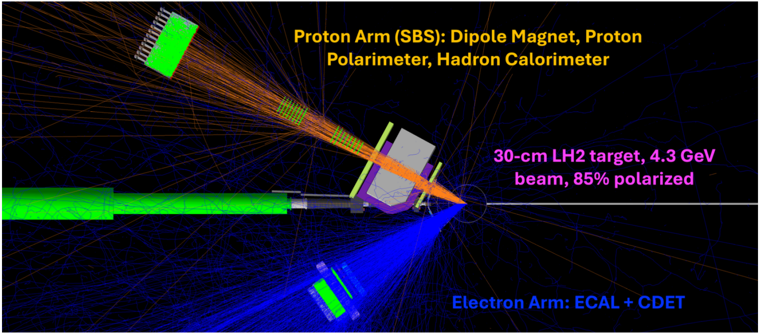
E12-24-007 Collaboration, shown at PAC52, 2024

GEp-2γ showed surprising ϵ-dependence of P_l.



A. J. R. Puckett et al., Phys. Rev. C 96, 055203 (2017)

We proposed a 2-day add-on to GEP-V (e^-) to improve uncertainty at $Q^2 = 3.7$ GeV^2



- E12-24-010, approved with 'A–' rating
- Goal to improve uncertainty to $\leq 1\%$
- Running in spring 2025