Measurement of the Beam-Normal Single Spin Asymmetry in Deep Inelastic Scattering using the SoLID Spectrometer

William Henry[1], **Michael Nycz[2]**, Ye Tian[3], Weizhi Xiong[4], Xiaochao Zheng[2]

[1]Jefferson Lab

[2]University of Virginia

[3]Syracuse University

[4]ShandongUniversity

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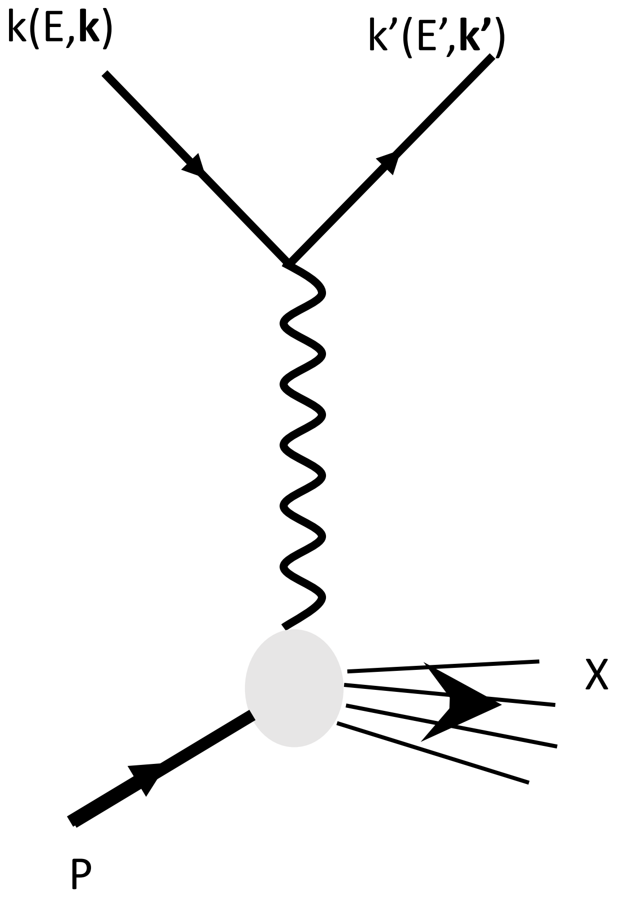
UNIVERSITY of VIRGINIA

Submitted to PAC 50

Introduction

- Beam-normal SSA can arise
  - e^- polarized ⊥ to scattering plane
  - Scatter off of unpolarized target
- Beam- (and target) normal SSA are zero at Born level due to time reversal invariance and parity conservation
  - N. Christ and T.D. Lee., Phys. Rev. 143 (1965)



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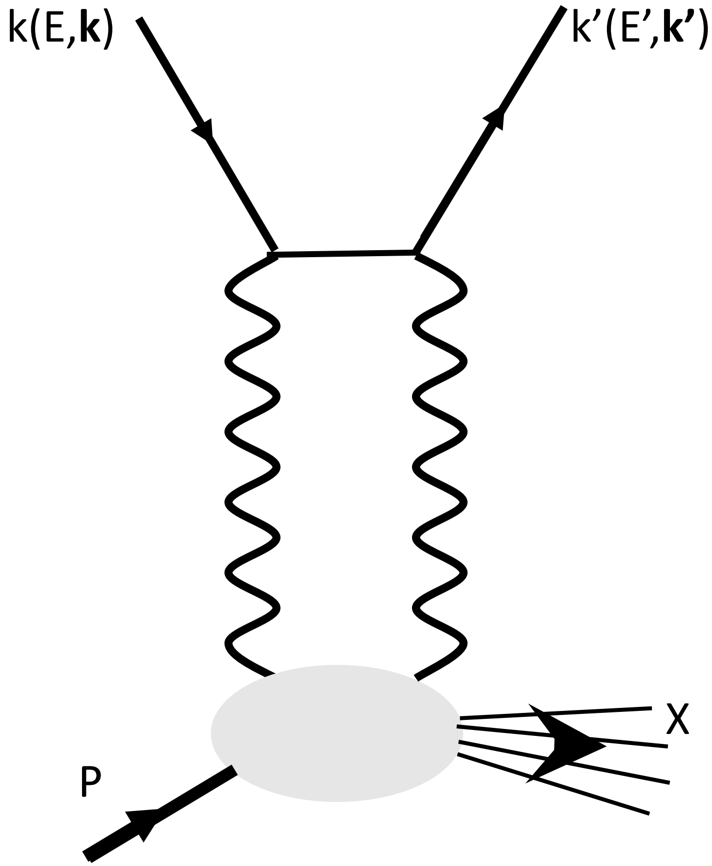

$$A_n \propto \frac{m_e \alpha_{\mathrm{EM}}}{Q} \epsilon_{\gamma\delta\lambda\mu} S^\gamma P^\delta k^\lambda k'^\mu$$

S= spin of the e^-

P= four-momentum of target

$k(k')$ = four-momentum of incident (scattered) e^-

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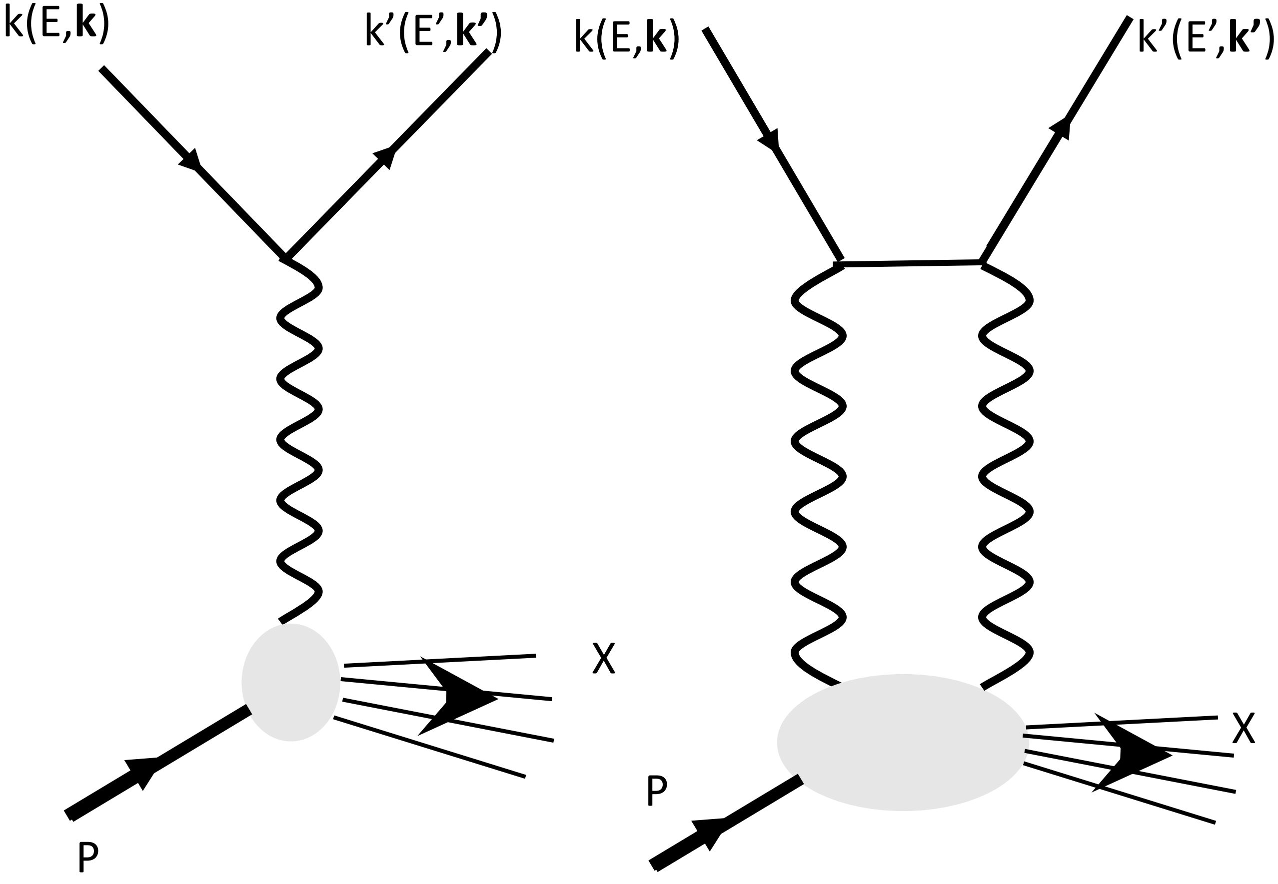
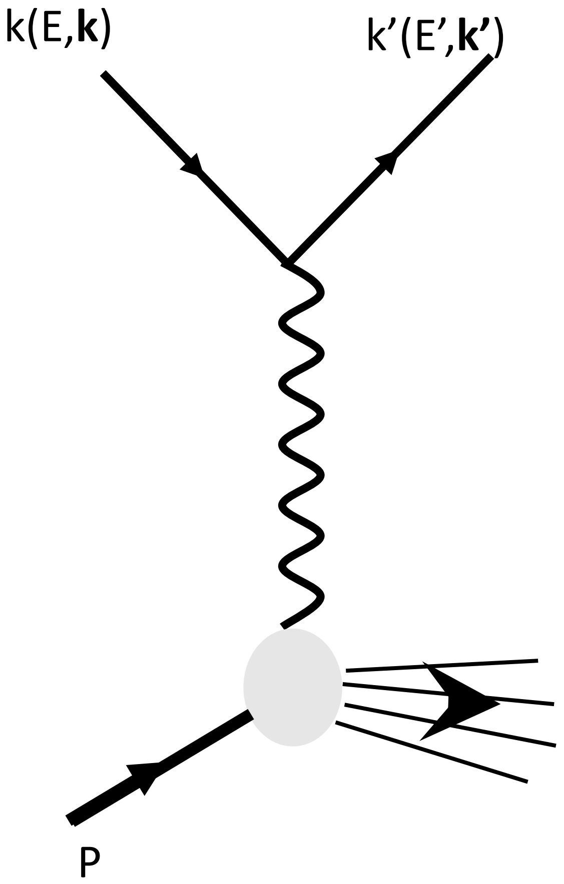
  - [N. Christ and T.D. Lee., Phys. Rev. 143 (1965)]
- A non-zero normal single-spin asymmetry would indicate multi-photon exchange
- Normal single-spin asymmetries provide access to the **imaginary** part of the TPE
  - Are due to the interference of single and two photon exchange processes

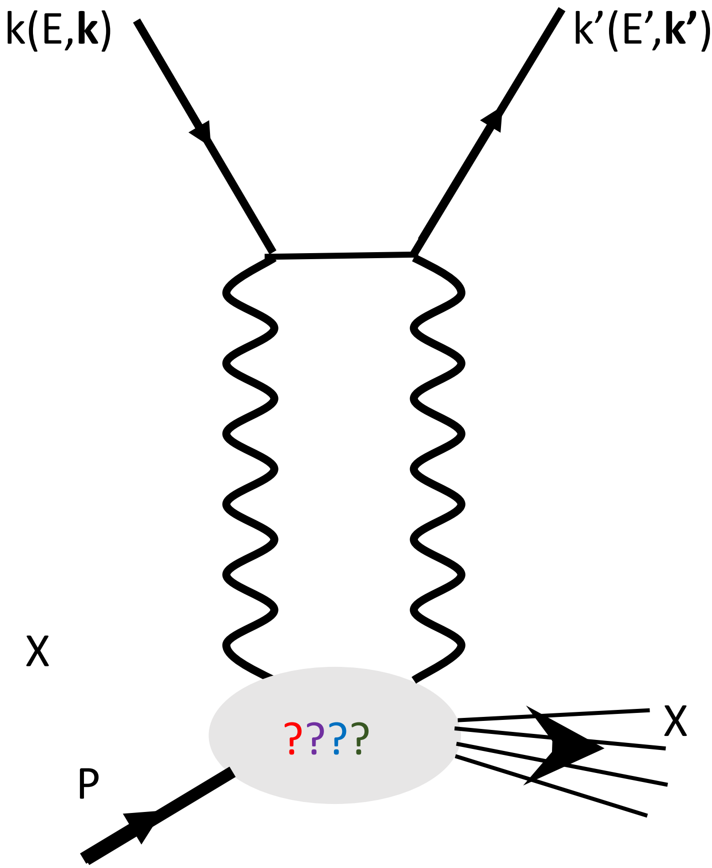


$$A_n \propto \boldsymbol{Im}\, T_{1\gamma} T_{2\gamma}^{*}$$

Introduction

- **Dominant** mechanism
  - two photons occurs between lepton and same quark?
  - two photons occurs between lepton and different quark





Theoretical Predictions

- $A_n = \frac{\alpha_{\mathrm{EM}} m}{2Q}$

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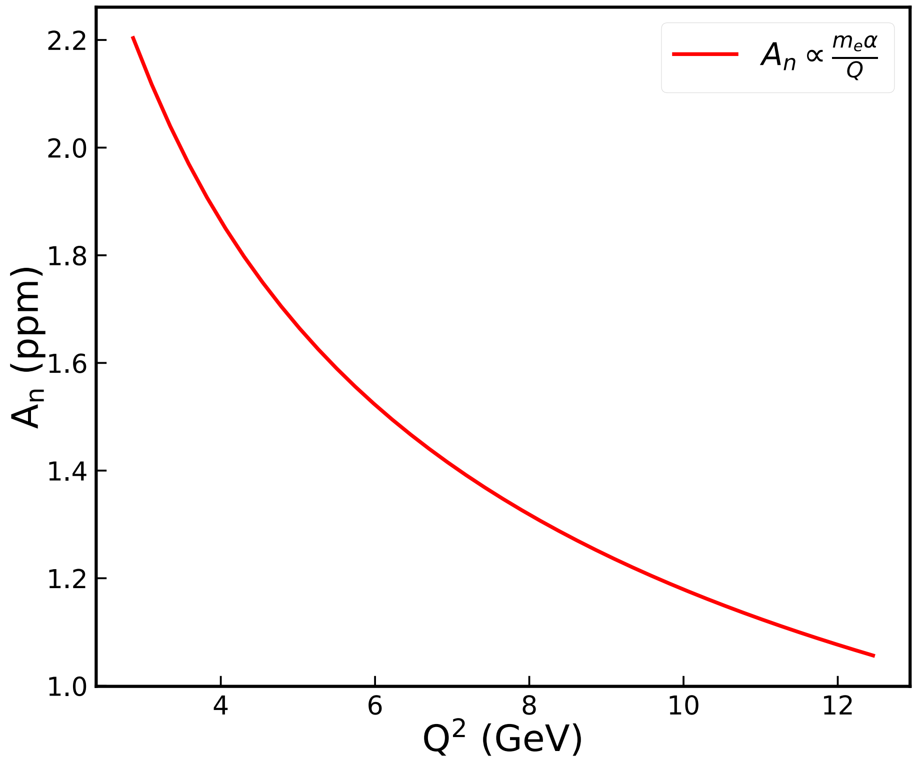

Theoretical Predictions

- $A_n = \frac{\alpha_{\text{EM}} m_l |\vec{S}_T| \sin(\varphi_s)}{2Q} \frac{y^2\sqrt{1-y}}{1-y+\frac{1}{2}y^2} \frac{\sum_q e_q^3 q(x)}{\sum_q e_q^2 q(x)}$
  - A. Metz et al., Phys. Lett. B 643 (2006)
  - Exchange of two photons occurs between lepton and the same quark
  - A_n: 10^{-6}-10^{-7}

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- Target-Normal Predictions:
  1. Exchange of two photons occurs between lepton and the same quark
     - A. Afanasev et al., Phys. Rev. D77 (2008) : TNSSA ~ 10^{-4}
  2. Exchange of two photons occurs between lepton and different quarks
     - A. Metz et al. Phys. Rev. D86 (2012):TNSSA ~ 10^{-2}
- JLab 6 GeV target- normal SSA
  - $(-1.09 \pm 0.38) \times 10^{-2}$

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- JLab 6 GeV target- normal SSA
  - $(-1.09 \pm 0.38) \times 10^{-2}$
- But…… Dominant process for target-normal SSA is still not well understood
  - **Assumption** is that the exchange of two photons occurs between the lepton and different quarks is **dominant** but not conclusive. **Need more experimental evidence**
- **Assumption** is that the exchange of two photons occurs between the lepton and a single quark for beam-normal SSA. **Need any experimental evidence to support**

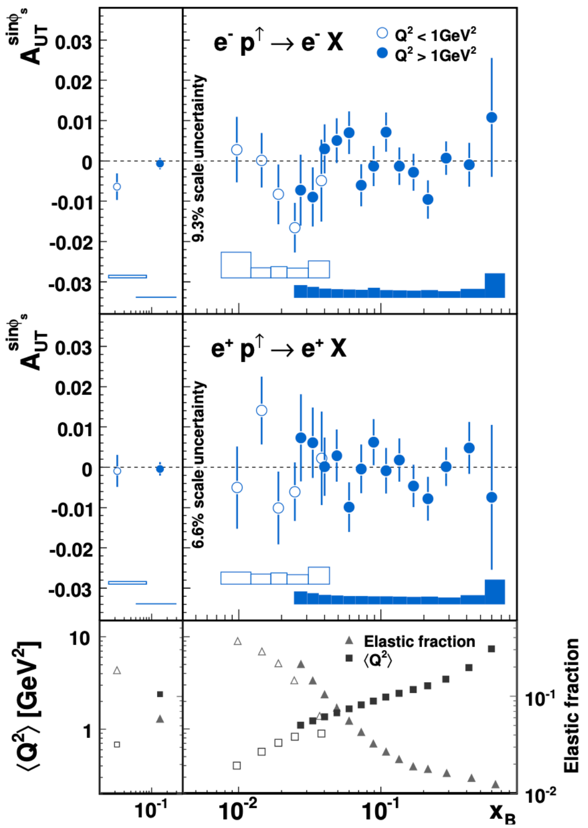
Motivation

- (Almost) non-existent experimental evidence for the beam-normal SSA
- M. Schlegel Phys. Rev.D 87
  - "In principle, single-spin observables in inclusive DIS with either the **lepton** or nucleon being transversely polarized **are equally fundamental**”
- DIS TPE data are limited
  - “Measurement of A_n to even 10% relative uncertainty, **would be a major step forward**. A measurement to **5 ppm** is good”
- A high precision measurement of the beam-normal SSA would be impactful in
  - Understanding the dominant mechanism(s) in BNSSA and TNSSA
  - Constraining TPE models

Normal Single Spin Asymmetries: DIS

- Investigations in the TPE date back to measurements in the 1960's
- Measurements:
  - Differences in the ratio of cross sections: $\frac{e^+}{e^-}$ or $\frac{\mu^+}{\mu^-}$
  - **Beam**- or target- normal single spin asymmetries
- Limited number of TPE measurements
  - BNSSA : (nearly) non-existent and **no planned measurements**
  - TNSSA : Measurements on proton and neutron (via ^{3}He)
    - Ay (E12-11-108A/E12-10-006 : Approved SoLID Run Group Experiment

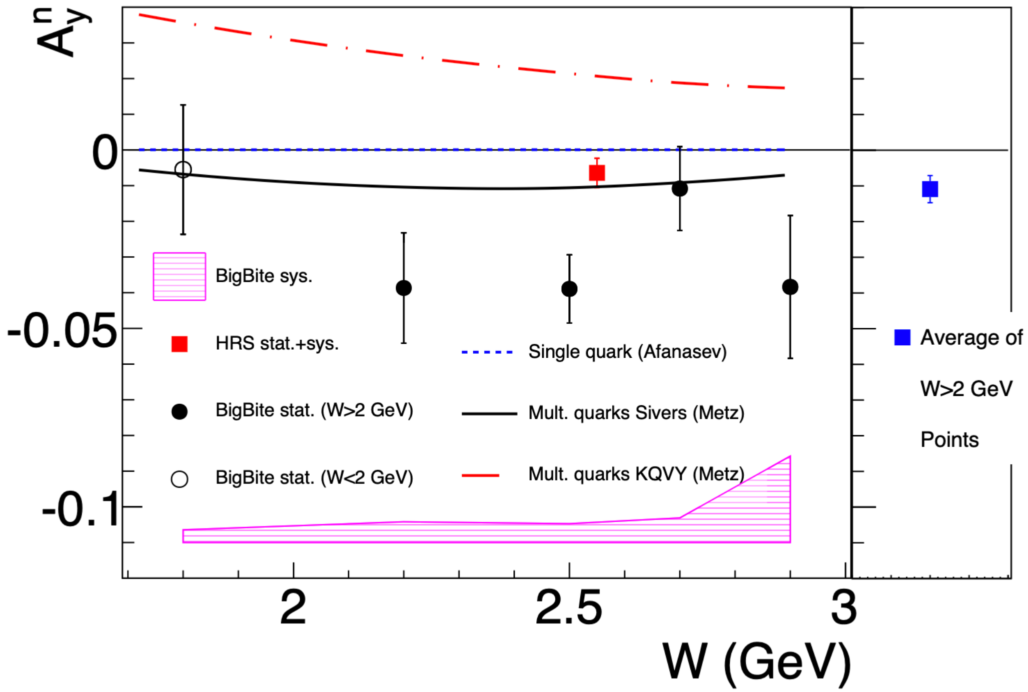
Target-Normal Single Spin Asymmetry



Neutron Asymmetries extracted:

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

$P_p (P_n)$ = Effective proton (neutron) polarization



A_y of the proton consistent with zero

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

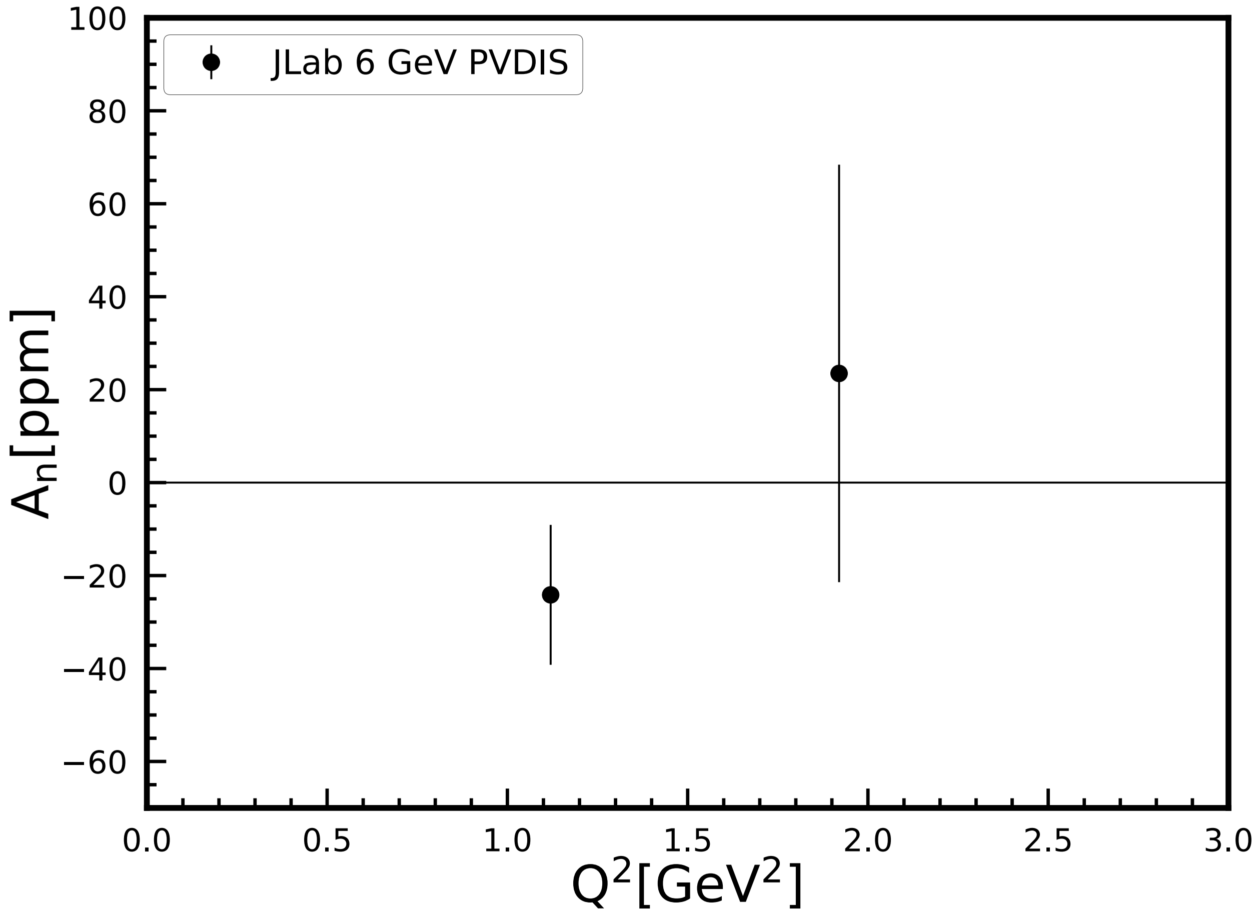
$A_y = (-1.09 \pm 0.38) \times 10^{-2}$

Non-zero: 2.89σ

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

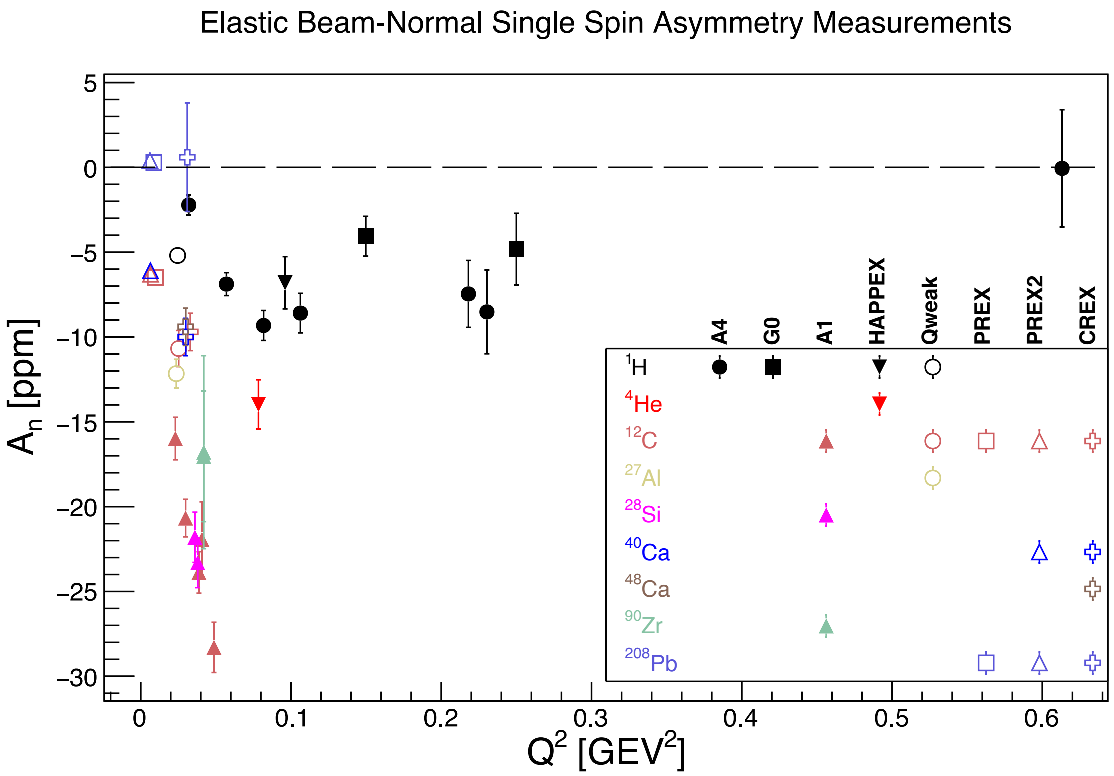
Beam-Normal Single Spin Asymmetry

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



Elastic Beam-Normal Single Spin Asymmetry

F. E. Maas et al., Phys. Rev. Lett. 94 (2005)
D. S. Armstrong et al., Phys. Rev. Lett. 99 (2007)
D. Androić et al., Phys. Rev. Lett. 107 (2011)
S. Abrahamyan et al., Phys. Rev. Lett. 109 (2012)
A. Esser et al., Phys. Rev. Lett. 121 (2018)
B. Gou et al., Phys. Rev. Lett. 124 (2020)
D. Androić et al., Phys. Rev. C 104 (2021)



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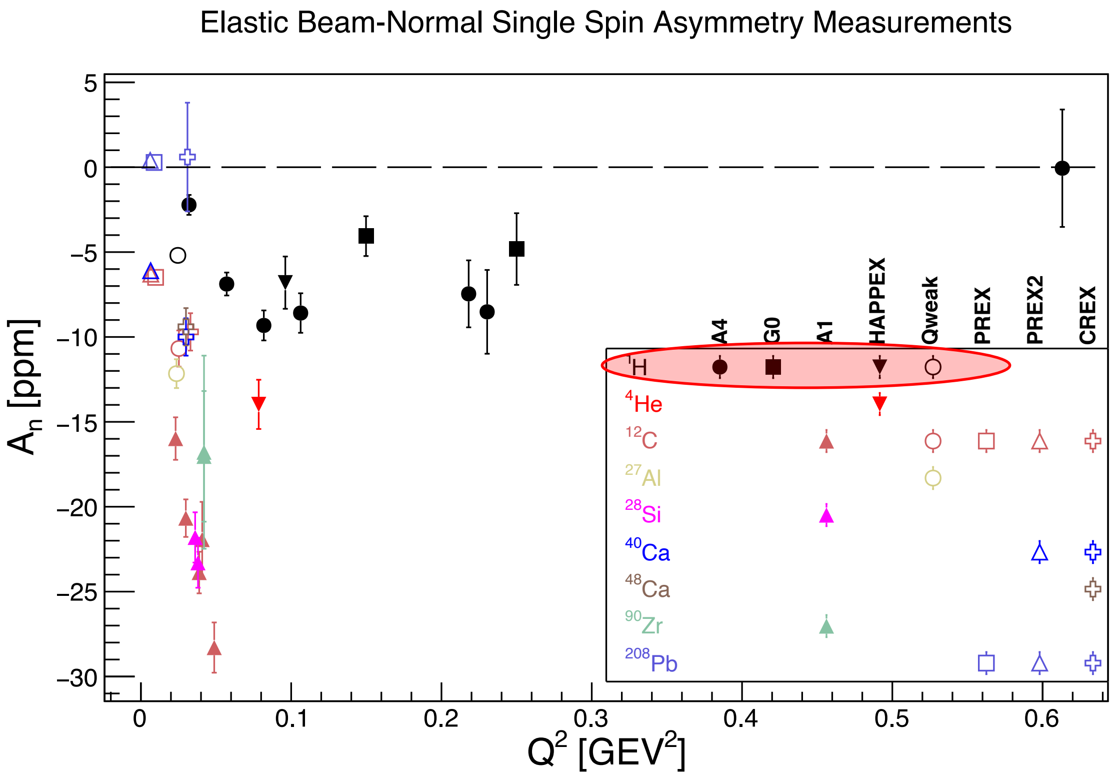

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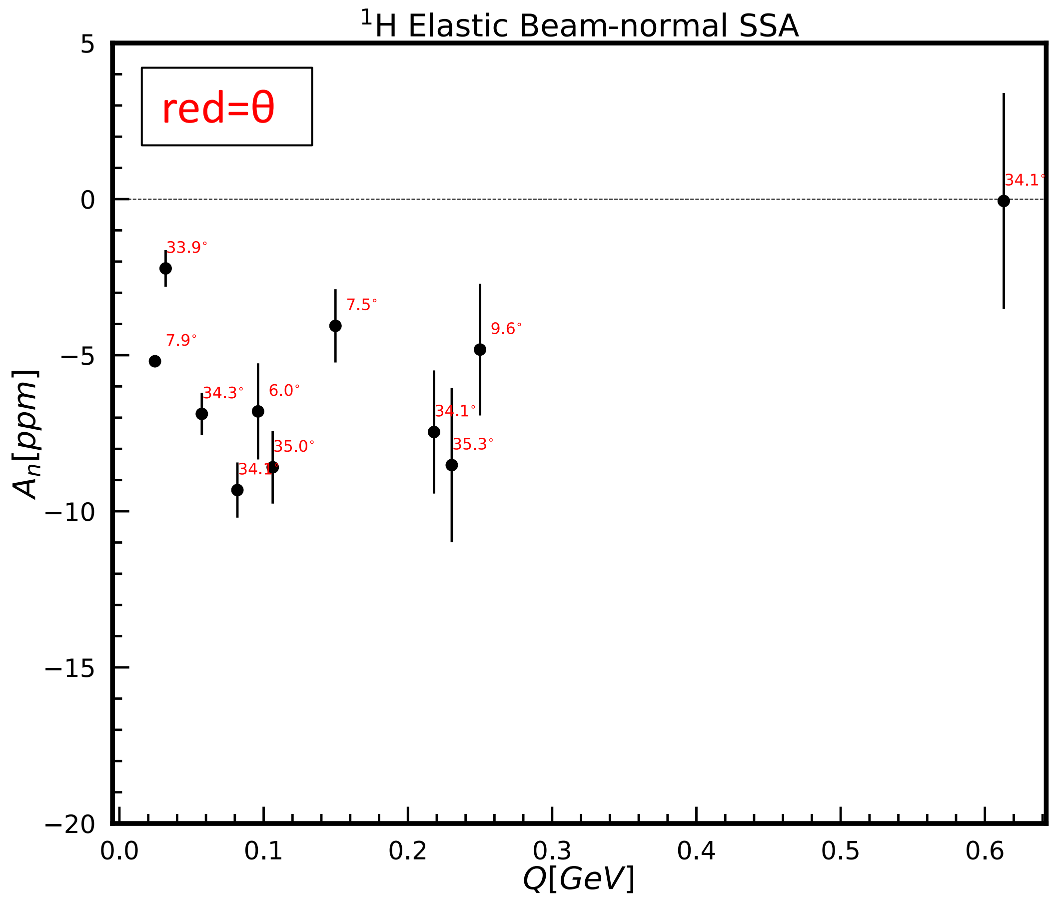
Elastic Beam-Normal Single Spin Asymmetry: ^{1}H



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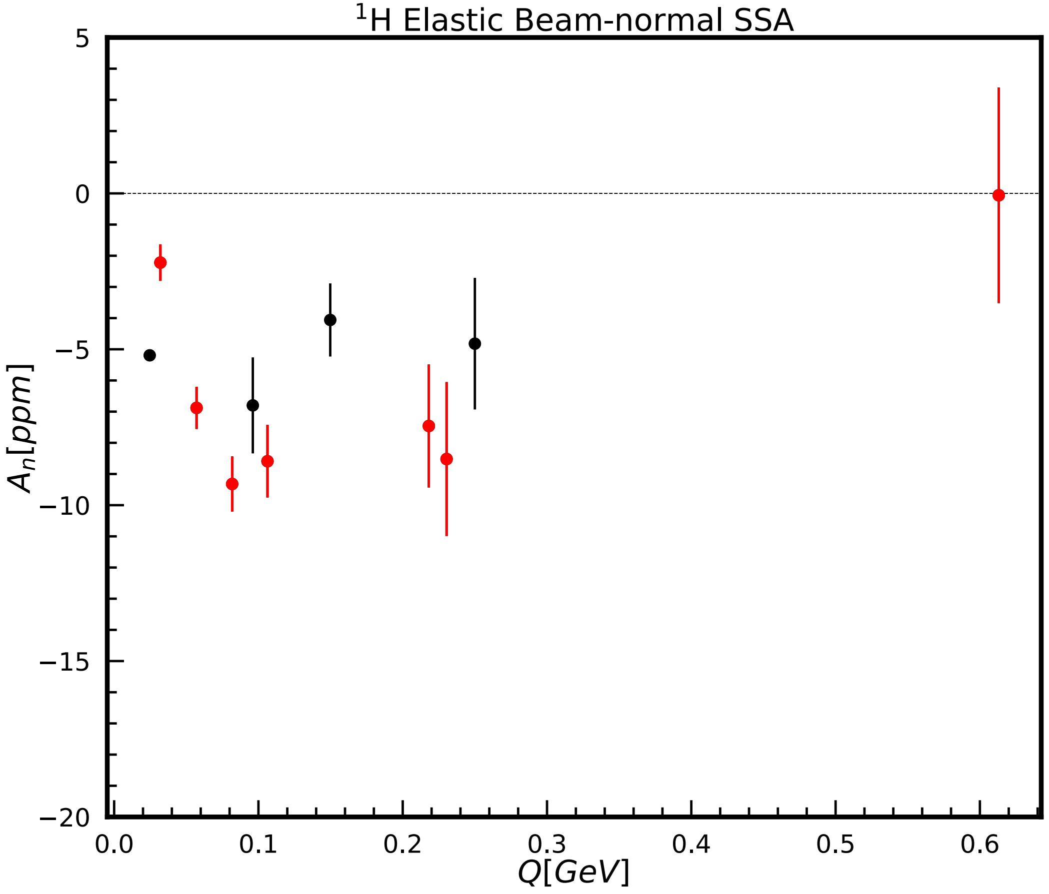
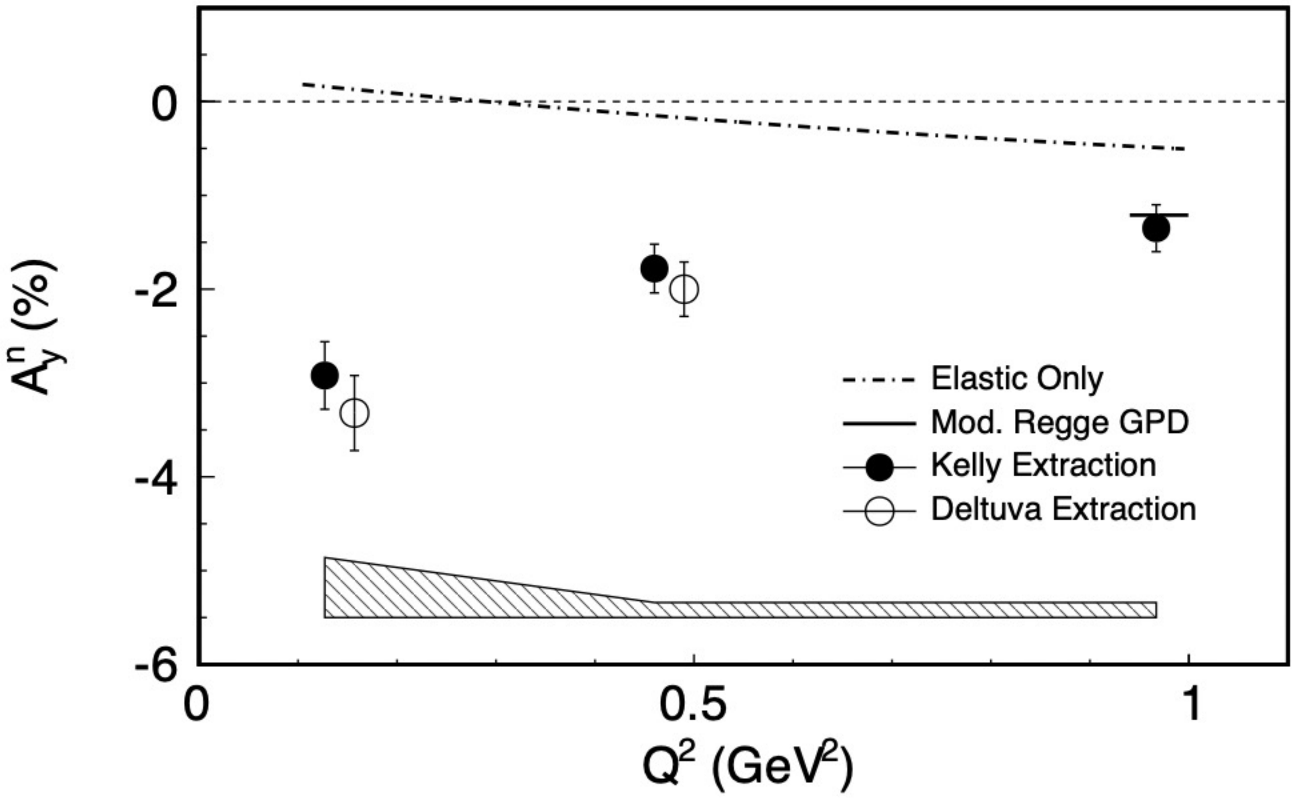


Target-Normal Single Spin Asymmetry

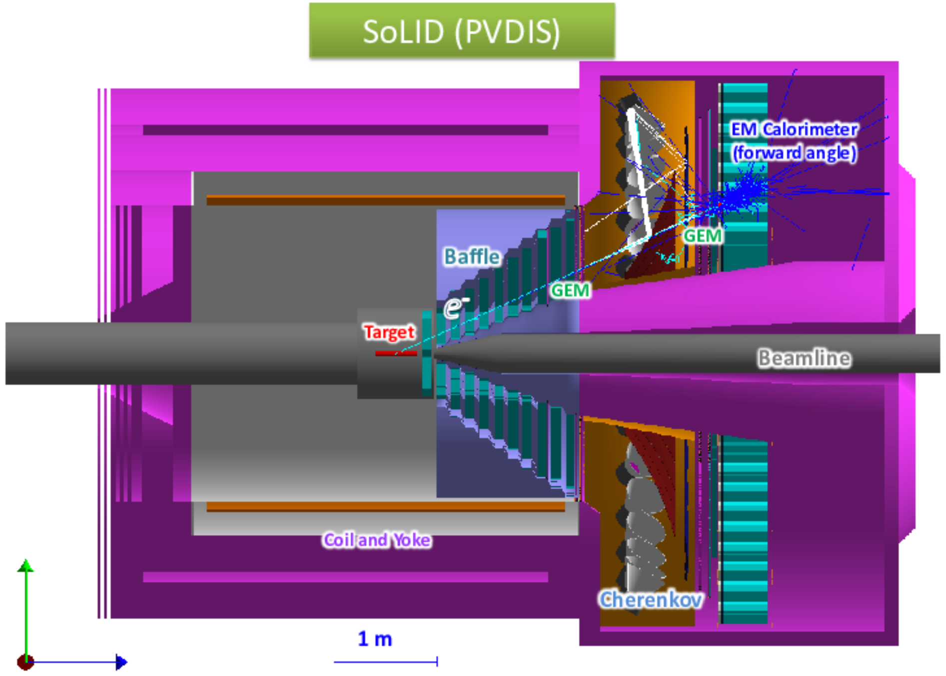
Highest Q^2 point is consistent with the relevant predictions
[Y.W. Zhang et al., Phys. Rev. Lett. 115 (2015)]



Experimental Overview

Experiment Overview: SoLID

- **First high precision Beam-normal SSA measurement in DIS**
  - **Precision at the few ppm level**
- SoLID configuration: PVDIS
  - Scattering angle: 22°< θ < 35 °
  - Large azimuthal coverage
- Transversely polarized e^- beam
- Beam Current
  - 70 μA
- PVDIS hydrogen target
- Beam-normal SSA measured from the ϕ dependence
  - $\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} = A_n \sin(\varphi)$



- **High luminosity and large azimuthal coverage of SoLID key to BNSSA measurement**
- **SoLID provides a unique opportunity to measure the DIS BNSSA**

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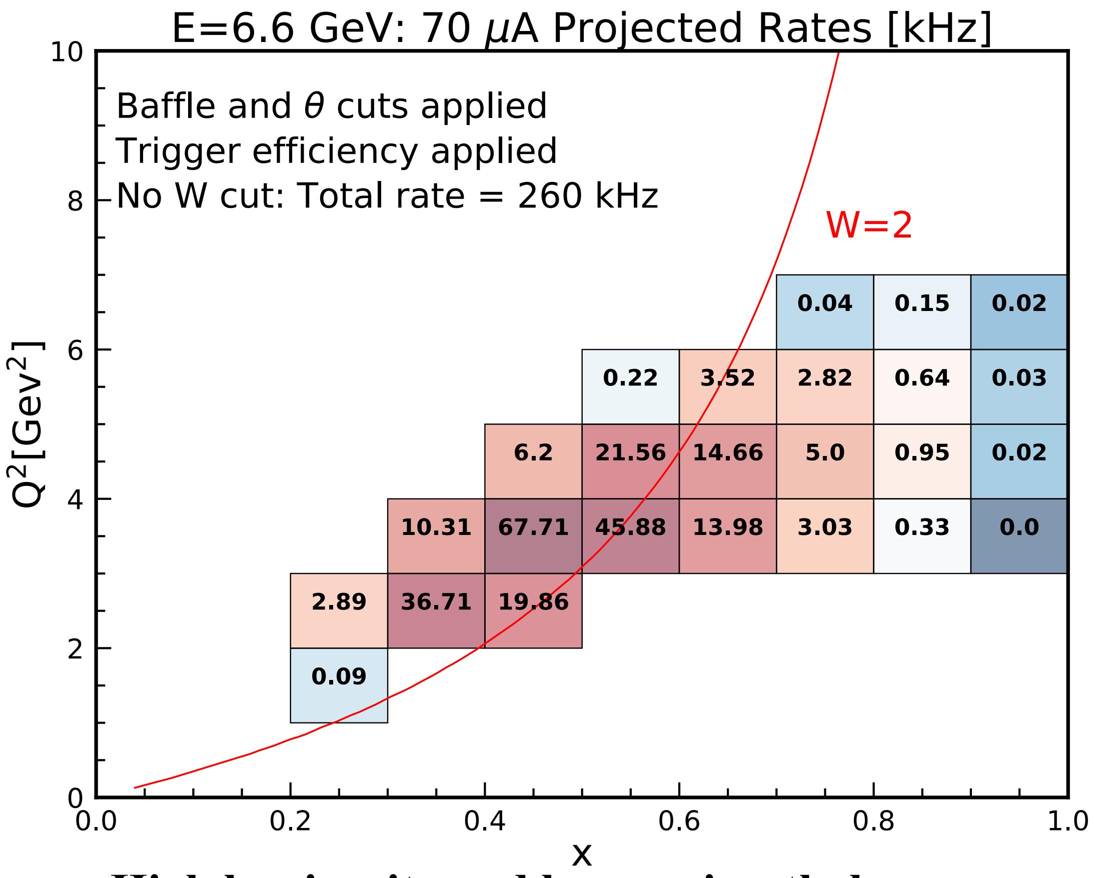

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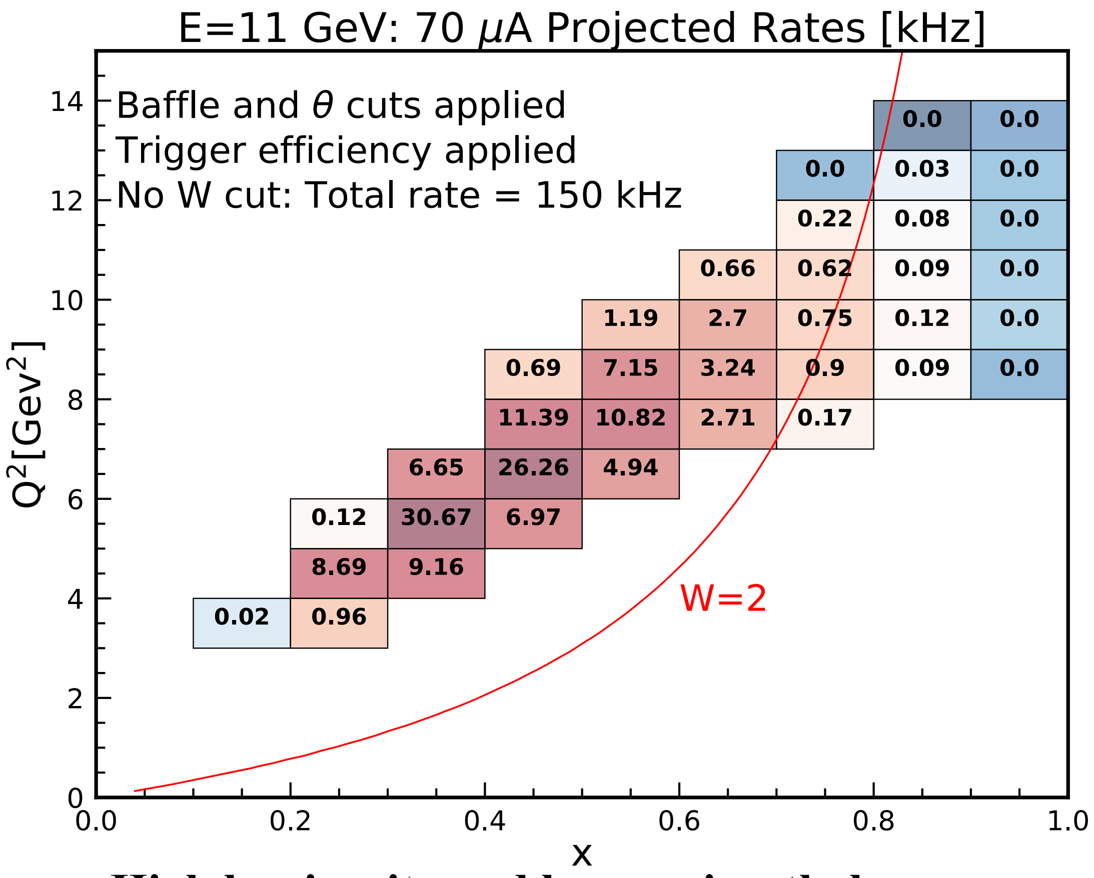

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Systematic Uncertainties

Systematic	Uncertainty
Target endcaps	5%
Polarimetry	3%
Radiative Corrections	1-2%
Particle background	1%
Q^2 determination	0.2%
Target polarization	Under 0.1 ppm
Total Systematic	**(6.0 – 6.2)%**

Uncertainties dominated by statistics

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Target Endcaps: Aluminum

Upstream: 120μm

Downstream: 150μm

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	E_{Beam} = 6.6 GeV	
Day	Activity	Time (Hours)
1	Spin Dance	16
1	90° Wien Rotation	2
8	90° Wien Rotation	2
8	Moller Measurement	12
8	90° Wien Rotation	2
15	90° Wien Rotation	2
15	Moller Measurement	12
15	90° Wien Rotation	2
22	Spin Rotator Flip	8
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29	Moller Measurement	12
29	90° Wien Rotation	2
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34	Moller Measurement	12
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Total (6.6 GeV)		108 hours (4.5 days)
	E_{Beam} = 11.0 GeV	
Day	Activity	Time (Hours)
1	Spin Dance	16
1	90° Wien Rotation	2
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Grand Total (6.6 GeV + 11.0 GeV)		4.3 PAC Days

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Radiative Correction Factor

6.6 GeV

$1.7\% < RC < 2.5\%$

11 GeV

$1.6\% < RC < 10.0\%$

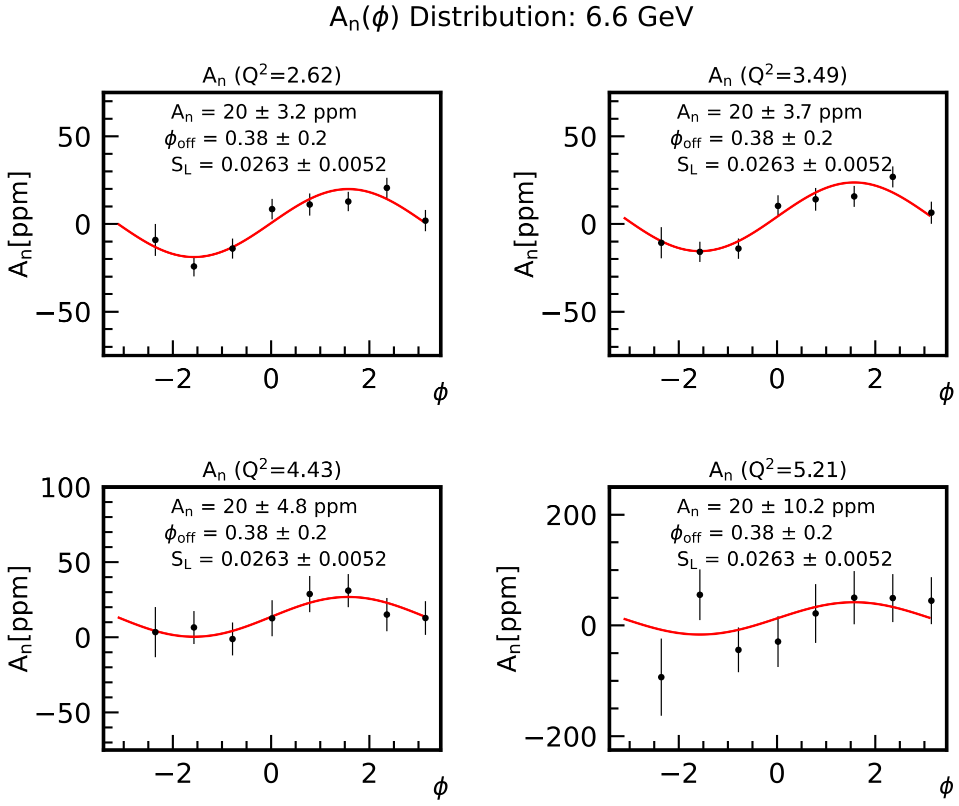
Projections

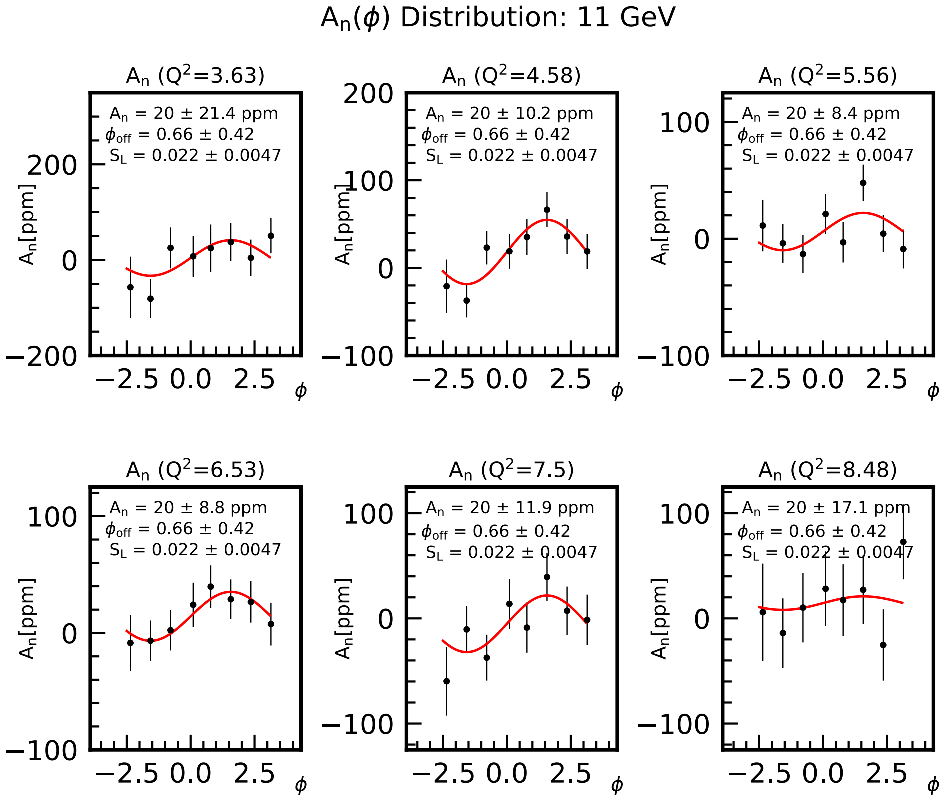
- Estimated the projected impact
- Utilized SoLID simulation for PVDIS configuration
  - 40-cm LH_2 Production
  - W >2, 22°< θ < 35 °, P_b=85%
- Generate pseudo-data:
  - $A^{i^{th}\text{bin}}_{raw,pseudo-data} = 20_{\text{ppm}} \sin(\phi) + r_i \Delta^i_{\text{stat}} + r_b\, A^i_{p,\text{PVDIS}}$
- Perform multi-parameter fit:

> - r_i and r_b: random number drawn from Normal distribution
> - r_b common across all bins at same beam energy

$$
\begin{aligned}
f_1 &= C_1 \sin(\varphi + \varphi_{\text{offset}}) + S_L A_{\text{PVDIS}} \\
f_2 &= C_2 \sin(\varphi + \varphi_{\text{offset}}) + S_L A_{\text{PVDIS}} \\
&\;\;\vdots \\
f_N &= C_N \sin(\varphi + \varphi_{\text{offset}}) + S_L A_{\text{PVDIS}}
\end{aligned}
$$

Projected Results: $C_n \sin(\varphi + \varphi_{\text{offset}}) + S_L A_{\text{PVDIS}}$





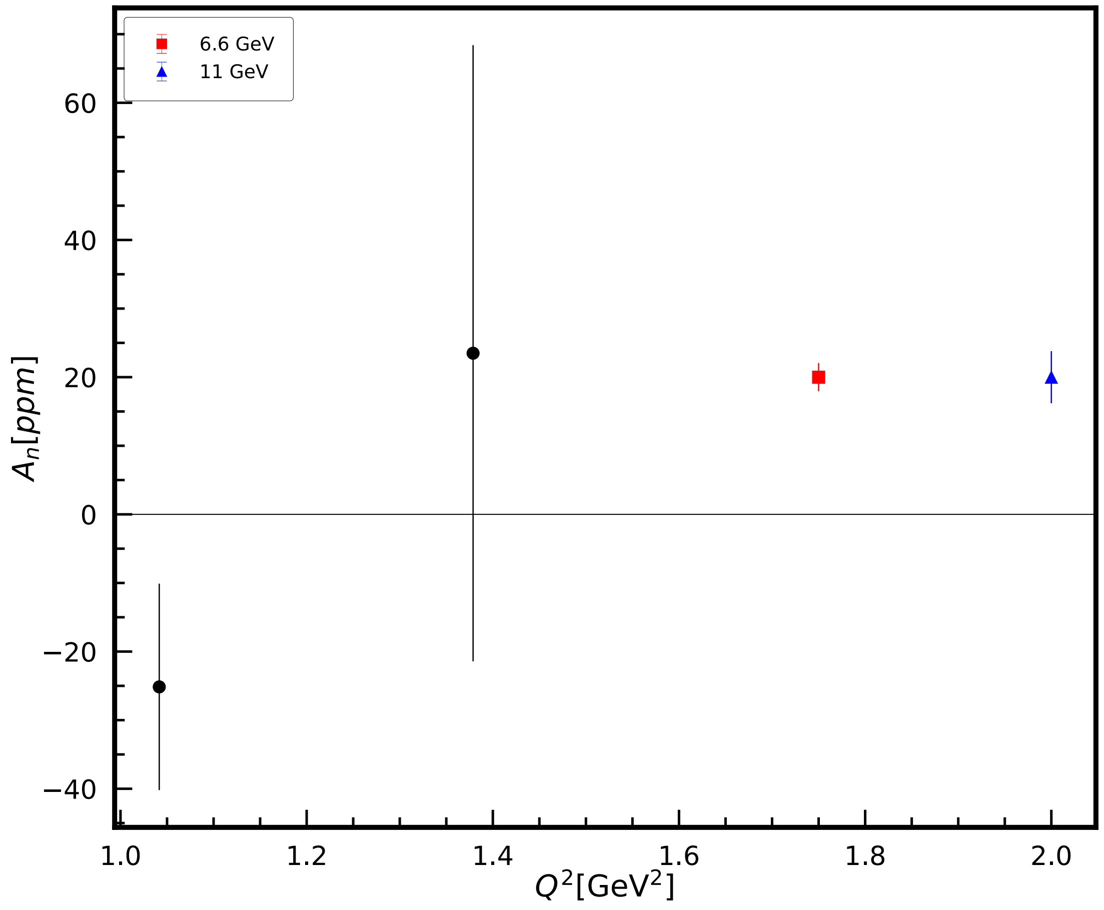
Projections: Result and Uncertainty

Combining Q^2 bins in each energy setting

$A_n = A_{measured} \pm 2.06$ ppm : 6.6 GeV

$A_n = A_{measured} \pm 3.80$ ppm : 11 GeV

Opportunity to detect non-zero BNSSA



Projected results not at expected Q^2 values

Projections: Result and Uncertainty

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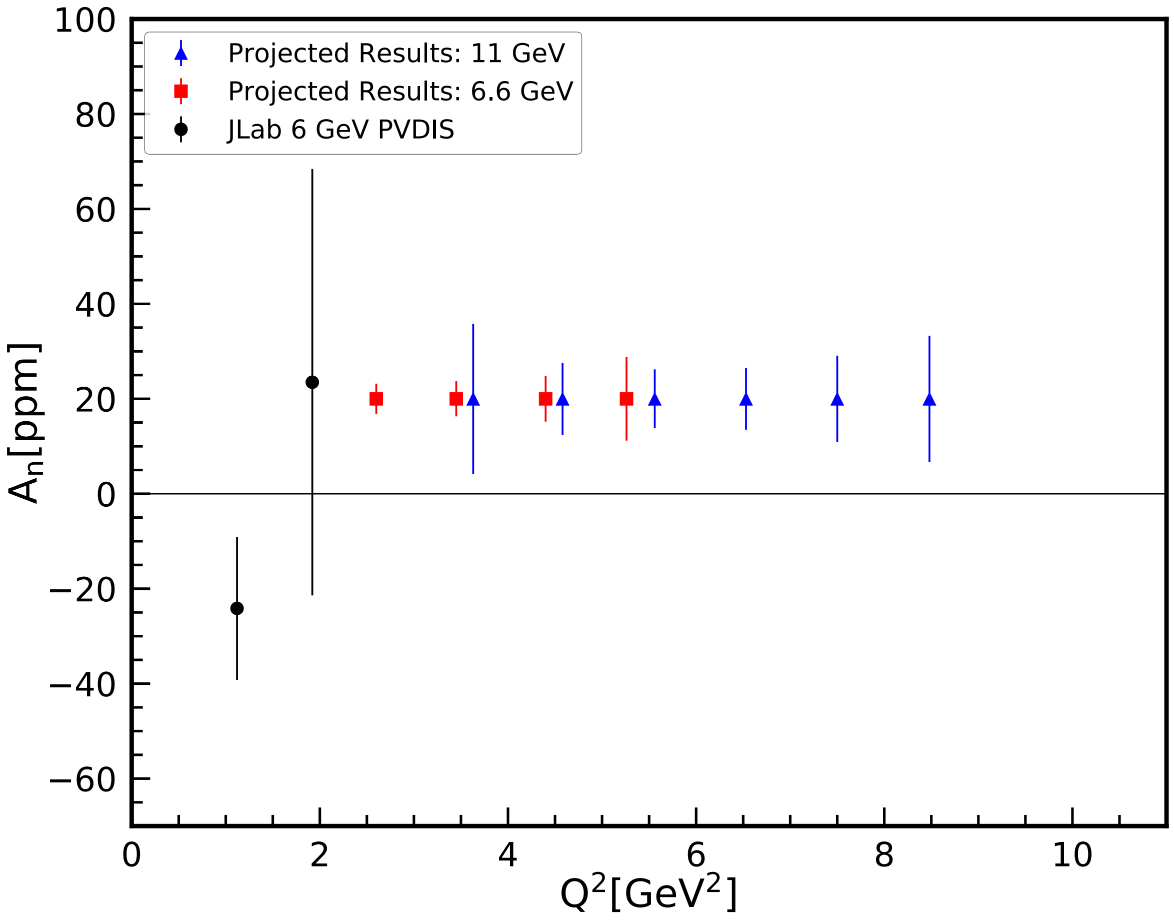
$A_n = A_{measured} \pm 2.06$ ppm : 6.6 GeV

$A_n = A_{measured} \pm 3.80$ ppm : 11 GeV

Opportunity to detect non-zero BNSSA

TAC Theory: "…it will be interesting to observe the Q^2 dependence of the asymmetry empirically, to test whether the scattering takes place on a single quark or involved more complicated nonperturbative multi-parton interactions."

The opportunity to observe a Q^2 dependence with sufficient precision is primarily due to the design SoLID



Beam Time Request

Purpose	**Time (Days)**	**Energy (GeV)**	**Beam Current (μA)**
Commissioning	2	varies	As needed
Polarimetry	4	varies	As needed
Pass Change	0.67	N/A	N/A
Reverse SoLID Polarity	0.67	N/A	N/A
Reverse polarity run	0.33	6.6	70
Reverse polarity run	0.33	11	70
40-cm LH_2 Production	17	6.6	70
40-cm LH_2 Production	11	11	70

A total of 38 PAC days

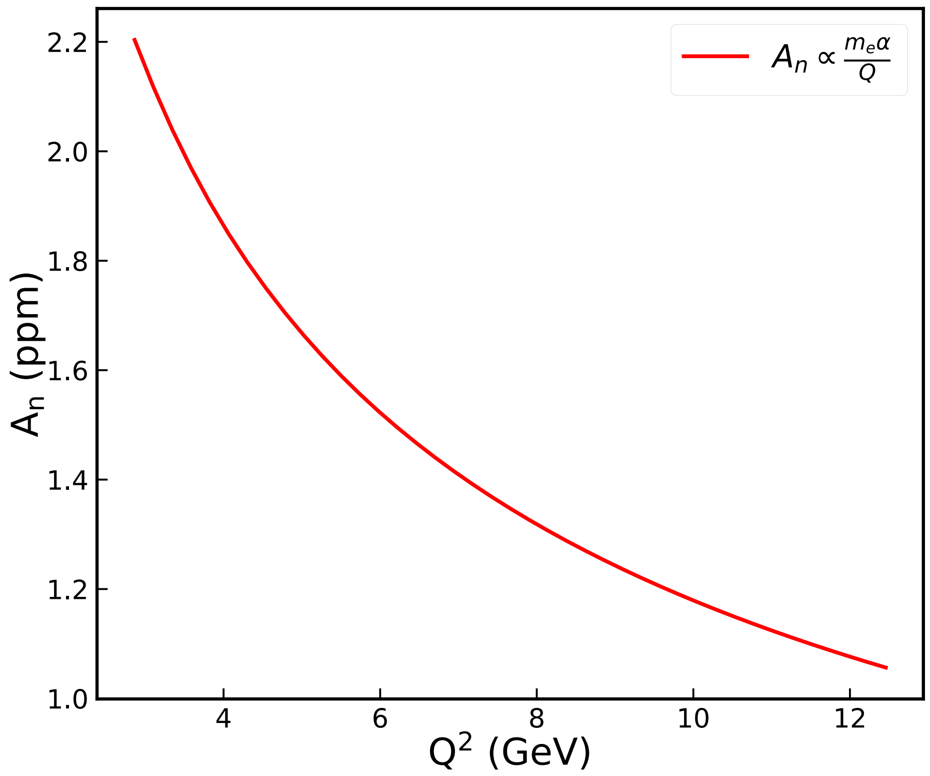
Summary

- The proposed experiment would be the first high-precision measurement of the beam-normal single spin asymmetry in deep inelastic scattering
- The beam-normal single spin asymmetry provides an essential tool for studying the two-photon exchange effect
- Important for theoretical models
  - Further insight into mechanism (single or two quark)
  - Complementary to the already approved target-normal single spin asymmetry
- **Any suggestions or comments are greatly appreciated!**
- **JLab 12 GeV and SoLID make this a realistic measurement**

Thank You

TAC : Enhancements of A_n?

- A. Metz et al., Phys. Lett. B 643 (2006)
- Exchange of two photons occurs between lepton and same quark
- $A_n \sim (10^{-6}\text{-}10^{-7})$
- M. Schlegel and A.Metz (2009)
  - "One might also speculate about enhanced results from effects beyond the naive parton model. In Refs. [8, 9, 10, 11] (double) logarithms of the type $\log(Q^2/m^2)$ were advocated in connection with the transverse beam SSA in elastic lepton-nucleon scattering. Such logarithmic terms might also increase the beam SSA in DIS considered here. However, further work is required in order to decide whether and how precisely such effects show up for the DIS case"
- TNSSA
  - "No very realistic numerical estimate of all the contributions. Therefore, it is difficult to say which of the two contributions (coupling to different quarks vs coupling to the same quark) dominates."



TAC: A_n input

“Reason for not using theory prediction in projection analysis”

- Theory prediction provides a baseline from which to view the experiment
    - Remaining question(s) regarding expected size of the asymmetry
- Input value used does not impact the estimate uncertainty (ppm)

TAC Exp: Radiative Corrections

”Assessment of radiative corrections”

- An estimate of the expected radiative correction for both the 6.6 GeV and 11 GeV energy settings was performed
- Simulated data was binned in x
  - Using leptonic kinematic quantities and the asymmetry was calculated: $A_{measured}$
  - Using hadronic kinematic quantities and the asymmetry was calculated: A_{true}
- The estimated RC was then given by
  - $RC = |A_{measured} - A_{true}|$
- 6.6 GeV
  - 1.7% > RC < 2.5%
- 11 GeV
  - 1.6% > RC < 10.0%

TAC Exp: Polarimetry

”Polarimetry uncertainty and plan”

- 1% polarimetry was based on the best expect performance possible for beam polarimetry. As the reviewer stated, 2-3% polarimetry uncertainty would still be reasonable and not adversely effect the impact of the experiment given other systematic uncertainties

TAC Exp: Polarimetry

”Polarimetry uncertainty and plan”

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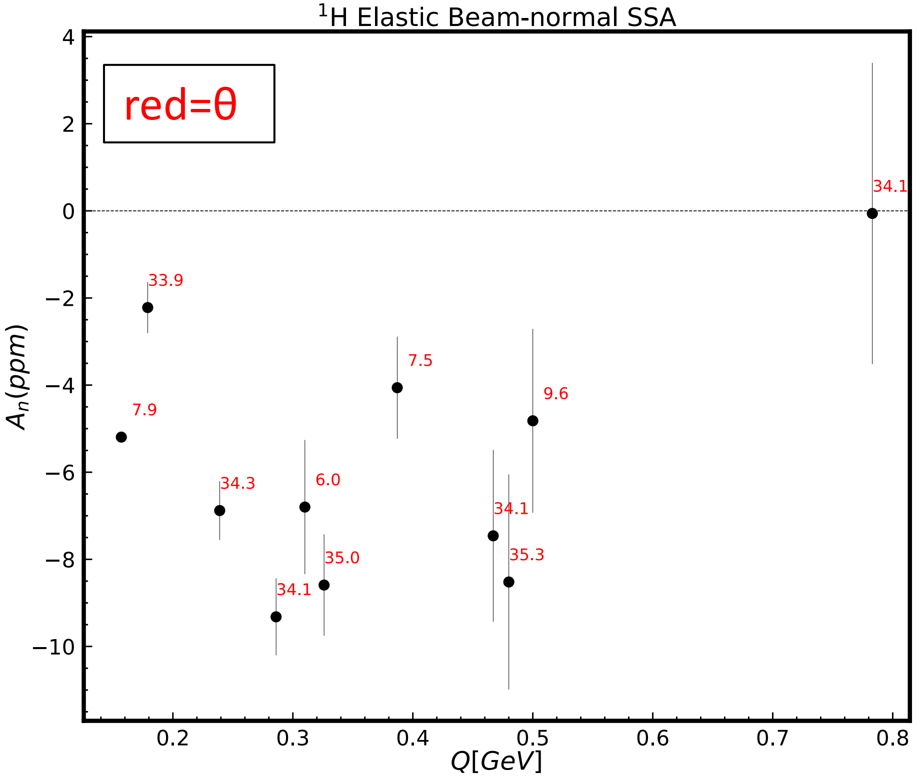
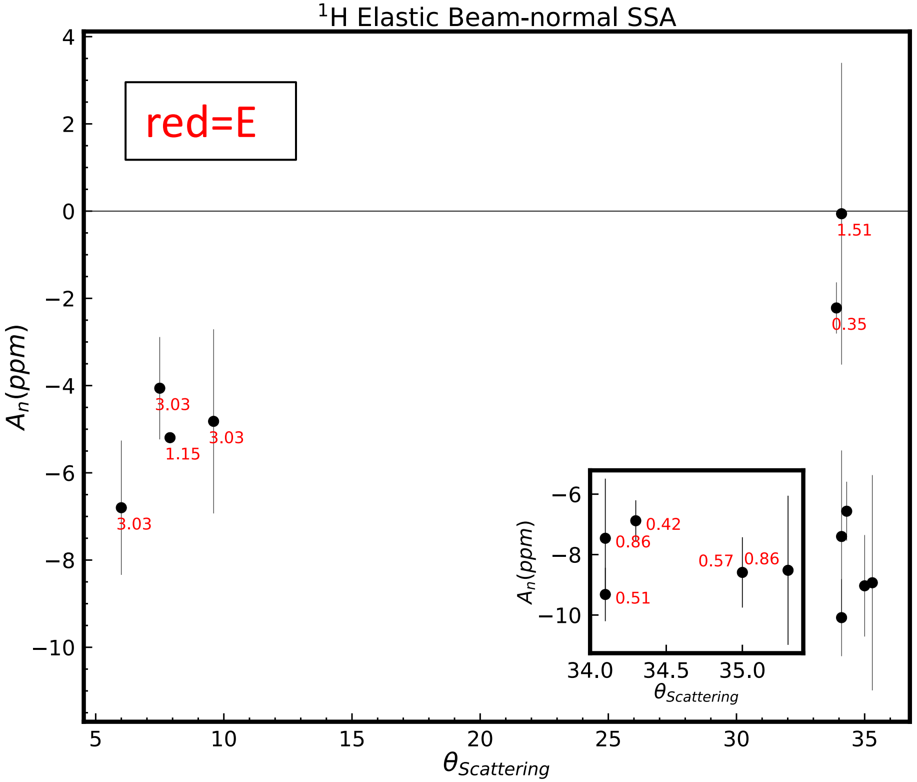


^{1}H Elastic Beam-normal SSA
red=θ
$A_n(ppm)$
$Q[GeV]$
33.9
7.9
34.3
34.1
6.0
35.0
7.5
34.1
35.3
9.6
34.1



^{1}H Elastic Beam-normal SSA
red=E
$A_n(ppm)$
$\theta_{Scattering}$
3.03
3.03
1.15
3.03
1.51
0.35
0.42
0.86
0.51
0.57
0.86

Large number of elastic results

DIS : large uncertaintes

No elastic measurement