The b_1 (E12-13-011) Polarized Target Experiment

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October 13, 2025

University of
New Hampshire

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  - Study time dependence of P_z, P_{zz} to help prepare for run plan for b_1 and A_{zz} experiments.

- **CLAS Approved Analysis of RGC:**
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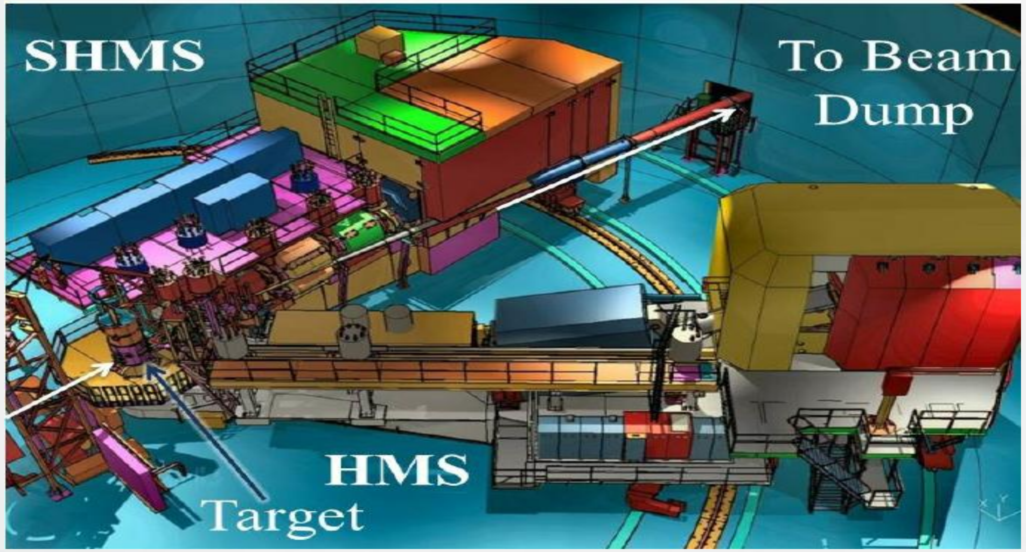
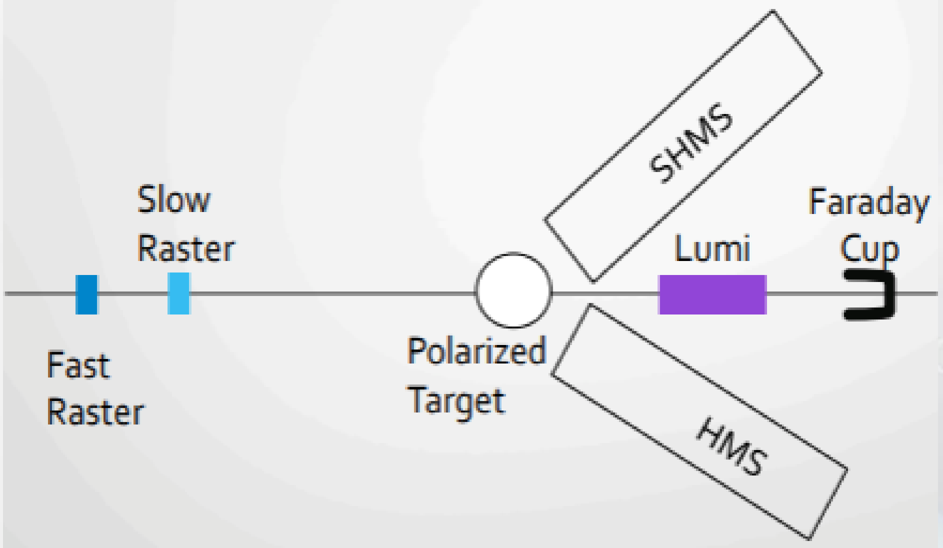
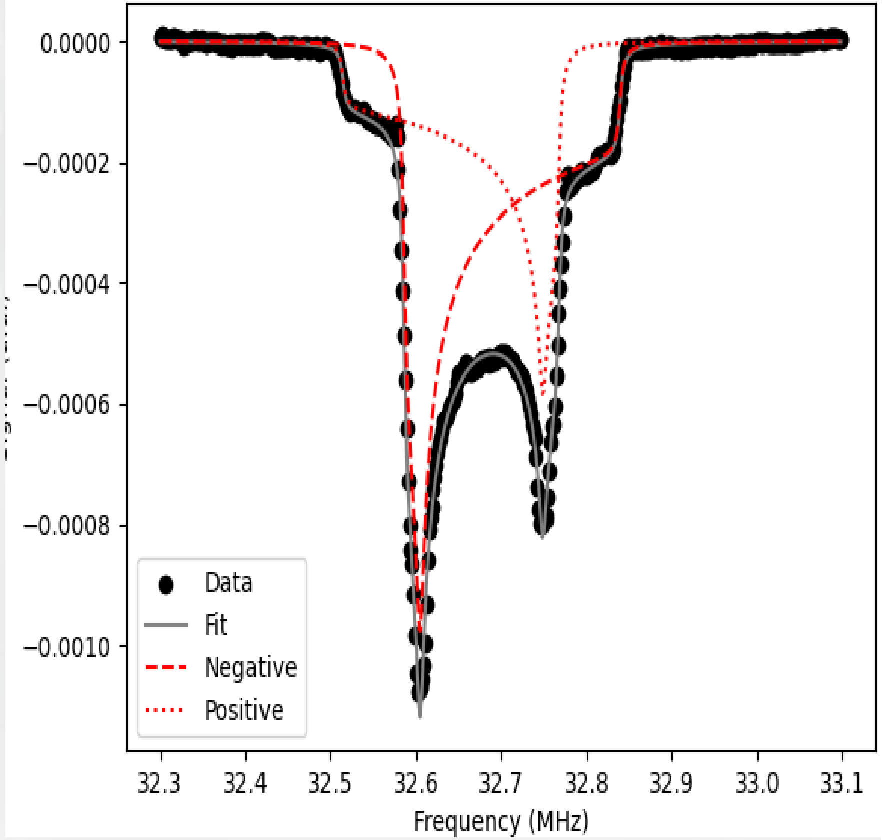
b_1 (E12-13-011) and A_{zz} (E12-15-005) Experiments in the Hall C (Jefferson Lab)

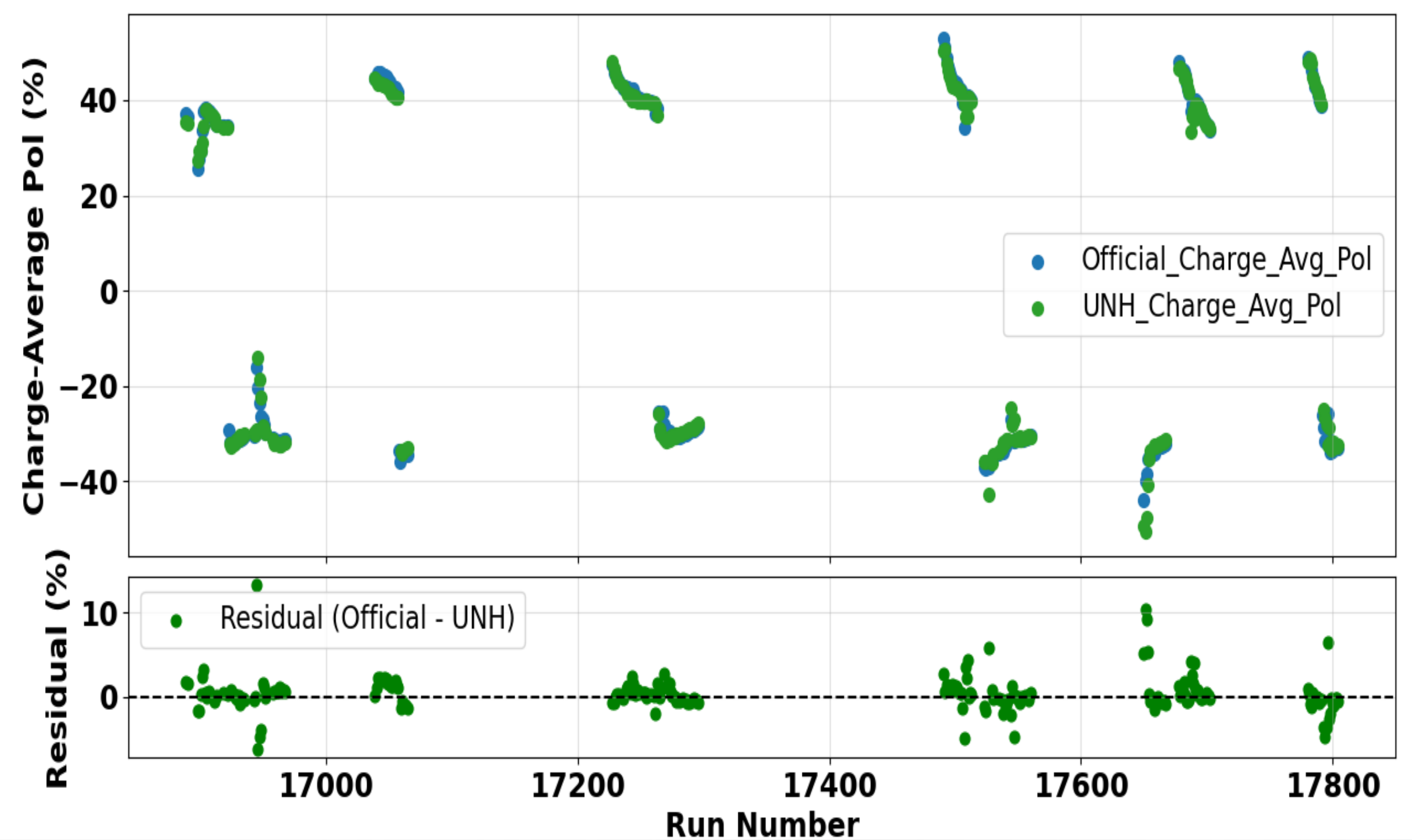
- **E12-13-011: The Deuteron Tensor Structure Function b_1.**
  - Approved by JLab with an A^- Physics Rating. Link
- **E12-15-005: Measurement of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries.**
  - Approved by JLab with an A^- Physics Rating. Link
- I am performing analysis on RGC data to prepare for the b_1 and A_{zz} experiments.





Offline Charged-Averaged Polarization

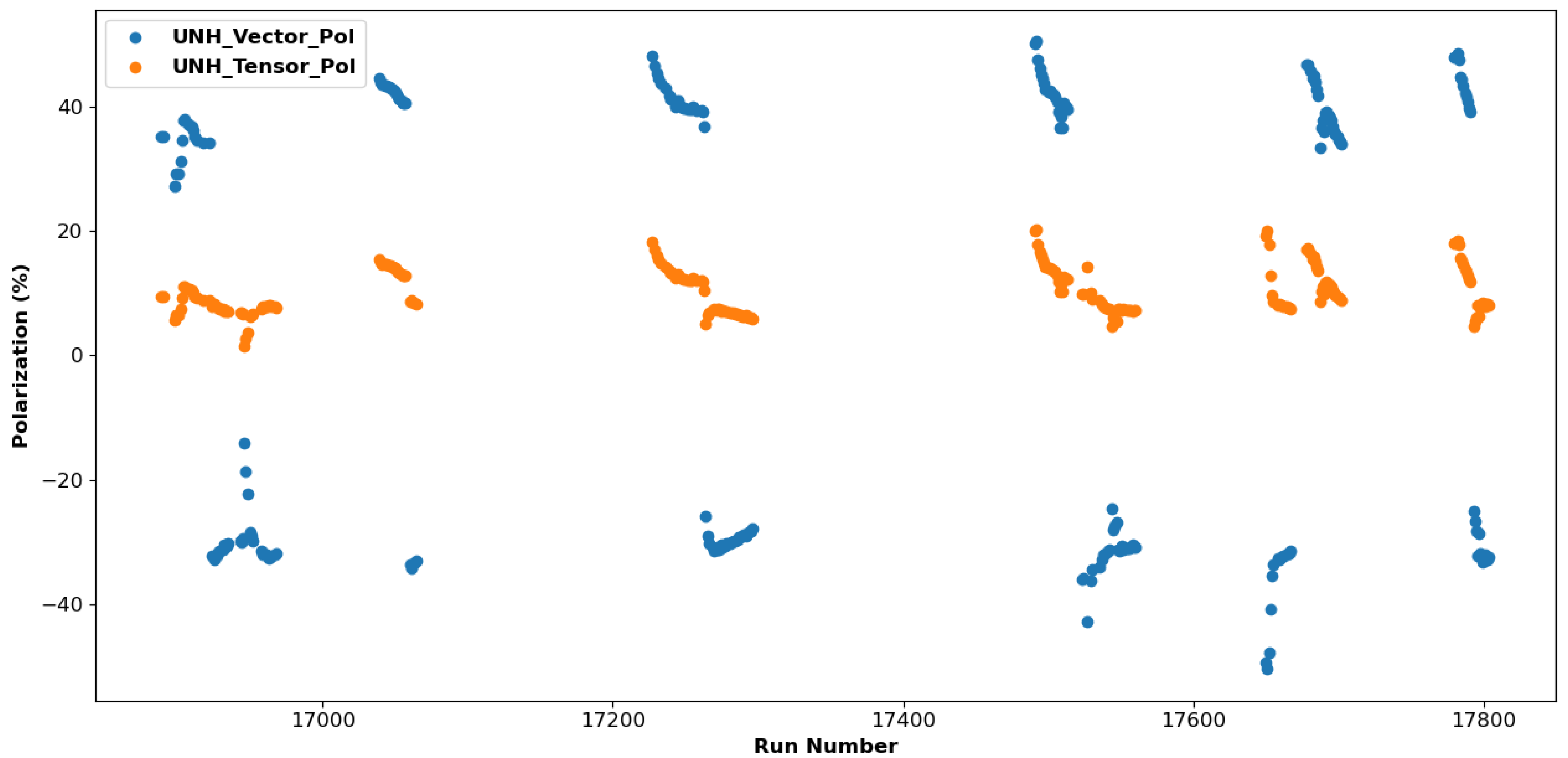




- I performed partial cross-check with UVA_JLab_MIT. The results are within 2% mostly.

- **Acknowledgement:** Special thanks to *Michael McClellan* for providing the C. Dulya-based line-shape fitting code.

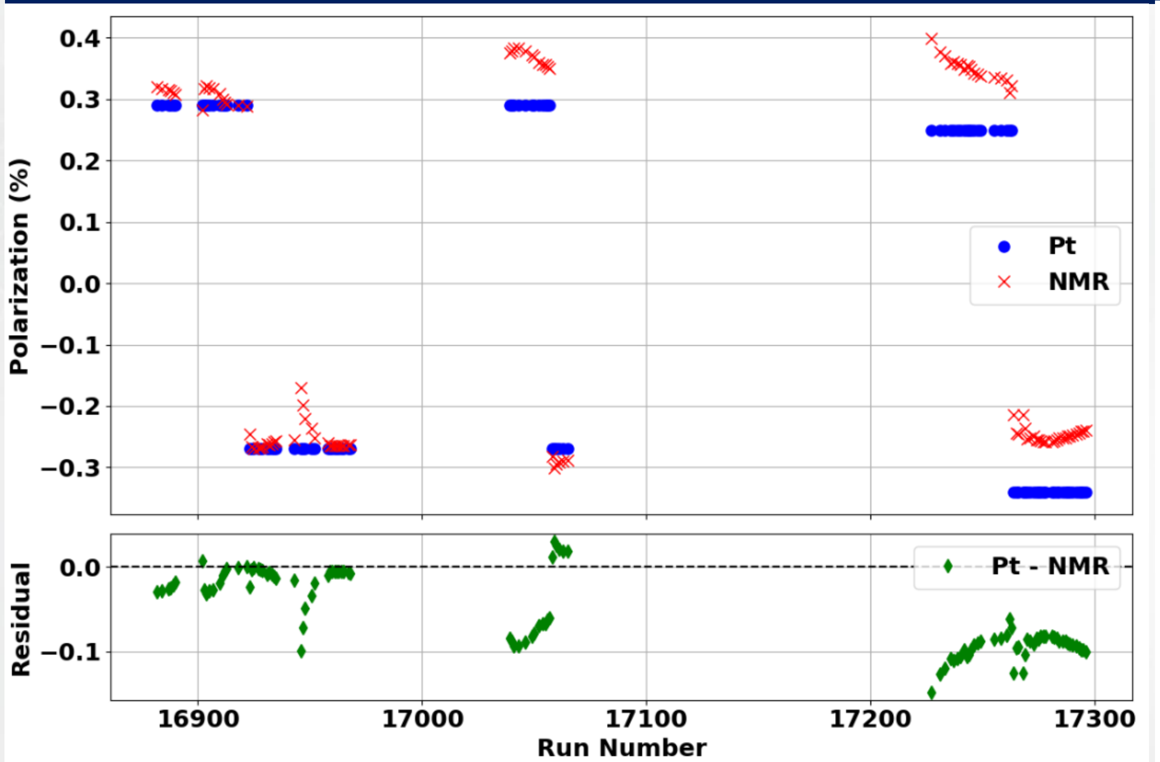
Offline Charged-Averaged Polarization

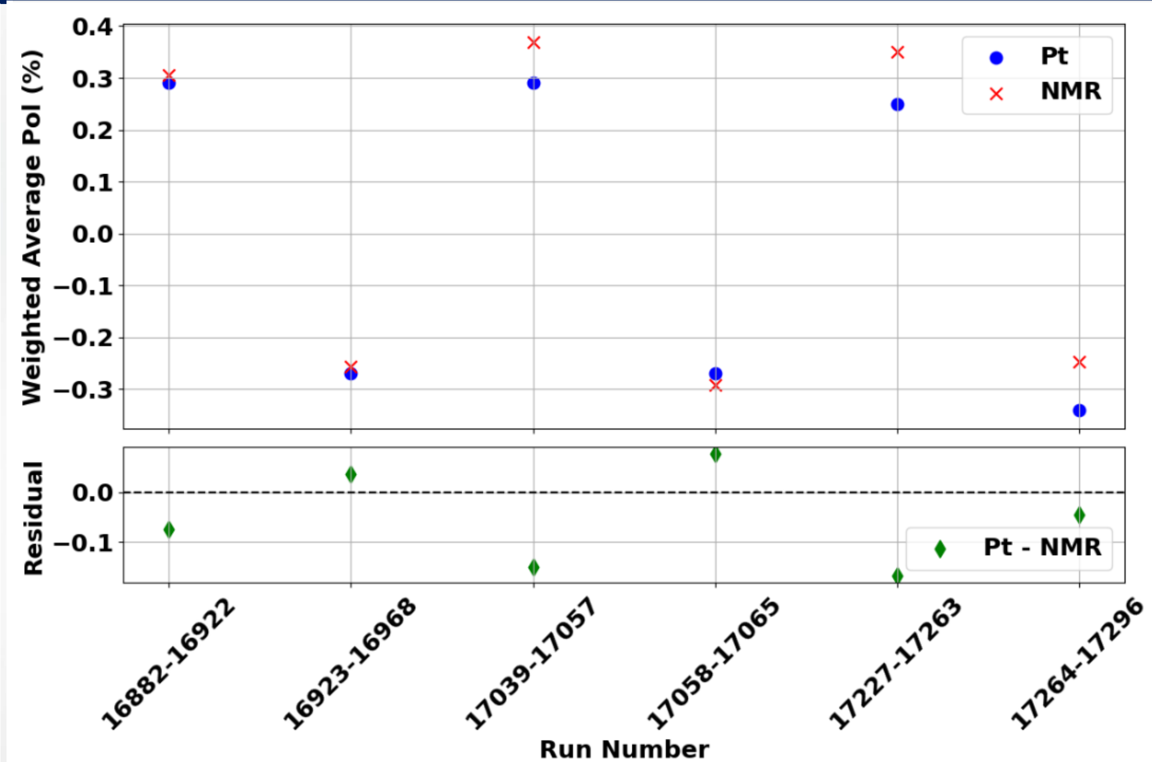


$$P_{zz} = 2 - \sqrt{4 - 3P_z^2}$$

- Maximum P_{zz} extracted from the UNH offline charge averaged polarization is 22.37%.
- **Acknowledgement:** Special thanks to *Michael McClellan* for providing the C. Dulya-based line-shape fitting code.

Comparison Between Target Polarization from NMR and $P_b \times P_t$





- Compared NMR target polarization with Quasi-elastic $P_b \times P_t$ polarization results.
- $P_b \times P_t$ results are lower than NMR, and we trust $P_b \times P_t$ as the actual fraction of the target hit by the beam.
- Intention to learn $P_b \times P_t$ method and implement for the b_1 and A_{zz} experiments.

- **Acknowledgement:**
  - Offline Charge Average Polarization: UVA and Jlab.
  - Quasi-elastic Analysis for $P_b \times P_t$: Noemie Pilleux.

τ and T_1 Extraction of RGC Data

Spin-up Polarization Formula:

$$P(t) = \frac{(R_{DNP} * T_1 * P_{max})}{(1 + R_{DNP} * T_1)} * \left(1 - e^{-t/\tau}\right)$$

$$\tau = \frac{T_1}{1 + R_{DNP} * T_1}$$

- τ is a time constant of polarization during DNP.
- R_{DNP}: Rate constant for DNP polarization transfer (depends on microwave power).
- T_1: Effective time constant during DNP.

- **Reference:** Nuclear Magnetism: Order and Disorder by A. Abragam, M. Goldman.
- **Acknowledgement:** Thanks to Prof. Dustin Keller for providing the equations for T_1 (effective) extraction during DNP.

τ and T_1 Extraction of RGC Data

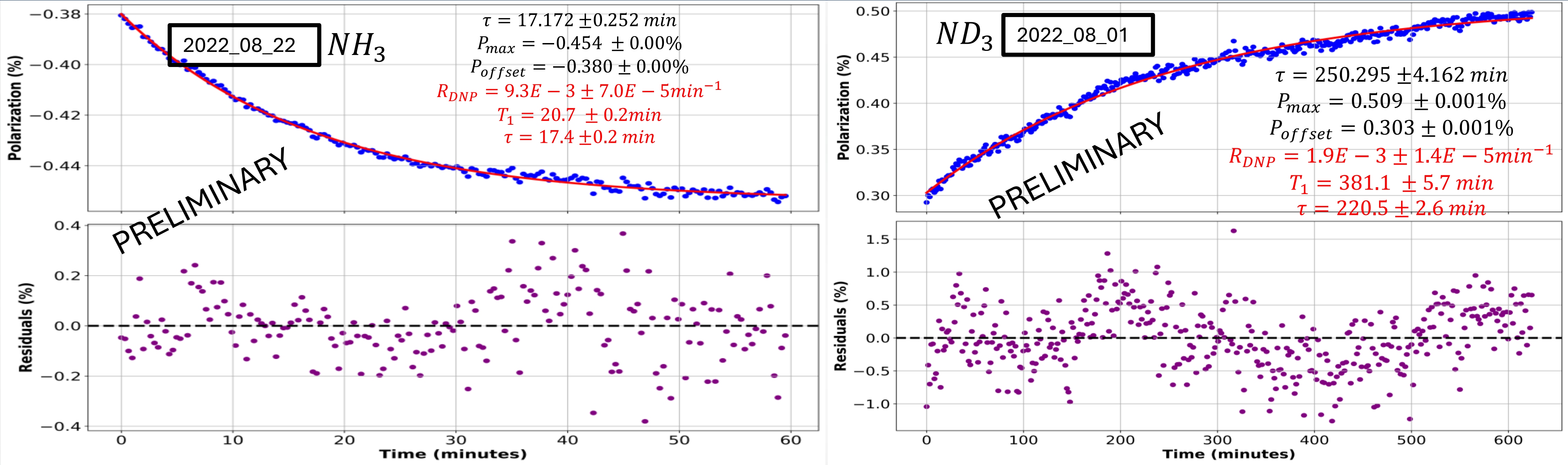
- My intension is to get the effective time dependence of target polarimetry τ and T_1 for the run $plan\ b_1$ and A_{zz} experiments.

  - **How long it takes us to spin-up and how often to replace the material for b_1 and A_{zz}.**

- Note: P_{max} values are **preliminary**, based on the RGC online polarization values, and these results will be updated once we receive the official offline polarization results from the UVA-JLab-MIT collaborative work.

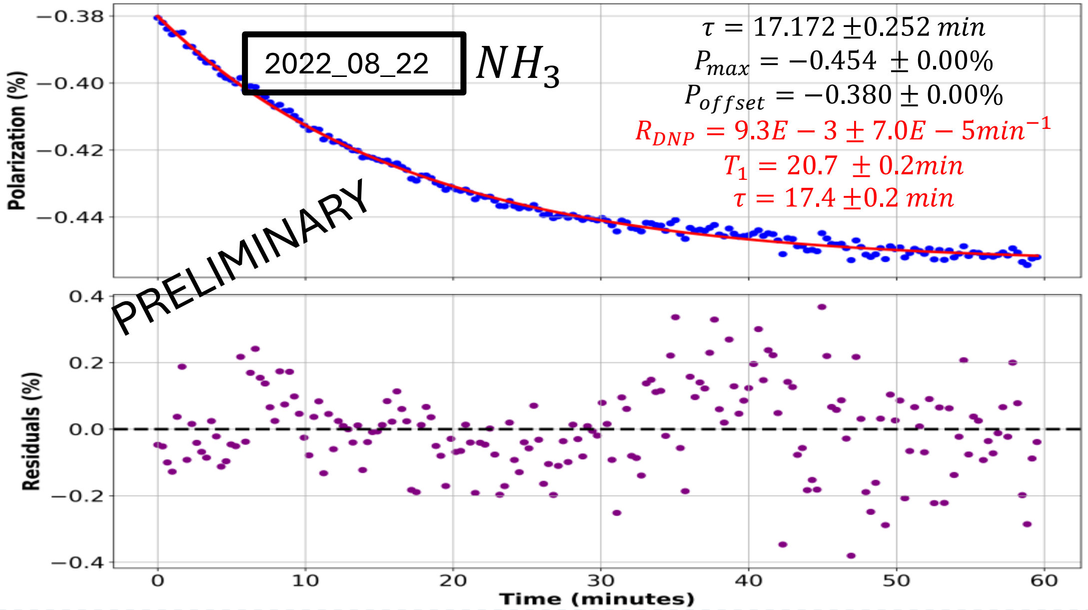
- **Acknowledgement:** Thanks to James Maxwell and Ishara Fernando providing the source of data.

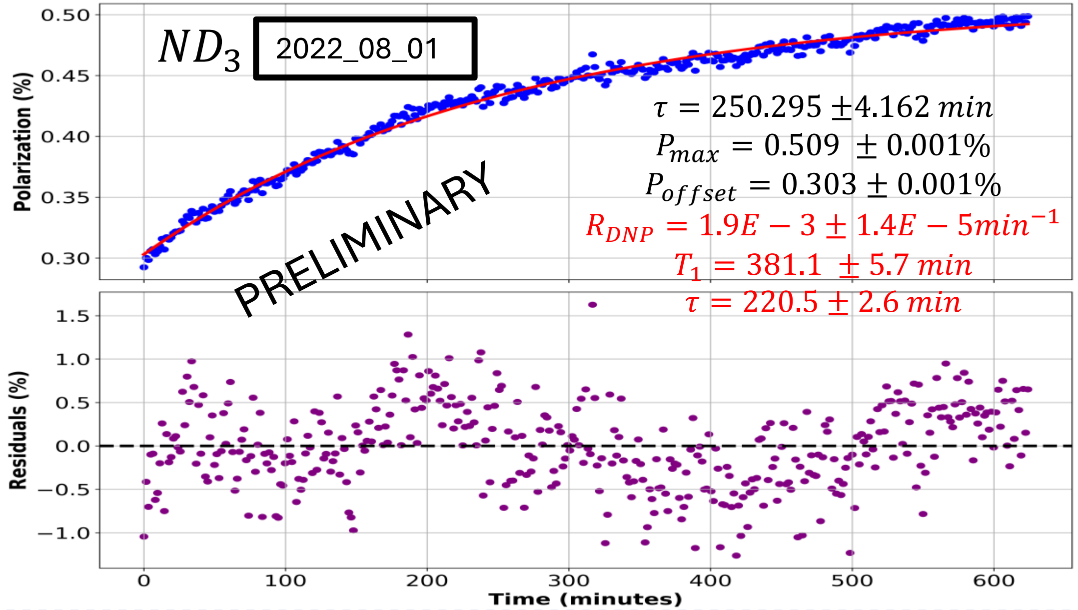
τ and T_1 Extraction of RGC Data

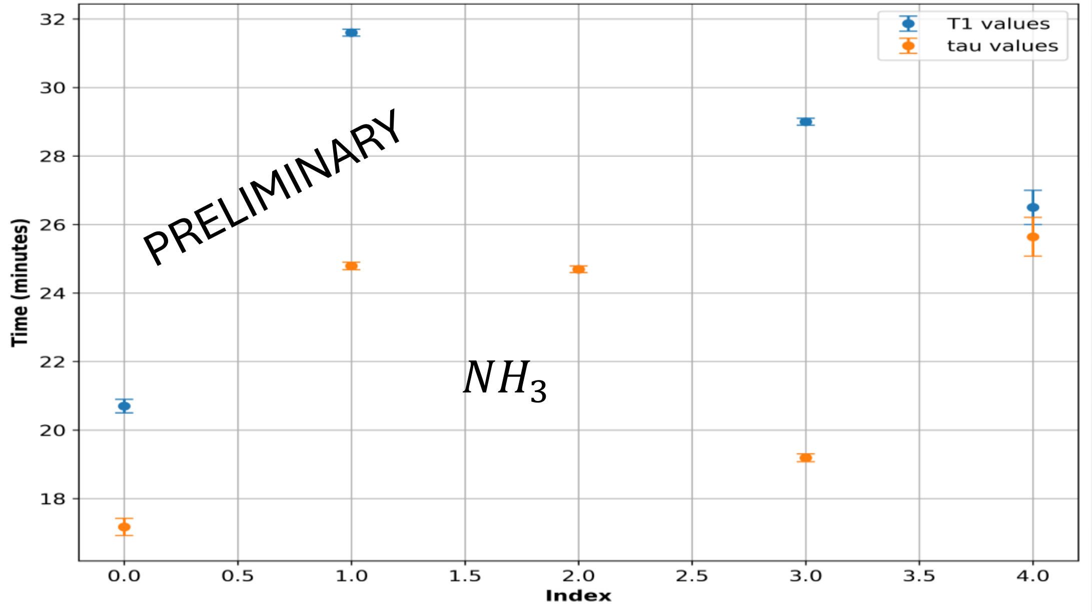


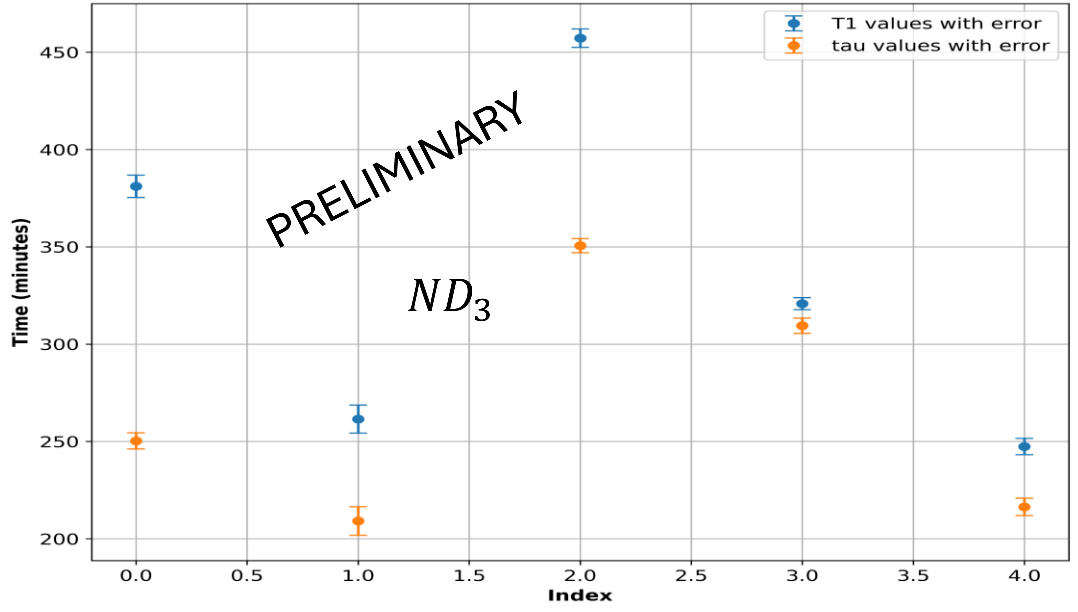
- Extract τ (spin-up time constant) and T_1 (Effective time constant) from RGC polarization data for NH_3 and ND_3.
- Exponential fit applied to time-dependent NMR polarization data; residual confirms good fit quality.

τ and T_1 Extraction of RGC Data









τ and T_1 Extraction of RGC Data

- NH_3 target τ (spin-up time) average is around 22 minutes.
- ND_3 target τ (spin-up time) average is around 275 minutes.
- My intention is to submit as a CLAS analysis note.

CAA Proposal

- **Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12.**

- Analyzing CLAS Run Group C (RGC) polarized deuteron data, which has small tensor polarization, to prepare for the upcoming b_1 and A_{zz} experiments.

- I am analyzing Inclusive DIS channel.

High Energy Physics - Phenomenology

[Submitted on 27 Feb 2025 (v1), last revised 11 Jun 2025 (this version, v3)]

Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12

Jiwan Poudel, Alessandro Bacchetta, Jian-Ping Chen, Dustin Keller, Ishara Fernando, Elena Long, David Ruth, Nathaly Santiesteban, Karl Slifer

We propose to analyze CLAS12 RG-C data to study the tensor transverse-momentum-dependent parton distribution functions (TMDs) on deuteron data. The deuteron is the lightest nucleus with spin-1, in essence a weakly bound system of two spin-1/2 nucleons. However, one of the most intriguing characteristics of the deuteron is that the tensor polarized structure provides direct access to the quark and gluon distribution of light nuclear system, which cannot be naively constructed from the proton and neutron. We will study the tensor polarized structure functions with the Semi-inclusive Deep Inelastic Scattering (SIDIS) eD \arrow eP_{h}X and Inclusive processes in the available data on deuterated ammonia (ND3) target. We will perform the first ever SIDIS analysis extraction of the tensor structure functions, which can be interpreted in term of completely unexplored tensor polarized TMDs. Our analysis will focus on the extraction of the tensor structure functions b1 from inclusive process, and F_{U(LL),T} and F^{cos 2\phi_{h}}_{U(LL)} from SIDIS. These last two structure functions carry information related to two tensor-polarized TMDs, f_{1LL} and h^{\perp}_{1LL}. These initial exploratory measurements of tensor-polarized structure functions will enable the first extraction of spin-1 TMDs and motivate more precise future measurements.

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2502.20044 **[hep-ph]**
(or arXiv:2502.20044v3 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.2502.20044

Physics Asymmetries

- Extracted Physics asymmetry for Summer22, Fall22, and Winter23 for $\boldsymbol{ND_3}$ target.
- Asymmetry calculated using:

$$A_{Physics} = \frac{1}{F_D P_b P_t}\left(\frac{\frac{N_p}{q_p} - \frac{N_n}{q_n}}{\frac{N_p}{q_p} + \frac{N_n}{q_n}}\right)$$

- Statistical Uncertainty:

$$\sigma_{physics} = \frac{1}{F_D P_b P_t}\sqrt{\left(\frac{2N_- q_- q_+}{(N_+ q_- + N_- q_+)^2}\right)^2 N_+ + \left(\frac{2N_+ q_- q_+}{(N_+ q_- + N_- q_+)^2}\right)^2 N_-}$$

- q_P is a positive charge accumulated by FCup and q_n is a negative charge accumulated by FCup.
- N_P number of counts for positive helicity and N_n numbers of counts for negative helicity.

- **Kinematics and Detector Cuts:**

  - Electron selection: PID = 11, trigger electrons in Forward Detector (FD).
  - Energy cut: Scattered electrons with $E > 2.6$ GeV.
  - DIS Selection: $Q^2 > 1\ GeV^2$.
  - W cut: W > 2 GeV to exclude resonance region.
  - Apply vertex distribution, PCAL and sampling fraction cuts.

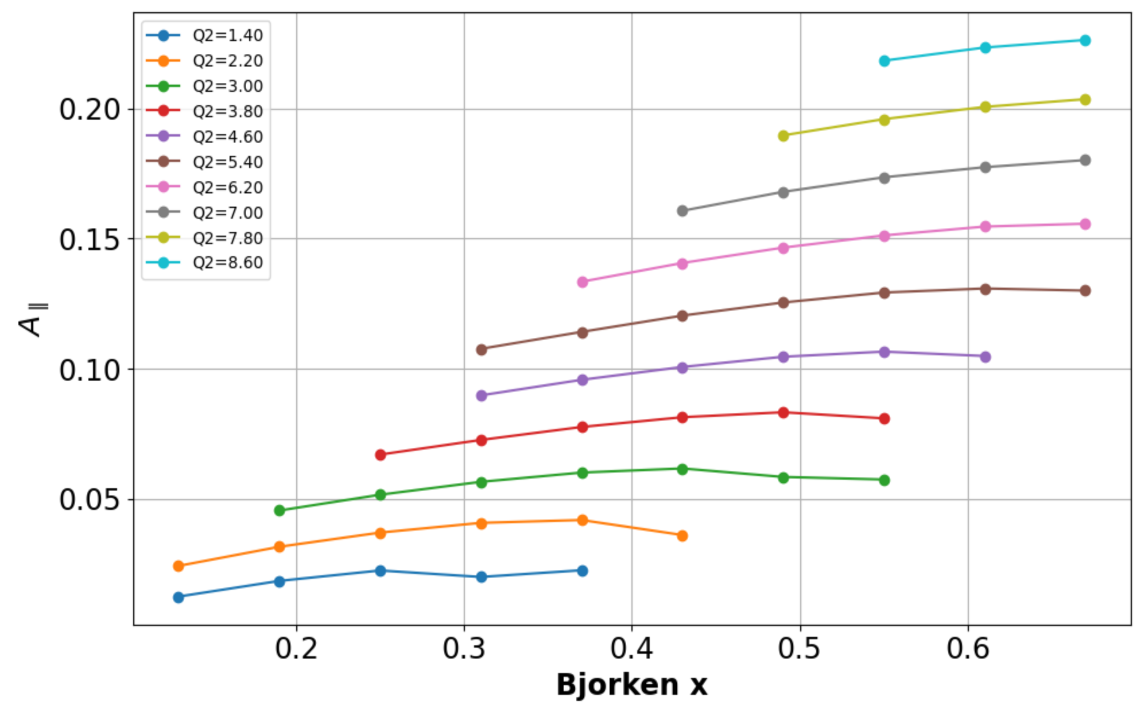
Physics Asymmetries

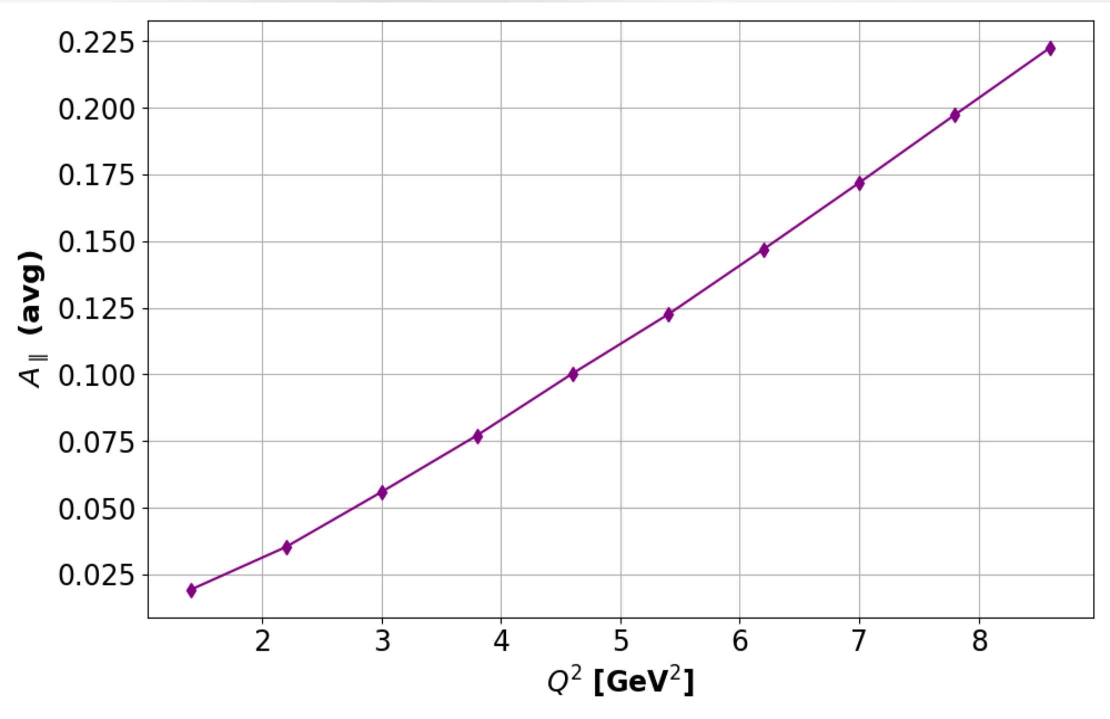
- My preliminary analysis assumes,
  - approximate **dilution factor** 0.27,
  - **beam polarization** 0.84 from Moller Scattering, and
  - **Target Polarization:** P_t values are taken from **Noemie's $\boldsymbol{P_b \times P_t}$ analysis**, Link.
    - She averaged over multiple runs for $\boldsymbol{P_b \times P_t}$ analysis.
    - Assigned corresponding P_t value for each run number based on her results.

- **Extracted Physics Asymmetries:**
  - I extracted parallel asymmetry for Summer22, Fall22, and Winter23 data sets.

- **Additional Notes:**
  - Using **T.B. Hayward's** documentation (Link) for **electron identification in DIS region**.
  - **Acknowledgement:** Thanks to Darren Upton, Derek Holmberg, and Prof. Sebastian Kuhn for their support.

Hall B Model





- There is a good initial agreement between my preliminary extracted asymmetries compared to Hall B model.
- **Note:** Data is not shown here because I need CLAS approval.
- **Acknowledgement:** Thanks to Darren Upton and Prof. Sebastian Kuhn for providing the Hall B model data.

Tensor Observables

- Extraction of tensor asymmetries from the Hall B Data:
- Cross-sections:

$$\frac{d\sigma}{dEd\Omega} = \frac{D_F P_b P_t N_{counts}}{qL.T\epsilon\Delta E\Delta\Omega}$$

- Where D_F is dilution factor, P_b beam polarization, P_t target polarization, N_{counts} are number of counts for positive and negative helicities, q Farday Cup charge, L.T live time, and $\Delta\Omega$ solid-angle.

- It's difficult to calculate $\Delta\Omega$ solid-angle.

- Yields:

$$Y = \frac{N_P + N_n}{q_P + q_n}$$

- Let σ_u denote the unpolarized cross section, P_i and Q_i vector and tensor polarization for configuration i. With the deuteron vector and tensor analyzing powers A_d^V and A_d^T respectively, the measured cross-sections are modeled as:

$$\sigma_1(P_1, Q_1) = \sigma_u\left(1 + P_1 A_d^V + Q_1 A_d^T\right), \quad (1)$$

$$\sigma_2(-P_2, Q_2) = \sigma_u\left(1 - P_2 A_d^V + Q_2 A_d^T\right). \quad (2)$$

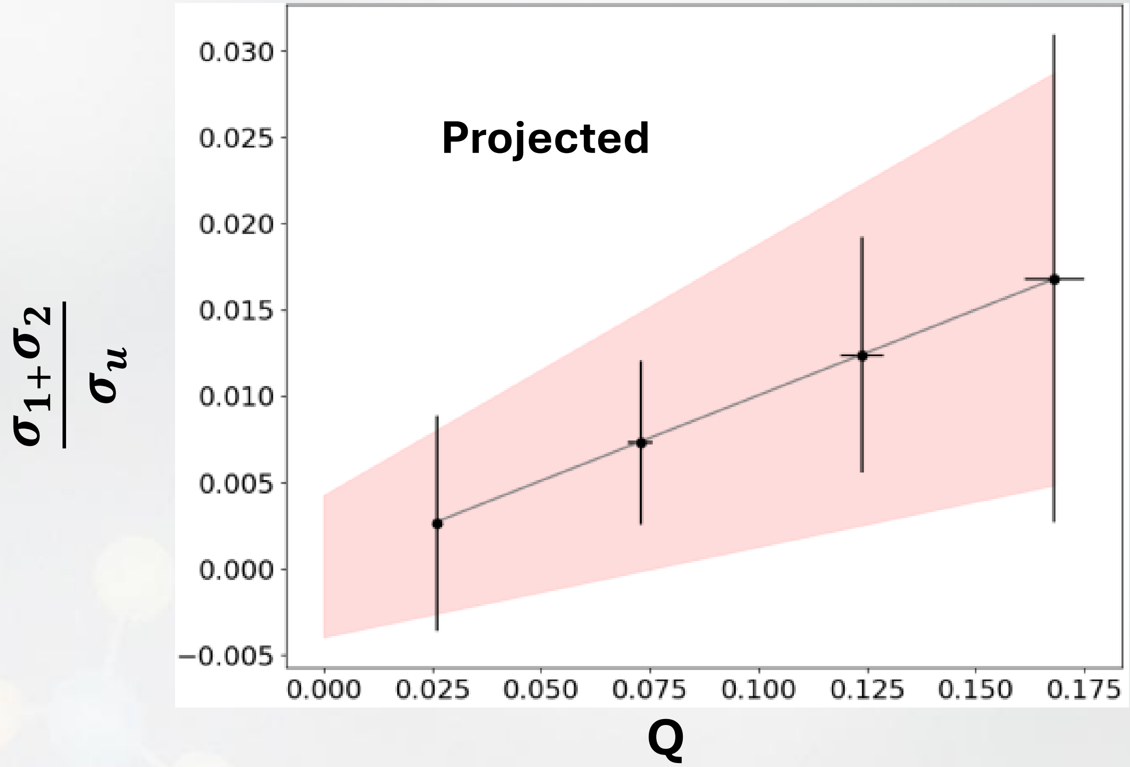
After adding Eqn. 1 and Eqn. 2 gives:

$$(\sigma_1 + \sigma_2)/\sigma_u = \left(2 + (P_1 - P_2)A_d^V + (Q_1 + Q_2)A_d^T\right).$$

Assuming: $P_1 \approx P_2$

$$(\sigma_1 + \sigma_2)/\sigma_u = \left(2 + (Q_1 + Q_2)A_d^T\right)$$

Tensor Observables



- Extracted Yields for Summer22, Fall22, and Winter23 for inclusive DIS region.
- Working on the extraction of un-polarized cross-sections and tensor asymmetry.
- **Reference:** Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12, Link.
- **Acknowledgement:** thanks to Prof. Karl and Prof. Nathaly for providing the equations and slides.

Projects Status

- Analyzing CLAS12 data to prepare for the upcoming $\boldsymbol{b_1}$ and $\boldsymbol{A_{zz}}$ experiments.
- **Extraction of tensor asymmetry:**
  - Extracted physics asymmetry in the inclusive DIS region.
  - Applied detector and kinematic cuts for electron PID using T.B. Hayward's Documentation Link.
  - Normalized using static dilution factor (assumed 0.27), beam polarization 0.84, and target polarization from Noemie's Elastic $P_b \times P_t$ extraction Link.
  - Cross check RGC Vector Asymmetry analysis for $P_b \times P_t$ vs NMR.
  - Compared with the Hall B Model provided by Darren Upton.
  - **Current Status:** Implementing dynamic dilution factor and extraction of A_1 from data.
- **Extraction of Yield:**
  - Extracted yield for Summer22, Fall22, and Winter23 $\boldsymbol{ND_3}$ data.
  - Performed the Extraction of the tensor asymmetry A_d^T and unpolarized cross-section.
  - **Current Status:** Working on improving the results and tensor asymmetry extraction for b_1 analysis.

Projects Status

- **NMR Polarization Analysis for ND_3 Data (2022-2023):**
  - Performed offline charge-averaged polarization for each run for Fall22.
  - Extracted τ (tau) and T_1 (effective) for both $\boldsymbol{NH_3}$ and $\boldsymbol{ND_3}$ targets.
  - **Goal:** Maintain JLab-UVA and UNH offline charge-averaged polarization agreement within 2% absolute difference.
    - Some runs exceed 2% but within 5% absolute difference.
  - $P_b \times P_t$ cross check with charge average polarization.
  - **Current Status:** Planning to perform offline charge-averaged polarization for Summer22 and Winter23 datasets.

- **James Online NMR Software:**
  - Prepared installation instructions for Ubuntu and macOS.
  - **Current Status:** Planning to modify and deploy in 103 Slifer Lab.

- **James Offline Polarization Software:**
  - Drafting installation documentation for Ubuntu and macOS.
  - **Current Status:** Planning to modify and deploy in 103 Slifer Lab.

Summary

- **b1 and Azz Experiment in Hall C:** UNH Nuclear Group planning to run b_1 and A_{zz} Experiments in Hall C to study deuteron Asymmetries and polarization.

- **Extraction of tensor asymmetry**: Extracted physics asymmetry for summer22, fall22, and winter23.
  - Apply kinematics and detector cuts.
  - Normalize by dilution factor, polarization of beam and target.
  - **Acknowledgement: Thanks to Prof. Sebastian and Darren providing the Hall B model data.**

- **Extraction of Yield:**
  - Extracted yield per run for summer22, fall22, and winter23.
  - Extracted tensor asymmetry and un-polarized cross-section.

- **RGC Target Data:**
  - Analysis note for τ and T_1 extraction for ND_3 and NH_3 materials.

Thanks

Please join the effort

Please join the effort:

- Karl Slifer (karl.slifer@unh.edu) [Spokesperson of b_1(E12-13-011) Experiment]
  - **E12-13-011: The Deuteron Tensor Structure Function b_1.** Link
- Elena Long (elena.long@unh.edu) [Spokesperson of A_{zz} (E12-15-005) Experiment]
  - **E12-15-005: Measurement of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries.** Link

Thanks

University of New Hampshire

UNH NPG

U.S. DEPARTMENT OF ENERGY | Office of Science

This work is supported by DOE contract *DE-FG02-88ER40410*

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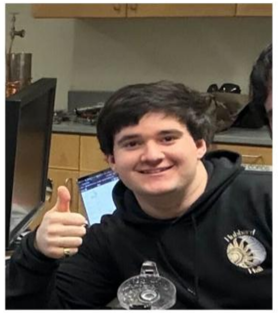

Eli Phippard

2025 UNH Polarized Target Group

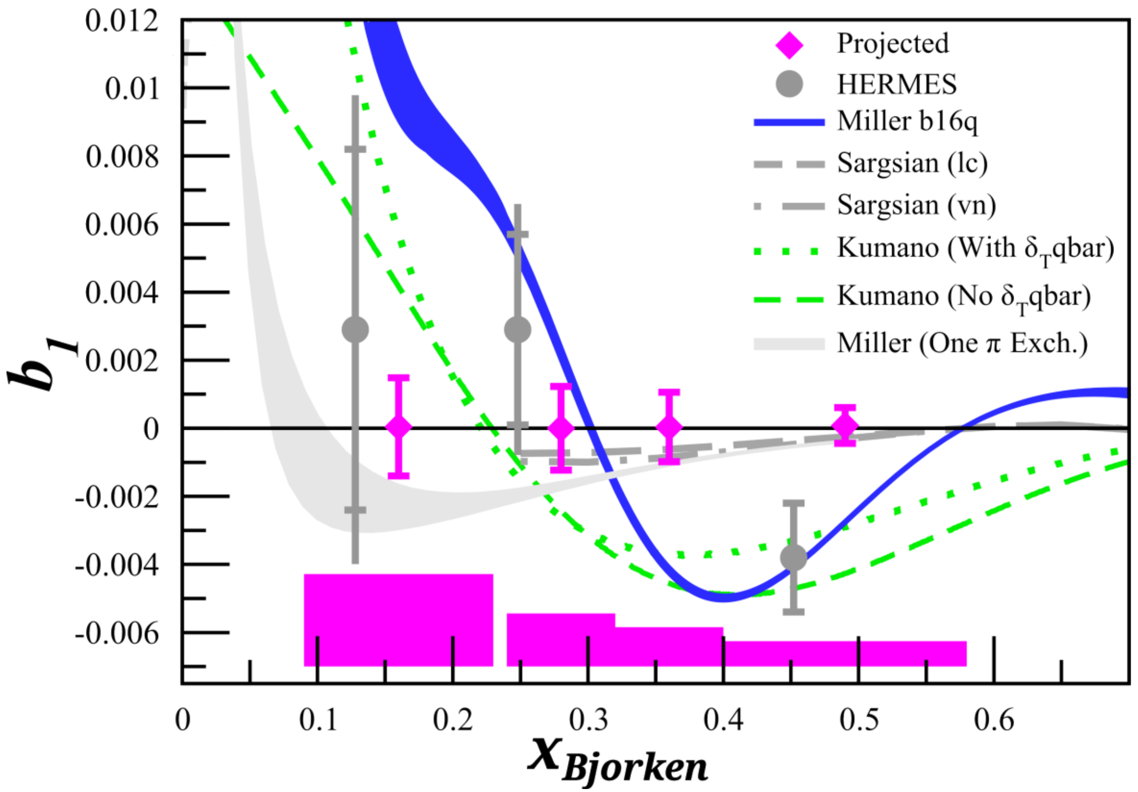
Backup Slides

b_1 (E12-13-011) and A_{zz} (E12-15-005) Experiments in the Hall C (Jefferson Lab)

b_1 (E12-13-011) Experiment in the Hall C (Jefferson Lab)

- Intended to improve upon HERMES 2005 data.
- Tensor Physics at quark level
- Hidden-color six-quark states,
- Tensor-polarized quark sea (violating sum rules).
- Enhanced D-wave nucleon motion.

E12-13-011: The Deuteron Tensor Structure Function b_1

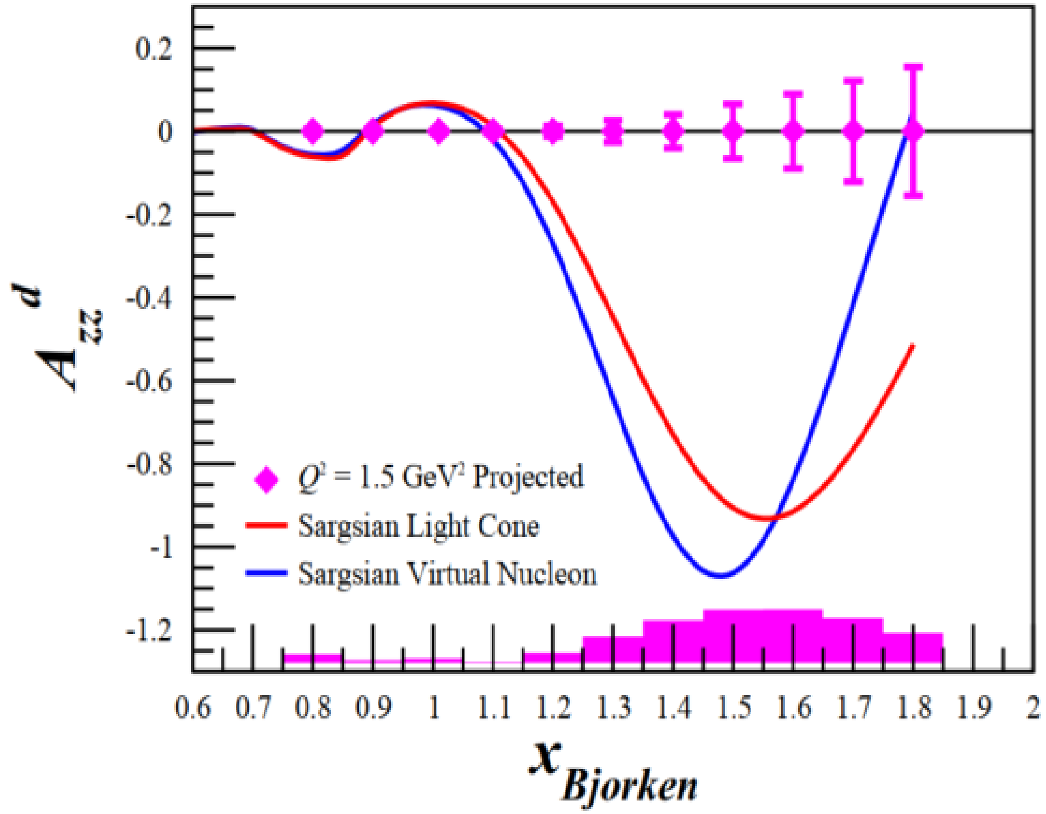


K. Slifer et al, Jlab E12-13-011.

A_{zz} (E12-15-005) Experiment in the Hall C (Jefferson Lab)

- **First-ever quasi-elastic A_{zz} measurement:** – a new window into deuteron structure,
- **Relevance to short-range correlation (SRC):** physics – probes a short-range correlations and deuteron wavefunctions dynamics,
- **Broad kinematic reach:** widest x-range covered by a single A_{zz} experiment,
- **Additional observable:** simultaneous extraction of T_{2o}.
- **Note:** Both experiments will conduct at the beam energy of 11.0 GeV with 115 nA beam current.
- Implement tensor enhancement techniques: selective semi-saturated (ssRF).
- **Both approved by JLab with A^{-} Physics Rating.**

E12-15-005: Measurement of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries.



E. Long et al, Jlab E12-15-005.

University of New Hampshire

Jefferson Lab
Thomas Jefferson National Accelerator Facility

b_1 (E12-13-011) and A_{zz} (E12-15-005) Experiments in the Hall C (Jefferson Lab)

b_1 Systematic Estimates

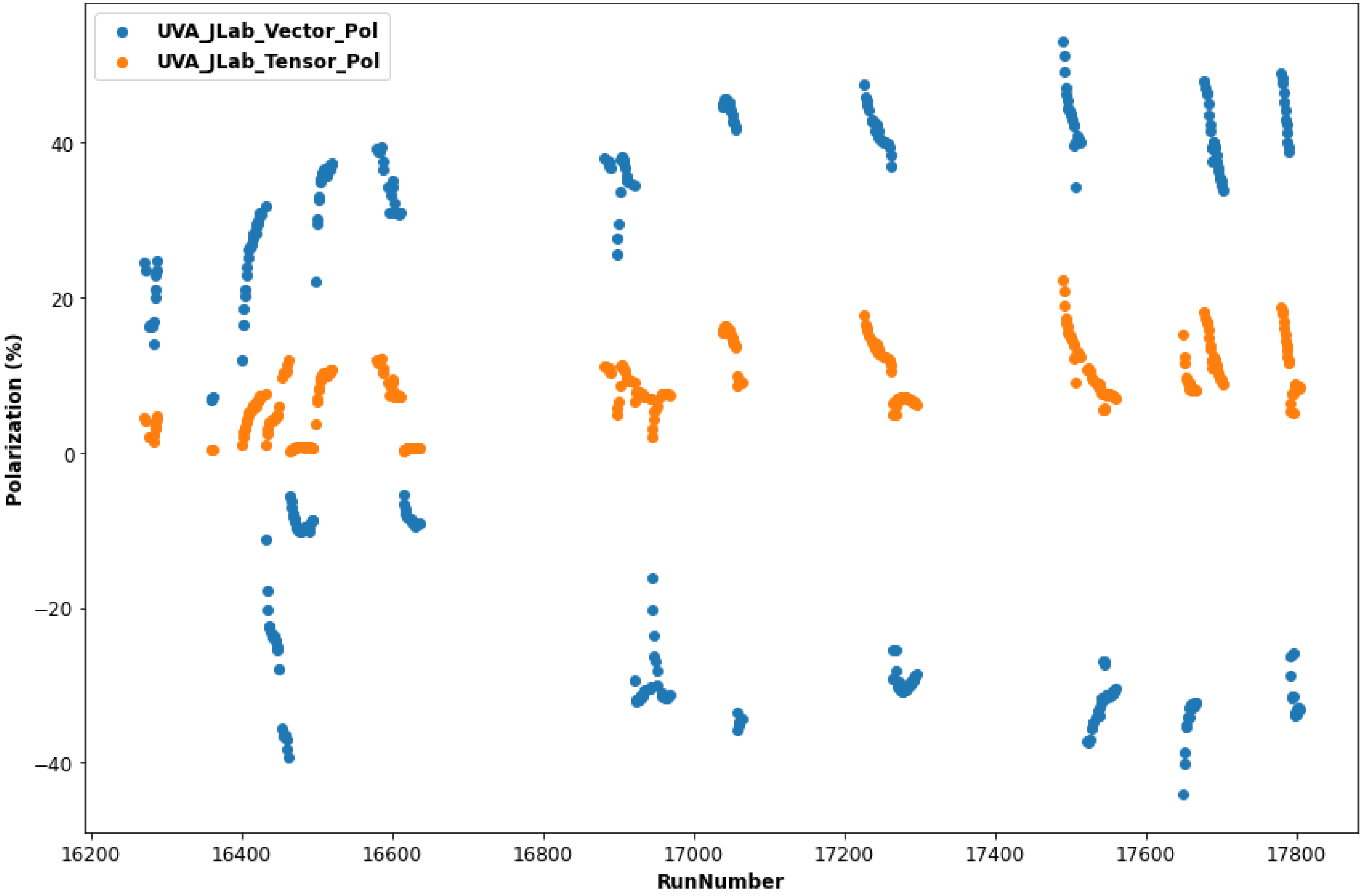
Source	Systematic
Polarimetry	8.0%
Dilution Factor/Packing Fraction	4.0%
Others	2.1%
Total	9.2%

A_{zz} Systematic Estimates

Source	A_{zz} Systematic	T_{20} Systematic
Polarimetry	6.0%	6.0%
Dilution Factor	6.0%	2.5%
Packing Fraction	3.0%	3.0%
Others	2.5%	2.5%
Total	9.2%	7.4%

- Both experiments require a highly ($\geq 30\%$) tensor-polarized deuterium target with precise measurement of tensor polarization.

Offline Charged-Averaged Polarization

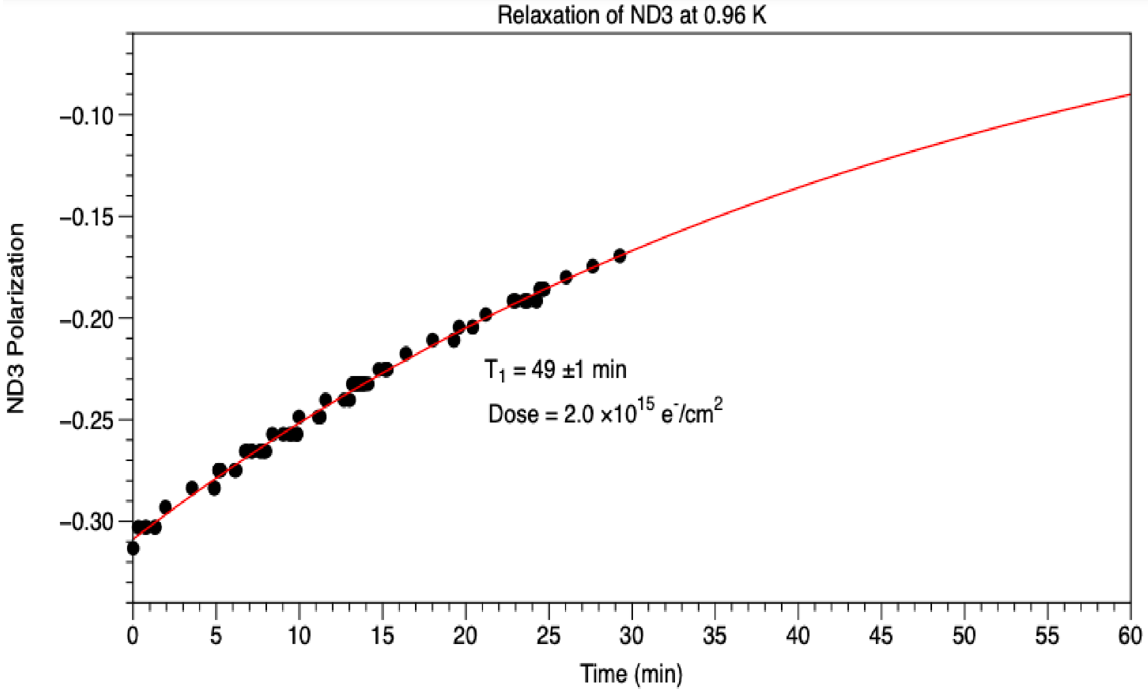


$$P_{zz} = 2 - \sqrt{4 - 3P_z^2}$$

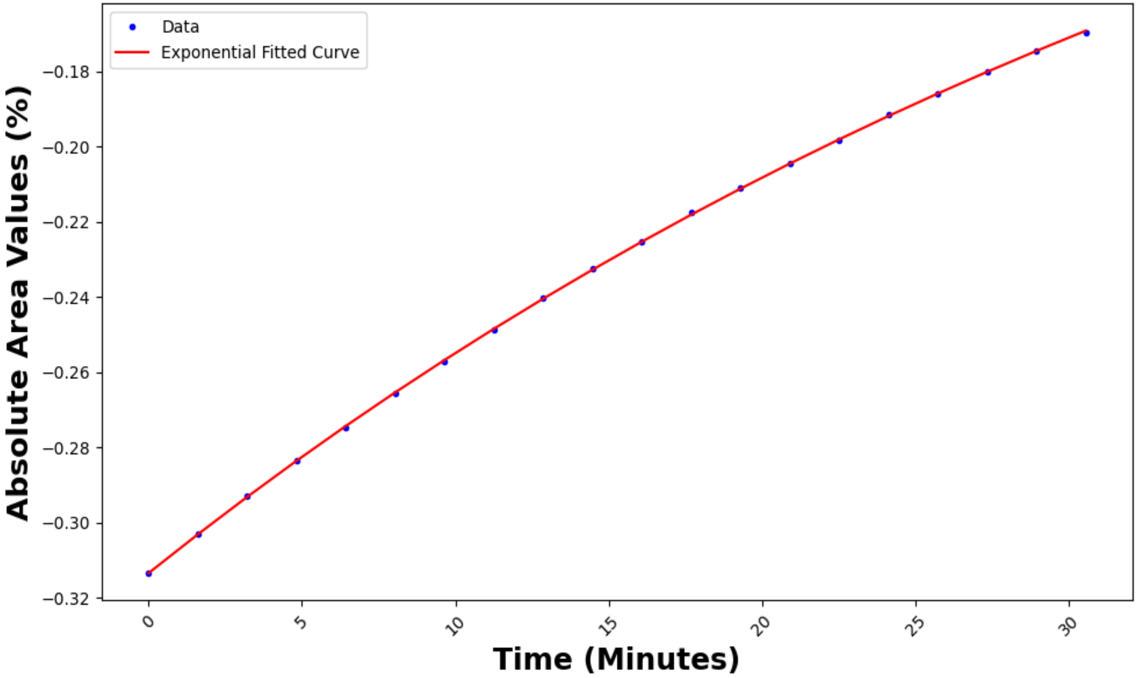
- Put your plot
- Maximum tensor polarization extracted from the UVA_Jlab offline data is around 22.37%.

- **Acknowledgement:** Thanks to Michael McClellan for lineshape fitting code.

T1 Extraction



https://logbooks.jlab.org/entry/4151869
T1 = 49 minutes (C. Keith)



T1 = 44 minutes (by Farooq)

τ and T_1 Extraction of RGC Data

Spin-up Polarization Formula:

$$-\left(P_{max} - P_{offset}\right) * \left(1 - e^{-\frac{t}{\tau}}\right) + P_{max}$$

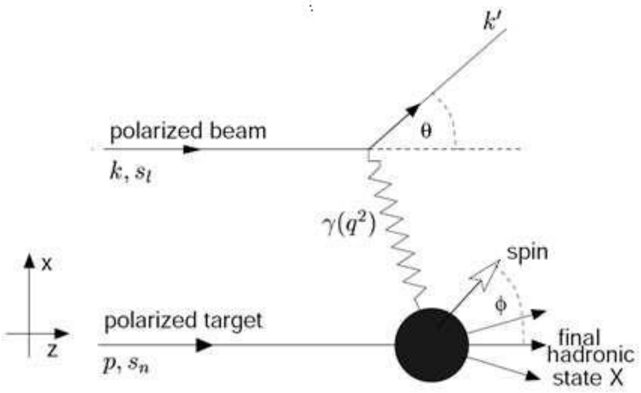
$$P(t) = \frac{(R_{DNP} * T_1 * P_{max})}{(1 + R_{DNP} * T_1)} * \left(1 - e^{-t/\tau}\right)$$

$$\tau = \frac{T_1}{1 + R_{DNP} * T_1}$$

- τ is a time constant of polarization during DNP.
- R_{DNP}: Rate constant for DNP polarization transfer (depends on microwave power).
- T_1: Effective time constant during DNP.

- **Reference:** Nuclear Magnetism: Order and Disorder by A. Abragam, M. Goldman.
- **Acknowledgement:** Thanks to Prof. Dustin Keller for providing the equations for T_1 (effective) extraction during DNP.

Polarized Inclusive Deep-Inelastic Scattering



Polarized electron-nucleon scattering

- Definition of kinematic variables:

$$Q^2 = -q^2 = 4EE'sin^2\frac{\theta}{2} = 2EE'(1 - cos\theta)$$

$$W = \sqrt{M^2 + 2M\upsilon - Q^2} \quad \text{where } \upsilon = E - E'$$

$$x = \frac{Q^2}{2M\upsilon} \quad , y = \frac{\upsilon}{E} \quad , \quad \gamma = \frac{\sqrt{Q^2}}{\upsilon} \; , \; \tau = \frac{\upsilon^2}{Q^2} = \frac{1}{\gamma^2}$$

$$\epsilon = \left(1 + 2(1+\tau)tan^2\frac{\theta}{2}\right)^{-1} \; , \quad \eta = \frac{\epsilon\sqrt{Q^2}}{E - \epsilon E'} \; , \quad D = \frac{1-\epsilon\frac{E'}{E}}{1+\epsilon R}$$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1}(1+\gamma^2) - 1$$

- These equations are taken from Nevzat thesis and paper:
  - **Spin Structure of the Deuteron** by Nevzat Guler
  - Precise Determination of the Deuteron Spin Structure ……… https://arxiv.org/abs/1505.07877

Polarized Inclusive Deep-Inelastic Scattering

- Q^2 is the squared four-momentum. υ is the energy of virtual photon.
- W is the mass of final hadronic state. X is the Bjorken variable.
- $\in$ is the relative flux of the two polarization states of the virtual photon (ratio of longitudinal polarization to the transverse polarization).
- D is the depolarization factor that represents how much of the incoming lepton's polarization is transferred to the virtual photon.
- R is the ratio of longitudinal to transverse virtual photon absorption.

$$g_1(x,Q^2) = \frac{F_1(x,Q^2)}{1+\gamma^2}(A_1 + \gamma A_2)$$

$$g_2(x,Q^2) = \frac{F_1(x,Q^2)}{1+\gamma^2}\left(-A_1 + \frac{A_2}{\gamma}\right)$$

$$A_1(x,Q^2) = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

$$A_2(x,Q^2) = \frac{2\sigma^{TL}_{1/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{\gamma[g_1(x,Q^2) + g_2(x,Q^2)]}{F_1(x,Q^2)}$$

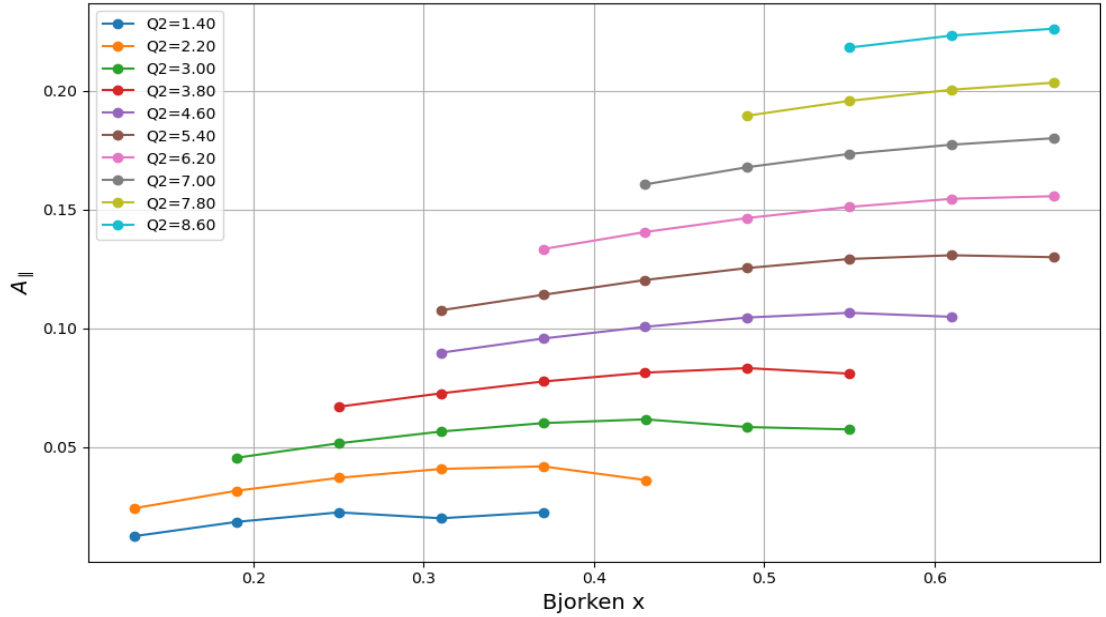
$A_{||}$ in terms of two virtual photon asymmetries A_1 & A_2:

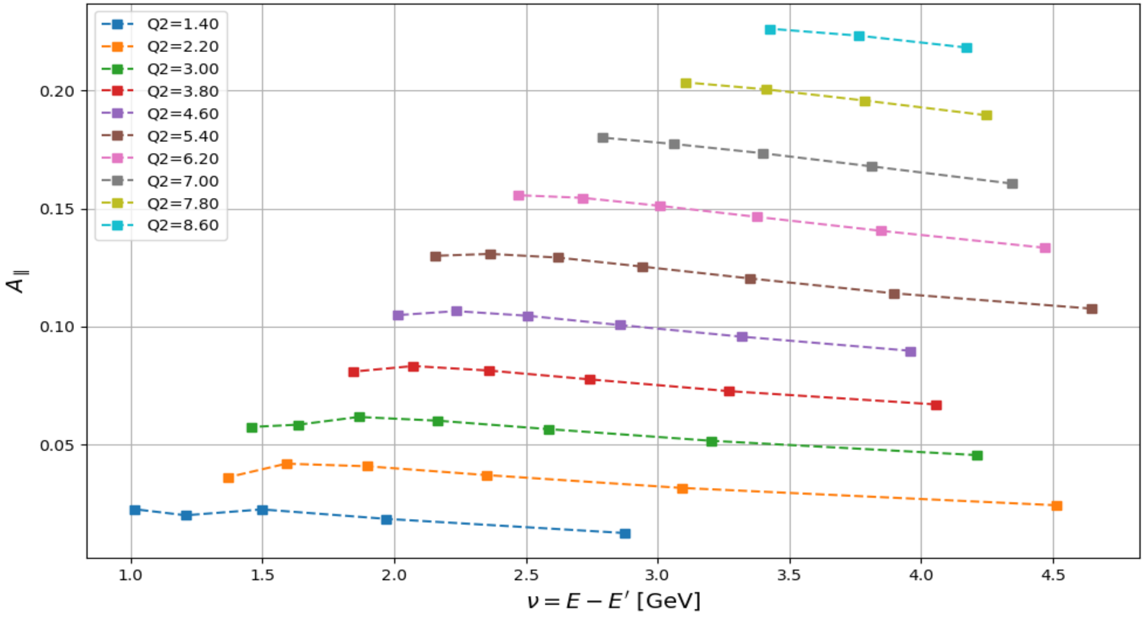
$$A_{||} = D[A_1(\upsilon,Q^2) + \eta A_2(\upsilon,Q^2)]$$

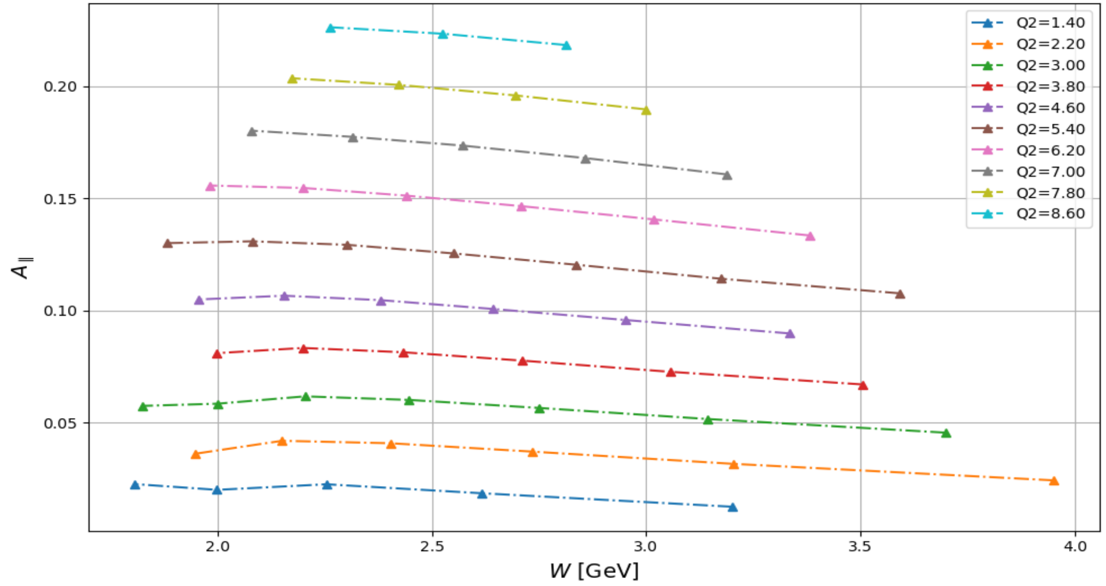
$$\frac{d^2\sigma}{dx dQ^2} = \left(\frac{4\pi\alpha^2}{Q^4}\right)\left[y^2 F_1(x,Q^2) + \left(\frac{1-y}{x} - \frac{My}{2E}\right)F_2(x,Q^2)\right]$$ from Darren's slide

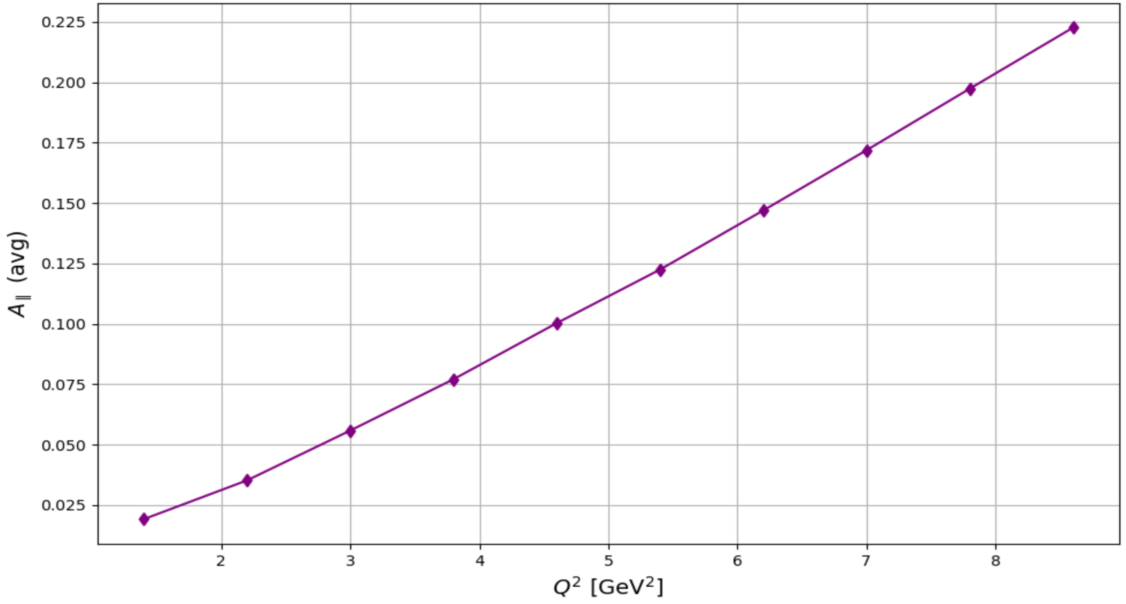
$$\sigma = \left(\frac{4\pi\alpha^2}{Q^4 x}\right)\left[\frac{Q^4}{4M^2E^2x}F_1(x,Q^2) + \left(1 - \frac{Q^2}{2MEx} - \frac{Q^2}{4E^2}\right)F_2(x,Q^2)\right]$$

Polarized Inclusive Deep-Inelastic Scattering (Model)

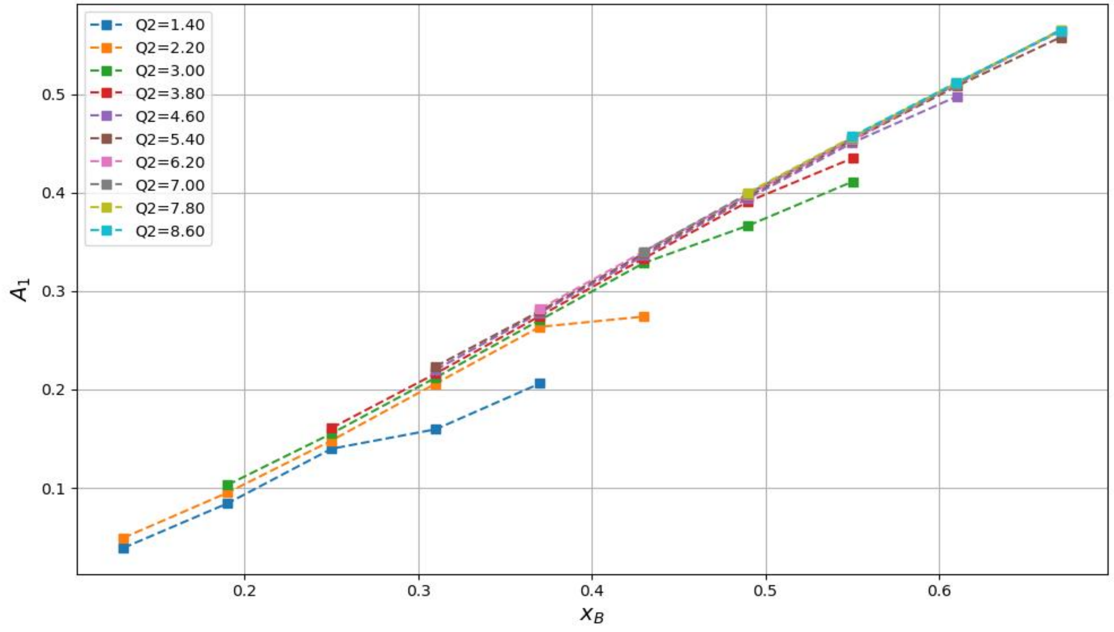


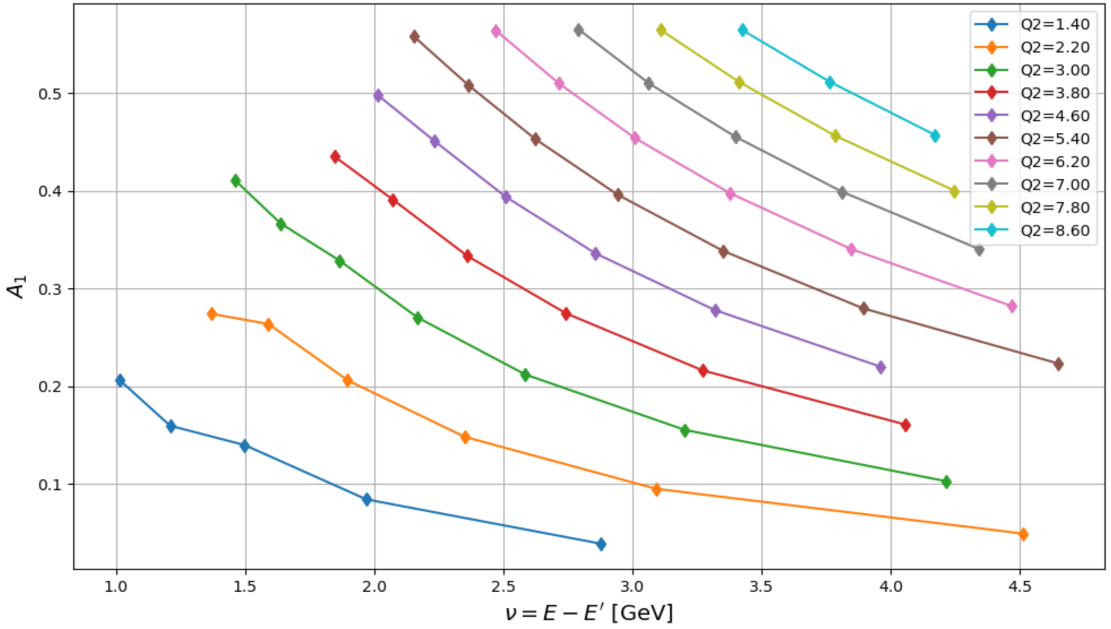


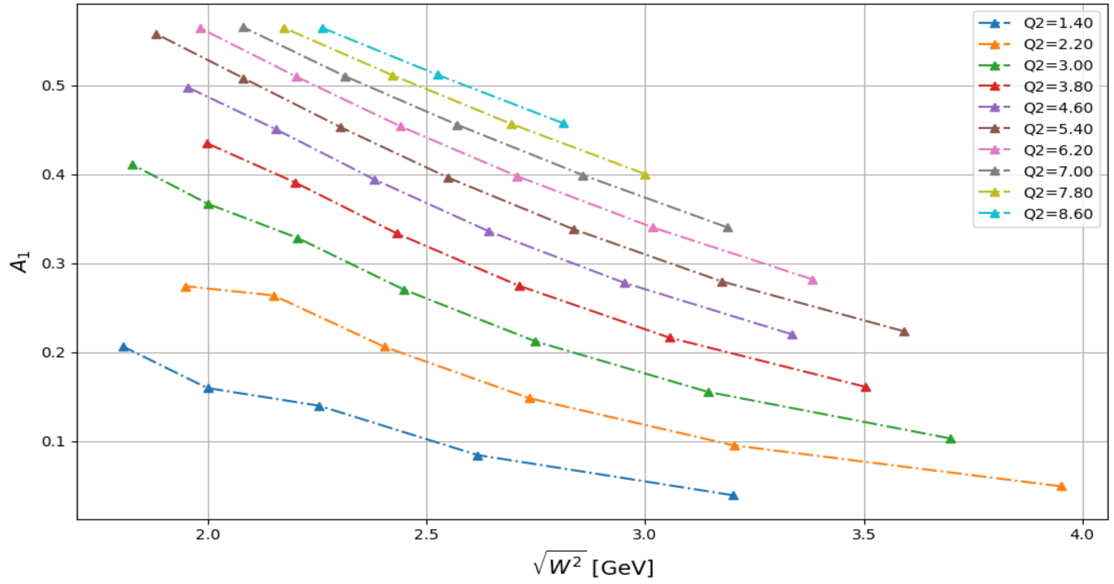


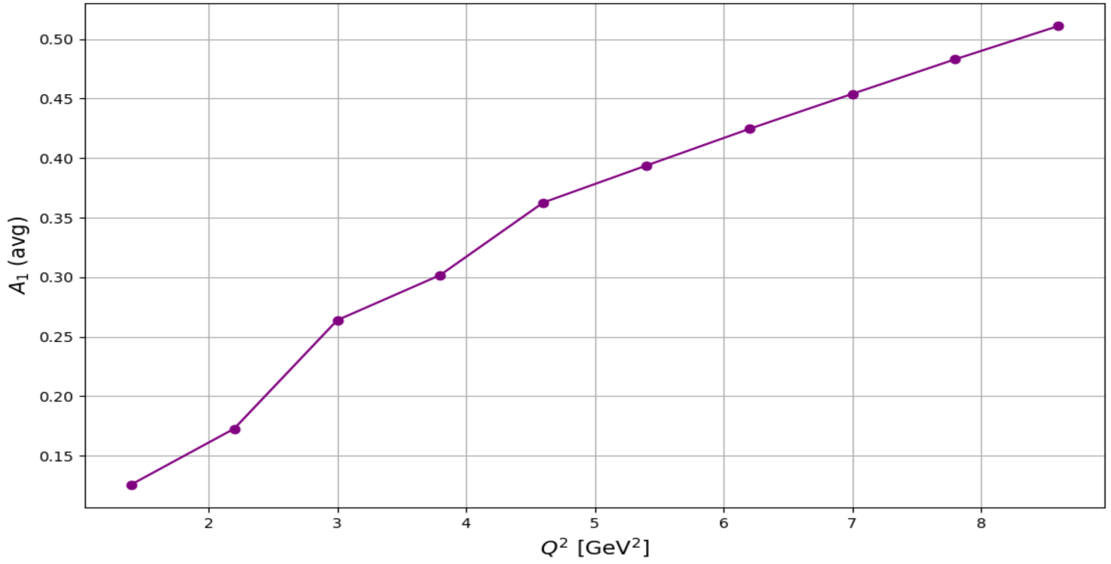


Polarized Inclusive Deep-Inelastic Scattering (Model)

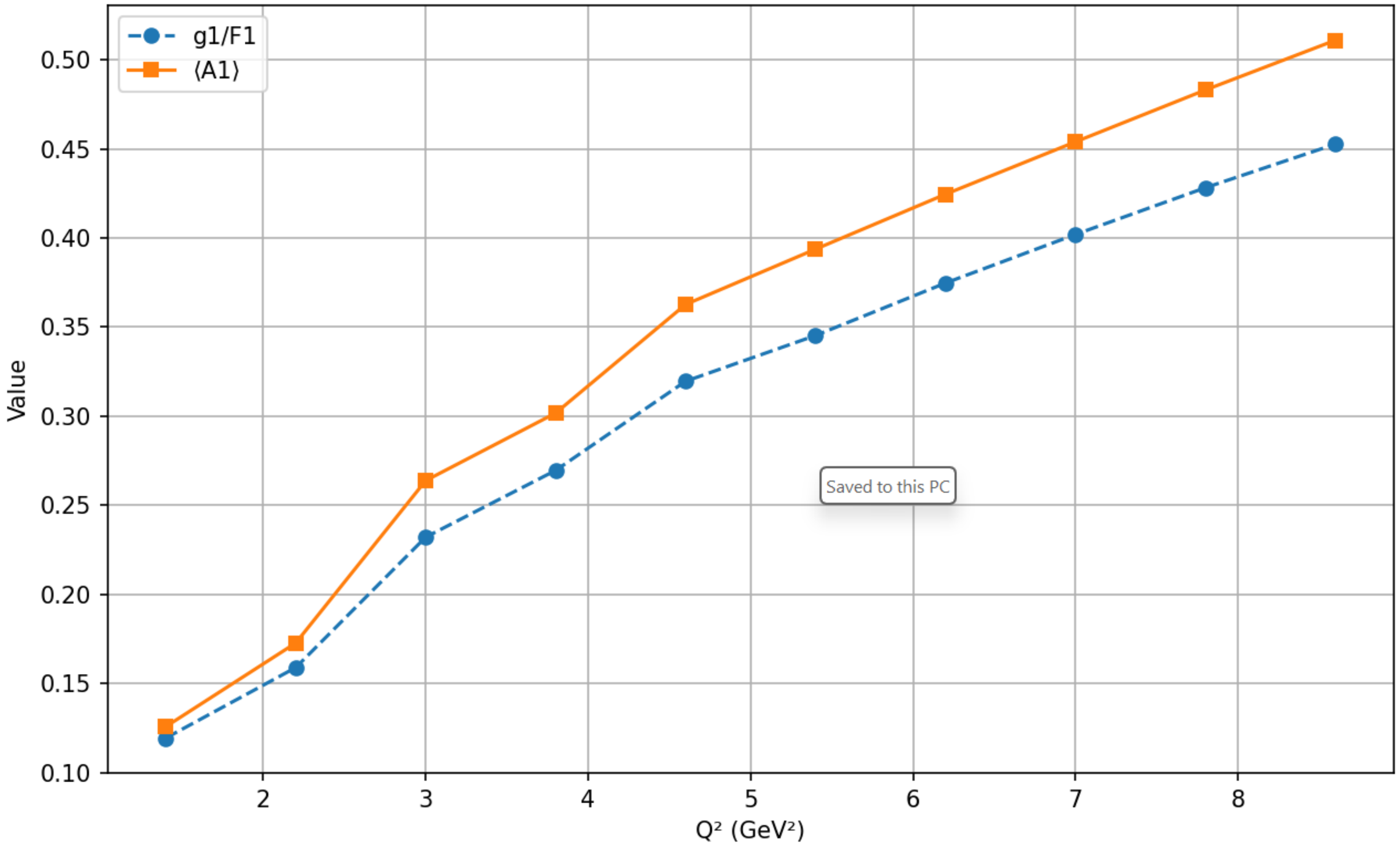








Polarized Inclusive Deep-Inelastic Scattering (Model)



- $\frac{g_1}{F_1} \approx A_1$ and help us to extract spin asymmetry in DIS.

$$A_1(x, Q^2) = \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

- A_1 can be extracted experimentally and reduced to the ratio $\frac{g_1}{F_1} \approx A_1$ when g_2 is very small.