PR12-26-002: Kinematic dependence of the beam-normal single-spin asymmetry on ^{208}Pb

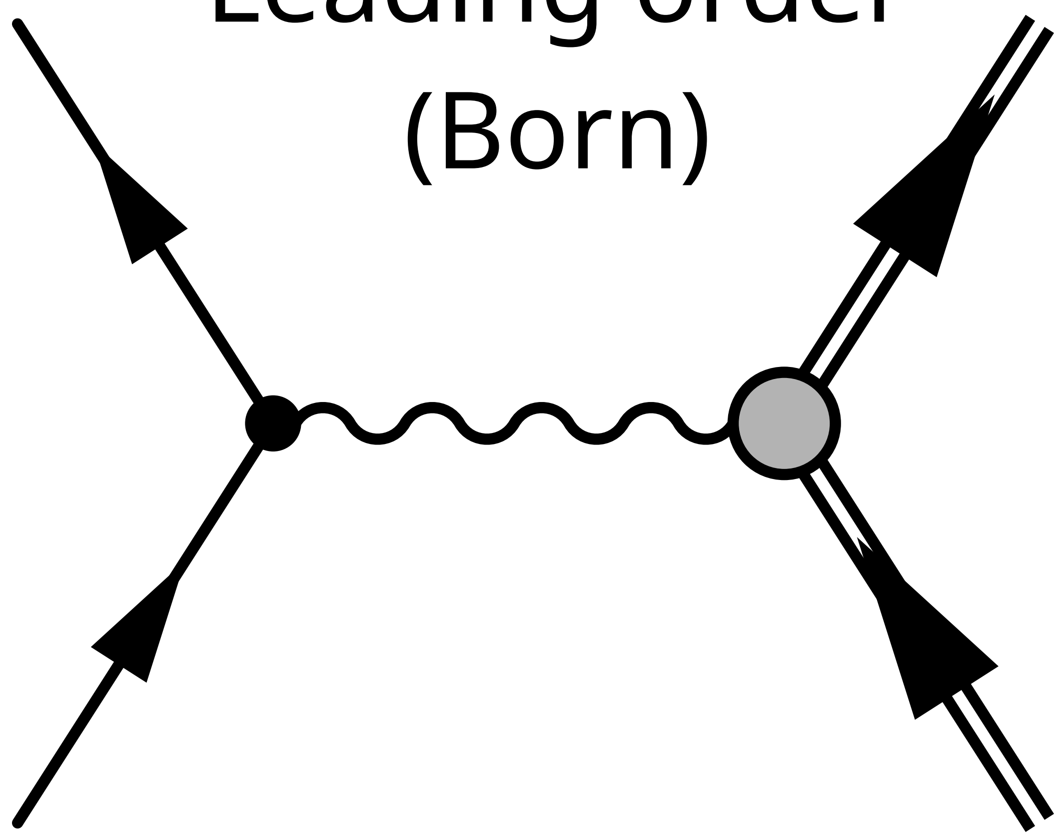
Patrick Achenbach, Tyler Kutz
JGU Mainz

Ciprian Gal, Chandan Ghosh, Sanghwa Park
Jefferson Lab

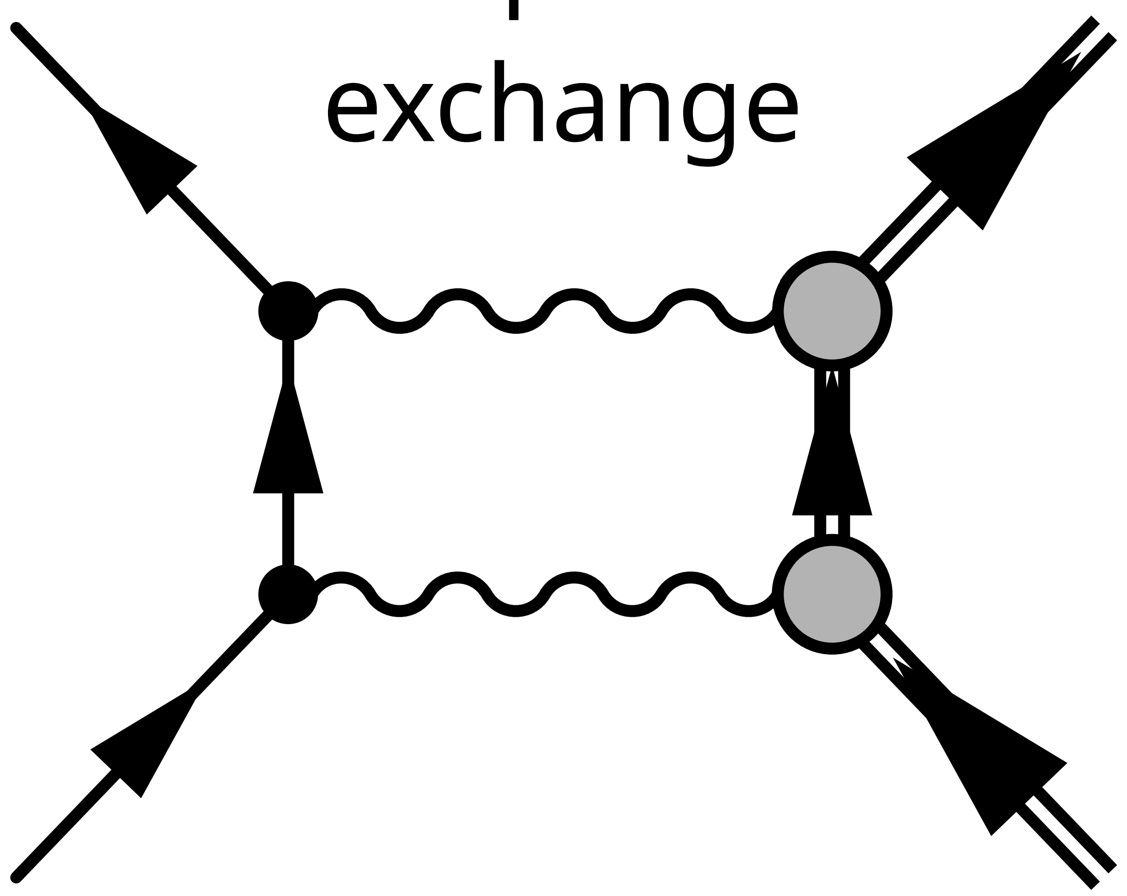
54th Jefferson Lab Program Advisory Committee Meeting
July 6-10, 2026

Beyond the Born approximation

Leading order (Born)



Two-photon exchange



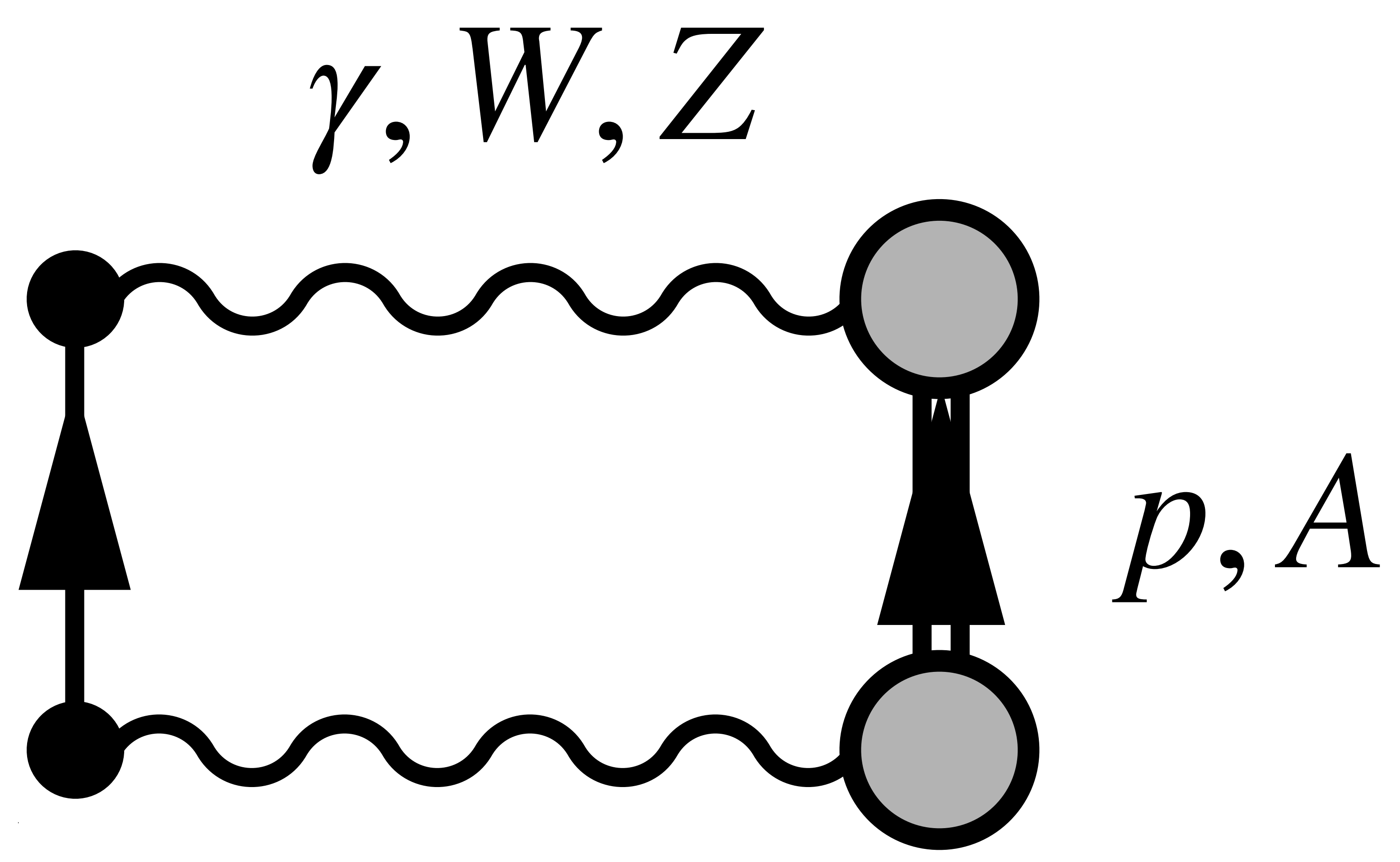
- Many electron scattering experiments interpreted in the **Born approximation** (one-photon exchange) $\rightarrow$ clean separation of leptonic, hadronic vertex
- Corrections for higher-order QED processes calculated theoretically
- Hard **two-photon exchange** not included in standard “radiative corrections”
- Treatment of off-shell intermediate hadron makes calculations difficult, model-dependent

“Box diagrams” are a *general challenge* to precision measurements

- $\gamma\gamma$-box (TPE):
  - Background asymmetries in parity-violating electron scattering (PVES)
  - Correction to Rosenbluth separation of G_E^p/G_M^p

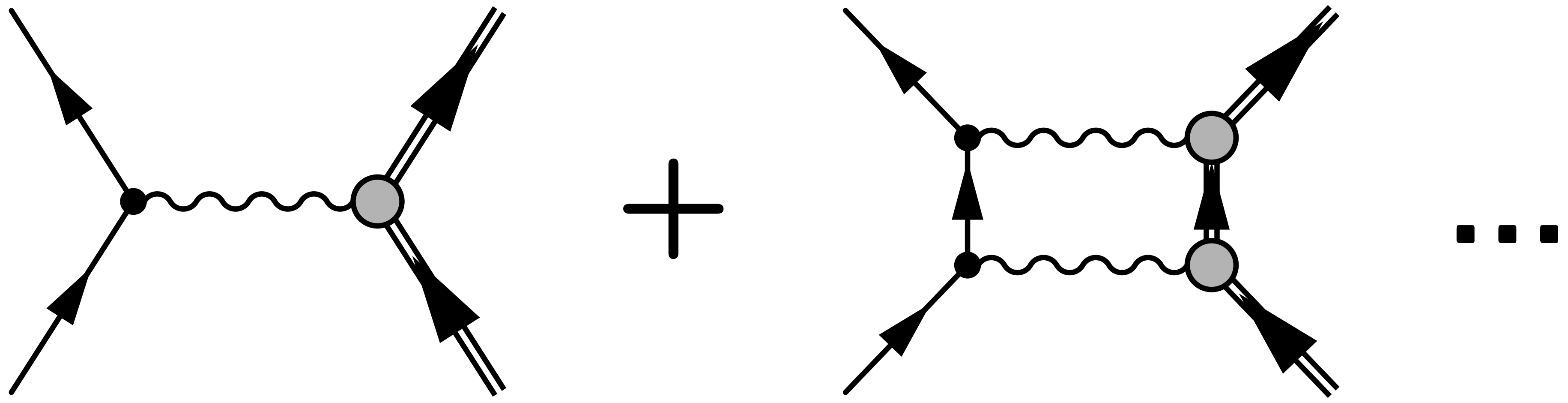
- γZ-box:
  - Radiative correction to weak mixing angle extractions from PVES

- γW-box:
  - Radiative correction to β-decay measurements used to extract CKM matrix elements

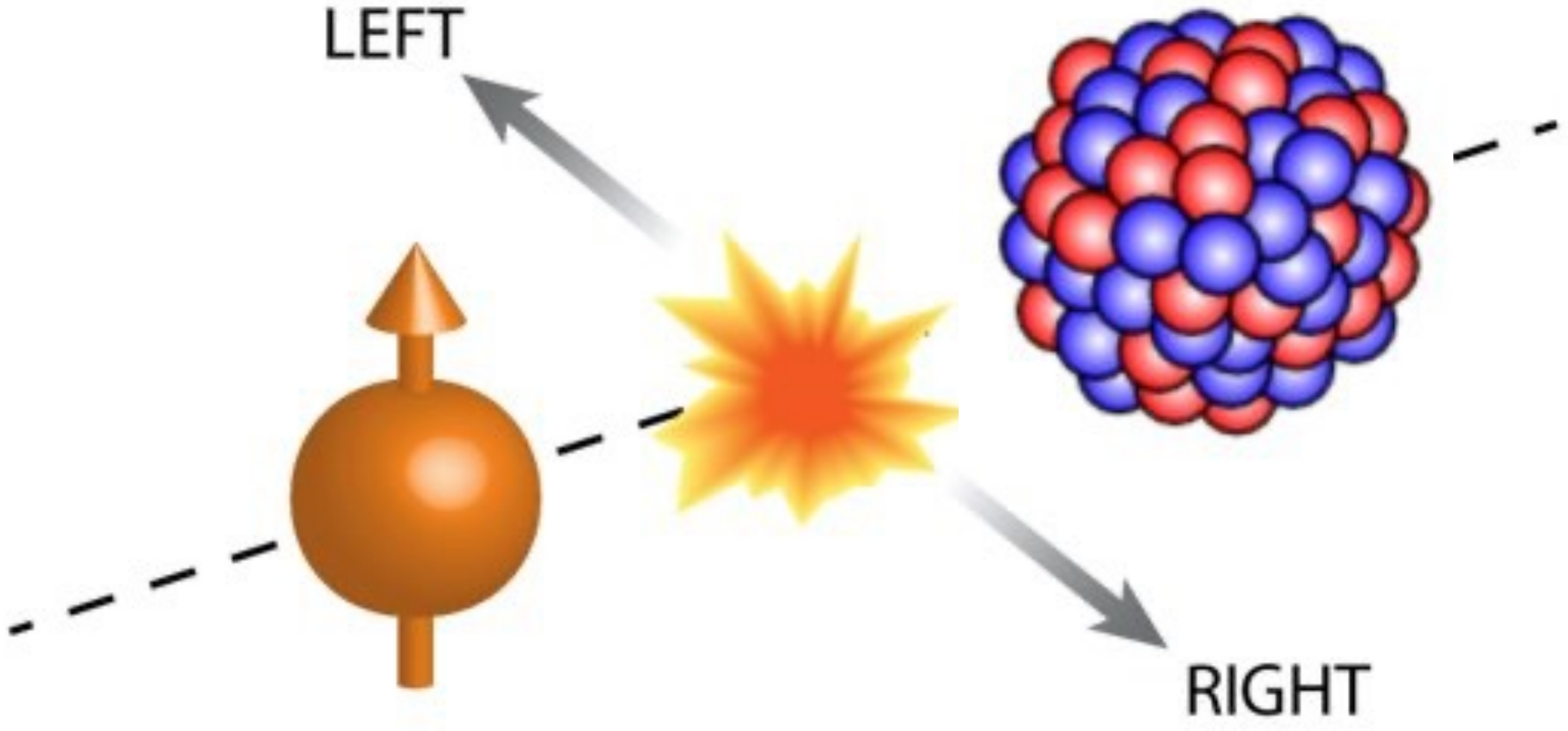


Increasing experimental precision demands better understanding of these effects

TPE gives rise to an asymmetry in transversely polarized electron scattering

$\mathcal{M} =$ 

$$A_n = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{2\mathcal{M}_{\mathrm{Born}}\mathcal{I}(\mathcal{M}_{\mathrm{TPE}})}{|\mathcal{M}_{\mathrm{Born}}|^2}$$

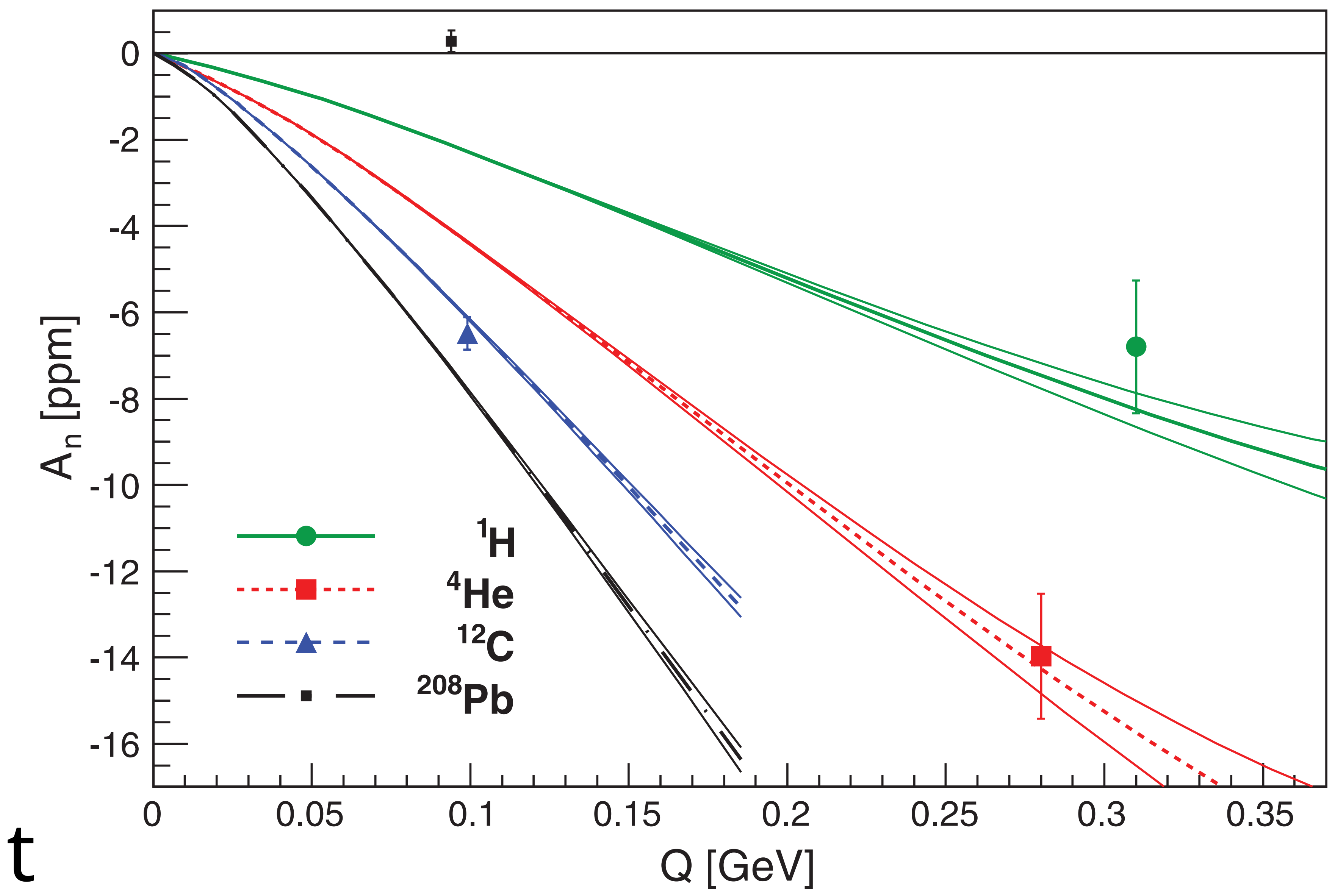


- Single-spin asymmetry (SSA) sensitive to interference with imaginary part of TPE diagram
  → vanishes in Born approximation due to time-reversal symmetry
- Background asymmetry in PVES
  → many SSA measurements carried out as systematic check by PVES experiments
- Understanding SSAs is fundamental to understanding two-photon interactions

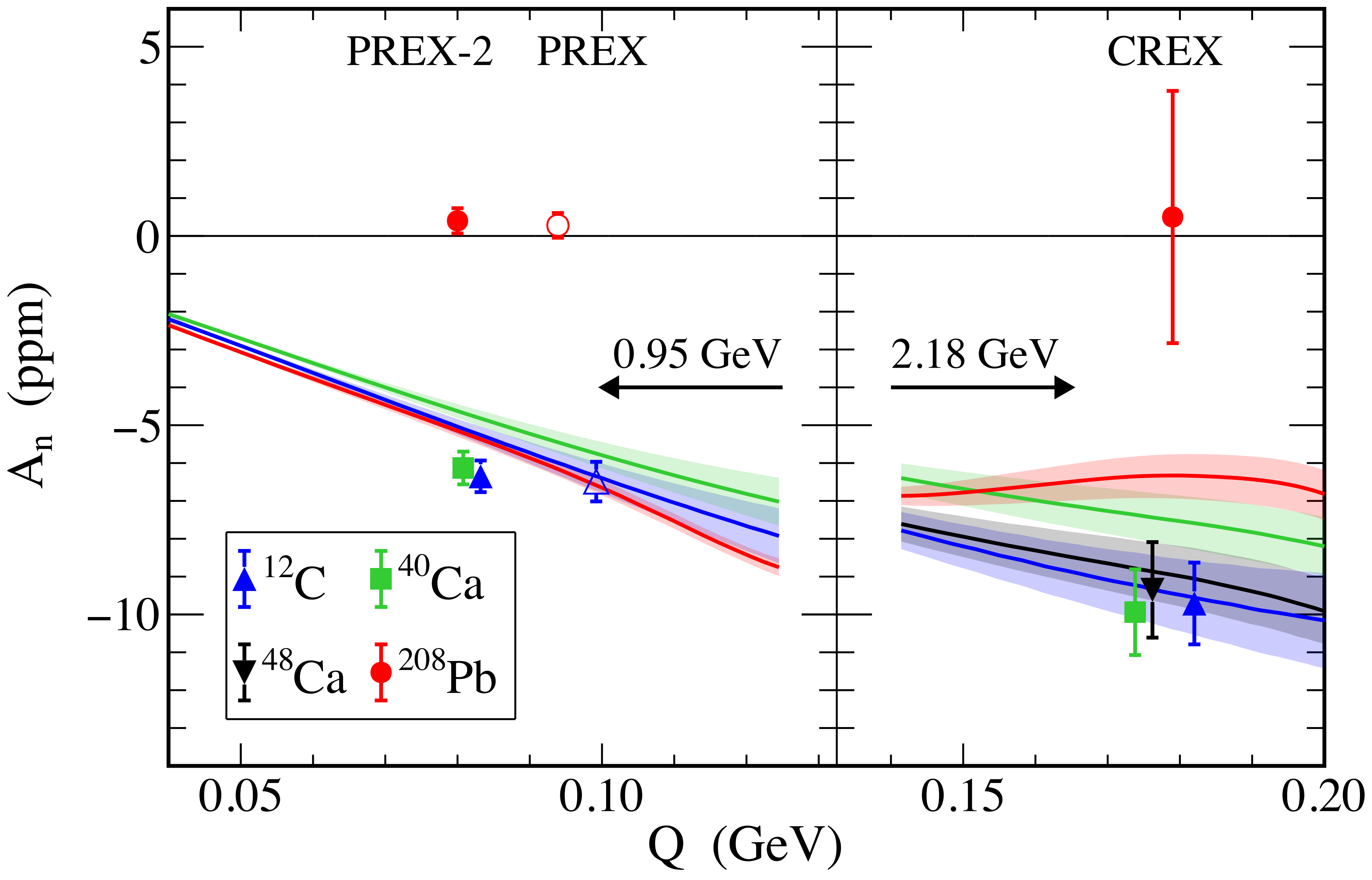
“PREX AT Puzzle”

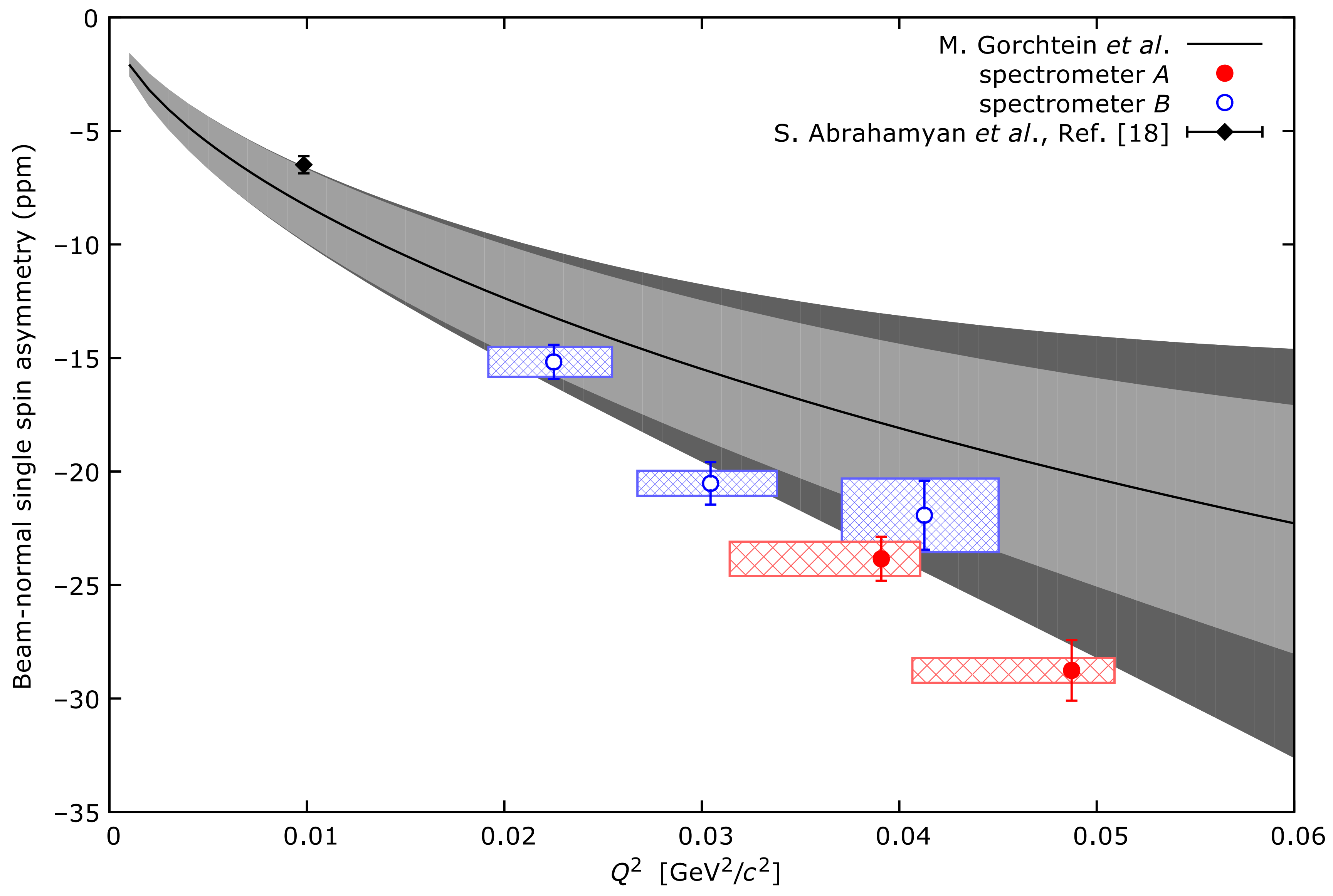
- For $Z \leq 40$ (^{90}Zr):
  - Little to no nuclear dependence
  - Reasonable agreement with theory
- ^{208}Pb in striking disagreement with model prediction
  - Measurements at three Q^2, all consistent with zero

HAPPEX/PREX, PRL 109, 192501 (2012)

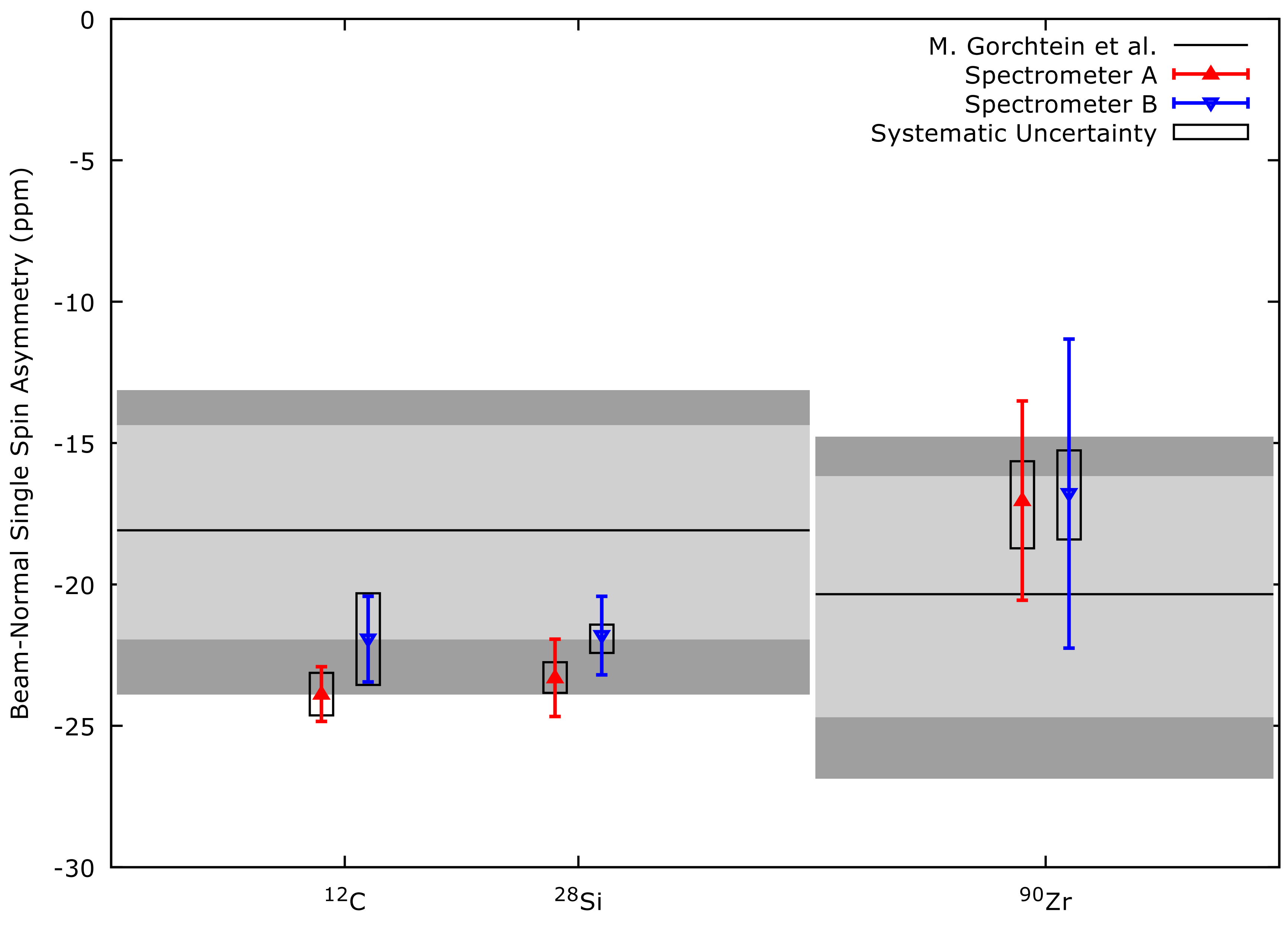


PREX/CREX, PRL 128, 142501 (2022)





Esser, Thiel, et al., PRL 121, 022503 (2018)

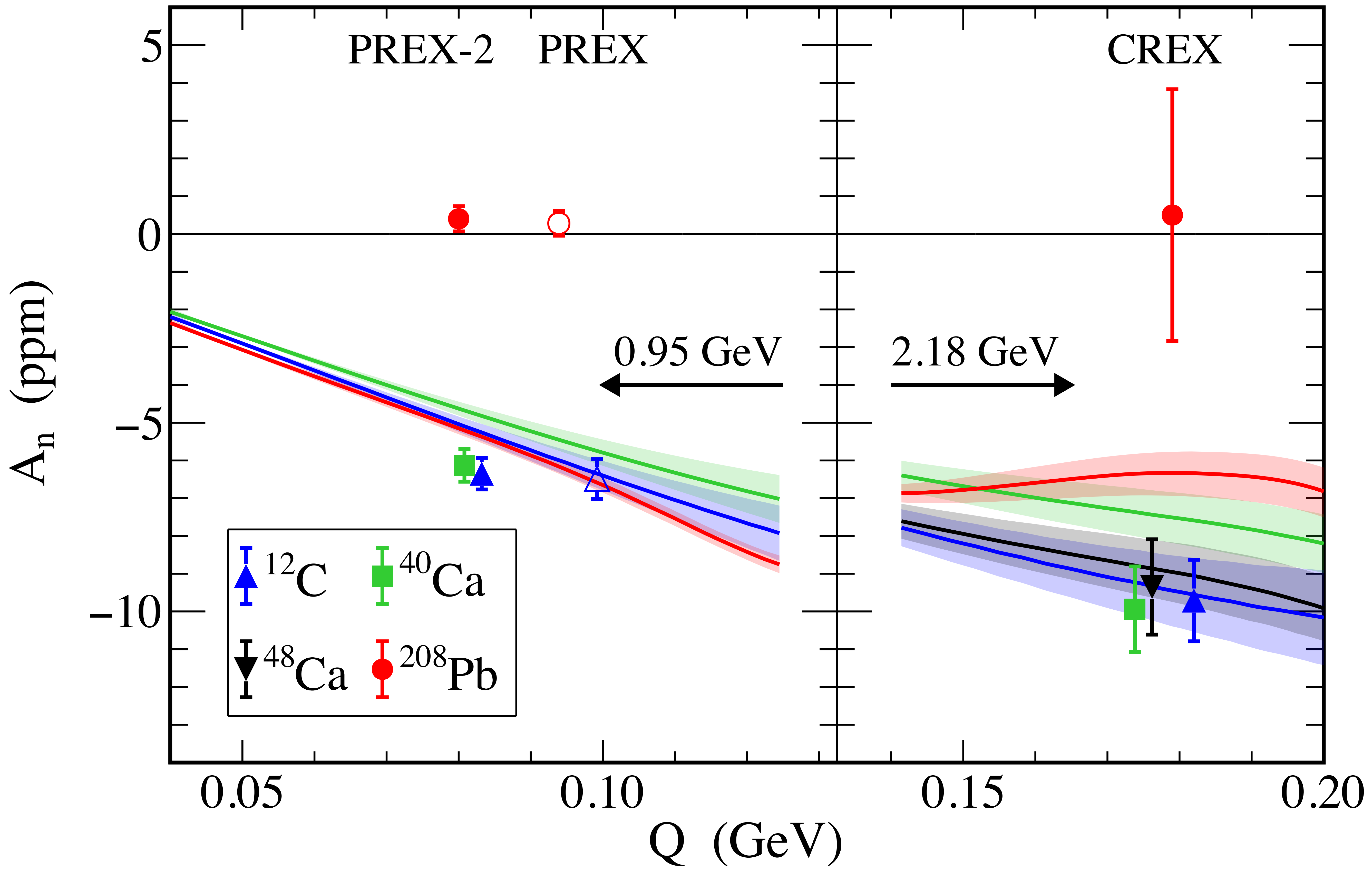


Esser, Thiel, et al., PRB 808, 135664 (2020)

“PREX AT Puzzle”

[PREX/CREX, PRL 128, 142501 (2022)](#)

- For $Z \leq 40$ (^{90}Zr):
  - Little to no nuclear dependence
  - Reasonable agreement with theory
- ^{208}Pb in striking disagreement with model prediction
  - Measurements at three Q^2, all consistent with zero



- Calculations by Koshchii, et al. PRC 103, 064316 (2021) include Coulomb distortion + inelastic states
- Persistent disagreement suggests *nuclear dependence* not accounted for in existing theoretical models

Towards a resolution: E12-24-007

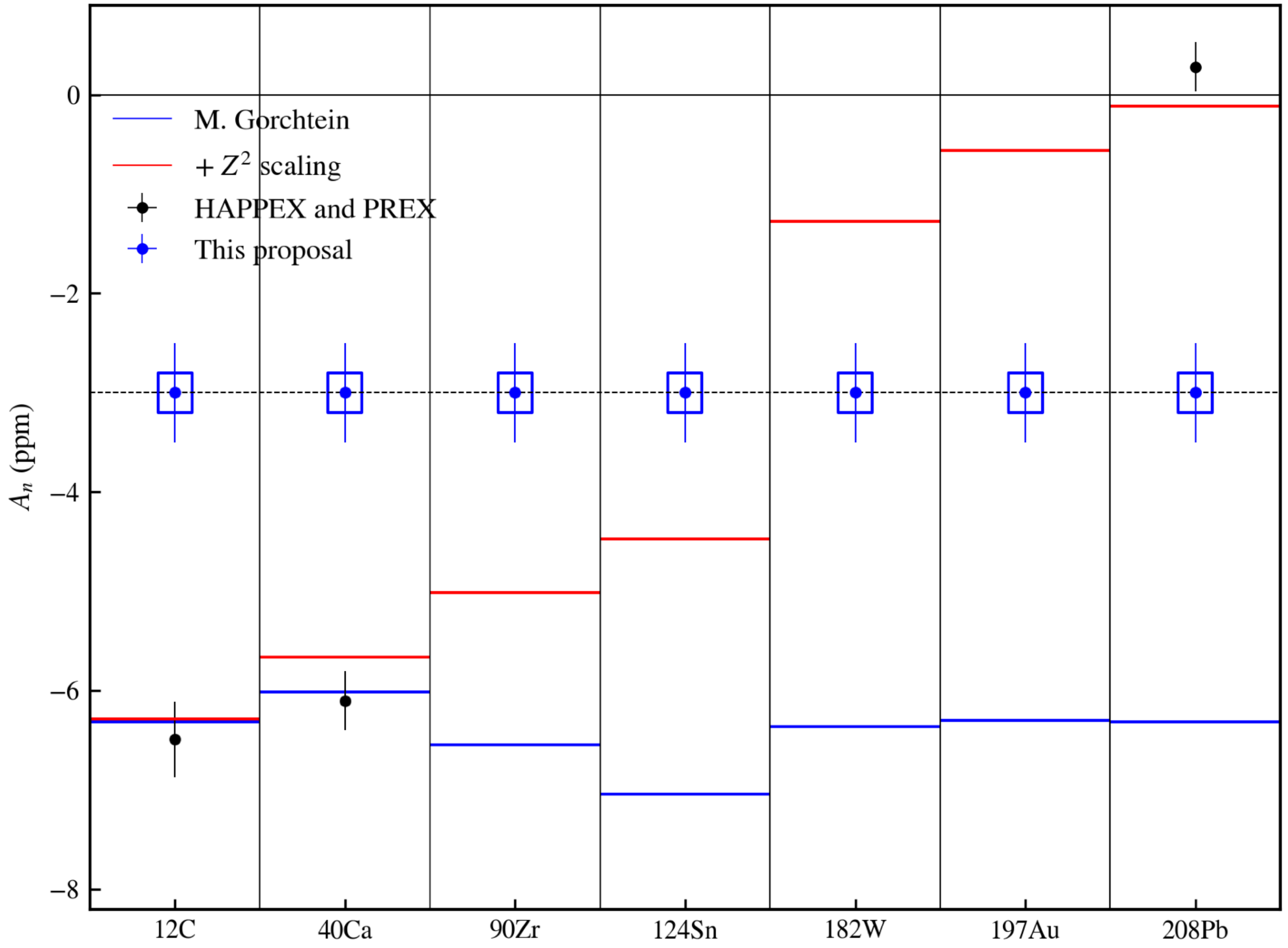
- Proposal to measure the *nuclear dependence* of A_n
  - Novel measurements of seven nuclei heavier than ^{90}Zr

- Proposed kinematics similar to PREX: E = 1 GeV, θ = 5.5°

- Test Z-vertex radiative correction hypothesis ("Z^2-scaling"): $A_n \approx A_0(Q^2)\left(1 - C \cdot \alpha Z^2\right)$

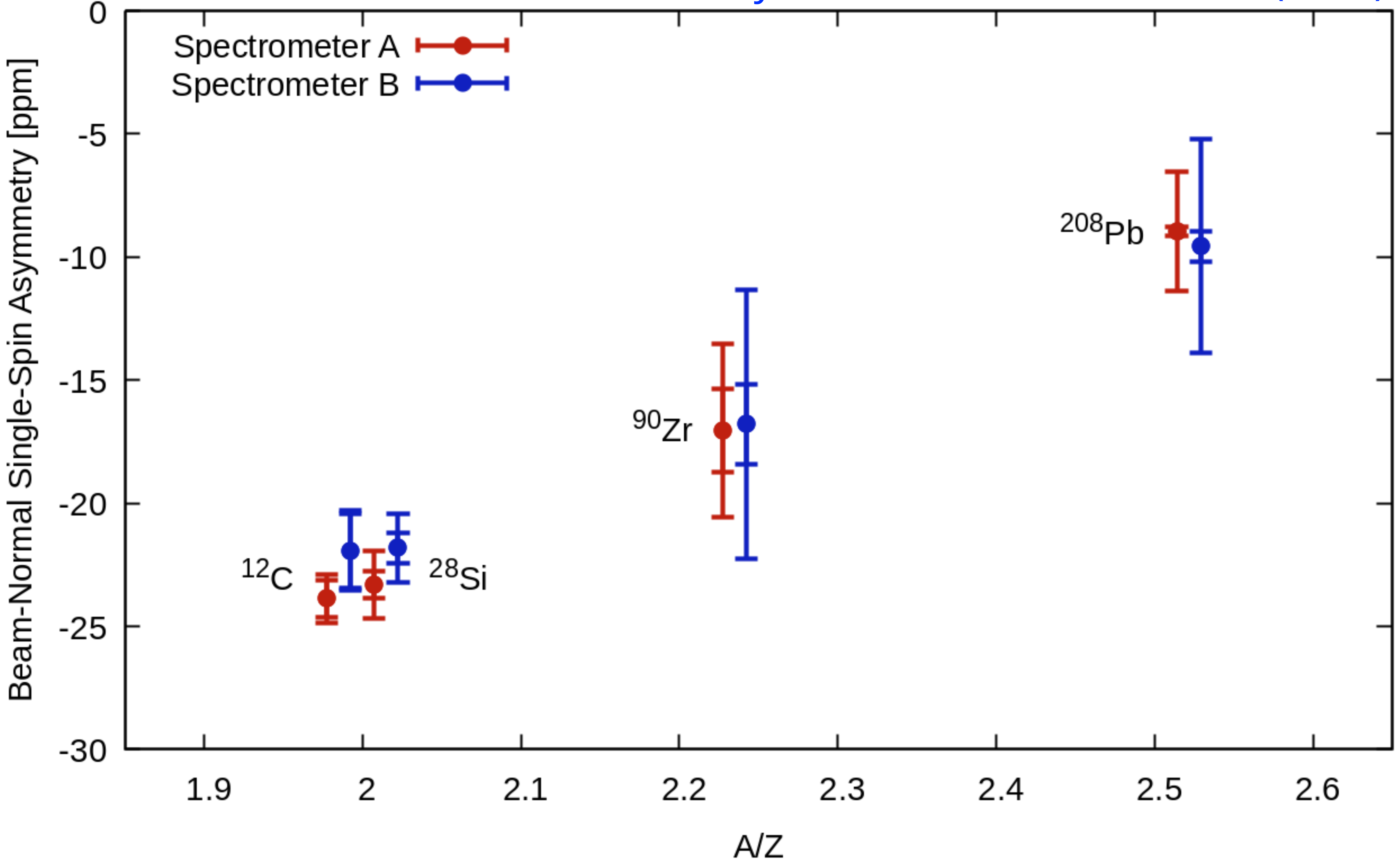
- E12-24-007 approved by PAC52 in 2024, planned to run 2027

Target	Proton number	Thickness (mg/cm^2)	Beam current (μA)	Rate (MHz)	Beam time (hours)	Position scan (hours)
^{12}C	6	1280.9	30	494	1.76	20
^{40}Ca	20	483.13	30	411	2.11	-
^{90}Zr	40	301.6	30	306	2.84	-
^{124}Sn	50	276.1	30	261	3.32	20
^{140}Ce	58	238.3	30	247	3.51	-
^{142}Nd	60	227.5	30	246	3.52	-
^{144}Sm	62	217.7	30	245	3.54	-
^{182}W	74	200.8	30	216	4.02	-
^{197}Au	79	193.8	30	207	4.20	20
^{208}Pb	82	191.1	30	200	4.34	20
^{232}Th	90	182.2	30	189	4.60	-
					Total production beam time	5.1 days



Update 2025: New results from A1 (MAMI)

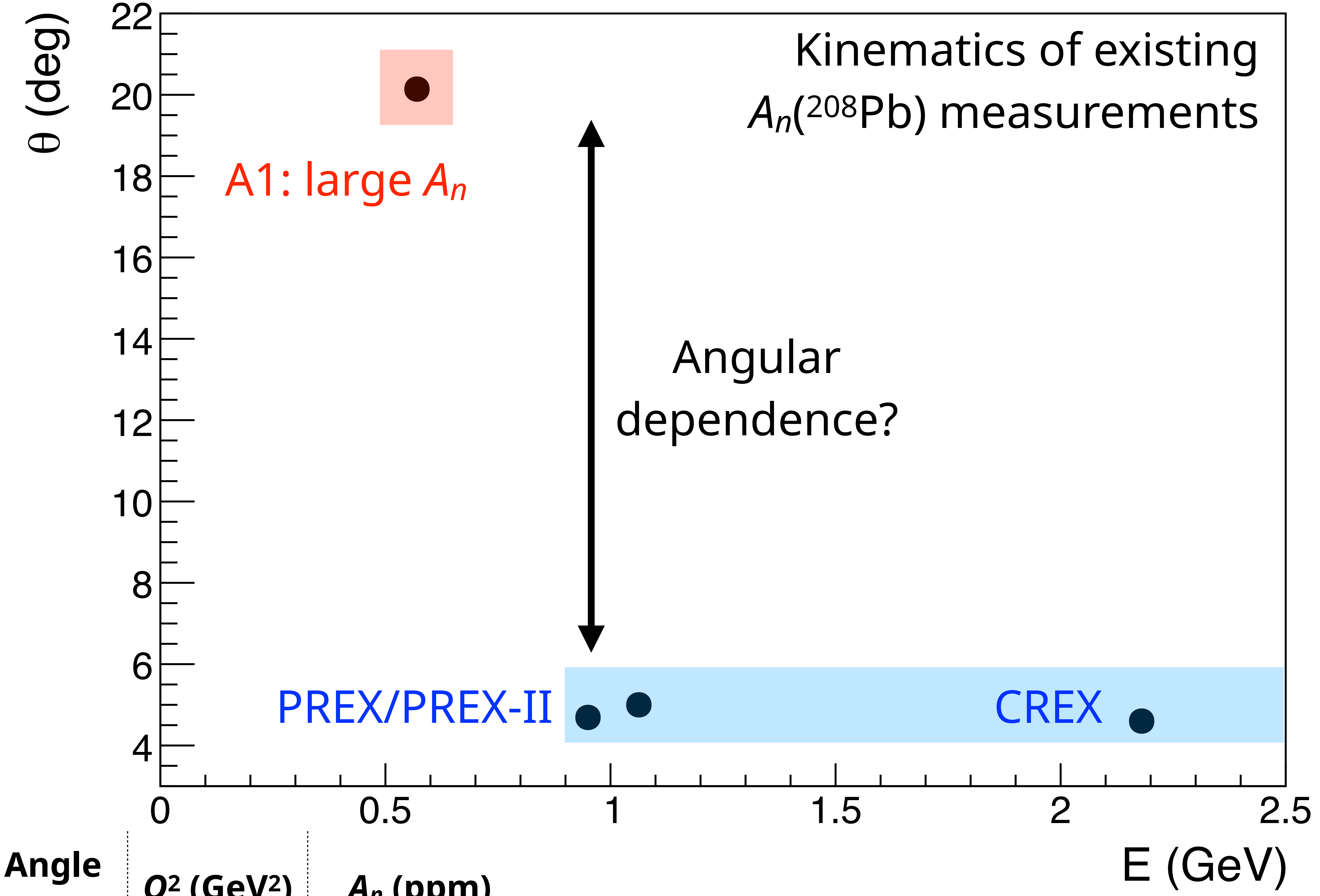
Esser, Kozyrev, et al., PRL 135, 232502 (2025)



- Lower energy (E = 0.57 GeV) and larger angle (θ = 20°) than JLab measurements
- **Large (negative) asymmetry:** A_n **= -9.1 ± 2.1 (stat.) ± 0.7 (syst.) ppm**

MAMI measurement suggests *kinematic dependence* not accounted for in existing theoretical models

Status

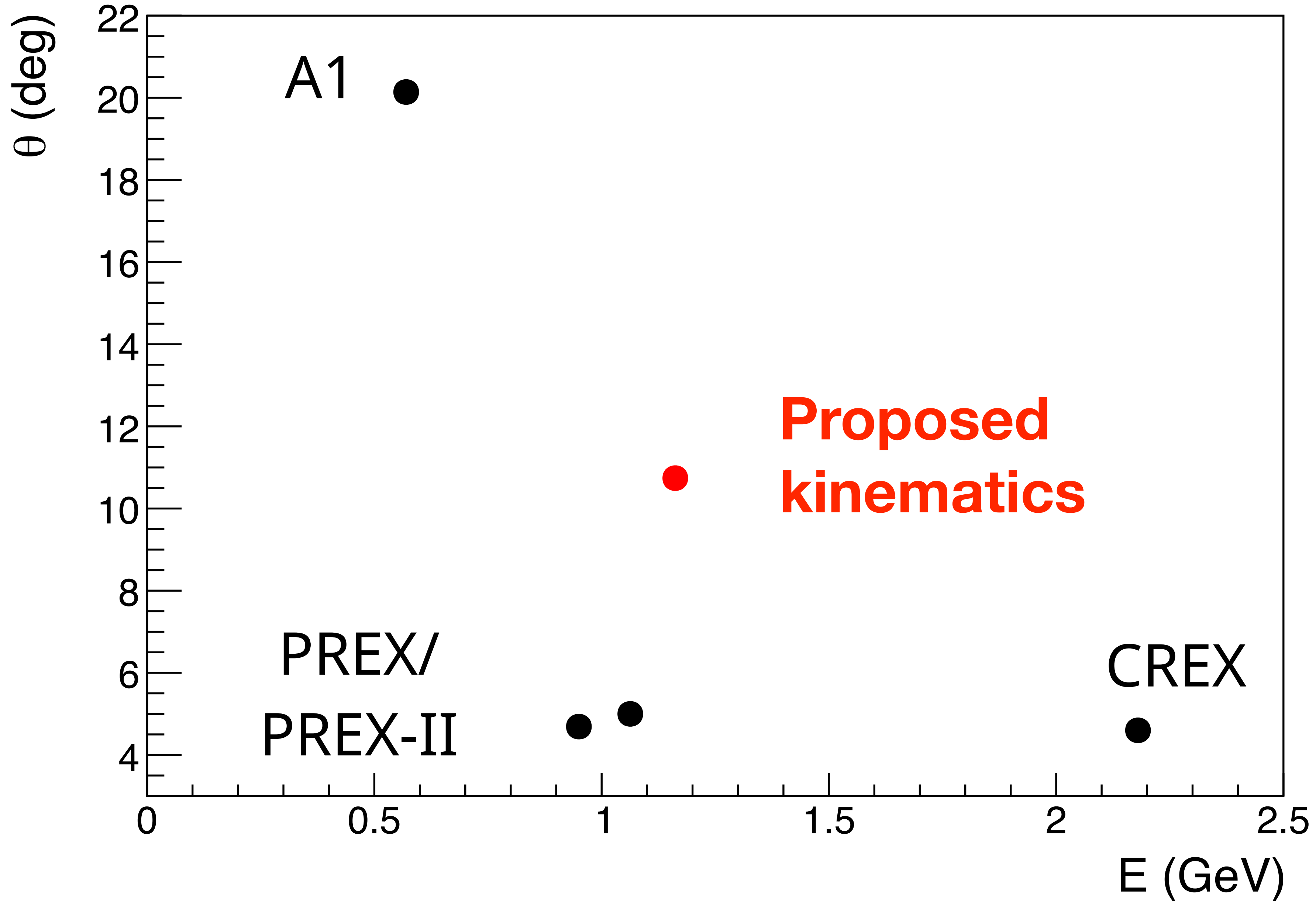


JLab experiments:
Vanishing A_n at 5°,
$0.95 < E < 2.18$ GeV

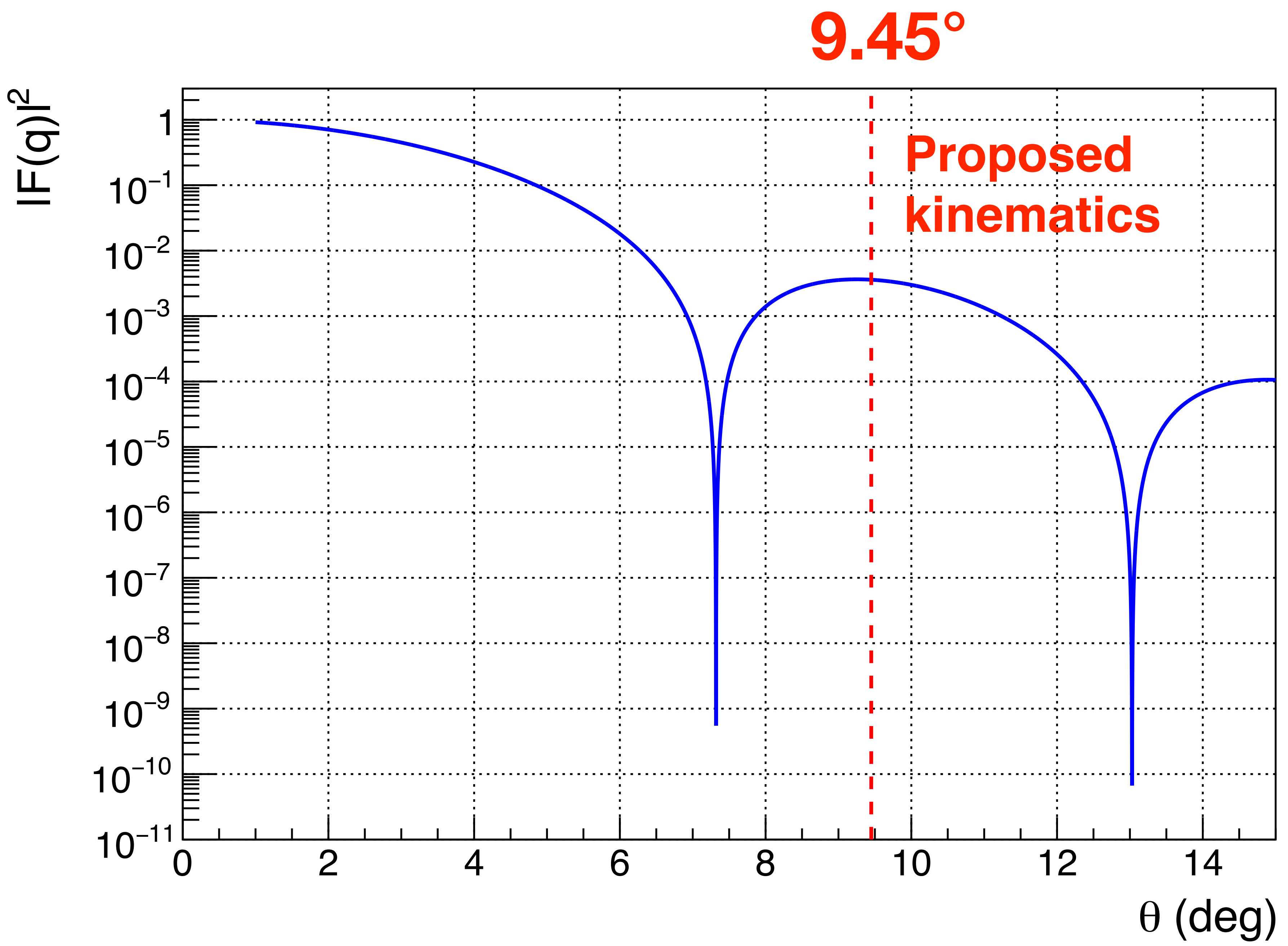
Experiment	E_{beam} (GeV)	Angle (deg)	Q^2 (GeV^2)	A_n (ppm)
PREX-I	1.063	6	0.00984	0.28 ± 0.25
PREX-II	0.95	4.69	0.0062	0.4 ± 0.2
CREX	2.18	4.60	0.031	0.6 ± 3.2
A1	0.57	20.14	0.04	-9.1 ± 2.2

Proposal PR12-26-002

- Measure A_n on ^{208}Pb at scattering angle in between JLab and MAMI measurements
- Must balance larger desired angle and decreasing cross section



Beam energy	1.162 GeV
Beam current	60 μA
Beam polarization	80% (transverse)
Target material	^{208}Pb
Target thickness	191.1 mg/cm^2
Scattering angle	9.45°
Rate	911 kHz
Beamtime (production)	9 days
Beamtime (commissioning)	1 day
Beamtime (total)	**10 days**

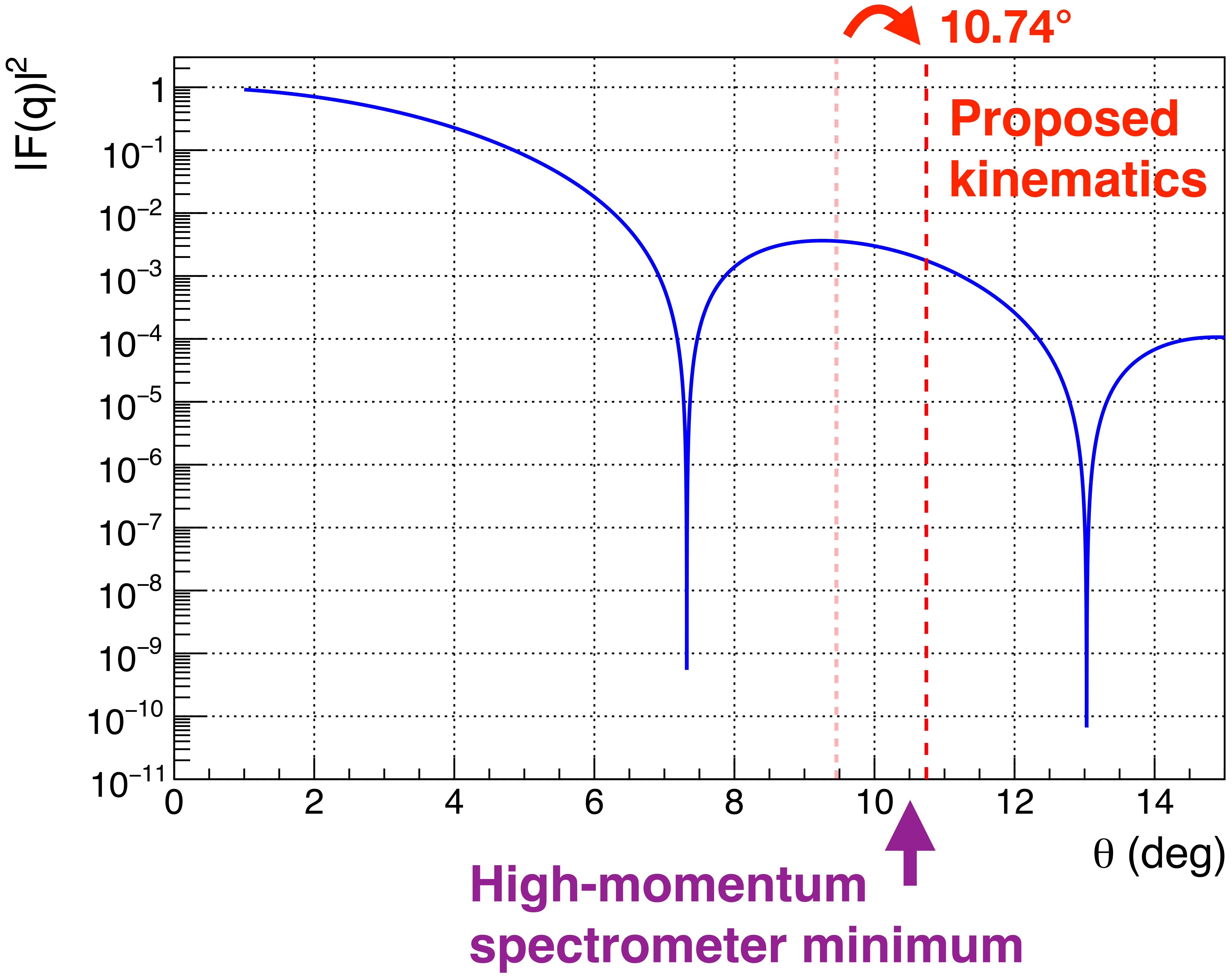


Update #1: Beam current of 25 μA (originally proposed 60 μA)

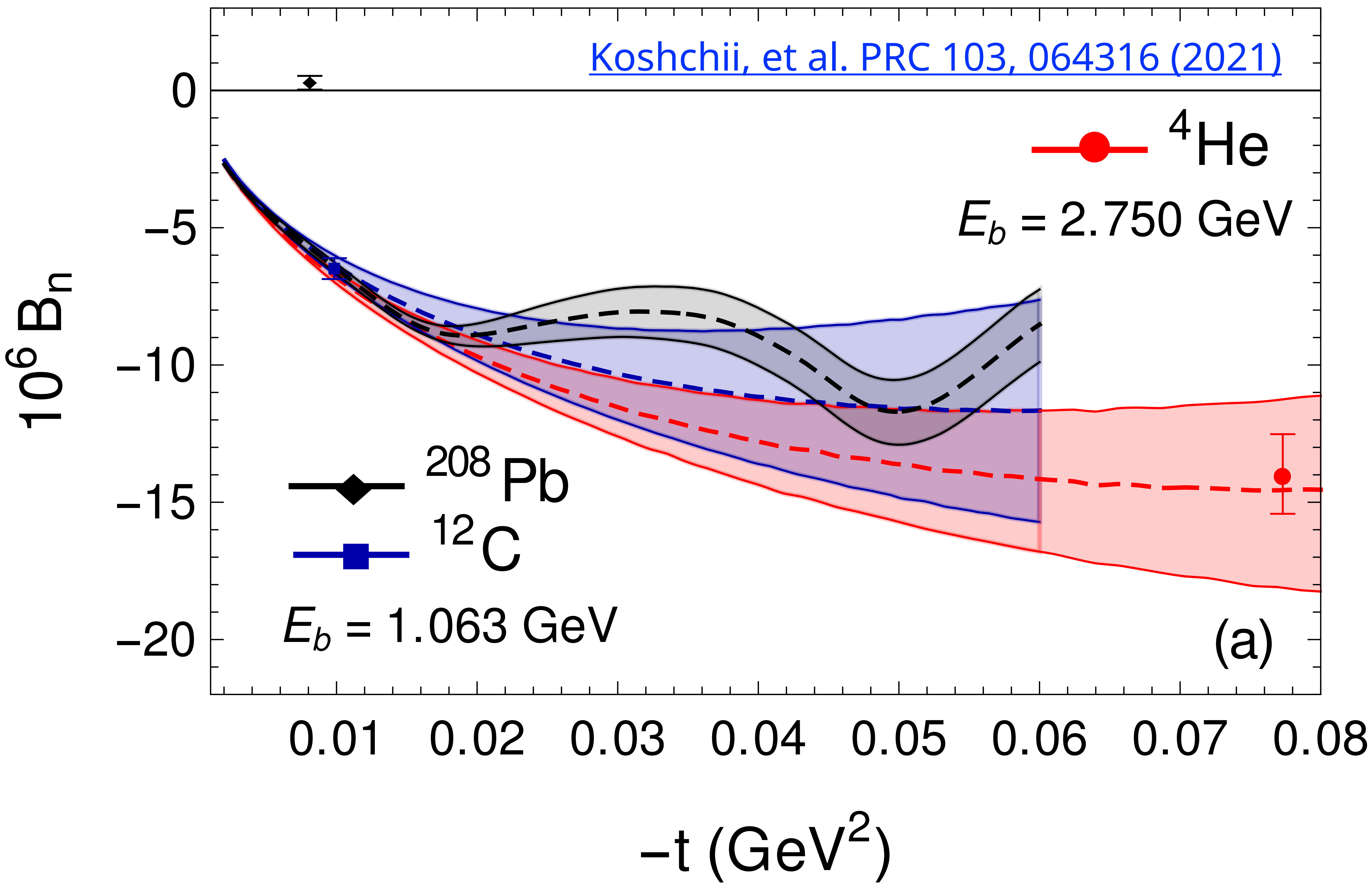
- Target ladder *will not* be cryogenically cooled, limiting beam current

Update #2: Scattering angle of 10.74° (originally proposed 9.45°)

- Allows use of *both spectrometers* in Hall C, recovering rate lost by lowering beam current
- Improved systematics with symmetric ϕ measurements



How big could the asymmetry be?



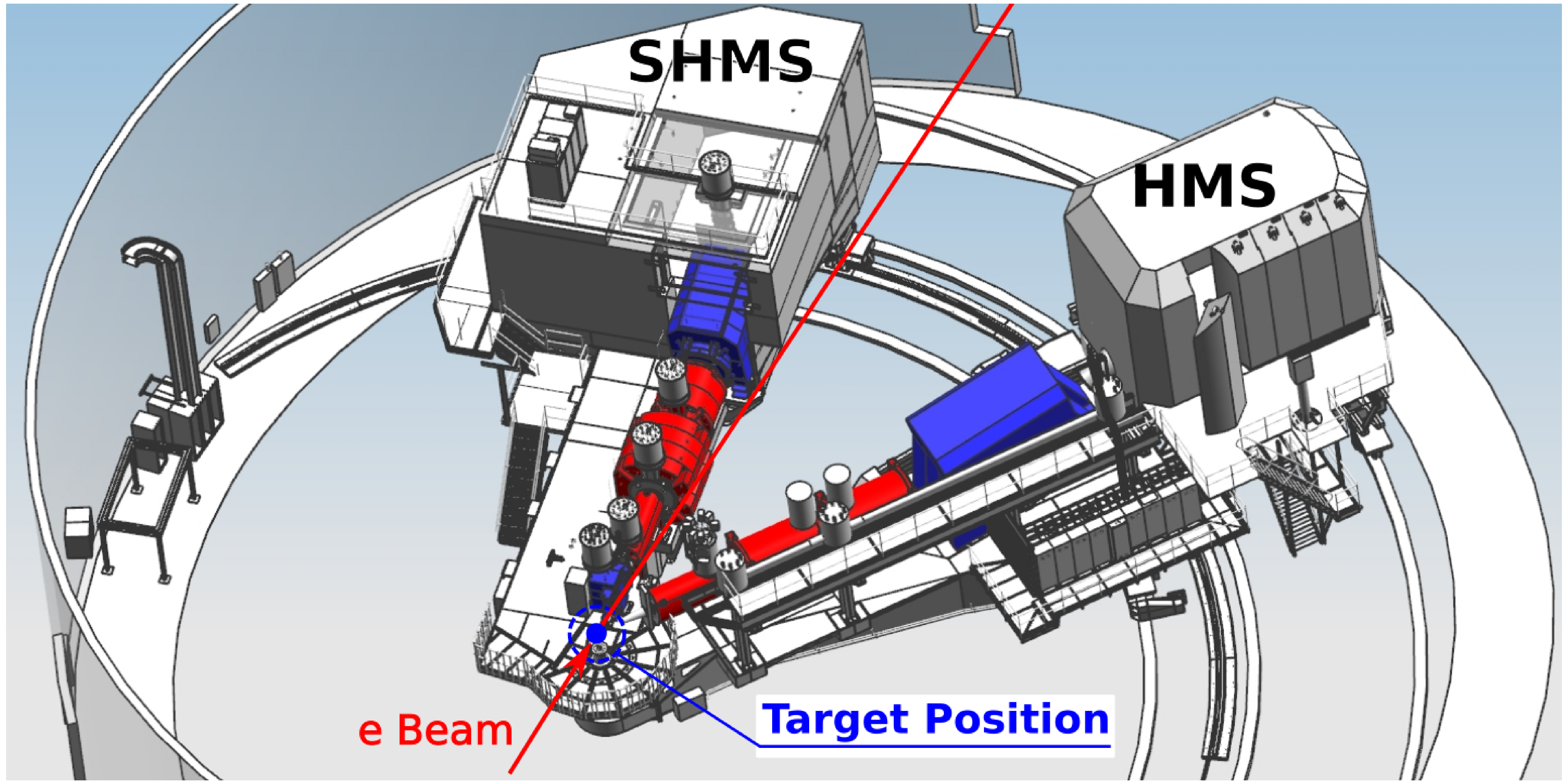
E = 1 GeV, θ = 10.74°

→ Q^2 = 0.035 GeV^2

- Recent theory calculations predict $A_n \approx$ -8 ppm
- Interpolating between JLab and MAMI measurements gives A_n of a few ppm

→ Aim to measure the asymmetry to a precision of 1.5 ppm

Experimental setup in Hall C



	SHMS	HMS
Scattering angle (deg)	5.5 - 40	10.5 - 80
Acceptance (msr)	≈ 4	≈ 6
Central momentum (GeV)	1 - 11	0.5 - 7

- 1 GeV transversely polarized beam at 25 μA
- Lead foil target sandwiched between graphite foils
  - Graphite facilities transfer of heat out of lead
  - Successfully implemented (at higher currents) for PREX/PREX-II
- Both the SHMS and HMS positioned at central scattering angle of 10.74°

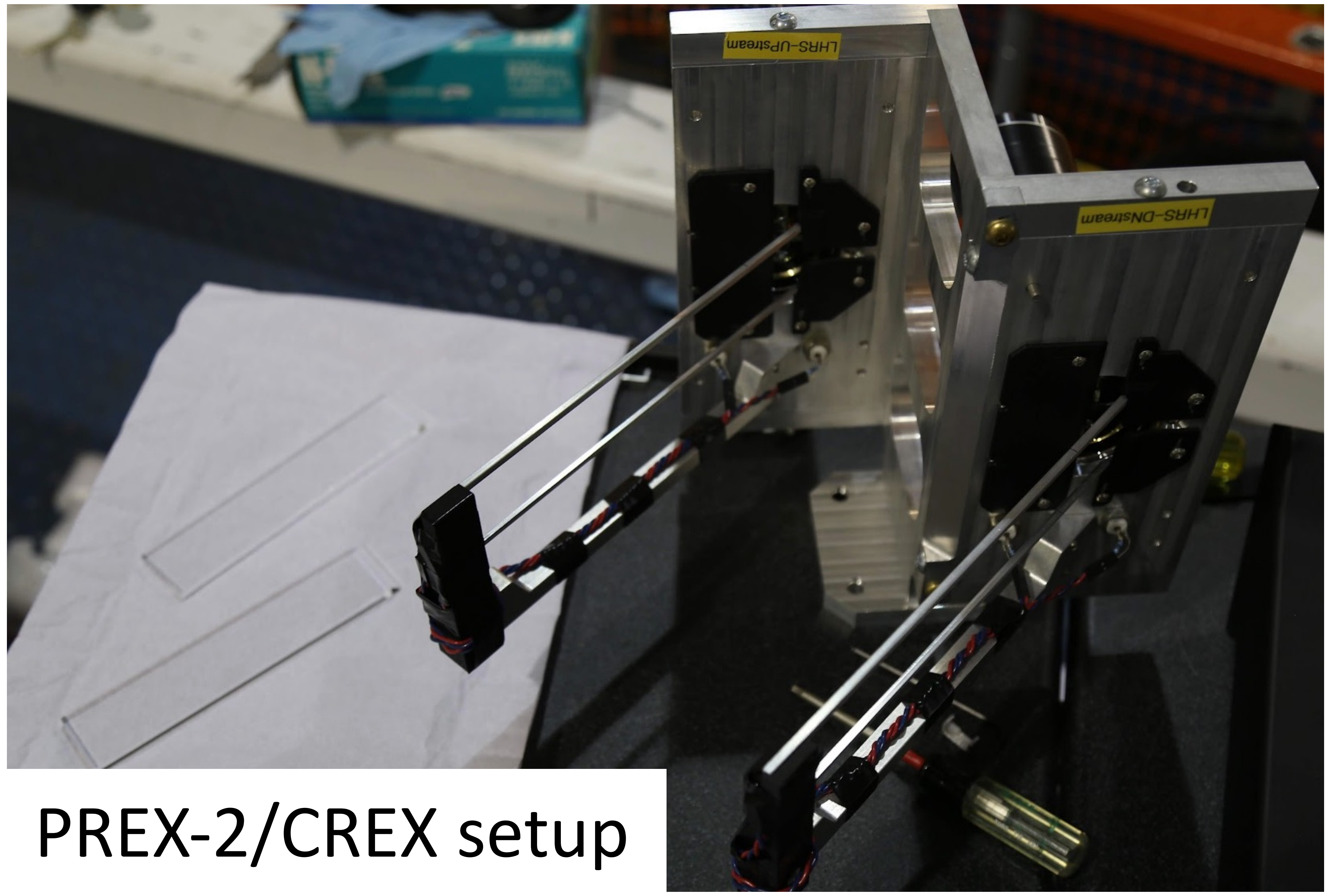
Use both spectrometers

Synergies with E12-24-007

- PR12-26-002 (this proposal) is identical in approach and methodology to E12-24-007, only with a different spectrometer setting
- If the proposed measurement were carried out in tandem with E12-24-007, it could take advantage of common requirements:
    1. Establishing parity-quality beam
    2. Spin-dance procedure for measuring transverse polarization in Hall C
    3. Target and detector setup (E12-24-007 will only use the SHMS…installation of detector in HMS could be done in parallel)
    4. Certain auxiliary runs for calibration and systematic studies
- While *advantageous*, running in tandem with E12-24-007 is not *critical* to this measurement

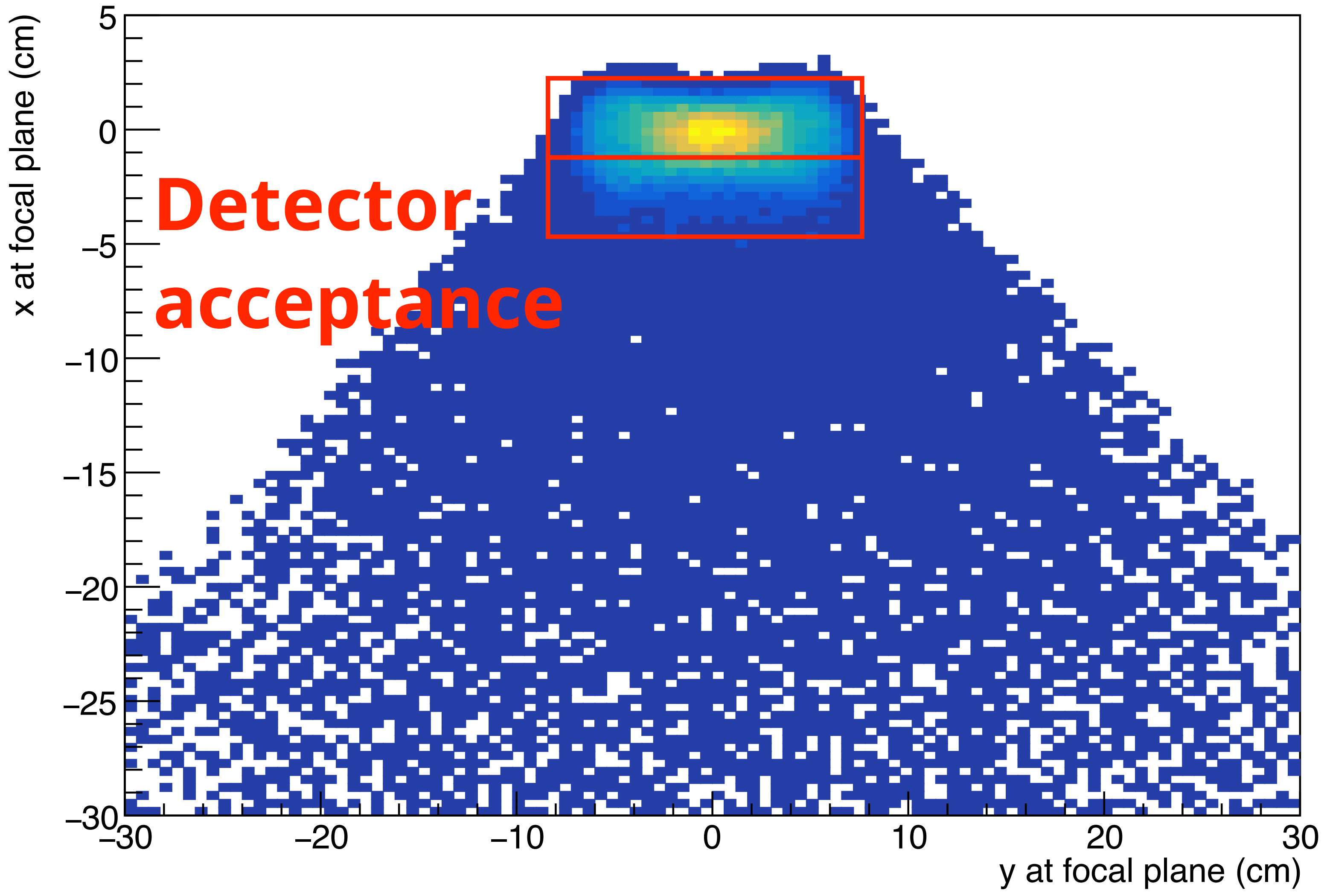
Detecting elastic electrons

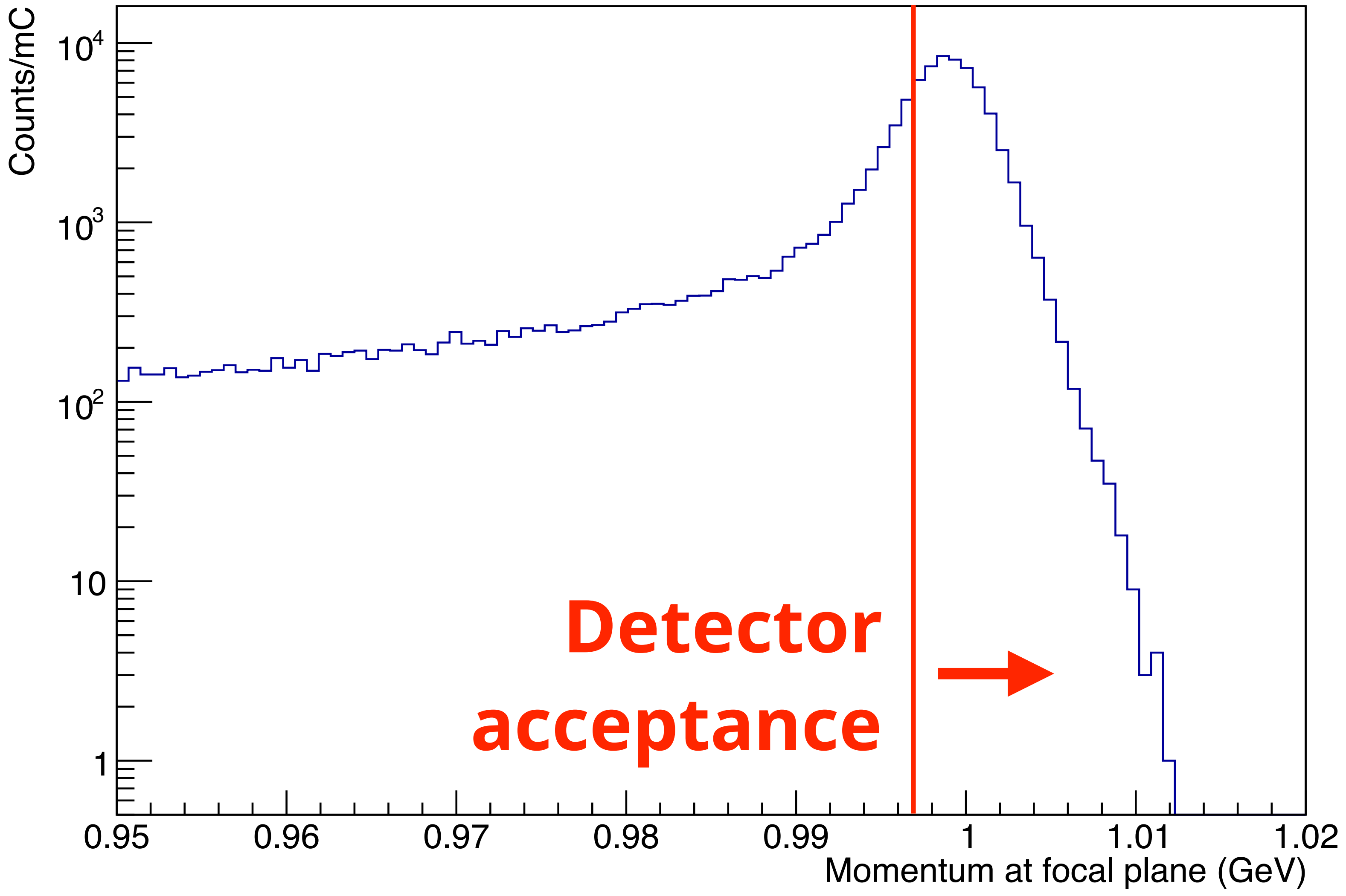
- Detect electrons with integrating quartz Cherenkov detector
  - Make use of setup, experience from PREX/CREX experiments
- First excited state of ^{208}Pb is 2.6 MeV below elastic peak
  - Well-separated by spectrometers
- Motion stage to optimize detector position
  - Adjust edge of quartz to maximize elastic acceptance, cut out inelastic events



PREX-2/CREX setup

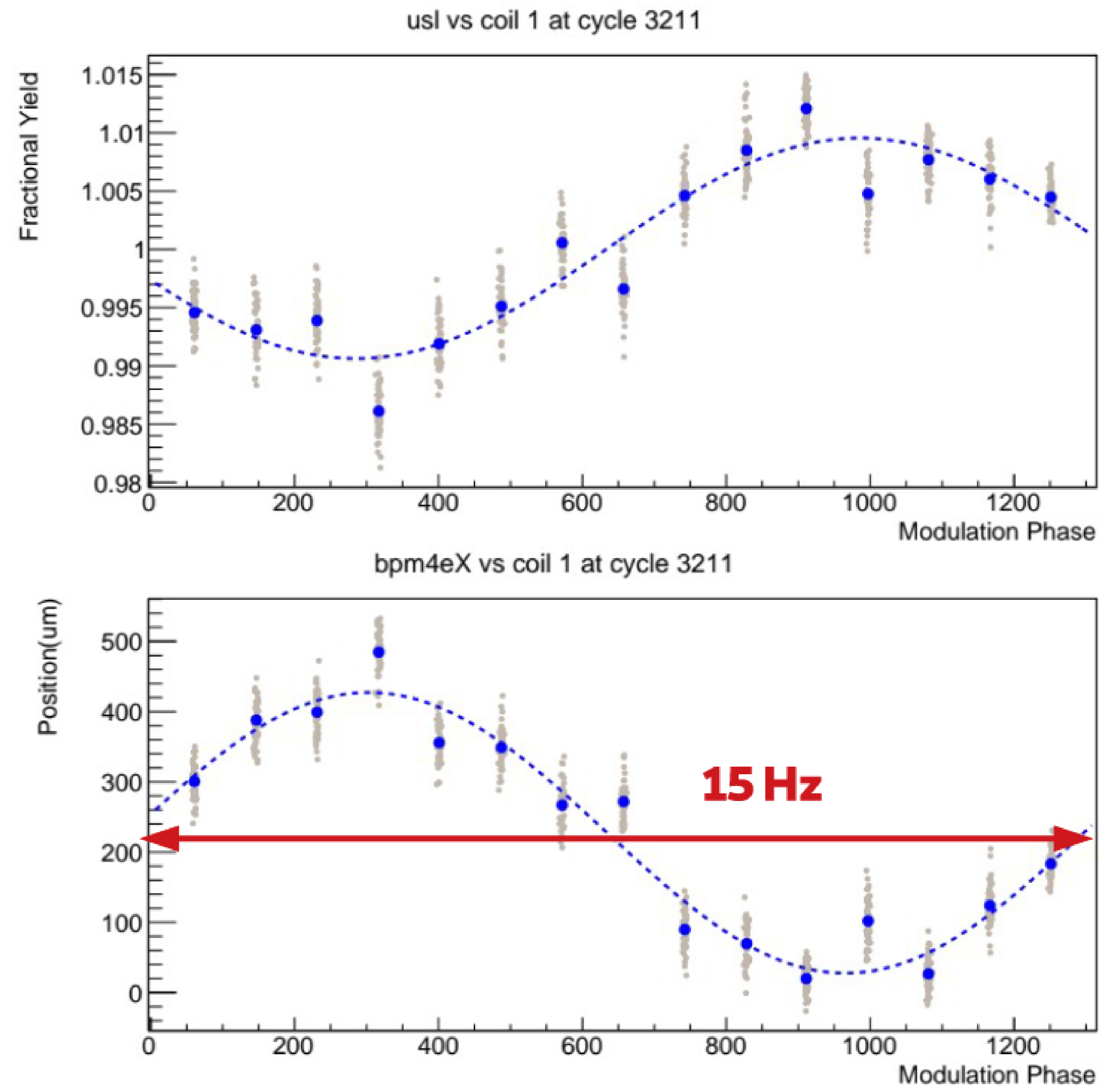
SIMC simulations for ^{208}Pb (E = 1.0 GeV, θ = 10.74°)

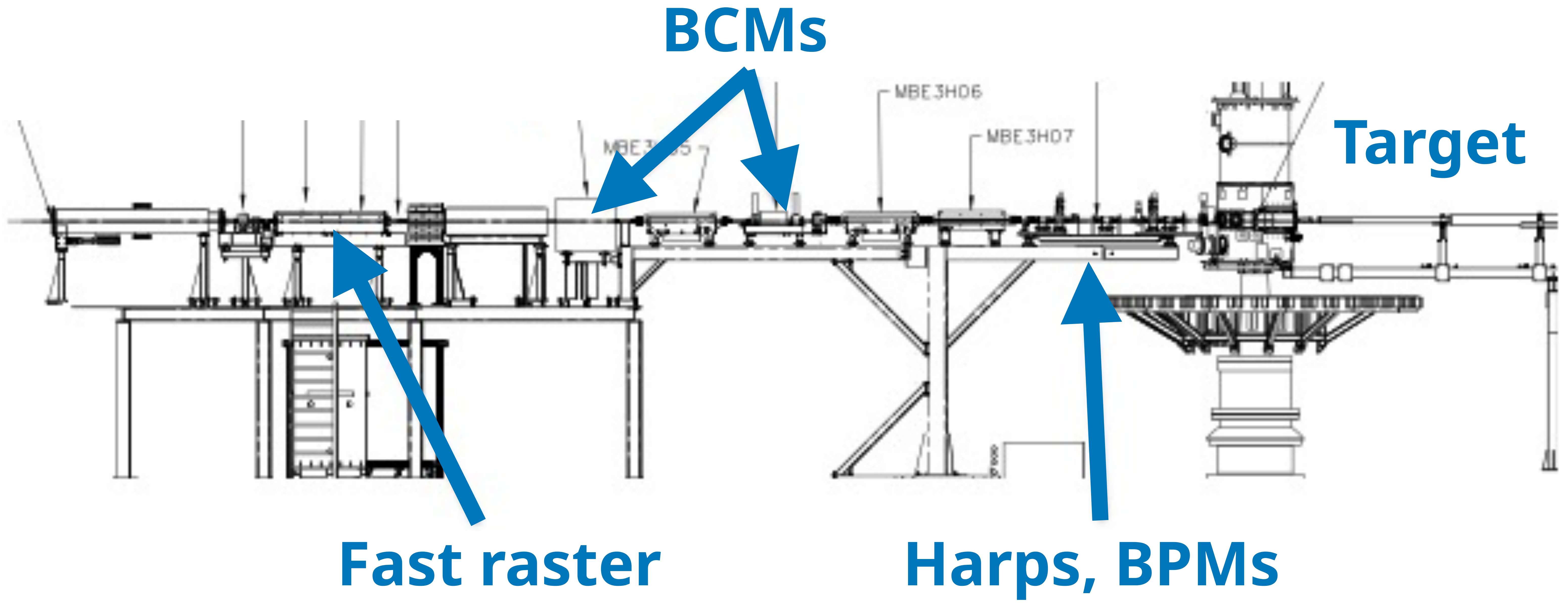




Polarized source and beam modulation

- Hall A polarized source (which will be set up for MOLLER) will be used by E12-24-007 in 2027
  → alternatively, Hall C source is capable of providing required beam quality
- Beam fluctuations (intensity, position, angle) induce noise in measured asymmetry
  → modulate beam to extract correction parameters
- Existing beam line instrumentation in Hall C (BPMs, BCMs) will be more than sufficient to measure beam properties





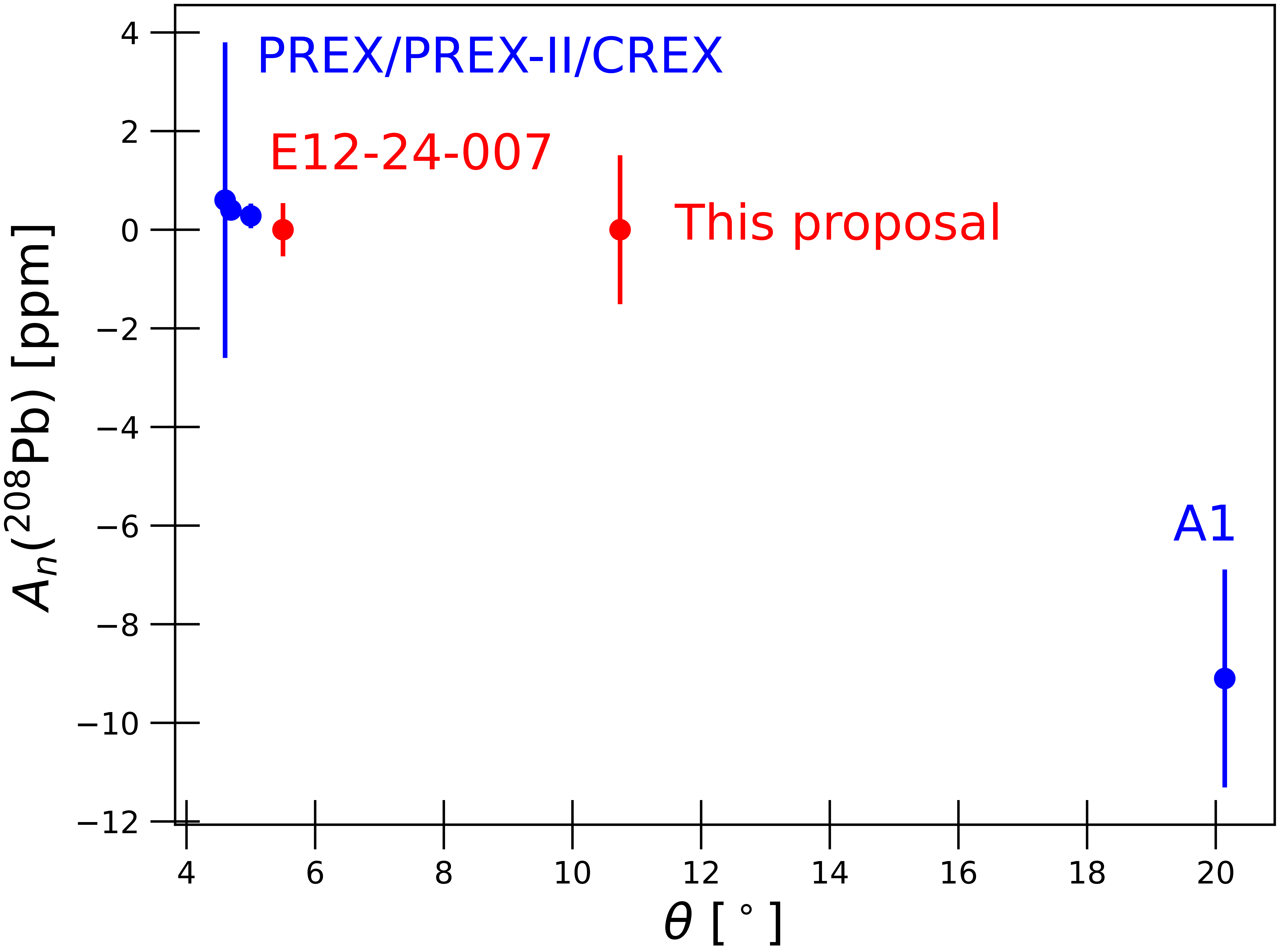
Systematic uncertainties

Effect	Uncertainty (ppb)	PREX-2 A_n acheived (ppb)
Inelastic contributions	130	$\leq$10
A_{false}	100	$\leq$80
Polarization	70	$\leq$60
Detector non-linearity	50	$\leq$30
Target impurities	50	$\leq$40
Total systematic	192	$\leq$113

- Take advantage of systematic control developed for recent/upcoming parity experiments (detectors, beam, analysis techniques)
- Uncertainty budget more conservative than what was achieved on A_n measurements from PREX/CREX
- Sources, size of systematics the same as E12-24-007

Projected results

Projected uncertainties;
central value set to 0



Beam time request

- For this measurement, we request 10 days of total beamtime (if run in tandem with E12-24-007)
  - 9 days of production data to reach a statistical precision of 1.5 ppm
  - 1 day of spectrometer measurements (after change to 10.74°)

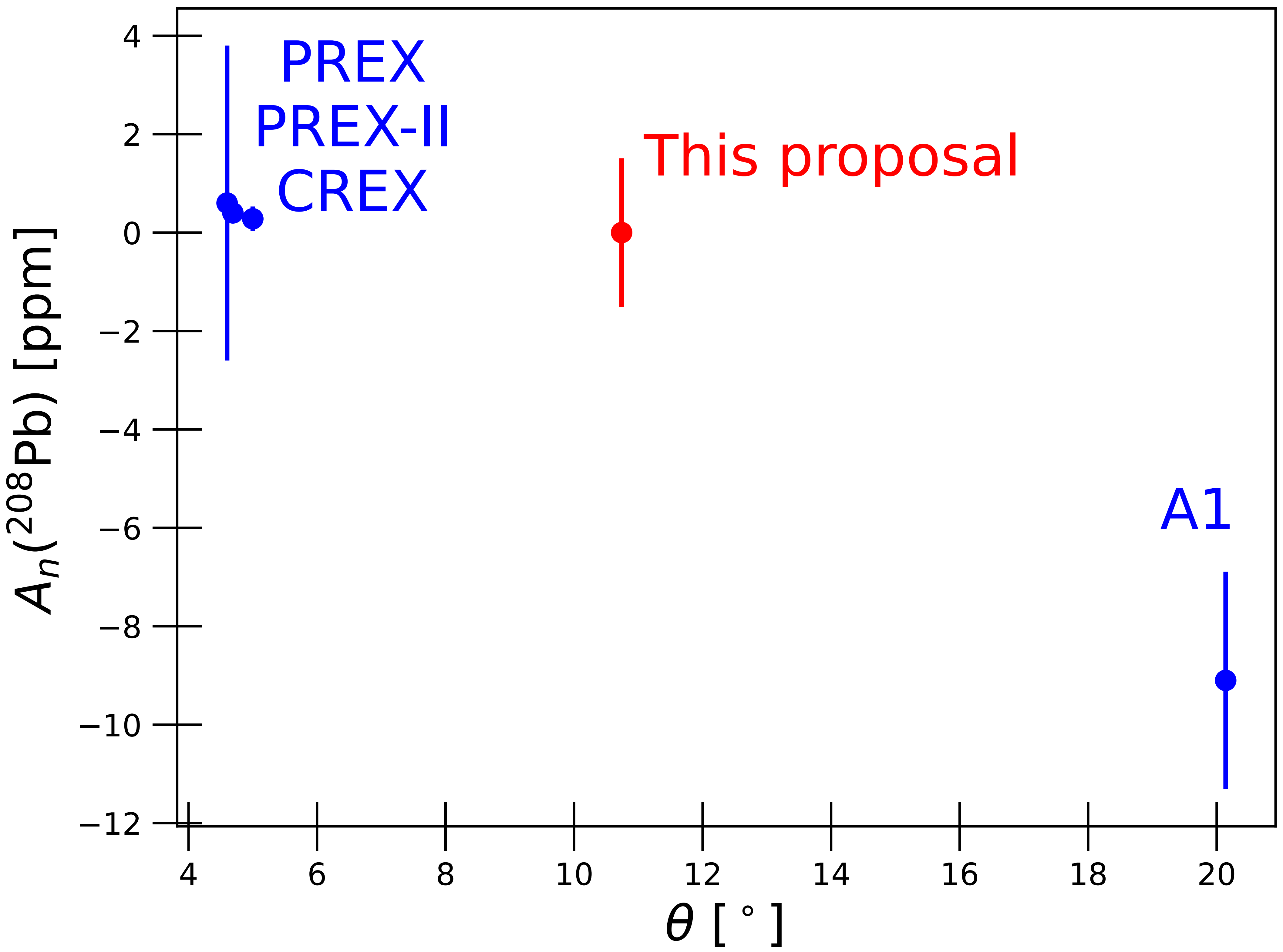
Beam energy	1.0 GeV
Beam current	25 μA
Beam polarization	80% (transverse)
Target material	^{208}Pb
Target thickness	191.1 mg/cm^2
Scattering angle	10.74°
Rate (SHMS + HMS)	664 kHz
Beamtime (production)	9 days
Beamtime (commissioning)	1 day
Beamtime (total)	**10 days**

- If run independently, this experiment would require additional commissioning for:
  - Establishing parity-quality beam (24 hours)
  - Measuring beam polarization (24 hours)
  - Spectrometer/detector commissioning (36 hours)

Beamtime (production)	9 days
Beamtime (commissioning)	4.5 days
Beamtime (total)	**13.5 days**

Summary

- Vanishing A_n on ^{208}Pb (in contrast to theoretical predictions) has been a puzzle since first JLab measurement in 2012 → E12-24-007 will study the *nuclear dependence* of the asymmetry
- The puzzle deepened in 2025 with the observation of a large A_n on ^{208}Pb at MAMI (at lower energy, larger angle than JLab)
- The JLab and MAMI measurements suggest an additional *kinematic dependence* not included in current models
- The proposed measurement would test this kinematic dependence and provide an important benchmark for theory calculations

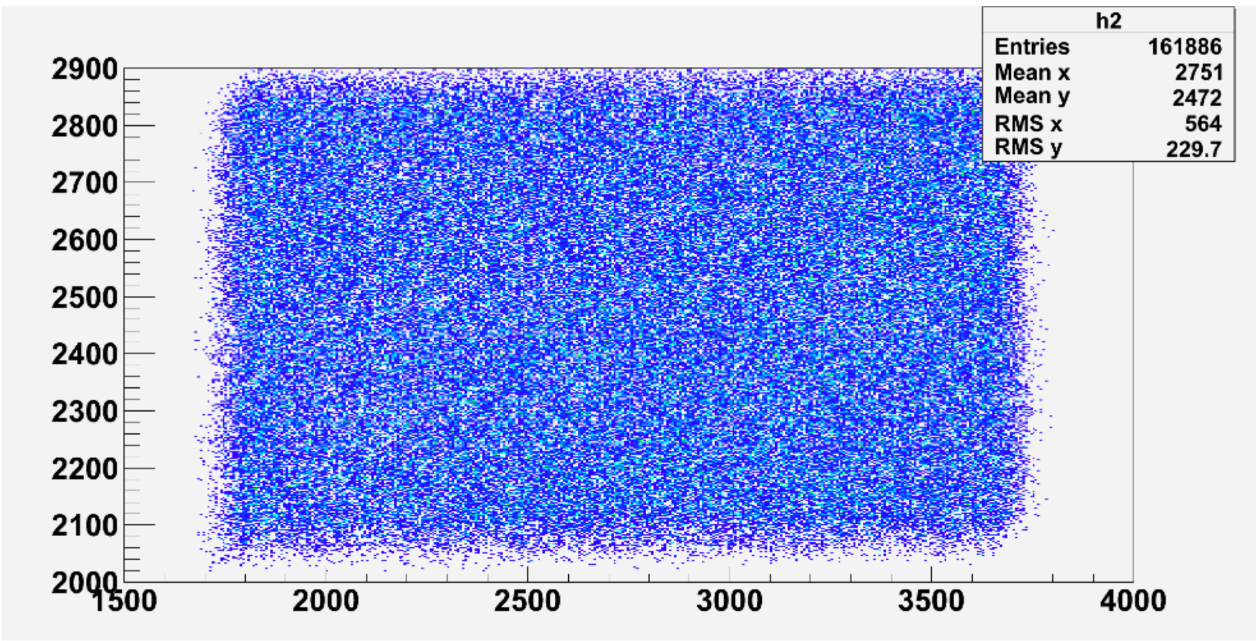


Backup

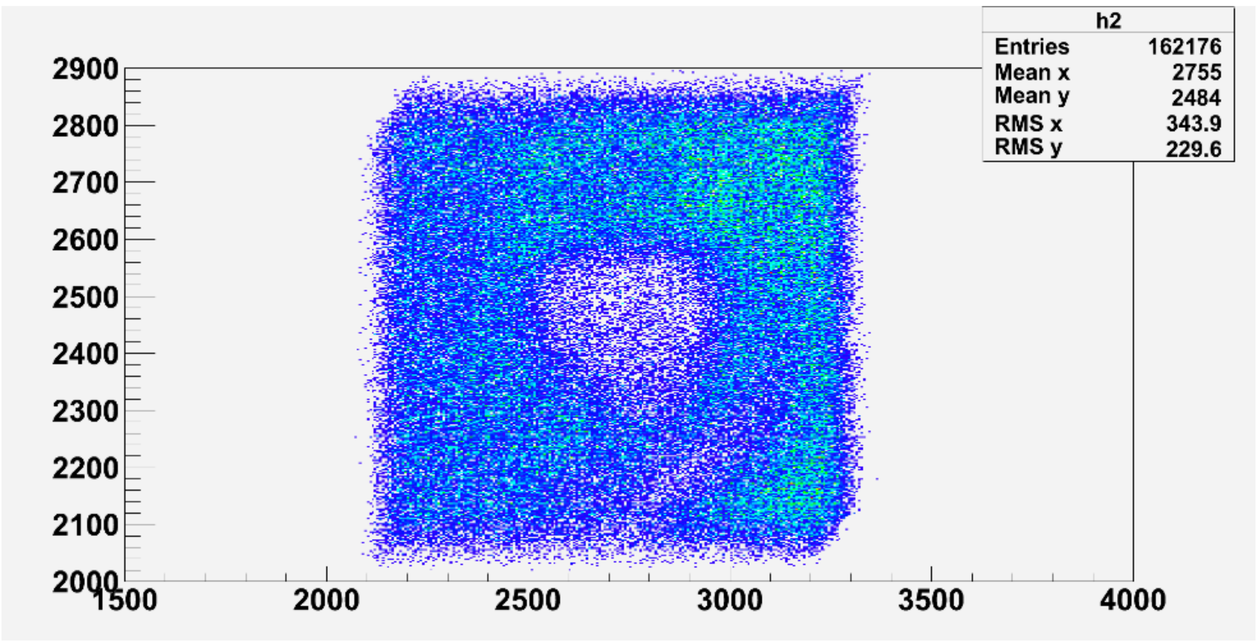
^{208}Pb target

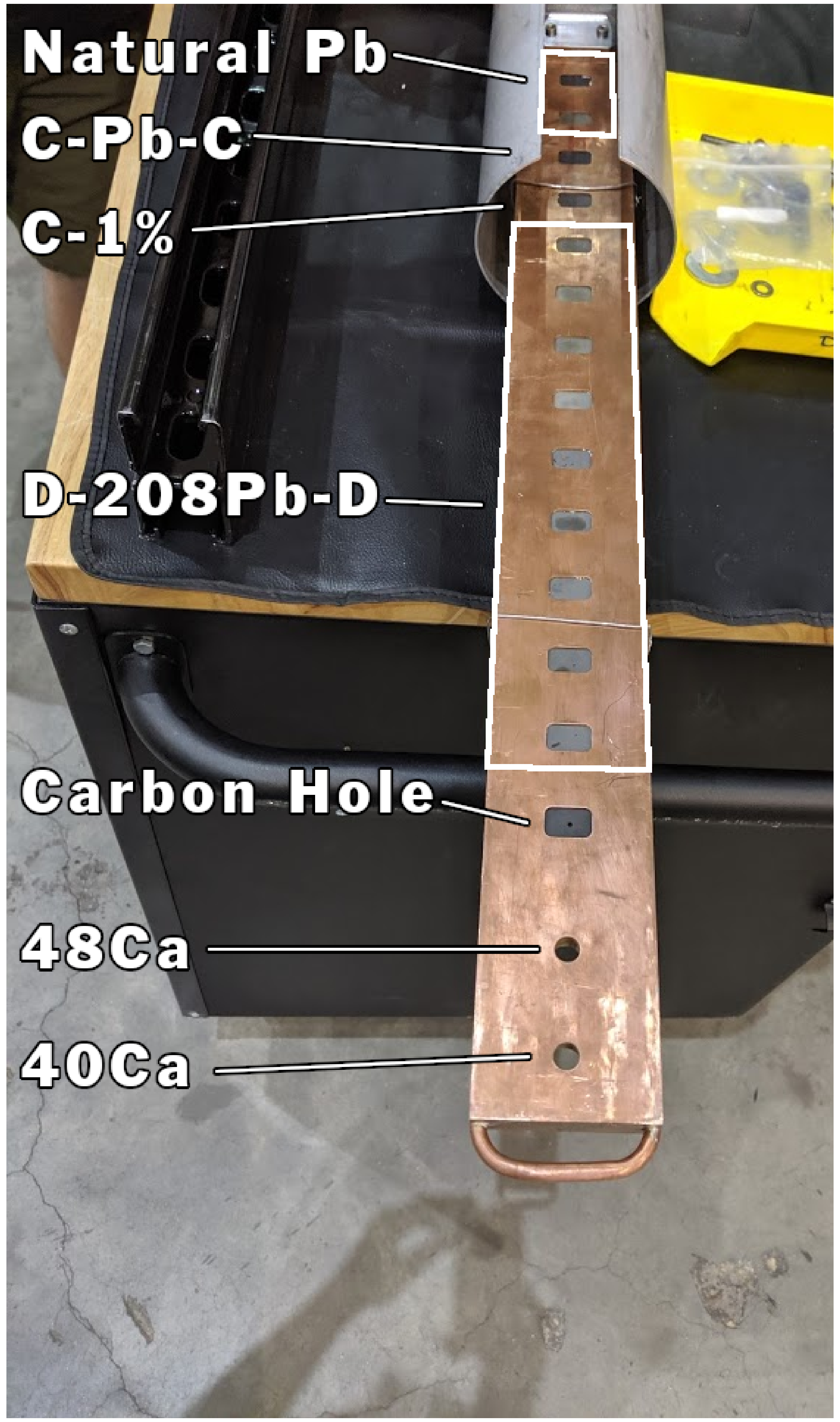
- From PREX-II experience, expect ^{208}Pb target to survive 17 C of beam on target
- At 25 μA, this corresponds to (almost) 8 days
- Considering proposed beamtime of 10 days, we plan to have a backup ^{208}Pb foil in the target ladder

New ^{208}Pb target



After 1 week at 70 μA

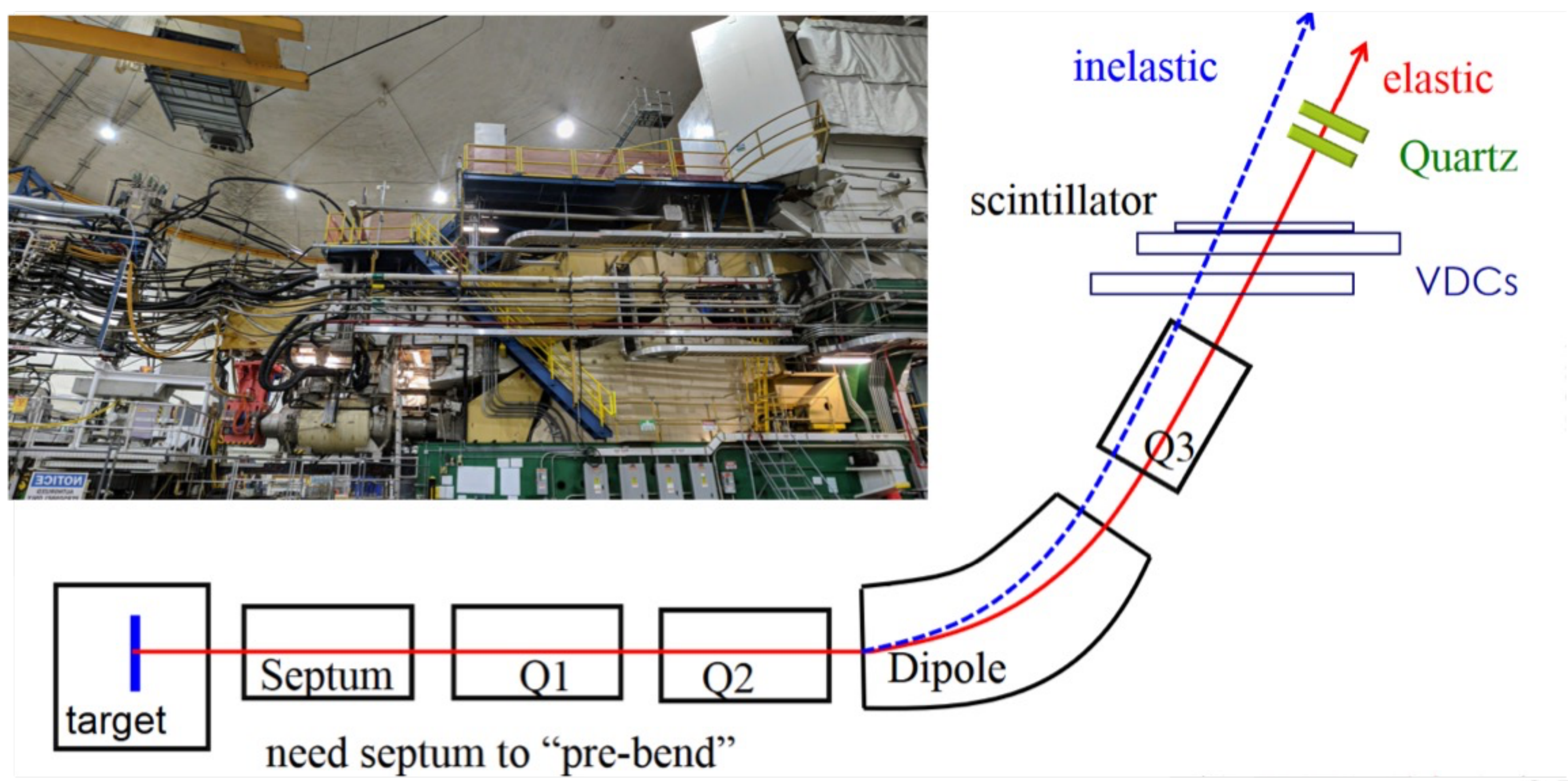




PREX-II target	Total charge (C)
Pb2	17.0
Pb10	16.6
Pb9	22.3
Pb8	17.4
Pb5	12.4
Pb7	21.9
Pb6	8.2

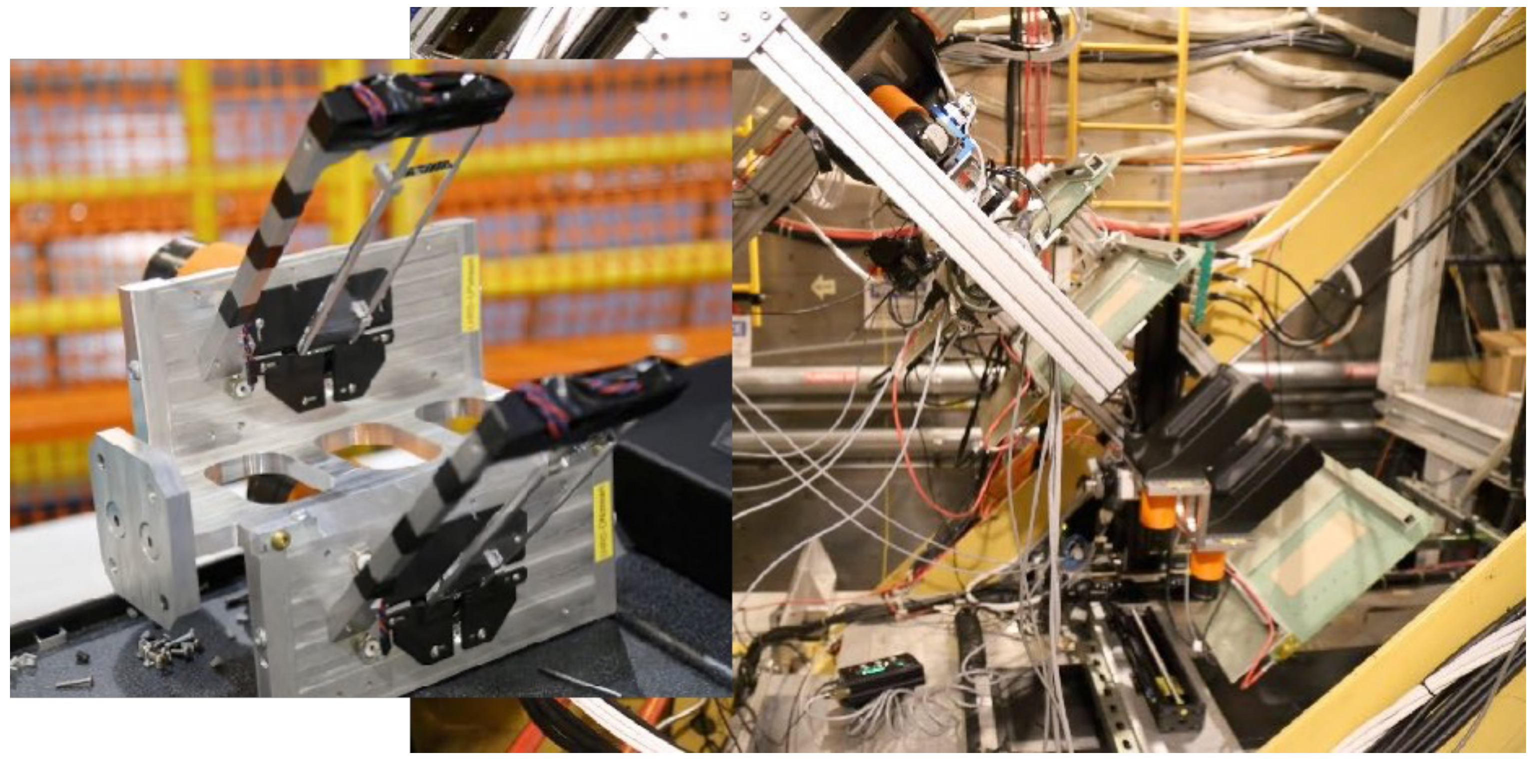
End of run

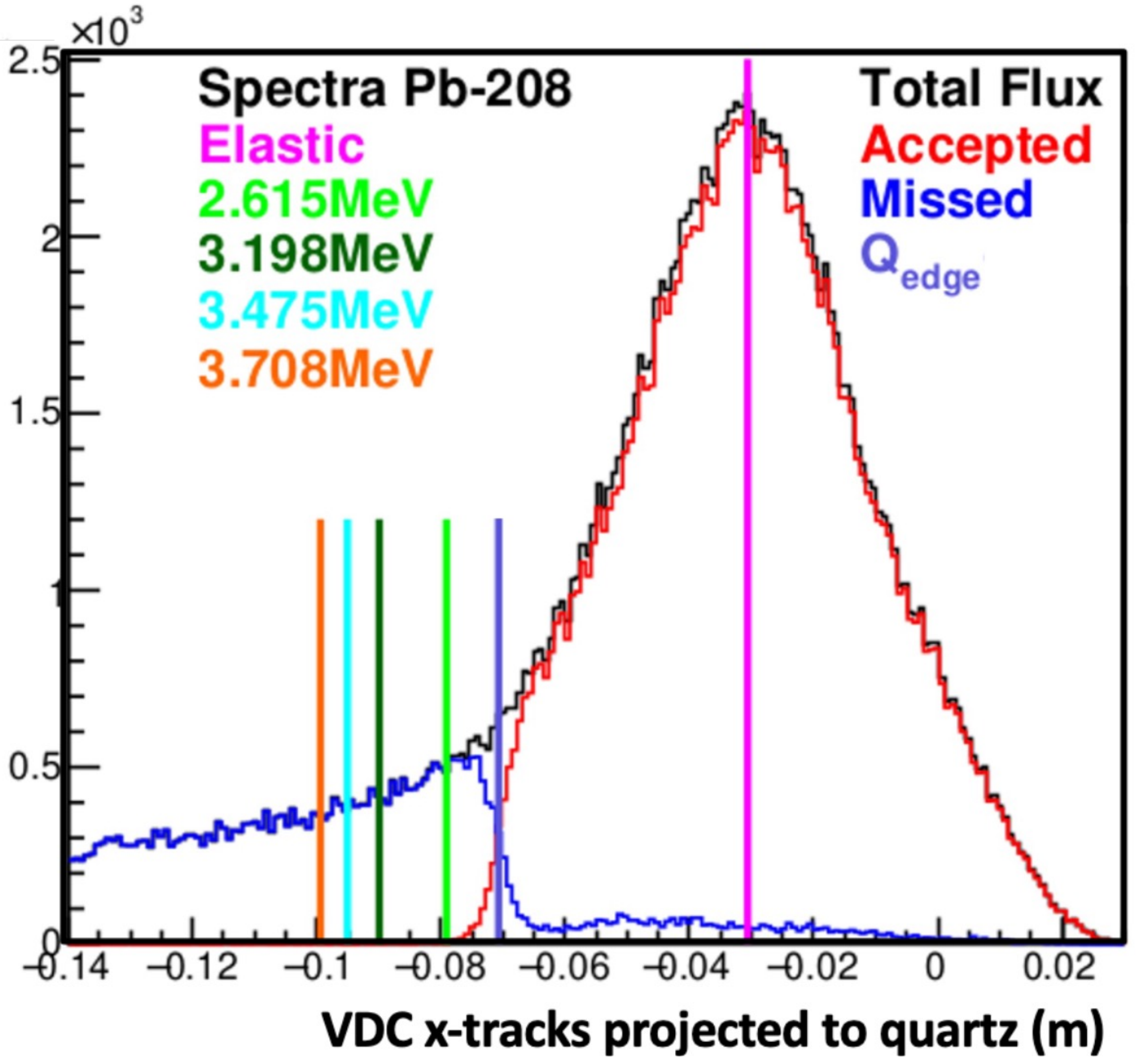
Separating inelastic states (slide from C. Gal)

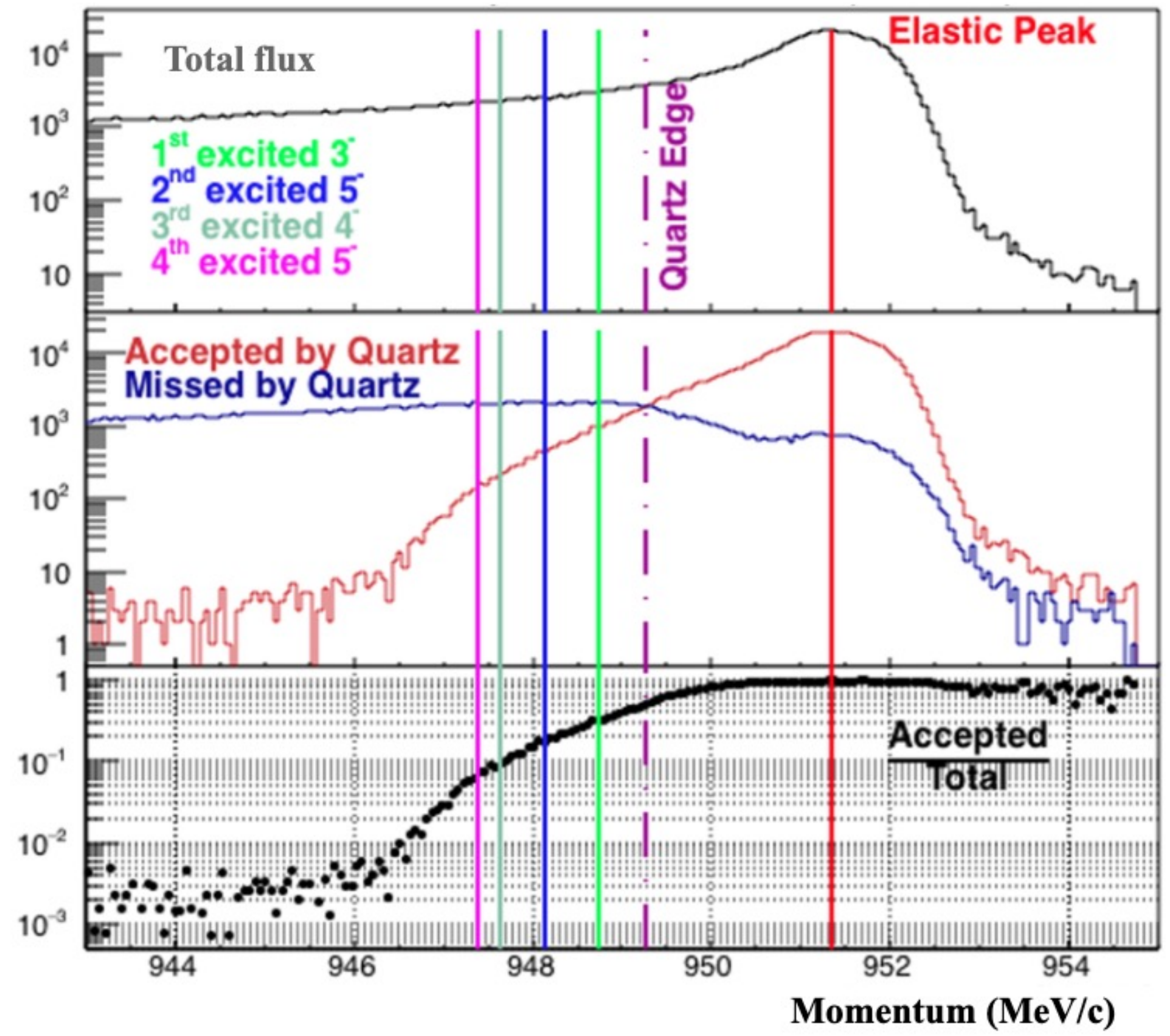


- High Resolution Spectrometer (HRS) in Hall A separates elastic electrons from inelastic events
- Detector position was adjusted (remotely controlled) for optimizing the acceptance for elastic events.
- Blue line is elastic tail – inelastic excited states are not visible
    - lines are just for guiding the eye and have arbitrary height

Integrating quartz detector installed during PREX/CREX







Theory report

This proposal aims to resolve the puzzle of the beam-normal single-spin asymmetry A_n for the ^{208}Pb nucleus, which PREX and CREX found to be vanishingly small, in contrast to measurements for lighter C and Ca nuclei which gave asymmetries of the order $A_n \approx -(5-10)$ ppm. While results for the lighter nuclei are generally consistent with theoretical estimates, the ^{208}Pb asymmetry cannot be accommodated theoretically, and this remains an unsolved problem. More recently, the A1 experiment at MAMI measured a ^{208}Pb asymmetry of $A_n = (-9.1 \pm 2.2)$ ppm at a beam energy of $E = 0.57$ GeV and four-momentum transfer squared $Q^2 = 0.04$ GeV^2, possibly indicating a nontrivial kinematic dependence of A_n, which is also not understood theoretically.

The specific proposal is to measure the beam-normal single-spin asymmetry on ^{208}Pb at $E = 1.162$ GeV and $Q^2 = 0.037$ GeV^2. This point would lie at kinematics between existing the JLab CREX and MAMI measurements. The motivation for this experiment is clear, and the results could shed light on the origins of the observed, and currently not understood, beam-normal asymmetries for ^{208}Pb, providing guidance for further theoretical studies of the asymmetries.

Response to TAC comments

Physics goals explicitly note systematic errors caused by an "asymmetric beam profile." Proponents need to explicitly define their required beam size, shape, convergence/divergence, and profile symmetry, as these parameters directly dictate target survival and error budgets.

We will require similar beam conditions as for the CREX measurement in Hall A. It should be noted that for the E12-24-007 run in 2027, the plan is to use the Hall A laser (which will be set up in preparation for MOLLER) for Hall C. The beam requirements for MOLLER are far more stringent than those for this experiment, and therefore we foresee no issues achieving adequate beam performance. We would rely on the same expertise should this experiment be run independently (without E12-24-007) at a later time.

Response to TAC comments

This experiment proposes running high beam currents (60 μA) on a sensitive lead solid target without providing the maximum temperature tolerances needed to prevent target melting, sublimation, or excessive gas boiling. This proposal provides good beam profile details in its appendix: they explicitly list a requirement for a 3x3 mm raster. It should be confirmed that the thermal calculations guarantee the lead target won't melt at 60 μA specifically using this 3x3 mm symmetric raster.

Due to developing details of the planned target ladder, it will indeed not be feasible to run at 60 μA. Instead, the current will be limited to 25 μA. However, the proposed measurement at $\theta \approx$ 10° will be able to run with both Hall C spectrometers, unlike E12-24-007. This was not accounted for in the proposal, and therefore even with the reduced current we would be able to achieve nearly the same statistical precision in the same beamtime.

Response to PAC comments

The proponents set out to solve the decade+ old PREX puzzle which only deepened with the recent measurement of a significantly non-zero An for 208Pb at MAMI. Can you please explain how the result of the proposed measurement would be used to solve the puzzle. Specifically:

a. One could envision two outcomes, (i) yet another surprising An=0 result, perhaps consistent with PREX/CREX, or (ii) a large negative An consistent with expectations based on extrapolation from the MAMI data. Please comment on the argumentation that will be used to solve the puzzle based on the possible outcomes one may envision.
b. Given the theoretical complexity of describing the inelastic excitations of a high-Z nucleus, and the scarcity of calculations or models tackling the issue, what is the information that theorists can potentially get out from the experimental results to advance the theoretical description of this very challenging scattering scenario involving 208Pb? In other words, how will the measurement make a difference for the development of a corresponding theory or model?

(Reply on following slide)

Response to PAC comments

If the proposed experiment measured a non-zero A_n, this would strengthen the hypothesis of an unknown kinematic dependence, and also suggest that the effect depends more strongly on scattering angle than on energy. Another measurement of $A_n = 0$, while surprising, would further constrain the phase space where kinematic dependence could explain the observed difference between JLab and MAMI experiments.

Current measurements suggest two behaviors that are not accurately described by theory: dependence on Z and dependence on kinematics. Theory unfortunately provides little guidance on which measurements could best resolve these puzzles. Conversely, experimental data to benchmark calculations is also relatively scarce. Existing measurements cover only a handful of nuclei between 4He and 208Pb, and at very few kinematic points. More thorough coverage of data will more effectively constrain theory than isolated clusters of measurements, and could provide better insight on the region of applicability of certain theoretical approaches used in calculating these observables.

E12-24-007 will provide benchmarks for possible Z-dependent effects not currently included in calculations. This proposal would provide a similar benchmark on the kinematic dependence. The fact that both PREX/PREX-II and CREX measured vanishing asymmetries restrict the possible energy dependence, at least above 1 GeV. However, there is a rather large gap between the scattering angles of the experiments at JLab and MAMI. This measurement would provide complementary constraints on the kinematic dependence by measuring a scattering angle approximately twice as large as PREX/CREX, and approximately half as large as MAMI.

Response to PAC comments

Would the proponents dare to speculate about the potential driving mechanisms which could cause the kinematical and nuclear dependence as indicated by past measurements and used as motivation for the present proposal?

As described in the E12-24-007 proposal and DOI:10.1103/PhysRevLett.128.142501, one (empirical) hypothesis for the nuclear dependence is contributions from radiative nuclear vertex diagrams that scale with Z^2. The underlying asymmetry $A_0(Q^2)$ already contains kinematic dependence that should be accounted for in existing calculations, but one could also speculate that the hypothetical radiative effect also depends on kinematics.

Response to PAC comments

In the proposal PAC52 E12-24-007, which is given as appendix to your work, please clarify for the empirical correction factor the inconsistency of the quoted C with respect to the reference DOI: 10.1103/PhysRevLett.128.142501 and the power of alpha which appears as alpha (section 5) and alpha^2 (section 2.3)

The correction term should be $C \cdot Z^2\alpha$, with the empirical constant $C \approx$ 0.02. In the E12-24-007 proposal, the power α^2 (Section 2.3) and value $C \approx$ 0.2 (Section 5) are typos.

Response to PAC comments

It is indeed very efficient to suggest running the proposed measurement together with the approved E12-24-007 from PAC52. However, if for some reason the runs would have to proceed separately, how much additional overhead on top of the 10 days would be needed, if any?

If run separately from E12-24-007, additional beamtime would be required for:
-Establishing parity-quality beam (24 hours)
-Measuring beam polarization (24 hours)
-Spectrometer commissioning (36 hours)

Beamtime for pointing measurements and Q^2 determination has already been included, as this would anyways be necessary due to the different spectrometer angle.

Therefore, if run separately, this proposal would need an additional 3.5 days of beamtime.

Response to PAC comments

What are the biggest experimental risks to achieving the needed uncertainty goal, if any, and what are the plans to mitigate these?

The biggest risk to achieving the uncertainty goal is the lifetime of the 208Pb target. The first plan to mitigate this is by limiting the beam current (as mentioned in the response to [the TAC comments]) Based on experience with similar targets from PREX-II, we expect the target to survive for approximately 17 C of beam on target. At 25 μA, this corresponds to almost 8 days, compared to the requested beamtime of 10 days. Therefore, the second strategy would be to include backup 208Pb foils in the target ladder.