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

PR12-24-007
JLab PAC52 Proposal

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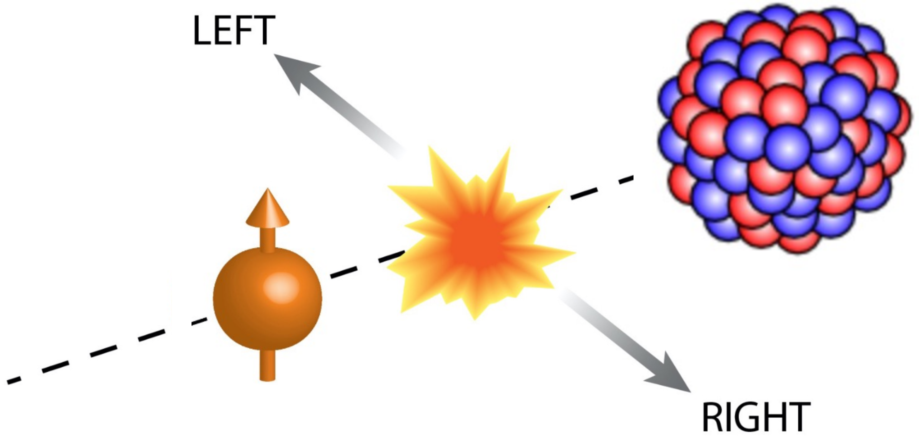
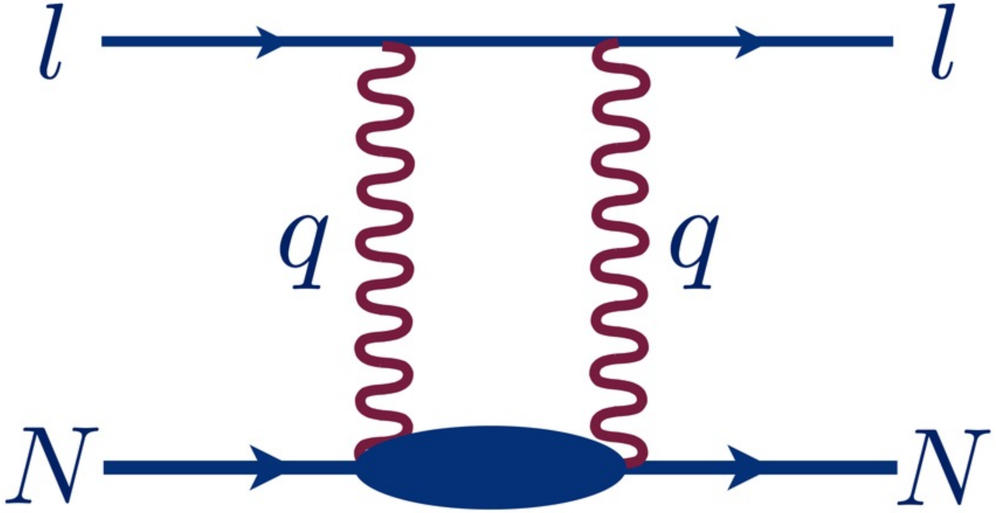
Jefferson Lab

Beam Normal Single Spin Asymmetry in elastic electron-nucleus scattering



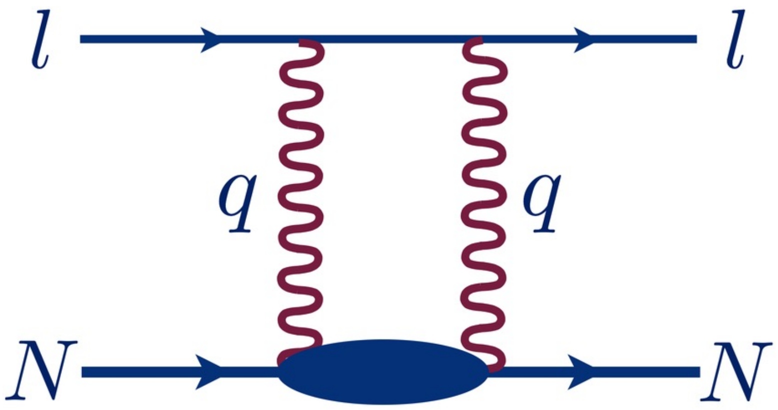
- The asymmetry arises from two-photon exchange. A single-photon exchange contribution vanishes under time-reversal symmetry.

$$A(\phi) = A_n(\theta, E_{beam}) P_n \cos(\phi)$$



$$A_n = \frac{2A_{Born}\mathcal{I}(A^*_{2\gamma})}{|A_{Born}|^2}$$

Beam Normal Single Spin Asymmetry in elastic electron-nucleus scattering



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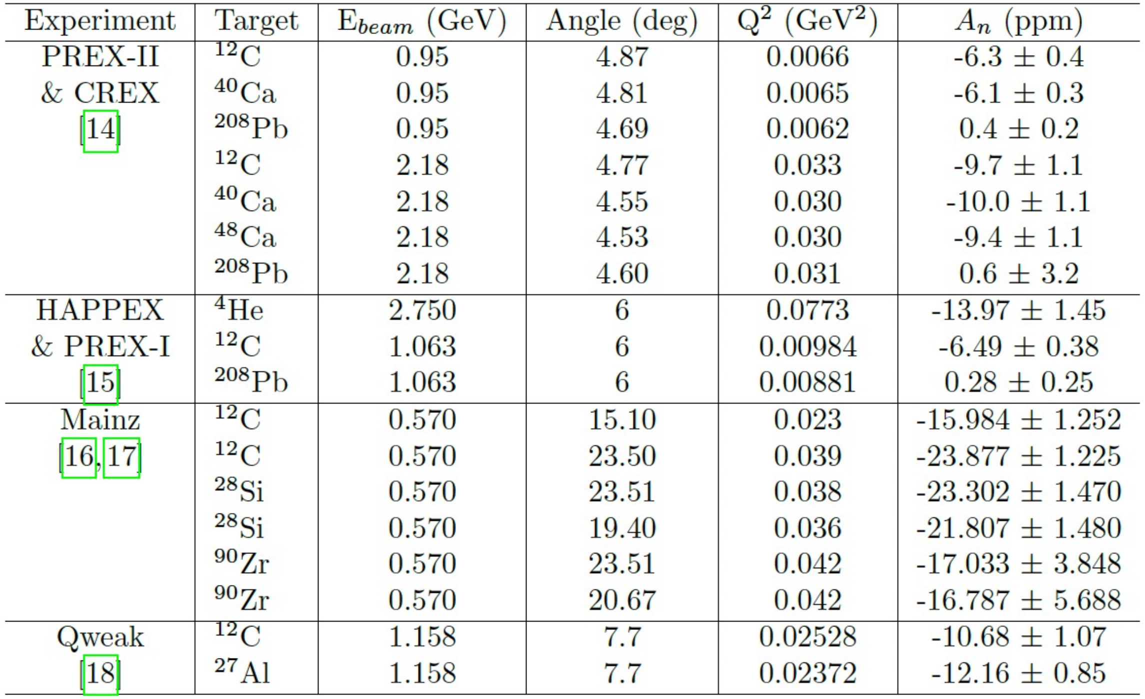
$$A(\phi) = A_n(\theta, E_{beam}) P_n \cos(\phi)$$

$$A_n = \frac{2A_{Born}\mathcal{I}(A^*_{2\gamma})}{|A_{Born}|^2}$$

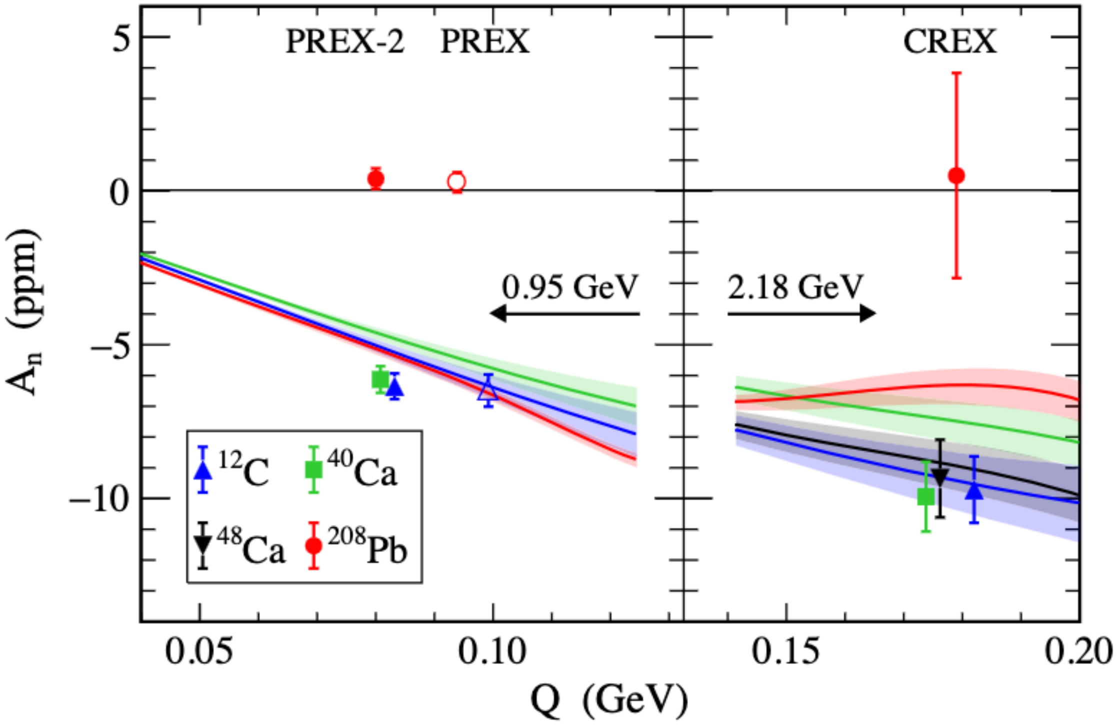
- The asymmetry A_n has been measured for several A > 1 target nuclei
  - Successful measurements from HAPPEX, Qweak, PREX, CREX experiments at JLab
  - Forward angle measurments - easier theoretical interpretation



Experiment	Target	E_{beam} (GeV)	Angle (deg)	Q^2 (GeV^2)	A_n (ppm)
PREX-II & CREX [14]	^{12}C	0.95	4.87	0.0066	-6.3 ± 0.4
	^{40}Ca	0.95	4.81	0.0065	-6.1 ± 0.3
	^{208}Pb	0.95	4.69	0.0062	0.4 ± 0.2
	^{12}C	2.18	4.77	0.033	-9.7 ± 1.1
	^{40}Ca	2.18	4.55	0.030	-10.0 ± 1.1
	^{48}Ca	2.18	4.53	0.030	-9.4 ± 1.1
	^{208}Pb	2.18	4.60	0.031	0.6 ± 3.2
HAPPEX & PREX-I [15]	^{4}He	2.750	6	0.0773	-13.97 ± 1.45
	^{12}C	1.063	6	0.00984	-6.49 ± 0.38
	^{208}Pb	1.063	6	0.00881	0.28 ± 0.25
Mainz [16, 17]	^{12}C	0.570	15.10	0.023	-15.984 ± 1.252
	^{12}C	0.570	23.50	0.039	-23.877 ± 1.225
	^{28}Si	0.570	23.51	0.038	-23.302 ± 1.470
	^{28}Si	0.570	19.40	0.036	-21.807 ± 1.480
	^{90}Zr	0.570	23.51	0.042	-17.033 ± 3.848
	^{90}Zr	0.570	20.67	0.042	-16.787 ± 5.688
Qweak [18]	^{12}C	1.158	7.7	0.02528	-10.68 ± 1.07
	^{27}Al	1.158	7.7	0.02372	-12.16 ± 0.85

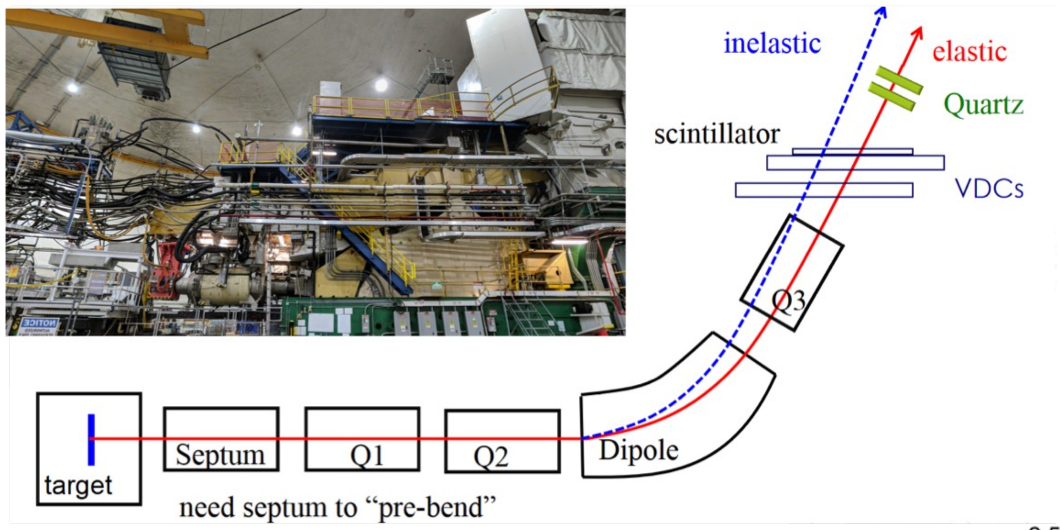
PREX A_T puzzle

- Most existing data focused on Z ≤ 20. The only heavy nuclei with larger Z is Pb208.
- For small Z, very small or no nuclear dependence observed on the asymmetry in good agreement with theory
- Pb208 results present a striking disagreement from a theoretical prediction
  - Measured at three different Q^2, all consistent with zero for Pb208.



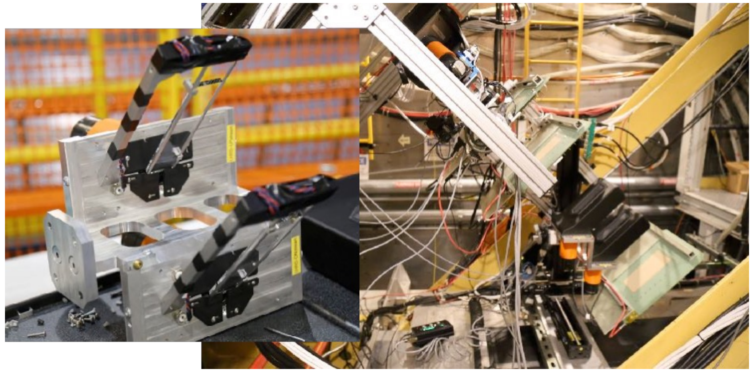
Pb208 results suggest there are missing contributions that are not accounted in the existing theoretical models

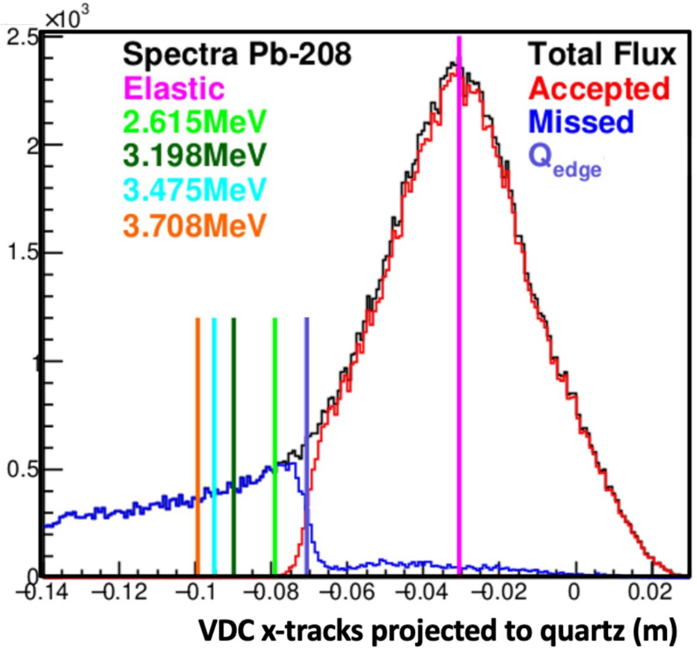
Measuring elastic events during PREX

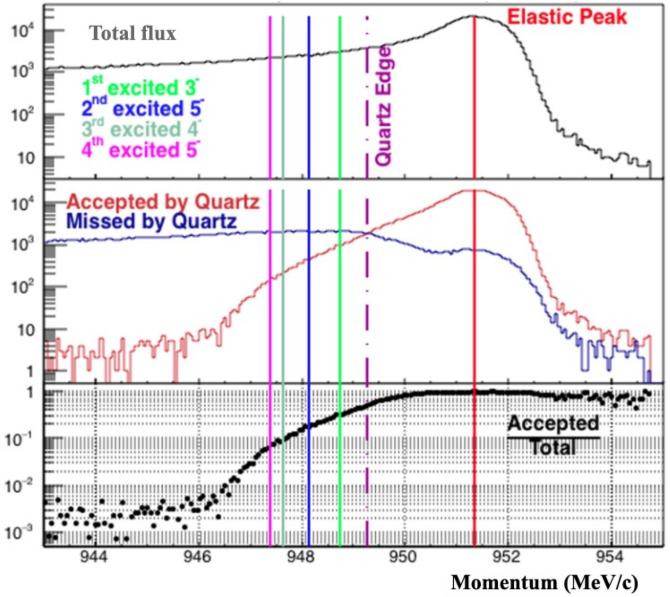


- High Resolution Spectrometer (HRS) in Hall A separates elastic electrons from inelastic events
- Detector position was adjusted (remotely controlled) for optimizing the acceptance for elastic events.
- Blue line is elastic tail – inelastic excited states are not visible
  - <u>lines are just for guiding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

Integrating quartz detector installed during PREX/CREX





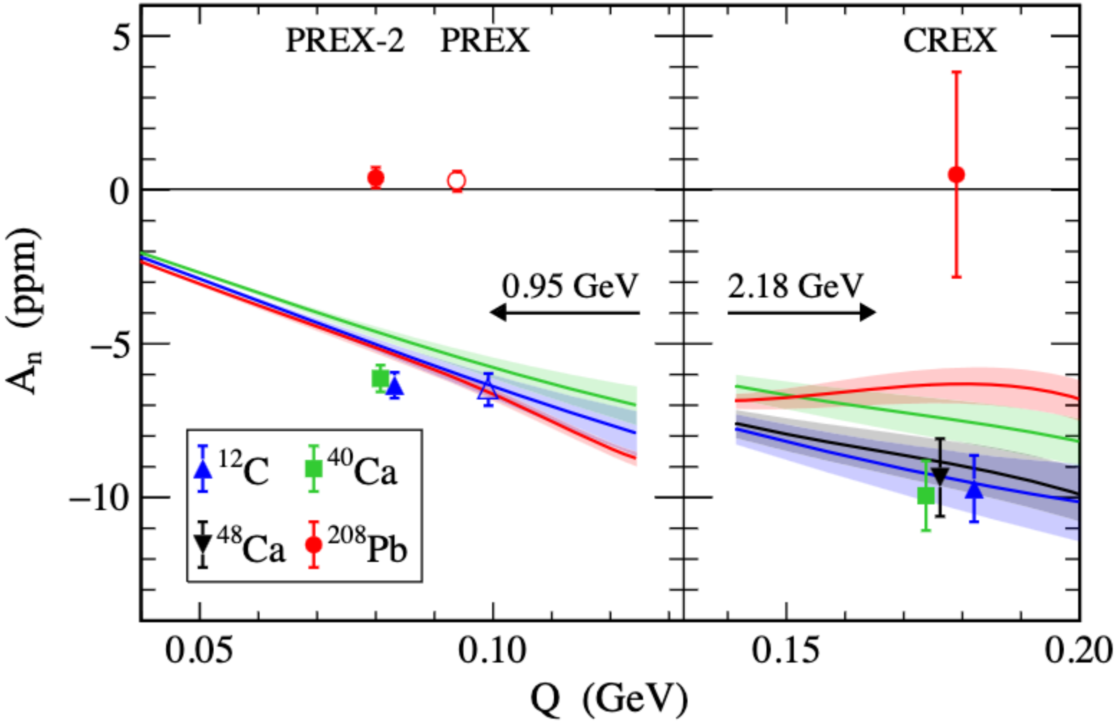


A_T theory basics

- For low and intermediate (Z<=20) nuclei a plane-wave formalism seems to provide adequate description of the data

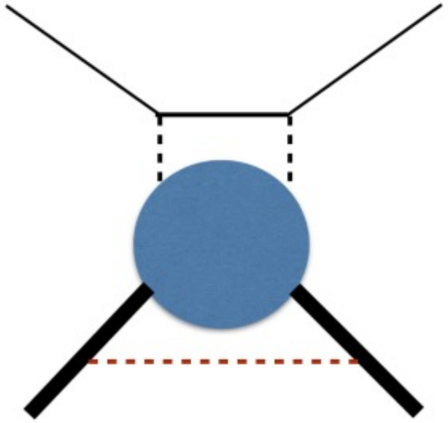
$$A_{\mathrm{n}} = \hat{A}_{\mathrm{n}} \frac{QA}{Z}$$

- This formalism is badly broken by the lead result
- Updates by O. Koshchii et. al. include Coulomb distortions and dependencies on A and Z
  - Additionally, uncertainties are estimated carefully (error bands on the curves)

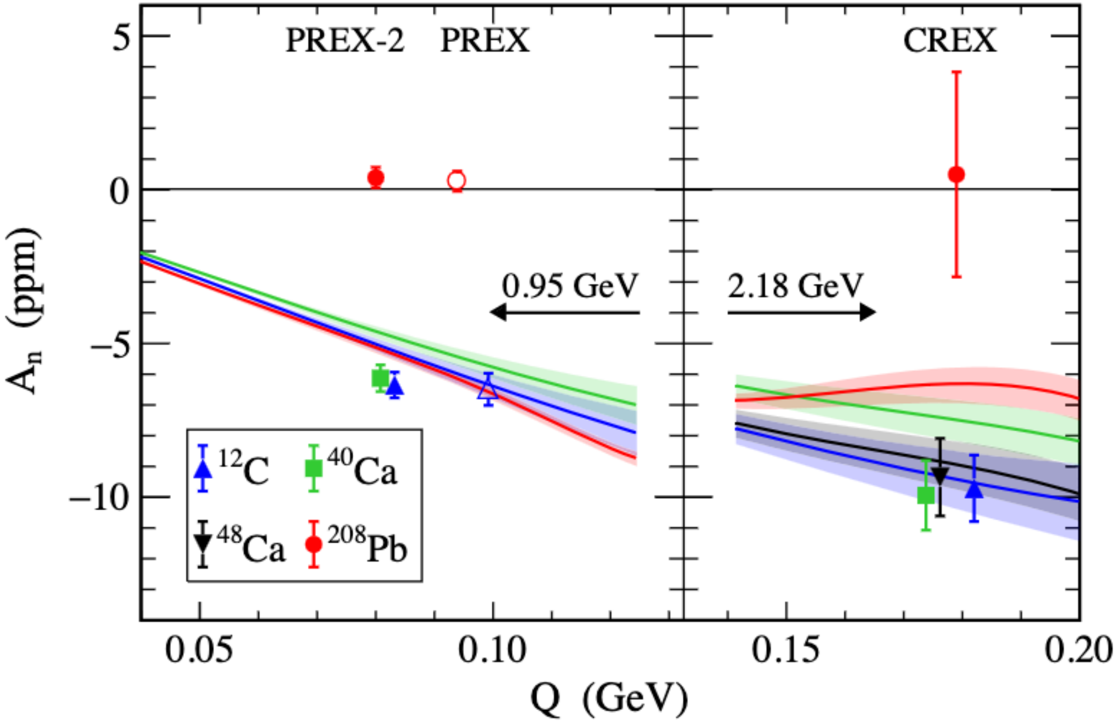


Pb208 results suggest there are missing contributions that are not accounted in the existing theoretical models

A_T theory suggestions



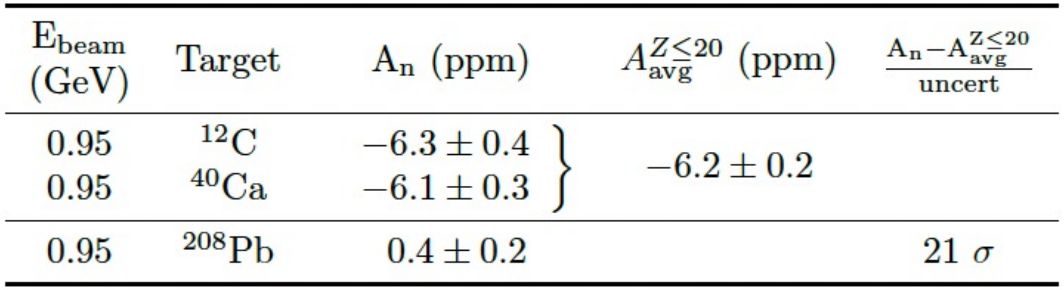
$$A_n \approx A_0(Q)(1 - C \cdot Z^2 \alpha),$$



Pb208 results suggest there are missing contributions that are not accounted in the existing theoretical models

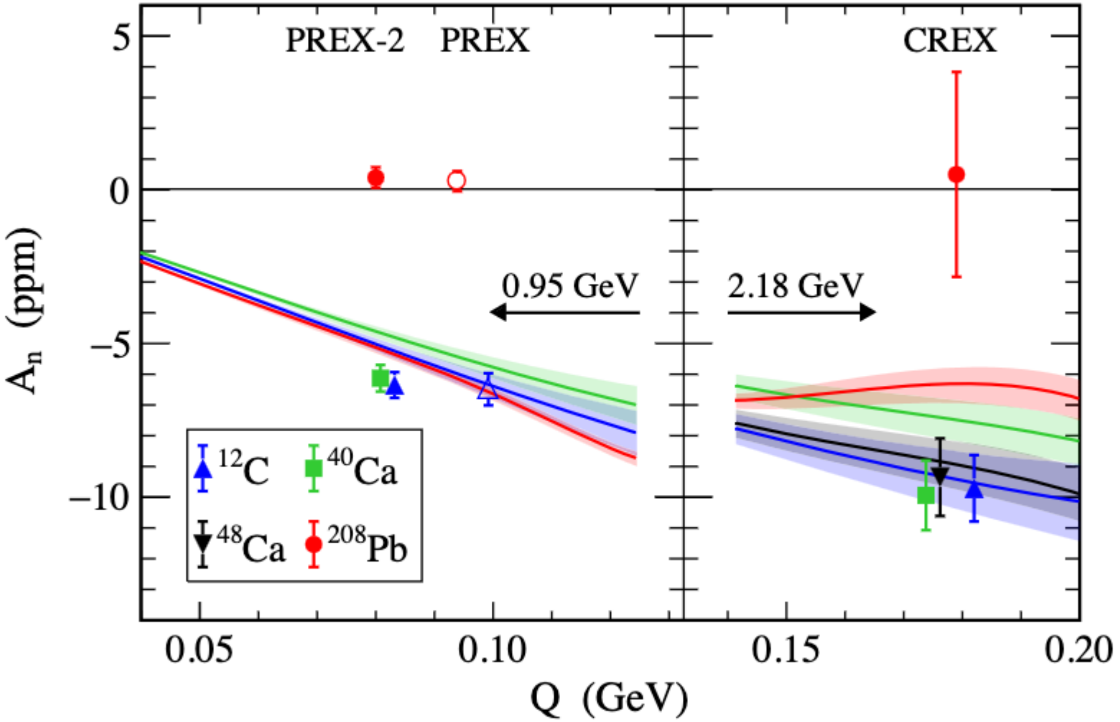
- In the PREX-2 A_T paper we suggested an empirically determined remedy by speculating that a radiative correction on the side of the nucleus could potentially be important
    - A fit to the small amount of data available at forward angles produces a C=0.02 which is consistent with Mainz Zr90 data

A_T puzzle naïve suggestion



E_{beam} (GeV)	Target	A_n (ppm)	$A_{avg}^{Z\leq 20}$ (ppm)	$\frac{A_n - A_{avg}^{Z\leq 20}}{\text{uncert}}$
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		21 σ

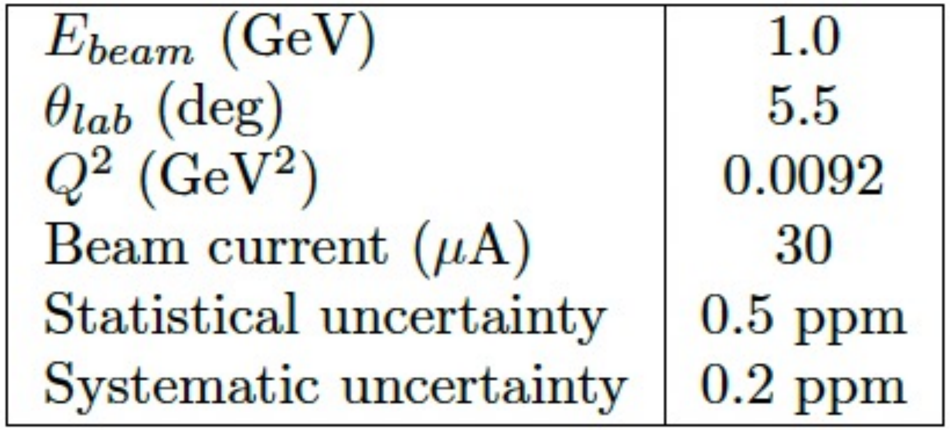
- The lead results are in fact positive (by 2 sigma)
- One possible explanation would be that another physics process produces a transverse asymmetry with the opposite sign as the TPE that is present in high Z (or A) nuclei
  - We are in touch with theorists exploring this possibility



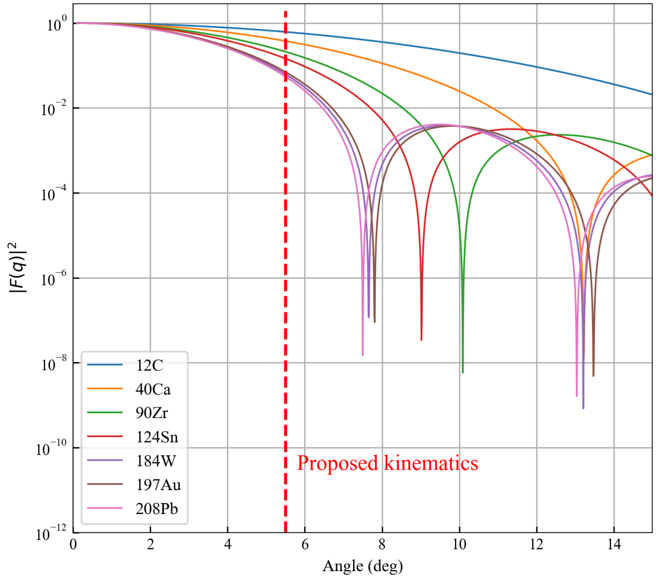
Pb208 results suggest there are missing contributions that are not accounted in the existing theoretical models

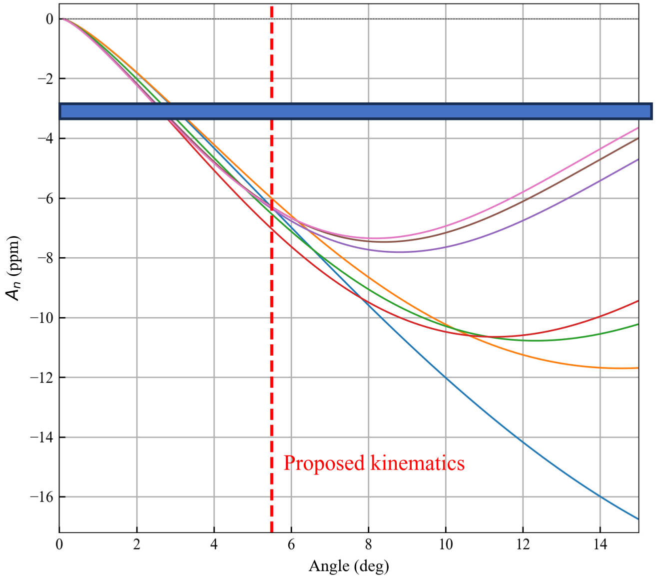
Proposed experiment

- We propose to measure the beam normal single spin asymmetry using targets with a broad range of Z (6 ≤ Z ≤ 90)
- The experiment aims to measure the asymmetries with an absolute uncertainty of 0.5 ppm (stat) ± 0.2 ppm (syst)
- New data on intermediate to heavy nuclei will allow us study nuclear dependence of the asymmetry



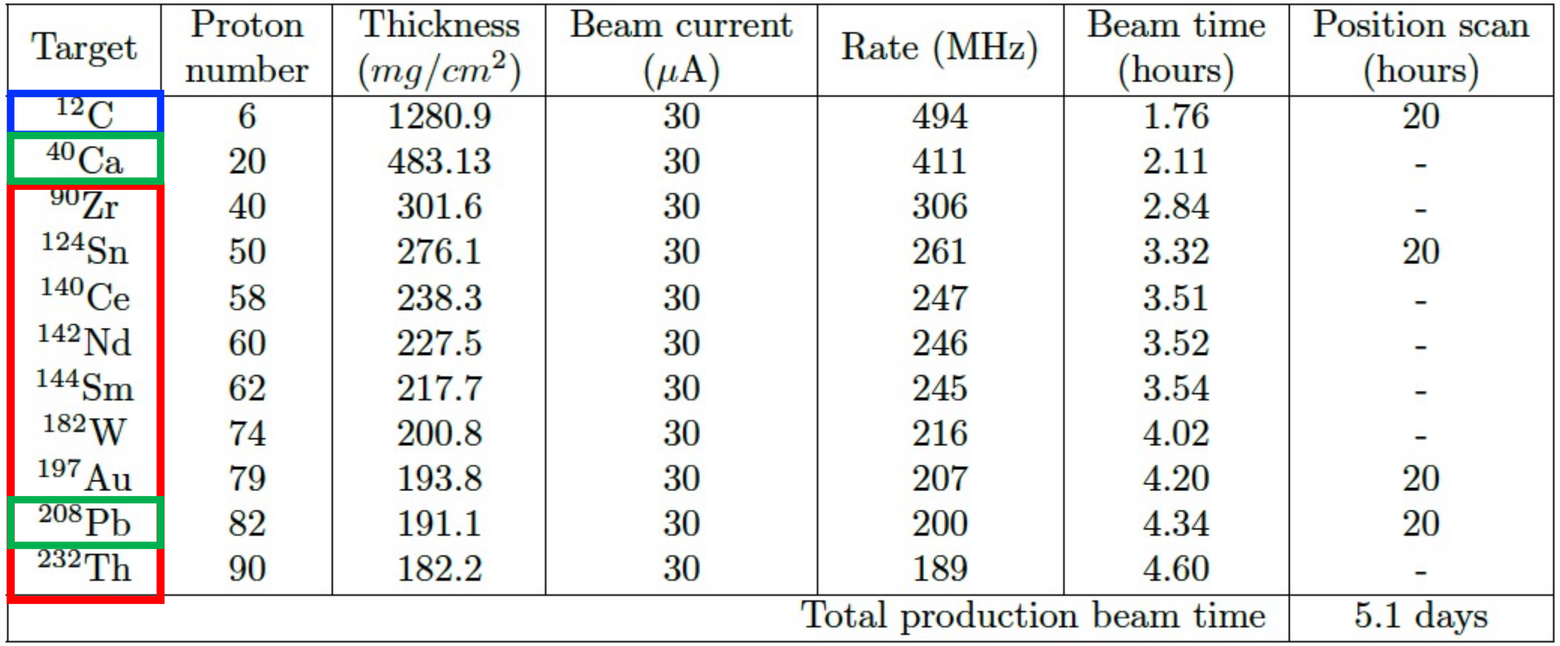
E_{beam} (GeV)	1.0
θ_{lab} (deg)	5.5
Q^2 (GeV^2)	0.0092
Beam current (μA)	30
Statistical uncertainty	0.5 ppm
Systematic uncertainty	0.2 ppm





List of proposed targets and rate estimations

We propose to measure the asymmetry for a set of targets with an atomic number Z range of $6 \leq Z \leq 90$



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

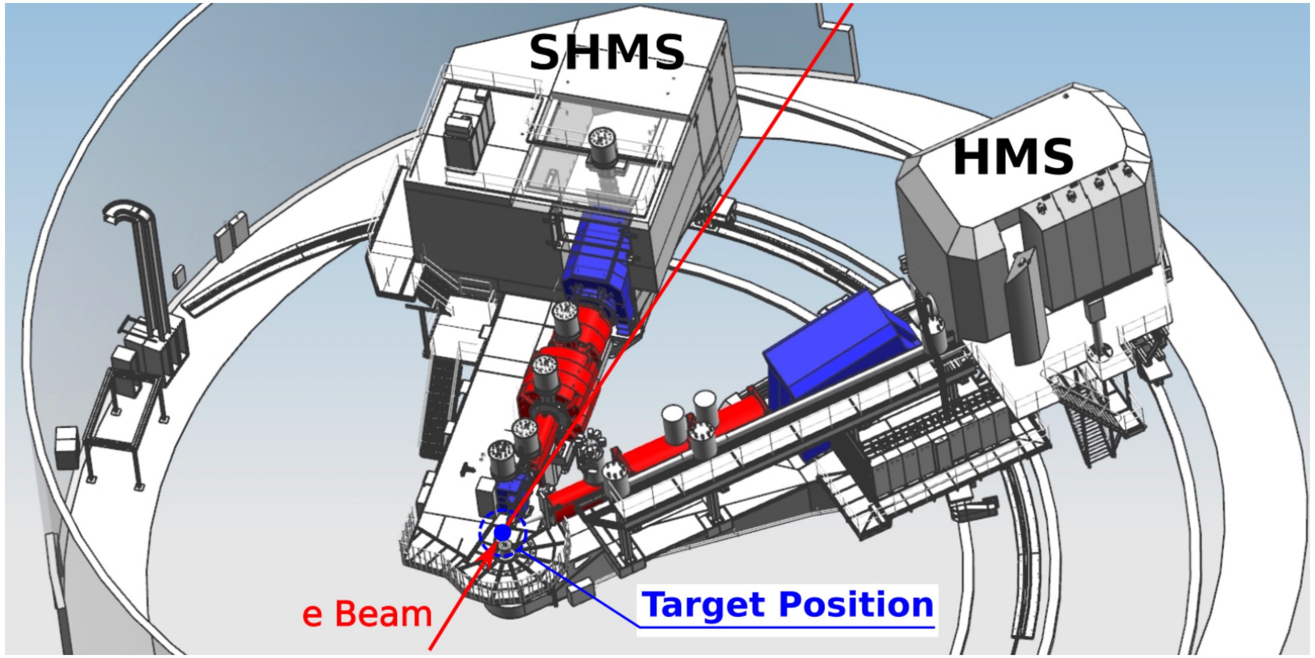
12C provides the baseline measurements

Important consistency check of 40Ca, 208Pb measurements from the previous JLab experiments using a different experiment setup and approach

Intermediate to heavy Z targets will provide important new inputs for studying nuclear dependence of the asymmetry

Experimental setup

- Hall C Super High Momentum Spectrometer (SHMS)

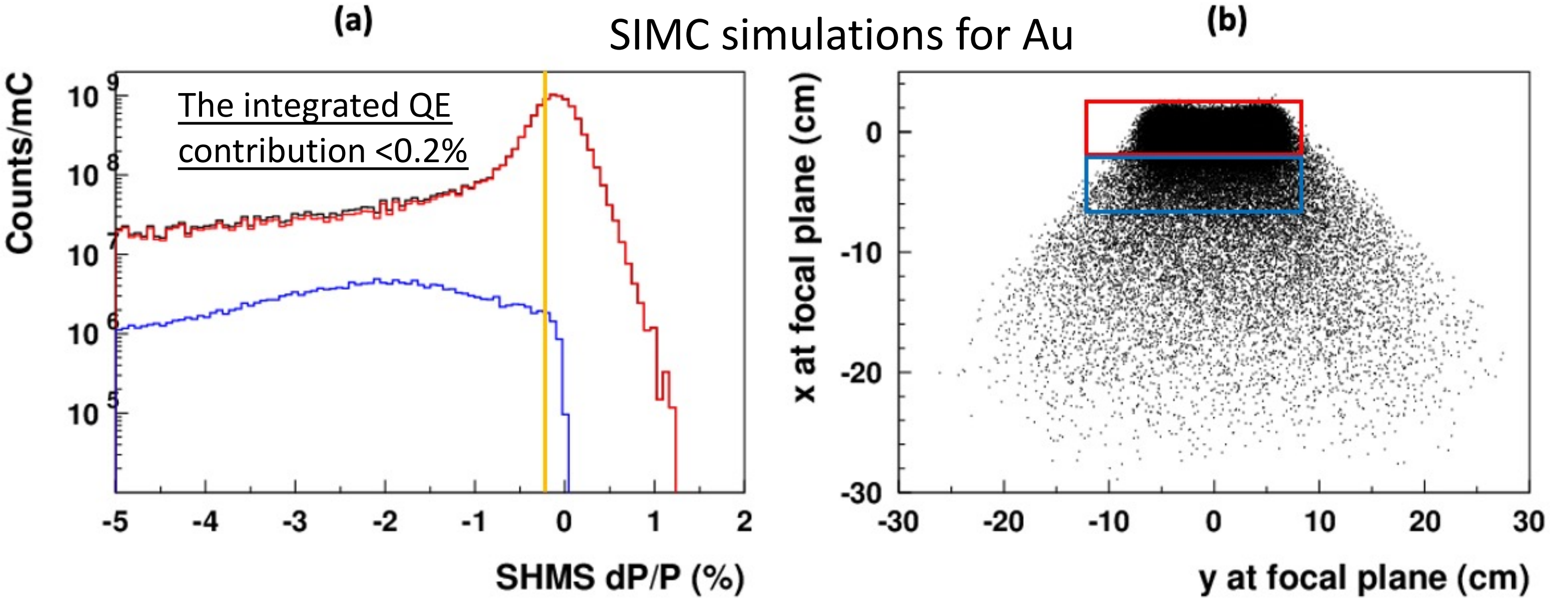


	SHMS	HMS
Scattering angle (deg)	5.5 - 40	10.5 - 80
Solid angle acceptance	$d\Omega\sim4$ msr	$d\Omega\sim6$ msr
Central momentum	1-11 GeV/c	0.5 - 7 GeV/c
Momentum resolution		

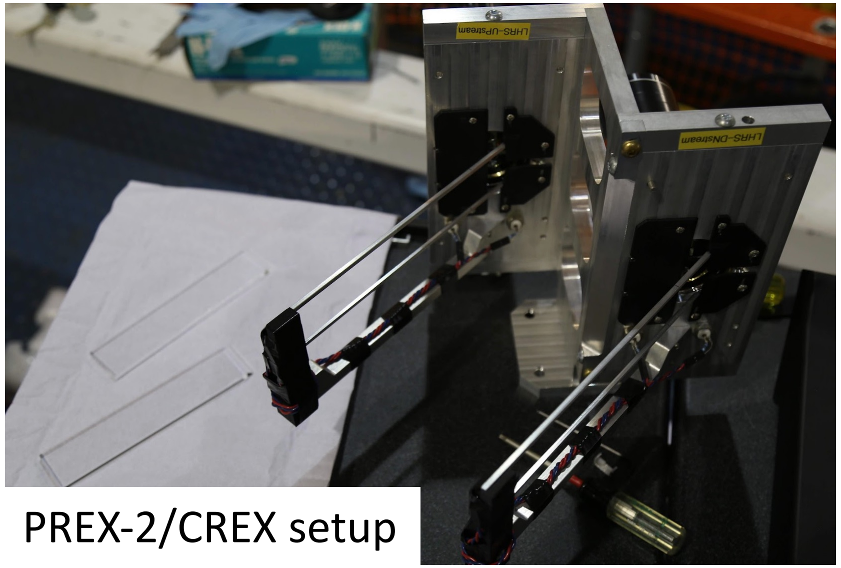
- The standard Hall C SHMS spectrometer will be used at a scattering angle of 5.5 deg with 1 GeV longitudinally polarized electron beam.
- The small scattering angle is chosen: 1) theoretical calculations based on the optical theorem is applicable 2) to maximize the FoM

Optimization for elastic electrons

- We plan to make use of most of the detector setup used for the PREX-2 and CREX experiments
- The detectors would sample different portions of the elastic peak
  - each is 3.5cm in width
- The motion stage would allow for mm precision positioning to facility a scan of the elastic peak
  - If the experiment is approved a possible enhancement would be the addition of a position sensitive detector



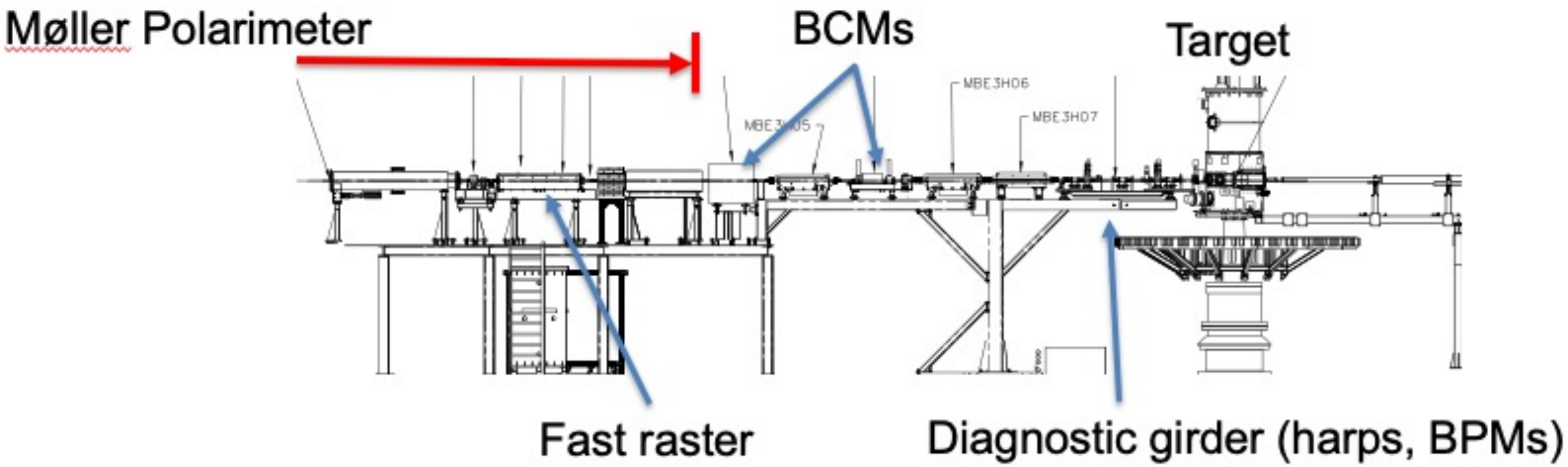
SIMC simulations for Au



PREX-2/CREX setup

- The quartz is coupled directly to the PMT
- The detectors would be placed with the long edge perpendicular to the dispersive direction

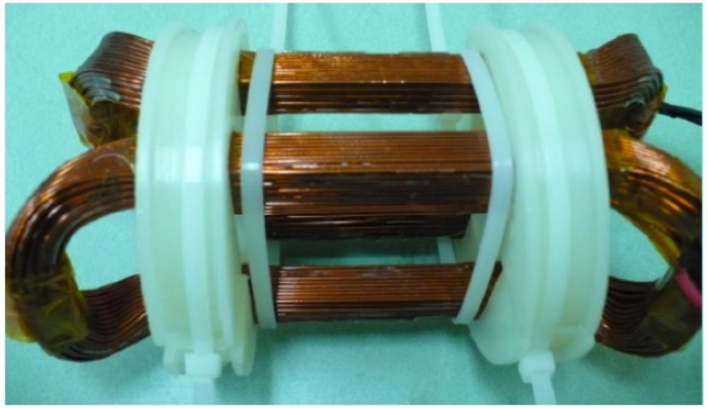
Electron beam, hall C beam line instrumentation



**courtesy of D. Gaskell

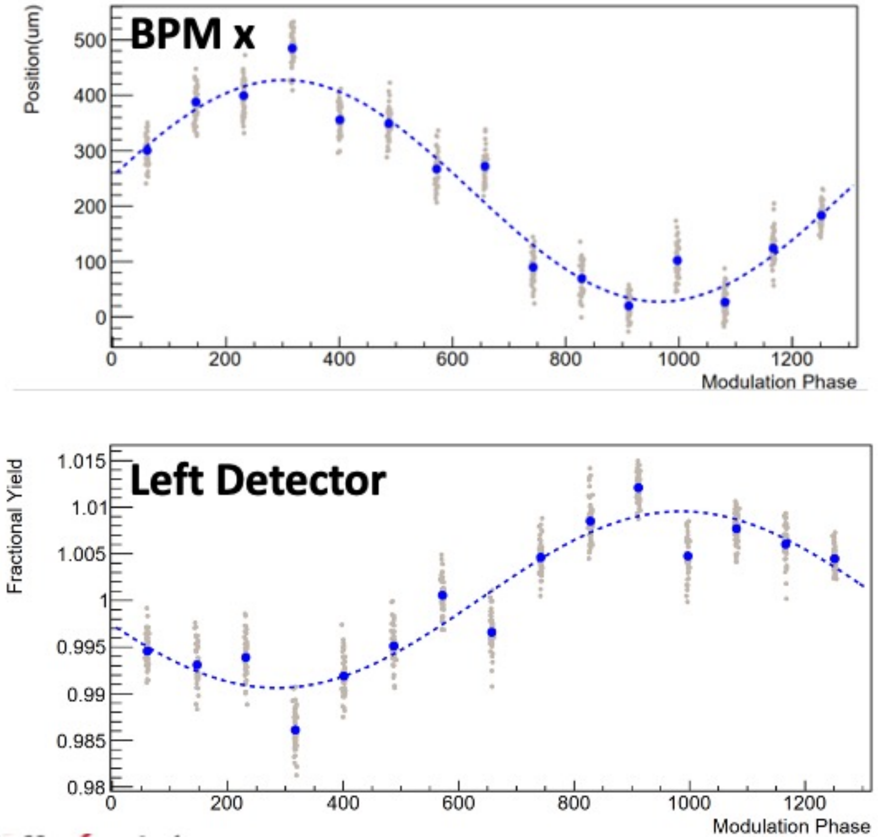
- We plan to take advantage of recent updates to the polarized source setup to reduce the helicity correlated beam asymmetries starting from the injector
  - We would like to have one slow helicity reversal per target: the insertable half wave plate
- Exiting beamline instrumentation (BPMs, BCMs) used previously for Qweak will be more than sufficient to monitor and determine beam properties

Beam modulations



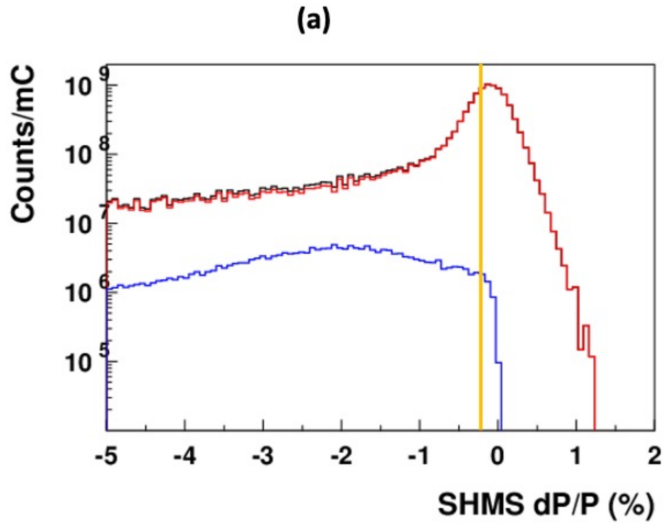
- To remove beam noise from our measurement we will need to employ the beam modulation system
    - It will span the phase space of motion in both position and angle and allow us to subtract out the impact of natural beam motion
- The air-core coils were used previously during Qweak and the collaboration has extensive expertise in a similar system used in hall A for PREX-2 and CREX
- We are confident that the parity systematics are well under control, so a one arm measurement is sufficient

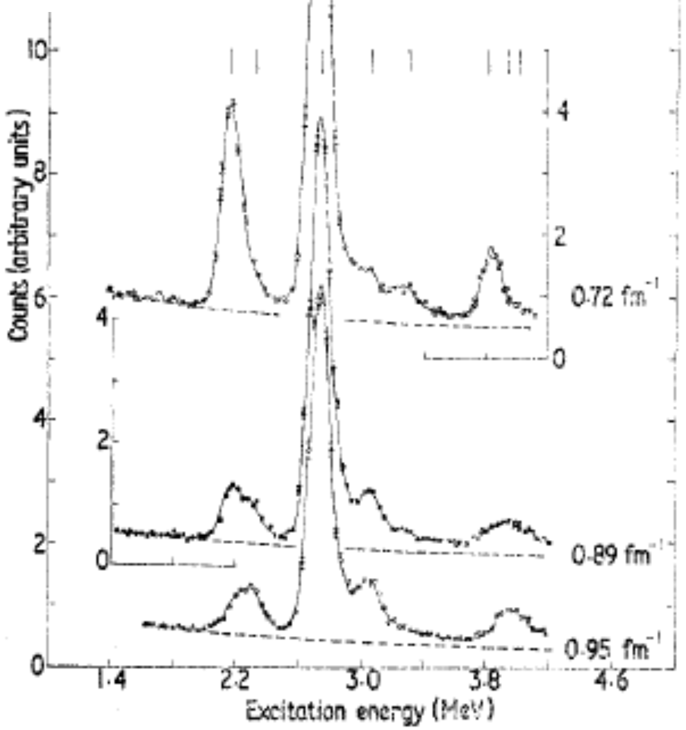
Modulation to calibrate sensitivity (α_i)



Inelastic nuclear states

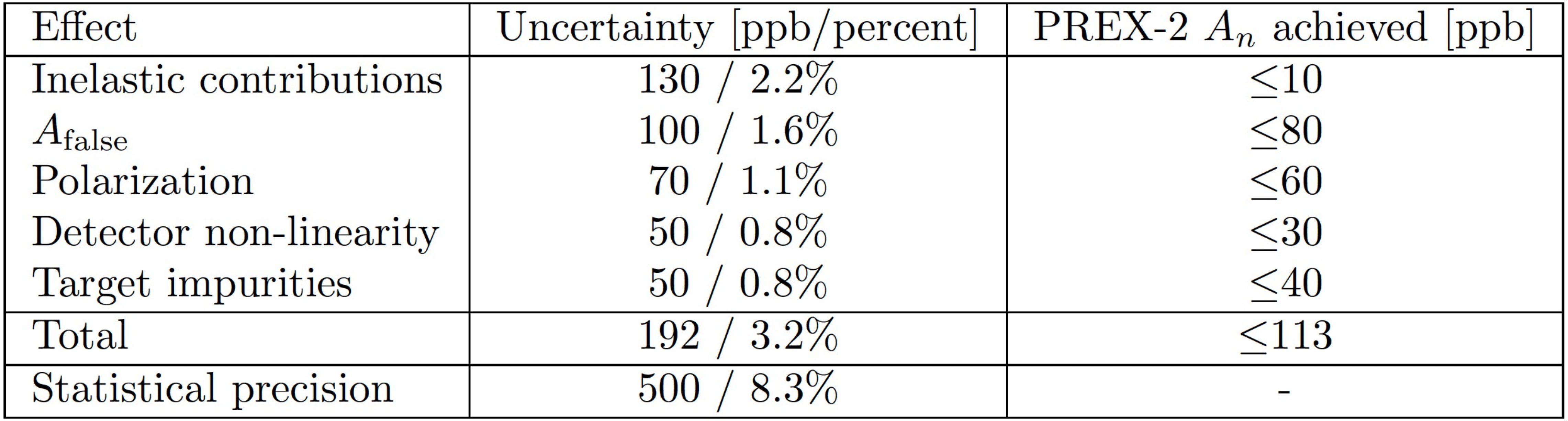
- Some of the targets have low lying inelastic nuclear states that could have a sizeable asymmetry
  - The rate contributions of each of these states can be estimated from existing experimental data and are much smaller than the elastic signal at this Q^2
  - Our systematic budget includes a conservative estimation of these possible asymmetries and their subtraction from the result
  - This analysis procedure was established by the Qweak Al27 A_T publication
- The scans will allow for multiple measurements that will empirically test this approach (possibly even determining the combined asymmetry of these nuclear excited states)





J. Phys. G: Nucl. Phys., Vol. 1, No. 5, 1975

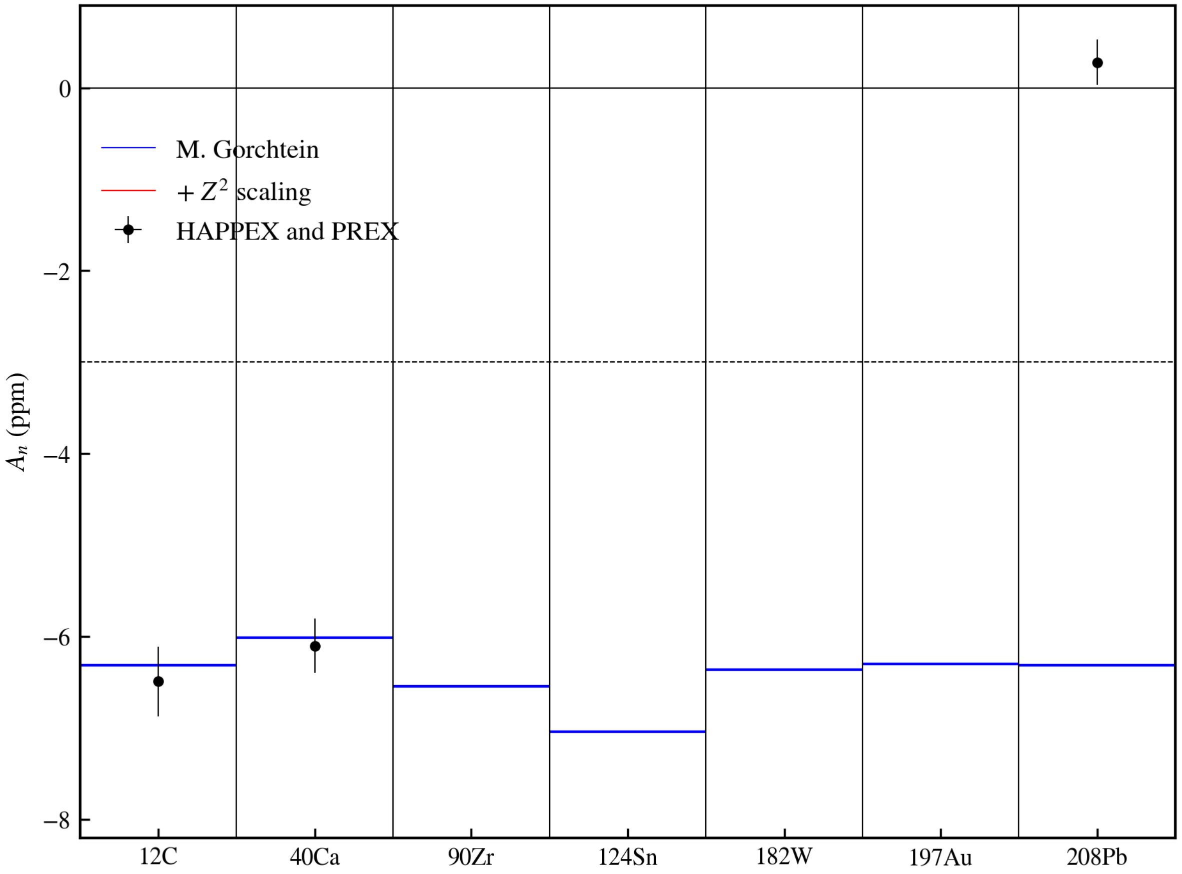
Systematic Uncertainties



Effect	Uncertainty [ppb/percent]	PREX-2 A_n achieved [ppb]
Inelastic contributions	130 / 2.2%	$\leq$10
A_{false}	100 / 1.6%	$\leq$80
Polarization	70 / 1.1%	$\leq$60
Detector non-linearity	50 / 0.8%	$\leq$30
Target impurities	50 / 0.8%	$\leq$40
Total	192 / 3.2%	$\leq$113
Statistical precision	500 / 8.3%	-

- The experiment takes advantage of recent progress made in the setup of the parity quality beam and analysis techniques used for parity experiments
    - The systematic budget is more conservative than what was obtained just a few years ago with PREX-2 and CREX

Projected results



- TPE calculations suggest 6-7 ppm asymmetries for all targets at the proposed kinematics

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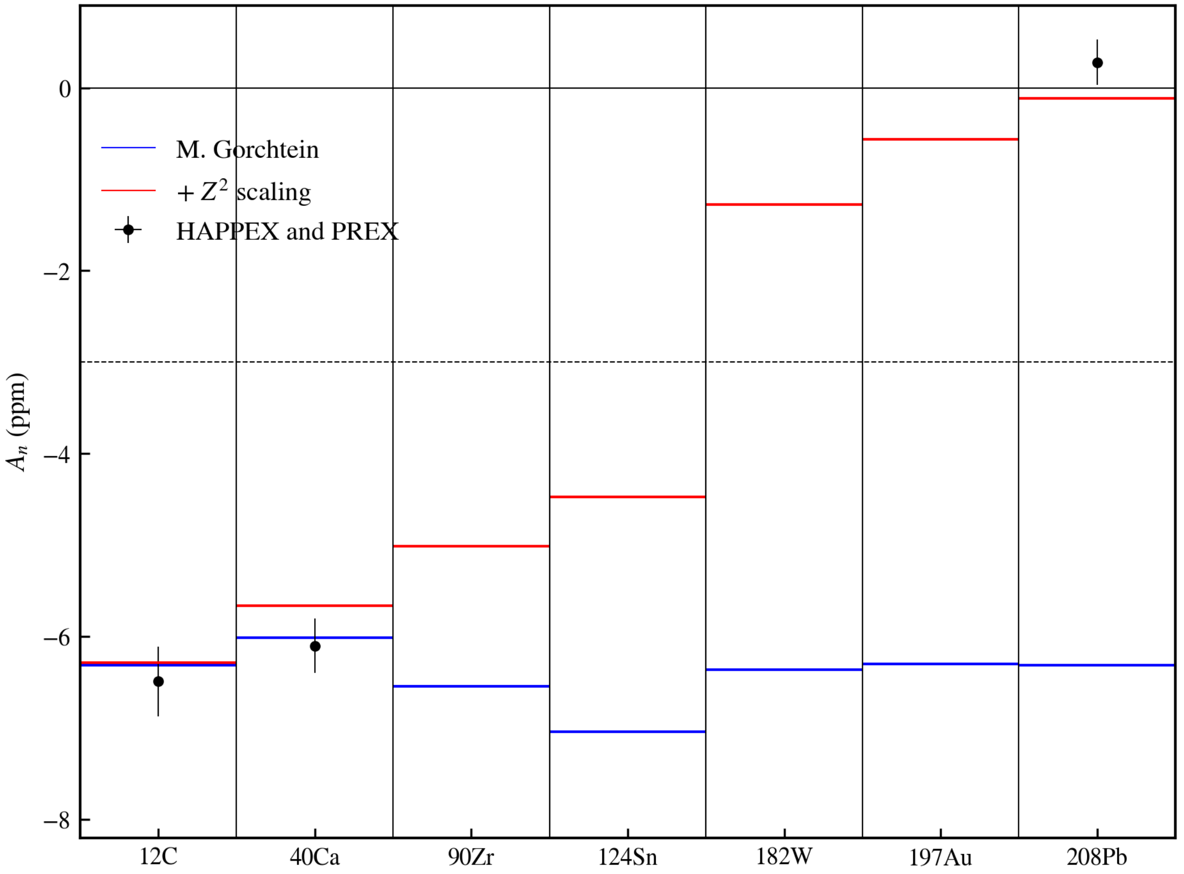
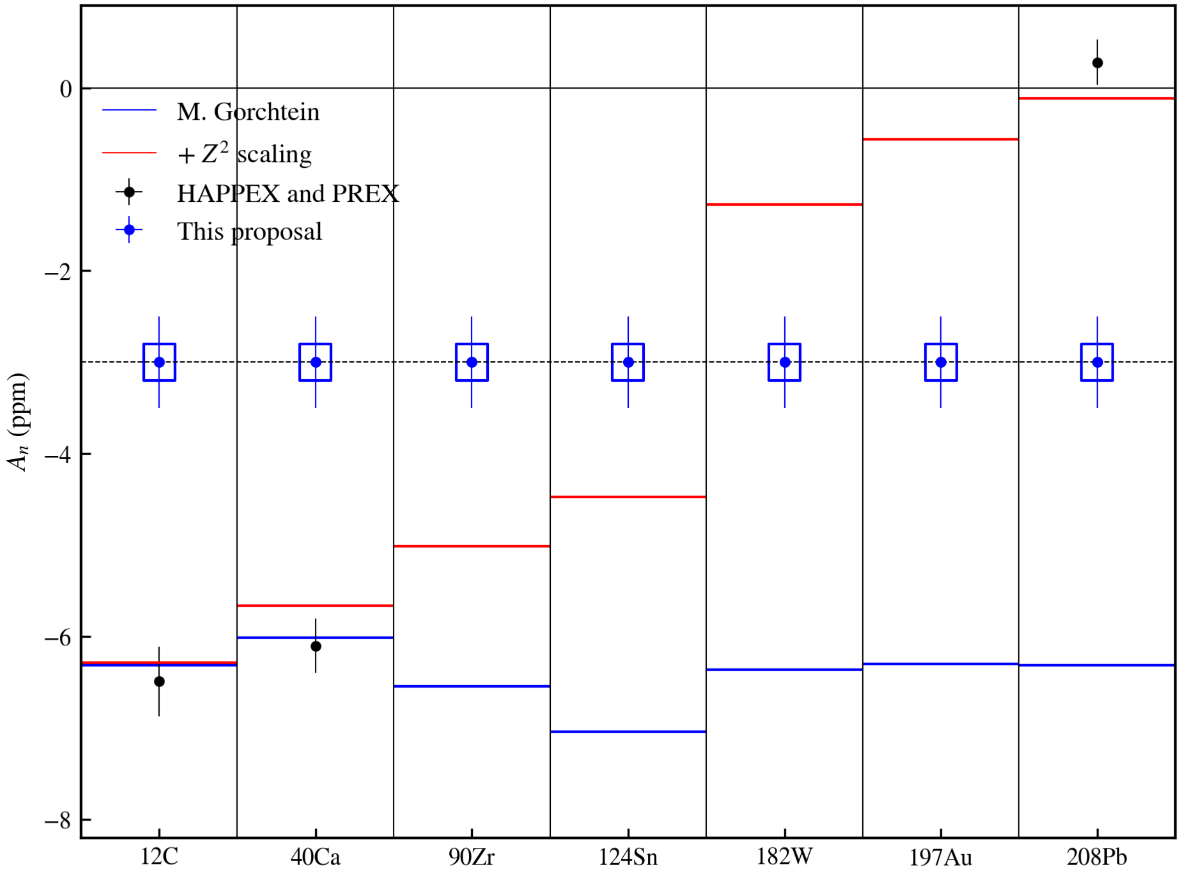


- TPE calculations suggest 6-7 ppm asymmetries for all targets at the proposed kinematics
- Empirical determination of asymmetry suppression assuming Z^2 corrections (https://arxiv.org/pdf/2111.04250)

$$A_n \approx A_0(Q)(1 - C \cdot Z^2 \alpha)$$

- Lack of data for Z > 40 makes it almost impossible to test models for the missing contributions

Projected results



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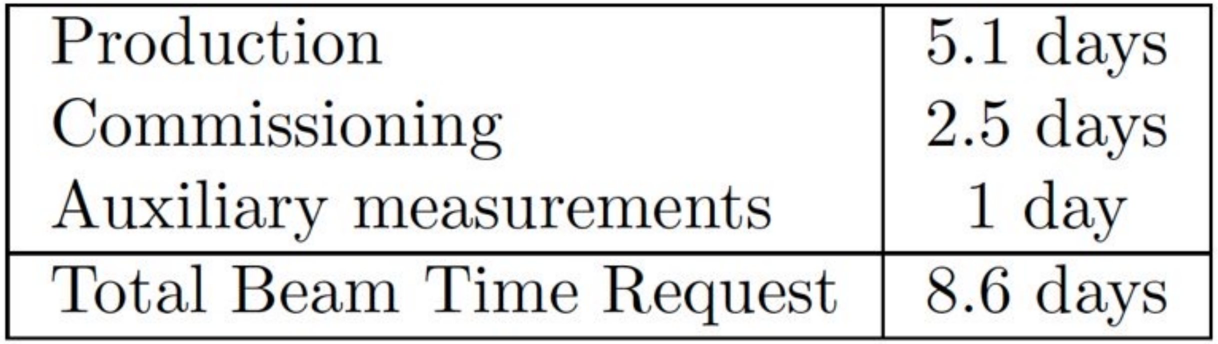
$$A_n \approx A_0(Q)(1 - C \cdot Z^2 \alpha)$$

- Lack of data for Z > 40 makes it almost impossible to test models for the missing contributions
- The precision proposed in this experiment will allow studying the nuclear dependence of the asymmetry

Beam Time Request



Production	5.1 days
Commissioning	2.5 days
Auxiliary measurements	1 day
Total Beam Time Request	8.6 days

- For this experiment, we request total 9 days of beam time
  - ~5 days for production data taking
    - including 4 position scans of elastic peak (C12, Sn124, Au197, Pb208)
  - 2.5 days commissioning include:
    - PQB setup and modulation system commissioning, spectrometer commissioning
  - 1 day for auxiliary measurements: electron beam polarization and Q^2 measurements

The collaboration

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David Armstrong
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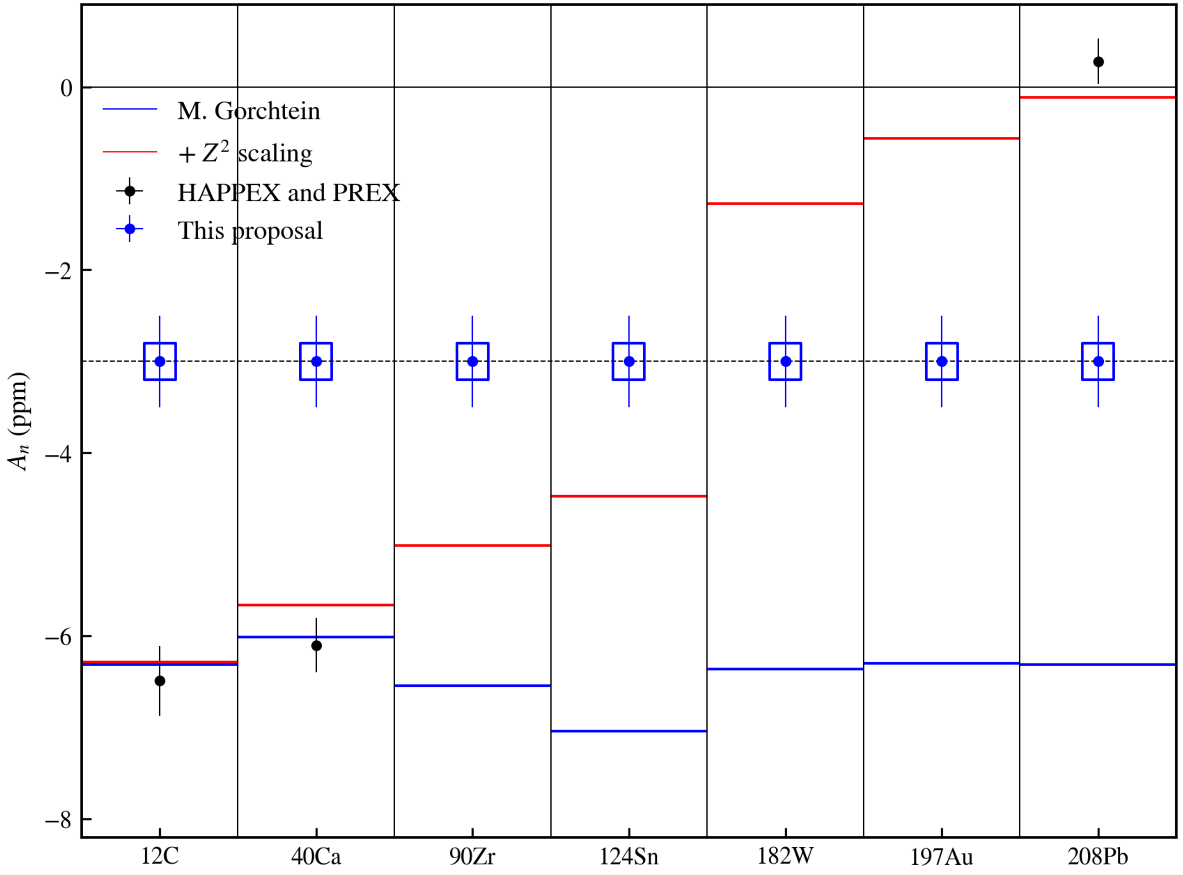
- The collaboration is made up of a significant portion of JLab parity group (Qweak, PREX, and CREX)
- If the experiment is approved several PIs have indicated their willingness to assign PhD students to this topic

Summary

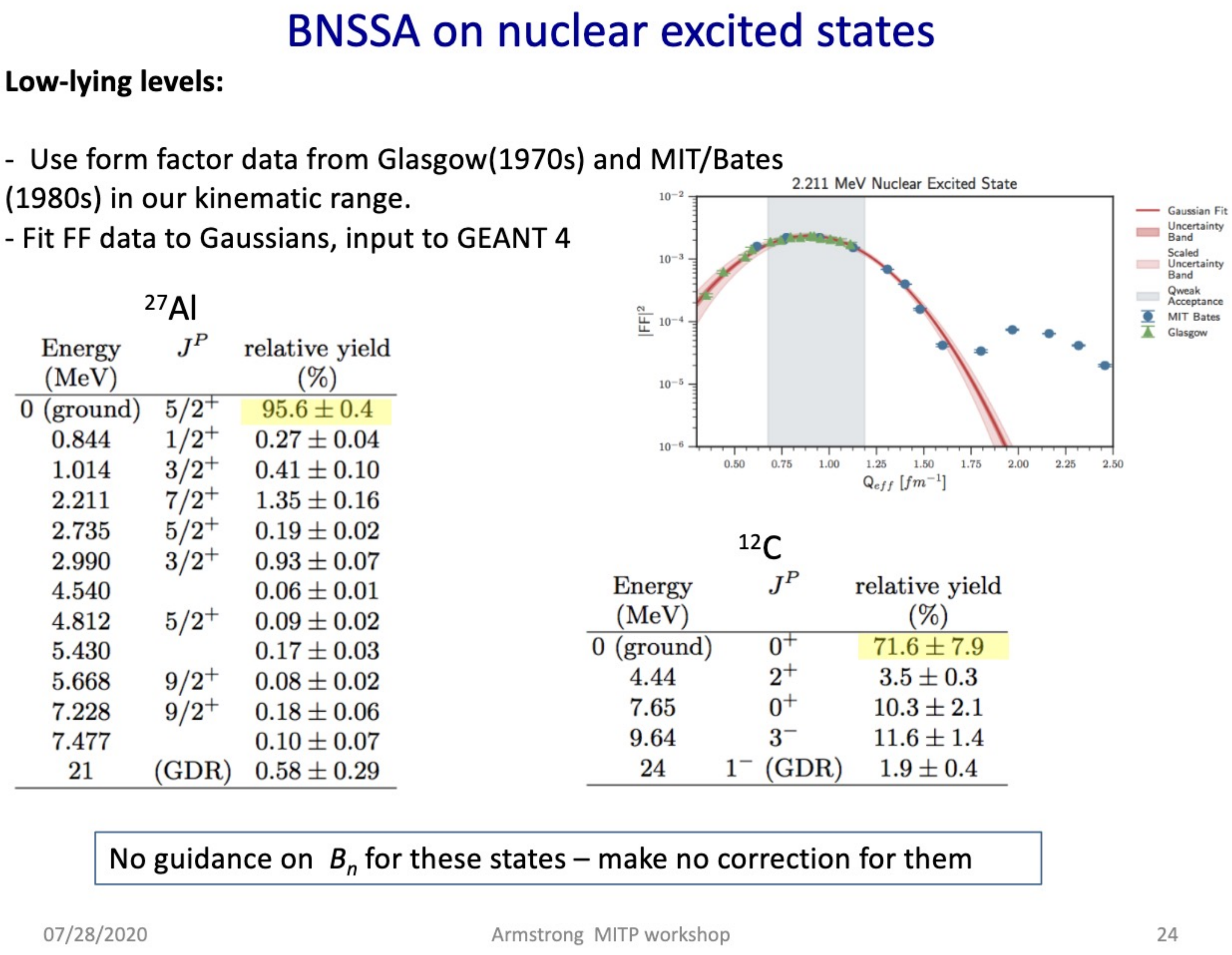
- The PREX A_T results remain a puzzle even after additional theoretical scrutiny
- We propose an experiment that takes advantage of recent PVES technical advances combined with the Hall C equipment to scan this observable over a wide range of Z targets
- This will provide a valuable new input for theory and hopefully give us answers to this interesting conundrum



Backup

Al27 excited states

- Even for Qweak where all of the inelastic states were accepted more than 95% of the signal was made up of elastic events



BNSSA on nuclear excited states

Low-lying levels:

- Use form factor data from Glasgow(1970s) and MIT/Bates (1980s) in our kinematic range.
- Fit FF data to Gaussians, input to GEANT 4

^{27}Al

Energy (MeV)	J^P	relative yield (%)
0 (ground)	$5/2^+$	95.6 ± 0.4
0.844	$1/2^+$	0.27 ± 0.04
1.014	$3/2^+$	0.41 ± 0.10
2.211	$7/2^+$	1.35 ± 0.16
2.735	$5/2^+$	0.19 ± 0.02
2.990	$3/2^+$	0.93 ± 0.07
4.540		0.06 ± 0.01
4.812	$5/2^+$	0.09 ± 0.02
5.430		0.17 ± 0.03
5.668	$9/2^+$	0.08 ± 0.02
7.228	$9/2^+$	0.18 ± 0.06
7.477		0.10 ± 0.07
21	(GDR)	0.58 ± 0.29

^{12}C

Energy (MeV)	J^P	relative yield (%)
0 (ground)	0^+	71.6 ± 7.9
4.44	2^+	3.5 ± 0.3
7.65	0^+	10.3 ± 2.1
9.64	3^-	11.6 ± 1.4
24	1^- (GDR)	1.9 ± 0.4

No guidance on B_n for these states – make no correction for them

07/28/2020 Armstrong MITP workshop 24

A_T puzzle naïve suggestion

$$A_n \sim \frac{\mathcal{I}(A^*_{2\gamma})}{Z} + \boxed{\frac{Q_Z Q^2}{M_Z^2}\cdot C}$$

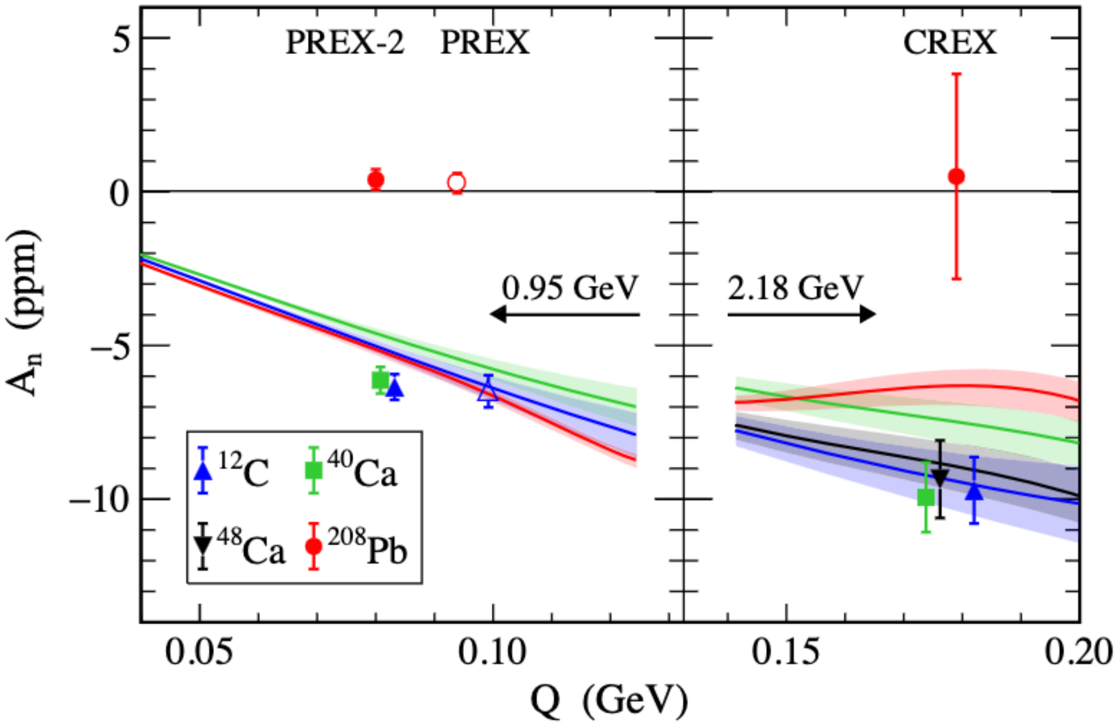
$$A_n \sim \frac{\mathcal{I}(A^*_{2\gamma})}{Z} + \boxed{\frac{A Q^2}{M_Z^2}\cdot \frac{M_Z}{\Lambda^2}}$$

Dipole operators

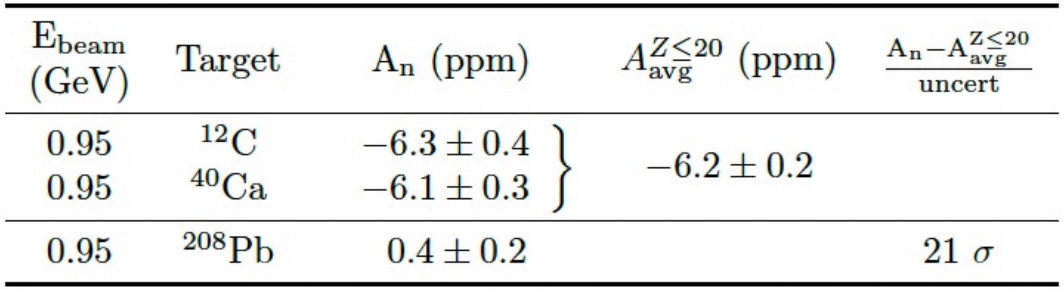
$$\boxed{\begin{aligned}
\mathcal{O}_{eW} &= (\bar{l}\sigma^{\mu\nu}e)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{eB} &= (\bar{l}\sigma^{\mu\nu}e)\varphi B_{\mu\nu},\\
\mathcal{O}_{uW} &= (\bar{q}\sigma^{\mu\nu}u)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{uB} &= (\bar{q}\sigma^{\mu\nu}u)\varphi B_{\mu\nu},\\
\mathcal{O}_{dW} &= (\bar{q}\sigma^{\mu\nu}d)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{dB} &= (\bar{q}\sigma^{\mu\nu}d)\varphi B_{\mu\nu}.
\end{aligned}}$$

- The lead results are in fact positive (by 2 sigma
- One possible explanation would be that another physics process produces a transverse asymmetry with the opposite sign as the TPE that is present in high N (or Z) nuclei
    - Initial SMEFT calculations** indicate a possible scaling with the total number of nucleons for a BSM contribution from dipole operators

** Thanks to F. Petriello and R. Boughezal (work motivated by BSM at EIC)

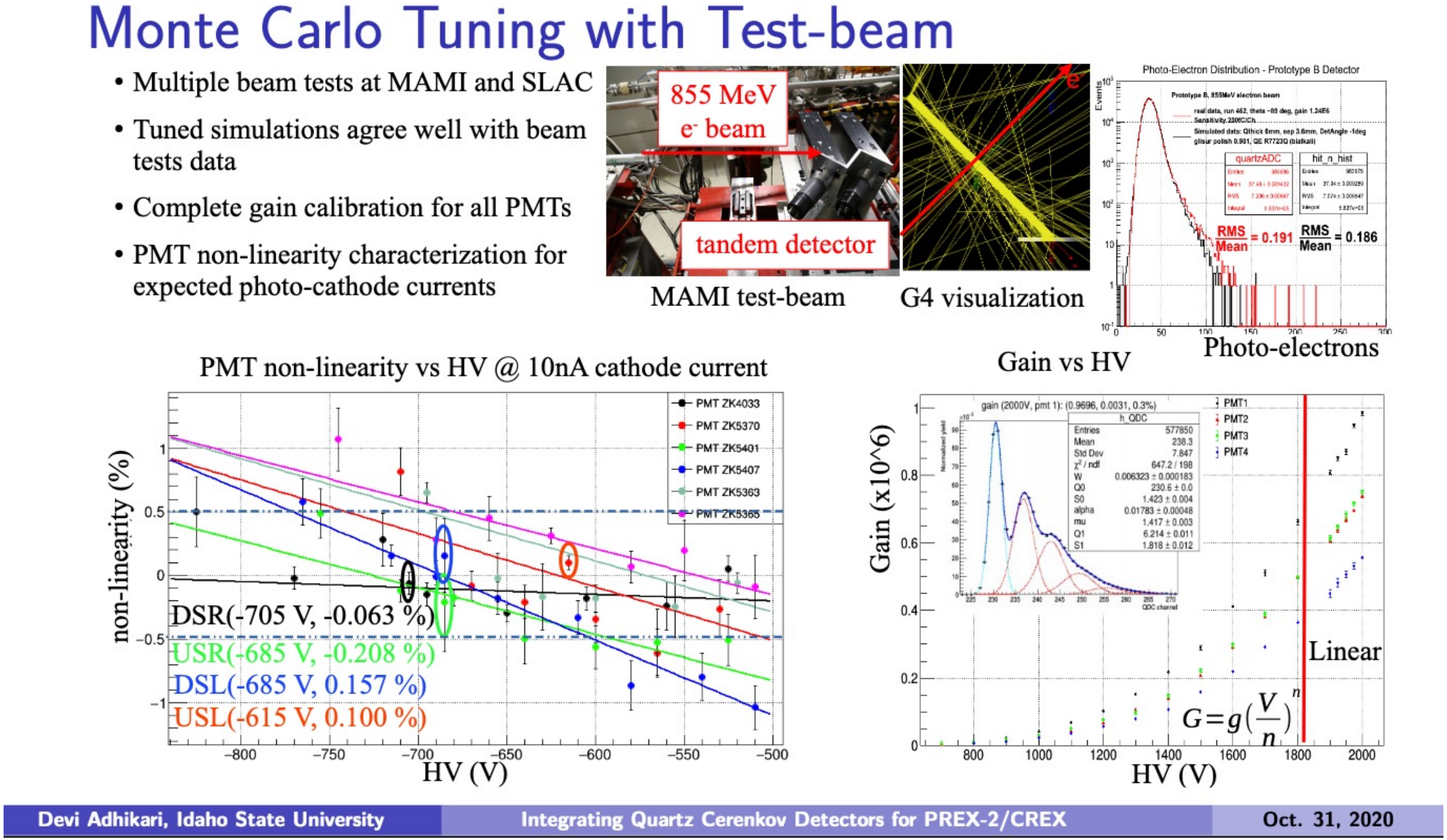


Pb208 results suggest there are missing contributions that are not accounted in the existing theoretical models



E_{beam} (GeV)	Target	A_n (ppm)	$A^{Z\leq 20}_{\text{avg}}$ (ppm)	$\frac{A_n - A^{Z\leq 20}_{\text{avg}}}{\text{uncert}}$
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		21 σ

Detector non-linearity



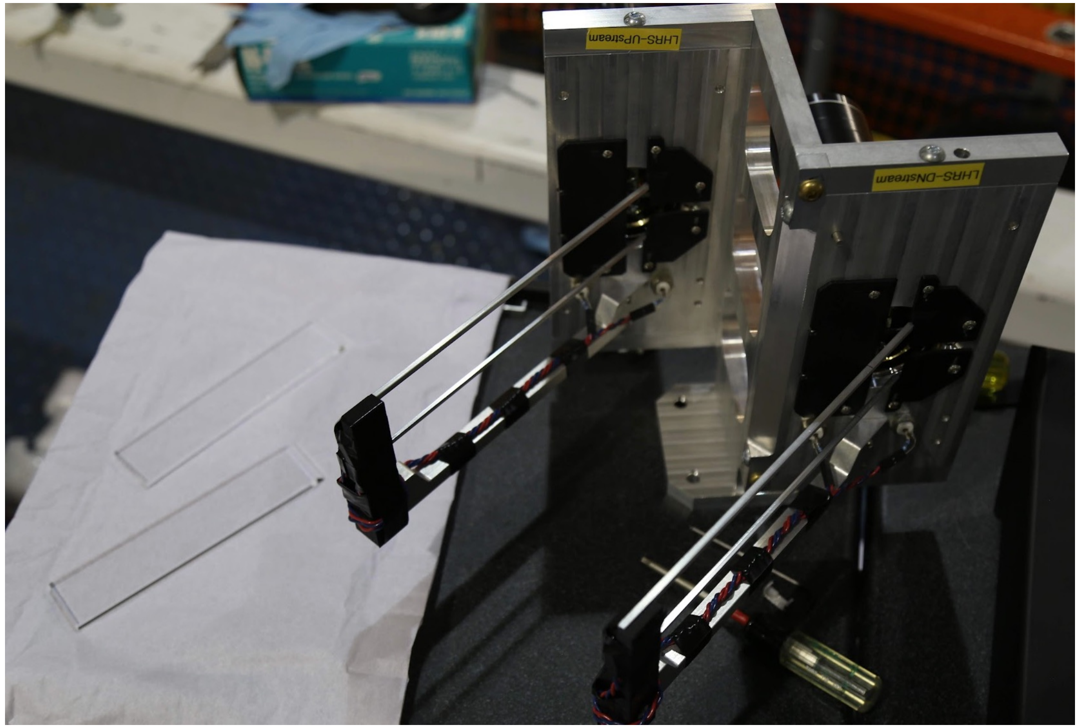
Monte Carlo Tuning with Test-beam

- Multiple beam tests at MAMI and SLAC
- Tuned simulations agree well with beam tests data
- Complete gain calibration for all PMTs
- PMT non-linearity characterization for expected photo-cathode currents

Devi Adhikari, Idaho State University | Integrating Quartz Cerenkov Detectors for PREX-2/CREX | Oct. 31, 2020

Detector motion

PREX-2/CREX setup



Theory Report

This proposal is significantly motivated by the unexpected result obtained on the beam normal single spin asymmetry An in elastic electron scattering on 208Pb by the PREX and CREX experiments in Hall A. The result shows a very small asymmetry as compared with the ones for lighter nuclei. This proposal for Hall C, will investigate nuclei in the Z range from 6 to 90. In addition to serve as a check of the PREX/CREX results, it will provide a picture of the evolution of the asymmetry with atomic number. For the Q2 and beam energies of previous experiments at JLab, An for 12C to 48Ca is in the range of 5 to 10 ppm. With the projected error budget of 0.55 ppm, the proposed experiment can achieve its goal.

The aim of the proposal is of high interest. The results will add important information on the asymmetry's Z dependence and to the elucidation of the present An puzzle in 208Pb.

Response to TAC comments

Given the small amount of beam time requested, one wonders if it wouldn't be better to focus on the targets with more widely separated states. The strategy in the referenced Q-weak BNSSA paper on Al for dealing with corrections for nuclear inelastic excitations was the following: 1) do a reasonable calculation of the yield for each state, and 2) because no calculation of the relevant inelastic BNSSA's was available, estimate it and assign what is hopefully a conservatively large uncertainty.

It would be ideal to have targets with a well separated elastic peak from excited states, but the separation of excited states from elastic is challenging for most of large Z target except Pb208. In order to study any missing/hidden contributions to the asymmetry calculations, it is critical to have a wide range of Z targets especially for Z > 40. We will follow the similar strategy done for Qweak Al measurement.

Response to TAC comments

A mild concern is the likelihood of localized rad damage to the existing pre-shower lead glass. From Table 4 of the proposal, roughly 250 MHz of electrons will be focused on a few 10's of cm2 area for 5 days. A crude calculation suggests the dose to the pre-shower layer would be of order 0.5 MRad, which would blacken and effectively ruin the affected blocks. This concern has been labelled mild however because, if the HGC is removed, there would be plenty of room to install a lead wall to absorb the 1 GeV electron showers before they reach the lead-glass calorimeters.

Indeed the HGC will not be used for this experiment, and therefore it can be removed.

Response to TAC comments

Another mild concern is achieving the systematic error of 0.2 ppm from false asymmetries in runs which might be as short as several hours. (Because targets may be measured in multiple positions.) This is sufficient time for two half-wave plate settings, but it would be an unusually brief time for feedback to average down the helicity correlated beam parameters. A crude estimates of sensitivity and position resolution suggest 0.2 ppm may be feasible in such short time scales, but the collaboration should state clearly what sensitivities and resolutions are expected for all helicity correlated beam parameters, and what the plans and time scales are for feedback.

As mentioned by the reviewer we believe there is no need for feedback to average out false beam asymmetries. The setup achieved for the injector during PREX-2 and CREX combined with the half-wave plate reversal will be sufficient to reach the 0.1 ppm systematic.

Response to PAC comments

(1) From the TAC report #3, in particular, whether the collaboration has a suitable design for an integrating mode detector with sufficient position sensitivity to separate (by making small adjustments of the detector position in the dispersive direction) elastic scattering from the low-lying inelastic transitions.

The base design that we discuss in the proposal is the one that was already in use during PREX-2 and CREX. The detectors had 3.5cm wide quartz in the dispersive direction. Moreover, the detectors were placed at an angle to be perpendicular to the dispersive direction in the HRS. Lastly, these detectors could be remotely moved and positioned to better than 1 mm.

The proposal and consequent physics output do not hinge on the ability of the detectors to completely remove the inelastic states. We have taken into account that for some of the targets such as 232Th the measurement will have an irreducible admixture of elastic and inelastic states and assigned a sizeable systematic related to the subtraction of this background from the final result. For such cases, we plan to follow the procedure outlined in the Qweak aluminum transverse analysis and estimate both the rates and associated asymmetry arising from the inelastic states.

Finally, to reduce this systematic and the dependence on theoretically estimated asymmetries for the inelastic states we have proposed to do measurements where different admixtures are present. This will allow us to empirically determine the size of the inelastic contribution and compare it to the models for select targets.

Response to PAC comments

(2) From the TAC report #7, about the feasibility of acquiring and utilizing the following targets listed in Table 6 of the proposal.

The list of targets was created in collaboration with Dave Meekins from the JLab target group. He has confidence that the targets can be procured and installed in a cryo ladder (similar to what was used during PREX-2 and CREX).

If approved, the experiment will undergo safety reviews internally at JLab which will include reviews from the RadCon group associated with the safety of the targets and radiation field created during and after the experiment.

Response to PAC comments

(3) On Fig.8, it would be nice to also see the data and theoretical expectation for the other intermediate Z targets listed in Tab. 4

Figure 8 shows the theoretical calculations for the targets we received from M. Gorchtein. We will engage with the theory community to get updated calculations for all proposed targets prior to the experimental data taking.

There are some targets that are not shown in the figure such as 140Ce, 142Nd, and 144Sm. However, as shown in Figure 5 the theoretical calculations have a very week nuclear dependence for the asymmetry. A simple interpolation would imply that these nuclei would also have a theoretically estimated asymmetry around 7ppm.

Section 2.2 of our proposal presents all of the relevant world data available on this observable. The only intermediate Z target data is the Zr results from Mainz (see figure 1 and table 1). However, the kinematics are such that a clean theoretical interpretation cannot be made. The small scattering angle for our proposal will avoid this pitfall.

The precision we propose for these measurements will be sufficient to determine if these medium Z nuclei continue to be consistent with theoretical expectations or deviate.

Response to PAC comments

(4) Could you please give details on the simulations of elastic, and inelastic and quasi-elastic simulations of Fig. 7? What is the uncertainty on the estimation of the mix between inelastic and elastic rates and is this considered in the estimation of the inelastic contribution systematics in Tab. 5?

The simulation includes spectrometer acceptance, radiative effects, multiple scattering, coulomb corrections.

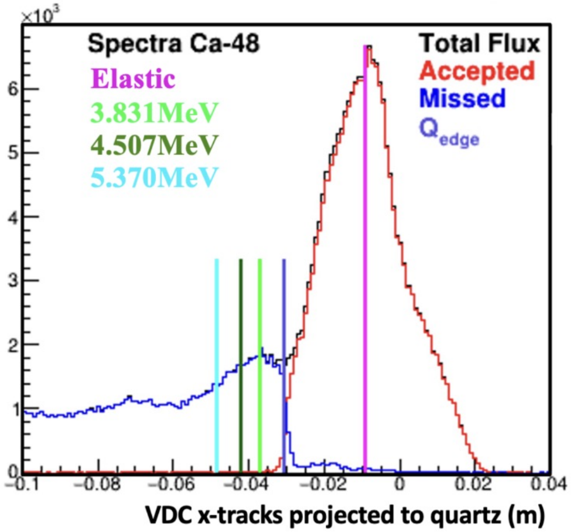
Elastic events are generated using SIMC (standard Hall C MC simulation package). The nuclear elastic form factors are calculated using a parametrization from H. de Vries: Nuclear Charge Density Distributions from Elastic Electron Scattering. in Atomic Data and Nuclear Data Tables 36, 495(1987).

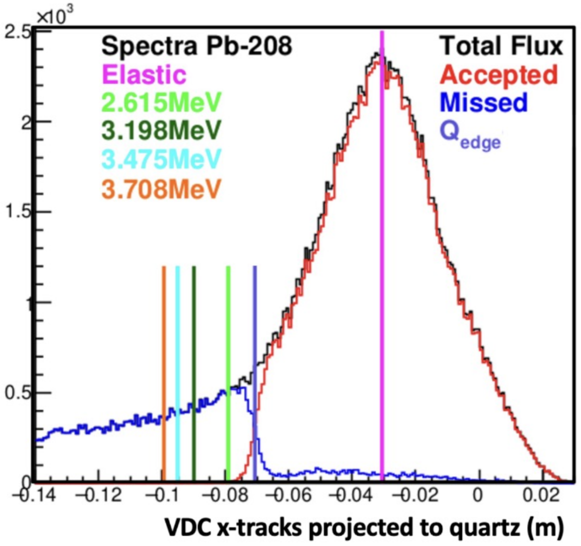
The QE contribution comes from F1F209 from Peter Bosted and Vahe Mamyan (https://arxiv.org/abs/1203.2262).

The inelastic is derived from a fit to the proton and deuteron structure functions from Arie Bodek et al (Phys. Rev. D 20, 1471 (1979)), multiplied by a correction to account for nuclear effects (a fit to the EMC effect)

Response to PAC comments

The systematic in table 5 labeled “Inelastic contributions” refers to inelastic nuclear resonant states (the first of which for each target is listed in table 6). These were not included in the simulation in figure 7. Their rates are going to be similar to the inelastic rates simulated. For an example below are the measured Ca48 and Pb208 spectra with the HRS at 2GeV and 1 GeV respectively:





While the resolution (and thus the separation) of the HRS during PREX-2 and CREX was better these plots clearly show the relative rates between the nuclear excited states and the elastic peak.

The estimation of the uncertainty in table 5 was based on previous experience with these types of measurements and the procedures established for the Qweak Al27 measurement. In that measurement all nuclear excited states had to be included and they assigned a 2.6% systematic. By comparison these measurements will only partially accept nuclear excited states for different targets, so we conservatively assign a 2.2% systematic for this contribution.

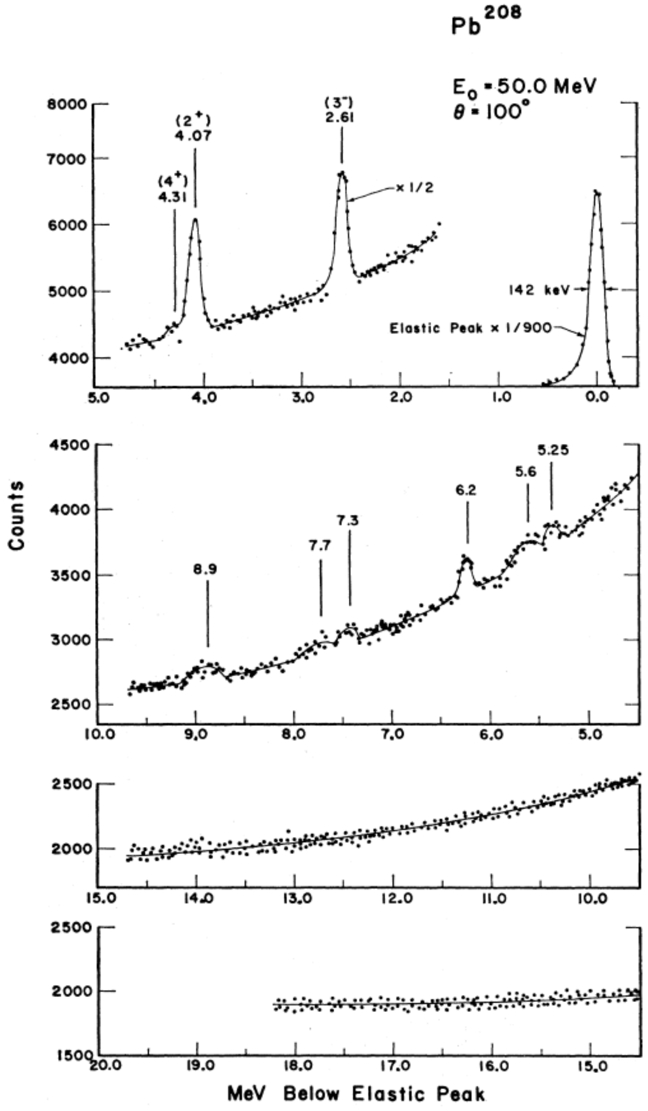
Response to PAC comments

(6) Could you explain how will be determined the asymmetry contamination for the lead and tin targets (target impurities) and how is estimated the 0.8% uncertainty in Tab. 5?

The lead and tin targets will require graphite backing to prevent them from melting. The asymmetry of Carbon has been well studied and can be calculated precisely together with rates based on the thickness of the graphite backing. Using the rate and asymmetry of Carbon the lead/tin asymmetry can be extracted from the combined result.

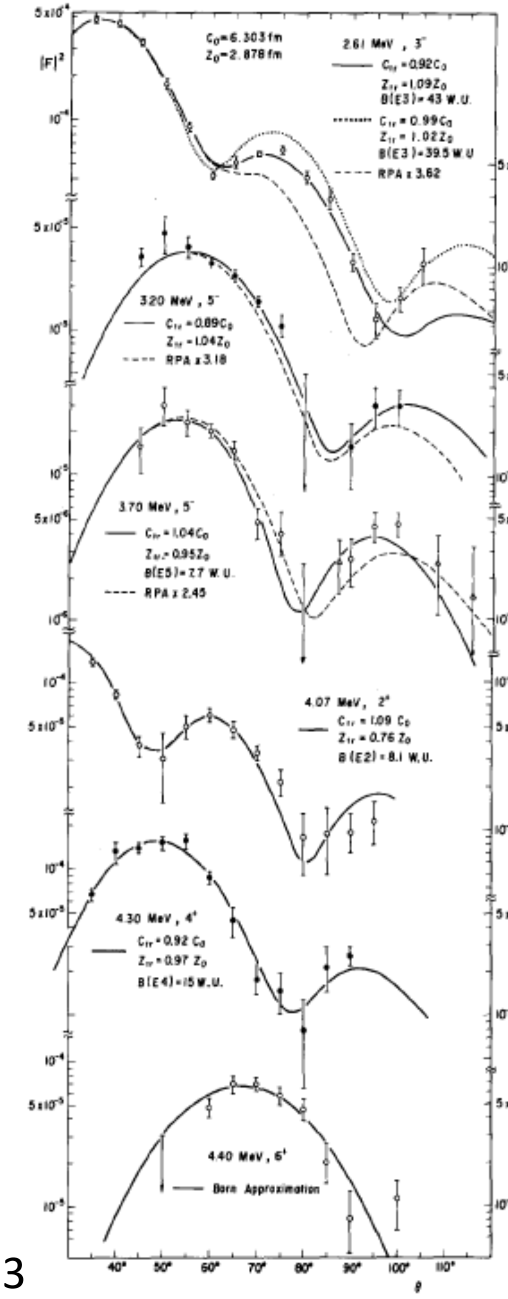
Moreover, we have included a pure Carbon target so the asymmetry and rates will be determined empirically as well. The subtraction method has been successfully employed for the PREX-I and PREX-2 experiments. PREX-2 ran at a similar Q2 value and achieved a 40ppb systematic uncertainty for the target impurities (Table II in [19]). We conservatively assigned 50ppb for this systematic.

208Pb Inelastic cross-sections and form factors



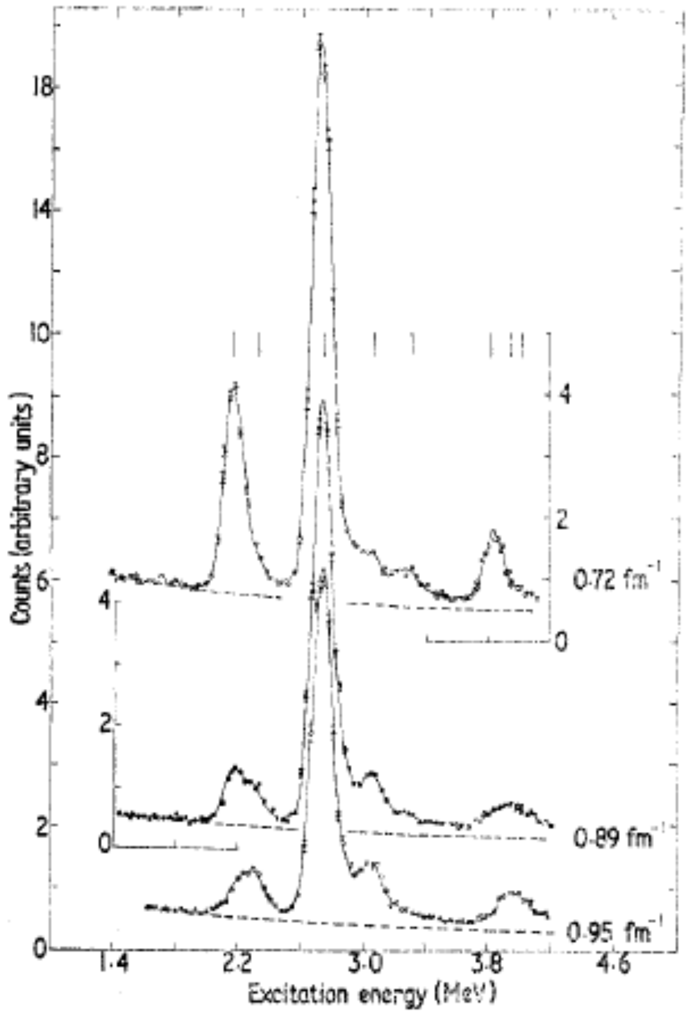
Phys. Rev. 165, 4, 1337 (1968)

We can use either inelastic cross-sections or form factors to estimate contributions of these states in our acceptance.



Phys. Lett. 37B, 4, 383 (1971)

90Zr Inelastic cross-sections and form factors



J. Phys. G: Nucl. Phys., Vol. 1, No. 5, 1975

We can use the inelastic cross-sections to estimate contributions of these states in our acceptance.