New transverse beam asymmetry measurements

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(for the PREX-II/CREX Collaboration)

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New transverse beam asymmetry measurements for ^{208}Pb, ^{48}Ca, ^{40}Ca, and ^{12}C

Outline

- Introduction to beam-normal single spin asymmetry
- PREX-II and CREX transverse asymmetry meas.
  - Experiment overview, apparatus and techniques
  - A_n measurement and kinematics
  - Sample focal Plane spectra, raw data, and uncertainties
- New A_n results (preliminary)
  - With past theory calc's and PREX-I and HAPPEX data
  - Phenomenological fits to new and old data
  - New data shown with new calc's from Gorchtein
- Summary

List of past and present undergraduate research assistants within past 6 years

Student	Contribution	Current Status
Kevin Rhine	LG Designs: SAMs and Shwr-max	Grad. 2015
Brady Lowe	DAQ setup, PMT gains, CREX det.	Grad. 2015; MS 2019
Blake French	CODA event-viewer, Cosmic-stand	Grad. 2015; job at Micron
Dayah Chrisman	PMT gain analysis macro	Grad. 2015; Grad.Stud. MSU
Will Gorman	Cosmic-ray data analysis	Grad. 2014;Grad.Stud. U of Roch.
Max Sturgeon	Bending Al. Light Guides for SAMs	Grad. 2017
Chase Juneau	CAD; reflectivity meas.	Grad. 2017; job at INL
Daniel Sluder	Shower-max support frame CAD, ...	Grad. 2016; MS 2018
Joey McCullough	GEM readout backplanes;SLAC tests	Grad. 2017; MS expected 2019
C. Royal Cole	SLAC testbeam stand	Grad. Dec 2018; Medical School
Eighdi Aung	GEM CAD	Grad. 2019; Grad. Stud. Va Tech
Rajul Chauhan	PREX-II/CREX det. motion control	Grad. 2019
Justin Gahley	SLAC testbeam stand motion control	Expected Grad. 2020
Alec Lepisto	3D printing parts; SLAC analysis	Expected Grad. 2021
Brandon Pearson	Designing and 3D printing parts	Expected Grad. 2021

Beam Normal Single Spin Asymmetry

Introduction

- Electron beam polarization ($\vec{P}_e$) is transverse to beam momentum; incident on unpolarized target
- Induces azimuthal parity-conserving asymmetry (A_n)

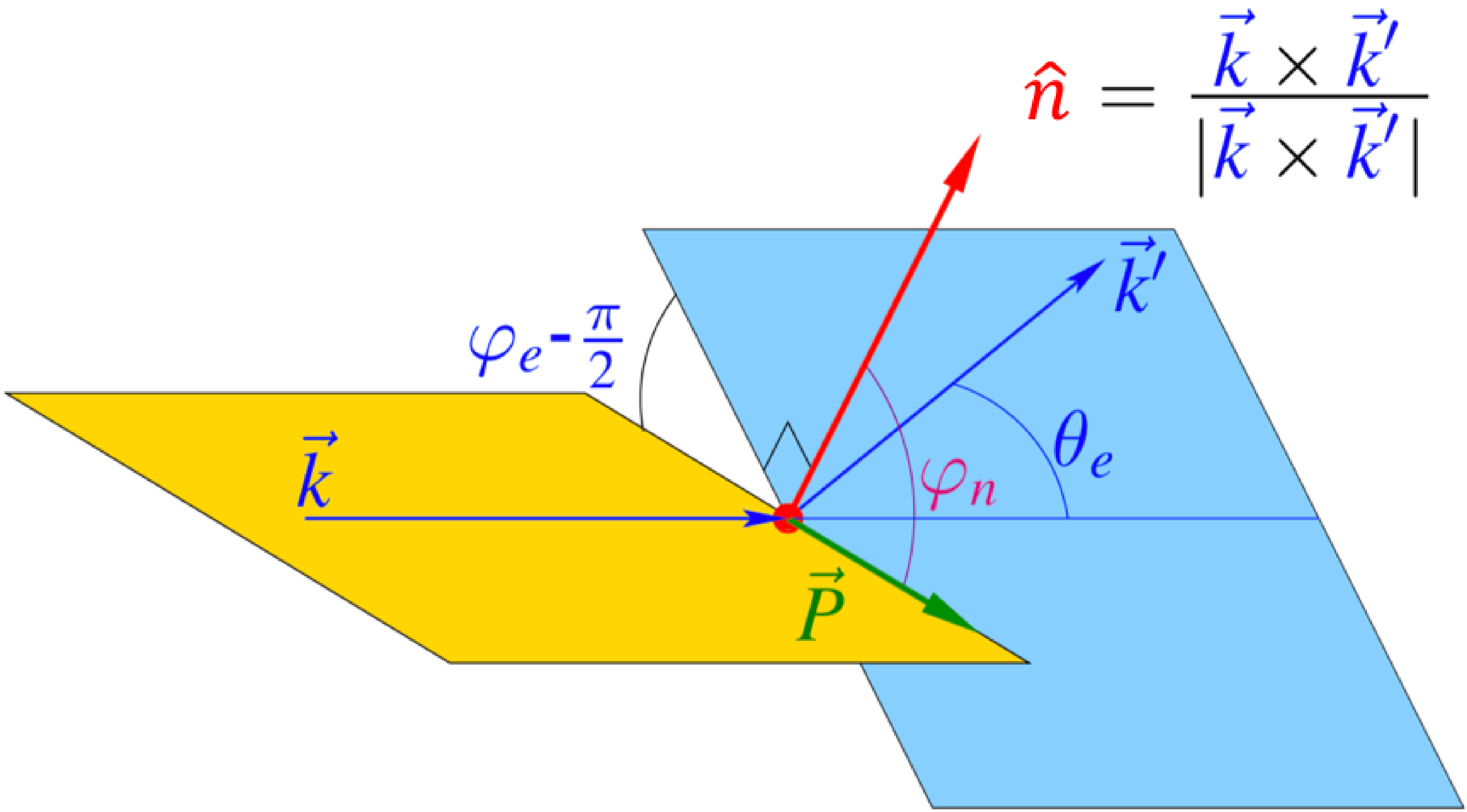
  $\longrightarrow A_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$, with $\uparrow$ ($\downarrow$) parallel (anti-parallel) to normal vector $\hat{n} = \frac{(\vec{k} \times \vec{k'})}{|\vec{k} \times \vec{k'}|}$; $\vec{k}$ ($\vec{k'}$) initial (final) electron mom.

  $\longrightarrow A_{meas}(\phi) = A_n \vec{P}_e \cdot \hat{n}$ where ϕ is angle between $\vec{P}_e$ and $\hat{n}$
- A_n vanishes in the Born approximation, thus can provide sensitive probe of two- or multi-photon exchange effects
- Order of magnitude: $A_n \sim \alpha_{em} \cdot \frac{m_e}{E_e} \sim 10^{-6} - 10^{-5}$

  $\longrightarrow$Historically very challenging measurement

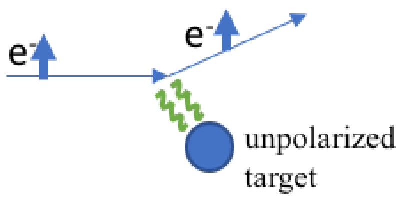
  $\longrightarrow$Precision measurements feasible with PV expt. setup

Scattering Plane Kinematics

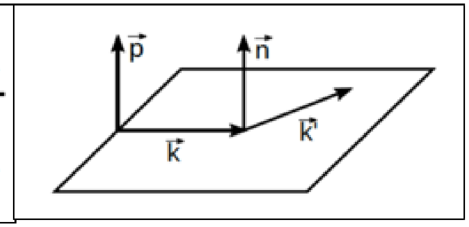


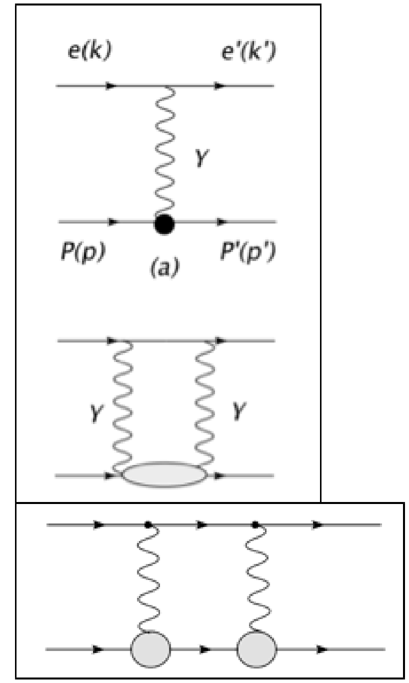
A_n Measurement

A_n is a direct probe of higher-order photon exchange



$$A_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$





https://arxiv.org/pdf/0801.4575.pdf

- *Incident beam is vertically polarized*
- *Change sign of vertical polarization*
- *Measure fractional rate difference*

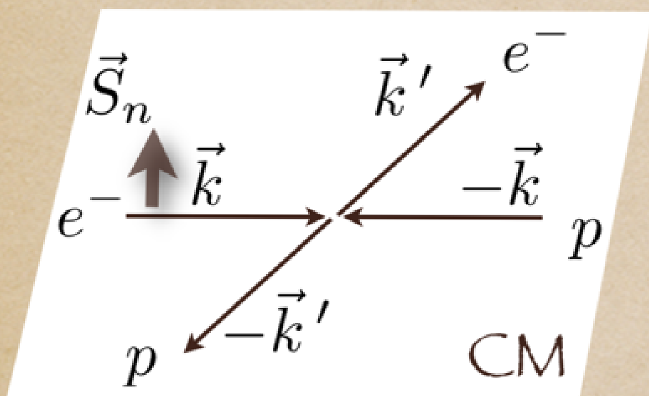
σ↑(↓) elastic scattering xsec for e-'s with spin $\boldsymbol{P}_e$ parallel (or antiparallel) to the normal vector defined by the scattering plane

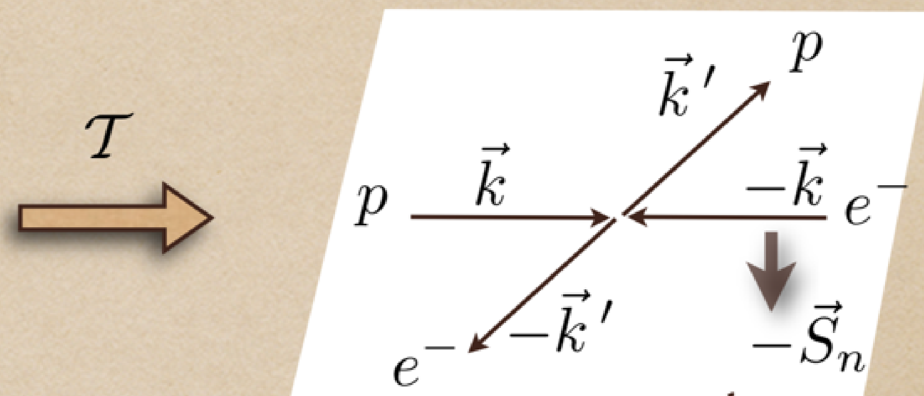
$$A_n^m = A_n \vec{P}_e \cdot \hat{n}$$

- A_n: beam-normal single spin asymmetry in elastic scattering of electrons polarized perpendicular to the scattering plane off unpolarized nucleons
- A_n is a direct probe of higher-order photon exchange.
- At higher energies, excited intermediate nuclear states become important for determining A_n.
- Measured via fractional rate difference between incident electron beam vertical polarization states on unpolarized target
- A_n can contribute systematic uncertainty to the extracted A_{PV} (in elastic electron scattering experiments like PREX and CREX) if the beam polarization has a transverse component and the apparatus lacks perfect symmetry

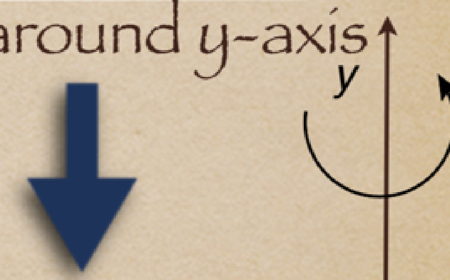
Why is A_n zero to first order?

Elastic e-p scattering with e polarized normal to the reaction plane





180° rotation around y-axis

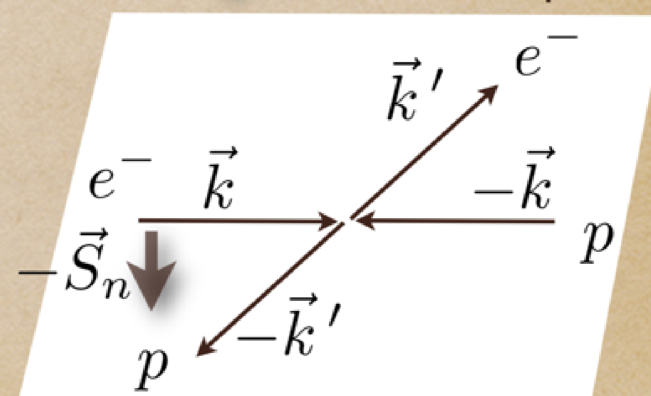


$$T(S_n, \vec{k}, \vec{k}') \rightarrow \eta_1 T^*(-S_n, -\vec{k}, -\vec{k}') \rightarrow \eta_1\eta_2 T^*(-S_n, \vec{k}, \vec{k}')$$

Mismatch between time-reversed states

is due to imaginary part of the amplitude

(T-reversal invariance is used!)



Beam Normal Single Spin Asymmetry

Measurement Motivations

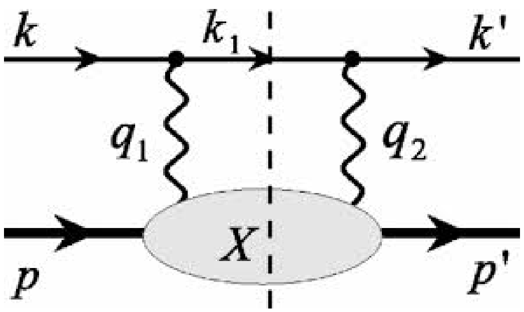
- One of the largest potential false asymmetries in precision PV electron scattering (PVeS) experiments
- As PVeS experiments push envelope of precision A_{PV} meas., corrections for BNSSA leakage become increasingly important
  - ⟶Leakage suppressed by axially symmetric detectors and minimizing transverse beam polarization components
  - ⟶But still has potential for large systematic contribution
  - ⟶PVeS experiments perform dedicated measurements of A_n to quantify size of potential systematic error
- Test theoretical framework of calculations, and specifically the 2γ exchange contribution, to further push the precision frontier

Beam Normal Single Spin Asymmetry

Calculation Motivations

- A_n provides direct access to absorptive part of the 2γ exchange amplitude (A. De Rujula *et. al.*, Nucl. Phys. B **35**, 365 (1971))
- General formalism developed: M. Gorchtein, P.A.M. Guichon, M. Vanderhaeghen, Nucl. Phys. A **741**, 234 (2004)

$$A_n = \frac{2\mathrm{Im}(T^*_{1\gamma} \cdot \mathrm{Abs} T_{2\gamma})}{|T_{1\gamma}|^2}$$



$\longrightarrow$Calculations sensitive to treatment of intermediate hadronic states $X = N$, πN, ...

- Understanding of 2γ exchange contributions here could be useful in extending framework to EW processes ($\Box_{\gamma Z}$, ...)

Beam Normal Single Spin Asymmetry

Motivation

- Theoretical and experimental inputs into understanding the imaginary part of $T_{2\gamma}$ can give better understanding of the real part (help resolve Rosenbluth$\Longleftrightarrow$Pol.Transfer discrepancy)

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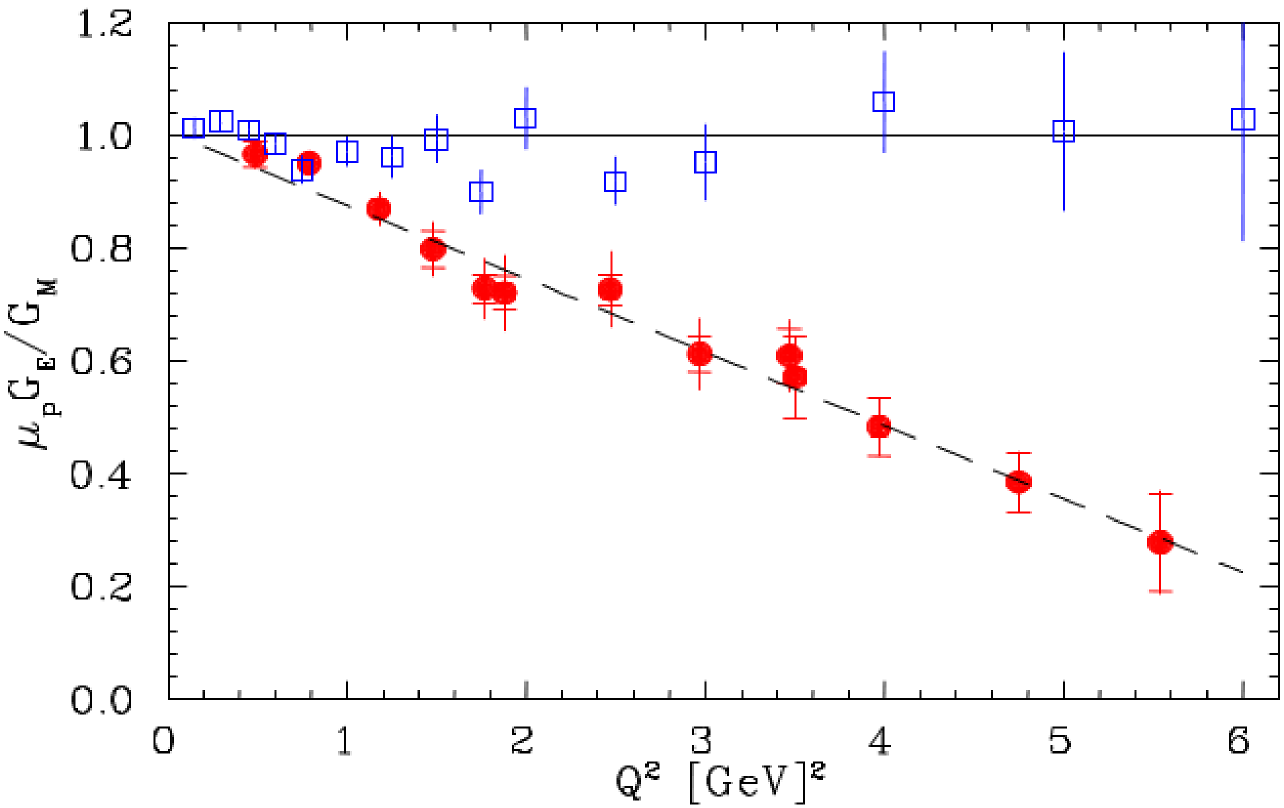


4 Decades of Technical Progress

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, rad-hard dets

1st generation

2nd generation

3rd generation

4th generation

E122 – 1st PVES Expt (late 70's at SLAC)

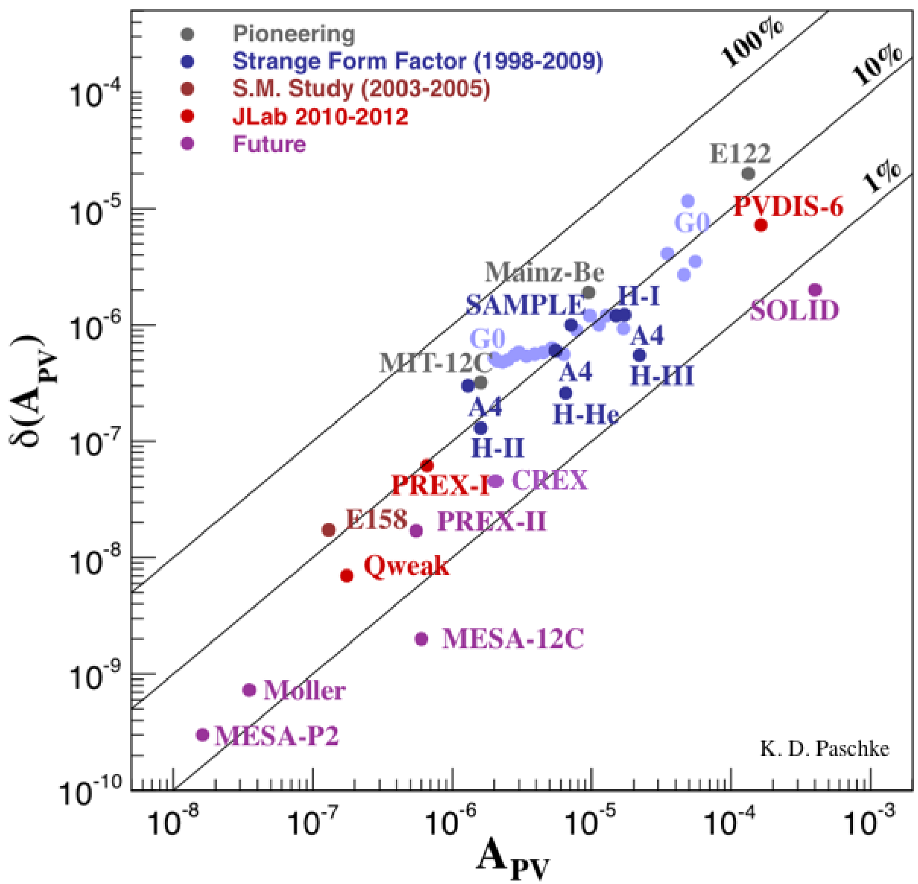
Mainz & MIT-Bates in mid 80's

JLab program launched in mid 90's

E158 at SLAC meas PV Møller scattering

MOLLER at JLab in mid 2020's

PVeS Experiment Summary



- Parity-violating electron scattering has become a precision tool!

PREX-II/CREX Overview

PREX-II:

0.95 GeV e^- beam, 70 μA

0.5 mm thick ^{208}Pb tgt (10% X_0)

5° scattered electrons

Q^2 =0.0063 GeV^2, A_{PV}~0.5ppm

δA_{PV} ~ 15 ppb (3%)

CREX:

2.18 GeV e^- beam, 150 μA

5 mm thick ^{48}Ca tgt (5% X_0)

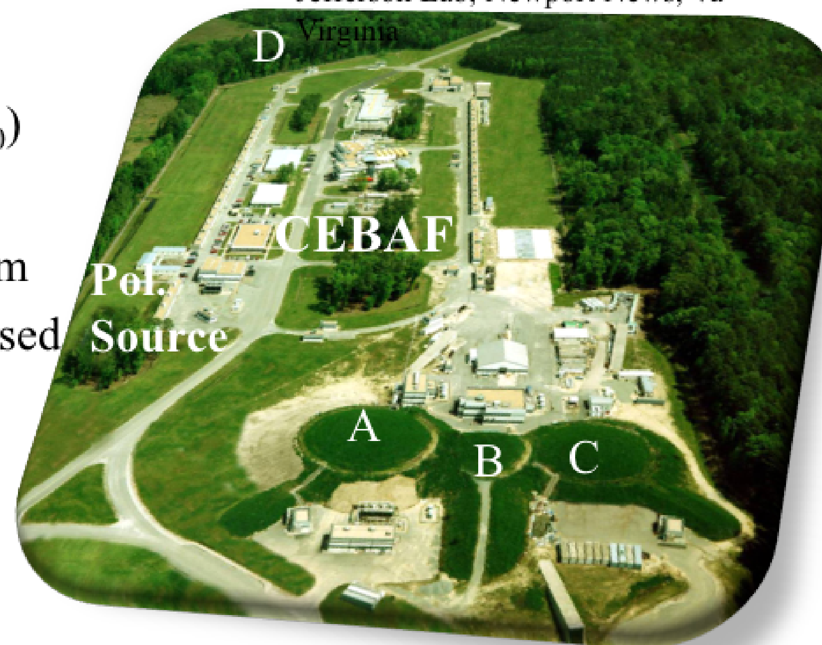
5° scattered electrons

Q^2 =0.030 GeV^2, A_{PV}~2ppm

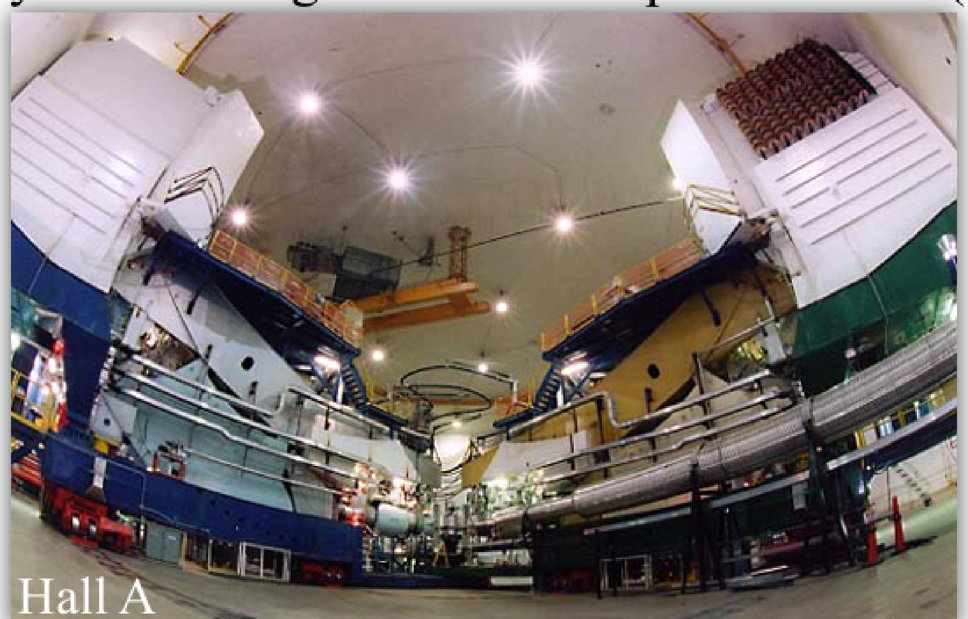
δA_{PV} ~ 80 ppb (4%) proposed

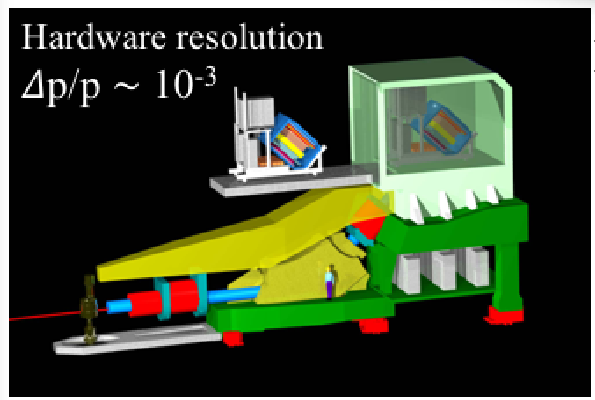
- high polarization, ~89% ; helicity reversal at 240 & 120 Hz
- **Dedicated A_n measurements on ^{208}Pb, ^{48}Ca, ^{40}Ca, and ^{12}C**

Jefferson Lab, Newport News, Va

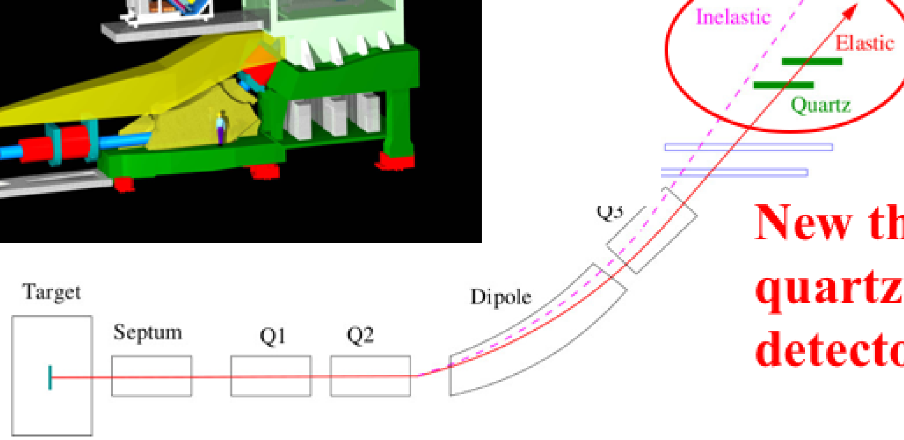


Symmetric High Resolution Spectrometers (HRS)





HRS and optics schematic

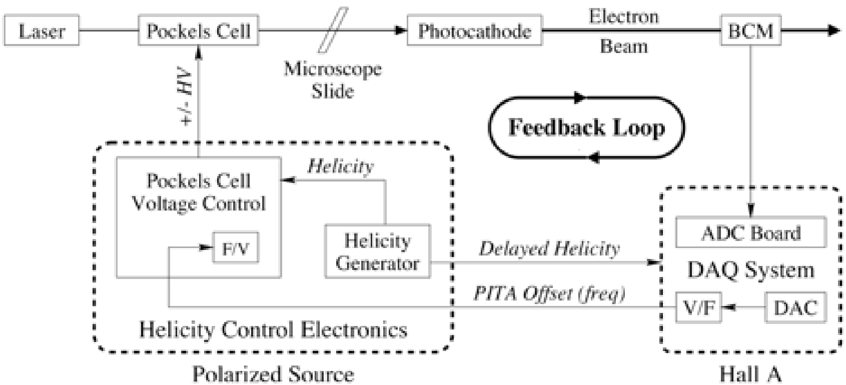


New thin quartz detectors

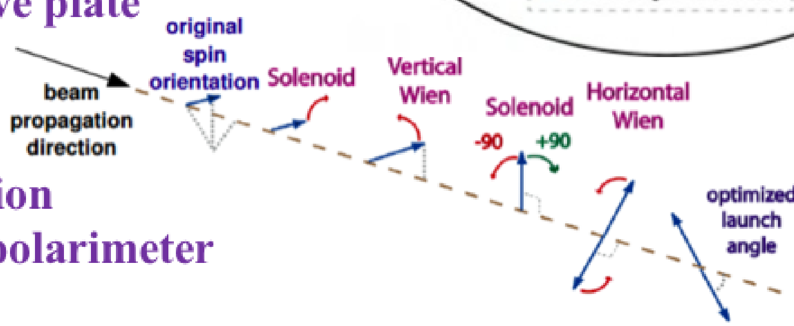
"Parity Quality" Beam Monitoring

(normalization and false-asymmetry systematics control)

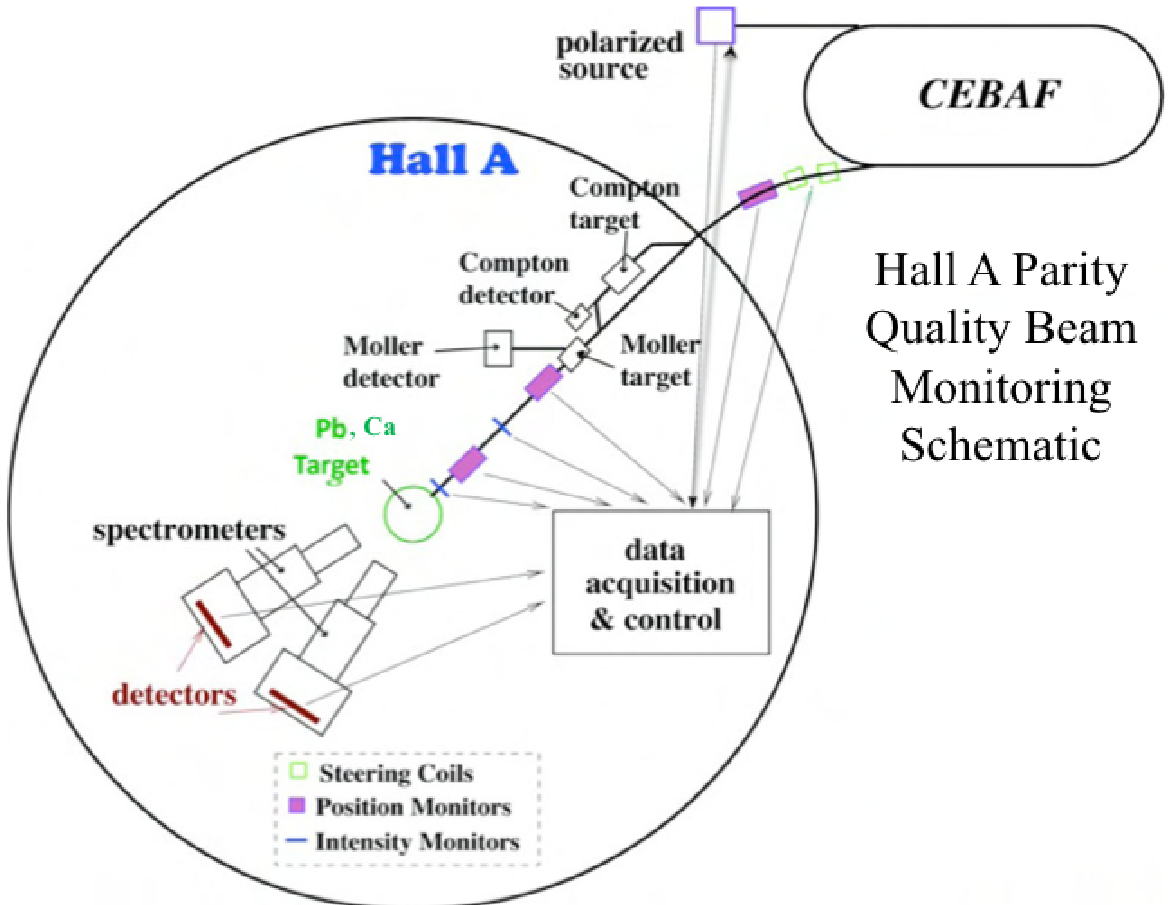
- Precision source-laser alignment
- Active feedback on charge asymmetry



- Precision beam position monitoring with active calibration of detector slopes (via beam modulation)
- Two independent methods for "slow" helicty reversals:
  1. Insertable half-wave plate
  2. Double Wien filter



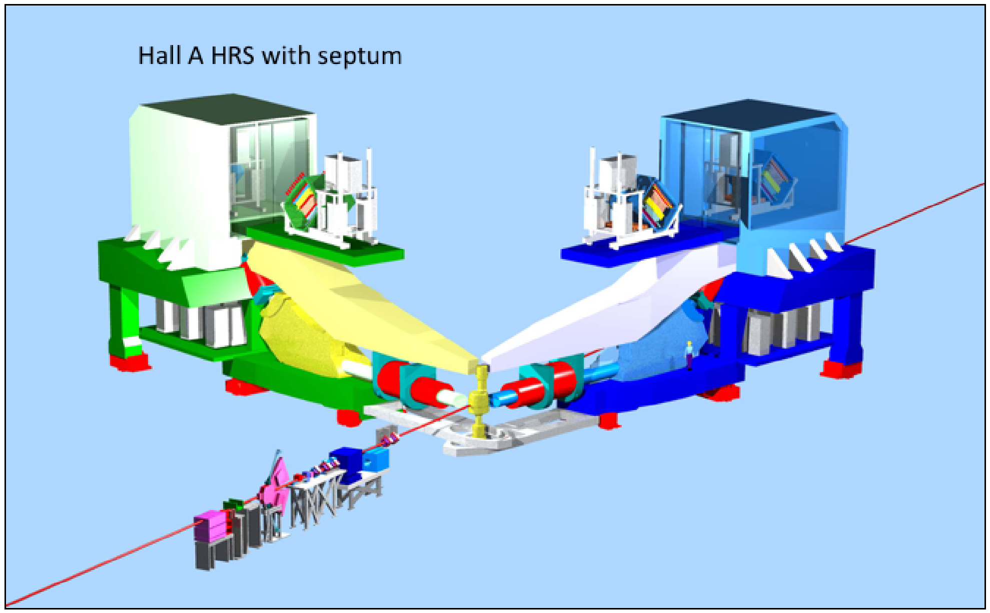
- Continuous beam polarization monitoring with Compton polarimeter

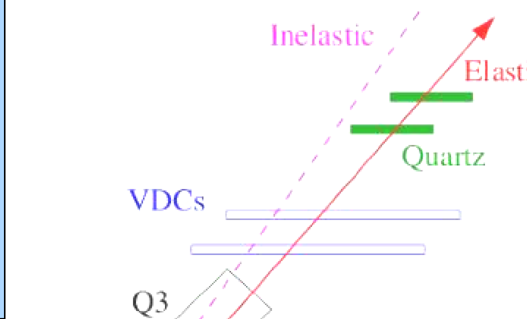
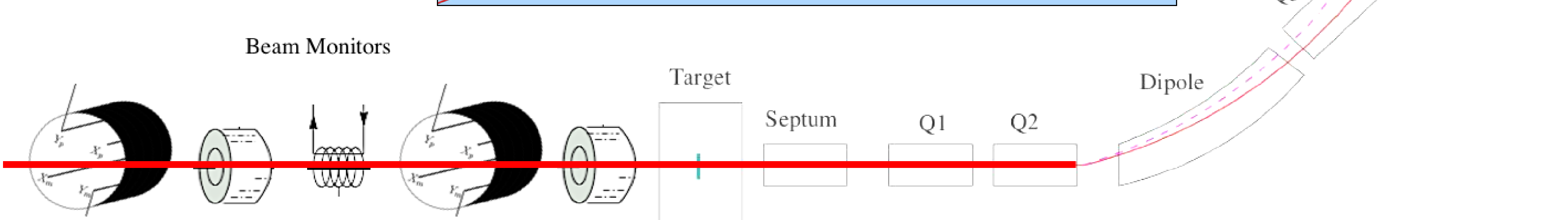


Hall A Parity Quality Beam Monitoring Schematic

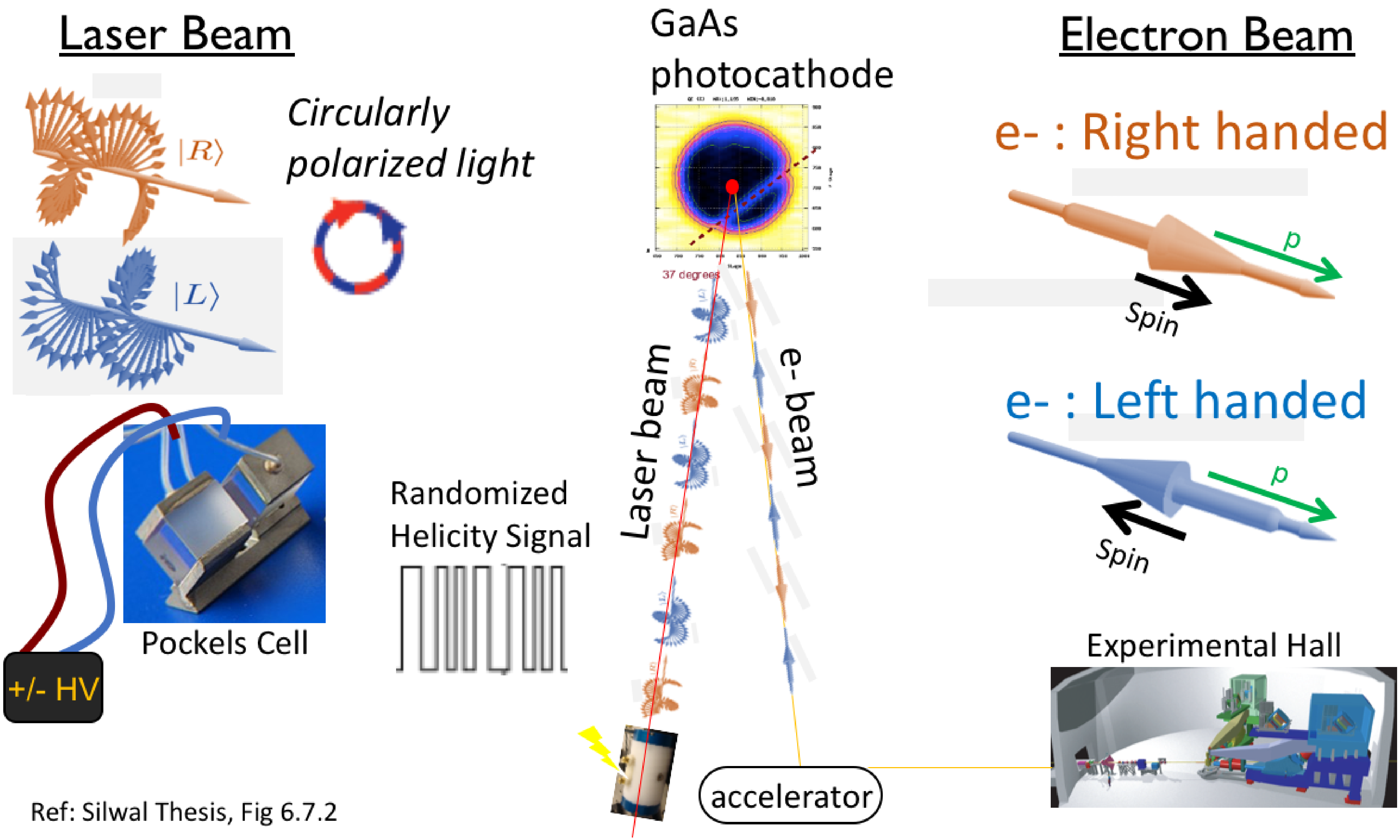
"Parity Quality" Beam Monitoring Summary

PREXII/CREX in Hall A

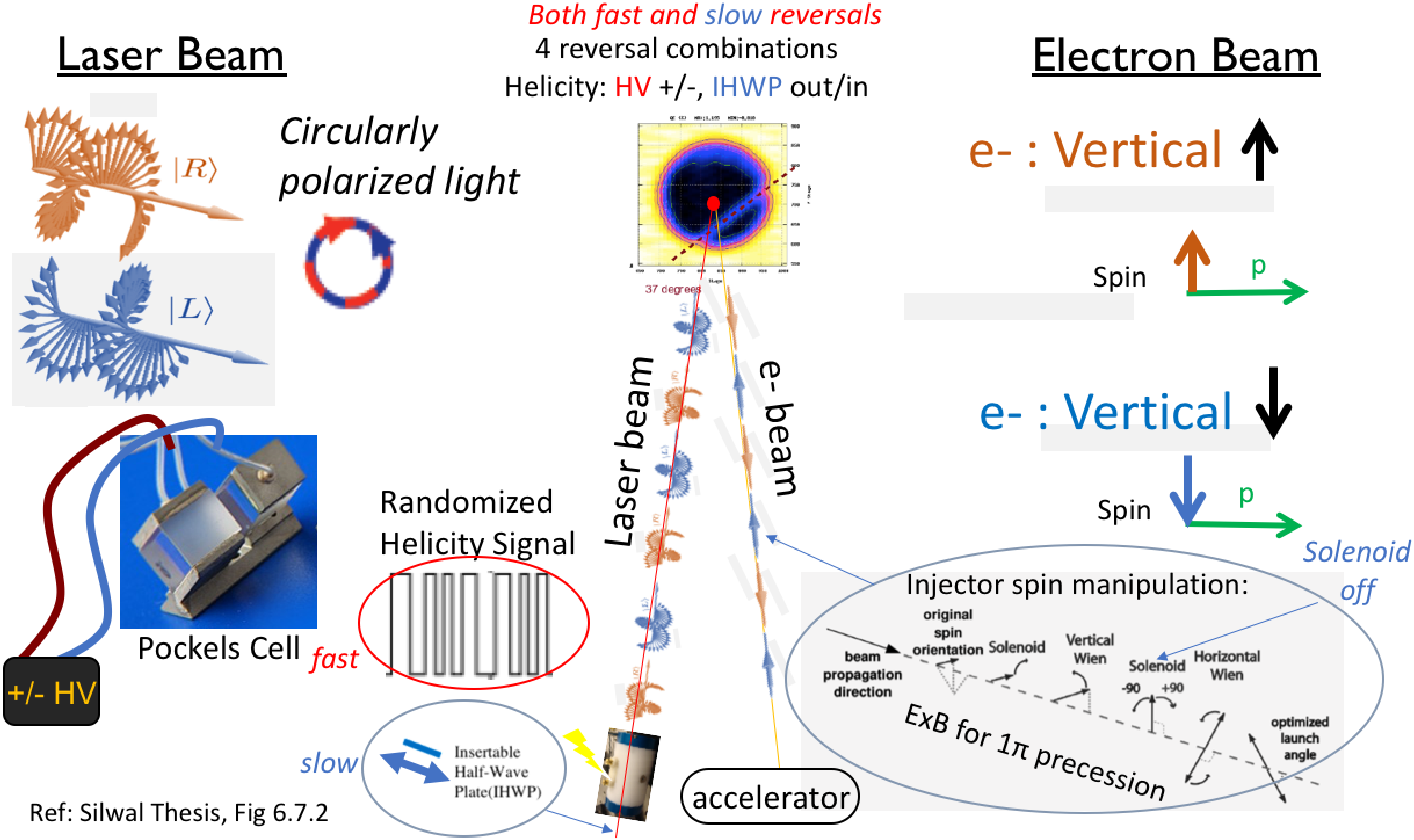


Beam from source to target

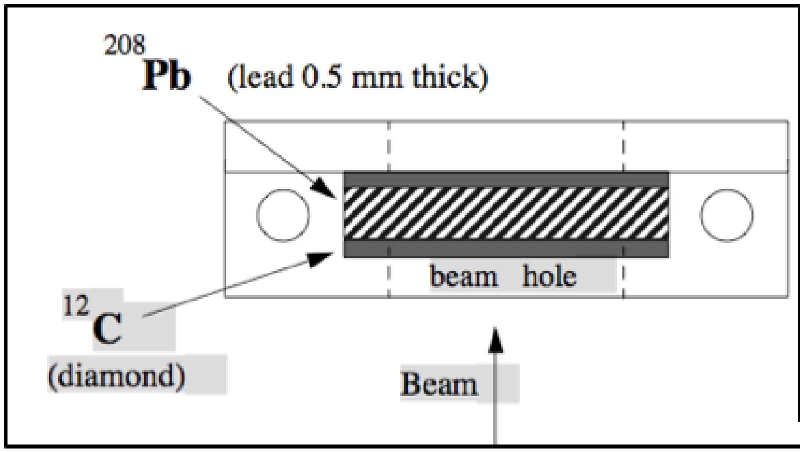


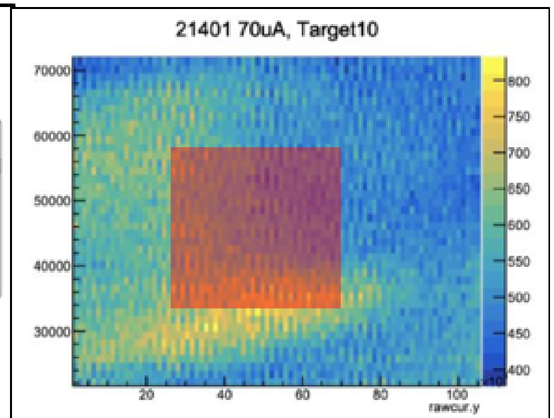
Beam from source to target



PREX-II/CREX Targets

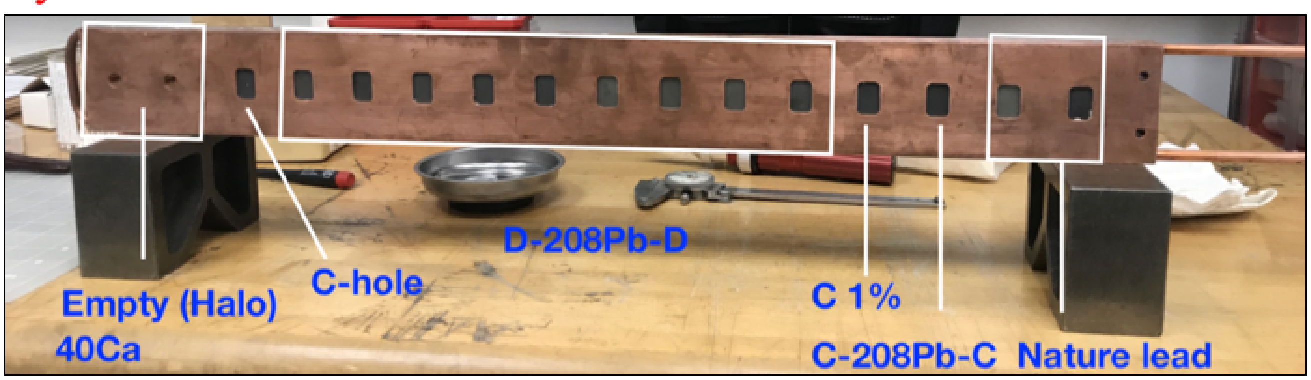
- **Diamond foils - excellent thermal conductivity**
- **^{12}C is isoscaler, spin-0, A_{pv} is well-measured, so benign background! (dilution, not false asymmetry)**
- **70uA limited in PREX due to target thermal properties**

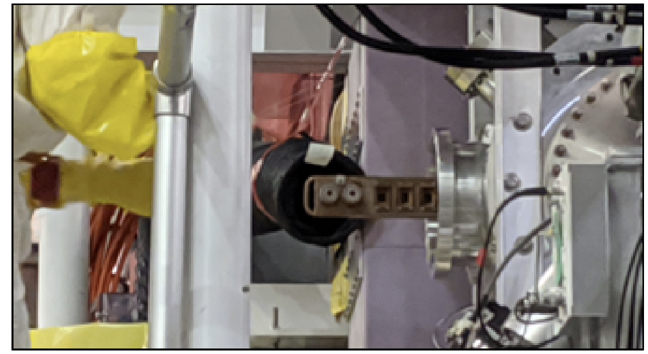


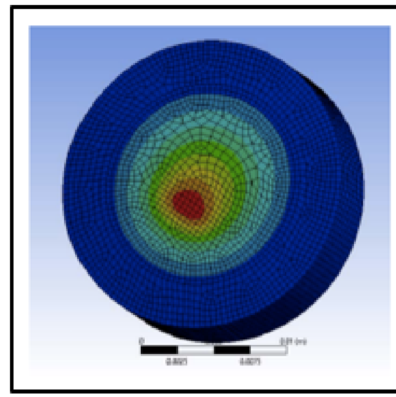


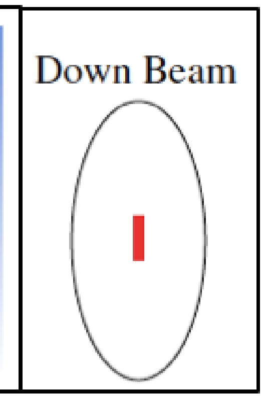
0.5mm lead, 0.25mm diamond sandwich, 1 sq. in. face

Synchronized 4x4mm raster handles non-uniform lead thickness







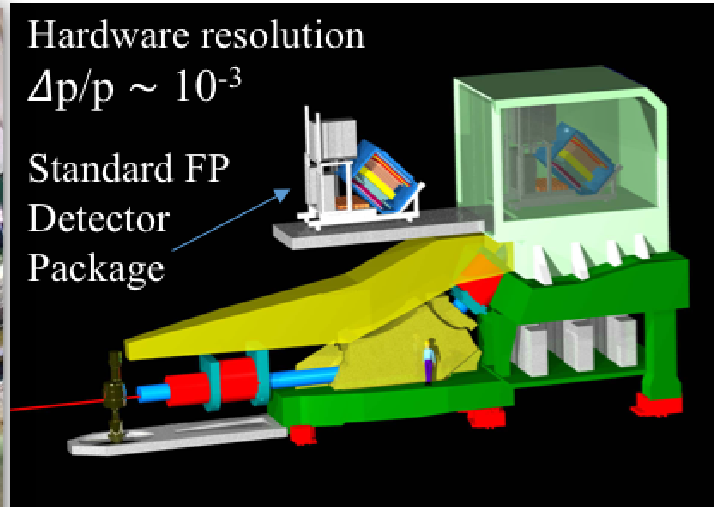


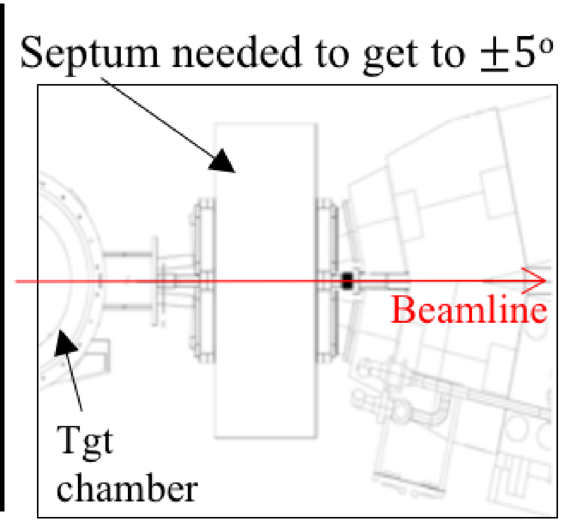
1.1g/cm2; ~2x2mm raster

- **Target has good thermal cond., so can run at 150uA**
- **New Target sandwiched 3 pucks together: ~92% ^{48}Ca**

*slide from Caryn Palatchi

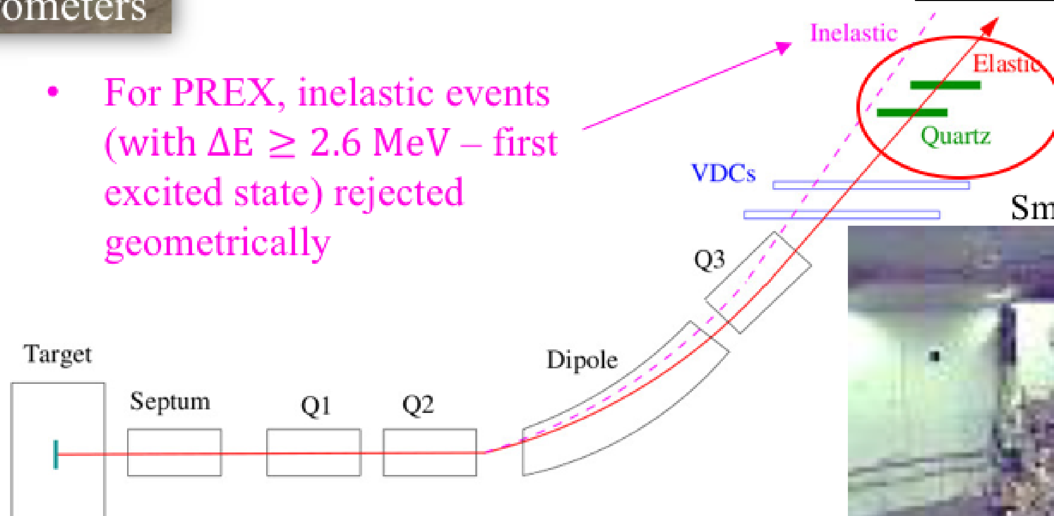
Spectrometer and Integrating Detector Focal Plane for Hall A Parity Violation Experiments





- Standard focal plane (FP) detector packages removed during high flux PV experiments
- Specialized focal plane detectors installed and positioned to **intercept only elastically scattered electrons** – uses precision optics and hardware resolution
- Integrated PE yields from detectors are proportional to electron flux

- For PREX, inelastic events (with $\Delta E \geq 2.6$ MeV – first excited state) rejected geometrically

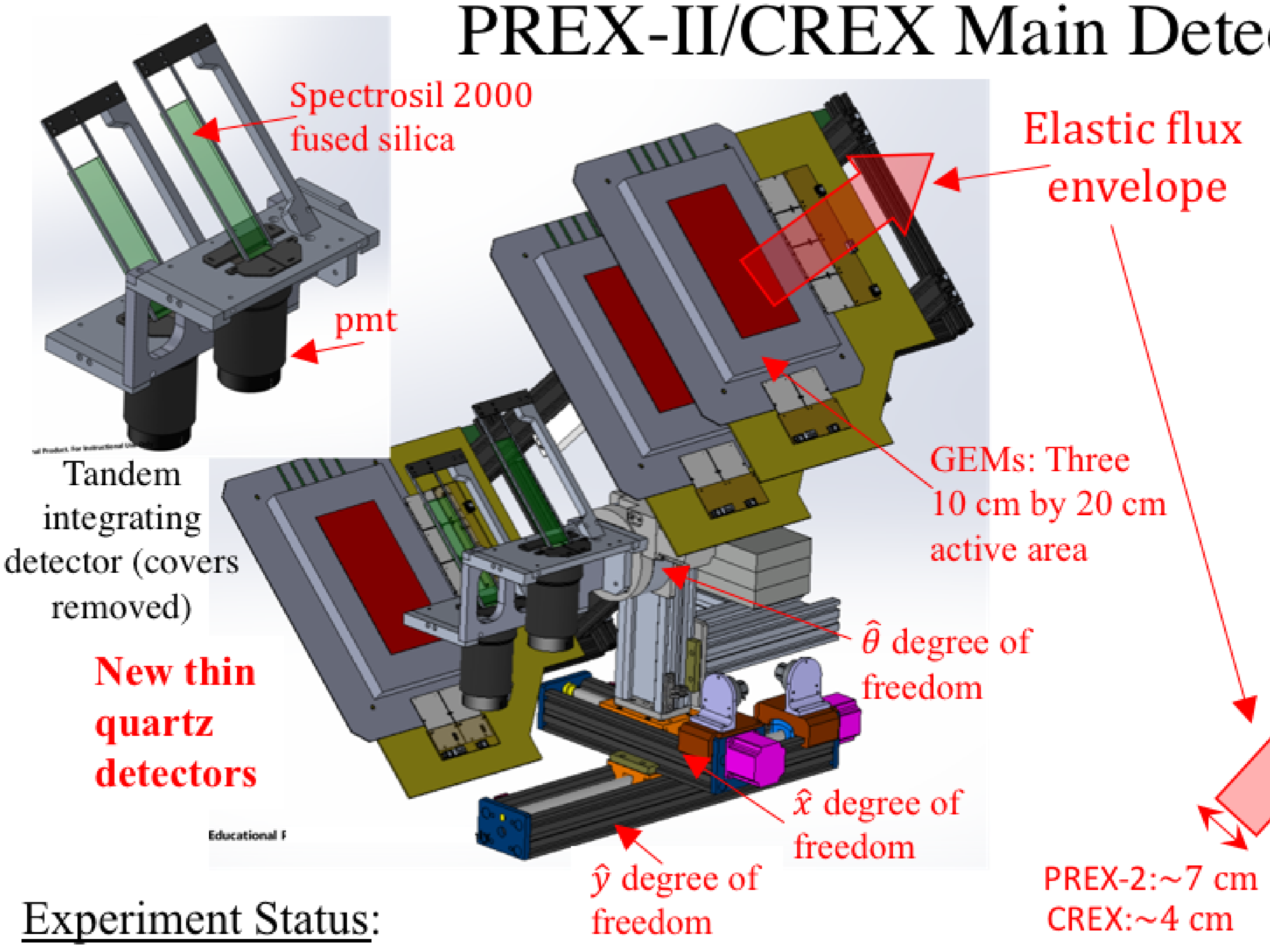


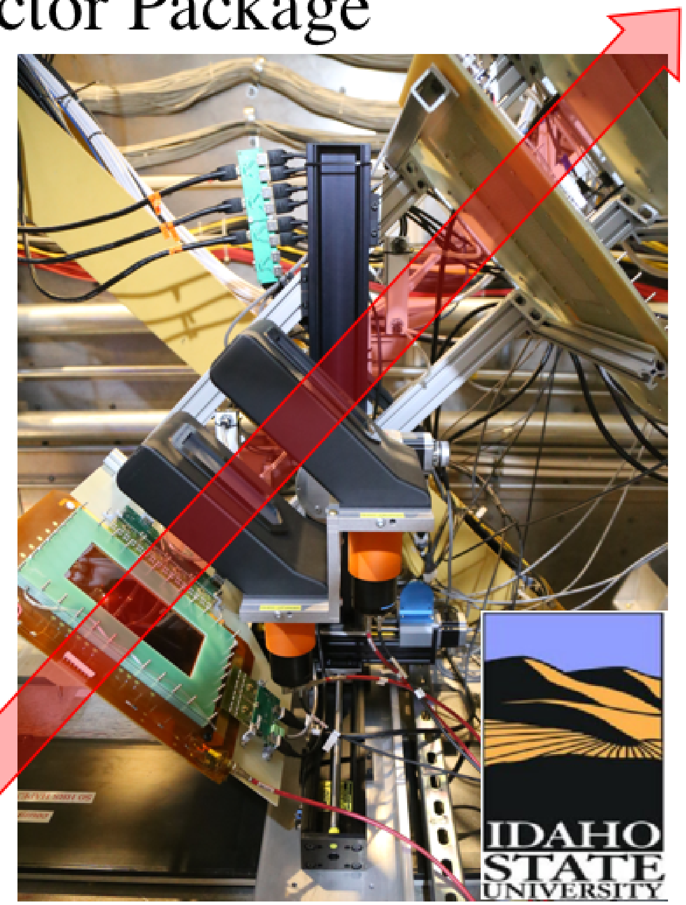
PREX Optics Schematic

PV Detectors positioned in FP inside shielded HRS huts

Smallest HRS angle: $\pm 12.5^{o}$

PREX-II/CREX Main Detector Package



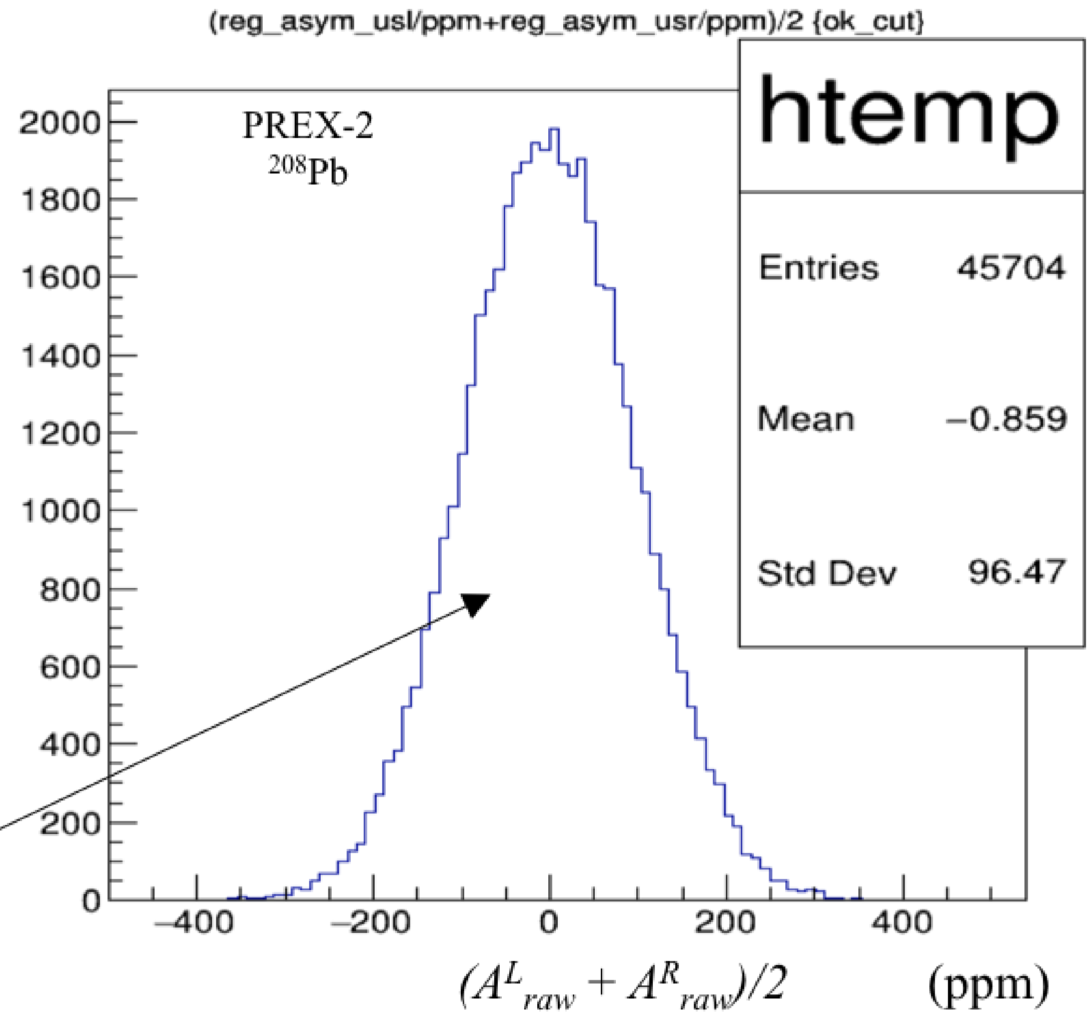


Experiment Status:

- PREX-II took place over summer 2019 and completed successfully in early September 2019
  - Measured ~0.5 ppm A_{PV} from ^{208}Pb with ~1 GeV beam at 5° θ_{lab} to ~3% stat. precision
  - Integrated flux rates were >2 GHz per arm (Left and Right HRS); 26% detector resolution
  - Achieved ~14 ppb statistical precision with a few nanometer control on beam positions
  - Overall systematic error well below 14 ppb; will extract neutron skin to ±0.07 fm error
- CREX (Calcium Radius Experiment) ran from Dec 2019 to March 2020 using same apparatus as PREX-II; will run for 4 – 6 more weeks in Aug – Sep 2020 (pandemic-pending)

Transverse Asymmetry (A_n) Measurement

- Symmetric beam-left and -right spectrometers positioned in the horizontal plane (±5°)
- With *vertical* transverse beam polarization (P_e), Left-arm measures $A^L{}_{raw} = A_n P_e \cos(0°)$ and Right-arm measures $A^R{}_{raw} = A_n P_e \cos(180°) = - A^L{}_{raw}$
- The average difference between $A^L{}_{raw}$ and $A^R{}_{raw}$, referred to as the double difference (dd), gives the BNSSA result: A_n (times P_e)
- The average sum of $A^L{}_{raw}$ and $A^R{}_{raw}$ yields a precision null-result given a high degree of symmetry in left-right and out-of-plane acceptances of two spectrometers



A_n Measurement Kinematics, Widths & Rates

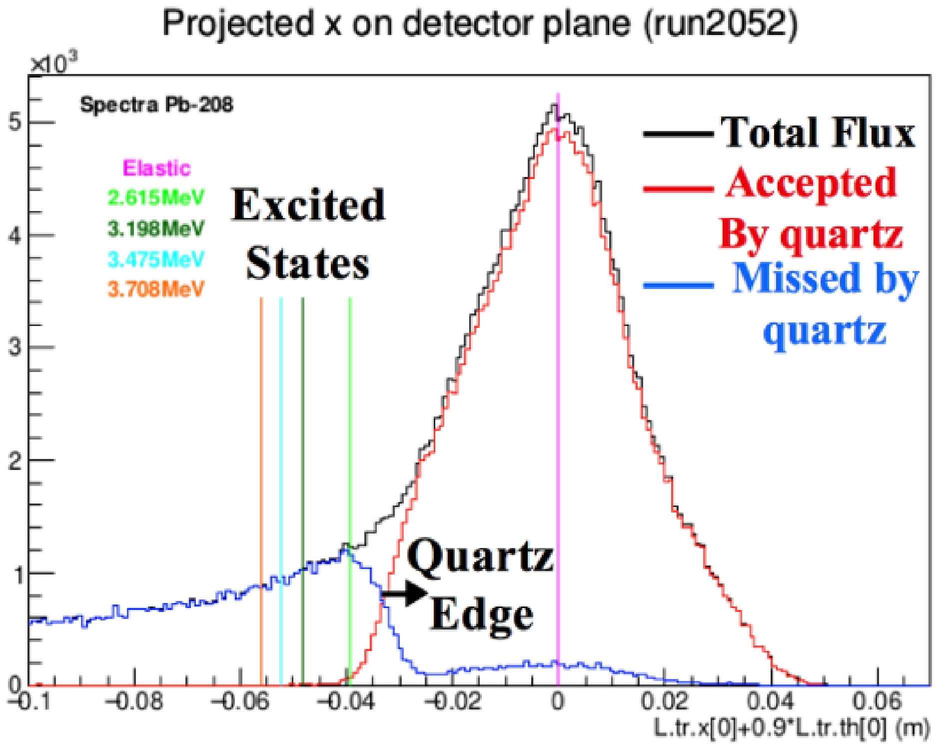
Experiment	Target	θ_{lab}	Q^2 (GeV^2)	E_b (GeV)	<cosϕ>
PREX-II	Carbon-12	5°	0.0066	0.95	0.966
	Pb-208	5°	0.0062	0.95	0.969
	Ca-40	5°	0.0066	0.95	0.974
CREX	Carbon-12	5°	0.033	2.183	0.963
	Pb-208	5°	0.032	2.183	0.963
	Ca-40	5°	0.030	2.183	0.964
	Ca-48	5°	0.030	2.183	0.964

Experiment	Target	I_b (μA)	A_{meas} dd rms @ 30Hz (ppm)	Rate per Arm (GHz)	Beam Pol.* (%)
PREX-II	Carbon-12	90	140	0.85	89.5
	Pb-208	70	93	2.2	89.5
	Ca-40	70	91	2.3	89.5
CREX	Carbon-12	150	580	0.048	86.9
	Pb-208	70	1270	0.010	86.9
	Ca-40	150	740	0.029	86.9
	Ca-48	150	810	0.025	86.9

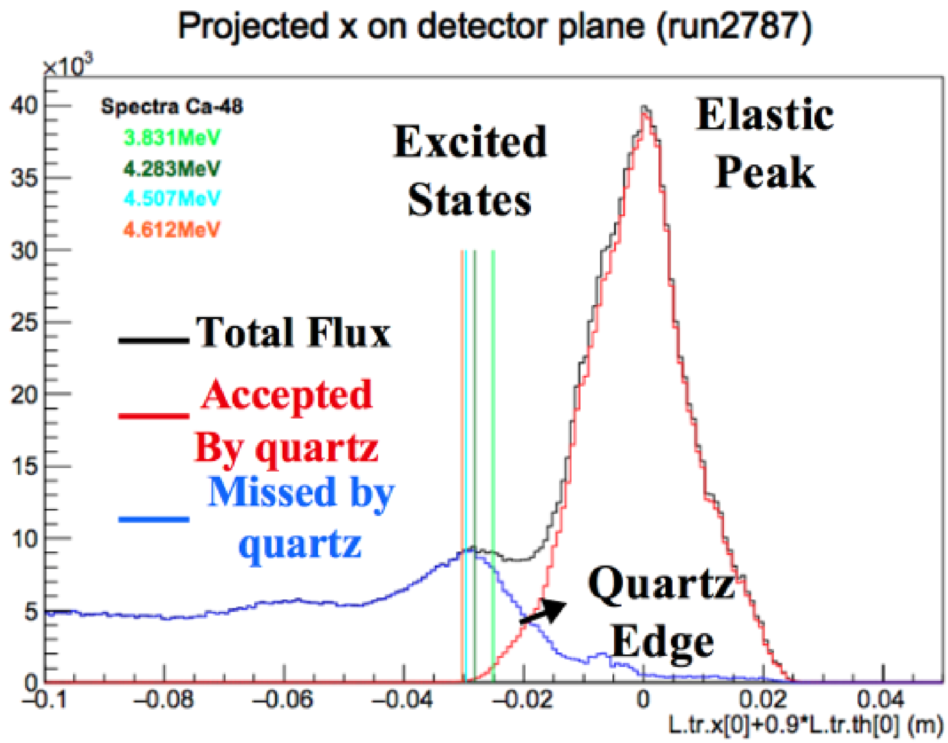
* Transverse beam polarization vector greater than 99% vertical

Integrated Focal Plane Spectra for A_{PV} and A_n

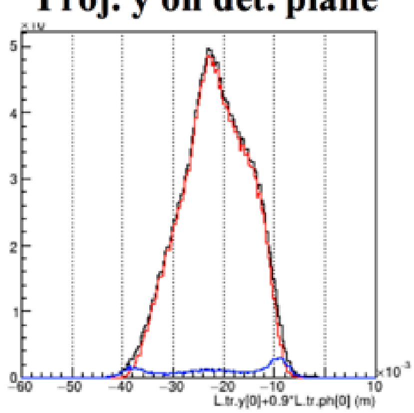
PREX-II ^{208}Pb Spectrum



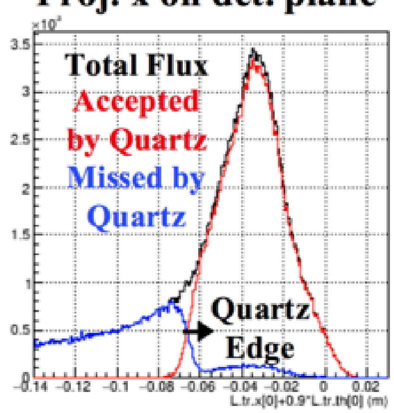
CREX ^{48}Ca Spectrum

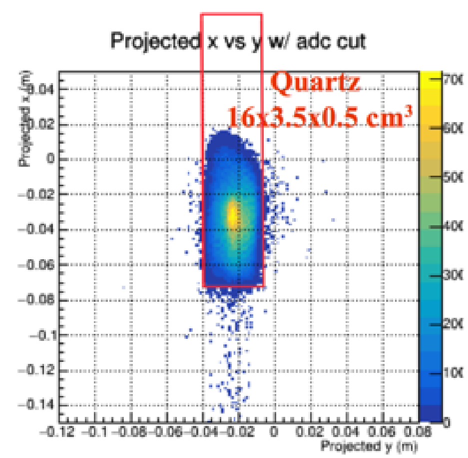


Proj. y on det. plane

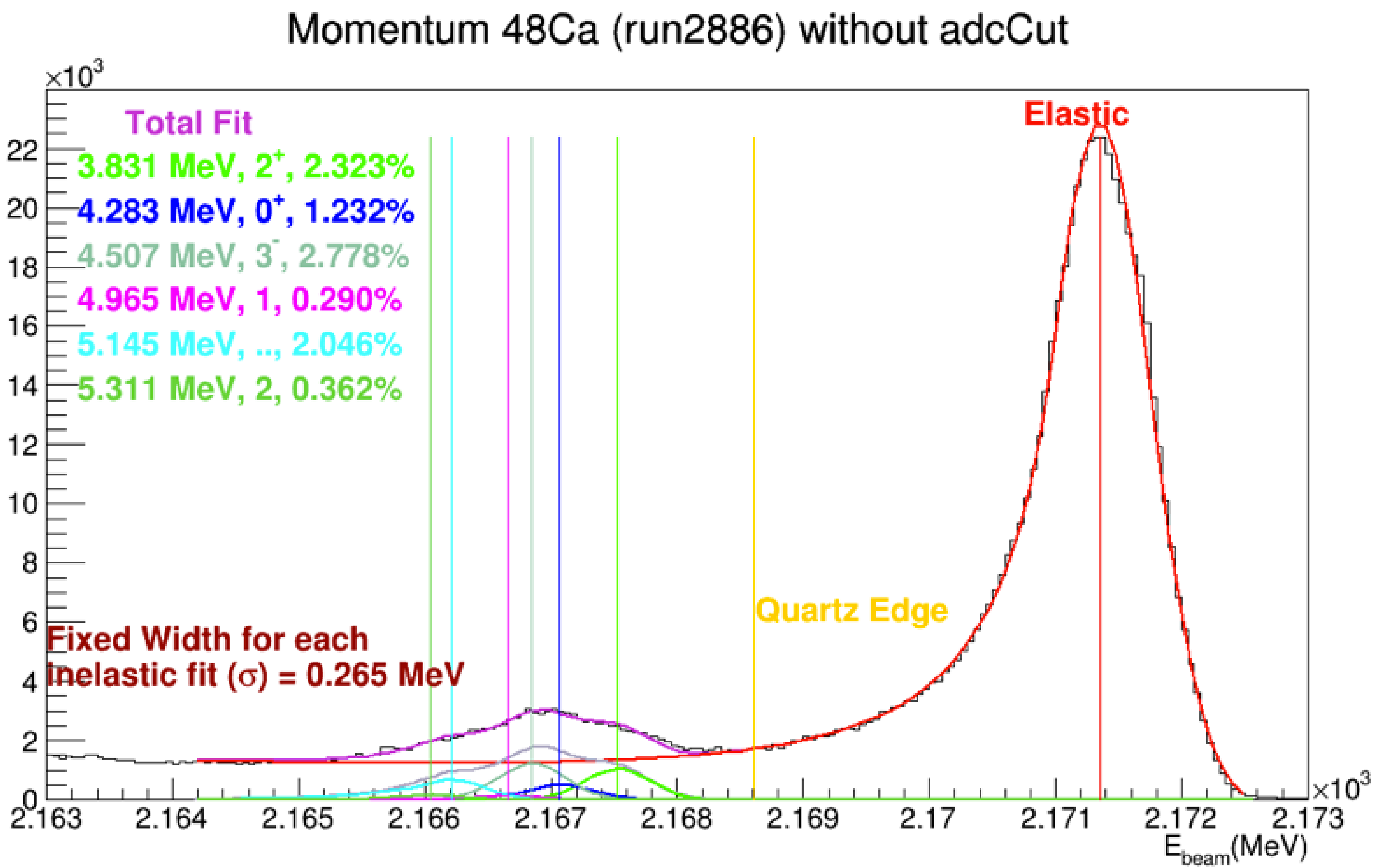


Proj. x on det. plane





^{48}Ca Inelastic level strength (preliminary) and contamination rejection by quartz

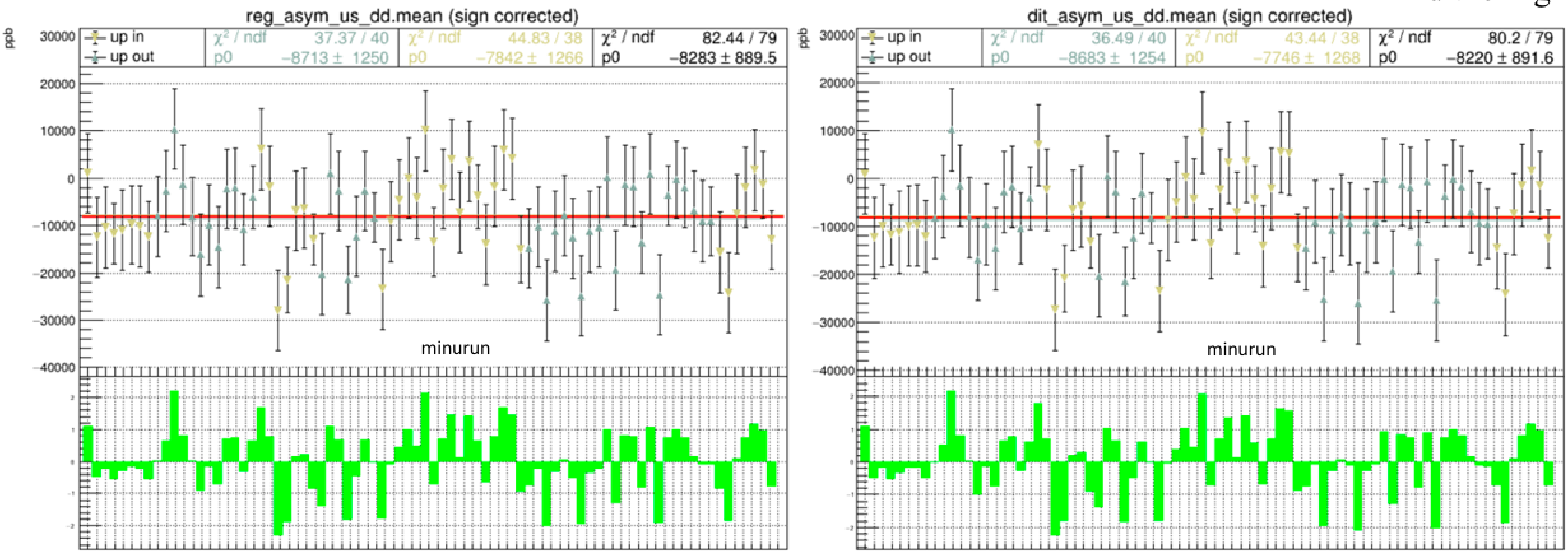


Raw Data: ^{48}Ca Transverse Running (at 2 GeV and 5°)

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

regression

dithering



- Left and Right arms symmetrically probe A_n with opposite sign and are combined via $A_{raw} = (A_{Larm} - A_{Rarm})/2$
- Sign corrected for IHWP state, several hours were spent at each IHWP state on each target, ~8hours of data shown above
- Beam corrections made via charge normalization
- α and β_i (so-called "detector slopes") calculated via beam noise regression and measured several times per hour using beam-dithering steering coils (beam modulation system). Both method's results are shown above

*slide from Caryn Palatchi

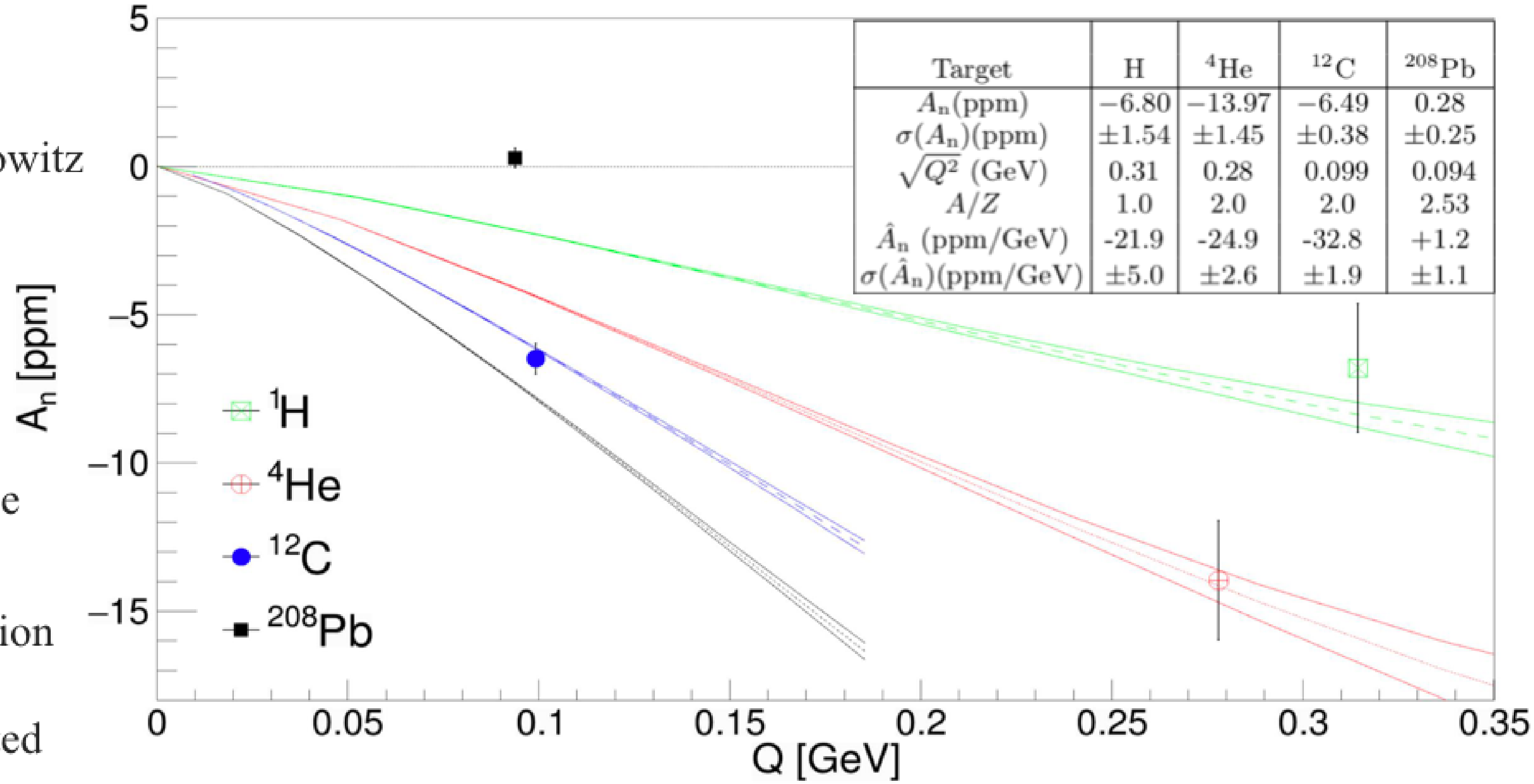
A_n measurement Uncertainties

- Beam polarization inferred from longitudinal polarization measurements taken before and after transverse running
  - P_e (CREX): 86.9% obtained by averaging both Compton and Moller measurements
  - P_e (PREX): 89.5% obtained by averaging only Moller measurements for in/out states
  - While detailed analysis completes, we are assigning a relative pol. uncertainty of 2%
- ^{208}Pb target dilution from ^{12}C-diamond foils accounted for via rate ratio calculation and weighted subtraction of the measured ^{12}C A_n from the measured ^{208}Pb A_n
- ^{48}Ca target impurities from ^{40}Ca (~8%) accounted for using same rate ratio calculation and subtraction of measured asymmetry; very small correction and error since measured asymmetries are nearly the same
- Beam asymmetry uncertainties:
  - 1 - 4% for ^{12}C, ^{40}Ca (and 0.06 ppm for ^{208}Pb) for PREX-II
  - 1 - 2% for ^{12}C, ^{40}Ca, ^{48}Ca (and 0.09 ppm for ^{208}Pb) for CREX
- Statistical uncertainties:
  - ~6% for ^{40}Ca,^{12}C (and 0.35 ppm for ^{208}Pb) for PREX-II
  - ~11% for ^{40}Ca,^{48}Ca,^{12}C (and 1.9 ppm for ^{208}Pb) for CREX

PREX-I and HAPPEX A_n Measurements (Previously Published)

OLD Model:

- Gorchtein & Horowitz 2008
- $A_n \sim Q\, A/Z$
- not strongly Z-dependent
- 2-photon exchange calculation
- includes a dispersion integral over intermediate excited states
- neglects Coulomb distortions

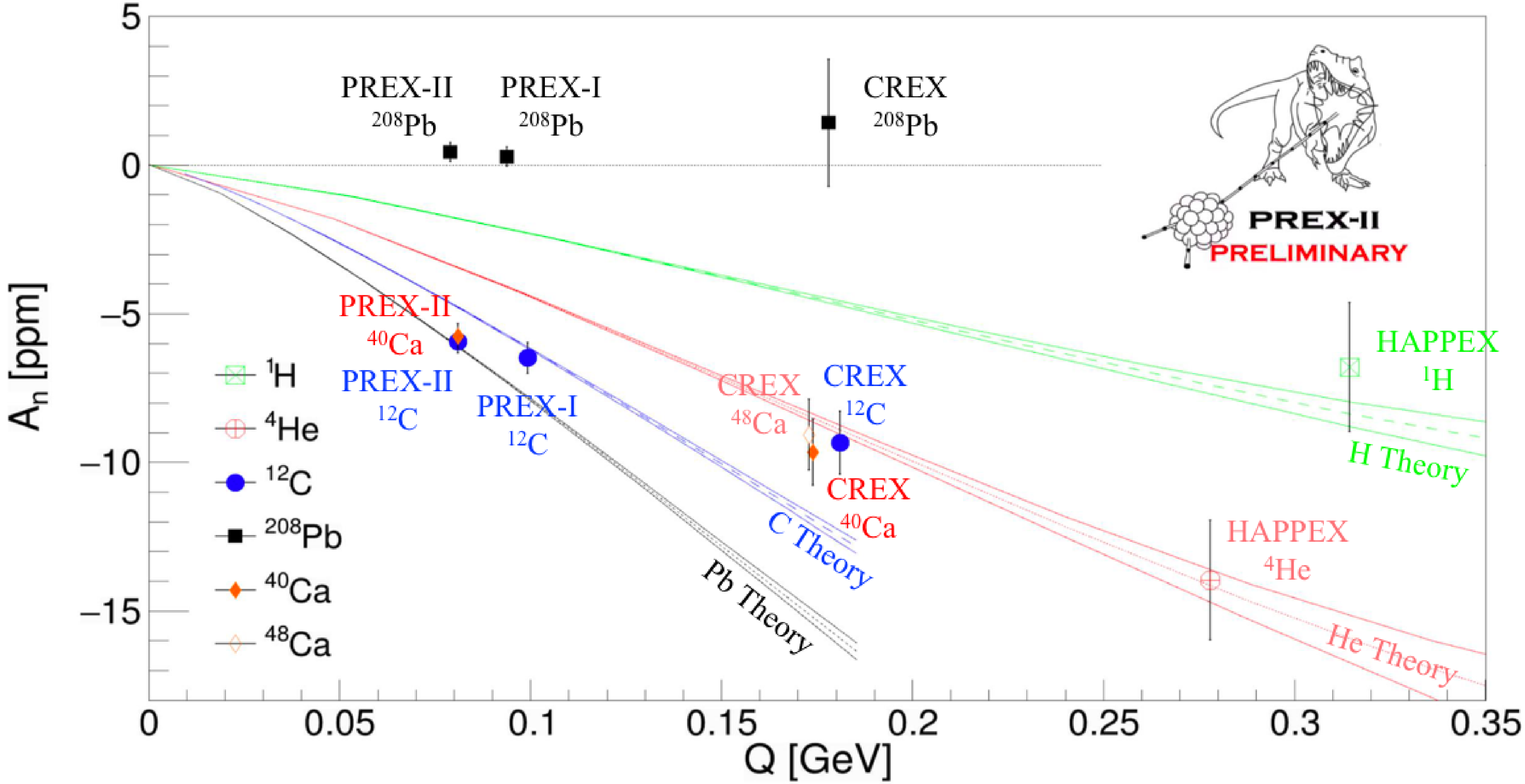


Target	H	^{4}He	^{12}C	^{208}Pb
A_n(ppm)	−6.80	−13.97	−6.49	0.28
$\sigma(A_n)$(ppm)	±1.54	±1.45	±0.38	±0.25
$\sqrt{Q^2}$ (GeV)	0.31	0.28	0.099	0.094
A/Z	1.0	2.0	2.0	2.53
$\hat{A}_n$ (ppm/GeV)	-21.9	-24.9	-32.8	+1.2
$\sigma(\hat{A}_n)$(ppm/GeV)	±5.0	±2.6	±1.9	±1.1

- S. Abrahamyan, *et al.* PRL **109**, 192501 (2012)
- M. Gorchtein, C. J. Horowitz, PRC **77**, 044606 (2008)

Surprising result: Wild disagreement for Pb measurement!

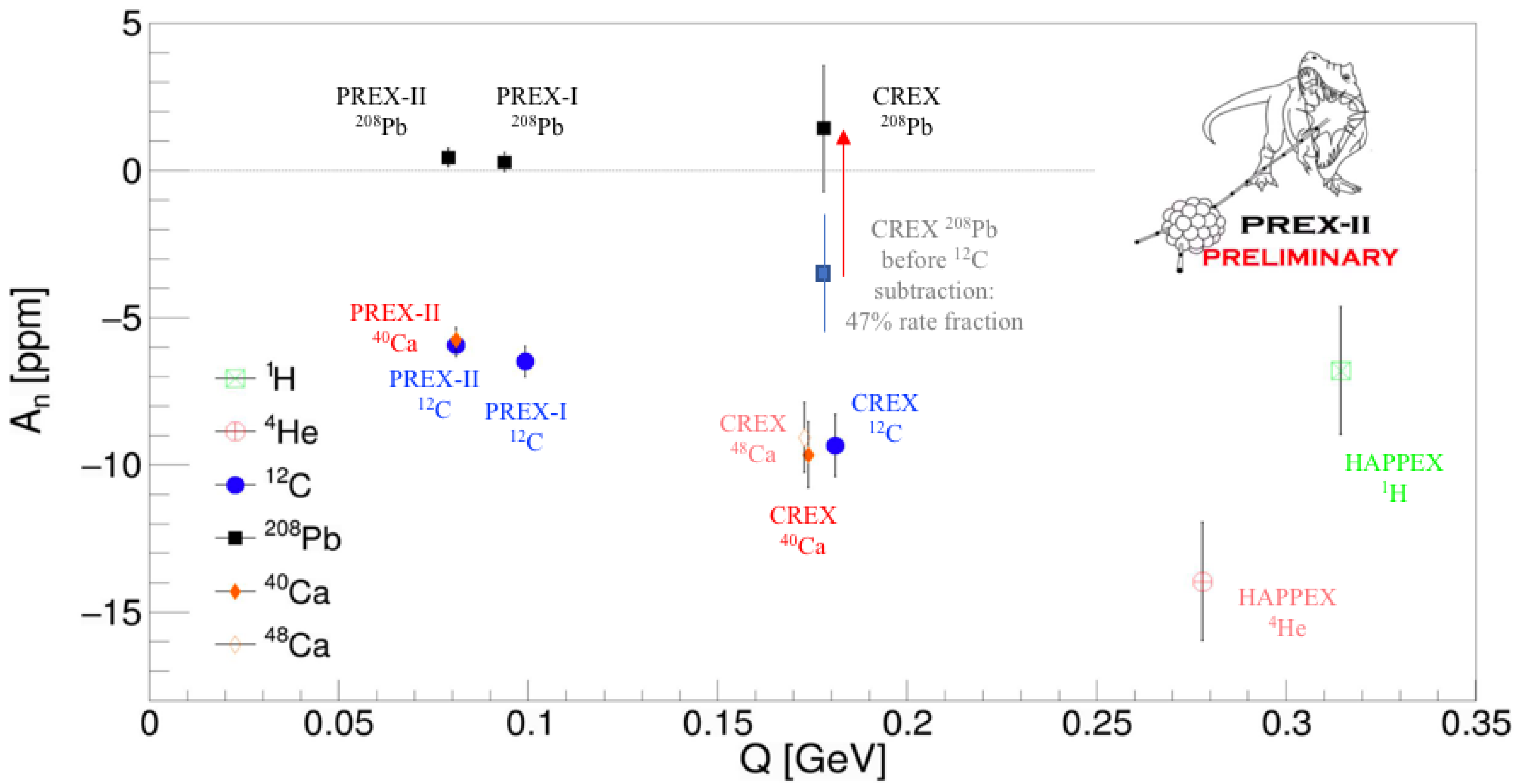
PREX-II and CREX A_n Results (with all Hall A meas.)



HAPPEX: E_{beam} = 2.8 - 3 GeV; θ_{lab} = 6° PREX: E_{beam} = 1.06 GeV; θ_{lab} = 5° CREX: E_{beam} = 2.18 GeV; θ_{lab} = 5°

PREX-II: E_{beam} = 0.95 GeV; θ_{lab} = 5° Surprising Pb result persists at different Q^2 values

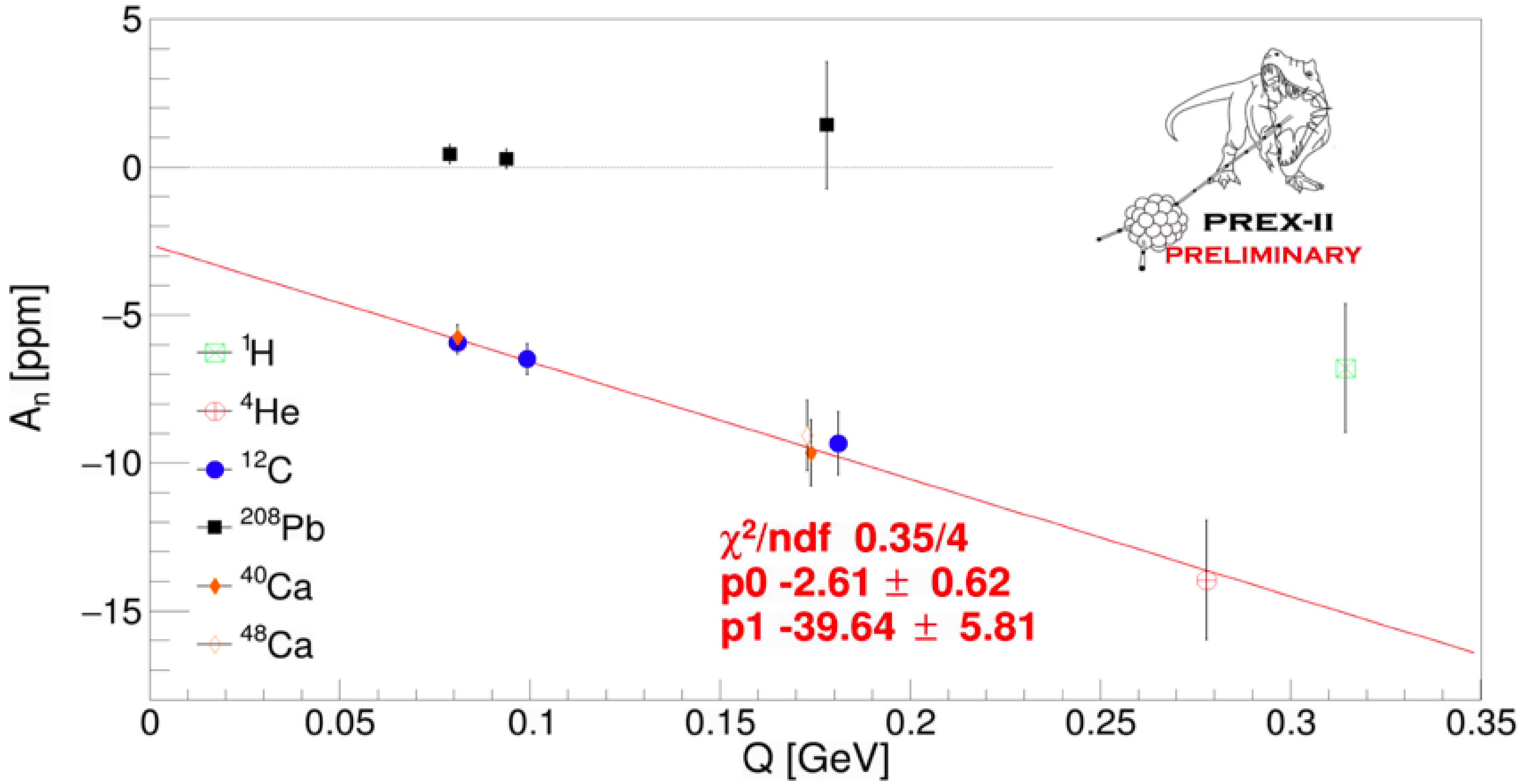
PREX-II and CREX A_n Results (with all Hall A meas.)



New A_n measurements (PREX-II,CREX) consistent with old measurements (PREX)

- ^{208}Pb A_n nearly 0 for multiple Q [from 0.08-0.17GeV] (**after ^{12}C diamond subtraction**)
- ^{12}C and ^{40}Ca A_n nearly overlap one another for 2 different Q [from 0.08-0.17GeV]
- ^{48}Ca and ^{40}Ca A_n overlap one another for these kinematics (despite differing A/Z)

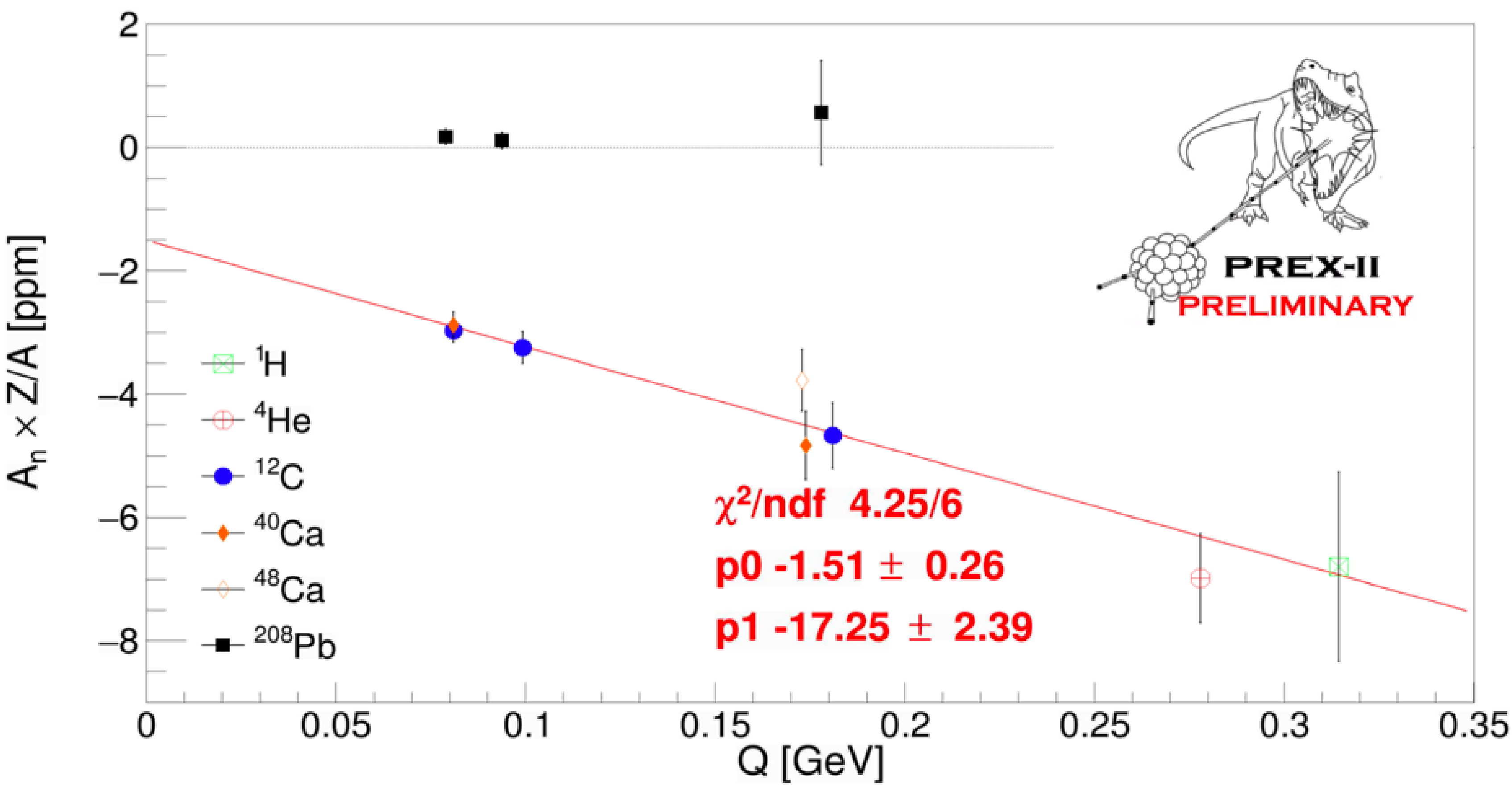
Global phenomenological fit presuming linear Q dependent model



(based on Gorchtein & Horowitc 2008: $A_n = \hat{A}_n \frac{QA}{Z}$)

- Observe: ^{4}He,^{12}C , ^{48}Ca, ^{40}Ca (measured at 5° and 6°) points appear to lie along linear fit
- Observe: offset is non-zero!
- Forcing a fit through (0,0) fails, indicating **A_n is not strictly proportionate to Q in this kinematic region, but perhaps Q to power less than 1**

Considering A/Z scaling



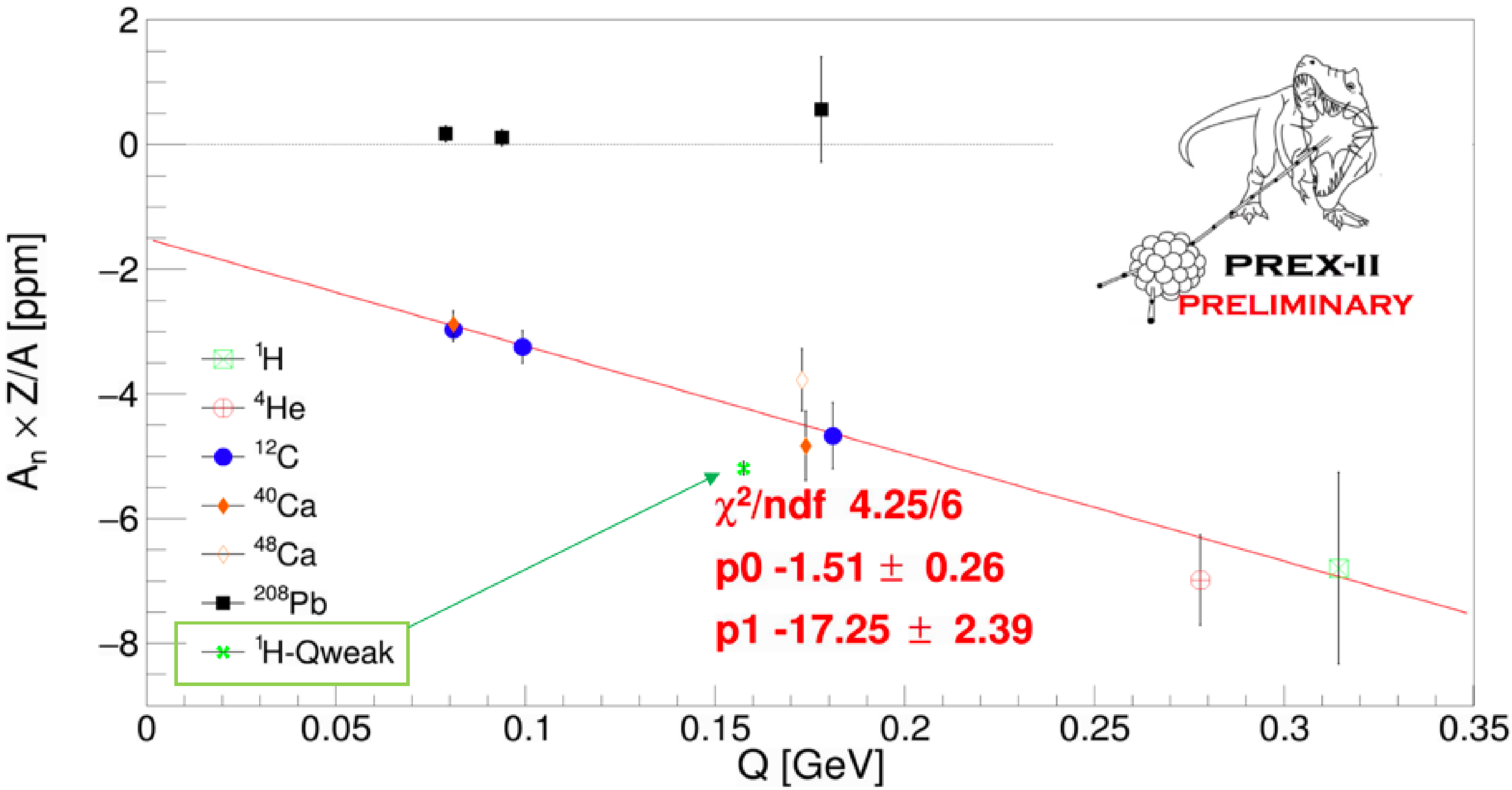
All points here HRS data forward angle scattering 5°, 6°

Target	A/Z
H	1.0
^{4}He	2.0
^{12}C	2.0
^{208}Pb	2.53
^{40}Ca	2.0
^{48}Ca	2.4

Plot with A_n normalized to A/Z to remove A, Z dependence

- For the light and A/Z=2 nuclei (^{1}H,^{4}He, ^{12}C, ^{40}Ca), A_n does appear to satisfy A/Z scaling

Considering A/Z scaling



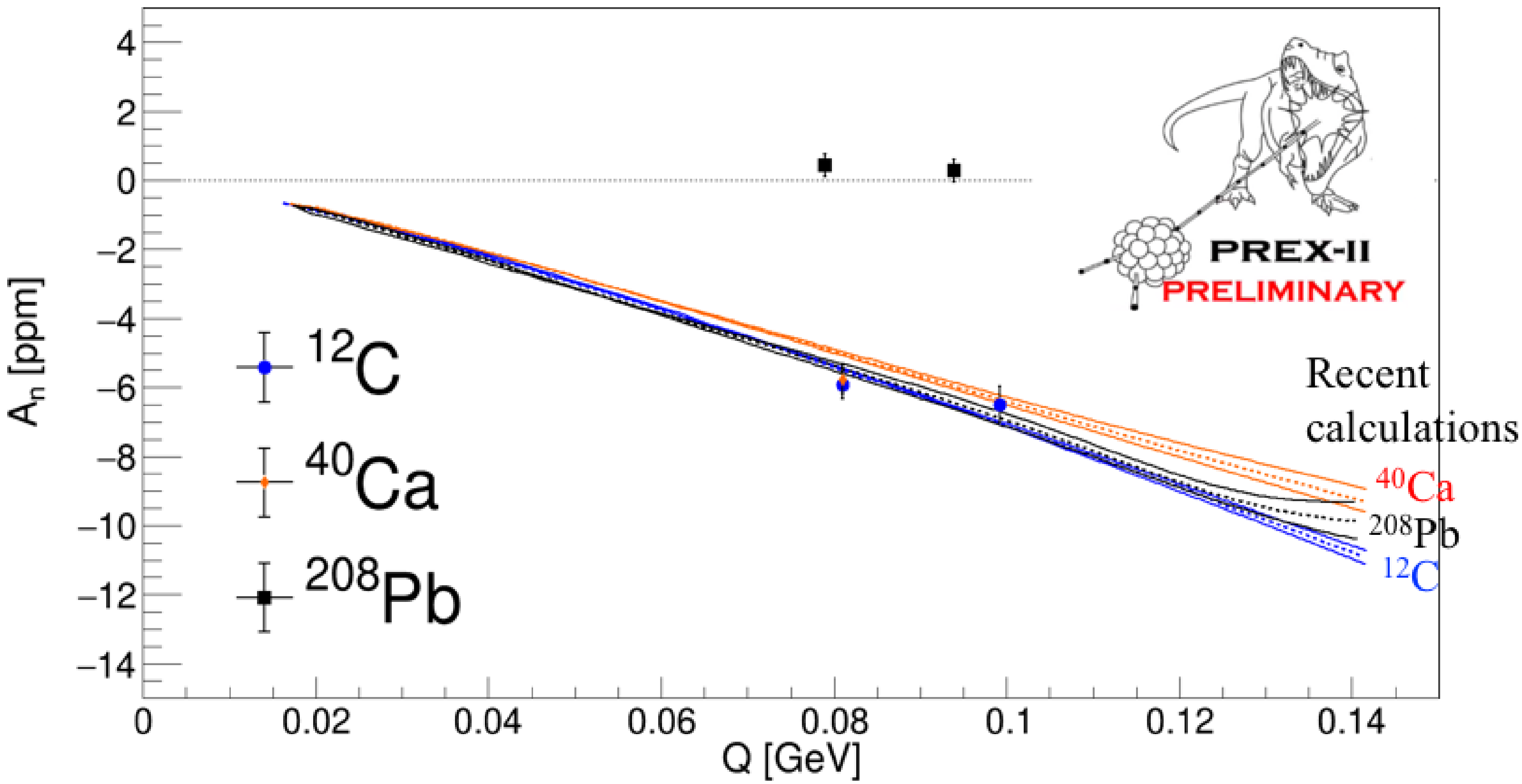
Plot with A_n normalized to A/Z to remove A, Z dependence

All points here HRS data forward angle scattering 5°, 6°

Target	A/Z
H	1.0
^{4}He	2.0
^{12}C	2.0
^{208}Pb	2.53
^{40}Ca	2.0
^{48}Ca	2.4

- For the light and A/Z=2 nuclei (^{1}H, ^{4}He, ^{12}C, ^{40}Ca), A_n does appear to satisfy A/Z scaling

PREX-I and PREX-II A_n Measurements with New Theory Curves

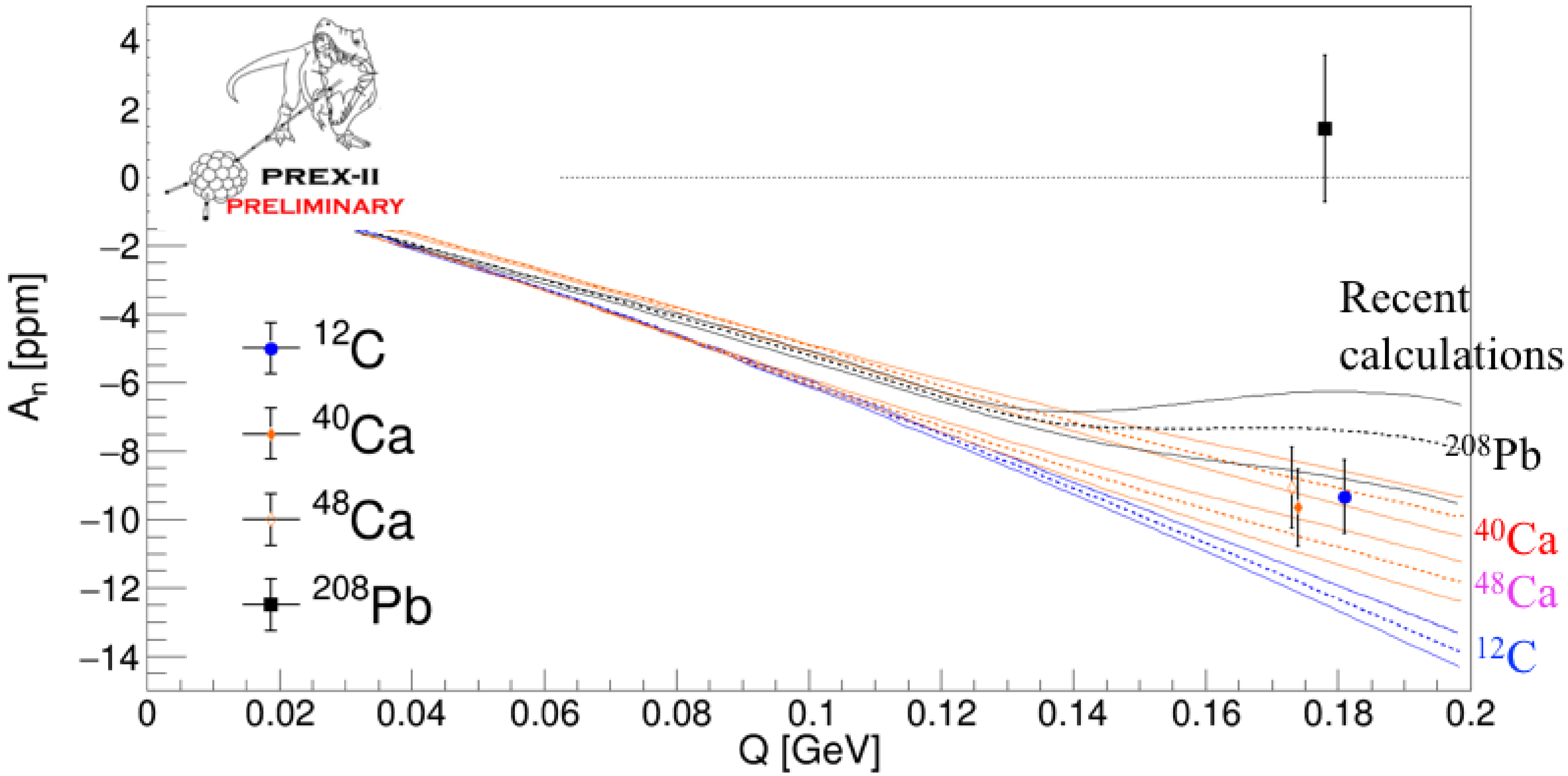


New calculations for
953 MeV and 5°:
by **Oleksandr Koshchii & Mikhail Gorchtein**

Target	Predicted A_n (ppm)	Measured A_n ± total error (ppm)
^{12}C	-5.53 ± 0.03	-5.9 ± 0.4
^{40}Ca	-5.01 ± 0.06	-5.8 ± 0.4
^{208}Pb	-5.49 ± 0.02	+0.3 ± 0.3

PRELIMINARY

CREX A_n Measurements with New Theory Curves

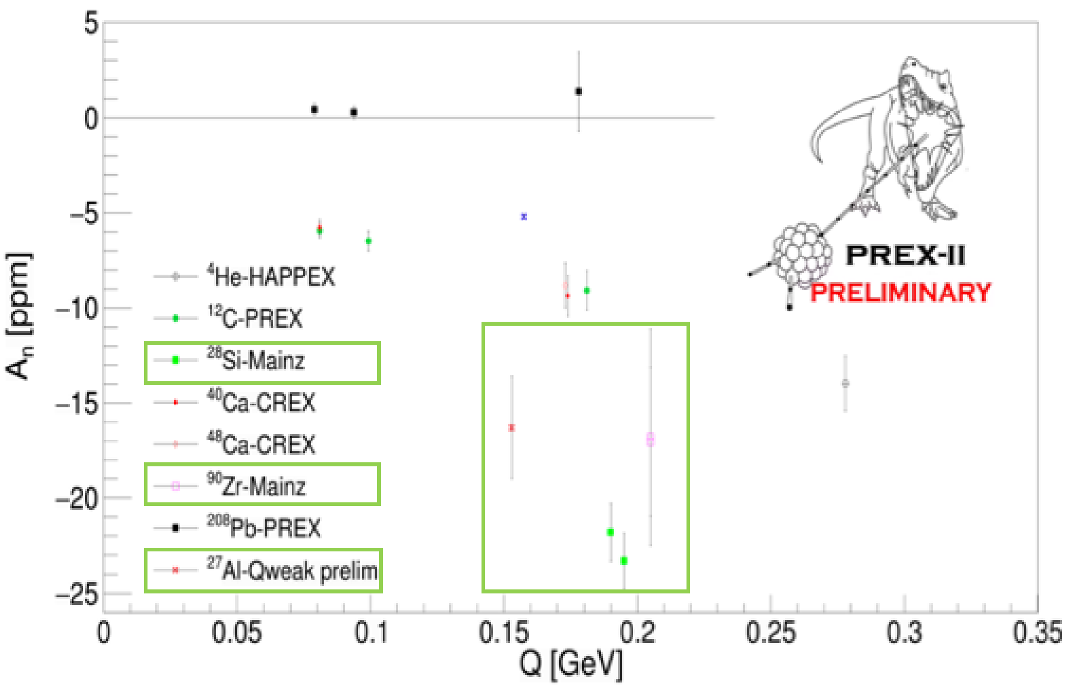


New calculations for
2180 MeV and 5°:
by **Oleksandr Koshchii & Mikhail Gorchtein**

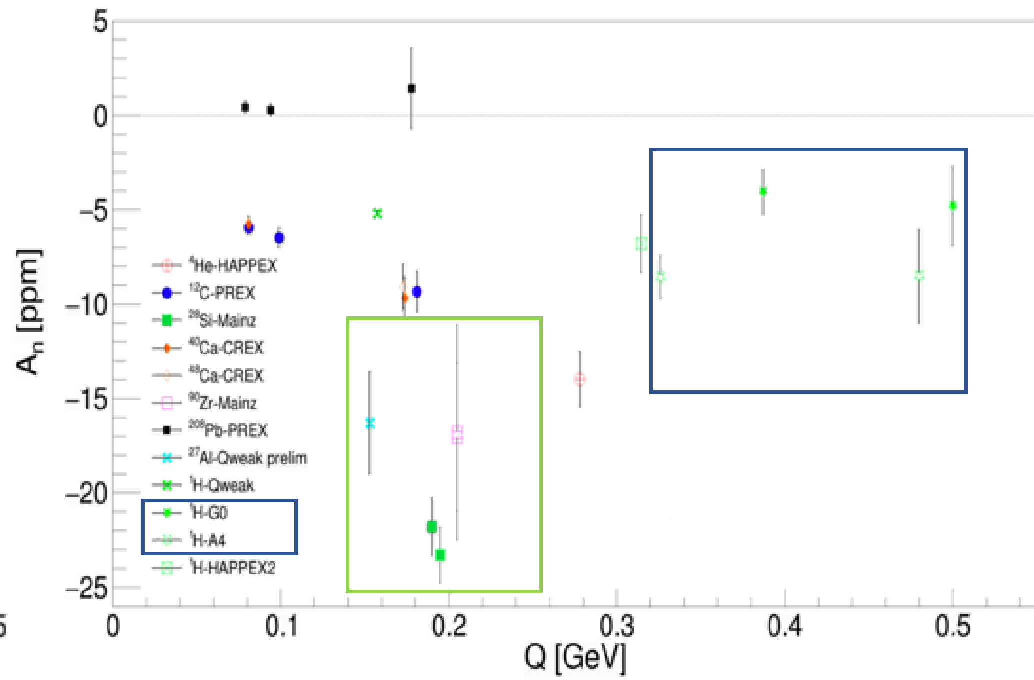
Target	Predicted A_n (ppm)	Measured A_n ± total error (ppm)
^{12}C	-12.34 ± 0.35	-9.3 ± 1.1
^{40}Ca	-8.78 ± 0.42	-9.7 ± 1.1
^{48}Ca	-10.45 ± 0.5	-9.1 ± 1.2
^{208}Pb	-7.52 ± 1.31	+1.4 ± 2.1

PRELIMINARY

Other Measurements



(smaller angle scattering)



(larger angle scattering included)

- Developing a landscape of A_n measurements for a range of A and Z at various kinematics
- HAPPEX, PREX and CREX measurements all small angle elastic scattering (5°,6°)

(Note: larger angle scattering measurements exist but require model corrections and may not be useful for comparison on the same diagram)

Summary

Achieved a systematic set of A_n measurements over a range of Z at various beam energies

Observed features for forward elastic electron scattering at 5°:

- **New A_n measurements (PREX-II, CREX) consistent with old measurements (HAPPEX, PREX-I)**
- **^{208}Pb A_n nearly zero for multiple Q** [from 0.08 - 0.17 GeV]
- ^{12}C and ^{40}Ca A_n overlap one another for two different Q [from 0.08 - 0.17 GeV]
- ^{48}Ca and ^{40}Ca A_n overlap one another for these kinematics despite differing A/Z
- While appearing linear with Q, A_n for ^{4}He, ^{12}C, ^{48}Ca, and ^{40}Ca does not appear strictly proportionate to Q in the kinematic range. Simple linear fit misses origin!
- For light and A/Z = 2 nuclei (^{1}H, ^{4}He, ^{12}C, and ^{40}Ca), A_n appears to satisfy A/Z scaling.

Wish: new theoretical calculations that treat dispersion corrections and Coulomb distortions simultaneously

Hope: might lead to new insights into the structure of heavy nuclei *[or just help guide and constrain theoretical calculations]*

Extra Slides

PRELIMINARY Uncertainties

Target	C12	Ca40	Pb208
False Asymmetry	0.06	0.2	0.06
Baem polarization	0.1	0.1	0.008
Linearity	0.1	0.1	0.008
Target impurities	0.00	0.00	0.3
Total systematic	0.2	0.3	0.3
Statistical	0.4	0.3	0.1
Total Error	0.4	0.4	0.3

PREX-II An Measurement uncertainties (ppm)

Target	C12	C40	Ca48	Pb208
False Asymmetry	0.2	0.003	0.09	0.09
Baem polarization	0.2	0.2	0.2	0.03
Linearity	0.2	0.2	0.2	0.03
Target impurities	0.00	0.00	0.6	0.9
Total systematic	0.3	0.2	0.7	0.9
Statistical	1.0	1.1	1.0	1.9
Total Error	1.1	1.1	1.2	2.1

CREX An Measurement uncertainties (ppm)