High-Precision Beam Polarimetry for the CREX Experiment

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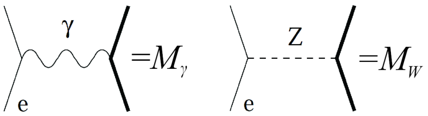
PVES & CREX

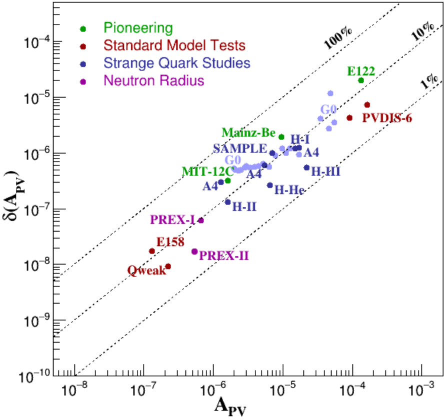
Parity Violating Electron Scattering & Helicity

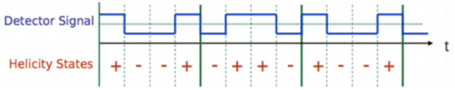


- Measure scattering asymmetry from left & right handed polarized electrons:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{\mathcal{M}_\gamma^* \mathcal{M}_W}{\mathcal{M}_\gamma^2} \quad (1)$$

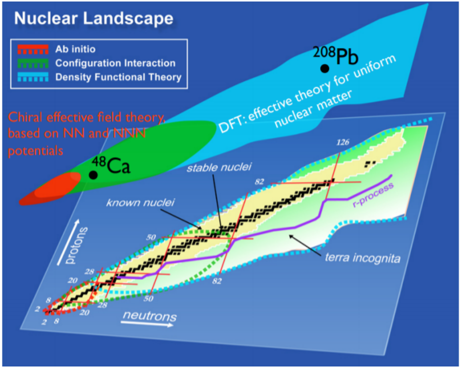
- Requires polarized electron beam with fast helicity-flipping
  - High beam polarization = higher asymmetry resolution



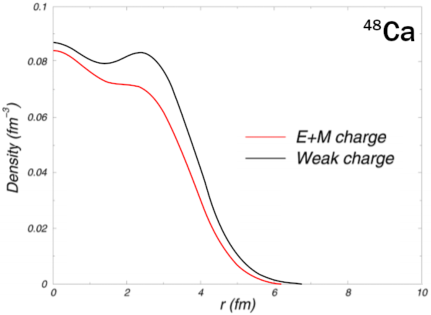


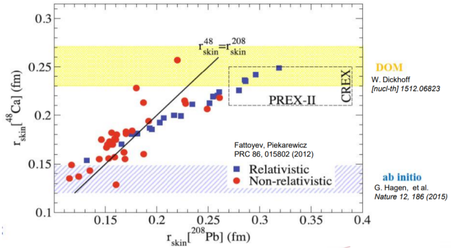
Above: Quartet helicity patterns that were used in CREX

CREX



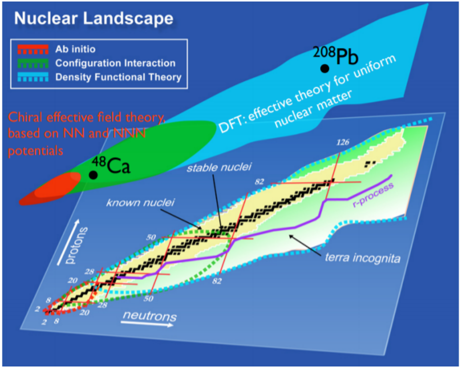
- PVES **C**alcium **R**adius **Ex**periment
- Target: 6 mm thick ^{48}Ca
- $E \simeq 2.2$ GeV, $\theta = 5^\circ$

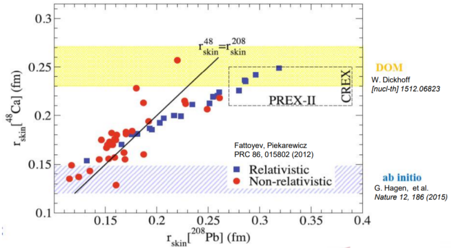




G. Hagen et. al. Nat. Phys. 12 (2015) 2 (186-190)

CREX





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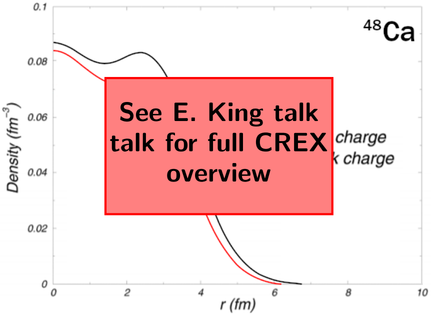

See E. King talk talk for full CREX overview

G. Hagen et. al. Nat. Phys. 12 (2015) 2 (186-190)

CREX Proposed Systematics

CREX Systematics Estimates from PAC40 Proposal

Source	Systematic
Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Nonlinearity	0.3%
Transverse Asymmetry	0.1%
Polarization	0.8%
Inelastic contribution	0.2%
Q^2	0.8%
Total Systematics	1.2%

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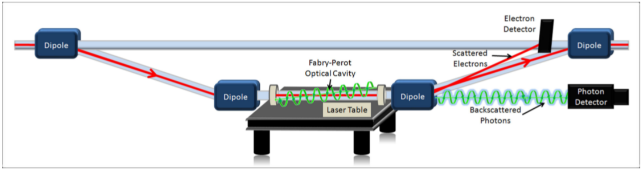
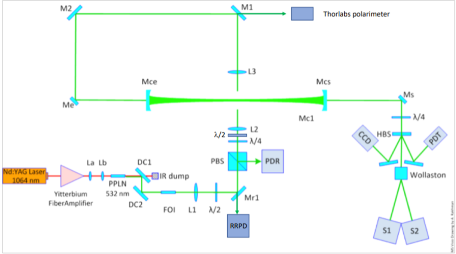
As proposed, beam polarimetry is a leading systematic. . . so how precise polarimetry can we do?

High-Precision Compton Polarimetry

Hall A Compton Polarimeter

Images Credit: *D. Gaskell (2019)*



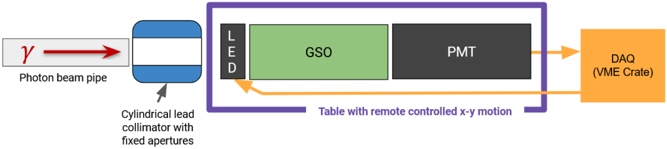


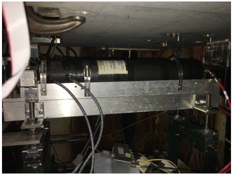
Optics table device layout

- Polarimeter consists of:
    - Magnetic chicane to steer beam
    - Fabry-Perot cavity on laser table
    - Photon calorimeter
    - High-speed DAQ system
- Laser/Amp outputs at $\lambda = 1064$ nm, but is doubled to $\lambda = 532$ nm
- Laser polarization measured on table

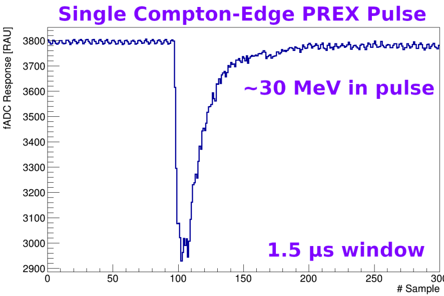
Compton Photon Detector

Images Credit: *J. C. Cornejo (2019)*





- Detector Components:
  - Pb Collimator
  - Pb Sync Shield
  - GSO scintillator
  - PMT and DAQ readout
- Signals read out per rapidly-flipping helicity state
- Measure helicity-correlated asymmetry
- LED's allow for *in-situ* detector tests



Example photon pulse with energy matching the PREX Compton-edge. The CREX Compton edge photons had about 4x greater energy

Polarimetry Measurement: Integrating Method

How to measure a Compton Asymmetry: Integrate the signal over pedestal per helicity state.
Measure signal S, for each laser state ON, OFF and helicity state $+, -$.
Helicity pattern difference (Δ), sum (Y), and asymmetry ($\mathcal{A}$) distributions are calculated:

$$\Delta_{ON} = S^+_{ON} - S^-_{ON}$$

$$\Delta_{OFF} = S^+_{OFF} - S^-_{OFF}$$

$$Y_{ON} = S^+_{ON} + S^-_{ON}$$

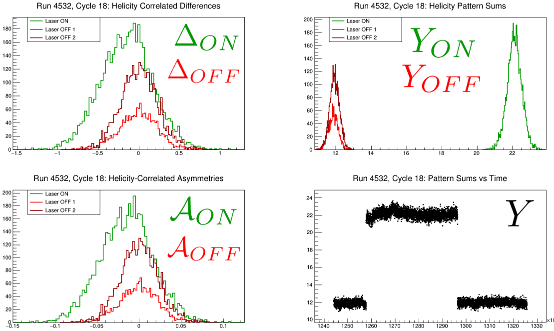
$$Y_{OFF} = S^+_{OFF} + S^-_{OFF}$$

$$\mathcal{A}_{ON} = \frac{\Delta_{ON}}{Y_{ON} - \langle Y_{OFF} \rangle}$$

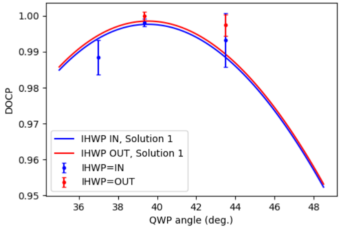
$$\mathcal{A}_{OFF} = \frac{\Delta_{OFF}}{\langle Y_{ON} \rangle - \langle Y_{OFF} \rangle}$$

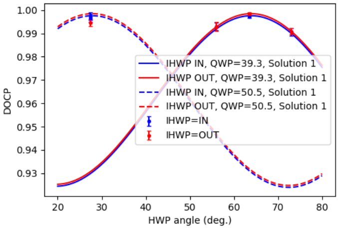
$$\mathcal{A}_{exp} = \langle \mathcal{A}_{ON} \rangle - \langle A_{OFF} \rangle = \mathcal{P}_e \mathcal{P}_\gamma \langle \mathcal{A}_l \rangle$$

With laser DOCP $\mathcal{P}_\gamma$, energy-weighted average analyzing power $\langle \mathcal{A}_l \rangle$, and beam polarization $\mathcal{P}_e$.



Laser Polarization





Above: Off-100% DOCP polarization points with the optical model fit. Image credit: D. Gaskell (2022)

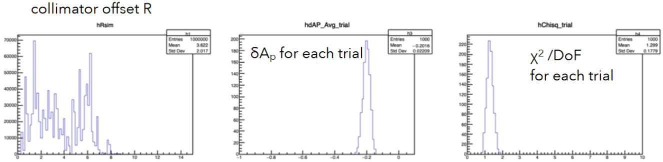
Laser DOCP Systematics

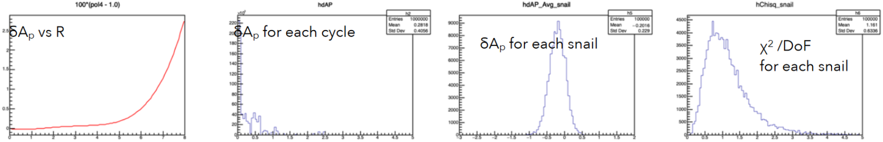
Source	$\delta P/P$
Fit params	0.13%
Time Dependence	0.05%
Birefringence	0.10%
Residuals	0.34%
Total	**0.36%**

- Laser polarization characterized by tests on table
- Optical model converged on one solution
- Mean laser polarization: **99.99%**
    - Includes periods of running off-100% DOCP

Collimator Offset

Selected 1 position/cycle
10 cycles/snail
Scaled R by 1.1
dPol ~0.20%
chisq/dof~1.16 (snail)
chisq/dof~1.3 (trial)



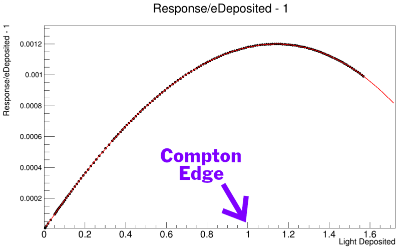


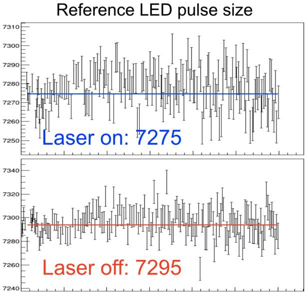
- Tracking photon beam position proved difficult
- Simulate cycle collimator offset from cyclewise offset distribution
- By rescaling distribution measure χ^2 for each simulated snail
- Match χ^2 matched to running conditions
- Calculate polarization correction for conditions
- Polarization correction of **0.2%** matches χ^2 of CREX run

Detector Corrections

Nonlinearity

- 1 kHz pulser system w/ load = CREX signal
  - Track $Yield(var + \Delta) - Yield(var)$
- Nonlinearity out to 2*CE
- Very small analyzing power correction ($\approx$0.02% for CREX)



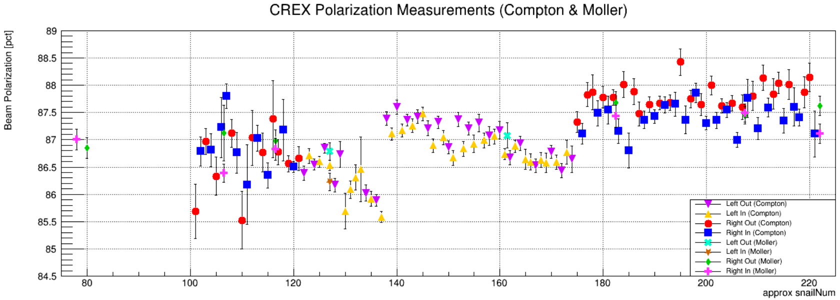


Gain Shift

- Evidence of small change in pulse size with background signal size
- Nonzero shift necessitates dynamic correction
- Bench tests of gain shift done
  - Analysis yielded correction factor for $\mathcal{A}_{exp}$
- Systematic from gain shift: **0.15%**

Left: *Evidence of a gain shift from a linearity run taken during beam operations*

CREX Compton Polarimetry Result



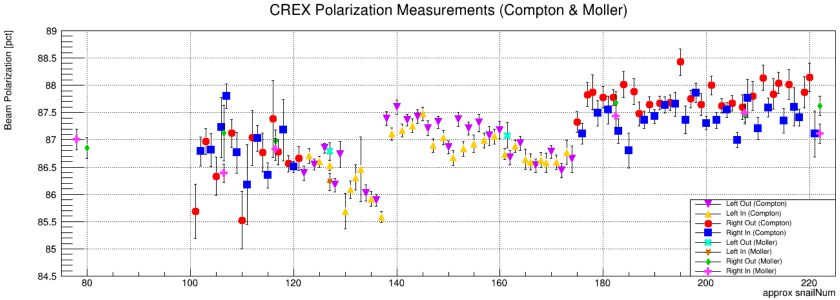
- Moller and Compton show superb agreement even with time-dependence

CREX Compton Result

$$\mathcal{P}_e = (87.15 \pm 0.38)\%$$

Result is 0.44% (relative) precision polarimetry measurement!

CREX Compton Polarimetry Result



- Moller and Compton show superb agreement even with time-dependence
- Moller average is **87.0** and previously reported 0.85% systematics

CREX Compton + Moller Result

$$\mathcal{P}_e = (87.10 \pm 0.33)\%$$

Result is ~~0.44%~~ 0.38% (relative) precision polarimetry measurement!

CREX Results & Beyond

CREX Results

CREX Asymmetry

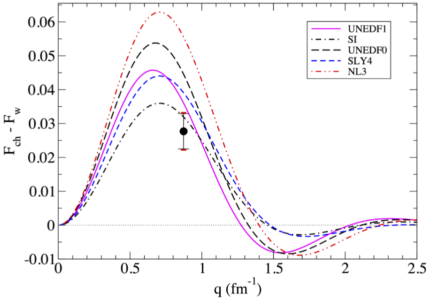
$$\mathcal{A}_{PV}^{48} = 2668 \pm 106(\text{stats}) \pm 39(\text{syst})$$
parts per billion

Uncert. Source	A_{PV} uncert. contribution
Acceptance normalization	0.90%
Inelastic Contamination	0.82%
Transverse asymmetry	0.49%
Polarization	0.39%
Radiative Corrections	0.37%
Beam Correction	0.27%
Nonlinearity	0.26%
Isotopic purity	0.11%
Total	**1.49%**

Published in PRL! D. Adhikari *et al* Phys. Rev. Lett. **129** 042501

Neutron Skin Thickness

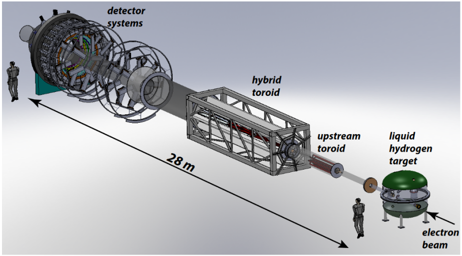
$$R_n^{48} - R_p^{48} = 0.121 \pm 0.035 \text{ fm}$$



Above: CREX measured $F_{ch} - F_W$ compared to one family of theory models with different weak radii.

Even *Higher* Precision Polarimetry?!

MOLLER



Above: Target, magnet, and detector concept for MOLLER experiment. Image courtesy of MOLLER collaboration.

- High precision measurement of weak mixing angle at low Q^2
- Expected $\mathcal{A}_{PV}$ ≈35.6 ppb

- MOLLER proposal calls for 0.4% overall polarimetry measurement
  - Not trivial to accomplish. . .
- Addition of electron detector to measure asymmetries at 11 GeV
  - Currently in development!!
- Extremely fast helicities at 2 kHz. . . detector needs upgrade!

See C. Palatchi talk
about MOLLER experiment!

Summary

Precision Determination of the Neutral Weak Form Factor of ^{48}Ca

(The CREX Collaboration)

D. Adhikari,[1] H. Albataineh,[2] D. Androic,[3] K.A. Aniol,[4] D.S. Armstrong,[5] T. Averett,[5] C. Ayerbe Gayoso,[5] S.K. Barcus,[6] V. Bellini,[7] R.S. Beminiwattha,[8] J.F. Benesch,[6] H. Bhatt,[9] D. Bhatta Pathak,[8] D. Bhetuwal,[9] B. Blaikie,[10] J. Boyd,[11] Q. Campagna,[5] A. Camsonne,[6] G.D. Cates,[11] Y. Chen,[8] C. Clarke,[12] J.C. Cornejo,[13] S. Covrig Dusa,[6] M. M. Dalton,[6] P. Datta,[14] A. Deshpande,[12,15,16] D. Dutta,[9] C. Feldman,[12,17] E. Fuchey,[14] C. Gal,[15,9,11,12] D. Gaskell,[6] T. Gautam,[18] M. Gericke,[10] C. Ghosh,[19,12] I. Halilovic,[10] J.-O. Hansen,[6] O. Hassan,[10] F. Hauenstein,[6] W. Henry,[20] C.J. Horowitz,[21] C. Jantzi,[11] S. Jian,[11] S. Johnston,[19] D.C. Jones,[20,6] S. Kakkar,[10] S. Katugampola,[11] C. Keppel,[6] P.M. King,[22] D.E. King,[23,20] K.S. Kumar,[19] T. Kutz,[12] N. Lashley-Colthirst,[18] G. Leverick,[10] H. Liu,[19] N. Liyanage,[11] J. Mammei,[10] R. Mammei,[24] M. McCaughan,[6] D. McNulty,[1] D. Meekins,[6] C. Metts,[5] R. Michaels,[6] M. Mihovilovic,[25,26] M.M. Mondal,[12,15] J. Napolitano,[20] A. Narayan,[27] D. Nikolaev,[20] V. Owen,[5] C. Palatchi,[11,15] J. Pan,[10] B. Pandey,[18] S. Park,[9,12] K.D. Paschke,[11,*] M. Petrusky,[12] M.L. Pitt,[28] S. Premathilake,[11] B. Quinn,[13] R. Radloff,[22] S. Rahman,[10] M.N.H. Rashad,[11] A. Rathnayake,[11] B.T. Reed,[21] P.E. Reimer,[29] R. Richards,[12] S. Riordan,[29] Y.R. Roblin,[6] S. Seeds,[14] A. Shahinyan,[30] P. Souder,[23] M. Thiel,[31] Y. Tian,[23] G.M. Urciuoli,[32] E.W. Wertz,[5] B. Wojtsekhowski,[6] B. Yale,[5] T. Ye,[12] A. Yoon,[33] W. Xiong,[23,34] A. Zec,[11] W. Zhang,[12] J. Zhang,[12,15,34] and X. Zheng[11]

Thank you to all of our 100+ collaborators!

- CREX: experiment of the current PVES generation
- CREX results released, now in PRL!
- CREX polarimetry most accurate of any Compton measurement thus far
- Controlled systematic uncertainties from photon detector/laser
- Many improvements forthcoming for more Compton measurements

Trans & Nonbinary Physicists

TRANS & NON-BINARY PHYSICISTS

The Trans and Nonbinary Physicists Discord server is an online community for transgender and nonbinary physicists — from enthusiasts to professors! — to socialize, network, and support one another. All are welcome, and so far we have over 200 members from across the world!

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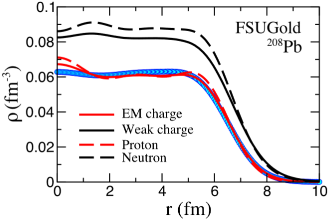
Questions, comments, concerns, observations?

Backup Slides

Weak Charge & Neutron Skin

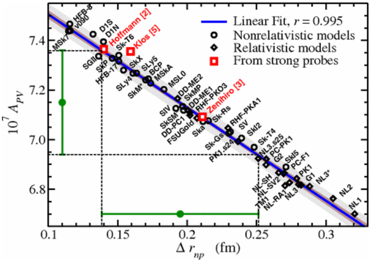
Image Credit: *M. Thiel et. al. (2019)*



- Theory predicts "neutron skin"
- Excess neutrons pushed radially outwards against surface tension due to pressure of nuclear matter
- Asymmetry correlated with EM & weak form factors:

$$A_{PV} \approx \frac{G_F q^2}{4\pi\alpha\sqrt{2}} \frac{F_W}{F_{ch}} \qquad (2)$$

	Proton	Neutron
EM Charge	1	0
Weak Charge	0.08	1



Current theory models predicting neutron radius and asymmetry highly correlated, but not constrained well by neutron radius measurements

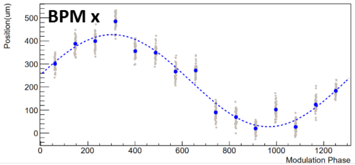
Image Credit *X. Roca-Maca et. al. (2011)*

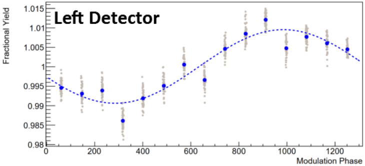
Beam Monitors & Modulation

Need to correct for false asymmetries:

$$A_{PV} = A_{raw} - A_Q - \sum_i \alpha_i \Delta x_i - \alpha_E A_E \qquad (3)$$

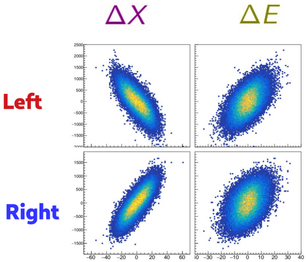
- Charge monitors track A_Q
- Position monitors track helicity correlated position & energy differences
- Feedback system helps minimize false asymmetries





Note here both detectors' position slopes are opposite signs, but the energy slopes are the same sign.

Image Credit: *T. Ye (2020)*

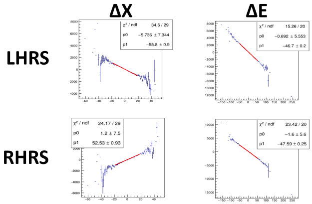


Beam Modulation:

- Detector response correlated with artificially-induced beam motion
- Used in concert with regression

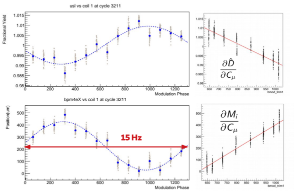
Beam Corrections

Regression



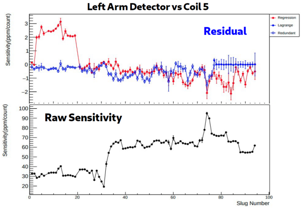
- Position, angle and energy information taken from position monitors
- Trajectories correlated with changes in measured A_{raw}

Modulation



- Magnetic coils alter beam trajectory periodically, in sequence
- Correlation slopes extracted from beam changes

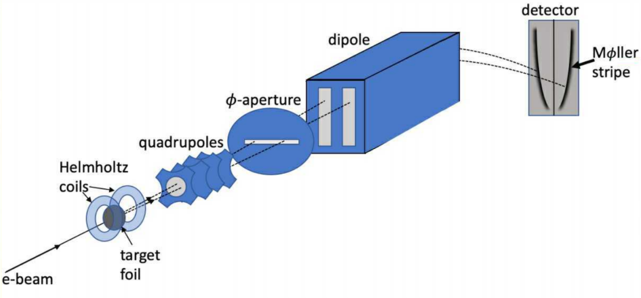
Lagrangian Multipliers

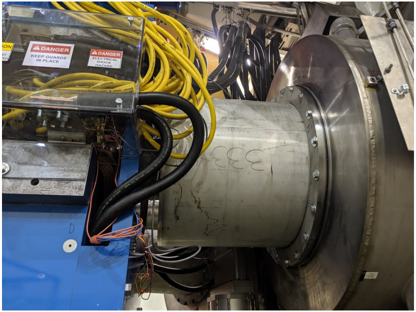


- Create set of Lagrangian multipliers to minimize regression correction
- Constraints come from modulation slopes

Møller Polarimeter

- Low-current polarization measurement
  - Invasive, cannot be run in situ with main experiment
- Designed for up to 11 GeV running





- 3-4 T fields magnetically saturates Fe foil target
- Spectrometer optics configured to minimize kinematic uncertainties
- Runs taken ≈weekly

PREX-II Results

PREX-II Asymmetry

$$\mathcal{A}_{PV} = 550 \pm 16(\text{stats}) \pm 8(\text{syst})$$
parts per billion

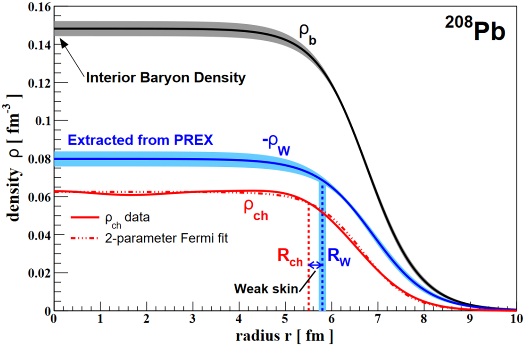
Neutron Skin Thickness

$$R_n - R_p = 0.283 \pm 0.071 \text{ fm}$$

Uncert. Source	A_{PV} **uncert. contribution**
Polarization	0.95%
Acceptance normalization	0.83%
Beam correction	0.54%
Detector nonlinearity	0.49%
Carbon contamination	0.26%
Charge Correction	0.04%
Inelastic Contamination	0.02%
Total	**1.48%**

PREX-II paper published in PRL!

Phys.Rev.Lett. 126 (2021) 17, 172502

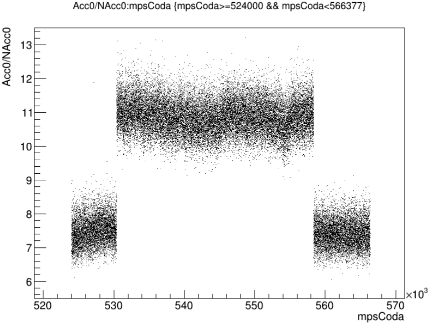


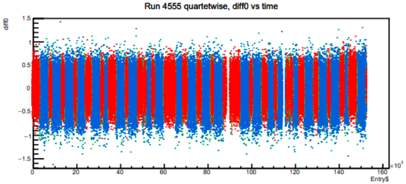
Above: New baryon density curves calculated from PREX-II results.

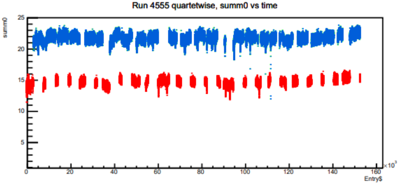
Compton Backup

Laser Cycling

- To handle shifts in background, we periodically flip off the laser
- Backgrounds calculated on cycle-to-cycle basis
- 1 cycle = a laser-on period, sandwiched by two laser off periods







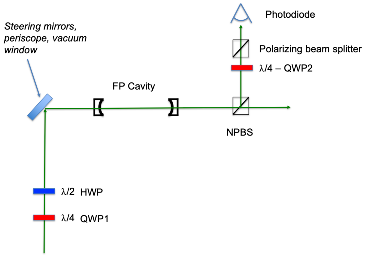
Top: Plot of helicity correlated differences vs time for one PREX-II run
Bottom: Plot of sums for same time period

In each plot, low variation of the integrated signal is likely indicative of healthy data.

In all plots, blue represents laser-on periods, red represents laser-off.

Data shown here was taken over a ≈90 minute period.

Laser Polarization Model

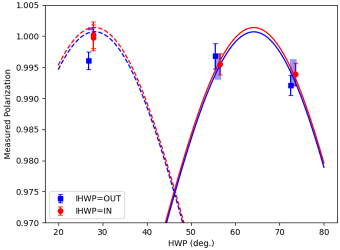


Before run:

- NPBS used to used to characterize DOCP in-cavity
- Complicated by birefringence of cavity mirrors
- Entrance scans, exit scans, cavity scans. . .

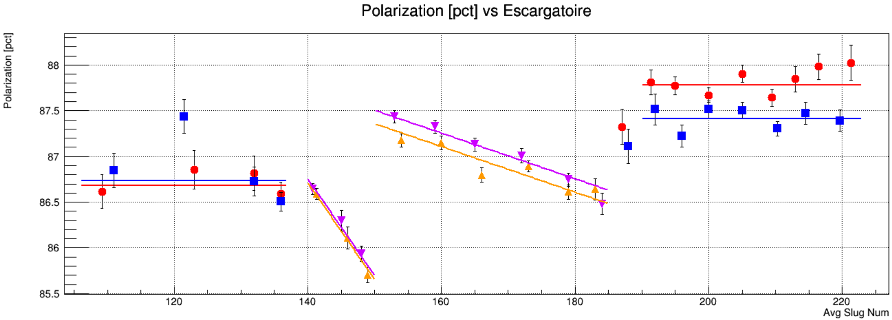
During run:

- Additional verification: running off 100%
- QWP/HWP changed for multiple snails to alter DOCP
- Saw polarization magnitude decrease
- Systematic look low
  - Study on birefringence parameters still pending



Compton Summary Presentation

Compton Polarization Mean: Piecewise Fits



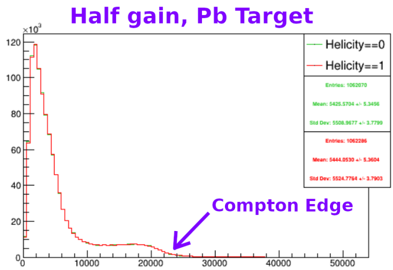
- Fit each run "piece" to either pol0 or pol1 depending on time-dependence
- Require pol1 slopes for IHWP OUT/IN per piece to be equal
- Average calculated from fit evaluations; uncertainties from fit parameters
- Average measured polarization: **(87.119 ± 0.016 (stat))%**

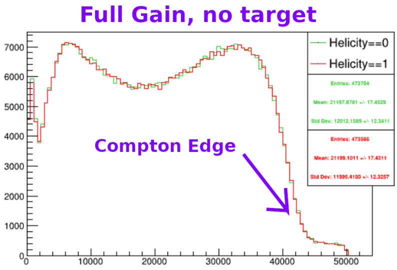
Model Uncertainty

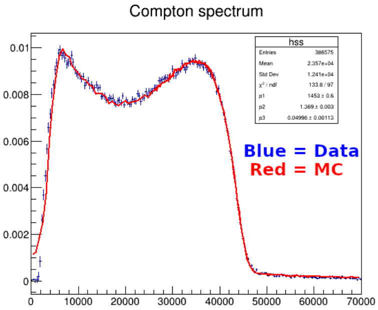
Model	Avg. Pol [pct]	Abs. Pol Uncert.
Escargatoire Average	87.118	0.018
Piecewise Fitting	87.119	0.016
Mini-Esc. Average	87.104	0.019

- All polarization averaging models agree CREX average is ≈87.1
- Model uncertainty for average is <0.1%
- Well below our leading systematic
- Total Compton statistics are on order of 0.02% relative
  - CREX compton polarimetry uncertainty will not be statistics-dominant

Compton Spectra

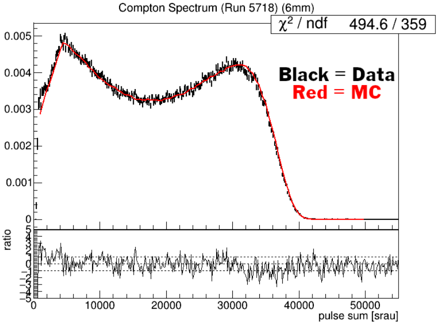




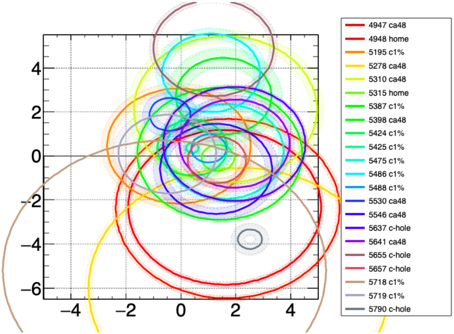


- Spectrum of integrated pulse energy
- MC fit to data well
  - Also can extract photon beam position systematic from fits
- Pb target: high backgrounds due to neutrons and detector Gd content
- Ca target: much lower backgrounds

Systematic: Collimator Offset (How it's supposed to work)

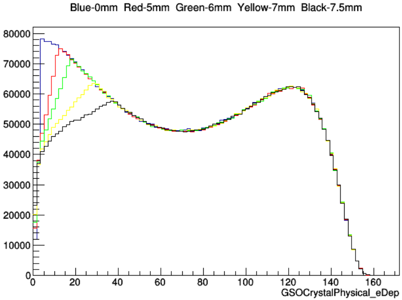


1. Simulate spectra with various offsets from collimator center
2. Match spectra from low-current spectrum runs
3. Best-fit simulation determines offset, chicane BPM positions recorded
4. Fit offsets and projected collimator points, mean position is collimator center
5. Use production BPM positions to determine dynamic collimator offset

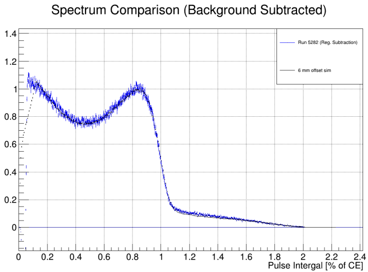


Systematic: Collimator Offset (What happened?)

- Problem: fitted center suggests some compton runs were >7 mm offset of collimator center
    - Would have been immediately noticeable in production spectra



Above: Simulated spectra with different offsets. Notice the effect of offset is visible at low energies.



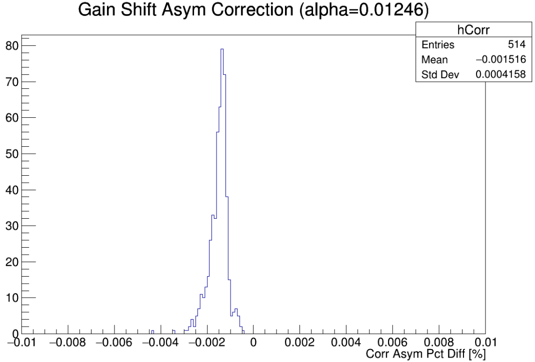
Above: Production spectrum (predicted to have 7 mm offset) compared with 6 mm simulated offset spectrum.

- No production spectra with a >6 mm offset found
- Possible causes:
    - BPM current calibration
    - Laser table differential movement
- Investigation of cause is limited by background

Systematic: Gain Shift

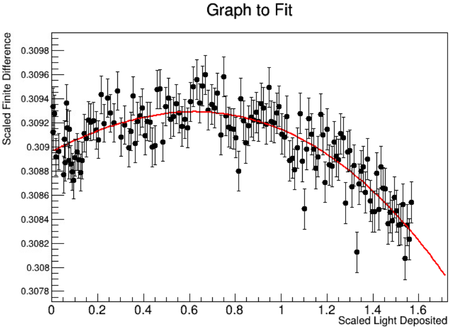
Gain Shift Measurement

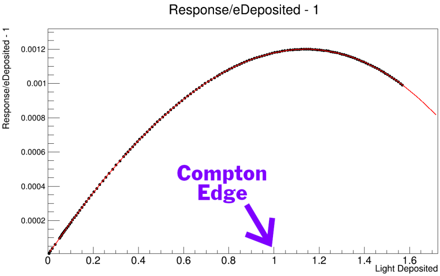
	LED Signal	SRAU Diff.	Pct Change
Beam Off	7058.98	0.0	0.0%
Beam On Las On	6987.89	71.09	-1.0071%



- Potential change in signal size at high PMT load
- Flash LED with constant brightness during production
- Measured brightness at different laser periods maps gain shift
  - This was only done once during all CREX running
- When scaled to correct signal size find 1.0246% gain shift which is a **0.15%** correction to asymmetry

Systematic: Nonlinearity





PMT response function with nonlinear terms:

$$Y(I) = I + \alpha I^2 + \beta I^3 + \gamma I^4 + \ldots$$

or equivalently. . .

$$\frac{Y}{I} - 1 = \alpha I + \beta I^2 + \gamma I^3 + \ldots$$

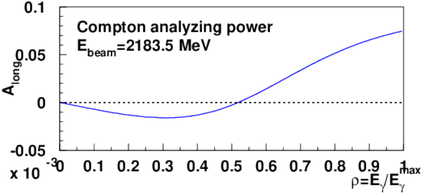
where I is light intensity and Y is detector response

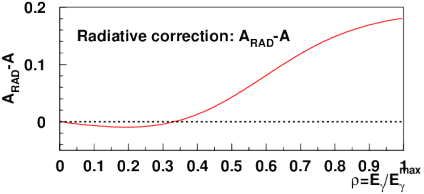
- In situ pulser system used to make measurements
- Parameters α, β, γ found to be smaller than expected (only 0.12% integral nonlinearity at CE)
- Nonlinearity affects analyzing power by **0.02%**

Beam-Related Systematics

Beam Energy

- CREX measured beam energy 2182.22±1.1 MeV slightly different from simulation energy
- Results in 0.103% correction to analyzing power
- After applying correction beam energy uncertainty is **0.05%**





Radiative Corrections

- Use “low energy” approximation to Born-asymmetry correction:

$$\mathcal{A}_{meas} = \mathcal{A}_{Born}(1 + \Delta\mathcal{A})$$

$$\Delta\mathcal{A} \simeq \frac{\alpha}{\pi}\frac{3cos(\theta) - 1}{4(\frac{E_\gamma}{E_e} + cos(\theta))}$$

- Find all asymmetries need to be corrected by -0.3%

Compton Systematics Table

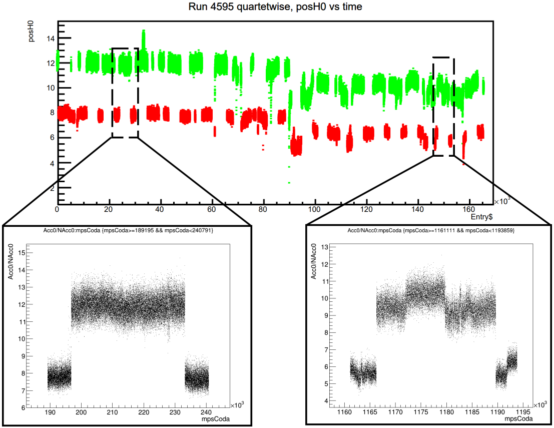
- Compton reporting one overall average rather than point-to-point correction
- Systematics:
  - Collimator offset limited by χ^2 calculation
  - Laser DOCP and optical model
  - Gain shift limited by upper bound
  - Model/time-dependence largely doesn't contribute
  - Small contributions from others
- Highly precise measurement due to new systematics upper-bounds

Source	Relative Correction	Uncertainty Contribution
Collimator Offset	-	0.20%
Laser DOCP	0.26%	0.36%
Gain Shift	-	0.15%
Model	-	0.02%
Beam Energy	0.103%	0.05%
Nonlinearity	-	0.02%
Rad Corrections	0.3%	<0.01%
Statistics	-	*0.02%*
Total	-	**0.44%**

Acknowledgments: J. C. Cornejo, M. Dalton, C. Gal, D. Gaskell, C. Palatchi, K. Paschke, A. Premithilake, B. Quinn

Pedestal Shifts/Beam Instabilities

- Pedestal shifts: problem throughout all PREX
  - Traced to attenuator box in Feb 2020
- Shift behavior highly variable in duration and magnitude
- Beam Instability:
  - Quick position instabilities cause us to miss photon target
  - High backgrounds from interception on cavity apertures
  - Periods of high laser-off asymmetry



Comparison of healthy cycle (left) and cycle with instantaneous pedestal shifts (right)