Photon Detector for Compton Polarimetry in the PREX-II Experiment

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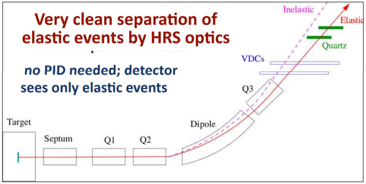
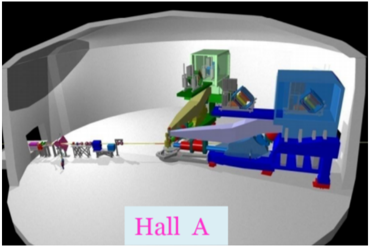
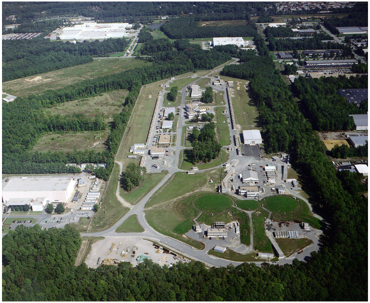
Context: PREX-II



- New generation of PVES experiments
- Pb-208 Tgt, 1 GeV beam
- 240 Hz beam helicity flipping
- Polarimetry among largest systematic uncertainties
- Two Hall polarimeters:
  - Moller Polarimeter
  - **Compton Polarimeter**

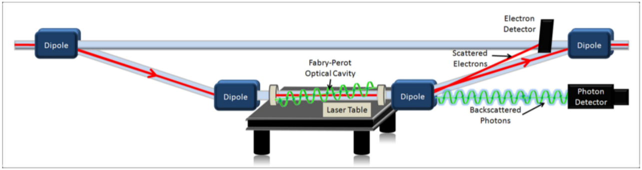


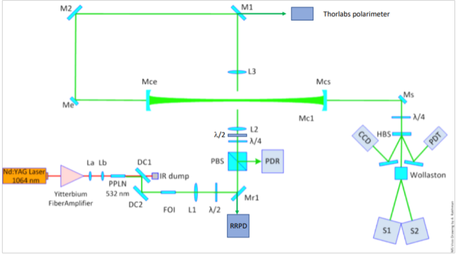


Top: JLab Hall A schematic
Bottom: JLab aerial view

Compton Polarimetry

Images Credit: *D. Gaskell (2019)*



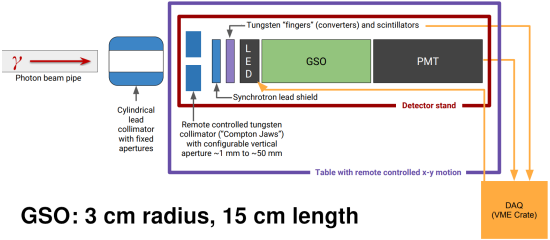


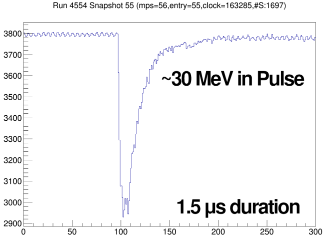
Optics table device layout

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

Compton Photon Detector

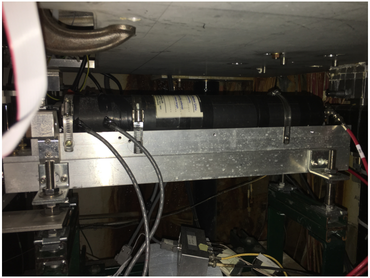
Images Credit: *J. C. Cornejo (2019)*





GSO: 3 cm radius, 15 cm length

- 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



Asymmetry and Polarization

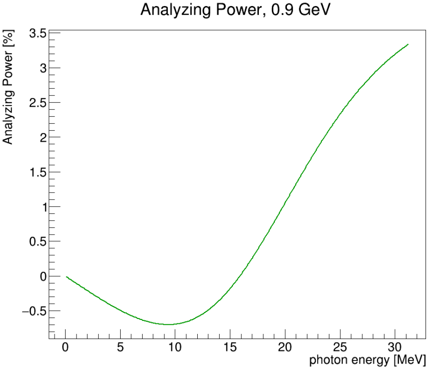
Scattering cross-section changes dependent on beam polarization $\mathcal{P}_e$ and laser polarization $\mathcal{P}_\gamma$:

$$\left(\frac{d\sigma}{d\rho}\right)_{compt} = \left(\frac{d\sigma}{d\rho}\right)_{unpol}(1 + \mathcal{P}_e\mathcal{P}_\gamma\mathcal{A}_l) \tag{1}$$

We then form an asymmetry between signal from positive and negative helicities:

$$\mathcal{A}_{exp} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \tag{2}$$

from which you can calculate an average polarization.



The “analyzing power” $\mathcal{A}_l$ plotted here is the theoretical measured asymmetry assuming 100% beam polarization.

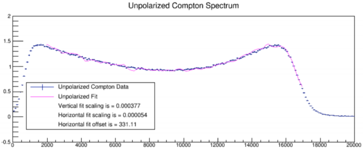
Polarimetry Measurement: Counting Method

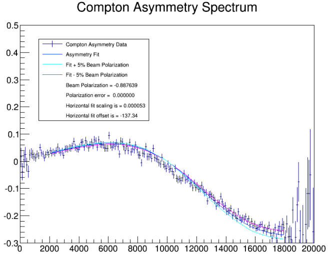
- Locate "compton edge" in spectrum
- Define arbitrarily small energy threshold ρ_{min}
- Count photon pulses between ρ_{min} and compton edge per helicity state
- Calculate asymmetry of photon number per asymmetry depending on helicity

Disadvantages:

- Need to define threshold (adds sensitivity to calibration and detector resolution)
- Sensitivity to dead-time
- High rate of pileup means distorted asymmetry spectrum

Images Credit: *A. Johnson (2016)*





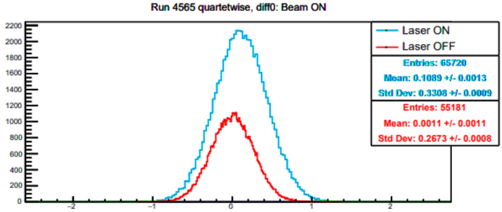
Top: Compton deposited energy spectrum for triggered pulses. The compton edge can be seen where the curve goes to zero at the far right.
Bottom: Asymmetry spectrum for same measurement, looks at asymmetry by energy deposition

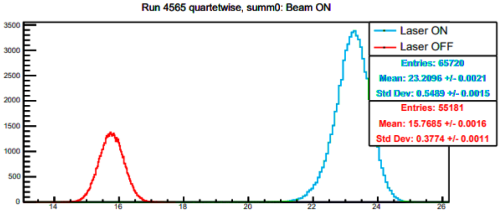
Polarimetry Measurement: Integrating Method

- No threshold, instead integrate total deposited photon energy per helicity state
- Calculate asymmetry using integrated energies

Disadvantages

- Lower signal-to-noise ratio
  - If noise is relatively uniform then it can be subtracted out
- Sensitivity to background fluctuations
  - Can be corrected with laser cycling
- Detector nonlinearity
  - Nonlinearity can be measured at any time

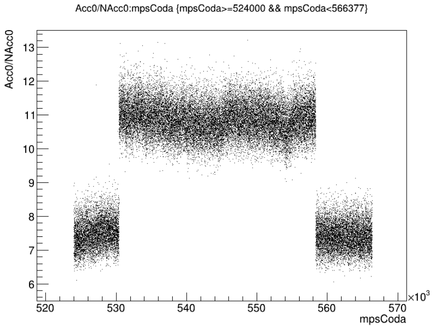


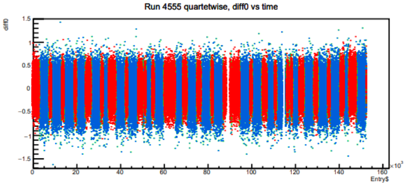


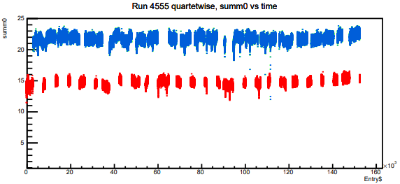
Top: A plot of helicity-correlated difference $E_+ - E_-$
Bottom: A plot of summed $E_+ + E_-$
In all plots, blue represents laser-on periods, red represents laser-off.

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







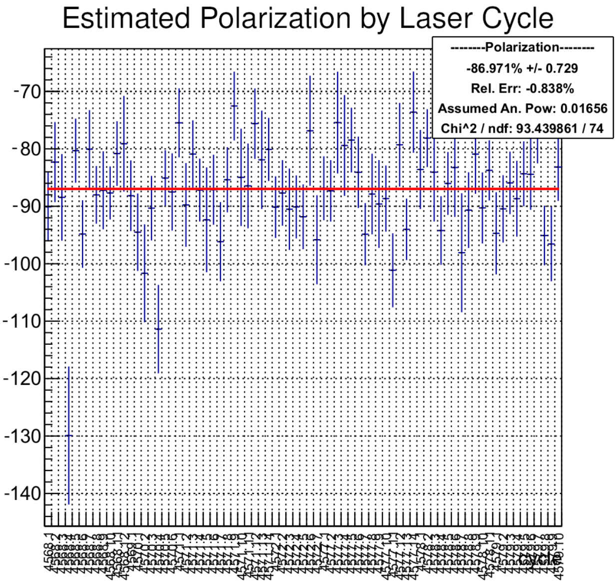
Top: Plot of helicity correlated differences vs time for one PREX-II run
Bottom: Plot of sums for same time period

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.

Early Look: PREX-II Compton Polarimetry Data

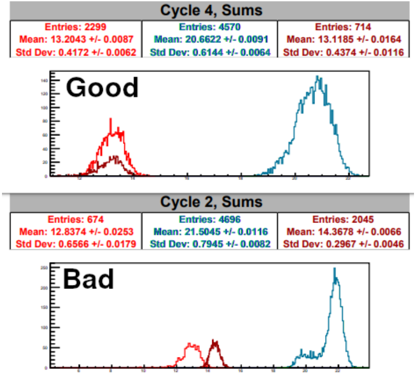


Some things to keep in mind:

- Errors shown here are purely statistical, no systematic corrections applied
- Rapid shifts in background largely responsible for outliers
- Data shown here is taken over ≈ 9.5 hours running

Diagnostics: Cycle Identification

Specific Example:



In all plots blue represents laser on and various shades of red represents laser off.

In this specific example, the bottom cycle is bad because the two laser off periods have different mean signals, indicating a background shift happened during the cycle.

In General:

- Benefit to using cycles: they individually act as system diagnostic
- Cycles become chronology of detector operations and health
- Outliers become clue to identify shifts in beam position, current instabilities, or other irregularities

Systematics: PMT Linearity

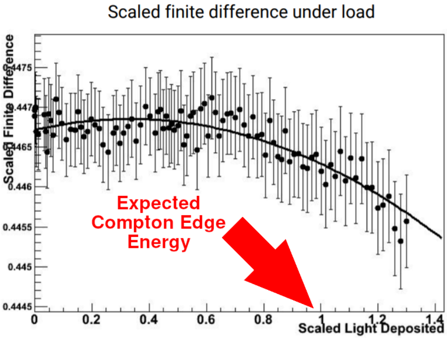
PMT and base in test stand at CMU

To measure non-linearity: flash two LEDs in rapid sequence, one at a variable brightness (var) and one at a fixed brightness (Δ)

Plot Yield(var+Δ)-Yield(var) vs Yield(var), perfectly linear PMT will produce slope of 0

Nonlinear systems will have a slope with polynomial parameters, which we fit to our scaled pulser data

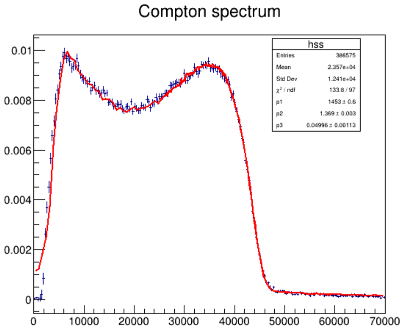
Images Credit: *J. Cornejo & B. Quinn (2019)*



Nonlinearity of this base/PMT combination is $\sim$0.1%. Difference taken between 0 and compton edge.

Systematics: Beam & Collimator Alignment

Image Credit: *A. Premithilake (2019)*



Photon spectrum plotted in blue, with MC fit in red.

The spectrum plotted in blue is actual data taken during PREX-II!

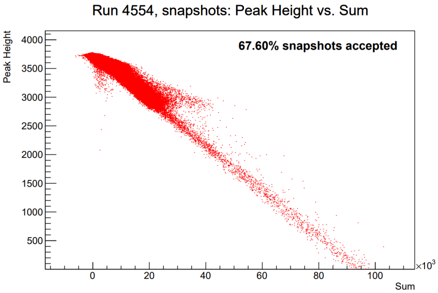
The MC fit here is taken from a simulation with a collimator 1.75 mm offset from beam. This corresponds to a $\approx 0.2\%$ change in our analyzing power.

Beam Alignment

- In addition to position monitors, we fit spectrum periodically throughout run
- Spectra were produced by simulation assuming various beam-collimator offsets
- Best fit helps identify likely collimator offset
- Once offset is matched to simulation then the simulation provides the analyzing power we use

Systematics: Pedestal Measurement

- All integrated sums calculated relative to electronics pedestal, which must be measured
- If sums are wrong then spectrum will have nonzero offset
- For asymmetry measurements:
  - To first order, pedestal handled by background subtraction
  - In event of beam instability, necessary to separate background and pedestal
- Take "snapshots" as diagnostic
- Snapshots record sum as well as pulse shape, which means pedestals can be checked

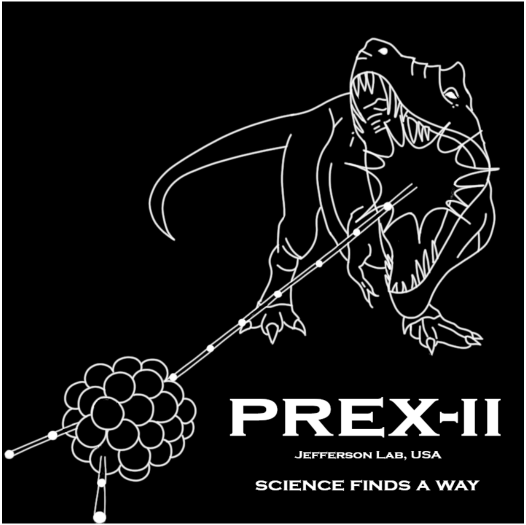


Plot of pulse peak height vs sum for partial selection of pulses. High correlation means fiding pedestal is possible.

Summary

- Compton polarimetry possible with polarized beam and polarized laser
- Photon Detector:
    - Comprised of scintillator-PMT combination
    - Reads out pulses, integrates energy on a helicity-window-basis
- High-Precision polarimetry done by calculating asymmetry across many short helicity state periods
- Goal: 1% precision polarization measurement for individual PREX-II run periods
    - Early results? Looking good! Statistics are in-line and system behaved as well as could be expected.
- Systematics:
    - PMT Nonlinearity actively being measured and applied to integrated energy calculations
    - Helicity-correlated backgrounds managed during run-time by optimizing beam optics
    - Detector alignment continuously measured and re-optimized during run period
- Systems to be run again for CREX run this December!

Questions, Comments, Criticisms, Observations?



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Backup Slides

Systematics: Compton Systematics

Systematic error sources for hall A compton polarimeter

	HAPPEX-III	2019 (Expected)*
Laser Polarization	0.8%	<0.1%
Signal Analyzing Power:		
Nonlinearity	0.3%	0.3%
Energy Uncert.	0.1%	0.1%
Collimator Pos.	0.05%	0.05%
Gain Shift:		
Background Uncert.	0.31%	0.31%
Pedestal	0.2%	0.2%
Total Systematics	**0.94%**	**0.49%**

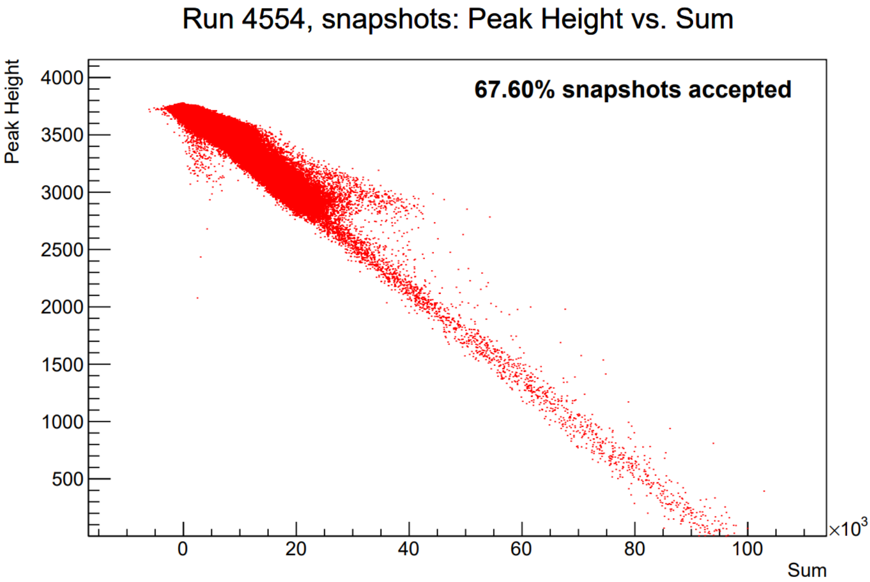
Source: *M. Friend, et al, NIM A676 (2012) 96-105*

*I presented this table on 2019-03-26, 2019 numbers have not yet been verified from our recent run period!

Systematics: CREX Improvements

- The primary difference between PREX-II and CREX is the run with a 2.2 GeV beam instead of a 0.95 GeV beam, and a Ca-48 target.
- Improvements to setup for CREX are mostly housekeeping
- Photon Detector:
  - PMT swap, and new linearity measurements
- DAQ:
  - DAQ timing to be changed to increase integration time
  - Better checks on background levels
- Electron Detector:
  - Wasn't used in PREX-II, will be revamped and used for CREX

Plots: Snapshots



Plots: PVES History