Precision Polarimetry at JLab, 6 GeV Era

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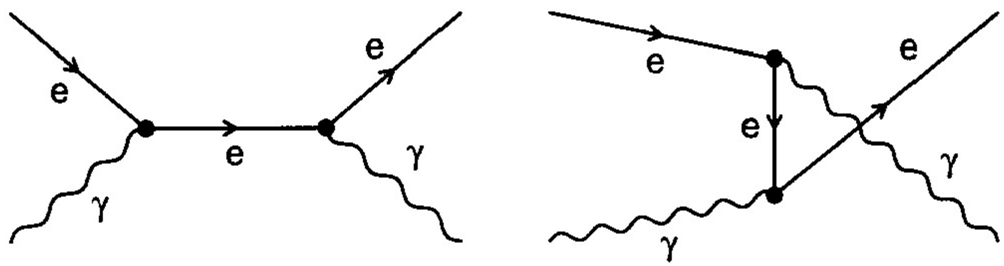
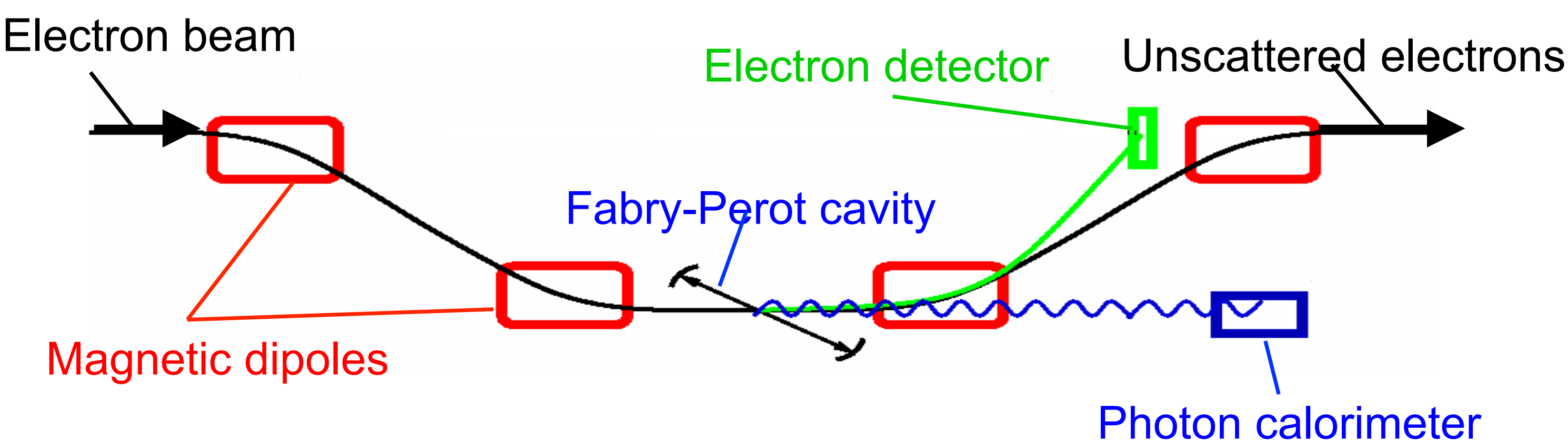
- Compton Scattering as a Polarimetry Tool
  - General Considerations
  - Complications and Systematic Errors
- JLab Hall A Compton Photon Calorimeter
  - GSO Performance (Simulations and benchmarks)
  - Integrating DAQ
- Polarimeter Performance Results

Compton Polarimetery

Electron beam passes through polarized photon beam
Spin-dependence of Compton scattering -> analyzing power



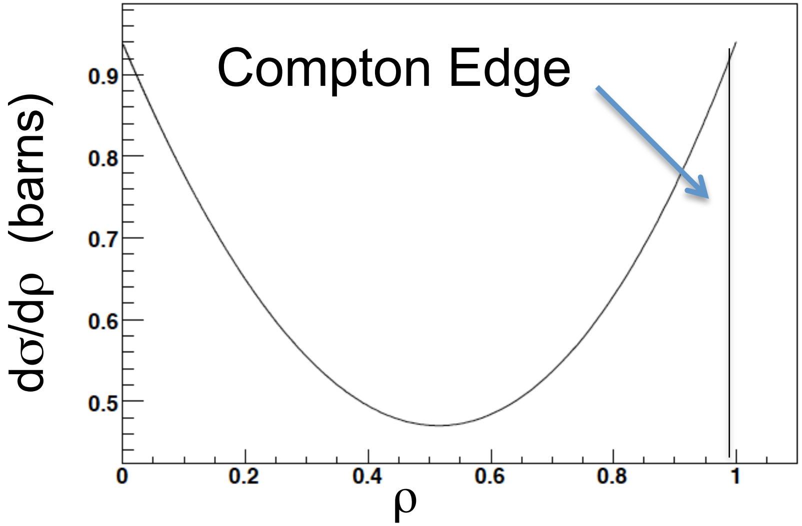


Unpolarized Cross Section

Very forward peaked (GeV electrons on eV photons)

Example:

Beam	E = 3.48 GeV
Cavity Photons	ω_0= 1.165 eV
Compton Edge	ω_{max}= 204 MeV



Max photon energy

$$\rho \equiv \omega/\omega_{max}$$

$$\omega_{max} = 4\frac{E^2\omega_0}{m_e^2c^4}a$$

$$a \equiv 1/(1 + \frac{4\omega_0 E}{m^2c^4})$$

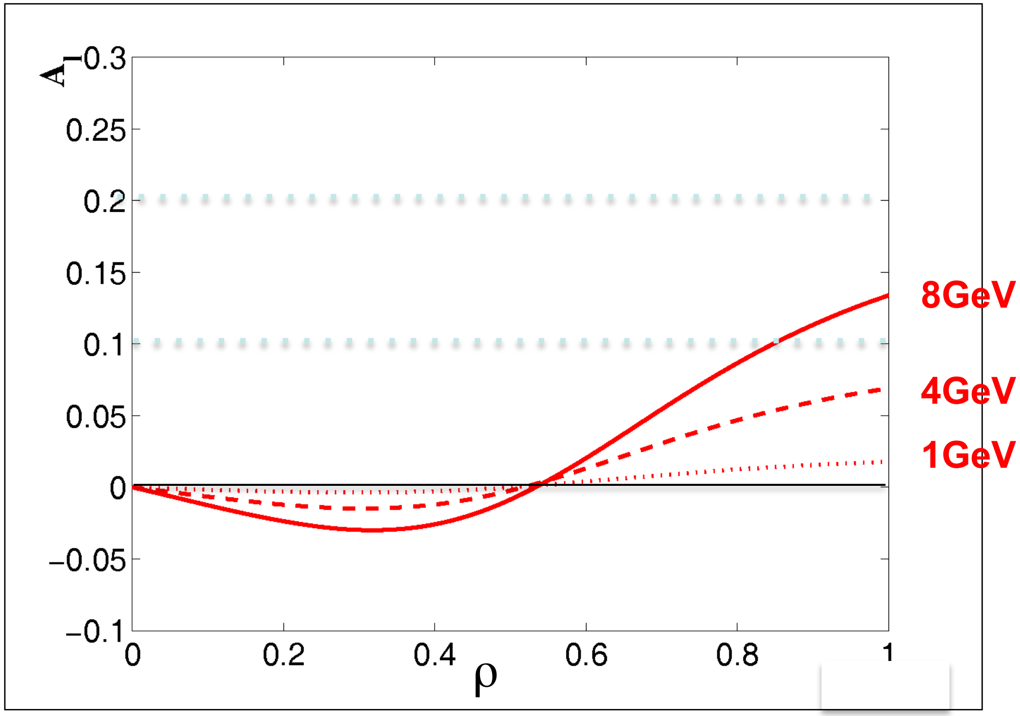
Klein-Nishina Formula

$$\left(\frac{d\sigma}{d\rho}\right)_{unpol} = 2\pi r_0^2 a \left[\frac{\rho^2(1-a)^2}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)}\right)^2\right]$$

Compton Analyzing Power

$$A_l(\rho) \equiv \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} = \frac{2\pi r_0^2}{d\sigma/d\rho} a(1-\rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^2}\right]$$

- Peak analyzing power 1% to 20%
- Strong dependence on scattered photon energy



λ=1064nm, ω_0=1.165 eV

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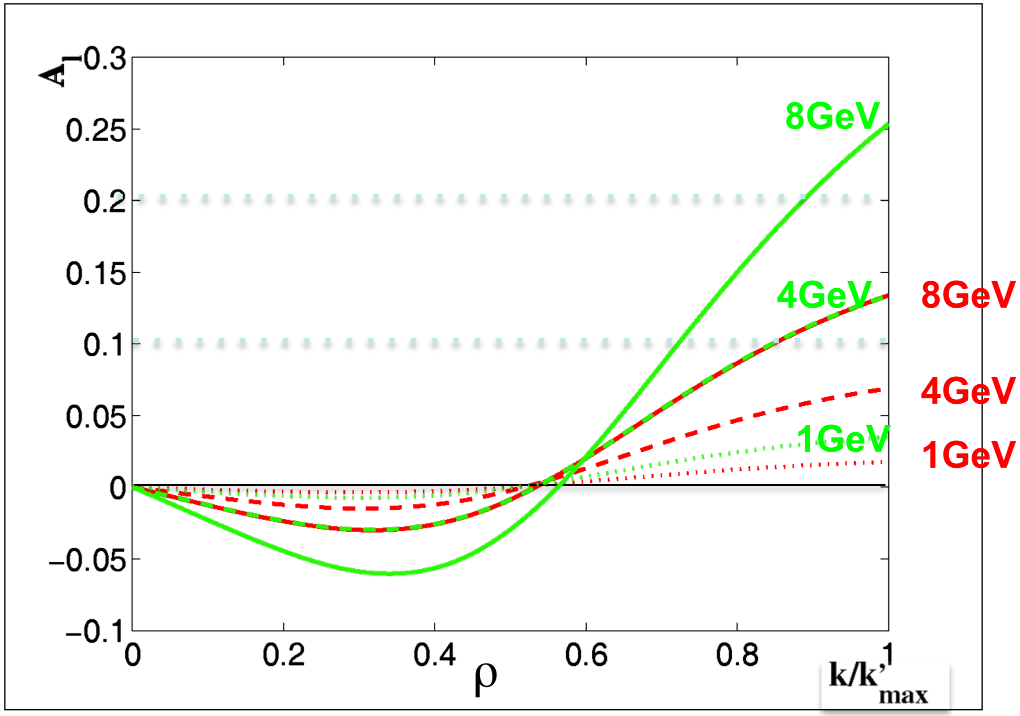


λ=1064nm, ω_0=1.165 eV

λ=532nm, ω_0=2.330 eV

Doubling laser -> energy doubles analyzing power

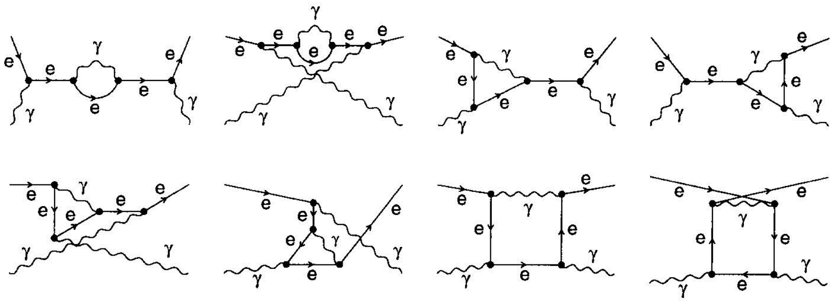
Negligible theoretical error

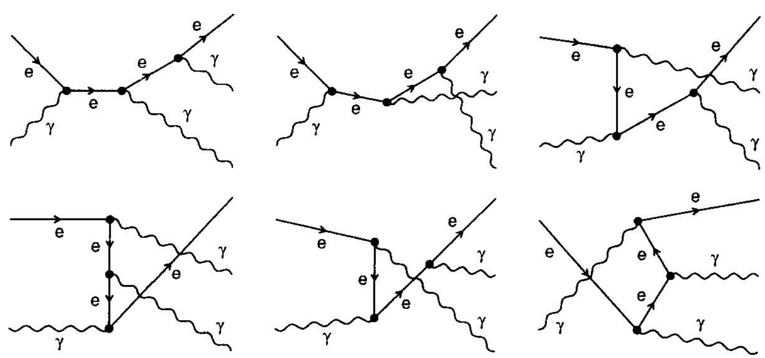
Higher order diagrams

Denner & Dittmaier Nucl. Phys. B540 (1999)

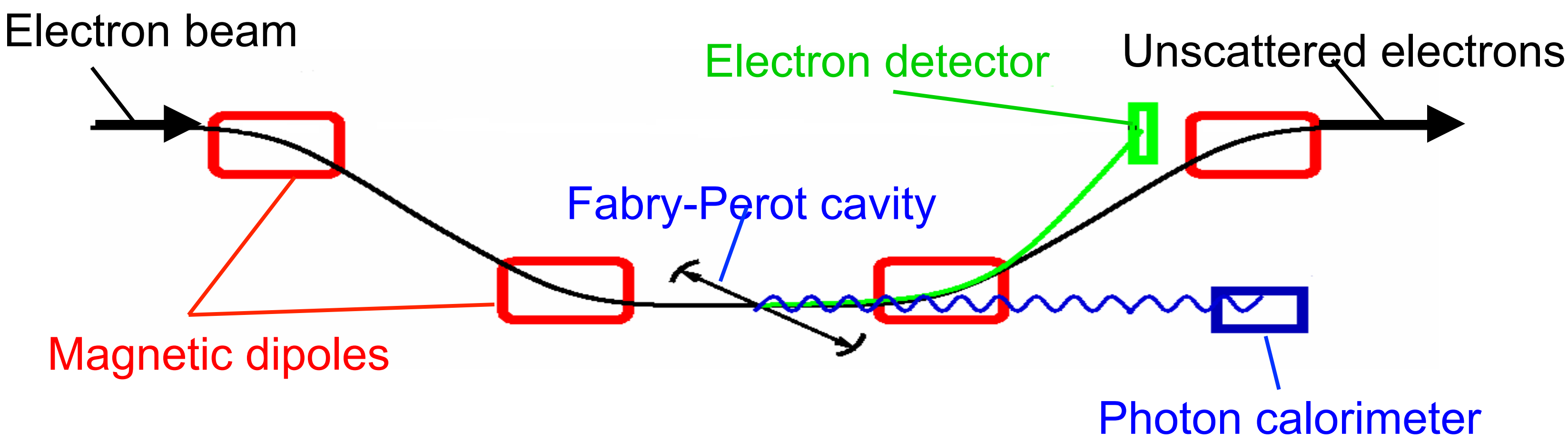
~0.3% correction to A_l at 3.5 GeV beam energy

Increases with energy





Experimental Challenges

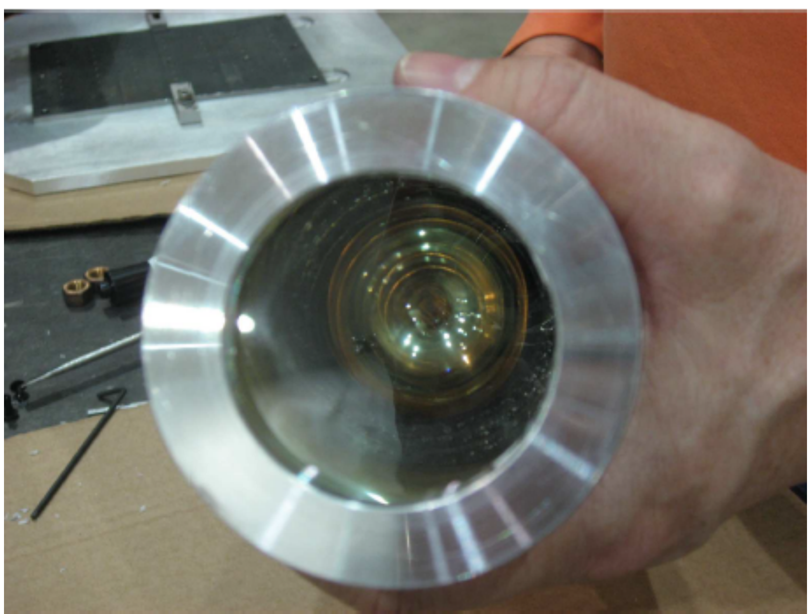


- Thresholds and non-linearities a problem
  (Strong energy dependence of A_l)
- Large dynamic range of photon energies
  (Compton edge varies from ~20 MeV to ~500 MeV)
- Electrons or photons can be detected
  - Scattered electrons near beam halo at low beam energies
  - Photon detection requires knowledge of resolution function

Hall A Compton Photon Calorimeter

- Single GSO crystal manufactured by Hitachi Chemical
  - 0.5% Ce-doped Gd_2SiO_5
  - 6 cm diam x 15 cm length

- Flash ADC integrates Compton signal
  - Customized Struck SIS3320 FADC
  - No threshold, Dead-timeless
  - 1 Primary Data word for each 1/30 sec helicity period
  - Auxiliary monitoring info



- Crystal Properties

	GSO	PbWO4	BGO	CeF_3	BriLanCe 380	PreLude 420
Density (g/cm^3)	6.70	8.30	7.13	6.16	5.29	7.1
Rad Length (cm)	1.39	0.90	1.12	1.68	~1.9	1.2
Moliere Radius (cm)	2.4	2.0	2.3	2.6	?	?
Decay time (ns)	~80	50	300	30	16	41
Light output (% NaI)	45%	0.4%	9%	6.6%	165%	84%
photoelectrons (# / MeV)	850	8	170	125	3150	1600

Energy Weighted Asymmetry:

$$E^{\pm} = LT\int_0^{E_{\max}} \varepsilon(E)E\frac{d\sigma}{dE}(E)\left(1 \pm P_e P_\gamma A_l(E)\right)dE$$

$$A_{Exp} = \frac{E^+ - E^-}{E^+ + E^-}$$

Longitudinal Compton Asymmetry

Actual Asymmetry Weighted by Detector Signal

$$S^{\pm} = LT\int_0^{E_{\max}} s(E)\frac{d\sigma}{dE}(E)\left(1 \pm P_e P_\gamma A_l(E)\right)dE$$

Average detector signal for photon energy *E*

$$A_{Exp} = \frac{S^+ - S^-}{S^+ + S^-} = P_e P_\gamma \frac{\gamma\int_0^{E_{\max}} A_l(E)s(E)\frac{d\sigma}{dE}(E)dE}{\int_0^{E_{\max}} s(E)\frac{d\sigma}{dE}(E)dE} = P_e P_\gamma A_{lS}$$

Energy Weighted Asymmetry:

$$E^{\pm} = LT\int_0^{E_{max}} \varepsilon(E)E\frac{d\sigma}{dE}(E)\ \ldots$$

$$A_{Exp} = \frac{E^+ - E^-}{E^+ + E^-}$$

average response function required

Actual Asymmetry Weighted by Dete…

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Statistical Considerations

$$P_e = \frac{1}{P_\gamma}\frac{1}{A_{ls}}A_{exp}$$

Goal: 0.01

Photon polarization ~1

Analyzing Power ~1/.02 (worst case)

Error on Integrated Signal Need <.0002

$$\sigma_{P_e} = \frac{1}{P_\gamma}\frac{1}{A_{ls}}\frac{\sigma_s}{s}$$

Energy Weighted Statistics

$$\left[\frac{\sigma_s}{s}\right]^2 = \frac{\int_0^{E_m} dE E^2 \, dN/dE}{\left[\int_0^{E_m} dE E \, dN/dE\right]^2} = \frac{\int_0^{1_m} d\rho \rho^2 \, dN/d\rho}{\left[\int_0^{1_m} d\rho \rho \, dN/d\rho\right]^2}$$

$$\frac{\sigma_s}{s} = 1.2\frac{1}{\sqrt{N}}$$

(Using Compton shape for dN/dρ)

100 kHz counting rate ➔ Statistical accuracy in a few hours

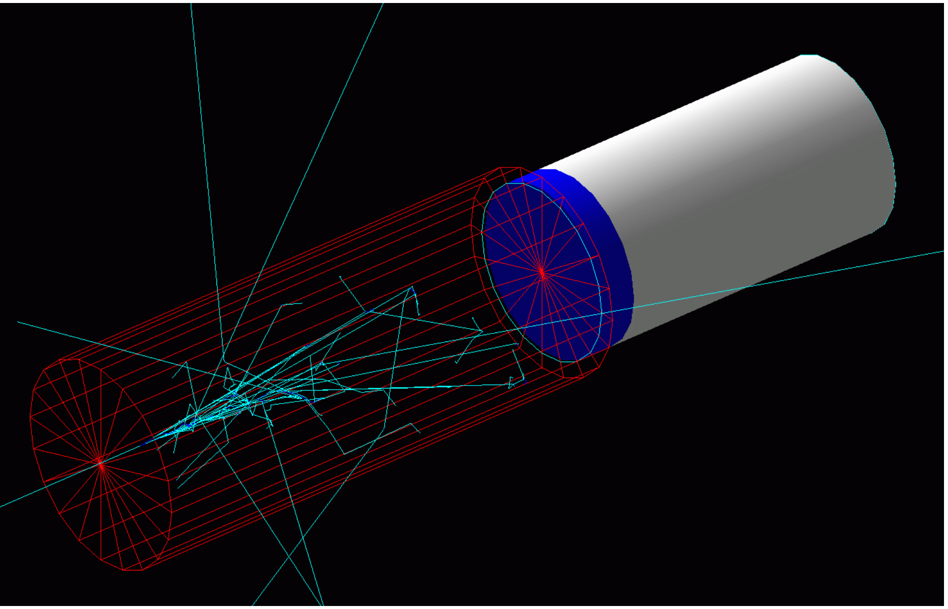
Systematic Considerations Dominate

$$S^{\pm} = LT\int_0^{E_{\max}} s(E)\frac{d\sigma}{dE}(E)\left(1 \pm P_e P_\gamma A_l(E)\right)dE$$

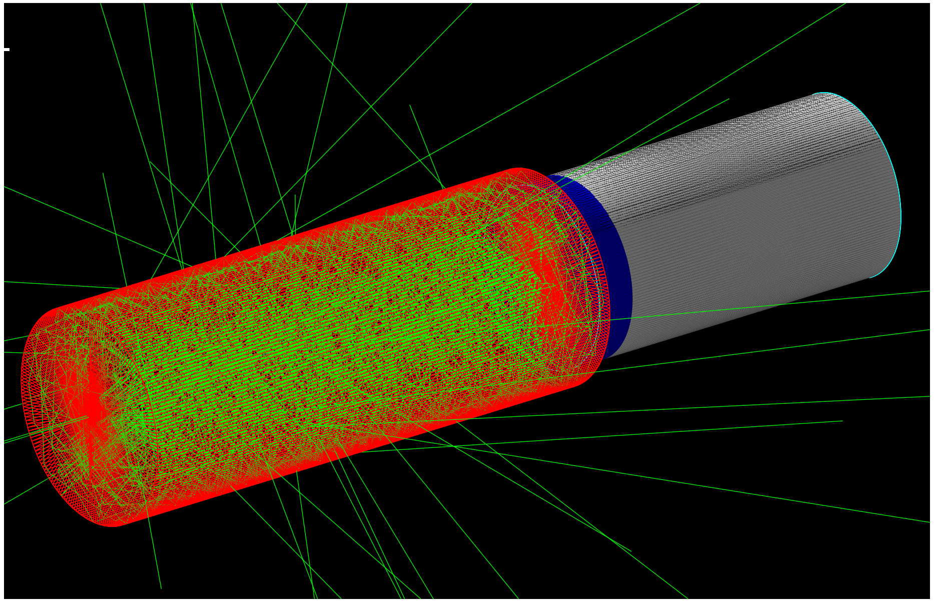
Function of detector and electronics response

Detector Response: GEANT4 Simulations Performed

Vahe Mamyan & Megan Friend



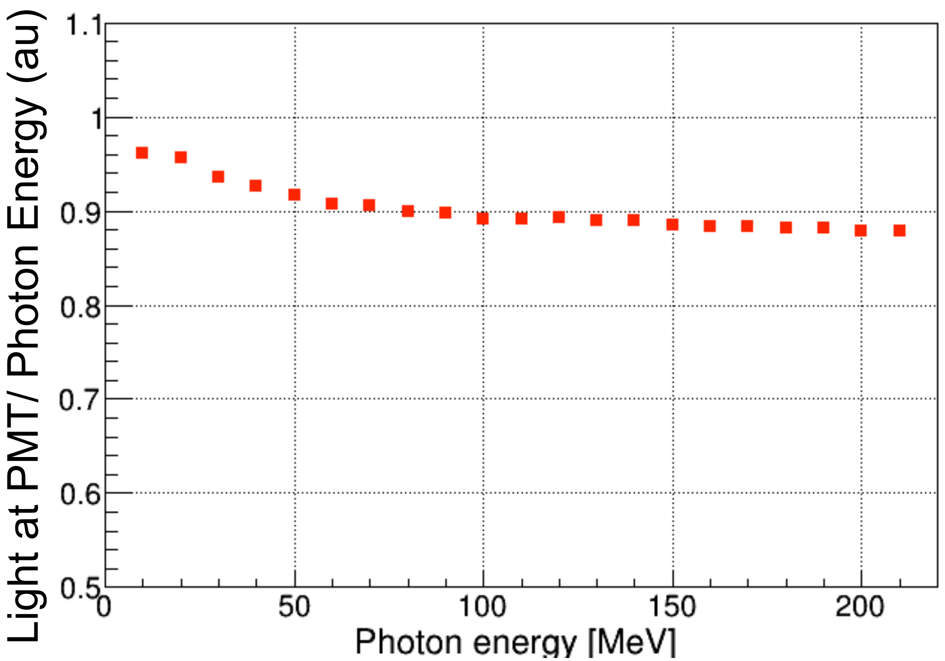
Shower Generation
200 MeV Photon Event



Optical Photon Tracking
30 MeV Photon Event

GEANT produces GSO average response, *s(E)*

$$A_{lS} =_{\gamma} \frac{\int_0^{E_{\max}} A_l(E) s(E) \frac{d\sigma}{dE}(E)\, dE}{\int_0^{E_{\max}} s(E) \frac{d\sigma}{dE}(E)\, dE}$$



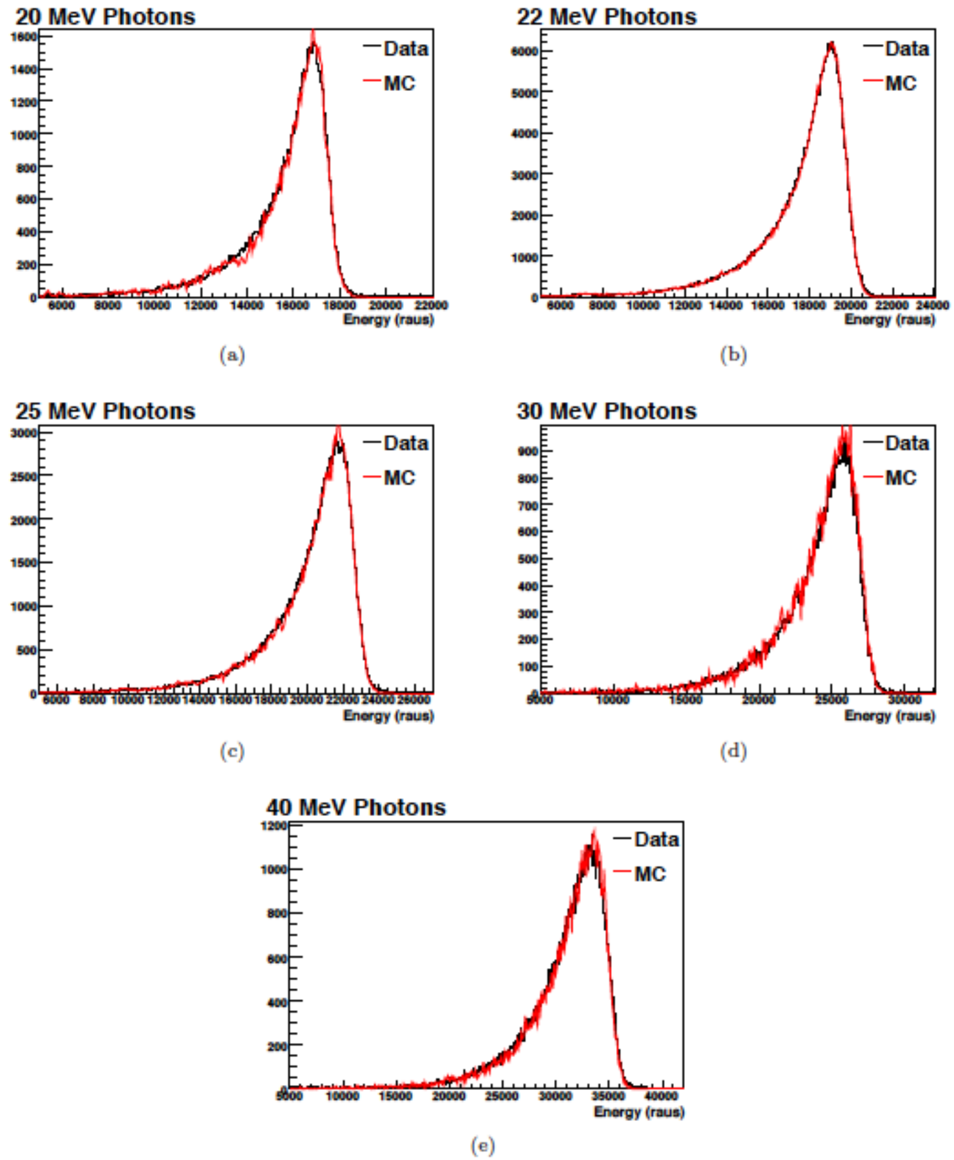
Verification of Detector Response Simulations

Tests at Duke's HIGS facility

"Monoenergetic" photons

20, 22, 25, 30, & 40 MeV

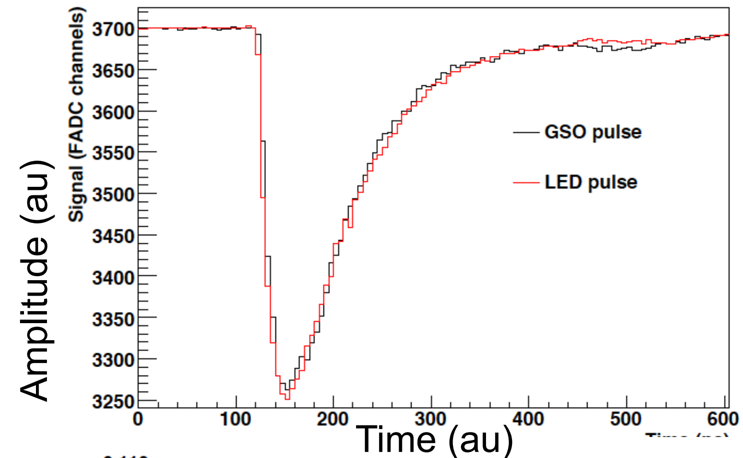
See D. Parno et. al.
NIM A (2013) DOI 10.1016

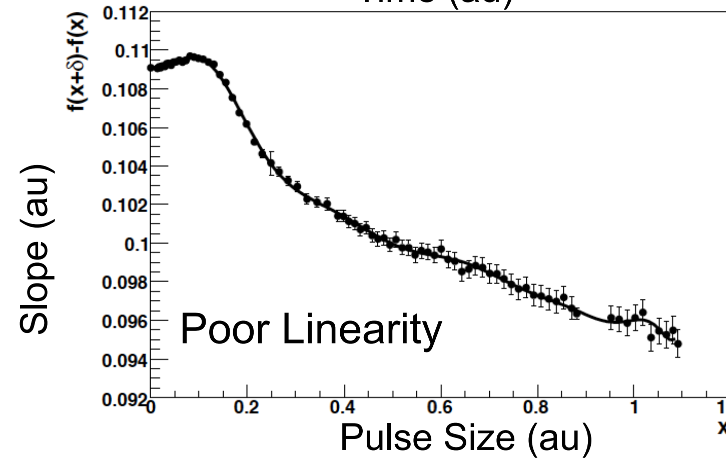


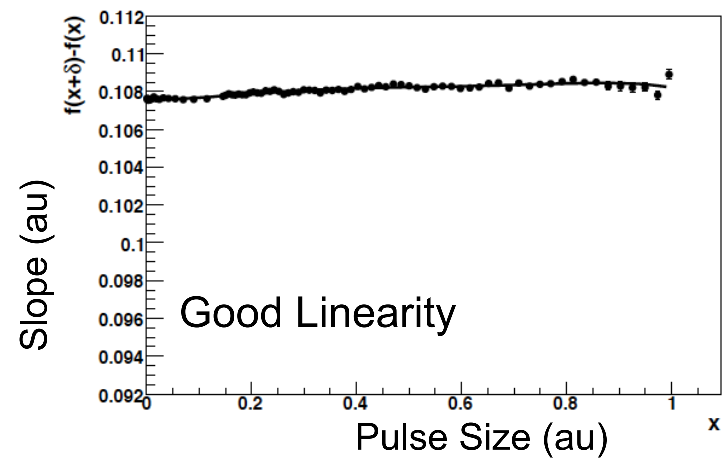
Systematic Considerations

PMT Linearity

Mapped with 2-LED Pulser System
- Simulated GSO pulse
- Measures PMT/Base linearity
- Monitors gain shifts







Systematic Considerations

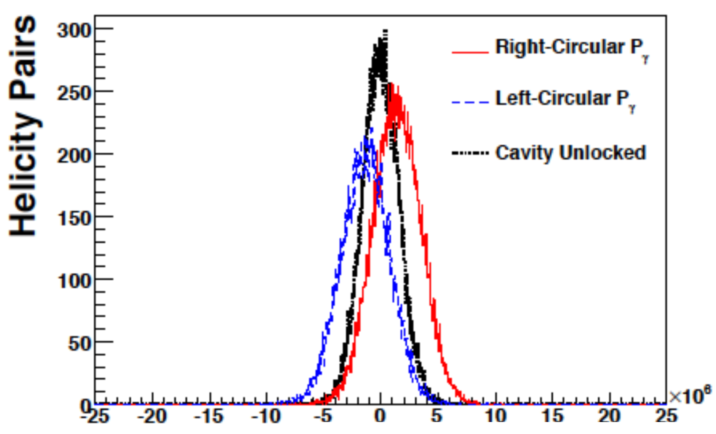
Time-Dependent Systematics & Background

Electron Beam Helicity Flipped at ~30 Hz (pseudo-random)
Fabry-Perot Cavity Laser Cycle:

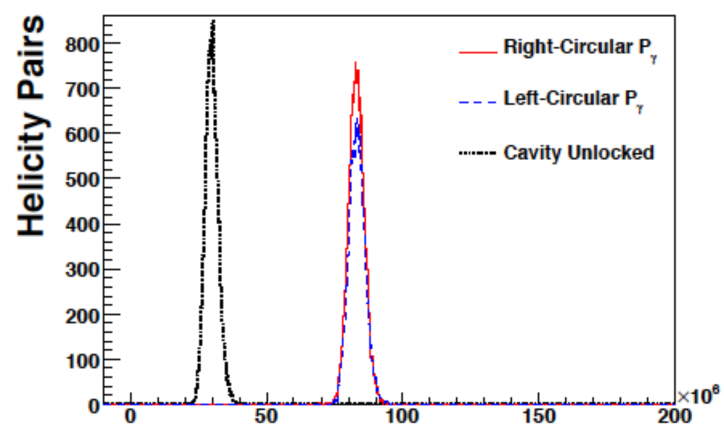
- 60 sec Locked on Right Circular Polarization
- 30 sec Unlocked (used for background subtraction)
- 60 sec Locked on Left Circular Polarization
- 30 sec Unlocked

Significant background

- Synchrotron Radiation and Beam-Halo Bremsstrahlung
- Synchrotron Radiation ~ E^4… potential problem for 12 GeV running



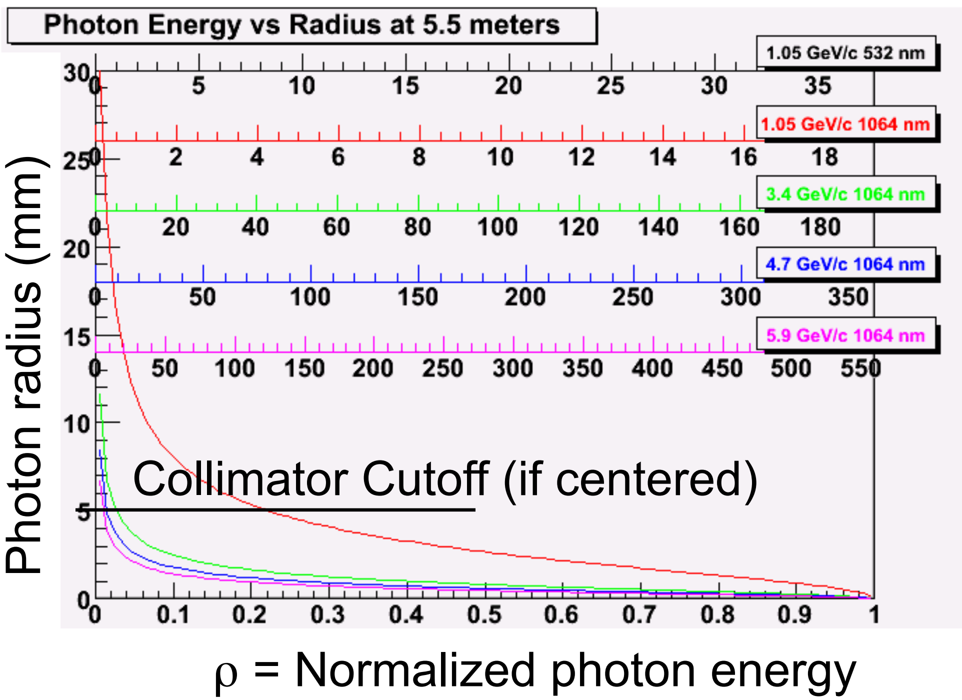
$S^+ - S^-$

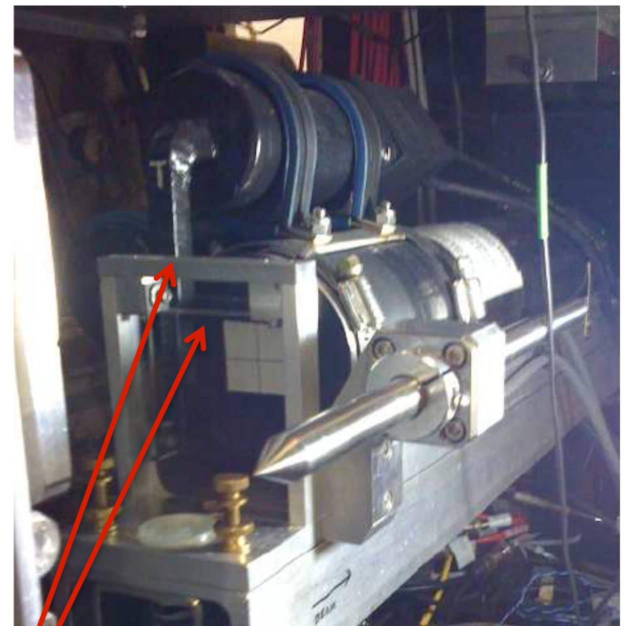


$S^+ + S^-$

Systematic Considerations

Geometry and Alignment





If misaligned, collimators can distort energy spectrum at low end

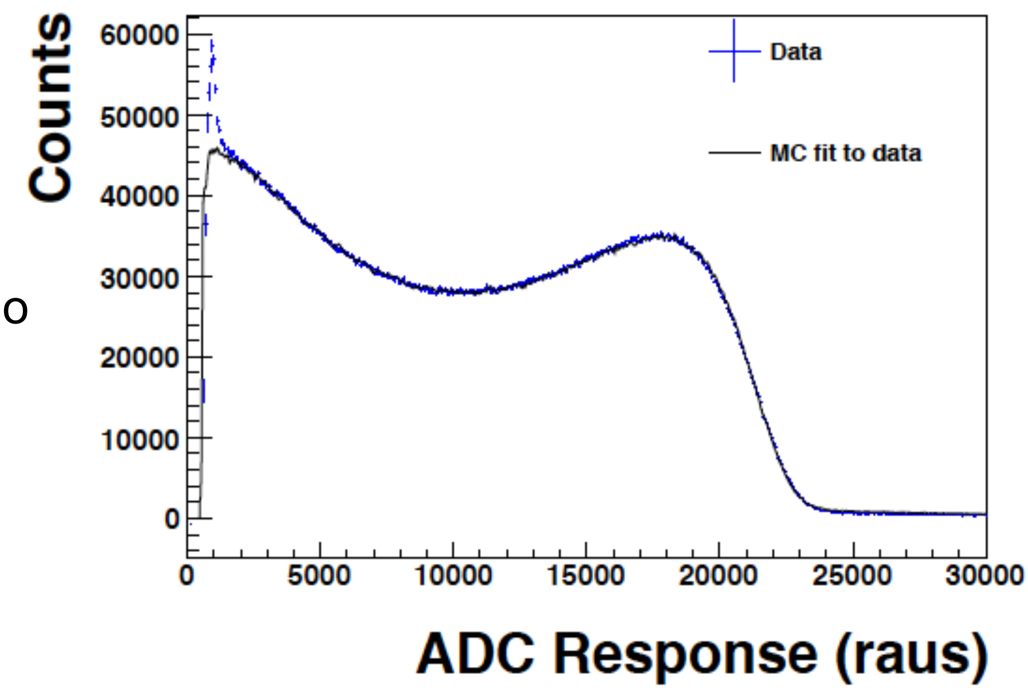
1mm tungsten radiators/ scintillators
Used for horizontal and vertical scans

Systematic Considerations

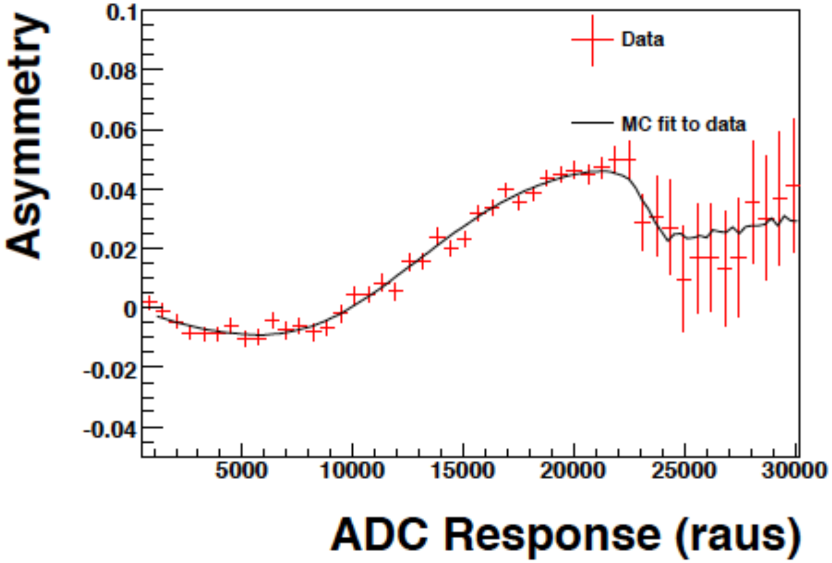
Verification

For each helicity period, FADC Data-stream includes:
- Signal Sum (Main analysis)
- Prescaled Integrated Triggered GSO Pulses
- Random Sampled FADC sample periods

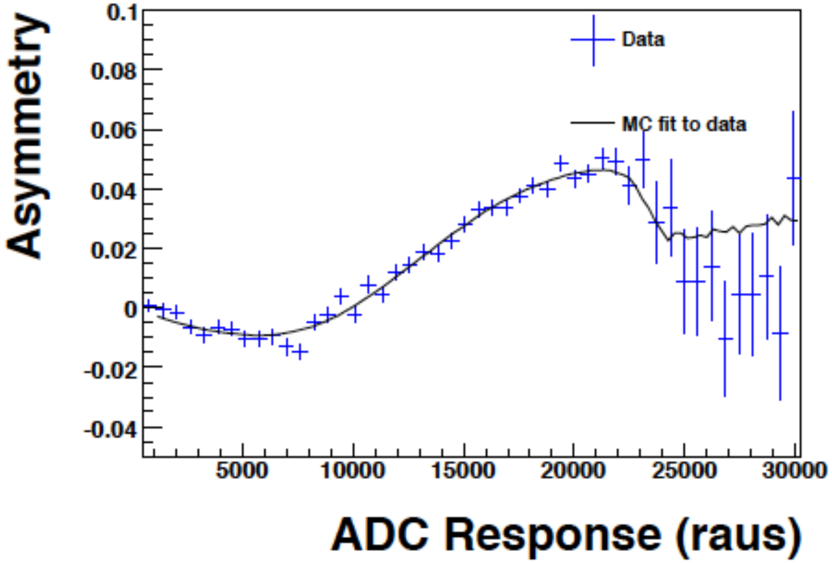
Triggered Compton GSO data
- Data compared to Monte Carlo



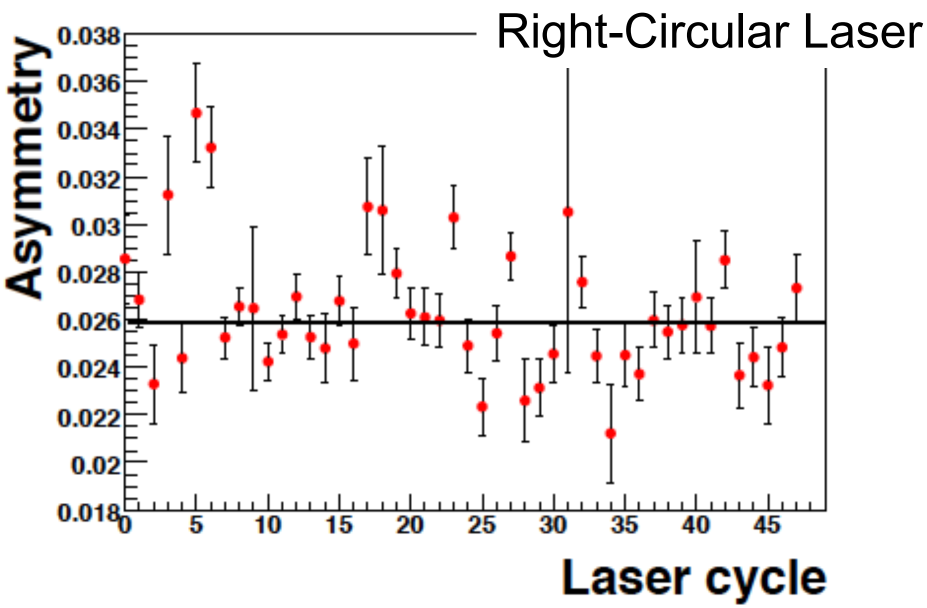
Prescaled triggered data can be used to measure polarization



(a)



(b)



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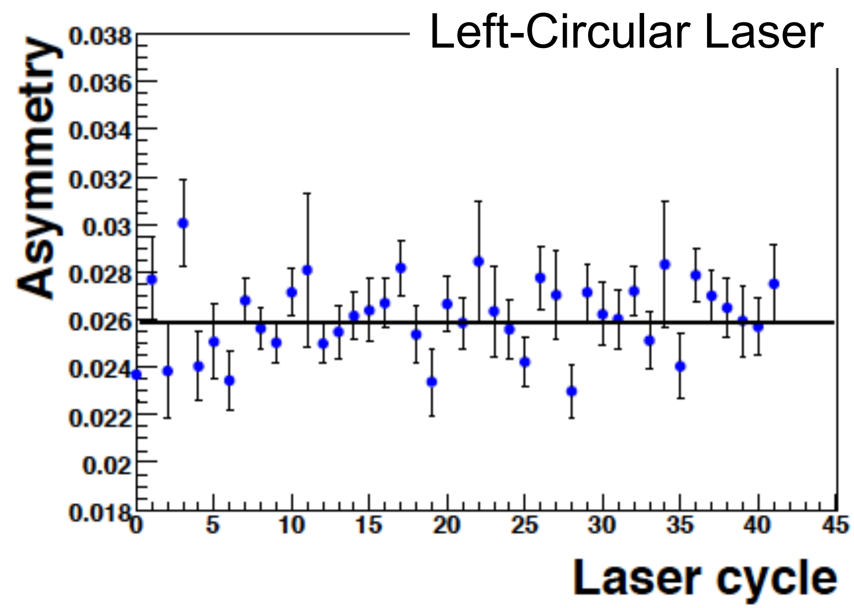

(b)

Figure 4.25: A typical Compton slug for (a) laser-right and (b) laser-left, where the asymmetry is positive after being scaled as in Eq. 4.58. Each data point is a separate laser-cycle including local background subtraction. Error bars are statistical as defined in Sec. 4.5.3.1, and the solid line is a constant fit to the data. Plots of all of the Compton slugs, as well as a table of the measured asymmetry and statistical error for each slug, are given in Appendix A.

Ph.D. Thesis of M. Friend

From: M. Friend et al., Upgraded photon calorimeter…

Systematic Errors	
Laser Polarization	0.80%
Signal Analyzing Power:	
Nonlinearity	0.30%
Energy Uncertainty	0.10%
Collimator Position	0.05%
Analyzing Power Total Uncertainty	0.33%
Gain Shift:	
Background Uncertainty	0.31%
Pedestal on Gain Shift	0.20%
Gain Shift Total Uncertainty	0.37%
Total Uncertainty	0.94%

Conclusion

- Accuracy of 1% has been achieved
- Significant improvements possible
  - Improved determination of photon polarization
  - Reduction in Synchrotron Radiation
    (Particularly for high electron beam energy)
  - Careful monitoring of gain shifts
    (Cavity on vs. Cavity off)

Example Compton Edge and Analyzing Powers

	ω_0 = 1.165 eV (IR)			ω_0 = 2.33 eV (green)		
E_e (MeV)	a	ω_{max} (MeV)	A_{max}	a	ω_{max} (MeV)	A_{max}
1,375	.976	33	.024	.953	64	.048
2,750	.953	129	.047	.911	246	.093
5,500	.911	492	.093	.836	903	.177
11,000	.817	1,806	.177	.718	3,101	.320