Hall A Compton Polarimeter at 11GeV

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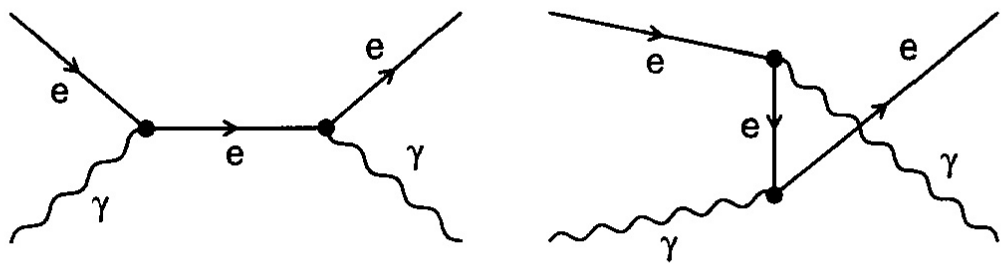
1. Compton Scattering Polarimetry
    - General Considerations
    - Complications and Systematic Errors
2. JLab Hall A Compton Photon Calorimeter
    - GSO Performance (Simulations and benchmarks)
    - Integrating DAQ
3. Systematic Considerations
4. Preparing for 11 GeV

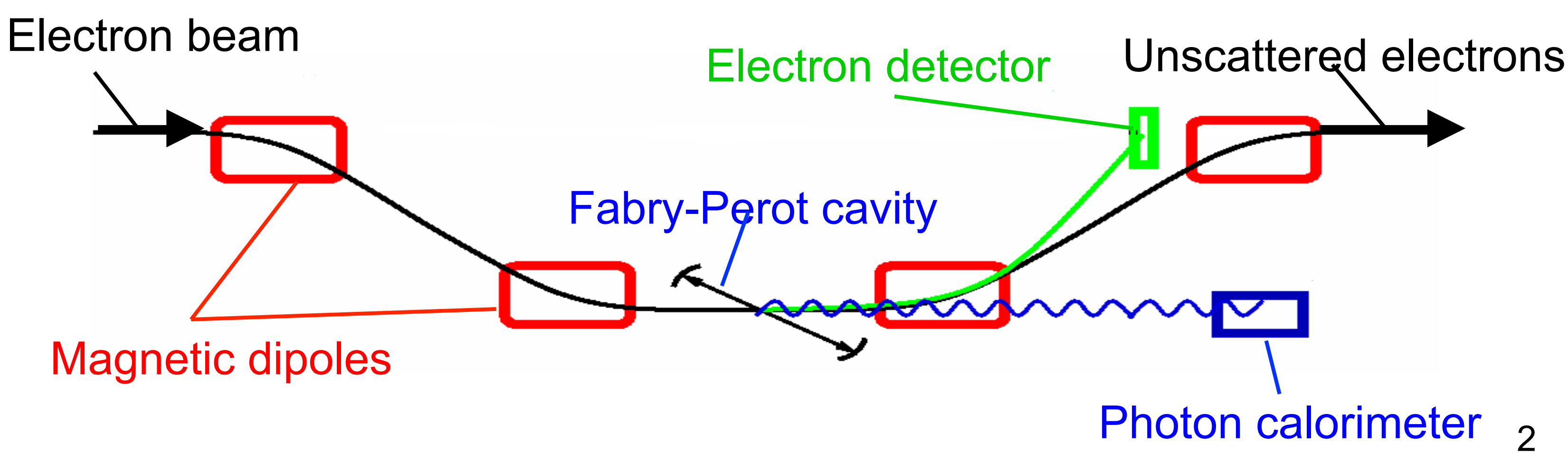
Hall A Compton 6 GeV Upgrade Team: M. Friend, D. Parno, F. Benmokhtar, A. Camsonne, G.B. Franklin, R. Michaels, S. Nanda, K. Paschke, B. Quinn, P. Souder

Hall A Compton 11 GeV Team: J. Benesch, A. Camsonne, D. Dutta, J.C. Cornejo, G.B. Franklin, C. Gai, D. Gaskill, J. Hoskins, A. Johnson, J. Mammel, R. Michaels, K. Paschke, B. Quinn, M. Shabastari, R. Spies, A. Sun, L. Thorne…

1. Compton Scattering Polarimetery

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



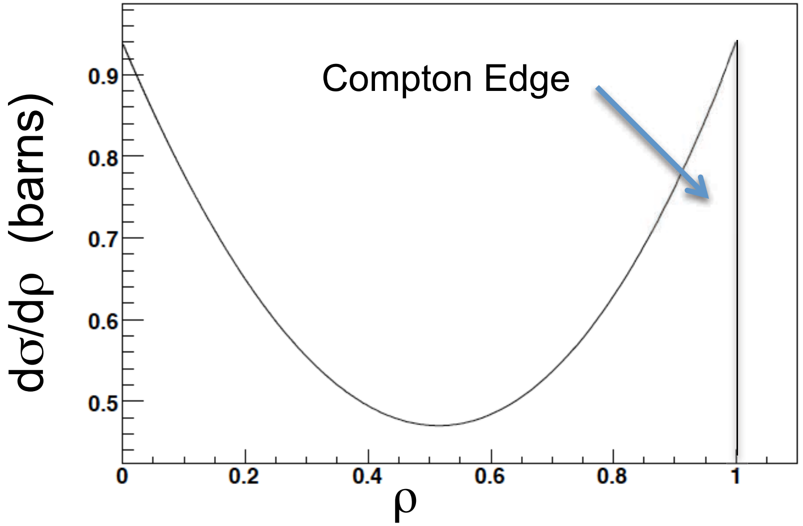


Unpolarized Cross Section

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

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

Note E^2 term

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

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

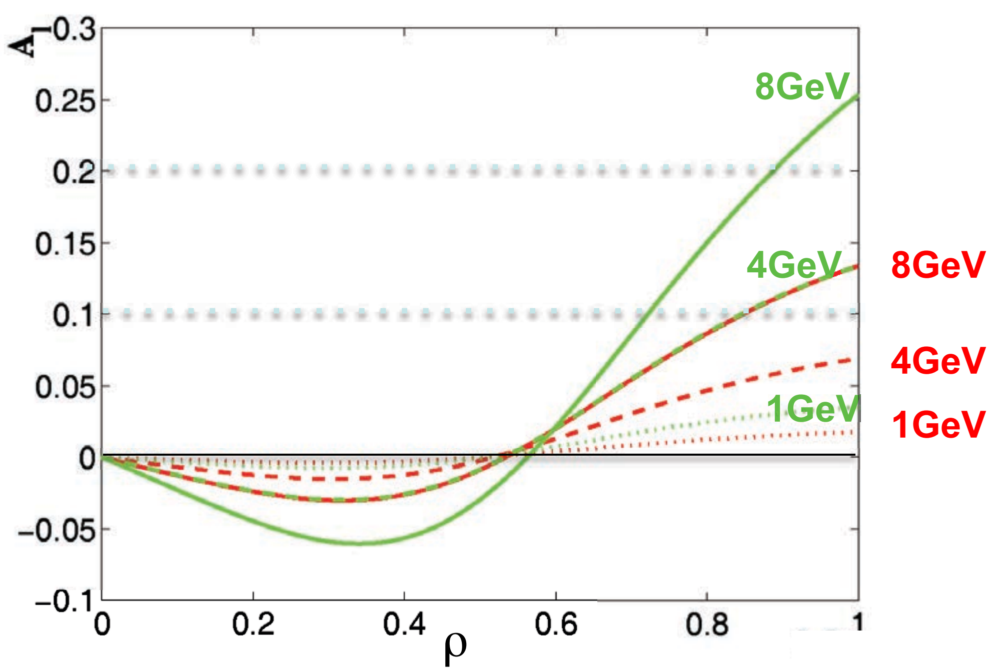
Klein-Nishina Formula

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

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 35%
- Strong dependence on scattered photon energy

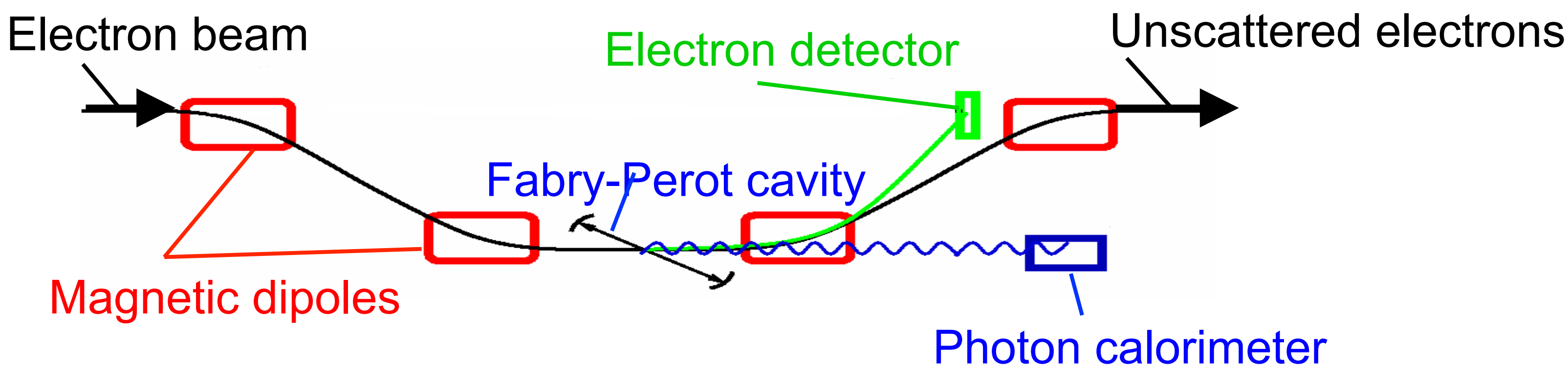


λ=1064nm, ω_0=1.165 eV

λ=532nm, ω_0=2.330 eV

Increases ~linearly with beam energy and photon energy.

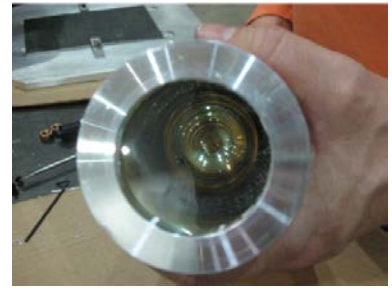
2. JLab Hall A Compton Polarimeter



- Experimental Challenges
  - Thresholds and non-linearities a problem
    (Strong energy dependence of A_l)
  - Large dynamic range of photon energies
    (Compton edge prop E^2, varies from ~20 MeV to ~3100 MeV)

- Measure electron and/or photon asymmetries
  - Scattered electrons detected in microstrip
  - Three possible photon asymmetries measurements
    1. Energy-dependent asymmetry (Record individual events)
    2. Integrate entire PMT signal (FADC Accumulator 0)
    3. Integrate signal above a threshold (FADC Accumulator 2)

Hall A Compton Photon Calorimeter



- Few GeV Running
  Single GSO crystal (Hitachi Chemical)
  0.5% Ce-doped Gd_2SiO_5
  6 cm diameter x 15 cm length

- Preparation Higher Energy Running
  4-element PbWO4 array
  6 cm x 6 cm x 20 cm

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

3) Systematic Considerations

Energy Weighted Asymmetry Avoids Thresholds

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

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

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 Avoids Thresholds

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

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

average response function required

Actual Asymmetry Weighted by Detecto…

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

Average detector signal for photon energy *E*

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

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 $dN/d\rho$)

100 kHz counting rate ➔ Statistical accuracy in a few hours

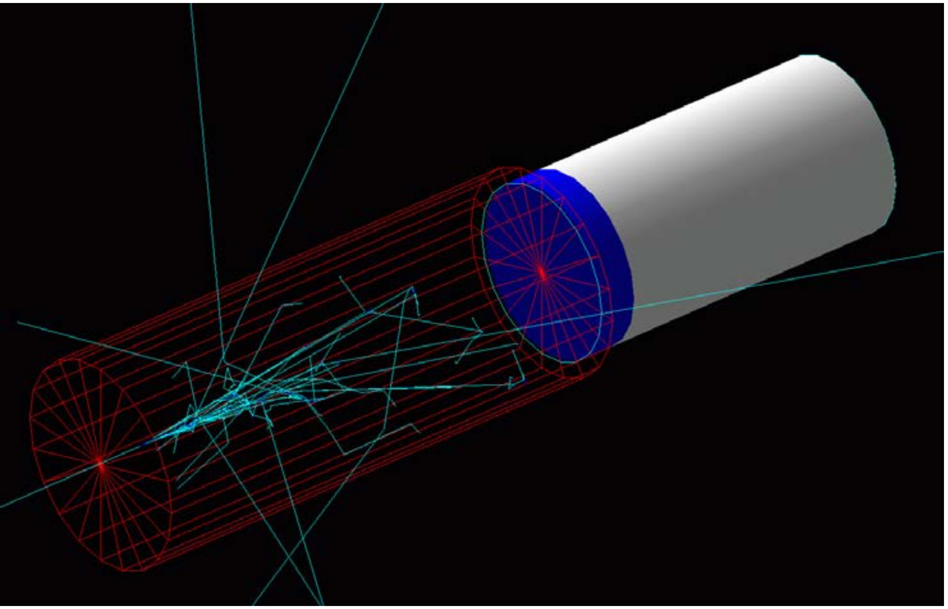
Systematic Considerations Dominate

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

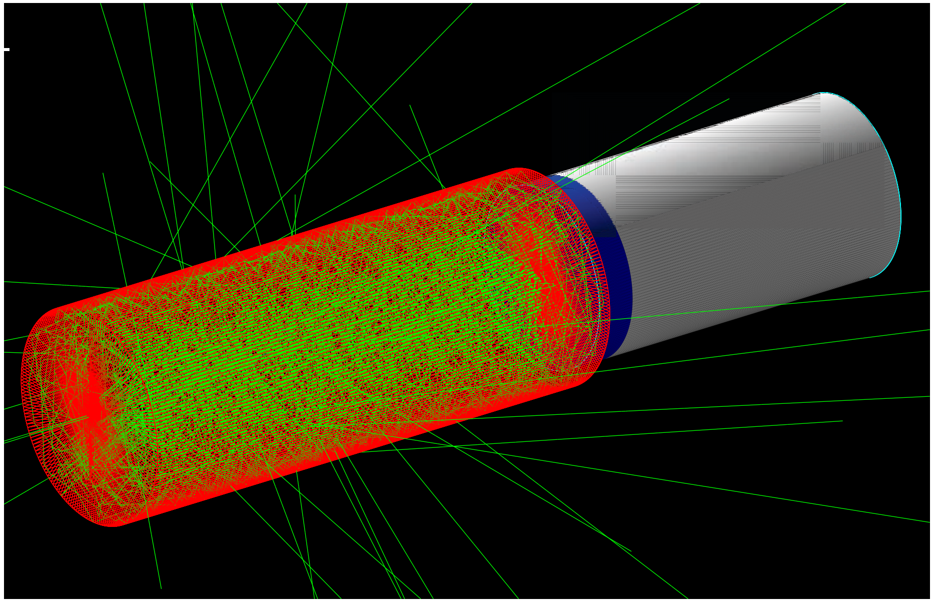
Function of detector and electronics response

Detector Response: GEANT4 Simulations Performed

Vahe Mamyan & Megan Friend



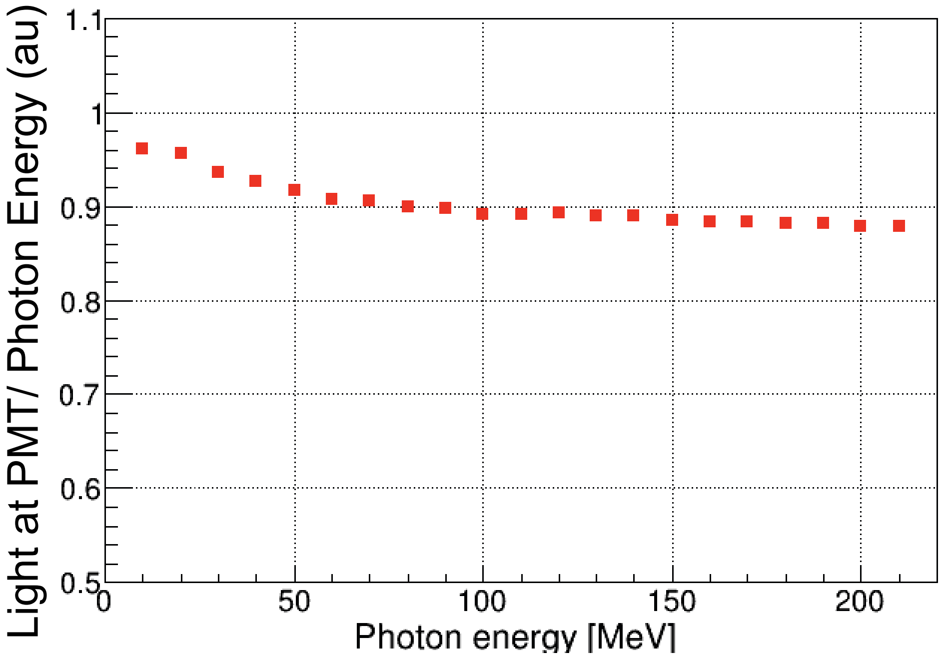
Shower Generation
200 MeV Photon Event



Optical Photon Tracking
30 MeV Photon Event

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

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



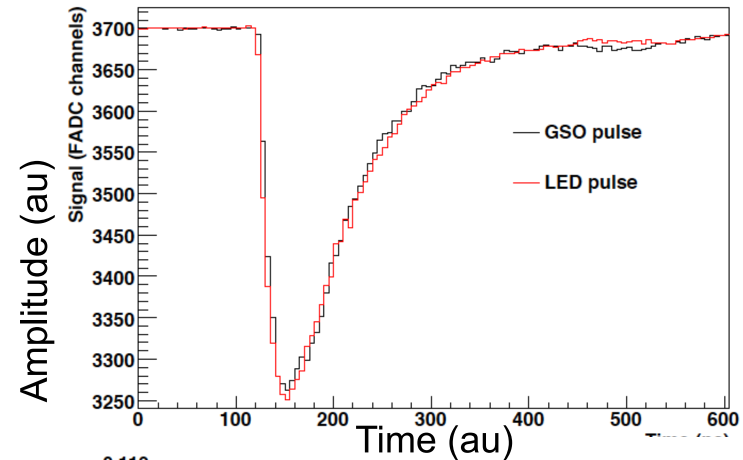
Systematic Considerations

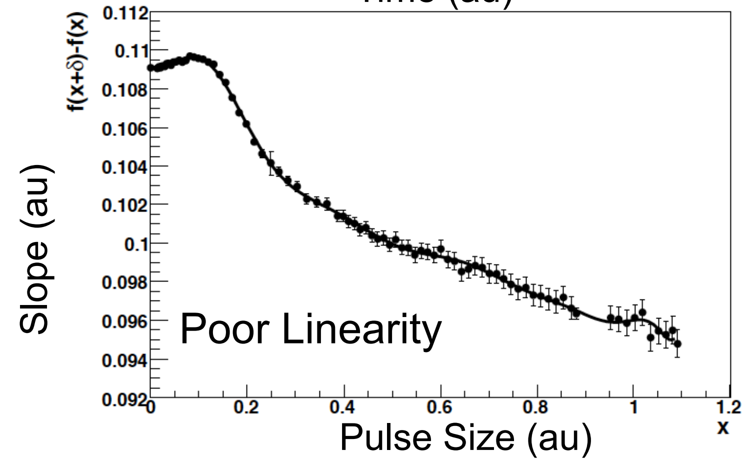
PMT Linearity

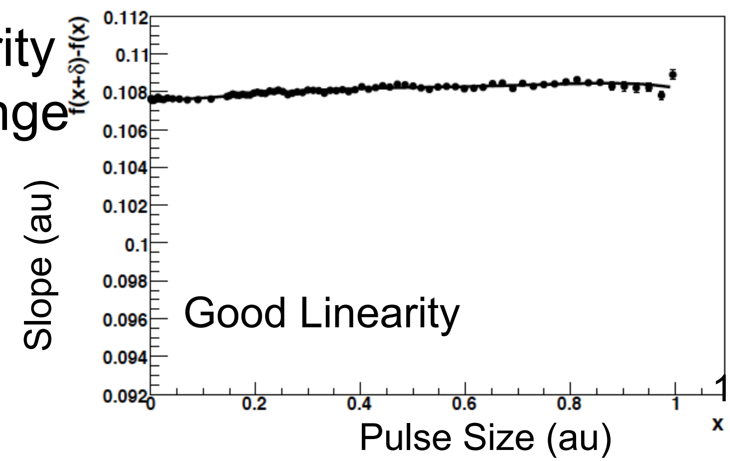
Mapped with "Mini-Megan"
- 2-LED Pulser System
- Simulated GSO pulse
- Measures PMT/Base linearity
- Monitors gain shifts

PMT base is designed to maximize linearity
- Tuned for actual PMT and photon range

Remaining non-linearity folded into
Monte Carlo







Analysis of prescaled scattering event triggers

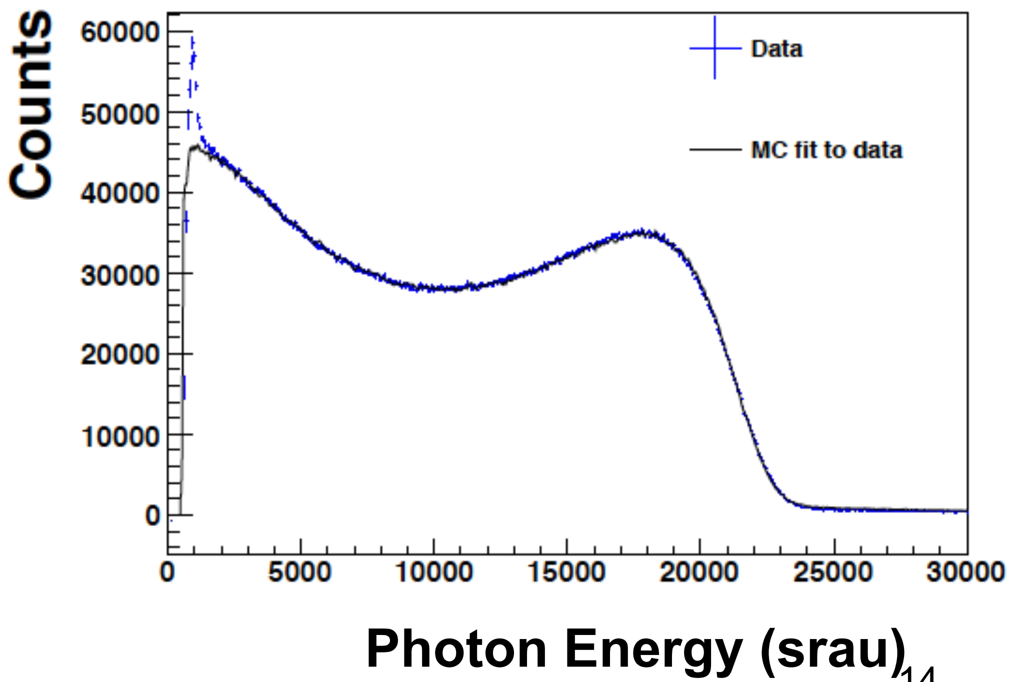
Verifies model of calorimeter response

For each helicity period, FADC Data-stream includes:

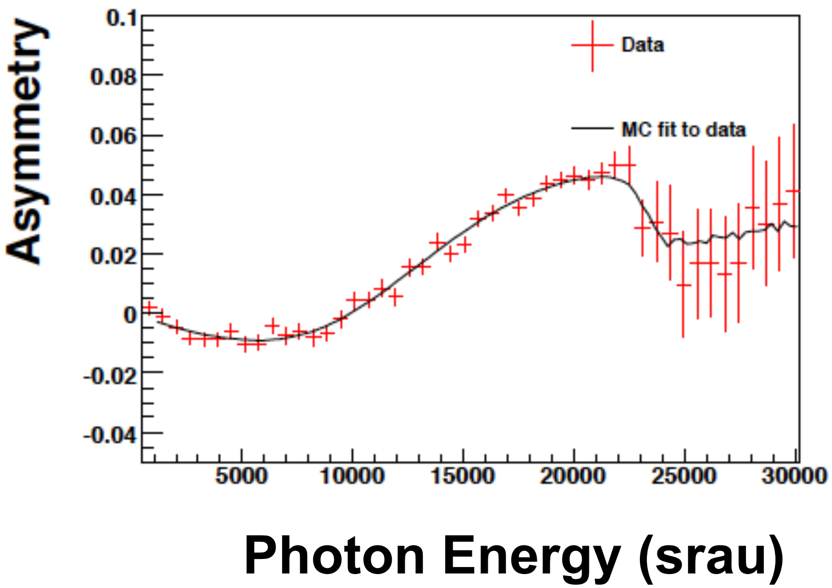
- Signal Sum (Main analysis)
- Prescaled Integrated Triggered GSO Pulses
- Random Sampled FADC Sample Periods

Triggered Compton GSO data

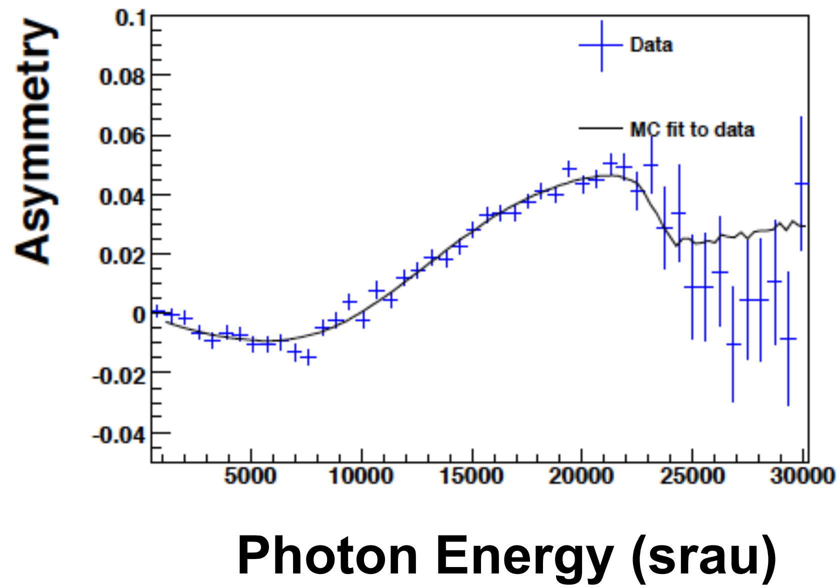
- Data compared to Monte Carlo



Prescaled triggered data can be used to measure polarization



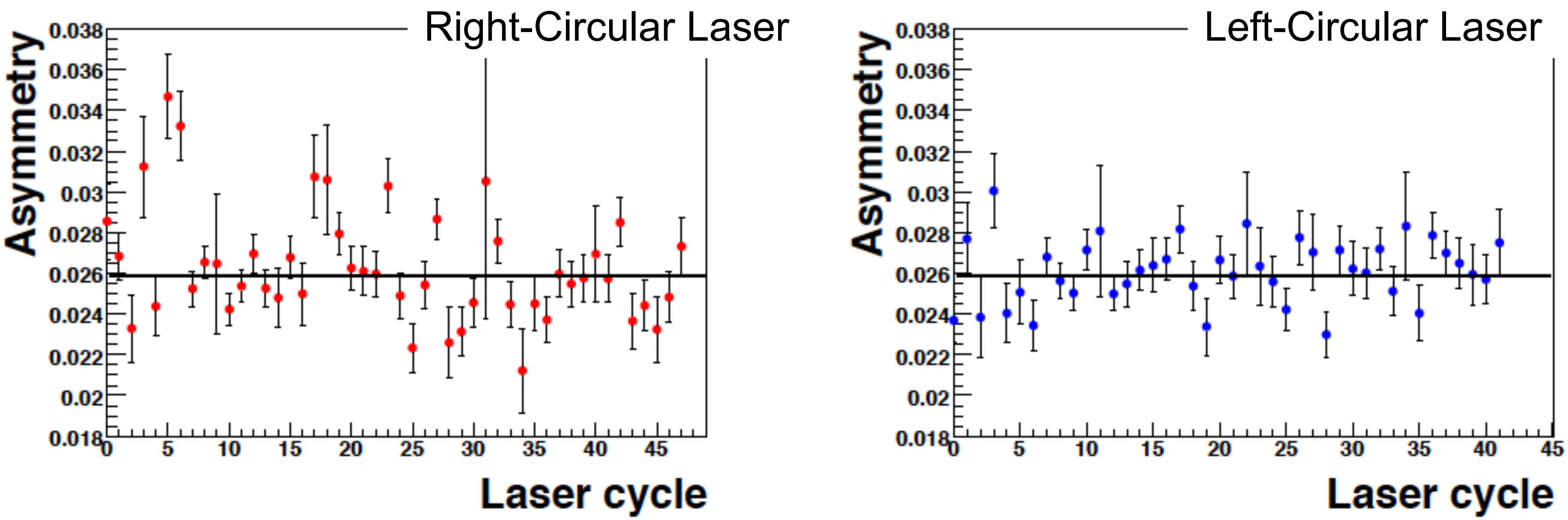
(a)



(b)

Asymmetries from FADC Accumulator

(Signal integrated over helicity window)



(a) (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

HAPPEX III Polarization Estimated Accuracy

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

New technique solves this

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%

4. Preparing for 11 GeV

Comparison to HAPPEX III Run

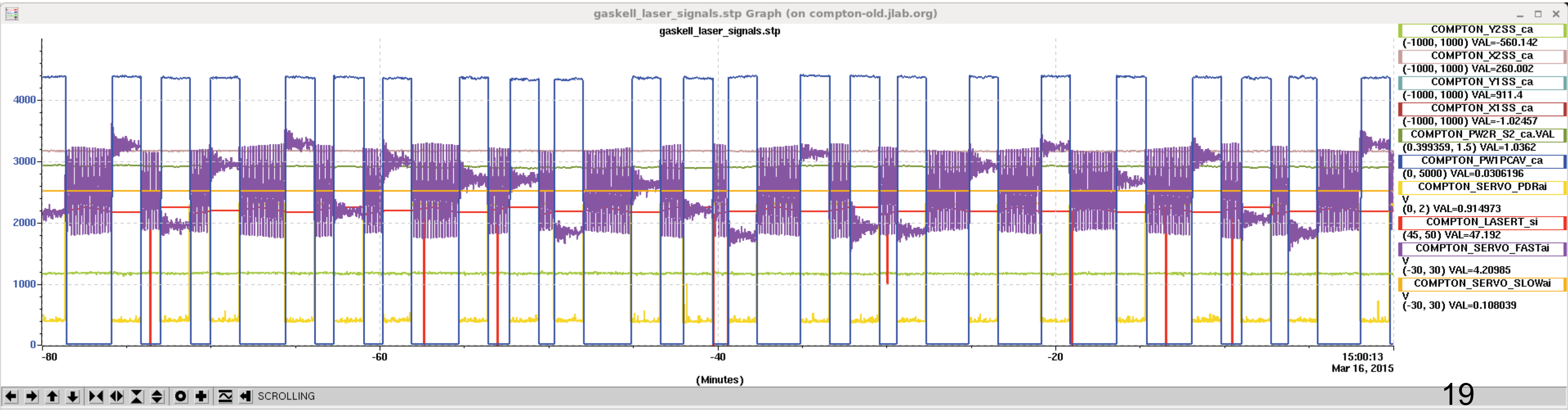
- Compton edge: 204 MeV -> 3.1 GeV
  GSO crystal -> $PbWO_4$ crystal
- Analyzing power increase x 6.4
- Synchrotron radiation background goes as E^4
  Modify chicane dipoles
- Reduce uncertainty in laser polarization

Compton Laser Status

Initially plagued by lower than expected gain after restoring cavity locking with moderate reflectivity mirrors
→ Excessive loss – problems with mirrors

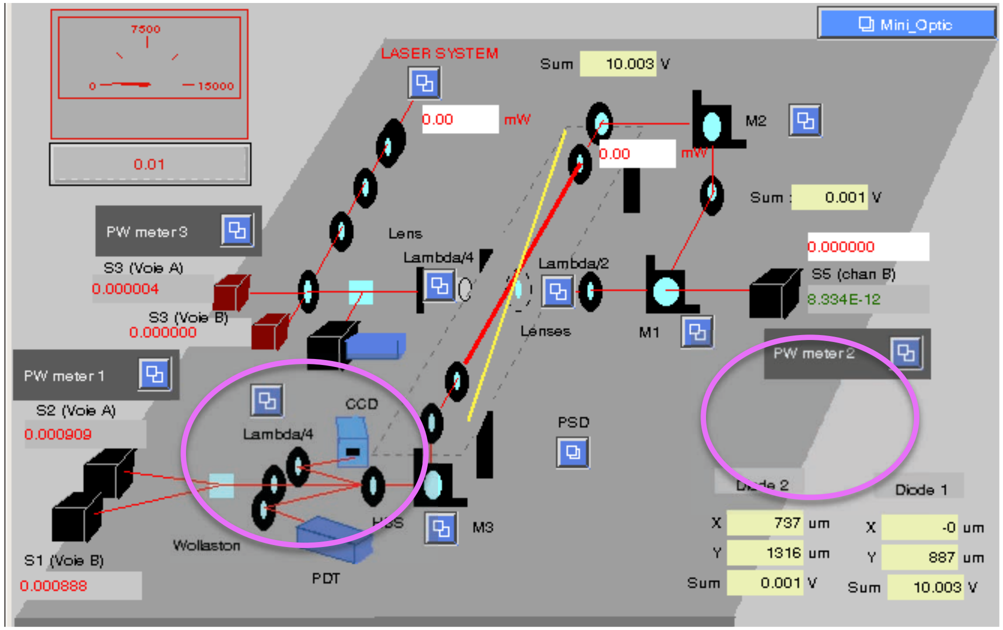
Replaced moderate *R* mirrors with high *R* (early 2015)

→ Was able to routinely achieving more than 4 kW of stored power
→ More recently, initial green power has been reduced, so stored power is 2 kW – but cavity gain remains high



New Compton Polarization Optimization

Polarization in cavity optimized by scanning full input polarization phase space and measuring reflected power → requires new (rotating) HWP, power meters
→ Controls updated, power meters installed
→ HWP installed, scanning and fitting routines developed



See talk by Dave Gaskell
Tuesday afternoon (Hall A Collaboration Meeting)

Analyzing Power at Higher Energies

Results from
“PbWO4 Compton Polarimeter Calorimeter”
Alexa Johnson (unpublished)

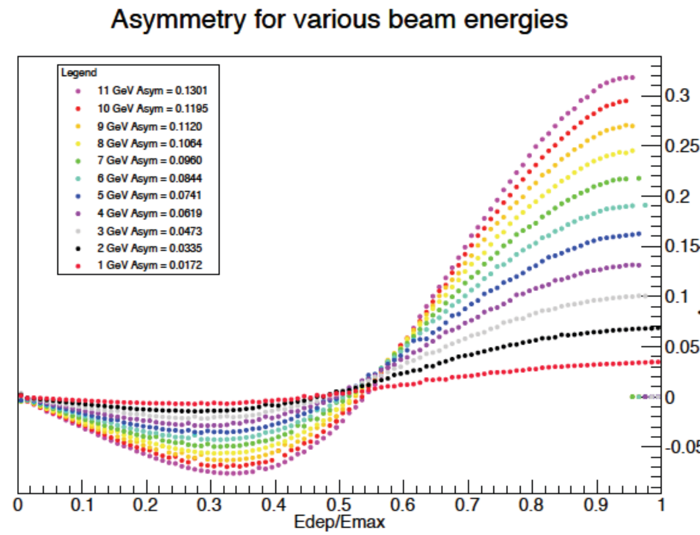


Figure 11: Asymmetry vs. ρ_{dep} for PbWO4 with beam energies of 1 - 11 GeV. The upper left insets show the signal-weighted integrated asymmetries.

Integrated signal analyzing power (GEANT4 for PbWO4, green laser)

$A_S = 0.0177E - 0.00057\, E^2$

E (GeV)	A_S
1.0	1.7%
3.5	5.5%
11.0	12.5%

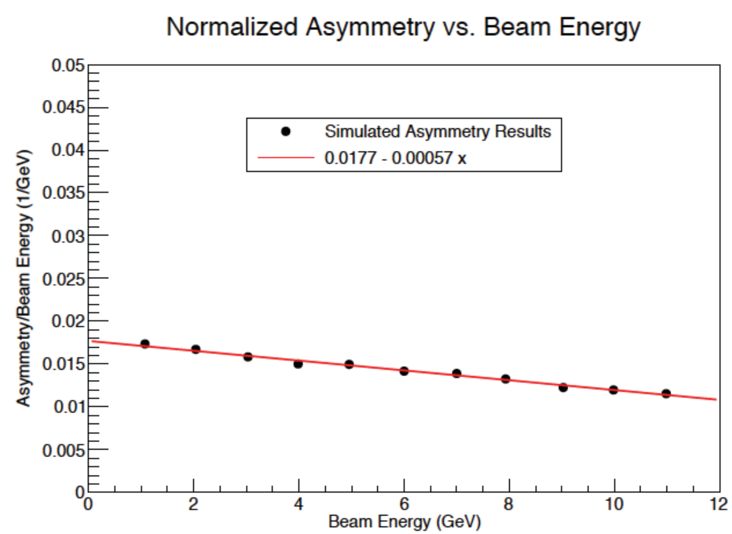


Figure 12: Normalized Asymmetry vs. E_{beam} for PbWO4 with beam energies 1-11 GeV. The asymmetry can be expressed as $A(E) = 0.0177E - 0.00057E^2$ where E is the electron beam energy in GeV.

To reach 1% accuracy in analyzing power

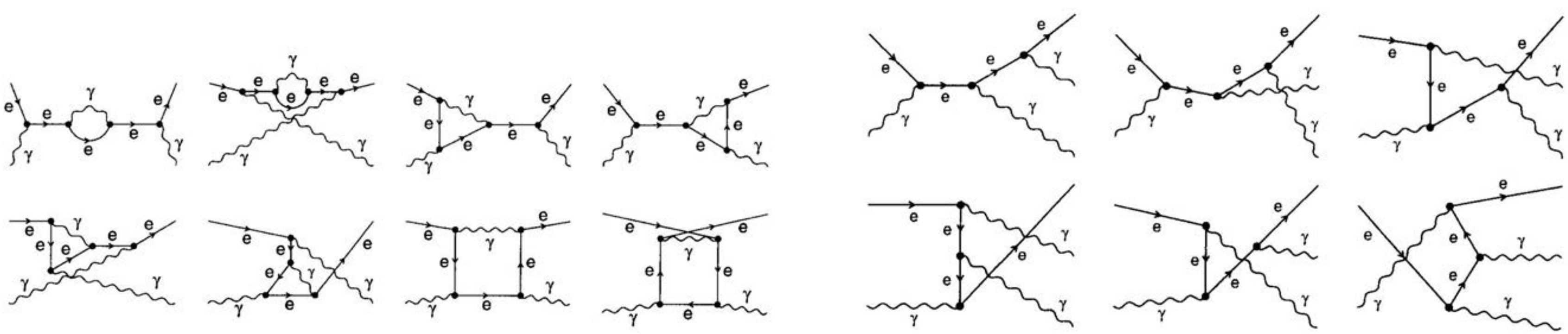
- Need to fold in PMT non-linearity
- Need to include higher order terms (not yet done)

Higher order diagrams

Denner & Dittmaier Nucl. Phys. B540 (1999)

~0.3% correction to A_l at 3.5 GeV beam energy

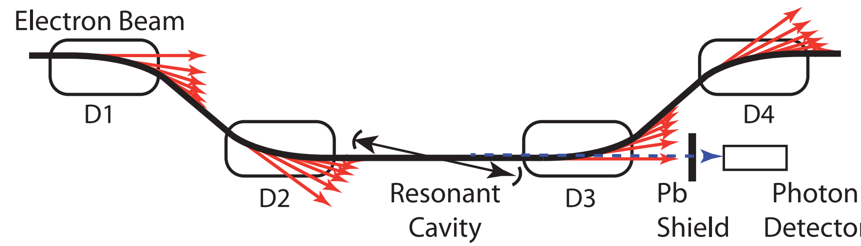
Increases with energy



Synchrotron Radiation Background Solved?

Synchrotron radiation a problem

Exit of D2 and entrance of D3



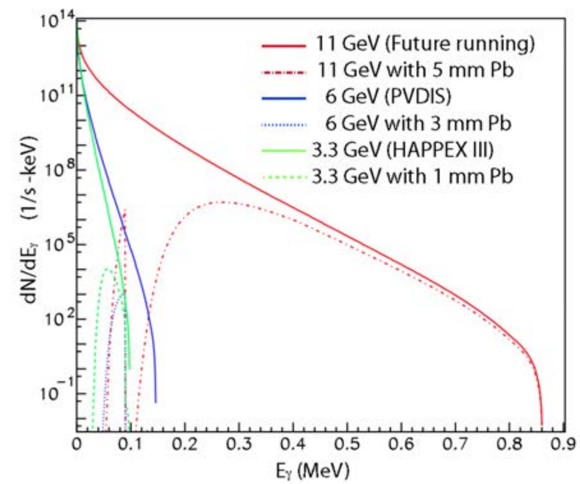
Problem:

Analyzing Power ~E

Signal ~E^2

Synch Radiation ~E^4

(for constant bend radius)



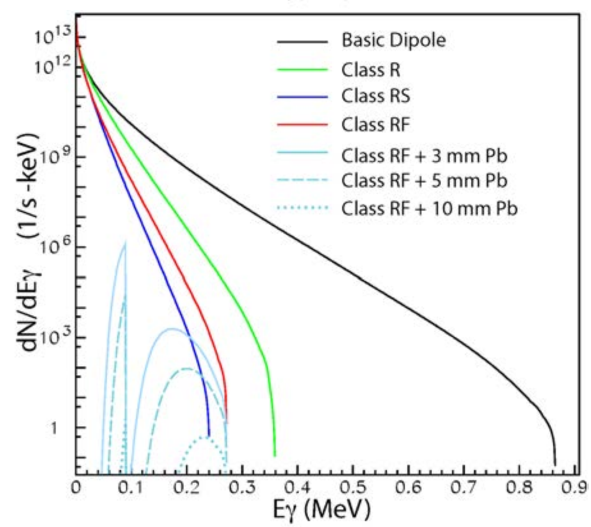
Solution:

Dipoles modified to extend fringe field

Reduce bend radius at D2 exit & D3 entrance

Synch radiation reduced orders of magnitude

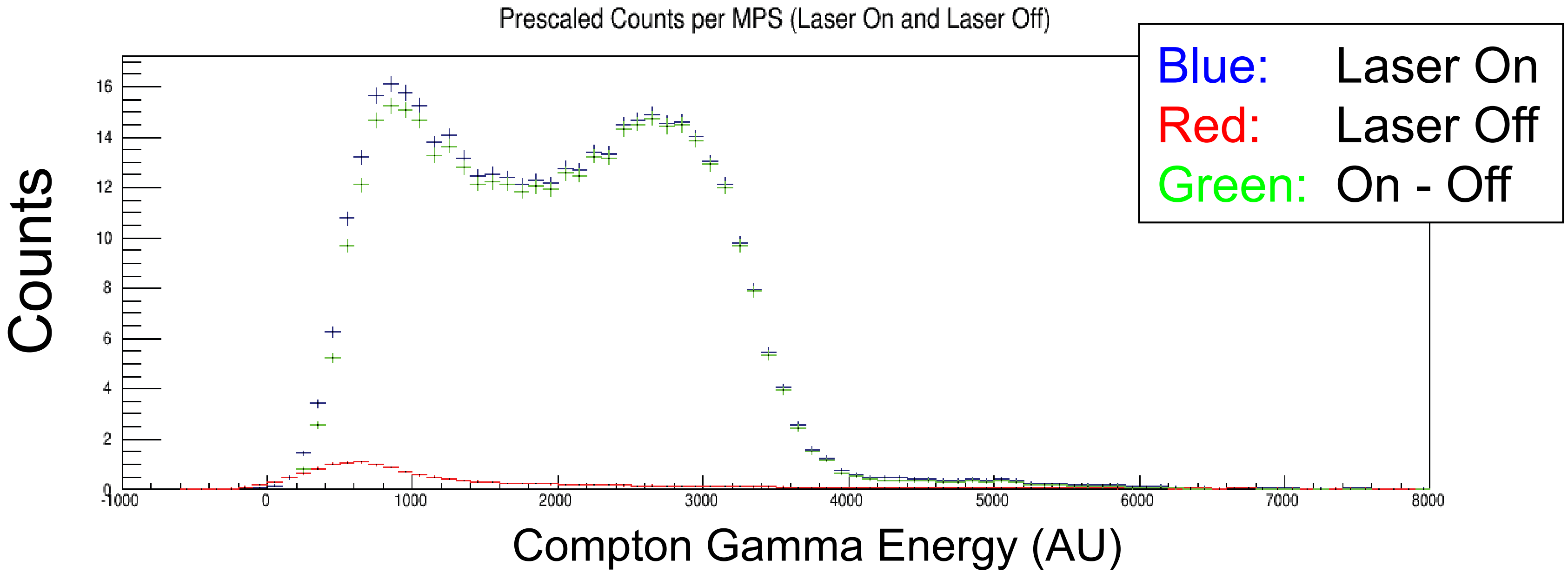
J. Benesch, G.B. Franklin, B.P. Quinn, and K.D. Paschke, “Simple modification of Compton polarimeter to redirect synchrotron radiation” PhysRevSTAB.18.112401 (2015)



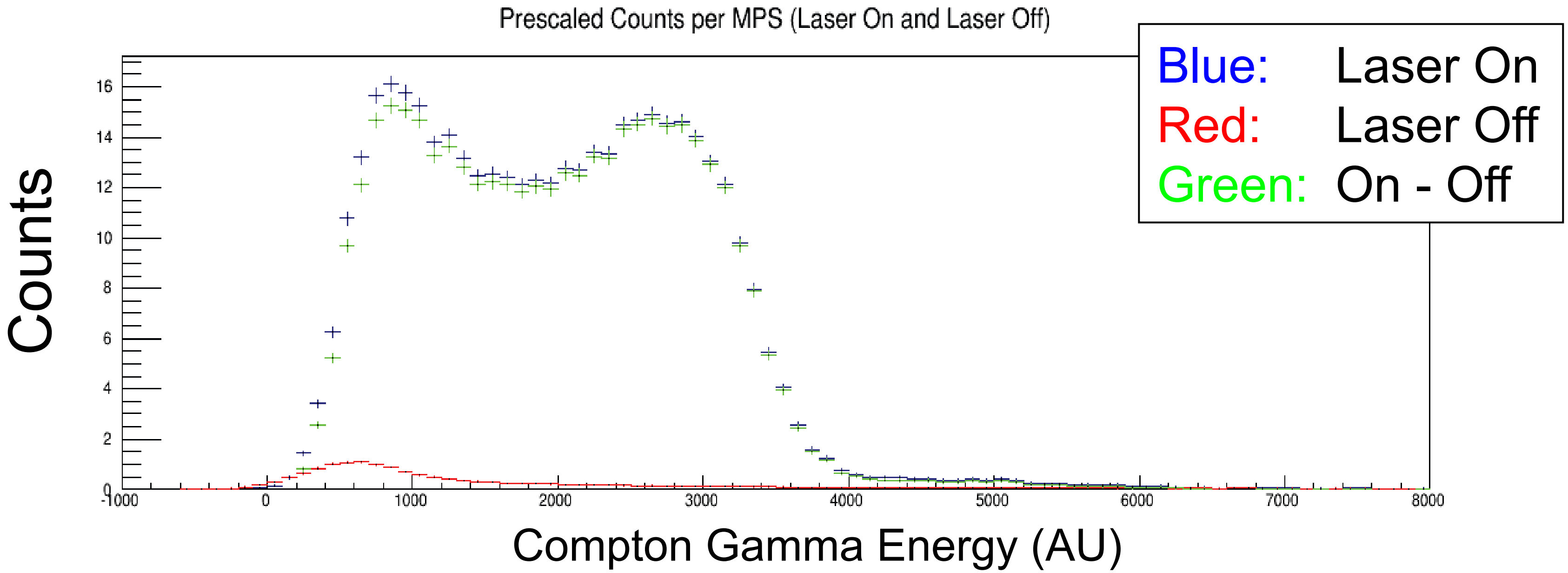
Sprint 2015 Test Run and DAQ tests

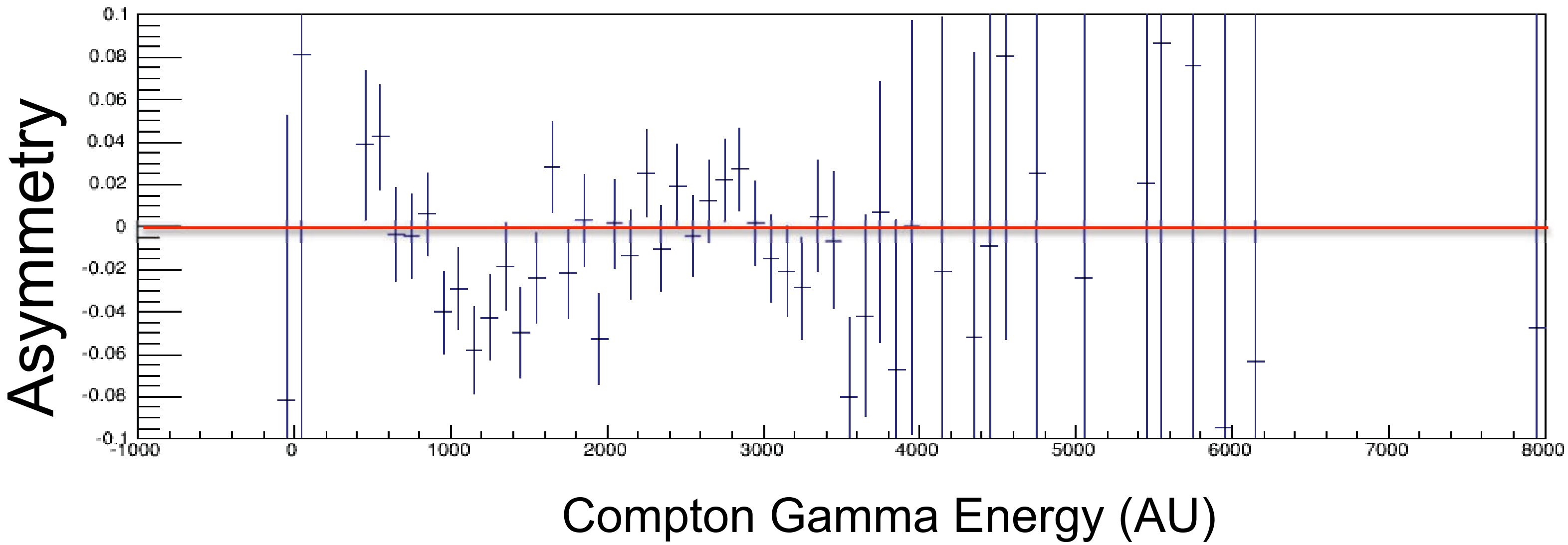
Short test of Compton, April 2015

Triggered Sample Events



Triggered Sample Events

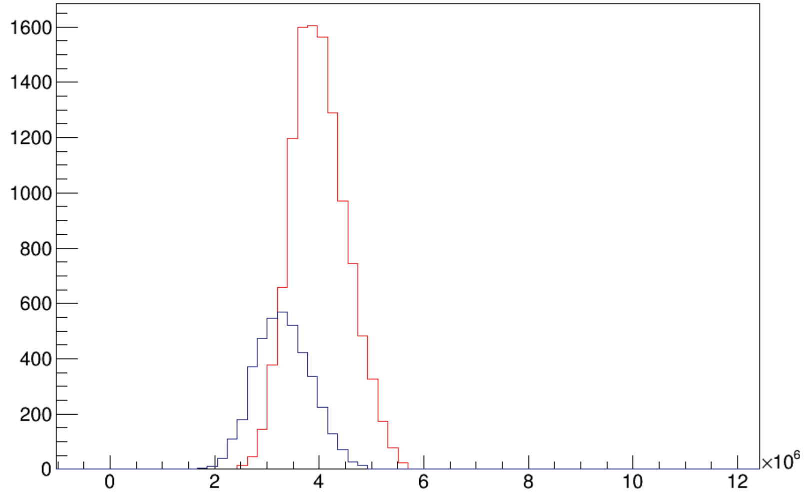




Integrated Signal S_0 (FADC Accumulator 0)

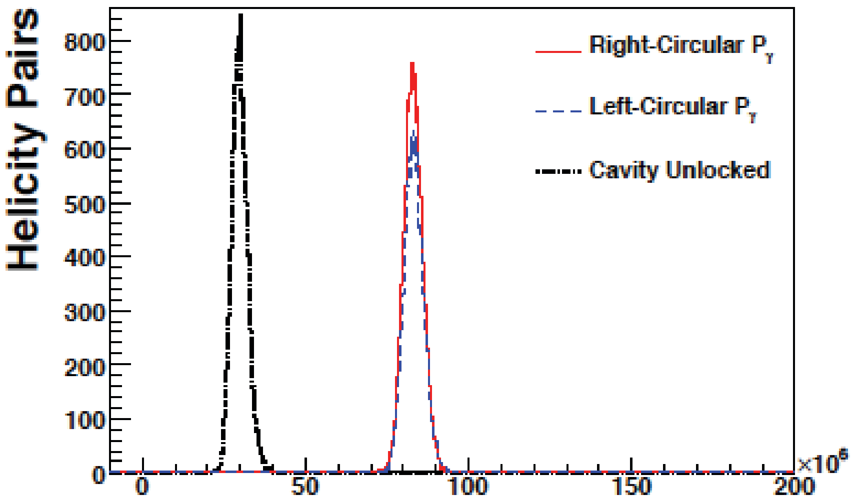
Spring 2005 Test Run
Beam 2.06 GeV, 5 μA
PbWO Crystal
No Pb synchrotron shielding

HAPPEX III
Beam 3.84 GeV, >70 μA
GSO Crystal
Pb synchrotron shielding



S_0 (summed raw FADC units)

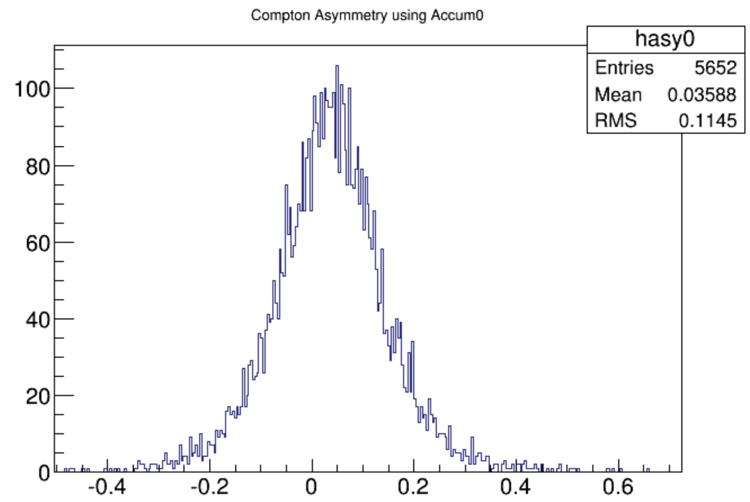
Signal ~0.7 x10^6 srau



S_0 (summed raw FADC units)

Signal ~55 x10^6 srau

Scaling Factors	= (Compton Pulse)	x	(Current)	x	(Pair Sum)	x	(Laser Power)
	= 6	x	16	x	2	x	1/3?
	= 64 x ?						



Acc0 Asymmetry

Raw prelim analysis shows A=3.5%
But large asymmetry with laser off
Follow up tests show helicity-bit correlated false asymmetry
Solution: “Pseudo-Delayed” helicity reporting

1. “Standard” delayed helicity effects everone
2. Delay-to-end-of-helicity window implemented
3. Reduces false helicity-bit correlation factor of 10
4. Estimate 0.4% false asymmetry
5. Compare to 12% analyzing power at 11 GeV

Conclusion

- Accuracy of 1% has been achieved in HAPPEX/Prex
- Significant improvements made
  - Improved determination of photon polarization
  - Reduction in Synchrotron Radiation
    (Particularly for high electron beam energy)
- Prompt helicity reporting probably OK
  (use pseudo-delay to Hal IA Compton VME)
- Laser/cavity working- but some reliability issues

Backup

Helicity-Bit Correlated Pedestal Shift

Run	S^{+}-S^{-} (rau)	
Spring 2015: Data Run	0.0200 ±0.0010	Run 1288
Revamped DAQ V1: Pulser	0.0489 ±0.0003	VME NIM/ECL
Revamped DAQ V2: Pulser	0.0140 ±0.0003	VME ECL only
Revamped DAQ V3: Pulser	0.0015 ±0.0002	Pseudo delayed Helicity reporting
2015 Run Delayed Hel. Analysis	0.0007 ±0.0004	Simulated full delayed reporting

Projected False Asymmetry (compare to 12% analyzing power at 11 GeV)

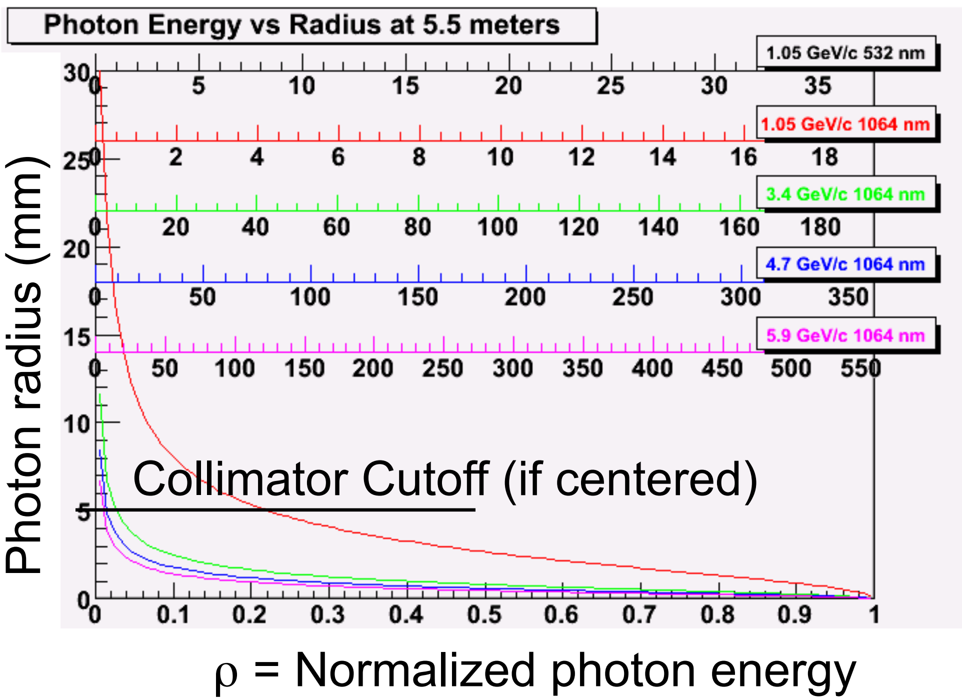
Run	S^{+}+S^{-} (rau)	A_false
Spring 2015: Data Run	0.20	10%
Assuming Pseudo-Delayed Reporting	0.20	0.75%
Expected Increased Signal Amplitude	0.40	0.38%
Increased counting rate ?	?	?

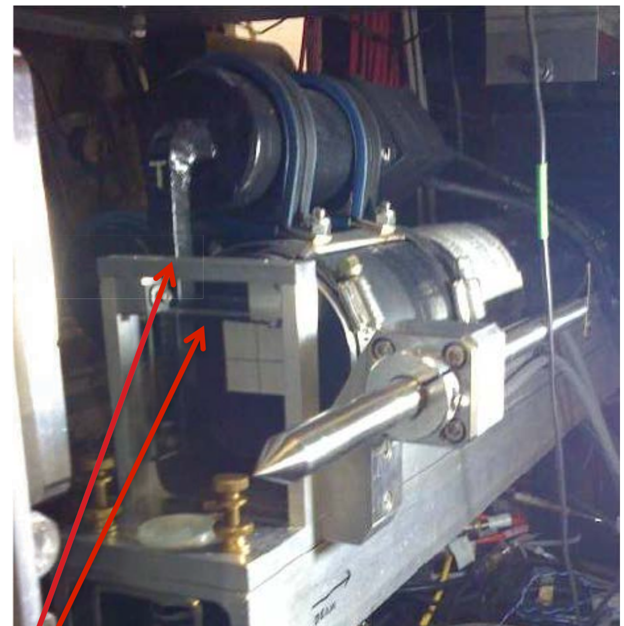
- Crystal Properties

	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

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

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

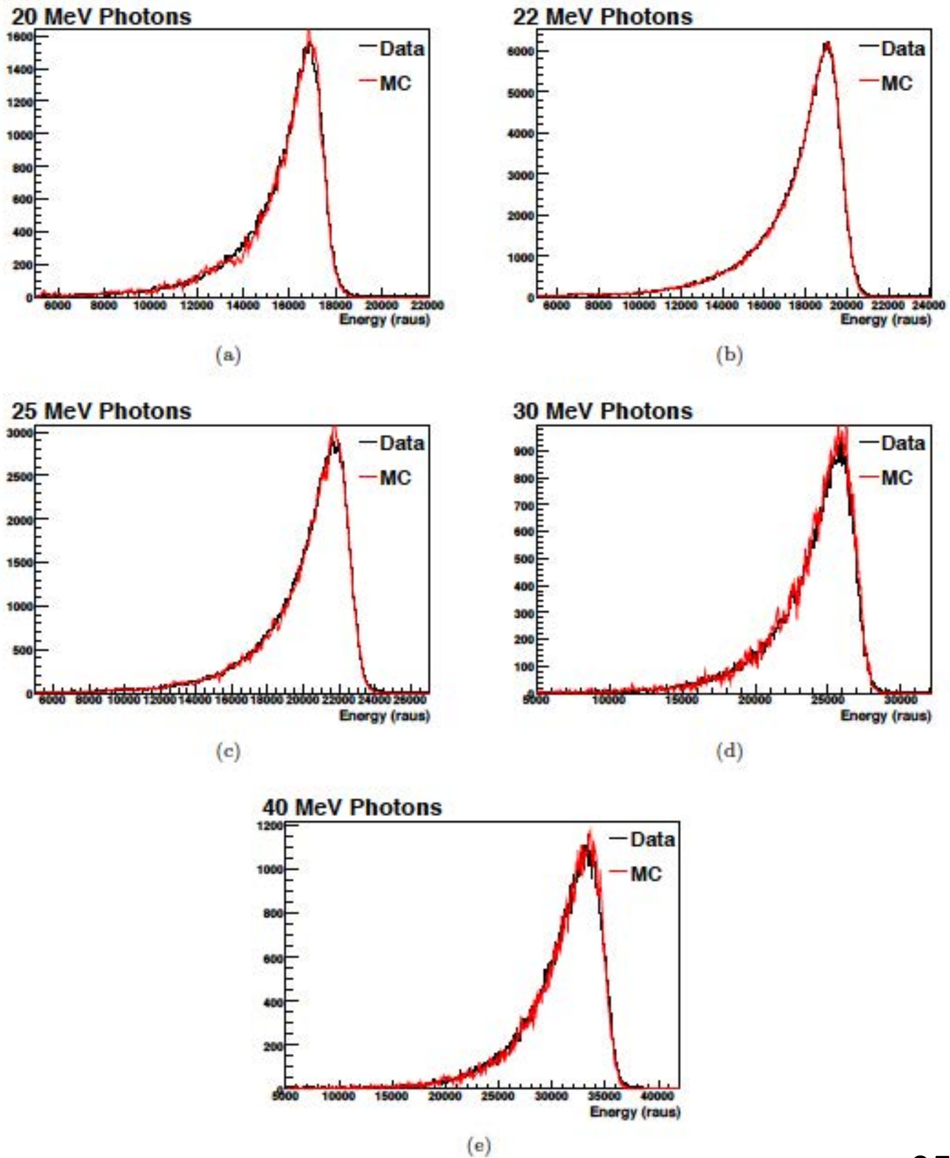
Verification of Detector Response Simulations

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



Analysis of Signal-Integrated Data (Accumulator 0)

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