Nuclear Structure Observables with Polarized Target and Polarized Real Photon Beam at MAMI

Dilli Paudyal

University of Regina

2016 Fall Meeting of the APS Division of Nuclear Physics, October 13 - 16, 2016

Expand the Compton effective Hamiltonian in incident- photon energy.

- Second Order $\rightarrow$ Scalar Polarizabilities

$$H_{eff}^{(2)} = -4\pi \left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2 \right] \tag{1}$$

- Third Order $\rightarrow$ Spin Polarizabilities

$$H_{eff}^{(3)} = -4\pi \left[\frac{1}{2}\gamma_{E1E1}\vec{\sigma}.(\vec{E} \times \dot{\vec{E}}) + \frac{1}{2}\gamma_{M1M1}\vec{\sigma}.(\vec{H} \times \dot{\vec{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j \right] \tag{2}$$

- These constants (γ) are spin dependent polarizabilities, (Meaning: γ_{M1E2} excited by electric quadruple $E2$ radiation and decays by magnetic dipole $M1$ radiation).
- Response of the proton spin to an applied electric or magnetic field, ‘stiffness ’ of proton spin against E.M. induced deformations relative to the spin axis.

Previous Results on Spin Polarizabilities

- Forward spin polarizability (Ahrens et al., PRL**87**, 022003 (2001))

$$\begin{aligned}\gamma_0 &= -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2} \\ &= (-1.0 \pm 0.08 \pm 0.10) \times 10^{-4} fm^4\end{aligned} \tag{3}$$

- Backward spin polarizability (Schumacher, Prog. Part. Nucl. Phys. **55**, 567 (2005))

$$\begin{aligned}\gamma_\pi^{disp.} &= -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2} \\ &= (8.0 \pm 1.8) \times 10^{-4} fm^4\end{aligned} \tag{4}$$

- Note: $\gamma_\pi^{\pi^0-pole}$ contributes -46.7 $\times 10^{-4} fm^4$.

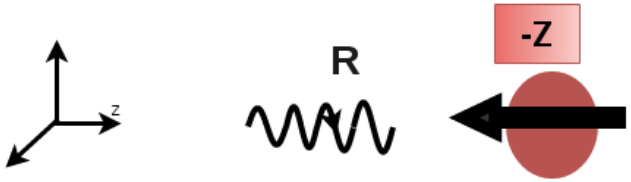
Best Way to extract Spin Polarizabilities.

- **Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy**
  - It is in the $\triangle$ (1232) resonance region ($E_\gamma = 250 - 350$ MeV) where their effect becomes significant.
- **In this energy region, it is possible to accurately measure polarization asymmetries using a variety of polarized beam and target combinations**
  - Various asymmetries respond differently to the individual spin polarizabilities at different E_γ and θ.
  - Measure three asymmetries at different E_γ, θ.
- **Our plan: Conduct a global analysis**
  - Include constraints from "known" γ_0, γ_π, α_{E1} and β_{M1}.
  - Extract all four spin polarizabilities independently with small statistical, systematic and model-dependent errors.

Double Polarization Asymmetry $\sum_{2z}$

Left helicity state of the beam, target Polarized in -z direction

(σ^{L}_{-z}).



Right helicity state of the beam, target Polarized in -z direction

(σ^{R}_{-z}).

Left helicity state of the beam, target Polarized in +z direction

(σ^{L}_{+z}).

Right helicity state of the beam, target Polarized in +z direction

(σ^{R}_{+z}).

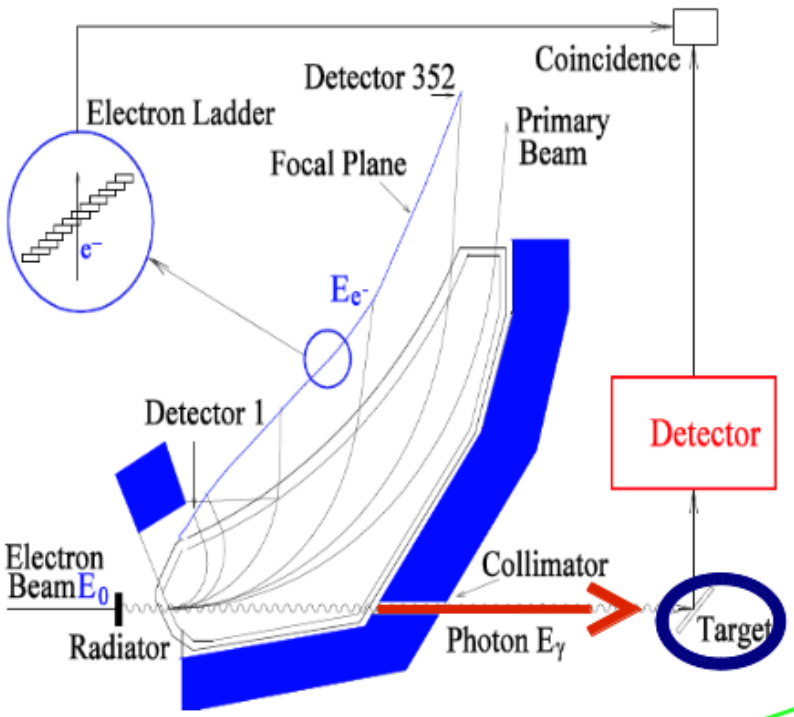
$\sum_{2z}$ in terms of Cross section and Number of events

$$\sum_{2z} = \frac{1}{P_\gamma P_t}\left(\frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}}\right), \tag{5}$$

- The degree of target polarization is different for positively and negatively polarized target, so in terms of Number of events the Asymmetry formula is

$$\sum_{2z} = \frac{1}{P_\gamma}\left(\frac{(N^R_{+z} + N^L_{-z}) - (N^L_{+z} + N^R_{-z})}{P_{+z}(N^R_{+z} + N^L_{-z}) + P_{-z}(N^L_{+z} + N^R_{-z})}\right) \tag{6}$$

Experimental Apparatus at MAMI

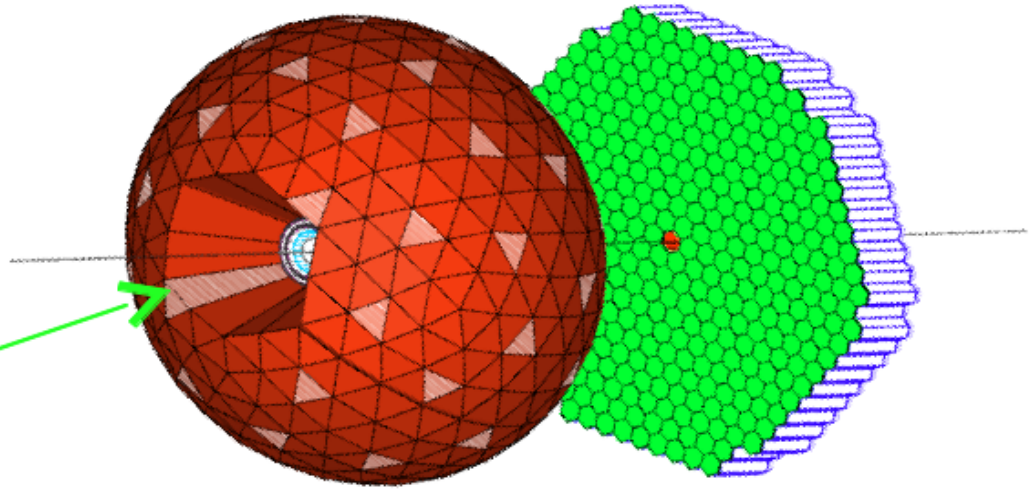


Crystal Ball

- 672 NaI crystals, separate PMT and 94 % solid angle coverage

TAPS

- 366 BaF2, 72 PbWO4 Crystals and 384 Veto Paddles



PID

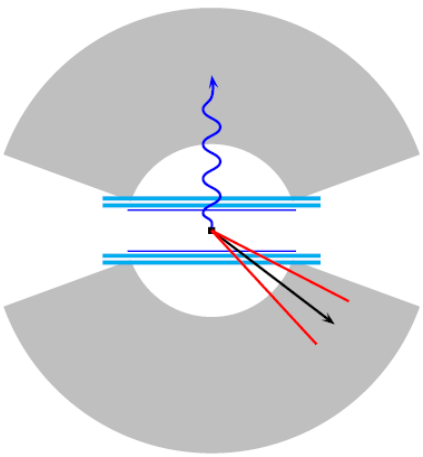
- Cylindrical detectors, 24 thin plastic scintillator strips,Identification of charged particles

MWPC

MWPC between PID and CB for track reconstruction of charged particles

Compton Scattering: Event Selection

- Require ONLY two tracks in the detector: One **neutral track** and one **charged track**.
- Require a cut on Coplanarity Angle, $\Delta\phi = |\phi_\gamma - \phi_{recoil}|$ and an Opening Angle, $cos(\Omega_{OA}) = \frac{\vec{p}_{miss} \cdot \vec{p}_{recoil}}{|\vec{p}_{miss}| \times |\vec{p}_{recoil}|}$.



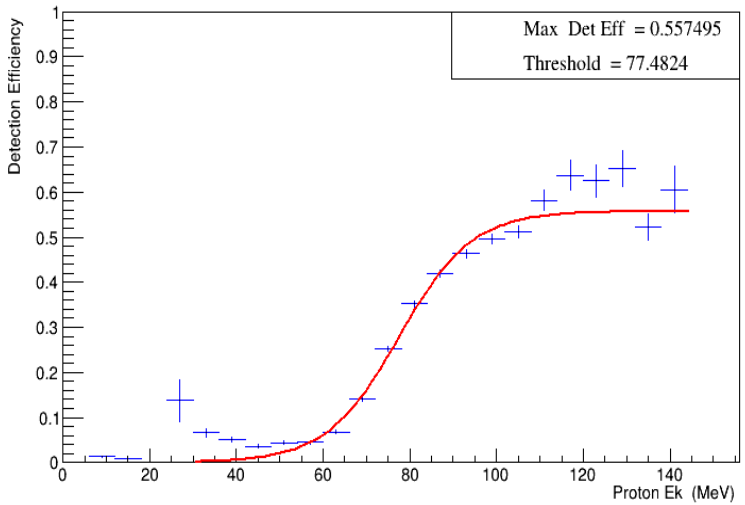
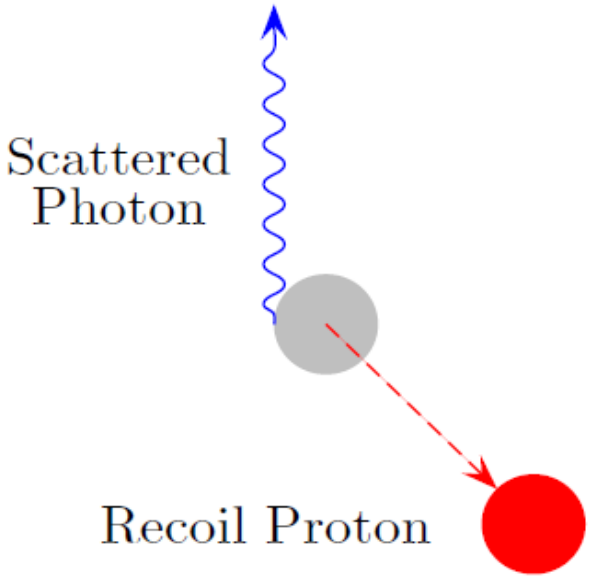
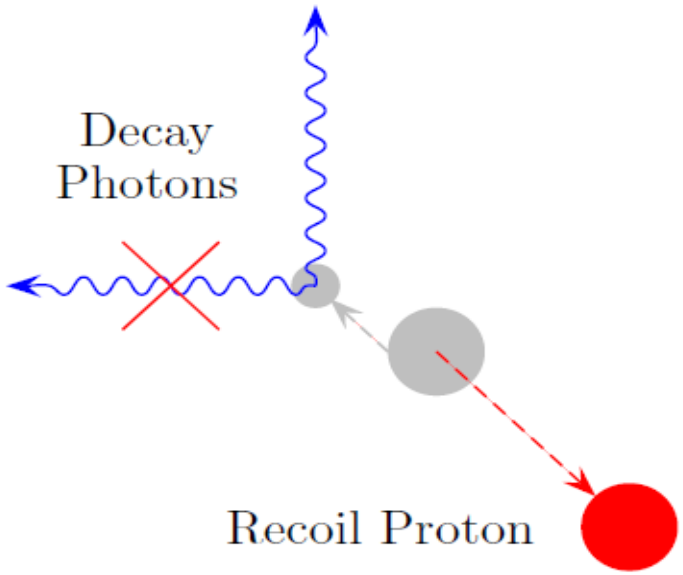


Figure: Left: Make an 'Opening angle' , requiring that the proton candidate is detected within a cone of its expected angle. Right: Charged particle detection efficiency.

π^0 Channel: Dominant Background



Compton Scattering

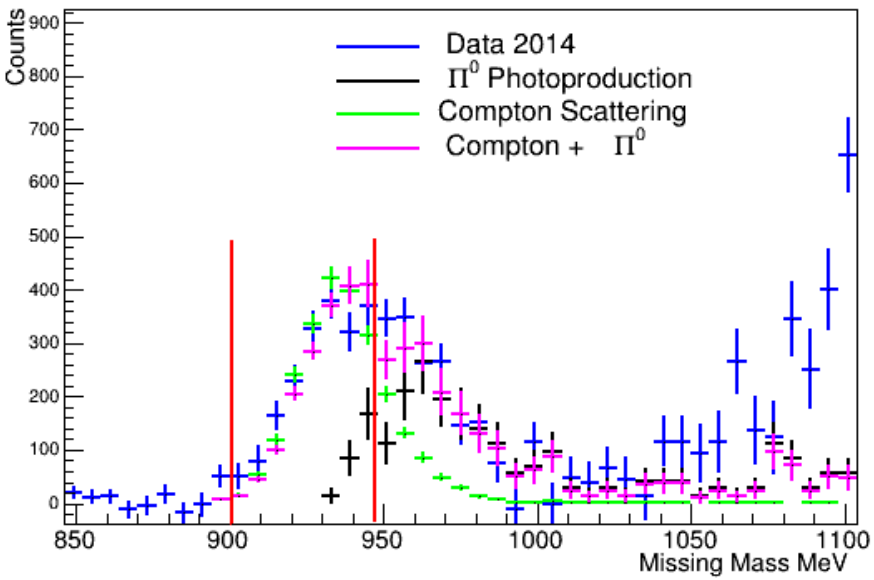


π^0 Photoproduction .

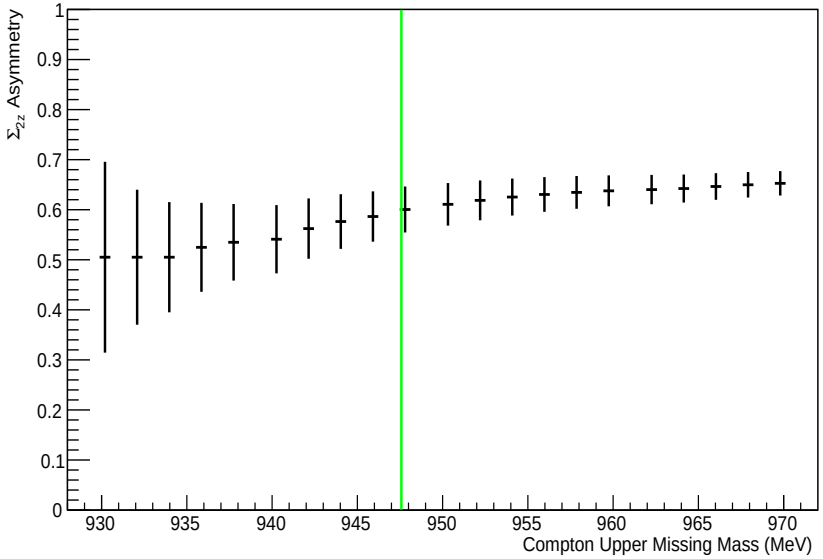
- Provides an excellent reaction for systematic checks and constraints. Due to the large cross-section (and clean reaction signal), π^0 production is an ideal reaction to perform systematic checks

Compton Missing Mass at E_γ = (285 - 305) MeV

$$m_{miss} = m_p = \sqrt{\left(E_{\gamma i} + m_p - E_{\gamma f}\right)^2 - \left(\vec{P}_{\gamma i} - \vec{P}_{\gamma f}\right)^2} \tag{7}$$



Comparison of missing mass for incident energy bin $E_\gamma = 285 - 305$ MeV at $\theta = 125 - 140^\circ$

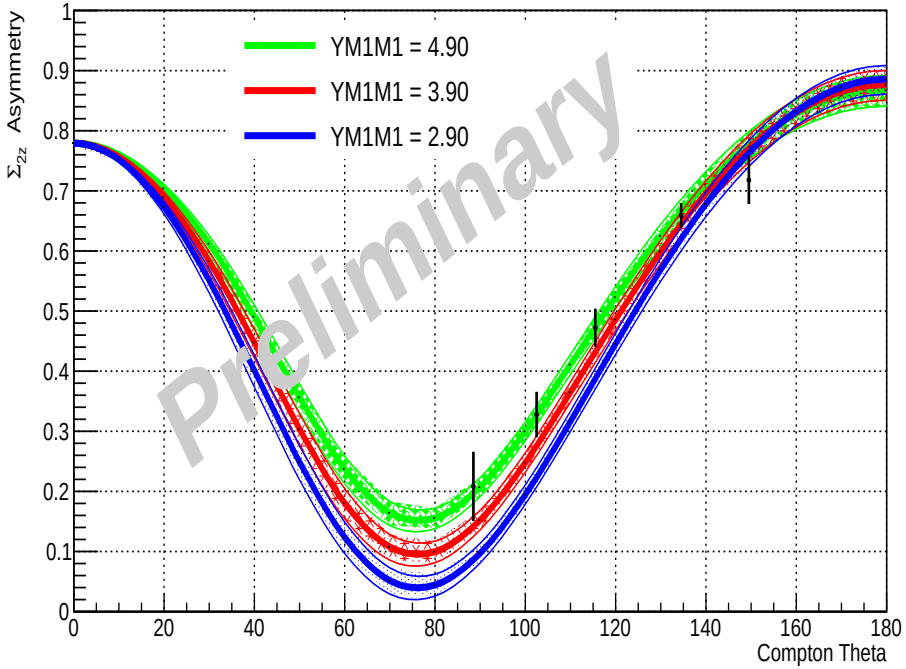


Compton $\sum_{2z}$ Asymmetry versus missing mass at $E_\gamma = 285 - 305$ MeV at $\theta = 125 - 140^\circ$

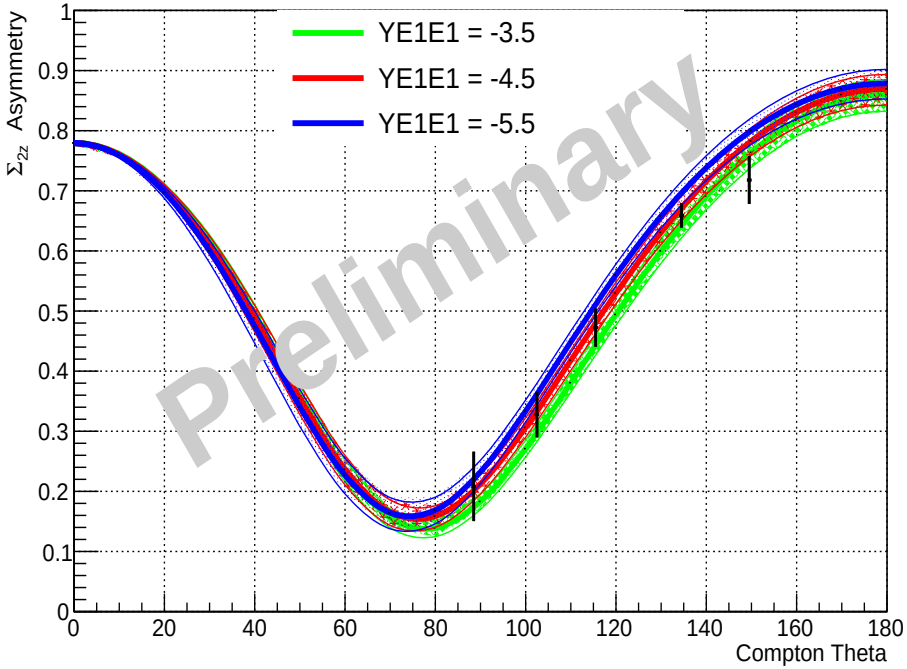
Figure: missing mass integration limit . Upper missing mass limit. (Max Limit: Consider missing mass cuts only above the proton mass, analyze π^0 photoproduction events as if it were Compton events and use them as a reference, asymmetry does not change by more than 4% moving to the right relative to the reference.)

Compton Sigma2z at E_γ = (285 - 305) MeV

- Curves are from DR calculation of Pasquini et al., making use of constraints on γ_0, γ_π, $\alpha_{E1} + \beta_{M1}$ and $\alpha_{E1} - \beta_{M1}$ to vary by their experimental errors.

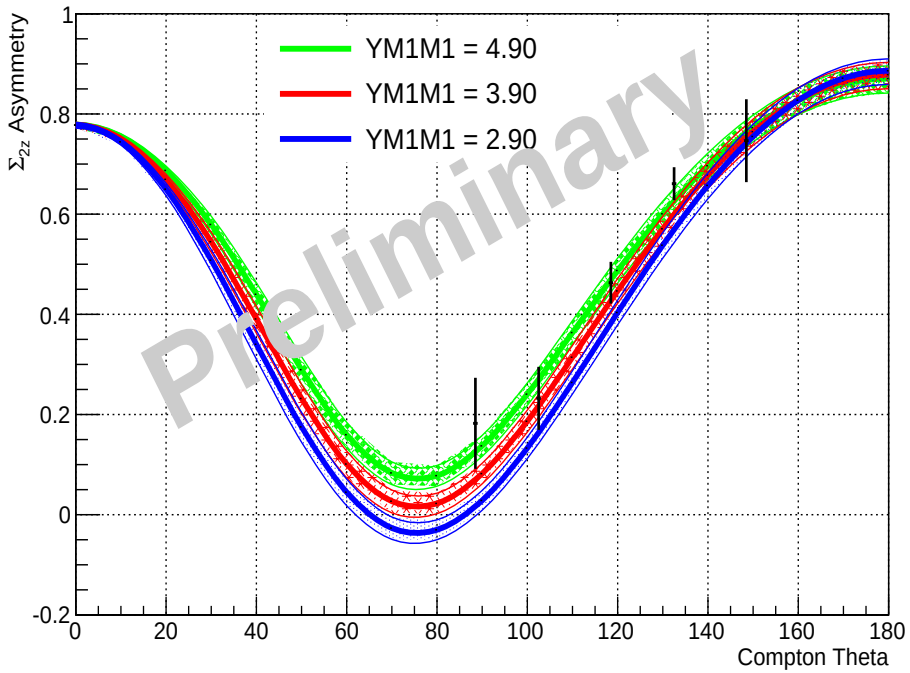


Fix $\gamma_{E1E1} = -3.7$, vary γ_{M1M1}

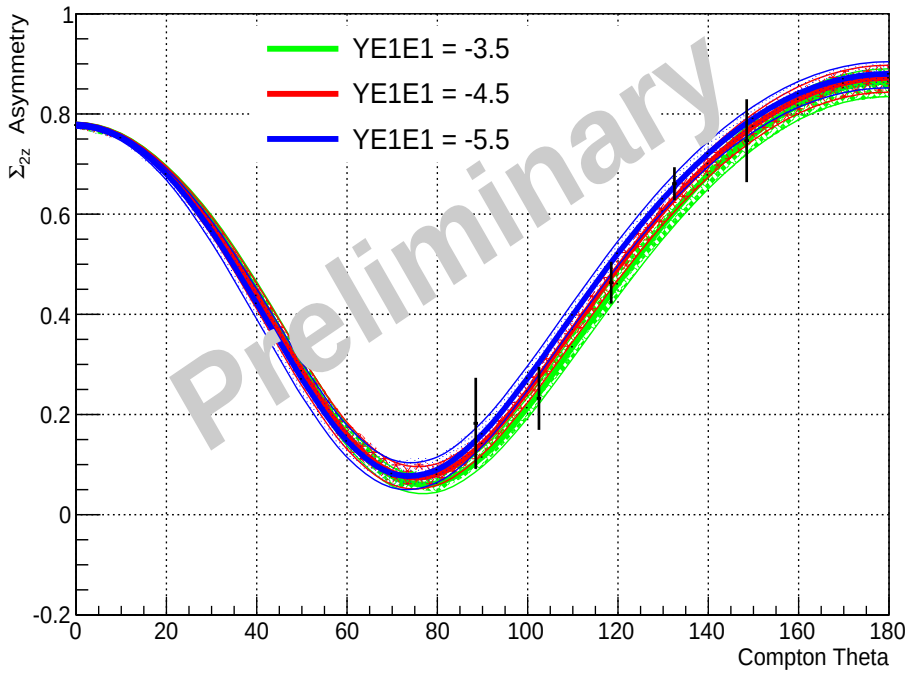


Fix $\gamma_{M1M1} = 2.9$, vary γ_{E1E1}

Compton Sigma2z at E_γ = (265 - 285) MeV



Fix $\gamma_{E1E1} = -3.7$, vary γ_{M1M1}



Fix $\gamma_{M1M1} = 2.9$, vary γ_{E1E1}

$\sum_{2z}$ Asymmetry Results:

- Preliminary Results on $\sum_{2z}$ Asymmetry from 2014 beamtime .
- Working on $\sum_{2z}$ Asymmetry from 2015 beamtime .

Proton Spin Polarizabilities Status and Future Work:

- Extract proton spin polarizabilities combining the $\sum_{2z}$ Asymmetry results from 2014 and 2015 beamtime
- Extract proton spin polarizabilities using the results from the series of all three Compton Scattering experiments ($\sum_{2x}$, $\sum_{3}$ and $\sum_{2z}$) Asymmetry experiments.

Supported by:

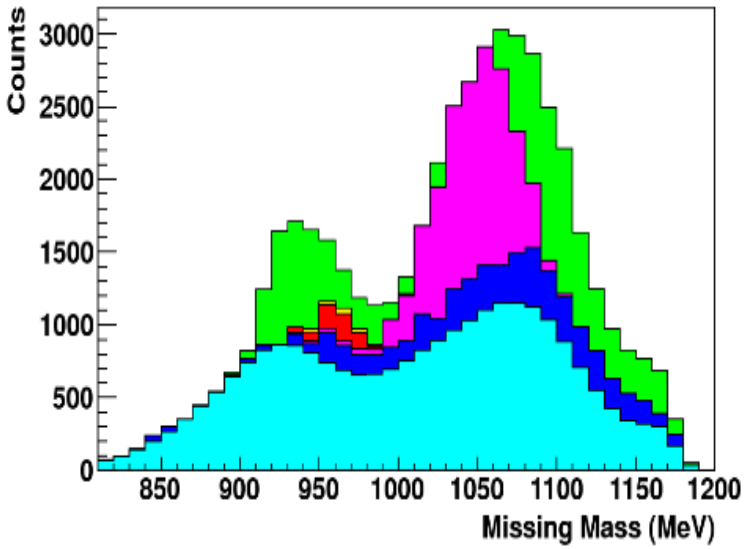
NSERC CRSNG

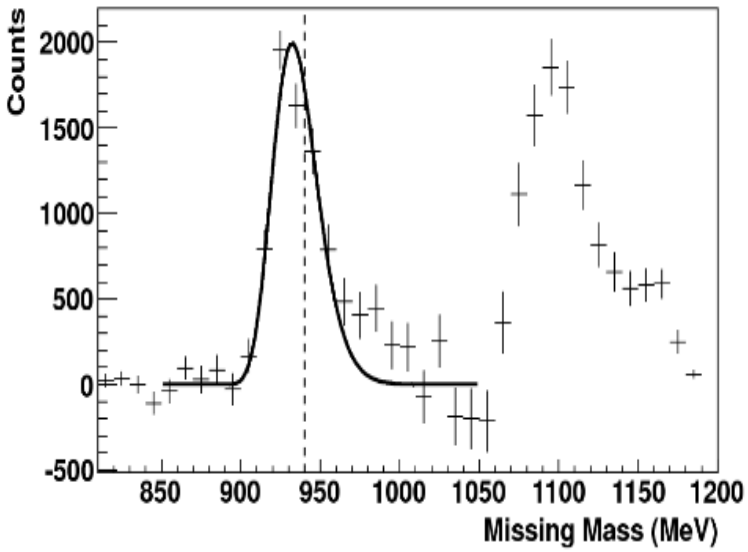
University of Regina

CINP ICPN Canadian Institute of Nuclear Physics / Institut canadien de physique nucléaire

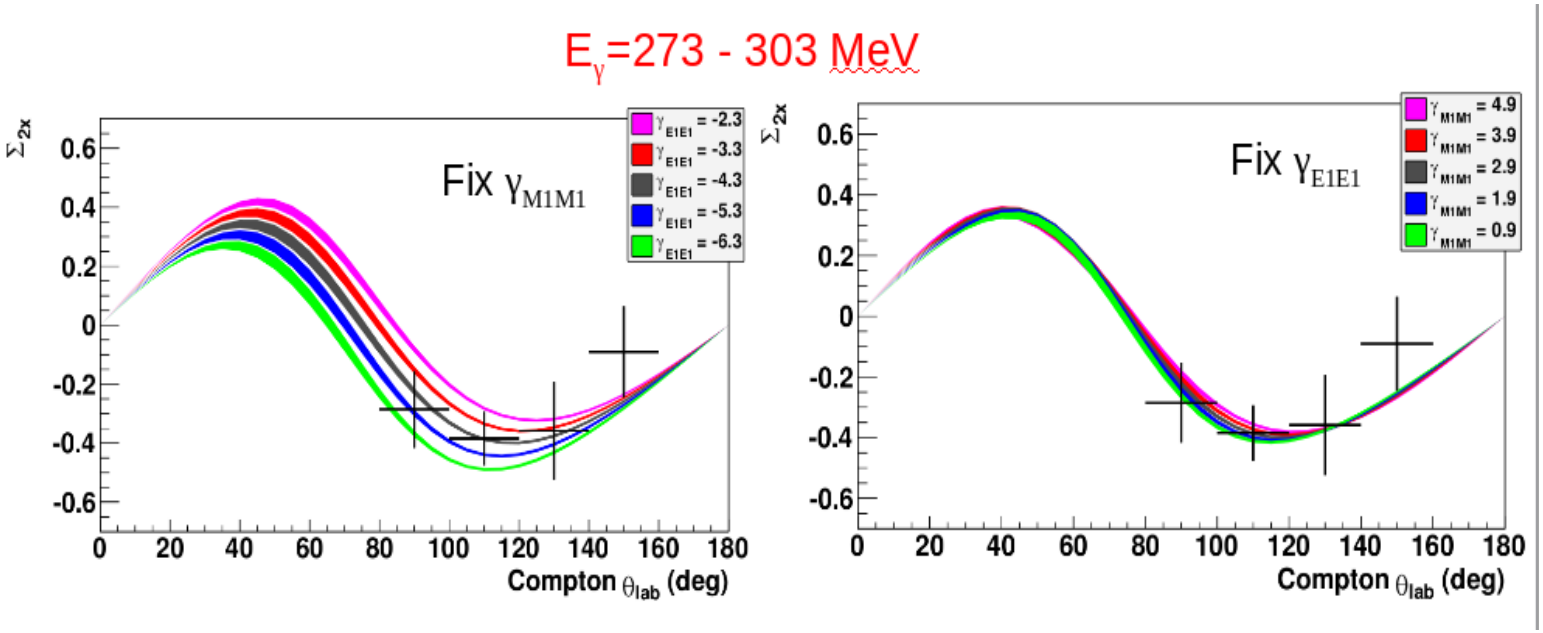
NSERC Grant: SAPPJ-2015-00023

Back Up Slides



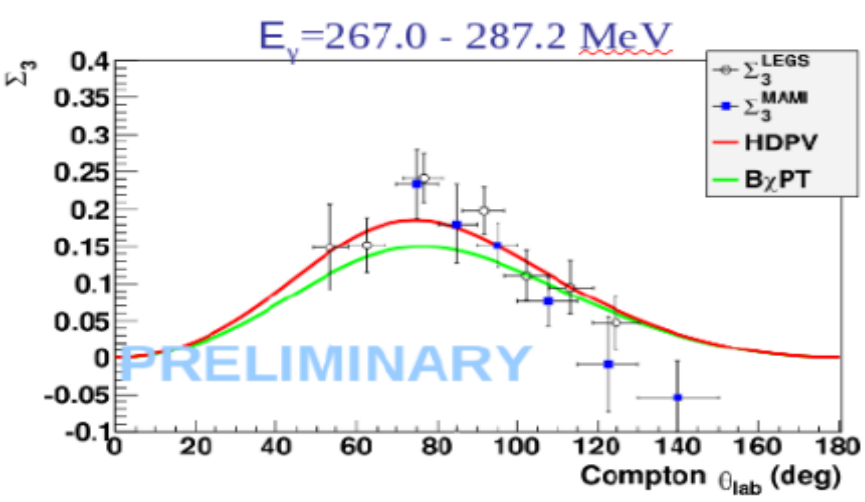


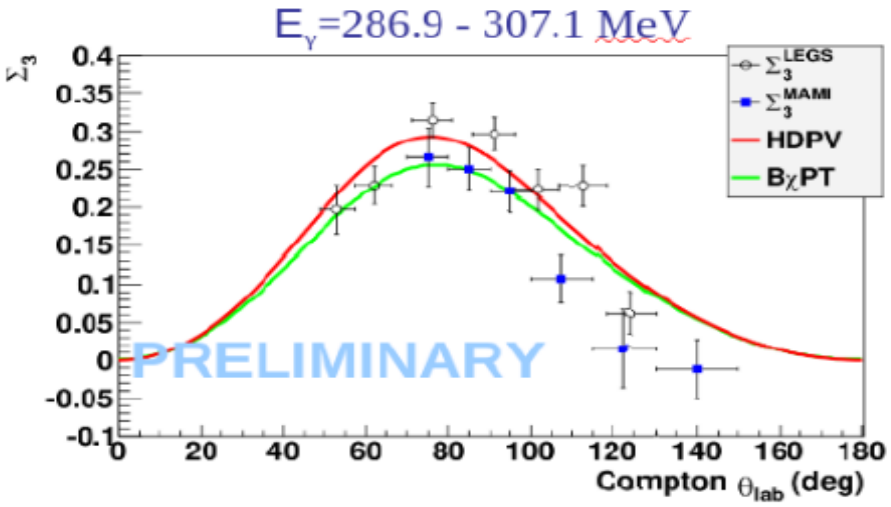
- MM distribution for $E_\gamma = 273 - 303$ MeV, $\theta_{\gamma'} = 100 - 120$ degree.
- Background contributions to MM: accidental coincidences , carbon/cryostat contributions (blue), reconstructed π_0. background where one decay γ escapes setup in: TAPS downstream hole and CB upstream hole.
- Right: Fully-subtracted MM spectrum with simulated Compton peak and conservative MM <940 MeV cut is applied to exclude neutral pion production,

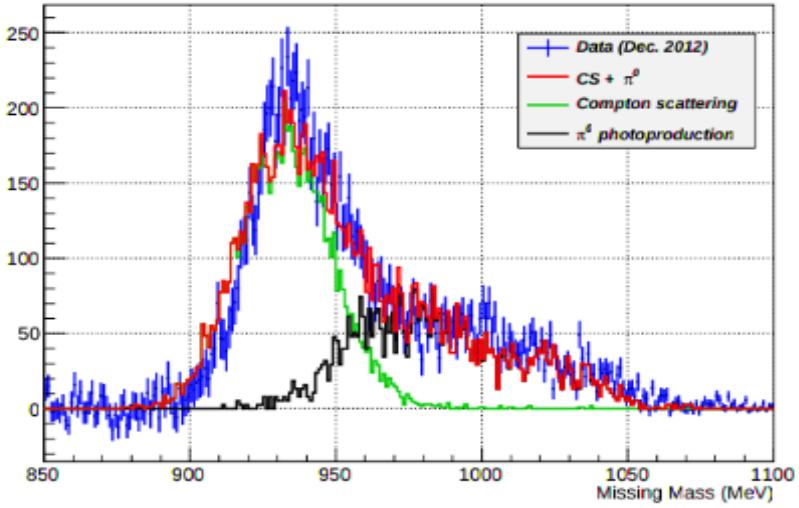


- New results. Physical Review Letters 114, 112501 (2015), arXiv:1408.1576 [nucl-ex]
- Measurement of a Σ_{2x} asymmetry on the nucleon. Curves are from DR calculation of Pasquini et al., making use of constraints on γ_0, γ_π,$\alpha_{E1} + \beta_{M1}$, $\alpha_{E1} - \beta_{M1}$ (allowed to vary within experimental errors).
- Checks were done with $B\chi PT$ calculation of Lensky and Pascalutsa.

Σ_3 âĂŞ Collicot, et al.







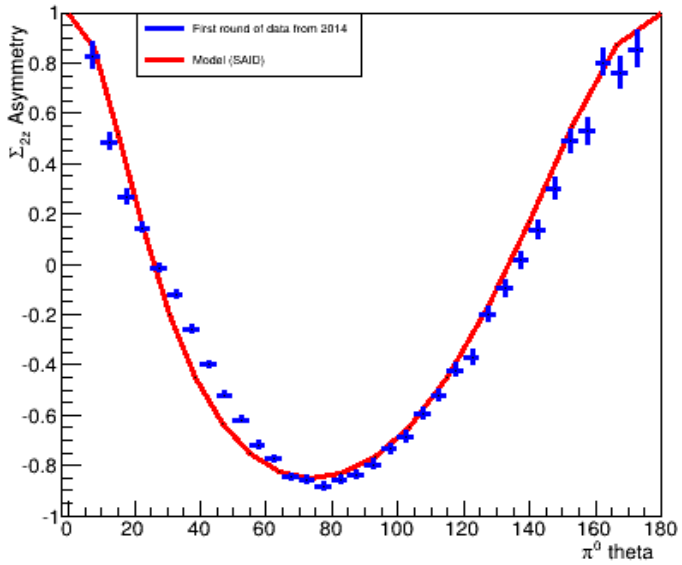
- **New MAMI and Older LEGS measurements along with two theoretical curves using their preferred polarizabilities**
- **Simulation of neutral pion photoproduction in Liquid hydrogen target matches background of the distribution quite well**

Frame Preliminary Combined Spin Polarizabilities

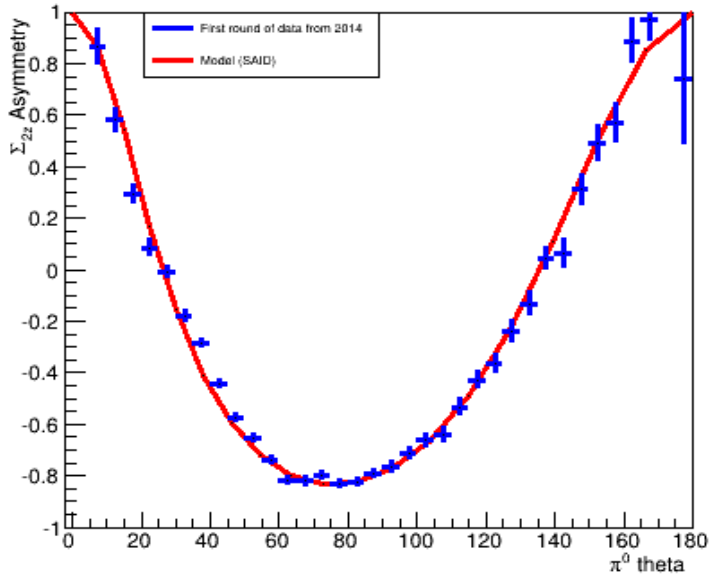
	HDPV	BχPT	Σ_{2x} and Σ_3^{LEGS}	Σ_{2x} and Σ_3^{MAMI}
γ_{E1E1}	-4.3	-3.3	-3.5±1.2	-5.0±1.5
γ_{M1M1}	2.9	3.0	3.16±0.85	3.13±0.88
γ_{E1M2}	-0.0	0.2	-0.7±1.2	1.7±1.7
γ_{M1E2}	2.2	1.1	1.99±0.29	1.26±0.43
γ_0	-0.8	-1.0	-1.03±0.18	-1.00±0.18
γ_π	9.4	7.2	9.3±1.6	7.8±1.8
$\alpha+\beta$			14.0±0.4	13.8±0.4
$\alpha-\beta$			7.4±0.9	6.6±1.7
χ^2/df			1.05	1.25

- Dispersion relation fits to Σ_{2x} along with either $\sum_3^{MAMI}$ or $\sum_3^{LEGS}$
- (Note: Pion pole contribution has been subtracted)

Π^0 Photoproduction Asymmetry



$E_\gamma = 285 - 305$ MeV



$E_\gamma = 310 - 330$ MeV

Figure: π^0 Asymmetry results (only 2014 beamtime)

Electron Beam Polarization

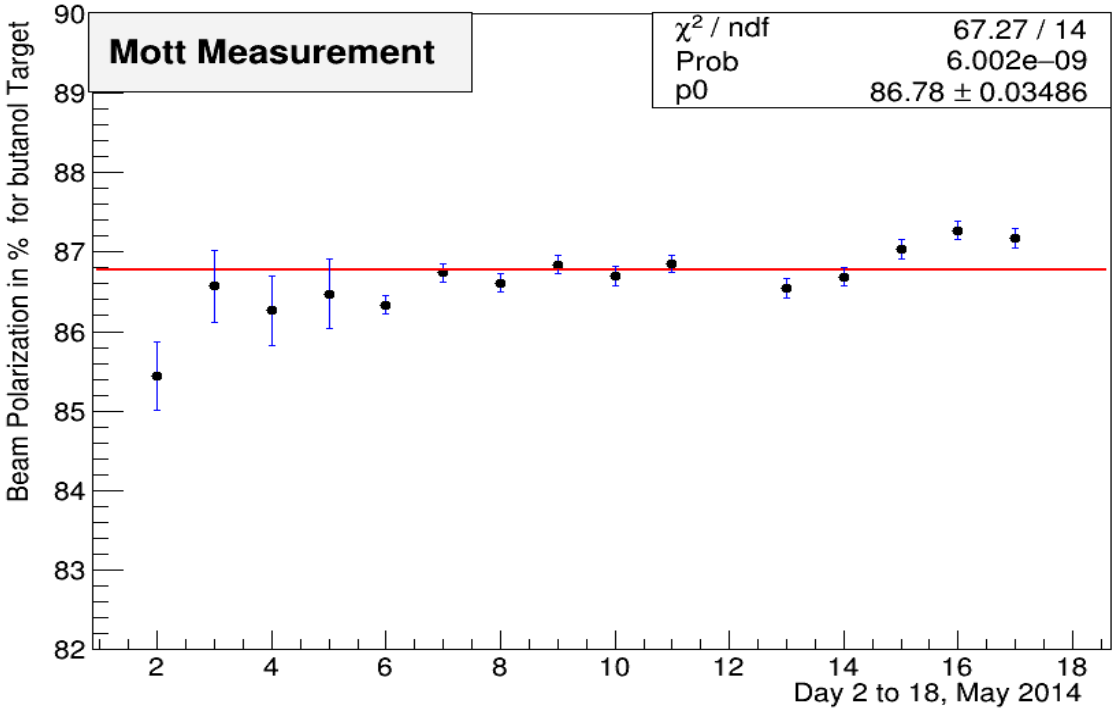


Figure: Electron Beam Polarization for the first round of 2014 butanol beamtime. Average Electron Beam Polarization: 86.63 ± 0.11

Photon Beam Polarization

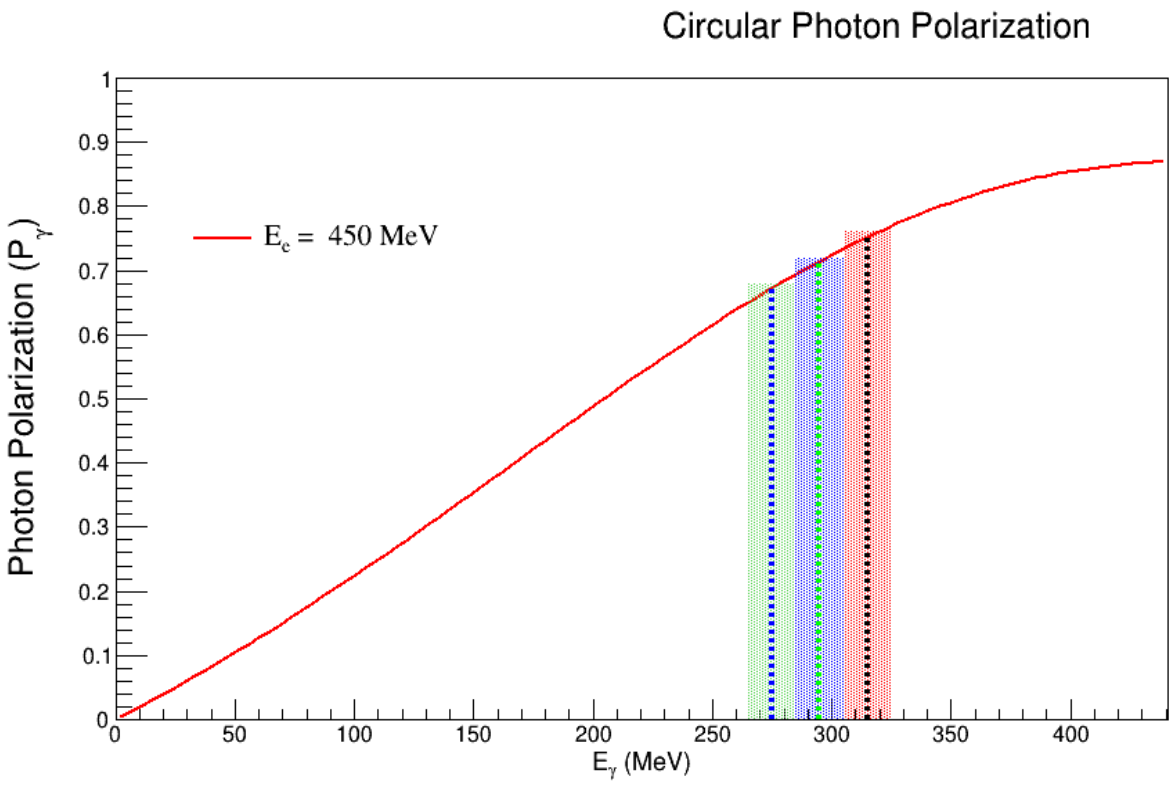


Figure: Average Photon Polarization: 68.43 ± 0.23 for $E_\gamma = 265 - 285$ MeV, Average Photon Polarization: 72.52 ± 0.21 for $E_\gamma = 285 - 305$ MeV and Average Photon Polarization: 76.23 ± 0.18 for $E_\gamma = 305 - 325$ MeV

Butanol Target Polarization

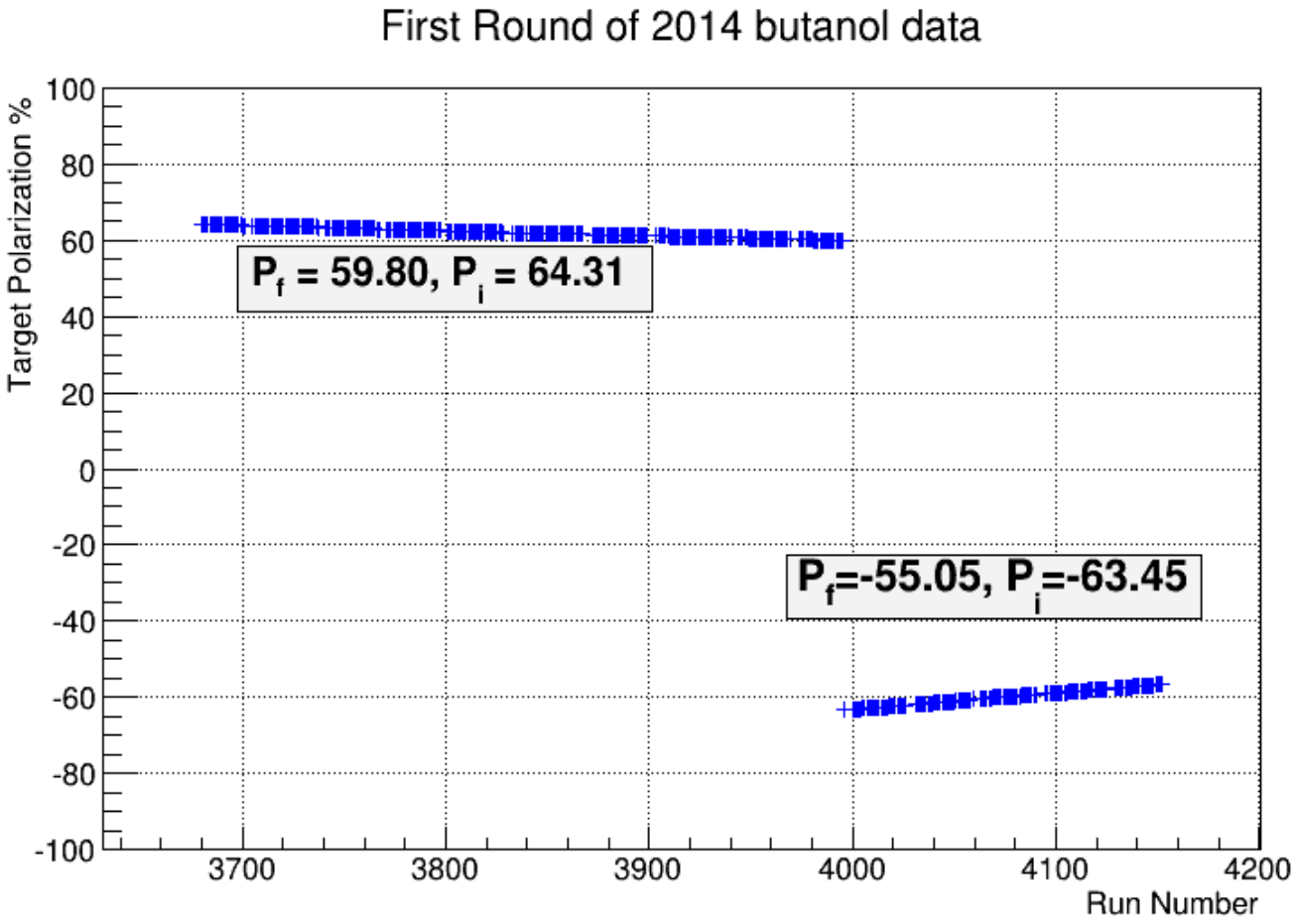


Figure: Average Target Polarization: 62.05 $\pm$ 0.83 for a butanol target polarized in +z direction, Average Target Polarization: 59.25 $\pm$ 0.88 for a butanol target polarized in -z direction.