Nuclear Compton Scattering and Proton Polarizabilities

P.P. Martel[1] R. Miskimen[2]
A2 Collaboration[3]

[1]Massachusetts Institute of Technology

[2]University of Massachusetts - Amherst
(supported by DE-FG02-88ER40415)

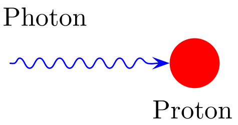
[3]Mainz Microtron (MAMI)

INT-12-3 Workshop - Electroweak Properties of Light Nuclei
Seattle, WA - Nov. 5, 2012

Outline

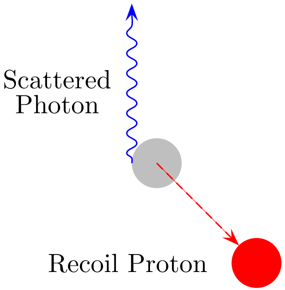
1. Compton Scattering
   - Equations for Interactions
   - Spin Polarizabilities
   - Sensitivities to SPs
2. Experiment
   - Equipment
3. Analysis
   - Event Selection
   - Backgrounds
   - Results
4. Conclusions

Electromagnetic Interactions



Compton scattering

Electromagnetic Interactions



Compton scattering

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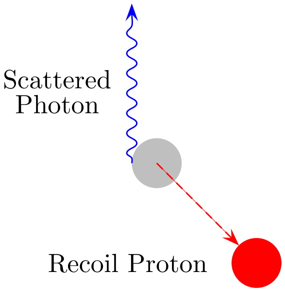
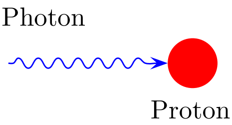
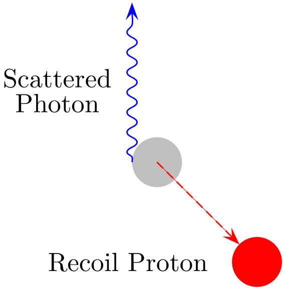


Compton scattering

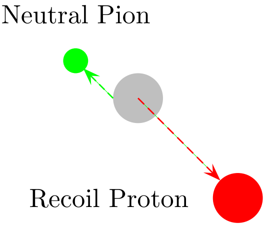


Pion photoproduction

Electromagnetic Interactions



Compton scattering



Pion photoproduction

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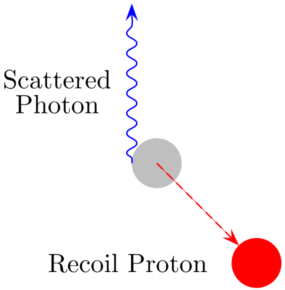
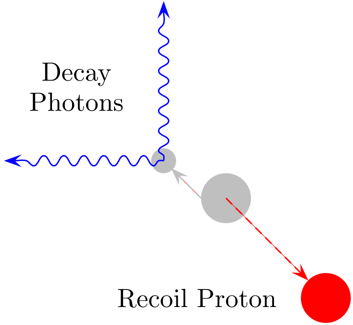




Compton scattering

Pion photoproduction

Compton Scattering Equations

Zeroth Order - Mass and Electric Charge

$$H_{\text{eff}}^{(0)} = \frac{\vec{\pi}^2}{2m} + e\phi \qquad (\text{where } \vec{\pi} = \vec{p} - e\vec{A})$$

First Order - Anomalous Magnetic Moment

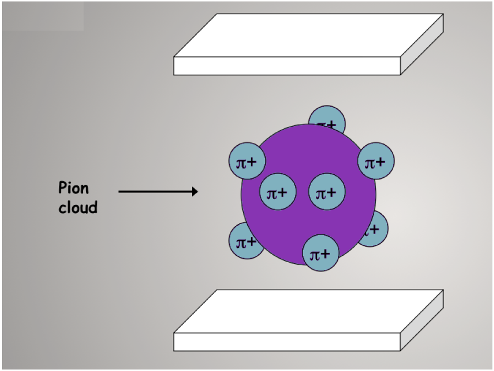
$$H_{\text{eff}}^{(1)} = -\frac{e(1+\kappa)}{2m}\vec{\sigma}\cdot\vec{H} - \frac{e(1+2\kappa)}{8m^2}\vec{\sigma}\cdot\left[\vec{E}\times\vec{\pi} - \vec{\pi}\times\vec{E}\right]$$

Second Order - Electric and Magnetic Polarizabilities

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

Electric Polarizability - α_{E1}

Describes the response of a proton to an applied electric field.



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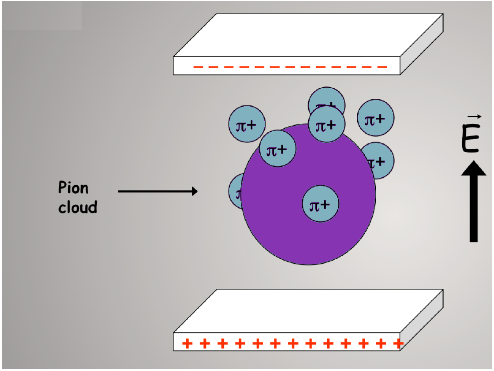
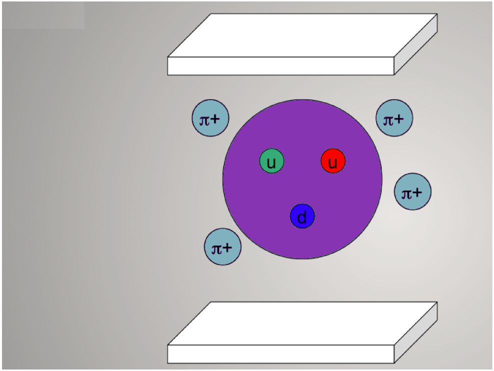


Induces a current in the pion cloud which vertically 'stretches' the proton.

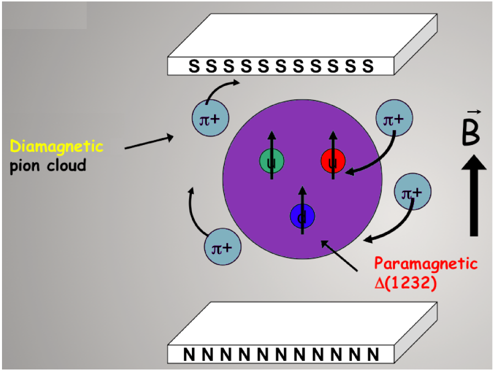
Magnetic Polarizability - β_{M1}

Describes the response of a proton to an applied magnetic field.



Magnetic Polarizability - β_{M1}

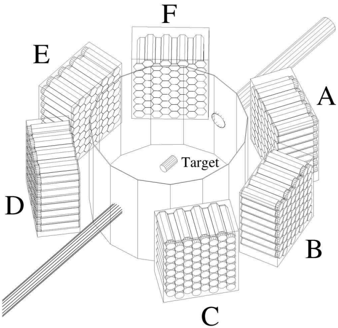
Describes the response of a proton to an applied magnetic field.

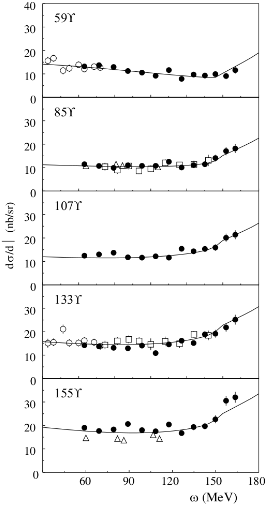


Induces a diamagnetic moment in the pion cloud that opposes the paramagnetic moment of the quarks.

Scalar Polarizabilities

Both α_{E1} and β_{M1} have been determined for the proton using unpolarized Compton scattering.





V. Olmos de Leon et al., *Eur. Phys. J.* A10, 207 (2001)

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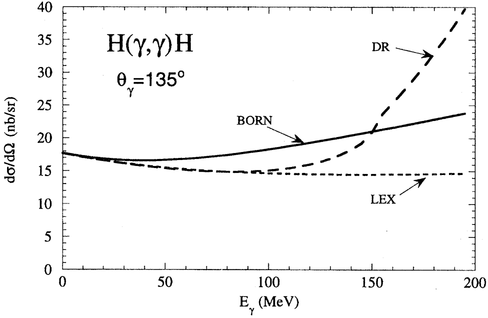
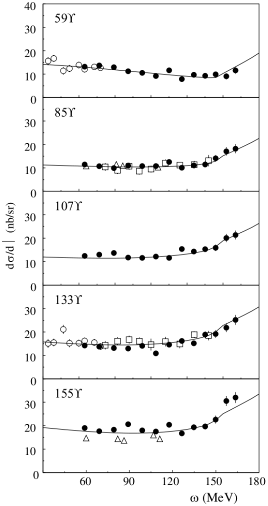
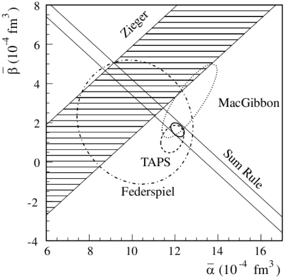




V. Olmos de Leon et al., *Eur. Phys. J.* A10, 207 (2001)

Scalar Polarizabilities

Data		$\bar\alpha+\bar\beta$ *fixed*	$\bar\alpha+\bar\beta$ *free*
TAPS (this work)	$\bar\alpha$	$12.1\pm0.4\mp1.0$	$11.9\pm0.5\mp1.3$
	$\bar\beta$	$1.6\pm0.4\pm0.8$	$1.2\pm0.7\pm0.3$
MacGibbon [27]	$\bar\alpha$	$11.9\pm0.5\mp0.8$	$12.6\pm1.2\mp1.3$
	$\bar\beta$	$1.9\pm0.5\pm0.8$	$3.0\pm1.8\pm0.1$
Federspiel [26]	$\bar\alpha$	$10.8\pm2.2\mp1.3$	$10.1\pm2.6\mp2.0$
	$\bar\beta$	$3.0\pm2.2\pm1.3$	$2.0\pm3.3\pm0.3$
Zieger [28]	$\bar\alpha-\bar\beta$	$6.4\pm2.3\pm1.9$	
Global Fit	$\bar\alpha$	$12.1\pm0.3\mp0.4$	$11.9\pm0.5\mp0.5$
	$\bar\beta$	$1.6\pm0.4\pm0.4$	$1.5\pm0.6\pm0.2$



Constrained with the Baldin (or BL, with Lapidus) Sum Rule:

$$\alpha+\beta=\frac{1}{2\pi^2}\int_{\omega_0}^{\infty}\frac{\sigma_{\rm tot}(\omega)}{\omega^2}d\omega$$

V. Olmos de Leon et al., *Eur. Phys. J.* A10, 207 (2001)

Scalar Polarizabilities

Data		$\bar\alpha+\bar\beta$ *fixed*	$\bar\alpha+\bar\beta$ *free*
TAPS (this work)	$\bar\alpha$	$12.1 \pm 0.4 \mp 1.0$	$11.9 \pm 0.5 \mp 1.3$
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Federspiel [26]	$\bar\alpha$	$10.8 \pm 2.2 \mp 1.3$	$10.1 \pm 2.6 \mp 2.0$
	$\bar\beta$	$3.0 \pm 2.2 \pm 1.3$	$2.0 \pm 3.3 \pm 0.3$
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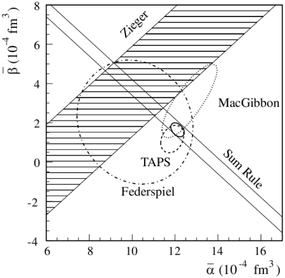

$$\alpha_{E1} = [12.1 \pm 0.3\,(\text{stat}) \mp 0.4\,(\text{syst}) \pm 0.3\,(\text{mod})] \times 10^{-4}\,\text{fm}^3$$
$$\beta_{M1} = [1.6 \pm 0.4\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.4\,(\text{mod})] \times 10^{-4}\,\text{fm}^3$$

V. Olmos de Leon et al., *Eur. Phys. J.* A10, 207 (2001)

Scalar Polarizabilities

Data		$\bar\alpha+\bar\beta$ *fixed*	$\bar\alpha+\bar\beta$ *free*
TAPS (this work)	$\bar\alpha$	$12.1 \pm 0.4 \mp 1.0$	$11.9 \pm 0.5 \mp 1.3$
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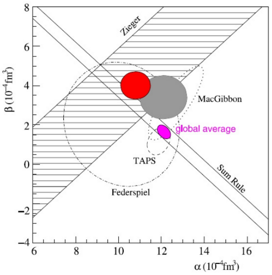


$$\alpha_{E1} = [10.8 \pm 0.7] \times 10^{-4}\,\mathrm{fm}^3$$
$$\beta_{M1} = [4.0 \pm 0.7] \times 10^{-4}\,\mathrm{fm}^3$$

V. Lensky, V. Pascalutsa, *Eur. Phys. J.* C65, 195 (2010)

Compton Scattering Equations

Third Order - Spin Polarizabilities

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

- These parameters describe the response of the proton **spin** to an applied electric or magnetic field. Analogous to a classical Faraday effect.
- To date, these have not been individually determined. However, two linear combinations of them have been.

Compton Scattering Equations

Third Order - Spin Polarizabilities

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

Forward and Backward Spin Polarizabilities

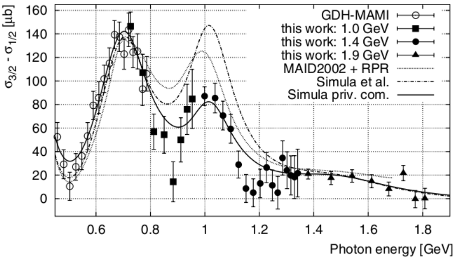
$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1E2} - \gamma_{M1M1}$$

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1E2} + \gamma_{M1M1}$$

Forward Spin Polarizability

GDH Experiments

- MAMI and ELSA
- Circular Photons
- Longitudinal Protons
- Measure Gerasimov, Drell, Hearn (GDH) Sum Rule



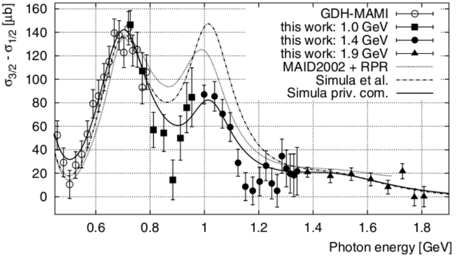
$$\frac{2\pi^2\alpha_e\kappa^2}{M^2} = \int_{\omega_0}^{\infty} \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega} d\omega$$

J. Ahrens et al., *Phys. Rev. Lett.* 87, 022003 (2001)
H. Dutz et al., *Phys. Rev. Lett.* 91, 192001 (2003)

Forward Spin Polarizability

GDH Experiments

- MAMI and ELSA
- Circular Photons
- Longitudinal Protons
- Measure Gerasimov, Drell, Hearn (GDH) Sum Rule
- Also get γ_0



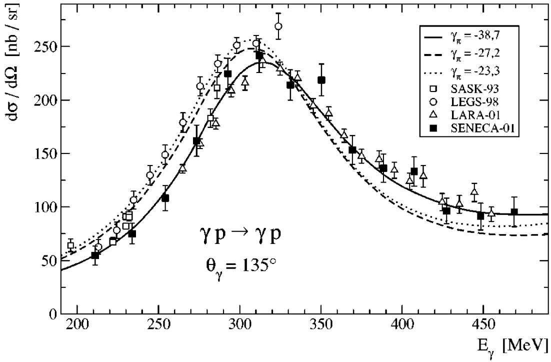
$$\gamma_0 = -\frac{1}{4\pi^2}\int_{\omega_0}^{\infty}\frac{\sigma_{3/2}(\omega)-\sigma_{1/2}(\omega)}{\omega^3}d\omega$$

$$\gamma_0 = (-1.0 \pm 0.08) \times 10^{-4}\ \mathrm{fm}^4$$

J. Ahrens et al., *Phys. Rev. Lett.* 87, 022003 (2001)
H. Dutz et al., *Phys. Rev. Lett.* 91, 192001 (2003)

Backward Spin Polarizability

Determined using a dispersive fitting to backward angle Compton scattering data, such as that taken at MAMI:



M. Camen, et al., *Phys. Rev.* C 65 (2002) 032202

$$\gamma_\pi = (8.0 \pm 1.8) \times 10^{-4}\ \text{fm}^4$$

Predicted Values

Extracting the proton spin polarizabilities would provide a useful test of nucleon structure.

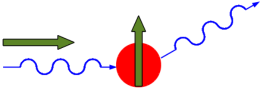
	$O(p^3)$	$O(p^4)$	$O(p^4)$	LC3	LC4	SSE	BGLMN	HDPV	KS
γ_{E1}	-5.7	-1.4	-1.8	-3.2	-2.8	-5.7	-3.4	-4.3	-5.0
γ_{M2}	1.1	0.2	0.7	0.7	0.8	.98	0.3	-0.01	-1.8
γ_{E2}	1.1	1.8	1.8	0.7	0.3	.98	1.9	2.1	1.1
γ_{M1}	-1.1	3.3	2.9	-1.4	-3.1	3.1	2.7	2.9	3.4
γ_0	4.6	-3.9	-3.6	3.1	4.8	.64	-1.5	-0.7	2.3
γ_π	4.6	6.3	5.8	1.8	-0.8	8.8	7.7	9.3	11.3

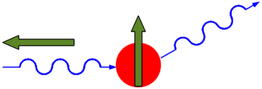
Table: Values for the spin polarizabilities. $O(p^n)$ are Chiral Perturbation Theory (ChPT) calculations. LC3 and LC4 are $O(p^3)$ and $O(p^4)$ Lorentz invariant ChPT calculations, respectively. SSE is a Small Scale Expansion calculation. The remaining three are all dispersion relation calculations.

Three Compton Scattering Experiments

- Circularly polarized photons, transversely polarized protons.

$$\Sigma_{2x} = \frac{N^R_{+x} - N^L_{+x}}{N^R_{+x} + N^L_{+x}}$$





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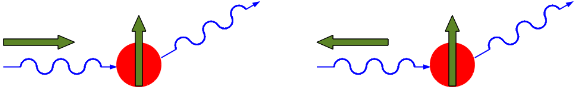
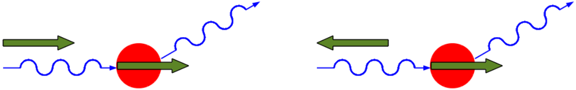


- Circularly polarized photons, longitudinally polarized protons.

$$\Sigma_{2z} = \frac{N^R_{+z} - N^L_{+z}}{N^R_{+z} + N^L_{+z}}$$



Three Compton Scattering Experiments

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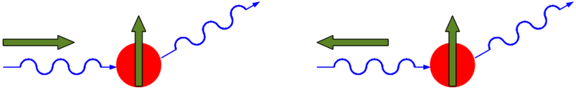

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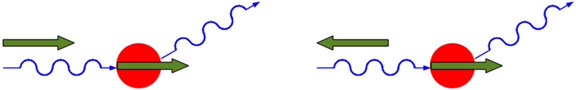
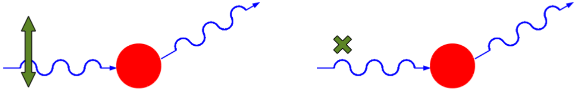


- Linearly polarized photons, unpolarized protons.

$$\Sigma_3 = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$

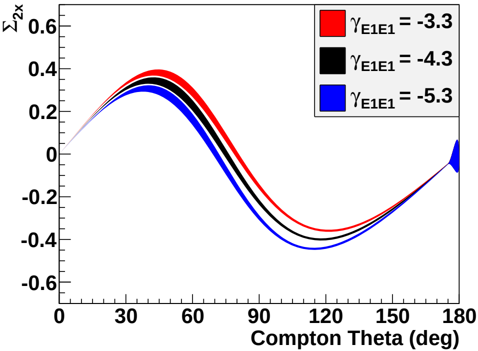


Sensitivities to SPs

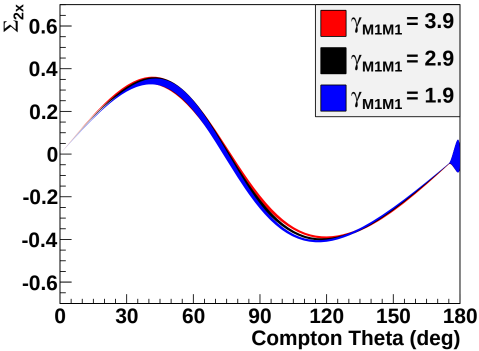
- To get a rough idea of the sensitivities, use a basis of γ_{E1E1}, γ_{M1M1}, γ_0, and γ_π.
- Use a dispersion theory calculation to produce theoretical asymmetries.
- Hold either γ_{E1E1} or γ_{M1M1} fixed, and perturb the other by some value.
- Allow α_{E1}, β_{M1}, γ_0, and γ_π to vary by their experimental errors.
- See how the asymmetries are affected by these perturbations, and see whether a measurement could differentiate them.

Circular Beam and Transverse Target - Σ_{2x}

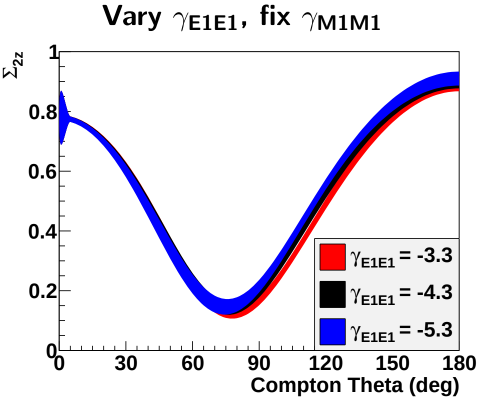
Vary γ_{E1E1}, fix γ_{M1M1}

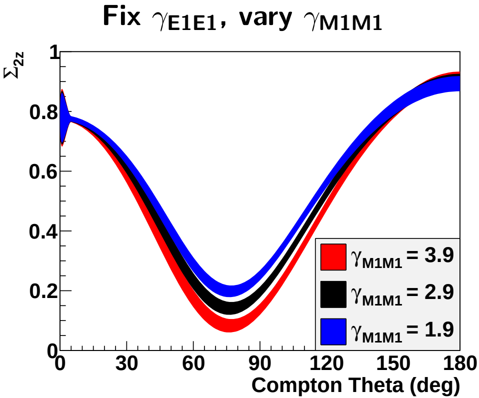


Fix γ_{E1E1}, vary γ_{M1M1}

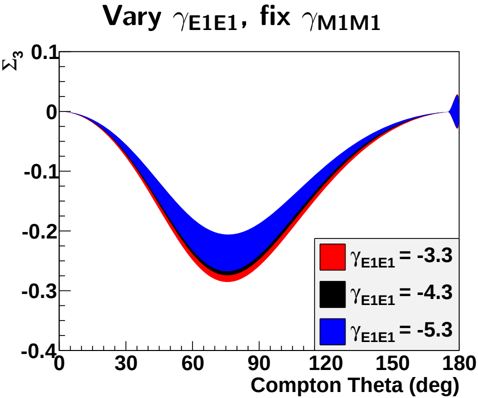


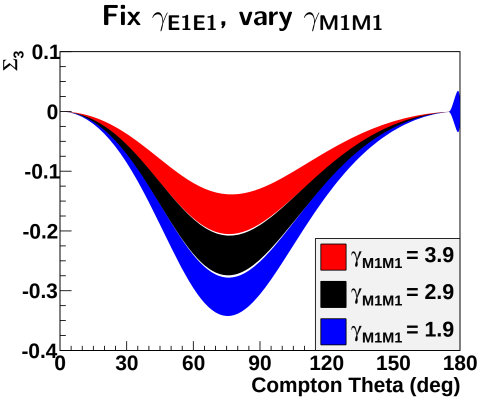
Circular Beam and Longitudinal Target - Σ_{2z}





Linear Beam and Unpolarized Target - Σ_3



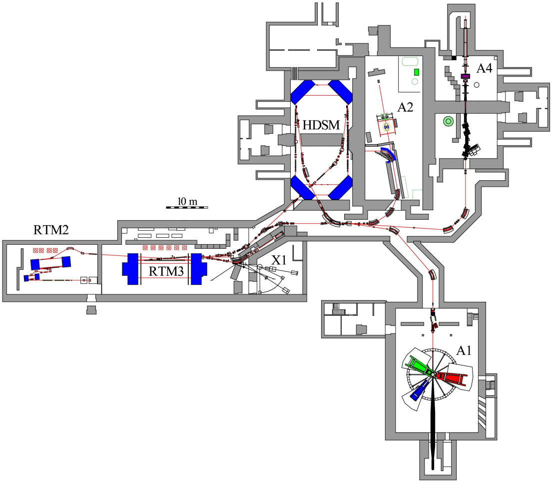


Collaboration

Extraction of SPs

- When all three experiments are completed, a full χ^2 fitting can be performed using the original basis of γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, and γ_{M1E2}, to extract all four of them.
- The experimental values for α_{E1}, β_{M1}, γ_0, and γ_π can be used to constrain the full fitting to achieve different levels of accuracy.
- Currently have about 550 hours for Σ_{2x} (two blocks: September 2010 and February 2011).
- But only about 90 hours for Σ_3 (test data from December 2008). More planned for the end of this year.

Mainz Microtron (MAMI) e^- Beam

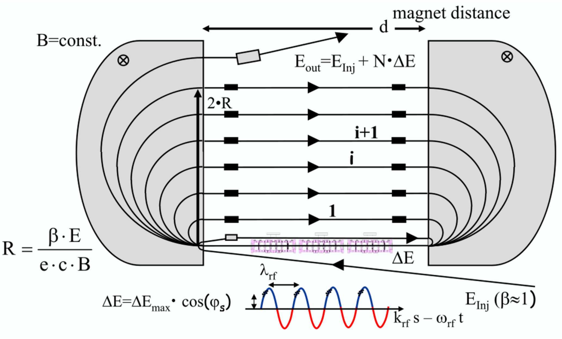


- Injector → 3.5 MeV
- RTM1 → 14.9 MeV
- RTM2 → 180 MeV
- RTM3 → 882 MeV
- HDSM → 1.6 GeV

For these experiments only the RTMs are required (450 MeV).

Racetrack Microtron (RTM)

- Linear accelerator (linac) sends e^- beam into dipole magnet.
- Magnetic field bends the beam into one of many exit lines.
- Second dipole magnet bends the beam back into the linac.
- Finally, 'kicker' magnet ejects the beam from the microtron.

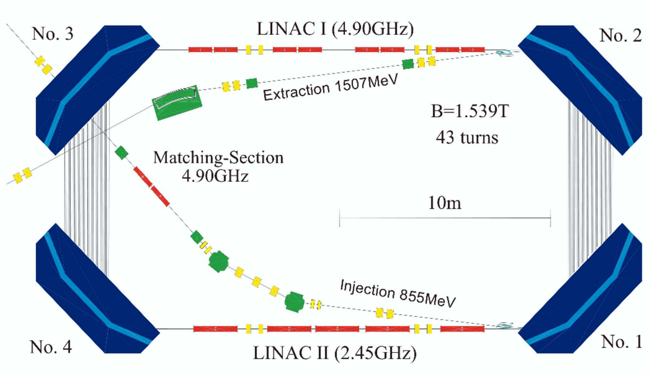


$$\Delta E = \frac{ec^2 B}{2\pi\nu_{rf}}$$

- $\nu_{rf} = 2.45$ GHz Klystron frequency

Harmonic Double Sided Microtron (HDSM)

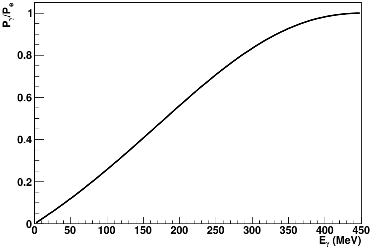
- Similar concept to the RTM, except with two linac sections and four dipole magnets.
- Allows for larger energies while keeping the magnet (and magnetic field) sizes smaller.



Polarized Photon Beam

- A high energy electron can produce Bremsstrahlung ('braking radiation') photons when slowed down by a material.
- If the electron beam is longitudinally polarized it produces a circularly polarized photon beam through a helicity transfer.

$$P_\gamma = P_e \frac{4E_\gamma E_e - E_\gamma^2}{4E_e^2 - 4E_\gamma E_e + 3E_\gamma^2}$$



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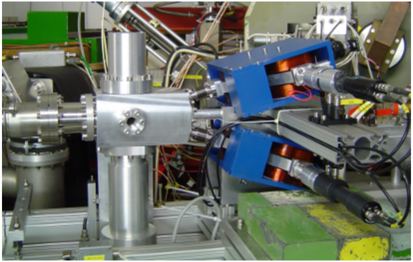

- P_e measured with a Mott polarimeter before the RTMs.

Polarized Photon Beam

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- If the electron beam is longitudinally polarized it produces a circularly polarized photon beam through a helicity transfer.
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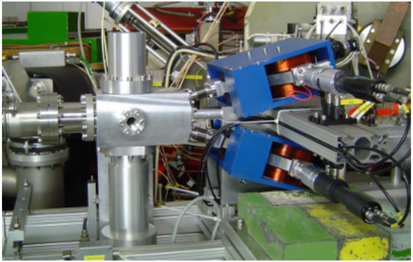
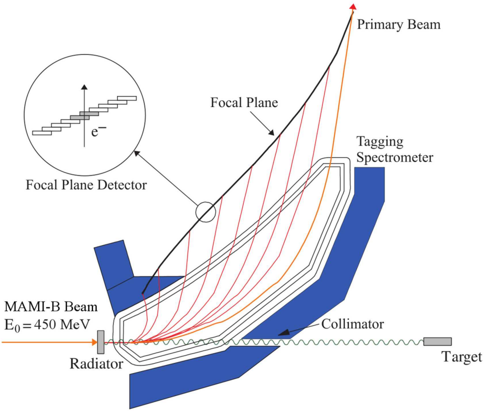


- Circular beam helicity can be flipped by alternating the e^- beam polarization (about 1 Hz).

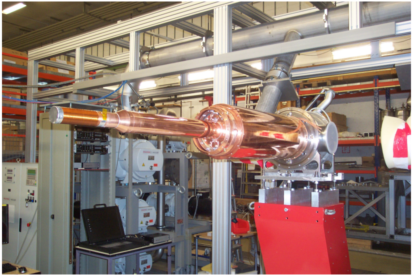
Photon Tagging



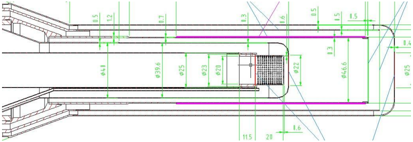
- e^- beam with energy E_0, strikes radiator producing Bremsstrahlung photon beam with energy distribution from 0 to E_0.
- Residual e^- paths are bent in a spectrometer magnet.
- With proper magnetic field, array of 353 detectors determines the e^- energy, and ‘tags’ the photon energy by energy conservation.

Polarized Target

Transversely/longitudinally polarized frozen spin butanol target utilizing Dynamic Nuclear Polarization (DNP).



^{3}He/^{4}He dilution refrigerator.



Schematic of target insert where hashed region is 2 cm of Butanol (C_4H_9OH).

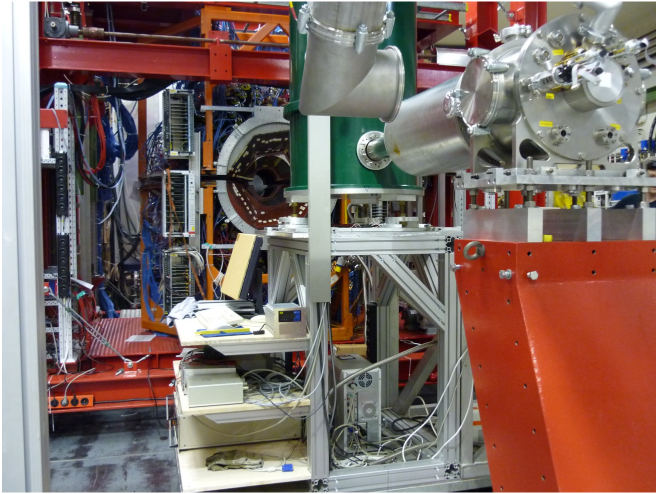
Frozen Spin Target

Polarizing protons through Dynamic Nuclear Polarization (DNP):

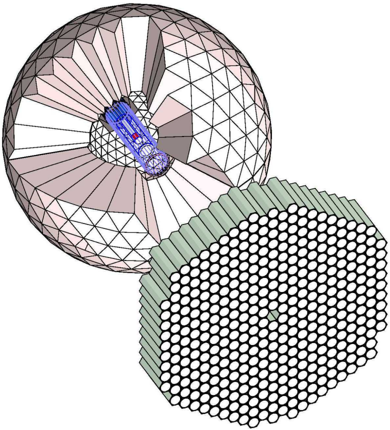
- Cool target to 0.2 Kelvin.
- Use 2.5 Tesla magnet to align electron spins.
- Pump $\approx$ 70 GHz microwaves (just above, or below, the Electron Spin Resonance frequency), causing spin-flips between the electrons and protons.
- Cool target to 0.025 Kelvin, 'freezing' proton spins in place.
- Remove polarizing magnet.
- Energize 0.6 Tesla 'holding' coil in the cryostat to maintain the polarization.
- Relaxation times $>$ 1000 hours.
- Polarizations up to 90%.

Frozen Spin Target

Polarizing protons through Dynamic Nuclear Polarization (DNP):



Detectors



Crystal Ball (CB)

- 672 NaI Crystals
- 24 Particle Identification Detector (PID) Paddles
- 2 Multiwire Proportional Chambers (MWPCs)

Two Arms Photon Spectrometer (TAPS)

- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Paddles

Crystal Ball/TAPS

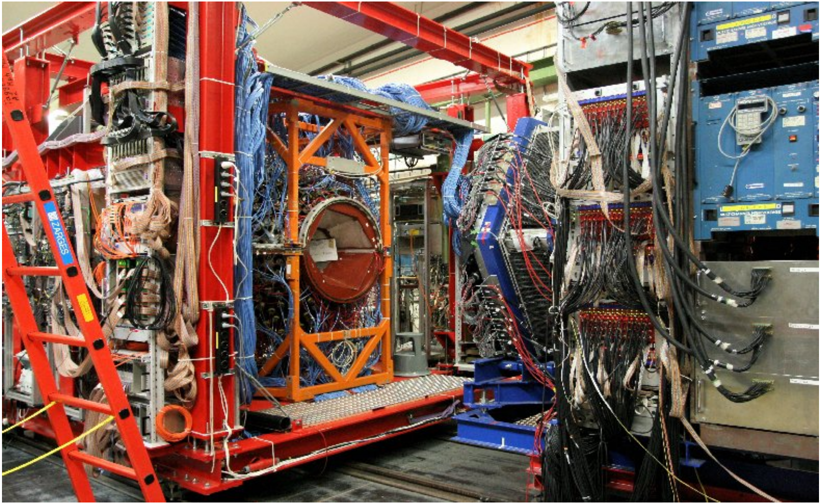
Crystal Ball

- Proposed at SLAC in 1974
- SLAC: 1974-1982 (J/ψ)
- DESY: 1982-1987 (b-quarks)
- Brookhaven: 1995-2002 (baryon resonances)
- MAMI: 2002-present
- $21^\circ < \theta < 159^\circ$
- Nearly all ϕ
- E resolution $\approx 3\%$
- θ resolution $\approx 2.5^\circ$

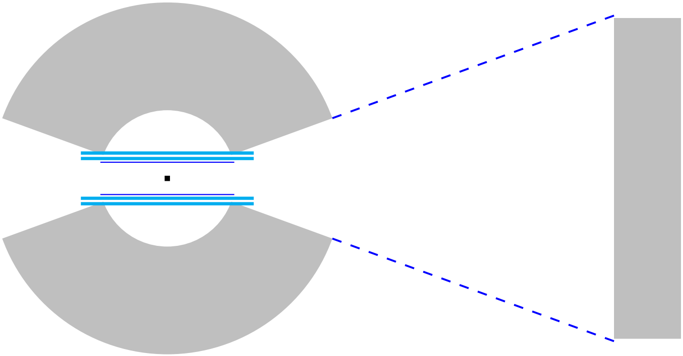
TAPS

- 1980s TAPS collaboration
- Designed for a range of experiments in various configurations such as a single wall (here), or multiple blocks (α, β, measurements)
- Fills in downstream hole
- E resolution $\approx 3\%$
- θ resolution $\approx 0.7^\circ$

Crystal Ball/TAPS

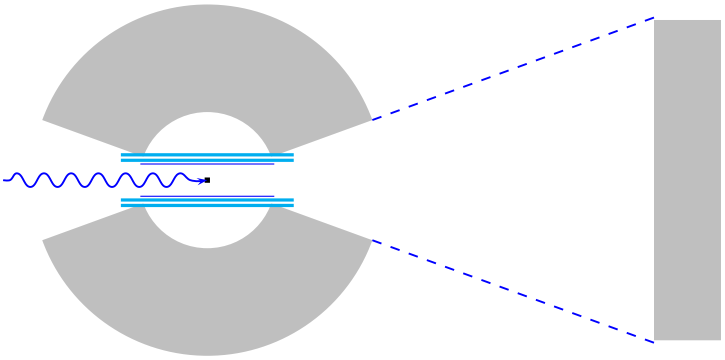


Event Selection



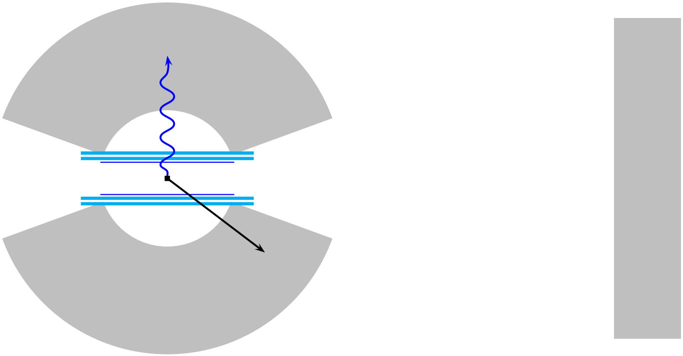
Cross section of CB and TAPS, with target cell in place.

Event Selection



Photon beam enters from the left, and strikes the target.

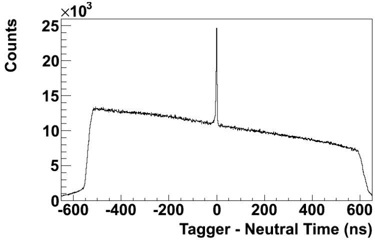
Event Selection



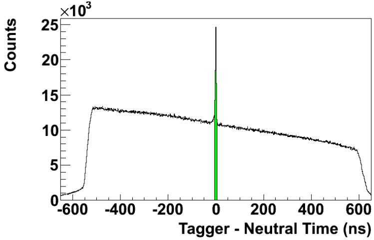
Require detection of ONLY one photon, and ONLY one charged particle, in time with a tagger hit.

Collaboration

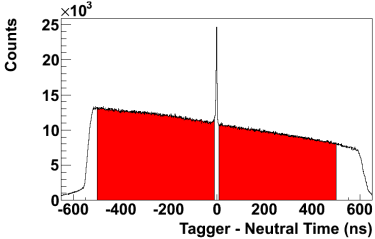
Accidentals - Prompt versus Random



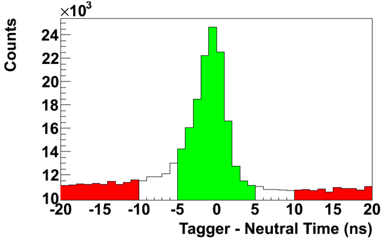
Time difference



Cut on prompts



Cut on randoms



Zoomed on peak

Compton Backgrounds

Butanol Target (C_4H_9OH)

- Compton off of H
- Coherent scatter off of C (or O)
- Incoherent scatter off of C (or O)
- Pion photoproduction off of H
- Coherent pion off of C (or O)
- Incoherent pion off of C (or O)

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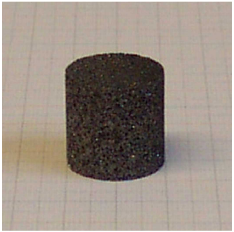

Subtract data taken on a carbon target, with density chosen to match the number of non-hydrogen nucleons in the butanol target.

Compton Backgrounds

Butanol Target (C_4H_9OH)

- Compton off of H
- Coherent scatter off of C (or O)
- Incoherent scatter off of C (or O)
- Pion photoproduction off of H
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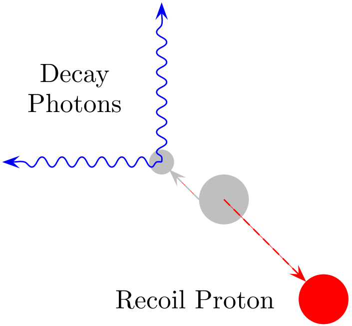
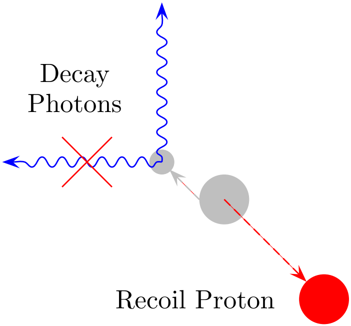
Pion Photoproduction



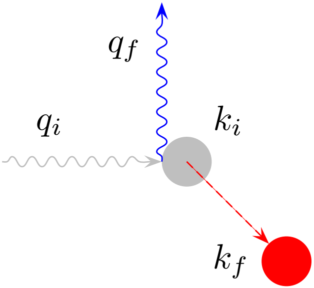
The cross section for π^0 photoproduction is about 100 times that of Compton scattering.

Pion Photoproduction



If one of the decay photons is lost, this can look like Compton.

Pion Photoproduction

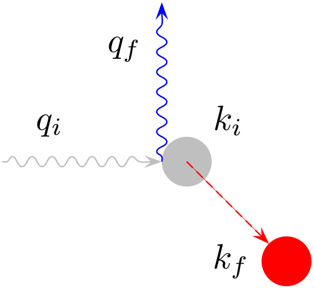


If one of the decay photons is lost, this can look like Compton.

$$k_f = q_i + k_i - q_f$$

$$k_f^2 = m_k^2 = (q_i + k_i - q_f)^2$$

Pion Photoproduction



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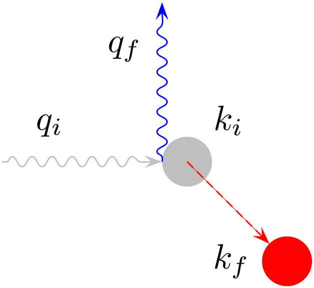
$$k_f^2 = m_k^2 = (q_i + k_i - q_f)^2$$

Missing Mass

$$m_{miss} = m_k = \sqrt{(E_{\gamma_i} + m_p - E_{\gamma_f})^2 - (\vec{p}_{\gamma_i} - \vec{p}_{\gamma_f})^2} \underset{\text{Compton}}{=} m_p$$

Pion Photoproduction



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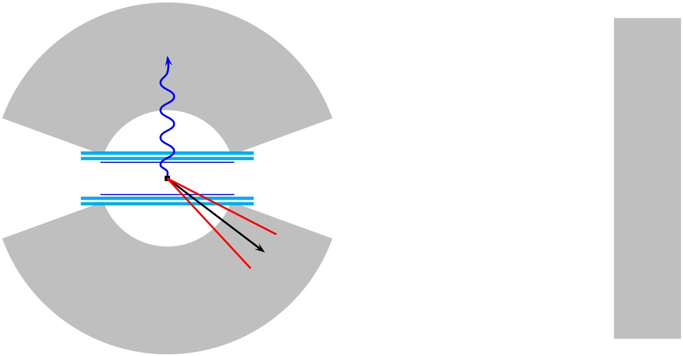
$$k_f = q_i + k_i - q_f$$

$$k_f^2 = m_k^2 = (q_i + k_i - q_f)^2$$

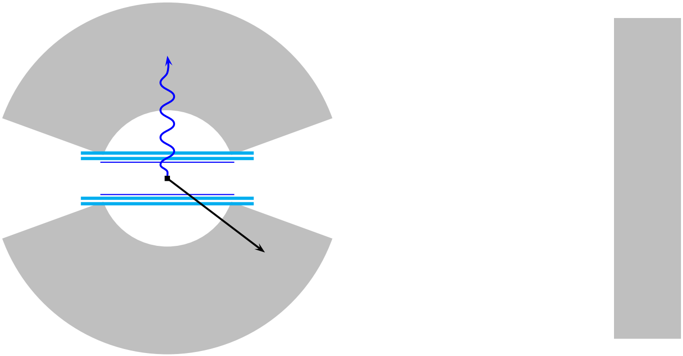
But isn't the proton detected anyway? Why not use that information? Since the proton is massive, and it must penetrate lots of material to reach a detector, it suffers from severe energy losses. However, it can be used for an opening angle cut.

Proton Opening Angle Cut



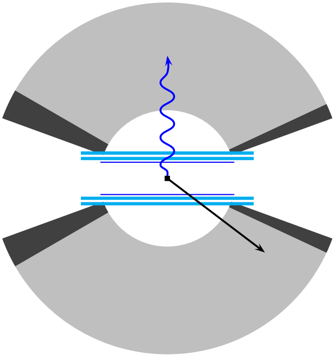
Make an ‘opening angle’ cut, requiring that the proton is detected within a cone of its expected angle.

Pion Background



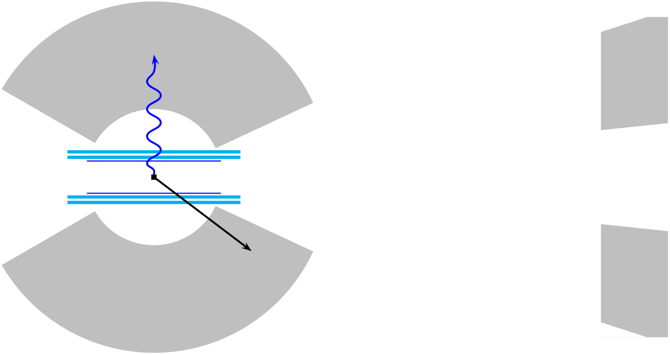
Given the coverage of the detector, how does a π^0 decay photon go missing?

Pion Background



Since the detector isn't great at the very forward/backward angles, some 'fiducial' cuts are made.

Pion Background



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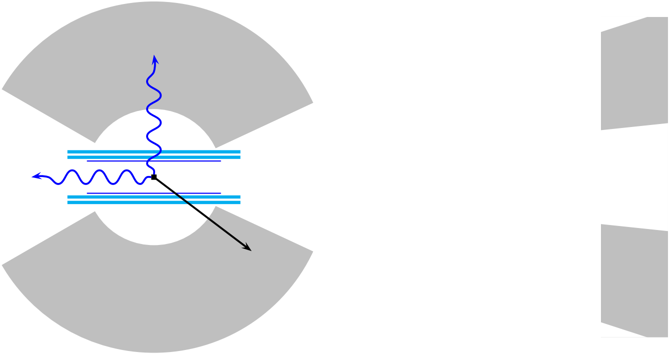
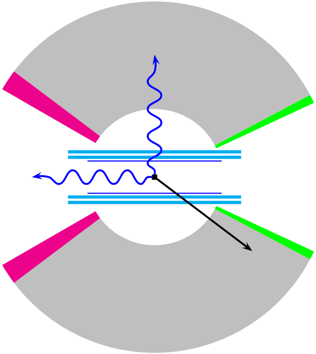
Pion Background



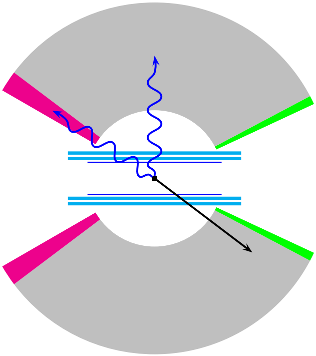
Obvious places where a π^0 decay photon can escape.
Can this background be modeled using real data?

Pion Background



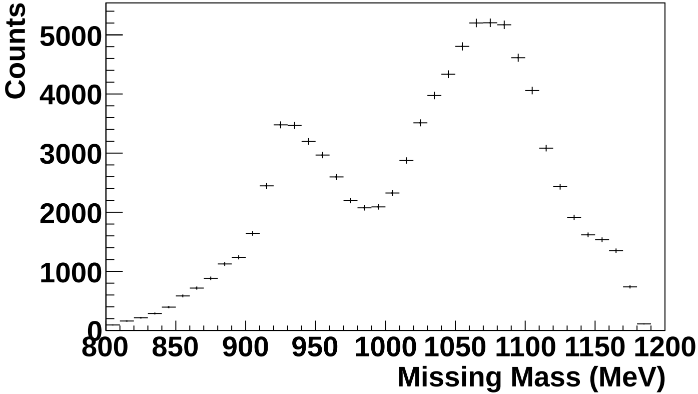
Establish a ‘ring’, with a solid angle related to a ‘hole’ in the detector.

Pion Background



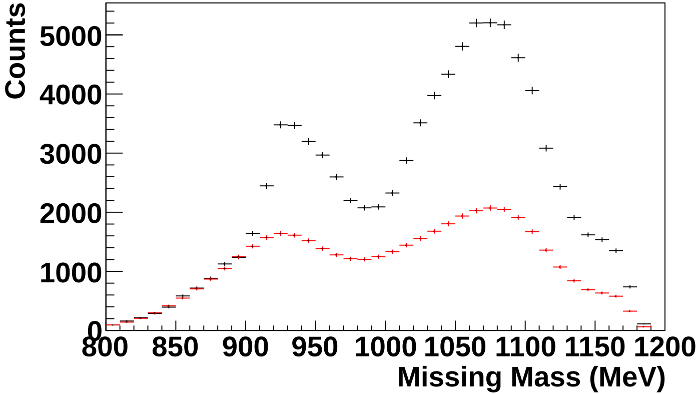
In instances where a π^0 decay photon is detected in the ring, ignore it and analyze the event like Compton.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



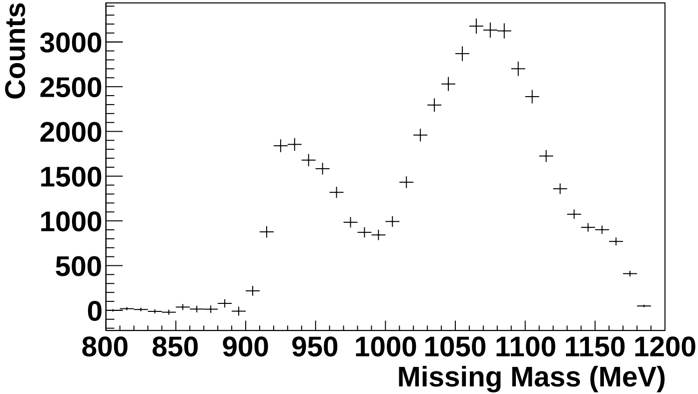
Initial missing mass distribution from the butanol target.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



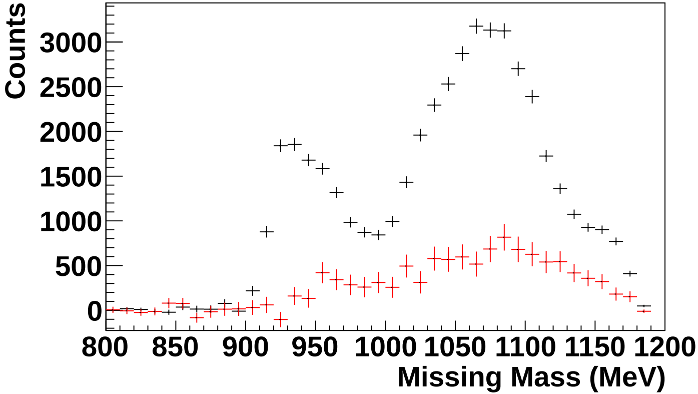
Background from accidental (random) events in tagger.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



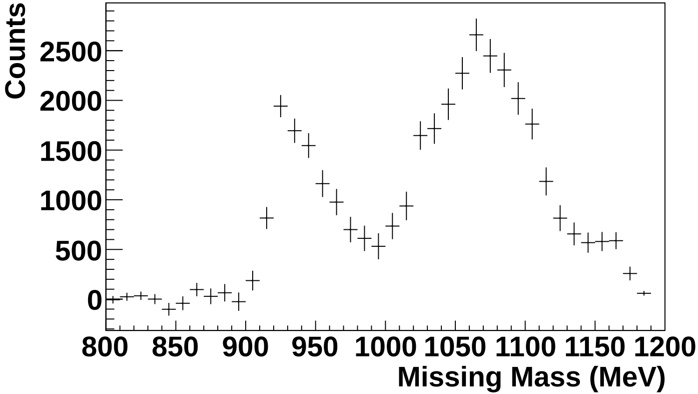
Distribution after removing accidentals.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



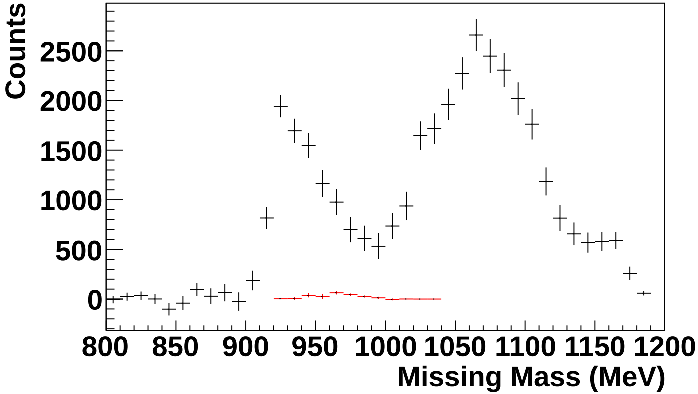
Background from the carbon target.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



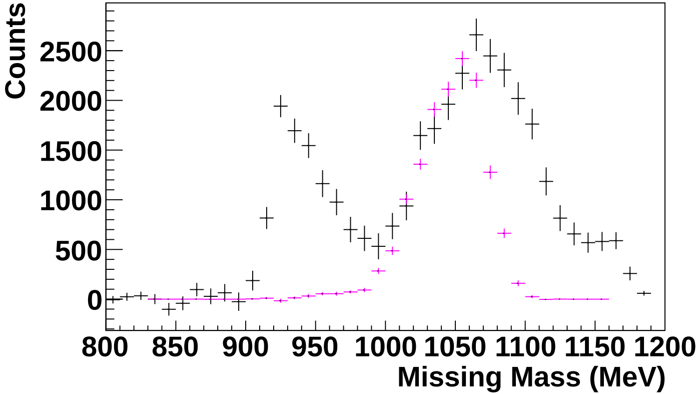
Distribution after removing carbon background.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



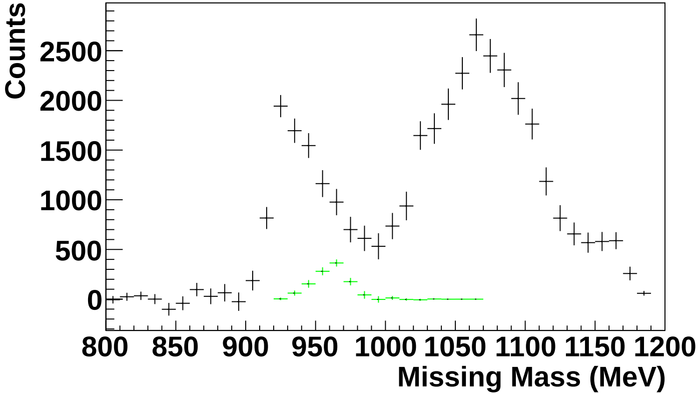
Background from π^0 photon in downstream (TAPS) hole.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



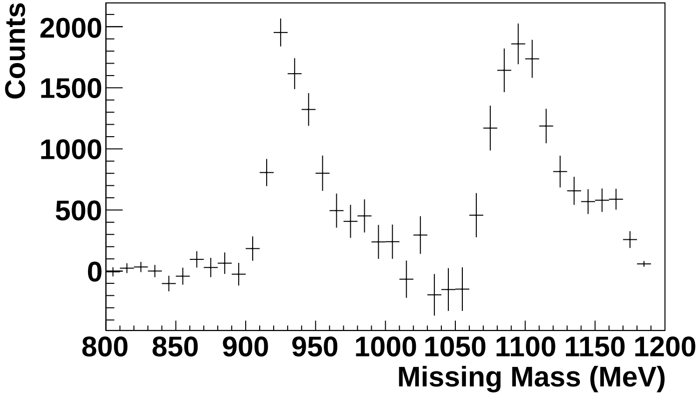
Background from π^0 photon in upstream (CB) hole.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



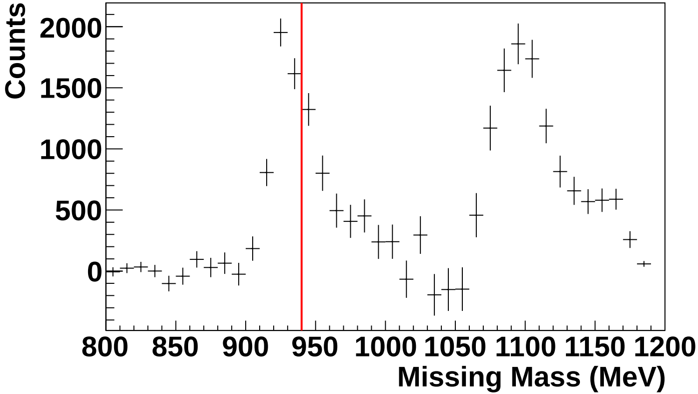
Background from π^0 photon between CB/TAPS.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



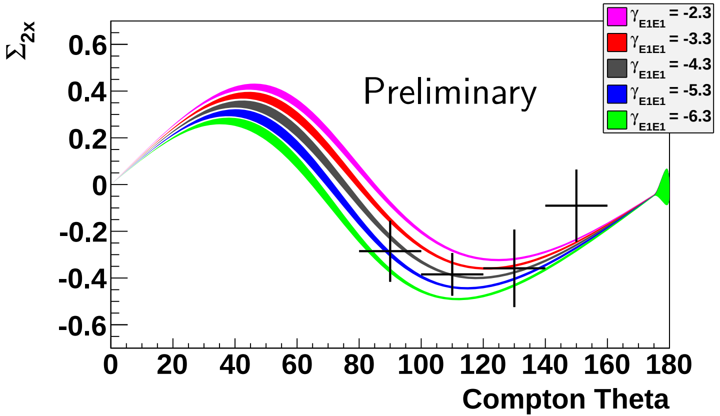
Final distribution after subtracting backgrounds.

Missing Mass - E_γ=273-303 MeV, $\theta_{\gamma'}$=100-120°



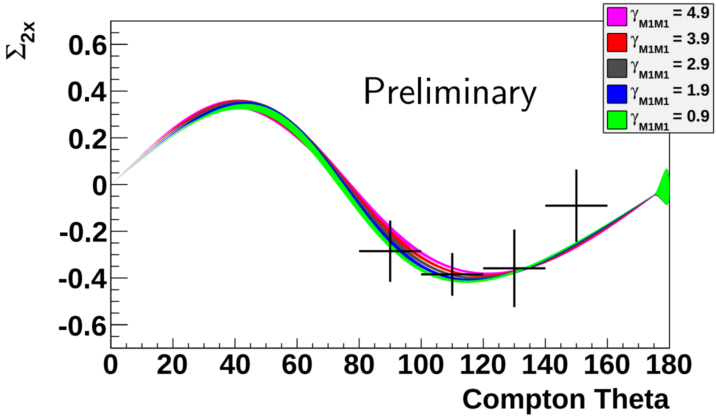
Total events determined by integrating up to proton mass.

Transverse Asymmetries - E_γ=273-303 MeV



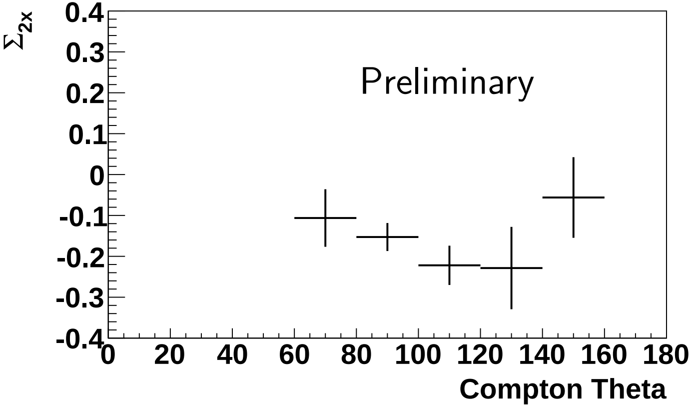
Vary γ_{E1E1}, holding γ_{M1M1} fixed at 2.9.

Transverse Asymmetries - E_γ=273-303 MeV



Vary γ_{M1M1}, holding γ_{E1E1} fixed at -4.3.

Transverse Asymmetries - E_γ=315-346 MeV



Above validity of dispersion relation.

Conclusions

- These are the first double polarized asymmetries, at these energies, observed in real Compton scattering off of the proton.
- Even with conservative integration limit, these asymmetries agree with a value for $\gamma_{E1E1} = -4.3 \times 10^{-4}\,\mathrm{fm}^4$.
- A global χ^2 fit using all available data is in progress, as well as further simulation to improve integration.
- Future:
  - Dedicated running on the unpolarized hydrogen target
  - Installation of, and running on, the longitudinal butanol target
- With all three experiments, the extraction of the proton spin-polarizabilities will provide an important test of nucleon structure.

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A2 Collaboration

Thanks go to:

- J. Annand - Glasgow
- P. Hall Barrientos - Glasgow
- B. Barnes - UMass
- A. Bernstein - MIT
- B. Briscoe - GWU
- C. Collicott - SMU/Dalhousie
- E. Downie - GWU
- D. Glazier - Edinburgh
- D. Hornidge - MTA
- G. Huber - Regina
- D. Middleton - Mainz/MTA
- A. Mushkarenkov - UMass
- M. Ostrick - Mainz
- B. Pasquini - Pavia
- S. Schumann - Mainz
- A. Thomas - Mainz

As well as many others in the A2 collaboration.