MAMI results for polarizabilities

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A2 Collaboration

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Mount Allison U., Saint Mary's U., and U. of Regina

ECT* - Nucleon Spin Structure at Low Q
Trento, Italy - 3 July 2018

Compton Scattering Equations

Zeroth Order - Mass and Electric Charge

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

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First Order - Anomalous Magnetic Moment

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

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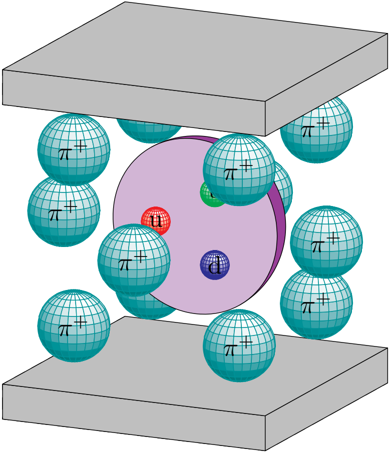
Second Order - Electric and Magnetic Polarizabilities

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

Electric Polarizability - α_{E1}

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



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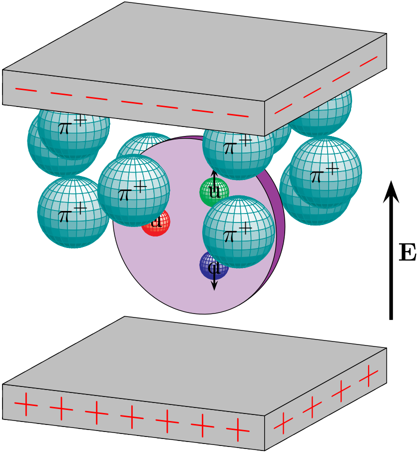
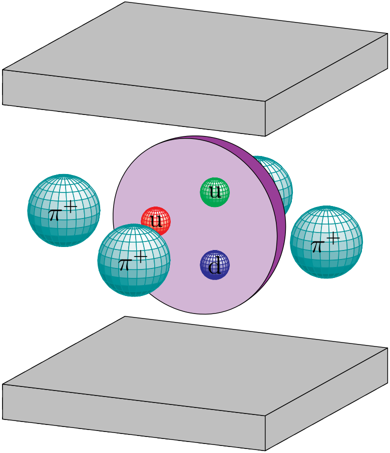


Induces a current in the pion cloud which vertically 'stretches' the proton (stretchability).

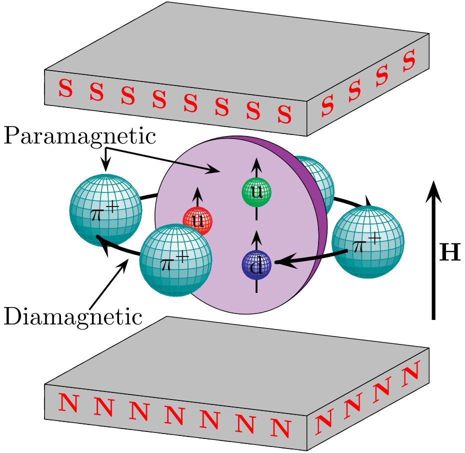
Magnetic Polarizability - β_{M1}

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



Magnetic Polarizability - β_{M1}

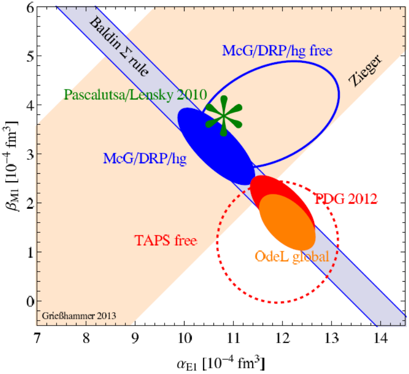
Describes the response of a proton to an applied magnetic field.



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

Scalar Polarizabilities

Determined using unpolarized Compton scattering (Note, errors are added in quadrature, see papers for details)



OdeL Global

$$\alpha_{E1} = (12.1 \pm 0.6) \times 10^{-4}\,\mathrm{fm}^3$$
$$\beta_{M1} = (1.6 \pm 0.7) \times 10^{-4}\,\mathrm{fm}^3$$

Baldin (Lapidus) Sum Rule:

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

V. Olmos de Leon *et al.* (A2), Eur. Phys. J. A 10, 207 (2001)

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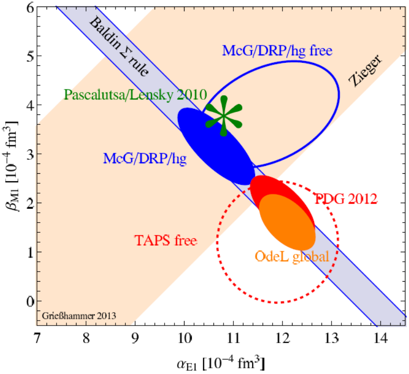

PDG 2012

$$\alpha_{E1} = (12.0 \pm 0.6) \times 10^{-4}\,\mathrm{fm}^3$$
$$\beta_{M1} = (1.9 \pm 0.5) \times 10^{-4}\,\mathrm{fm}^3$$

Baldin (Lapidus) Sum Rule:

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

V. Olmos de Leon *et al.* (A2), Eur. Phys. J. A 10, 207 (2001)

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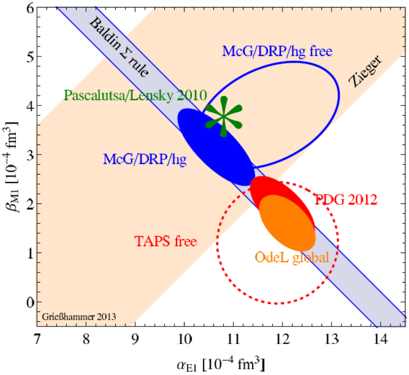


Pascalutsa/Lensky

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

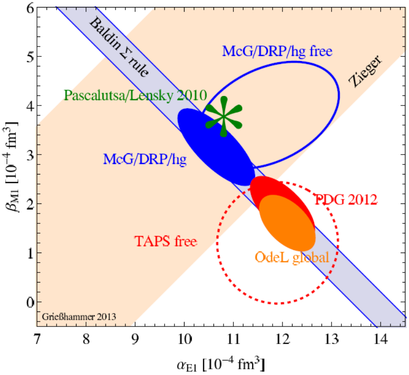
Baldin (Lapidus) Sum Rule:

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

Lensky, Pascalutsa, Eur. Phys. J. C 65, 195 (2010)

Scalar Polarizabilities

Determined using unpolarized Compton scattering (Note, errors are added in quadrature, see papers for details)



McG/DRP/hg

$$\alpha_{E1} = (10.65 \pm 0.5) \times 10^{-4}\,\mathrm{fm}^3$$
$$\beta_{M1} = (3.15 \pm 0.5) \times 10^{-4}\,\mathrm{fm}^3$$

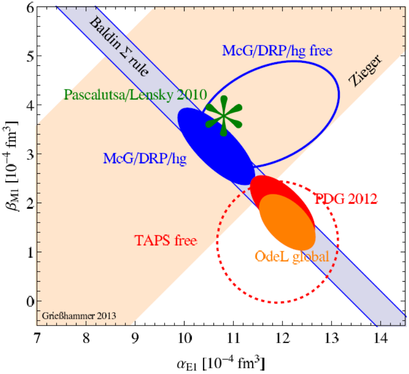
Baldin (Lapidus) Sum Rule:

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

McGovern, Phillips, Grießhammer, Eur. Phys. J. A 49, 12 (2013)

Scalar Polarizabilities

Determined using unpolarized Compton scattering (Note, errors are added in quadrature, see papers for details)



PDG 2013/2014

$$\alpha_{E1} = (11.2 \pm 0.4) \times 10^{-4}\,\mathrm{fm}^3$$
$$\beta_{M1} = (2.5 \pm 0.4) \times 10^{-4}\,\mathrm{fm}^3$$

Baldin (Lapidus) Sum Rule:

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

Perhaps we can do better.

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.

Spin Polarizabilities

Forward Spin Polarizability

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1E2} - \gamma_{M1M1} = (-1.0 \pm 0.08) \times 10^{-4}\ \mathrm{fm}^4$$

Determined at MAMI and ELSA through the GDH experiments

J. Ahrens *et al.* (GDH/A2), Phys. Rev. Lett. 87, 022003 (2001)
H. Dutz *et al.* (GDH), Phys. Rev. Lett. 91, 192001 (2003)

Backward Spin Polarizability

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1E2} + \gamma_{M1M1} = (8.0 \pm 1.8) \times 10^{-4}\ \mathrm{fm}^4$$

Determined with dispersive fits to back-angle Compton scattering

M. Camen *et al.* (A2), Phys. Rev. C 65, 032202 (2002)

Spin Polarizabilities

Change of Basis

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

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

Using the above relations, we can express the two mixed terms

$$\gamma_{E1M2} = -\gamma_{E1E1} - \frac{1}{2}\gamma_0 - \frac{1}{2}\gamma_\pi$$

$$\gamma_{M1E2} = -\gamma_{M1M1} - \frac{1}{2}\gamma_0 + \frac{1}{2}\gamma_\pi$$

This leaves us with two unknown and two known (with error) terms.

Predicted Values

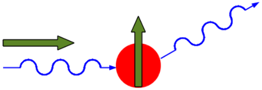
	K-mat.	HDPV	DPV	L_χ	HBχPT	BχPT
γ_{E1E1}	-4.8	-4.3	-3.8	-3.7	-1.1 ± 1.8 (th)	-3.3
γ_{M1M1}	3.5	2.9	2.9	2.5	2.2 ± 0.5 (st) ± 0.7 (th)	3.0
γ_{E1M2}	-1.8	-0.02	0.5	1.2	-0.4 ± 0.4 (th)	0.2
γ_{M1E2}	1.1	2.2	1.6	1.2	1.9 ± 0.4 (th)	1.1
γ_0	2.0	-0.8	-1.1	-1.2	-2.6	-1.0
γ_π	11.2	9.4	7.8	6.1	5.6	7.2

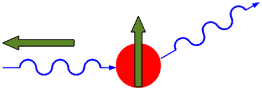
- Spin polarizabilities in units of 10^{-4} fm^4
- K-matrix: calculation from Kondratyuk *et al.*, Phys. Rev. C 64, 024005 (2001)
- HDPV, DPV: dispersion relation calculations, B.R. Holstein *et al.*, Phys. Rev. C 61, 034316 (2000) and B. Pasquini *et al.*, Phys. Rev. C 76, 015203 (2007), D. Drechsel *et al.*, Phys. Rep. 378, 99 (2003)
- L_χ: chiral lagrangian calculation, A.M. Gasparyan *et al.*, Nucl. Phys. A 866, 79 (2011)
- HBχPT and BχPT are heavy baryon and covariant, respectively, chiral perturbation theory calculations, J.A. McGovern *et al.*, Eur. Phys. J. A 49, 12 (2013), V. Lensky *et al.*, Phys. Rev. C 89, 032202 (2014)

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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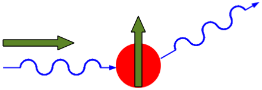
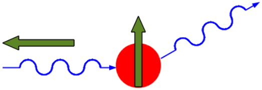
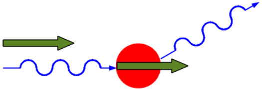
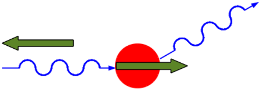




- Circularly polarized photons, longitudinally polarized protons.

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





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- Circularly polarized photons, transversely polarized protons.

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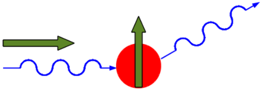
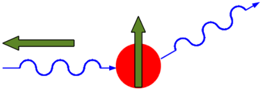

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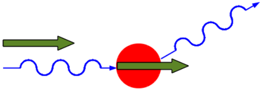
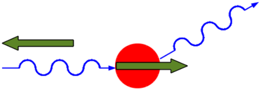
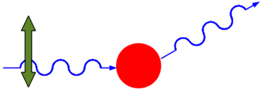
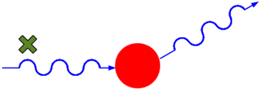
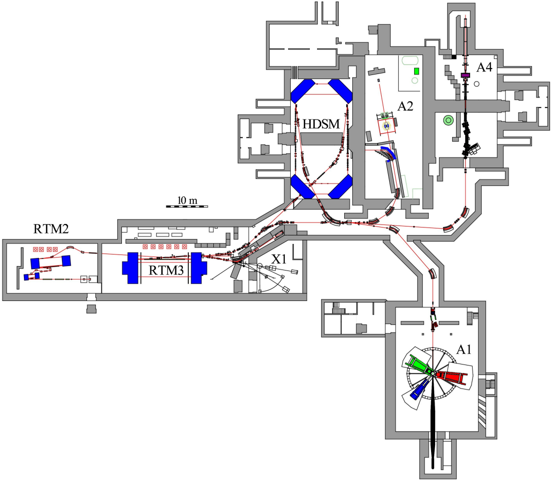



- Linearly polarized photons, unpolarized protons.

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

Mainz Microtron (MAMI) e^- Beam



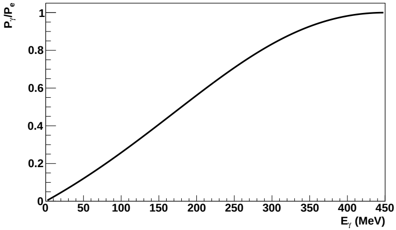
- Injector → 3.5 MeV
- RTM1 → 14.9 MeV
- RTM2 → 180 MeV
- RTM3 → 883 MeV
- HDSM → 1.6 GeV

For these experiments only the RTMs are required (450 or 883 MeV).

Polarized Photon Beam

A high energy electron can produce Bremsstrahlung (‘braking radiation’) photons when slowed down by a material.

- Longitudinally polarized electron beam produces circularly polarized photon beam (helicity transfer)
- P_e measured with a Mott polarimeter before the RTMs.
- Circular beam helicity flipped by alternating the e^- beam polarization ($\approx$ 1 Hz).

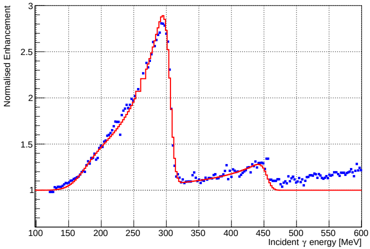


$$P_\gamma = P_e \frac{4E_\gamma E_e - E_\gamma^2}{4E_e^2 - 4E_\gamma E_e + 3E_\gamma^2}$$

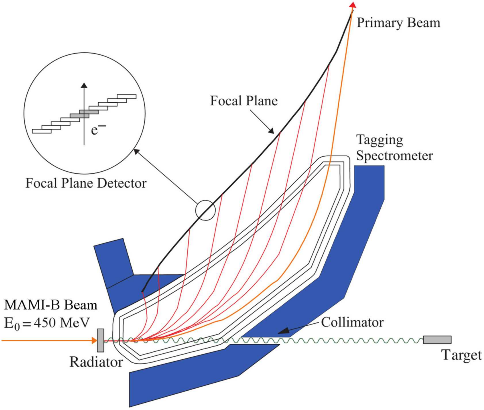
Polarized Photon Beam

A high energy electron can produce Bremsstrahlung (‘braking radiation’) photons when slowed down by a material.

- Diamond radiator produces linearly polarized photon beam (coherent Bremsstrahlung)
- Polarization determined by fitting the Bremsstrahlung distribution.
- Linear beam orientation typically flipped every two hours.



Photon Tagging



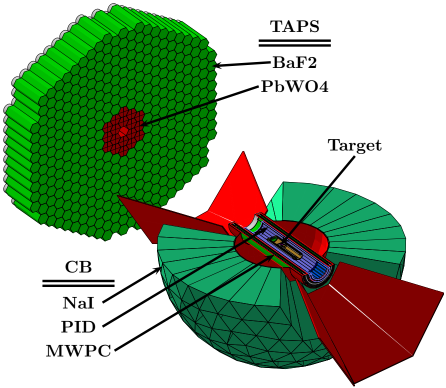
- e^- beam with energy E_0, strikes radiator producing Bremsstrahlung photon beam with energy distribution from 0 to E_0.
- Residual e^- paths are bent in a spectrometer magnet.
- With proper magnetic field, array of 352 detectors determines the e^- energy, and ‘tags’ the photon energy by energy conservation.

Frozen Spin Target

How are the protons actually polarized? 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 and energize 0.6 Tesla ‘holding’ coil in the cryostat to maintain the polarization.
- Relaxation times $>$ 1000 hours, polarizations up to 90%.

Detectors



Crystal Ball (CB)

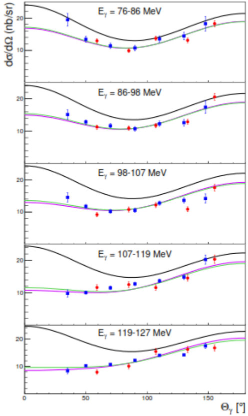
- 672 NaI Crystals
- 24 Particle Identification Detector (PID) Paddles
- 2 Multiwire Proportional Chambers (MWPCs)

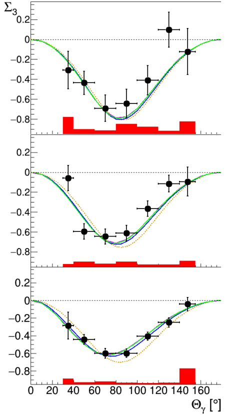
Two Arms Photon Spectrometer (TAPS)

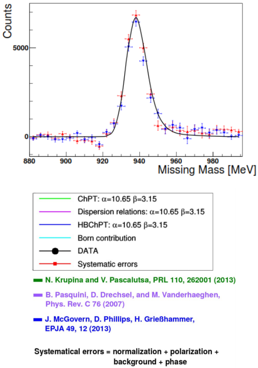
- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Paddles

Σ_3/σ_0 - α and β

- Measure σ_0 and Σ_3 at energies below π^0 threshold
- Test run in June 2013, Eur. Phys. J. A 53, 14 (2017)

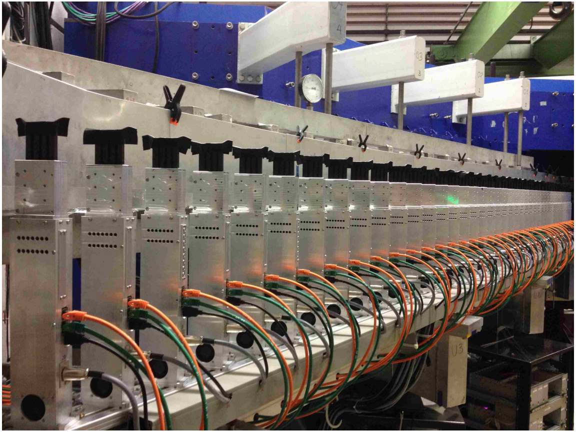






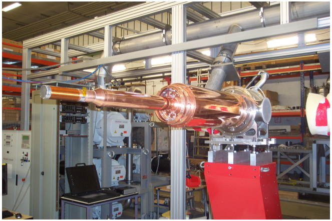
Need more data!

Tagger upgrade



Three weeks of data in Nov 2017, one in Feb 2018, three in Mar 2018, and three starting today!

Beamtimes



Polarized frozen spin butanol target

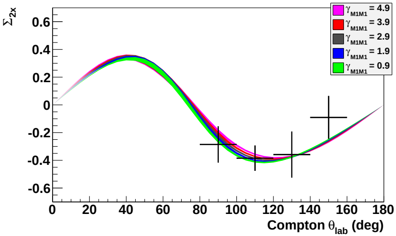
- 2 cm - Butanol (C_4H_9OH)
- Σ_{2x} - Sep 2010/Feb 2011 - 500 h
- Σ_{2z} - May 2014/Jun 2015 - 600 h

Unpolarized liquid hydrogen target

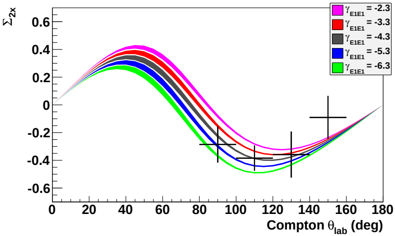
- 10 cm - LH2
- Σ_3 (Delta) - Dec 2012 - 150 h
- Σ_3/σ_0 (Threshold) - Various...

Transverse Target - E_γ=273-303 MeV

Fix γ_{E1E1}



Fix γ_{M1M1}

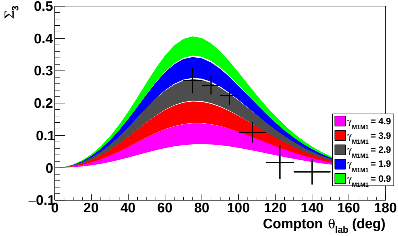


Determine the other two using γ_0 and γ_π, while allowing them, α_{E1}, and β_{M1} to vary by their experimental errors.

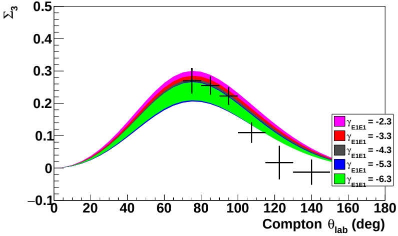
Martel *et al.* (A2) Phys. Rev. Lett. 114, 112501 (2015)

Hydrogen Target - E_γ=287-307 MeV - Preliminary

Fix γ_{E1E1}



Fix γ_{M1M1}



Determine the other two using γ_0 and γ_π, while allowing them, α_{E1}, and β_{M1} to vary by their experimental errors.

C. Collicott, Ph.D. thesis, Dalhousie University (2015)

Fitting

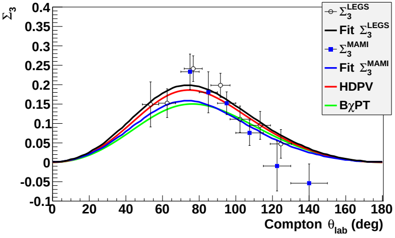
Dispersion relation fitted to Σ_{2x} along with either Σ_3^{MAMI} or Σ_3^{LEGS} - G. Blanpied *et al.*, Phys. Rev. C 64, 025203 (2001)

	Σ_{2x} and Σ_3^{LEGS}	Σ_{2x} and Σ_3^{MAMI}
$\bar{\gamma}_{E1E1}$	-3.5 $\pm$ 1.2	-5.0 $\pm$ 1.5
$\bar{\gamma}_{M1M1}$	3.16 $\pm$ 0.85	3.13 $\pm$ 0.88
$\bar{\gamma}_{E1M2}$	-0.7 $\pm$ 1.2	1.7 $\pm$ 1.7
$\bar{\gamma}_{M1E2}$	1.99 $\pm$ 0.29	1.26 $\pm$ 0.43
γ_0	-1.03 $\pm$ 0.18	-1.00 $\pm$ 0.18
γ_π	9.3 $\pm$ 1.6	7.8 $\pm$ 1.8
$\bar{\alpha} + \bar{\beta}$	14.0 $\pm$ 0.4	13.8 $\pm$ 0.4
$\bar{\alpha} - \bar{\beta}$	7.4 $\pm$ 0.9	6.6 $\pm$ 1.7
χ^2/dof	1.05	1.25

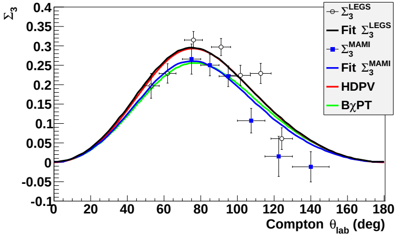
Scalar polarizabilities in units of 10^{-4} fm^3
Spin polarizabilities in units of 10^{-4} fm^4

Hydrogen Target - Preliminary

E_γ=267-287 MeV



E_γ=287-307 MeV

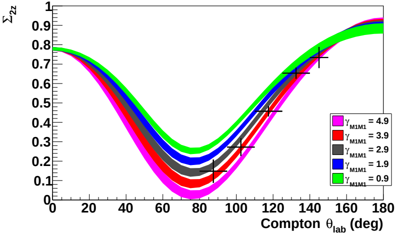


Added dispersion calculations with the fitted polarizability values.
Fit with LEGS → HDPV. Fit with MAMI → BχPT.

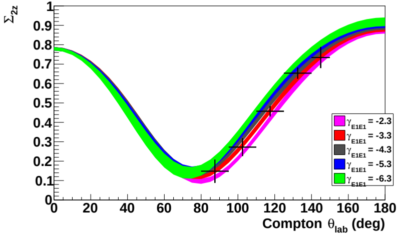
C. Collicott, Ph.D. thesis, Dalhousie University (2015)

Longitudinal Target - Preliminary

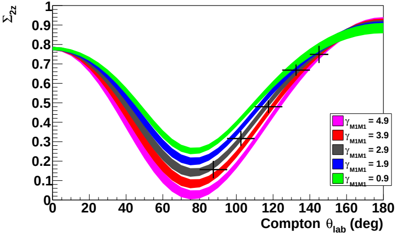
E_γ=265-285 MeV Fix γ_{E1E1}



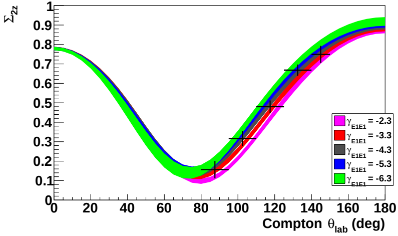
E_γ=265-285 MeV Fix γ_{M1M1}



E_γ=285-305 MeV Fix γ_{E1E1}



E_γ=285-305 MeV Fix γ_{M1M1}



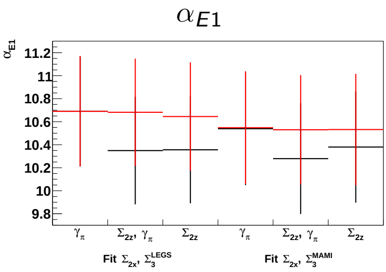
Why still preliminary?

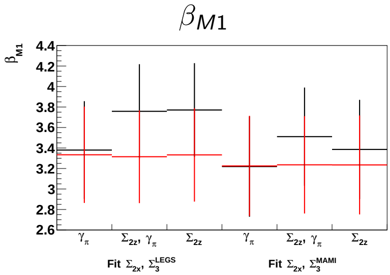
Σ_3 (Delta) data is 5 1/2 years old, the Σ_{2z} data is 3-4 years old. What's the hold-up?

- Σ_3 is essentially done. Needed some additional checks of the systematics from the polarization of the beam, which have been done. Paper in production now.
- Σ_{2x} was done (or so we thought). Paper sent through internal review, found a discrepancy with another analysis. Under investigation now, but all parties appear to be converging. Hopefully submitted soon.

For now, assuming those numbers are correct, how well do they improve our polarizability extraction?

Fitting - Scalar Polarizabilities

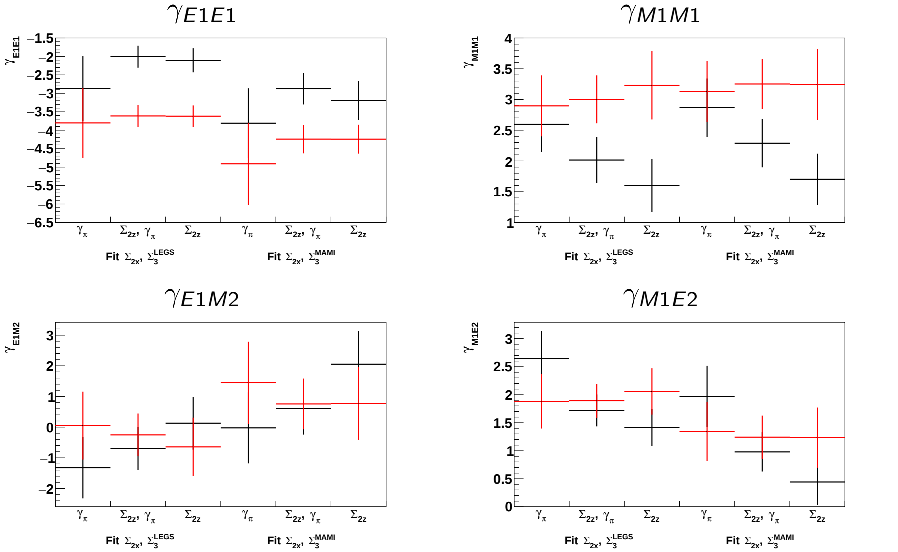




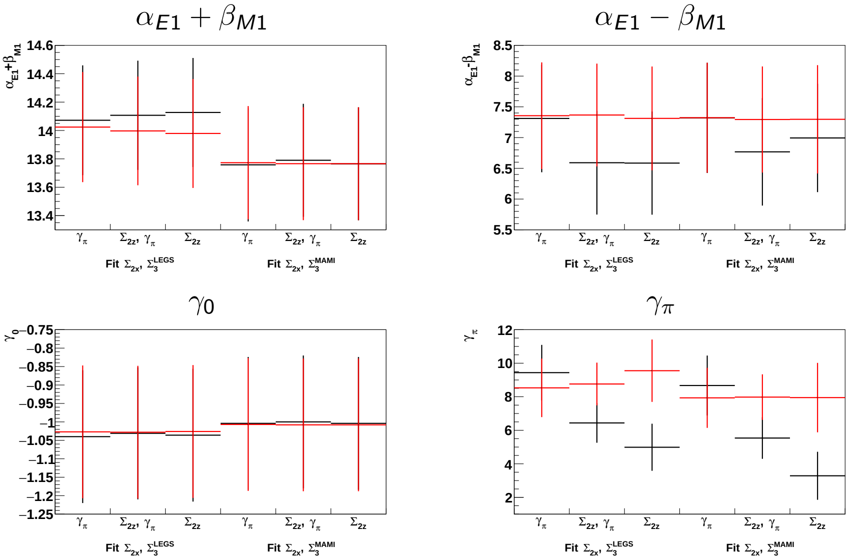
Fitting the Σ_{2x} results as well as either the Σ_3^{LEGS} (left three points) or the Σ_3^{MAMI} results (right three points), using BχPT (black) or HDPV (red), each set of three points (L-R) represent:

- Using the γ_π constraint
- Fitting Σ_{2z} and using the γ_π constraint
- Fitting Σ_{2z} without the γ_π constraint

Fitting - Spin Polarizabilities



Fitting - Constraints



Should we be measuring these asymmetries in the Delta?

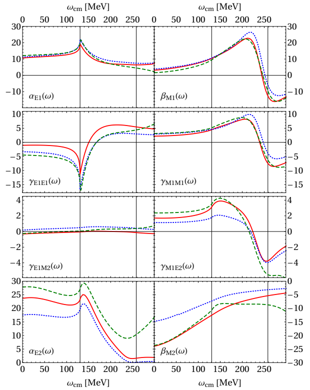


Figure 1: (Colour online) Real parts of the dominant dynamical polarisabilities for low-energy Compton scattering from the proton, plotted as a function of cm photon energy. The units are 10^{-4} fm^n where $n = 3$ for α_{E1} and β_{M1}, $n = 4$ for the γ_i, and $n = 5$ for α_{E2} and β_{E2}. Red (solid): this work; green (dashed): DR-based by Pasquini *et al.* [21]; blue (dotted) 3rd-order covariant χPT by Lensky *et al.* [22]. Note that each row has its distinct plot scale.

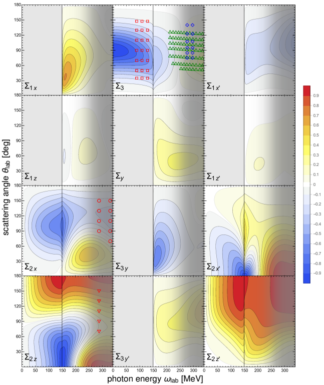


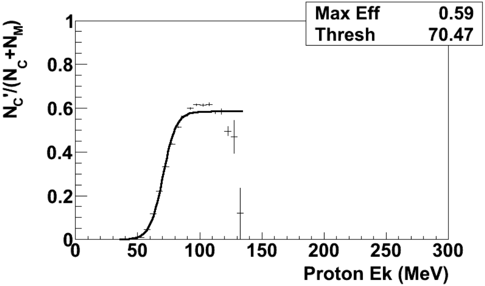
Figure 5: (Colour online) Contour plots of the asymmetries and polarisation-transfer observables; see text and sect. 3.1 for details. Data included as available, for Σ_3: open (green) triangles △ from LEGS [39], open (red) squares □ from MAMI [9], open (blue) diamonds ◇ preliminary from MAMI [16, 18]; for Σ_{2x}: open (red) circles ○ MAMI data from [8, 15]; open (red) inverted triangle ▽ preliminary from MAMI [18]. Symbol sizes do not reflect error bars, nor the size of energy or angle bins.

Griesshammer, McGovern, Phillips, Eur. Phys. J. A (2018) 54: 37

Kinematics Limited by Proton Detection

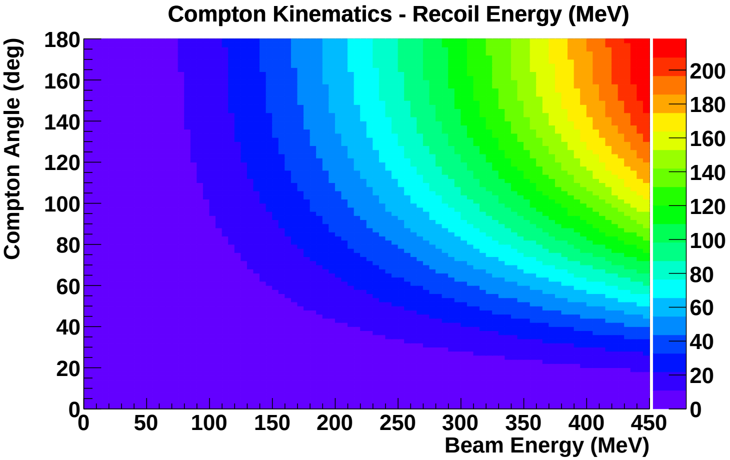
Event reconstruction relies on detection of the recoil proton to reject backgrounds. Using π^0 events, an 'identification' efficiency can be determined.

$$\epsilon = \frac{N'_C(\theta_{OA})}{N_C + N_M}$$



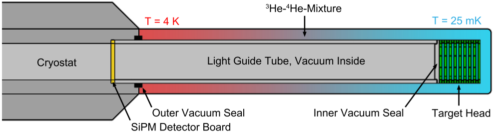
- $N'_C(\theta_{OA})$ - charged particle satisfies opening angle cut
- N_C - any charged particle
- N_M - missed recoil particle

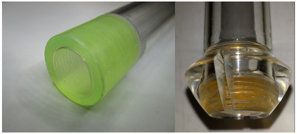
So what phase space do we have to work with?



Requiring the proton then clearly limits our kinematic range.

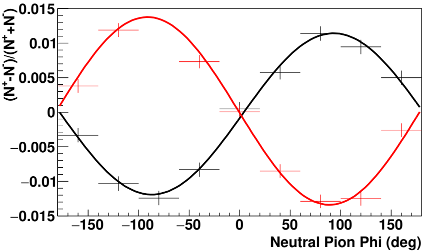
Active Target





Requirements

- Polarizable Scintillator
- High light output
- High rate capability
- Low thermal energy input
- Detectors working at 4K



Targets from UMass Amherst

Tested at MAMI - Pol > 50%

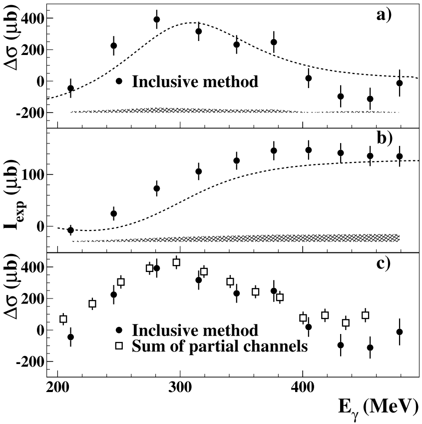
GDH Sum Rule

Where are the deuteron results from MAMI?

- Longitudinally polarized deuterated butanol data already taken
- Analysis of $\sigma_P - \sigma_A$ for π^0 well underway
- Total inclusive also being looked at

And what about ^{3}He?

Physics Letters B 723 (2013) 7177



Conclusions

- Test run for Σ_3 below threshold published in EPJA
- Full program for Σ_3 below threshold wrapping up, analysis should be quite fast.
- Σ_{2x}, Σ_{2z}, and Σ_3 have all been measured in the Delta
- Σ_{2x} results published in PRL, other two are in production
- Future:
  - Combine with results from all of the α_{E1} and β_{M1} runs
  - More data for higher energy Σ_3, to address LEGS/MAMI difference (for free from May/Sep 2018 runs on π^0 TFF)
  - Implementation of active target to expand kinematic range
  - Improvement in simulation to remove π^0 backgrounds and increase statistics
- Rebuild polarized ^{3}He target for GDH study?

Conclusions

Thank you all for listening!

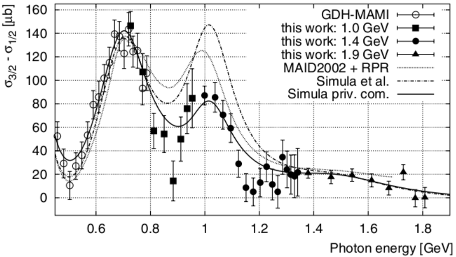
Backup Slides

You want more info...

Forward Spin Polarizability

GDH Experiments

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



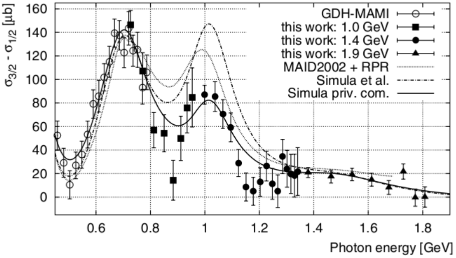
$$\frac{2\pi^2\alpha_e\kappa^2}{M^2} = \int_{\omega_0}^{\infty} \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega} d\omega$$

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



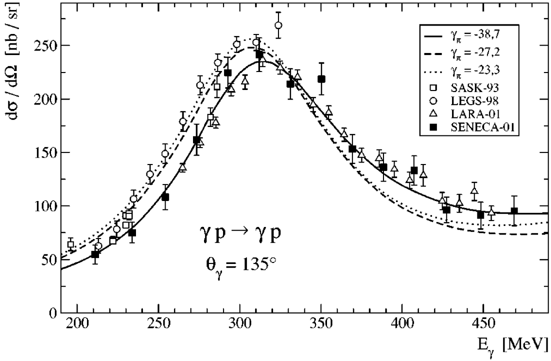
$$\gamma_0 = -\frac{1}{4\pi^2}\int_{\omega_0}^{\infty}\frac{\sigma_{3/2}(\omega)-\sigma_{1/2}(\omega)}{\omega^3}d\omega$$

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

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

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

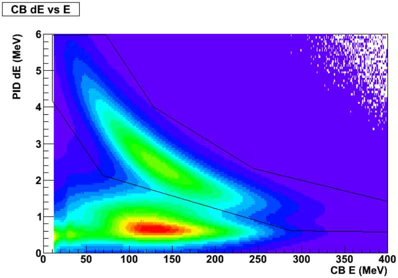
Crystal Ball - Charged Particle Detection

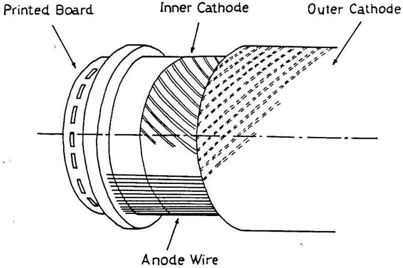
Particle Identification Detector (PID)

- Barrel of 24 plastic paddles
- Each covers $15 < \theta < 159°$, and $15°$ in ϕ
- Plot ΔE in PID vs E in NaI

Multiwire Proportional Chamber (MWPC)

- Two chambers: anode wires sandwiched by two layers of cathode strips
- Voltage between wires and strips increases when gas is ionized





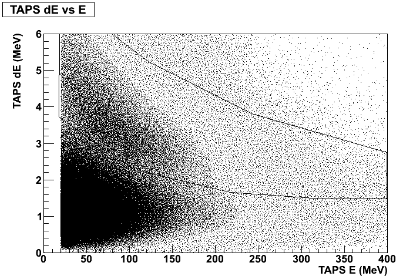
TAPS - Charged Particle Detection

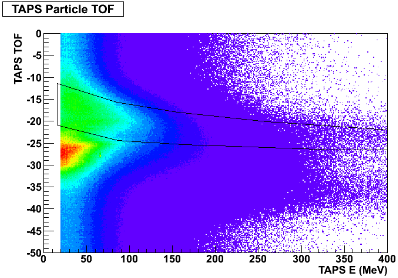
Veto scintillators

- 5mm plastic scintillators in front of each crystal
- Same method as PID (plot ΔE vs E)

Time of Flight

- Given its increased distance from the target, massive particles take noticeably longer to reach TAPS
- Plot time vs E, identify nucleons





Backgrounds

Butanol Target (C_4H_9OH)

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

Hydrogen Target (LH_2)

- Compton off H
- Pion photoproduction off H

Backgrounds

Butanol Target (C_4H_9OH)

- Compton off H
- Coherent scatter off C (or O)
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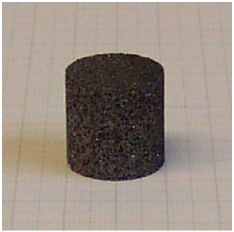
Hydrogen Target (LH_2)

- Compton off H
- Pion photoproduction off H



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

Backgrounds

Butanol Target (C_4H_9OH)

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

Hydrogen Target (LH_2)

- Compton off H
- Pion photoproduction off H

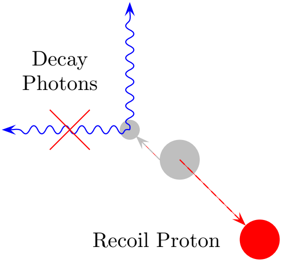
Backgrounds

Butanol Target (C_4H_9OH)

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

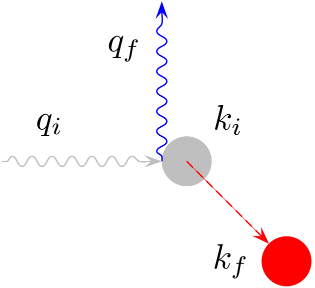
Hydrogen Target (LH_2)

- Compton off H
- Pion photoproduction off H



π^0 photoproduction $\approx$ 100 times more likely. If one of the decay photons is lost, this can look like Compton.

Compton Missing Mass



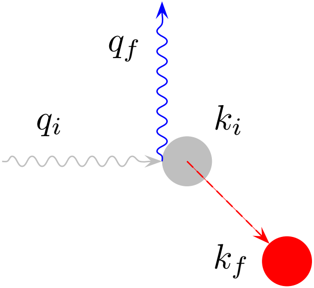
$$k_f = q_i + k_i - q_f$$

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

Missing Mass

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

Compton Missing Mass



$$k_f = q_i + k_i - q_f$$

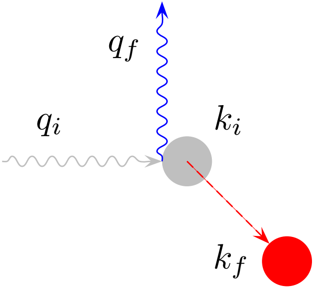
$$k_f^2 = m_k^2 = (q_i + k_i - q_f)^2$$

Q: Why not use the proton information itself?

Missing Mass

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

Compton Missing Mass



$$k_f = q_i + k_i - q_f$$

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

Q: Why not use the proton information itself?

A: Too much energy loss.

Missing Mass

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