Accessing Nucleon Polarizabilities with Compton Scattering

13th European Research Conference on
Electromagnetic Interactions with Nucleons and Nuclei

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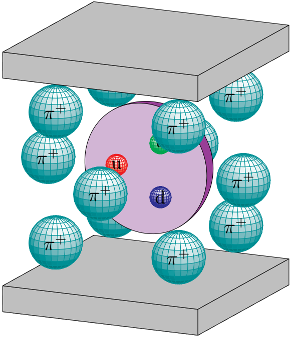
Nucleon Polarizabilities



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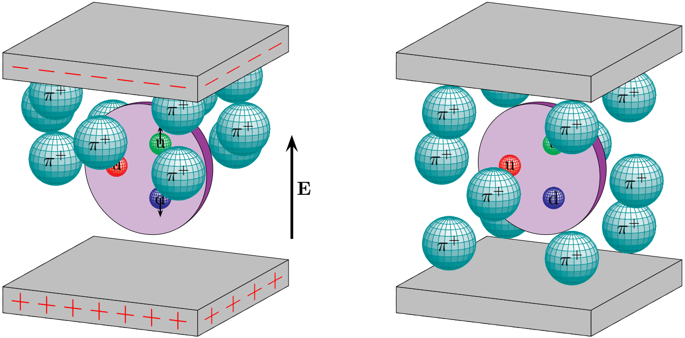
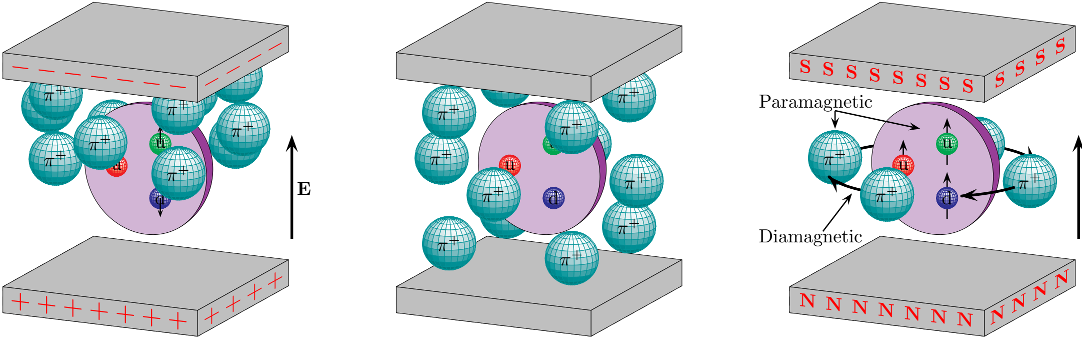


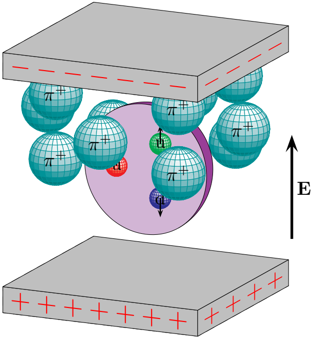
Electric polarizability α_{E1}



Electric polarizability α_{E1}

Magnetic polarizability β_{M1}

Nucleon Polarizabilities



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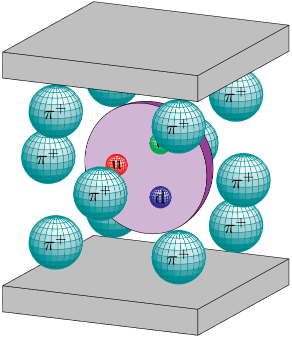
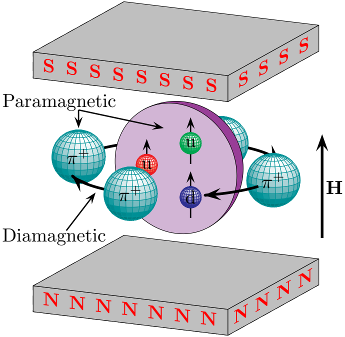
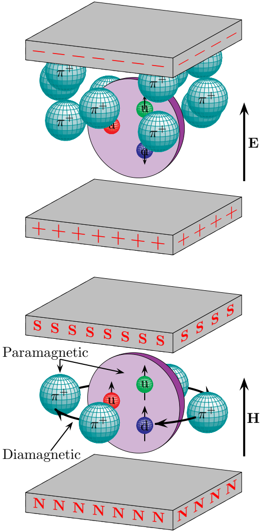


How could we measure this?



Magnetic polarizability β_{M1}

Compton Scattering



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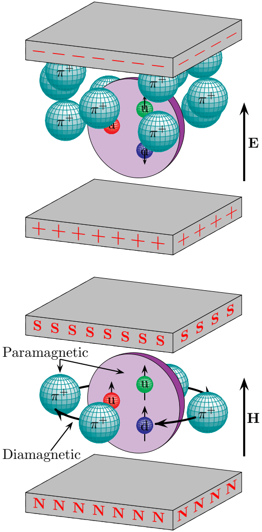

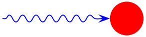

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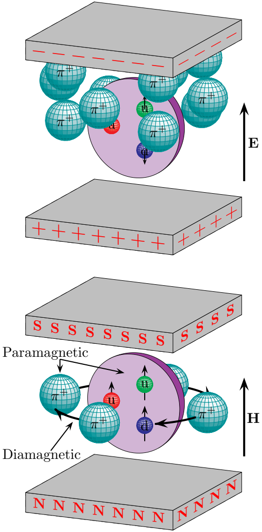

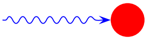

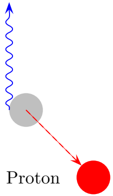

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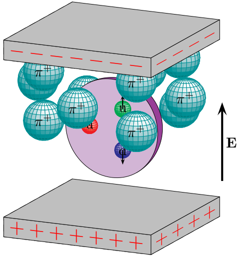

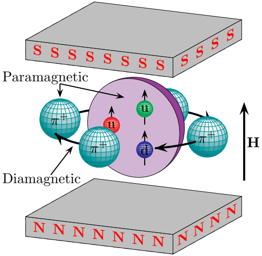

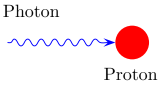

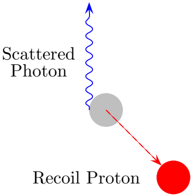

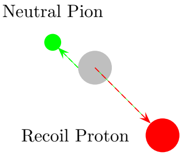

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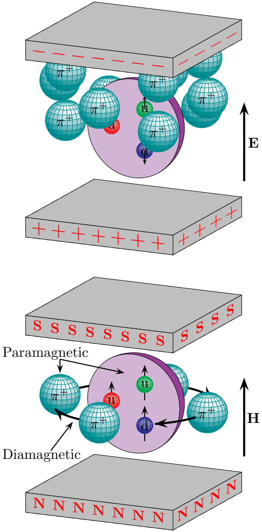

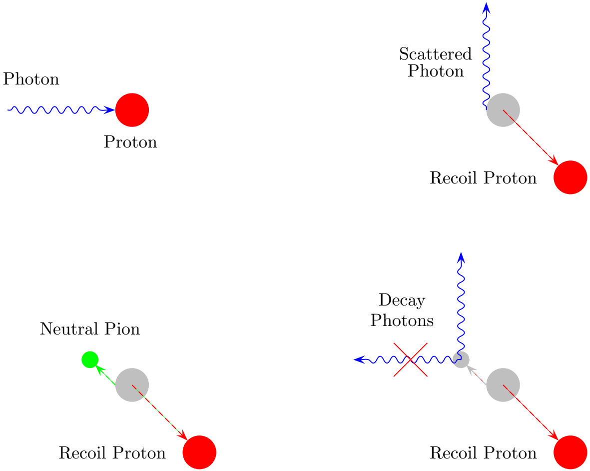

Compton Scattering Equations

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

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

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Second Order - Electric and Magnetic Polarizabilities

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

Compton Scattering Equations

Third Order - Spin Polarizabilities

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

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Presently Known Values

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

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

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M. Camen *et al.* (A2), PRC 65, 032202 (2002)

Compton Scattering Equations

A2

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$$\gamma_{E1M2} = -\gamma_{E1E1} - \frac{1}{2}\gamma_0 - \frac{1}{2}\gamma_\pi \qquad \gamma_{M1E2} = -\gamma_{M1M1} - \frac{1}{2}\gamma_0 + \frac{1}{2}\gamma_\pi$$

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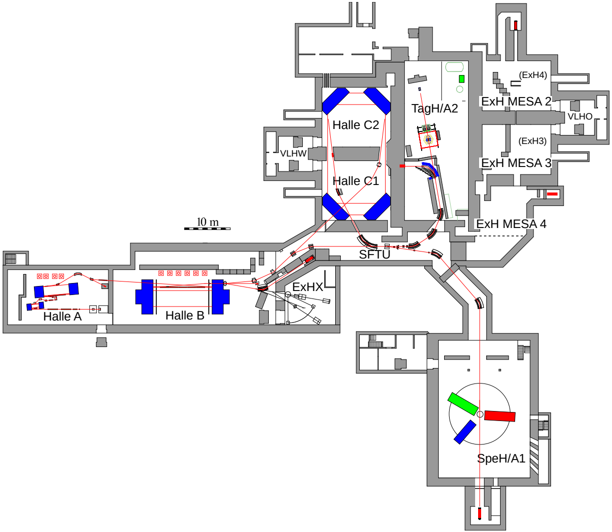
$$\gamma_{E1M2} = -\gamma_{E1E1} - \frac{1}{2}\gamma_0 - \frac{1}{2}\gamma_\pi \qquad \gamma_{M1E2} = -\gamma_{M1M1} - \frac{1}{2}\gamma_0 + \frac{1}{2}\gamma_\pi$$

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

Mainz Microtron (MAMI) e^- Beam



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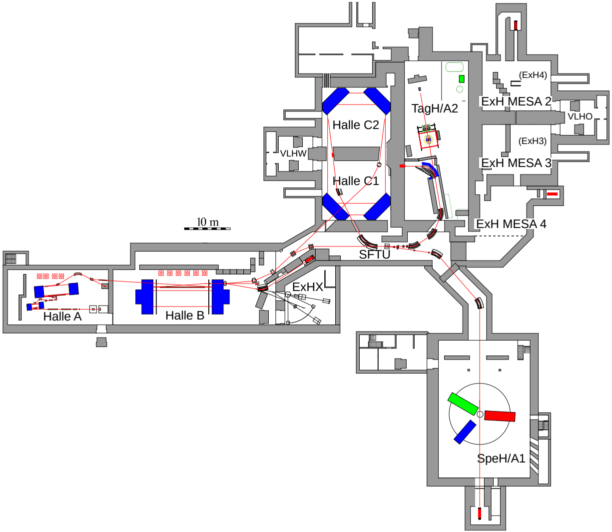
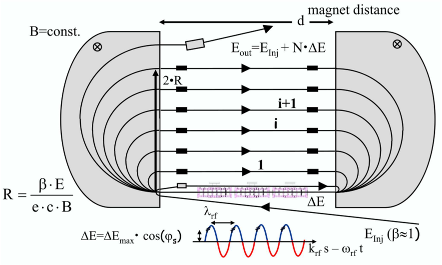


Racetrack Microtron (RTM)

- Linac sends e^- beam into dipole
- Dipoles return the beam beam back into the linac at increasing radii
- 'Kicker' magnet ejects the beam



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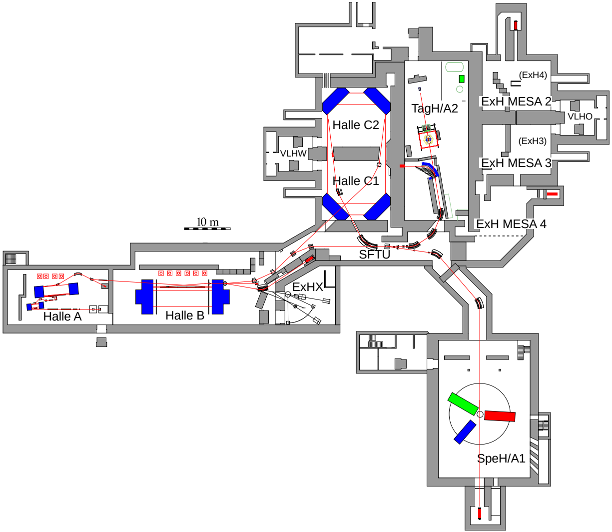

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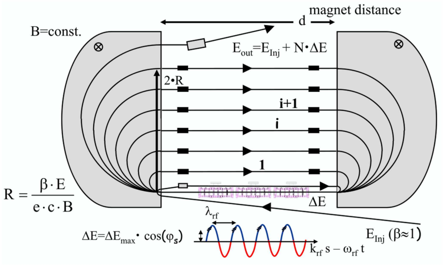

180 MeV – 1.6 GeV (15 MeV steps)

Polarized Photon Beam

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

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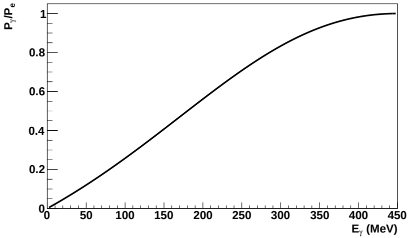


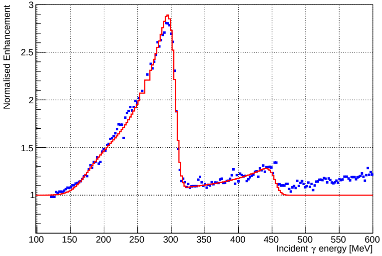
$$P_\gamma = P_e \frac{4E_\gamma E_e - E_\gamma^2}{4E_e^2 - 4E_\gamma E_e + 3E_\gamma^2}$$

- $P_e \approx 80\%$
- Helicity flipped every second

Polarized Photon Beam

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

- Longitudinally polarized electrons produce circularly polarized photons (helicity transfer).
- Diamond radiator produces linearly polarized photons (coherent Bremsstrahlung).



- Coherent edge is tunable
- Polarization plane can be flipped (usually every hour)

Polarized Photon Beam

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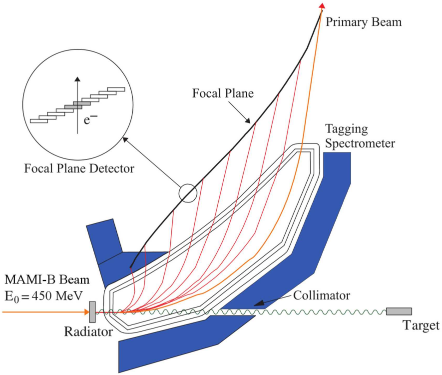
- Residual electron paths bent in a spectrometer magnet.



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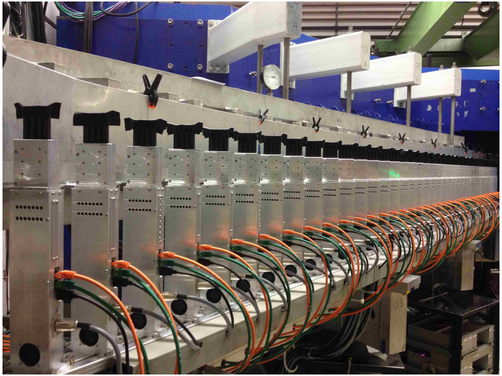
- Detector array determines the e^- energy, and 'tags' the photon energy by energy conservation.



Targets

Unpolarized protons

- Simple - LH2

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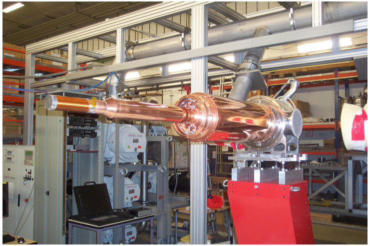
Polarized protons

- Frozen Spin Target - Butanol (C_4H_9OH)
- Dynamic Nuclear Polarization (DNP)
- $P_T^{max} > 90\%$, $\tau > 1000$ h



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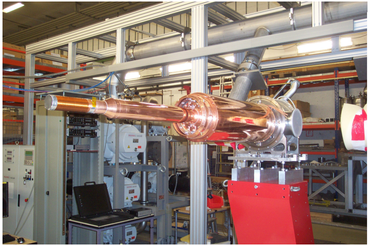
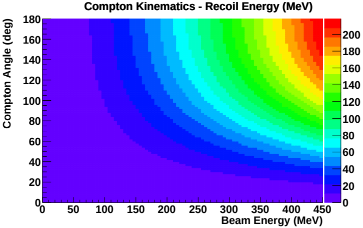
Low energy polarized protons

- Rejecting backgrounds
- 70 MeV detection threshold
- Limited to top right of plot





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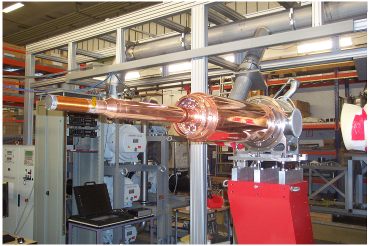

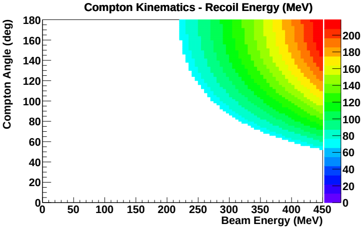

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- Dynamic Nuclear Polarization (DNP)
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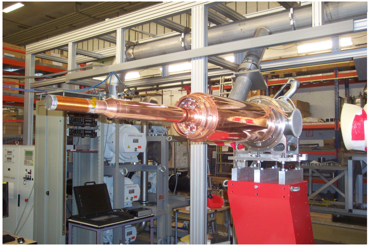
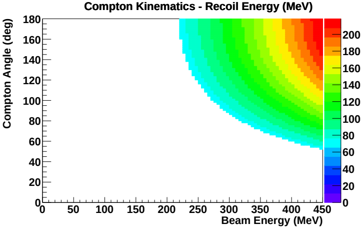
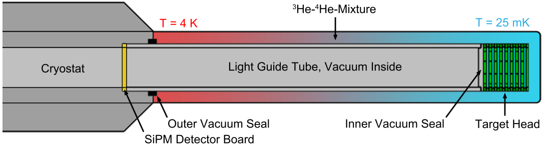
Low energy polarized protons

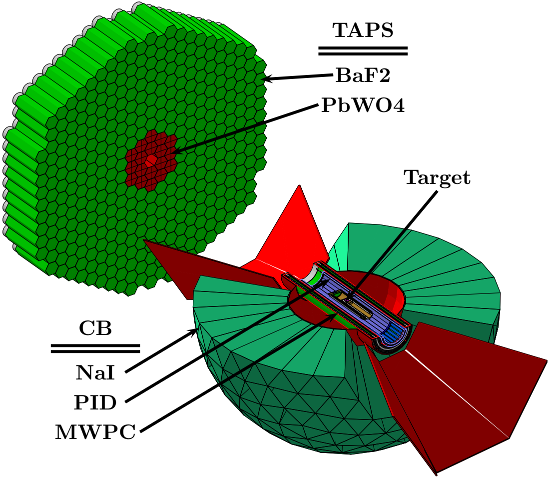
- Polarizable scintillators
- Light guide to detectors
- $P_T^{max} > 50\%$, $\tau > 70$ h







Detectors



Crystal Ball (CB)

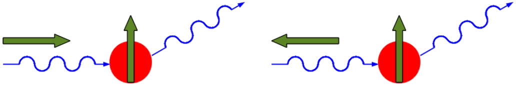
- 672 NaI Crystals
- 24 Particle Identification Detector (PID) Paddles
- 2 Multiwire Proportional Chambers (MWPCs)

Two Arms Photon Spectrometer (TAPS)

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

Σ_{2x} - 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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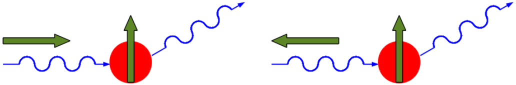
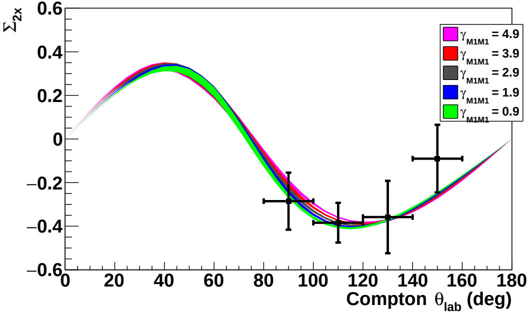
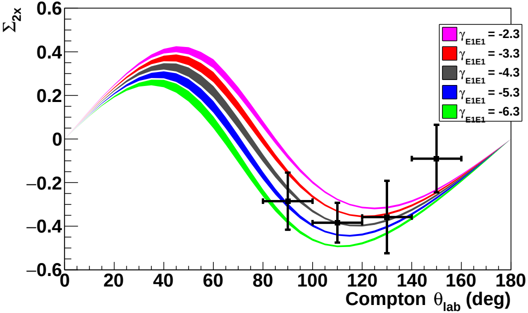


PM *et al.* (A2)
PRL 114, 112501 (2015)

E_γ=273-303 MeV - Fix γ_{E1E1}



E_γ=273-303 MeV - Fix γ_{M1M1}



Fix one ($\gamma_{\mathrm{E1E1/M1M1}}$), vary other. Band from γ_0, γ_π, α_{E1}, and β_{M1} errors.

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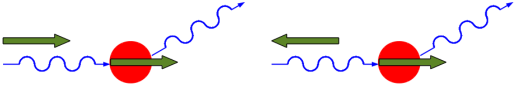

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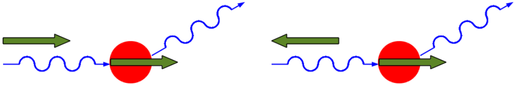
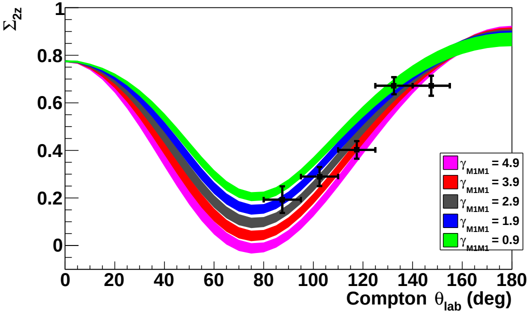


D. Paudyal *et al.* (A2)
arXiv:1909.02032 (2019)

E_γ=265-285 MeV - Fix γ_{E1E1}



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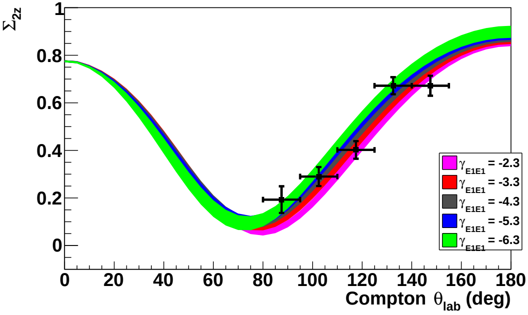

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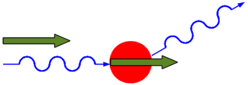
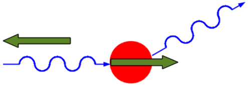
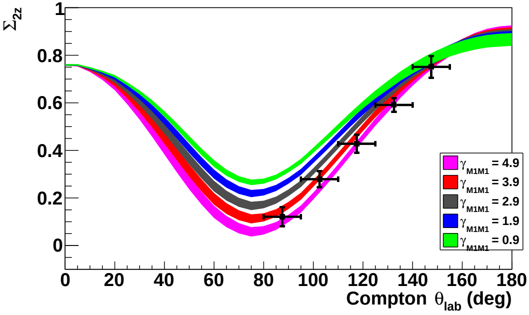
$$\Sigma_{2z} = \frac{N^R_{+z} - N^L_{+z}}{N^R_{+z} + N^L_{+z}}$$





D. Paudyal *et al.* (A2)
arXiv:1909.02032 (2019)

E_γ=285-305 MeV - Fix γ_{E1E1}



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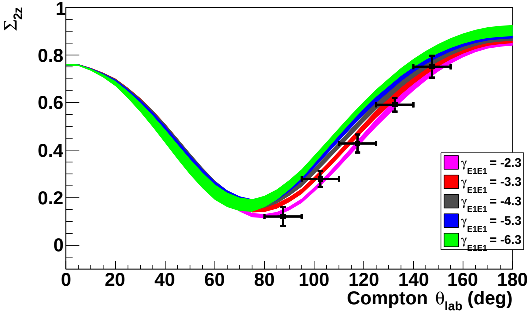

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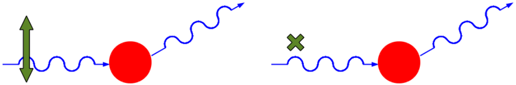
Σ_3 - Linearly polarized photons, unpolarized protons

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



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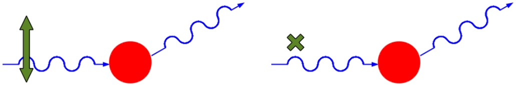
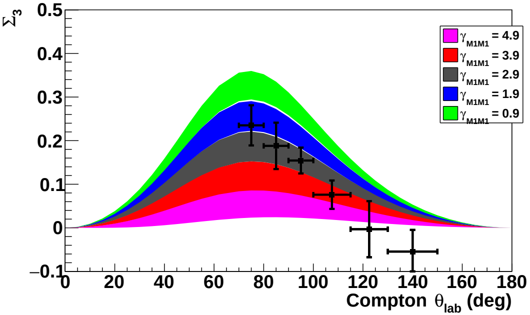


C. Collicott *et al.* (A2)
Draft in progress (2019)

E$_\gamma$=267-287 MeV - Fix γ_{E1E1}



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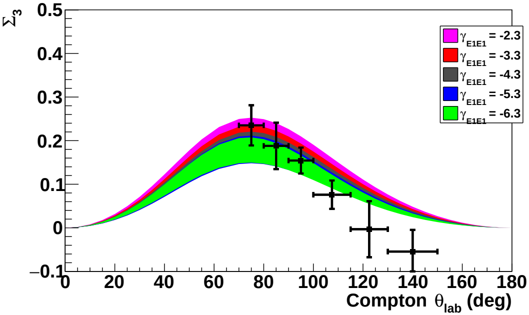

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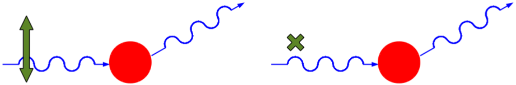
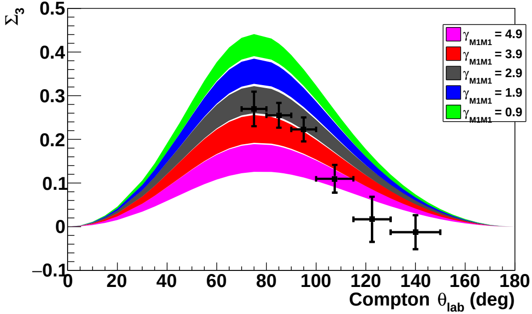
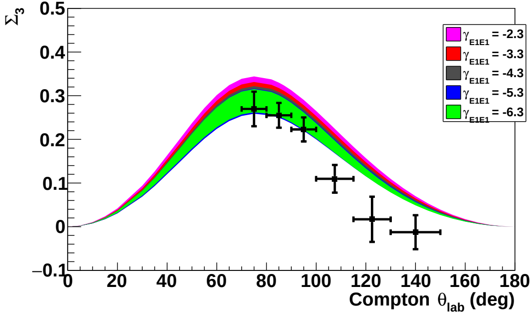


C. Collicott *et al.* (A2)
Draft in progress (2019)

E_γ=287-307 MeV - Fix γ_{E1E1}



E_γ=287-307 MeV - Fix γ_{M1M1}



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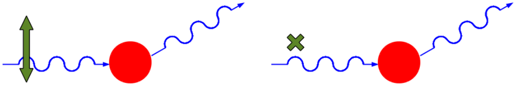

C. Collicott *et al.* (A2)
Draft in progress (2019)

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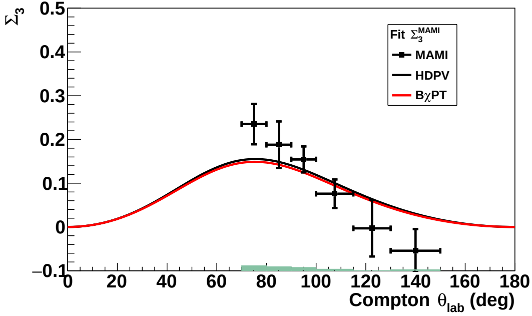
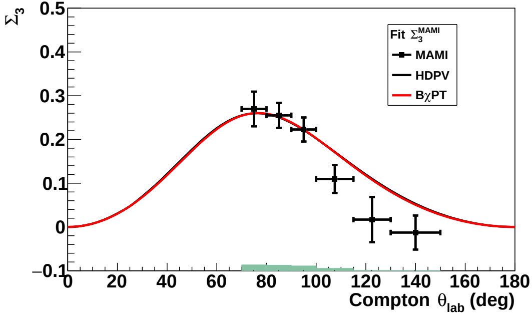


E_γ=287-307 MeV



Fit all observables with dispersion (HDPV) or chiral perturbation (BχPT) theories.

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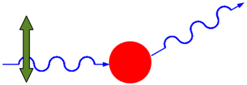

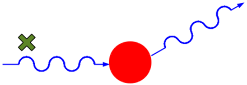

C. Collicott *et al.* (A2)
Draft in progress (2019)

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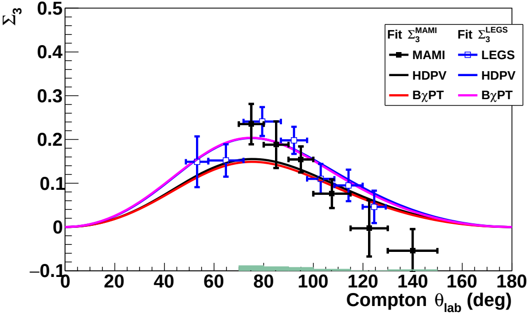

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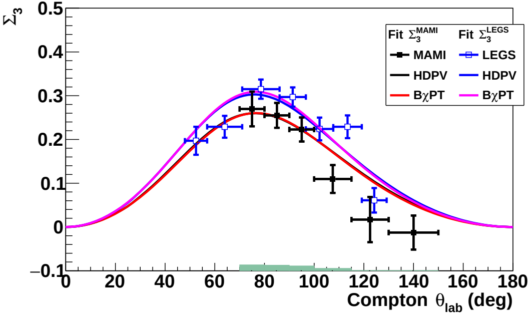
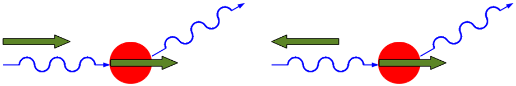


Already performed fits in previous paper with older Σ_3 data from LEGS.

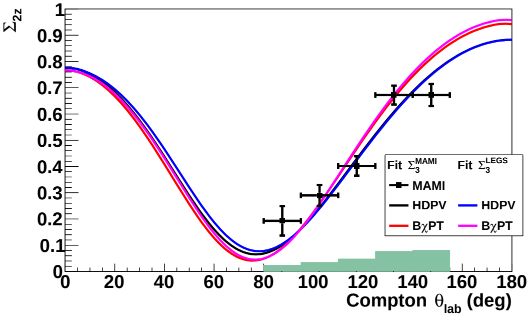
Σ_{2z} - Circularly polarized photons, longitudinally polarized protons

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

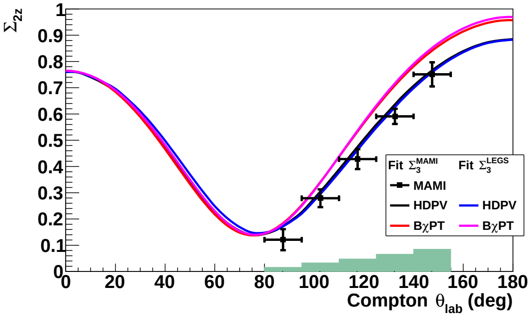


C. Collicott *et al.* (A2)
Draft in progress (2019)

Σ_{2z} - E_γ=265-285 MeV



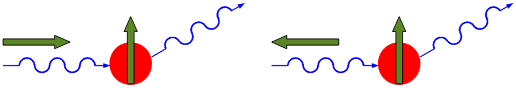
Σ_{2z} - E_γ=285-305 MeV



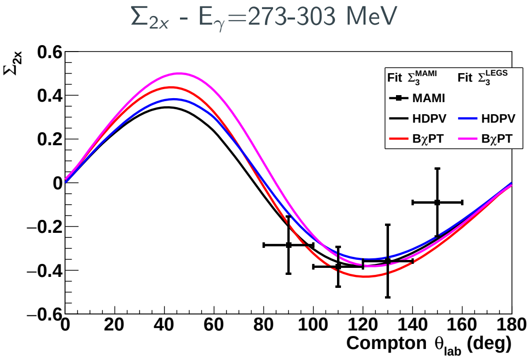
Large systematic errors at back angles permit these BχPT fits (model dependencies?).

Σ_{2x} - Circularly polarized photons, transversely polarized protons

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



C. Collicott *et al.* (A2)
Draft in progress (2019)



Best opportunity to improve - Run again late 2020/early 2021

What about the Neutron?

The situation is even worse for the neutron (difficult with an unstable target)

- Low-energy neutron scattering
- Elastic Compton scattering from deuterium
- Quasi-free Compton scattering from deuterium
- Compton scattering from heavier nuclei

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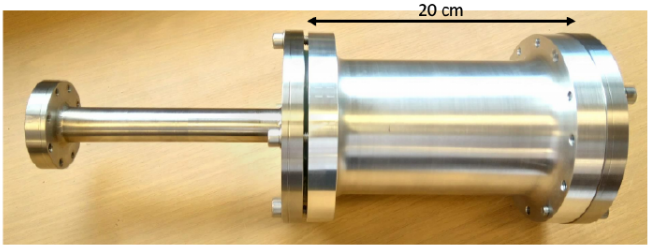

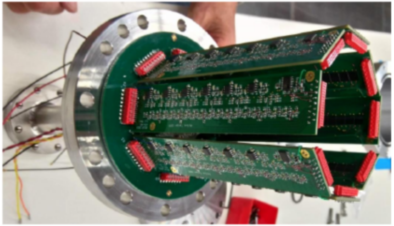

Conclusions

Regarding the proton

- Scalar polarizabilities → See E. Mornacchi's talk next
- Spin polarizabilities have been individually extracted for the first time
- Analyses finished: one published, one submitted, one being written
- More data on tape from which Σ_3 can be extracted → LEGS vs MAMI
- First test of an active polarized target has taken place → Will improve the extraction (model dependence, static vs dynamic polarizabilities)
- Another run with the transverse butanol target to optimize what we have

Regarding the neutron

- Active helium target in development
- Ran with liquid ^{4}He target this past summer
- Active polarized deuterated target for neutron spin polarizabilities