Polarizabilities of the Nucleon

12th International Workshop on the Physics of Excited Nucleons

Philippe Martel

Institute for Nuclear Physics
Johannes Gutenberg University of Mainz

Bonn, Germany - 11 June 2019

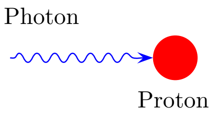
The Proton

Why do we not understand it?

- Rutherford discovered it in 1917!
- Most of the visible mass in the universe
- Should be easy to say what happens in an electric or magnetic field...

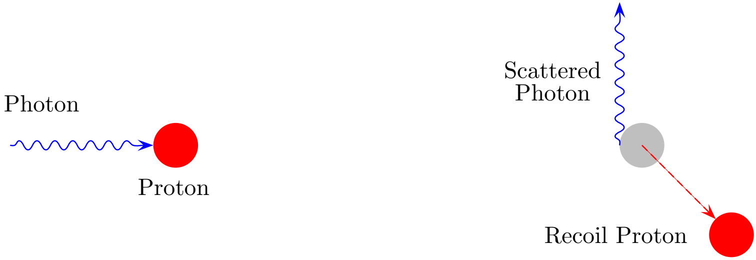
Why do we not understand it?

- Rutherford discovered it in 1917!
- Most of the visible mass in the universe
- Should be easy to say what happens in an electric or magnetic field...



Why do we not understand it?

- Rutherford discovered it in 1917!
- Most of the visible mass in the universe
- Should be easy to say what happens in an electric or magnetic field...



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

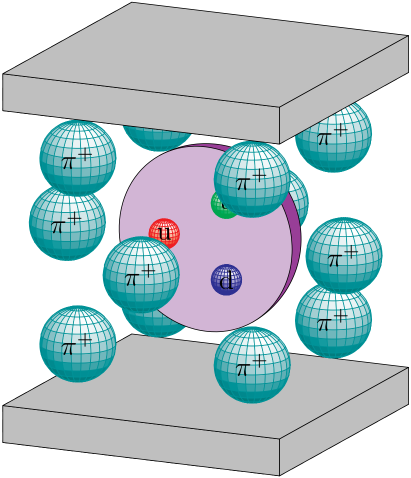
$$H_{\text{eff}}^{(1)} = -\frac{e(1+\kappa)}{2m}\,\vec{\sigma}\cdot\vec{H} - \frac{e(1+2\kappa)}{8m^2}\,\vec{\sigma}\cdot\left[\vec{E}\times\vec{\pi} - \vec{\pi}\times\vec{E}\right]$$

Second Order - Electric and Magnetic Polarizabilities

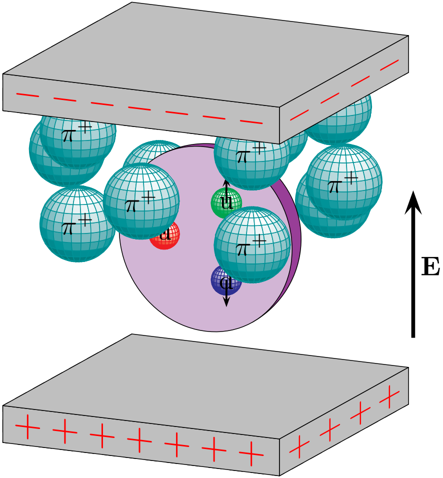
$$H_{\text{eff}}^{(2)} = -4\pi\left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2\right]$$

Electric Polarizability - α_{E1}

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



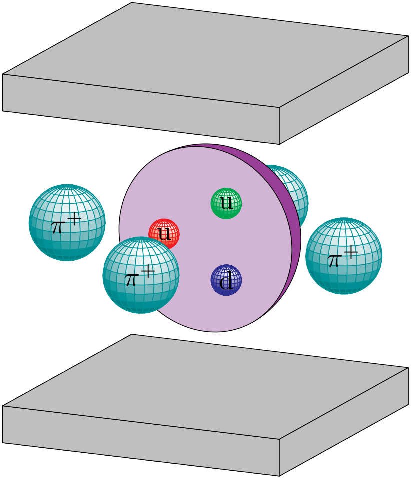
Describes the response of a proton to an applied electric field.



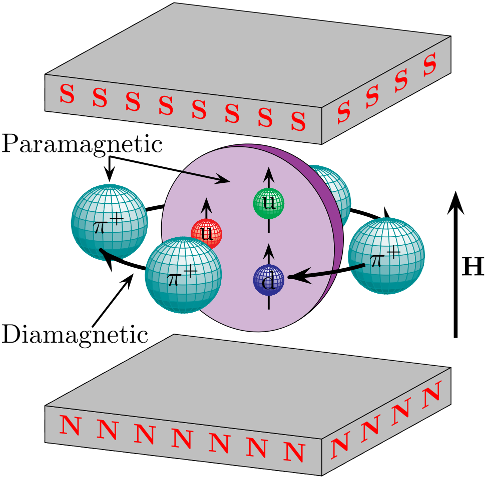
Induces a current in the pion cloud which vertically 'stretches' the proton (stretchability).

Magnetic Polarizability - β_{M1}

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



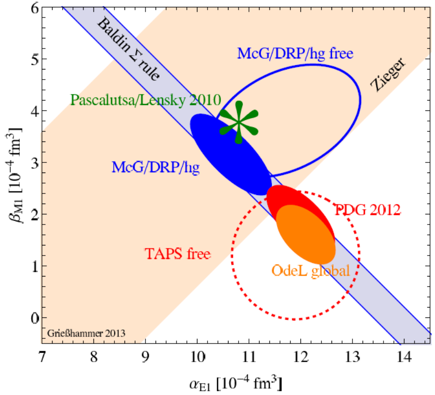
Describes the response of a proton to an applied magnetic field.



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

Scalar Polarizabilities

Unpolarized Compton scattering
OdeL *et al.* (A2), EPJA 10, 207 (2001)



VL, VP, EPJC 65, 195 (2010)
JMcG, DRP, HG, EPJA 49, 12 (2013)

Baldin (Lapidus) Sum Rule:

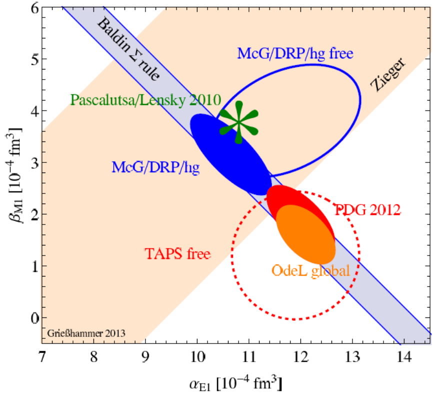
$$\alpha + \beta = \frac{1}{2\pi^2} \int_{\omega_0}^{\infty} \frac{\sigma_{\mathrm{tot}}(\omega)}{\omega^2} d\omega$$

PDG 2012

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

Scalar Polarizabilities

Unpolarized Compton scattering
OdeL *et al.* (A2), EPJA 10, 207 (2001)



VL, VP, EPJC 65, 195 (2010)
JMcG, DRP, HG, EPJA 49, 12 (2013)

Baldin (Lapidus) Sum Rule:

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

PDG 2012

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

PDG 2013/2014

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

Compton Scattering Equations

Third Order - Spin Polarizabilities

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

- These parameters describe the response of the proton **spin** to an applied electric or magnetic field. Analogous to a classical Faraday effect.
- These had not been individually determined previously, except for two linear combinations of them.

Spin Polarizabilities

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

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

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

Spin Polarizabilities

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

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

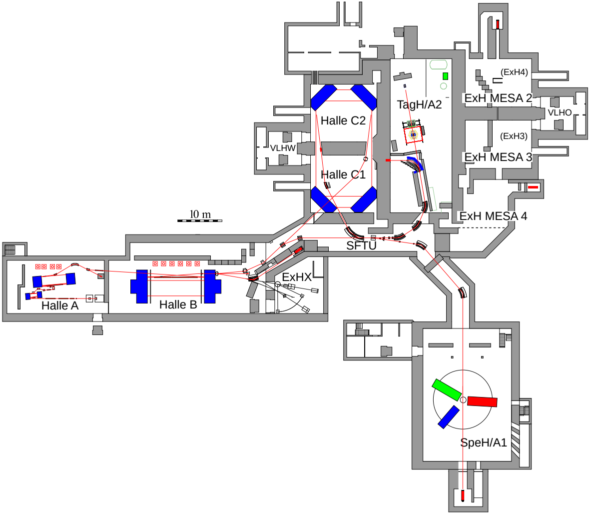
M. Camen *et al.* (A2), Phys. Rev. C 65, 032202 (2002)

Change of Basis

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

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

Mainz Microtron (MAMI) e$^-$ Beam

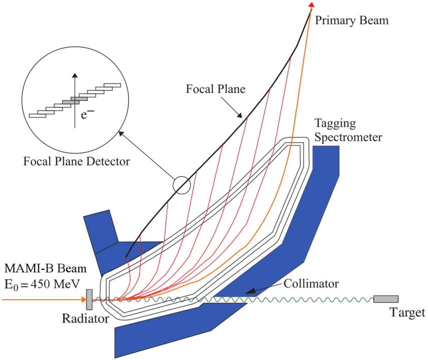


- Injector → 3.5 MeV
- RTM1 → 14.9 MeV
- RTM2 → 180 MeV
- RTM3 → 883 MeV
- HDSM → 1.6 GeV

Selectable energy from 180 Mev up, in steps of 15 MeV.

Polarized Photon Beam

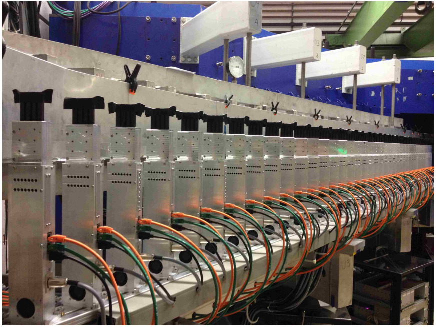
A high energy electron can produce Bremsstrahlung (‘braking radiation’) photons when slowed down by a material.



- Longitudinally polarized electrons produce circularly polarized photons (helicity transfer).
- Diamond radiator produces linearly polarized photons (coherent Bremsstrahlung).
- Residual electron paths bent in a spectrometer magnet.
- Detector array determines the e^- energy, and ‘tags’ the photon energy by energy conservation.

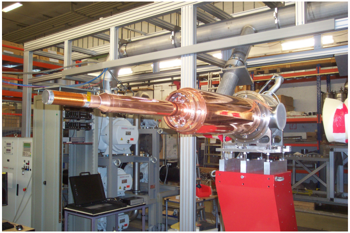
Polarized Photon Beam

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).
- Residual electron paths bent in a spectrometer magnet.
- Detector array determines the e^- energy, and 'tags' the photon energy by energy conservation.

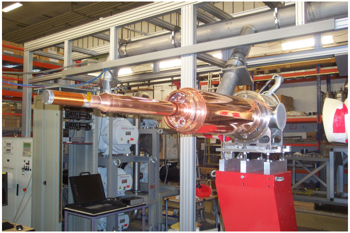
Targets



Polarized frozen spin butanol target

- Dynamic Nuclear Polarization (DNP)
- Butanol (C_4H_9OH) for polarized protons or D-Butanol (C_4D_9OD) for polarized deuterons
- $P_T^{max} > 90\%$, $\tau > 1000$ h

Targets



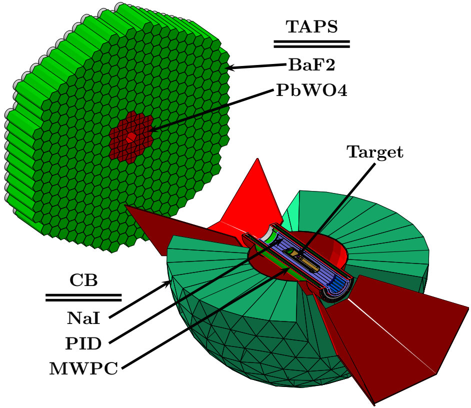
Polarized frozen spin butanol target

- Dynamic Nuclear Polarization (DNP)
- Butanol (C_4H_9OH) for polarized protons or D-Butanol (C_4D_9OD) for polarized deuterons
- $P_T^{max} > 90\%$, $\tau > 1000$ h

Unpolarized targets

- LH2/LD2
- ^{4}He
- Solid targets (C, Al, Pb, etc.)

Detectors



Crystal Ball (CB)

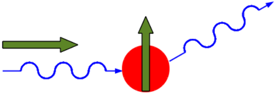
- 672 NaI Crystals
- 24 Particle Identification Detector (PID) Paddles
- 2 Multiwire Proportional Chambers (MWPCs)

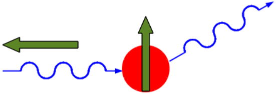
Two Arms Photon Spectrometer (TAPS)

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

Circularly polarized photons, transversely polarized protons.

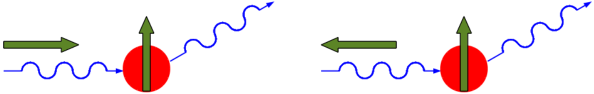
$$\Sigma_{2x} = \frac{N^R_{+x} - N^L_{+x}}{N^R_{+x} + N^L_{+x}}$$



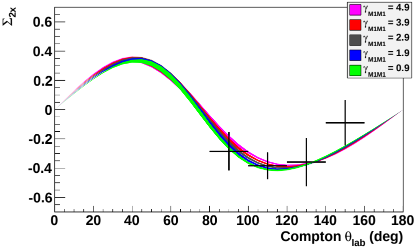


Circularly polarized photons, transversely polarized protons.

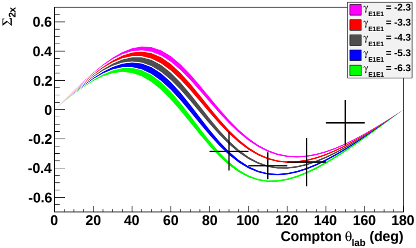
$$\Sigma_{2x} = \frac{N^R_{+x} - N^L_{+x}}{N^R_{+x} + N^L_{+x}}$$



E_γ=273-303 MeV - Fix γ_{E1E1}



E_γ=273-303 MeV - Fix γ_{M1M1}

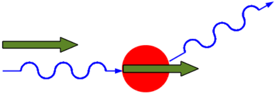


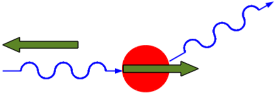
Fix one ($\gamma_{\mathrm{E1E1/M1M1}}$), vary other. Band from γ_0, γ_π, α_{E1}, and β_{M1} errors.

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

Circularly polarized photons, longitudinally polarized protons.

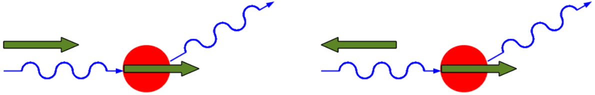
$$\Sigma_{2z} = \frac{N^R_{+z} - N^L_{+z}}{N^R_{+z} + N^L_{+z}}$$



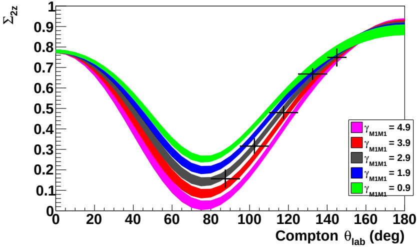


Circularly polarized photons, longitudinally polarized protons.

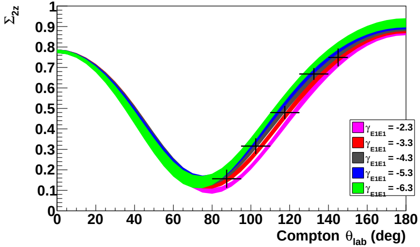
$$\Sigma_{2z} = \frac{N^R_{+z} - N^L_{+z}}{N^R_{+z} + N^L_{+z}}$$



E_γ=285-305 MeV - Fix γ_{E1E1}



E_γ=285-305 MeV - Fix γ_{M1M1}



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

D. Paudyal, Ph.D. thesis, University of Regina (2017)

Σ_3 - Dec 2012 - Preliminary

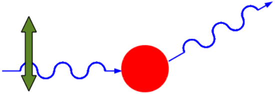
Linearly polarized photons, unpolarized protons.

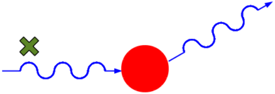
$$\Sigma_3 = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$

Σ_3 - Dec 2012 - Preliminary

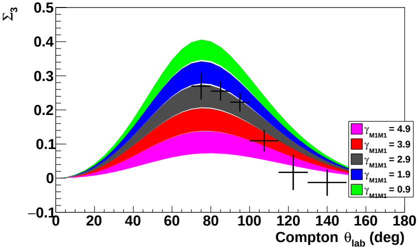
Linearly polarized photons, unpolarized protons.

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

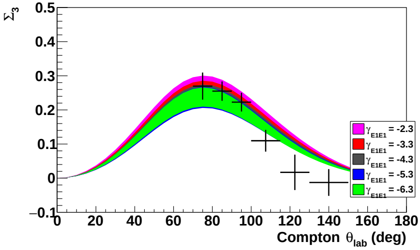




E_{γ}=287-307 MeV - Fix γ_{E1E1}



E_{γ}=287-307 MeV - Fix γ_{M1M1}



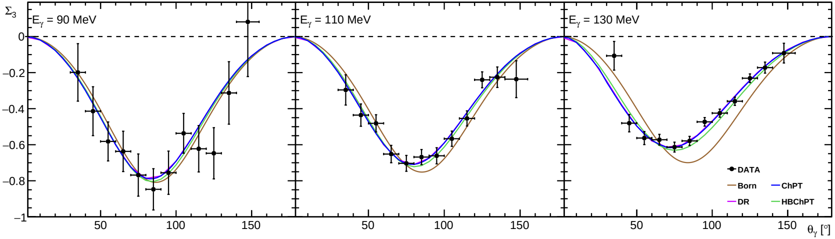
Fix one ($\gamma_{\mathrm{E1E1/M1M1}}$), vary other. Band from γ_0, γ_π, α_{E1}, and β_{M1} errors.

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

Σ_3 - Nov 2017 and Feb/Mar/Jul 2018 - Preliminary

Linearly polarized photons, unpolarized protons.

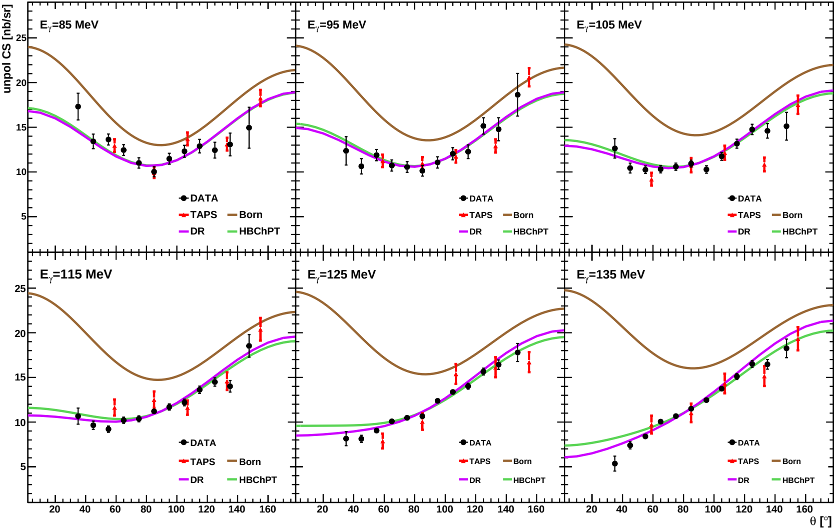
$$\Sigma_3 = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$



Much higher statistics than June 2013 run, EPJA 53, 14 (2017)

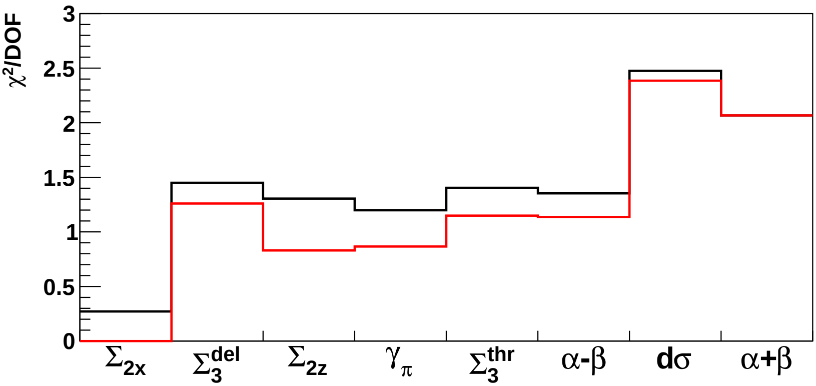
Work by E. Mornacchi (Ph.D. student in A2)

$d\sigma$ - Nov 2017 and Feb/Mar/Jul 2018 - Preliminary



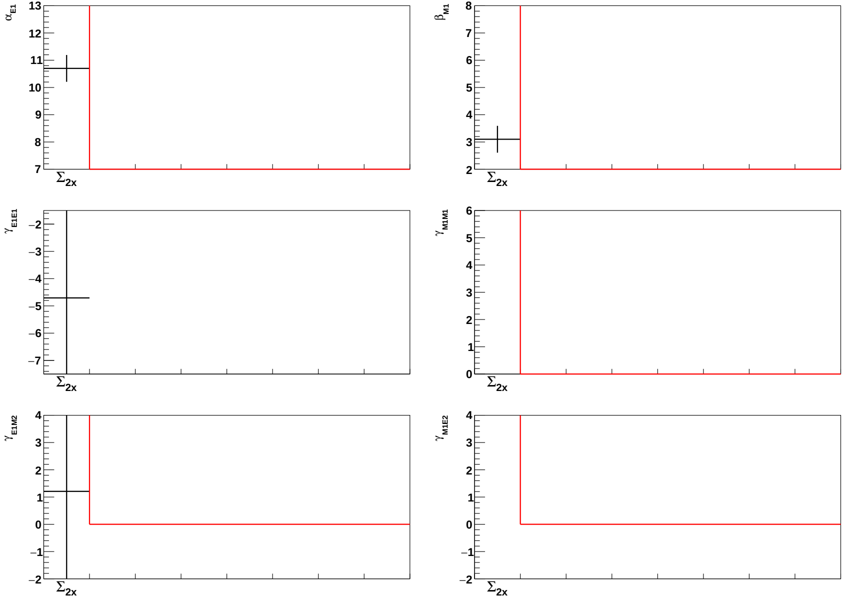
Work by E. Mornacchi (Ph.D. student in A2)

Fitting - Black BχPT, Red HDPV - Needs Updating

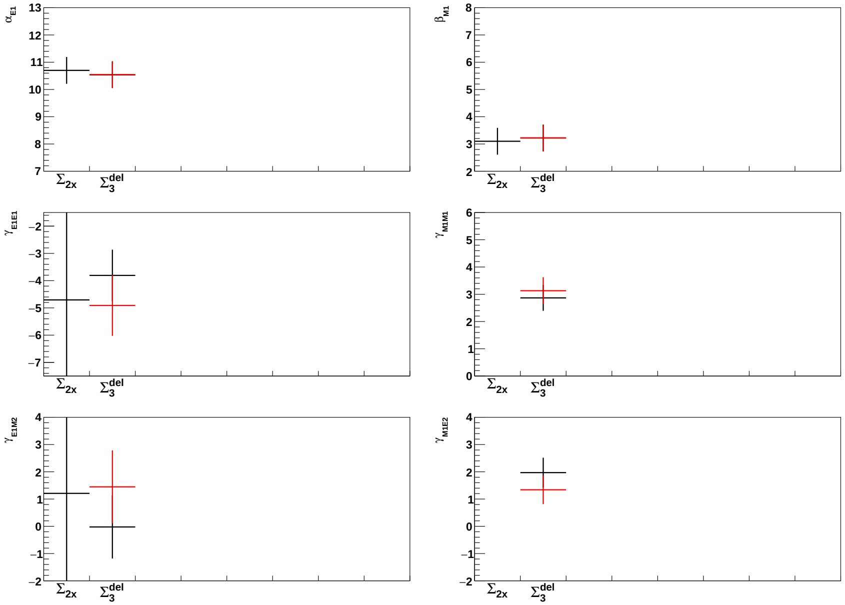


- Fit Σ_{2x} data
- Add high E_γ Σ_3 data
- Add Σ_{2z} data
- Remove γ_π constraint
- Add low E_γ Σ_3 data
- Remove $\alpha - \beta$ constraint
- Add low E_γ $d\sigma$ data
- Remove $\alpha + \beta$ constraint

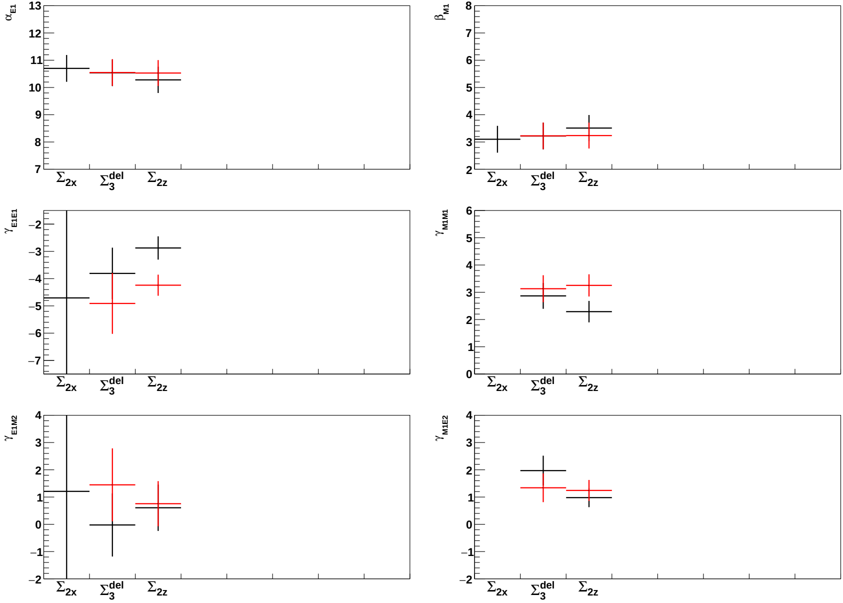
Fitting - Black BχPT, Red HDPV - Needs Updating



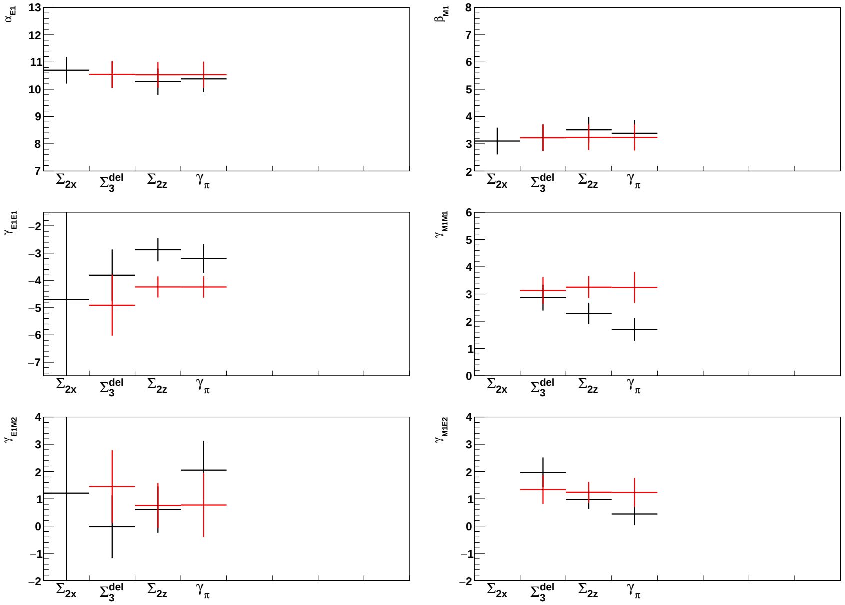
Fitting - Black BχPT, Red HDPV - Needs Updating



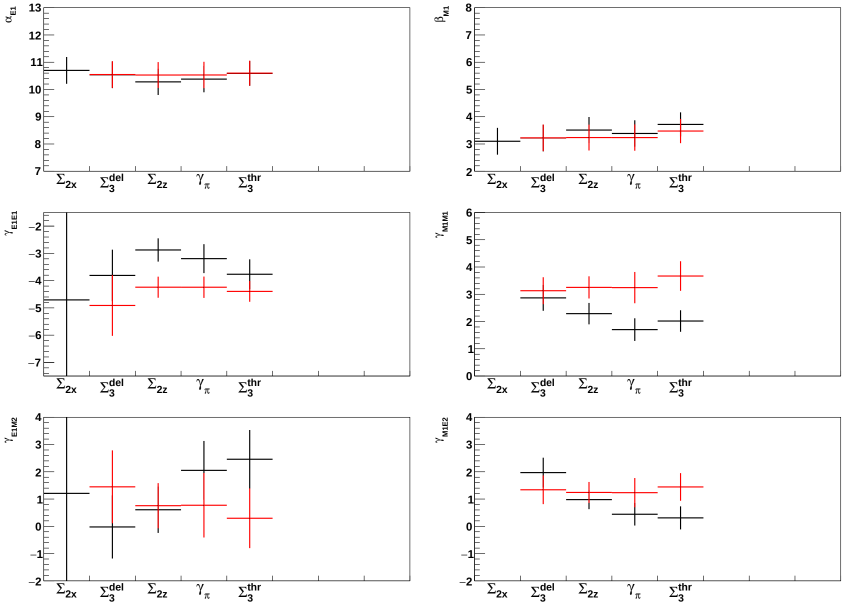
Fitting - Black BχPT, Red HDPV - Needs Updating



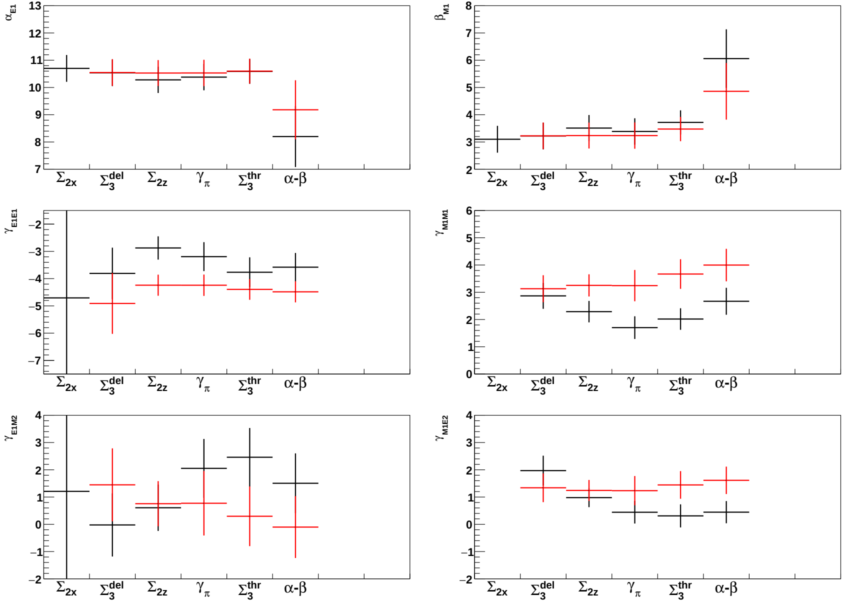
Fitting - Black BχPT, Red HDPV - Needs Updating



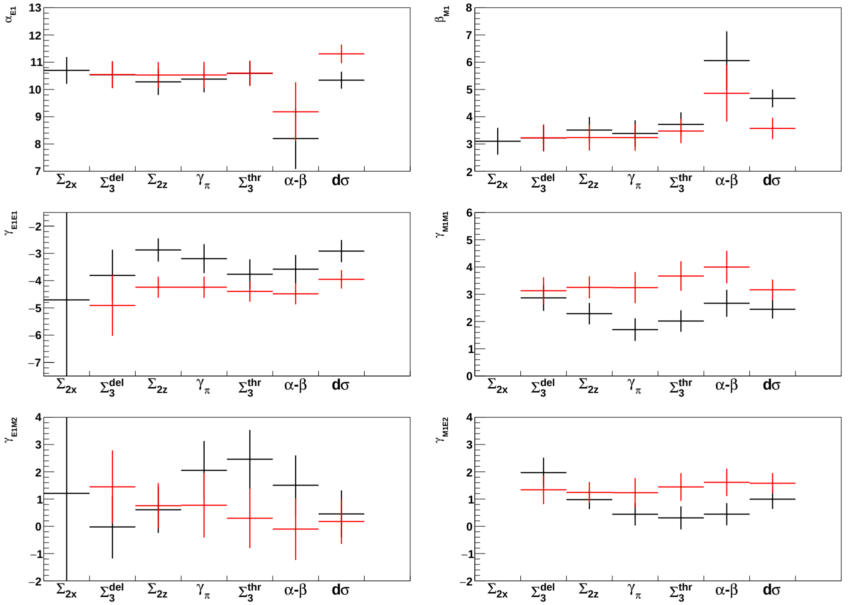
Fitting - Black BχPT, Red HDPV - Needs Updating



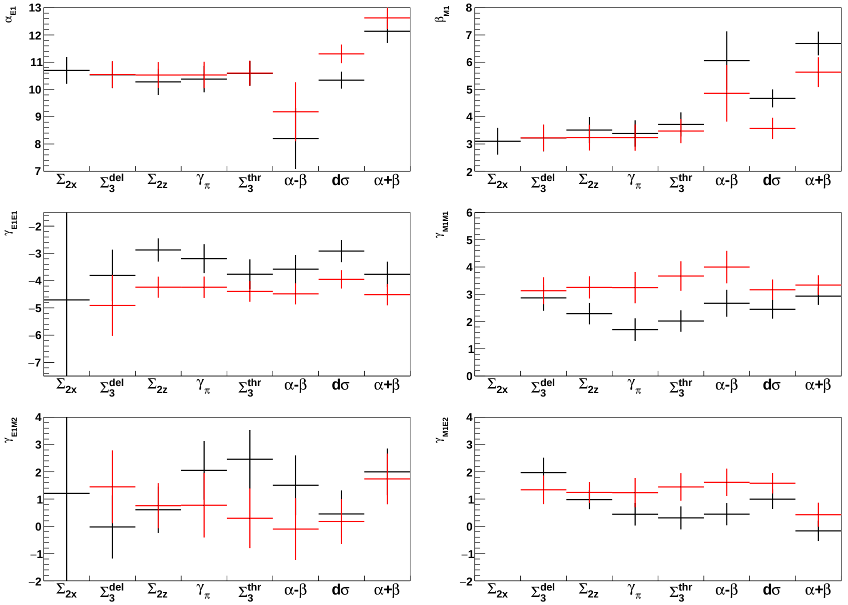
Fitting - Black BχPT, Red HDPV - Needs Updating



Fitting - Black BχPT, Red HDPV - Needs Updating

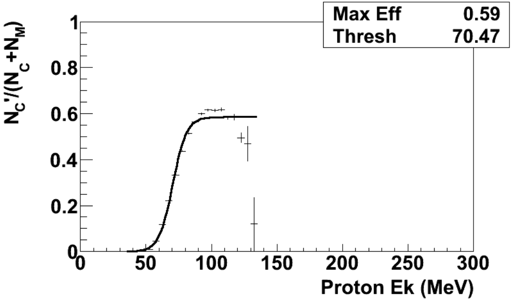


Fitting - Black BχPT, Red HDPV - Needs Updating



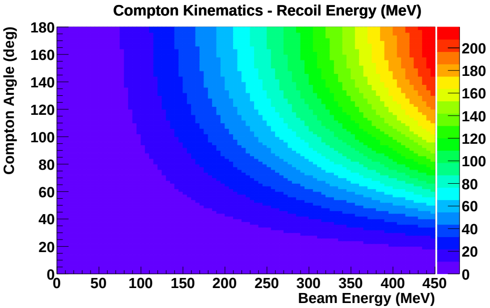
Future - Active Target

Event reconstruction relies on detection of the recoil proton to reject backgrounds, but efficiency is low.



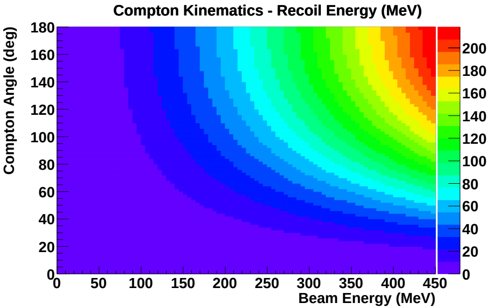
Future - Active Target

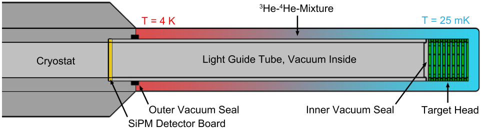
Event reconstruction relies on detection of the recoil proton to reject backgrounds, but efficiency is low.



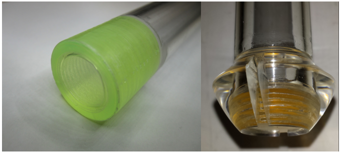
Future - Active Target

Event reconstruction relies on detection of the recoil proton to reject backgrounds, but efficiency is low.



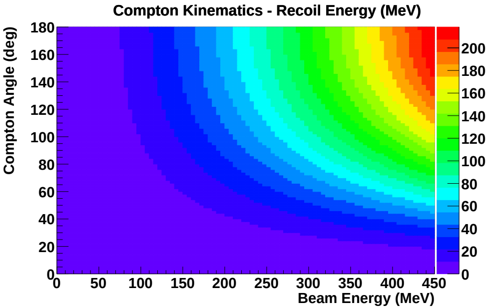


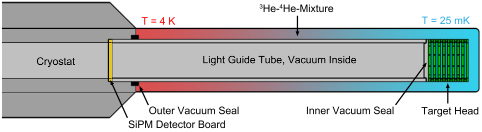
Light guide target head

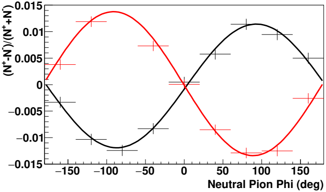


Polarizable scintillators in target cryostat

Event reconstruction relies on detection of the recoil proton to reject backgrounds, but efficiency is low.







Polarizable scintillators in target cryostat

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

What about the Neutron?

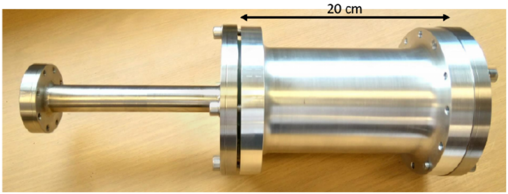
The situation is even worse for the neutron (difficult with an unstable target)

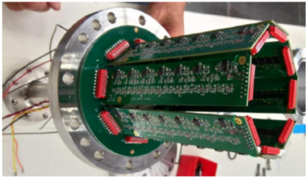
- Low-energy neutron scattering
- Elastic Compton scattering from deuterium
- Quasi-free Compton scattering from deuterium
- Compton scattering from heavier nuclei
- Elastic Compton scattering from ^{3}He
  Shukla, Nogga, and Phillips, NPA **819**, 98 (2009)

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
- Elastic Compton scattering from ^{3}He
  Shukla, Nogga, and Phillips, NPA **819**, 98 (2009)





Conclusions

Regarding the proton

- Scalar polarizabilities will have an improved (at least equal and independent) extraction once analysis is finished
- Spin polarizabilities have been individually extracted for the first time, and will be improved once analysis is finished
- First test of an active polarized target has taken place
- Future runs with this active target will improve the extraction (model dependence, static vs dynamic polarizabilities)

Conclusions

Regarding the proton

- Scalar polarizabilities will have an improved (at least equal and independent) extraction once analysis is finished
- Spin polarizabilities have been individually extracted for the first time, and will be improved once analysis is finished
- First test of an active polarized target has taken place
- Future runs with this active target will improve the extraction (model dependence, static vs dynamic polarizabilities)

Regarding the neutron

- Active helium target in development
- Run with liquid ^{4}He target begins next week
- Active polarized deuterated target can be used for the neutron spin polarizabilities

You want more info...

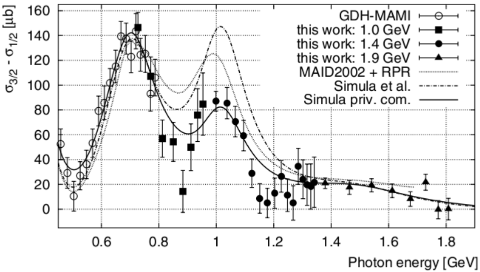
Predicted Values

	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)

GDH Experiments

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



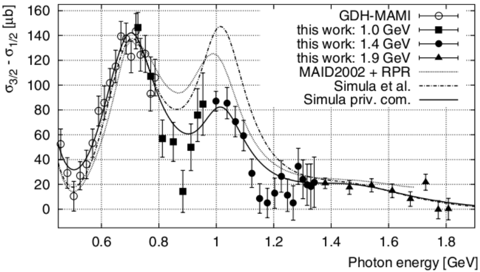
$$\frac{2\pi^2\alpha_e\kappa^2}{M^2} = \int_{\omega_0}^{\infty} \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega} d\omega$$

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

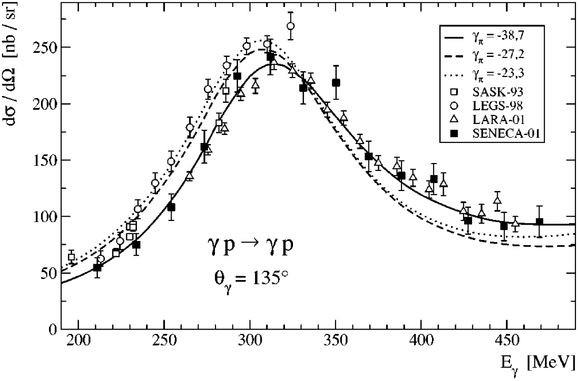


$$\gamma_0 = -\frac{1}{4\pi^2}\int_{\omega_0}^{\infty}\frac{\sigma_{3/2}(\omega)-\sigma_{1/2}(\omega)}{\omega^3}d\omega$$

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

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

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

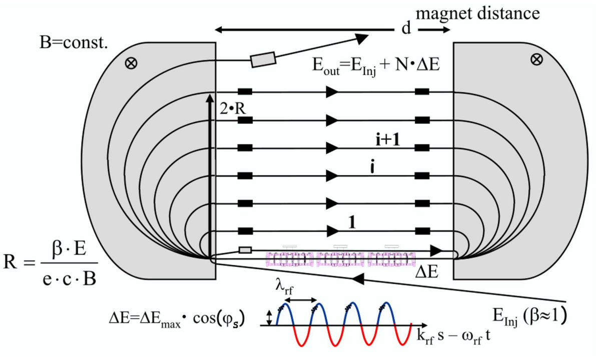


M. Camen *et al.*, Phys. Rev. C 65 (2002) 032202

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

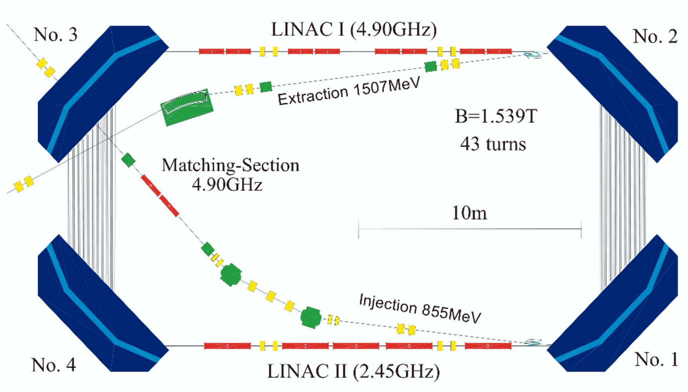
Racetrack Microtron (RTM)

- 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.



Harmonic Double Sided Microtron (HDSM)

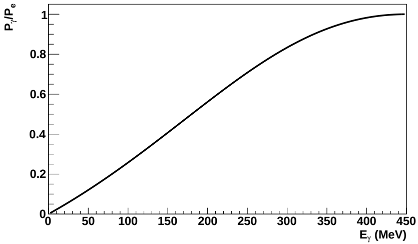
- Similar concept to the RTM, except with two linac sections and four dipole magnets.
- Allows for larger energies while keeping the magnet (and magnetic field) sizes smaller.



Polarized Photon Beam

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

- 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 (≈ 1 Hz).

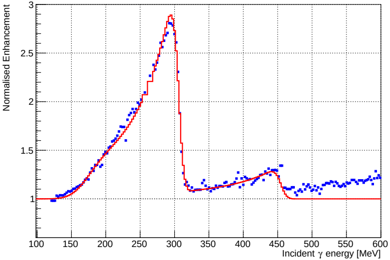


$$P_\gamma = P_e \frac{4E_\gamma E_e - E_\gamma^2}{4E_e^2 - 4E_\gamma E_e + 3E_\gamma^2}$$

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.



Frozen Spin Target

How does Dynamic Nuclear Polarization (DNP) actually work:

- 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%.

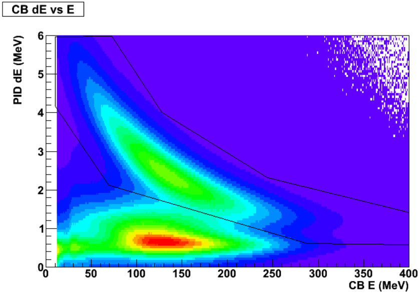
Crystal Ball - Charged Particle Detection

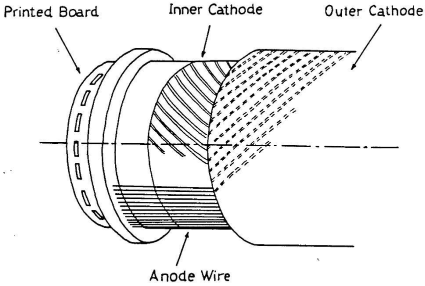
Particle Identification Detector (PID)

- Barrel of 24 plastic paddles
- Each covers $15 < \theta < 159^\circ$, 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





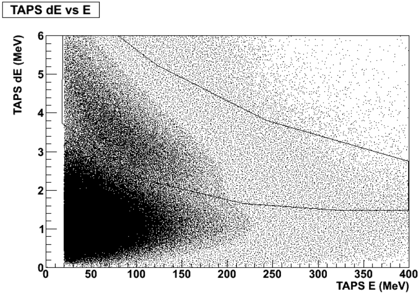
TAPS - Charged Particle Detection

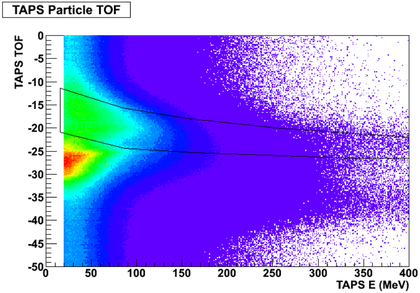
Veto scintillators

- 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)
- 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

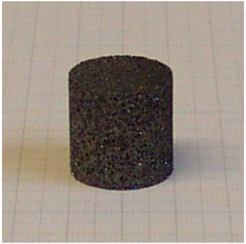
Backgrounds

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



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

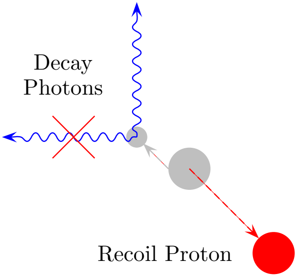
Backgrounds

Butanol Target (C_4H_9OH)

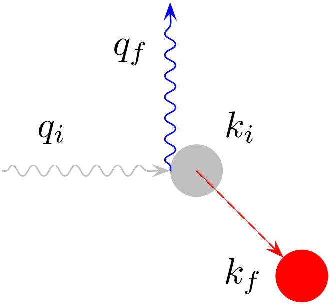
- Compton off H
- Coherent scatter off C (or O)
- Incoherent scatter off C (or O)
- Pion photoproduction off H
- Coherent pion off C (or O)
- Incoherent pion off C (or O)

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.



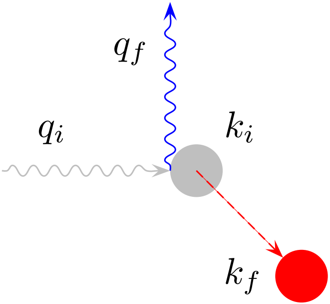
$$k_f = q_i + k_i - q_f$$

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

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



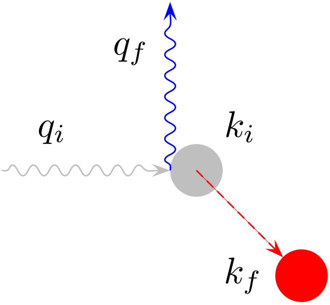
$$k_f = q_i + k_i - q_f$$

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

Q: Why not use the proton information itself?

Missing Mass

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



$$k_f = q_i + k_i - q_f$$

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

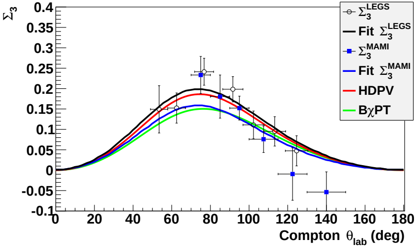
Q: Why not use the proton information itself?

A: Too much energy loss.

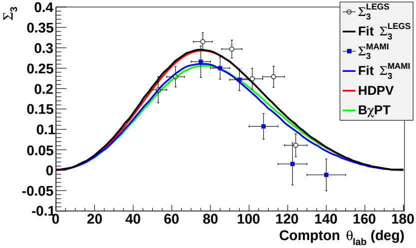
Missing Mass

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

E_γ=267-287 MeV



E_γ=287-307 MeV

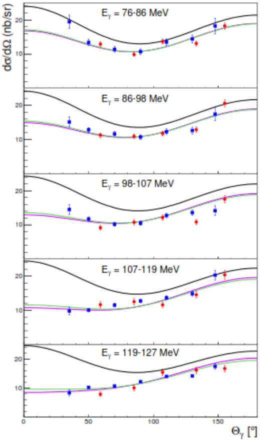


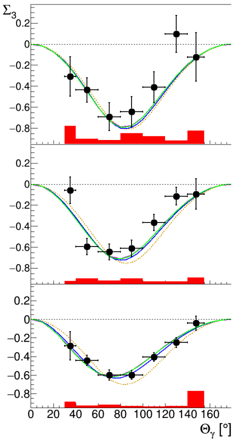
Added dispersion calculations with the fitted polarizability values.
Fit with LEGS → HDPV. Fit with MAMI → BχPT.

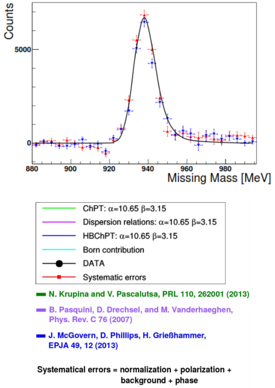
C. Collicott, Ph.D. thesis, Dalhousie University (2015)

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)







$\beta = 2.8^{+2.3}_{-2.1}$ (BChPT) or $\beta = 3.7^{+2.5}_{-2.3}$ (HBChPT). Need more data!