The Nucleon Polarizability Program at MAMI-A2

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A2 Collaboration @ Mainz Microtron

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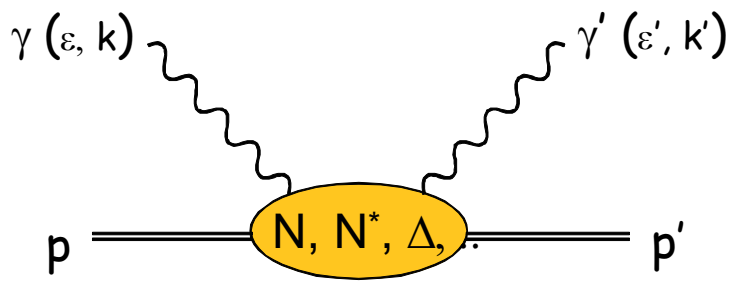
Nucleon Scalar Polarizabilities



Low energy outgoing photon plays role of applied E.M. dipole field

Nucleon response: POLARIZABILITIES

- **Polarizabilities are fundamental constants that describe the nucleon.**
- **They limit precision in many areas of physics:**
  - In astrophysics, they determine neutron star properties.
  - In atomic physics, they yield an appreciable correction to Lamb shift and hyperfine structure.
  - Uncertainty in scalar polarizability is the largest uncertainty in proton radius extraction from H excitation spectrum

Proton Scalar Polarizabilities

- **Accessed via Compton scattering of Real Photons** $\gamma+N\rightarrow\gamma+N$
- 2nd and higher order terms describe polarizabilities and evidence of proton's internal structure.

$$H_{eff}^{(2)} = \frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2$$

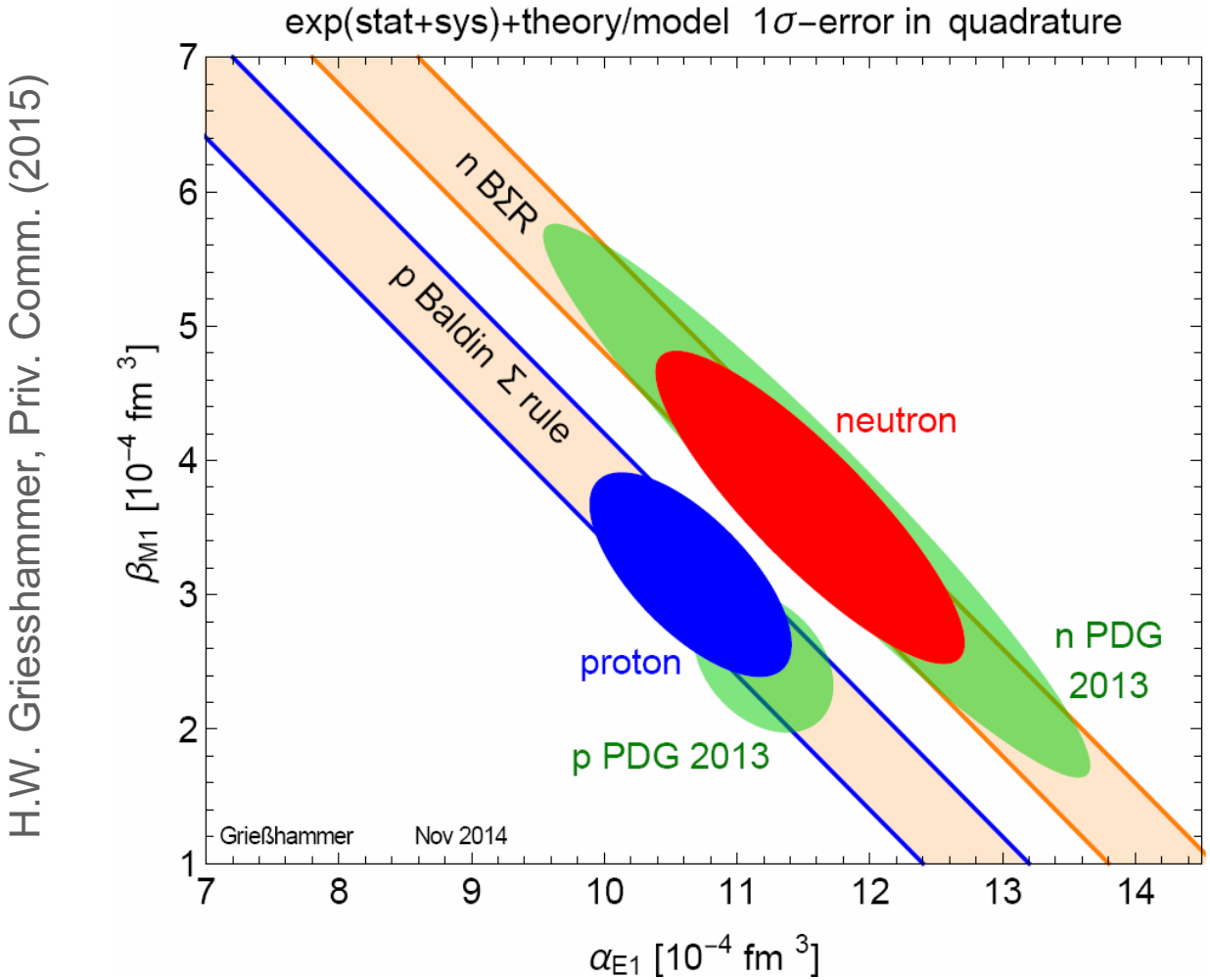
Experimental values (PDG2014):

$\alpha_{E1}=(11.2\pm0.4)\text{x}10^{-4}\ \text{fm}^3$ $\beta_{M1}=(2.5\pm0.4)\text{x}10^{-4}\ \text{fm}^3$

Size of α_{E1} measures "stiffness" of system to electric deformation.

- For ^{1}H atom, expect: $\alpha_E^H = \frac{9}{2}a_B^3 = \frac{27}{8\pi}\text{Vol}$
- **But proton data indicate:** $\alpha_E^p \cong 3\times10^{-4}\,\text{Vol}$
- **The proton is very "stiff", because:** $\frac{\alpha_E^p}{\alpha_E^H} \approx \frac{E_{bind}^H}{E_{bind}^p} \approx \frac{\alpha_{EM}^2}{\alpha_{Strong}^2} \approx 10^{-4}$

Reanalysis of Compton Data Constraints



- Electric polarizability α_{E1} well constrained by experimental data.
- Magnetic polarizability β_{M1} less certain.
- Neutron data are particularly uncertain.

How to obtain more accurate values of α_{E1}, β_{M1}

- **Desire for more precise proton β_{M1} has motivated a new generation of experiments.**
- Combinations of cross sections with linearly polarized photon beam
  - Leading order contribution from α and β

$$\frac{d\sigma^{\parallel}}{d\Omega} = \frac{d\sigma^{\parallel}_{Powell}}{d\Omega} - \frac{e^2}{2\pi m_p}\left(\frac{\upsilon'}{\upsilon}\right)^2 \upsilon\upsilon'\left(\alpha_{E1}\cos\theta^2 + \beta_{M1}\cos\theta\right) + O\left(\upsilon^3\right)$$

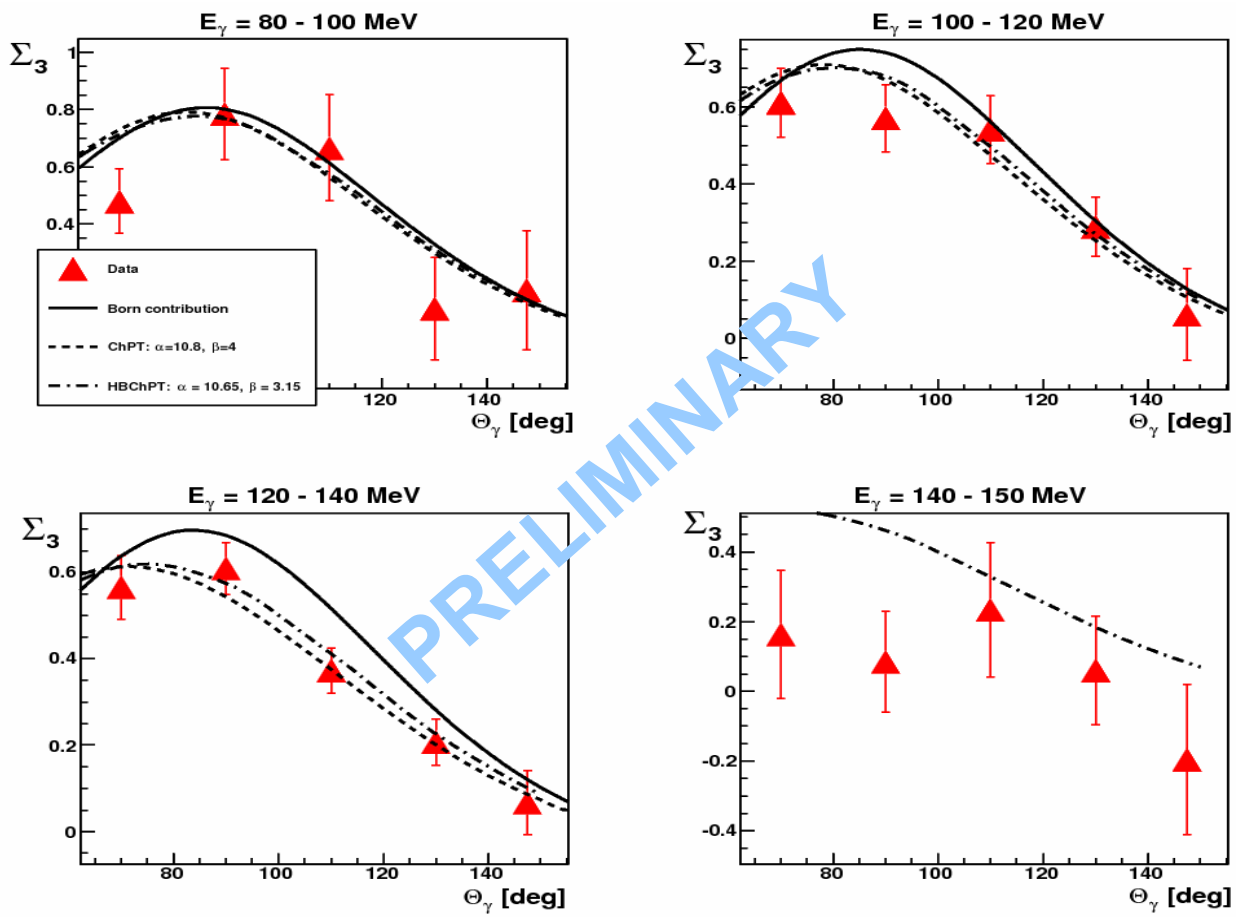
$$\frac{d\sigma^{\perp}}{d\Omega} = \frac{d\sigma^{\perp}_{Powell}}{d\Omega} - \frac{e^2}{2\pi m_p}\left(\frac{\upsilon'}{\upsilon}\right)^2 \upsilon\upsilon'\left(\alpha_{E1} + \beta_{M1}\cos\theta\right) + O\left(\upsilon^3\right)$$

- **New work by Krupina & Pascalutsa** [PRL **110**, 262001 (2013)]
  → At low energies, use beam asymmetry Σ_3 to extract β_{M1}

$$\Sigma_3 \equiv \frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\sigma^{\perp} + d\sigma^{\parallel}}$$
$$= \Sigma_3^{Born} - f_3(\theta)\beta_{M1}\upsilon^2 + O\left(\upsilon^4\right)$$

α_{E1}, β_{M1} from Σ_3 Asymmetry – Sokhoyan, et al.

Only 1/3 of approved data taken so far.



Curves:

χPT: Krupina and Pascalutsa, PRL **110**, 262001 (2013)

HBχPT: J. McGovern, D. Phillips, H. Griesshammer, EPJA **49**, 12 (2013)

Spin Polarizabilities of the Proton

To include spin, next term in Hamiltonian:

$$H_{eff}^{(3)} = -\frac{1}{2}\begin{bmatrix} \gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1M1}\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} \\ +2\gamma_{E1M2}H_{ij}\sigma_i E_j - 2\gamma_{M1E2}E_{ij}\sigma_i H_j \end{bmatrix}$$

involves one field derivative wrt either time or space $\dot{\vec{E}} = \partial_t \vec{E}, \quad E_{ij} = \frac{1}{2}\left(\nabla_i E_j + \nabla_j E_i\right)$

e.g. γ_{M1E2} excited by electric quadrupole (E2) radiation and decays by magnetic dipole (M1) radiation

- **"Stiffness" of proton spin against E.M.-induced deformations relative to the spin axis.**
  - Defines the frequency of proton's spin precession induced by variable E.M. fields.
  - Higher order in incident-photon energy, small effect at lower energies.
- Each spin polarizability is dominated by a pion-pole contribution.
  → The dispersive (interesting) part is relatively small.

Proton Spin Polarizability Predictions

	Kmat	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	-0.0	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.
Pion Pole Subtracted.

K-matrix:
Kondratyuk et al., PRC 64, 024005 (2001)

HDPV, DPV (Dispersion Relation):
Holstein et al., PRC **61**, 034316 (2000)
Drechsel et al., Phys.Rep. **378**, 99 (2003)
Pasquini et al., PRC **76**, 015203 (2007)

L_χ (Chiral Lagrangian):
Gasparyan et al., NP **A866**, 79 (2011)

HBχPT, BχPT (Heavy Baryon & Covariant Chiral PT):
McGovern et al., EPJ **A49**, 12 (2013)
Lensky et al, PRC **89**, 032202 (2014)

Linear combinations of Spin Polarizabilities

One can extract the spin polarizabilities using knowledge of α_{E1}, β_{M1}, the linear combinations γ_0,γ_π, and Subtracted Dispersion Relations.

Backward Spin Polarizability

(unpolarized Compton scattering)

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

$$\gamma_\pi = (-38.7 \pm 1.8) \cdot 10^{-4}\ \mathrm{fm}^4$$

Schumacher, Prog. Part. Nucl. Phys. **55**, 567(2005)

Pion pole contributes -46.7

Dispersive part 8.0±1.8 known only to ≈25%.

Forward Spin Polarizability

(polarized beam and target)

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

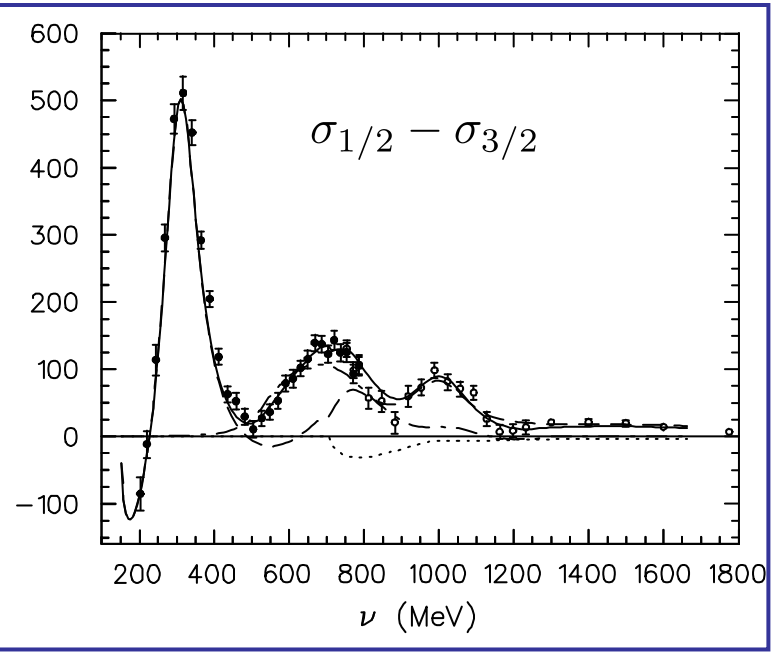
$$\gamma_0 = \frac{1}{4\pi^2} \int_{\nu_{thr}}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\nu^3}\, \mathrm{d}\nu$$

$$\gamma_0 = -(1.00 \pm 0.08 \pm 0.10) \times 10^{-4}\ \mathrm{fm}^4$$

Ahrens et al., PRL**87**, 022003 (2001)

Known to ≈10%.

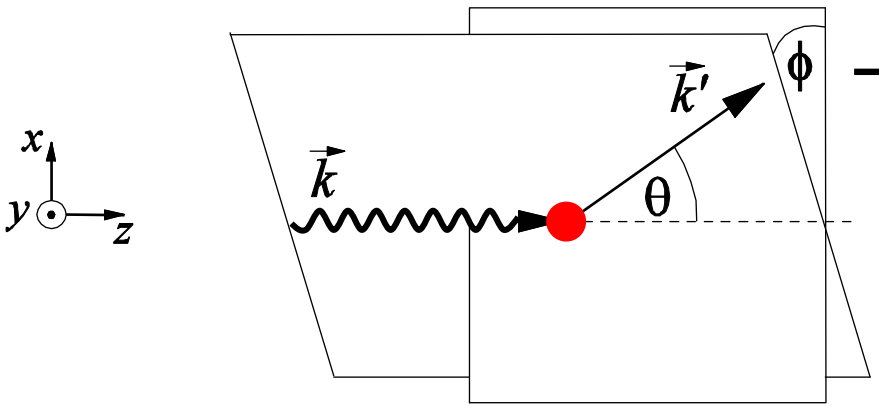
Pion pole contribution cancels.



Better way to extract Spin Polarizabilities

- **Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy**
  - It is in the Δ resonance region (E_γ=200-300 MeV) where their effect becomes significant.
- **In this energy region, it is possible to accurately measure polarization asymmetries using a variety of polarized beam and target combinations**
  - The various asymmetries respond differently to the individual spin polarizabilities at different E_γ and θ.
  - Measure three asymmetries at different E_γ, θ.
- **Our plan is to conduct a global analysis:**
  - Include constraints from "known" γ_0, γ_π, α_{E1}, β_{M1}.
  - Extract all four spin polarizabilities independently with small statistical, systematic and model-dependent errors.

Asymmetries with Linearly Polarized γ



azimuthal angle between the scattering plane and the photon polarization vector

- ϕ = 0 and unpolarized target $\rightarrow \Sigma_3$
- ϕ = 0 and transversely polarized target in the y direction $\rightarrow \Sigma_{3y}$
- ϕ = 45° and longitudinally pol. target $\rightarrow \Sigma_{1z}$
- ϕ = 45° and transv. pol. target in the x direction $\rightarrow \Sigma_{1x}$

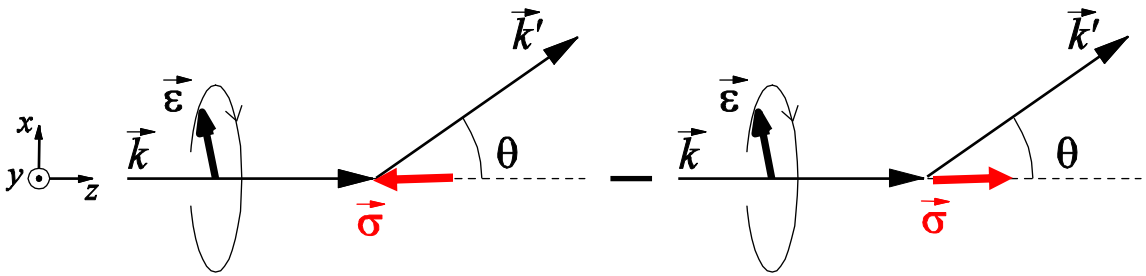
$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

Asymmetry is measured with linearly polarized photons, parallel and perpendicular to the scattering plane, and unpolarized target.

Double Spin Asymmetries w/ Circularly Polarized γ

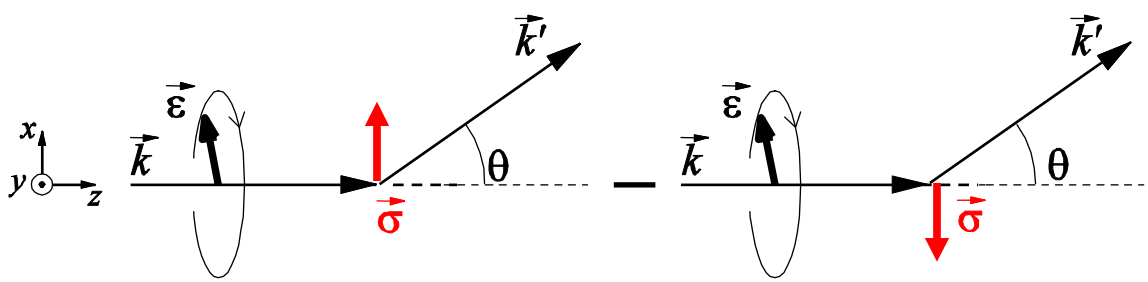
❖ Longitudinal asymmetry

$$\left[\Sigma_{2z} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\uparrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\downarrow}}{Sum}\right]_{h=\pm 1}$$



❖ Transverse asymmetry

$$\left[\Sigma_{2x} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\rightarrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\leftarrow}}{Sum}\right]_{h=\pm 1}$$



Sensitivity to Spin Polarizabilities

	Polarization			
Polarization Asymmetry	Beam	Target	E_γ Range (MeV)	Spin Polarizability
Σ_{2z}	**Circular**	**Longitudinal**	**200-300**	γ_{M1M1}
Σ_{2x}		**Transverse**	**200-300**	γ_{E1E1}
Σ_3	**Linear**	**None**	**200-300**	γ_{M1M1}
Σ_{3y}		**Transverse**	**200-300**	γ_{E1E1}
Σ_{1z}		**Longitudinal**	**200-300**	**Both**
Σ_{1x}		**Transverse**	**150-250**	**Both**

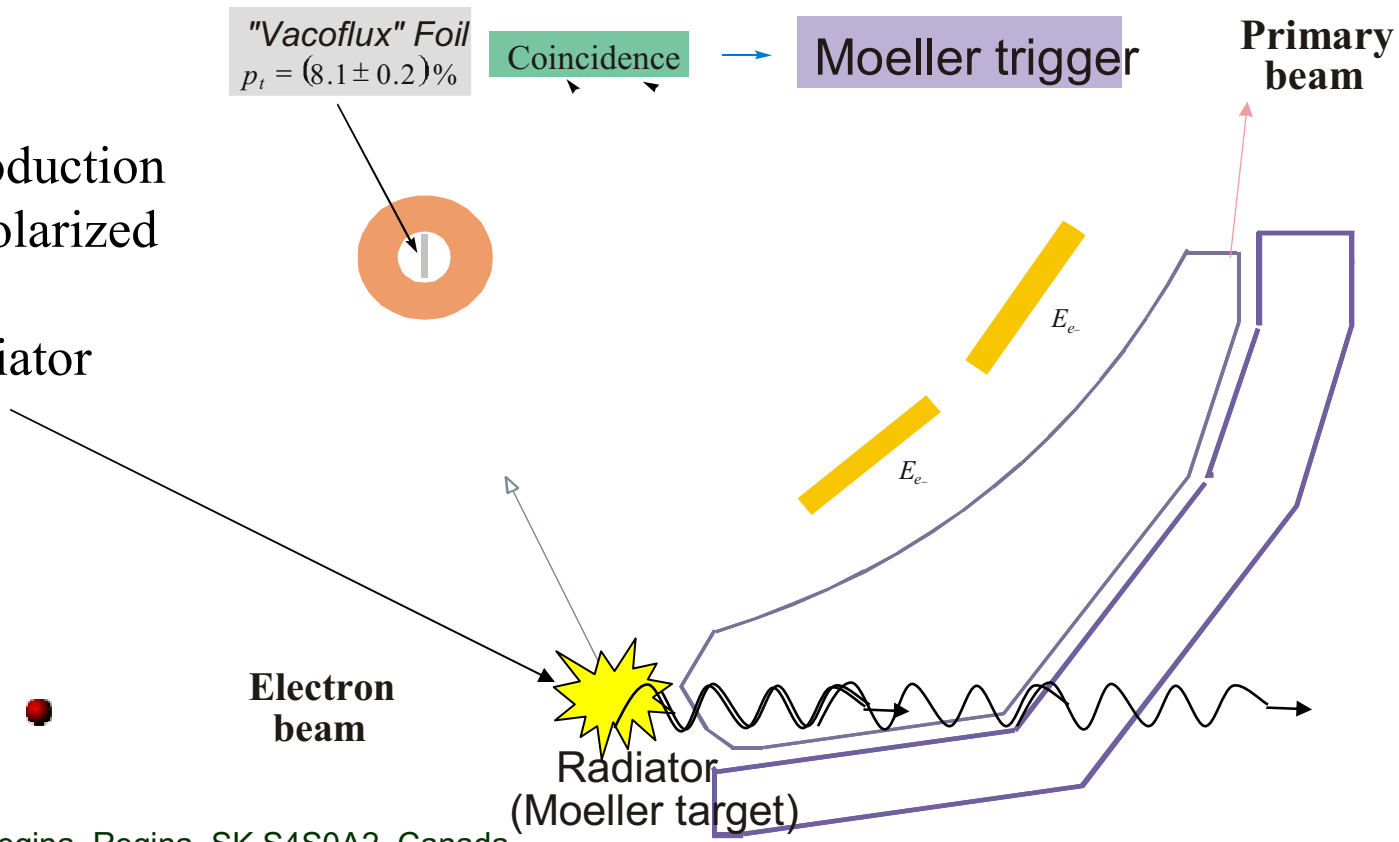
A2 Tagging system (Glasgow,Mainz)

1. Production and energy measurement of Bremsstrahlung photons

2. Determination of the degree of polarization of the electron beam (Moeller Polarimeter); Circularly pol. photons

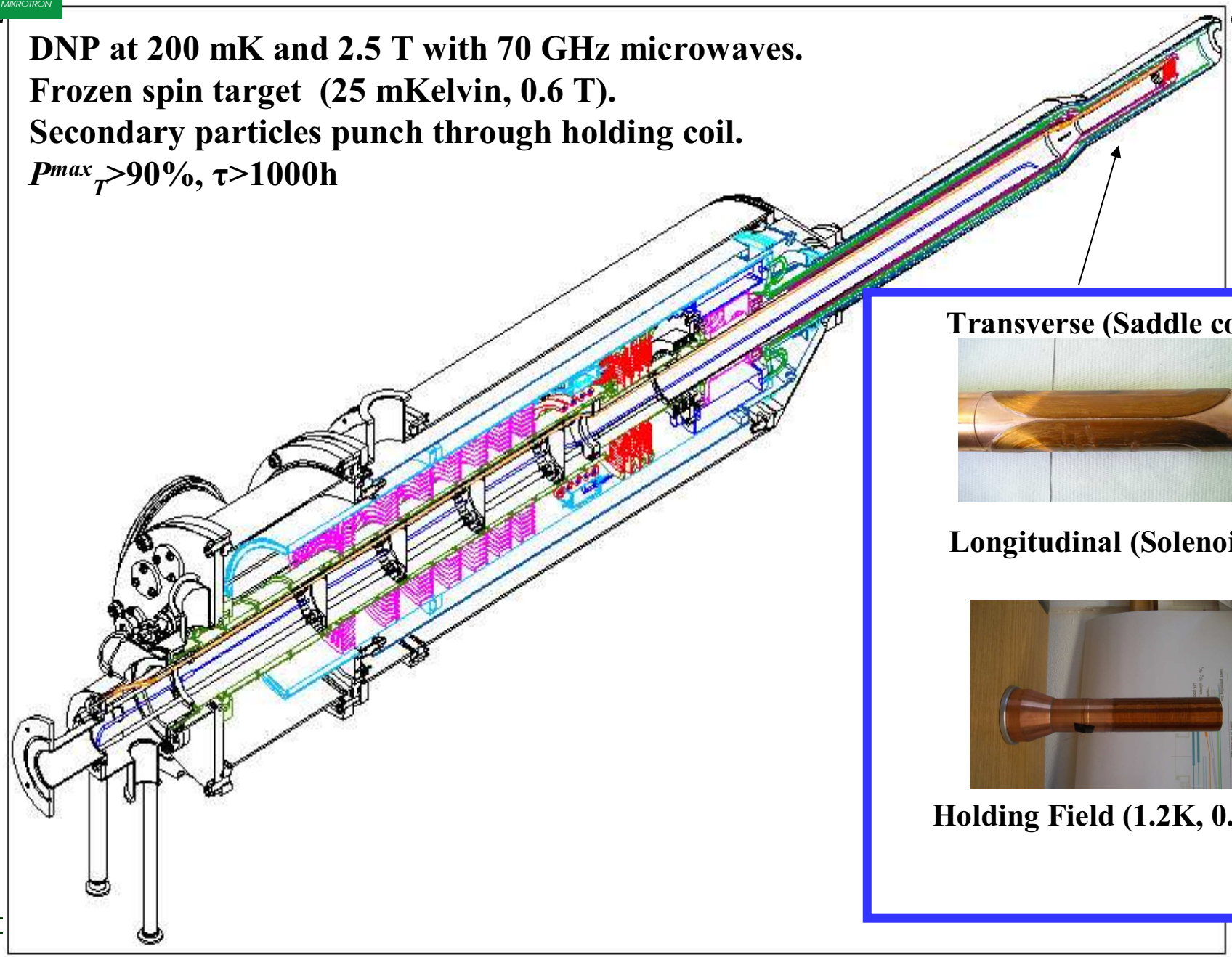
$$A = \frac{N^+ - N^-}{N^+ + N^-} = a\vec{p}_t\vec{p}_b\cos(z)$$

3. Coherent production of linearly polarized photons on a diamond radiator



Frozen Spin Butanol Target

DNP at 200 mK and 2.5 T with 70 GHz microwaves.
Frozen spin target (25 mKelvin, 0.6 T).
Secondary particles punch through holding coil.
P^{max}_{T}>90%, τ>1000h



Transverse (Saddle coil)

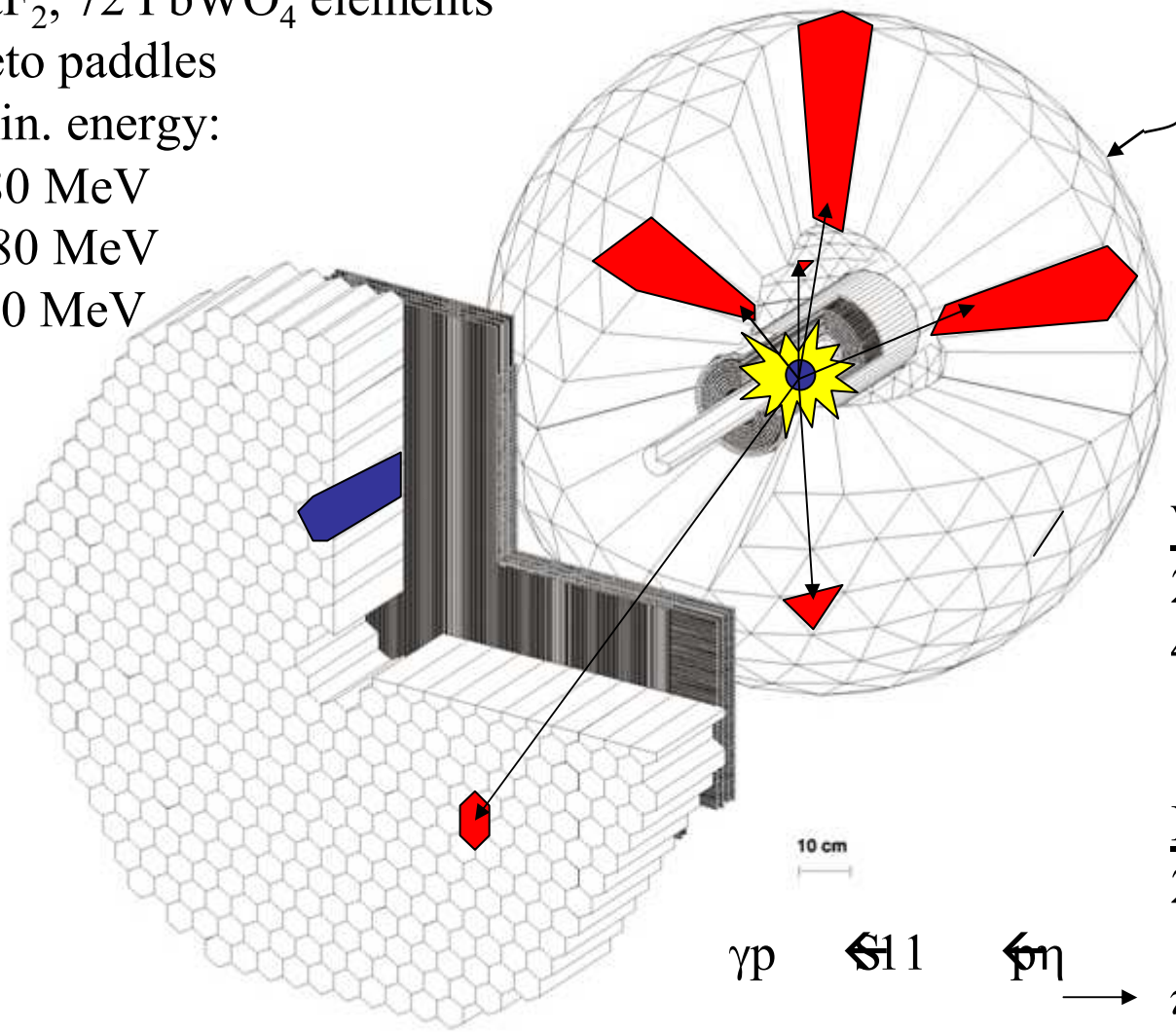
Longitudinal (Solenoid)

Holding Field (1.2K, 0.6T)

4π photon Spectrometer @ MAMI

TAPS:

366 BaF_2, 72 $PbWO_4$ elements
384 Veto paddles
Max. kin. energy:
π^{+-} : 180 MeV
K^{+-} : 280 MeV
P : 360 MeV



Crystal Ball:

672 NaI detectors
Max. kin. energy:
μ^{+-} : 233MeV
π^{+-} : 240 MeV
K^{+-} : 341 MeV
P : 425 MeV

Vertex detector:

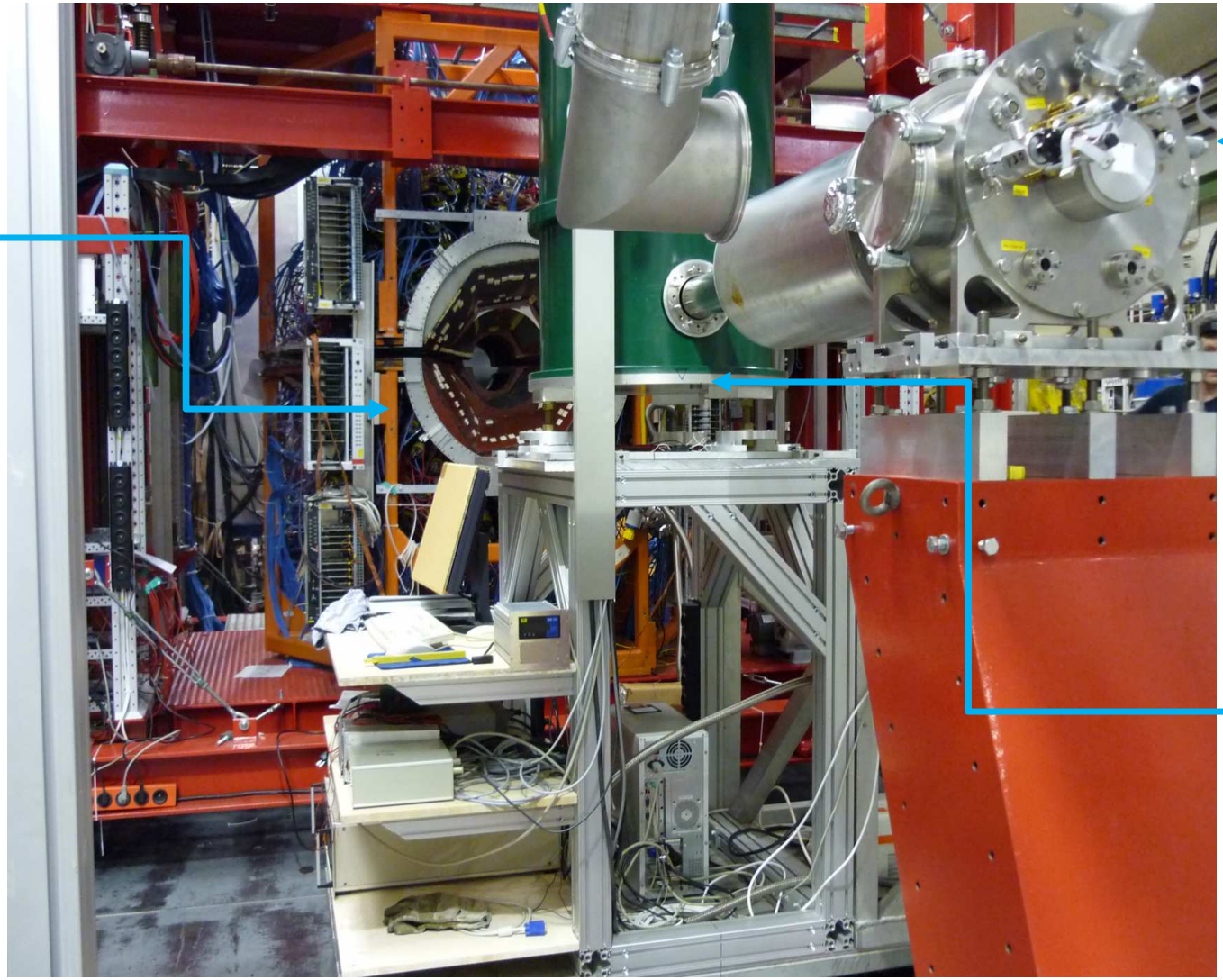
2 Cylindr. MWPCs
480 wires, 320stripes

PID detector:

24 thin plastic detectors

$\gamma p \to S11 \to p\eta \to \pi^0\pi^0\pi^0 \to \gamma\gamma\gamma\gamma\gamma\gamma$

Setup in the A2 – Tagger Hall



First Beam with Transverse Polarization in December, 2009. Runs 2010-11.
Longitudinal Polarization runs 2012, 2014, 2015.

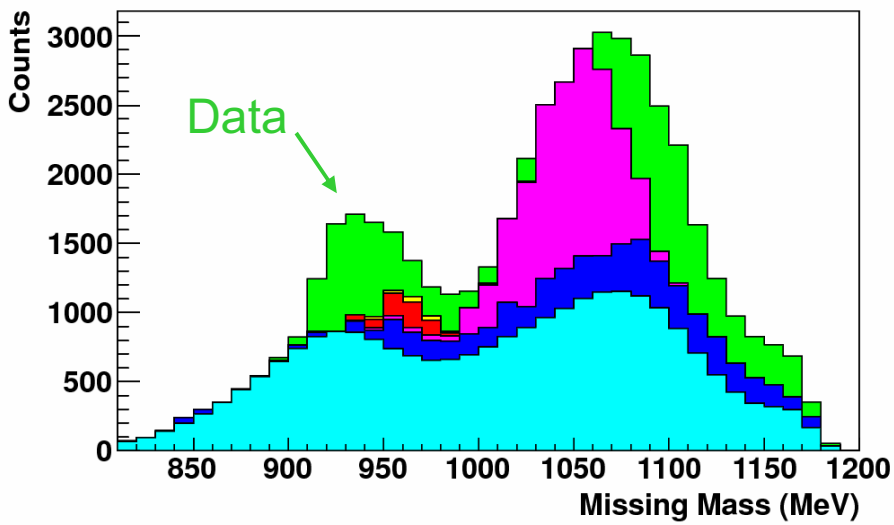
Dr. G.M Huber, Univ. of Regina, Regina, SK S4S0A2, Canada.

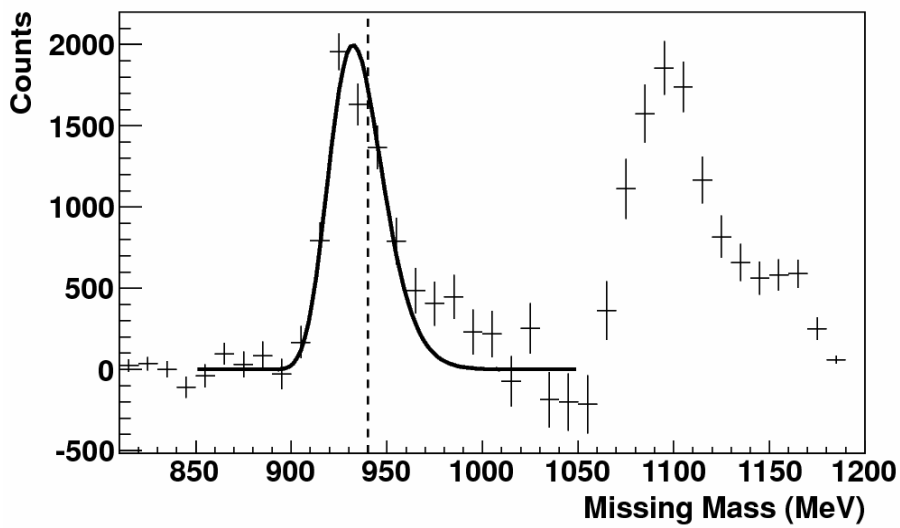
Asymmetries – Experimental Challenges

- **Small Compton scattering cross sections.**
- **Large backgrounds:**
  - π^0 photoproduction cross section is about *100 times* that of Compton scattering.
  - Coherent and incoherent reactions of C, O, He in polarized target.
- In Δ–region, proton tracks can be used to suppress backgrounds,
  - but energy losses in the LH_2 target, frozen-spin cryostat, and CB-TAPS are considerable.
- Under certain conditions, π^0 photoproduction can mimic Compton scattering.

Σ_{2x} – Martel, et al.

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





Background contributions to MM:

- accidental coincidences
- carbon/cryostat contributions
- reconstructed π^0 background where one decay γ escapes setup in:
  - TAPS downstream hole
  - CB upstream hole

Fully-subtracted MM spectrum:

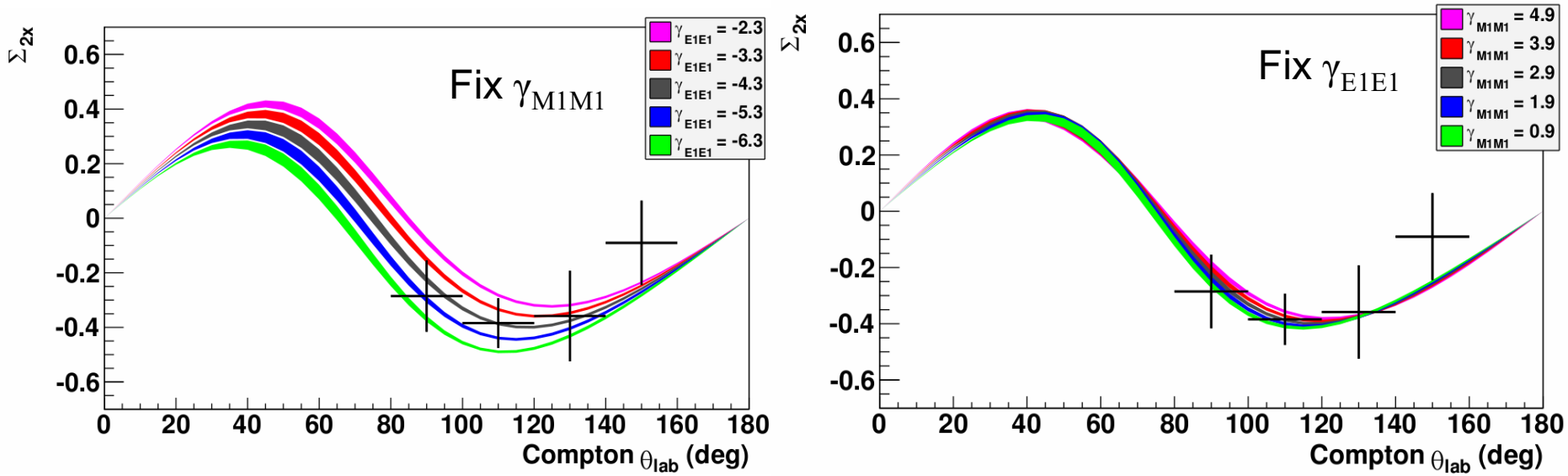
- conservative MM<940 MeV integration limit
- simulated Compton peak

Σ_{2x} – Martel, et al.

New results!

Physical Review Letters **114**, 112501 (2015), arXiv:1408.1576 [nucl-ex]

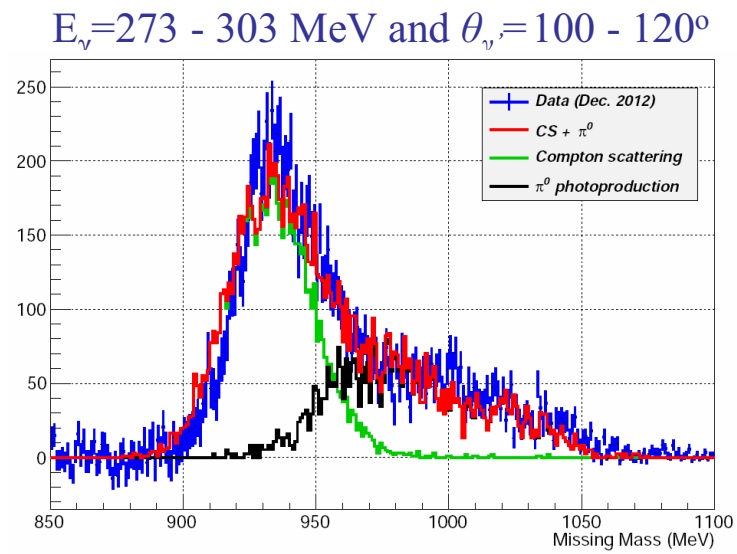
E_γ=273 - 303 MeV



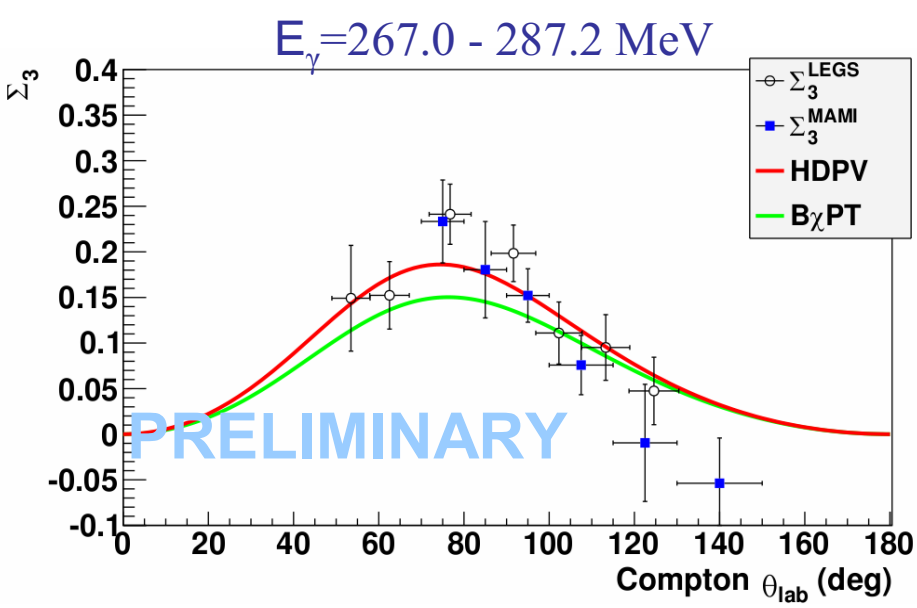
- First measurement of a double-spin Compton scattering asymmetry on the nucleon.
- Curves are from DR calculation of Pasquini et al., making use of constraints on $\alpha_{E1}+\beta_{M1}$, $\alpha_{E1}-\beta_{M1}$, γ_0, γ_π (allowed to vary within experimental errors).
- Checks were done with BχPT calculation of Lensky & Pascalutsa.

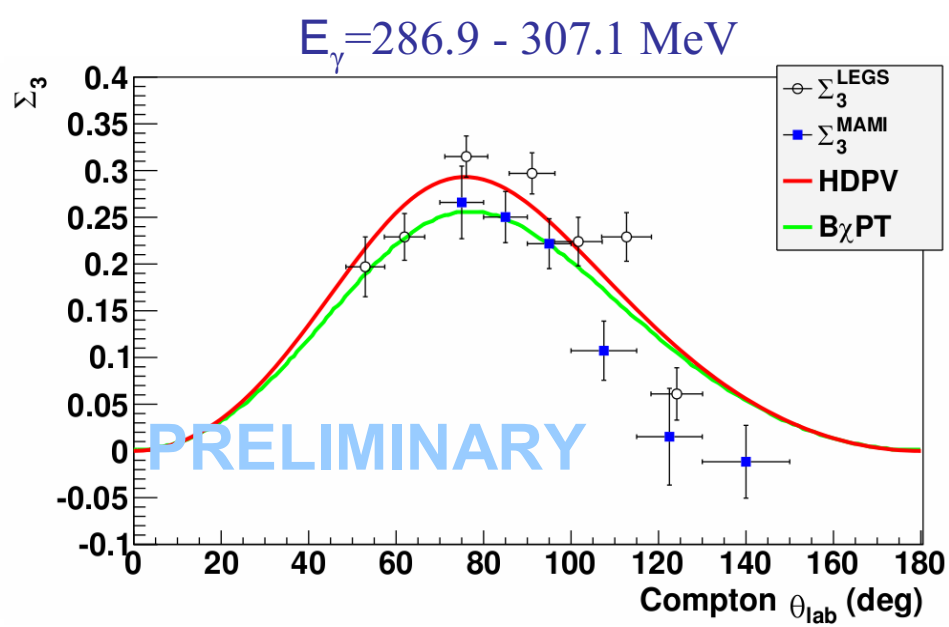
Σ_3 – Collicott, et al.

Simulation of π^0 photoproduction in LH_2 target matches background of the distribution quite well.



New (MAMI) and older (LEGS) Σ_3 measurements along with two theoretical curves using their preferred polarizabilities





Dr. G.M Huber, Univ. of Regina, Regina, SK S4S0A2, Canada.

LEGS = Blanpied et al., PRC **64**, 025203 (2001)

PRELIMINARY - Combined Spin Polarizability Analysis

- **Dispersion relation fits to Σ_{2x} along with either Σ_3^{MAMI} or Σ_3^{LEGS}.**
- Pion-pole contribution has been subtracted.

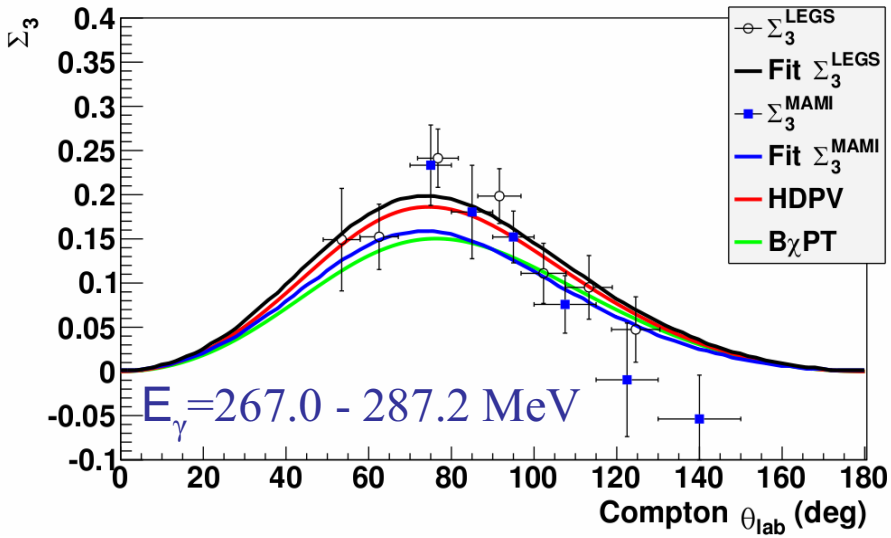
	HDPV	BχPT	Σ_{2x} and Σ_3^{LEGS}	Σ_{2x} and Σ_3^{MAMI}
γ_{E1E1}	-4.3	-3.3	-3.5±1.2	-5.0±1.5
γ_{M1M1}	2.9	3.0	3.16±0.85	3.13±0.88
γ_{E1M2}	-0.0	0.2	-0.7±1.2	1.7±1.7
γ_{M1E2}	2.2	1.1	1.99±0.29	1.26±0.43
γ_0	-0.8	-1.0	-1.03±0.18	-1.00±0.18
γ_π	9.4	7.2	9.3±1.6	7.8±1.8
$\alpha+\beta$			14.0±0.4	13.8±0.4
$\alpha-\beta$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

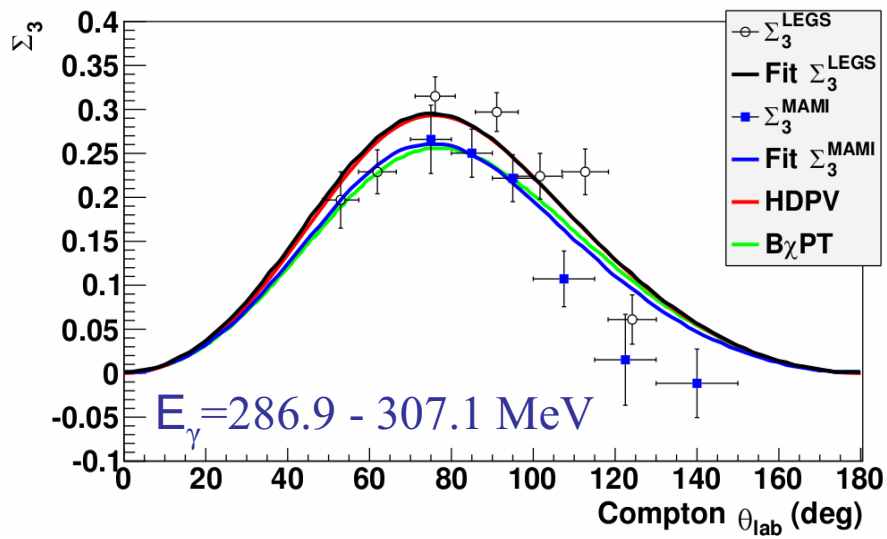
Spin polarizabilities in units of 10^{-4} fm^4.
Scalar polarizabilities 10^{-4} fm^3.

Effect of Σ_3 Data on Σ_{2x} Fits - PRELIMINARY

1) Dispersion Relation Calcs w/ fitted polarizability values

Fit with Σ_3^{LEGS} → HDPV. Fit with Σ_3^{MAMI} → BχPT.

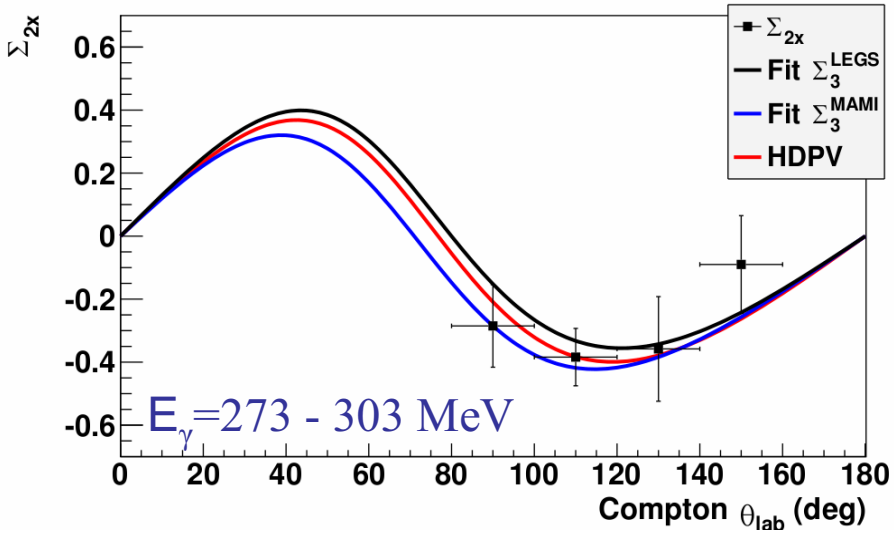




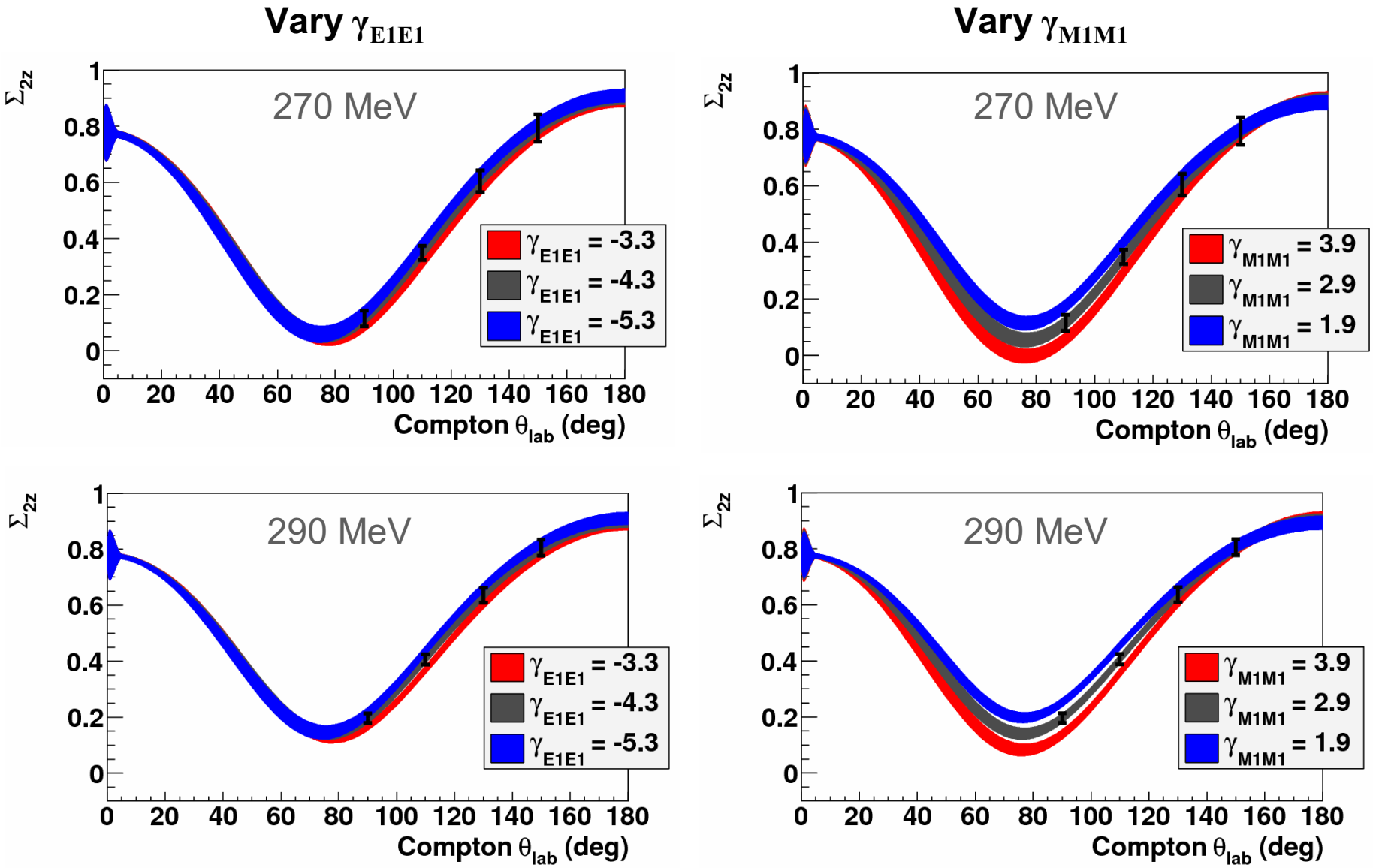
2) Look at Σ_{2x} with different Σ_3 fits

→ Clearly shows importance of the Σ_3 constraint.

→ Planned Σ_{2z} data will further constrain spin polarizabilities.



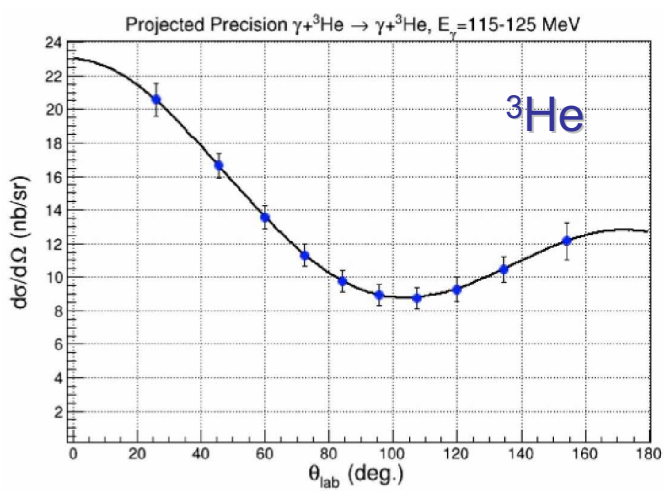
Σ_{2z} – Estimated Experimental Precision

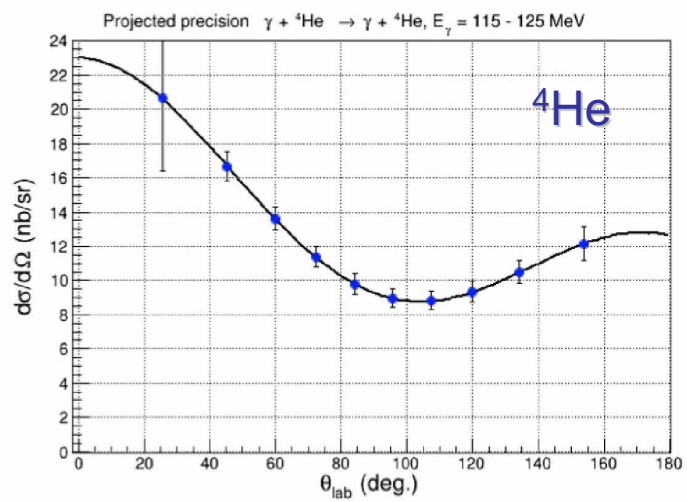


Neutron Scalar Polarizabilities

In certain kinematic regions, proton acts like a spectator and scattering is done from neutron.

- **A relatively new idea is to use ^{3}He instead of ^{2}H target:**
  - → χPT calcs by Shukla, Nogga, Phillips [NP **A819**, 98 (2009)]
  - → α^n_{E1}, β^n_{M1} determined from fit to Angular distributions vs. Energy





J. Annand et al. working on high-pressure active He gas scintillator target.

- Proposal A2-01-2013 for ^{3}He(γ,γ)^{3}He given `A' rating by PAC.
- Expected good separation of backgrounds from target windows and π^0 production.

Summary

Polarizabilities are an important tool for testing QCD via χPT and DRs in the non-perturbative regime.

- **Σ_{2x} has been measured for the first time.**
  - Published in recent PRL.
  - Plans to acquire more data but not yet scheduled.
- **Σ_3 data taken to supplement existing data.**
  - Higher energy analysis for spin polarizability finished.
  - Plan to acquire more low energy data for α_{E1}, β_{M1} in 2016.
- **Σ_{2z} data partly taken, more scheduled for July 2015.**

- **Future:**
  - Improvements in simulation to remove π^0 backgrounds would allow less restrictive MM cut to be used, increase statistics.
  - Plan to combine results with ongoing α_{E1}, β_{M1} studies.
  - Implement active target to expand kinematic range.
  - Extend measurements to neutron.