The Nucleon Polarizability Program at MAMI-A2

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Catholic University of America
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A2 Collaboration @ Mainz Microtron

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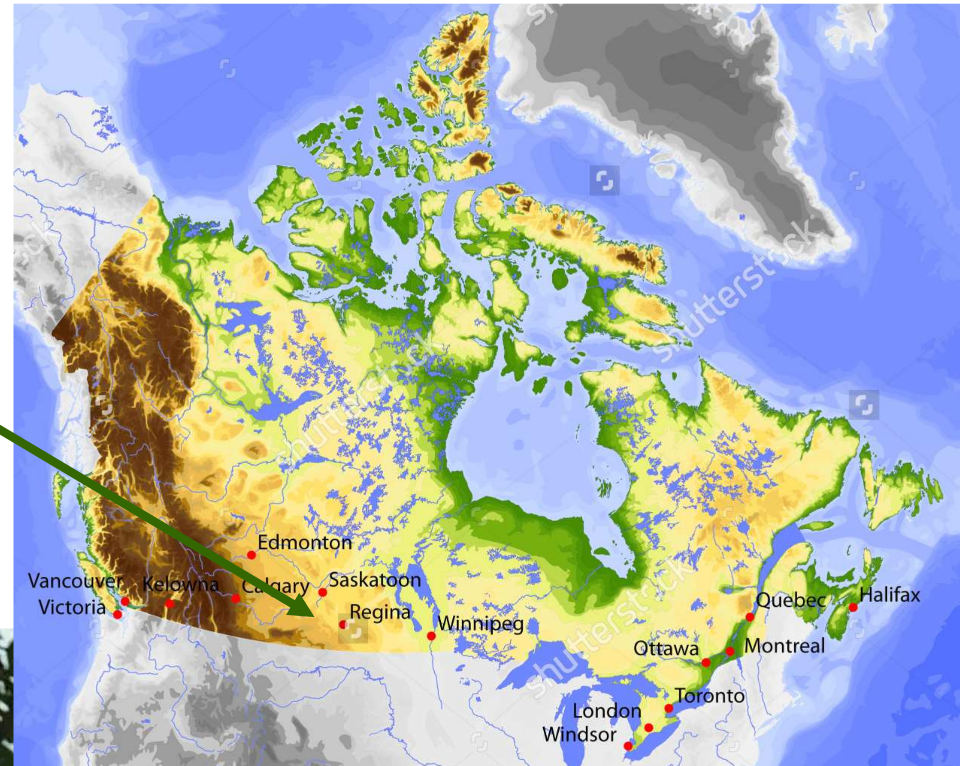
J. Annand (Glasgow), J. Arends (Mainz)

Regina, Saskatchewan CANADA



Regina is named after Queen Victoria, and is capital of the province of Saskatchewan

University of Regina

- **Founded 1974.**
- **15,276 students, incl. ~2,000 Grad Students (2017).**
- **Physics Dept. offers B.Sc., M.Sc. and Ph.D. degrees.**

Particle Data Group: Baryon Listings

p $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MASS (MeV)

VALUE (MeV)
938.272013±0.000023

p MAGNETIC MOMENT

VALUE (μ_N)
2.792847356±0.000000023

Valence quarks: uud

p CHARGE RADIUS

VALUE (fm)
0.8768±0.0069

p ELECTRIC DIPOLE MOMENT

VALUE (10^{-23} e cm)
< 0.54

p ELECTRIC POLARIZABILITY α_p

VALUE (10^{-4} fm^3)	*DC*
12.0 ±0.6	**OUR AVERAGE**

p MAGNETIC POLARIZABILITY β_p

VALUE (10^{-4} fm^3)	*D*
1.9 ±0.5	**OUR AVERAGE**

Response to a deformation force

p MEAN LIFE

LIMIT (years)	*PARTICLE*
>5.8 × 10^{29}	***n***
>2.1 × 10^{29}	***p***

p DECAY MODES

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What is a Polarizability?

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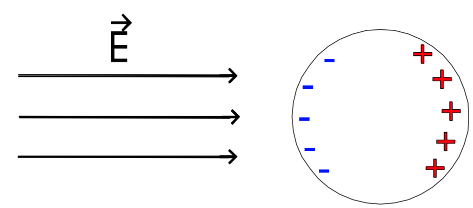
A measure of response of system to a quasi-static field.

e.g. Electric Polarizability α_E

Applied E induces EDM

$$\vec{p} = \alpha_E \vec{E}$$



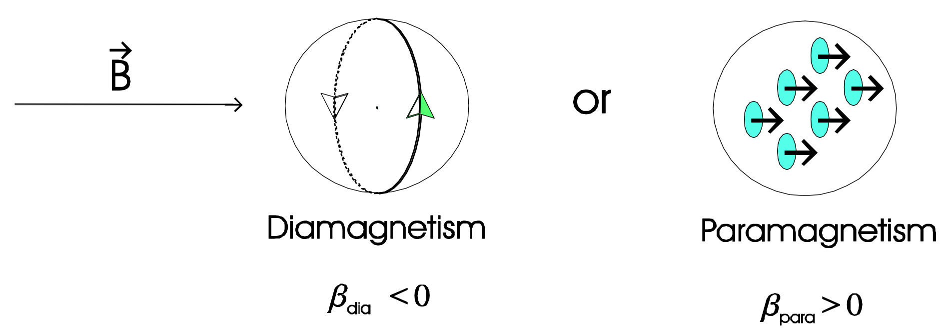
with energy density

$$u_E = -\frac{1}{2}\alpha_E \vec{E}^2$$

Similarly, applied H induces MDM

$$\vec{m} = \beta_E \vec{H}$$

$$u_M = -\frac{1}{2}\beta_M \vec{H}^2$$



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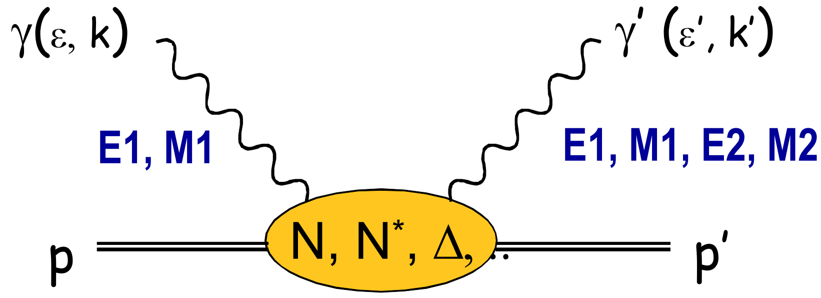
Nucleon Scalar Polarizabilities



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

Nucleon response: POLARIZABILITIES

Nucleon Polarizabilities of interest to many fields:

- 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

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How to measure 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.

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

- Compton scattering angular distribution

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{m^2}\left(\frac{\omega'}{\omega}\right)^2 \left(\frac{1}{2}\left(1+\cos^2\theta\right) - \frac{m\omega\omega'}{\alpha}\left[\begin{array}{c} \frac{\alpha_{E1}+\beta_{M1}}{2}\left(1+\cos\theta\right)^2 \\ +\frac{\alpha_{E1}-\beta_{M1}}{2}\left(1-\cos\theta\right)^2 \\ +\ldots \end{array} \right] \right)$$

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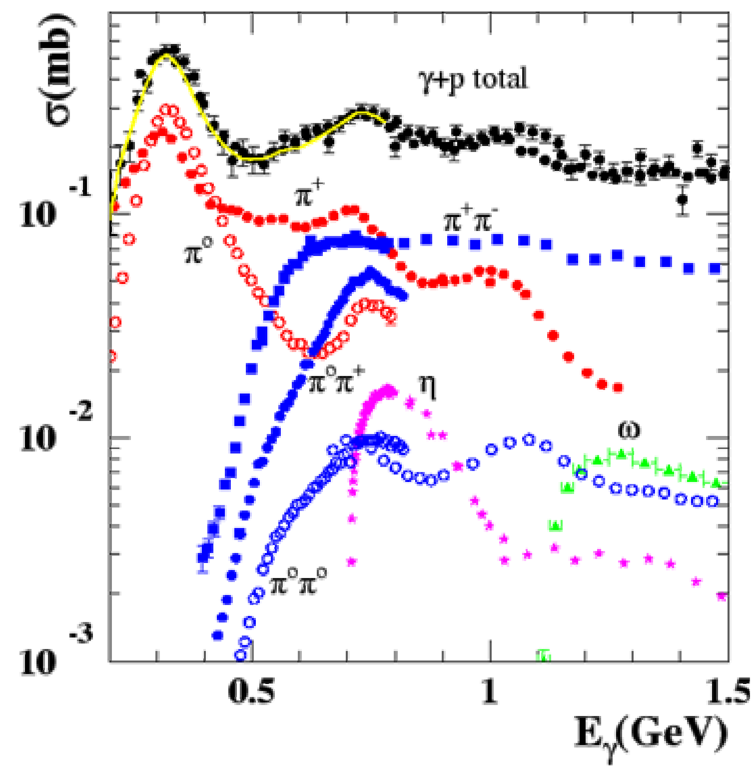
Polarizabilities from Real Compton Scattering

1. Total inclusive photoabsorption cross section:

$$\alpha_{E1} + \beta_{M1} = \frac{1}{2\pi^2} \int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu^2} \sigma_{abs}(\nu)$$

Baldin Sum Rule (1960)

Sum Rule is model independent
→ but a model is needed to evaluate integral beyond experimental data.



$$\alpha_{E1} + \beta_{M1} = (13.8 \pm 0.4) \cdot 10^{-4}\ \text{fm}^3$$

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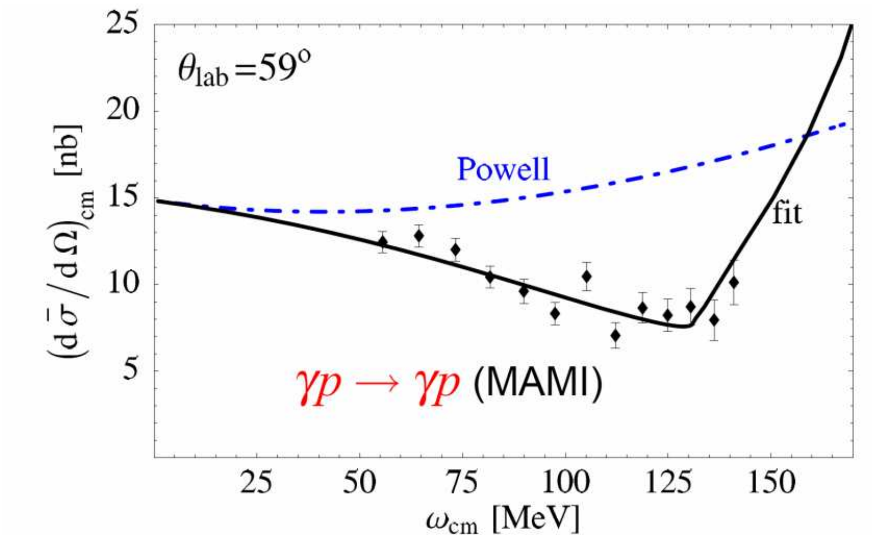
Polarizabilities from Real Compton Scattering

2. Compton scattering angular distribution vs energy (ν)



Olmos de Leon et al., EPJ A10 (2001)

Powell cross section: photon scattering off a pointlike nucleon with anomalous magnetic moment.

Disperson relation analysis used to extract α β from the data.

$$\alpha_{E1} - \beta_{M1} = (10.5 \pm 0.9) \cdot 10^{-4}\ \text{fm}^3$$

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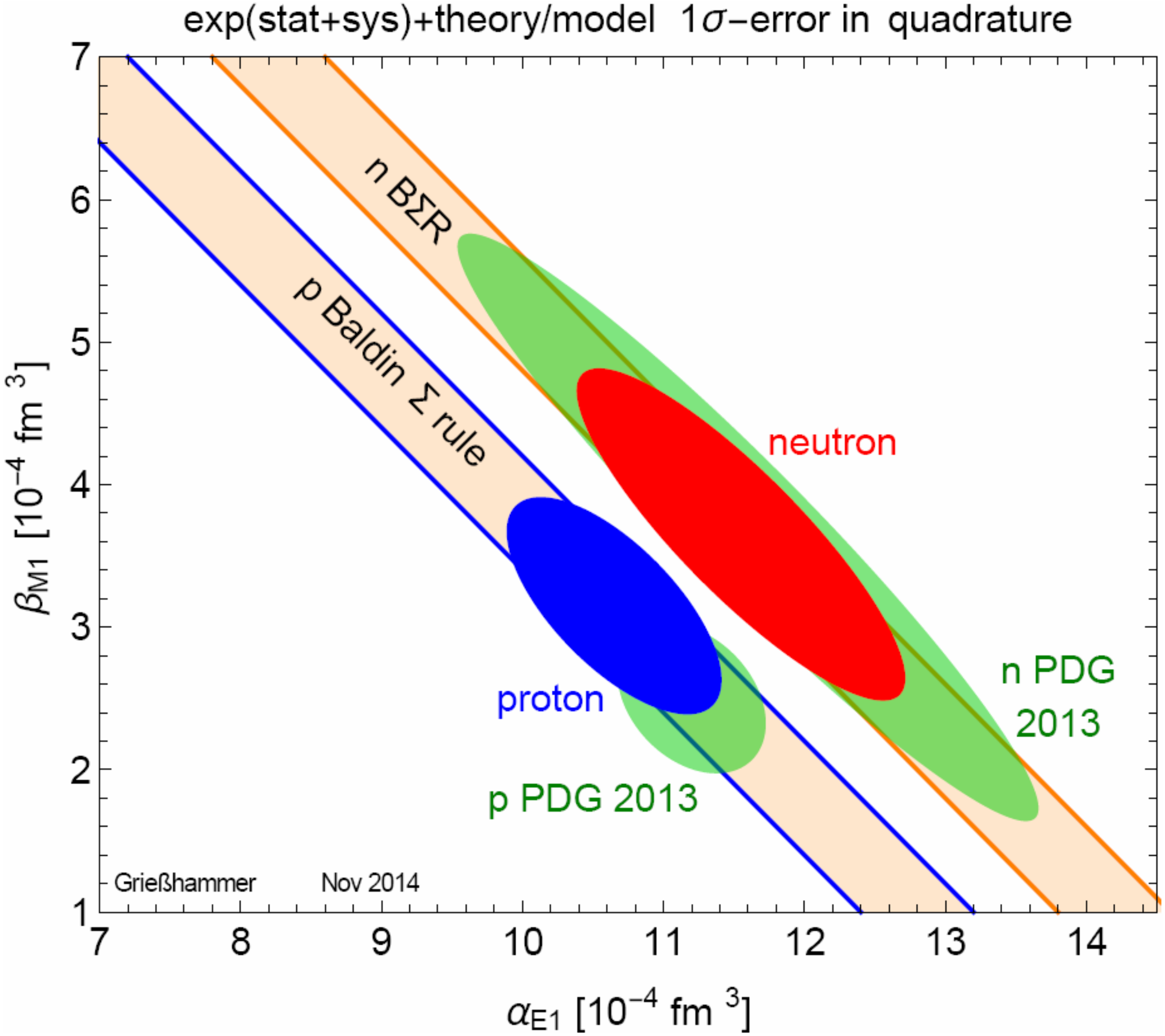
Global Analysis of Compton Data Constraints



H.W. Griesshammer, Priv. Comm. (2015)

- Electric polarizability α_{E1} well constrained by experimental data.
- Magnetic polarizability β_{M1} less certain.
  - Diamagnetism is important in the nucleon, but uncertainty ~25%.
- Neutron data are particularly uncertain.

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A simple picture of what the results mean

Experimental values (PDG2014):

α_{E1}=(11.2±0.4)x10^{-4} fm^3 β_{M1}=(2.5±0.4)x10^{-4} fm^3

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

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

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More detailed explanation

- Need to take into account that the proton is surrounded by a virtual meson cloud in order to quantitatively understand the observed α_{E1}, β_{M1} polarizabilities.

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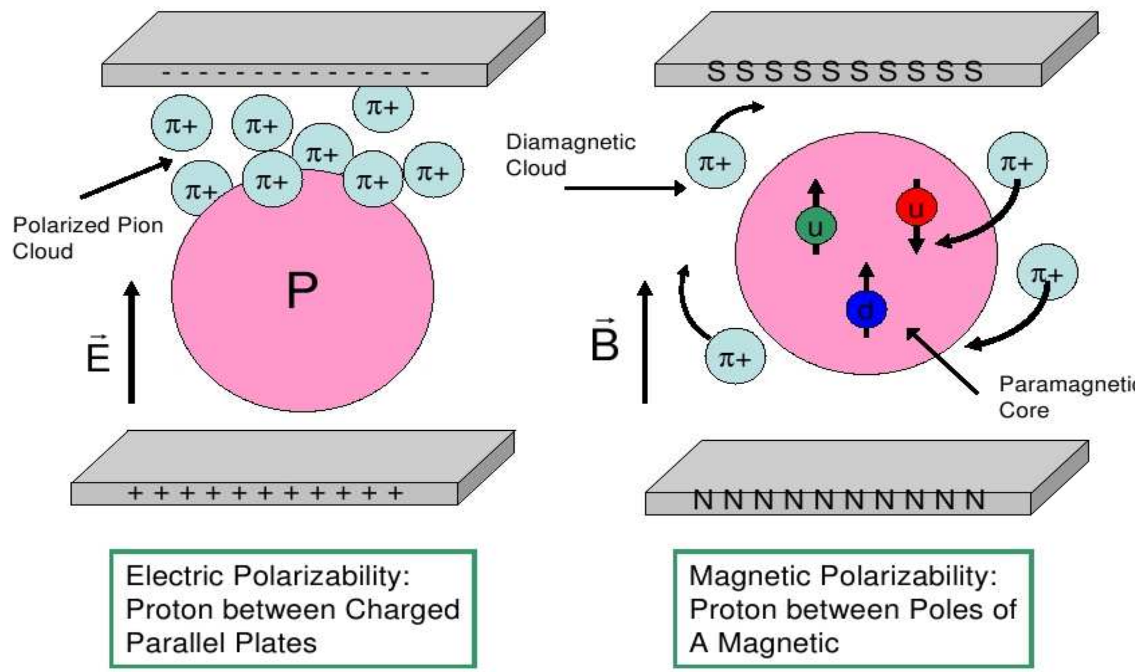
- p(J=½)→Δ(J=3/2) dipole transition makes very strong paramagnetic contribution to $\beta_M \sim 10^{-3}$ fm^3.
- Partially offset by strong diamagnetic component from meson cloud.



B. Holstein, MAMI and Beyond Conference, 2008.

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

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- **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}

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

$$= \Sigma_3^{Born} - f_3(\theta)\,\beta_{M1}\upsilon^2 + O\left(\upsilon^4\right)$$

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Pioneering α_{E1}, β_{M1} from Σ_3 Asymmetry

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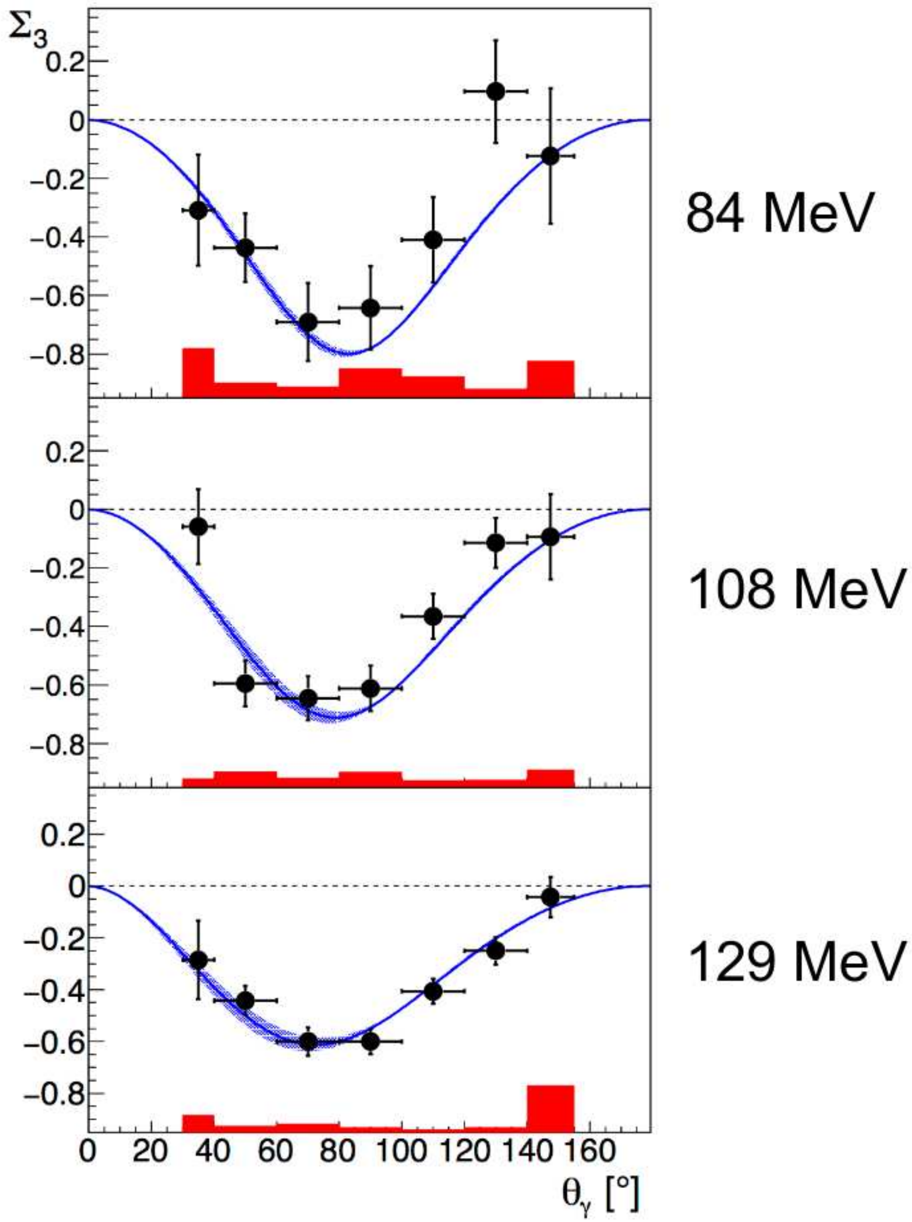

V. Sokhoyan, et al., EPJA 53, 14 (2017)

First use of linearly polarized photon beam asymmetry Σ_3 below pion threshold to determine proton magnetic polarizability.

Fit results using BChPT gives:

$$\beta_{M1} = 2.8^{+2.3}_{-2.1} \times 10^{-4}\ \mathrm{fm}^3$$

- Only 1/3 of approved data taken so far:
- New data run with upgraded photon tagger focal plane with drastically reduce the statistical uncertainties.

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Proton Spin (Vector) Polarizabilities

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To include spin, next term in Hamiltonian:

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

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

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.

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Proton Spin Polarizability Predictions

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	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)

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Linear combinations of Spin Polarizabilities

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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)

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

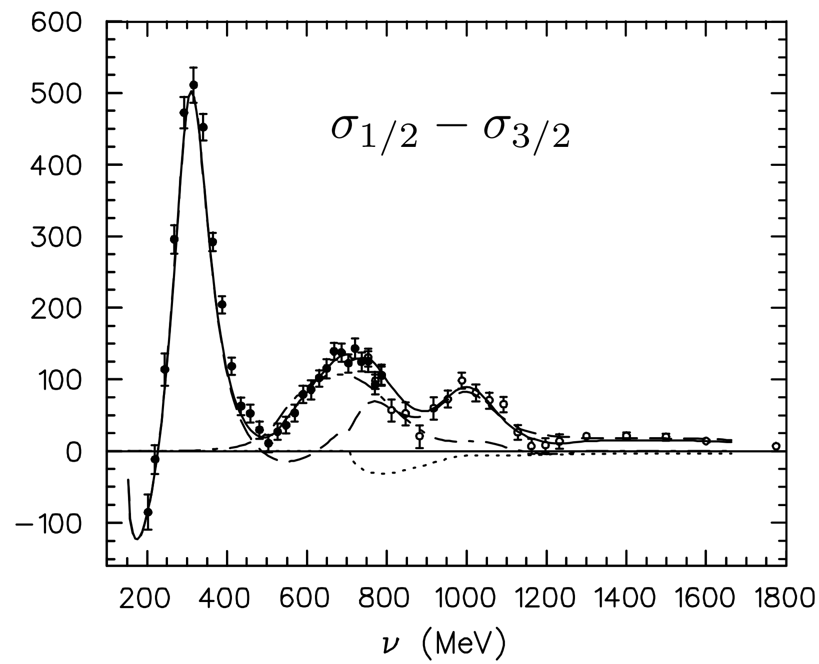
$$\gamma_0 = \frac{1}{4\pi^2}\int_{\nu_{thr}}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\nu^3}\,\mathrm{d}\nu$$

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

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

Known to ≈10%.

Pion pole contribution cancels.



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Better way to extract Spin Polarizabilities

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- **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.
- **Then 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

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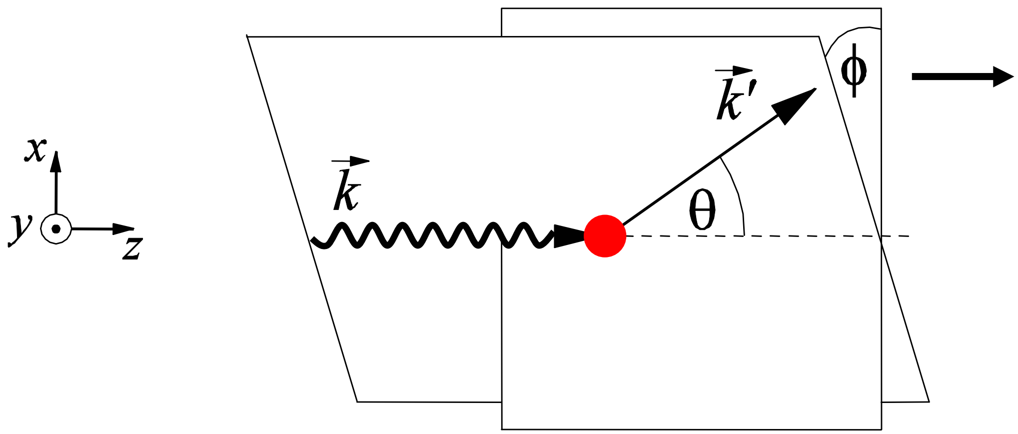

azimuthal angle between the scattering plane and the photon polarization vector

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

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

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

Double Spin Asymmetries w/ Circularly Polarized γ

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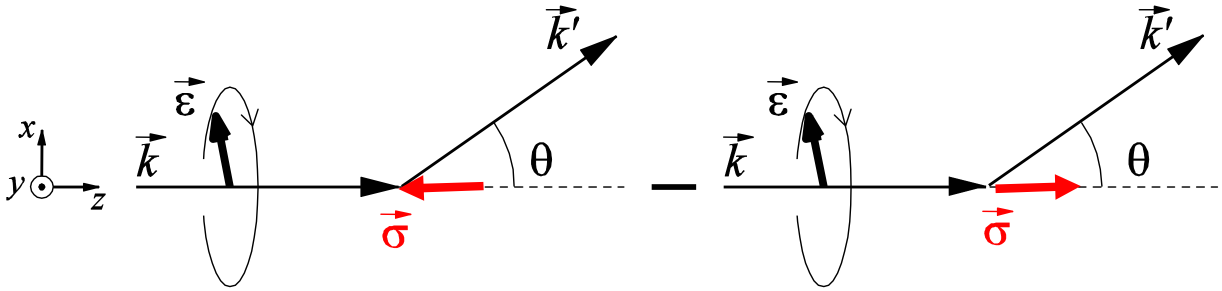
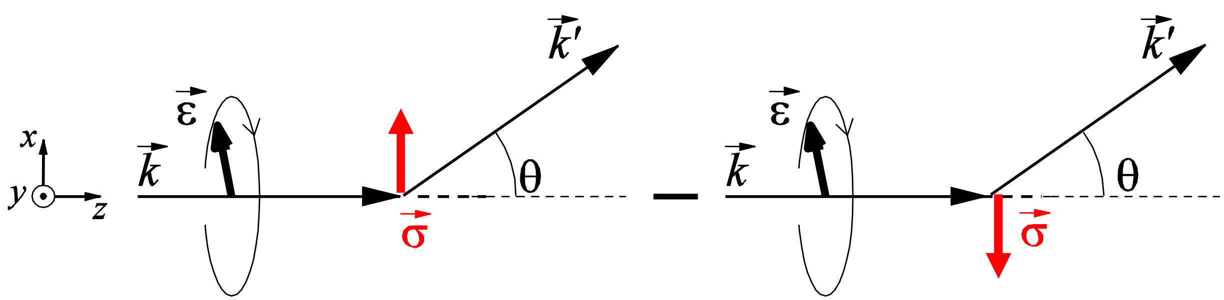
- Longitudinal asymmetry

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



- Transverse asymmetry

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



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**

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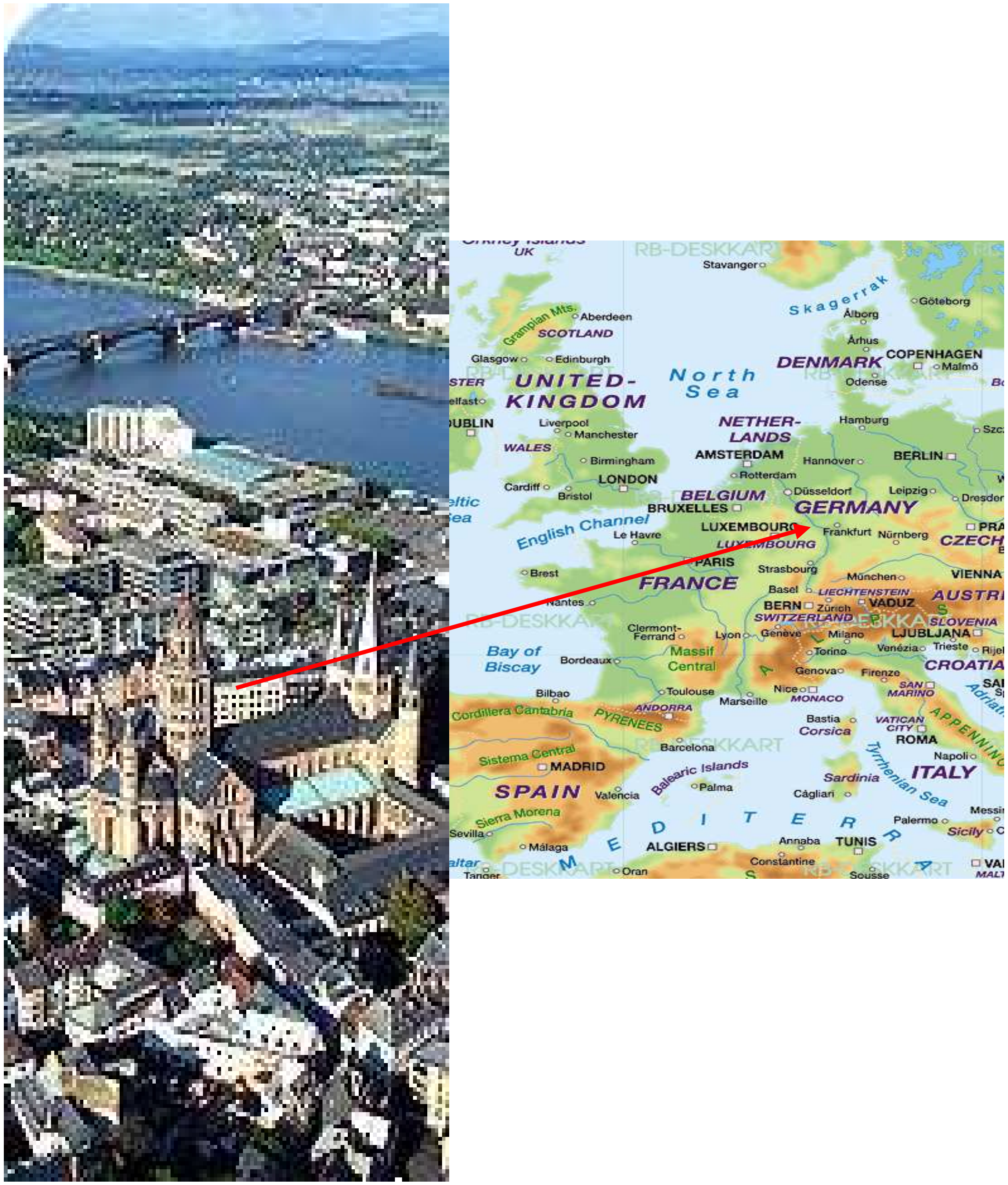
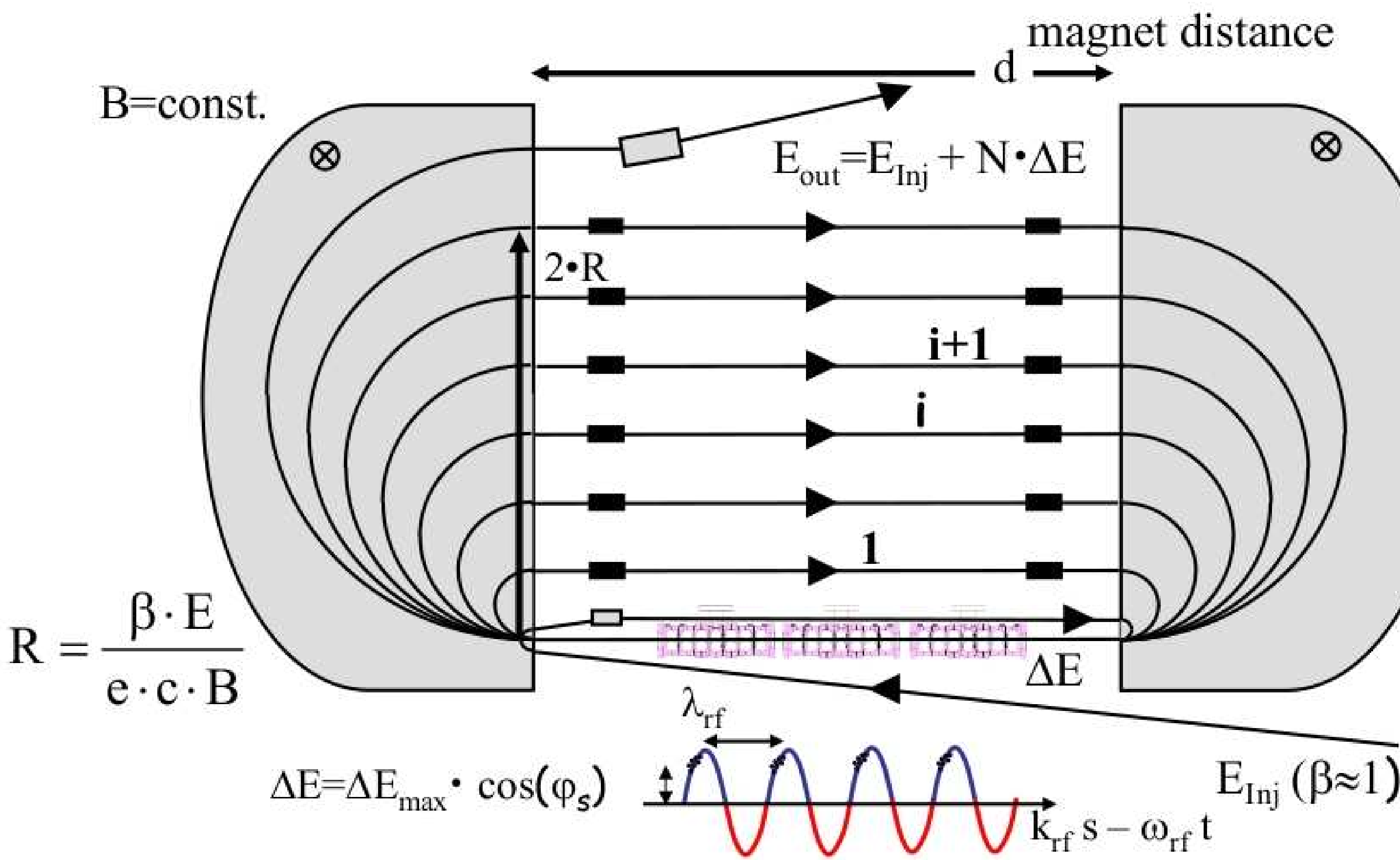
Mainz Microtron MAMI



- **Major facility upgrade in 2000's:**
  - Upgraded accelerator.
  - Upgraded detectors.
  - New frozen spin target.
- **"Ultimate" polarized observables laboratory:**
  - → polarized beam.
  - → polarized target.
  - → recoil polarization.
- **Nearly 4π Detector Coverage.**

Race Track Microtron Concept

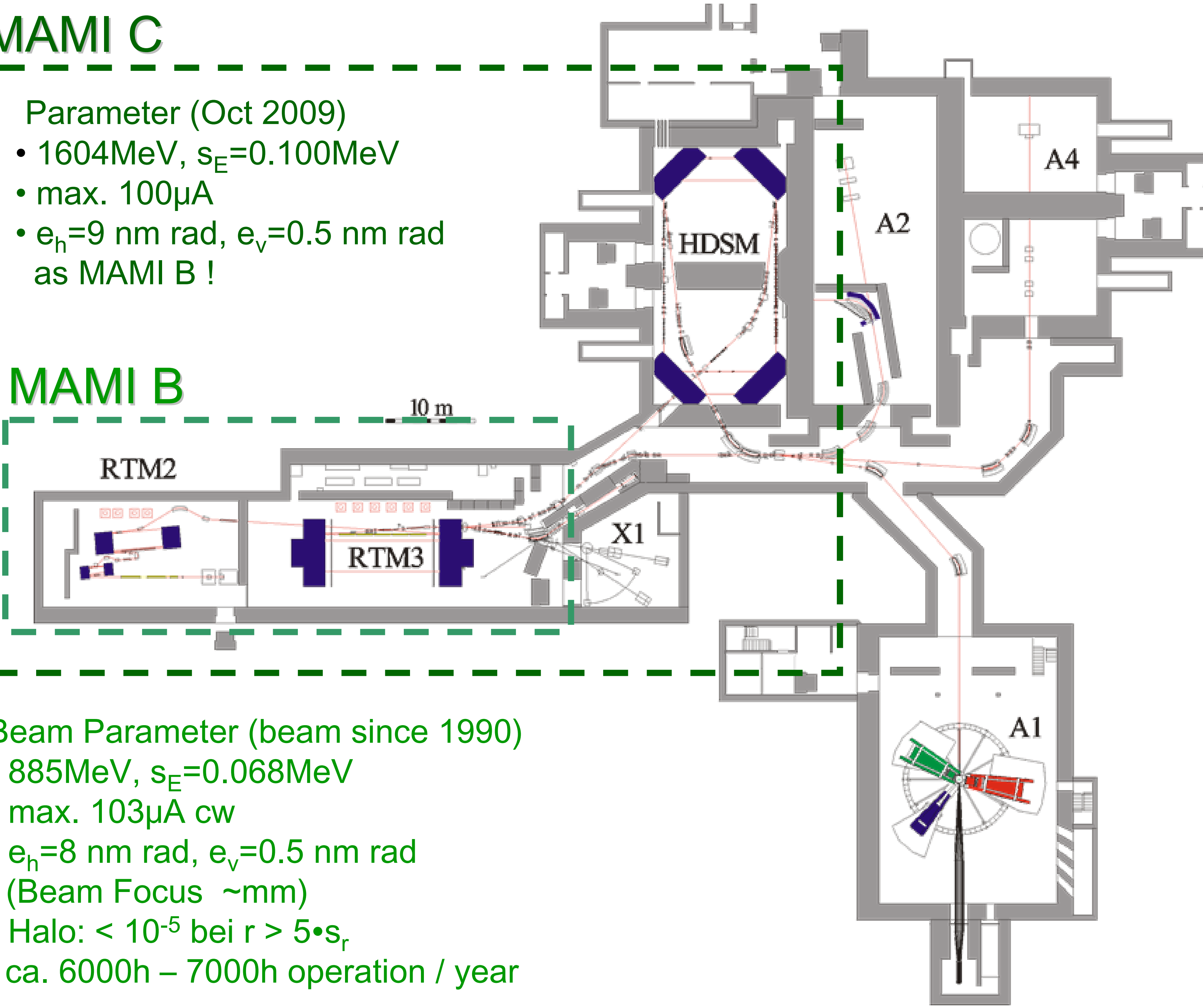


- 2 m long, 25 kW Hf, 18 MeV acceleration
- Need 1km Linac to get 800 MeV
- Solution → multiple passes! → Race Track Microtron (RTM)

MAMI C

Parameter (Oct 2009)
- 1604MeV, s_E=0.100MeV
- max. 100µA
- e_h=9 nm rad, e_v=0.5 nm rad as MAMI B !

MAMI B



Beam Parameter (beam since 1990)
- 885MeV, s_E=0.068MeV
- max. 103µA cw
- e_h=8 nm rad, e_v=0.5 nm rad (Beam Focus ~mm)
- Halo: < 10^{-5} bei r > 5•s_r
- ca. 6000h – 7000h operation / year

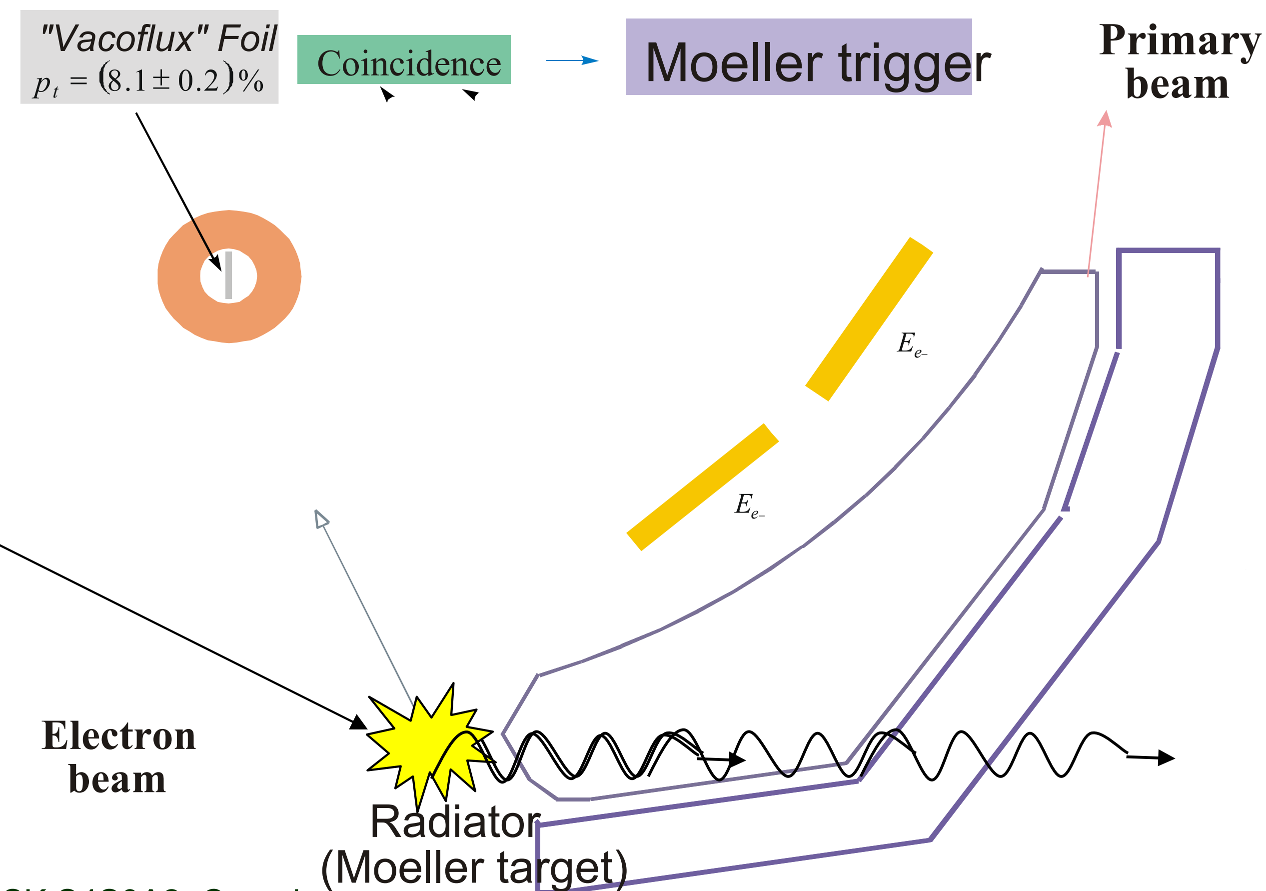
A2 Tagging system (Glasgow,Mainz)

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



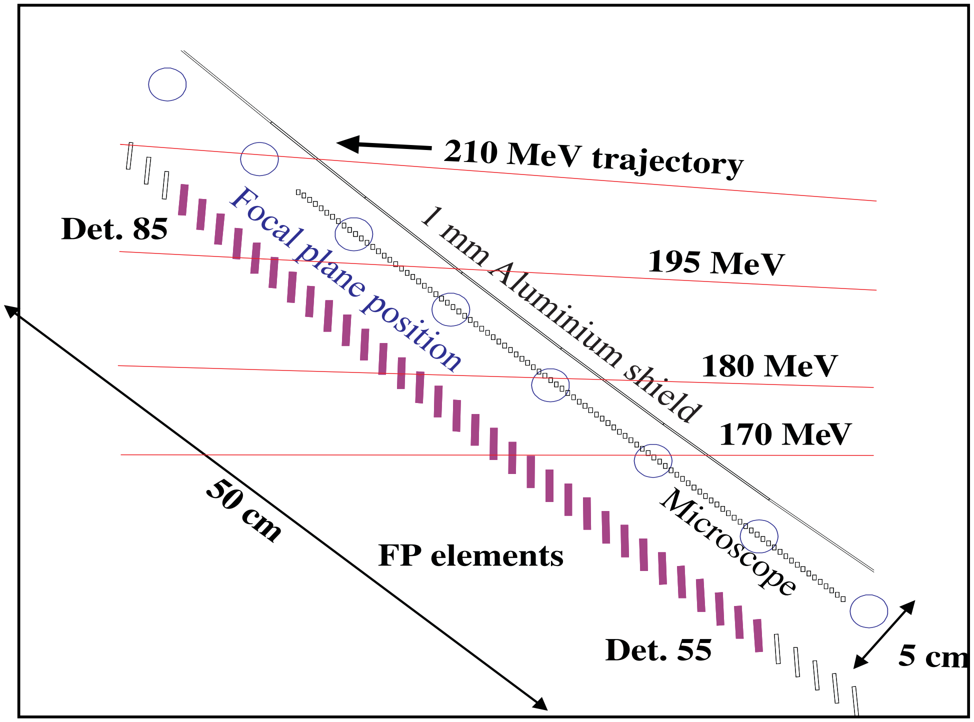
A2 Tagger Detectors and Tagger Microscope

Energy resolution of our standard tagger ladder (352 plastics) **4 MeV per Channel**.

- **96 Plastic Scintillator** Fibers (3x2 mm).
- 1/3 Overlap of the fibers with its neighbor. Overlap region defines the Microscope channel ***µch*** **(191 channels)**.
- Energy resolution: **0.3 MeV per microscope channel (*µch*)**.
- Microscope Tagger is positioned in the electron energy range of the reaction threshold,

  e.g. Beam energy E_0=883 MeV corresponds to a p**hoton energy range from 674 MeV to 730 MeV**

  (*η-threshold* ~707 MeV).

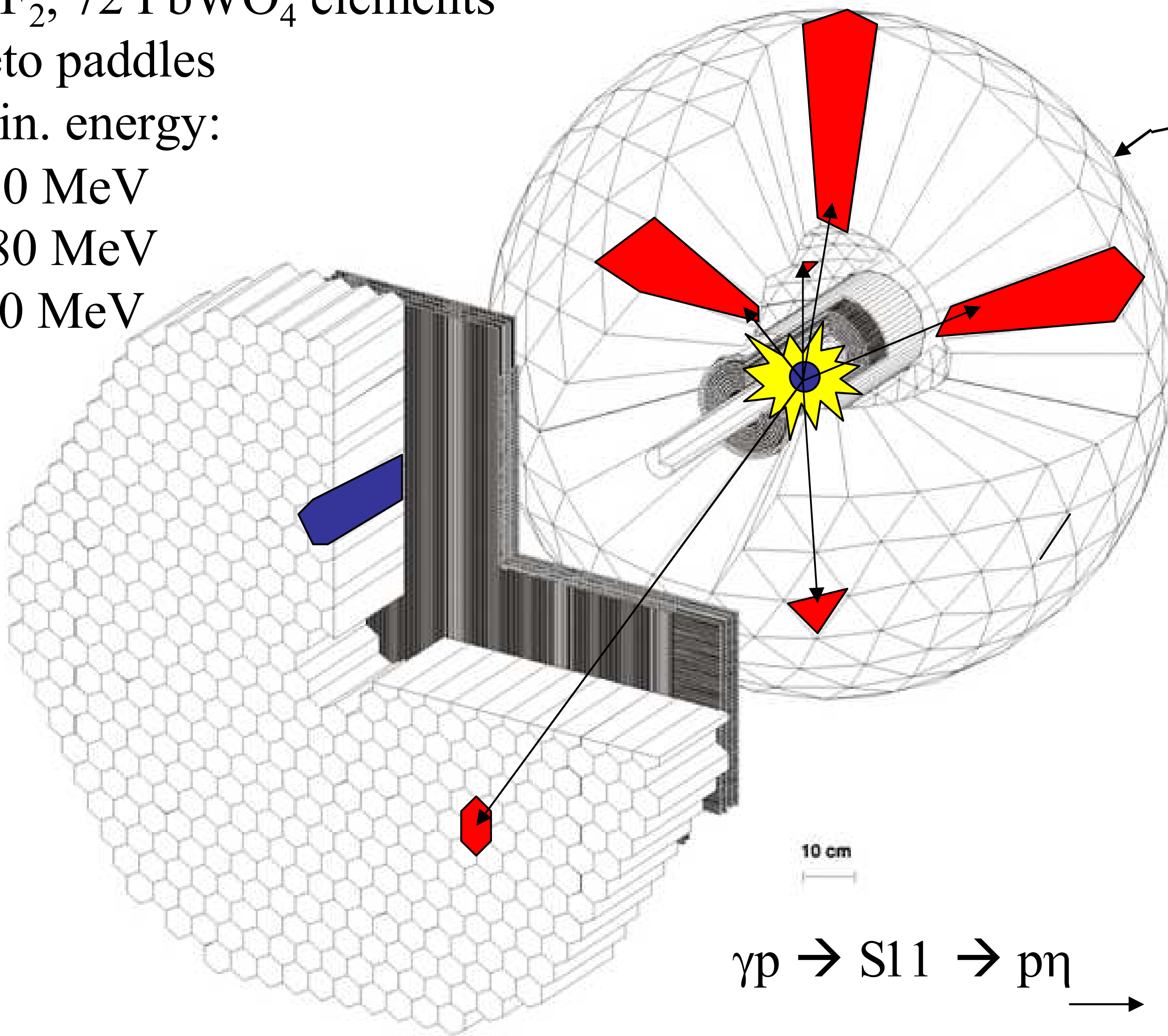


Dr. G.M Huber, Univ. of Regina, Regina, SK S4S0A2, Canada.

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

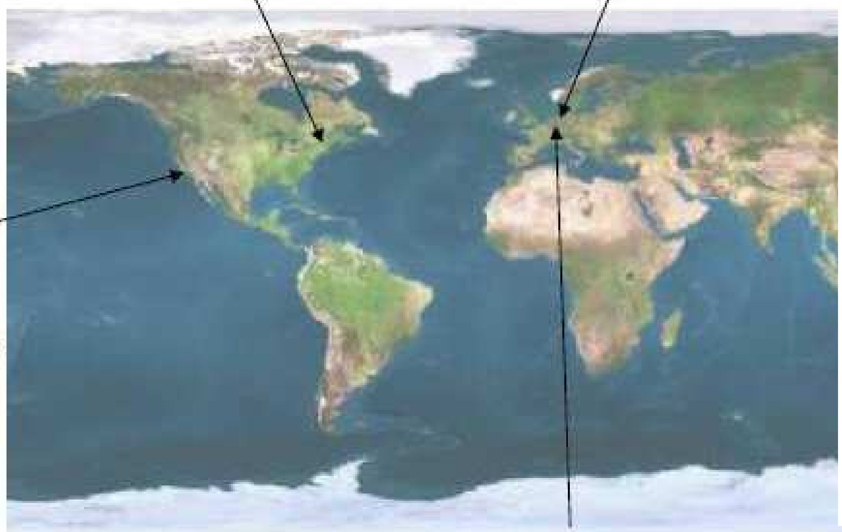
$\gamma p \rightarrow S11 \rightarrow p\eta$
$\rightarrow \pi^0\pi^0\pi^0$
$\rightarrow \gamma\gamma\gamma\gamma\gamma\gamma$

Crystal Ball Detector Arrival at Frankfurt Airport

1996-2002
BNL-AGS
(E_{cm} = 1.2 – 1.53 GeV)
$N^*, \Delta, \Lambda^*, \Sigma$,
η decays, medium. mod

1982-1986
DORIS
(Ecm = 9 -10 GeV)
Y spectroscopy
radiative Υ decays

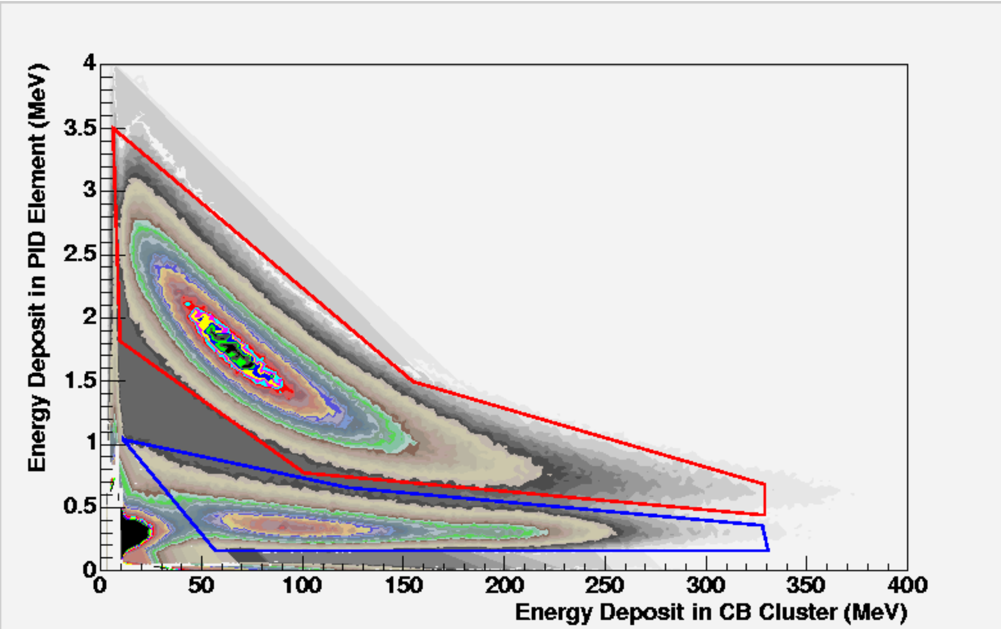
1976
Conceived
1978 -1981
SPEAR
(E_{cm} = 3 - 7 GeV)
ψ,ψ' spectroscopy
radiative ϕ decays
τ decays
D decays,
$\gamma\gamma \rightarrow \gamma\gamma$,
η, η', f

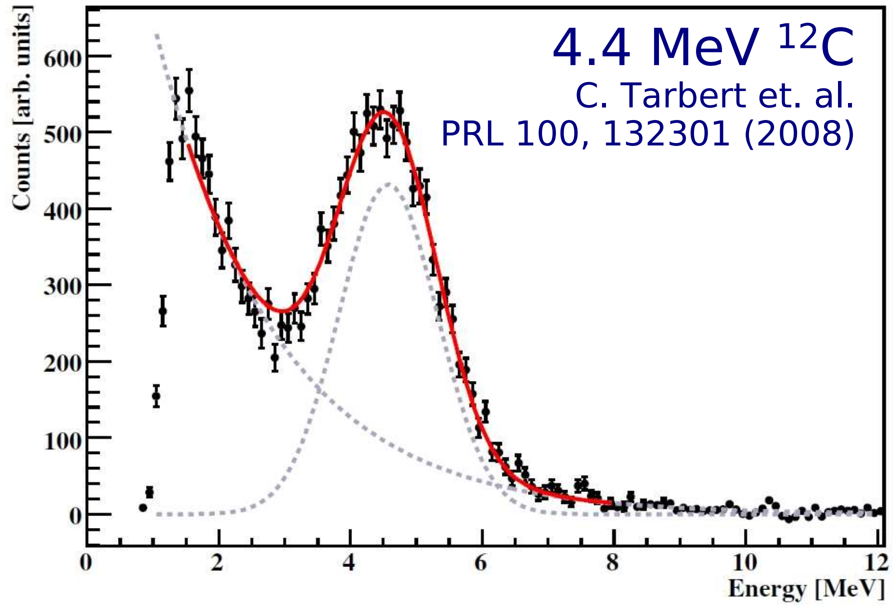


2002
MAMI
(E_{cm} = 1.2 -1.9 GeV)

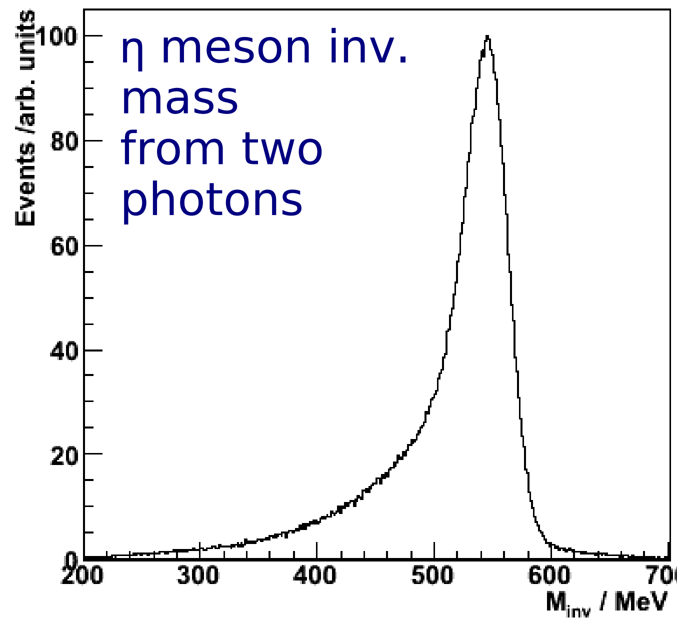
- Accurate separation of final states → good detector resolution.
- Sensitivity to small σ processes → 4π detector acceptance, large γ flux.
- Access to polarization observables → polarized beam, target, recoil.

Crystal Ball: Particle Calorimetry and Identification





- Wide energy range with good resolution
- Energy resolution: $\Delta E/E = 0.020 \bullet E[\mathrm{GeV}]^{0.36}$
- Angular resolution: $\sigma_\theta = 2 \quad 3° \sigma_\varphi = \sigma_\theta / \sin(\theta)$
- MWPC → Charged particle tracking
- ΔE (PID) / E (CB) locus → particle id.
- High photon & neutron efficiency



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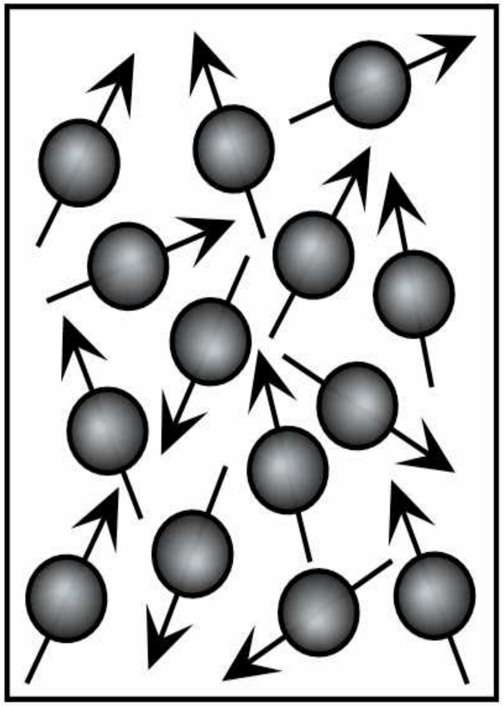
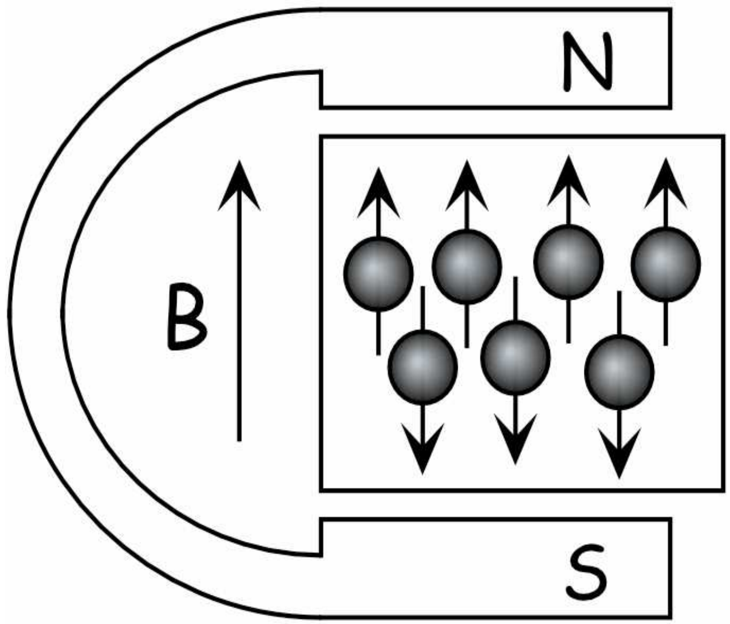
Polarized Solid Target

Polarization = Orientation of Spins in a magnetic field





$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

P=100% is not so easy to realize: Complicated interplay between

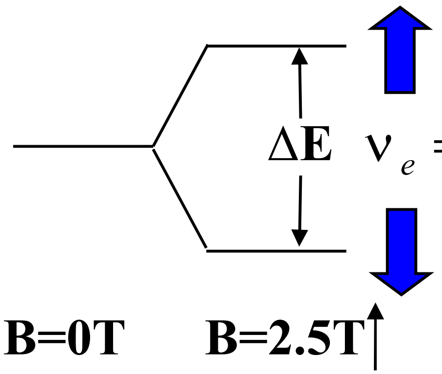
Polarizing force ~ magnetic field **B**

and

Depolarizing force ~ thermal motion of spins (temperature **T** – relaxation)

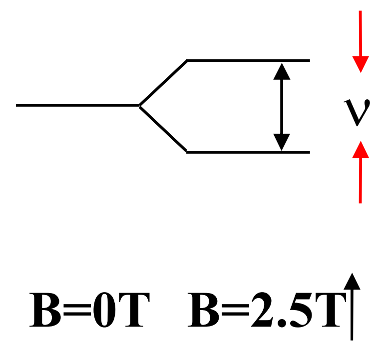
Physics of Solid Polarized Targets

Magnetic moment in magnetic field: $E = -\vec{\mu} \cdot \vec{B} = -g\mu_o m B$



$$\nu_e = \frac{\Delta E}{h} = 70GHz$$

electron



$$\nu_p = 106MHz$$

proton

Thermal equilibrium
Boltzmann distribution

$$\frac{N(E+\Delta E)}{N(E)} = e^{-\frac{\Delta E}{kT}}$$

Spin1/2

$$P = \frac{N_+ - N_-}{N_+ + N_-} = \tanh\frac{\mu B}{kT}$$

T=1K B=5T ⇨ **P_e=99.76%** **P_p=0.51%**

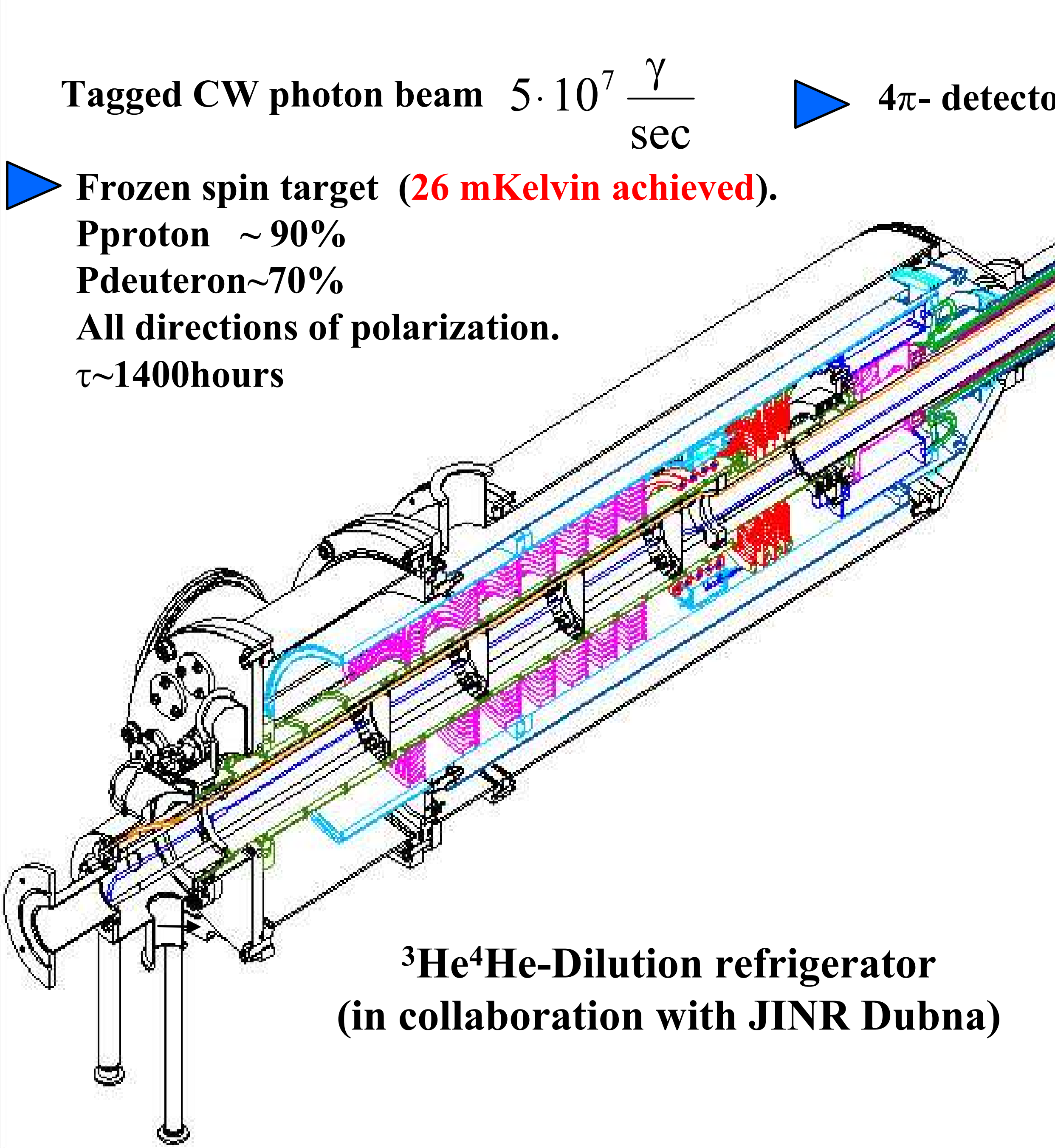
Trick: Transfer the high electron polarization to the nucleon via μ-wave irradiation (DNP)

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

Polarized Target for Crystal Ball

Tagged CW photon beam $5 \cdot 10^7 \frac{\gamma}{\text{sec}}$ ▶ 4π- detector

▶ Frozen spin target (26 mKelvin achieved).
Pproton ~ 90%
Pdeuteron~70%
All directions of polarization.
τ~1400hours



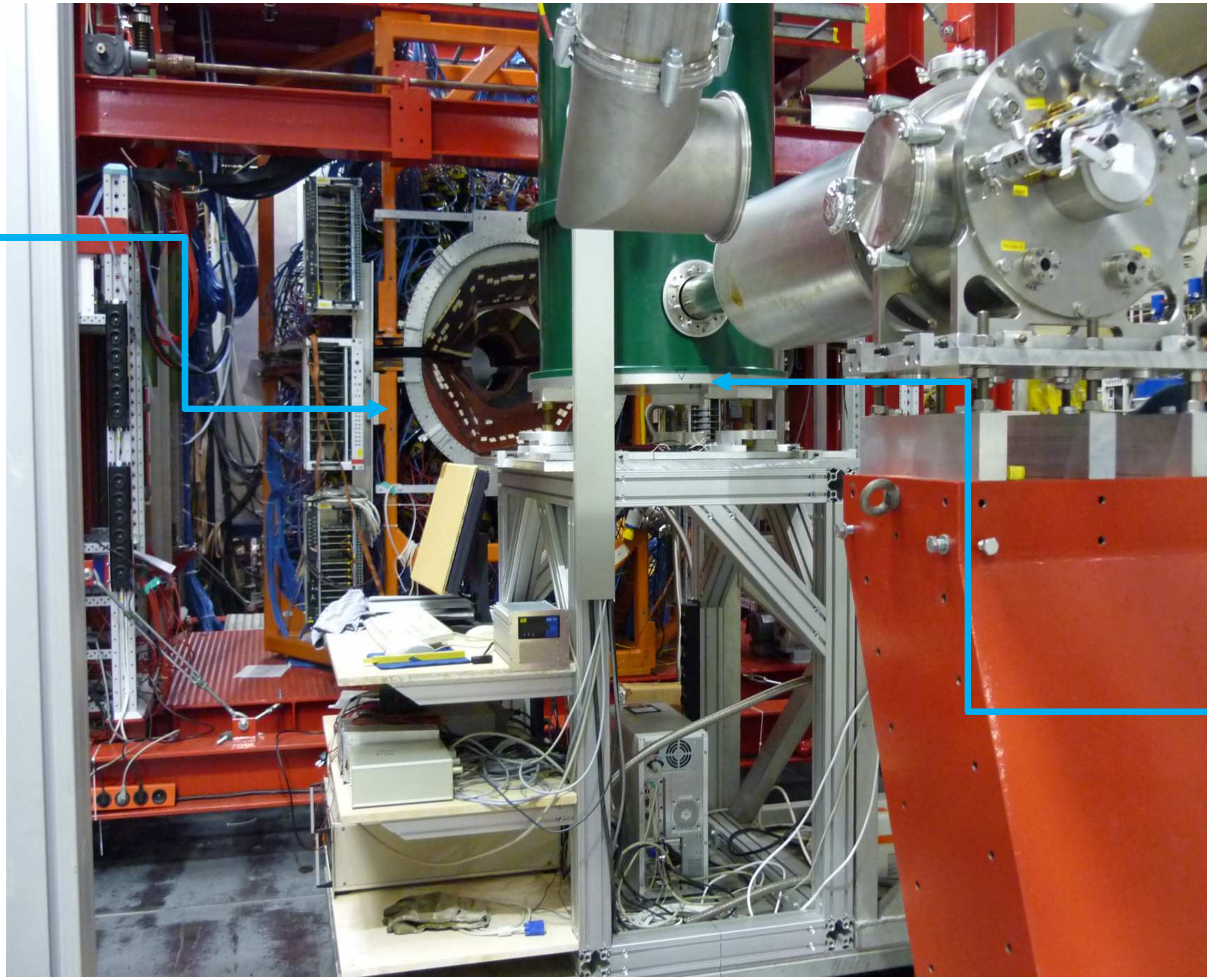
$^3He^4He$-Dilution refrigerator
(in collaboration with JINR Dubna)

Transverse (Saddle coil)

Longitudinal (Solenoid)

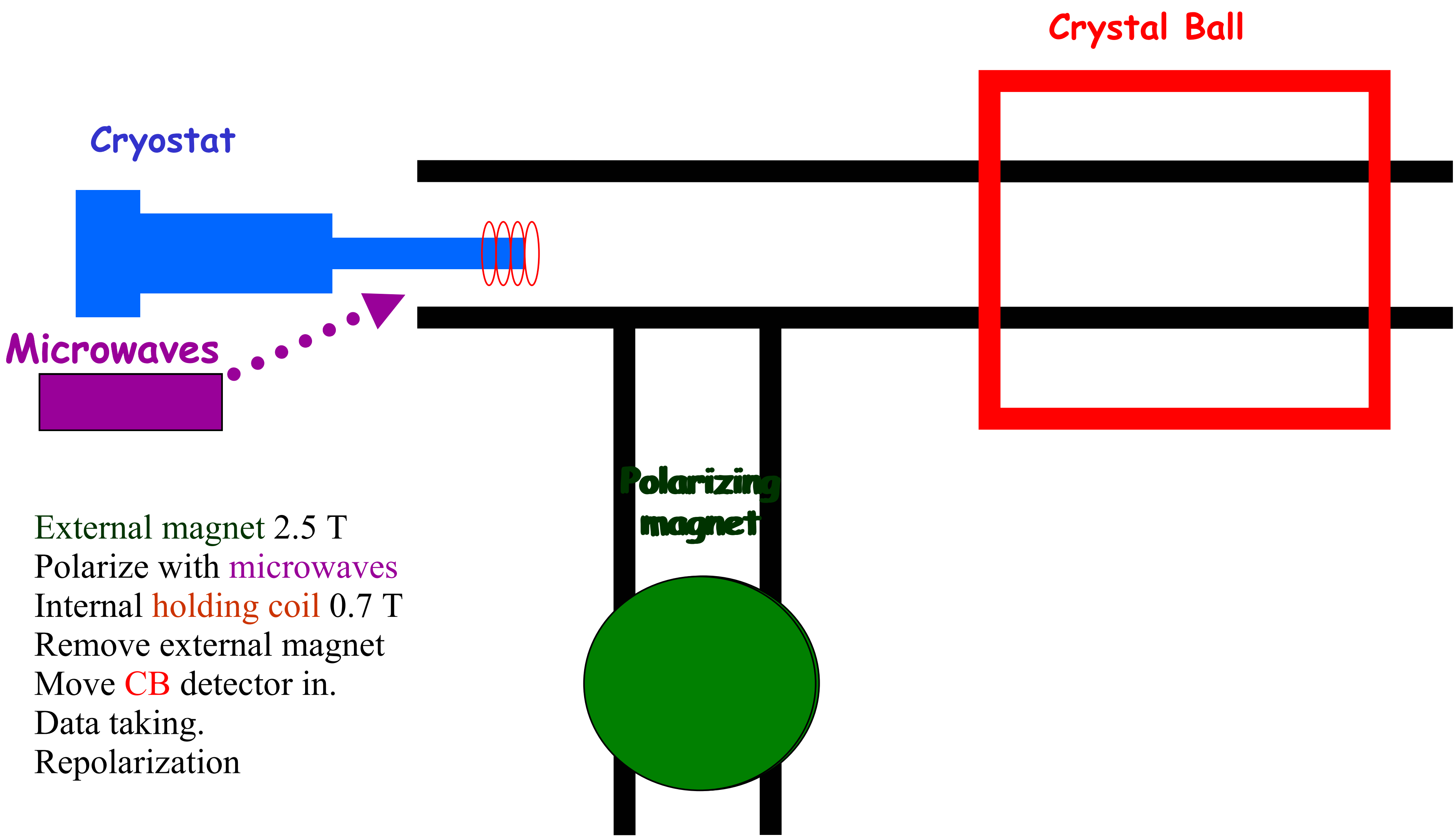
Internal
Holding Field (1.2K, 0.6T)

Setup in the A2 – Tagger Hall



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

Frozen Spin Target Waltz



1. External magnet 2.5 T
2. Polarize with microwaves
3. Internal holding coil 0.7 T
4. Remove external magnet
5. Move CB detector in.
6. Data taking.
7. Repolarization

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.

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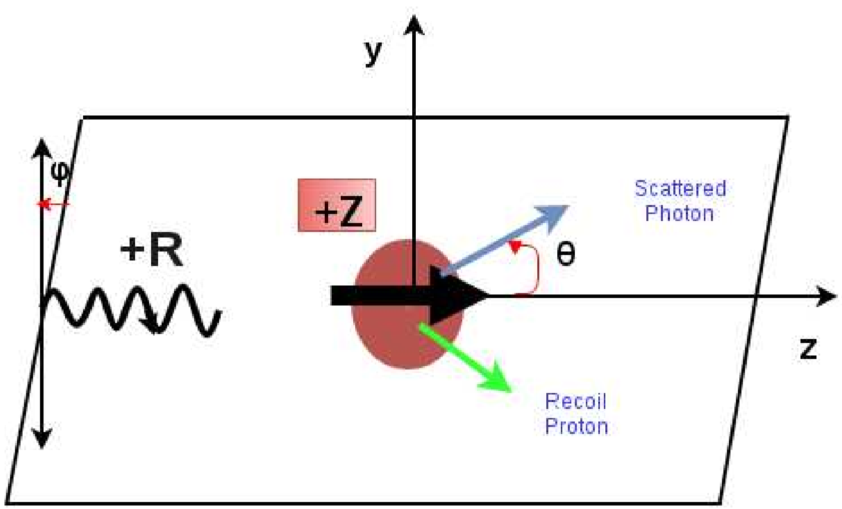
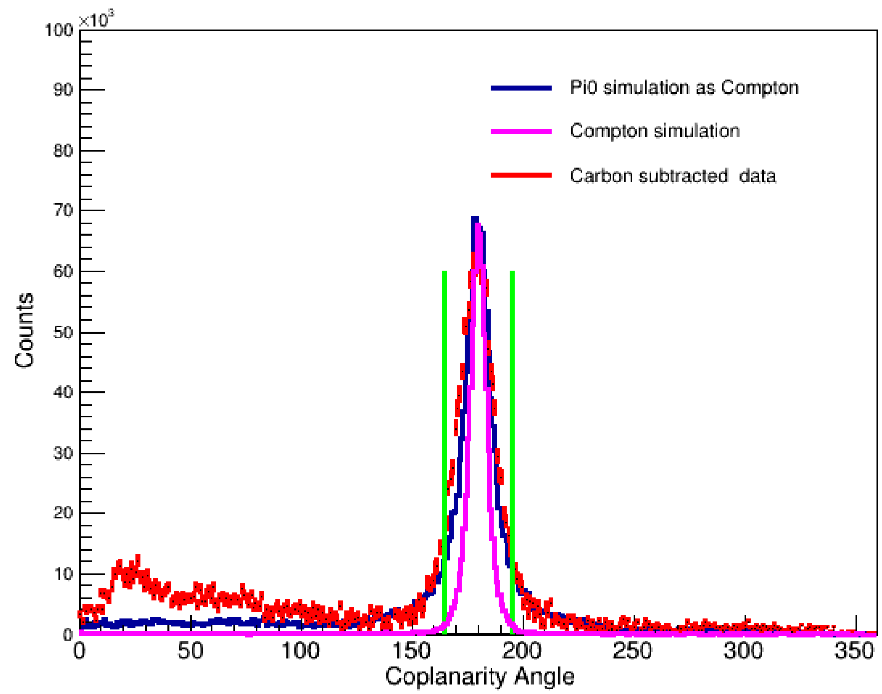
Compton Scattering Event Selection

- Momentum Conservation requires the reaction to be coplanar.
- Require ONLY one neutral and one charged track.
- Require a cut on Coplanarity Angle

$$\Delta\varphi = |\varphi_\gamma - \varphi_{recoil}| = 180^o \pm 15^o$$





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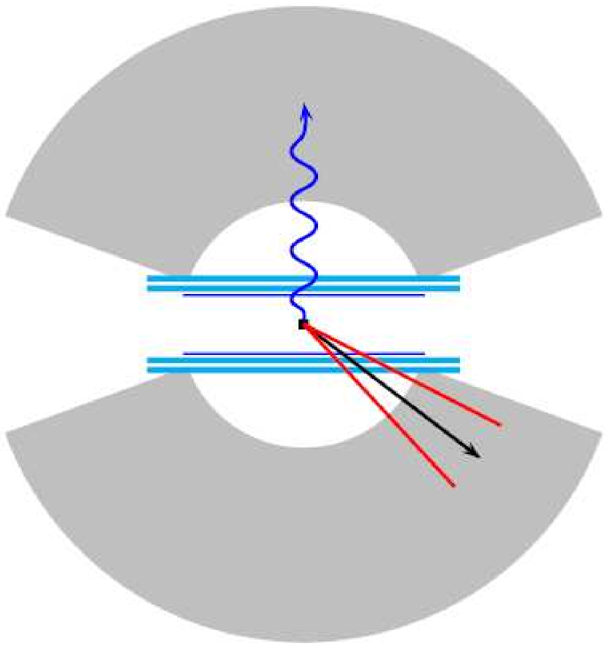
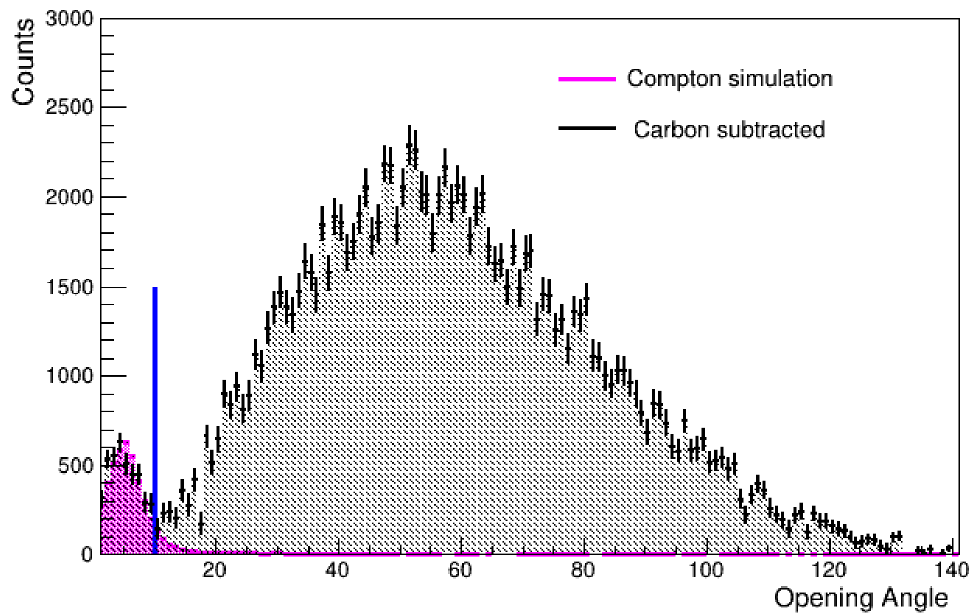
Compton Event Selection (2)

- Use the detected photon information to calculate the angle of the scattered proton, and compare it to the actual detected proton angle.

$$\text{Opening Angle } \cos\Theta_{OA} = \frac{\vec{p}_{miss} \bullet \vec{p}_{recoil}}{|\vec{p}_{miss}| \times |\vec{p}_{recoil}|}$$





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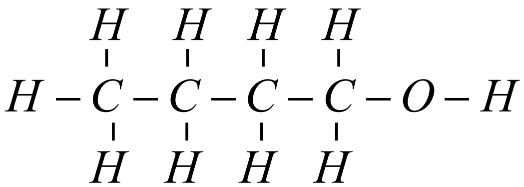
Backgrounds from Butanol Target



- **Butanol (C_4H_9OH)** doped with free electrons is needed for target material due to its large electron dipole moment.
  - Compton scattering off H
  - Coherent scattering off C,O
  - Incoherent scattering off C,O
  - Pion production off H
  - Coherent pion off C,O
  - Incoherent pion off C,O
- Backgrounds also arise from the liquid He cryogen.

- Density of carbon target is chosen to match the number of non-hydrogen nucleons in the Butanol target.
- Dedicated carbon target runs taken for data subtraction.

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π^0 Channel used for Carbon Target Normalization

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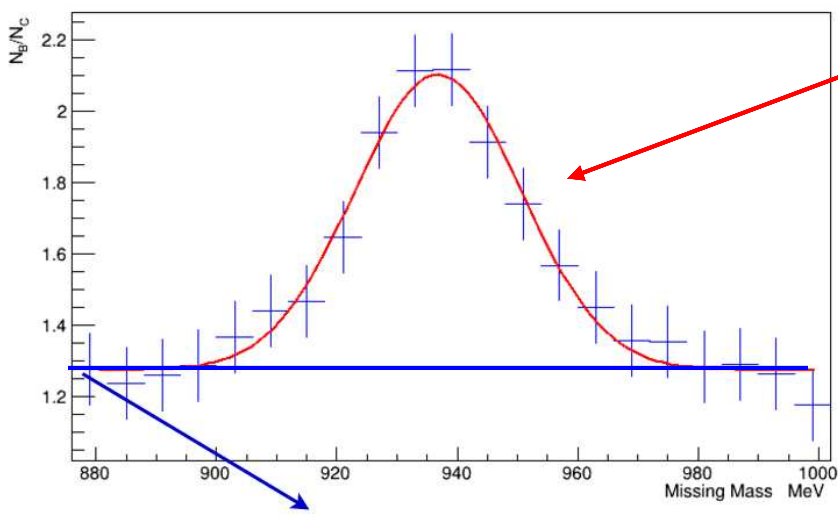
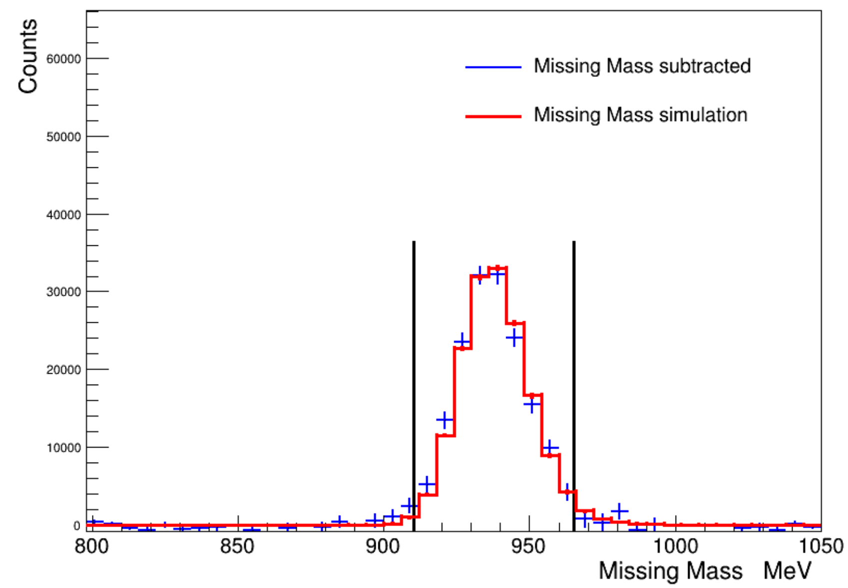
- Butanol target data:
  - Detect ONLY two photons and reconstruct $\pi^0 \rightarrow \gamma\gamma$.
- Compute mass of undetected recoil nucleon.



Gaussian peak: π^0 photoproduction off ^{1}H

- Constant background underneath is incoherent pion production off non H nucleons in butanol.
- Used to normalize carbon target data, together with live-time corrected tagger scalers.



- Butanol – normalized Carbon data.
- Compared to π^0 simulation (125º 140º).

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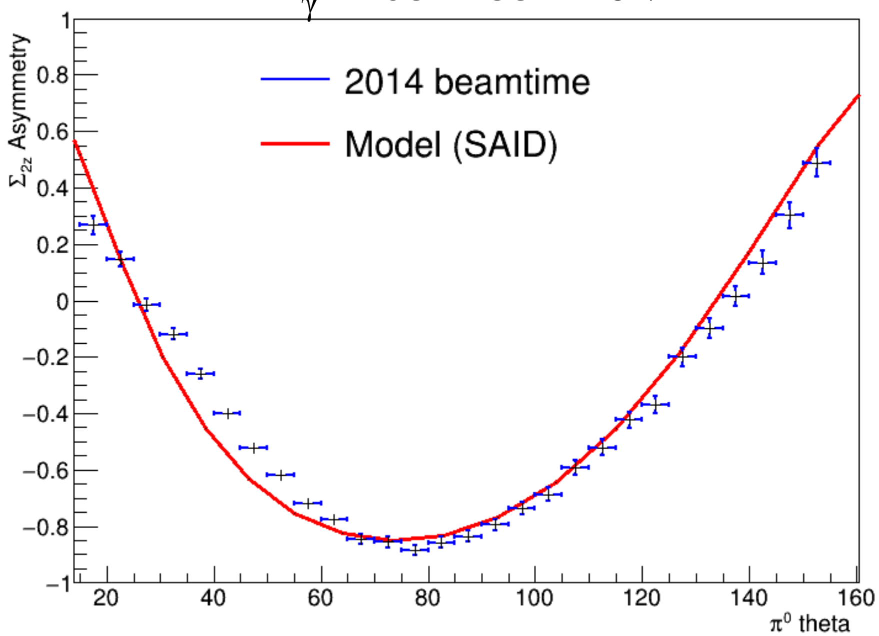
Confirm with π^0 Σ_{2z} Asymmetry

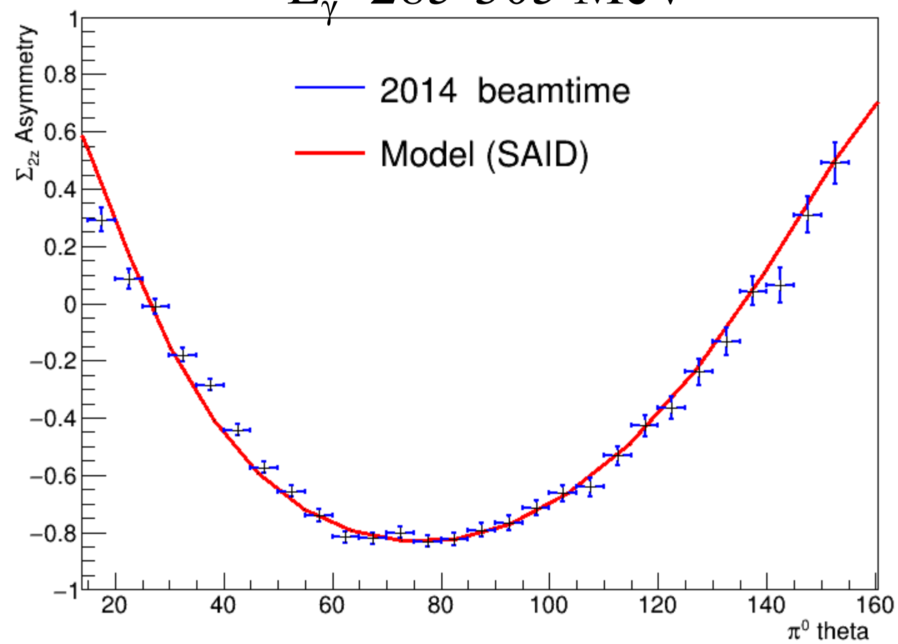
- Compute Σ_{2Z} Asymmetry for π^0 photoproduction.
- If non-H contributions are subtracted properly, the results should compare well to SAID isobar model.

$$\Sigma_{2z} = \frac{1}{P_{circ}^{\ \gamma}}\left(\frac{(N^R_{+z}+N^L_{-z})-(N^L_{+z}+N^R_{-z})}{P^t_{+z}(N^R_{+z}+N^L_{-z})-P^t_{-z}(N^L_{+z}+N^R_{-z})}\right)$$

E_γ=265-285 MeV



E_γ=285-305 MeV



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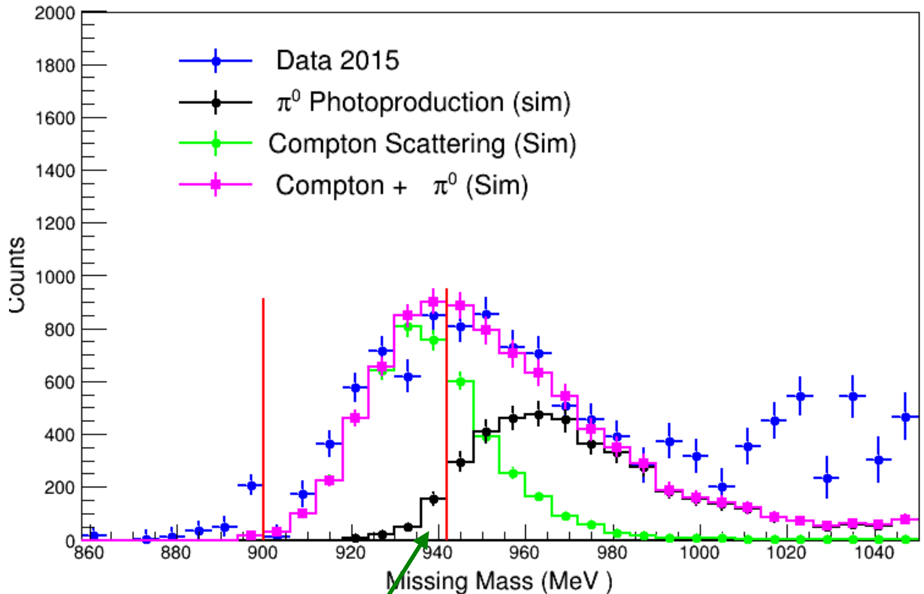
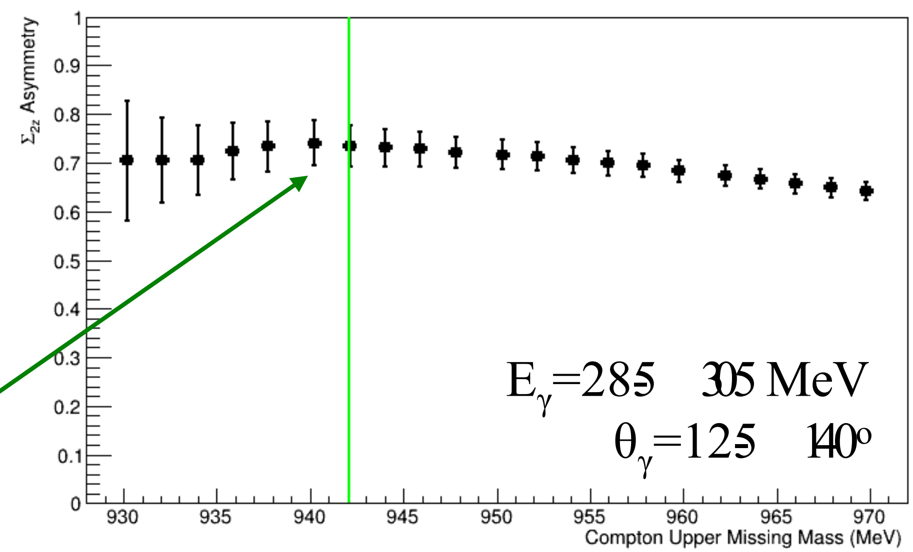
Compton Event Selection (3)

- Compute recoil mass for one neutral and one charged track data.



$$m_{miss} = \sqrt{(E_{\gamma i} + m_p + E_{\gamma f})^2 - (\vec{p}_{\gamma i} - \vec{p}_{\gamma f})^2}$$
$$= m_p$$

- To maximize statistics, compute Σ_{2z} for different m_{miss} cuts.
- Upper cut limit chosen at lower of:
  - Simulated π^0 contamination <5%.
  - Σ_{2z} varies by <5% from reference value.



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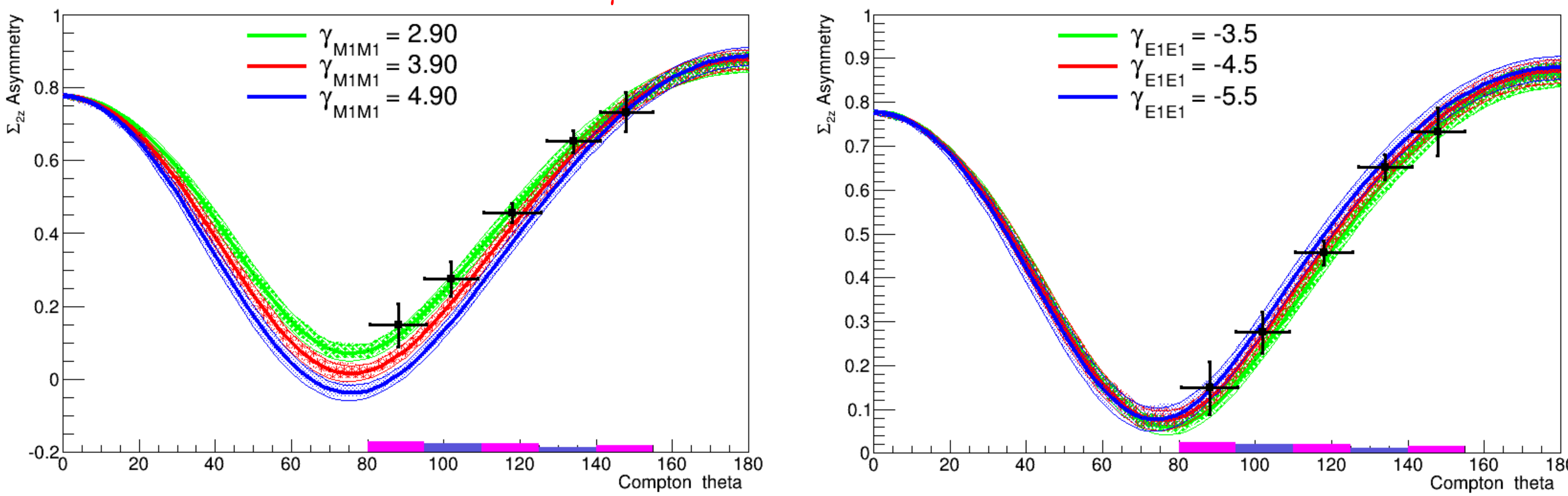
Compton Σ_{2Z} Results



- Error bars include statistical and random systematic uncertainties.
- Correlated systematic uncertainties shown as blocks at bottom.
- Curves are from HDPV 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).
- Comparisons were also done with BχPT calculation of Lensky & Pascalutsa.
- Σ_{2z} clearly sensitive to γ_{M1M1}, not very sensitive to γ_{E1E1}.

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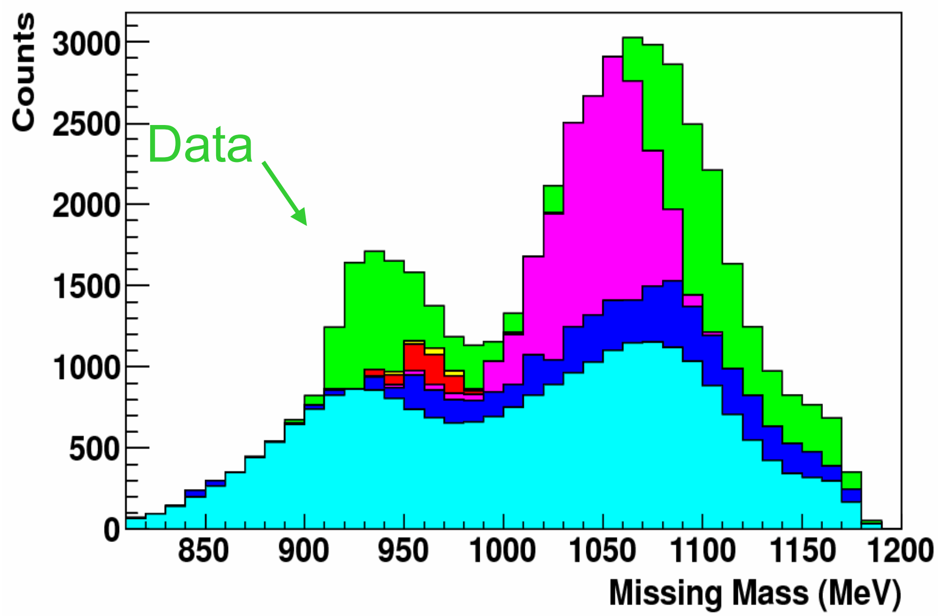
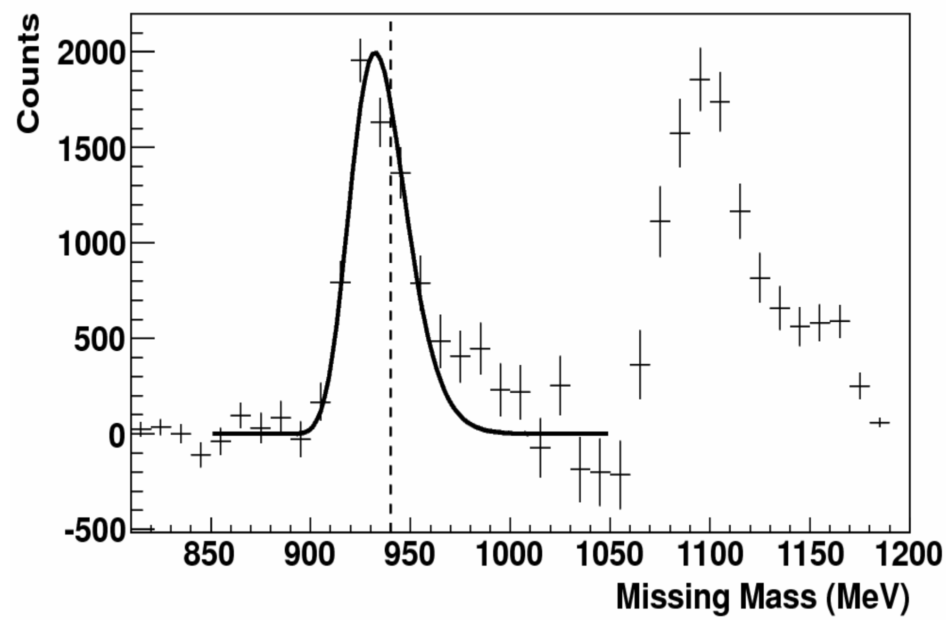
Σ_{2x} – Transversely Polarized Target

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

P. Martel et al., PRL **114** 112501 (2015).

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Σ_{2x} – Transversely Polarized Target

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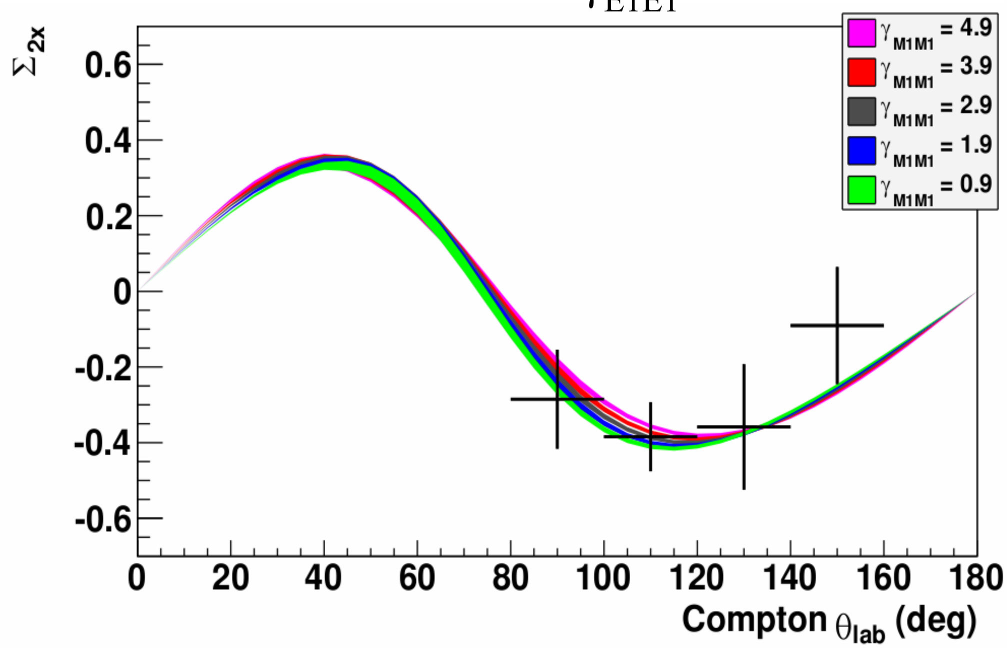
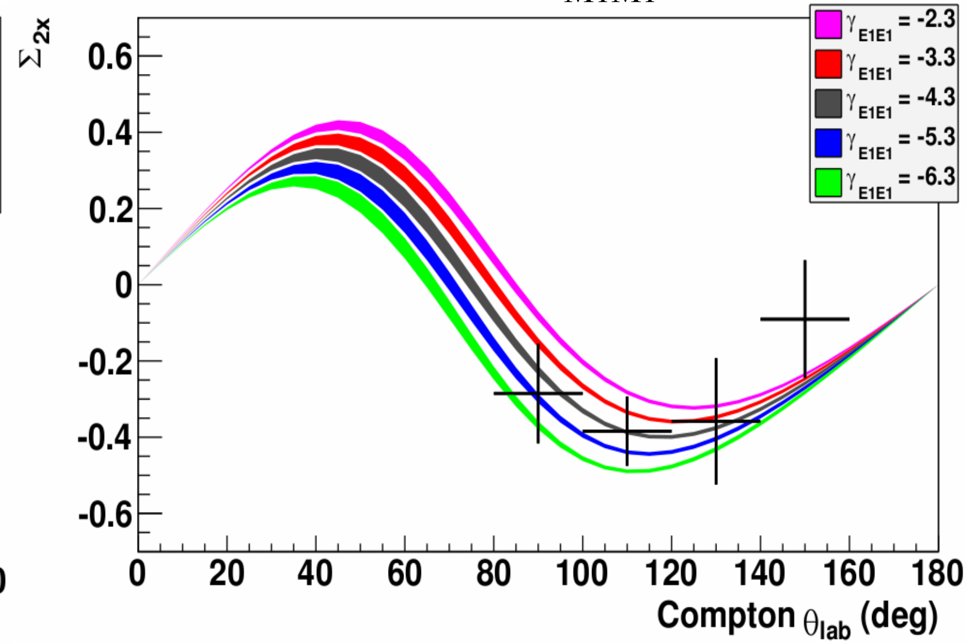
E_γ=273 - 303 MeV

Fix γ_{E1E1}



Fix γ_{M1M1}



- First measurement of a double spin Compton scattering asymmetry on the nucleon.
- Curves are from HDPV 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_{2x} clearly sensitive to γ_{E1E1}, not very sensitive to γ_{M1M1}.

P. Martel et al., PRL **114** 112501 (2015).

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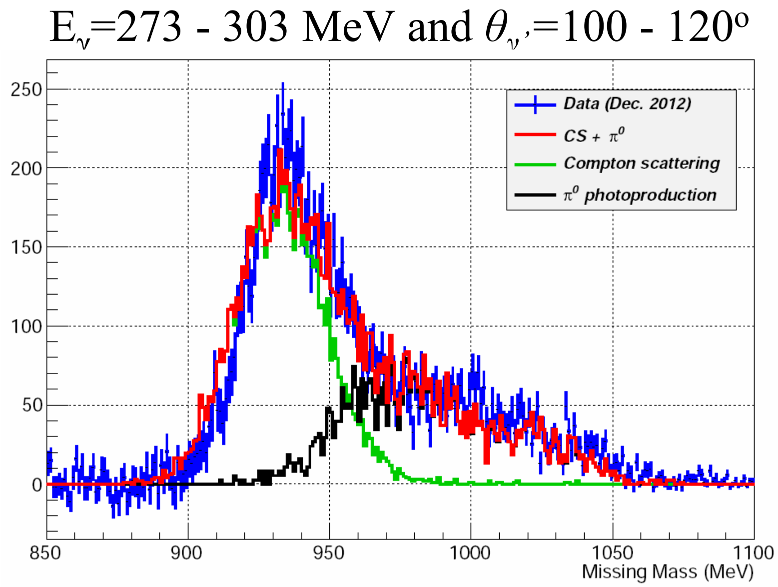
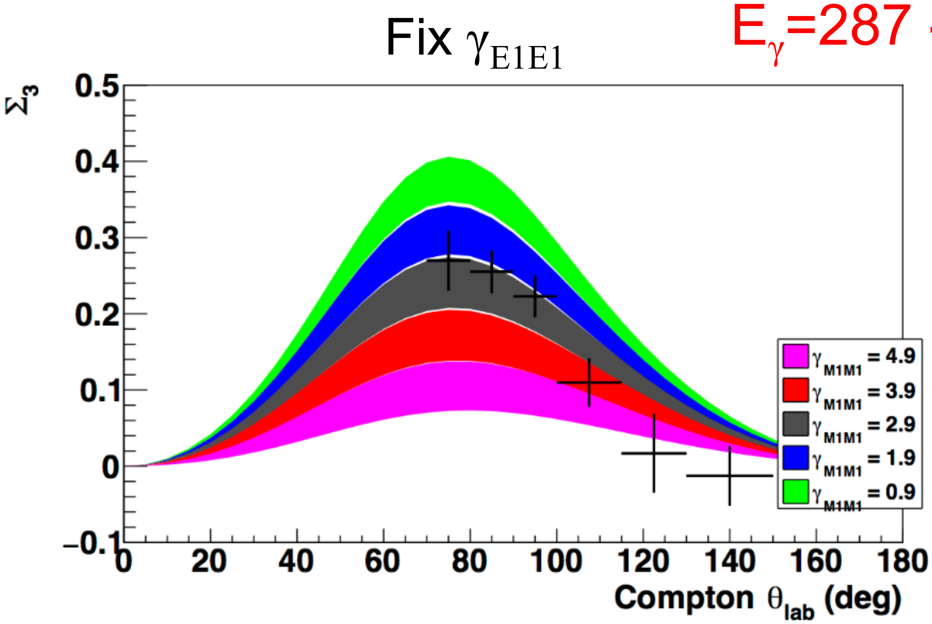
Σ_3 above pion production threshold

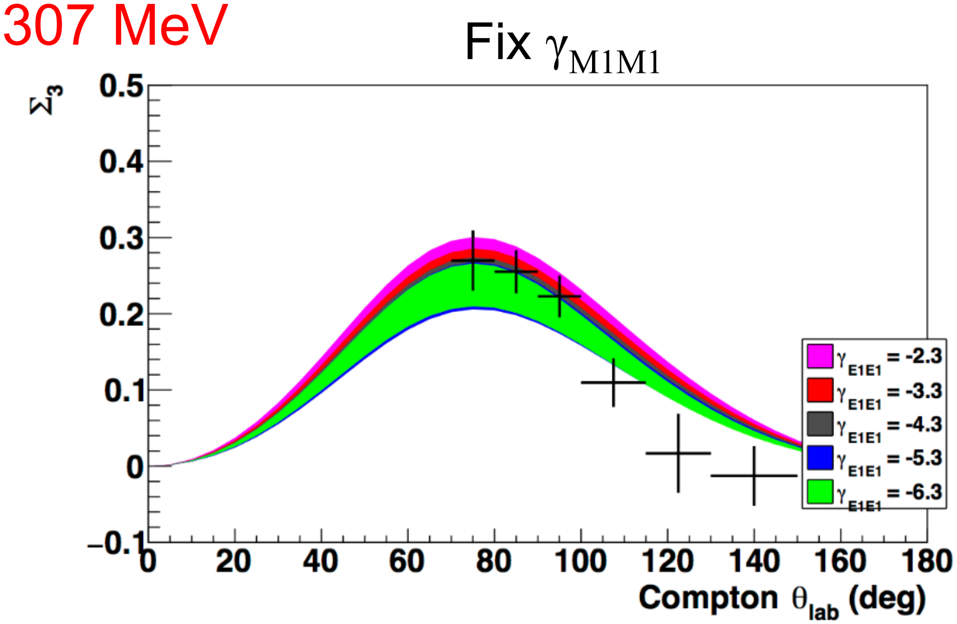
Simulation of π^0 photoproduction in LH_2 target matches background of the distribution quite well.



Σ_3 measurements along with HDPV 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).

E_γ=287 - 307 MeV





C. Collicott et al., manuscript in preparation.

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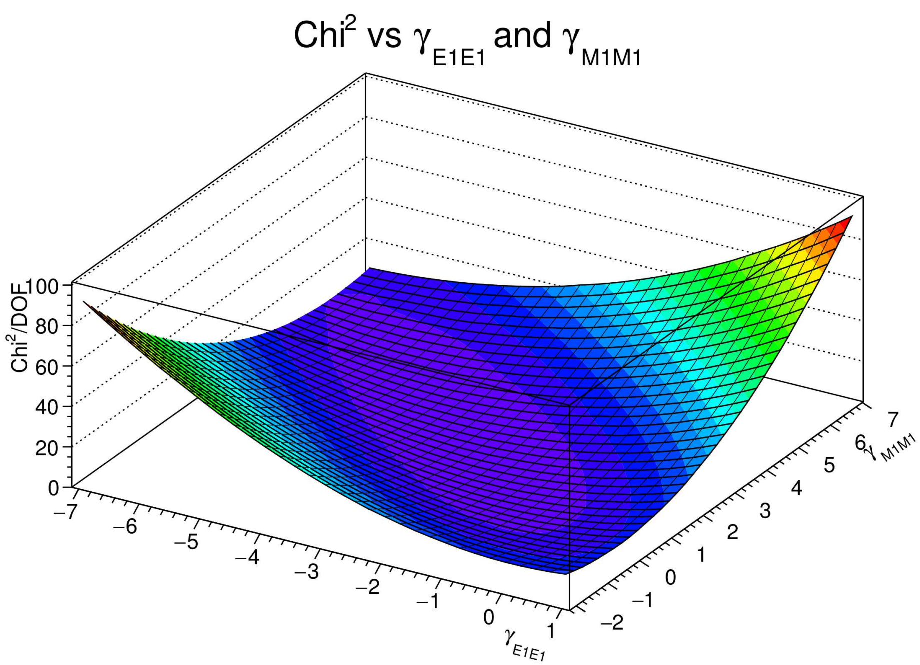
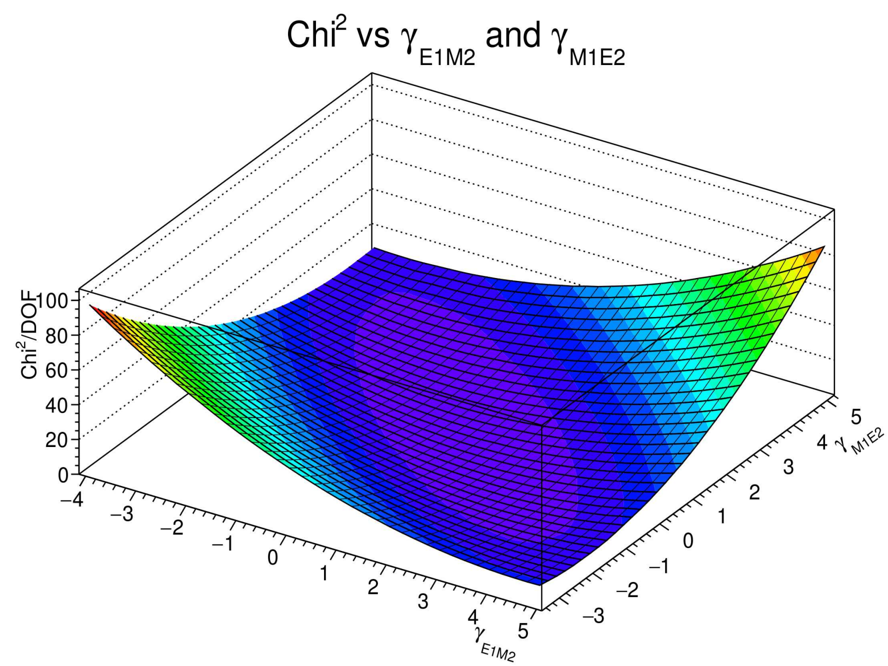
Global Compton Analysis

- **Global Fit:**
  - Includes MAMI results for Σ_{2z}, Σ_{2x}, Σ_3 and prior γ_0, γ_π, α_{E1}, β_{M1}.
  - Goal is to extract all four spin polarizabilities independently with small statistical, systematic and model-dependent errors.
- **Fits done separately for:**
  - HDPV calculation of Pasquini et al. (shown below).
  - BχPT calculation of Lensky & Pascalutsa (very similar).





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PRELIMINARY - Combined Spin Polarizability Analysis

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- **Dispersion relation and BχPT results are reasonably consistent.**
- Pion-pole contribution has been subtracted.

	HDPV Pred.	HDPV 2015 $\Sigma_{2x}+\Sigma_3^{MAMI}$	HDPV 2017 $+\Sigma_{2z}$ Fit	BχPT Pred.	BχPT 2017 Fit
γ_{E1E1}	-4.3	-5.0±1.5	-4.24±0.39	-3.3	-2.87±0.42
γ_{M1M1}	2.9	3.13±0.88	3.25±0.40	3.0	2.29±0.39
γ_{E1M2}	-0.0	1.7±1.7	0.76±0.83	0.2	0.60±0.85
γ_{M1E2}	2.2	1.26±0.43	1.24±0.39	1.1	0.98±0.35
γ_0	-0.8	-1.00±0.18	-1.00±0.18	-1.0	-0.99±0.35
γ_π	9.4	7.8±1.8	7.98±1.36	7.2	5.54±1.25
$\alpha+\beta$		13.8±0.4	13.77±0.40		13.78±0.40
$\alpha-\beta$		6.6±1.7	7.29±0.86		6.76±0.87
χ^2/df		1.25	0.83		1.30

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

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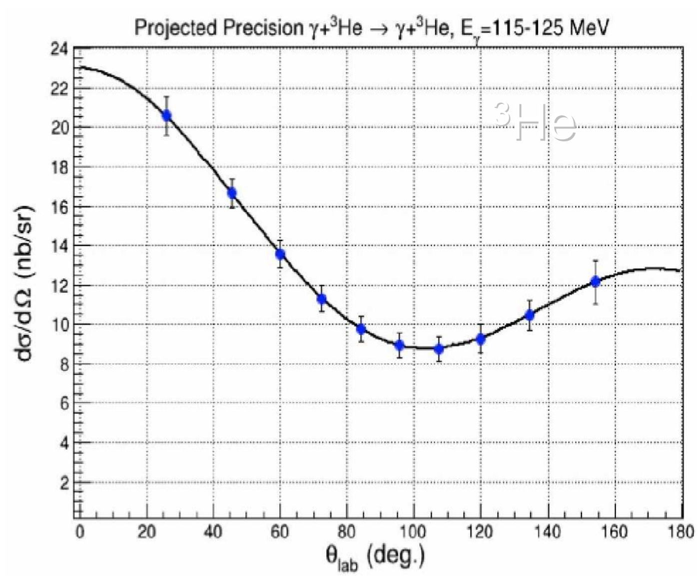
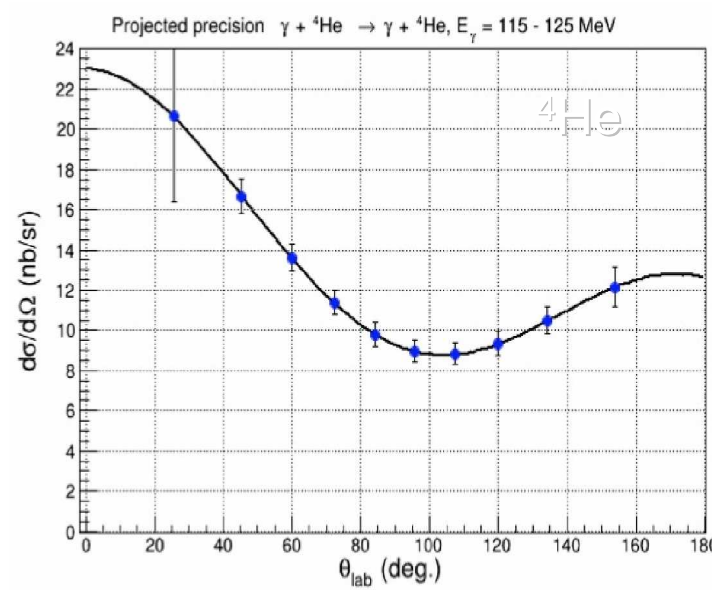
Neutron Scalar Polarizabilities

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 has made a high-pressure active ^{3}He gas scintillator target.

- Proposal A2-10-2013 for ^{3}He$(\gamma,\gamma)^3$He given `A' rating by PAC.
- Expected good separation of backgrounds from target windows and π^0 production.

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MAMI Compton Program Summary

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

- **Σ_{2x}, Σ_{2z} have been measured for the first time.**
  - Plans to acquire more Σ_{2x} data, but not yet scheduled.
- **Σ_3 data taken to supplement existing data from LEGS.**
  - Additional Σ_3 data taking below pion threshold for α_{E1}, β_{M1} underway.

Global Analysis Results:

- Uncertainties in γ_{E1E1}, γ_{M1M1}, γ_{E1M2} improved by factors of 2-4, uncertainty in γ_{M1E2} remained unchanged.

Future:

- Implement active target to expand kinematic range.
- Extend measurements to neutron.

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Systematic Uncertainties

Correlated Systematic Uncertainties → Added in Quadrature and shown as Blocks in Fig.	
Target Polarization	±2%
Photon (Electron) Beam Polarization	±1%
Carbon Target Scaling Factor	≈ ±8-12%
Random Systematic Uncertainties → Added in Quadrature to the Statistical Uncertainties	
Cuts on reconstructed proton missing mass	≈ ±10%

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Compton Σ_{2Z} Results

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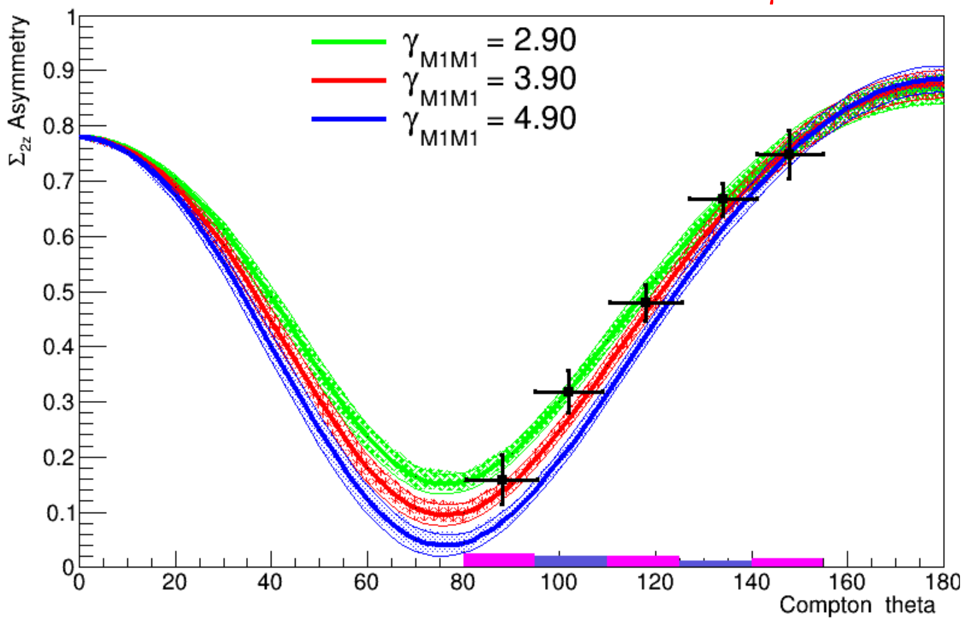
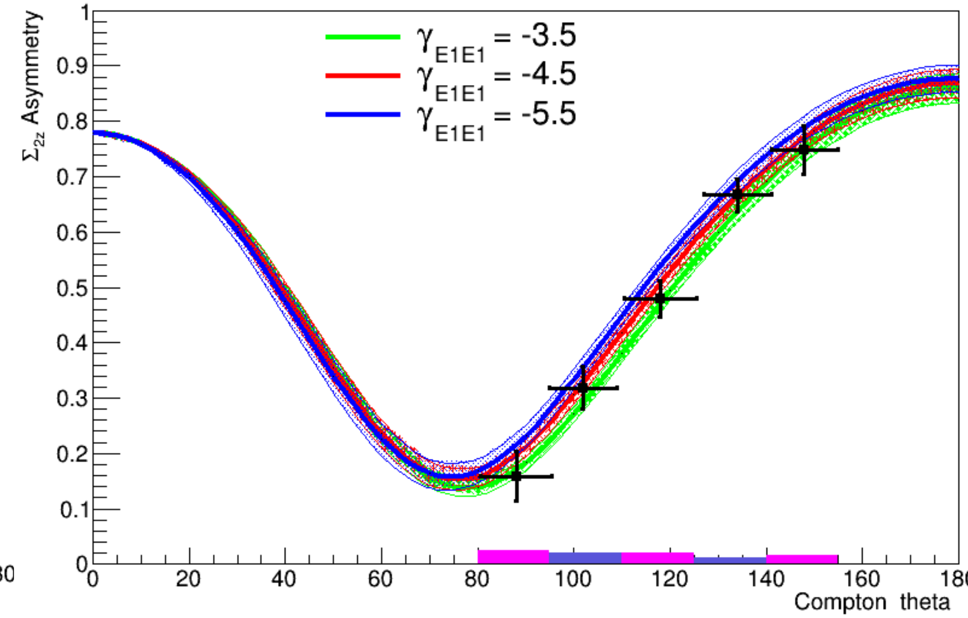
Fix γ_{E1E1} E_γ=285 - 305 MeV Fix γ_{M1M1}





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