Measurement of the Proton Polarizabilities at MAMI

Vahe Sokhoyan

for the A2 Collaboration

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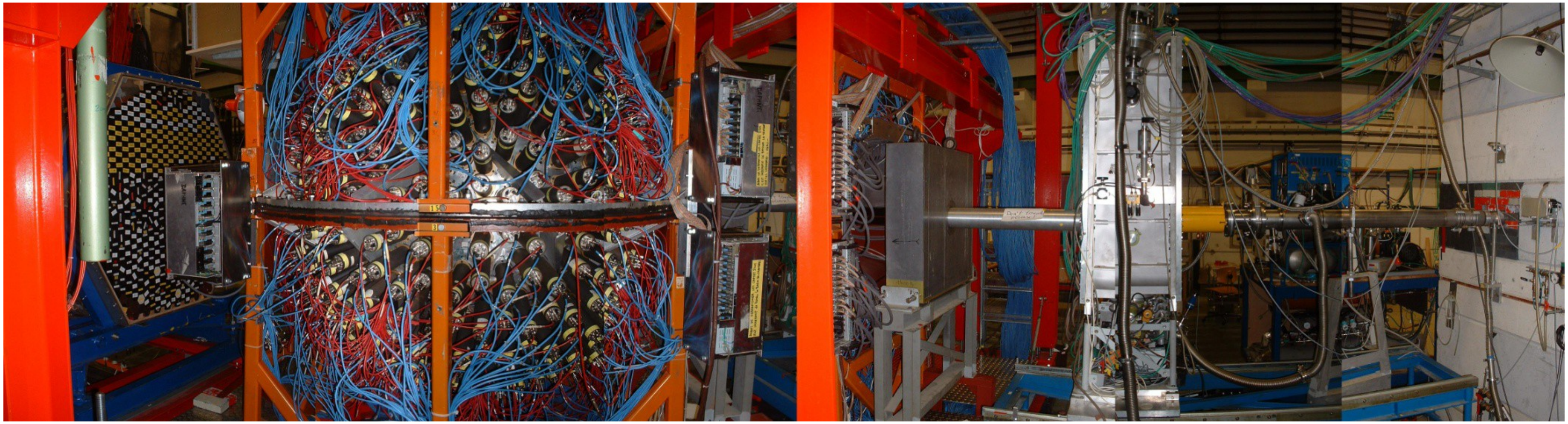
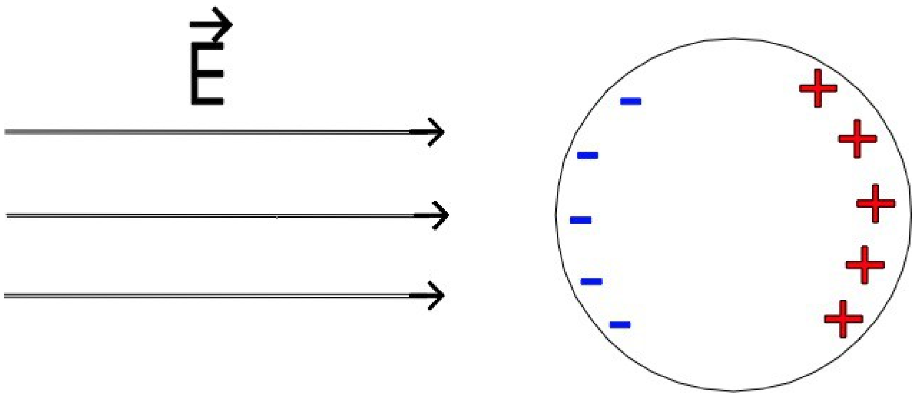


Contents

- Scalar and spin polarizabilities
- Compton scattering on the proton
- Experimental setup
- Results
- Ongoing work and future plans
- Summary and outlook

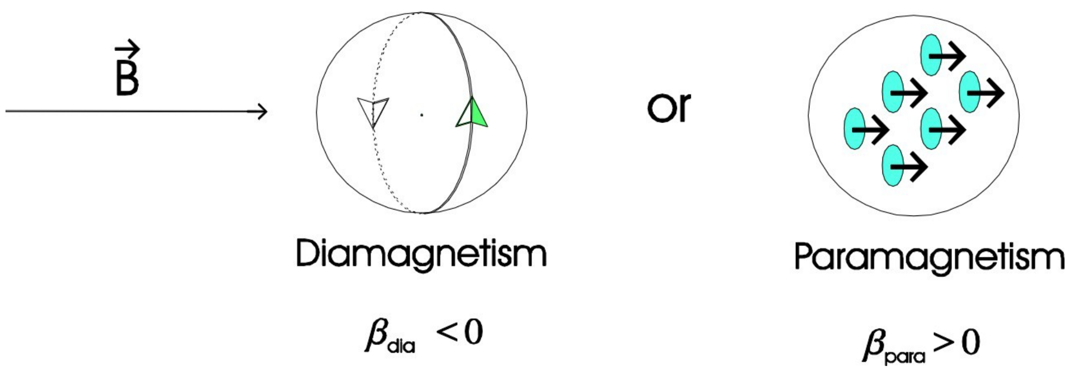
Scalar polarizabilities

Proton Electric Polarizability



- α_{E1}: electric polarizability
- Proton between charged parallel plates: "stretchability"

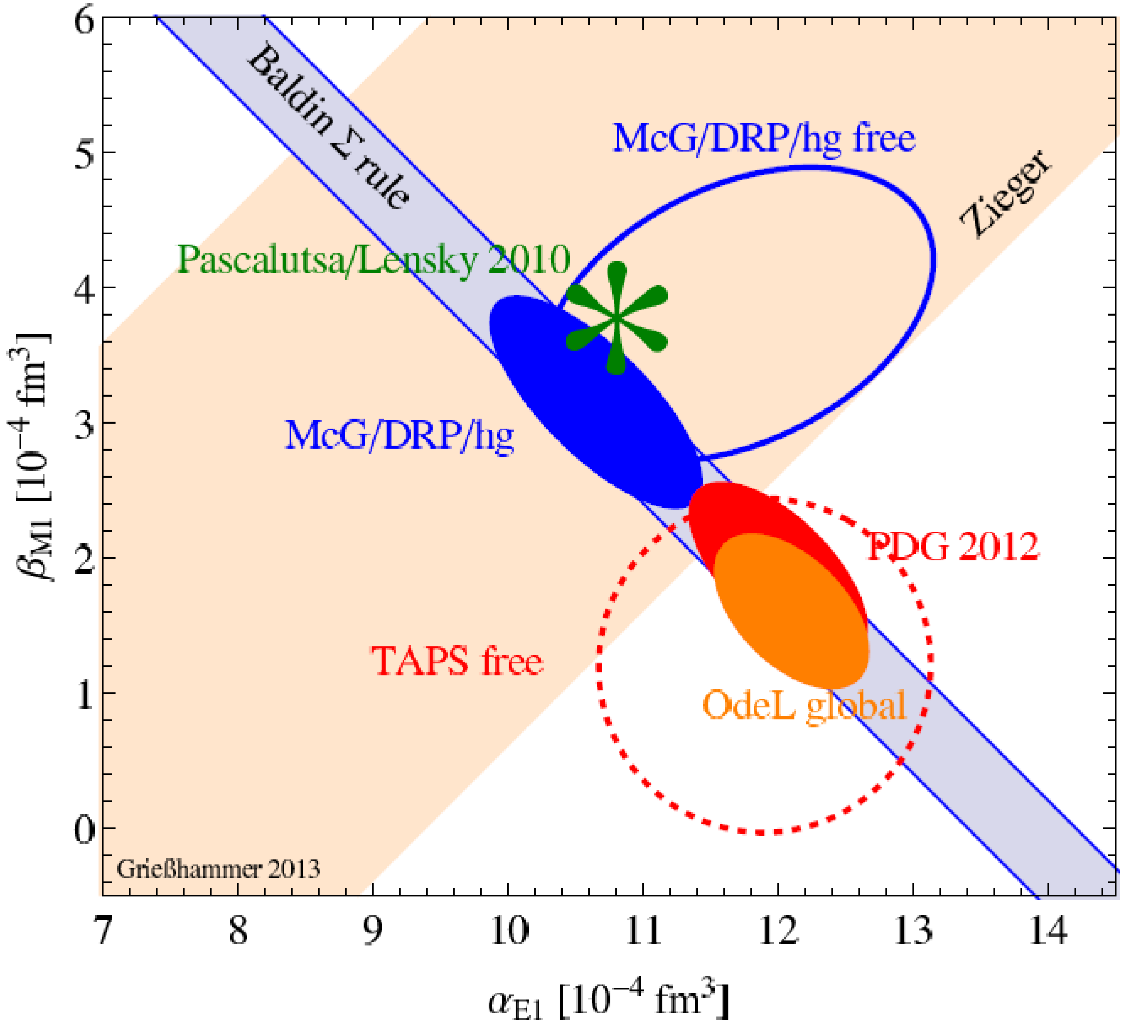
Proton Magnetic Polarizability



- β_{M1}: magnetic polarizability
- Proton between poles of a magnet: "alignability"

- Fundamental properties of the proton
- Important to astrophysics, atomic physics, spin polarizability measurements, etc.

Existing data and model predictions

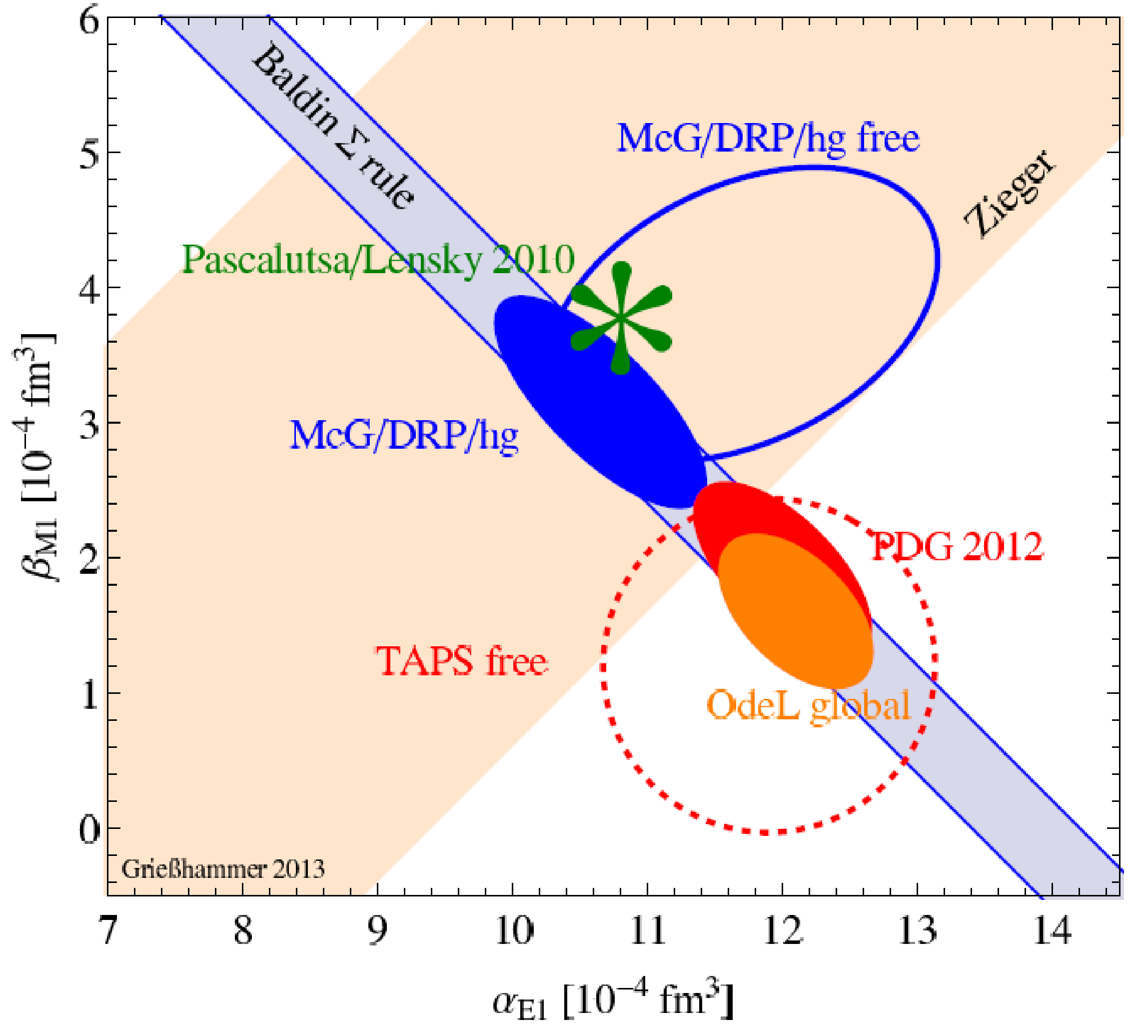


PDG (2012) values:

α_{E1} = (12.0 ± 0.6) × 10^{-4} fm^3

β_{M1} = (1.9 ± 0.5) × 10^{-4} fm^3

Existing data and model predictions



PDG (2012) values:

$\alpha_{E1} = (12.0 \pm 0.6) \times 10^{-4}\ \text{fm}^3$

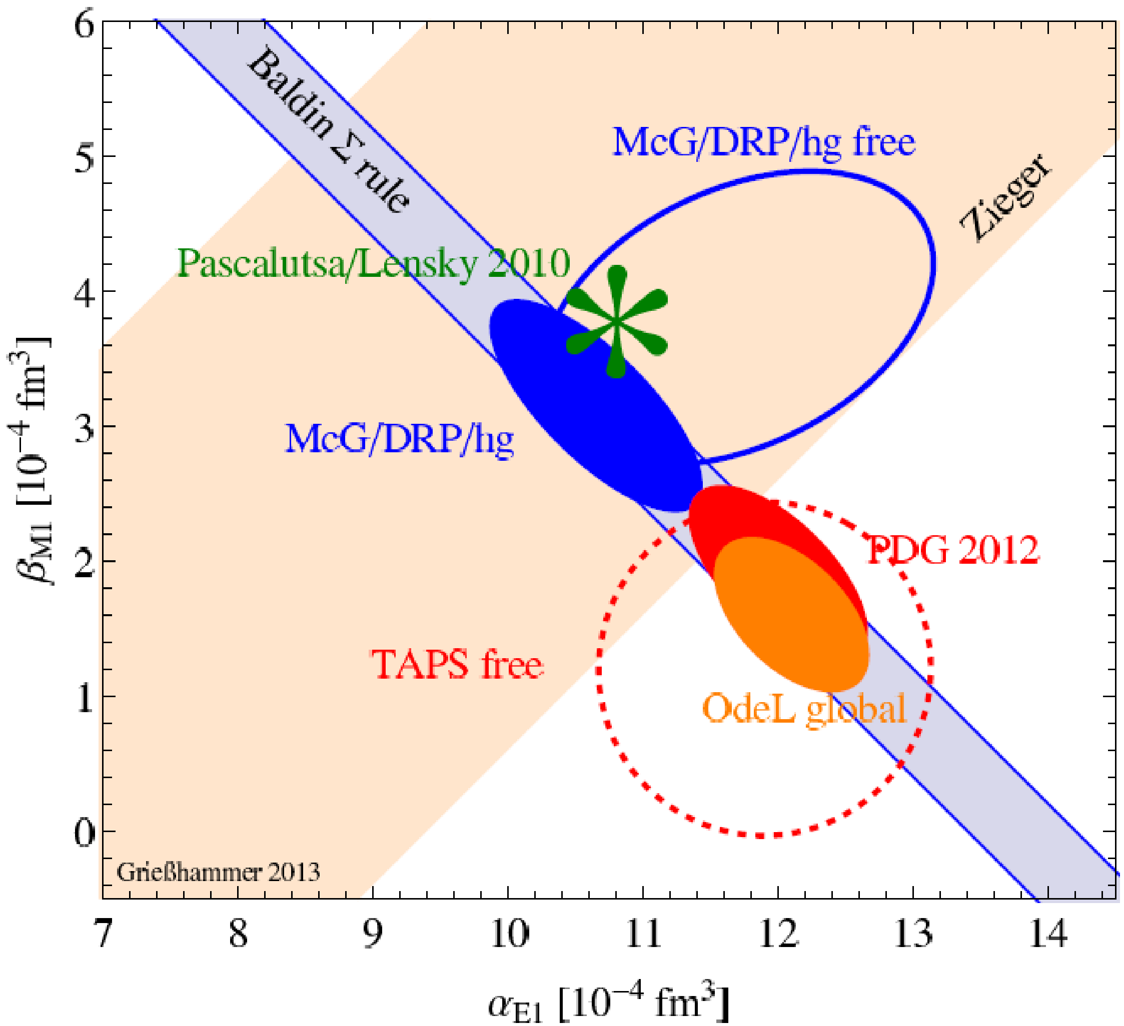
$\beta_{M1} = (1.9 \pm 0.5) \times 10^{-4}\ \text{fm}^3$

New (2013) PDG values:

$\alpha_{E1} = (11.2 \pm 0.4) \times 10^{-4}\ \text{fm}^3$

$\beta_{M1} = (2.5 \pm 0.4) \times 10^{-4}\ \text{fm}^3$

Existing data and model predictions



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New (2013) PDG values:

α_{E1} = $(11.2 \pm 0.4) \times 10^{-4}$ fm^3

β_{M1} = $(2.5 \pm 0.4) \times 10^{-4}$ fm^3

Significant change between reviews without introducing new experimental data? New quality data needed!

In the low energy range Σ_3 is purely dependent on β

Krupina and Pascalutsa, PRL 110, 262001 (2013)

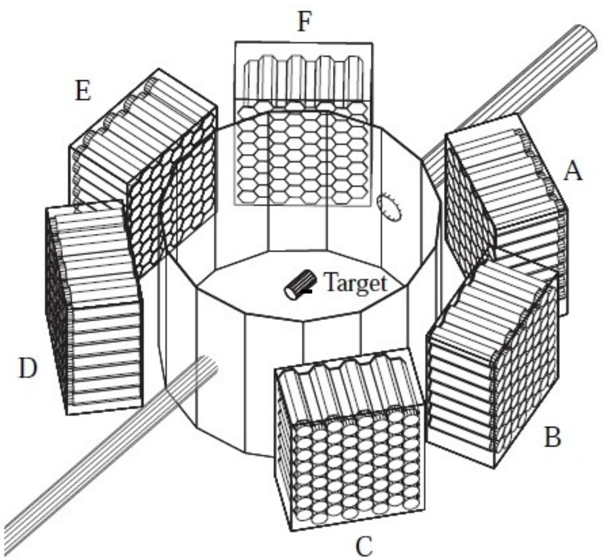
Talk of N. Krupina (this session)

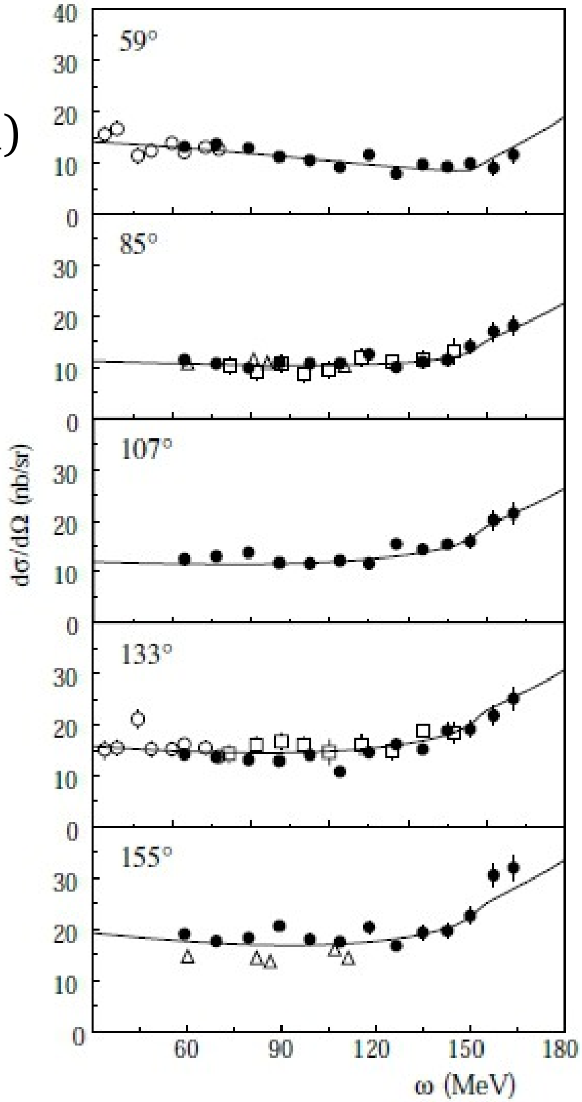
Existing data

- Highest statistics data set:

V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001)

- 200 hours of Compton scattering
- 20 cm lH_2 target with TAPS
- 180 MeV electron beam
- E_γ = 55-165 MeV, 59° < Θ < 155°
- 1/3 acceptance of CB System!





Triangles: P.S. Baranov et al., Phys. Lett. B 52, 22 (1974);
P.S. Baranov et al., Sov. J. Nucl. Phys. 21, 355 (1975)
Open circles: F.J. Federspiel et al., Phys. Rev. Lett. 67, 1511 (1991)
Squares B.E. MacGibbon et al., Phys. Rev. C 52, 2097 (1995)
Curve: R.A. Arndt et al., Phys. Rev. C 53, 430 (1996)

Measurement of α and β

Originally suggested measurement: cross section difference between linearly polarized photons parallel and perpendicular to reaction plane

$$\frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega}$$ proportional to α

$$z = \cos\theta \qquad \frac{z^2 d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega}$$ proportional to β

➔ **Independent** extraction of α & β possible!

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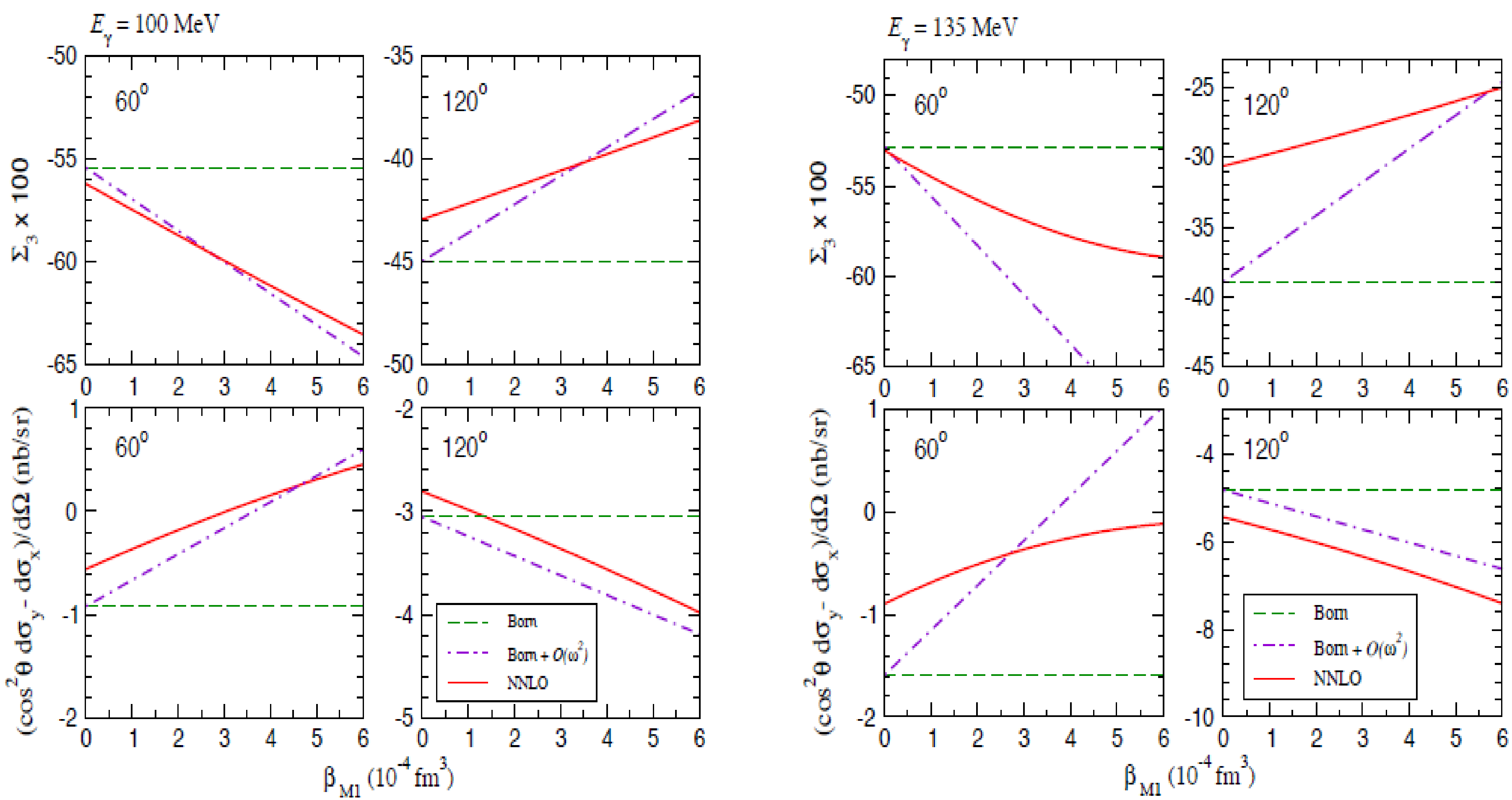
$z = \cos\theta$ $$\frac{z^2 d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega}$$ proportional to β

- **Independent** extraction of α & β possible!
- New work by Krupina and Pascalutsa [PRL 110, 262001 (2013)]
- At low energies, the beam asymmetry, Σ_3, is the best way to extract β

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

Talk of N. Krupina (this session)

Measurement of α and β



Krupina and Pascalutsa, PRL 110, 262001 (2013)

Systematical cross-checks

Goal: Determination of α and β

- We measure $\sigma_{\perp}$, $\sigma_{\parallel}$, σ_{unpol}

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 \cos(2\phi)\right]$$

- Measurement of the beam asymmetry Σ_3

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

- Measurement of absolute cross-sections
- Challenging with linearly polarized beam

Spin polarizabilities

- These parameters describe the response of the proton spin to an applied electric or magnetic field
- Nucleon has 4 spin or vector polarizabilities:

$$\gamma_{E1E1} \quad \gamma_{M1M1} \quad \gamma_{M1E2} \quad \gamma_{E1M2}$$

- Intimately connected to the nucleon's spin structure:

Fundamental properties of the proton!

- Higher order in incident-photon energy, small effect at lower energies
- Need theoretical help in extracting values

Spin polarizabilities

γ	Theory p^4HB	ϵ^3SSE	NNLO	DRs	Kmatrix	Experiment
$E1E1$	−1.4	−5.4	−4.5	−4.3	−5.0	no data
$M1M1$	3.3	1.4	3.7	2.9	3.4	no data
$E1M2$	0.2	1.0	−0.9	0.0	−1.8	no data
$M1E2$	1.8	1.0	2.2	2.1	1.1	no data
0	−3.9	2.0	−0.7	−0.7	2.3	$-1.01 \pm 0.08 \pm 0.13$
π	6.3	6.8	11.3	9.3	11.3	8.0 ± 1.8

- Proton spin polarizability predictions and measurements in units of 10^{-4} fm^4
- Note the large absolute error on γ_π

- Forward spin polarizability has been determined by a "GDH-type" of sum rule

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

- Backward spin polarizability has been determined from a dispersive analysis of backward-angle Compton scattering

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

Spin polarizabilities

What to do?

- Use Compton scattering to probe them!
- Measurements with polarized photons and targets
- Low sensitivity at low energies, so we need higher energies, into Δ region
- Three asymmetries, $\boldsymbol{\Sigma}_3$, $\boldsymbol{\Sigma}_{2x}$, and $\boldsymbol{\Sigma}_{2z}$ were chosen to obtain the spin polarizabilities of the proton

Asymmetries

1. Beam: circular, Target: longitudinal

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

2. Beam: circular, Target: transverse

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

3. Beam: linear, parallel and perpendicular to scattering plane
Target: unpolarized

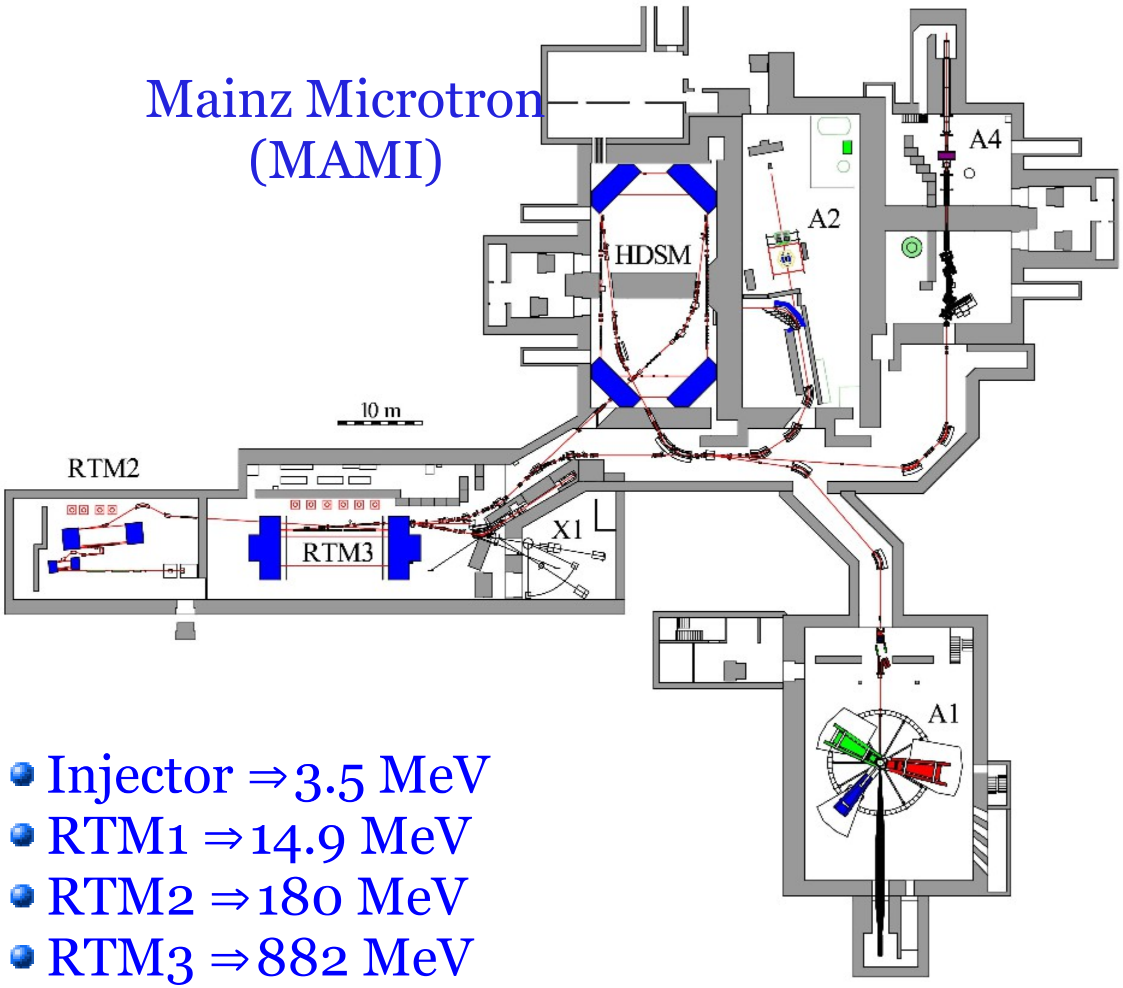
$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

By measuring three asymmetries at different energies and angles, we can conduct an in-depth global analysis to extract all four spin polarizabilities with small statistical, systematic, and model-dependent errors (R.Miskimen, P.Martel, A. Mushkarenkov)

D. Babusci et al., PRC 58 1013 (1998)

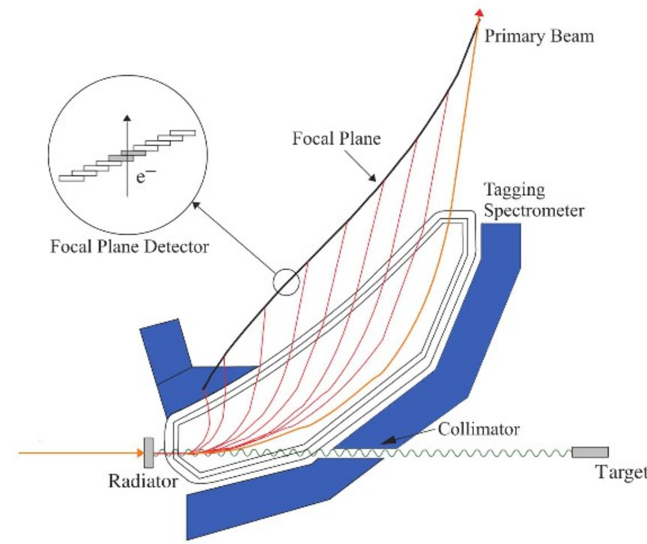
Experimental setup

Mainz Microtron (MAMI)



- Injector ⇒ 3.5 MeV
- RTM1 ⇒ 14.9 MeV
- RTM2 ⇒ 180 MeV
- RTM3 ⇒ 882 MeV
- HDSM ⇒ 1.6 GeV

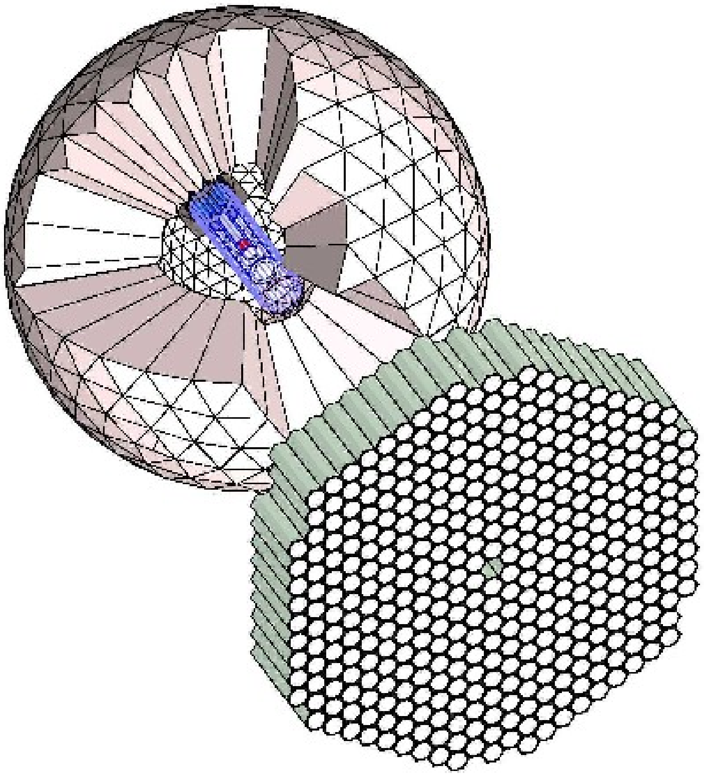
Tagger

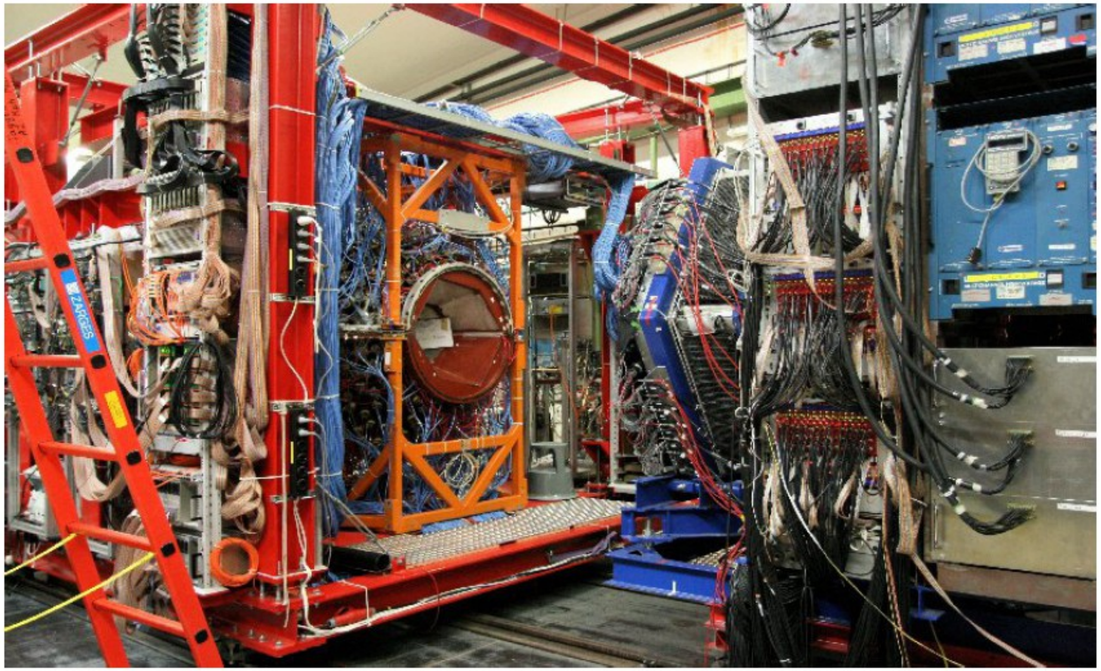


$$E_\gamma = E_o - E_{e-}$$

- High-Flux, Tagged, Bremsstrahlung Photon Beam: Unpolarized, Linear, and Circular
- Polarized and Unpolarized Targets

Experimental setup





Crystal Ball:

- 672 NaI Crystals
- 24 Particle Identification Detector Paddles
- 2 Multiwire Proportional Chambers

TAPS:

- 366 BaF2 and 72 PbWO4 Crystals
- 384 Veto Detectors

Selection

Selection of $\gamma p \rightarrow \gamma p$ at low energies:

- $E_{\gamma(beam)}$ = 80 – 150 MeV
- Selecting events with 1 γ
- Proton does not reach detectors at low energies
- $E\gamma$ cuts determined from MC
- Missing mass cut

➔ Subtraction of random timing background

➔ Subtraction of empty target contribution

➔ Comparison with Monte Carlo

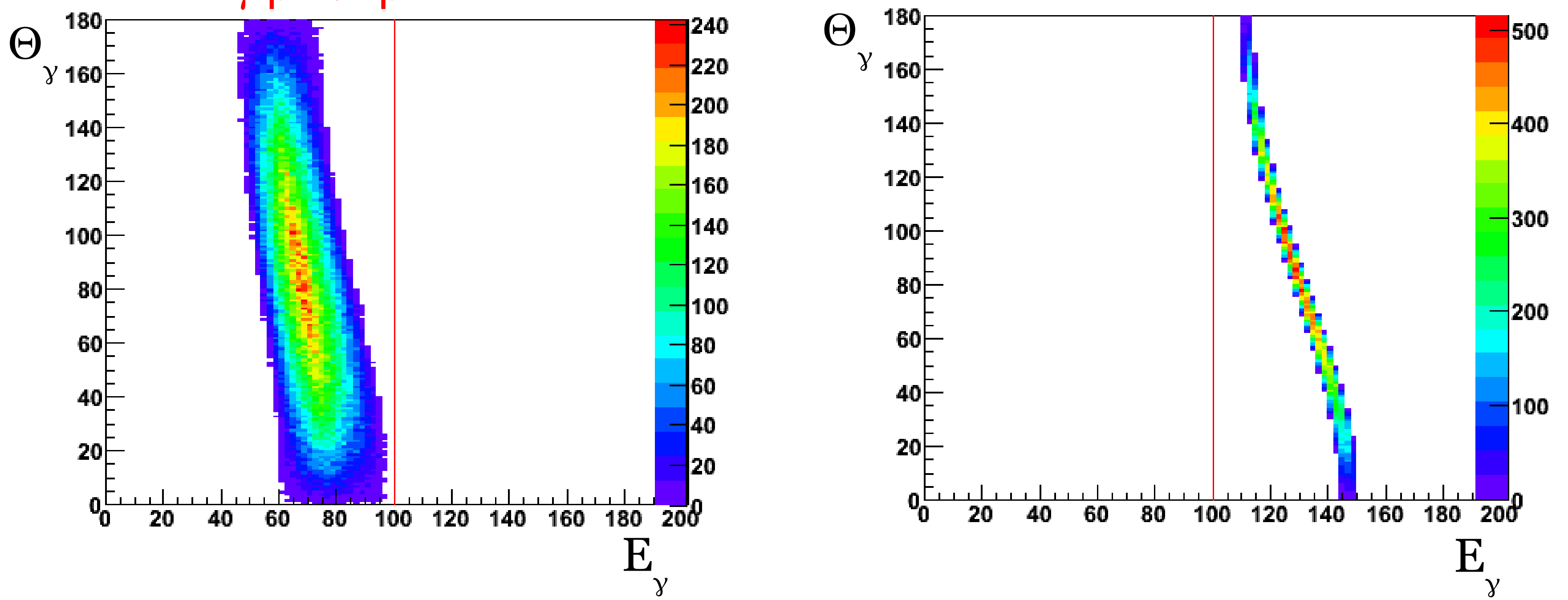
Elimination of π^0 background

- Main background source for Compton scattering: $\gamma\, p \rightarrow p\pi^0$
- Background production mechanism: 1 γ lost
- Kinematics similar to Compton scattering
- Significantly (~100 times) higher cross-section

Low energy range:

- Can be removed at ~ 150 MeV (e.g. 145 – 150 MeV)
- Cut on E_γ

$\gamma\, p \rightarrow p\pi^0$ $\qquad\qquad$ $\gamma\, p \rightarrow \gamma p$



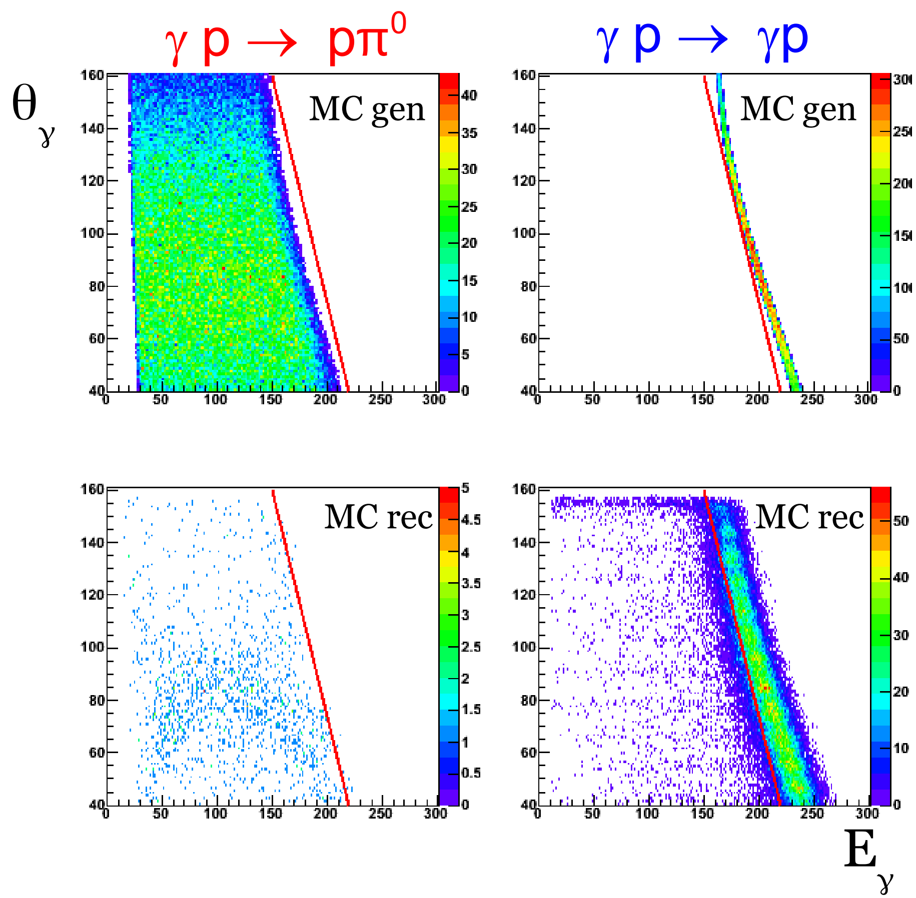
Elimination of π^0 background

- Main background source for Compton scattering: $\gamma\, p \to p\pi^0$
- Background production mechanism: 1 γ lost
- Kinematics similar to Compton scattering
- Significantly higher cross-section
- Higher energies: 1 γ can take the largest part of the π^0 energy

Up to ~ 250 MeV:

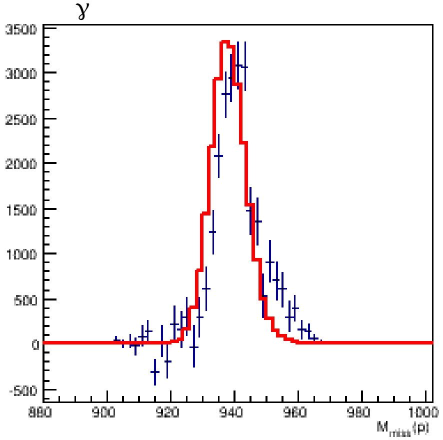
2D (E, θ) cut!

$E\gamma$ = 245-255 MeV

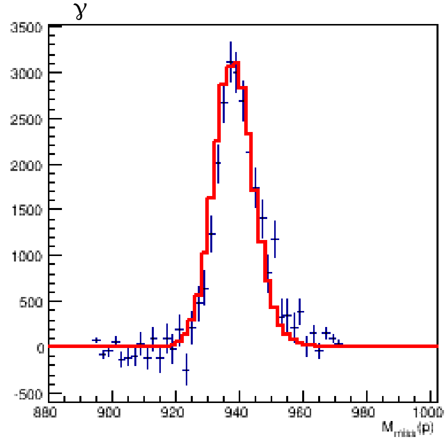


Comparison with Monte Carlo

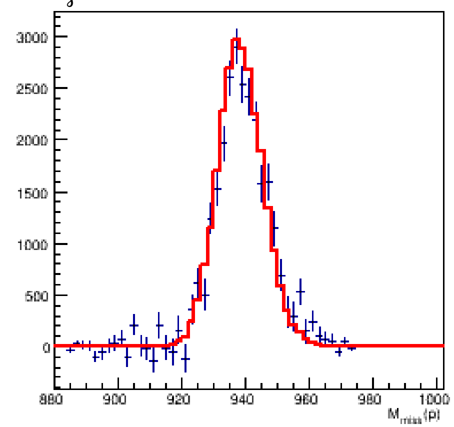
E_γ = 80 -100 MeV



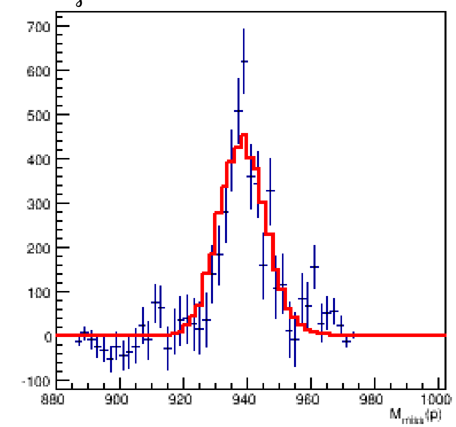
E_γ = 100 -120 MeV



E_γ = 120 -140 MeV



E_γ = 140 -150 MeV



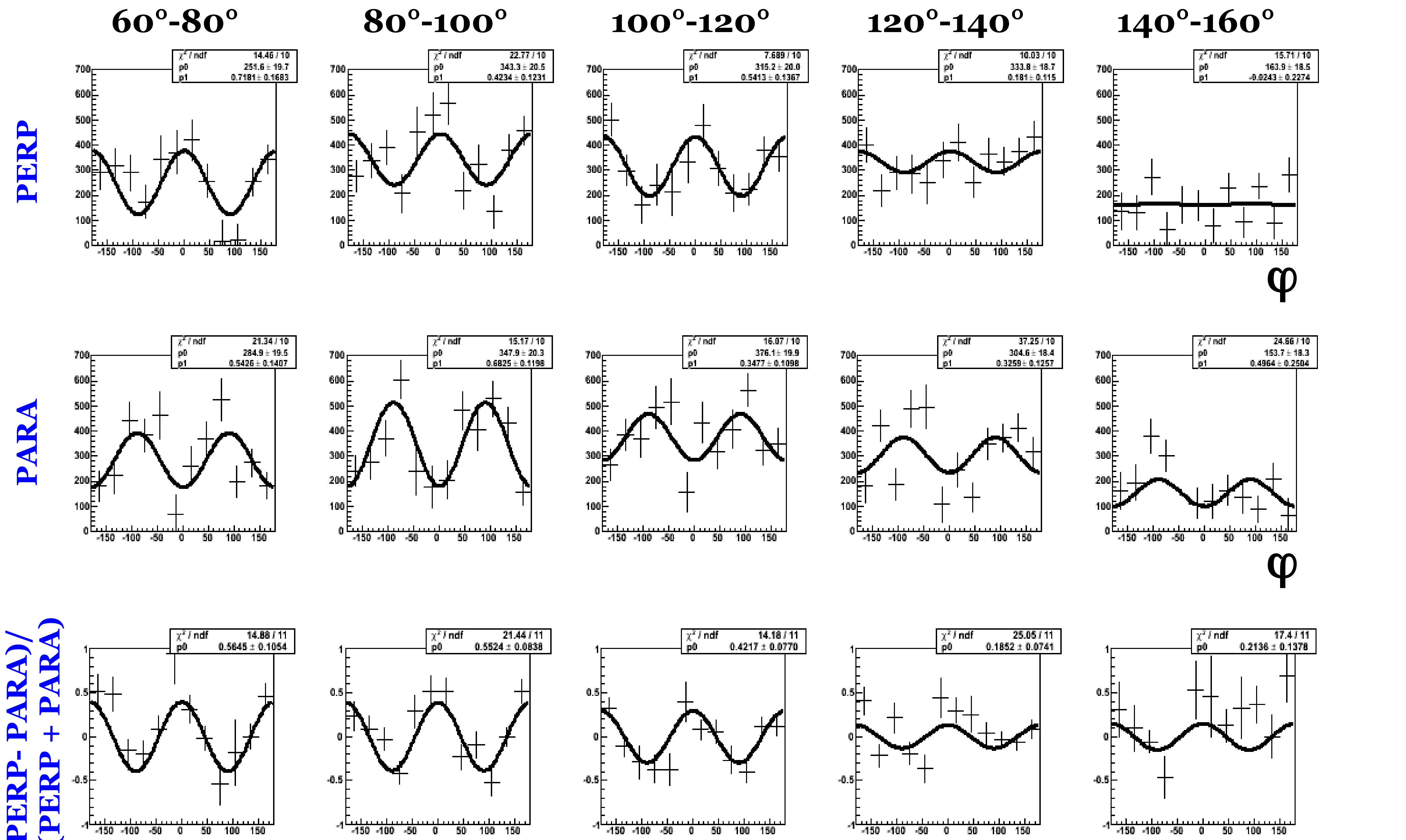
Red: Monte Carlo, Blue: Data

$\Theta_\gamma = 60^\circ - 160^\circ$

- Good agreement between data and Monte Carlo
- Low background contamination in all energy bins

Preliminary

Preliminary asymmetries (E_γ = 120 -140 MeV)

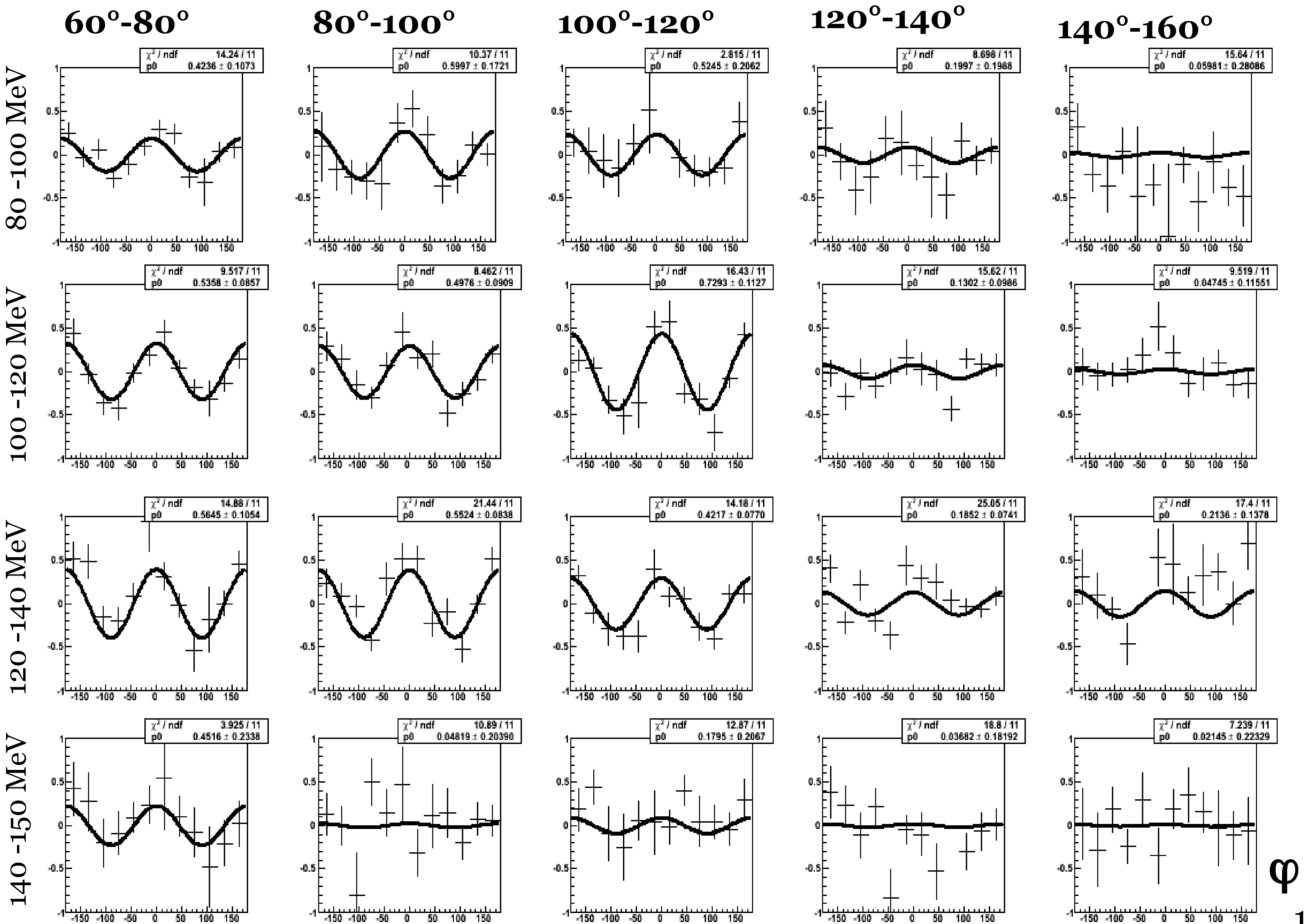


φ

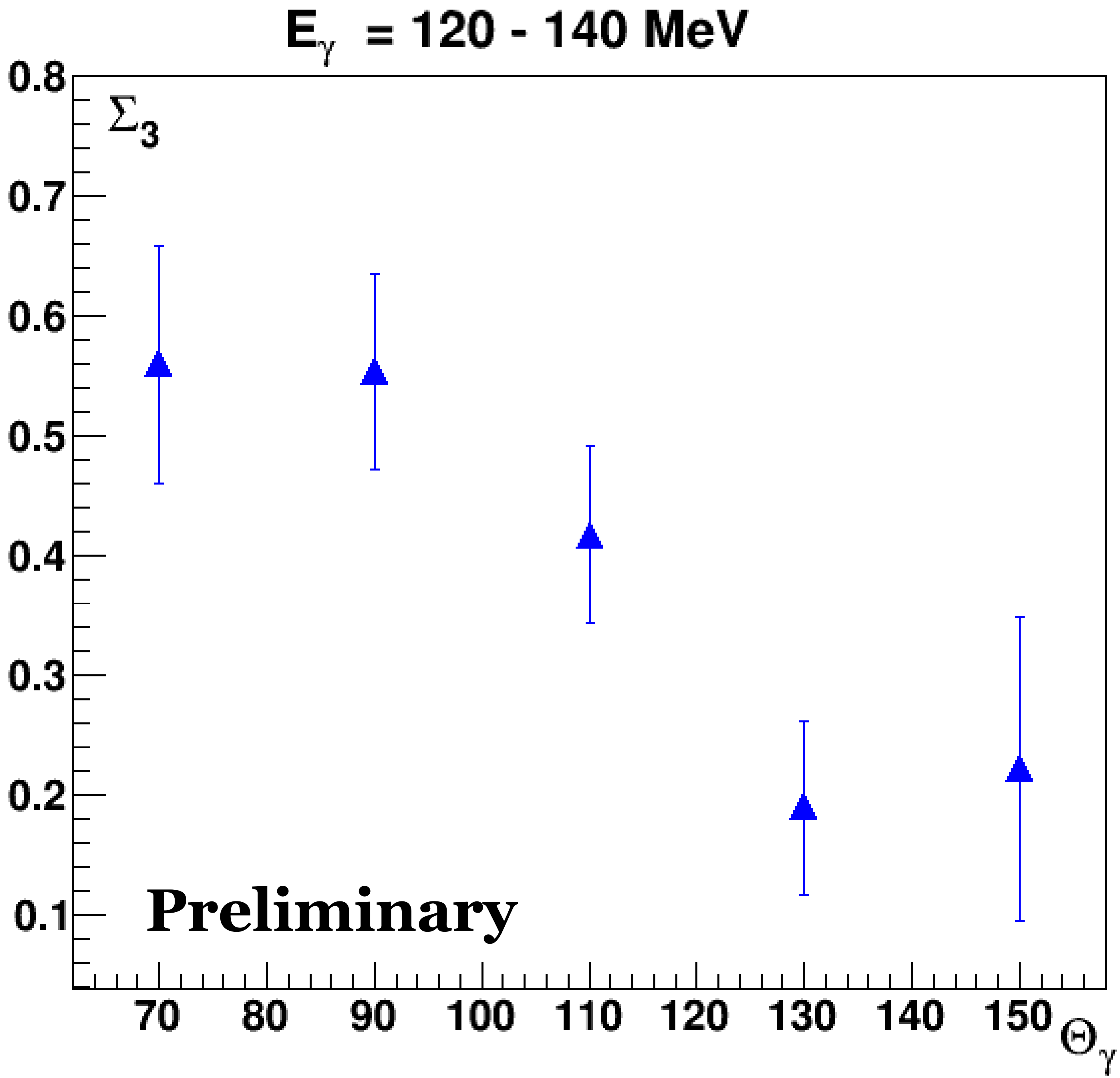
Preliminary

Binning in Θ_γ

Preliminary asymmetries



Σ_3 : Preliminary results



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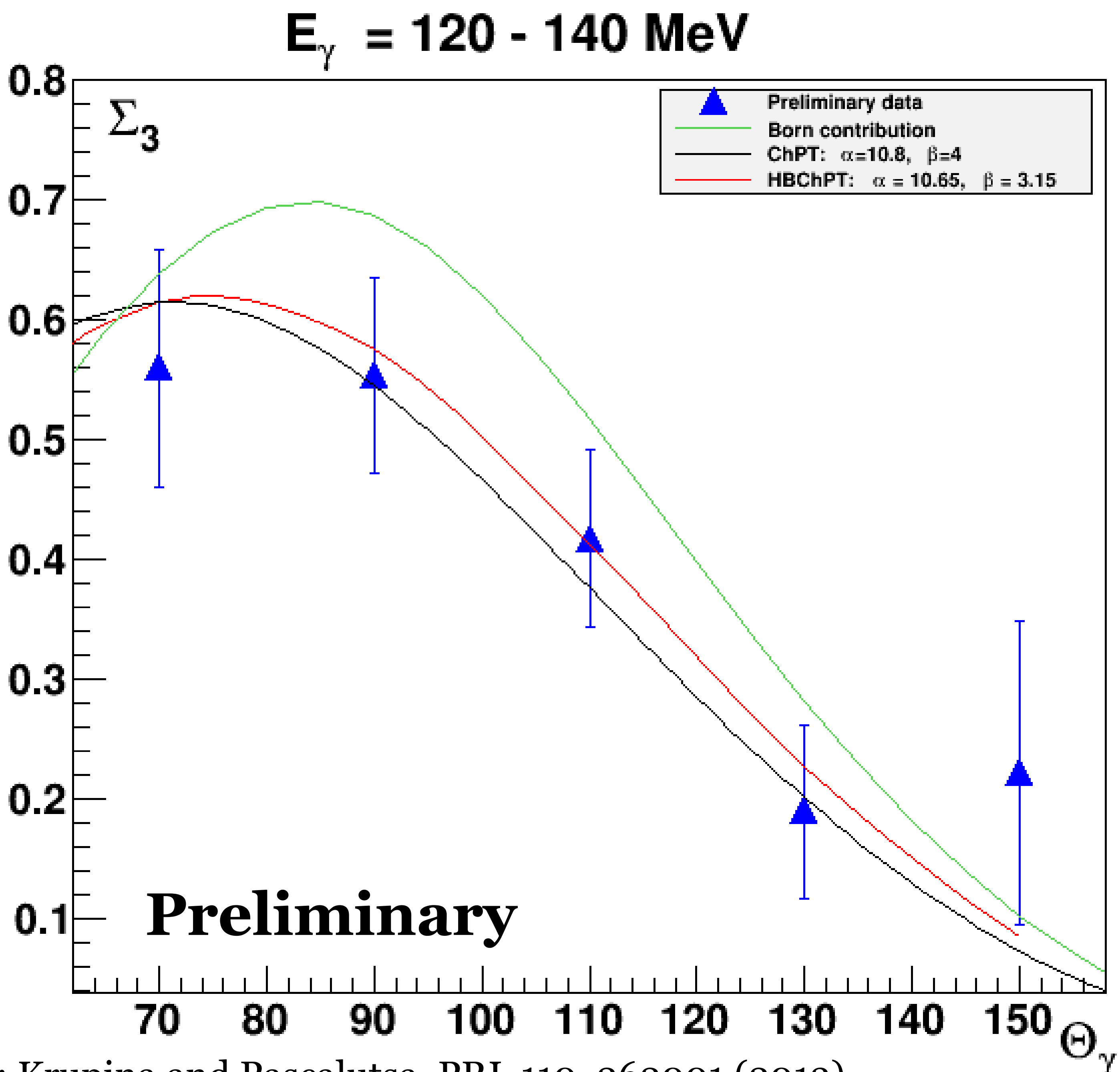
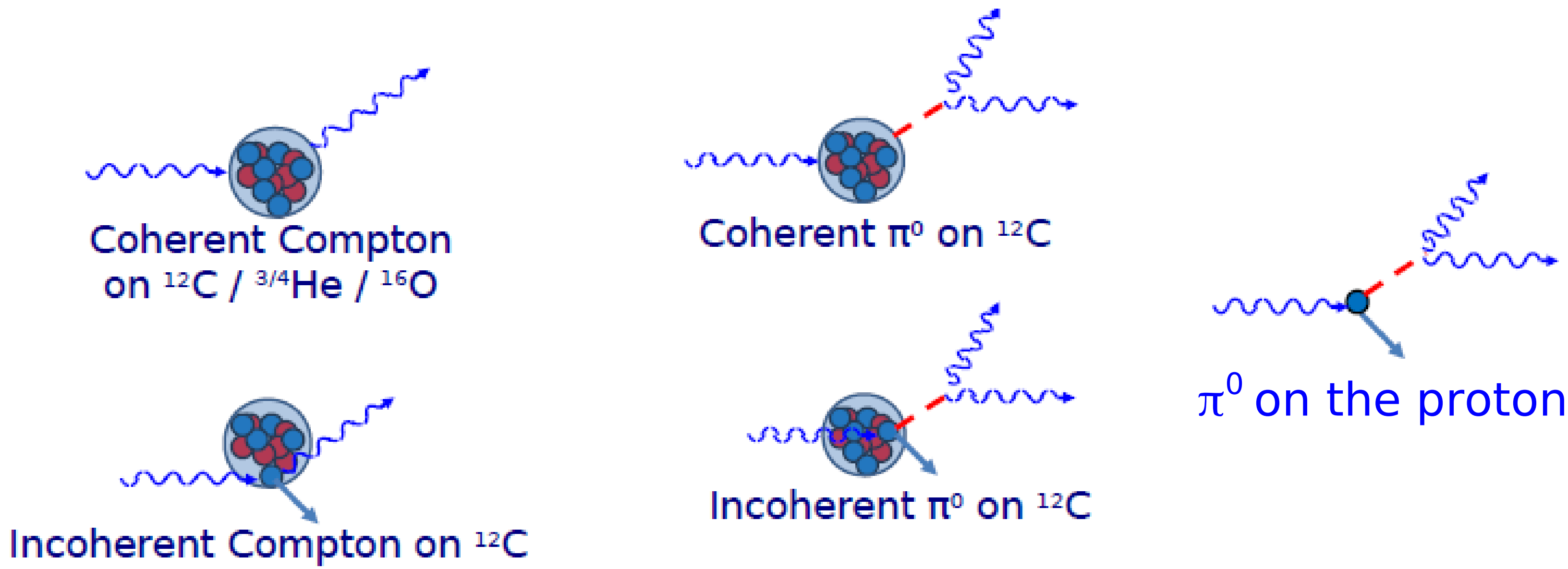


Curves: Krupina and Pascalutsa, PRL 110, 262001 (2013),
J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)

Σ_{2x} : Experimental challenges

- Small Compton scattering cross sections
- Large backgrounds
- Butanol target (C_4H_9OH): Coherent and incoherent reactions off C, O and He
- Proton tracks are required to suppress backgrounds, but energy losses e.g. in the target are considerable.



P. Martel (UMass, KPH Mainz)

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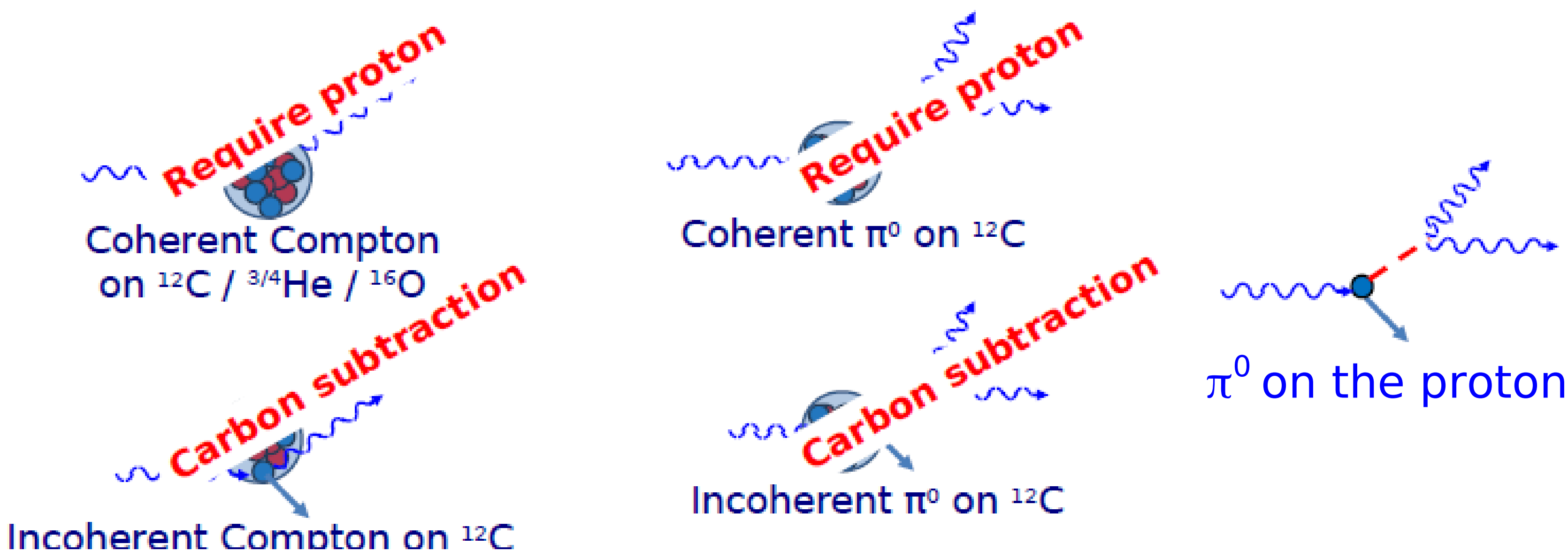

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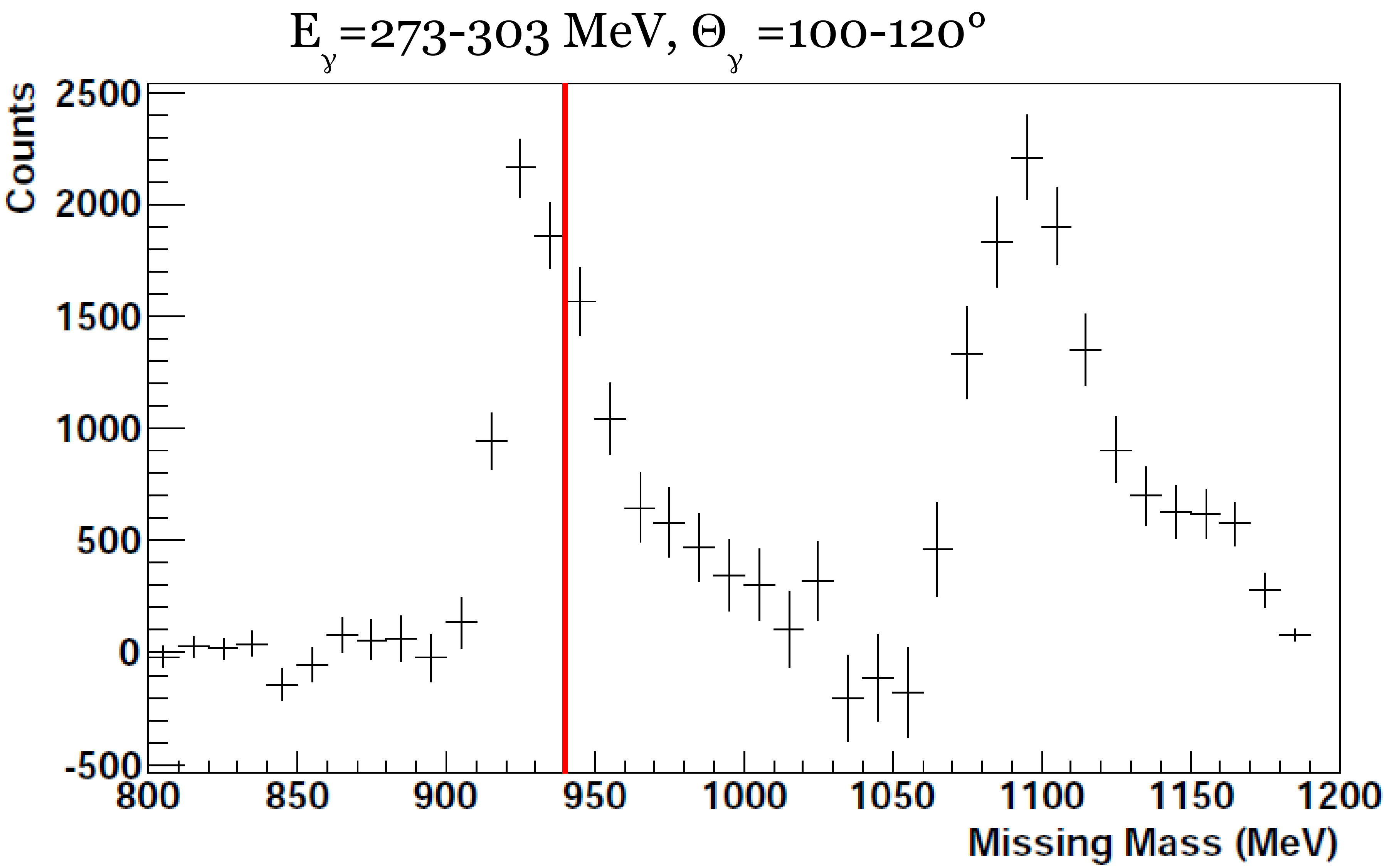
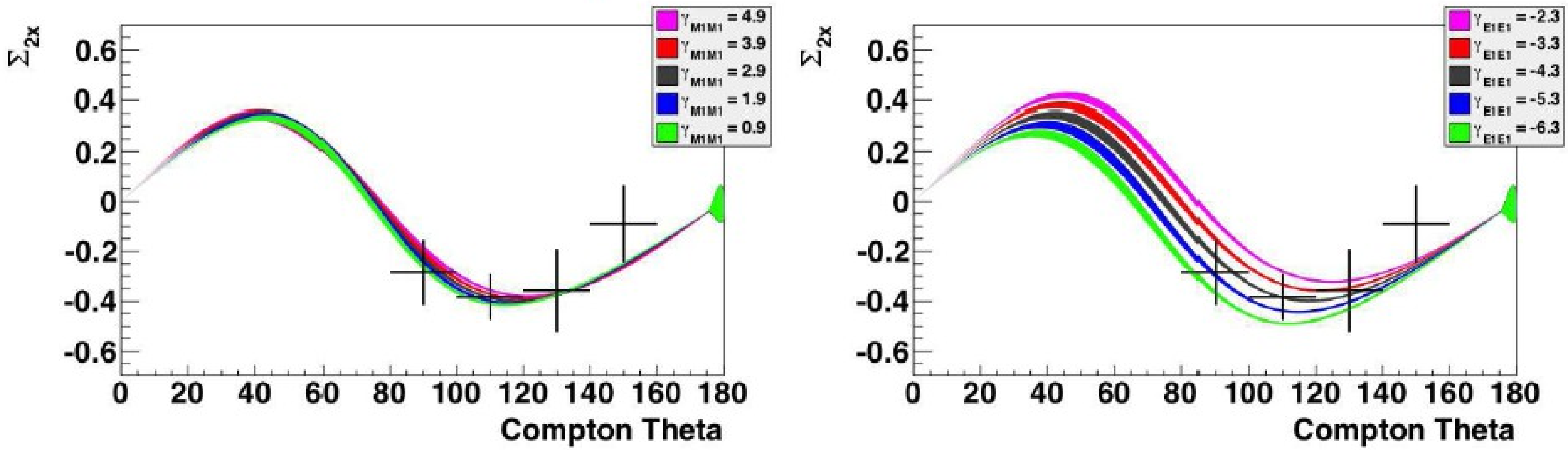
Σ_{2x}: Preliminary results



P. Martel (UMass, KPH Mainz)

Σ_{2x}: Preliminary results

$E_\gamma = 273 - 303\,\mathrm{MeV}$



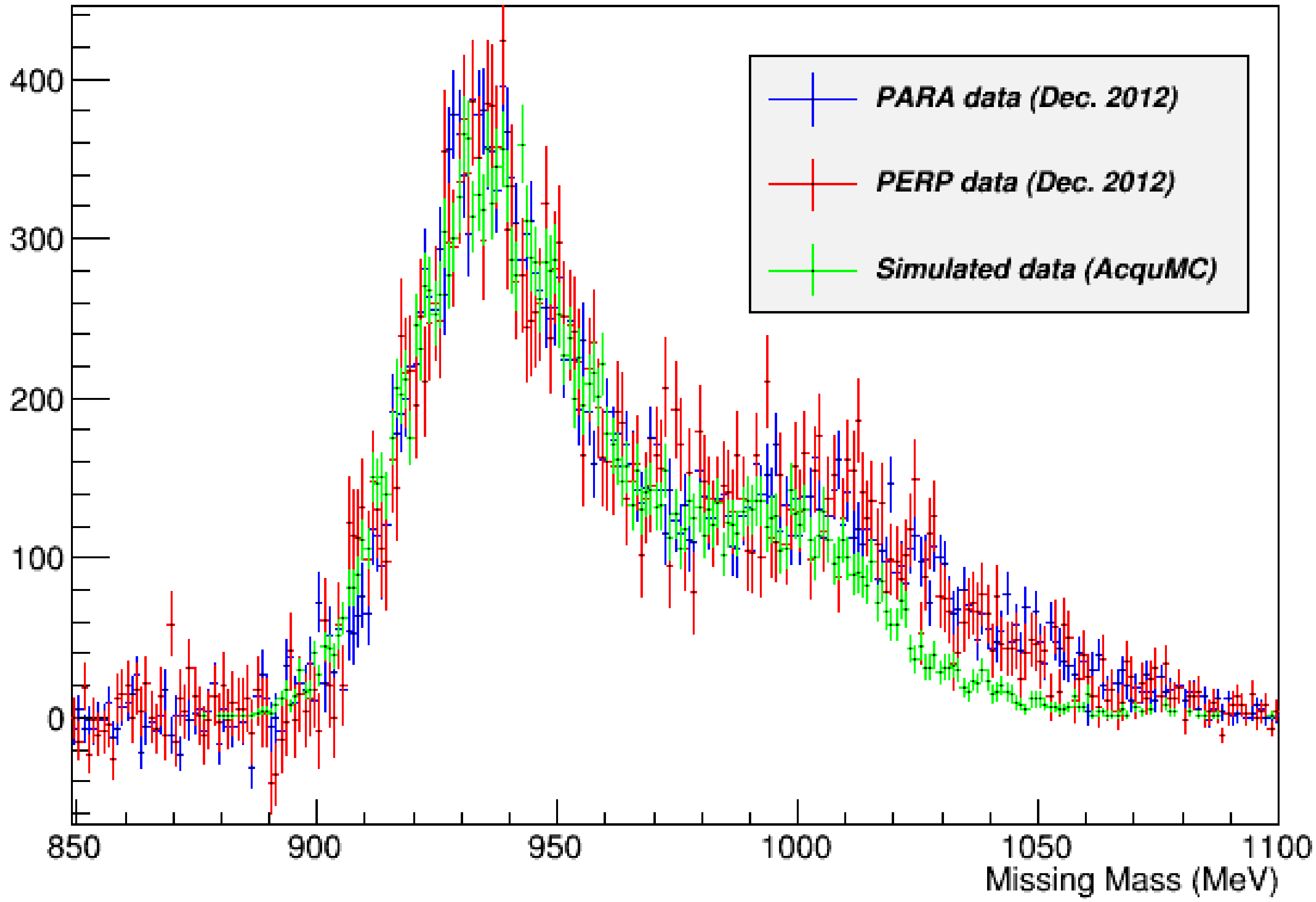
- First measurement of a double-polarized Compton scattering asymmetry on the nucleon, Σ_{2x}
- Curves are from DR calculation of Pasquini et al.
  Data have sensitivity to the γ_{E1E1} spin-polarizability, with a preliminary estimate of

$$\gamma_{E1E1} = (-4.6 \pm 1.6) \times 10^{-4}\ \mathrm{fm}^4$$

P. Martel (UMass, KPH Mainz)

Beam asymmetry Σ_3 at higher energies

Missing mass comparison (E_γ = 270-290 MeV)

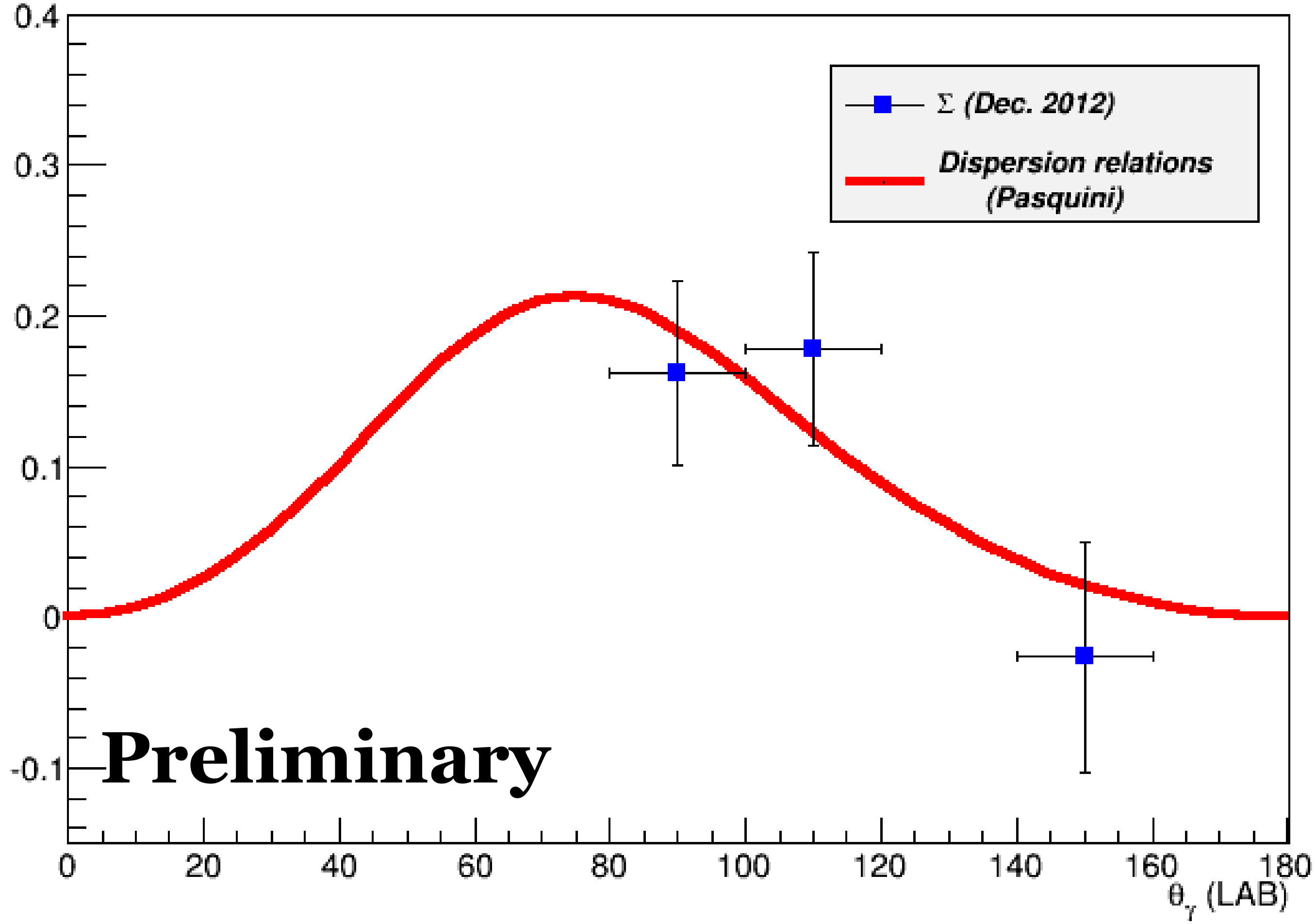


ASimulated data includes both $\gamma p \to \gamma p$ and $\gamma p \to p\pi^0$

C. Collicott (Mainz, DAL, SMU)

Beam asymmetry Σ_3 at higher energies

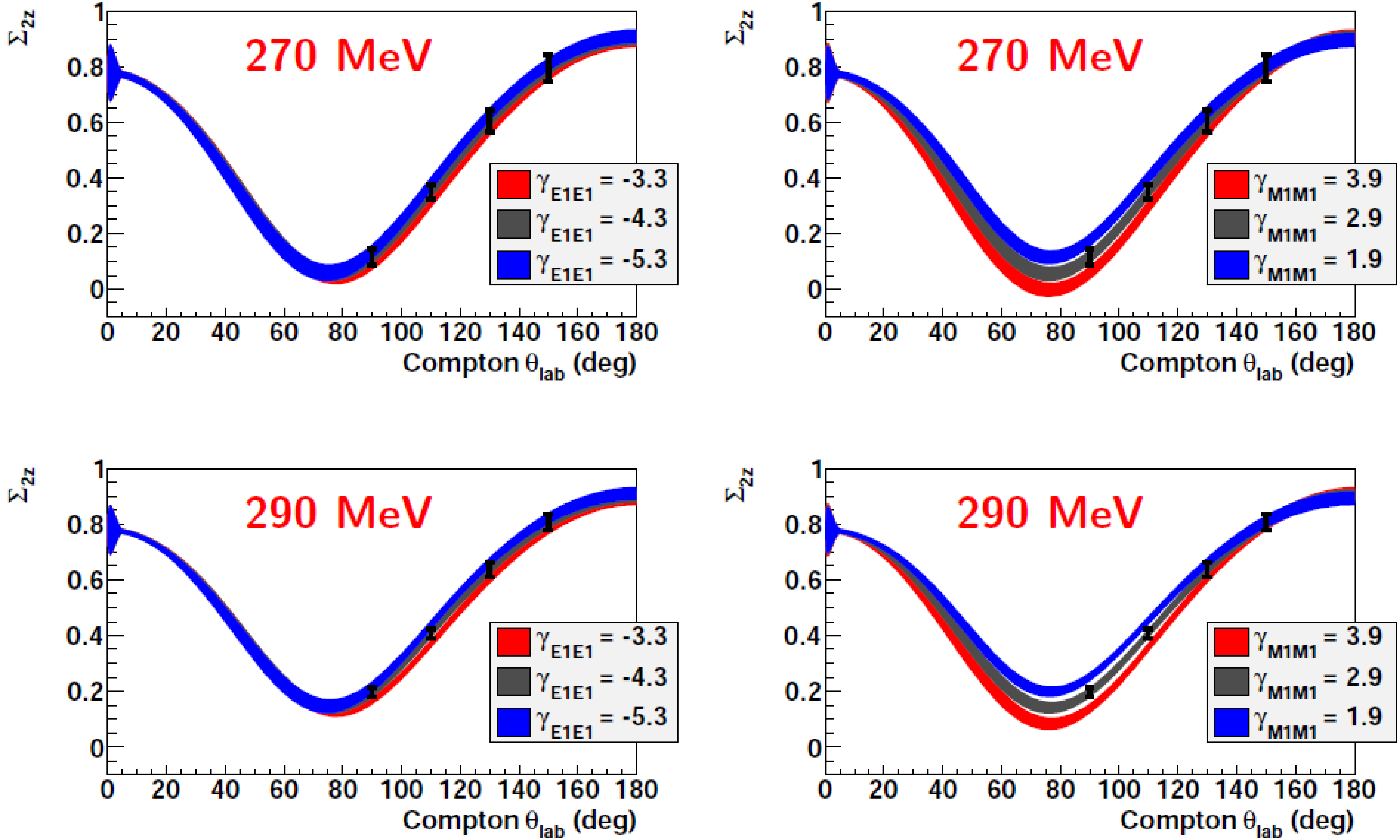
Compton scattering Σ_3 asymmetry (E_γ = 270-290 MeV)



C. Collicott (Mainz, DAL, SMU)

Σ_{2z}: Estimated experimental precision

Vary γ_{E1E1} | Vary γ_{M1M1}



Current Status

Experiment	Status
Σ_{2x}	✓ February 2011
Σ_3 high energy	✓ December 2012
α, β (Σ_3 low energy)	✓ June 2013
Σ_{2z}	May 2014

Summary

Scalar polarizabilities:

- Events with signature of Compton scattering clearly identified
- Low-background data set obtained for the energy range 80-150 MeV
- Σ_3 measured below pion threshold for the first time, analysis in progress

Spin polarizabilities:

- Double polarization observable Σ_{2x} measured for the first time in the Δ region
- The asymmetries agree with a value of $\gamma_{E1E1} = (-4.6 \pm 1.6) \times 10^{-4}$ fm^4
- Publication on Σ_{2x} in preparation (P.Martel et al.)
- Σ_3 measured in the Δ region, analysis in progress (C. Collicott et al.)

Outlook

Short-term:

- Finish analysis and publish Σ_{2x}, Σ_3, and α, β results
- Measurement of Σ_{2z} will be performed in May (2014)
- Remeasure the observables $\Sigma_{3,}$ Σ_{2x} and Σ_{2z} with significantly higher statistics
- Complete extraction of the proton spin polarizabilities

Medium and Long term:

- Development and installation of an active polarized target (prototype ready)
- Repeat the entire program on the neutron
- Installation of an active He gas target

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Thank you for your attention!

Backup

Real Compton Scattering – Hamiltonian

Expand the Hamiltonian in incident-photon energy.

0th order $\longrightarrow$ charge, mass

1st order $\longrightarrow$ magnetic moment

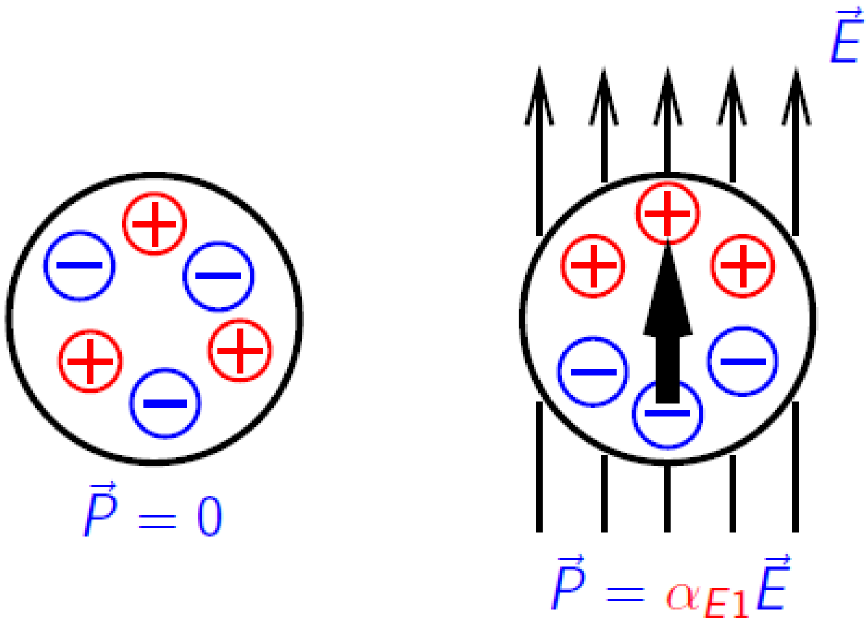
2nd order $\longrightarrow$ **scalar polarizabilities**:

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

3rd order $\longrightarrow$ **spin (or vector) polarizabilities**:

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

Electric Dipole Polarizability

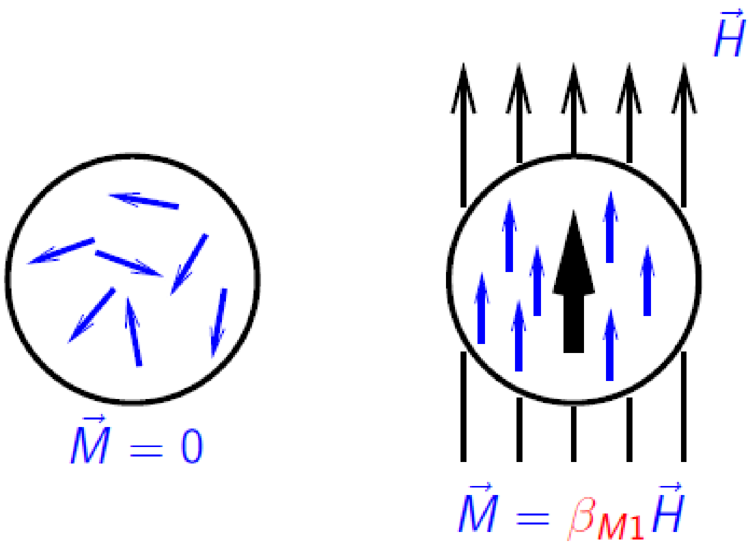


- Apply an electric field to a composite system
- Separation of Charge, or **"Stretchability"**
- Proportionality constant between electric dipole moment and electric field is the electric dipole polarizability, α_{E1}.

Provides information on force holding system together.

Scalar Polarizabilities – Conceptual

Magnetic Dipole Polarizability



- Apply a magnetic field to a composite system
- Alignment of dipoles or **"Alignability"**
- Proportionality constant between magnetic dipole moment and magnetic field is the magnetic dipole polarizability, β_{M1}.
- Two contributions, paramagnetic and diamagnetic, and they cancel partially, giving $\beta_{M1} < \alpha_{E1}$.

Provides information on force holding system together.

Previous Data – γ_0

Forward spin polarizability has been determined by a "GDH-type" of sum rule

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

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

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

Known to $\approx 10\%$.

Previous Data – γ_π

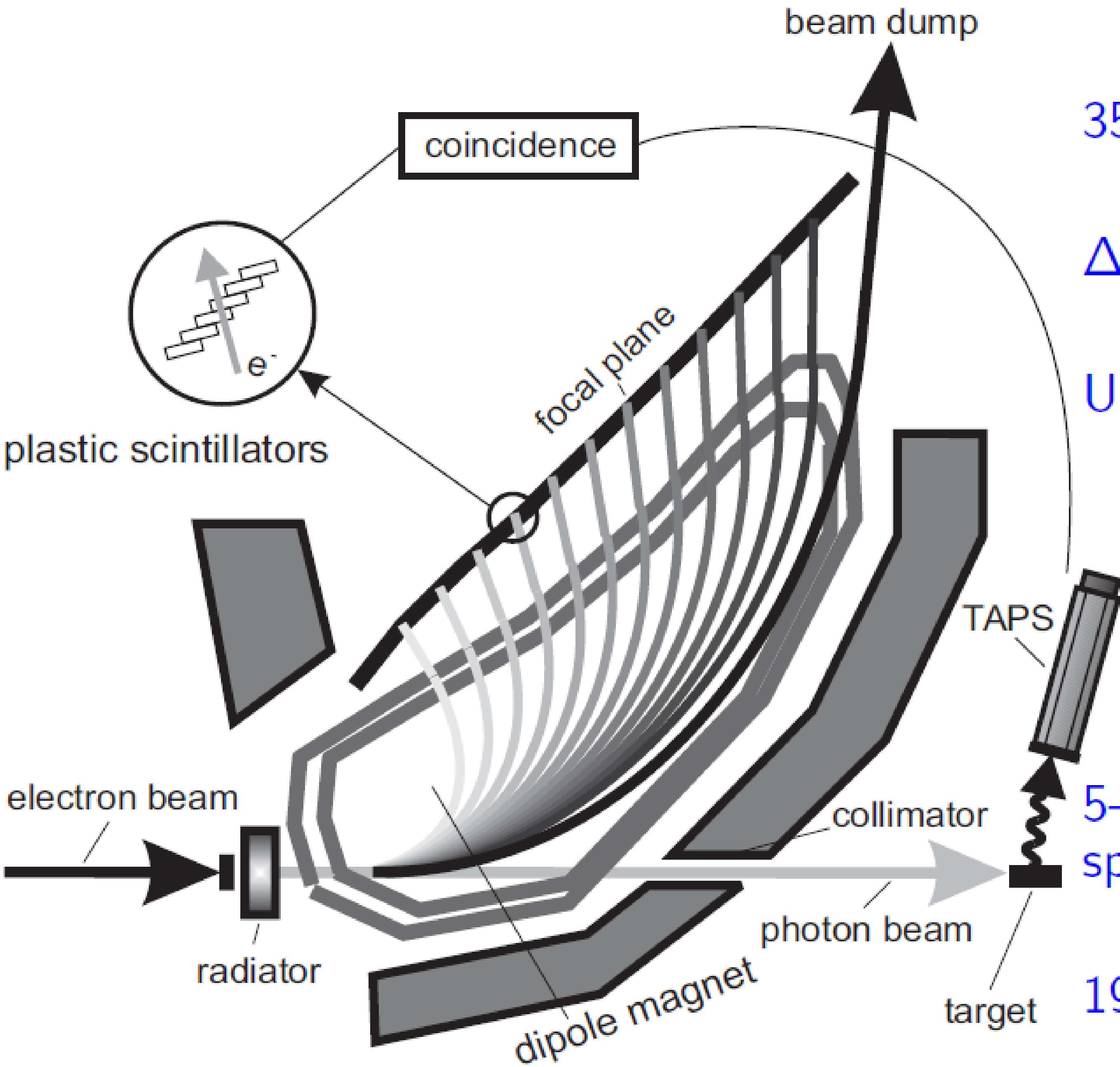
Backward spin polarizability has been determined from a dispersive analysis of backward-angle Compton scattering

$$\gamma_\pi = -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2}$$
$$= (-38.7 \pm 1.8) \times 10^{-4}\ \mathrm{fm}^4$$

where the pion pole contributes -46.7 and the dispersive part 8.0 ± 1.8.

Note that the dispersive part is known *only* to about $\approx 25\%$!

Incident Photon Beam – Glasgow-Mainz Photon Tagger



352 channels

$\Delta E = 4\,\mathrm{MeV}$ at 1.6 GeV

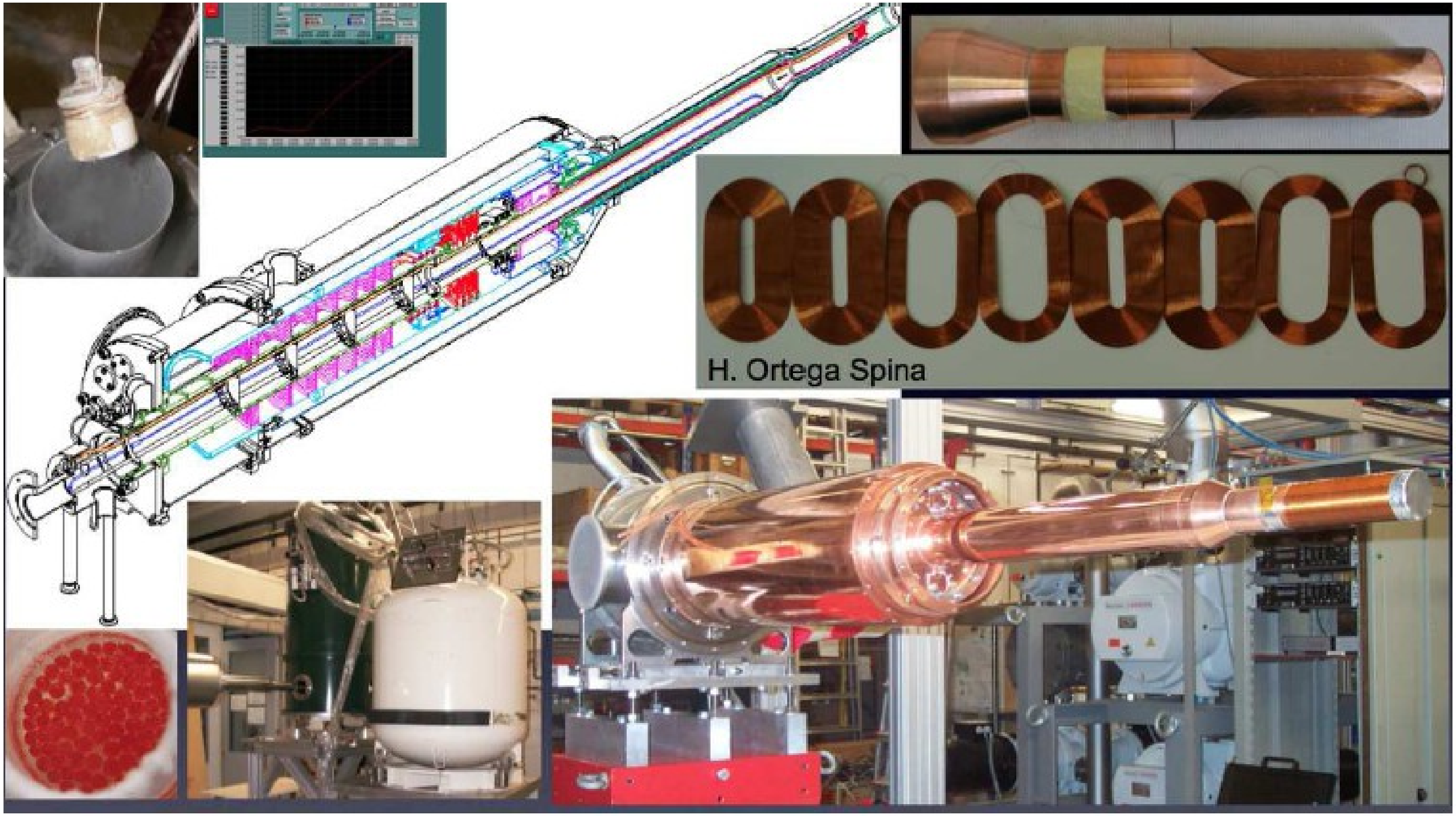
Up to $\sim 10^8 \gamma/\mathrm{s}$

Refurbished to work at 1.6 GeV

5–94% of Bremsstrahlung spectrum

191-channel microscope

Polarized Target



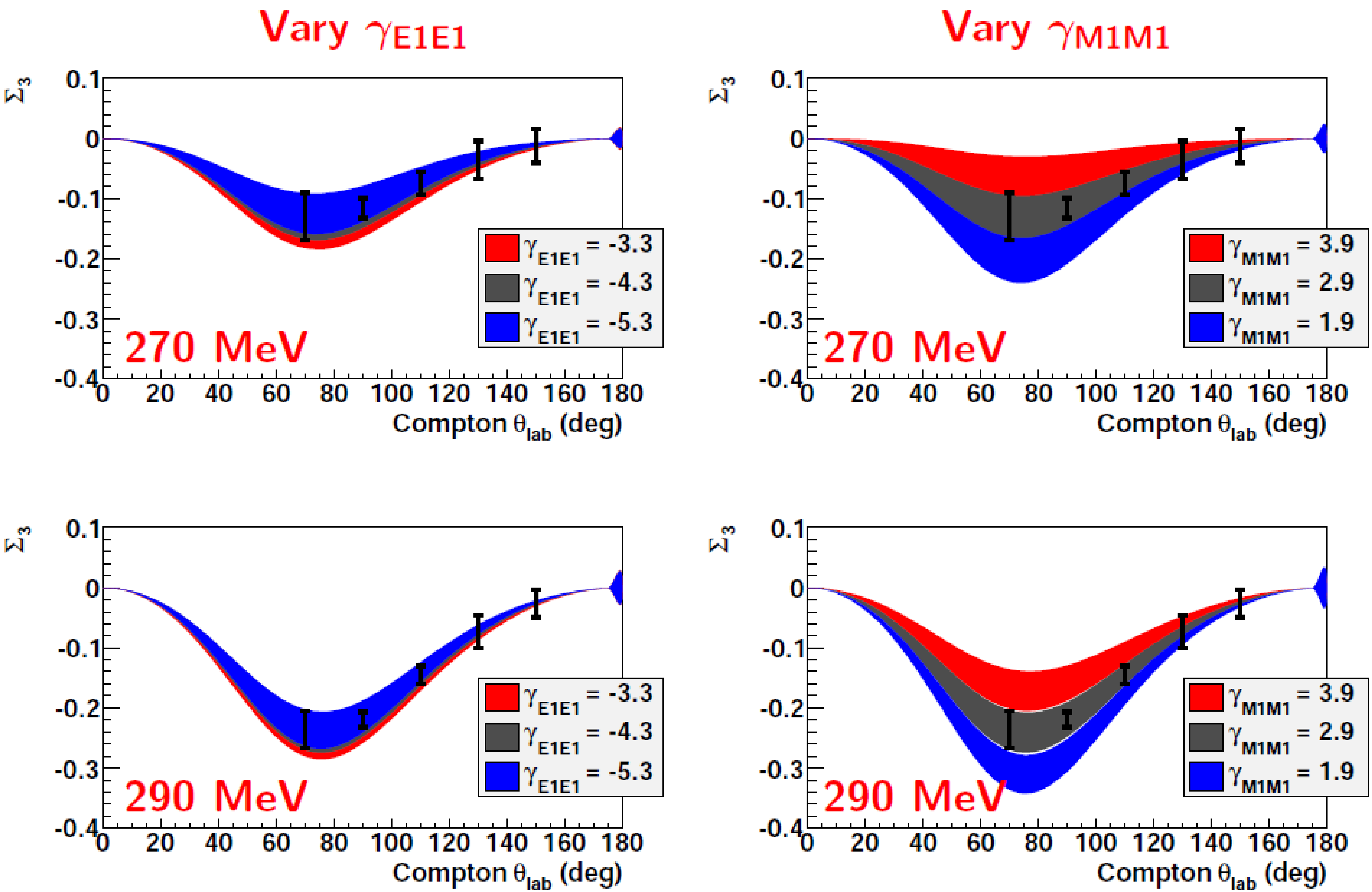
Dynamical Nucleon Polarization

Target material is butanol, $C_4H_{10}O$

Dilution cryostat with bath of liquid $^3He/^4He$, $T < 30\,mK$

$P_p \approx 90\%$ with a relaxation time of $\tau > 1000$ hours.

Σ_3 – Estimated Experimental Precision



Predicted Values

Extracting the proton spin polarizabilities would provide a useful test of nucleon structure.

	$O(p^3)$	$O(p^4)$	$O(p^4)$	LC3	LC4	SSE	BGLMN	HDPV	KS
γ_{E1}	-5.7	-1.4	-1.8	-3.2	-2.8	-5.7	-3.4	-4.3	-5.0
γ_{M2}	1.1	0.2	0.7	0.7	0.8	.98	0.3	-0.01	-1.8
γ_{E2}	1.1	1.8	1.8	0.7	0.3	.98	1.9	2.1	1.1
γ_{M1}	-1.1	3.3	2.9	-1.4	-3.1	3.1	2.7	2.9	3.4
γ_0	4.6	-3.9	-3.6	3.1	4.8	.64	-1.5	-0.7	2.3
γ_π	4.6	6.3	5.8	1.8	-0.8	8.8	7.7	9.3	11.3

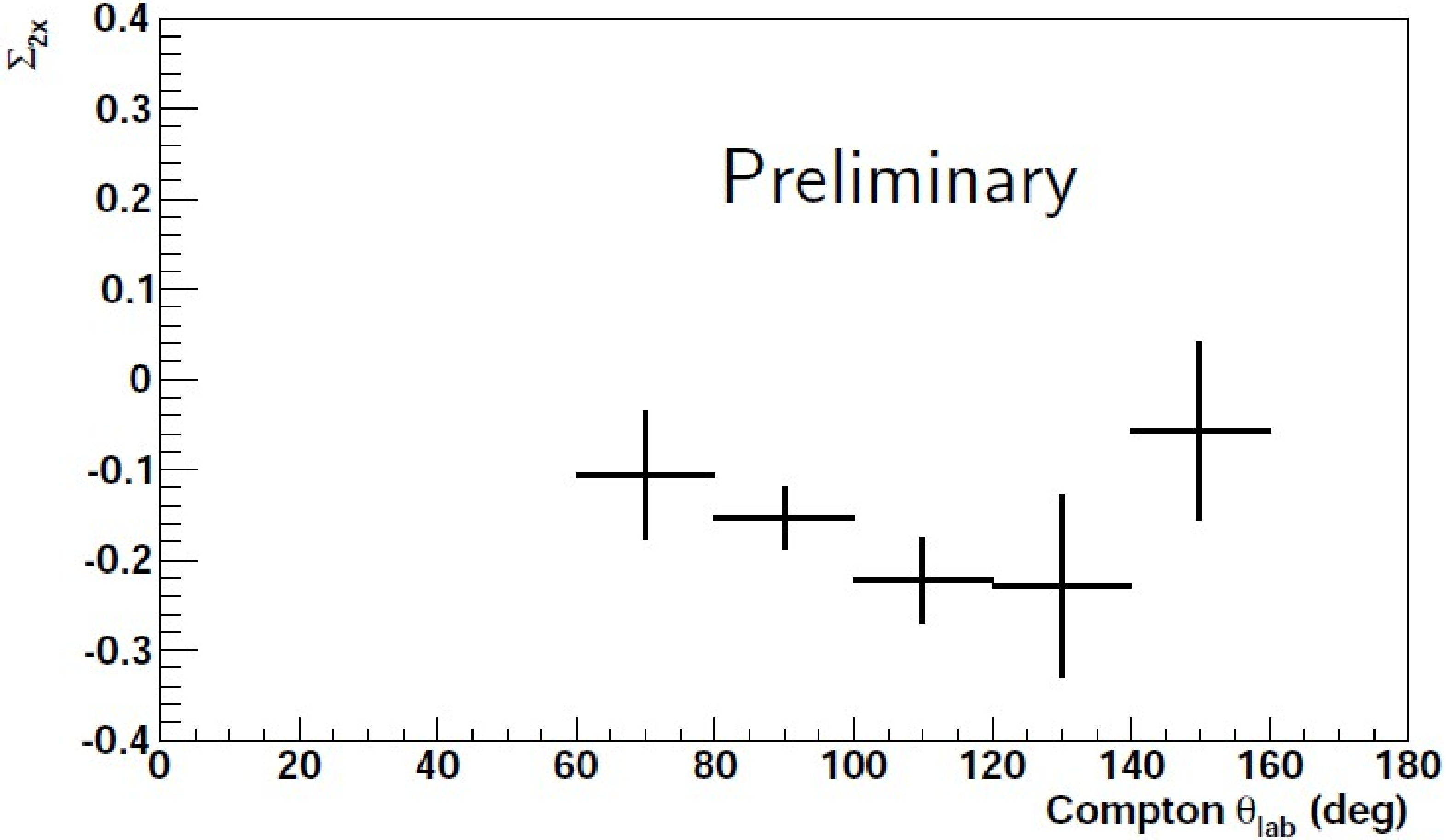
Table: Values for the spin polarizabilities. $O(p^n)$ are Chiral Perturbation Theory (ChPT) calculations. LC3 and LC4 are $O(p^3)$ and $O(p^4)$ Lorentz invariant ChPT calculations, respectively. SSE is a Small Scale Expansion calculation. The remaining three are all dispersion relation calculations.

Frozen Spin Target

Polarizing protons through Dynamic Nuclear Polarization (DNP):

- Cool target to 0.2 Kelvin.
- Use 2.5 Tesla magnet to align electron spins.
- Pump $\approx$ 70 GHz microwaves (just above, or below, the Electron Spin Resonance frequency), causing spin-flips between the electrons and protons.
- Cool target to 0.025 Kelvin, ‘freezing’ proton spins in place.
- Remove polarizing magnet.
- Energize 0.6 Tesla ‘holding’ coil in the cryostat to maintain the polarization.
- Relaxation times $>$ 1000 hours.
- Polarizations up to 90%.

Transverse Asymmetries - E_γ=315-346 MeV



Above validity of dispersion relation.

Compton scattering: Polarisabilities

The polarisabilities can be defined in terms of the angular momentum and parity of the incident and scattered photon.

A photon with total angular momentum L, is said to be electric (EL) or magnetic (ML) if its parity satisfies:

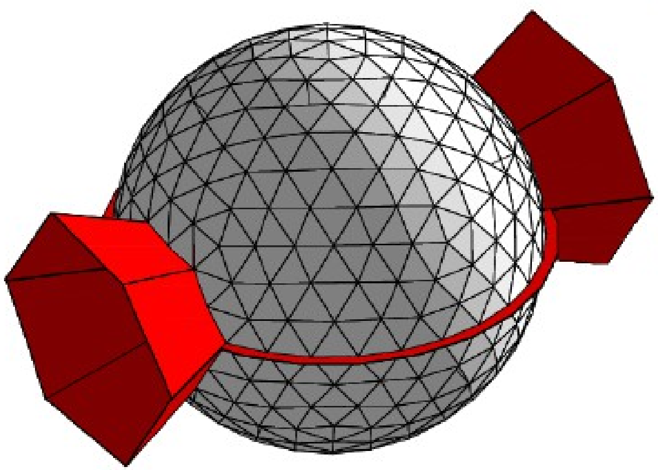
$$\pi_{EL} = (-1)^{L} \qquad \pi_{ML} = (-1)^{L+1}$$

The γ_{M1E2} polarisability, for example, can now be described in terms of the incoming and outgoing photon properties. In this case, the incoming and outgoing photons carry total angular momentum and parity given by 2^{+} and 1^{+} respectively.

Crystal Ball

The CB is a highly segmented NaI(TI) detector (composed of 672 individual crystals) which surrounds the MWPCs, PID and target.

- There are two gaps in the CB (beam entrance/exit) which results in an angular coverage for the CB system (CB, MWPCs, and PID) of $(\theta = 20^\circ \rightarrow 160^\circ)$ and $(\phi = 0^\circ \rightarrow 180^\circ)$



- The huge CB angular coverage is ideal for Compton scattering experiments to suppress the huge π^0 background!
- Excellent photon detection: $\sigma_E \approx 4\%$ $\quad \sigma_\theta \approx 2^\circ$ $\quad \sigma_\phi \approx \frac{2^\circ}{\sin\theta}$ (better than crystal size!).

Low Energy Expansion for parallel polarization:

$$\frac{d\sigma}{d\Omega}^{\parallel} = \frac{d\sigma}{d\Omega}^{\parallel}_{\text{Born}} - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\left(\alpha_{E1} z^2 + \beta_{M1} z\right) + O(\nu^3)$$

Low Energy Expansion for perpendicular polarization:

$$\frac{d\sigma}{d\Omega}^{\perp} = \frac{d\sigma}{d\Omega}^{\perp}_{\text{Born}} - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\left(\alpha_{E1} + \beta_{M1} z\right) + O(\nu^3)$$

Difference: dependent purely on α:

$$\frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega} = \left(\frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega}\right)_{\text{Born}} - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\alpha_{E1}(1 - z^2) + O(\nu^3)$$

Difference multiplied by $z^2 = \cos^2(\theta)$: dependent purely on β:

$$\frac{z^2 d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega} = \left(\frac{z^2 d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega}\right)_{\text{Born}} - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\beta_{M1} z(z^2 - 1) + O(\nu^3)$$

Low Energy Expansion: limited validity, dependence similar to ChPT

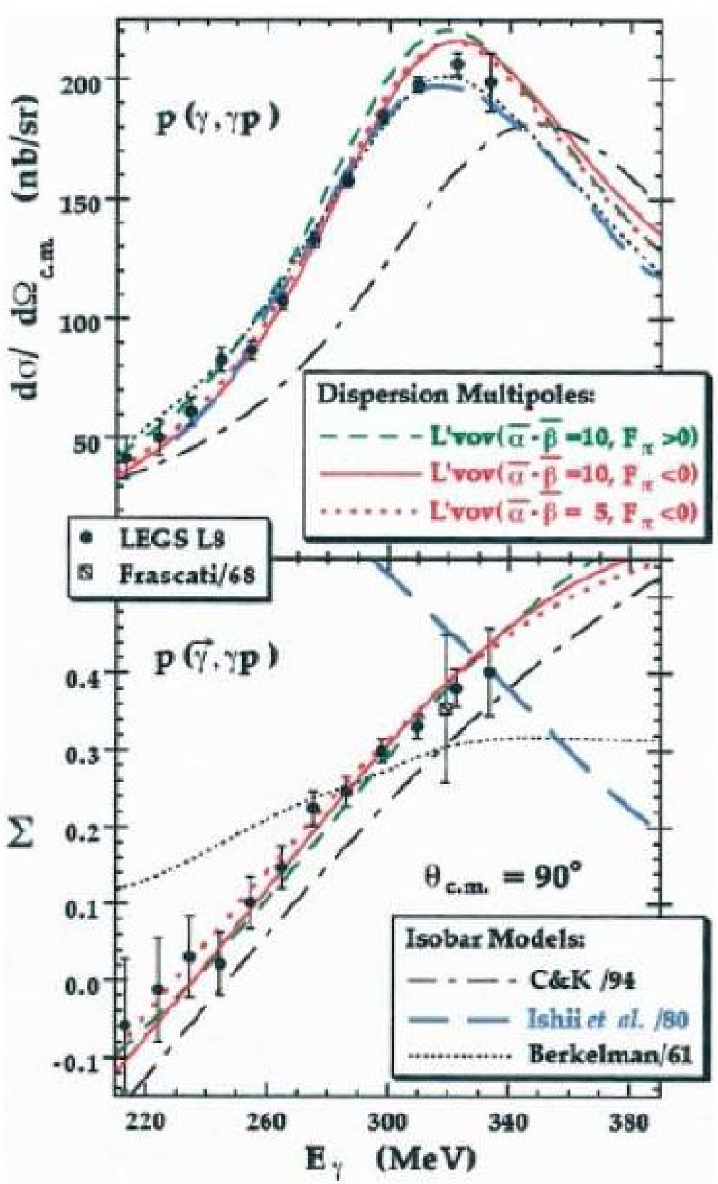
General information

Standard A2 Equipment is required:

- MAMI electrons
- Glasgow-Mainz Tagger
- CB-TAPS detector system
- Cryogenic Targets

Run Parameter	Σ_{2x}/Σ_{2z}	Σ_3 and α_{E1}, β_{M1}
Electron Beam Energy	450 MeV	883 MeV
Target	butanol	LH_2
Radiator	Copper	Diamond
Tagged Energy Range	100 – 400 MeV	100 – 400 MeV
Channel Energy Resolution	1 MeV	2 MeV
Beam Polarization	circular	linear
Target Polarization	transverse/longitudinal	none

Beam asymmetry Σ_3 : existing data

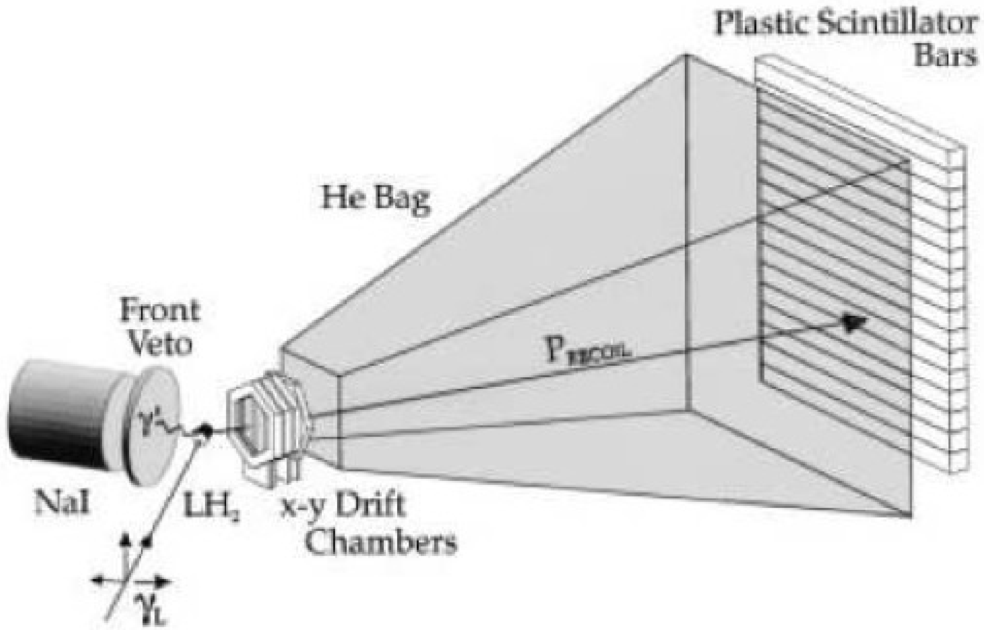


LEGS $\vec{\gamma} p \to \gamma p$

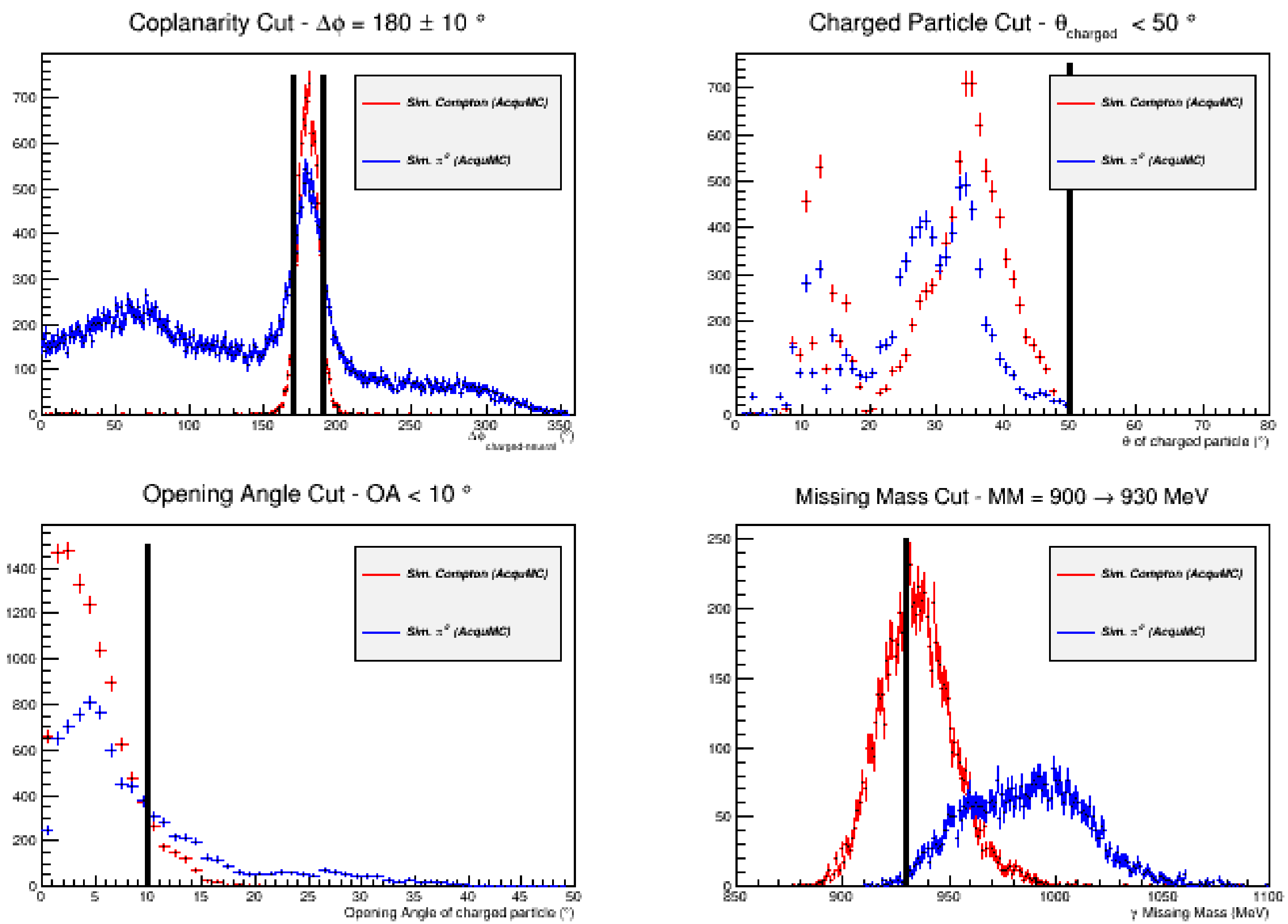
$d\sigma / d\Omega$ and Σ_3

$E_\gamma = 200 - 350\,\mathrm{MeV}$

$\theta_{\gamma'} = 90°$ ONLY!

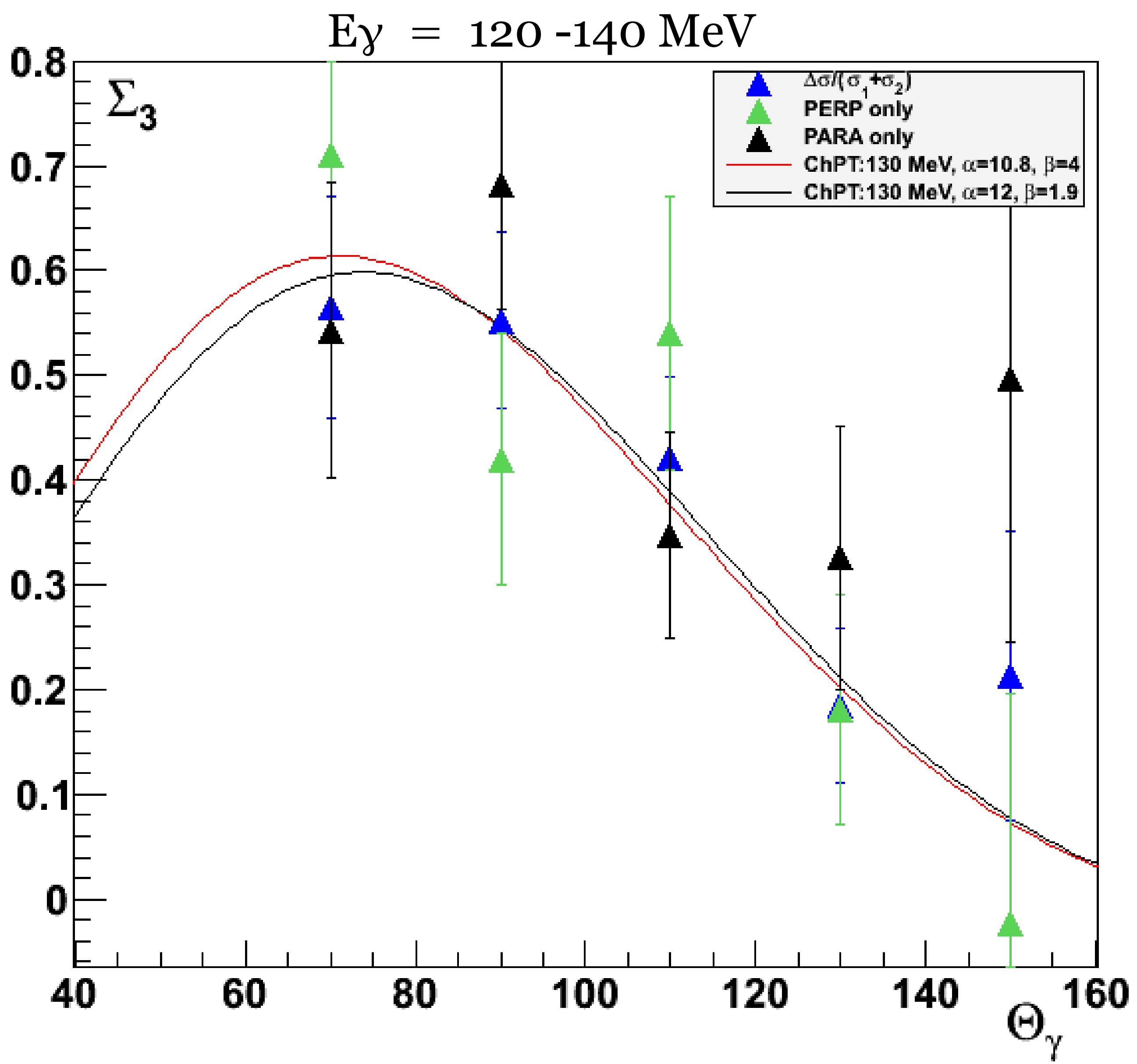


Beam asymmetry Σ_3 at higher energies



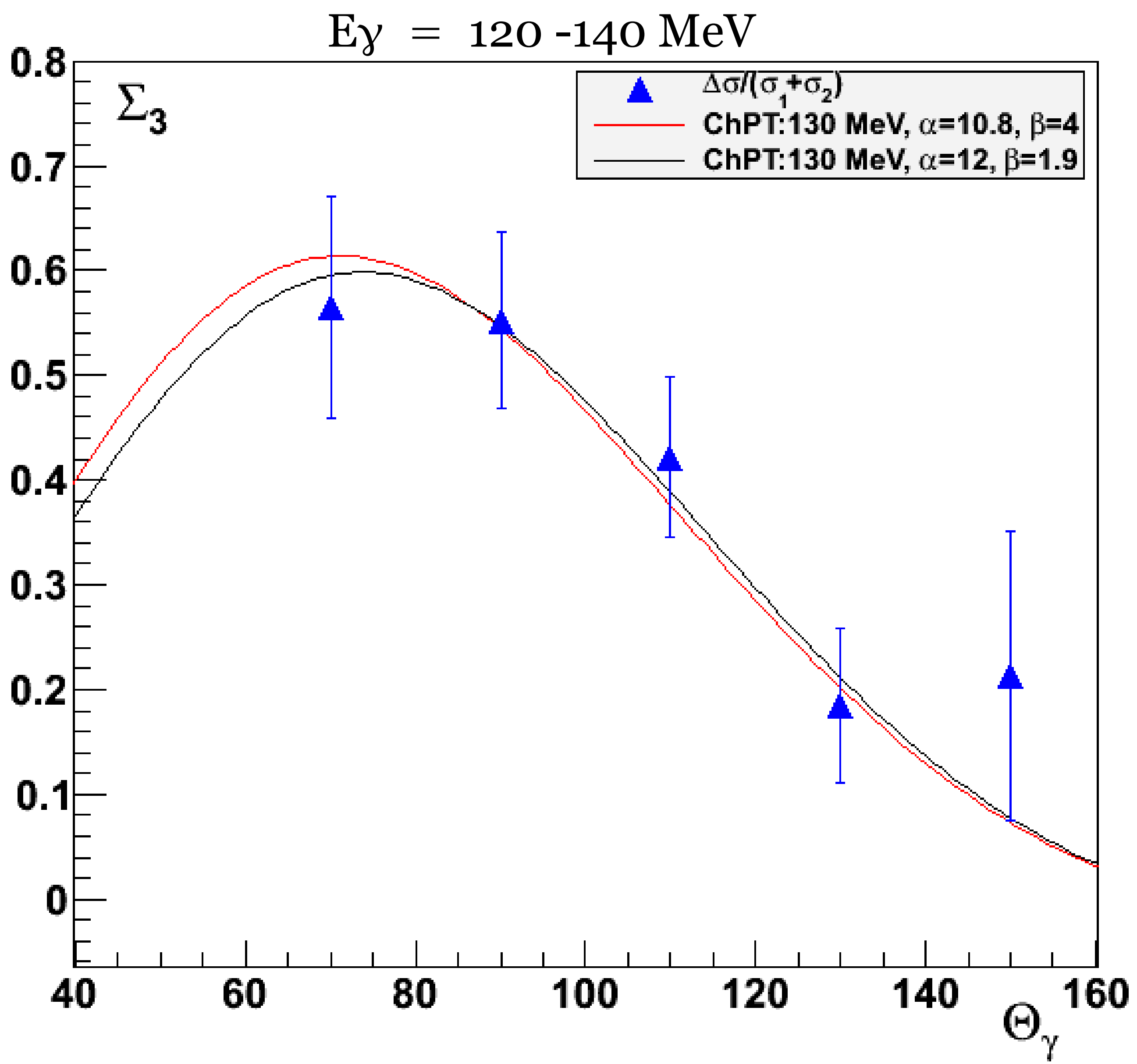
C. Collicott (Mainz, DAL, SMU)

Beam asymmetry Σ_3 : systematic cross-checks



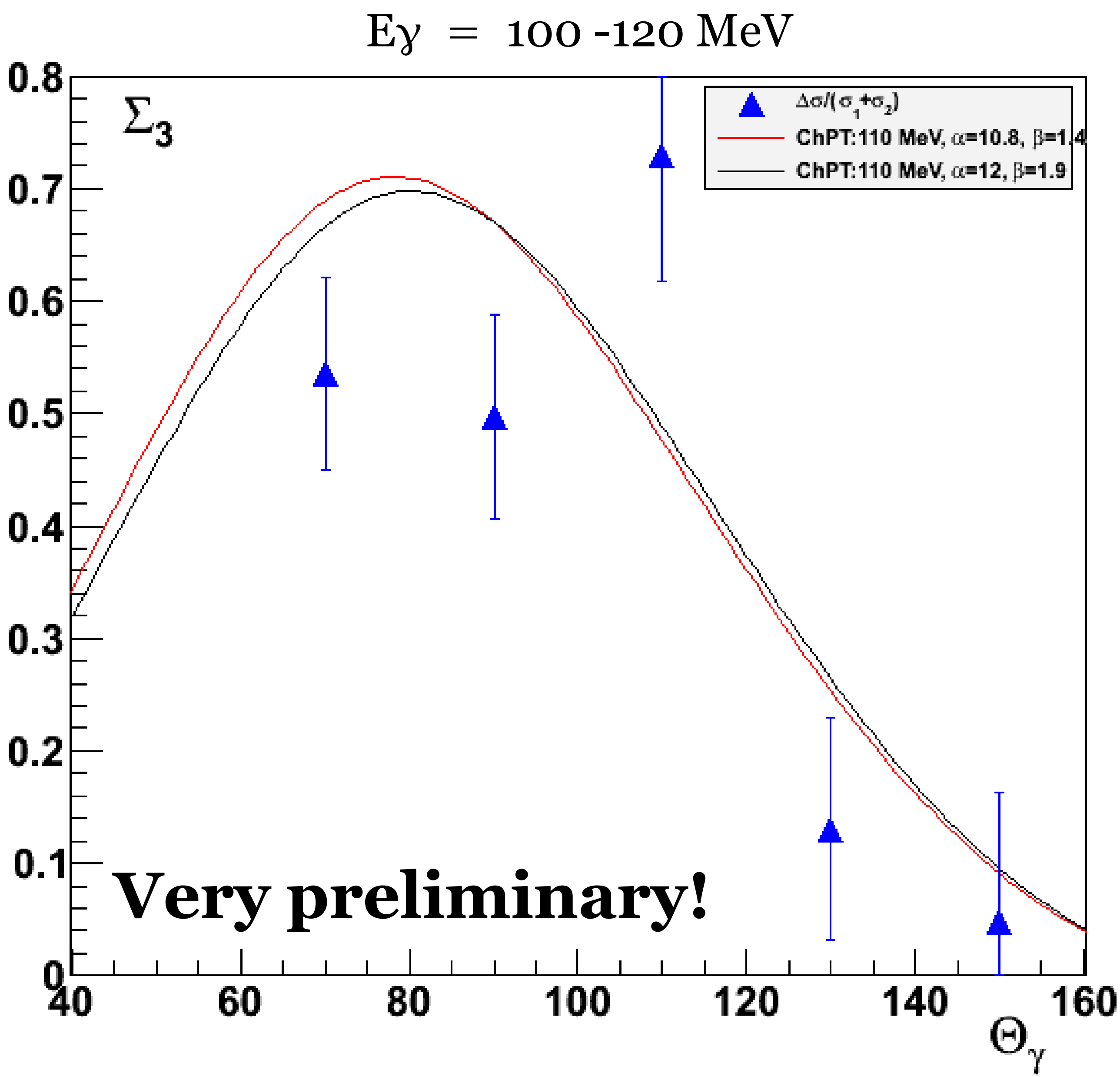
Very Preliminary

Beam asymmetry Σ_3 : Preliminary results

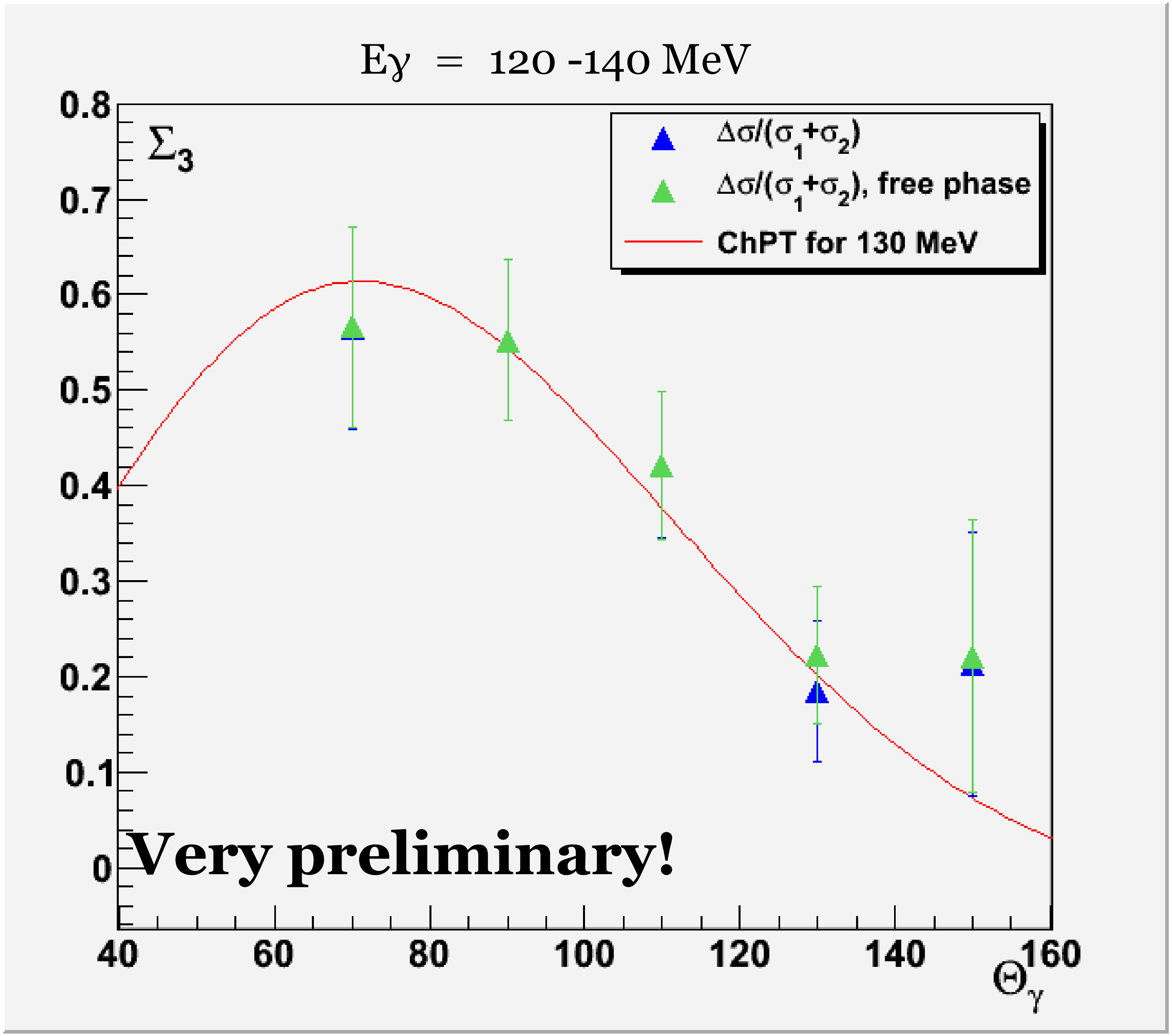


Very Preliminary

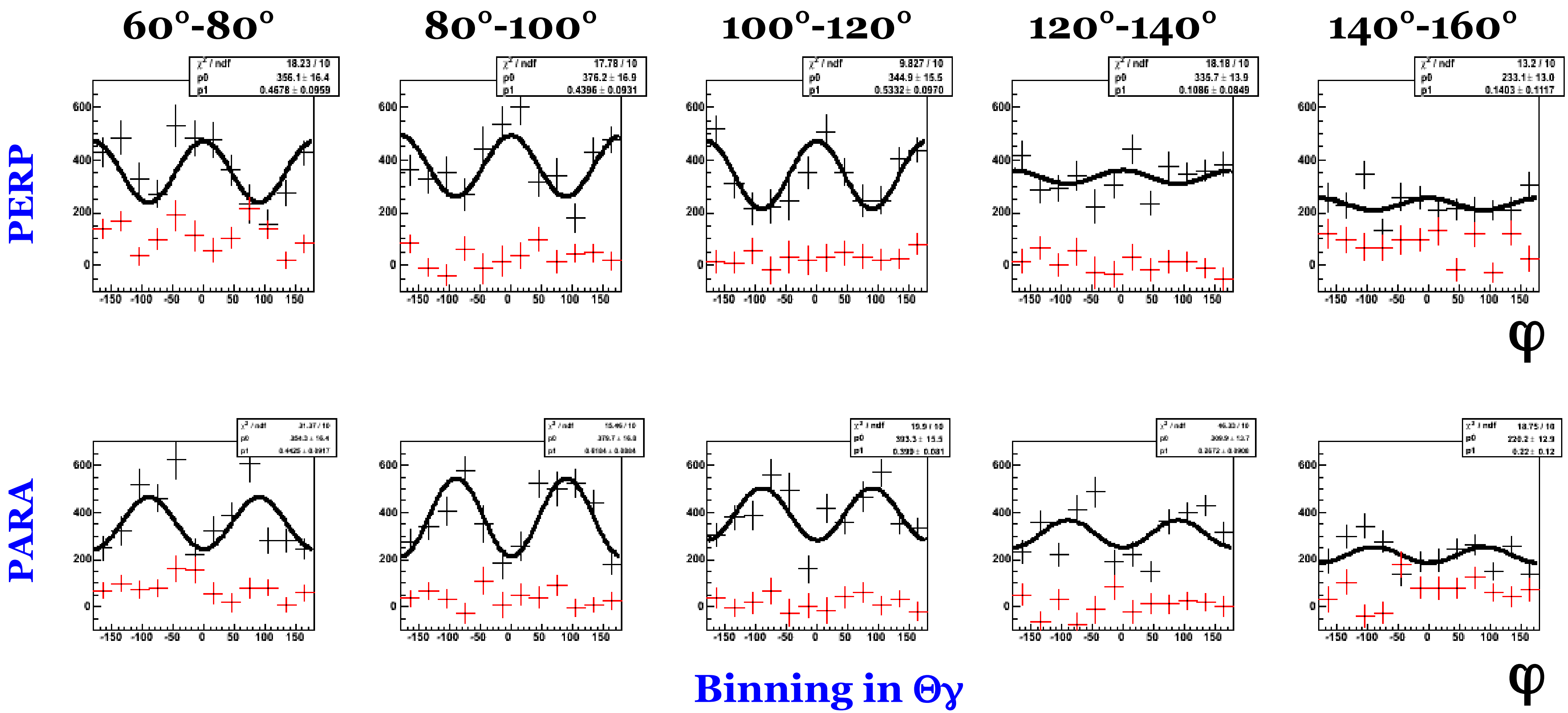
Beam asymmetry Σ_3 : Preliminary results



Beam asymmetry Σ_3 : Preliminary results



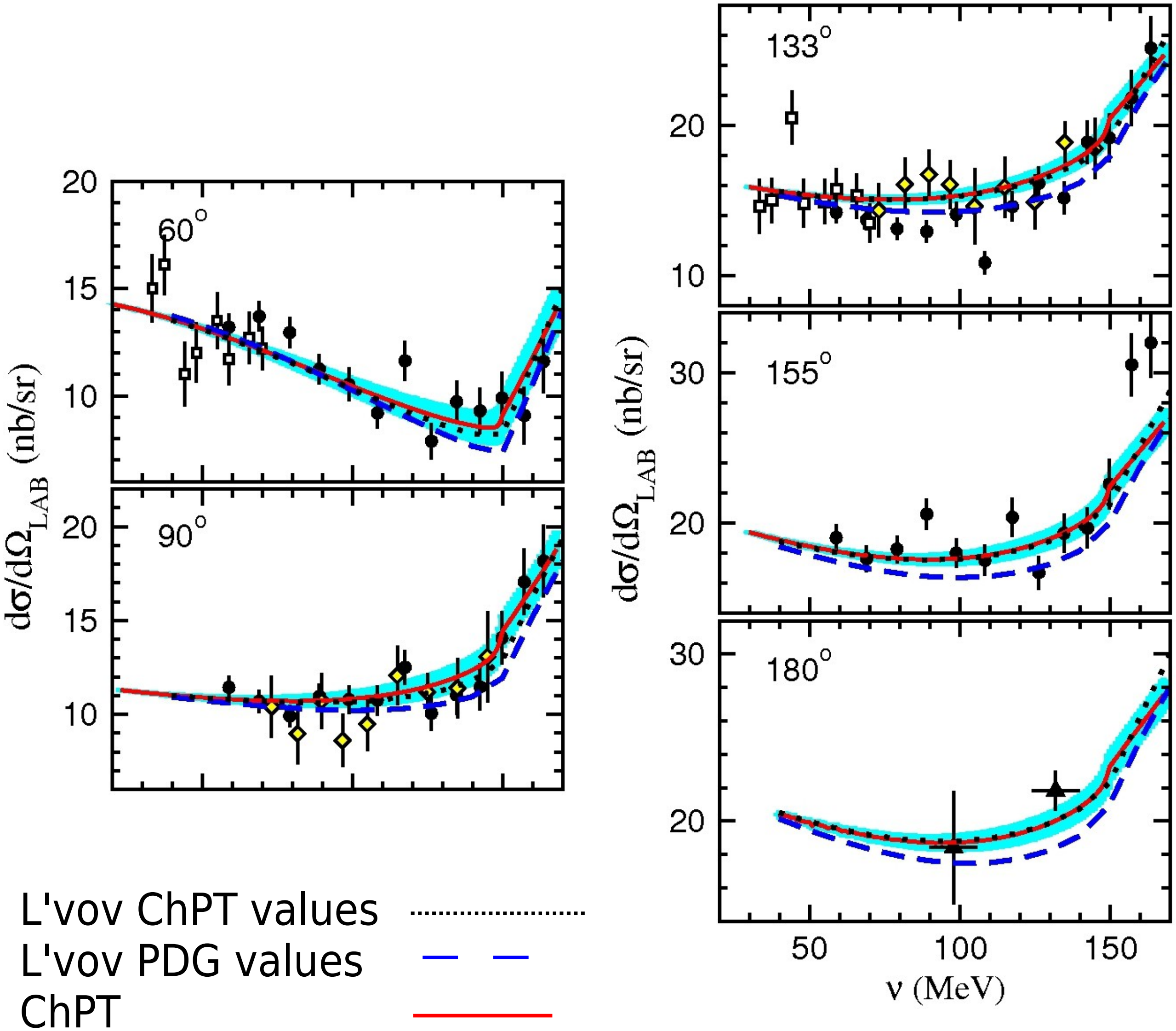
φ – full and empty target contributions



Preliminary

Existing data and model predictions

Agreement between Pascalutsa (ChPT) and L'vov (Dispersion Relations)



Squares: Illinois,

F. J. Federspeil et al. Phys. Rev. Lett. **67** 1511 (1991)

Triangles: MAMI,

A. Zieger et al. Phys. Lett. B **278** 34 (1992)

Diamonds: SAL,

E. L. Hallin et al. Phys. Rev. C **48** 1497 (1993)

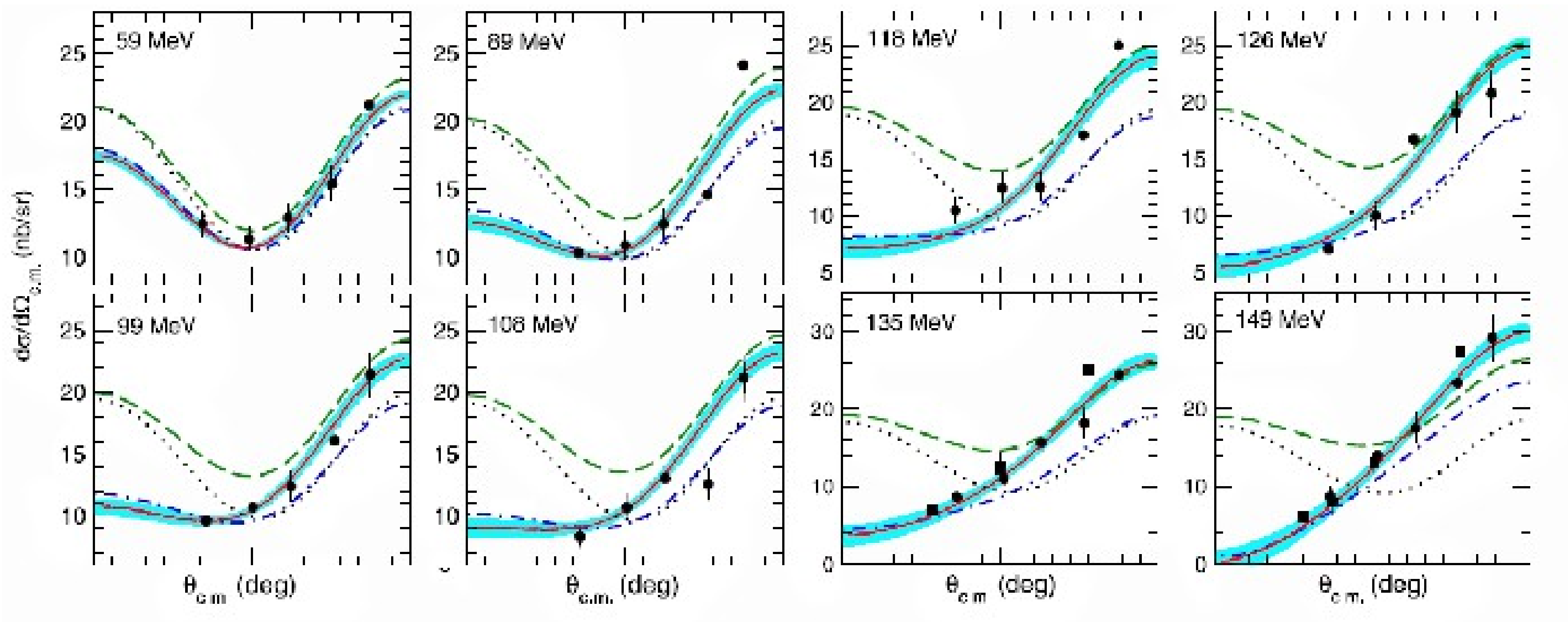
Circles: MAMI,

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

Dotted curves etc. different parts of calc.

Solid curve with error band, final calc

Existing data and model predictions



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

Squares: SAL, E. L. Hallin et al. Phys. Rev. C **48** 1497 (1993)

The curves are: Klein–Nishina (i.e, Compton scattering off a classical pointlike particle with the charge and mass of the proton) — dotted, Born graphs and Wess-Zumino-Witten (WZW)-anomaly — green dashed, adding the p3 πN loop contributions of BPT— blue dash-dotted. The result of adding the contributions, i.e., the complete NNLO result, is shown by the red solid line with band

Measurement of α and β

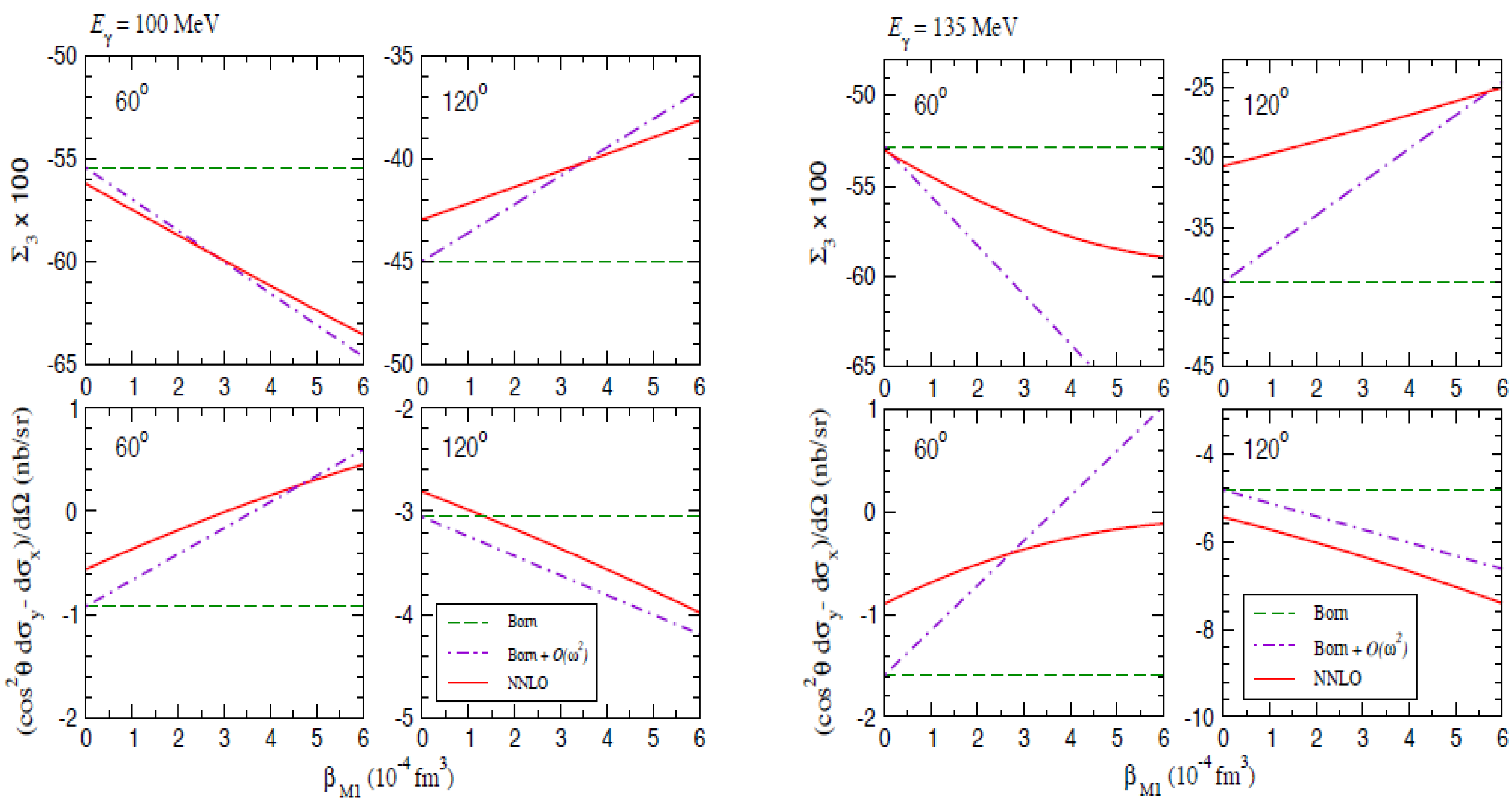
$$\Sigma_3 = \Sigma_3^{(B)} - \frac{4M\omega^2 \cos\theta \sin^2\theta}{\alpha_{em}(1+\cos^2\theta)^2} \beta_{M1} + O(\omega^4), \quad (6)$$

where $\Sigma_3^{(B)}$ is the pure Born contribution, while

$$\omega = \frac{s - M^2 + \frac{1}{2}t}{\sqrt{4M^2 - t}}, \quad \theta = \arccos\left(1 + \frac{t}{2\omega^2}\right) \quad (7)$$

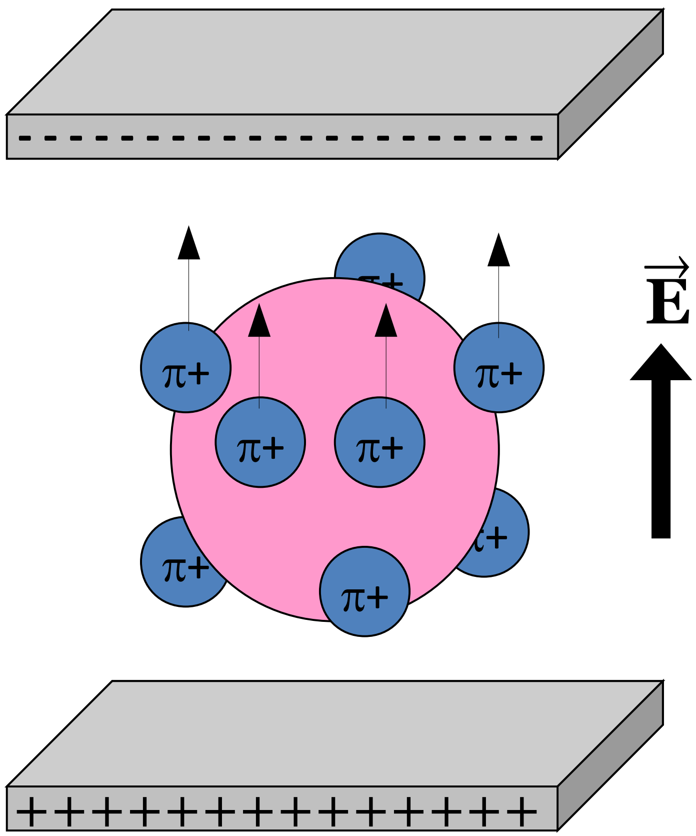
are the photon energy and scattering angle in the Breit (brick-wall) reference frame. In fact, to this order in the LEX the formula is valid for ω and θ being the energy and angle in the lab or center-of-mass frame.

Measurement of α and β

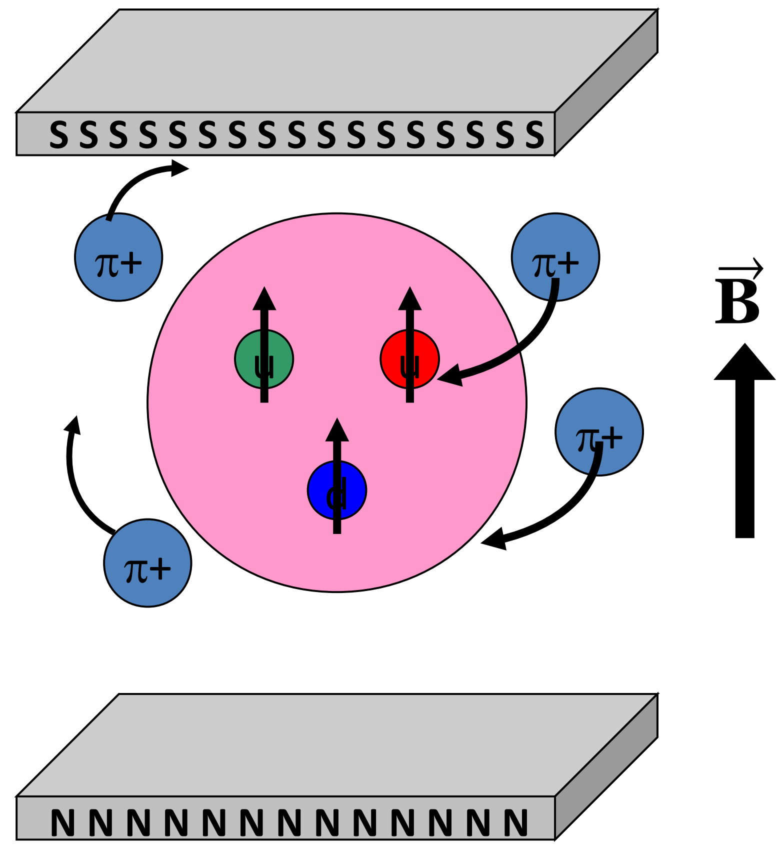


Scalar polarizabilities

Proton Electric Polarizability



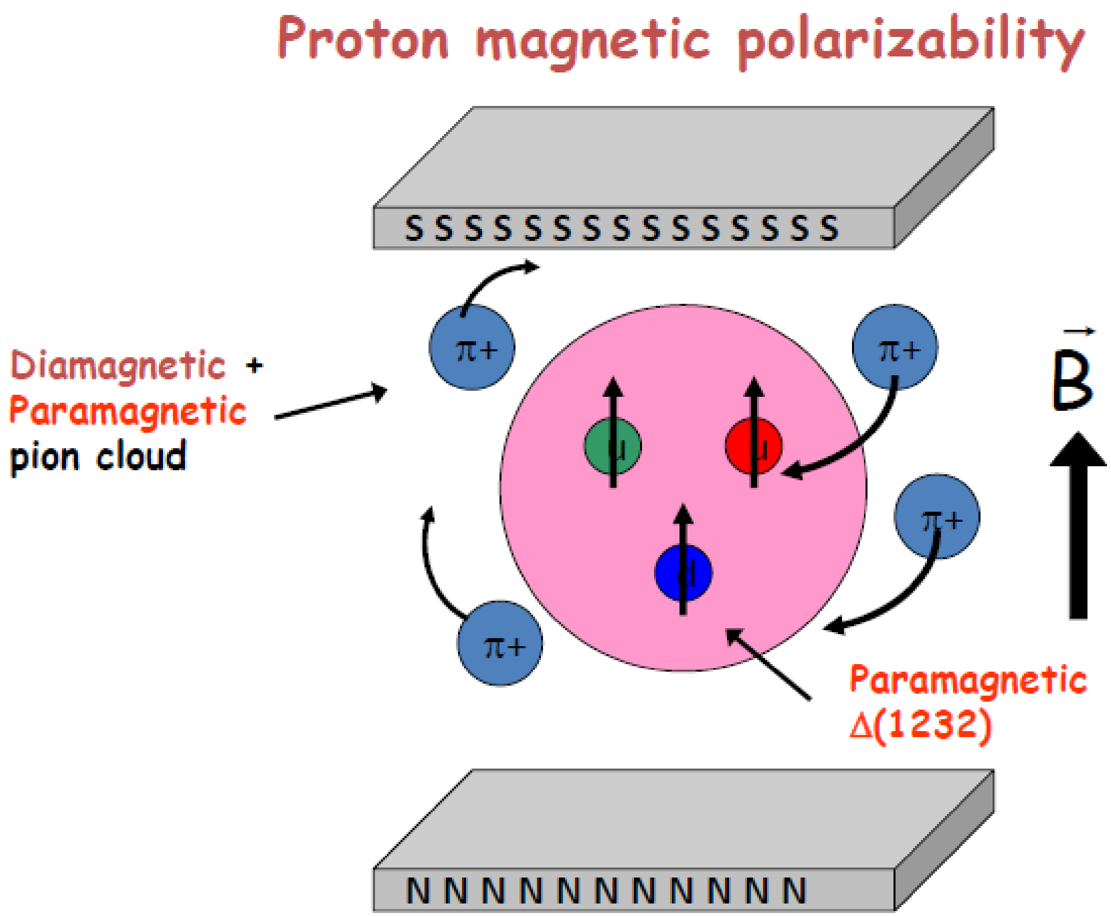
Proton Magnetic Polarizability



- α: electric polarizabilty
- Proton between charged parallel plates: "stretchability"

- β: magnetic polarizability
- Proton between poles of a magnet: "alignability"

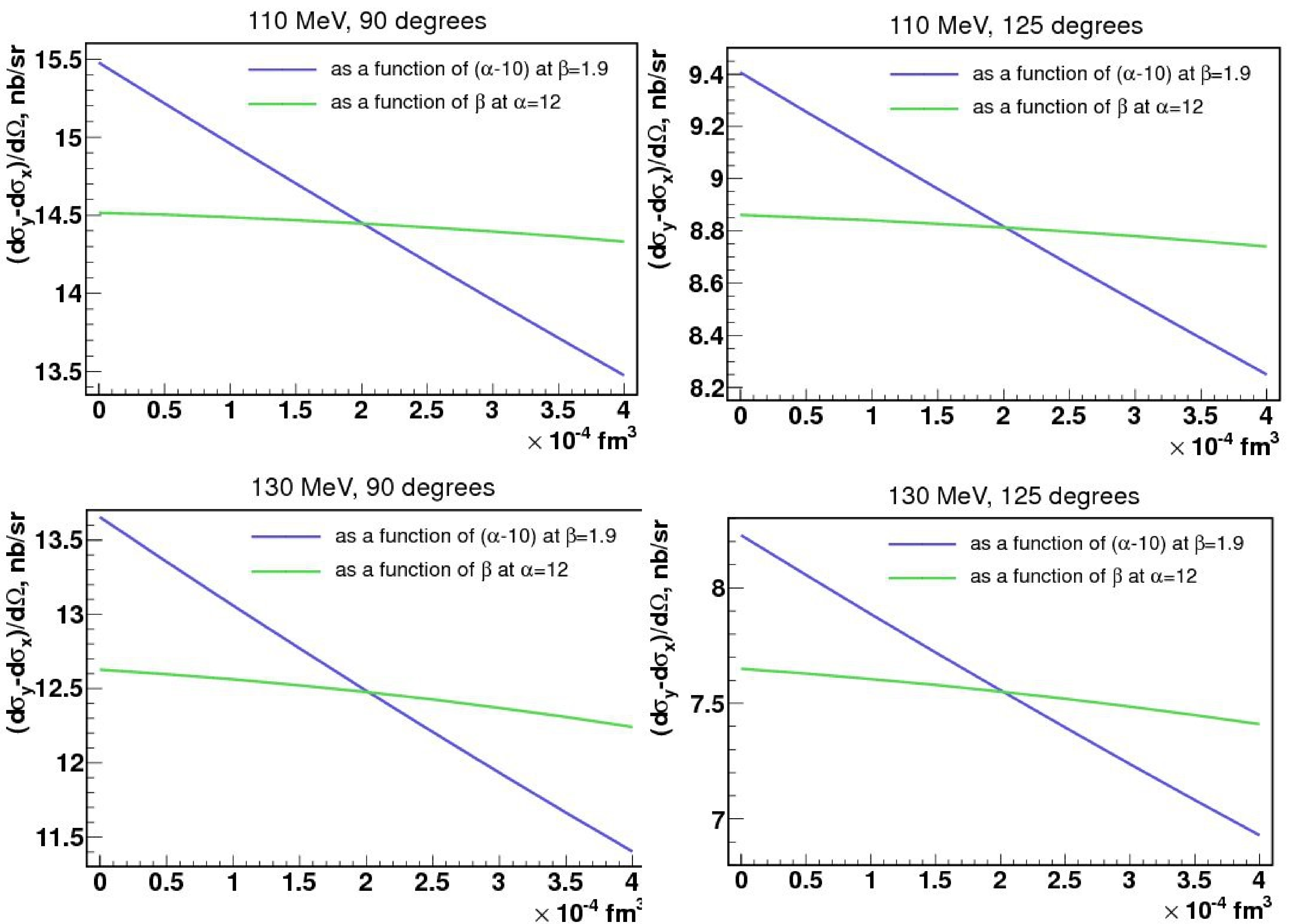
First look in December 2012 data



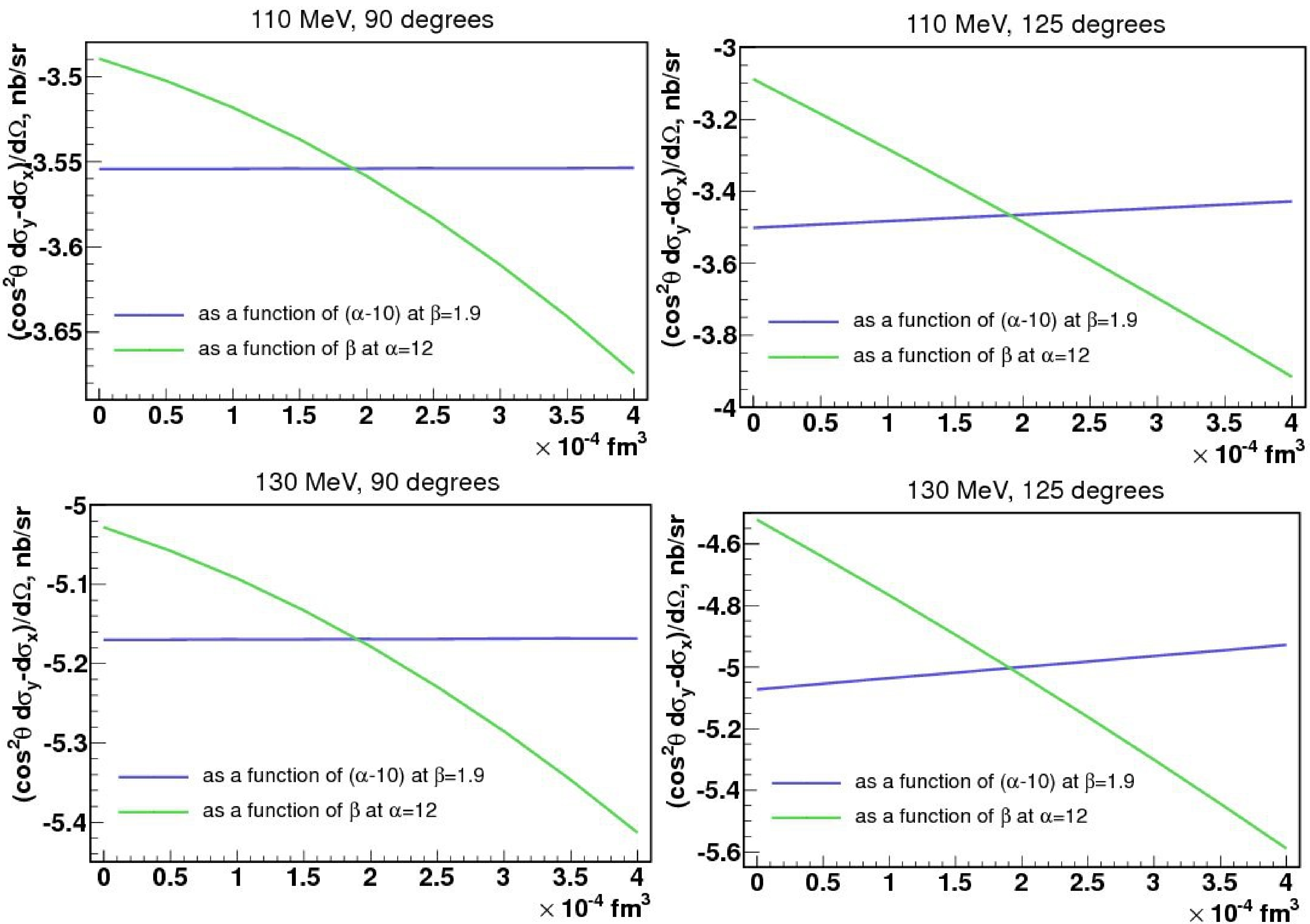
Magnetic polarizability: proton between poles of a magnetic

Rory Miskimen (Bosen 2009)

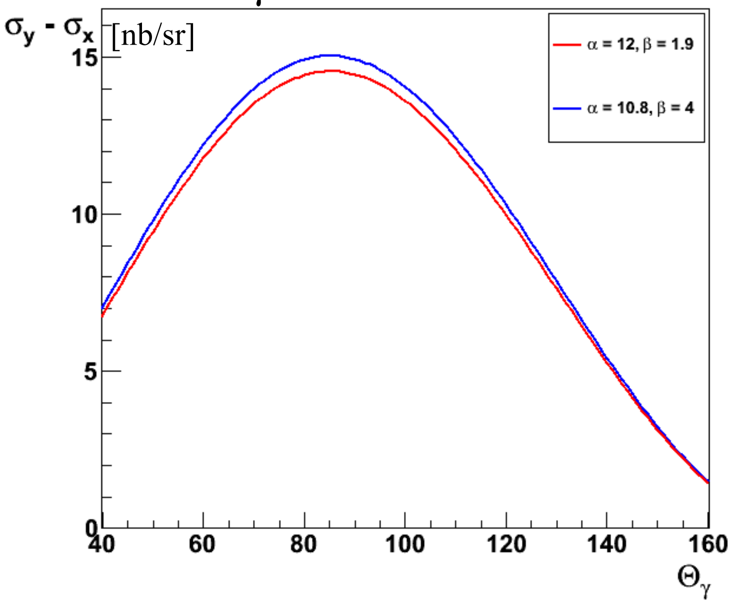
Sensitivity to α



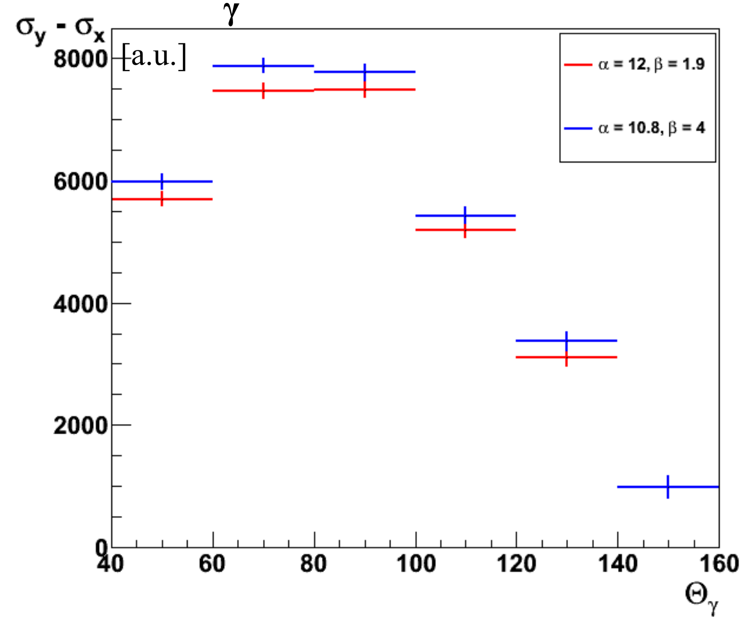
Sensitivity to β



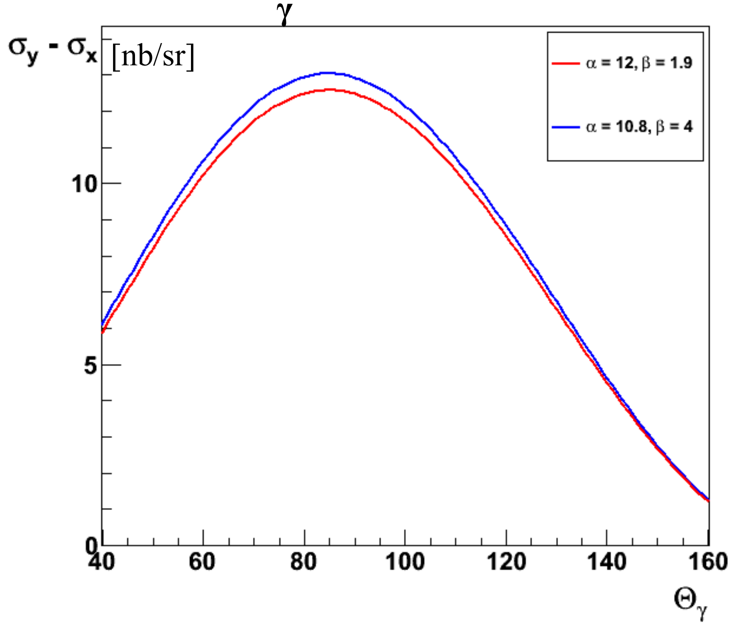
$E_\gamma = 110$ MeV



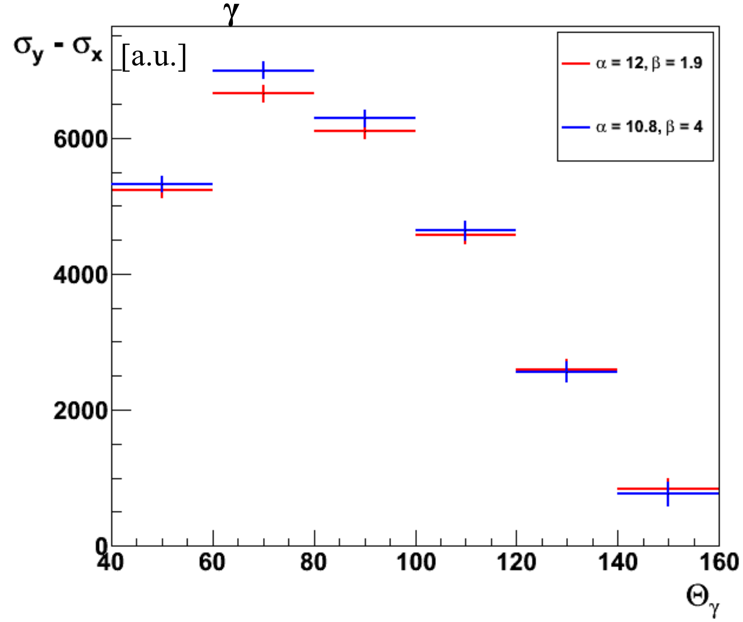
$E_\gamma = 105 – 115$ MeV

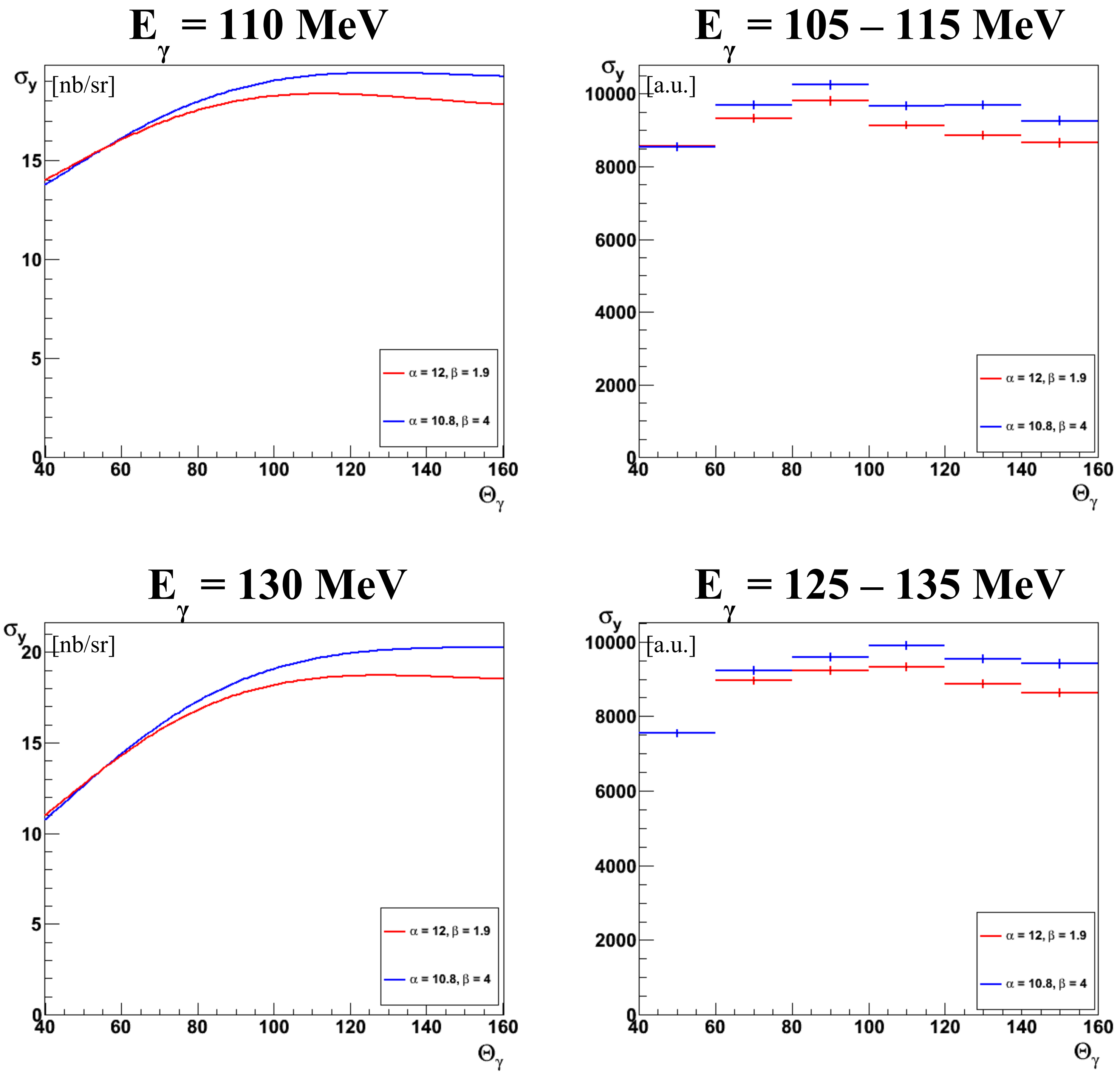


$E_\gamma = 130$ MeV



$E_\gamma = 125 – 135$ MeV




E γ = 110 MeV
σy [nb/sr]
Θγ
α = 12, β = 1.9
α = 10.8, β = 4
E γ = 105 – 115 MeV
σy [a.u.]
Θγ
α = 12, β = 1.9
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E γ = 130 MeV
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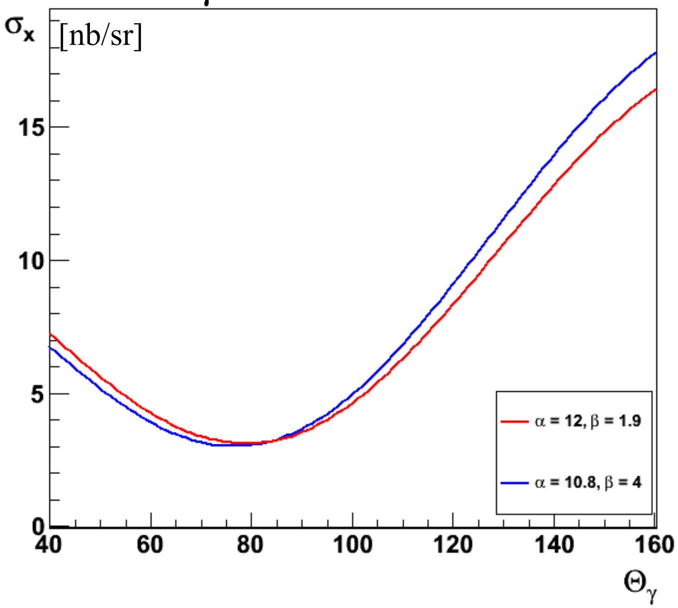
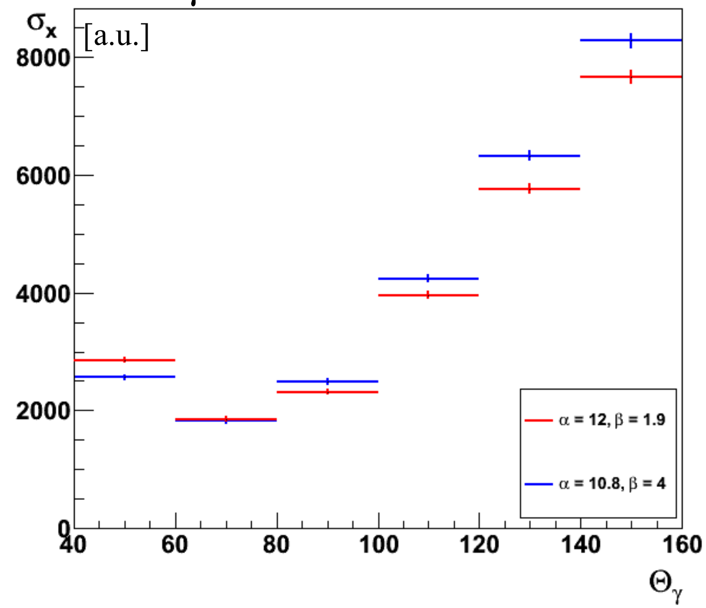
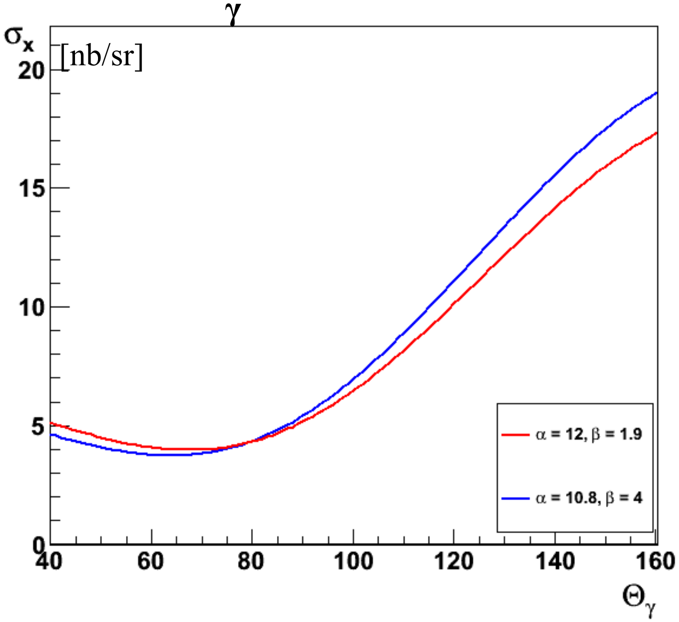
E_γ = 110 MeV



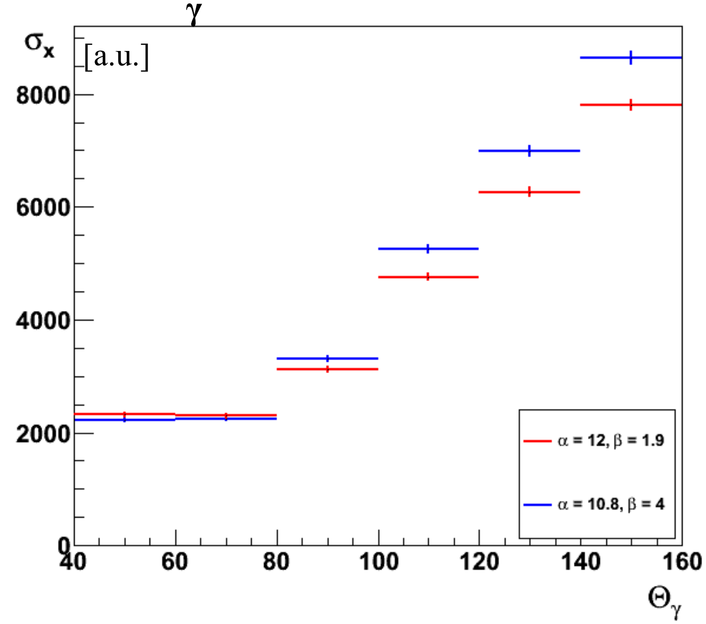
E_γ = 105 – 115 MeV



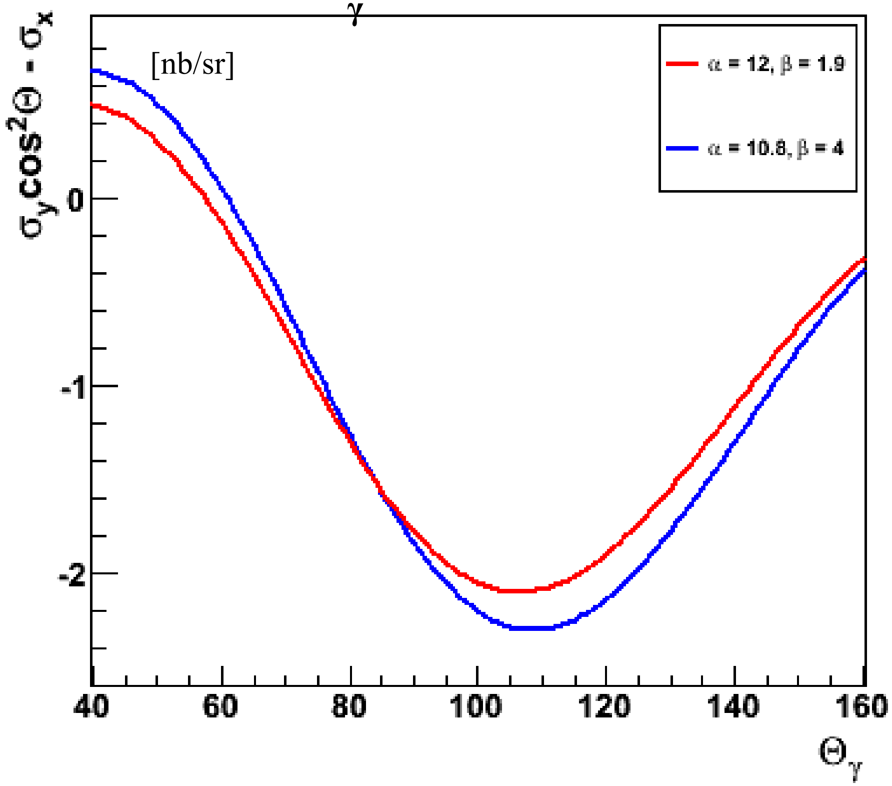
E_γ = 130 MeV



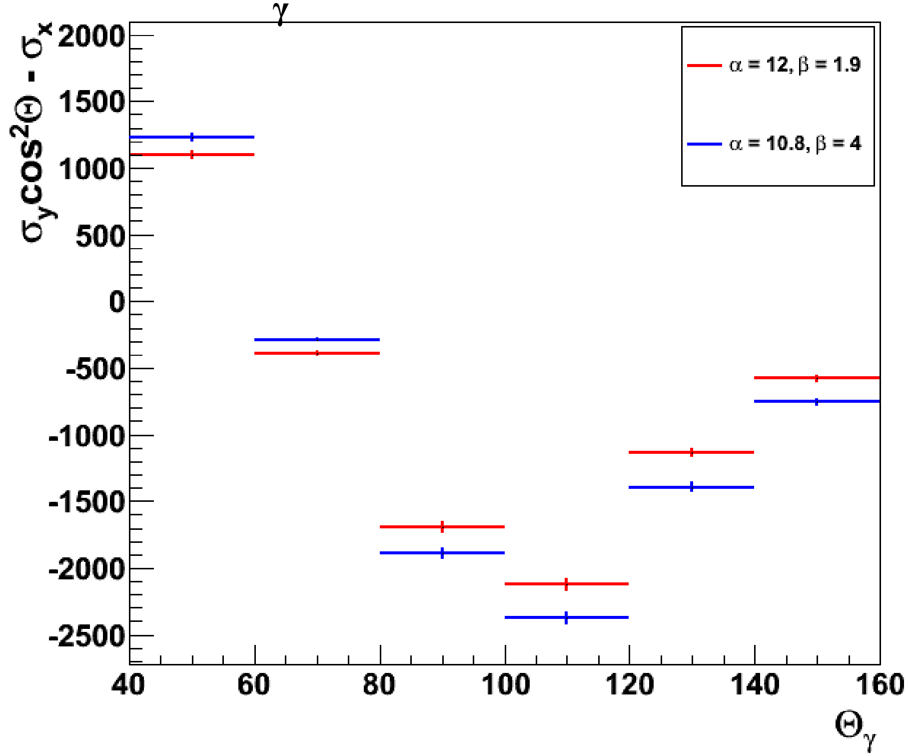
E_γ = 125 – 135 MeV



$E_\gamma = 110$ MeV



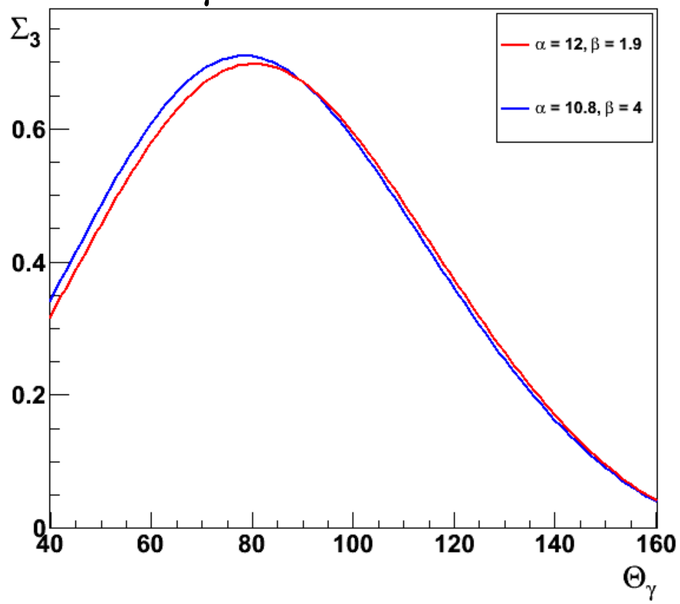
$E_\gamma = 105 – 115$ MeV



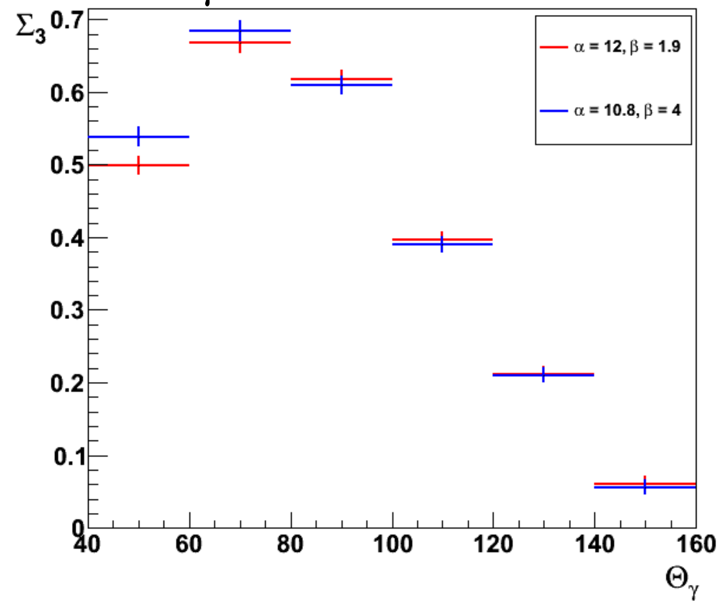
New data will allow to distinguish between different predictions!

- Independent measurement of α and β
- First measurement of α and β using polarization observables

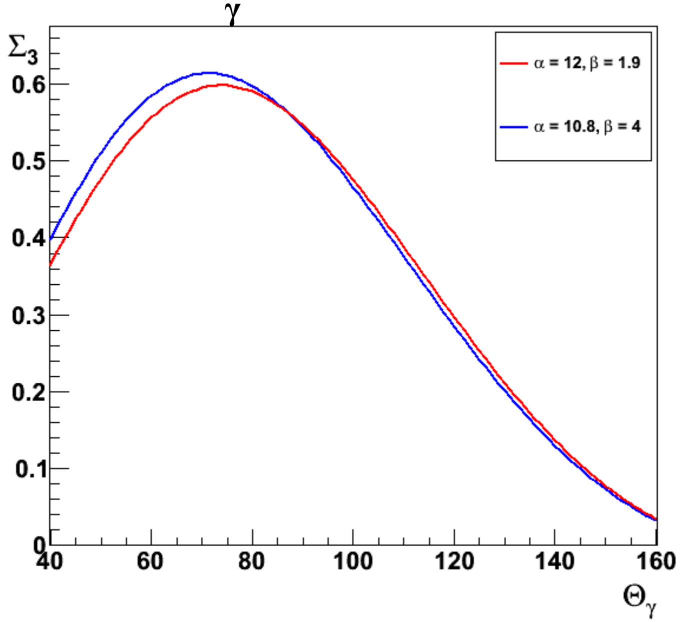
$E_\gamma = 110$ MeV



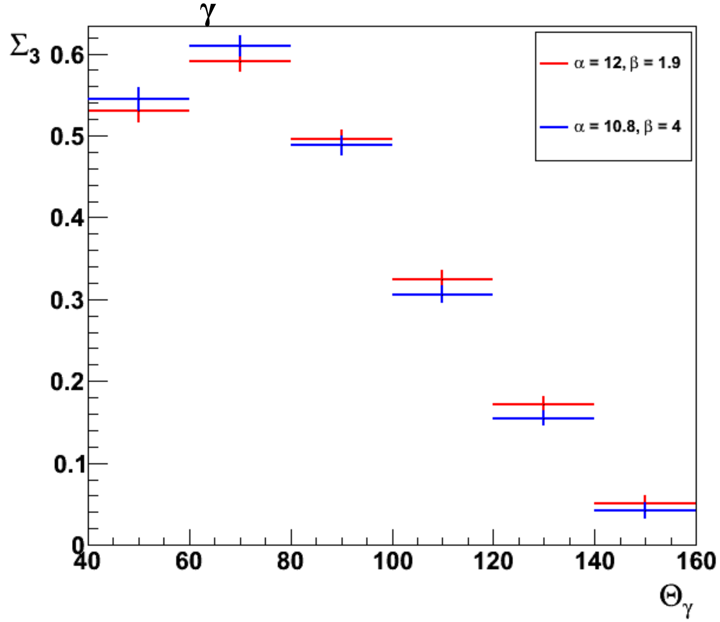
$E_\gamma = 105 – 115$ MeV



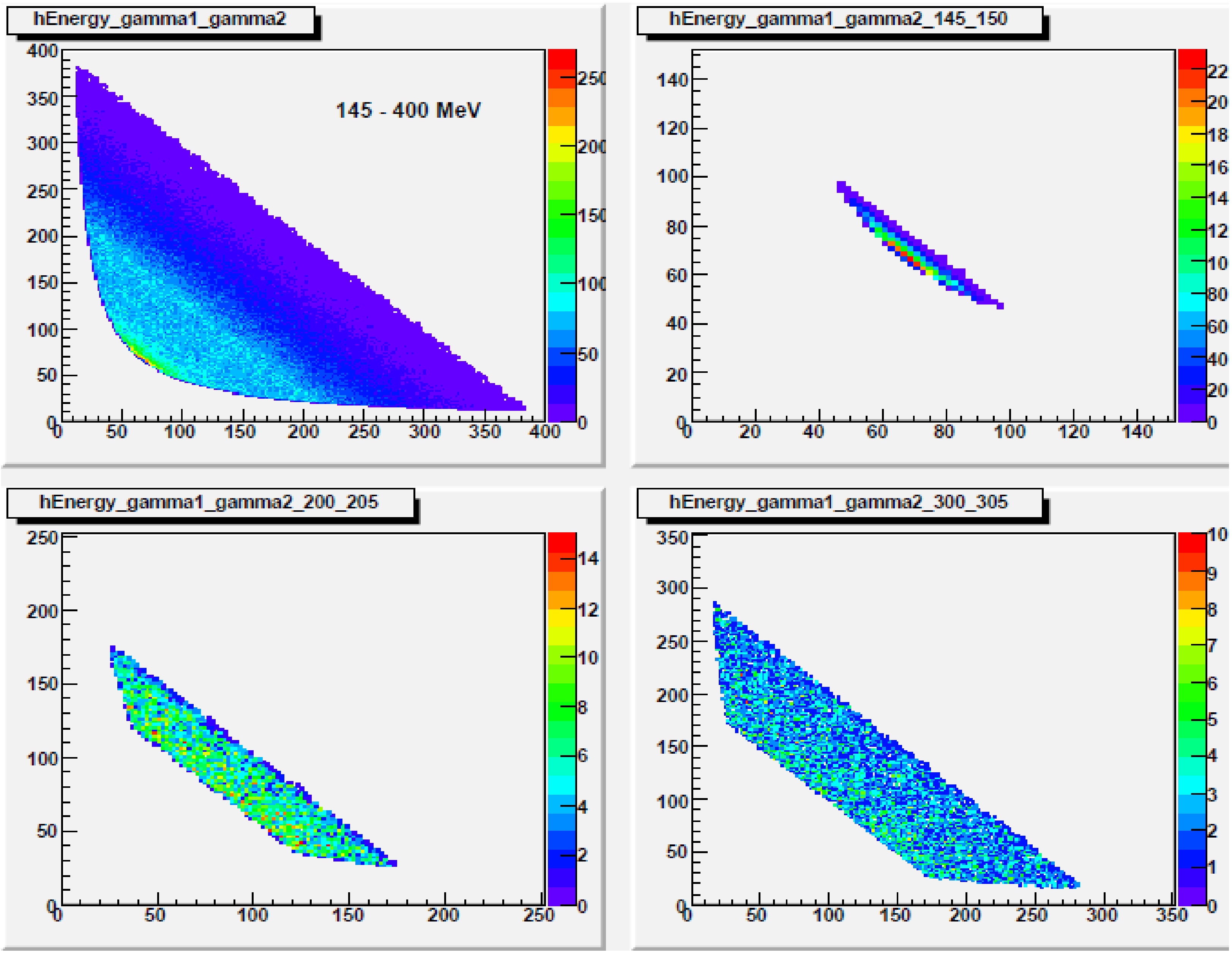
$E_\gamma = 130$ MeV



$E_\gamma = 125 – 135$ MeV



Kinematics


hEnergy_gamma1_gamma2
145 - 400 MeV
hEnergy_gamma1_gamma2_145_150
hEnergy_gamma1_gamma2_200_205
hEnergy_gamma1_gamma2_300_305