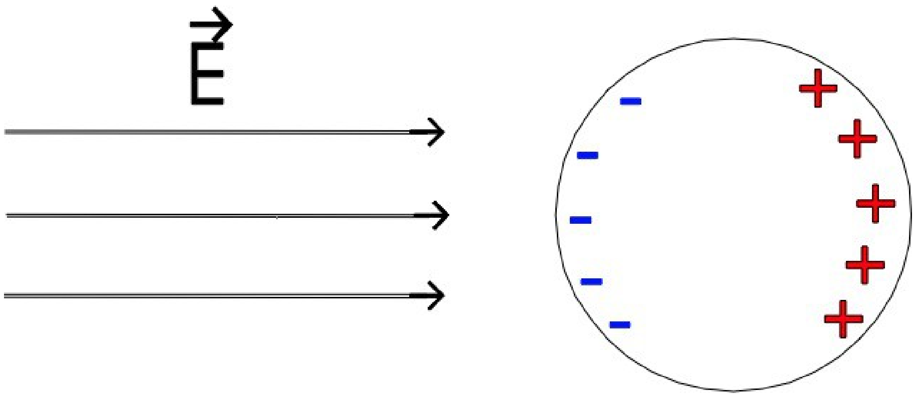
Measurement of the Proton Scalar Polarizabilities via Compton Scattering

E. J. Downie, D. Hornidge,
P. Martel, V. Sokhoyan

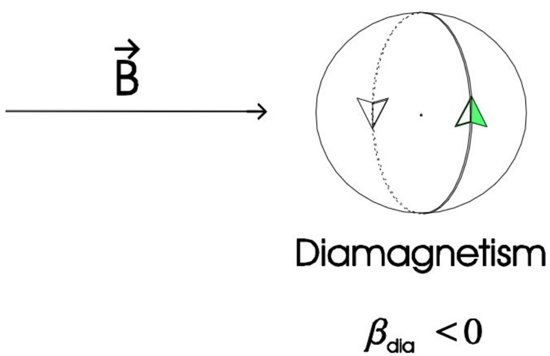
Scalar polarizabilities

Proton Electric Polarizability

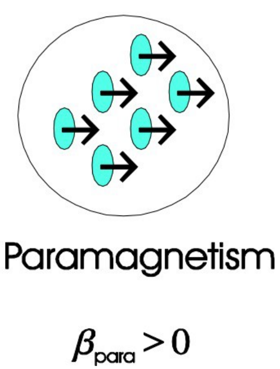


- α_{E1}: electric polarizability
- Proton between charged parallel plates: "stretchability"

Proton Magnetic Polarizability



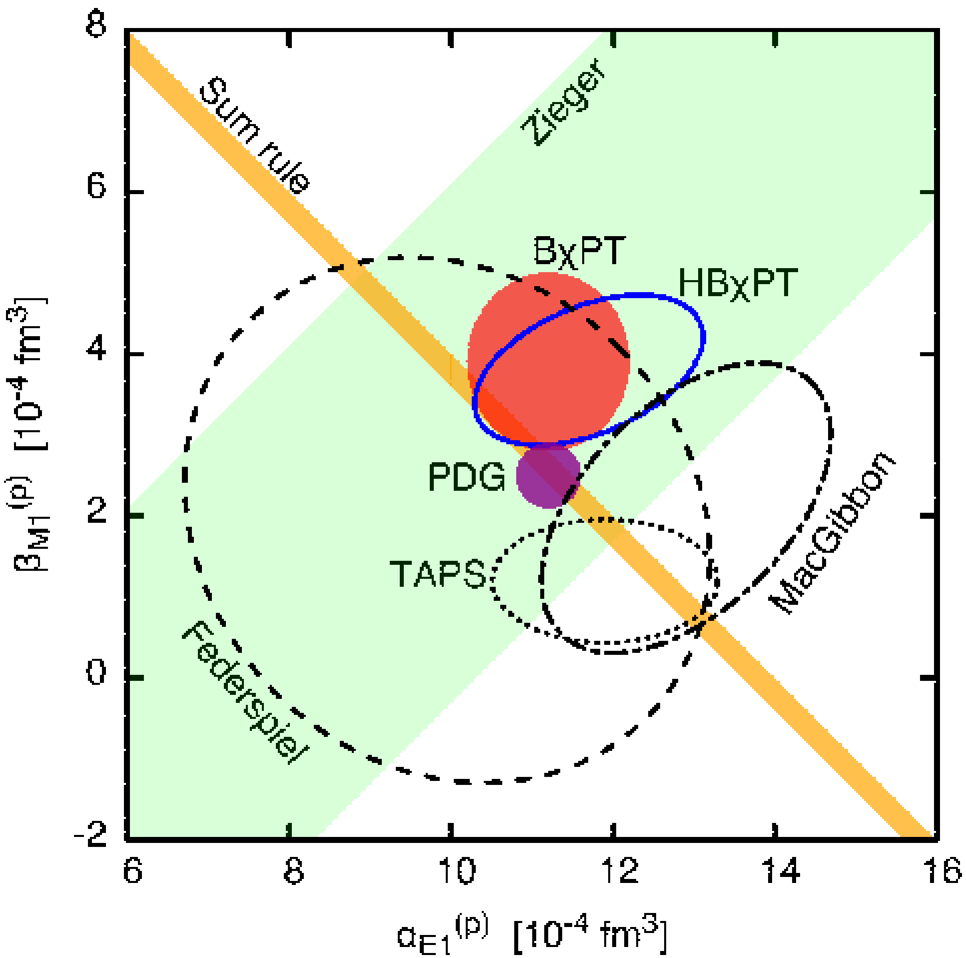
or



- 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 (e.g. for proton radius puzzle)

Existing data and model predictions



PDG (2012) values:

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

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

New (2014-2016) PDG values:

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

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

- Significant change between reviews without introducing new experimental data?
- Global database not entirely consistent

Goal: high-precision measurement of the scalar polarizabilities of the proton

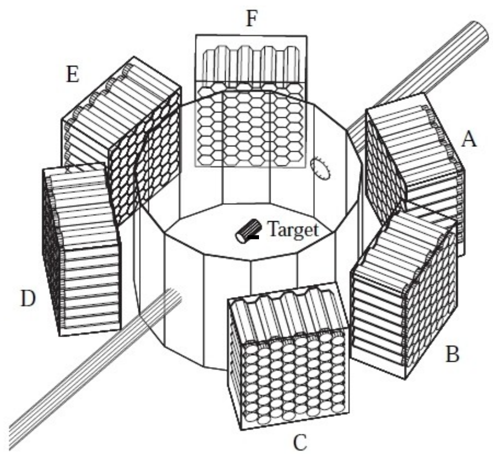
- New high-precision unpolarized cross-sections
- New high-quality data on the beam asymmetry Σ_3
- New single data set with small statistical and systematic errors

Compton scattering on the proton: Existing data

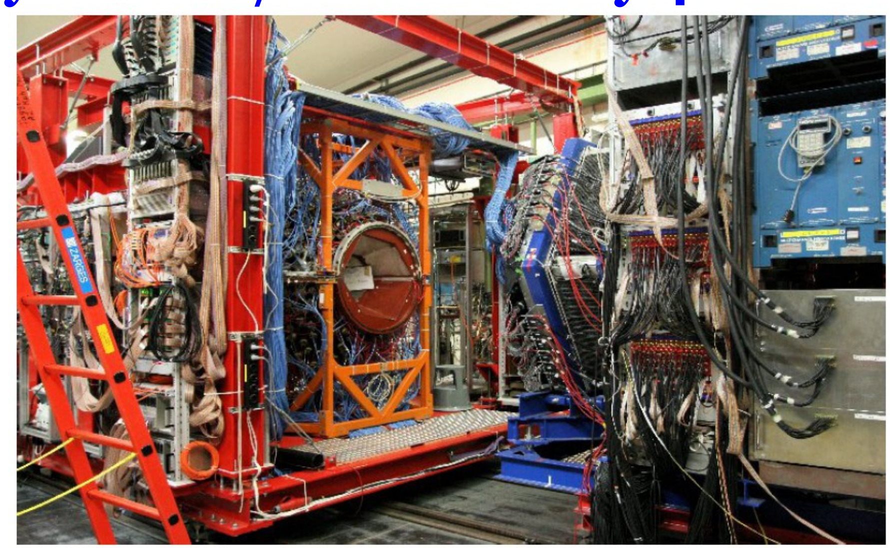
- Highest statistics data set:

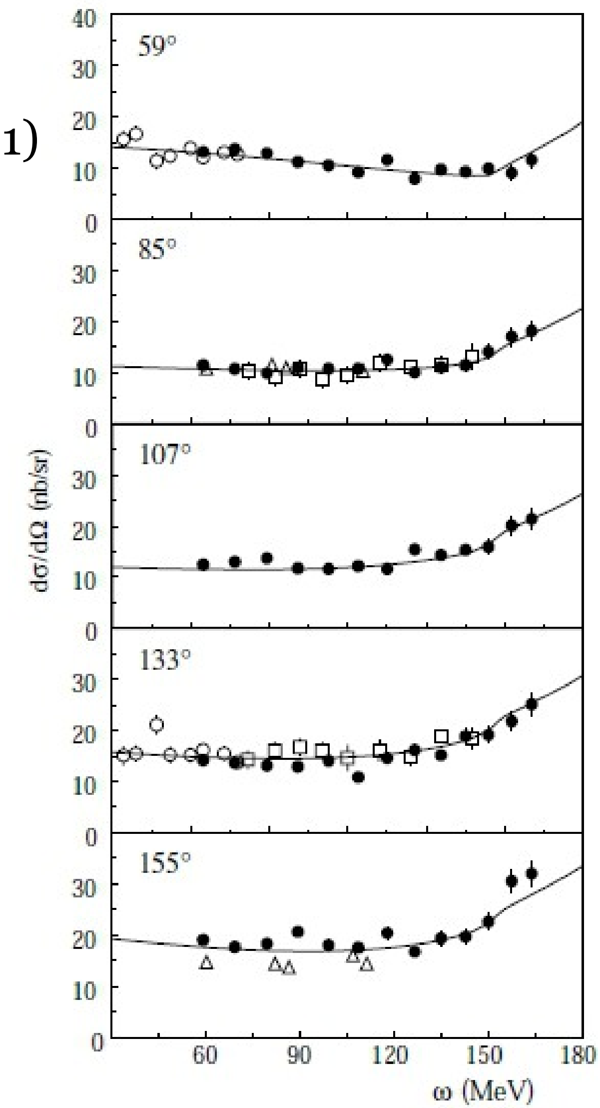
V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001)

- 1/3 acceptance of CB System!



Crystal Ball/TAPS: Nearly 4π coverage





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)

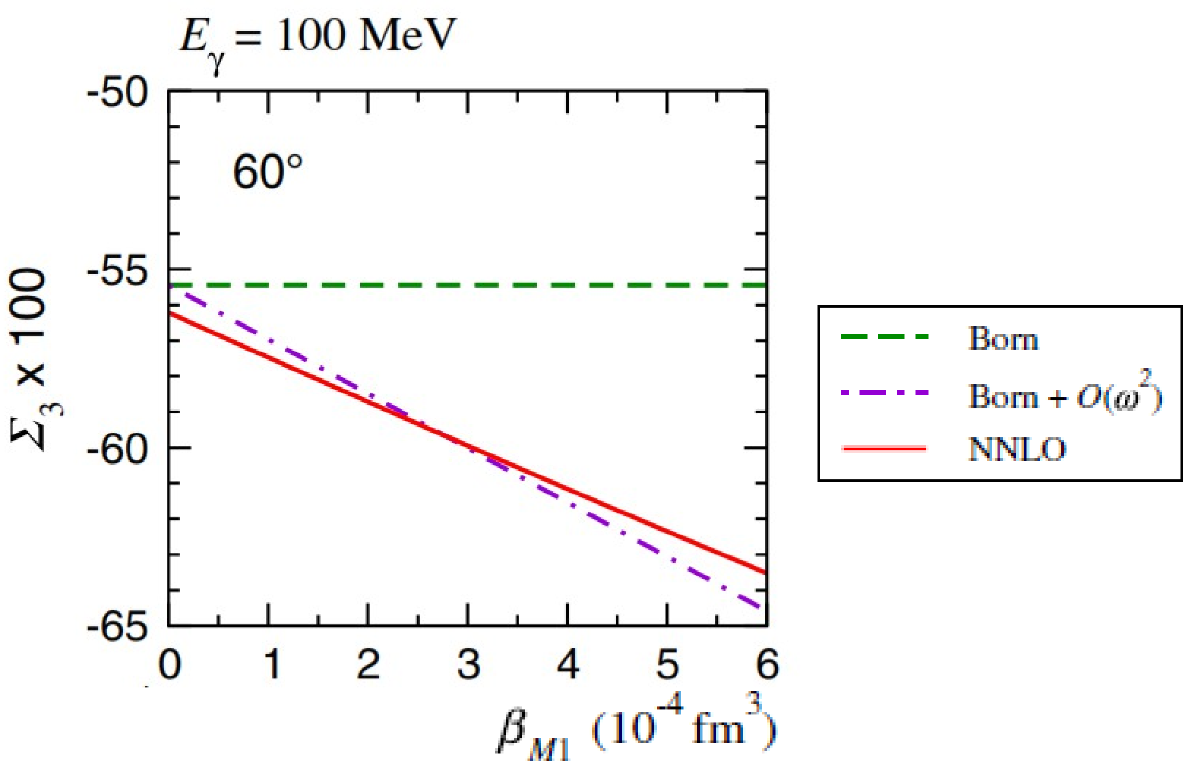
Beam asymmetry

At low energies, the measurement of the beam asymmetry, Σ_3 is an alternative way to extract β_{M1} (N. Krupina and V. Pascalutsa [PRL 110, 262001 (2013)])

- Measurements with linearly polarized photons and liquid hydrogen target

$$\boxed{\Sigma_3 \equiv \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp}}$$

$$\boxed{\sigma_{pol} = \sigma_{unpol}(1 \pm \delta_l\, \Sigma_3 \cos 2\phi)}$$



Pilot experiment at MAMI

750 hours recommended by the PAC 2012
(E. J. Downie et al., MAMI-A2/06-2012)

- Experiment performed in June 2013
- E_{beam} = 883 MeV
- Radiators: Diamond, Copper
- 10 cm liquid hydrogen target
- Trigger: CB energy sum > 40 MeV
- Linear polarization maximum ~130 MeV

Data taken:

Full target:

- Diamond with perpendicular orientation: ~69 h
- Diamond with parallel orientation: ~67 h
- Amorphous radiator ~42 h

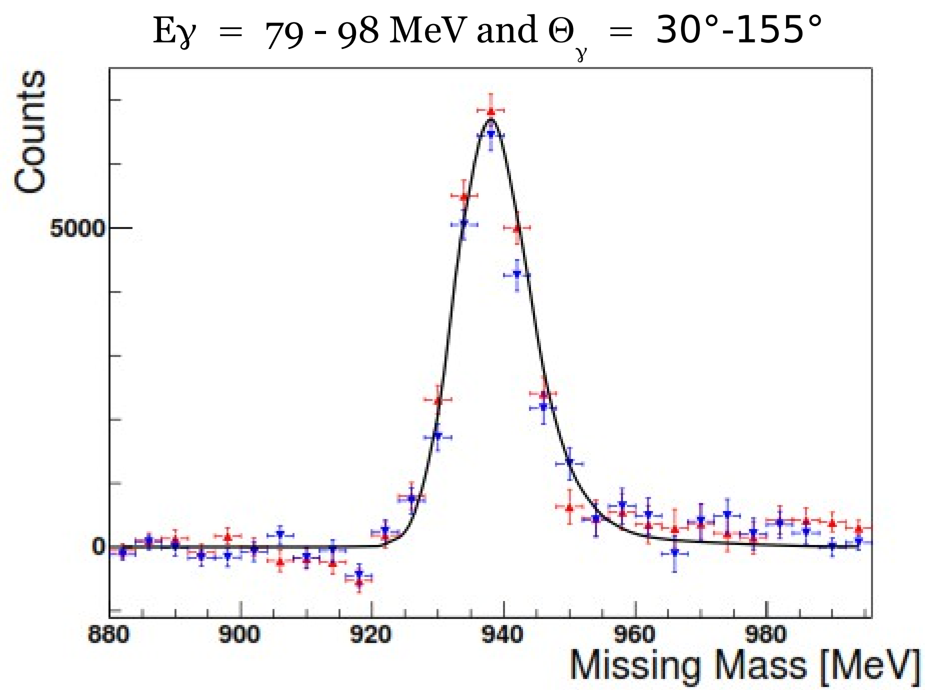
Empty target:

- Diamond with parallel orientation: ~55 h
- Diamond with perpendicular orientation: ~55 h
- Amorphous radiator ~39 h

Pilot experiment: Event selection

Selection of $\gamma p \rightarrow \gamma p$:

- $E\gamma_{(beam)}$ = 79 – 139 MeV
- Selecting events with 1 γ
- Missing mass cut
- Subtraction of random timing background
- Subtraction of empty target contribution

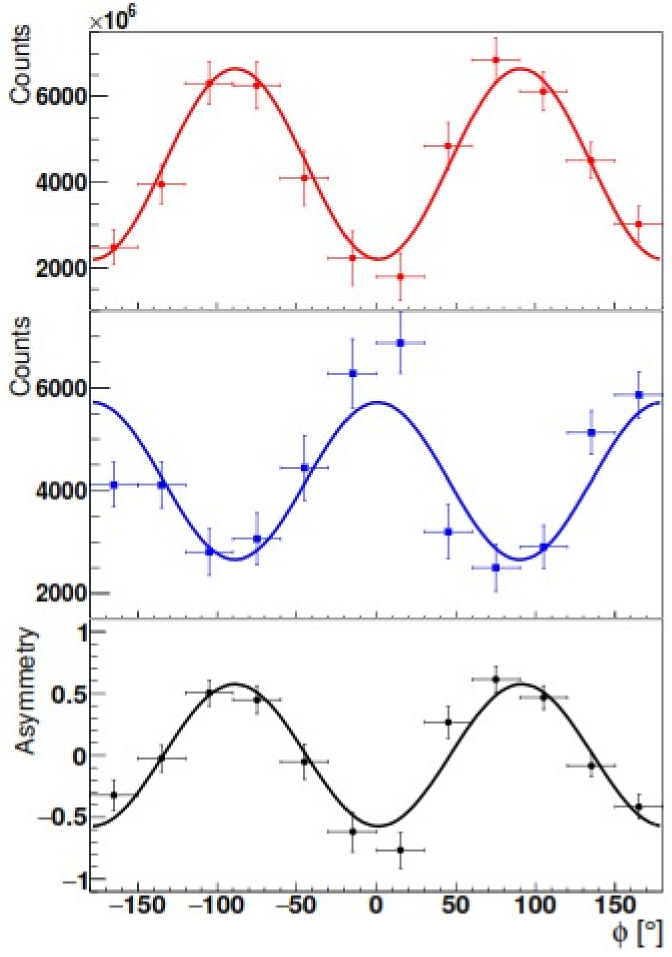


Red: PARA, Blue: PERP,
Black curve : Monte Carlo

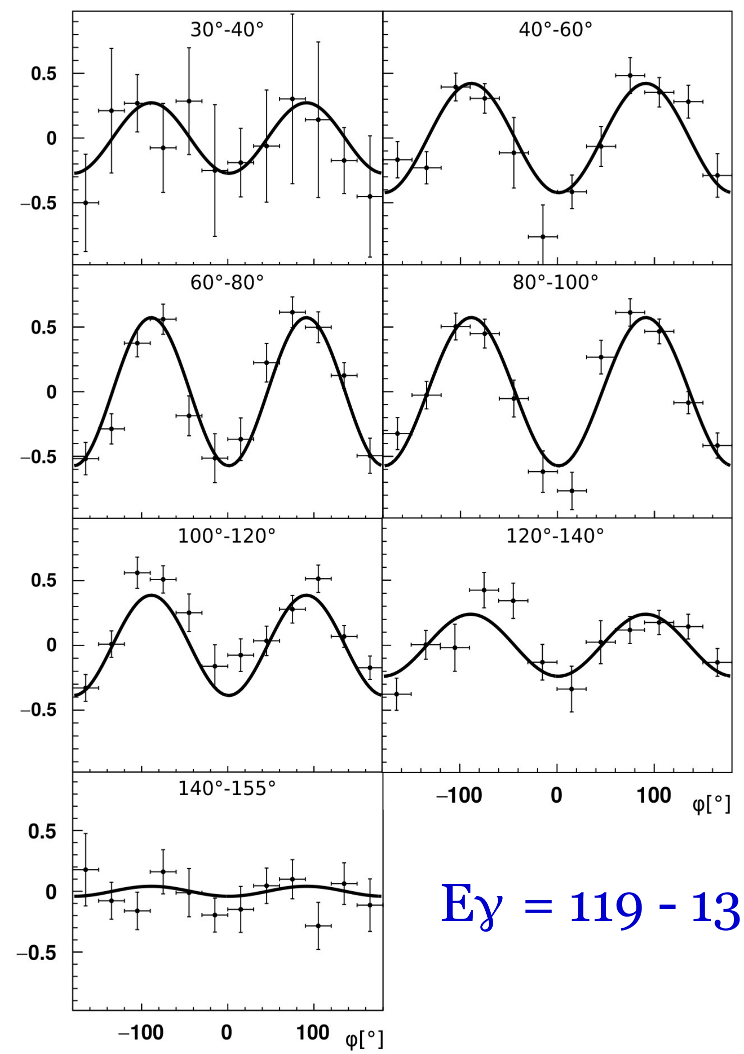
- More than 200,000 Compton scattering events ($E\gamma$ = 79 - 139 MeV and Θ_γ = 30°-155°)
- Low background contamination in all energy bins
- Good agreement between PARA and PERP for the unpolarized component

Pilot experiment: Data quality

$$\sigma_{pol} = \sigma_{unpol}(1 \pm \delta_l \, \Sigma_3 \cos 2\phi) \qquad \Sigma_3 \equiv \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$$

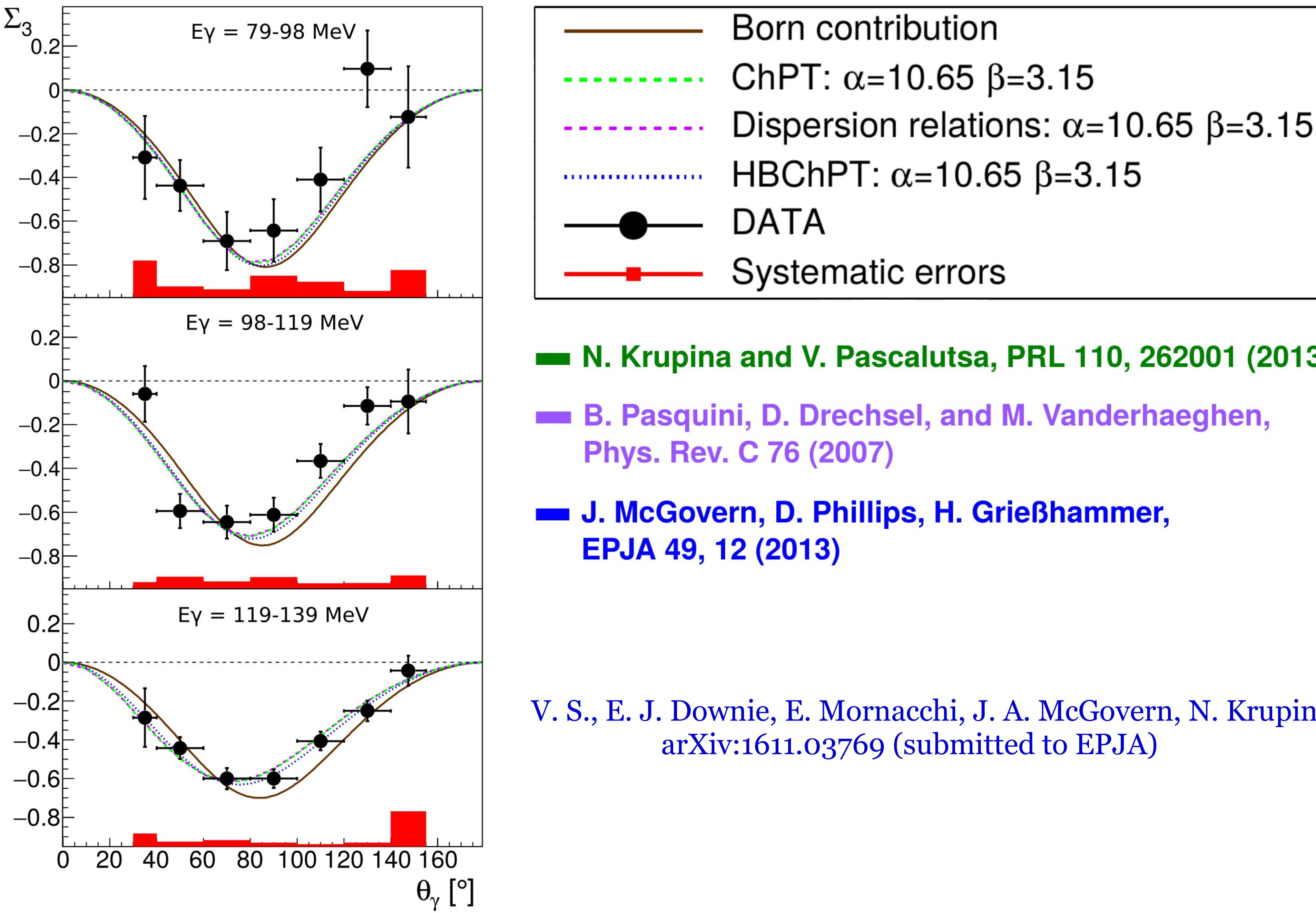


PARA and PERP, Asymmetry



Eγ = 119 - 139 MeV

Pilot experiment: Beam asymmetry



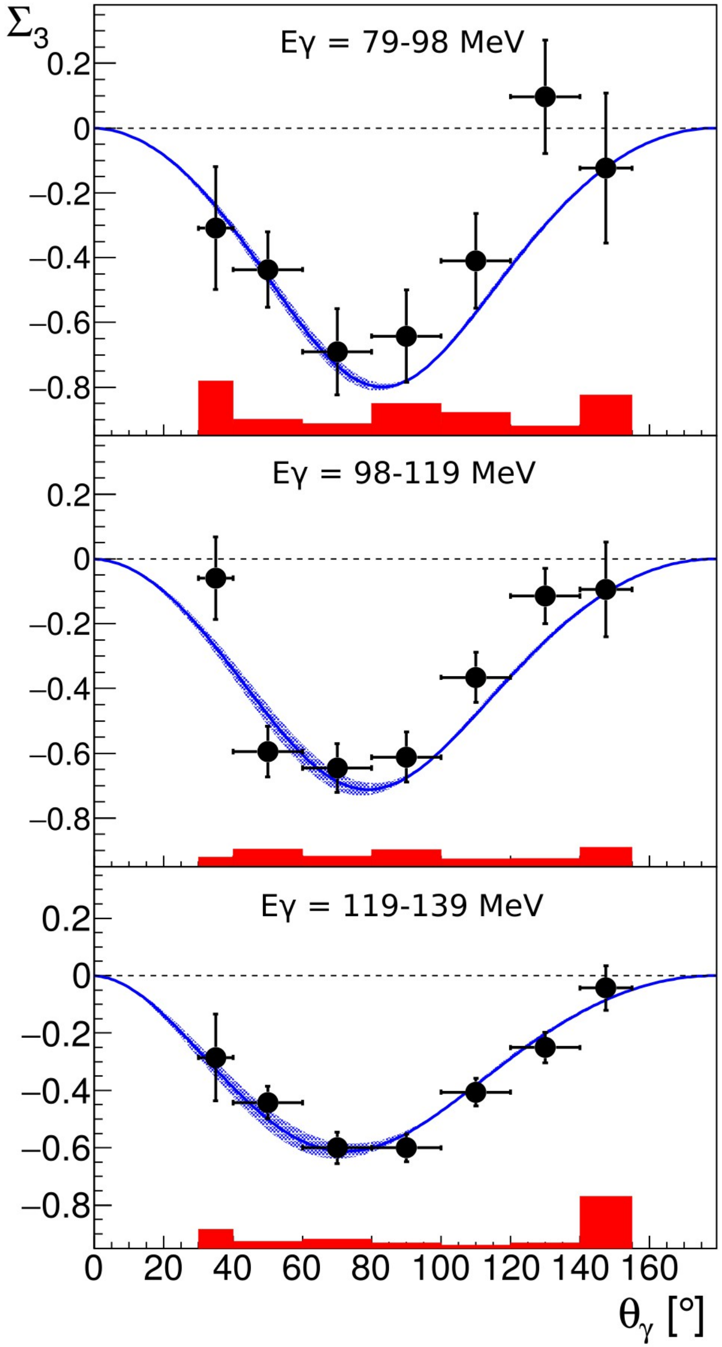
N. Krupina and V. Pascalutsa, PRL 110, 262001 (2013)

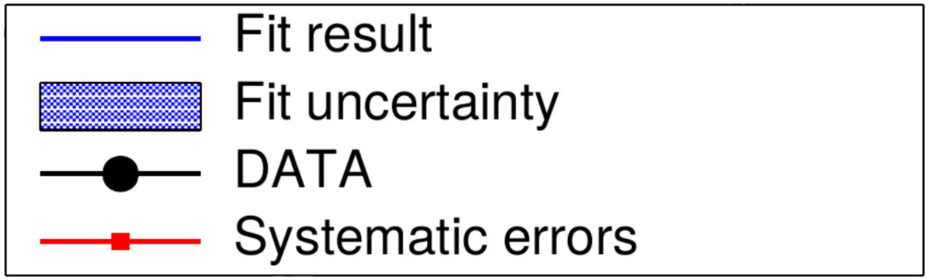
B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76 (2007)

J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)

V. S., E. J. Downie, E. Mornacchi, J. A. McGovern, N. Krupina
arXiv:1611.03769 (submitted to EPJA)

Pilot experiment: Beam asymmetry





Fit on our Σ_3 results using Baldin sum rule constraint gives:

BChPT framework:

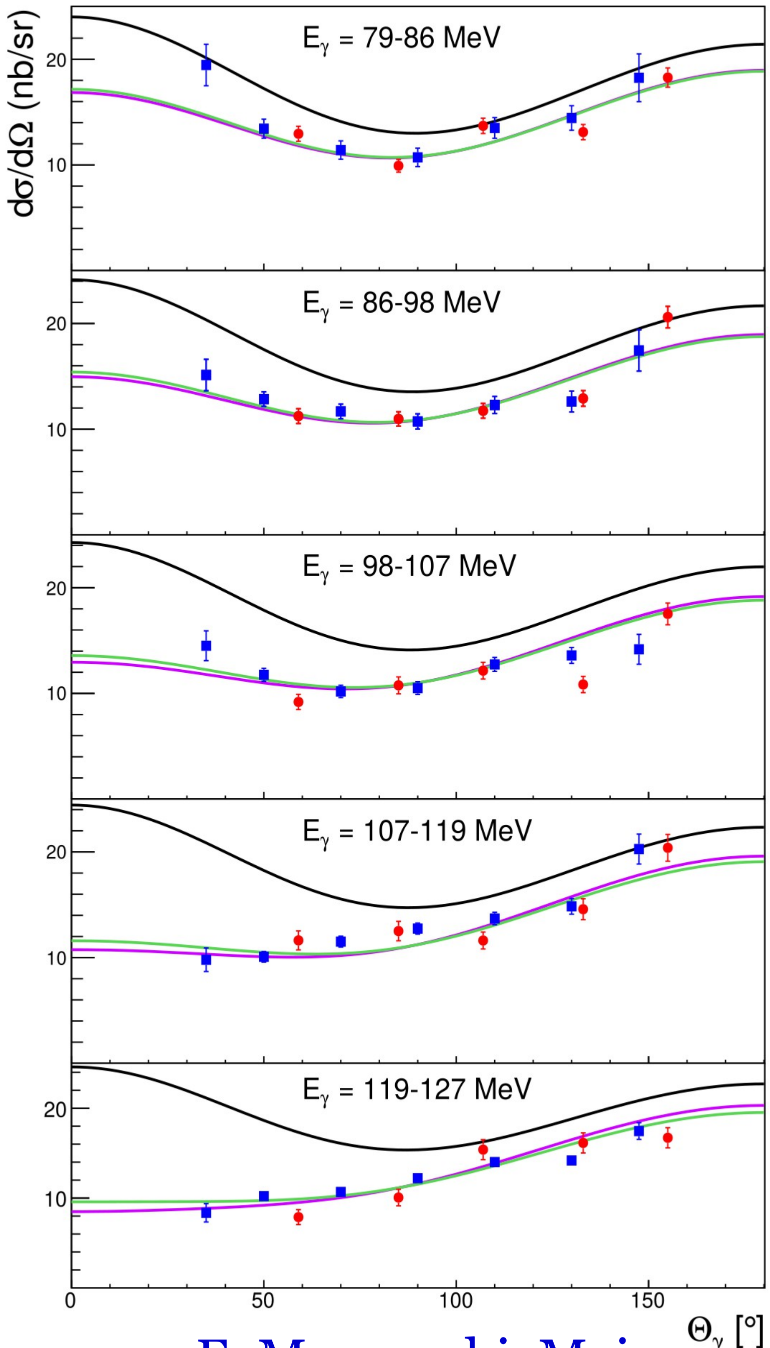
$$\beta_{M1} = 2.8^{+2.3}_{-2.1} \times 10^{-4}\ \mathrm{fm}^3$$
$$\chi^2/\mathrm{ndf} = 19.2/20$$

HBChPT framework:

$$\beta_{M1} = 3.7^{+2.5}_{-2.3} \times 10^{-4}\ \mathrm{fm}^3$$
$$\chi^2/\mathrm{ndf} = 17.1/20$$

V. S., E. J. Downie, E. Mornacchi, J. A. McGovern, N. Krupina
arXiv:1611.03769 (submitted to EPJA)

Pilot experiment: Unpolarized cross-sections



Blue points: pilot experiment data, red: Olmos et al.
(V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001))

Black curve: Born contribution, green curve:BChPT, violet curve: DR (α = 10.65 fm^3, β= 3.15 fm^3)

- Agreement with Olmos et al.
- Compatible (or better) statistics in the new sample
- Extension of the angular coverage in the forward direction
  (~20% systematic error due to flux normalization)

ChPT fit: **β = (2.8 ± 1.3) × 10^{-4} fm^3** constrained with Baldin sum rule $\alpha + \beta = 14.0 \times 10^{-4}$ fm^3 (Work of V. Pascalutsa, N. Krupina and V. Lensky)

The uncertainty in polarizabilities scales linearly with the error of the unpolarized cross-section or Σ_3

Achieved (pilot) and expected (proposed) precision

BChPT fits from P. Martel			Error from ChPT fit (10^{-4} fm^3)		
			With Baldin		
Experiment	Compton ev.		Σ_3	$\frac{d\sigma}{d\omega}$	$\Sigma_3, \frac{d\sigma}{d\omega}$
Pilot	$\approx$ 200000	$\Delta\alpha_{E1}$ $\Delta\beta_{E1}$	2.5	1.3	1.1
Proposed	$\approx$ 4000000	$\Delta\alpha_{E1}$ $\Delta\beta_{E1}$	0.7	0.4	0.3

- Highest statistics data set: Olmos et al. (~50% of the existing data)

Data		$\bar{\alpha} + \bar{\beta}$ *fixed*	$\bar{\alpha} + \bar{\beta}$ *free*
TAPS (this work)	$\bar{\alpha}$ $\bar{\beta}$	$12.1 \pm 0.4 \mp 1.0$ $1.6 \pm 0.4 \pm 0.8$	$11.9 \pm 0.5 \mp 1.3$ $1.2 \pm 0.7 \pm 0.3$

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

- World data errors: $\Delta\alpha_{E1} \approx 0.76 \times 10^{-4}$ fm^3, $\Delta\beta_{M1} \approx 0.62 \times 10^{-4}$ fm^3

→ Improved precision compared to the available data from different experiments based on a **single measurement!**

Proposed improvements

Proposed experiment: 600 hours of Compton scattering on the proton

- Measurement of the unpolarized cross-section and beam asymmetry Σ_3
- 10 cm LH2 target, Eγ = 883 MeV

Improvement in statistics:

- Reduced number of Cu and empty target runs → improvement in statistics ~2.5 times

	Diamond (both settings)		Copper radiator	
Experiment	Full target	Empty target	Full target	Empty target
Pilot	116 hours	110 hours	42 hours	39 hours
Proposed	500 hours	70 hours	30 hours	-

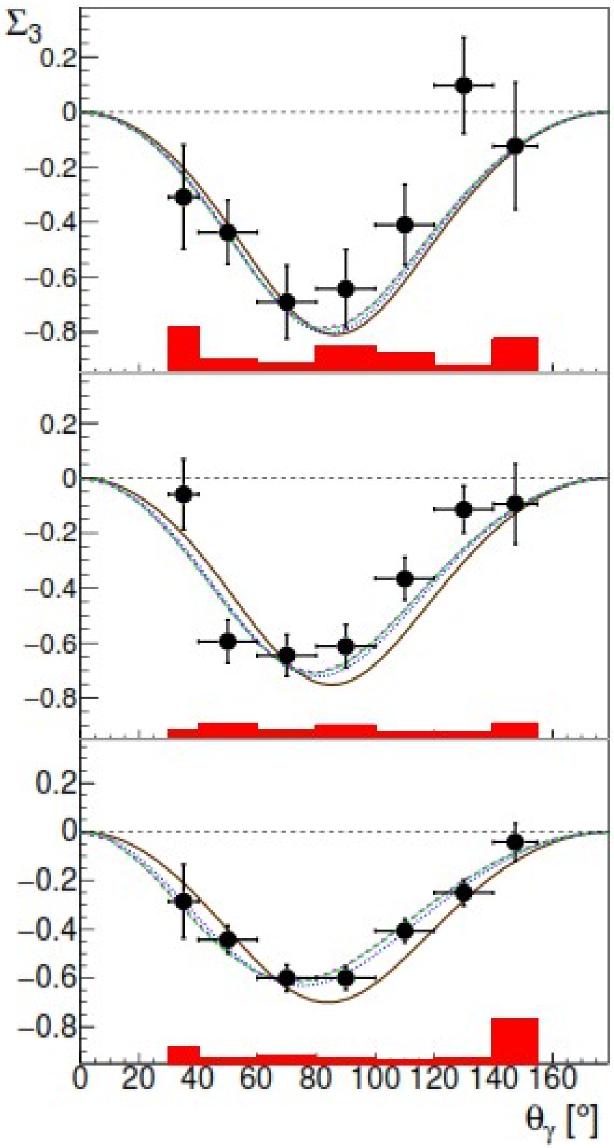
- Tagger upgrade → improvement in rates ~5 times
- Decrease of the statisitical error **~3.5 times** (corrected for the scaling of the random hits)

Improvement in systematics:

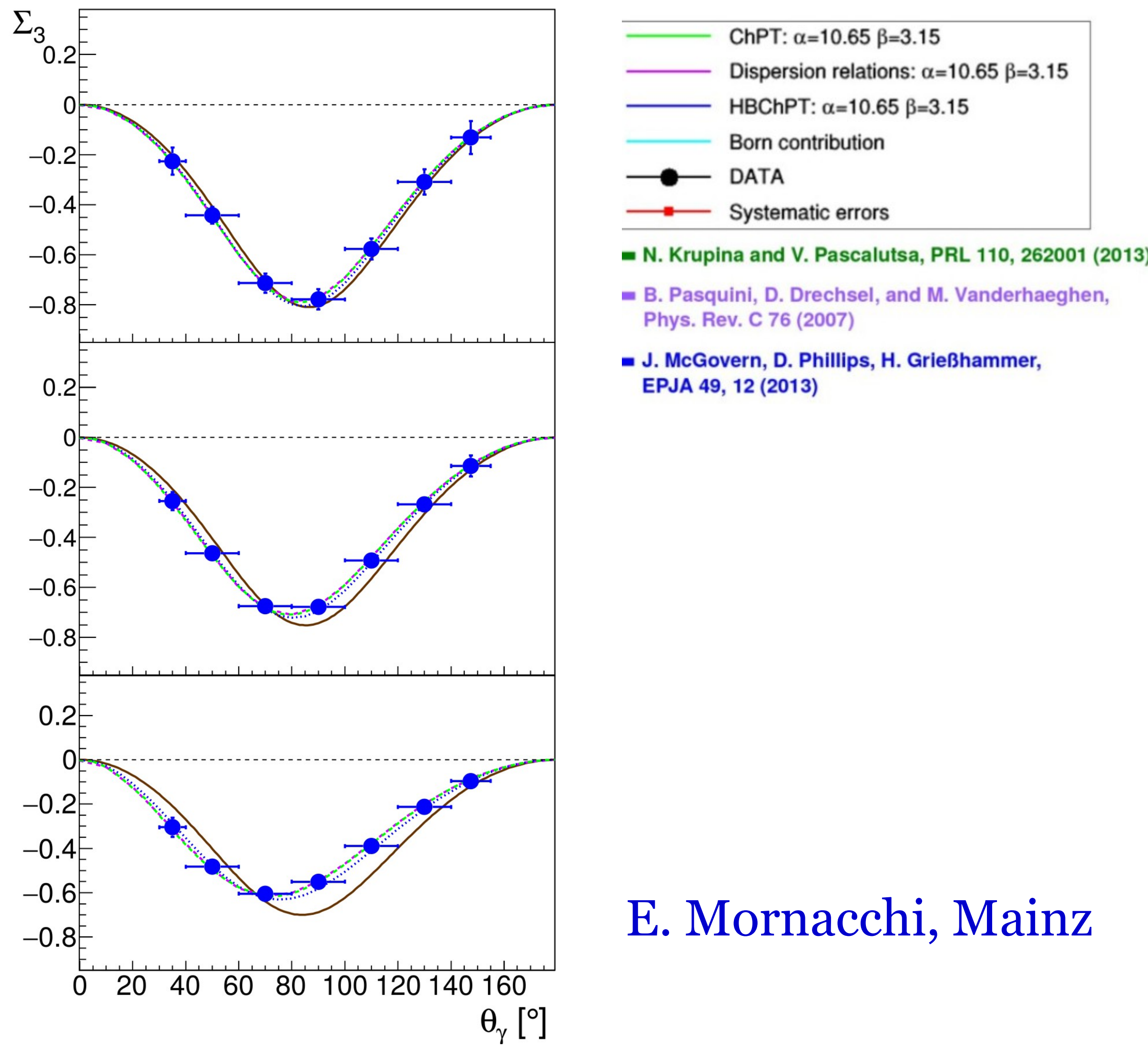
- Stable linear polarization with the new setup
- Improvement in the tagger performance
- Pair spectrometer information will be available
- Smaller systematic errors (flux normalization, background subtraction)

Beam asymmetry Σ_3: Expected precision

Pilot experiment



Proposed experiment (Monte Carlo simulation)

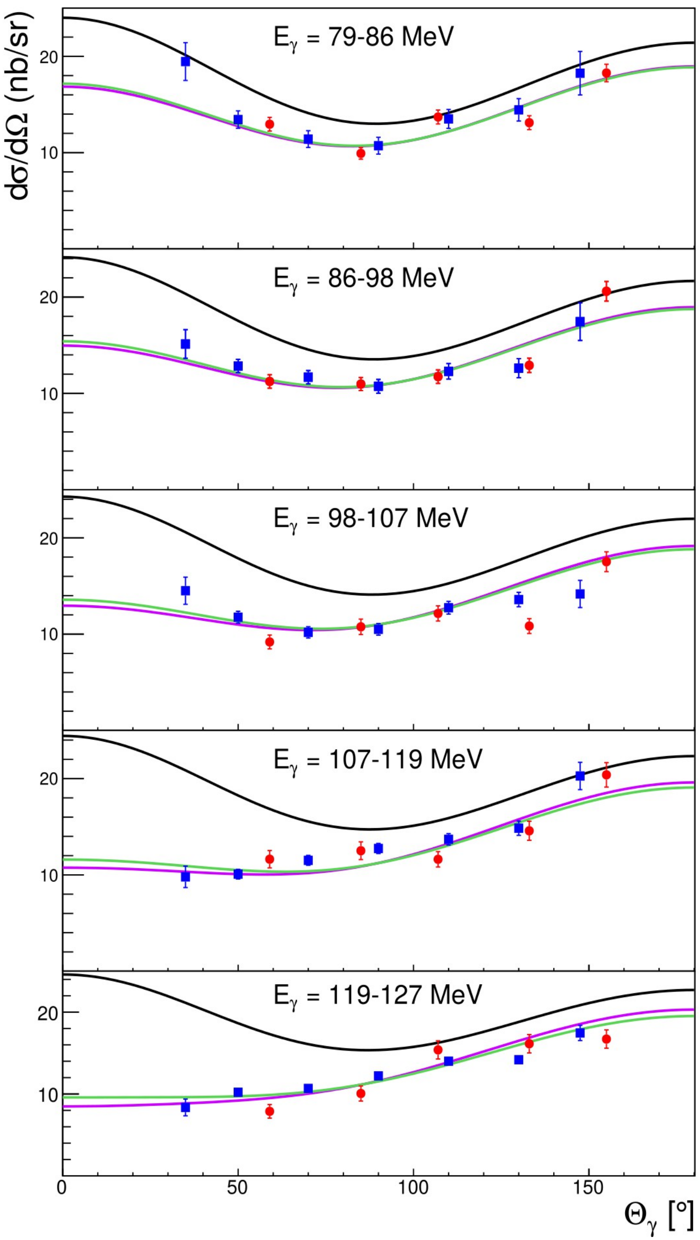


E. Mornacchi, Mainz

V. S., E. J. Downie, E. Mornacchi, J. A. McGovern, N. Krupina
arXiv:1611.03769 (submitted to EPJA)

Pilot expriment: Unpolarized cross-sections

Pilot experiment



Blue points: pilot experiment data, red: Olmos et al.
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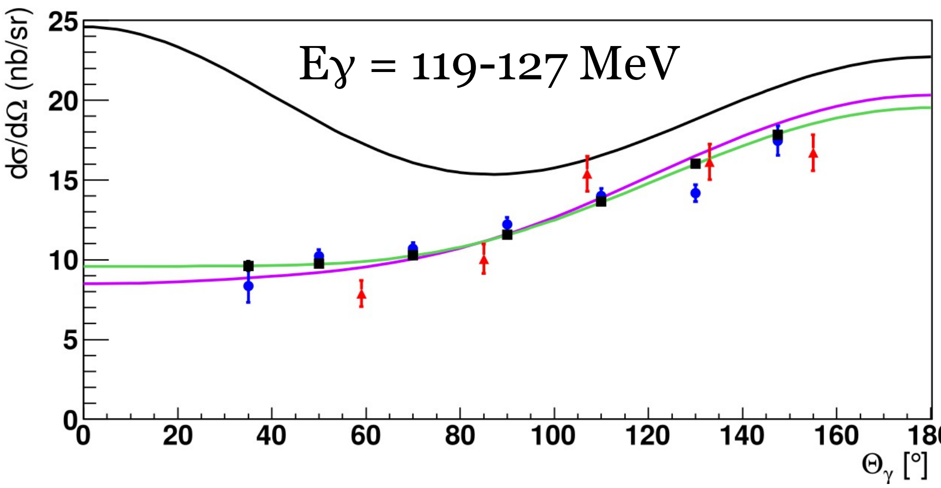
Black curve: Born contribution, green curve:BChPT, violet curve: DR (α = 10.65 fm^3, β= 3.15 fm^3)

Proposed experiment (Monte Carlo simulation)
Black points: expected precision



E. Mornacchi, Mainz

Summary

<u>Proposed experiment: 600 hours of Compton scattering on the proton</u>

- Successful pilot experiment (June 2013)

- Systematic effects well-understood and required statistical accuracy estimated within BChPT (V. Pascalutsa, N. Krupina, V. Lensky, P. Martel) and HBChPT (J. McGovern)

- High-precision measurement of the unpolarized cross-section and beam asymmetry for Compton scattering on the proton

→ Determination of scalar polarizabilities of the proton with unprecedented high precision from a single data set

→ Extraction of the scalar polarizabilities with twice reduced uncertainties

Summary

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Thank you for your attention!

Backup

Compton scattering

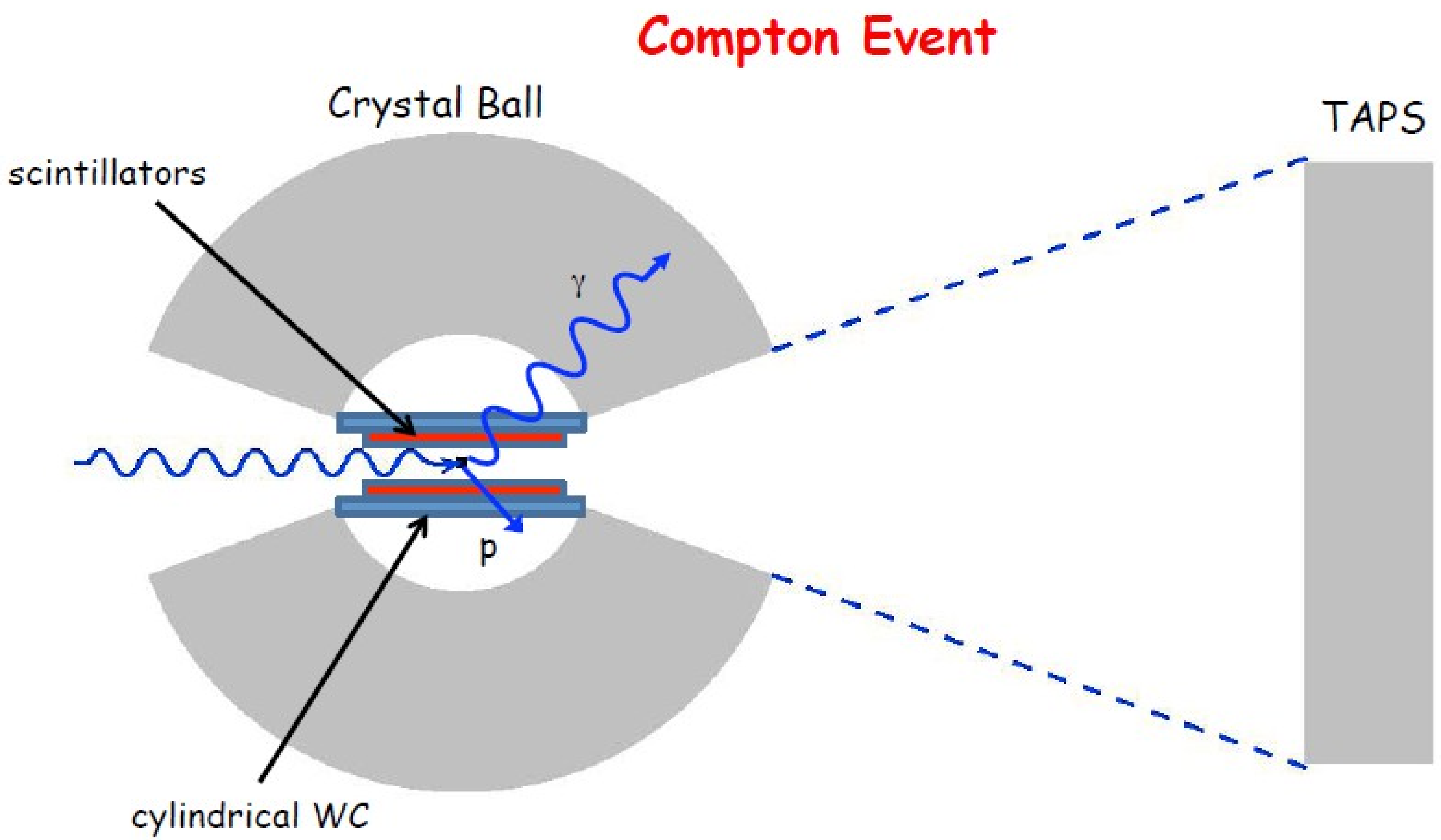
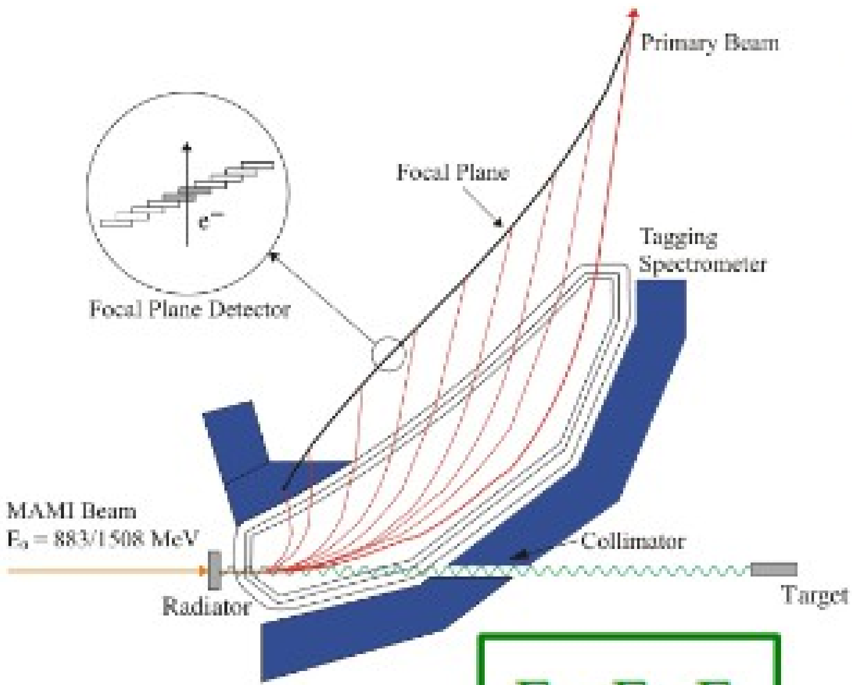
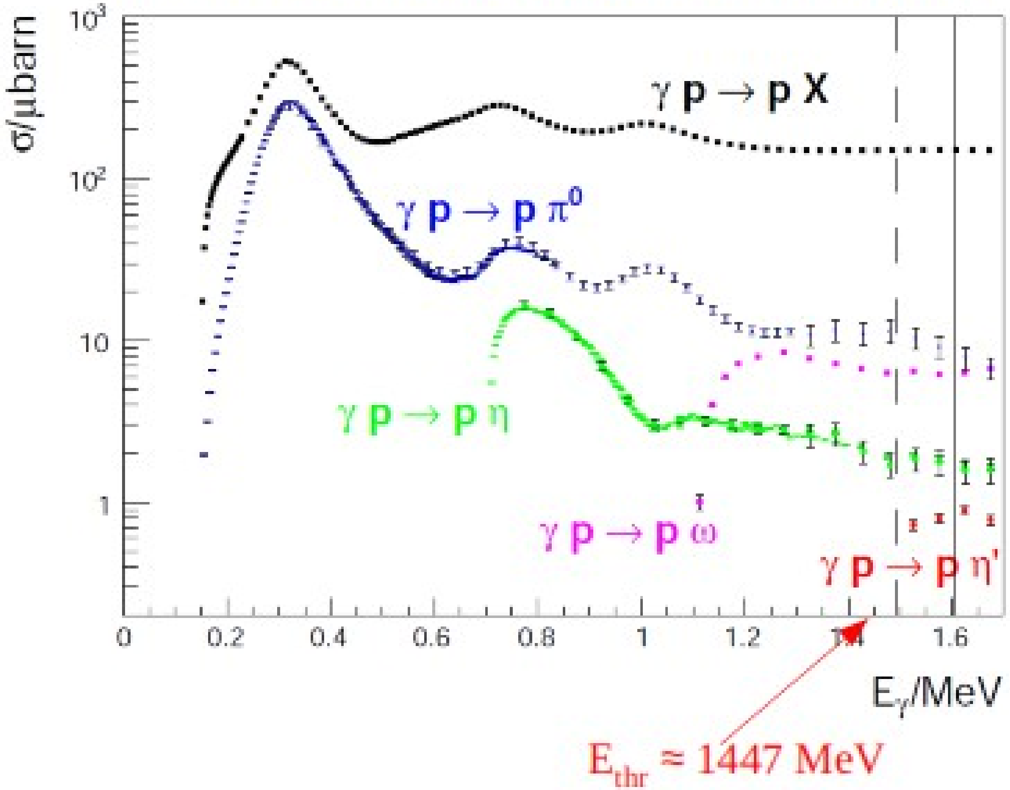


Figure: R. Miskimen

Polarized active target (slide taken from M. Unverzagt)



$E_\gamma = E_0 - E_{e-}$



High energy resolution: $\Delta E_\gamma \approx 2$MeV at $E_{e-}=883$ MeV

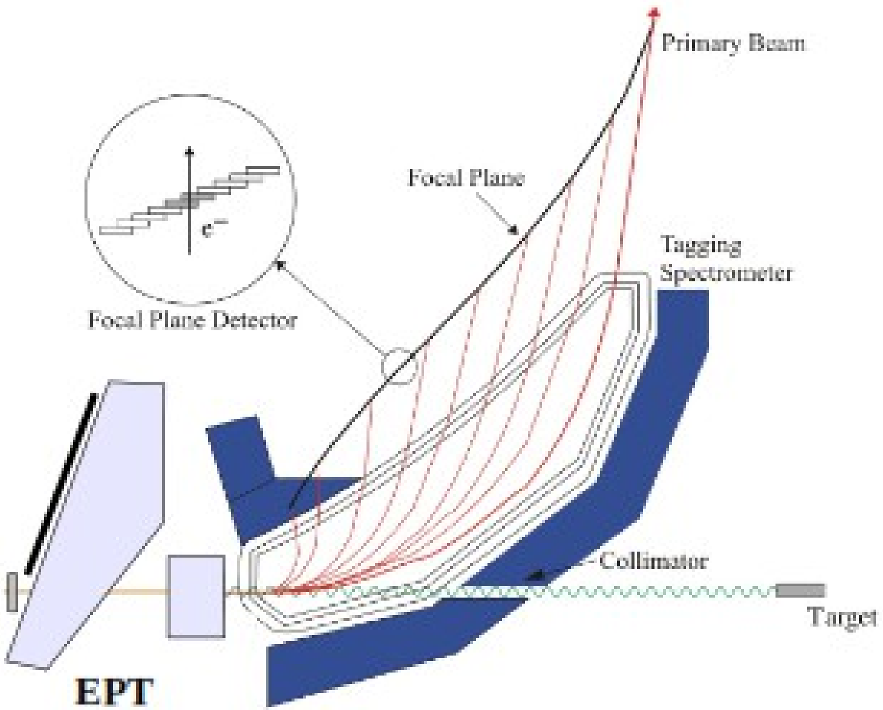
$\Delta E_\gamma \approx 4$MeV at $E_{e-}=1558$ MeV

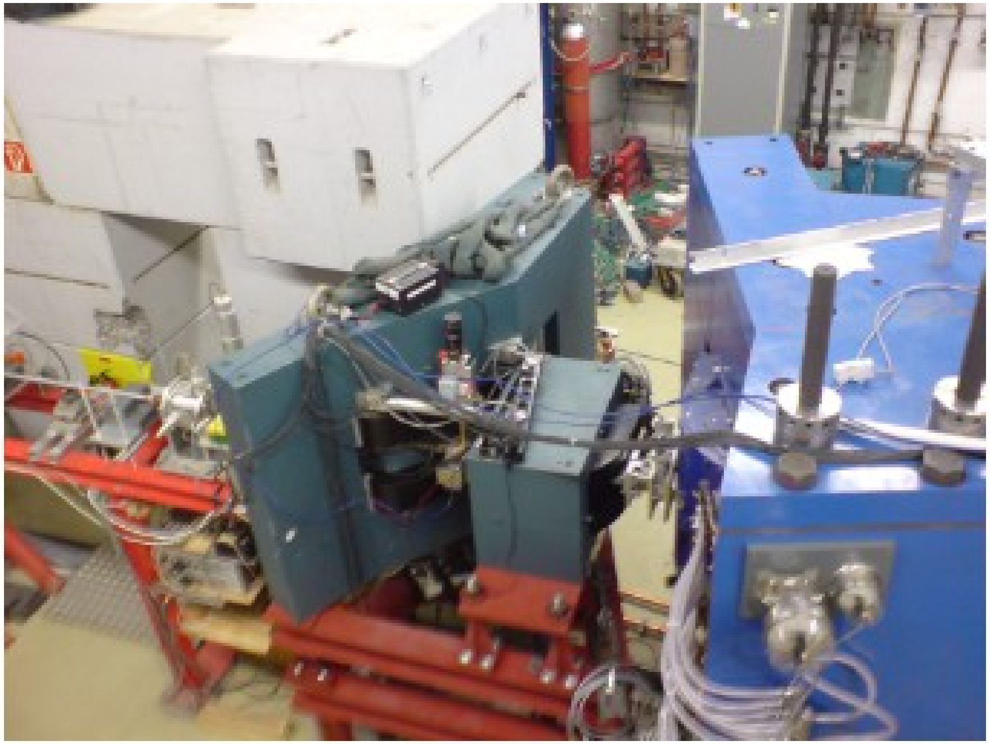
Linearly and circularly polarised photon-beam

Tagging range: 5.1 to 93% of E_γ → Maximum energy tagged for E_0=1604 MeV is 1491 MeV

EPT (slide taken from M. Unverzagt)

- Installation of EPT during 2012





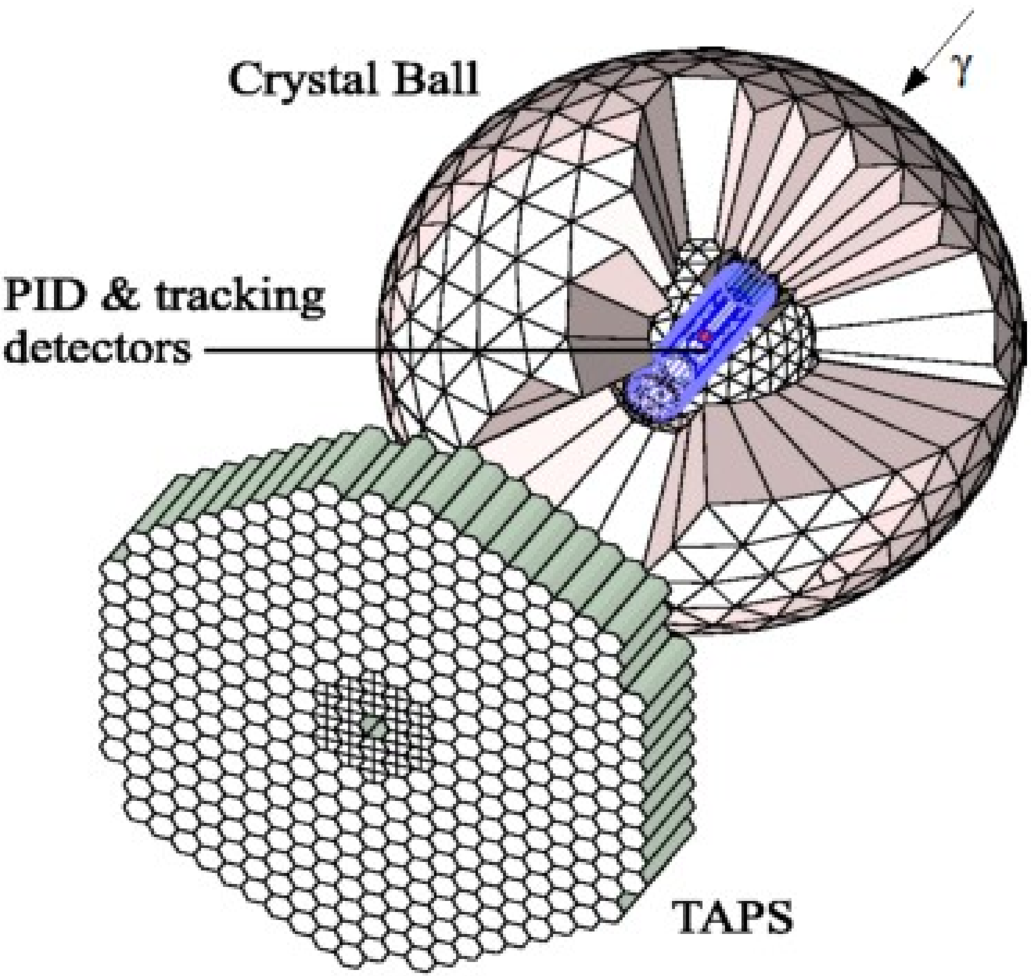
Same working principle as main tagging spectrometer

$E_\gamma \approx 1445\text{-}1595$ MeV

$\Delta E_\gamma \approx 2.5$MeV

Non-permanent installation infront of main Tagger

Crystal Ball/TAPS (slide taken from M. Unverzagt)



Crystal Ball:

672 NaI(Tl) crystals

93,3% of total solid angle

Each crystal equipped with PMT

$$\frac{\sigma}{E_\gamma} = \frac{2\%}{(E_\gamma / GeV)^{0.25}} \qquad \sigma(\theta) = 2^\circ \ldots 3^\circ$$

$$\Delta t = 2.5 \text{ ns FWHM} \qquad \sigma(\phi) = \frac{2^\circ \ldots 3^\circ}{\sin(\theta)}$$

TAPS:

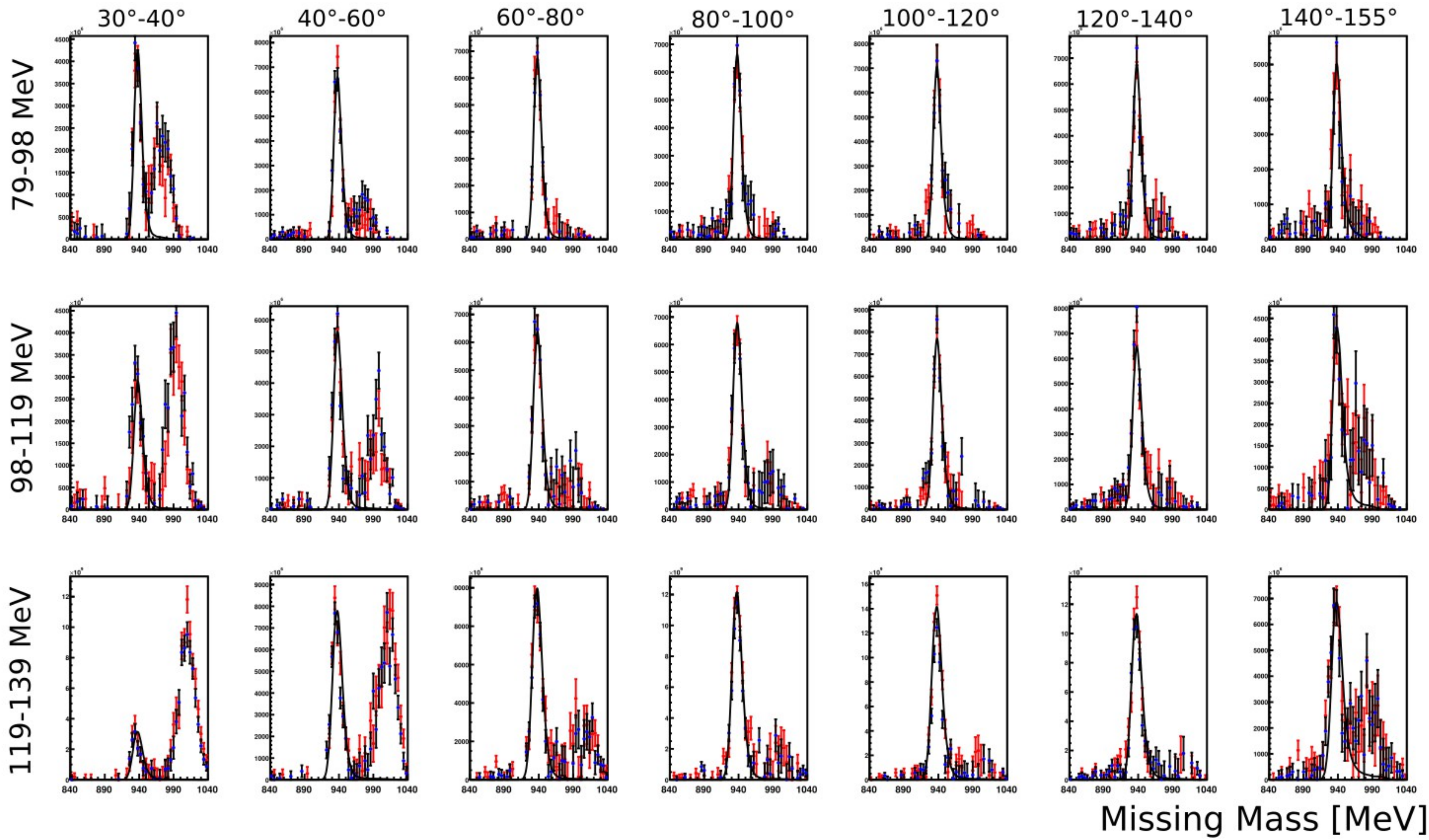
Up to 510 BaF_2 crystals

Polar acceptance: 4-20°

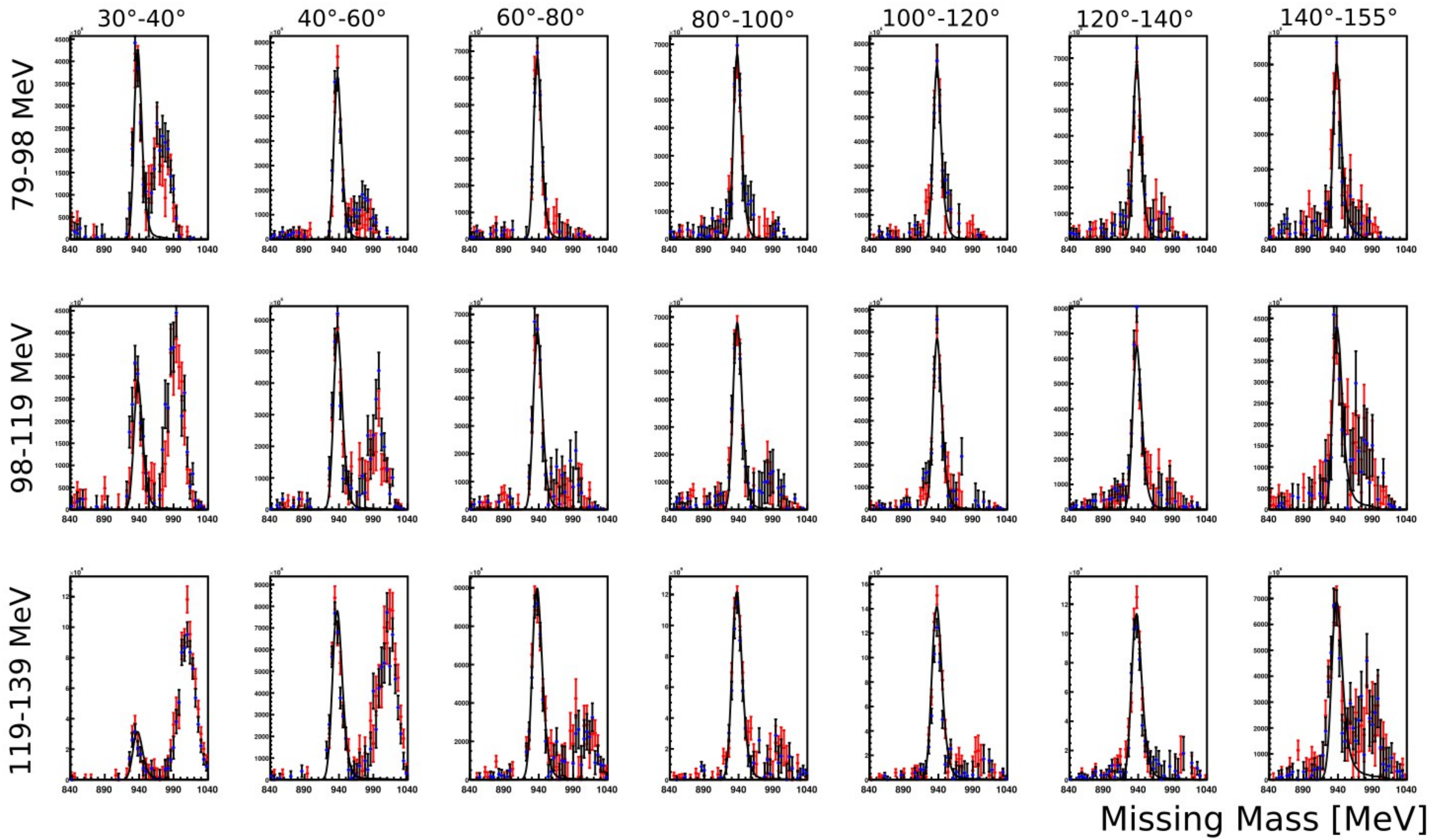
$\Delta t = 0.5$ ns FWHM

$$\frac{\sigma}{E_\gamma} = \frac{0{,}79\,\%}{\sqrt{E_\gamma / GeV}} + 1{,}8\%$$

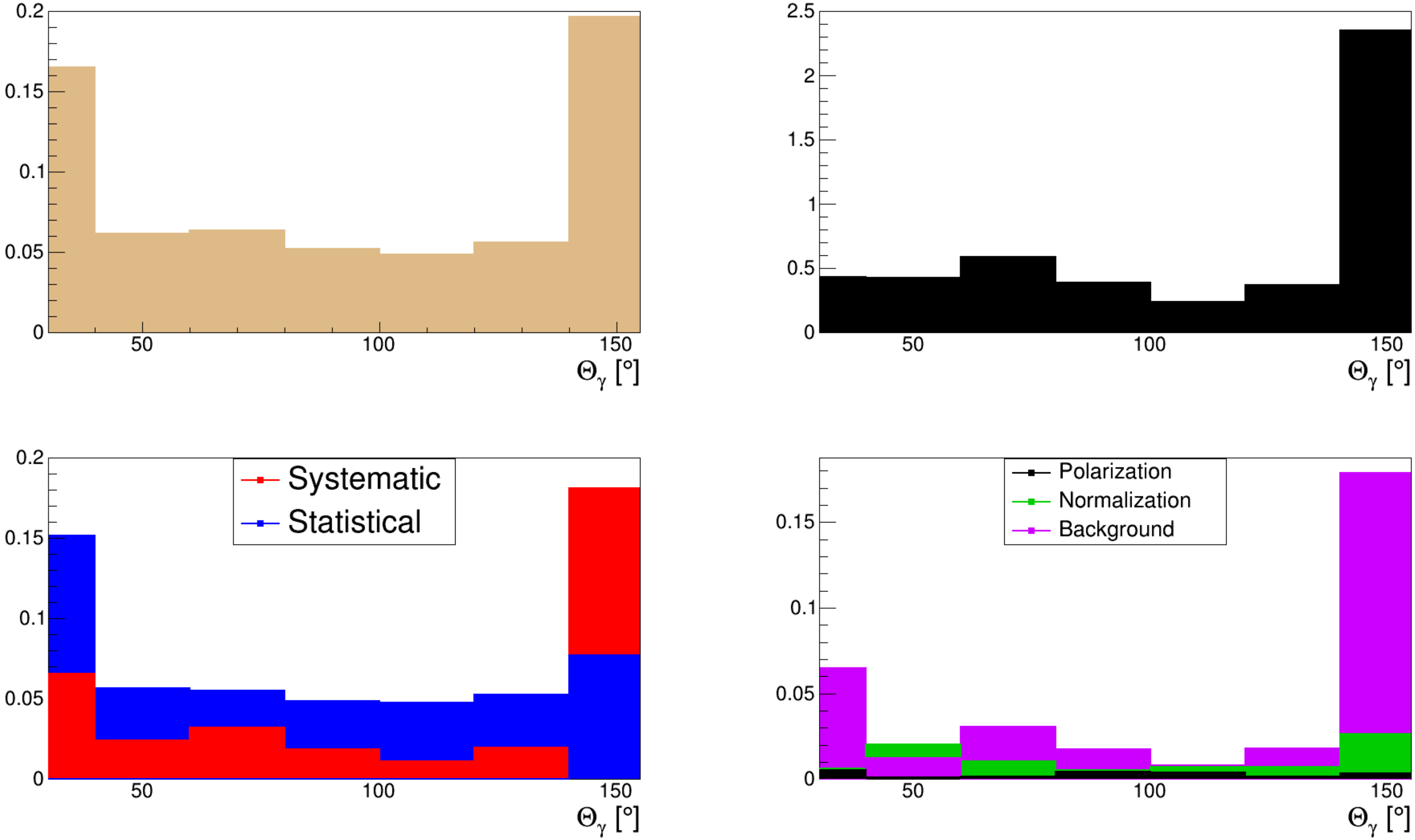
Missing mass



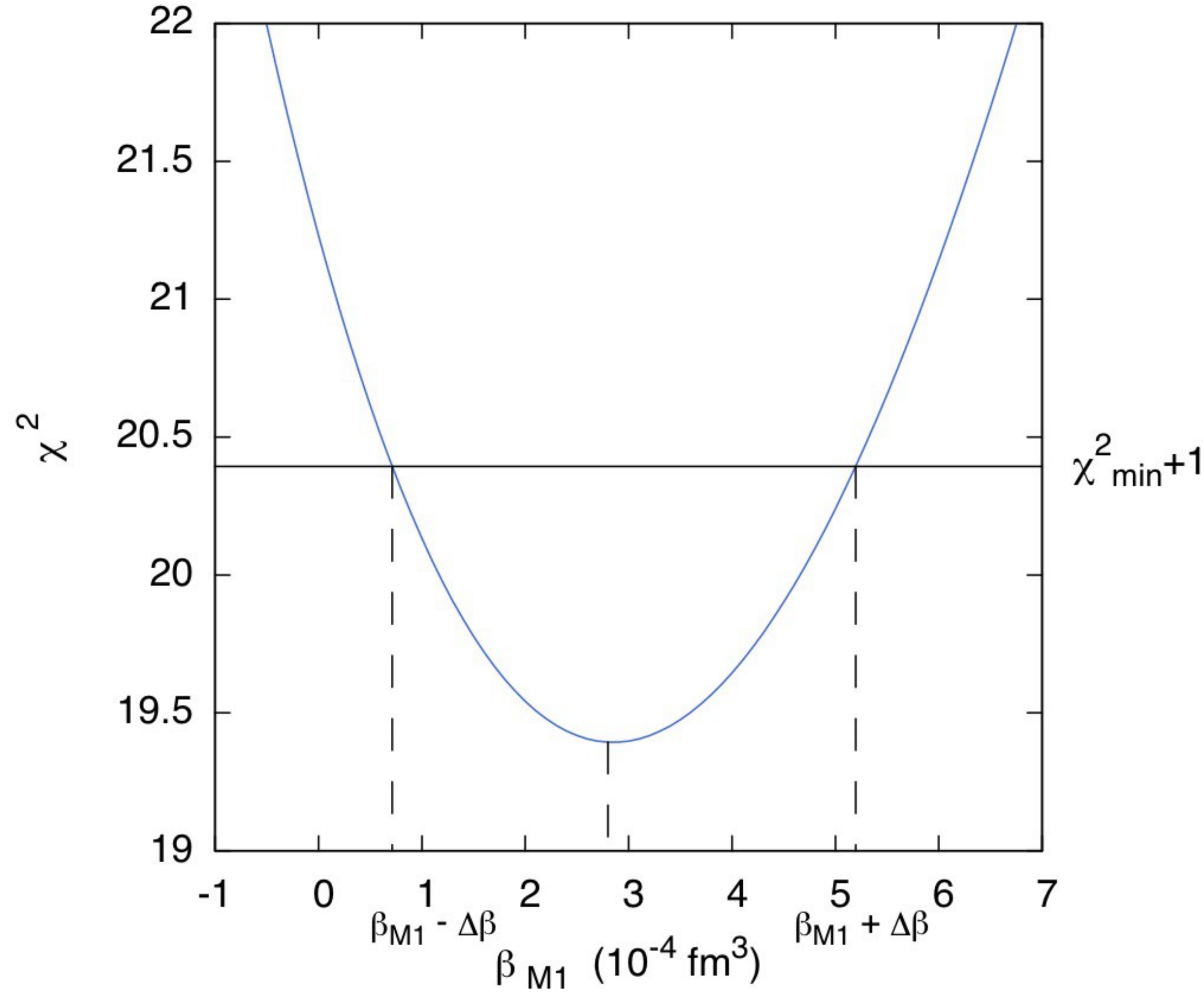
Missing mass



Statistical and systematic errors



Beam asymmetry Σ_3 : fits



Measurement of α and β

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

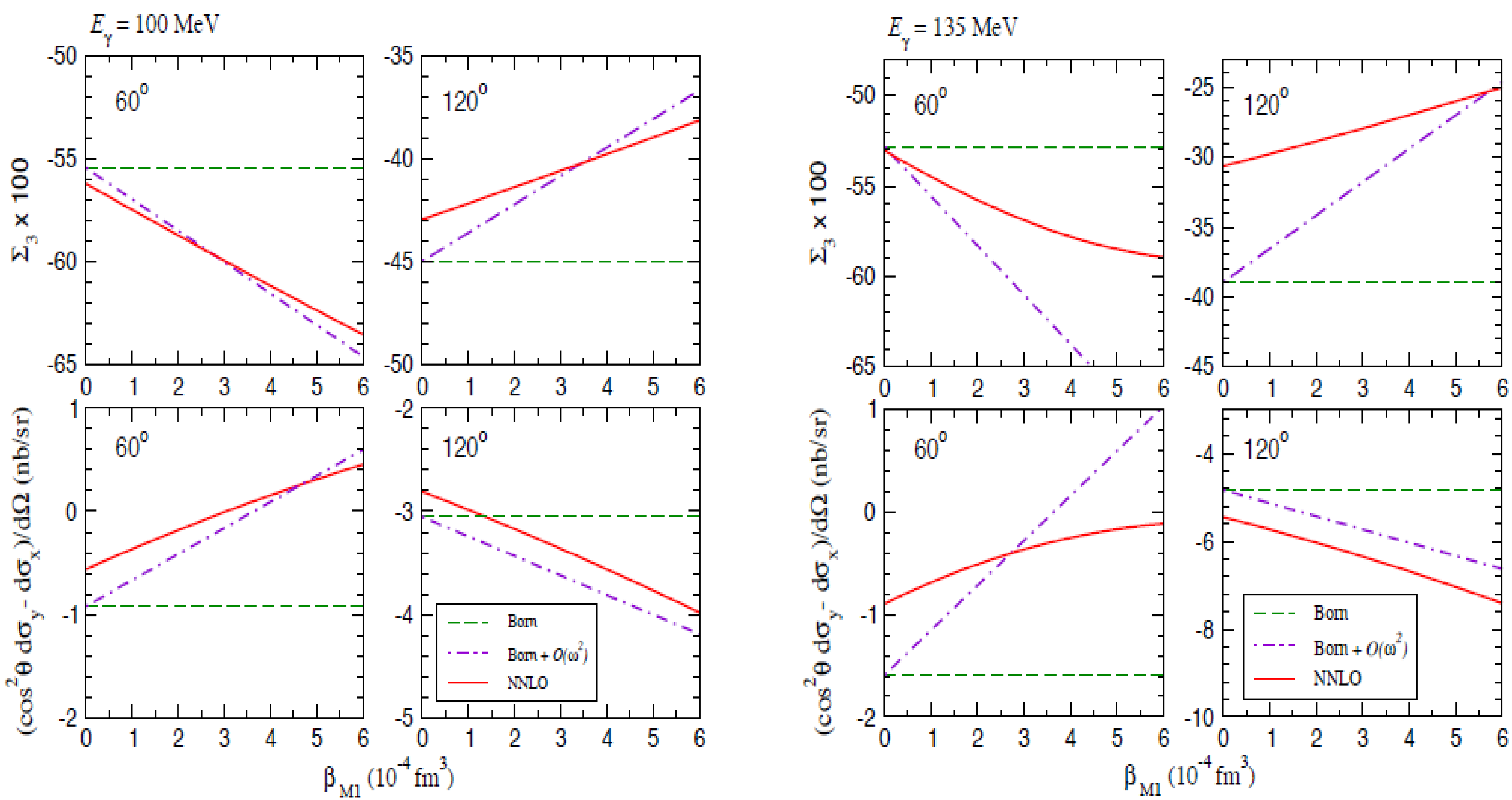
where $\Sigma_3^{(\mathrm{B})}$ is the pure Born contribution, while

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

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.

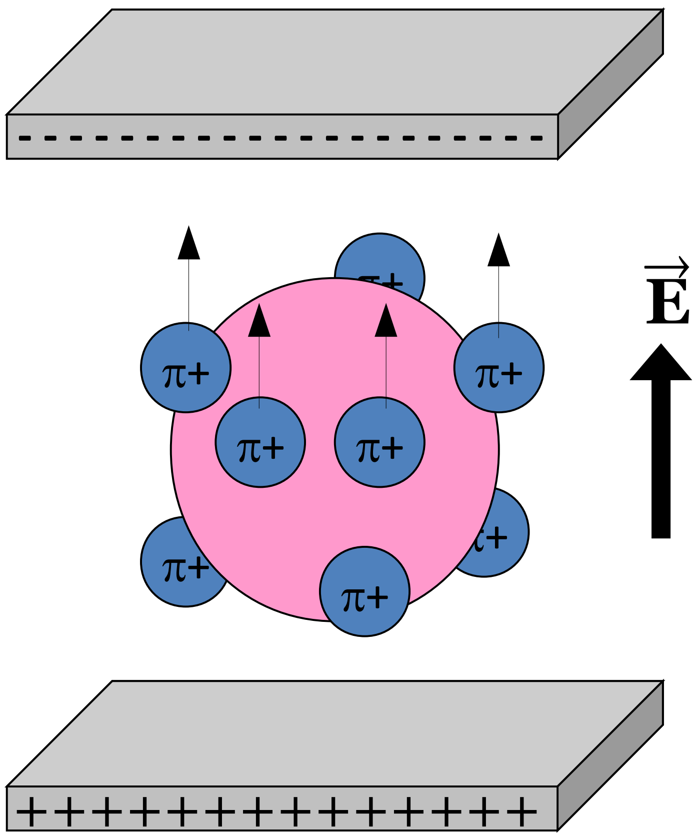
N. Krupina and V. Pascalutsa [PRL 110, 262001 (2013)]

Measurement of α and β

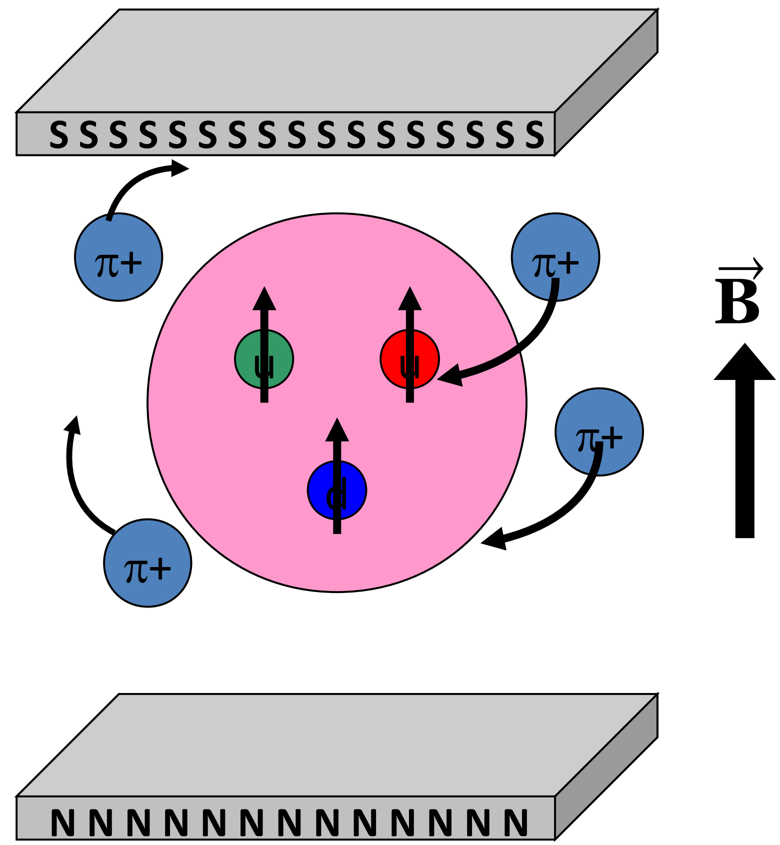


Scalar polarizabilities

Proton Electric Polarizability



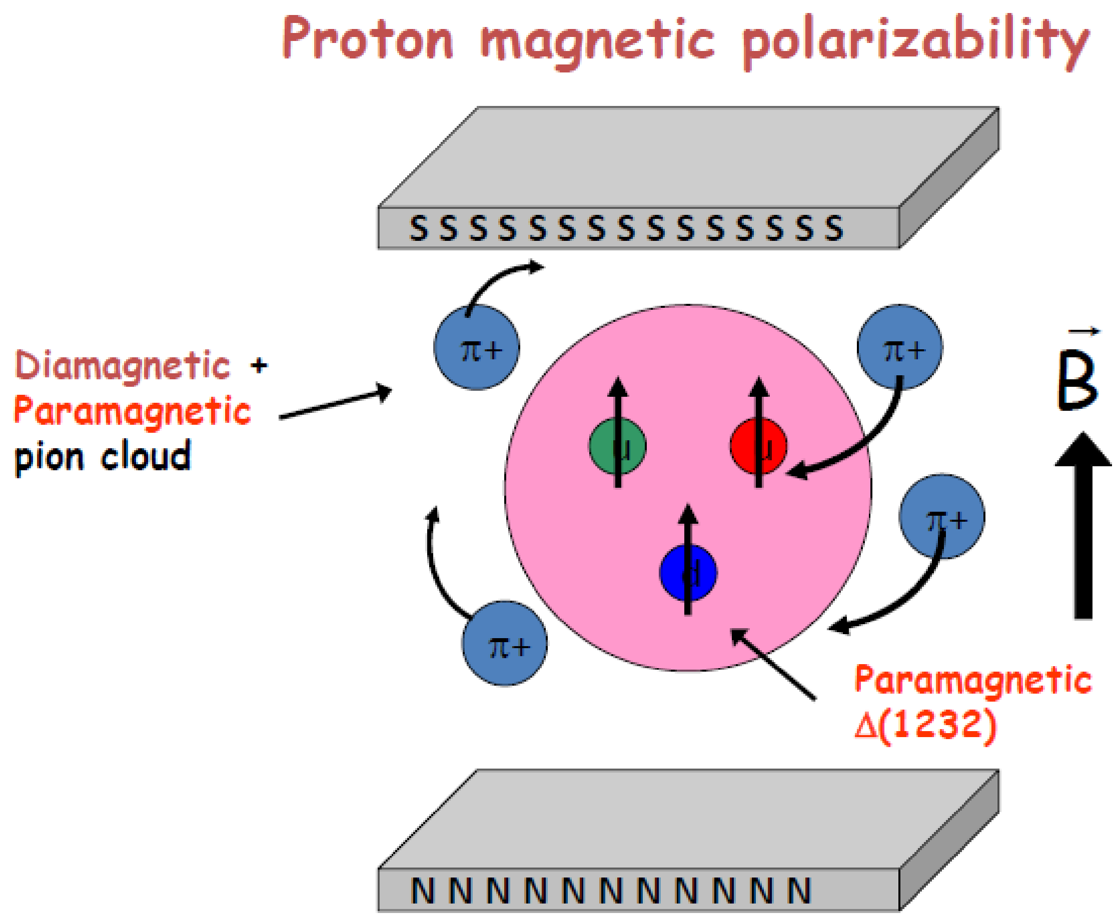
Proton Magnetic Polarizability



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

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

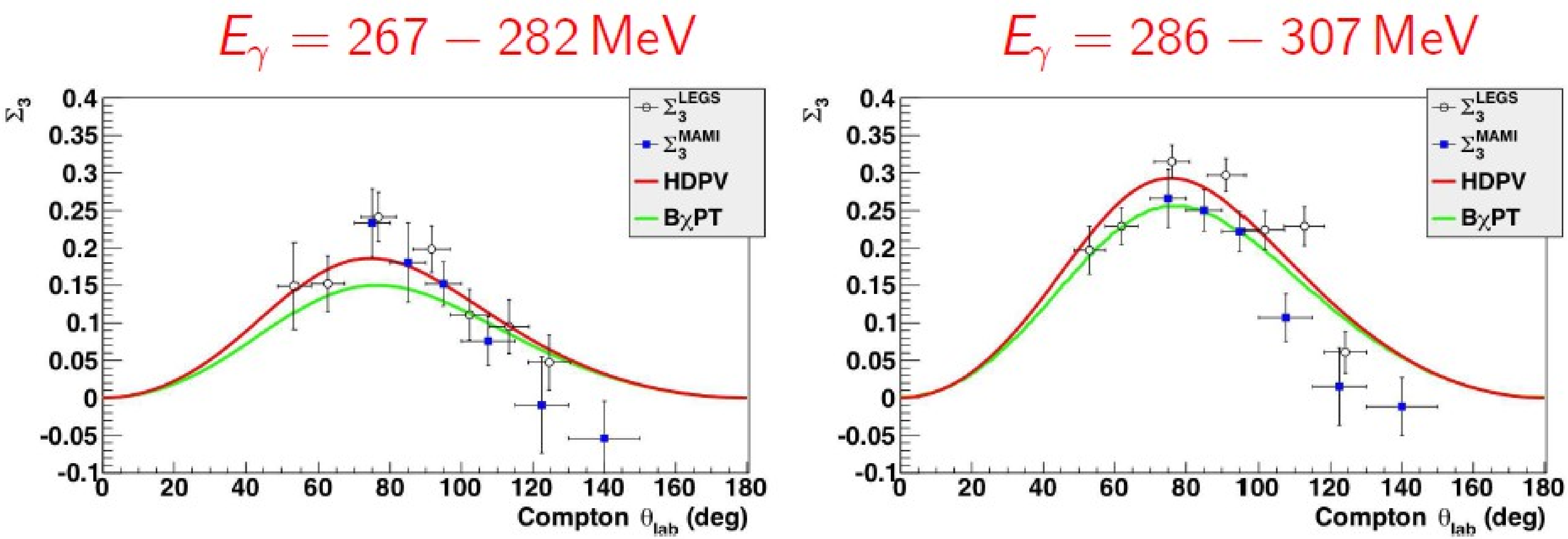
First look in December 2012 data



Magnetic polarizability: proton between poles of a magnetic

Rory Miskimen (Bosen 2009)

Spin polarizabilites



- Recent data (MAMI) and older data (LEGS) are shown along with Dispersion Relation (HDPV) and ChPT (BχPT) predictions.

G. M. Huber, C. Collicott, arXiv:1508.07919 (2015)

Achieved (pilot) and expected (proposed) precision

BChPT fits (P. Martel)

			Errors from ChPT fit ($10^{-4}\,\mathrm{fm}^3$)					
			With Baldin			Without Baldin		
Experiment	Compton events		Σ_3	$\frac{d\sigma}{d\omega}$	$\Sigma_3,\ \frac{d\sigma}{d\omega}$	Σ_3	$\frac{d\sigma}{d\omega}$	$\Sigma_3,\ \frac{d\sigma}{d\omega}$
Pilot	$\approx 200,000$	$\Delta\alpha_{E1} \approx$	2.5	1.3	1.1	3.8	1.4	1.3
		$\Delta\beta_{M1} \approx$				2.5	1.7	1.4
Proposed	$\approx 4,000,000$	$\Delta\alpha_{E1} \approx$	0.7	0.4	0.3	1.1	0.4	0.4
		$\Delta\beta_{M1} \approx$				0.7	0.5	0.4

- Competing with experiments (not global average which includes double counting of the data)
- Highest statistics data set: Olmos et al. (~50% of the existing data)

Data		$\bar{\alpha}+\bar{\beta}$ *fixed*	$\bar{\alpha}+\bar{\beta}$ *free*
TAPS	$\bar{\alpha}$	$12.1 \pm 0.4 \mp 1.0$	$11.9 \pm 0.5 \mp 1.3$
(this work)	$\bar{\beta}$	$1.6 \pm 0.4 \pm 0.8$	$1.2 \pm 0.7 \pm 0.3$

- After combination of statistical and systematic errors:
  $\Delta\alpha = (12.1 \pm 0.89) \times 10^{-4}\ \mathrm{fm}^3$ and $\Delta\beta = (1.6 \pm 1.08) \times 10^{-4}\ \mathrm{fm}^3$
- World data errors (without double counting): $\Delta\alpha \approx 0.76 \times 10^{-4}\ \mathrm{fm}^3$, $\Delta\beta \approx 0.62 \times 10^{-4}\ \mathrm{fm}^3$

→ Improved precision compared to the available data from different experiments based on a **single measurement!**