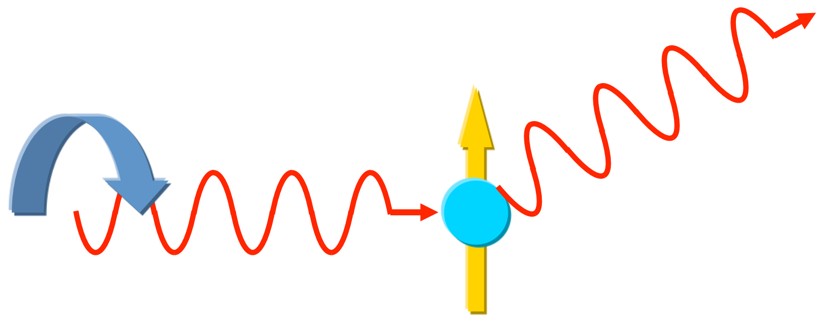
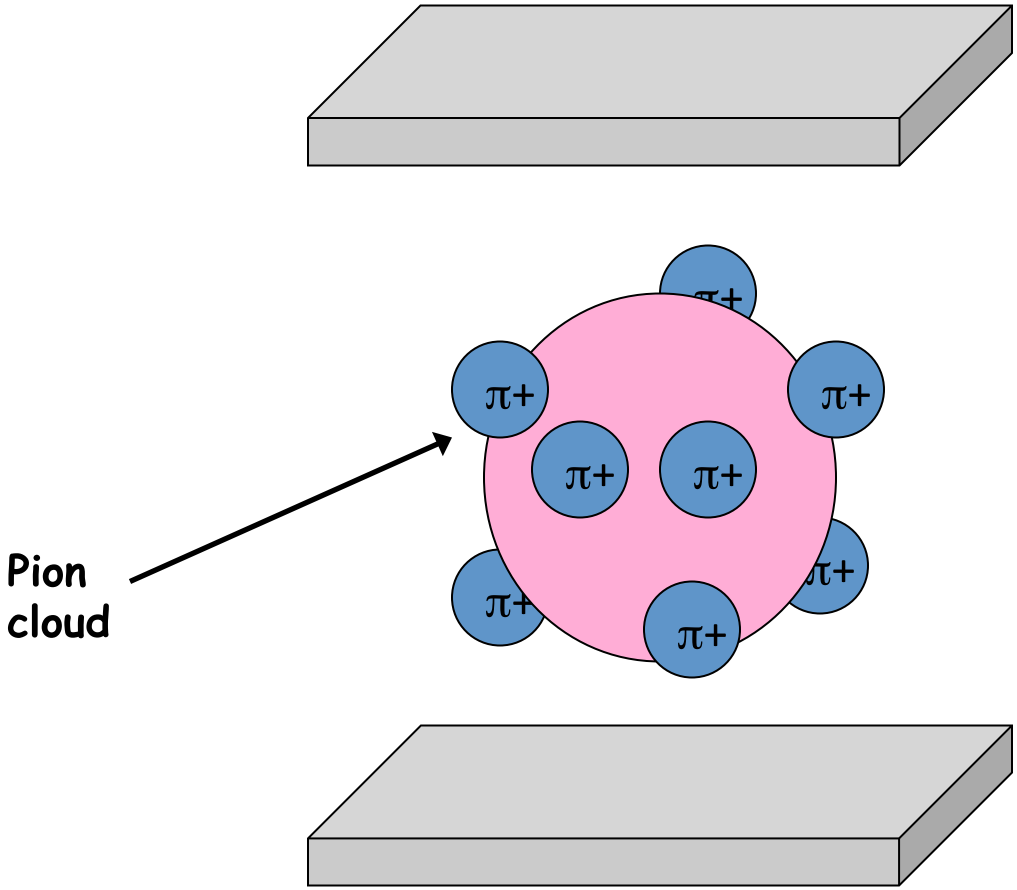
Hadron polarizabilities: new results and future plans

R. Miskimen
University of Massachusetts, Amherst
Hirschegg 2014



Proton electric polarizability



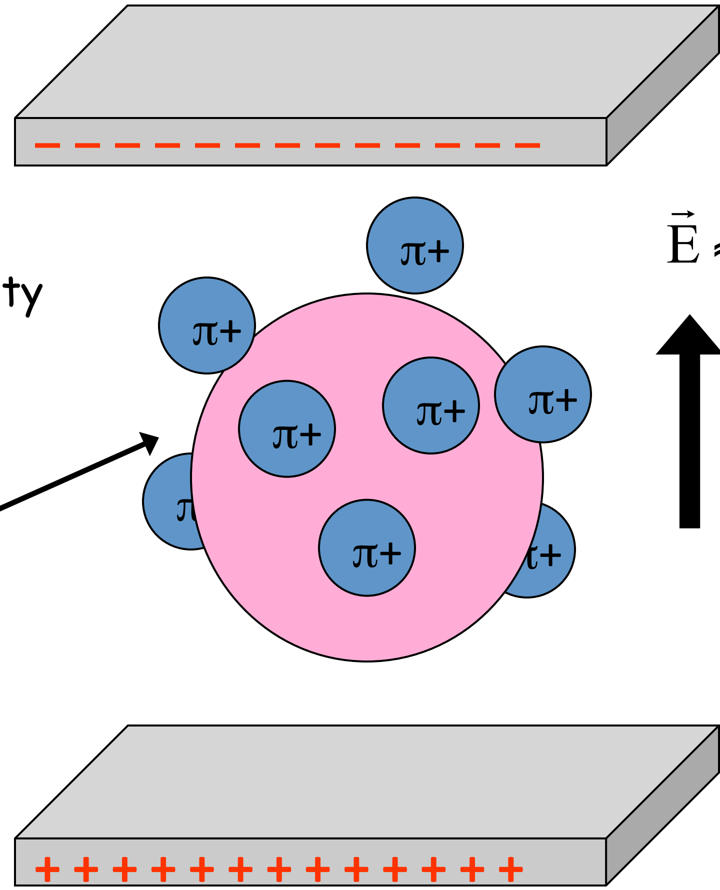
Electric polarizability: proton between charged parallel plates

Proton electric polarizability

$\vec{D} = \alpha \vec{E}$

α = electric polarizability

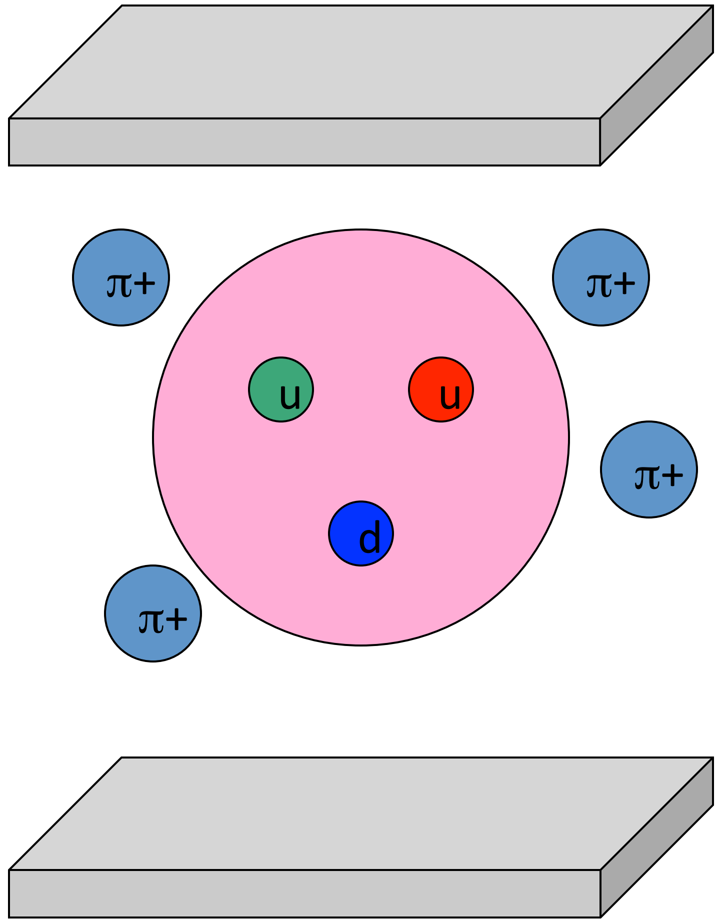
= 10 × Volume × 10^{-4}



$$\vec{E} \approx \frac{100\text{MeV}}{1\text{fm}} = 10^{23}\,\text{volts/m}$$

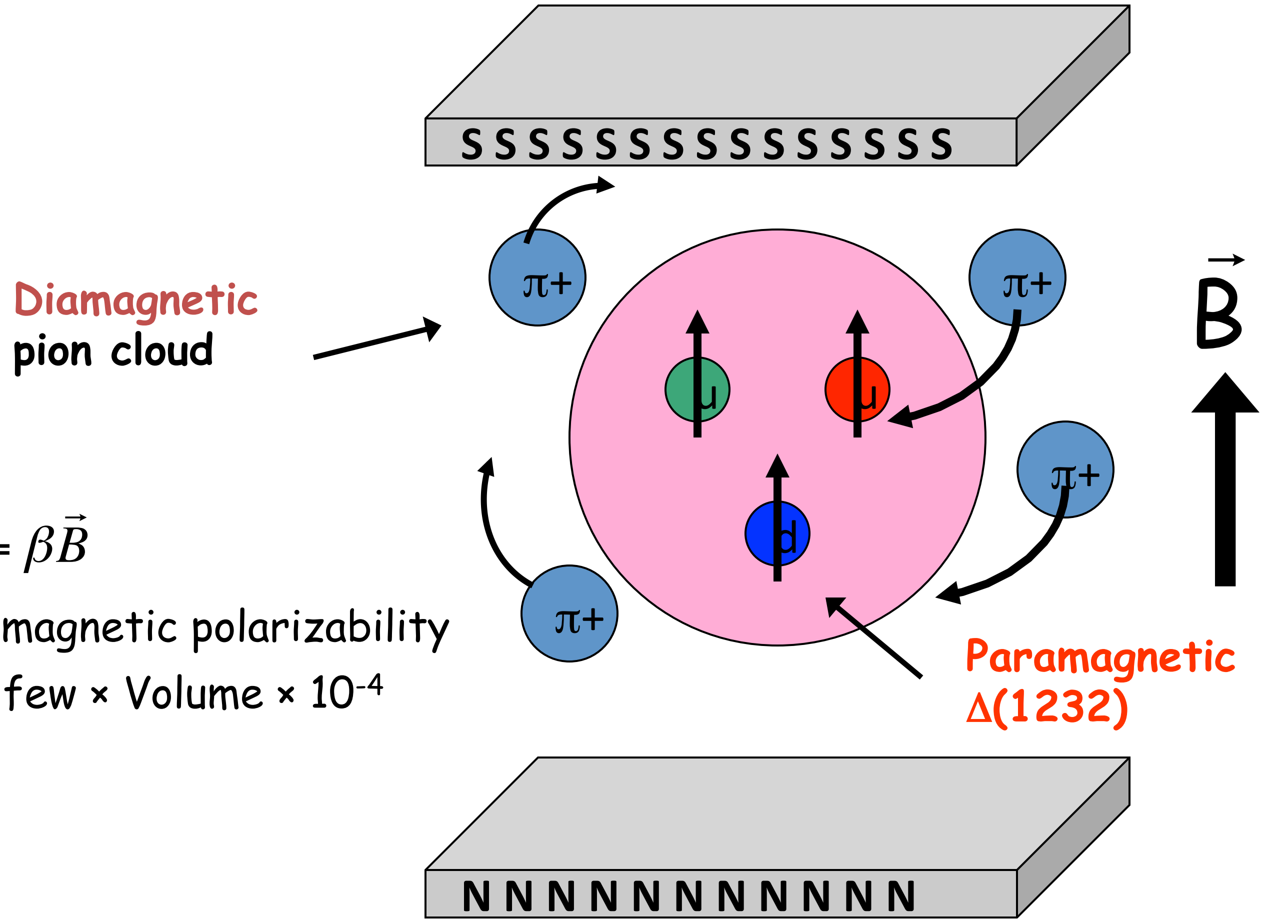
Electric polarizability: proton between charged parallel plates

Proton magnetic polarizability



Magnetic polarizability: proton between poles of a magnetic

Proton magnetic polarizability



$$\vec{M} = \beta \vec{B}$$

β = magnetic polarizability

= few × Volume × 10^{-4}

Magnetic polarizability: proton between poles of a magnetic

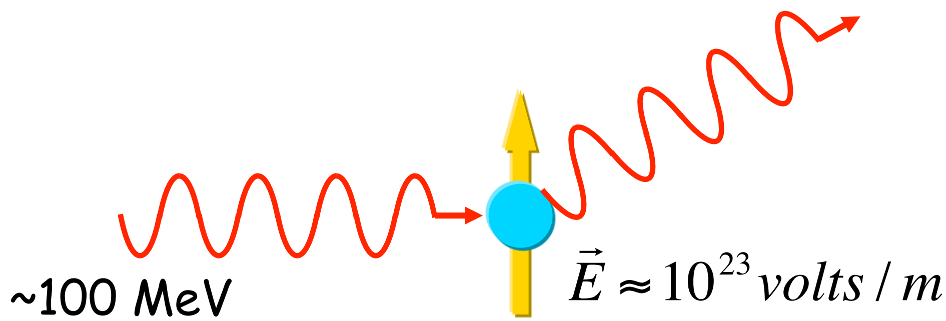
Why measure polarizabilities?

- Polarizabilities are intrinsic properties of hadrons, as fundamental as magnetic moments and masses
- Test theories for nucleon and meson structure
- Input for corrections to μH and μD Lamb shift (see MVdh's talk)
- Knowledge of $\beta_p - \beta_n$ limits calculations of E.M. part of M_n-M_p
- Pion polarizability should be included in calculations of hadronic light-by-light scattering for $(g\text{-}2)_\mu$
- . . .

Outline

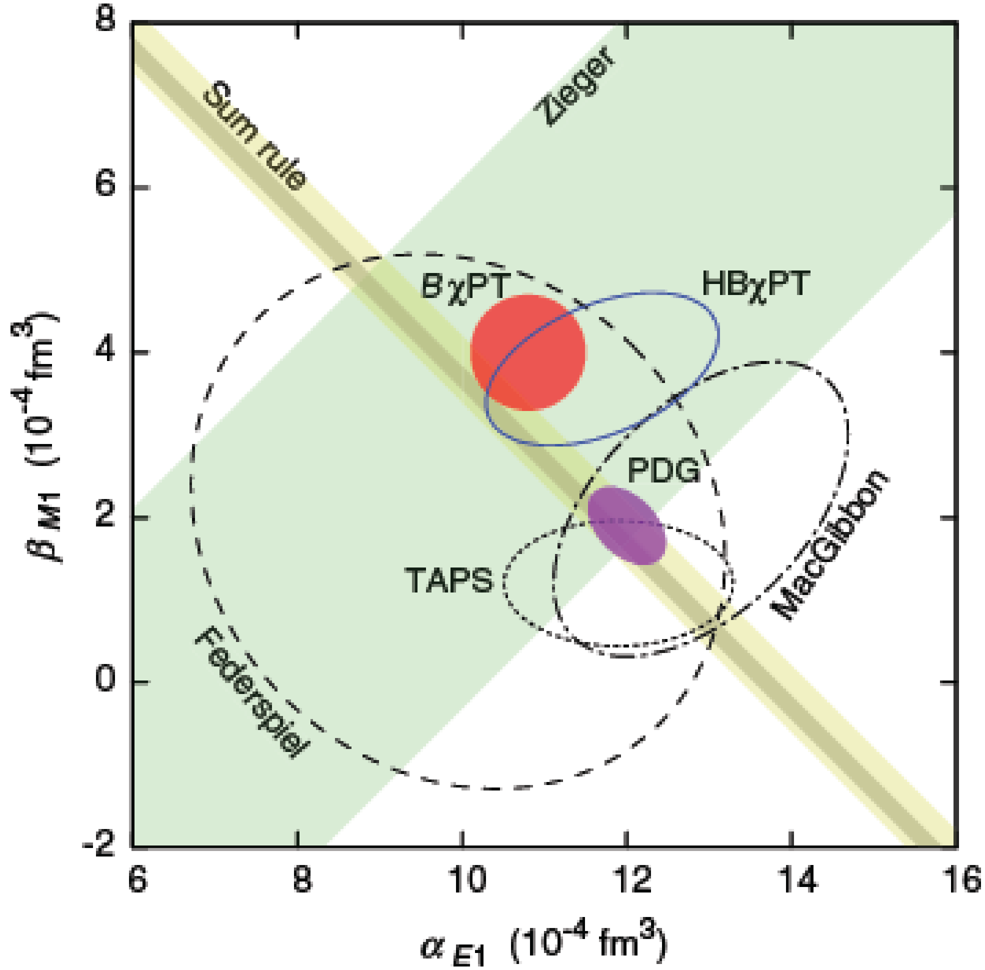
- Measurements of the scalar polarizabilities of the proton, α and β, in real and virtual Compton scattering. Preliminary results with linearly polarized photons
- Measurements of the vector polarizabilities, the spin-polarizabilities, in double-polarized Compton scattering. New results
- Experimental status for the pion polarizability, new measurement at Jefferson Lab

Compton Scattering and the electric and magnetic polarizabilties of the proton



$$H = H_{Born}(e, \vec{\mu}) - 4\pi \underbrace{\left(\frac{1}{2}\alpha \vec{E}^2 + \frac{1}{2}\beta \vec{H}^2 \right)}_{\approx 10\%}$$

Analysis of unpolarized Compton scattering data



Baldin sum rule:

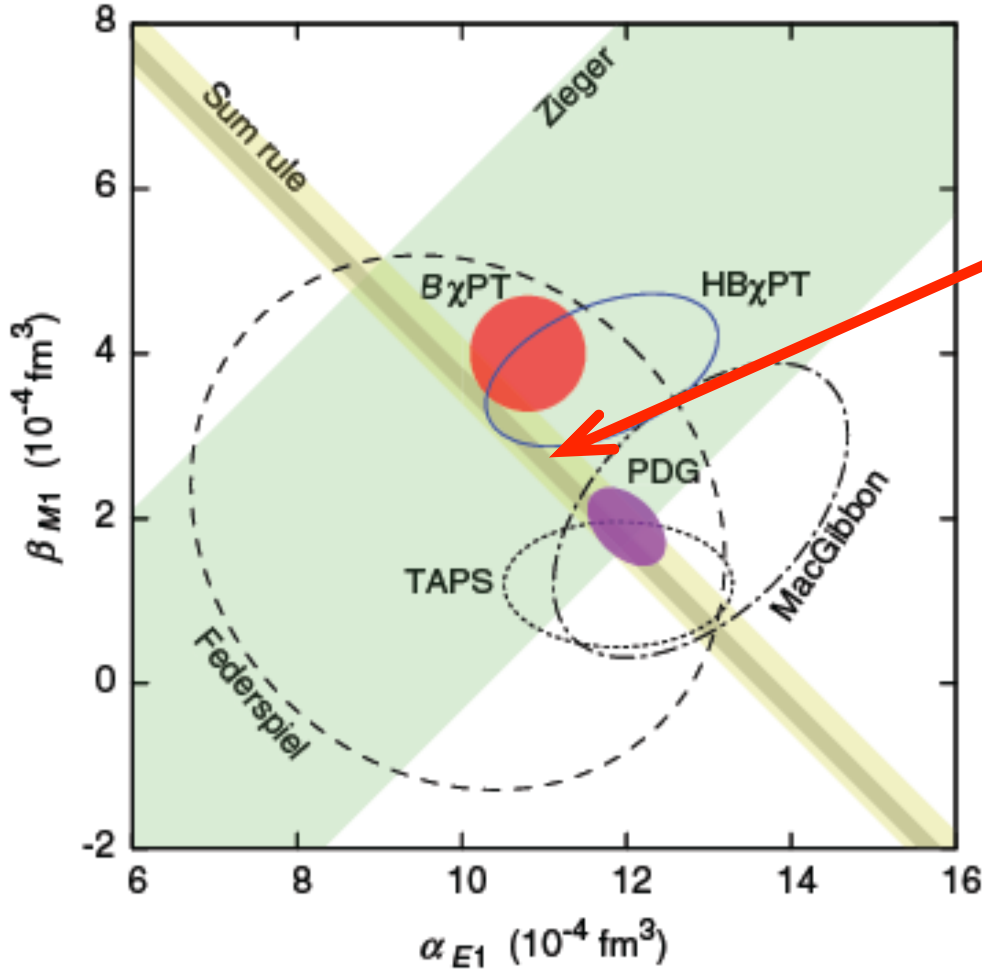
$$\alpha + \beta = \frac{1}{2\pi^2} \int_{\omega_0}^{\infty} \frac{\sigma_{total}(\omega)}{\omega^2} d\omega$$

Theory:

BChPT - Lensky & V.P., EPJC(2010)

HBChPT - Griesshammer, McGovern, Phillips, EPJA (2013)

Analysis of unpolarized Compton scattering data



PDG 2013
$\alpha = 11.2 \pm 0.4 \times 10^{-4}$ fm^3
$\beta = 2.5 \pm 0.4 \times 10^{-4}$ fm^3

Baldin sum rule:

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

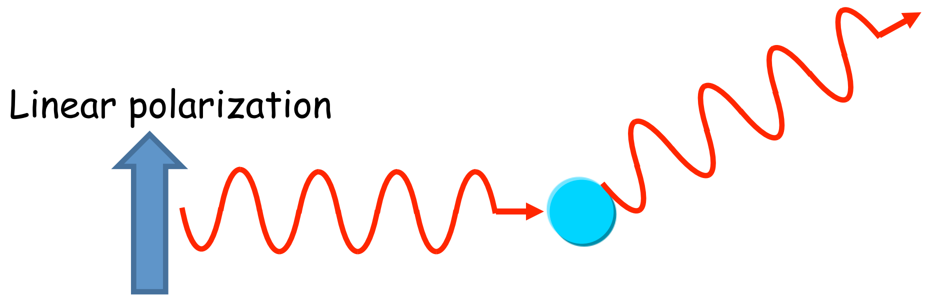
Theory:

BChPT - Lensky & V.P., EPJC(2010)

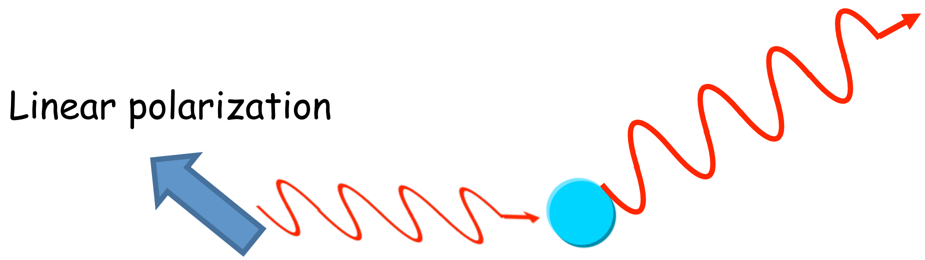
HBChPT - Griesshammer, McGovern, Phillips, EPJA (2013)

Compton scattering with linearly polarized photons at MAMI-Mainz[†]

$$\frac{d\sigma_{\parallel}}{d\Omega}$$



$$\frac{d\sigma_{\perp}}{d\Omega}$$



To second order in the low energy expansion:

$$\alpha \propto \left(\frac{d\sigma_{\perp}}{d\Omega} - \frac{d\sigma_{\perp}^{(Born)}}{d\Omega}\right) - \left(\frac{d\sigma_{\parallel}}{d\Omega} - \frac{d\sigma_{\parallel}^{(Born)}}{d\Omega}\right)$$

$$\beta \propto \cos^2\theta \left(\frac{d\sigma_{\perp}}{d\Omega} - \frac{d\sigma_{\perp}^{(Born)}}{d\Omega}\right) - \left(\frac{d\sigma_{\parallel}}{d\Omega} - \frac{d\sigma_{\parallel}^{(Born)}}{d\Omega}\right)$$

† Mainz proposal MAMI-A2/06-2012, Spokespersons <u>E. Downie</u>, J. Annand, D. Hornidge, R. Miskimen

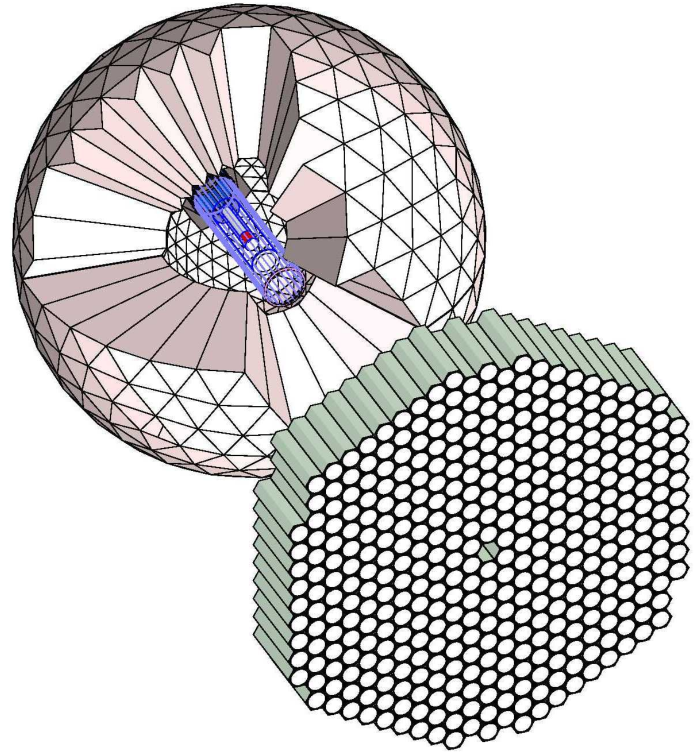
Crystal Ball and TAPS

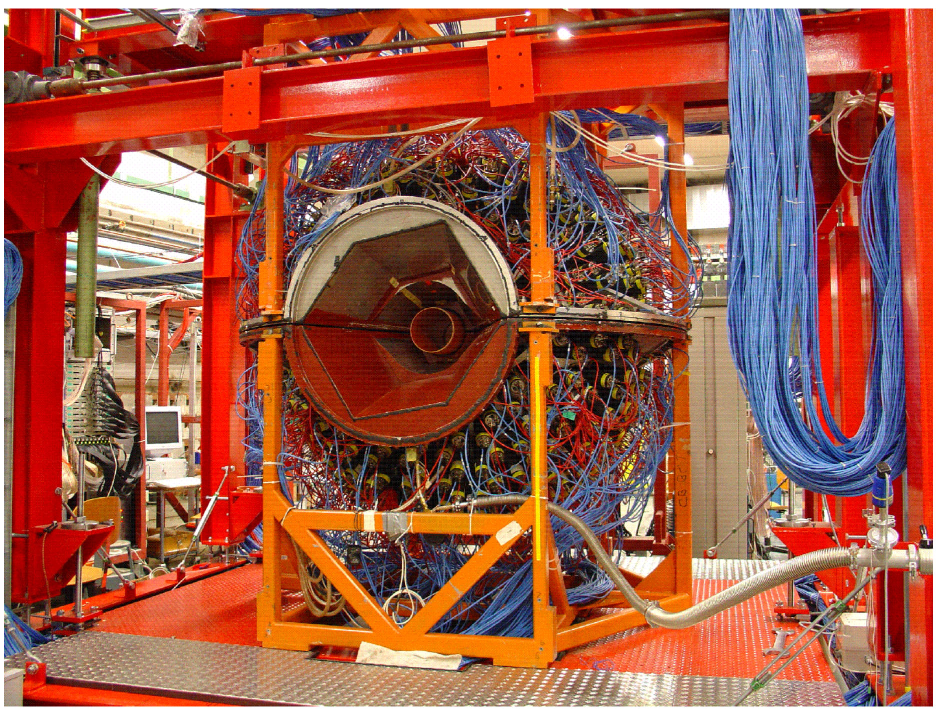
≈ 4π photon detection, 4° < θ < 160°

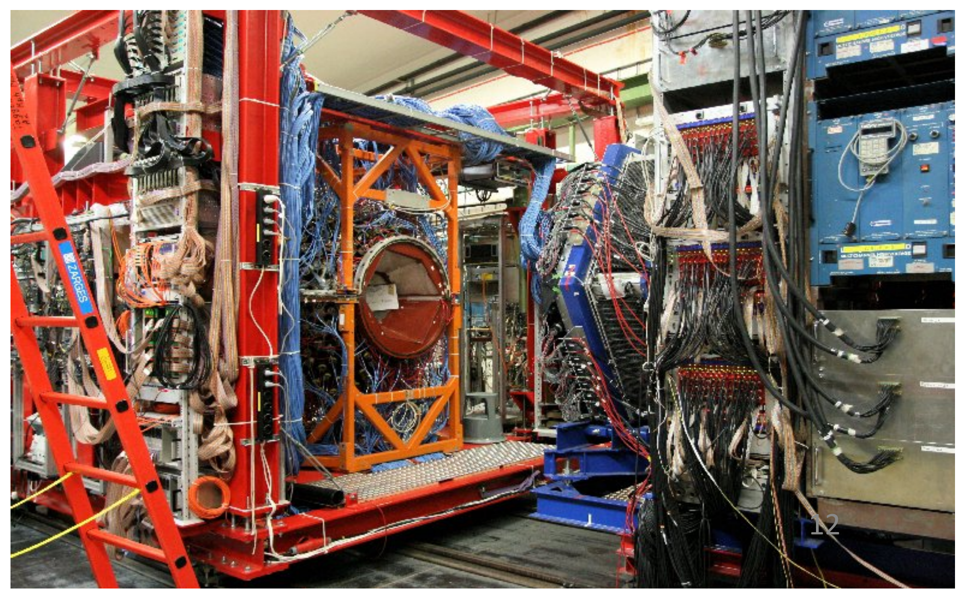
CB: 672 NaI crystals, ΔE~3%, Δθ~2.5°

TAPS: 366 BaF_2 and 72 $PbWO_4$ crystals
ΔE~5%, Δθ~0.7°

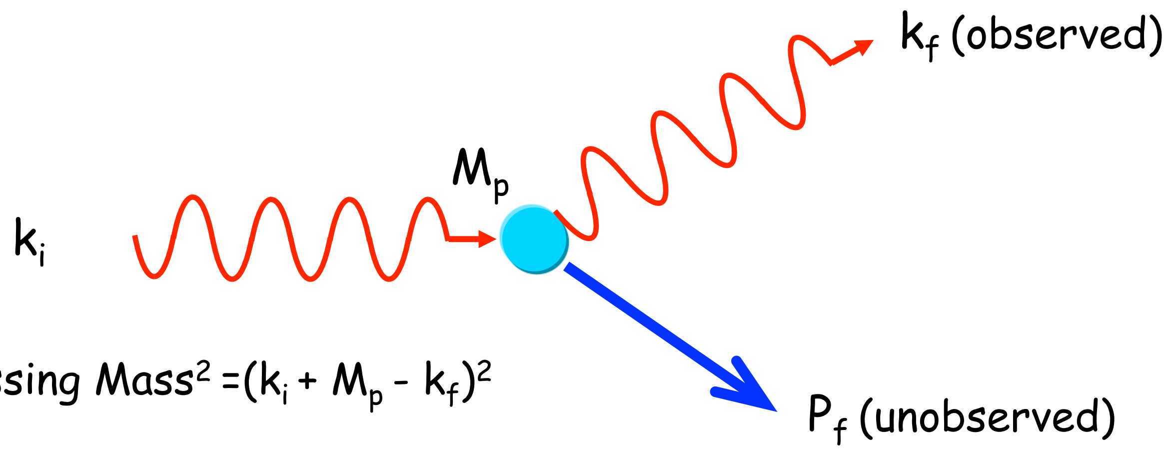
See Bernd Krusche's talk for details of the Mainz facility



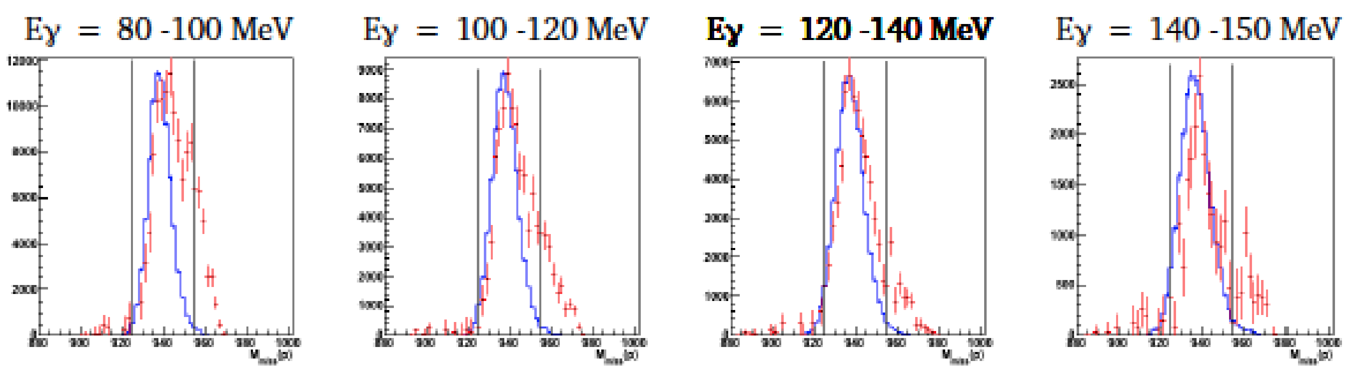




Compton scattering kinematics



Missing Mass^2 $=(k_i + M_p - k_f)^2$



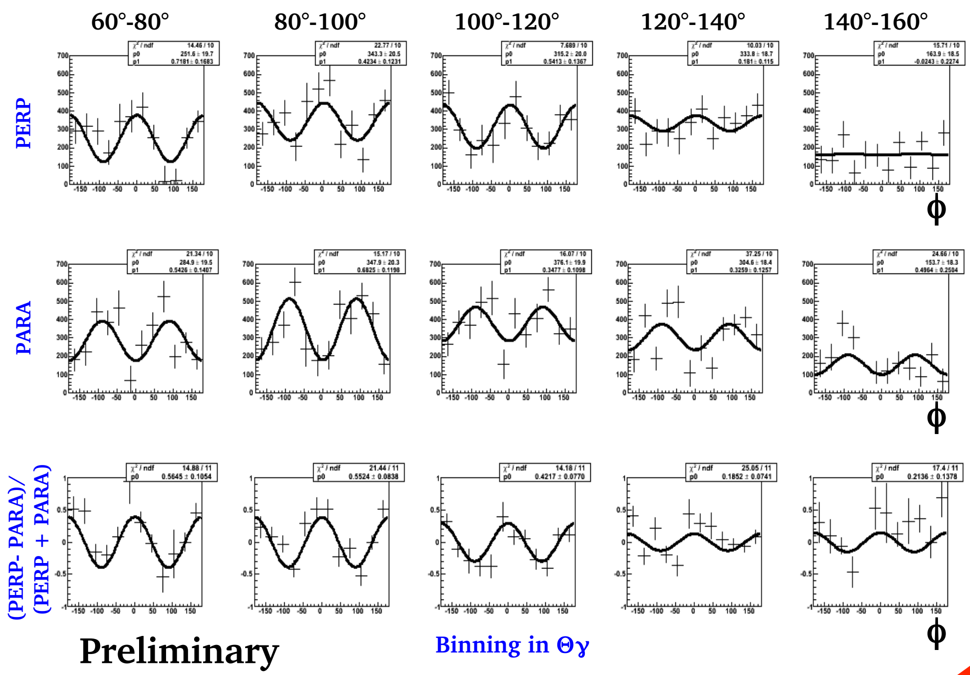
Red: data, Blue: Monte Carlo

Θ_γ = 40° -160°

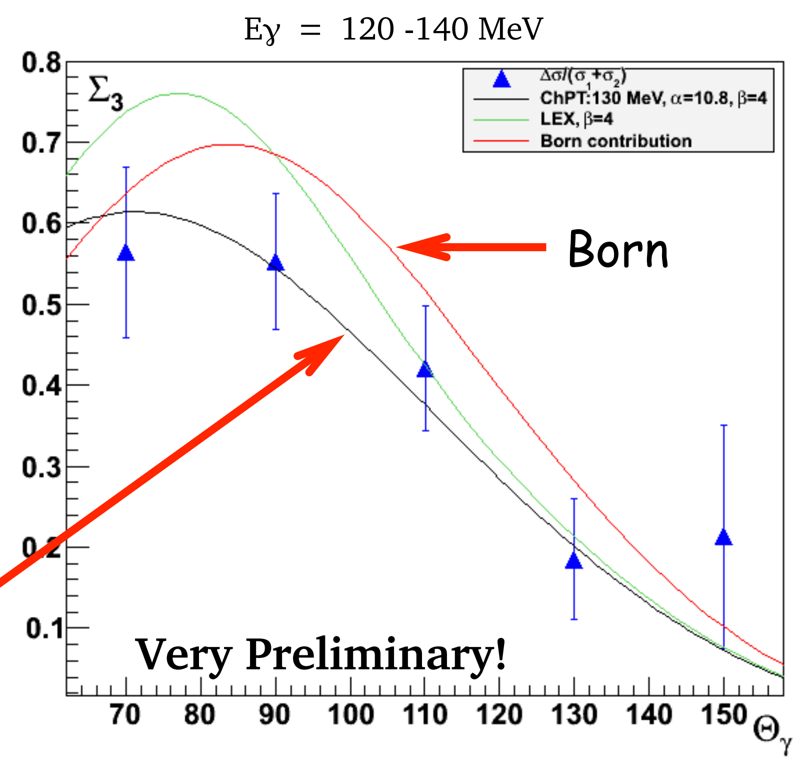
- (Eγ=120 -140 MeV) Data: σ = 7.83 MeV, Monte Carlo: σ = 6.77 MeV
- Low background contribution above 120 MeV
- → Background below 120 MeV under investigation

Preliminary results

ϕ distributions ($E\gamma$ = 120 -140 MeV)



Beam asymmetry Σ_3 : Preliminary results

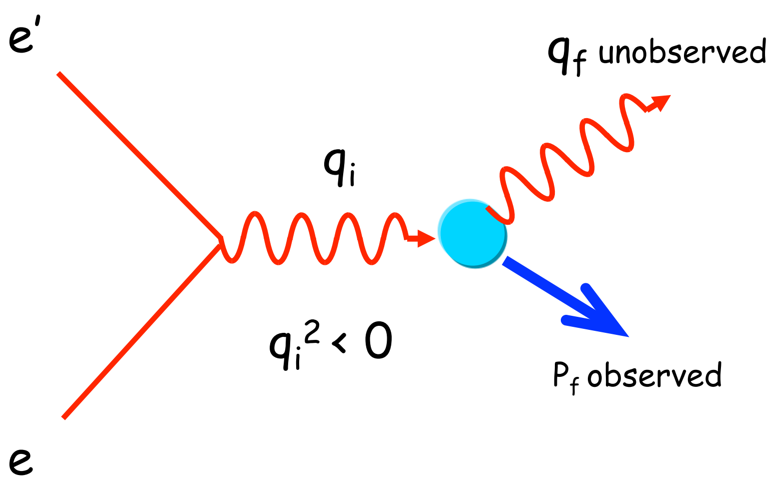


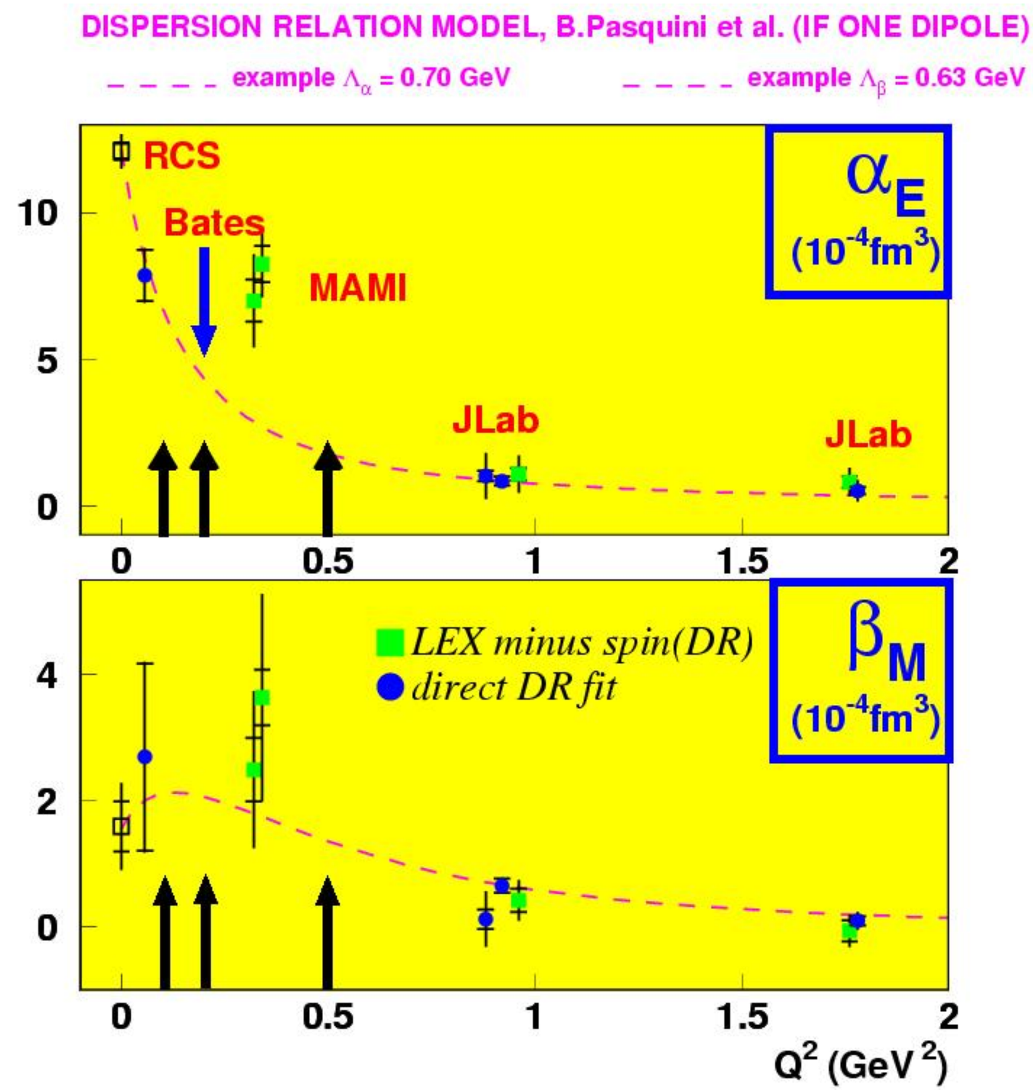
Curves: N. Krupina, V. Pascalutsa [PRL 110, 262001 (2013)]

α = 10.8
β = 4

From Vahe Sokhoyan

Virtual Compton scattering: mapping out the polarizability distributions in the proton at MAMI-A1





See Harald Merkel for details

Measurements of the vector polarizabilities of the proton: the spin-polarizabilities

- At $O(\omega^3)$ four nucleon structure terms involving nucleon spin-flip operators enter the Real Compton Scattering expansion.

$$H_{eff}^{(3),spin} = -\frac{1}{2}4\pi\left(\gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1M1}\vec{\sigma}\cdot\vec{B}\times\dot{\vec{B}} - 2\gamma_{M1E2}E_{ij}\sigma_j H_j + 2\gamma_{E1M2}H_{ij}\sigma_j E_j\right)$$

Where the scalar polarizabilities describe the response of nucleon charge and magnetization distributions to an external electromagnetic field, *spin-polarizabilities describe the response of the nucleon spin to an incident polarized photon.*

Measurements of spin-polarizabilities

The GDH experiments at Mainz and ELSA used the Gell-Mann, Goldberger, and Thirring sum rule to evaluate γ_0

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

$$\gamma_0 = \lim_{Q^2 \to 0} \frac{16\alpha M^2}{Q^6} \int_0^1 x^2 \left[g_1(x,Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x,Q^2) \right] dx$$

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

$$\gamma_0 = (-1.01 \pm 0.08 \pm 0.10) \times 10^{-4}\,\mathrm{fm}^4$$

Backward spin polarizability from analysis of backward angle Compton scattering

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

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

The pion-pole contribution has been subtracted from γ_π

Proton spin-polarizability measurements and predictions in units of 10^{-4} fm^4

	O(p^3)	O(p^4)	O(p^4)	LC3	LC4	SSE	BGLMN	HDPV	KS	DPV	L_χ	Lattice	Experiment
γ_{E1E1}	-5.7	-1.4	-1.8	-3.2	-2.8	-5.7	-3.4	-4.3	-5.0	-3.8	-3.7	?	No data
γ_{M1M1}	-1.1	3.3	2.9	-1.4	-3.1	3.1	2.7	2.9	3.4	2.9	2.5		No data
γ_{E1M2}	1.1	0.2	.7	.7	.8	.98	0.3	-0.01	-1.8	.5	1.2		No data
γ_{M1E2}	1.1	1.8	1.8	.7	.3	.98	1.9	2.1	1.1	1.6	1.2		No data
γ_0	4.6	-3.9	-3.6	3.1	4.8	.64	-1.5	-.7	2.3	-1.1	-1.2		-1.01 ±0.08 ±0.10
γ_π	4.6	6.3	5.8	1.8	-.8	8.8	7.7	9.3	11.3	7.8	6.1		8.0± 1.8

O(p^n) = ChPT, Hemmert, Holstein, McGovern

LC3 and LC4 = O(p^3) and O(p^4) Lorentz invariant ChPT calculations, Scherer

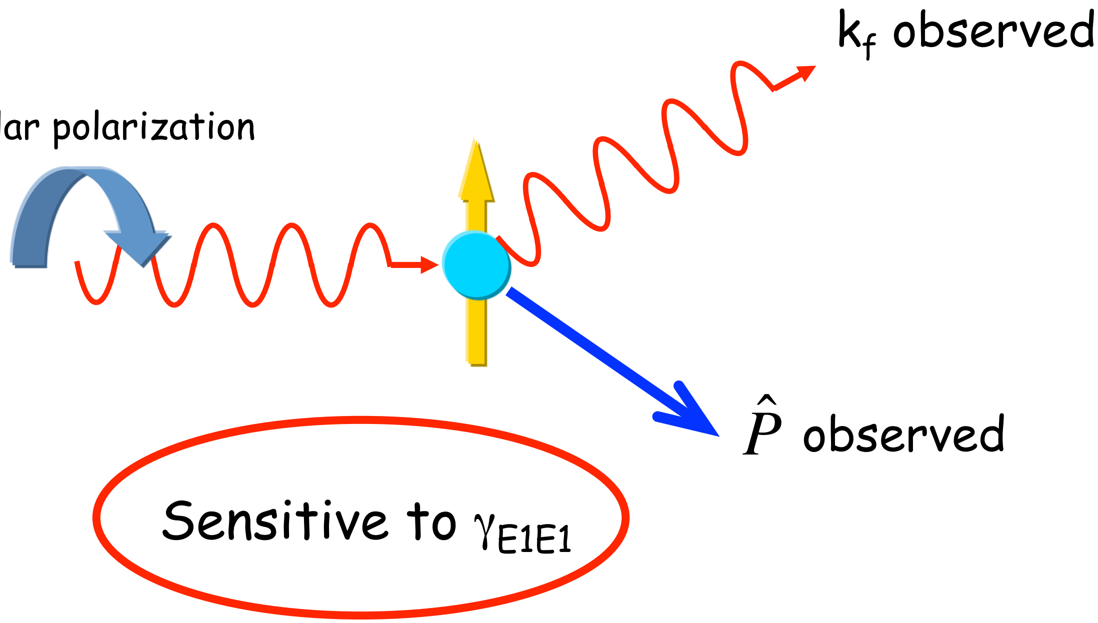
SSE = small scale expansion, Hemmert, Holstein

Dispersion theory calculations, Dreschel, Holstein, Pasquini, VDH, and others

$L\chi$ = Chiral lagrangian calculation, Gasparyan, Lutz

Measurements of double-polarized Compton scattering with transverse polarized target at MAMI-Mainz†

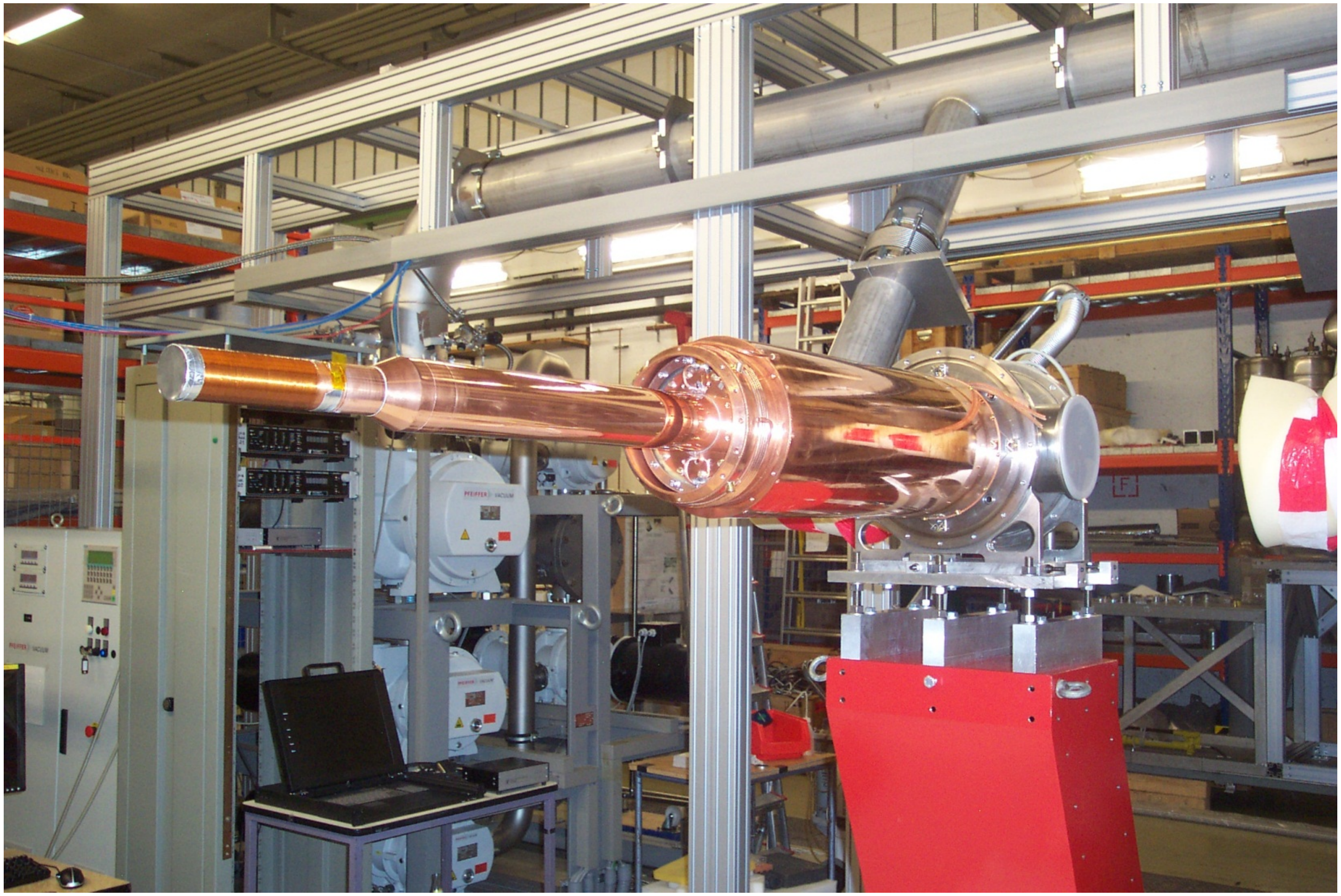
$$\Sigma_{2x} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



† Mainz proposal MAMI-A2/05-2012, Spokespersons D. Hornidge, J. Annand, E. Downie, R. Miskimen

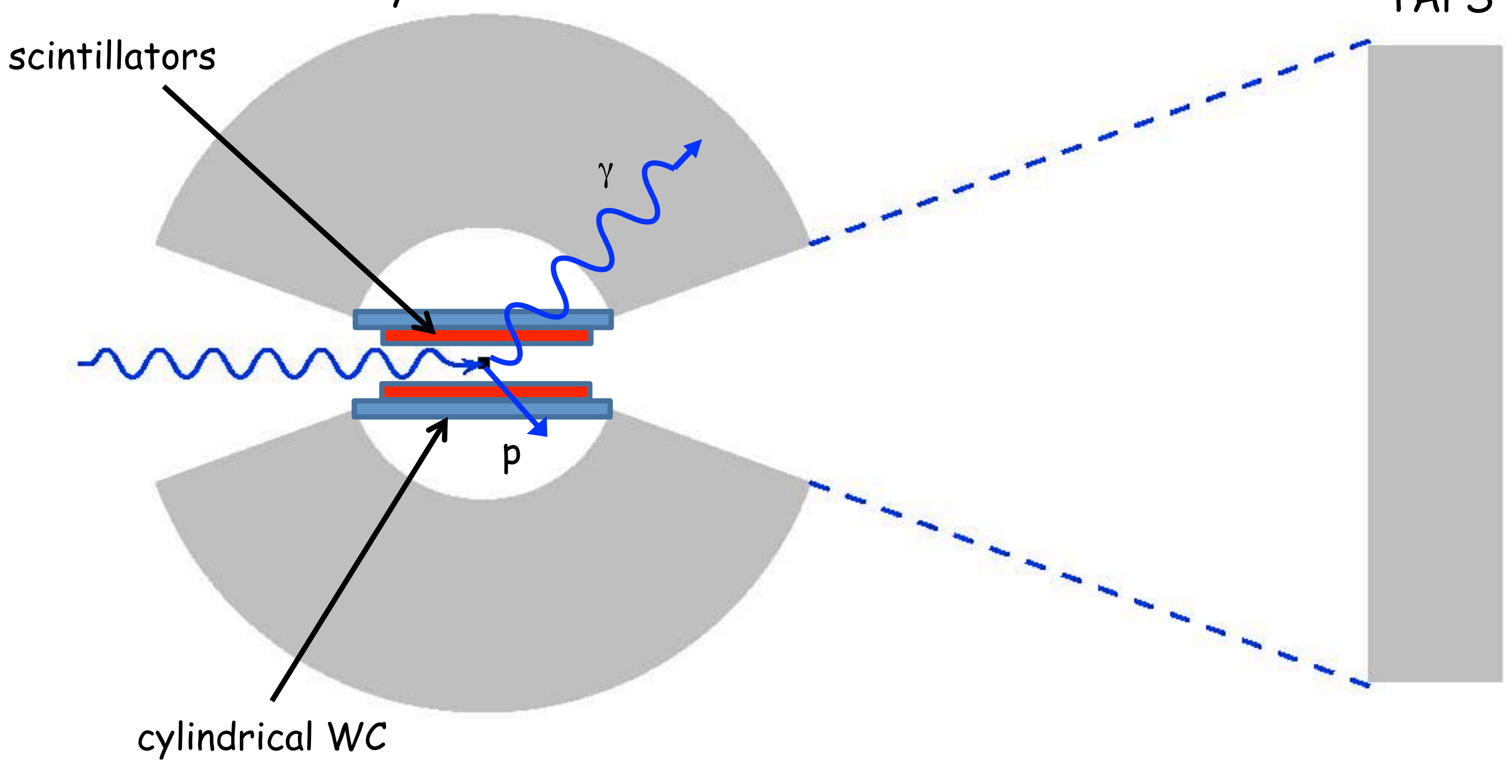
Frozen spin target

- 2 cm butanol
- target polarized at 25 mK
- 0.6 T holding field
- P ~ 90%
- > 1000 hours relaxation time



Event Selection

$$\frac{\sigma(\gamma p \to \gamma p)}{\sigma(\gamma p \to \pi^0 p)} \approx \frac{1}{100} \quad !$$



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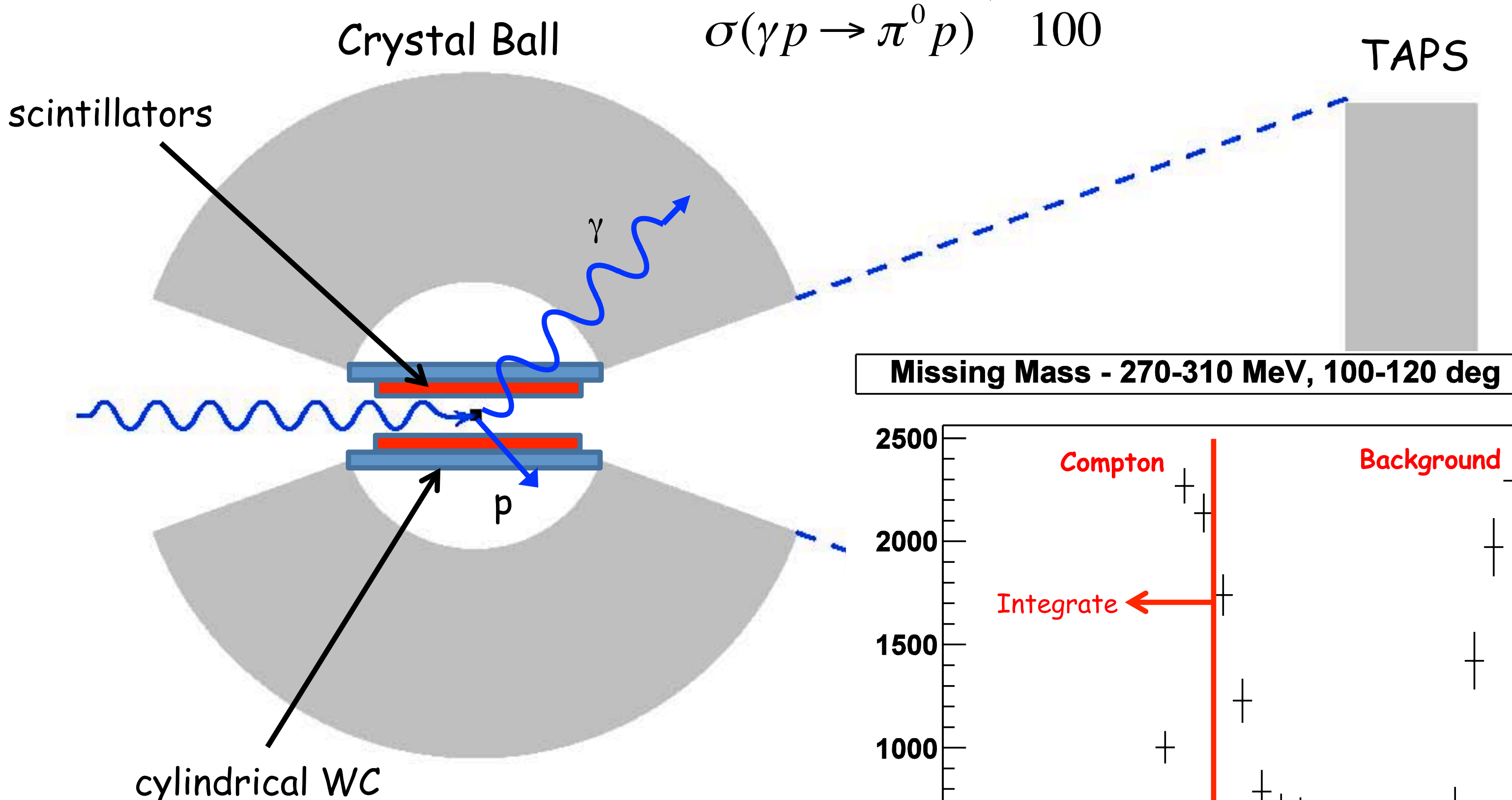
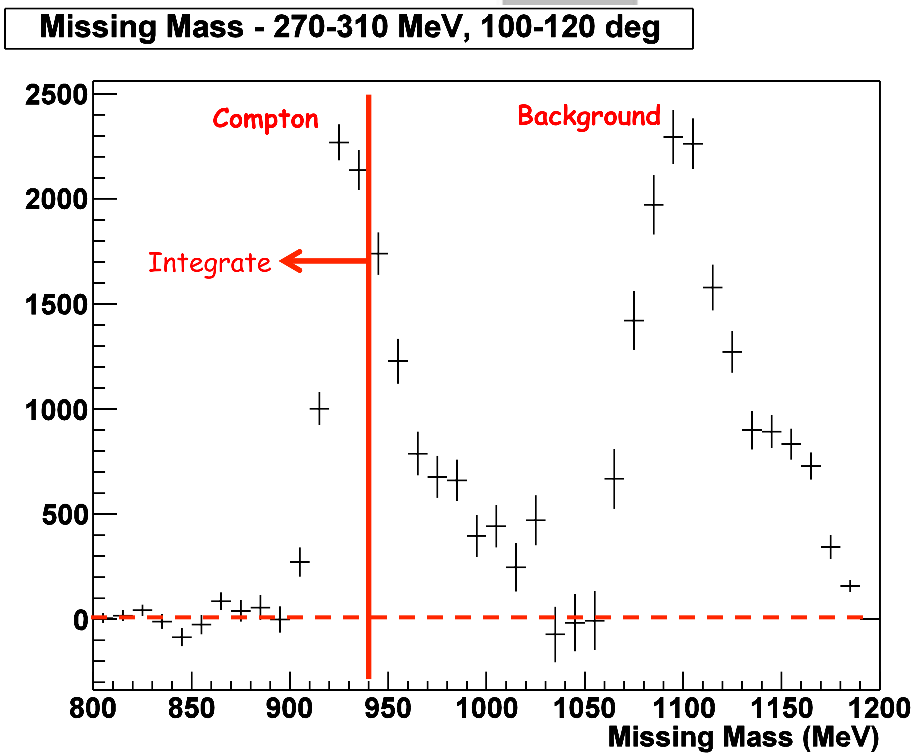
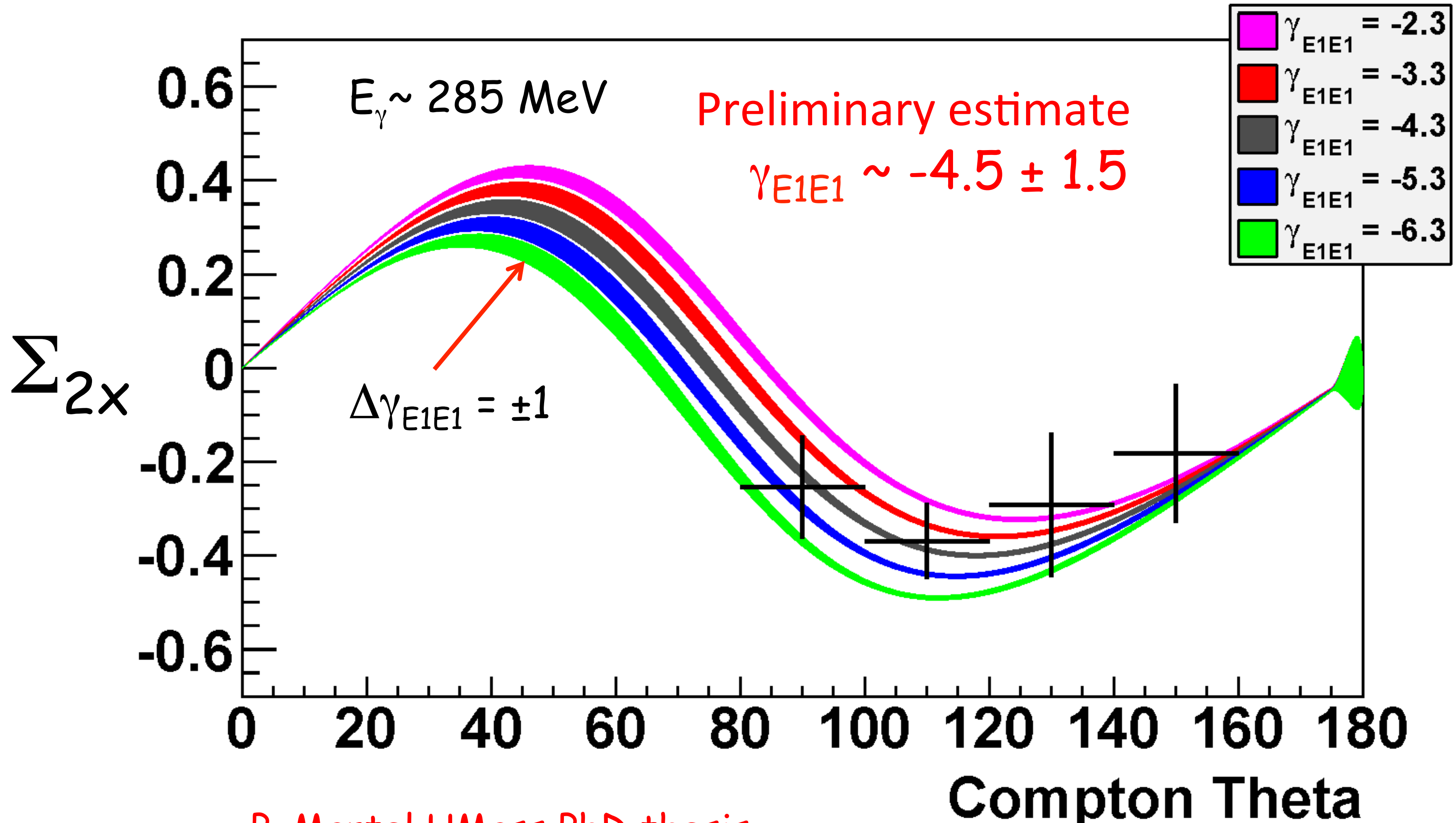




Preliminary results



P. Martel UMass PhD thesis

Analysis of polarized Compton scattering data

Parameters to fit: the 2 scalar and 4 vector polarizabilities

Theoretical models we use:

a. Dispersion model, (Drechsel, Pasquini, Vanderhaeghen)
b. Baryon chiral perturbation theory, with pion, nucleon and Δ degrees of freedom, (Lensky, Pascalutsa)

The data we fit:

4 double-spin asymmetry points, Σ_{2x}, Mainz

$\alpha-\beta$ = 7.6 ± 1.7 Grießhammer, McGovern, Phillips, Feldman analysis

$\alpha+\beta$ = 13.8 ± .4 Baldin sum rule

γ_0 = -1.01 ± .18 GGT sum rule

γ_π = 8.0 ± 1.8 Compton scattering

79 linear polarization asymmetry points, Σ_3 , LEGS collaboration at BNL

Proton spin-polarizability measurements and predictions in units of 10^{-4} fm^4

	$O(p^3)$	$O(p^4)$	$O(p^4)$	LC3	LC4	SSE	BGLMN	HDPV	KS	DPV	L_χ	Lattice	Experiment
γ_{E1E1}	-5.7	-1.4	-1.8	-3.2	-2.8	-5.7	-3.4	-4.3	-5.0	-3.8	-3.7	?	**-3.2± 1.1**
γ_{M1M1}	-1.1	3.3	2.9	-1.4	-3.1	3.1	2.7	2.9	3.4	2.9	2.5		**3.2± .8**
γ_{E1M2}	1.1	0.2	.7	.7	.8	.98	0.3	-0.01	-1.8	.5	1.2		**-.9± 1.1**
γ_{M1E2}	1.1	1.8	1.8	.7	.3	.98	1.9	2.1	1.1	1.6	1.2		**2.0± .2**
γ_0	4.6	-3.9	-3.6	3.1	4.8	.64	-1.5	-.7	2.3	-1.1	-1.2		-1.01 ±0.08 ±0.10
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$O(p^n)$ = ChPT, Hemmert, Holstein, McGovern

LC3 and LC4 = $O(p^3)$ and $O(p^4)$ Lorentz invariant ChPT calculations, Scherer

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$L\chi$ = Chiral lagrangian calculation, Gasparyan, Lutz

Low energy QCD and charged pion polarizability

$$L_{QCD}(p^4) = L^{chiral-even}(p^4) + L^{chiral-odd}(p^4)$$

Charged pion polarizability

$$\alpha_\pi = -\beta_\pi = \frac{4\alpha}{m_\pi F_\pi^2}\left(L_9^r - L_{10}^r\right)$$

P^6 corrections are small

$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}\, fm^3$$

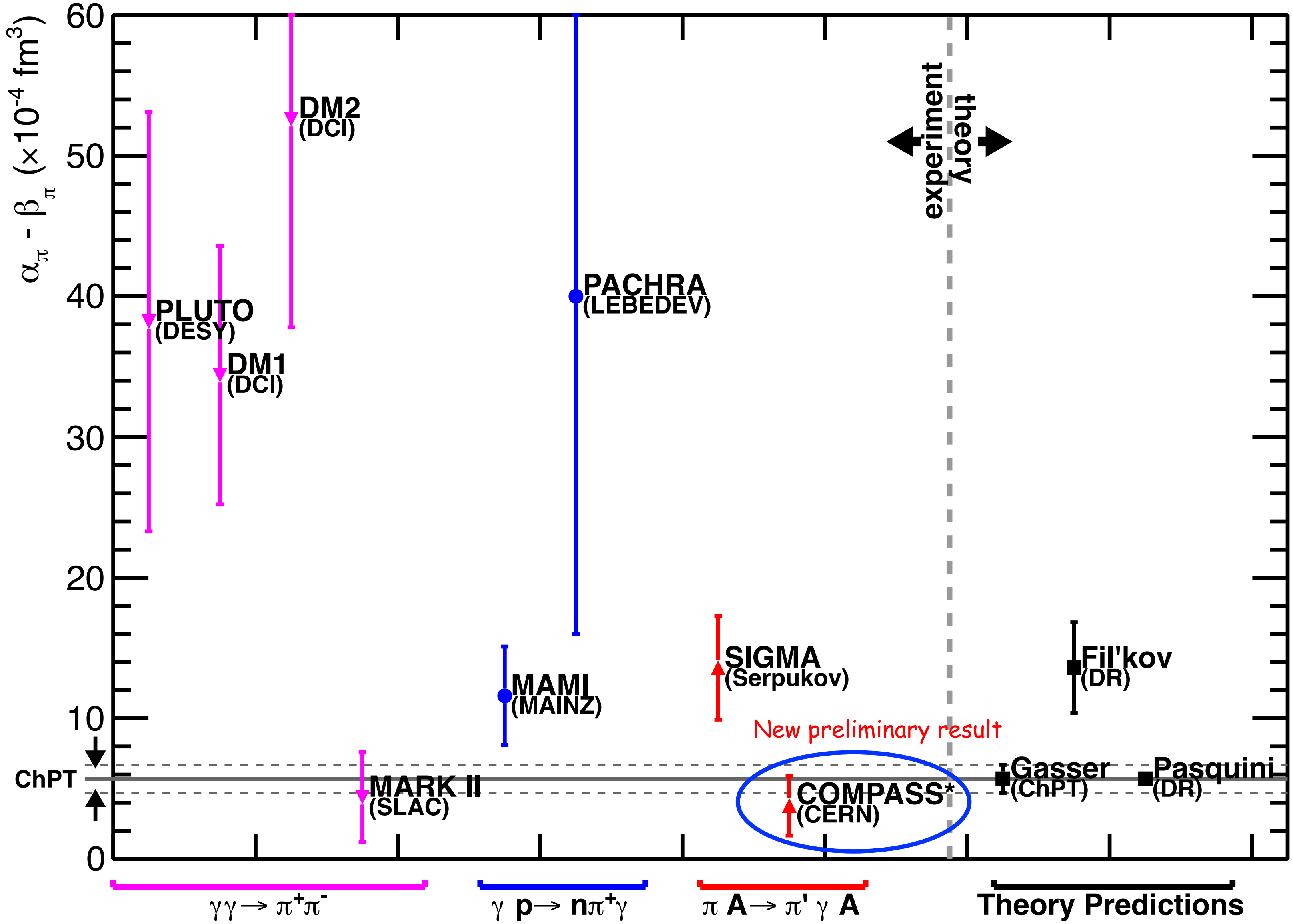
$$\alpha_\pi + \beta_\pi = (0.16 \pm 1.0) \times 10^{-4}\, fm^3$$

$$\pi^0 \to \gamma\gamma$$

$$A_{\gamma\gamma} = \frac{\alpha N_C}{3\pi F_\pi}$$

Primex result

$\Gamma(\pi^0 \to \gamma\gamma) = 7.80$ eV $\pm$ 2.8%



*COMPASS result from DNP2013 abstract NJ00005

See Stephan Paul for details

Hadronic light-by-light scattering correction to $(g-2)_\mu$ and the charged pion polarizability

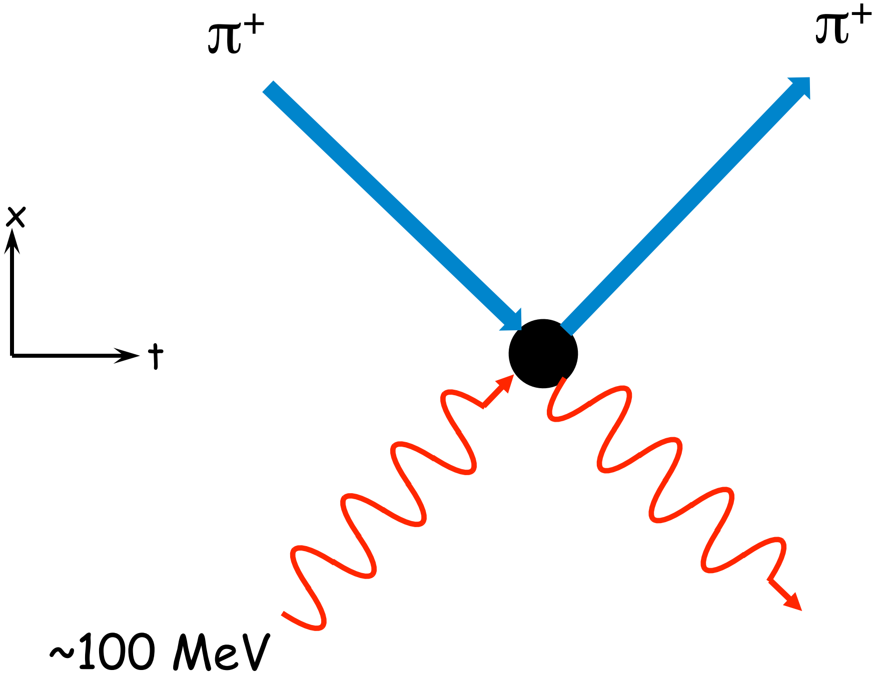
$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{TH} = 287(83) \times 10^{-11}$ (W. Marciano, arXiv: 1001.4528/hep-ph)

Model calculation by Ramsey-Musolf shows that including the pion polarizability in the HLBL *increases the discrepancy between experiment and the standard model* by as much as $\approx 60 \times 10^{-11}$, depending on the value of $\alpha_\pi - \beta_\pi$, and the choice of QCD model

Projected error on the Fermi Lab $(g\text{-}2)_\mu$ measurement is $\Delta a_\mu = \pm\, 16{\times}10^{-11}$

Engel, Patel, Ramsey-Musolf, Phys. Rev. D 86, 037502 (2012)
Engel, Ramsey-Musolf, arXiv:1309.2225v1 [hep-ph] 2013

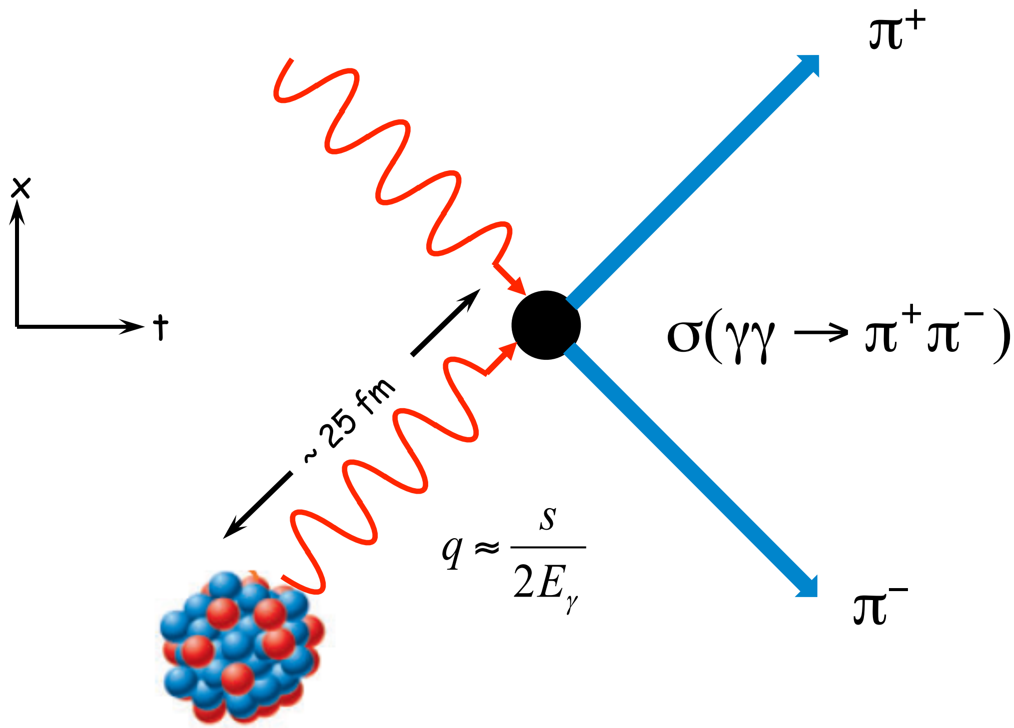
Compton Scattering on the pion



$$H = H_{Born}\left(e,\vec{\mu}\right) - 4\pi\left(\frac{1}{2}\alpha_{\pi}\vec{E}^{2} + \frac{1}{2}\beta_{\pi}\vec{H}^{2}\right)$$

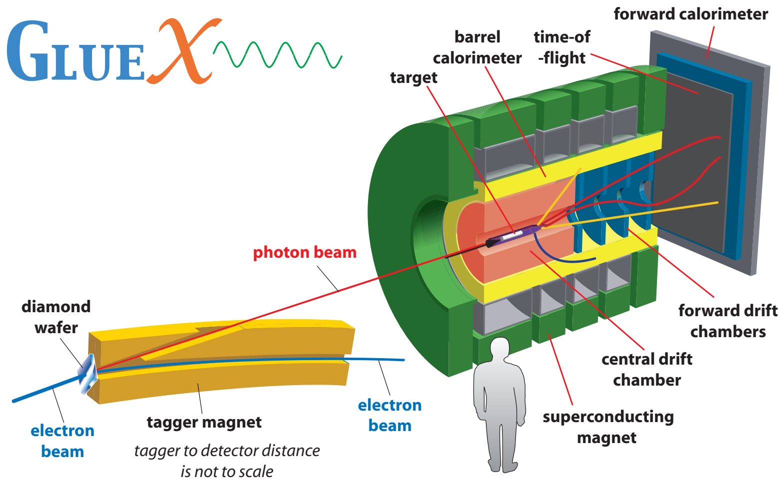
Crossing symmetry (x ↔ t):

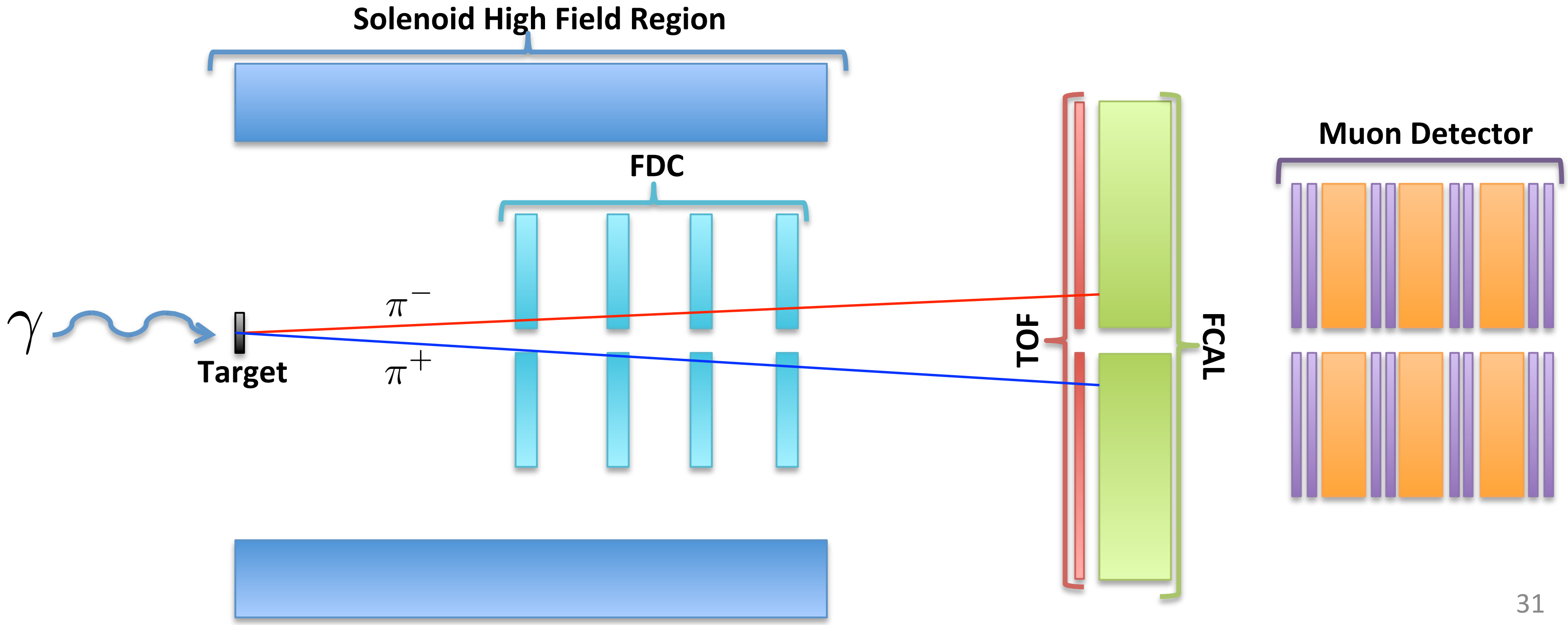
Compton scattering ⟺ $\gamma\gamma \to \pi^+\pi^-$

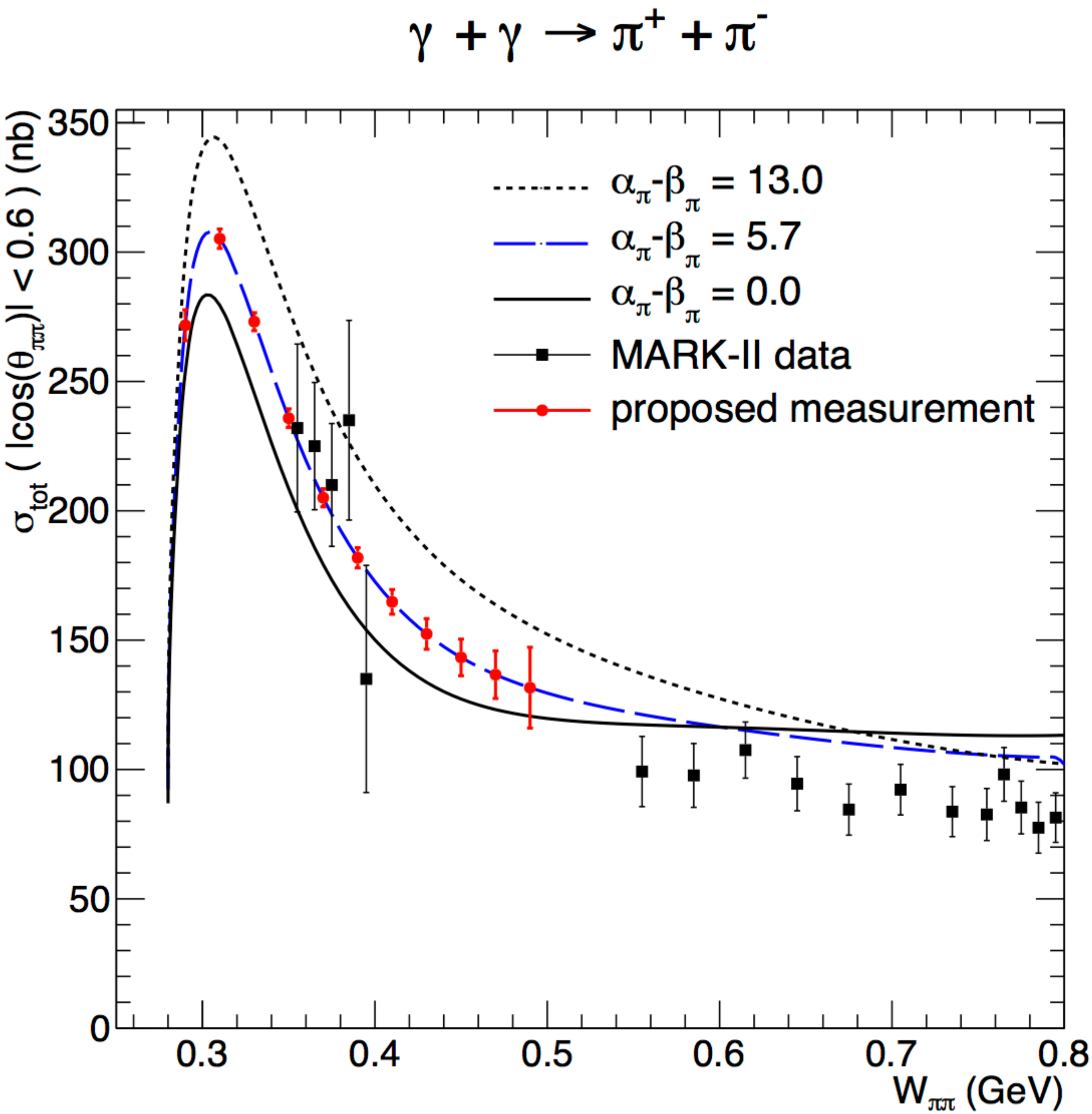


$$\frac{d^2\sigma_{\mathrm{Pr}\,imakoff}}{d\Omega dM} = \frac{2\alpha Z^2}{\pi^2}\frac{E_\gamma^4\beta^2}{M}\frac{\sin^2\theta}{Q^4}\left|F(Q^2)\right|^2\left(1+P_\gamma\cos 2\varphi_{\pi\pi}\right)\sigma(\gamma\gamma\to\pi\pi)$$

Proposed experimental setup at JLab/GlueX







γ + γ → π⁺ + π⁻
σ_tot (|cos(θ_ππ)| < 0.6) (nb)
W_ππ (GeV)
α_π-β_π = 13.0
α_π-β_π = 5.7
α_π-β_π = 0.0
MARK-II data
proposed measurement
0
50
100
150
200
250
300
350
0.3
0.4
0.5
0.6
0.7
0.8

Summary

- New data on the linear-polarization asymmetry Σ_3 has been taken at Mainz.
- Presented first results for a double-polarized Compton scattering asymmetry on the proton below 2π threshold
- Analysis using dispersion and BChPT calculations
- Results obtained for γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, γ_{M1E2} are in good agreement with dispersion theory calculations

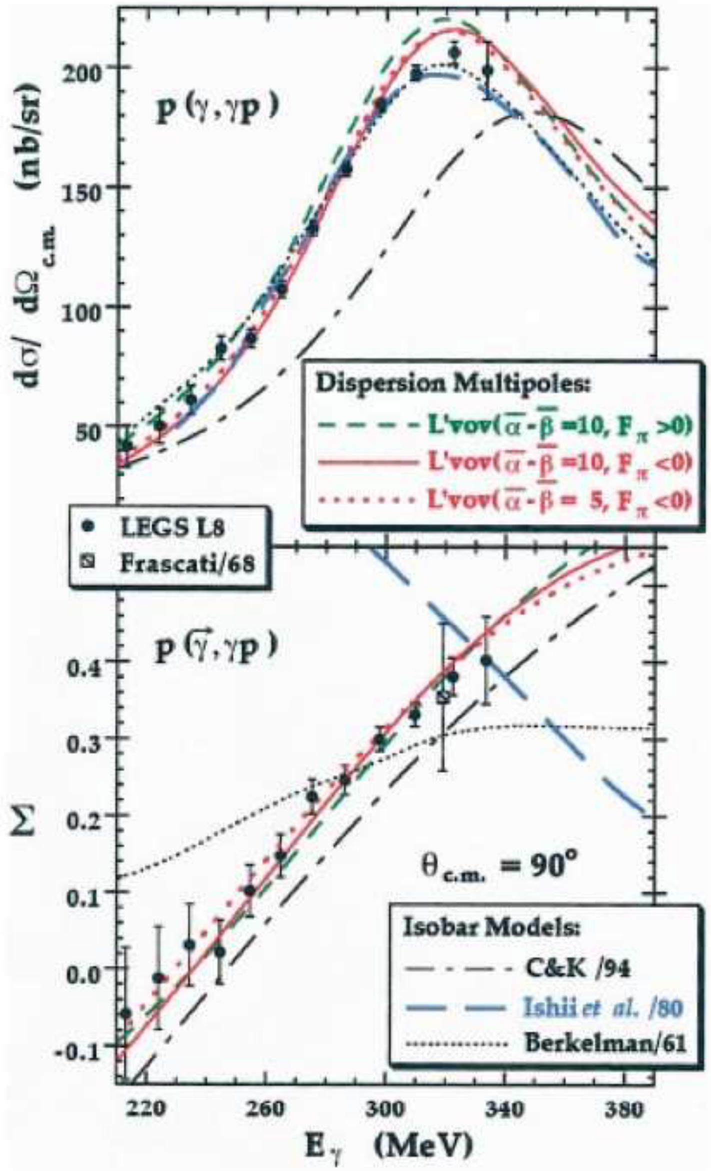
Advertisement

- Data on the double-polarized asymmetry with longitudinal target Σ_{2z} will be taken this spring, will constrain γ_π
- A precision measurement of the charged pion polarizability is being prepared for JLab/GlueX

Thank you!

and special thanks to P. Martel, V. Sokhoyan, and the Mainz A2 collaboration

Blanpied et al., PRC 64, 25203 (2001)



LEGS

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

$d\sigma/d\Omega$ and $\boldsymbol{\Sigma}_3$

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

$\theta_{\gamma'} = 90^\circ$ **ONLY!**