Recent results on Compon scattering @ MAMI and on the extraction of the proton polarizabilities

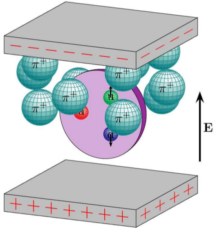
Muonic Atoms @ PSI2022

Edoardo Mornacchi

Johannes Gutenberg University of Mainz

Mainz, October 15th 2022

Proton scalar polarizabilities



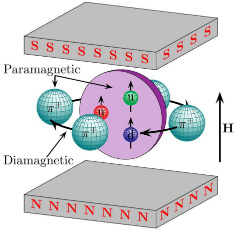
Describe the response of a proton to an applied electric field:

- Electric dipole moment

$$\vec{p} = \boxed{\alpha_{E1}} \times \vec{E}$$

Electric polarizability

- "Stretchability" of the proton



Picture: P. Martel

Describe the response of a proton to an applied magnetic field:

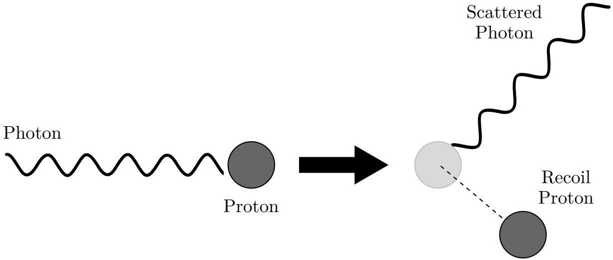
- Magnetic dipole moment

$$\vec{m} = \boxed{\beta_{M1}} \times \vec{H}$$

Magnetic polarizability

- "Alignability" of the proton

Nuclear Compton scattering



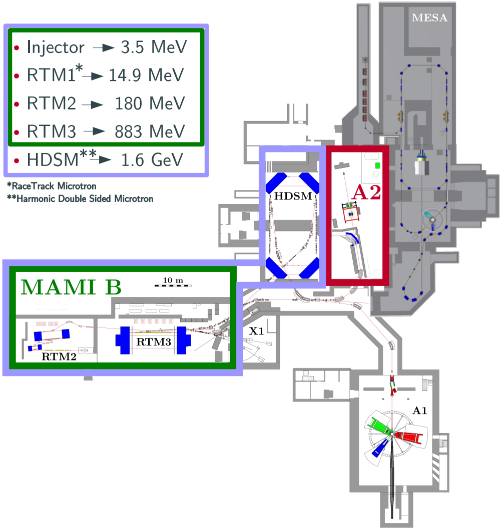
$$\gamma(k) + P(q) \rightarrow \gamma(k') + P(q')$$

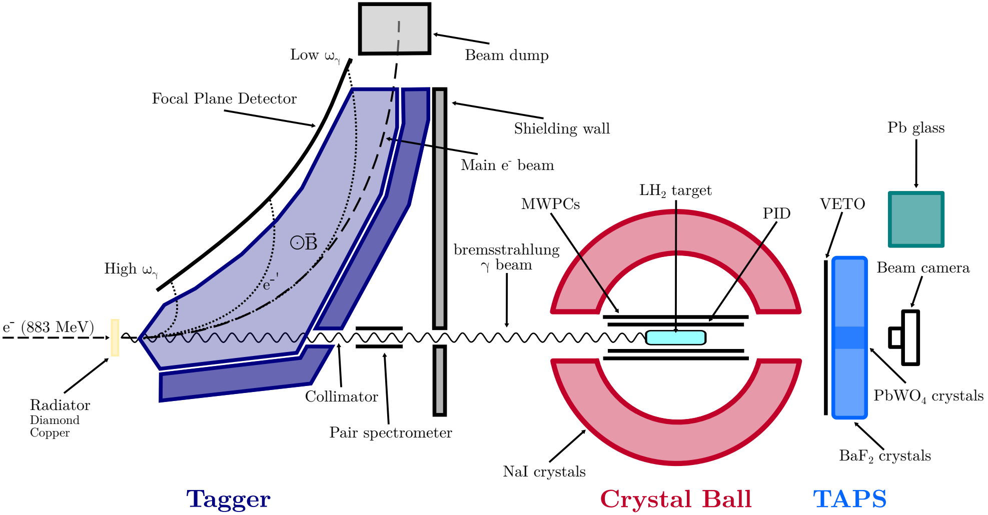
The internal structure of the proton can be accessed by measuring unpolarized cross-section and polarization observables for Compton scattering

A2@MAMI Measurement

MAinz MIcrotron (MAMI)

- Continuous electron beam
- Polarized or unpolarized electrons
- $I_{e^-}^{\max} = 20\ \mu A$ or $100\ \mu A$ (pol/unpol)




Beam dump
Low ω_γ
Focal Plane Detector
Shielding wall
Main e$^-$ beam
Pb glass
$\odot\vec{B}$
MWPCs
LH$_2$ target
PID
VETO
bremsstrahlung
γ beam
High ω_γ
e$^{-\prime}$
Beam camera
e$^-$ (883 MeV)
Radiator
Diamond
Copper
Collimator
Pair spectrometer
PbWO$_4$ crystals
BaF$_2$ crystals
NaI crystals
Tagger
Crystal Ball
TAPS

Experiment

New high precision data collected during two separated beamtimes in the first half of 2018

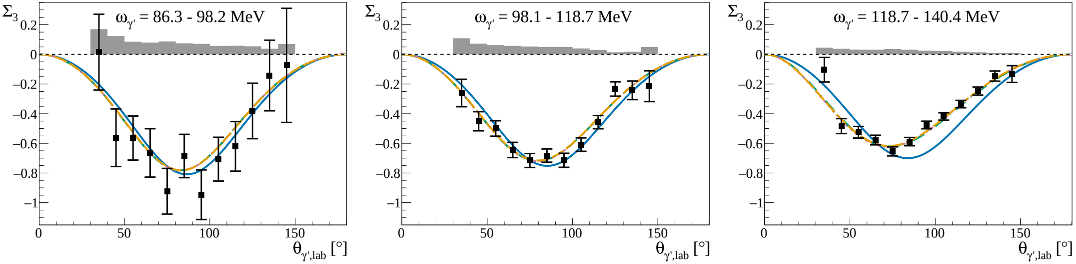
Data analysis to select Compton scattering events in $\omega_\gamma = 85 - 140$ MeV and $\theta_{\gamma'} = 30^\circ - 150^\circ$:

- Single neutral cluster events
- Subtraction of random coincidences in the tagging spectrometer
- Subtraction of the empty target contribution
- Background rejection using missing mass cut

1.2 millions Compton scattering events in the relevant kinematic region!

Perform a simultaneous measurement of the unpolarized differential cross-section and the beam asymmetry Σ_3

Results on the beam asymmetry Σ_3



A2: Phys. Rev. Lett. **128** (2022)

Systematic errors

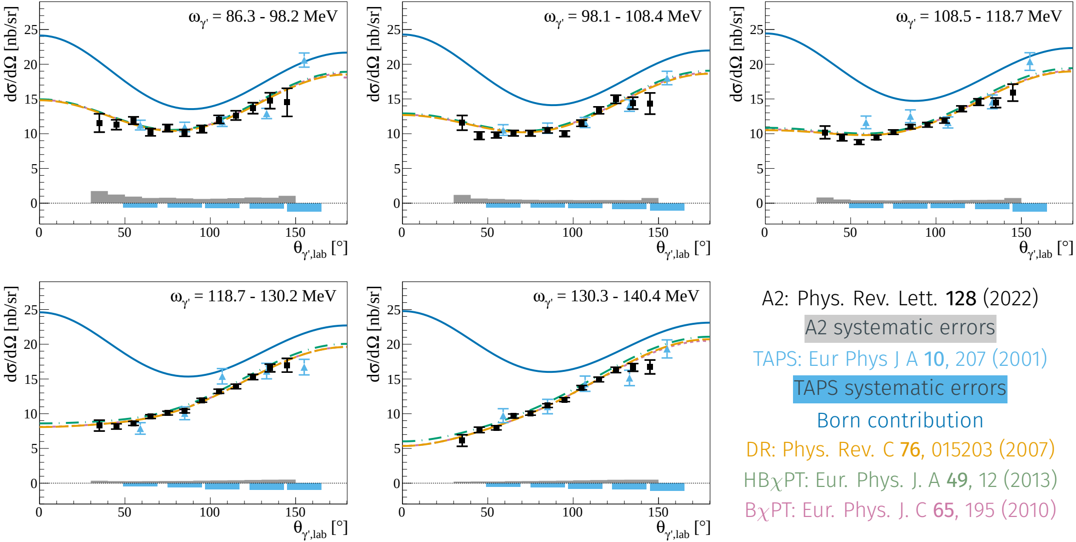
Born contribution

DR: Phys. Rev. C **76**, 015203 (2007)

BχPT: Eur. Phys. J. C **65**, 195 (2010)

HBχPT: Eur. Phys. J. A **49**, 12 (2013)

Results on the unpolarized cross-section



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A2 systematic errors

TAPS: Eur Phys J A **10**, 207 (2001)

TAPS systematic errors

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Extracting the scalar polarizabilities

- Only new data used as input
- Systematic errors included as normalization factor (S) for each individual dataset
- Baldin sum rule constraint added as an additional point with its error
- Spin polarizabilities fixed to the most recent experimental evaluation
- Scalar polarizabilities always in units of 10^{-4} fm^3

$$\chi^2(\mathcal{P}) = \sum_j^{N_{sets}} \left(\sum_i^{N_{pt}^j} \left(\frac{s_j O_{ij}^{exp} - O_{ij}^{thr}(\mathcal{P})}{s_j \Delta O_{ij}^{exp}} \right)^2 + \left(\frac{s_j - 1}{\Delta s_j} \right)^2 \right)$$

Extracting the scalar polarizabilities

E. Mornacchi (A2), Phis. Rev. Lett. ***128****, 132503 (2022)*

	HDPV	BChPT	HBChPT
α_{E1}	11.23 ± 0.49	10.65 ± 0.50	11.10 ± 0.52
β_{M1}	2.79 ± 0.32	3.28 ± 0.33	3.36 ± 0.38
S_σ	1.011 ± 0.015	1.013 ± 0.015	1.043 ± 0.016
S_Σ	0.994 ± 0.015	0.996 ± 0.015	1.001 ± 0.015
χ^2/DOF	$82.10/93 = 0.89$	$82.96/93 = 0.89$	$83.16/93 = 0.89$

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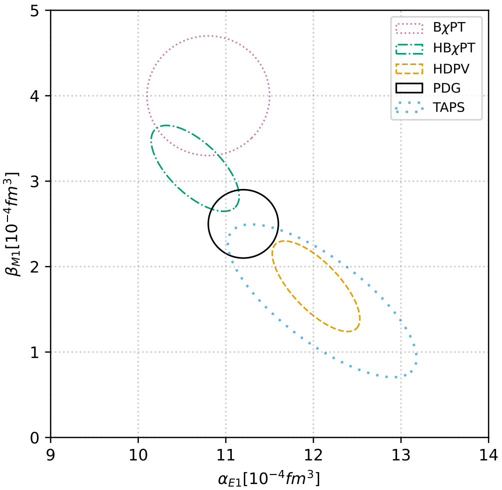

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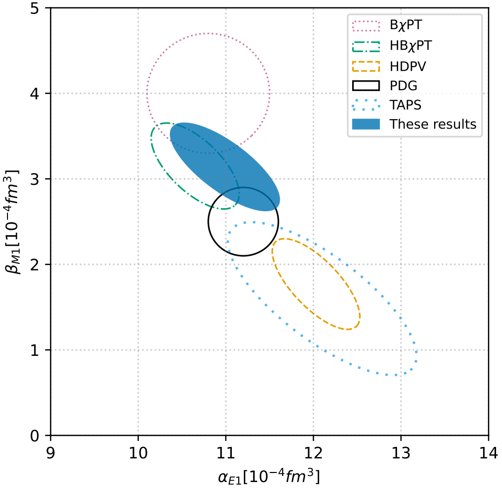
$$\alpha_{E1} = 10.99 \pm 0.16 \pm 0.47 \pm 0.17 \pm 0.34$$
$$\beta_{M1} = 3.14 \pm 0.21 \pm 0.24 \pm 0.20 \pm 0.35$$



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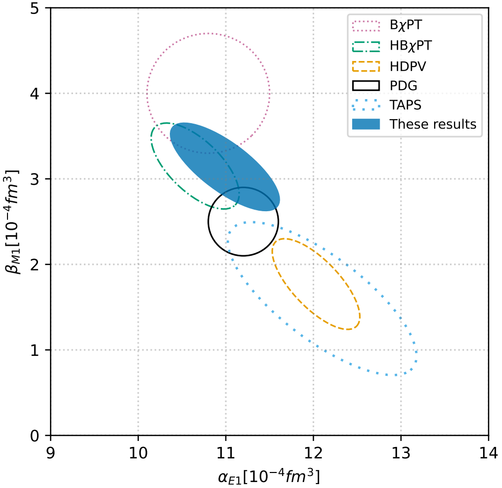
- Highest precision Compton scattering dataset below π-photoproduction threshold!
- Precise extraction of the scalar polarizabilities from one single dataset



Global leading-order polarizabilities extraction

Method

- fixed-t Dispersion relation model
- Three different PWA solution used: MAID-2021, SAID-MA19, BnGA-2019
- All six polarizabilities are treated as free parameters
- Parametric bootstrap technique needed to include all possible sources of systematic uncertainties

$$e_{i,j}^{(0)} \rightarrow e_{i,j}^{(b)} = (1 + \delta_{j,b})(e_{i,j}^{(0)} + r_{i,j,b}\sigma_{i,j}^{(0)})$$

  - inclusion of common systematic uncertainties without any *a priori* distribution assumption
  - probability distribution of the fit parameters obtained by the procedure
  - uncertainties on nuisance model parameters are taken into account in the sampling procedure
  - fit p-value is provided if goodness-of-fit distribution is not given by the χ^2

As many data points as possible were initially included in the fit!

- All existing unpolarized low-energy data ($E_\gamma < 150$ MeV)
  - 14 datasets, 218 points[1]
- New-generation (a.k.a. photon-tagged) unpolarized high-energy data ($E_\gamma = [150 - 300]$ MeV)
  - 6 datasets, 156 points
- Polarized ($\sigma_{||}$, $\sigma_\perp$, Σ_{2x}, Σ_{2z}, and Σ_3) data
  - 7 datasets, 137 points[2]

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[1] including 10 above-thr points from TAPS
[2] 65 below- and 72 above-thr

Datasets

First author	# of points	$\theta_{\gamma'}$ [°]	E_γ [MeV]
Unpolarized low-energy data			
Baranov	7	90, 150	82 – 111
Bernardini	2	135	120, 139
de Leon	55	59 – 155	59 – 150
Federspiel	16	60, 135	30 – 70
Goldansky	5	75 – 150	55
Hallin	13	45 – 135	130 – 150
Hyman	12	50, 90	60 – 130
Li	8	55, 90, 125	81
MacGibbon	8	90, 135	70 – 100
MacGibbon	10	90, 135	100 – 140
Mornacchi	60	35 – 145	85 – 140
Oxley	4	70 – 150	60
Pugh	16	45, 90, 135	55 – 125
Zieger	2	180	98, 132

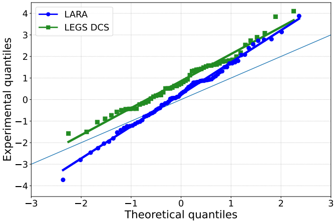
First author	# of points	$\theta_{\gamma'}$ [°]	E_γ [MeV]
Unpolarized high-energy data			
Blanpied	57	51 – 126	213 – 298
Camen	5	136	210 – 293
Molinari	4	90 (cms)	250 – 289
Peise	8	75 (cms)	200 – 291
Wissmann	6	131	199 – 295
Wolf	76	48 – 148	264 – 294

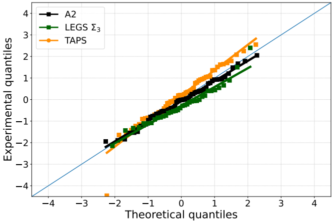
First author	Observable	# of points	$\theta_{\gamma'}$ [°]	E_γ [MeV]
Polarized low-energy data				
Li	$\sigma_{\parallel}$	5	55, 90, 125	83
Li	$\sigma_{\perp}$	3	55, 90, 125	83
Mornacchi	Σ_3	36	35 – 145	92, 108, 129
Sokhoyan	Σ_3	21	60 – 150	87, 109, 129
Polarized high-energy data				
Blanpied	Σ_3	58	65 – 135	213 – 298
Martel	Σ_{2x}	4	90 – 150	285
Paudyal	Σ_{2z}	10	85 – 150	275, 295

Inconsistencies among unpolarized high-energy data are known to exist, especially between LARA (Wolf) and LEGS (Blanpied) datasets! As fist, a consistency check of the database was performed:

- Fit all six polarizabilities using MAID-2021 alternatively including LARA or LEGS
- Using the polarizability best-values, the residual were calculated
- For every big dataset, the residual normal distribution was assessed using a probability plot

All datasets had normally distributed residual, except both LARA and LEGS





LARA and LEGS DCS datasets were excluded from the fit!

The final database included

- All existing unpolarized low-energy data ($E_\gamma < 150$ MeV)
  - 14 datasets, 218 points[3]
- New-generation (a.k.a. photon-tagged) unpolarized high-energy data ($E_\gamma = [150 - 300]$ MeV)
  - 4 datasets, 23 points
- Polarized ($\sigma_{||}$, $\sigma_\perp$, Σ_{2x}, Σ_{2z}, and Σ_3) data
  - 7 datasets, 137 points[4]

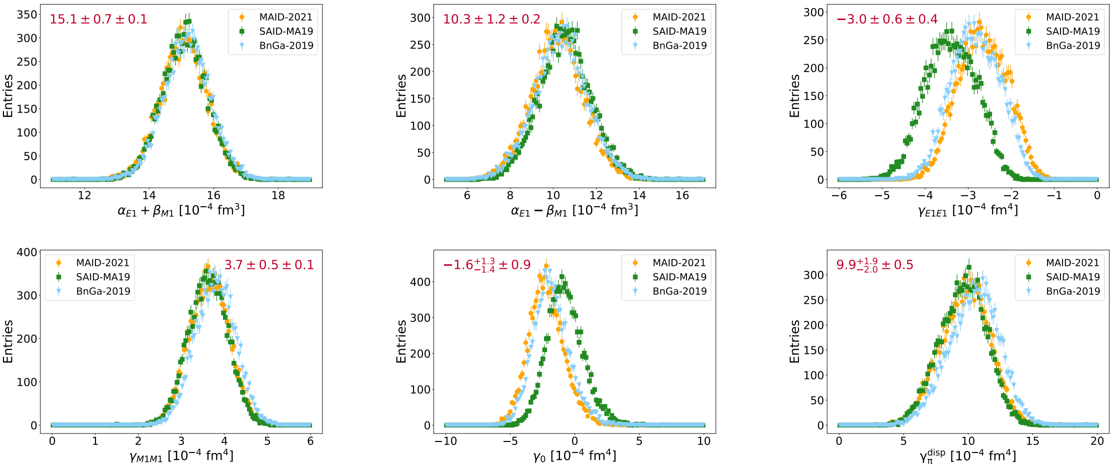
For a total of 388 data points divided in 25 datasets!

[3] including 10 above-thr points from TAPS
[4] 65 below- and 72 above-thr

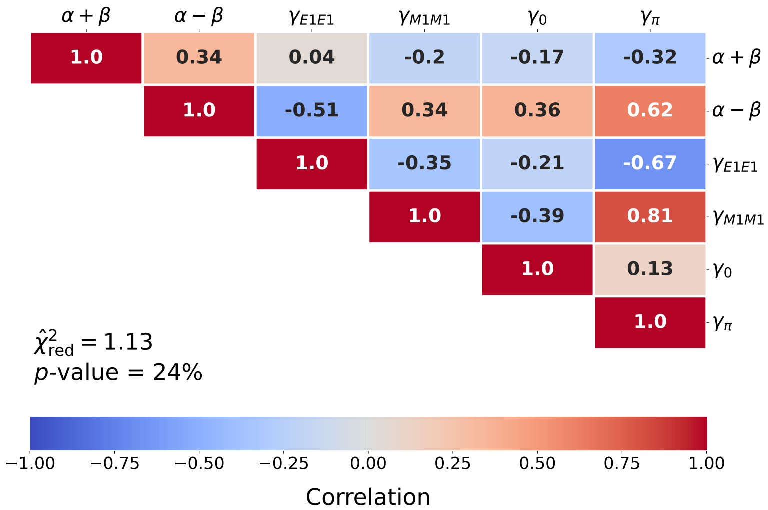
Fit

- Six free parameters
  - $\alpha_{E1} + \beta_{M1}$, $\alpha_{E1} - \beta_{M1}$, γ_{E1E1}, γ_{M1M1}, γ_0, and $\gamma_\pi^{\mathrm{disp}}$
- N = 10^4 bootstrap cycles
- Point-to-point systematic errors added in quadrature to statistical ones
- Common systematic errors are assumed to be uniform distributed (unless otherwise specified)
- Polarizability best-values are the mathematical average of the three results using the three different PWAs

Parameter distributions



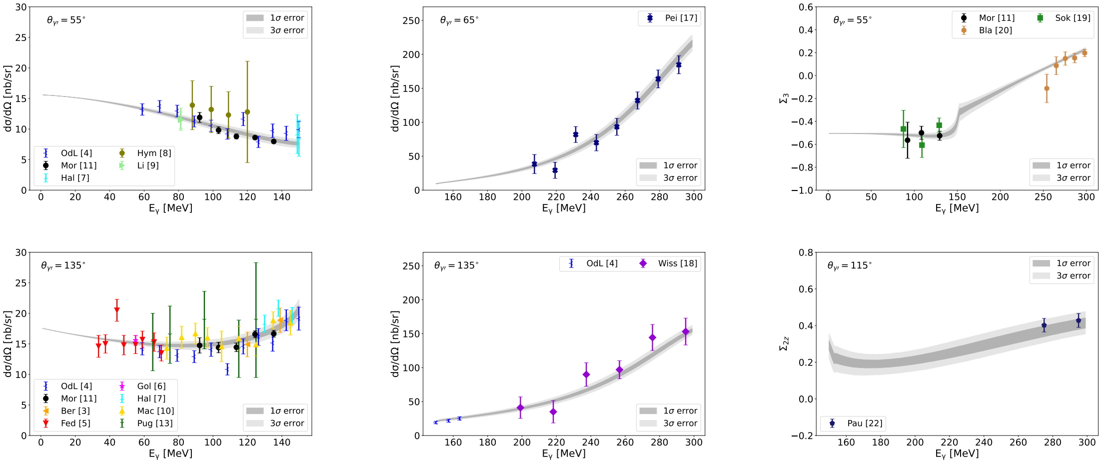
Fit results



$\hat{\chi}^2_{\text{red}} = 1.13$

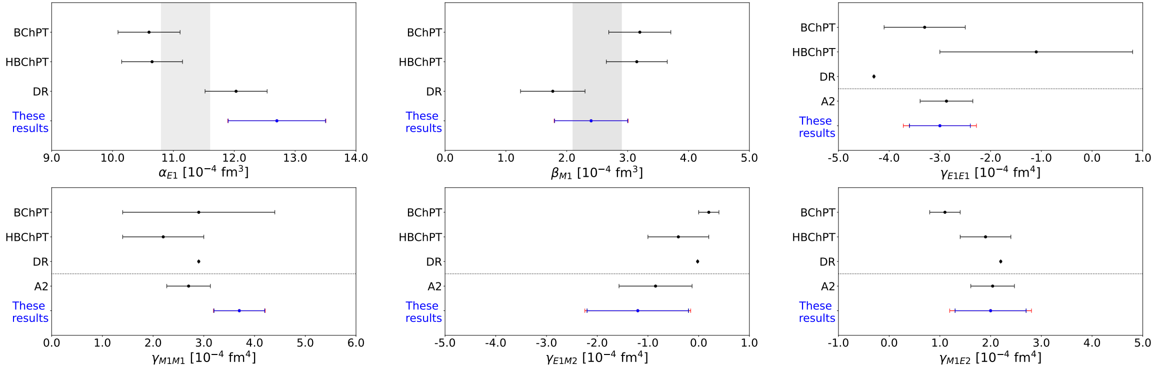
p-value = 24%

Fit results



E.M., S. Rodini, B. Pasquini, P. Pedroni, Phys. Rev. Lett. **129**, *102501 (2022).*

Polarizability results



$$\alpha_{E1} = 12.7 \pm 0.8 \pm 0.1; \quad \beta_{M1} = 2.4 \pm 0.6 \pm 0.1; \quad \gamma_{E1E1} = -3.0 \pm 0.6 \pm 0.4$$

$$\gamma_{M1M1} = 3.7 \pm 0.5 \pm 0.1; \quad \gamma_{E1M2} = -1.2 \pm 1.0 \pm 0.3; \quad \gamma_{M1E2} = 2.0 \pm 0.7 \pm 0.4$$

E.M., S. Rodini, B. Pasquini, P. Pedroni, Phys. Rev. Lett. **129***, 102501 (2022).*

The current situation at the end of this long journey....

- E.M. *et al.* (A2), Phys. Rev. Lett. **128**, 132503 (2022)

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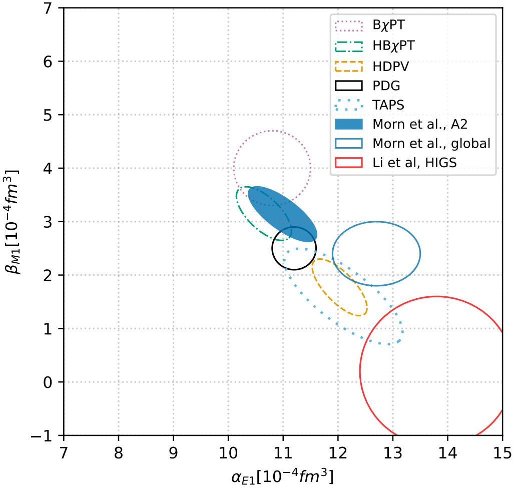
- Li *et al.* (HIGS), Phys. Rev. Lett. **128**, 132502 (2022)

  $$\alpha_{E1} = 13.8 \pm 1.2 \pm 0.1 \pm 0.3$$
  $$\beta_{M1} = 0.2 \mp 1.2 \pm 0.1 \mp 0.3$$

- E.M., S. Rodini, B. Pasquini, and P. Pedroni, Phys. Rev. Lett. **129**, 102501 (2022)

  $$\alpha_{E1} = 12.7 \pm 0.8 \pm 0.1$$
  $$\beta_{M1} = 2.44 \pm 0.6 \pm 0.1$$



Conclusions

- This year has been very prolific for proton Compton scattering!
  - The highest statistics Compton scattering dataset below threshold was finally published by the A2 Collaboration
  - The HIGS Collaboration published a complementary dataset at lower energy

- The first concurrent extraction of the six leading-order proton polarizabilities has been performed using fixed-t DRs and Bootstrap fitting technique!
  - Polarizability values in agreement with the existing ones
  - Competitive errors with those of the previous extractions performed using constraints
  - High correlation still exists among γ_{M1M1} and γ_{π}

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Thanks for your attention!