HADRON 2023

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Recent and ongoing studies from the A2 Collaboration at MAMI

Hadron Conference 2023

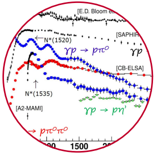
Edoardo Mornacchi
Johannes Gutenberg University of Mainz

Genova, June 6th 2023

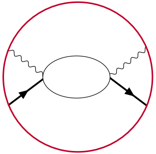
MAINZER MIKROTRON

FOR 5327

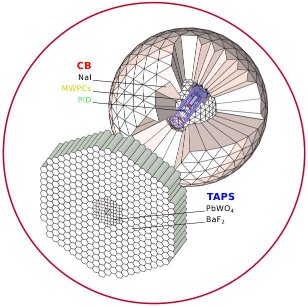
Baryon spectroscopy



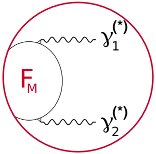
Compton scattering



A2@MAMI

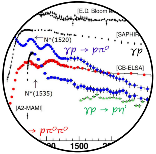


Meson decays



Di-baryon spectroscopy

Baryon spectroscopy



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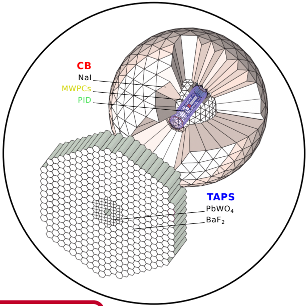

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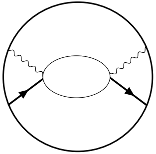

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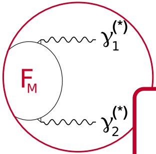

See Ref.:
L. Heijkenskjöld [A2]
EPJ Web Conf. ***212*** *(2019)*

Di-baryon spectroscopy

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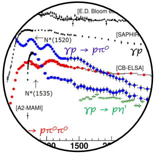

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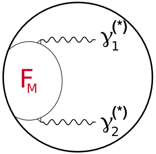

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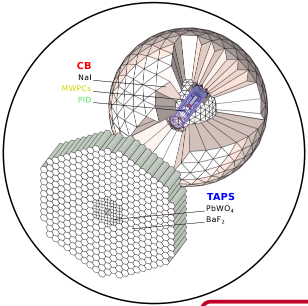

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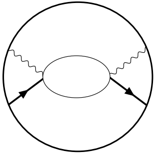
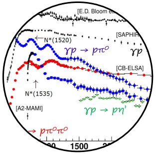


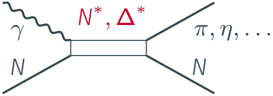
Di-baryon spectroscopy

See Ref.:
M. Bashkanov et al. [A2], Phys. Rev. Lett. 124 (2020)

Baryon spectroscopy



Determination of the N^* resonance spectrum via π (η) photoproduction:



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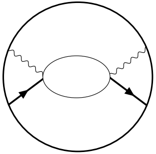
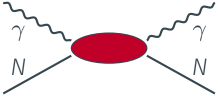
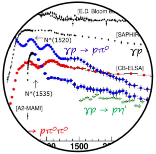


Determination of the N structure via Compton scattering:



Baryon spectroscopy



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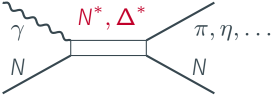


Sum rules

Fundamental relations between photon absorption and scattering:

- GDH*

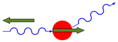
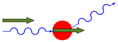
$$\frac{1}{2\pi^2}\int_0^\infty d\nu\,\frac{(\sigma_P(\nu)-\sigma_A(\nu))}{\nu} = \frac{\alpha}{M^2}\kappa$$

- Baldin

$$\alpha_{E1}+\beta_{M1} = \frac{1}{2\pi^2}\int_0^\infty d\nu\,\frac{\sigma_{unpol}(\nu)}{\nu^2}$$

- GGT⋆

$$\gamma_0 = \frac{1}{4\pi^2}\int_0^\infty d\nu\,\frac{(\sigma_P(\nu)-\sigma_A(\nu))}{\nu^3}$$

σ_A:  σ_P: 

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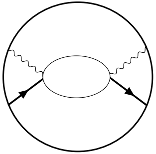

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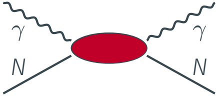
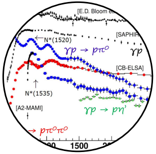


* Gerasimov-Drell-Hearn

⋆ Gell-Mann, Goldberger, and Thirring

Baryon spectroscopy



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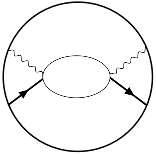

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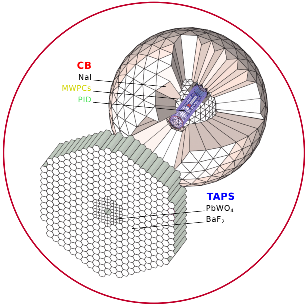

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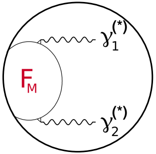
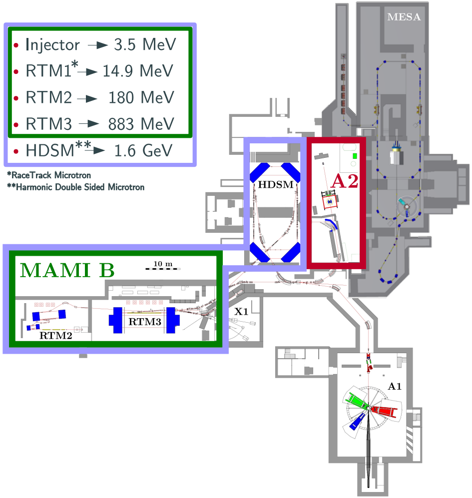


Di-baryon spectroscopy

- 4-stage microtron
- Continuous polarized or unpolarized electron beam
- $I_{e^-}^{\max} = 20\ \mu A$ or $100\ \mu A$ (pol/unpol)
- Linac & 3 RTMs (MAMI B) $\rightarrow$ 883 MeV
- HDSM (MAMI C) $\rightarrow$ 1604 MeV



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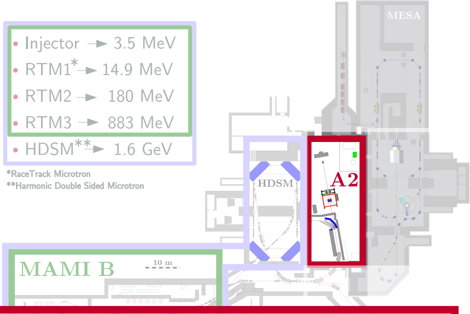
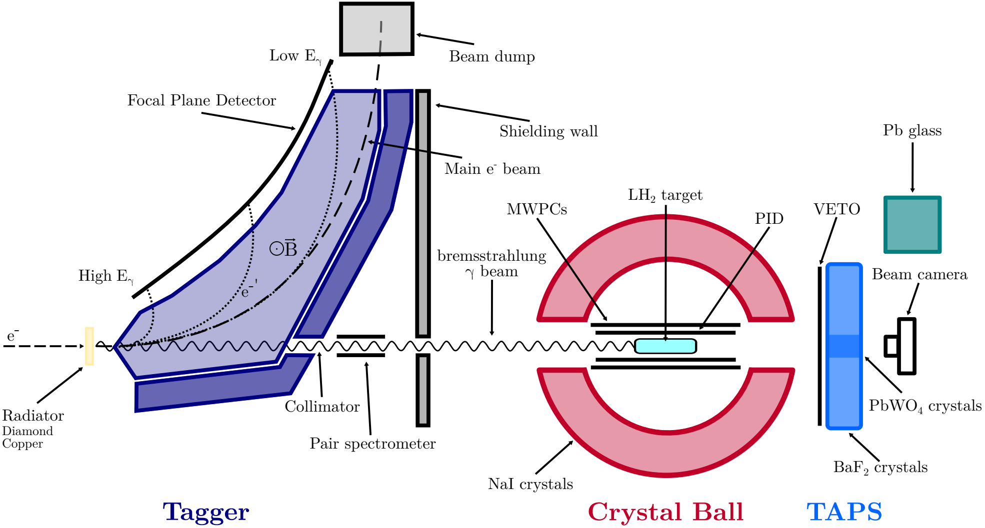
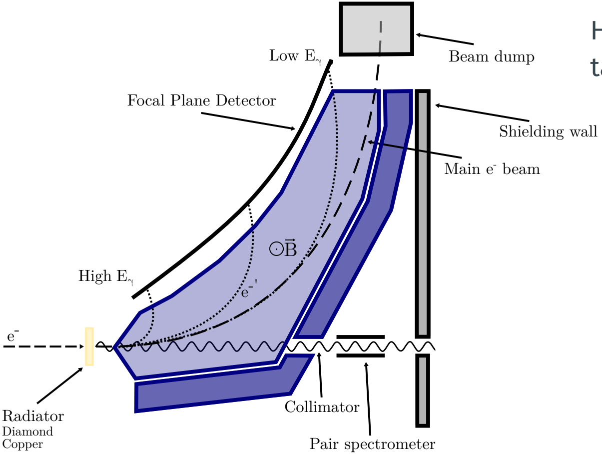


A2 setup


Beam dump
Low E_γ
Focal Plane Detector
Shielding wall
Main e- beam
Pb glass
LH_2 target
MWPCs
PID
VETO
$\odot\vec{B}$
bremsstrahlung
γ beam
High E_γ
e-'
Beam camera
e-
$PbWO_4$ crystals
Radiator
Diamond
Copper
Collimator
Pair spectrometer
BaF_2 crystals
NaI crystals
Tagger
Crystal Ball
TAPS

Photon tagging system

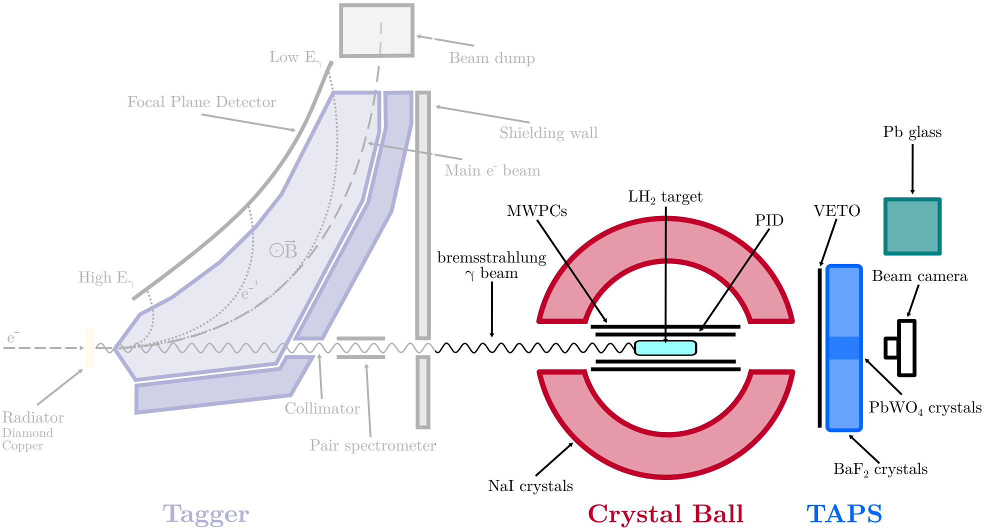


Tagger

High intensity (linearly polarized) tagged photon beam:

- $E_\gamma = E_0 - E_{e^-}$
- For $E_0 = 883$ MeV:
  - $E_\gamma = 40 - 800$ MeV
- For $E_0 = 1604$ MeV:
  - $E_\gamma = 70 - 1500$ MeV
- γ flux on target $\sim 3 \times 10^7 \gamma/s$

A2 setup



Beam dump
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Focal Plane Detector
Shielding wall
Main e⁻ beam
$\odot\vec{B}$
High E_γ
e⁻'
e⁻
Radiator
Diamond
Copper
Collimator
Pair spectrometer
bremsstrahlung
γ beam
MWPCs
LH_2 target
PID
VETO
Pb glass
Beam camera
$PbWO_4$ crystals
BaF_2 crystals
NaI crystals
Tagger
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TAPS

Unpolarized target:

- Liquid hydrogen target (LH_2)
- 10 cm long cell
- T = 20 K

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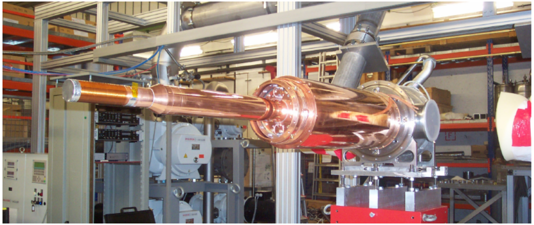
Polarized target:



- Butanol (C_4H_9OH)
- 2 cm long cell
- T = 25 mK
- Polarization $>$ 90%
- Relaxation time $>$ 1000 h

Crystal Ball

Highly segmented EM calorimeter

$\Delta E/E = 0.020 \cdot E[\text{GeV}]^{0.36}$

$\sigma_\phi = \sigma_\theta / \sin\theta$

$\sigma_\theta = 2 - 3^\circ$

TARGET

Liquid Hydrogen

10-cm capton cell

TAPS

Highly segmented EM calorimeter

$\Delta E/E = 0.018 + 0.008/E[\text{GeV}]^{0.5}$

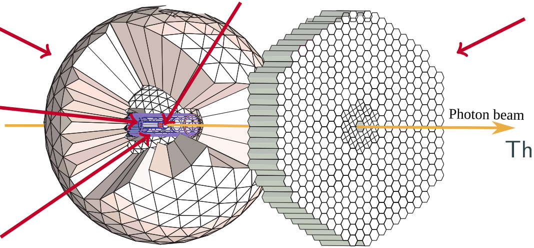
$\sigma_\phi = 14 \ldots 0.95^\circ$

$\sigma_\theta < 1^\circ$

Particle ID

Barrel of thin scintillators

$\Delta\phi = 15^\circ$



TAPS-Veto

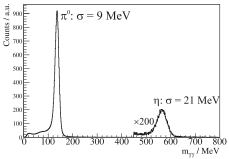
Thin scintillators before each TAPS crystal

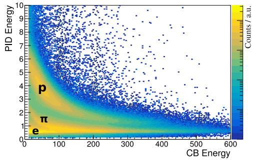
Multiwire Proportional Chambers

Precise charged tracking/positioning

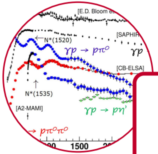
$\sigma_\theta \sim 2^\circ$

$\sigma_\phi \sim 3^\circ$





Baryon spectroscopy



See talk.:
R. Beck
Tue 6th at 9:00

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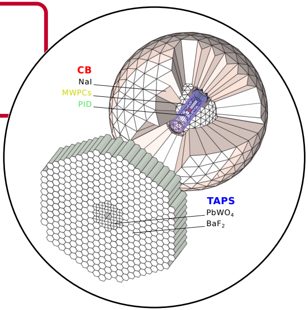

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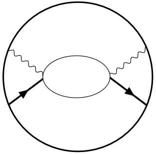

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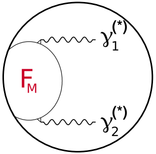

Di-baryon spectroscopy

Study of nucleon's excited states

A full understanding of baryon resonance spectrum is essential for understanding the nucleon internal structure:

- probe to understand pQCD
- access to the different degree of freedoms of the nucleon

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A good tool to access baryon resonance is $\gamma N \to \pi(\eta)N$:

- Electromagnetic (EM) vertex is fully understood
- 4 matrix elements are needed to fully describe it
- To fully disentangle and access all possible states, different observables has to be measured

Beam		Target			Recoil		Both	
		x	y	z			x	
					x'	z'	x'	z'
Unpolarized	σ		T				$T_{x'}$	$T_{z'}$
Linear	Σ	H	P	G	$O_{x'}$	$O_{z'}$	$L_{z'}$	$L_{x'}$
Circular		F		E	$C_{x'}$	$C_{z'}$		

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Measured or planned at A2

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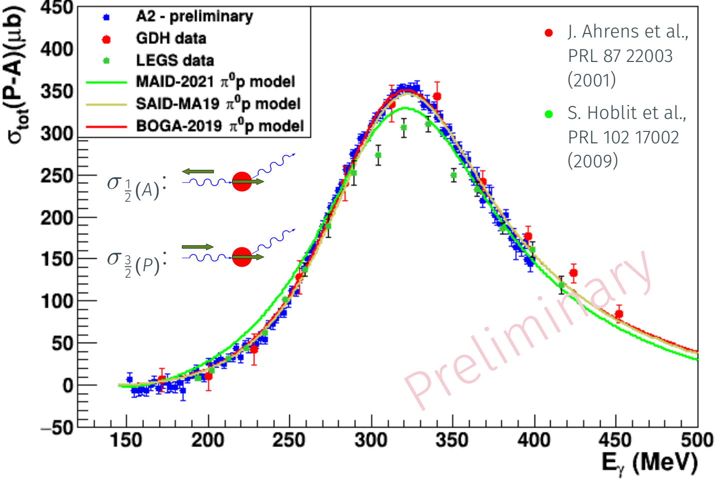
- 4 matrix elements are needed to fully describe it
- To fully disentangle and access all possible states, different observables has to be measured
- EM iterations do not conserve isospin. One needs to measure both proton and neutron targets to access the full isospin decomposition
- Light nuclei (deuterium) are used as effective neutron target. Nuclear effects corrections needed to unambiguously extract the free-neutron information

Helicity dependent $\vec{\gamma}\vec{p} \to p\pi^0$ cross section in the $\Delta(1232)$ region

114 bins in $E_\gamma = [150 - 400]$ MeV $\to \Delta E\gamma \approx \pm 1$ MeV



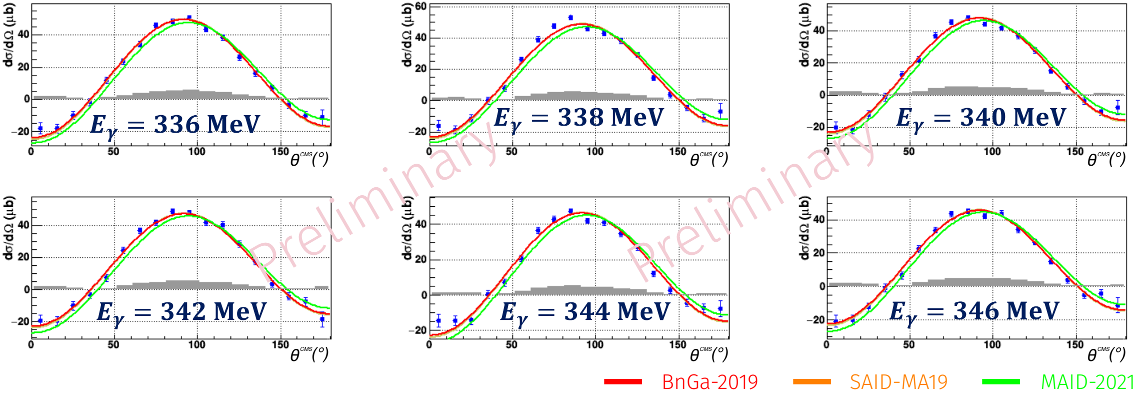
Significant improvement both in statistics and quality compared to existing data!

The determination of the quadrupole strength $E2$ in the $\gamma N \to \Delta$ transition gives fundamental information on the proton structure

$$R_{EM} = \frac{E_2}{M_1} = \frac{E^{3/2}_{1+}}{M^{3/2}_{1+}} = \frac{IM\left[E^{3/2}_{1+}\right]}{IM\left[M^{3/2}_{1+}\right]}$$

$$(\sigma_P - \sigma_A) \propto -|E_{0+}|^2 - |M_{1-}|^2 - 3|E_{1+}|^2 + |M_{1+}|^2 - 6E^*_{1+}M_{1+} + \ldots$$

Legendre fit to $\vec{\gamma}\vec{p} \rightarrow p\pi^0$ data in the $\Delta(1232)$ region



$$\frac{d\sigma_{(P-A)}}{d\Omega}(W,\theta) = \sum_{k=0}^{2l_{max}} (a_{l max})_k(W) P_k(cos\theta) \rightarrow R_{EM} \simeq \frac{1}{3}\cdot\frac{(a_l)_0}{(a_l)_2} + \frac{1}{6} = (-2.32 \pm 0.15_{(sys+stat)})\%$$

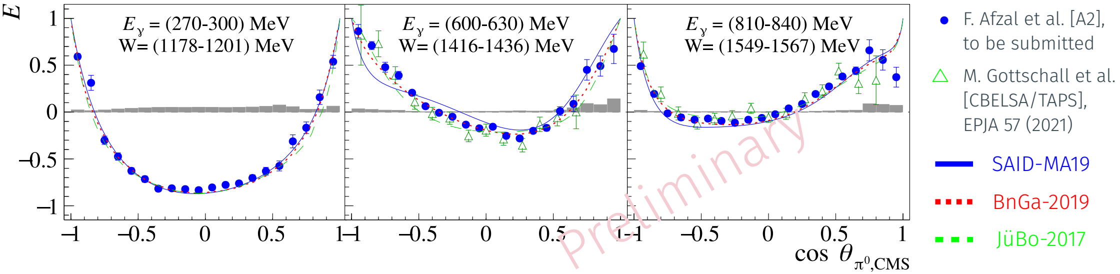
Interference between different multipoles

Associated Legendre polynomials

Previous extractions →

- (-2.5 ±0.2 ±0.2)% R. Beck et al., PRL 78 606 (1996)
- (-2.5 ±0.1 ±0.2)% R. Beck et al., PRC 61 35204 (2000)

Simultaneous measurement of double polarization E and G for $\gamma p \to p\pi^0$

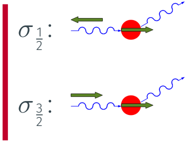


Elliptically polarized photons (long. pol. e^- + diamond) and longitudinally polarized target:

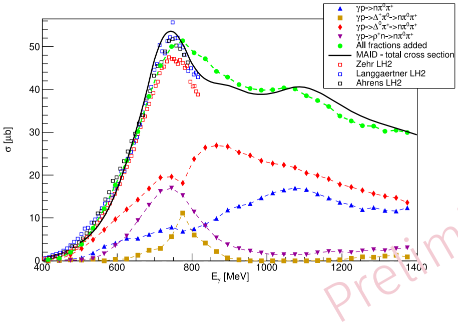
$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega_0}(\theta)\,[1 - P_{lin}\cos(2(\alpha-\phi)) - P_z(-P_{lin}\mathbf{G}\sin(2(\alpha-\phi)) + P_{circ}\mathbf{E})]$$

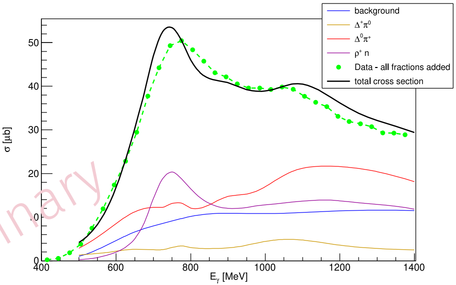
- Excellent agreement between A2 (diamond) and CBELSA/TAPS (amorphous)
- Time and cost efficient measurement possible!

$$E = \frac{\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}}$$



Unpolarized $\gamma p \rightarrow n\pi^0\pi^+$ cross section





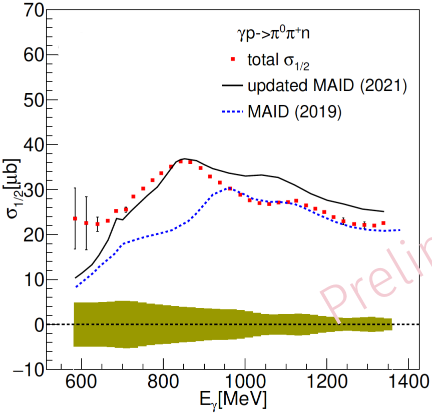
Free proton data:

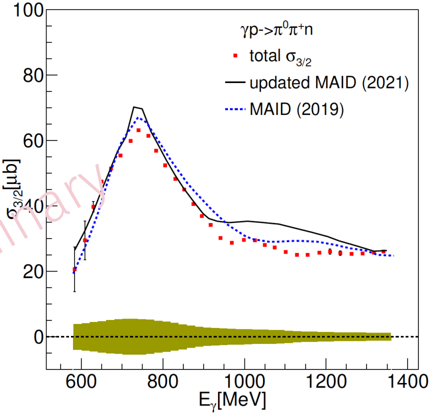
- F. Zehr et al., EPJA 48 98 (2012)
- W. Langgärtner et al., PRL 87 52001 (2001)
- J. Ahrens et al., PLB 551 49 (2003)

First decomposition of all intermediate reaction states (full event-by-event kinematic reconstruction)

Precise diff. cross section also measured, *paper in preparation*

Helicity dependent $\vec{\gamma}\vec{p} \to n\pi^0\pi^+$ cross section





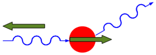
New data

MAID-2019

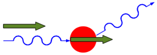
Update MAID

Relevant impact on the PWA 2π model

$\sigma_{\frac{1}{2}}(A)$:

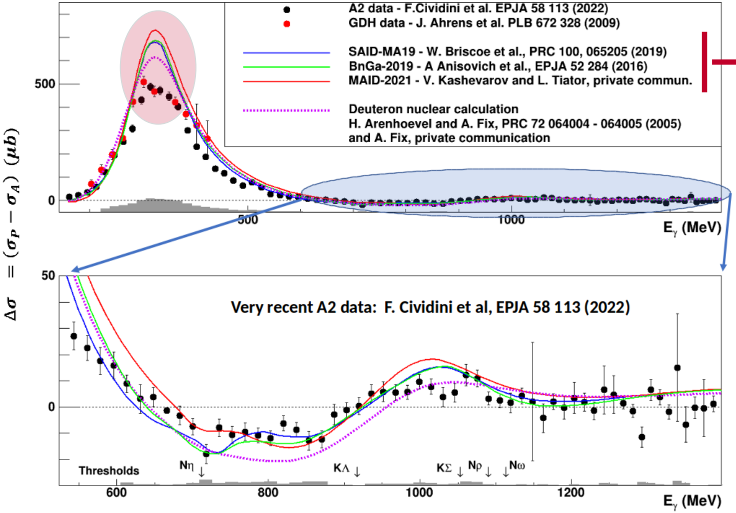


$\sigma_{\frac{3}{2}}(P)$:



Unpol/pol $\vec{\gamma}\vec{n} \to p\pi^-\pi^0$ also measured, *paper in preparation*

Helicity dependent $\vec{\gamma}\vec{D} \to \gamma B(B = np \text{ or } d)$ cross section

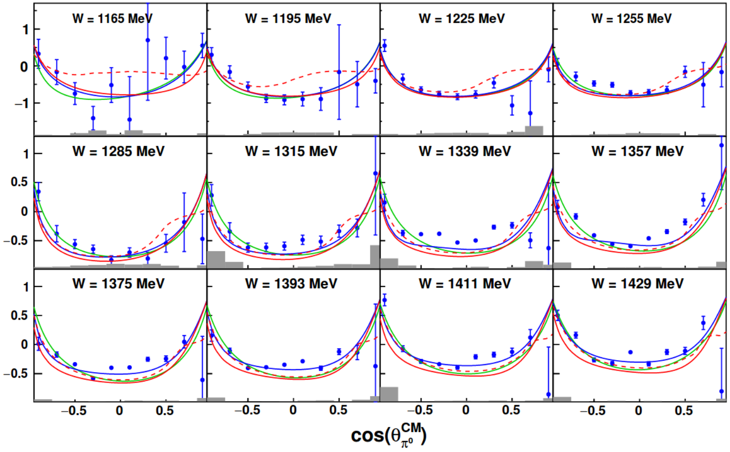


PWA models for free p + free n

Predicted decrease in cross-section (due to FSI) in the Δ(1232) region is not sufficient to describe data

Precise diff. cross section also measured: *F. Cividini et al. [A2], EPJA 58 113 (2022)*

E asymmetry for π^0 photoproduction on quasi free neutron



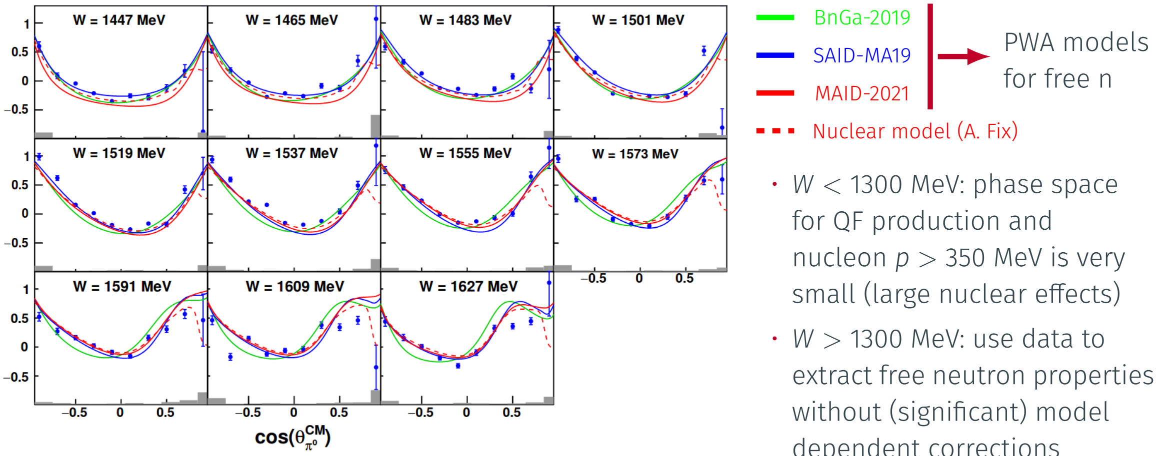
- BnGa-2019
- SAID-MA19
- MAID-2021

→ PWA models for free n

- Nuclear model (A. Fix)

- $W < 1300$ MeV: phase space for QF production and nucleon $p > 350$ MeV is very small (large nuclear effects)
- $W > 1300$ MeV: use data to extract free neutron properties without (significant) model dependent corrections

Precise E on proton also measured:
F. Cividini et al. [A2], EPJA 58 113 (2022)



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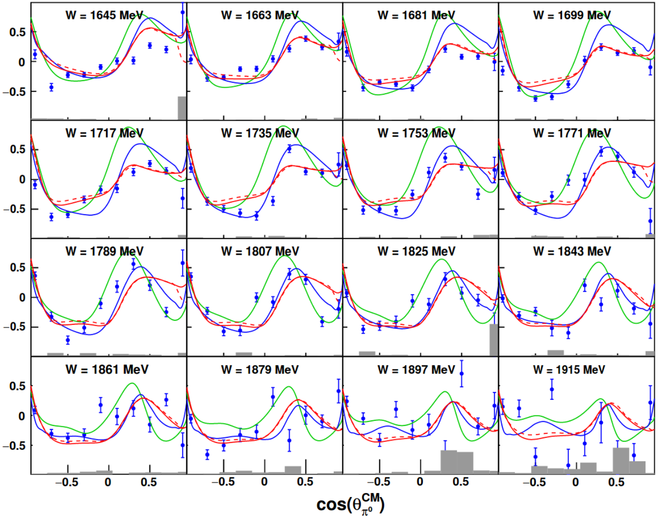

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Precise E on proton also measured:
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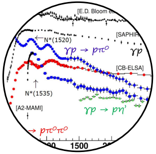
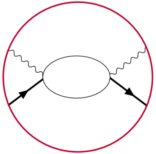
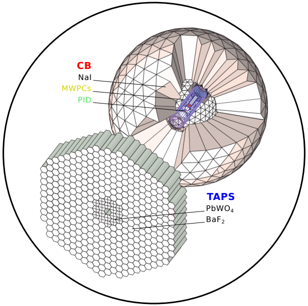
Baryon spectroscopy



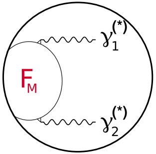
Compton scattering



A2@MAMI



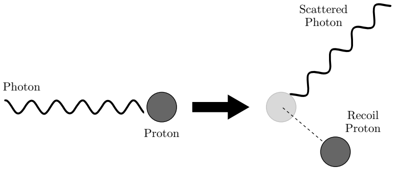
Meson decays



Di-baryon spectroscopy

Accessing hadron internal structure — measuring unpolarized and polarized Compton scattering observables:

- Clear probe to understand non-pQCD
- Gives access to structure-dependent properties:
  - scalar polarizabilities: α_{E1} and β_{M1}
  - spin polarizabilities: γ_{E1E1}, γ_{M1M1}, γ_{M1E2}, and γ_{E1M2}



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

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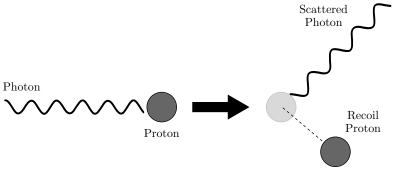

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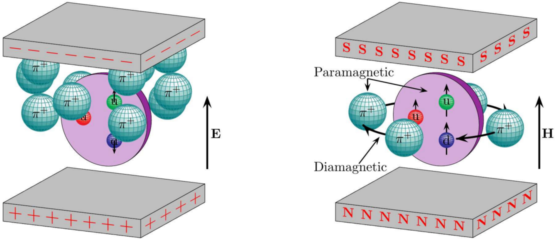

Describe response of a nucleon to:

- External electric field
  $$\vec{p} = \boxed{\alpha_{E1}} \times \vec{E}$$
- External magnetic field
  $$\vec{m} = \boxed{\beta_{M1}} \times \vec{H}$$

Accessing hadron internal structure — measuring unpolarized and polarized Compton scattering observables:

- Clear probe to understand non-pQCD
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  - scalar polarizabilities: α_{E1} and β_{M1}
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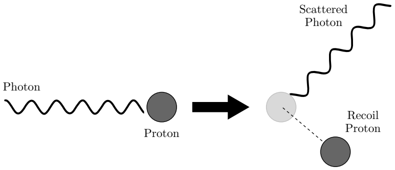
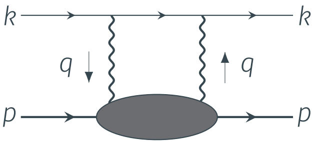
- Contribute to 2γ exchange in μH Lamb shift



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



$$\Delta E^{(2\gamma)} = \Delta E^{(el)} \rightarrow \text{Nucleon form factor}$$
$$+ \Delta E^{(inel)} \rightarrow \text{Nucleon structure function}$$
$$+ \Delta E^{(sub)} \rightarrow \text{Nucleon polarizabilities}$$

Compton scattering - Hamiltonian

- Zeroth order: mass (m) and electric charge (e)

$$H_{\text{eff}}^{(0)} = \frac{\vec{\pi}^2}{2m} + e\phi \qquad (\text{where } \vec{\pi} = \vec{p} - e\vec{A})$$

- First order: anomalous magnetic moment (k)

$$H_{\text{eff}}^{(1)} = -\frac{e(1+k)}{2m}\vec{\sigma}\cdot\vec{H} - \frac{e(1+2k)}{8m^2}\vec{\sigma}\cdot\left[\vec{E}\times\vec{\pi} - \vec{\pi}\times\vec{E}\right]$$

- Second order: scalar polarizabilities α_{E1} and β_{M1}

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

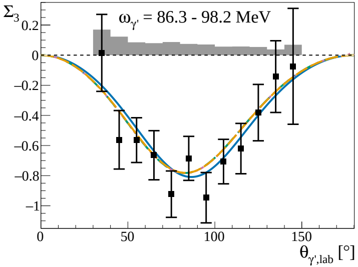
- Third order: spin polarizabilities γ_{E1E1}, γ_{M1M1}, γ_{M1E2} and γ_{E1M2}

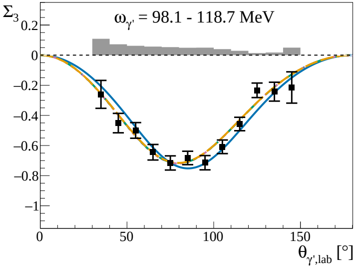
$$H_{\text{eff}}^{(3)} = -4\pi\left[\frac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \frac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\right]$$

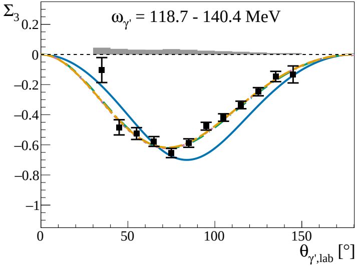
Theory needed:

- Dispersion Relation (DR)
- Chiral Perturbation Theory (χPT)

They can be used to fit Compton scattering data







A2: Phys. Rev. Lett. **128** 132503 (2022)

Systematic errors

Born contribution

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

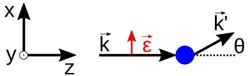
HBχPT: Eur. Phys. J. A **49**, 12 (2013)

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

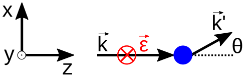
Beam asymmetry:

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

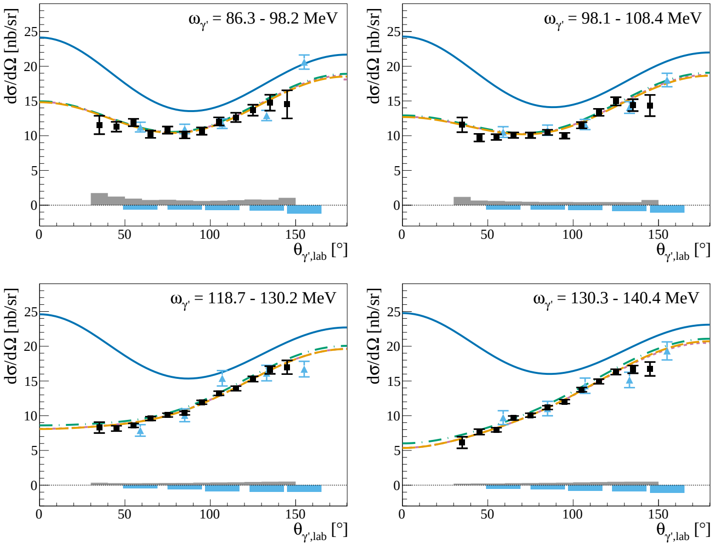
PARALLEL



PERPENDICULAR



Results on the unpolarized cross-section



A2: Phys. Rev. Lett. **128** 132503 (2022)

A2 systematic errors

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

TAPS systematic errors

Born contribution

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Extracting the scalar polarizabilities

- Only new data used as input
- Systematic errors included as normalization factor (S) for each individual data set
- Baldin sum rule constraint added as an additional point with its error

$$\alpha_{E1} + \beta_{M1} = \int_{\omega_0}^{\infty} d\omega \frac{\sigma_{tot}(\omega)}{\omega^2} = 13.8 \pm 0.4$$

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

Extracting the scalar polarizabilities

- Only new data used as input
- Systematic errors included as normalization factor (S) for each individual data set
- 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

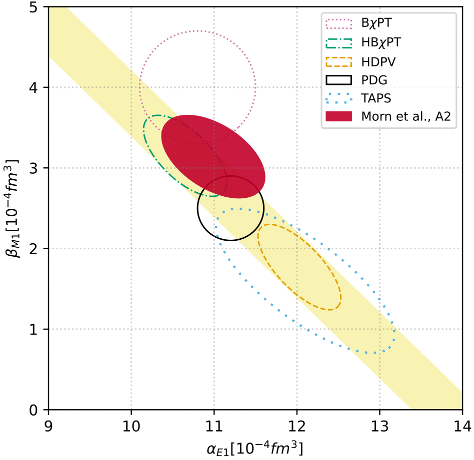
$$\chi^2(\mathcal{P}) = \sum_j^{N_{sets}} \left(\sum_i^{N_{pt}^j} \left(\frac{s_j O_{ij}^{exp} - O_{ij}^{thr}(\mathcal{P})}{s_j \Delta O_{ij}^{exp}} \right)^2 + \left(\frac{s_j - 1}{\Delta s_j} \right)^2 \right)$$

E. Mornacchi (A2), Phys. 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	$82.10/93 = 0.89$	$82.96/93 = 0.89$	$83.16/93 = 0.89$

$$\alpha_{E1} = 10.99 \pm 0.16_{\mathrm{stat.}} \pm 0.47_{\mathrm{sys.}} \pm 0.17_{\gamma_S} \pm 0.34_{\mathrm{mod.}}$$

$$\beta_{M1} = 3.14 \pm 0.21_{\mathrm{stat.}} \pm 0.24_{\mathrm{sys.}} \pm 0.20_{\gamma_S} \pm 0.35_{\mathrm{mod.}}$$



Extracting the scalar polarizabilities

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

	HDPV	BChPT	HBChPT
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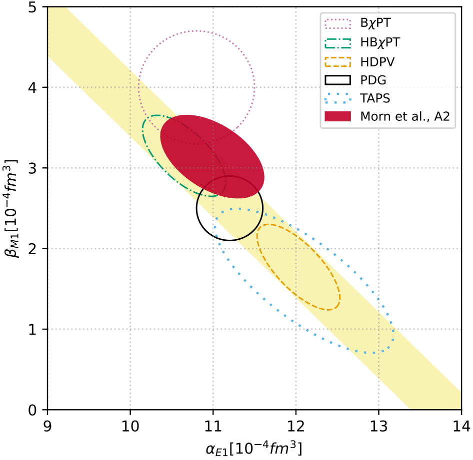
χ^2/DOF	$82.10/93 = 0.89$	$82.96/93 = 0.89$	$83.16/93 = 0.89$

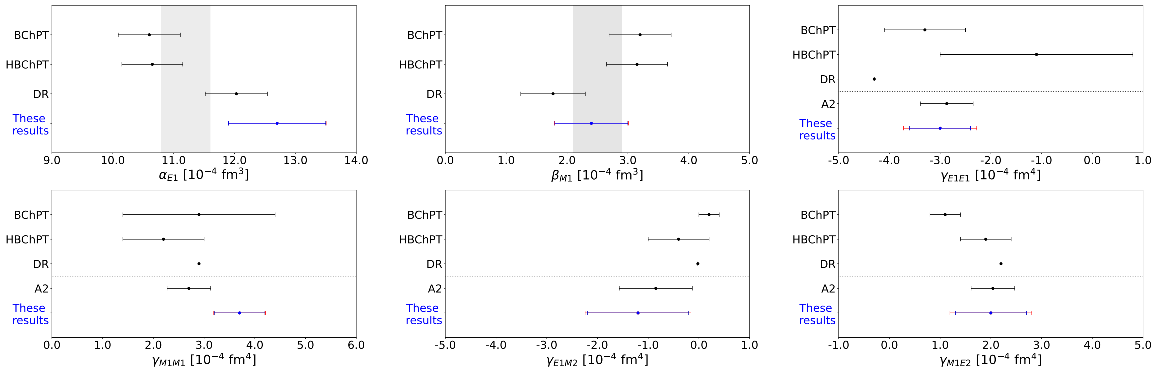
- Highest precision Compton scattering data set below π-photoproduction threshold!
- Precise extraction of the scalar polarizabilities from one single data set



- Using all available datasets as input: 25 datasets, 388 data points
- 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

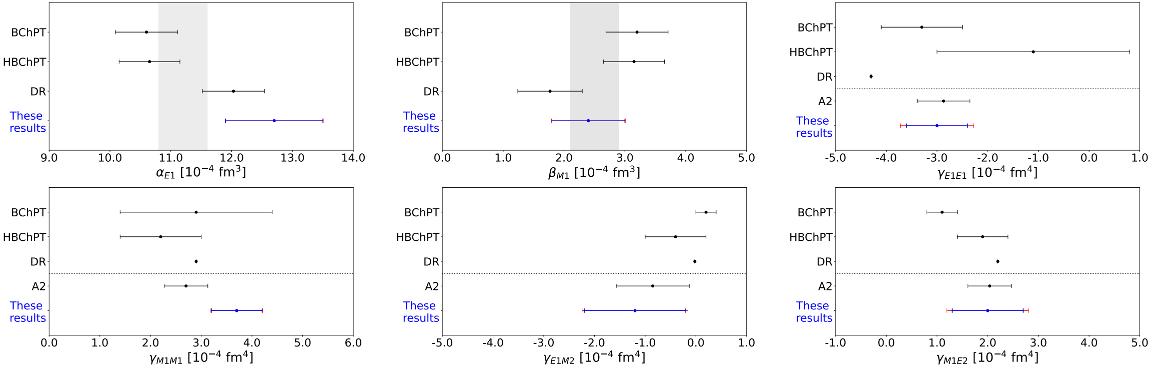


$$\alpha_{E1} = 12.7 \pm 0.8_{\text{fit.}} \pm 0.1_{\text{mod.}} \qquad \beta_{M1} = 2.4 \pm 0.6_{\text{fit.}} \pm 0.1_{\text{mod.}} \qquad \gamma_{E1E1} = -3.0 \pm 0.6_{\text{fit.}} \pm 0.4_{\text{mod.}}$$

$$\gamma_{M1M1} = 3.7 \pm 0.5_{\text{fit.}} \pm 0.1_{\text{mod.}} \qquad \gamma_{E1M2} = -1.2 \pm 1.0_{\text{fit.}} \pm 0.3_{\text{mod.}} \qquad \gamma_{M1E2} = 2.0 \pm 0.7_{\text{fit.}} \pm 0.4_{\text{mod.}}$$

E. Mornacchi et al., Phys. Rev. Lett. ***129****, 102501 (2022)*

Extracting all the six leading-order polarizabilities

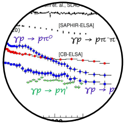


- First simultaneous & self-consistent extraction of the six static proton polarizabilities
- Errors competitive with the existing extractions obtained with constraints

E. Mornacchi et al., Phys. Rev. Lett. ***129***, *102501 (2022)*

A2 Collaboration has an intensive program to study the nucleon internal structure!

Photon absorption

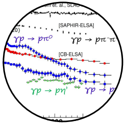


- High precision data measured for different final states and observables
- Simultaneous measurement of E and G thanks to elliptical polarization
- Relevant improvement to different PWAs

Conclusions

A2 Collaboration has an intensive program to study the nucleon internal structure!

Photon absorption



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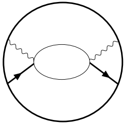
Photon scattering



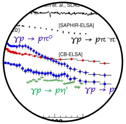
- Highest statistics Compton scattering data set below π-threshold published
- First concurrent extraction of the six LO proton polarizabilities
- New physics program on neutron planned in A2 with improved detector system

Many more results expected in the next few years. Stay tuned!

Conclusions

A2 Collaboration has an intensive program to study the nucleon internal structure!

Photon absorption



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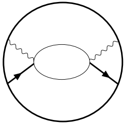
- Relevan…

Photon scattering



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Thanks for your attention!

Many more results expected in the next few years. Stay tuned!