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# Recent results on Compon scattering from A2@MAMI

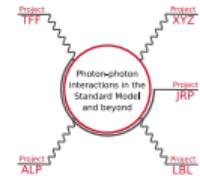
Low-Q and  $\mu$ ASTI workshop

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Edoardo Mornacchi

Johannes Gutenberg University of Mainz

Kolymbari, May 15<sup>th</sup> 2023

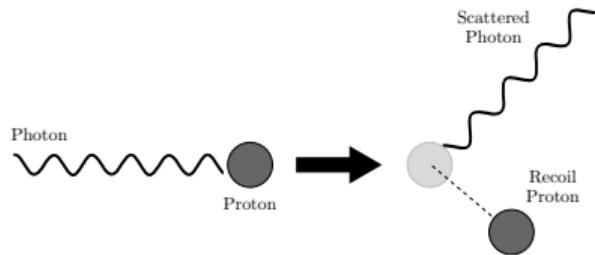


FOR 5327

# Nuclear Compton scattering

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:  $\alpha_{E1}$  and  $\beta_{M1}$
  - spin polarizabilities:  $\gamma_{E1E1}$ ,  $\gamma_{M1M1}$ ,  $\gamma_{M1E2}$ , and  $\gamma_{E1M2}$

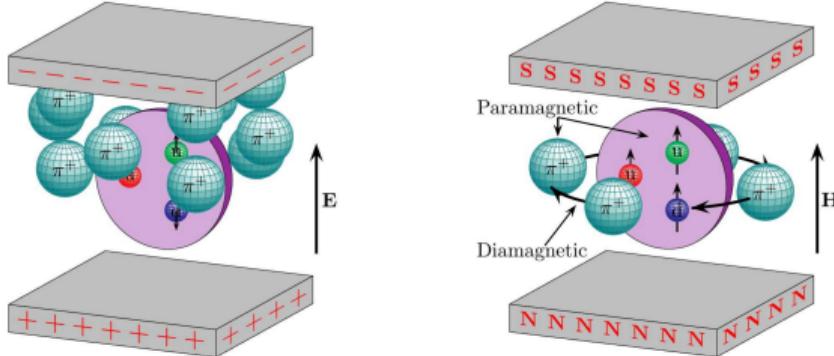


$$\gamma(k) + P(q) \rightarrow \gamma(k') + P(q')$$

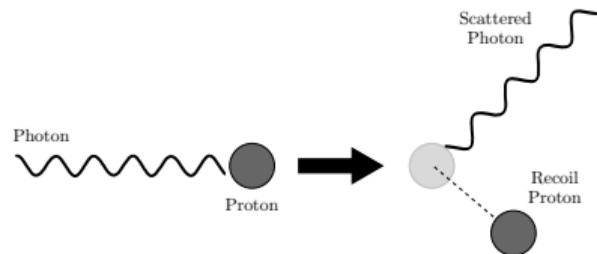
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Figures: P. Martel, PhD thesis (2013)



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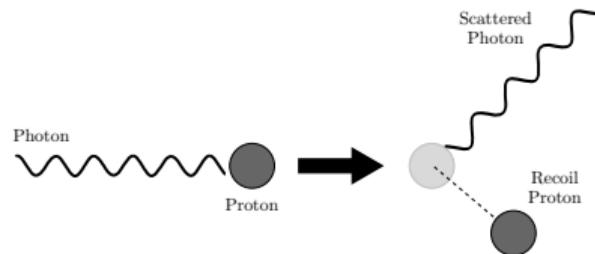
Describe response of a nucleon to:

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

# Nuclear Compton scattering

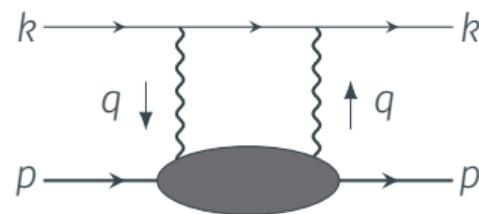
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$$\gamma(k) + P(q) \rightarrow \gamma(k') + P(q')$$

Contribute to  $2\gamma$  exchange in  $\mu$ H Lamb shift



$$\Delta E^{(2\gamma)} = \Delta E^{(\text{el})} + \Delta E^{(\text{inel})} + \Delta E^{(\text{sub})}$$

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

Taken from: M. Vanderhaeghen,  $\mu$ Atom@PSI22

# Compton scattering - Hamiltonian

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

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

- First order: anomalous magnetic moment ( $k$ )

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

- Second order: scalar polarizabilities  $\alpha_{E1}$  and  $\beta_{M1}$

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

- Third order: spin polarizabilities  $\gamma_{E1E1}$ ,  $\gamma_{M1M1}$ ,  $\gamma_{M1E2}$  and  $\gamma_{E1M2}$

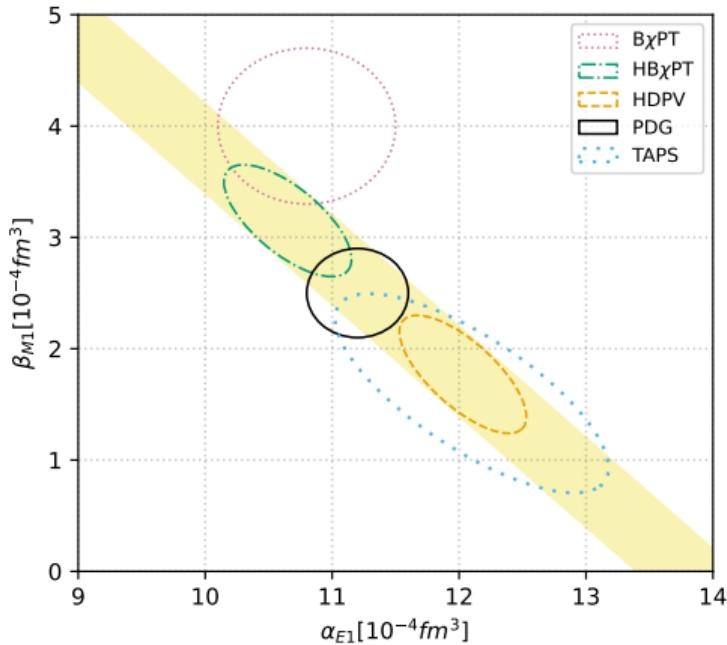
$$H_{\text{eff}}^{(3)} = -4\pi \left[ \frac{1}{2} \gamma_{E1E1} \vec{\sigma} \cdot (\vec{E} \times \dot{\vec{E}}) + \frac{1}{2} \gamma_{M1M1} \vec{\sigma} \cdot (\vec{H} \times \dot{\vec{H}}) \right. \\ \left. - \gamma_{M1E2} E_{ij} \sigma_i H_j + \gamma_{E1M2} H_{ij} \sigma_i E_j \right]$$

## Theory needed:

- Dispersion Relation (DR)
- Chiral Perturbation Theory ( $\chi$ PT)

They can be used to fit Compton scattering data

# Scalar polarizabilities - existing results (before 2022)



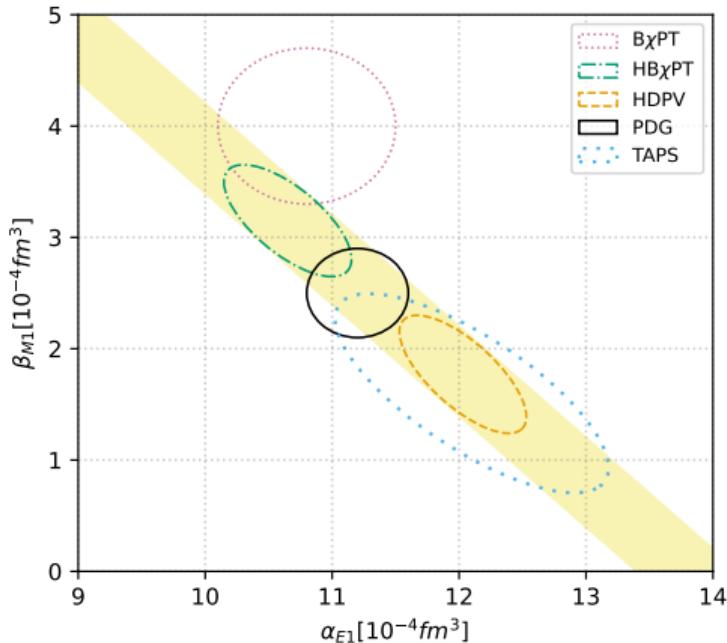
Various  $\alpha_{E1}$  and  $\beta_{M1}$  extractions:

- Different experimental inputs
- Different theoretical inputs
- Different fitting strategies

Baldin sum rule from optical theorem:

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

# Scalar polarizabilities - existing results (before 2022)



Various  $\alpha_{E1}$  and  $\beta_{M1}$  extractions:

- Different experimental inputs
- Different theoretical inputs
- Different fitting strategies

New high-precision  
dataset needed!

Baldin sum rule from optical theorem:

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

Only two linear combinations of the spin polarizabilities were measured from different physics:

## Forward spin polarizability

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1E2} - \gamma_{M1M1} = (-1.01 \pm 0.08 \pm 0.10) \times 10^{-4} fm^4$$

Determined at MAMI and ELSA in the GDH experiment

- J. Ahrens et al. (GDH/A2), PRL 87, 022003 (2001)
- H. Dutz et al. (GDH), PRL 91, 192001 (2003)

## Backward spin polarizability

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1E2} + \gamma_{M1M1} = (8.0 \pm 1.8) \times 10^{-4} fm^4$$

Determined with dispersive fits to back-angle Compton scattering

- M. Camen et al. (A2), Phys. Rev. C 65, 032202 (2002)

# Compton scattering experiments - Beam asymmetry

A2

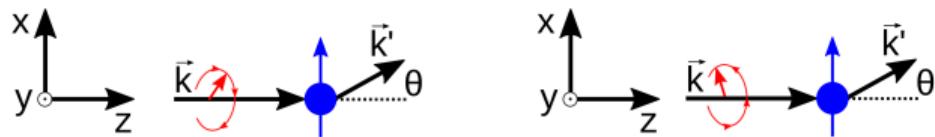
- Linearly polarized beam & unpolarized target ( $\alpha_{E_1}$ ,  $\beta_{M_1}$  and  $\gamma_{M_1 M_1}$ )

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



- Circularly polarized beam & transversely polarized target ( $\gamma_{E_1 E_1}$ ):

$$\Sigma_{2x} = \frac{d\sigma_{+x}^R - d\sigma_{+x}^L}{d\sigma_{+x}^R + d\sigma_{+x}^L}$$



- Circularly polarized beam & longitudinally polarized target ( $\gamma_{M_1 M_1}$ ):

$$\Sigma_{2z} = \frac{d\sigma_{+z}^R - d\sigma_{+z}^L}{d\sigma_{+z}^R + d\sigma_{+z}^L}$$



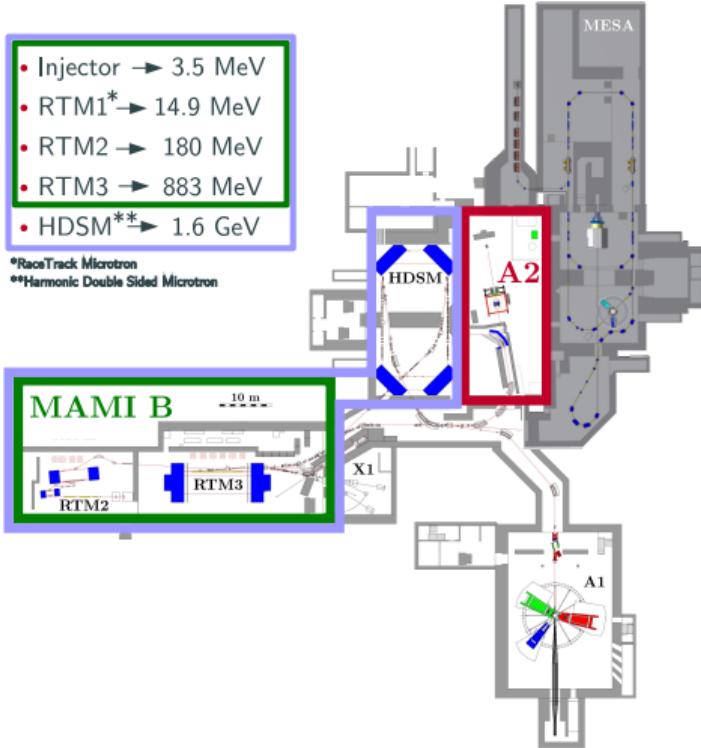
## A2@MAMI Collaboration

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

- Injector  $\rightarrow 3.5 \text{ MeV}$
- RTM1\*  $\rightarrow 14.9 \text{ MeV}$
- RTM2  $\rightarrow 180 \text{ MeV}$
- RTM3  $\rightarrow 883 \text{ MeV}$
- HDSM\*\*  $\rightarrow 1.6 \text{ GeV}$

\*RaceTrack Microtron  
\*\*Harmonic Double Sided Microtron

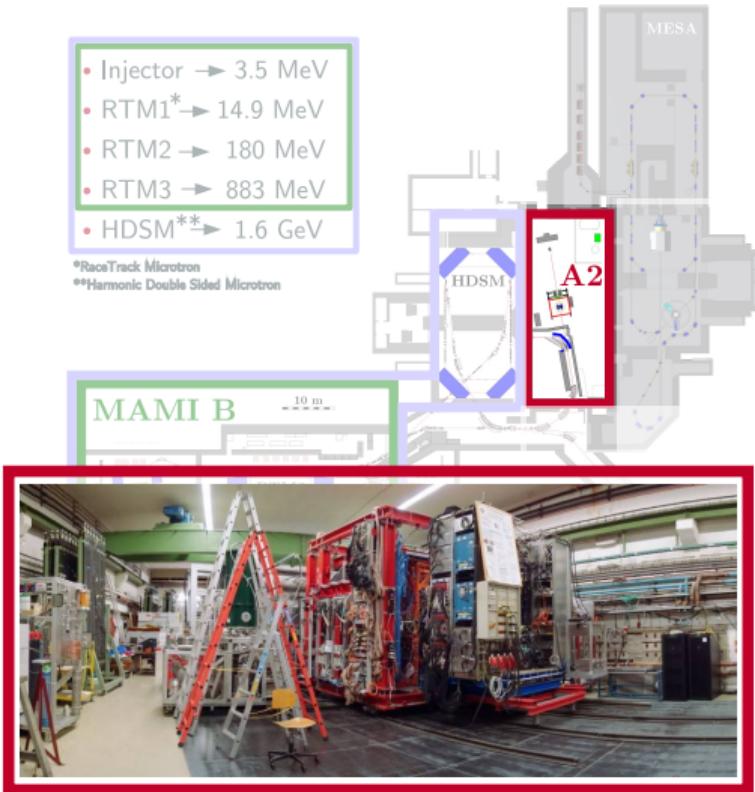


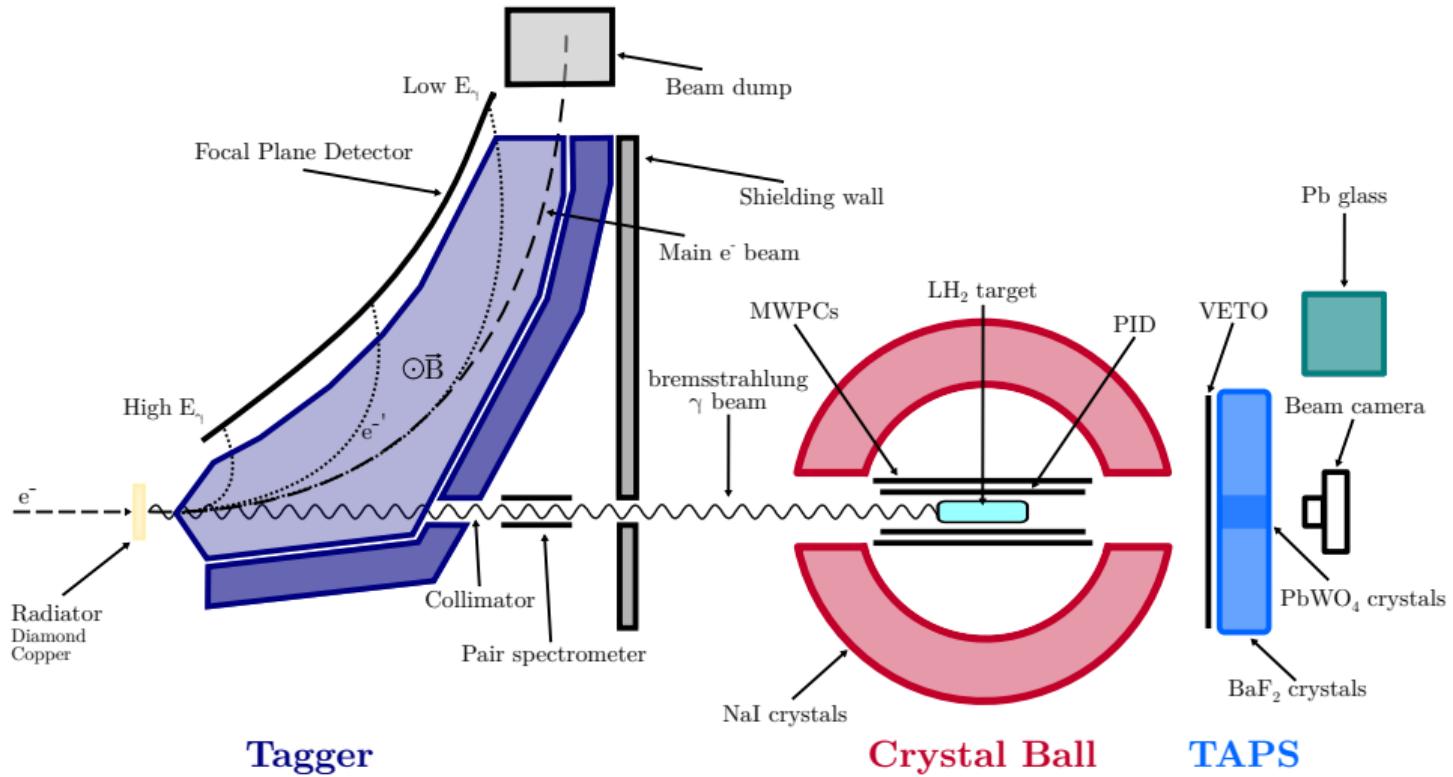
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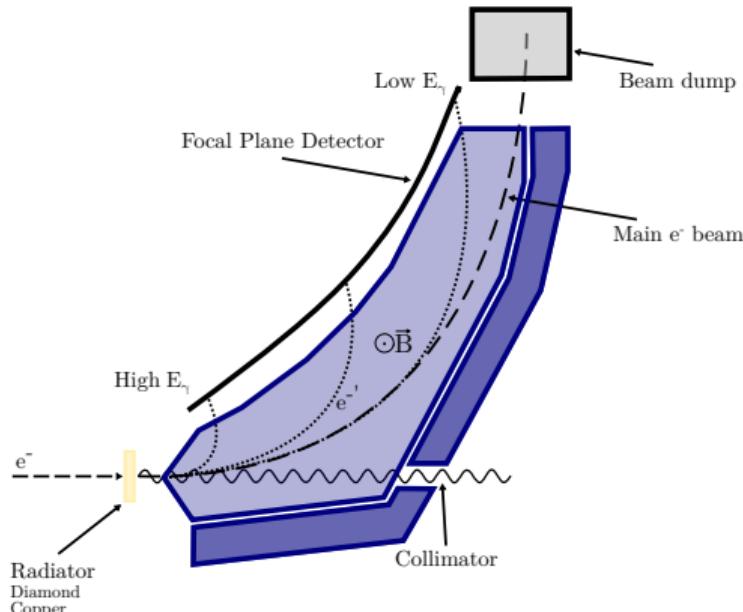




# Photon tagging system

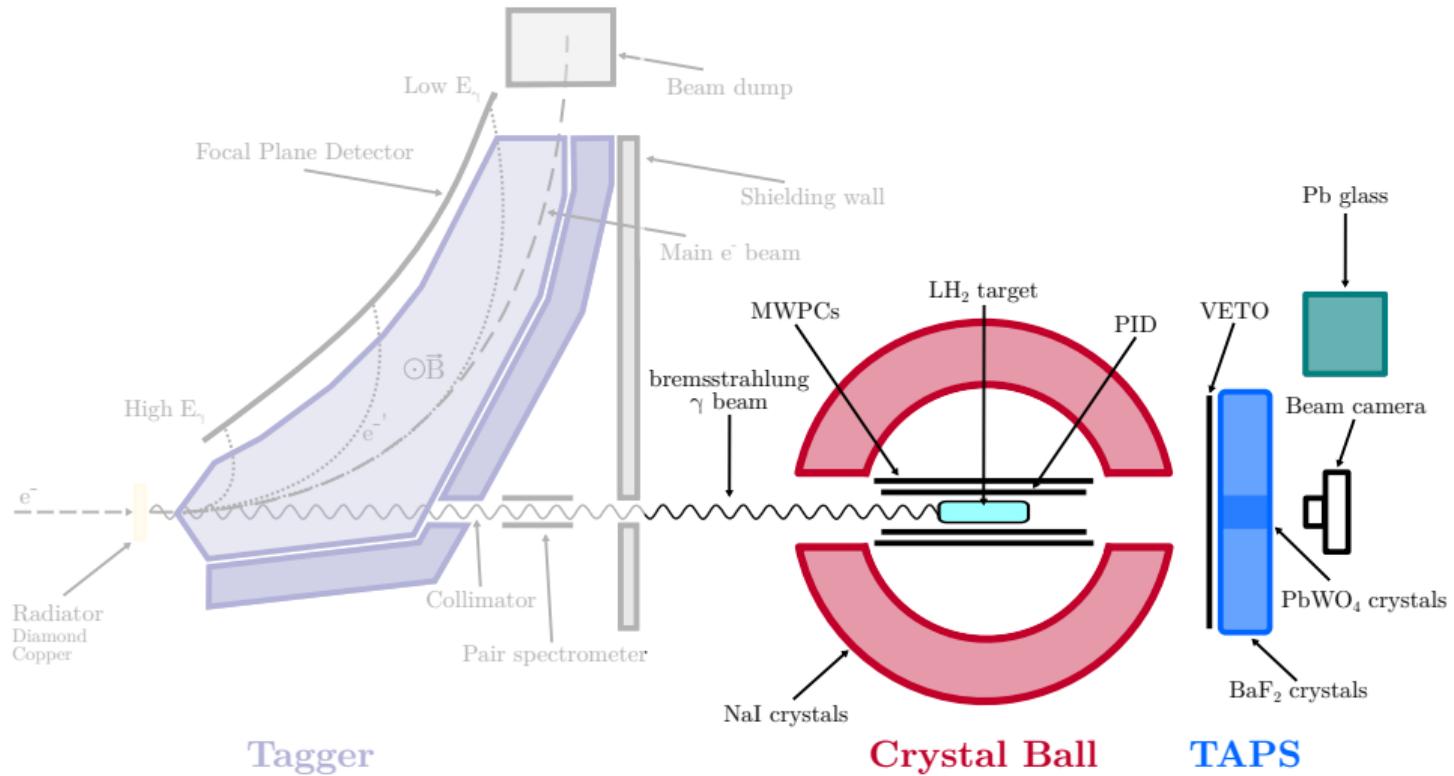
High intensity (linearly polarized) tagged photon beam:

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



**Tagger**

# A2 setup



# Target

Unpolarized target ( $d\sigma/d\Omega$  &  $\Sigma_3$ ):



- Liquid hydrogen target ( $\text{LH}_2$ )
- 10 cm long cell
- $T = 20 \text{ K}$

# Target

Unpolarized target ( $d\sigma/d\Omega$  &  $\Sigma_3$ ):



Polarized target ( $\Sigma_{2x}$ & $\Sigma_{2z}$ ):



- Liquid hydrogen target ( $\text{LH}_2$ )
- 10 cm long cell
- $T = 20 \text{ K}$
- Butanol ( $\text{C}_4\text{H}_9\text{OH}$ )
- 2 cm long cell
- $T = 25 \text{ mK}$
- Polarization  $> 90\%$
- Relaxation time  $> 1000 \text{ h}$

# Detection apparatus

## Crystal Ball

Highly segmented EM calorimeter

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

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

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

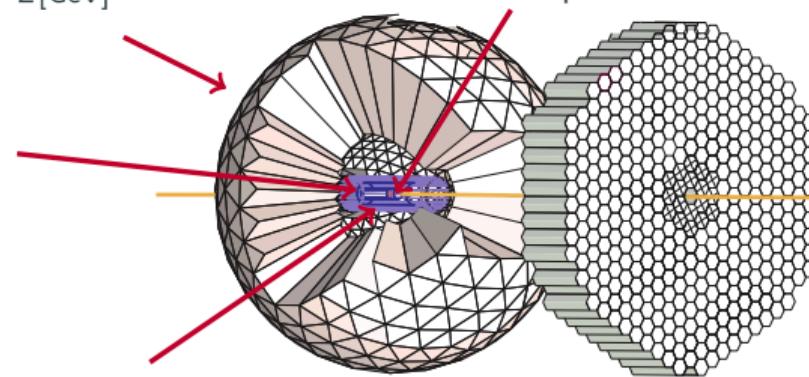
## Particle ID

Barrel of thin scintillators

$$\Delta\phi = 15^\circ$$

## TARGET

Liquid Hydrogen  
10-cm capton cell



## TAPS

Highly segmented EM calorimeter

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

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

$$\sigma_\theta < 1^\circ$$

## TAPS-Veto

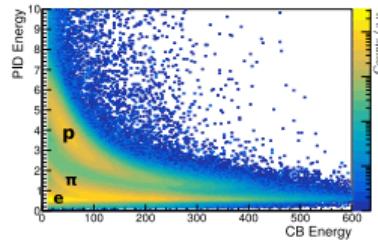
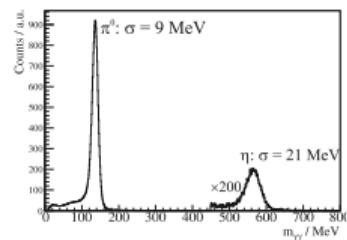
Thin scintillators before each TAPS crystal

## Multiwire Proportional Chambers

Precise charged tracking/positioning

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

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



New high precision measurement

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# Experiment

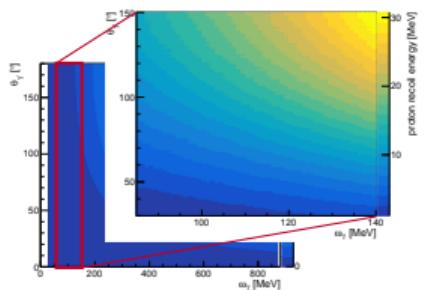


Data analysis to select Compton scattering events in  $\omega_\gamma = 85 - 140$  MeV and  $\theta_{\gamma'} = 30^\circ - 150^\circ$

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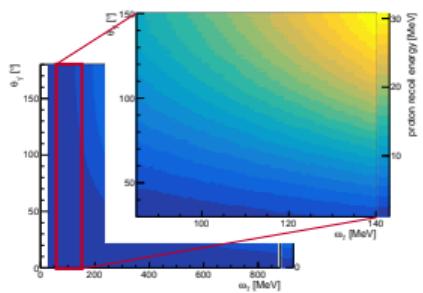
## 1. Events with one neutral cluster



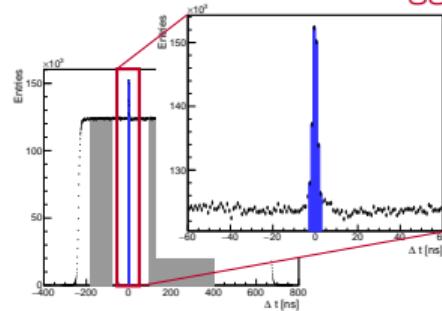
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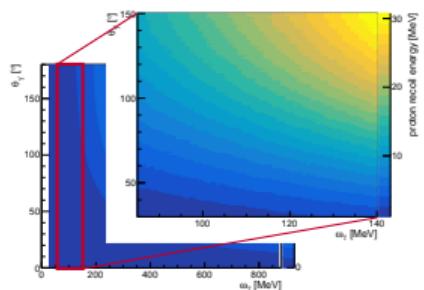
## 2. Subtraction of randoms in tagger



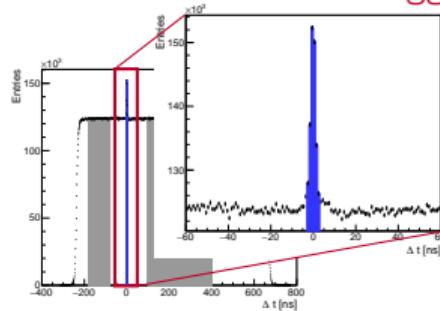
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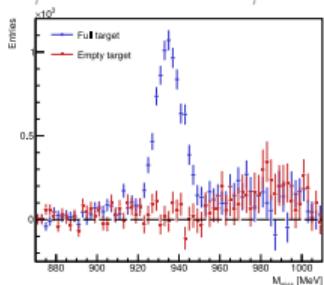


## 2. Subtraction of randoms in tagger



## 3. Subtraction of the empty target

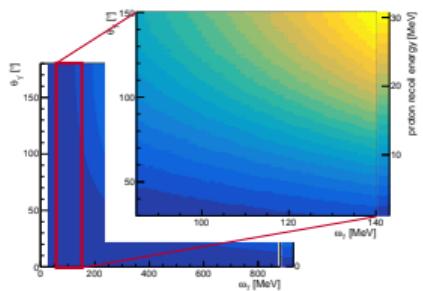
$$\omega_{\gamma'} = 124.1 \text{ MeV} \text{ and } \theta_{\gamma'} = 135^\circ$$



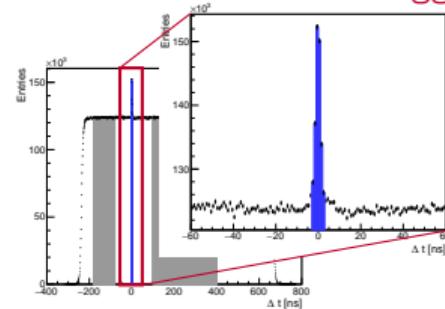
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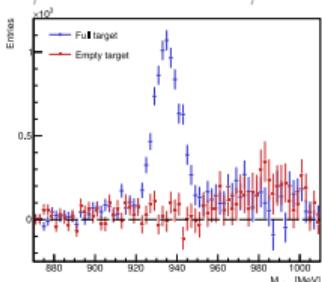


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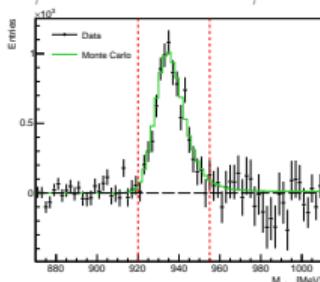
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## 4. Bkg rejection with missing mass cut

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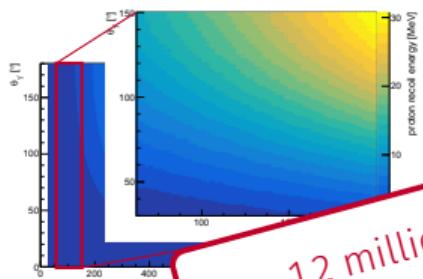


# Experiment

A2

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

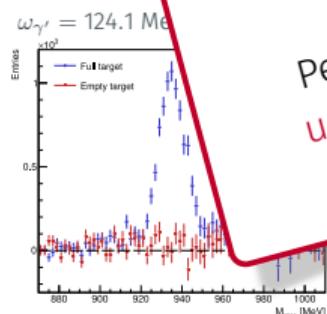
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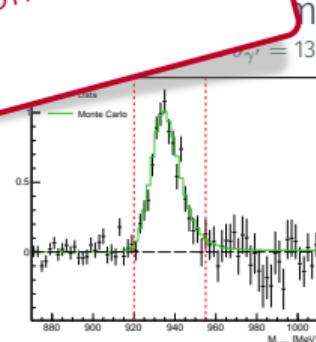
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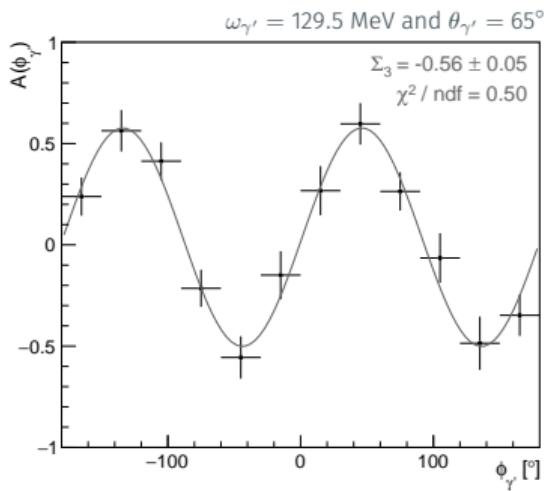
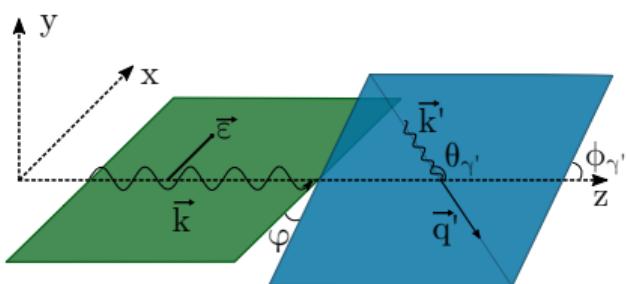
Perform a simultaneous measurement of the unpolarized differential cross-section and the beam asymmetry  $\Sigma_3$



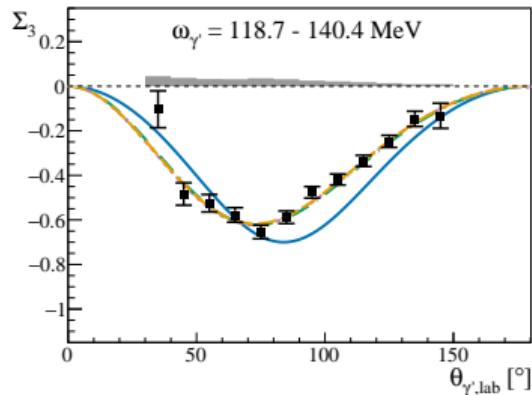
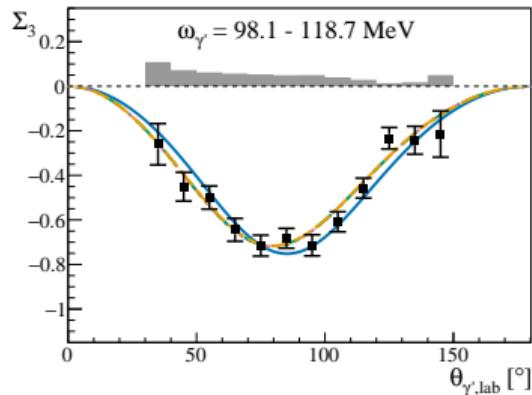
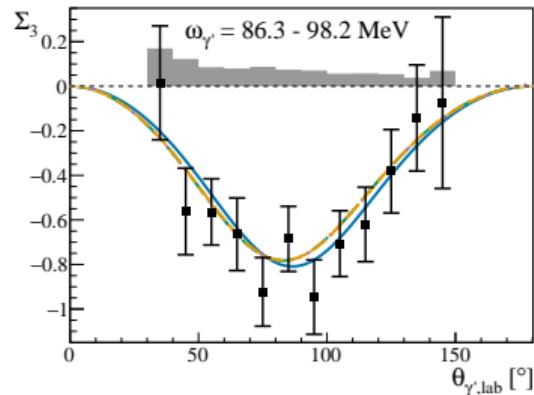
# Extraction of the beam asymmetry $\Sigma_3$

The beam asymmetry can be **extracted** by measuring the polarized cross-section with two orthogonal orientation of the polarization plane:

$$A(\varphi) = \Sigma_3 \cos(2\varphi) = \frac{N^{\parallel}(\omega_{\gamma}, \theta_{\gamma'}, \varphi) - N^{\perp}(\omega_{\gamma}, \theta_{\gamma'}, \varphi)}{p_{\gamma}^{\perp} N^{\parallel}(\omega_{\gamma}, \theta_{\gamma'}, \varphi) + p_{\gamma}^{\parallel} N^{\perp}(\omega_{\gamma}, \theta_{\gamma'}, \varphi)}$$



# Results on the beam asymmetry $\Sigma_3$



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

Systematic errors

Born contribution

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

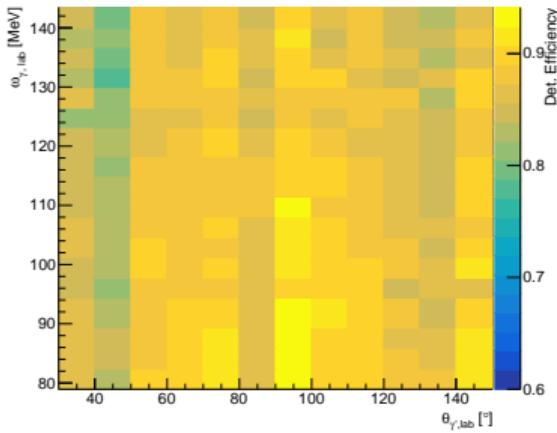
$B\chi$ PT: Eur. Phys. J. C **65**, 195 (2010)

$HB\chi$ PT: Eur. Phys. J. A **49**, 12 (2013)

# Extraction of the unpolarized cross-section

The unpolarized cross-section can be determined by precisely measuring the **detection**, **reconstruction** and tagging efficiencies:

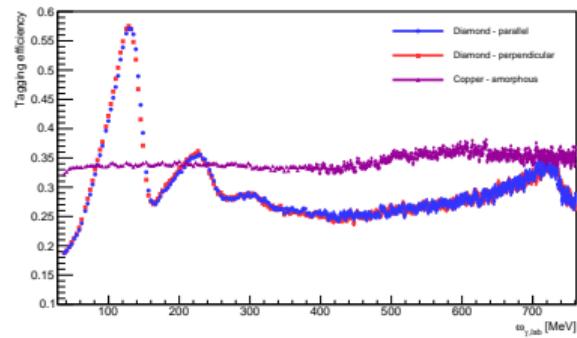
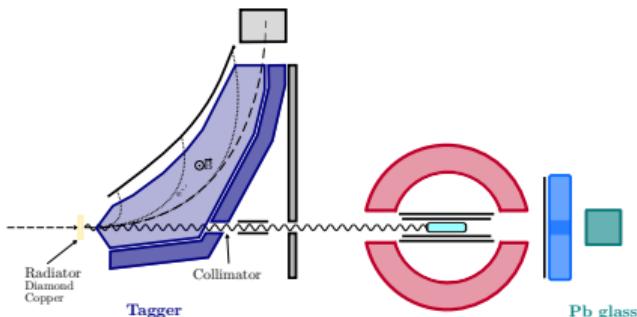
$$\frac{d\sigma}{d\Omega}(\omega_\gamma, \theta_{\gamma'}) = \frac{N_{\gamma'}(\omega_\gamma, \theta_{\gamma'})}{d\Omega} \frac{1}{N_p} \frac{1}{\epsilon_{rec}(\omega_\gamma, \theta_{\gamma'})} \frac{1}{N_{e^-}(\omega_\gamma) \epsilon_{tagg}(\omega_\gamma)}$$



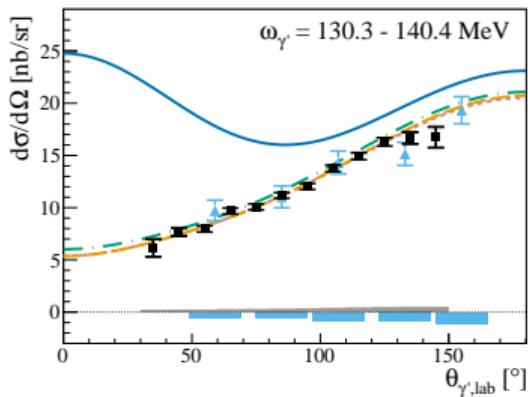
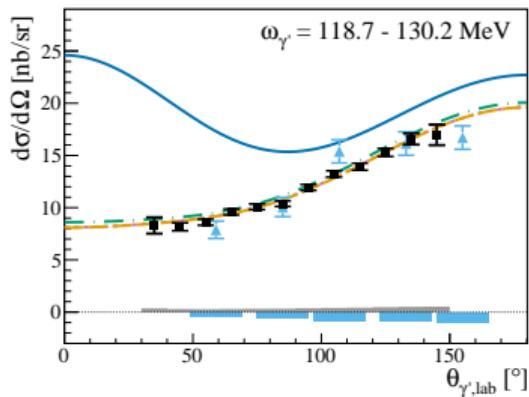
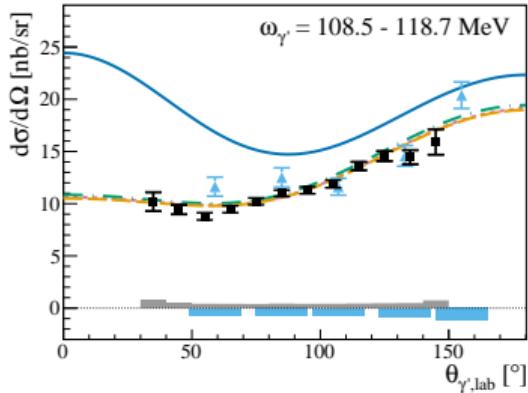
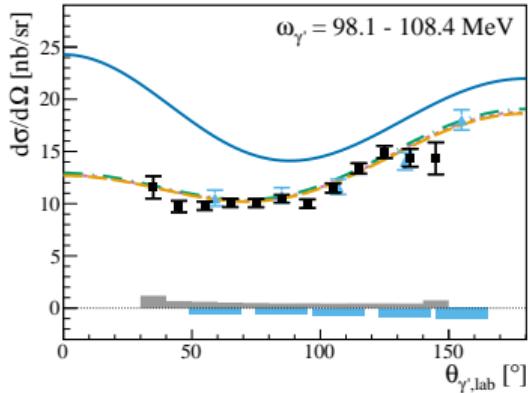
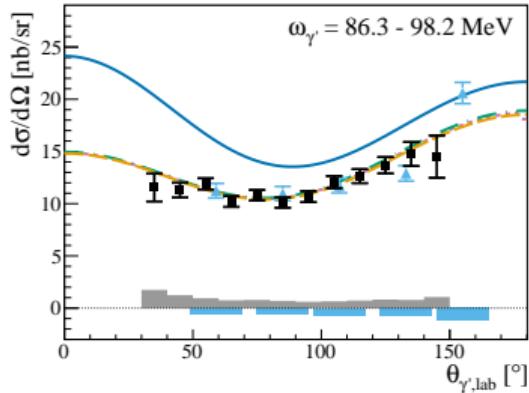
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# Results on the unpolarized cross-section



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

A2 systematic errors

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

TAPS systematic errors

Born contribution

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

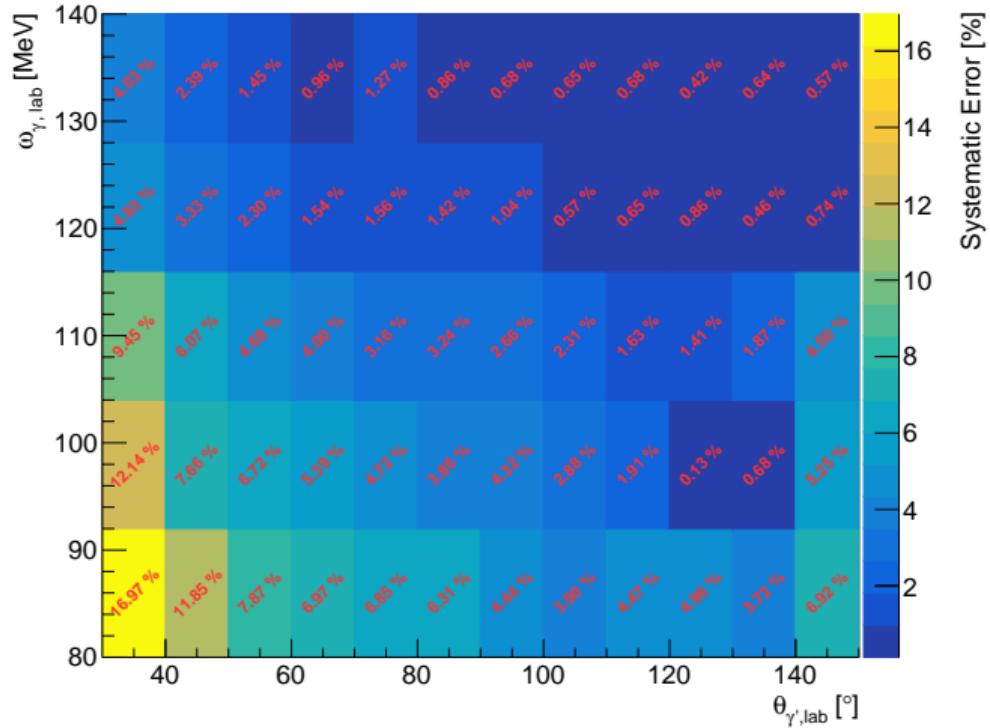
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# Systematic errors

|            |                                   |           |
|------------|-----------------------------------|-----------|
| UCS        | Event selection and MC correction | 2%        |
|            | Target density                    | 1%        |
|            | Flux normalization                | 2%        |
|            | Background                        | uncorr.   |
|            | <b>TOTAL</b>                      | <b>3%</b> |
| $\Sigma_3$ | Linear polarization               | 5%        |
|            | Background                        | uncorr.   |
|            | <b>TOTAL</b>                      | <b>5%</b> |

# Background contamination



- Higher for low  $\omega_{\gamma}$  and forward  $\theta_{\gamma'}$  ( $\sim 17\%$ )
- Lower for high  $\omega_{\gamma}$  and backward  $\theta_{\gamma'}$  ( $\sim 0.5\%$ )
- Average  $\sim 2\%$

# 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

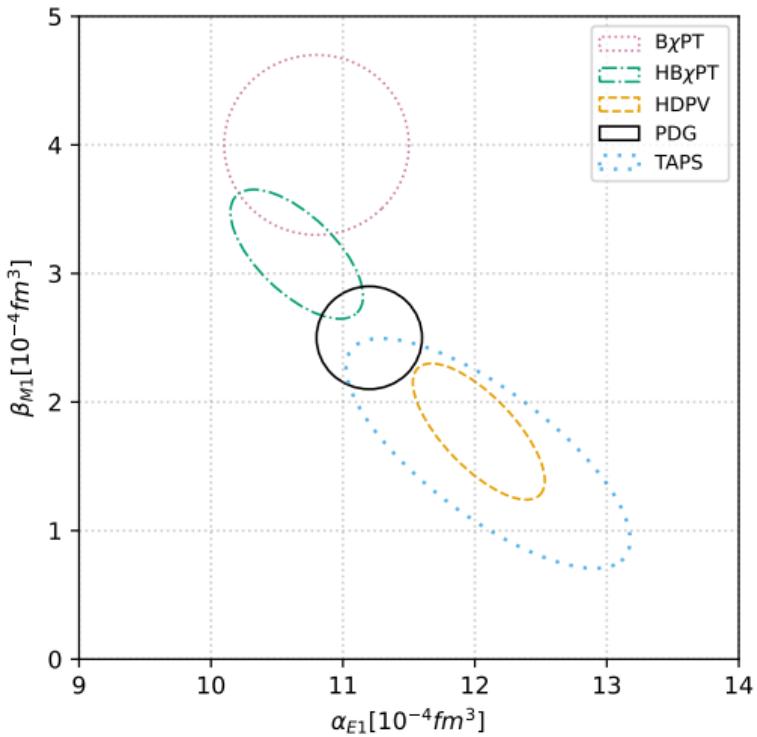
E. Mornacchi (A2), Phys. Rev. Lett. 128, 132503 (2022)

|                     | HDPV              | BChPT             | HBChPT            |
|---------------------|-------------------|-------------------|-------------------|
| $\alpha_{E1}$       | $11.23 \pm 0.49$  | $10.65 \pm 0.50$  | $11.10 \pm 0.52$  |
| $\beta_{M1}$        | $2.79 \pm 0.32$   | $3.28 \pm 0.33$   | $3.36 \pm 0.38$   |
| $s_\sigma$          | $1.011 \pm 0.015$ | $1.013 \pm 0.015$ | $1.043 \pm 0.016$ |
| $s_\Sigma$          | $0.994 \pm 0.015$ | $0.996 \pm 0.015$ | $1.001 \pm 0.015$ |
| $\chi^2/\text{DOF}$ | $82.10/93 = 0.89$ | $82.96/93 = 0.89$ | $83.16/93 = 0.89$ |

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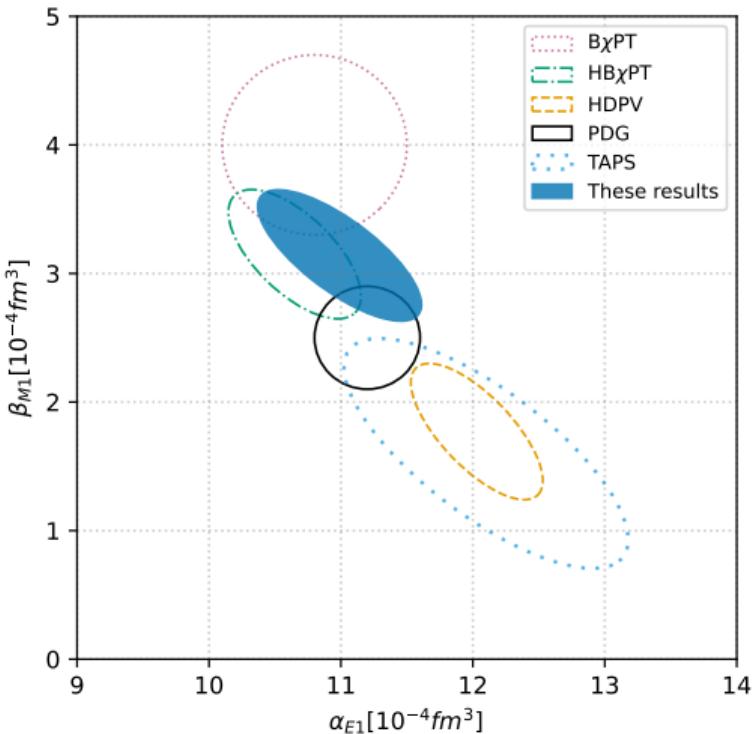
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$$\beta_{M1} = 3.14 \pm 0.21 \pm 0.24 \pm 0.20 \pm 0.35$$

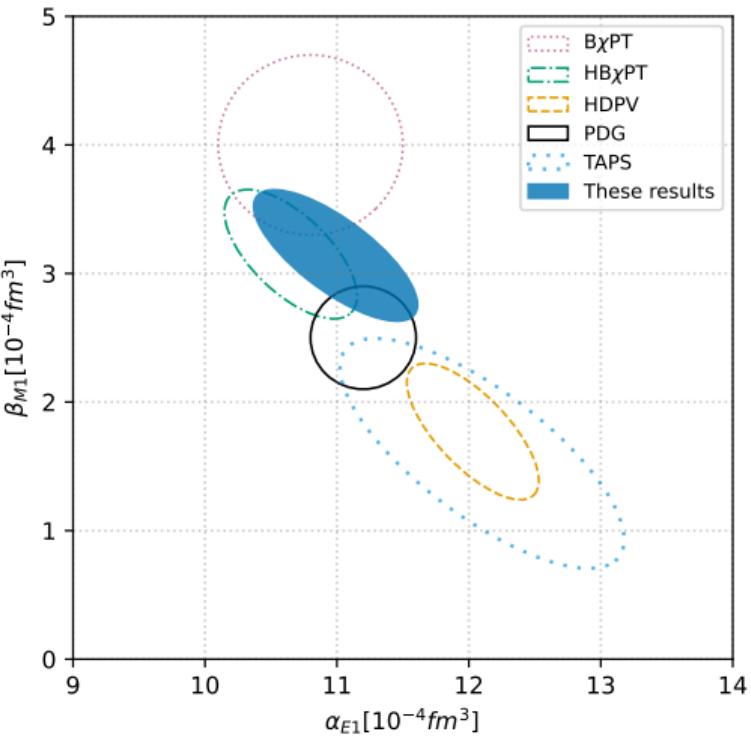


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- Highest precision Compton scattering dataset below  $\pi$ -photoproduction threshold!
- Precise extraction of the scalar polarizabilities from one single dataset



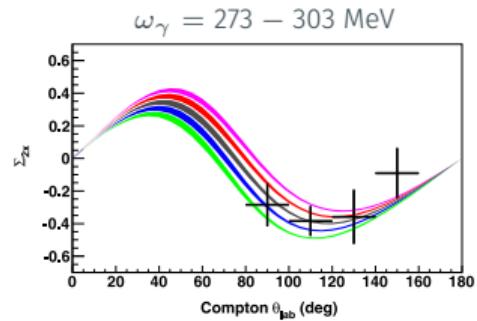
## Results on spin polarizabilities

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# A2 measurements - published



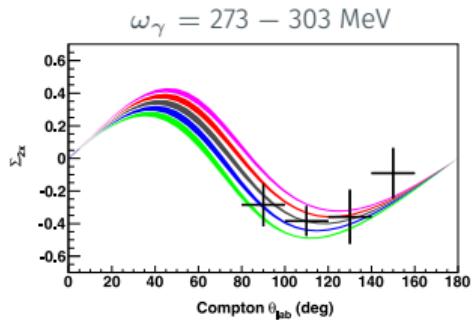
$\Sigma_{2x}$  - Martel et al. (A2) Phys. Rev. Lett. 114 (2015)



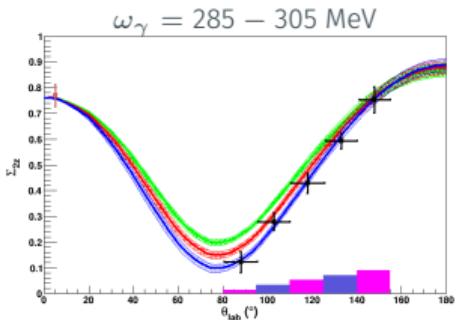
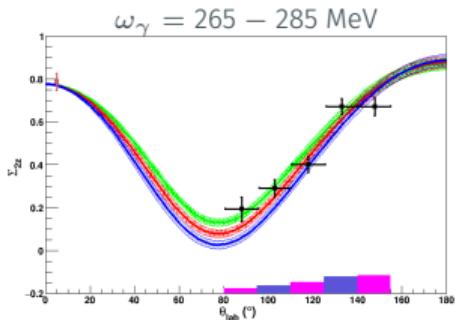
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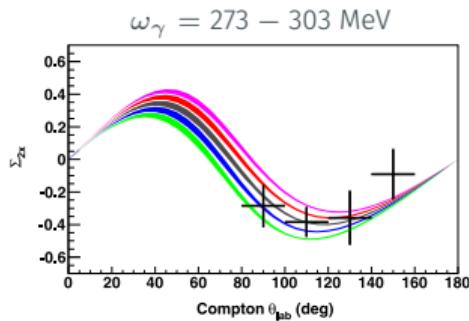
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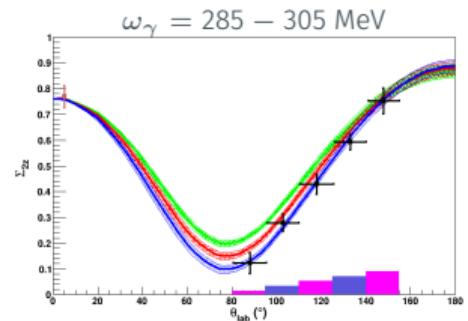
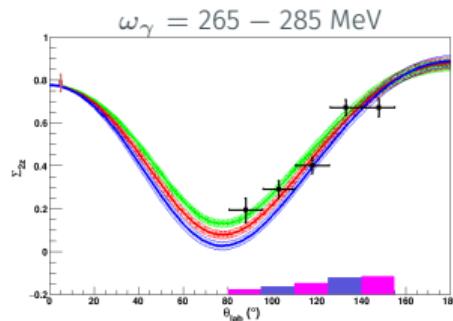
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Extraction of the spin polarizabilities:

- $\Sigma_{2x}$ ,  $\Sigma_{2z}$ , and  $\Sigma_3^{LEGS}$
- $\gamma_{E-} = \gamma_{E1E1} - \gamma_{M1E2}$  and  
 $\gamma_{M-} = \gamma_{M1M1} - \gamma_{E1M2}$  as fitted parameters
- $\alpha_{E1} \pm \beta_{M1}$ ,  $\gamma_0$ , and  $\gamma_\pi$  fixed

|                 | $\Sigma_{2z}$ , $\Sigma_{2x}$ , and $\Sigma_3^{LEGS}$ data fits |                  |                  |
|-----------------|---|------------------|------------------|
|                 | HDPV  | B $\chi$ PT      | Weighted average |
| $\gamma_{E1E1}$ | $-3.18 \pm 0.52$  | $-2.65 \pm 0.43$ | $-2.87 \pm 0.52$ |
| $\gamma_{M1M1}$ | $2.98 \pm 0.43$   | $2.43 \pm 0.42$  | $2.70 \pm 0.43$  |
| $\gamma_{E1M2}$ | $-0.44 \pm 0.67$  | $-1.32 \pm 0.72$ | $-0.85 \pm 0.72$ |
| $\gamma_{M1E2}$ | $1.58 \pm 0.43$   | $2.47 \pm 0.42$  | $2.04 \pm 0.43$  |
| $\chi^2/dof$    | 1.14  | 1.36             |                  |

## A2 measurements - ongoing

$\Sigma_3 - \omega_\gamma \approx 270 - 300$  MeV:

- Preliminary analysis by C. Collicott  
(PhD thesis, Dalhousie University (2015))
  - limited statistics
  - unpublished mainly due to problem in controlling  $\pi^0$  background
- New analysis in ongoing:
  - high statistics!
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$d\sigma/d\Omega - \omega_\gamma \approx 150 - 300$  MeV

- Analysis on same dataset used for low energy data
  - data are very well understood
  - $\pi^0$ -bkg not-so relevant up to  $\sim 220/230$  MeV
  - even more (not-so-well) understood data on tape
  - low manpower!

## Neutron polarizabilities

---

# Neutron polarizabilities

The data are much more scarce compare to proton as there is no free neutron target!  
Possible alternatives would be:

- Elastic scattering on deuterium
  - energy resolution  $\sim 2$  MeV needed
  - impossible at MAMI
  - existing results from MAX-Lab
- Elastic scattering on  $^3\text{He}$ 
  - energy resolution  $\sim 4$  MeV needed
  - possible with an active target
- Elastic scattering on  $^4\text{He}$ 
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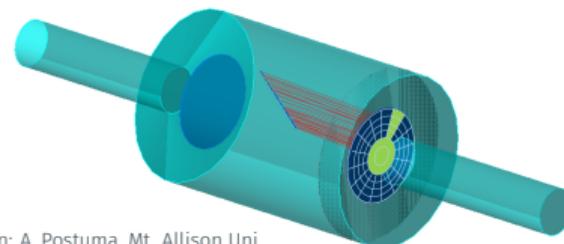
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Active TPC to fit in the CB:

- Extremely high energy resolution ( $\sim 100$  KeV)
- Good angular and tracking resolution
- Possibility to use with different gas
- Project stopped due to geopolitical situation



Simulation: A. Postuma, Mt. Allison Uni

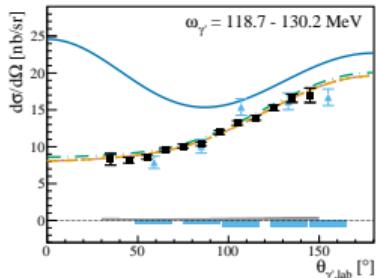
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# Conclusions



The last two years have been very prolific for proton Compton scattering!

- The highest statistics Compton scattering dataset below threshold was finally published by the A2 Collaboration
  - $\omega_\gamma = 85 - 140$  MeV with broad angular coverage  $\theta_{\gamma'} = 30 - 150^\circ$
  - first precise extraction of  $\Sigma_3$  below the  $\pi$ -thr (36 bins)
  - high-precision measurement of  $d\sigma/d\Omega$  below the  $\pi$ -thr (60 bins)

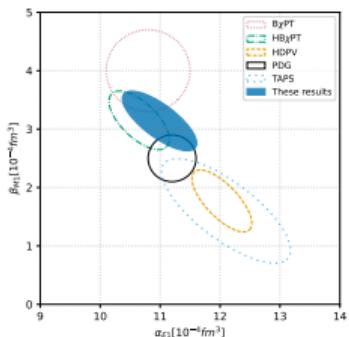
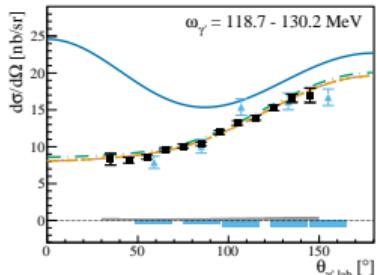


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  - high-precision measurement of  $d\sigma/d\Omega$  below the  $\pi$ -thr (60 bins)
- Extraction of the proton scalar polarizabilities from the new dataset
  - comparable errors to the world average **from one single consistent dataset**
  - central values independent from the inclusion of the Baldin sum rule



# Conclusions

The last two years have been very prolific for proton Compton scattering!

- 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!

See talks:  
C. Howell, Mon, 12:45  
P. Pedroni, Mon, 17:30

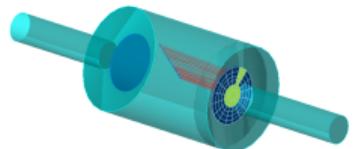
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What about the future?

- It's time to move on to the neutron polarizabilities
  - theory on  ${}^3\text{He}$  and  ${}^4\text{He}$  is ready
  - active TPC is needed to detect the recoil particles



The last two years have been very prolific for proton Compton scattering!

- The HIGS Collaboration published a complementary dataset at lower energy
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Thanks for your  
attention!  
...in the future?

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