Compton Scattering and the Nucleon Polarizabilities

Precision Hadron Structure at MAMI

David Hornidge

Mount Allison University
Sackville, NB
CANADA

CAP Congress
Simon Fraser University
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THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

Outline

- Motivation
- Proton - scalar and spin polarizabilities
- Neutron - scalar polarizabilities
- Summary and Outlook

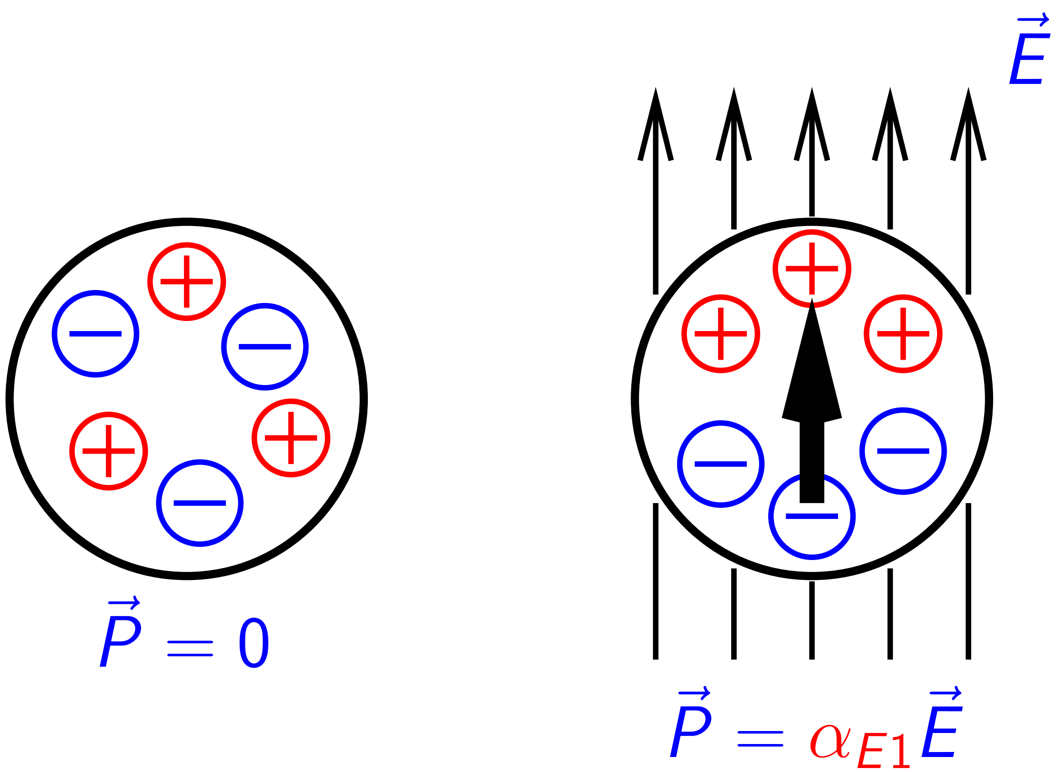
How do we test QCD in the non-perturbative regime?

High-precision measurements of polarization observables.

- **Hadron Polarizabilities:**
  - Fundamental structure constants
  - Response of internal structure to external fields
  - Fertile meeting ground between theory and experiment
  - Best accessed via **Compton scattering**, both real and virtual
- **Theoretical Approaches:**
  - Dispersion Relations
  - Chiral Perturbation Theory
  - Lattice QCD

Scalar Polarizabilities - Conceptual

Electric Dipole Polarizability

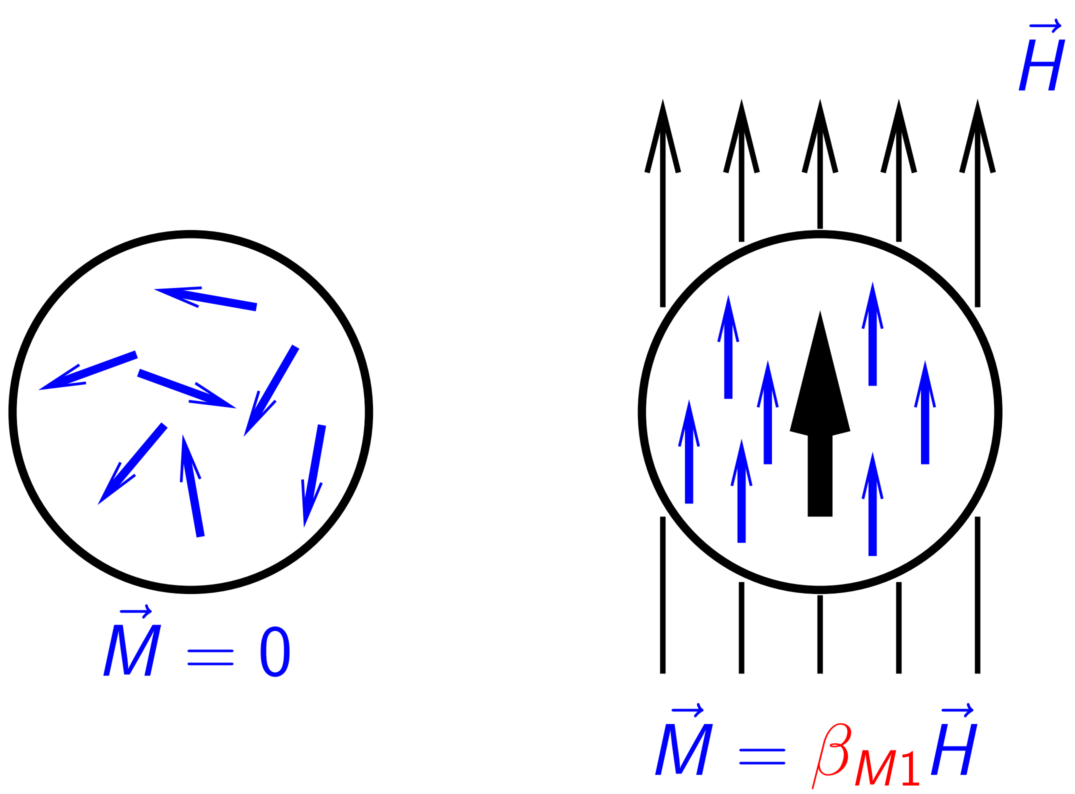


- Apply an electric field to a composite system
- Separation of Charge, or **"Stretchability"**
- Proportionality constant between electric dipole moment and electric field is the electric dipole polarizability, α_{E1}.

Provides information on force holding system together.

Scalar Polarizabilities - Conceptual

Magnetic Dipole Polarizability



- Apply a magnetic field to a composite system
- Alignment of dipoles or **"Alignability"**
- Proportionality constant between magnetic dipole moment and magnetic field is the magnetic dipole polarizability, β_{M1}.
- Two contributions, paramagnetic and diamagnetic, and they cancel partially, giving $\beta_{M1} < \alpha_{E1}$.

Provides information on force holding system together.

How about subatomic particles?

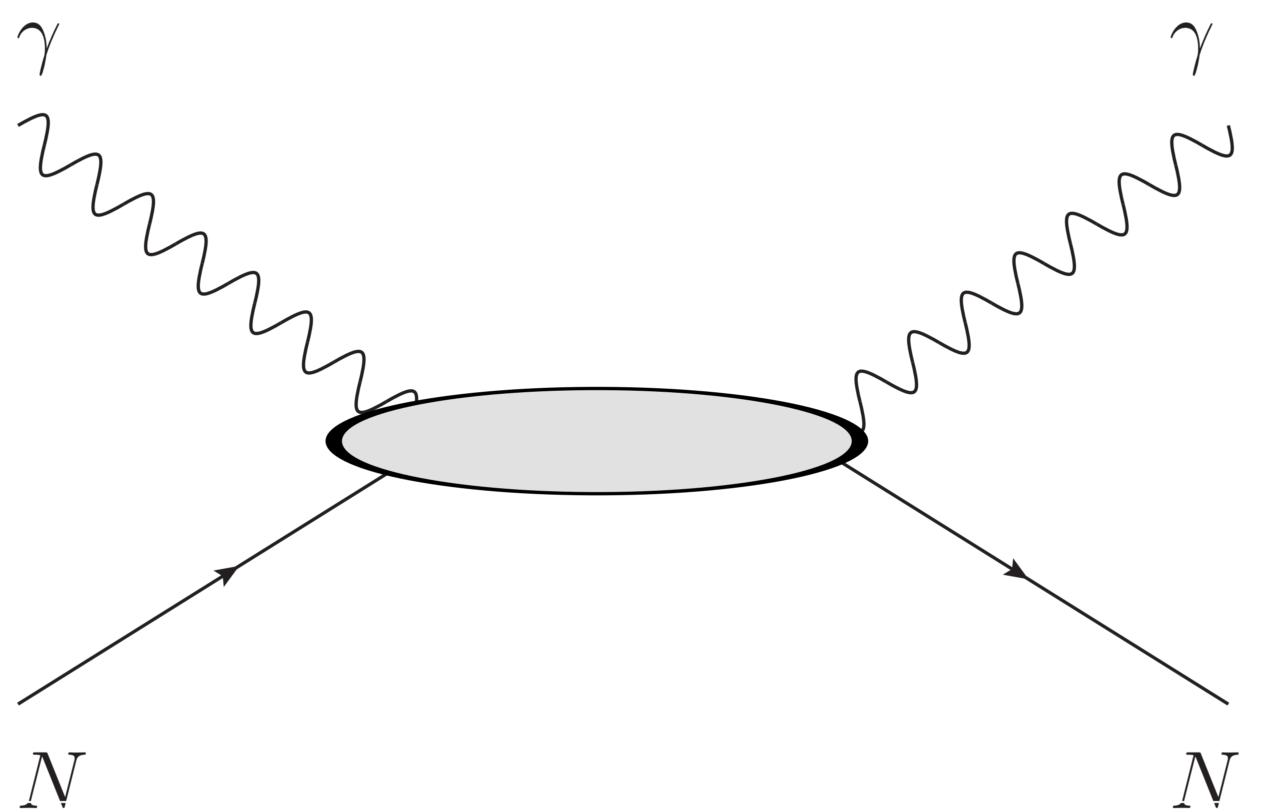
- We obviously can't just put a proton between the plates of a capacitor or the poles of a magnet and measure its deformation. What to do?
- The answer of course is Compton scattering!
- What kind of fields can we get from from a high-energy photon?
- Naively, for a 100-MeV photon:

$$E = \frac{V}{d} \simeq \frac{100\ \text{MV}}{10^{-15}\ \text{m}} \simeq 10^{23}\ \text{V/m}$$

A HUGE field!

Real Compton Scattering from the Nucleon

- The outgoing photon *plays the role of the applied EM field.*
- Nucleon Response.
- POLARIZABILITIES!
- Global response to the internal degrees of freedom.



Compton Scattering - Hamiltonian

Expand the Hamiltonian in incident-photon energy.

0th order $\longrightarrow$ charge, mass

1st order $\longrightarrow$ magnetic moment

2nd order $\longrightarrow$ **scalar polarizabilities**:

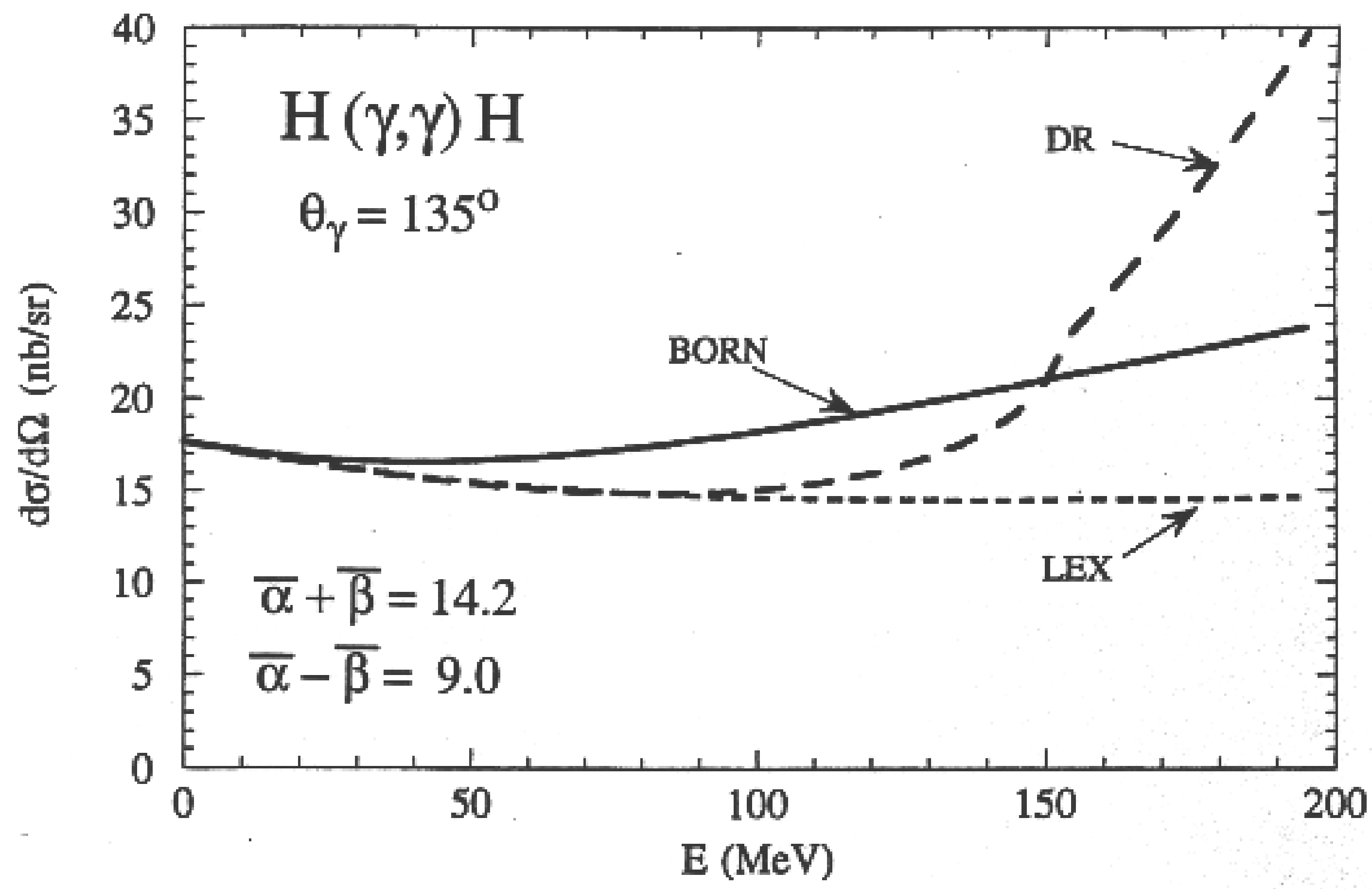
$$H_{\text{eff}}^{(2)} = -4\pi \left[\frac{1}{2} \alpha_{E1} \vec{E}^2 + \frac{1}{2} \beta_{M1} \vec{H}^2 \right]$$

3rd order $\longrightarrow$ **spin (or vector) polarizabilities**:

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

Low-Energy Expansion - LEX

How do you extract polarizabilities from Compton scattering data?



LEX:

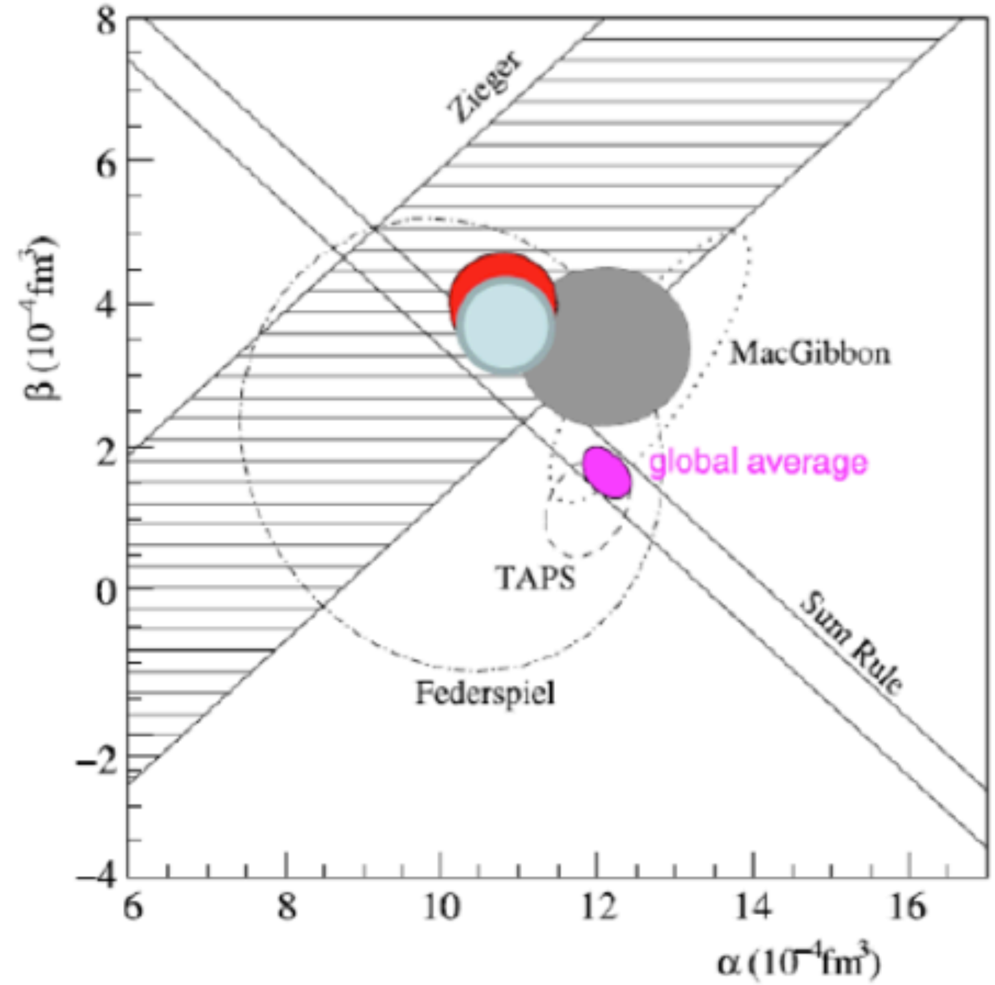
$$\frac{d\sigma}{d\Omega}(\nu,\theta) = \frac{d\sigma}{d\Omega}^{\text{Born}}(\nu,\theta) - \nu\nu'\left(\frac{\nu'}{\nu}\right)\frac{e^2}{2m}\left[(\alpha_{E1}+\beta_{M1})(1+z^2)(\alpha_{E1}-\beta_{M1})(1-z^2)\right]$$

with $z = \cos\theta$

Measure low energies and precise cross sections/asymmetries!

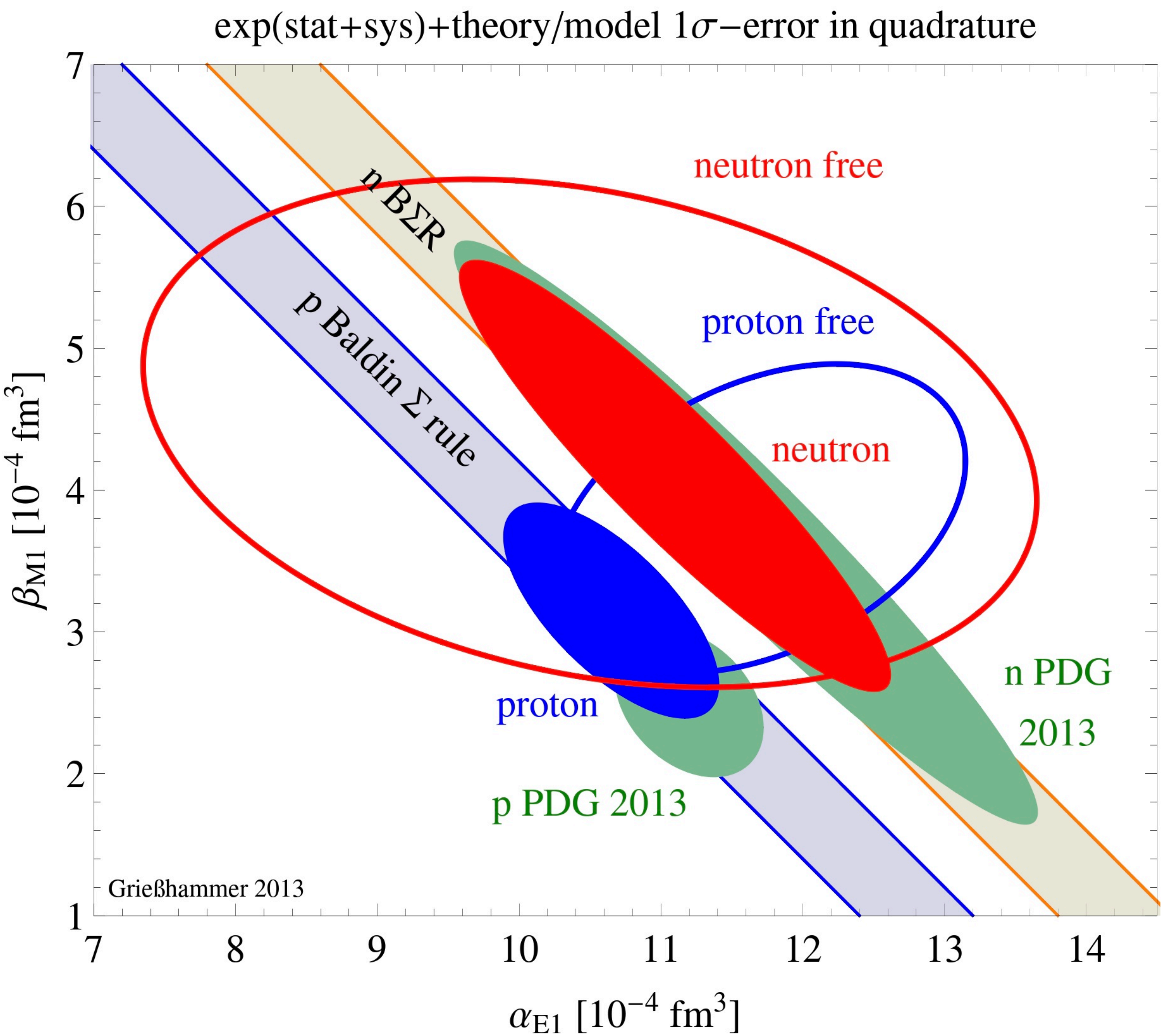
Comparison of DRs with EFTs

Fit to UNPOLARIZED cross section → sensitivity to $\alpha_{E1} - \beta_{M1}$ and $\alpha_{E1} + \beta_{M1}$



- Particle Data Group (PDG) [analysis based on DRs]
- Heavy Baryon ChPT [Beane, Malheiro, McGovern, Phillips, van Kolck, NPA747 (2005)]
- Baryon ChPT with Δ [Lensky and Pascalutsa, EPJC65 (2010)]
- Partially Covariant Baryon ChPT with Δ [McGovern, Phillips, Griesshammer, EPJA49 (2013)]

Proton and Neutron



MPG, EPJA49 12 (2013)

Nucleon Scalar Polarizabilities

Take aways:

- Still lots of work to do.
- Especially for the neutron.
- EFTs give consistently higher values than DRs for β_{M1}

Use polarization observables below pion threshold

Linearly Polarized Beam

Different dxs combinations are dependent only on α_{E1} or β_{M1}:

$$\frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega} = f_1(\text{Born}) - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\alpha_{E1}(1 - z^2) + O(\nu^3)$$

$$\frac{z^2 d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega} = f_2(\text{Born}) - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\beta_{M1} z(z^2 - 1) + O(\nu^3)$$

Recent work by Krupina and Pascalutsa [PRL **110**, 262001 (2013)]

At low energies $\Rightarrow$ use beam asymmetry Σ_3 to extract β_{M1}:

$$\Sigma_3 \equiv \frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\sigma^{\perp} + d\sigma^{\parallel}} = \Sigma_3^{\text{NB}} - f_3(\theta)\beta_{M1}\nu^2 + \mathcal{O}(\nu^4).$$

Spin Polarizabilities of the Proton

- Nucleon has four vector or spin polarizabilities:

$$\gamma_{E1E1} \quad \gamma_{M1M1} \quad \gamma_{M1E2} \quad \gamma_{E1M2}$$

- Similar to the scalar polarizabilities but higher in order.
- Intimately connected to the nucleon's spin structure. **Fundamental Structure Constants!**
- Higher order in incident-photon energy, so they have a smaller effect at lower energies.
- Need theoretical help in extracting values from data.

Spin Polarizabilities - Pre-2015 Status

	K-mat.	HDPV	DPV	L_χ	HBχPT	BχPT
γ_{E1E1}	-4.8	-4.3	-3.8	-3.7	-1.1 ± 1.8 (th)	-3.3
γ_{M1M1}	3.5	2.9	2.9	2.5	2.2 ± 0.5 (st) ± 0.7 (th)	3.0
γ_{E1M2}	-1.8	-0.02	0.5	1.2	-0.4 ± 0.4 (th)	0.2
γ_{M1E2}	1.1	2.2	1.6	1.2	1.9 ± 0.4 (th)	1.1
γ_0	2.0	-0.8	-1.1	-1.2	-2.6	-1.0
γ_π	11.2	9.4	7.8	6.1	5.6	7.2

- Spin polarizabilities in units of 10^{-4} fm^4
- K-matrix: calculation from Kondratyuk et al., PRC **64**, 024005 (2001)
- HDPV, DPV: dispersion relation calculations, Holstein et al., PRC **61**, 034316 (2000) and Pasquini et al., PRC **76**, 015203 (2007), Drechsel et al., PR **378**, 99 (2003)
- L_χ: chiral lagrangian calculation, Gasparyan et al., NPA **866**, 79 (2011)
- HBχPT and BχPT are heavy baryon and covariant, respectively, ChPT calculations, McGovern et al., EPJA **49**, 12 (2013), Lensky et al., PRC **89**, 032202 (2014)

How to measure the spin polarizabilities?

- Use **Compton scattering**.
- Requires polarization degrees of freedom.
- Small effect at low energies so we need higher energies, into the Δ-region.
- We have chosen three asymmetries:

$$\Sigma_{2x} \quad \Sigma_{2z} \quad \Sigma_3$$

that we can use to help obtain the spin polarizabilities of the proton.

Spin Polarizability Extraction

Use γ_0, γ_π, α_{E1}, and β_{M1} along with the three asymmetries.

The various asymmetries respond differently to the individual spin polarizabilities at different energies and angles.

We will conduct an in-depth global analysis, and should be able to extract **all four spin polarizabilities independently** with small statistical, systematic, and model-dependent errors!

Institut für Kernphysik

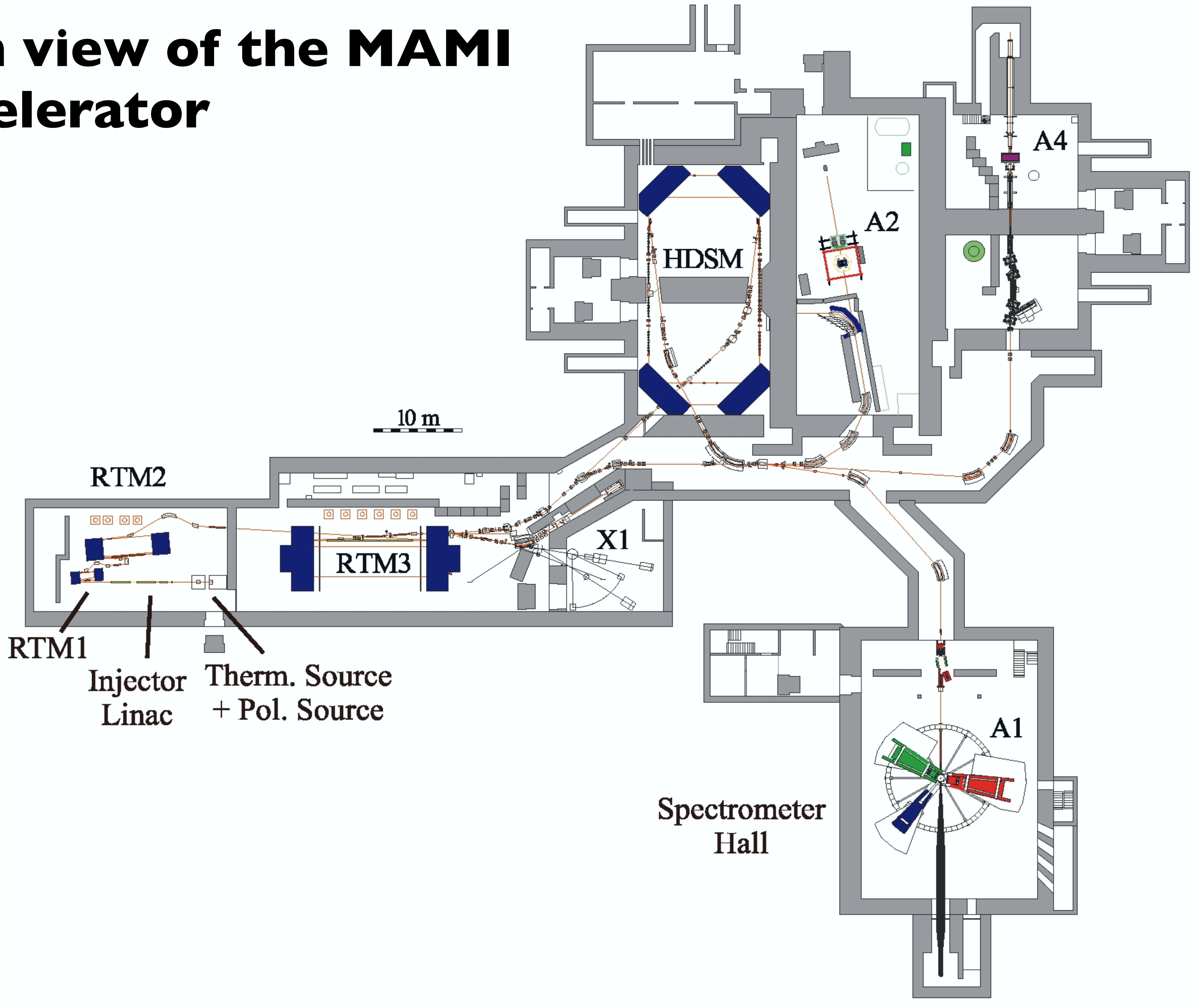
On the Johannes Gutenberg University Campus. Student population of c. 35k.

Houses the MAMI electron accelerator.

Approximately 200 staff members.

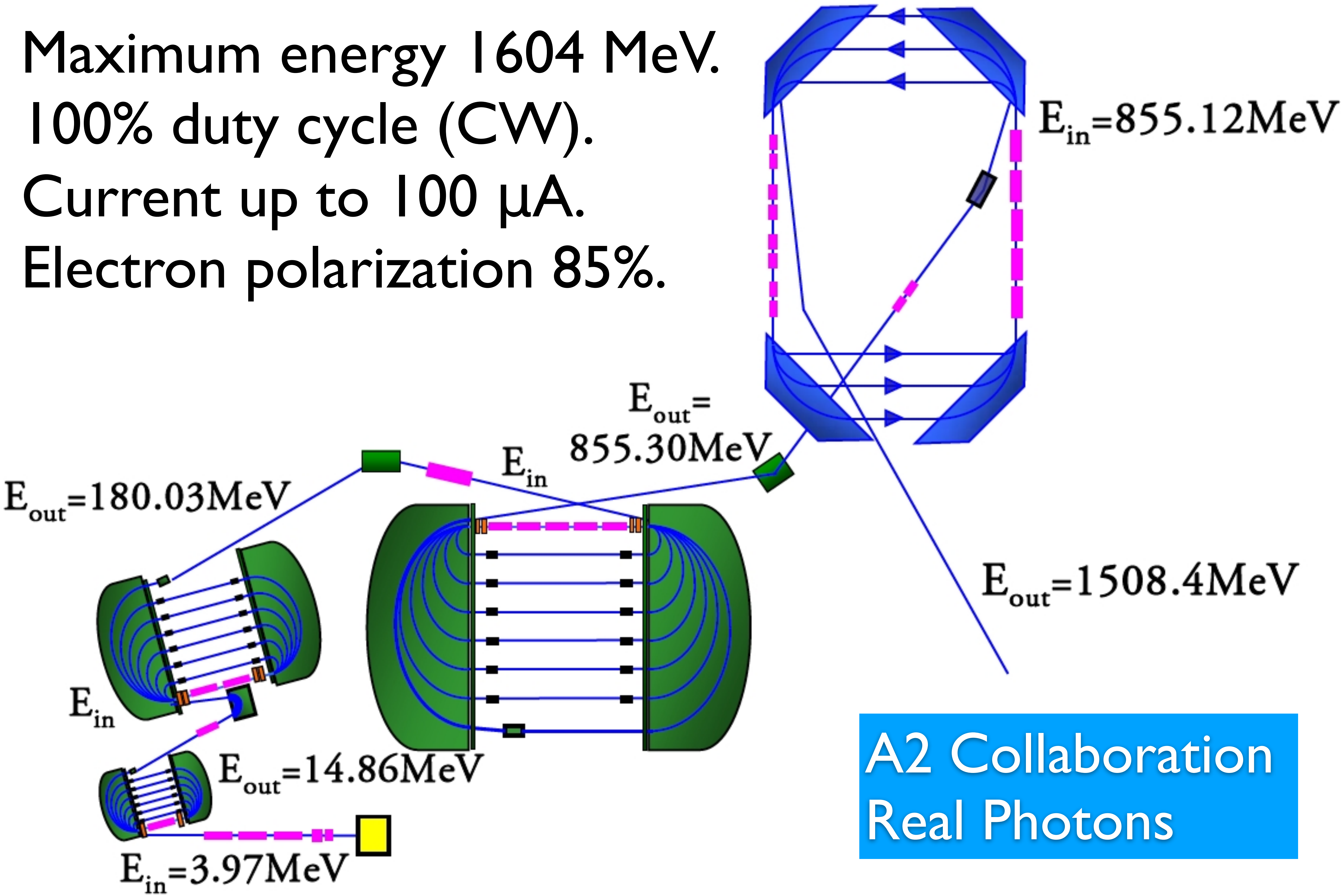
Mainz, Germany

Plan view of the MAMI Accelerator



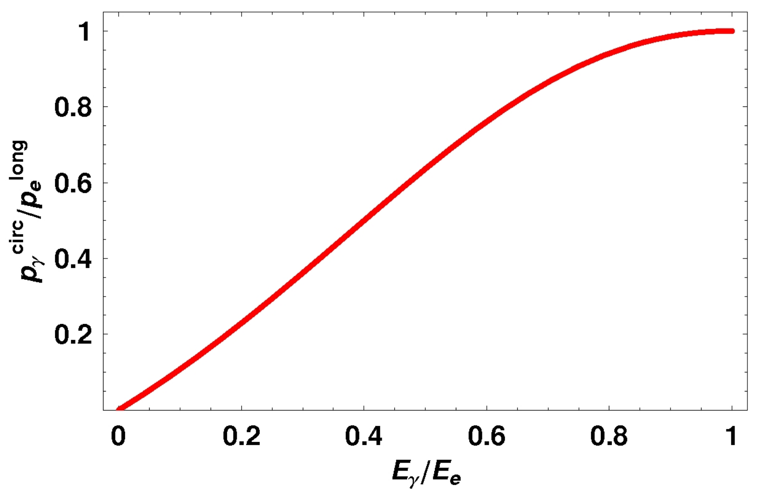
MAMI - Schematic

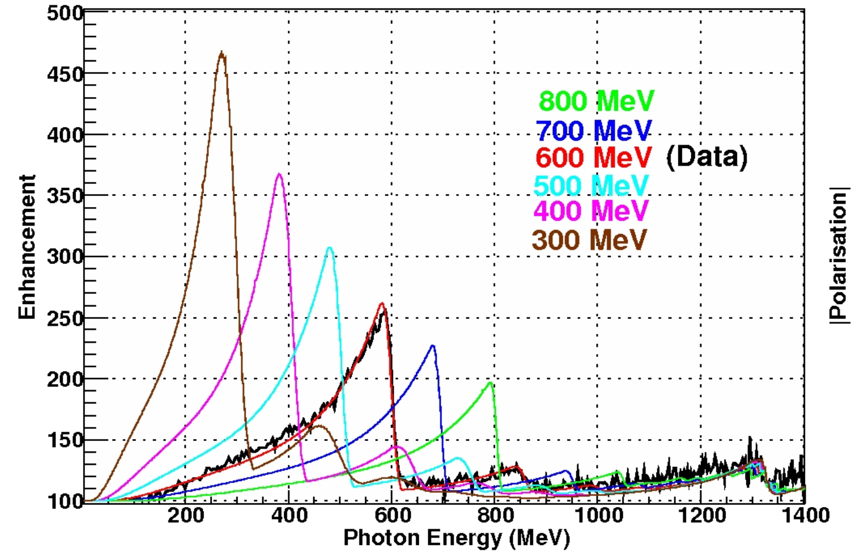
- Maximum energy 1604 MeV.
- 100% duty cycle (CW).
- Current up to 100 μA.
- Electron polarization 85%.

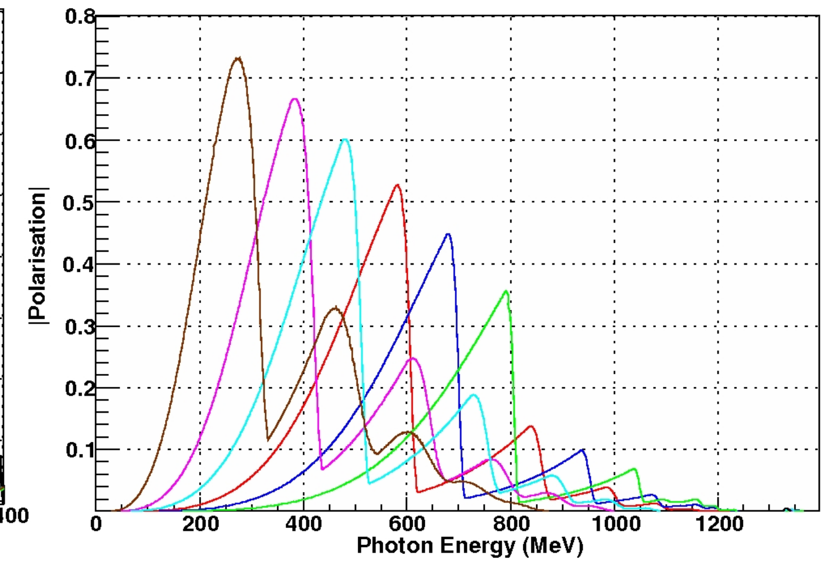


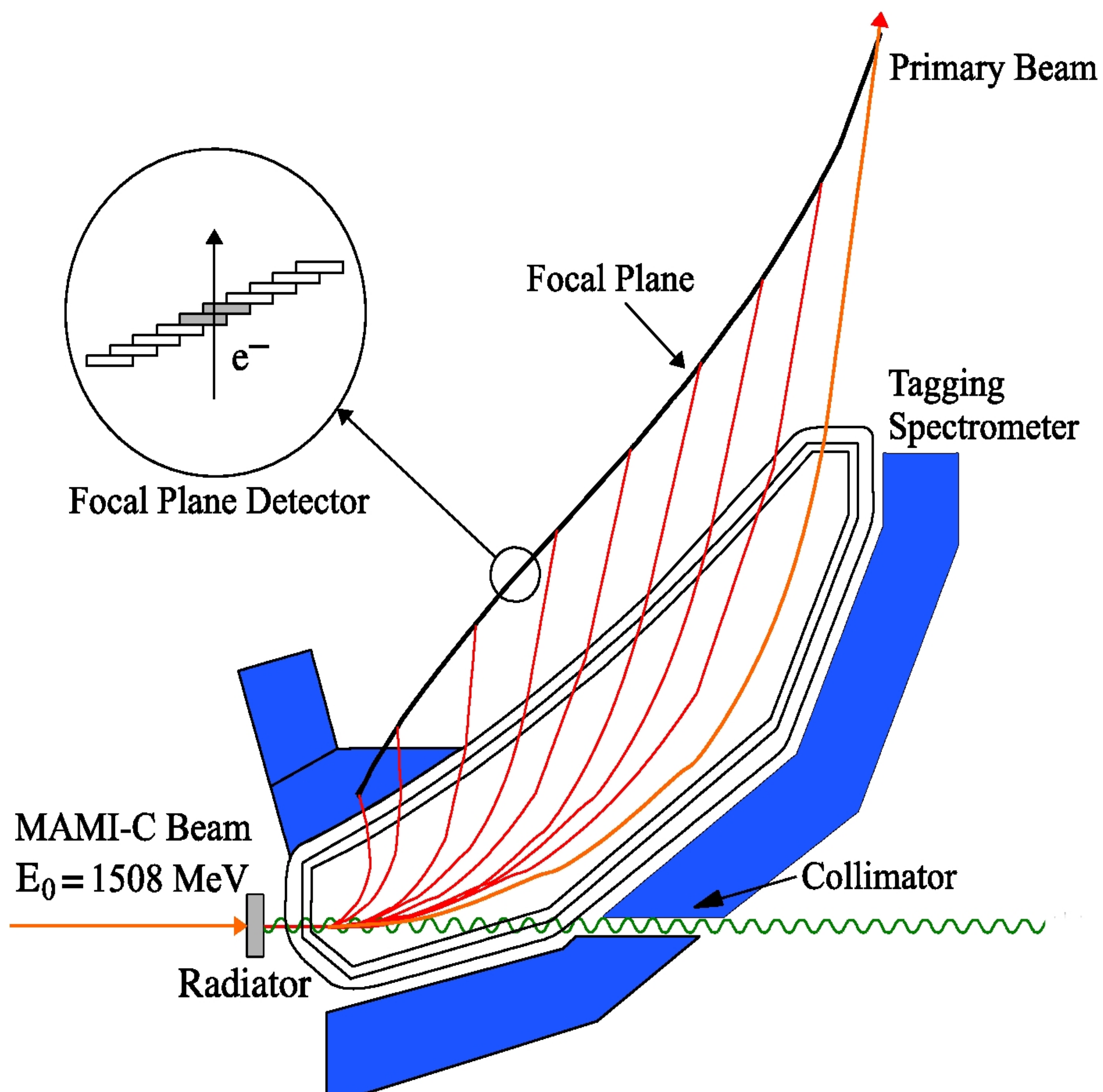
A2 Collaboration
Real Photons

Real Photons - Glasgow Photon Tagger









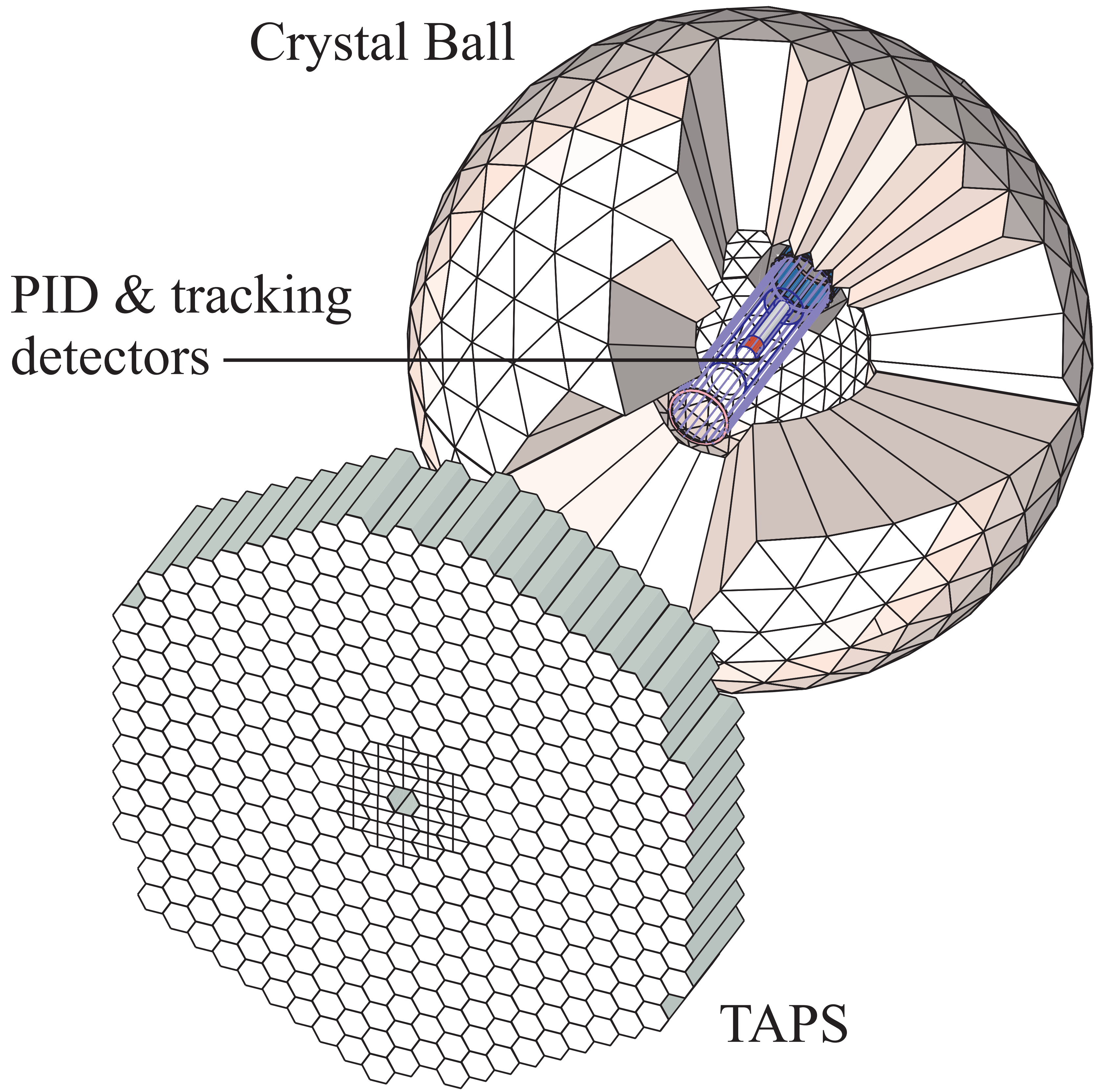
- Detects post-bremsstrahlung electron, $E_\gamma = E_e - E_{e'}$
- 352 channels.
- ≈5-95% of spectrum tagged.
- Energy resolution 1-4 MeV
- Circularly polarized photons
- Linearly polarized photons
- Timing coincidence

Reaction Targets

- LH_2/LD_2: unpolarized protons/deuterons
- Liquid $^4He/^3He$
- Frozen Spin: polarized protons/deuterons
- Solid Targets: C, Pb, and many more...
- Gas target: polarized ^3He
- **Active Polarized Proton target**
- **High-Pressure Active Helium target**

New!

CB-TAPS @ MAMI Detector System



Total # of Signals:

- 672 NaI(Tl) in CB
- 24 plastics in PID
- 320 strips in MWPC
- 480 wires in MWPC
- 384 BaF_2 in TAPS
- 384 plastics in TAPS veto
- (352 in Tagger)

Gives:

- Energy
- Time
- Position
- Particle Type

Experimental Status

Important part of CRC1044.

Experiment	**Status**	
$\boldsymbol{\Sigma_{2x}}$	February 2011	$\surd$
$\boldsymbol{\Sigma_3}$	December 2012	$\surd$
$\boldsymbol{\Sigma_{2z}}$	2014/2015	$\surd$
$\boldsymbol{\alpha_{E1}, \beta_{M1}}$	June 2013, 2017/2018	$\surd$

NOTE: Complementary measurements planned for HIGS!

High-flux, monoenergetic beam, with $\approx$ 100% polarization.

Pilot Experiment to Measure Proton α_{E1}, β_{M1}

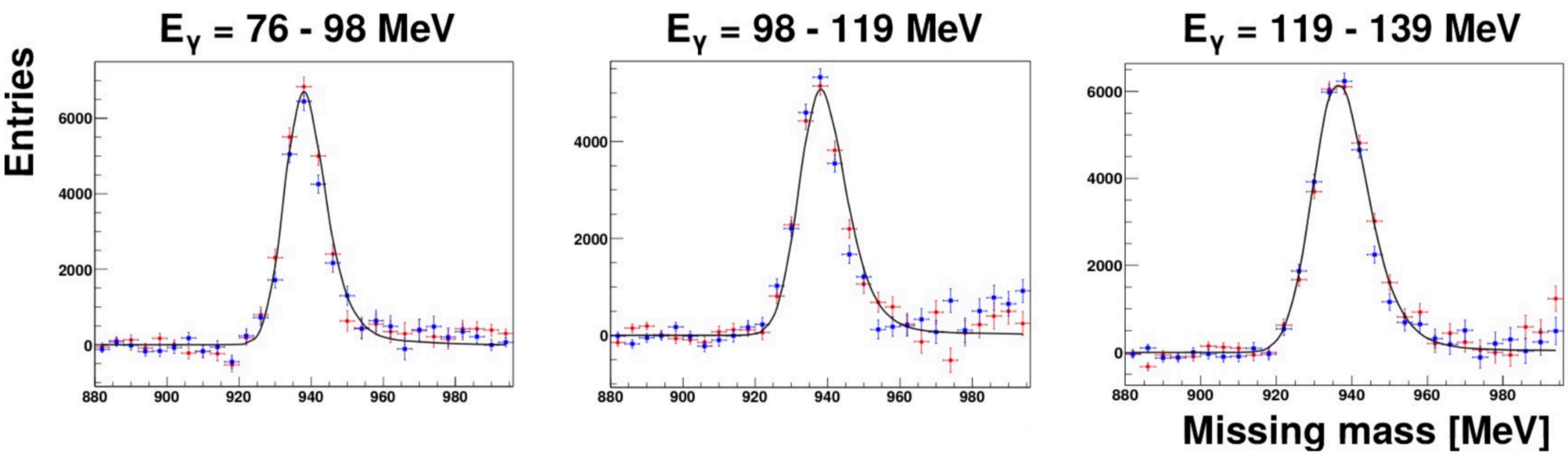
Work of E. Mornacchi and V. Sokhoyan

Low-energy Compton scattering, $\boxed{\vec{\gamma} p \to \gamma p}$.

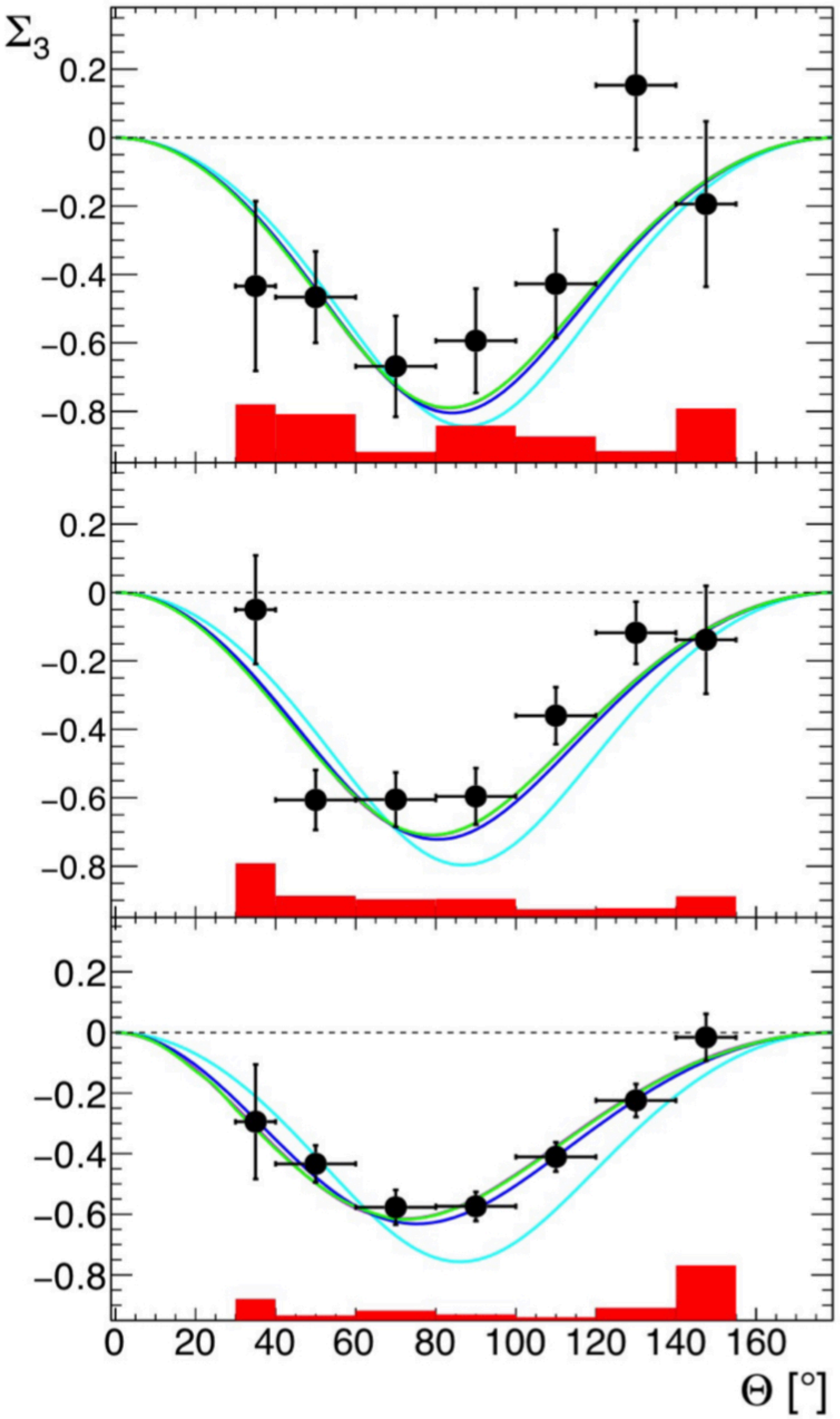
Linearly polarized beam, (unpolarized) liquid hydrogen target.

High-statistics cross sections, $d\sigma/d\Omega$, and beam asymmetry, Σ_3.

Most important data are below pion threshold.



α_{E1}, β_{M1} Results - Asymmetries



Data are at three energies: 76 – 98 MeV, 98 – 119 MeV, and 119 – 139 MeV.

Systematic errors in red.

Curves:

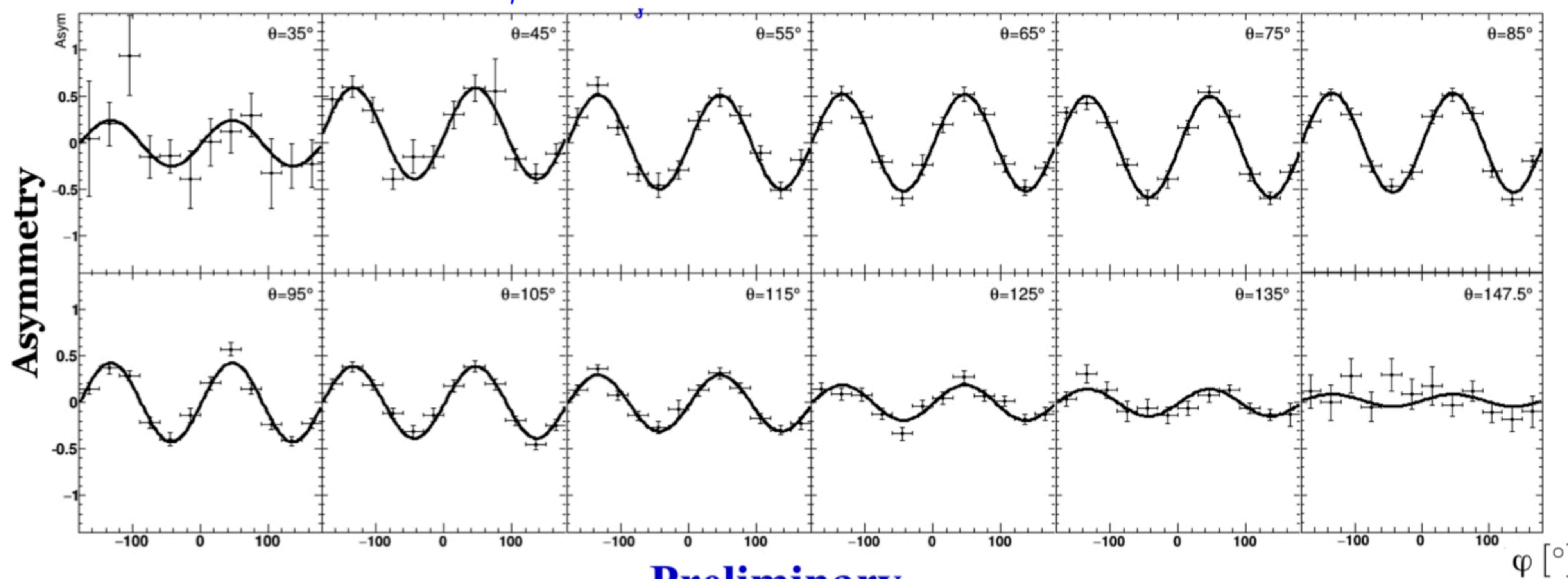
- Born contribution
- BChPT: Krupina and Pascalutsa, PRL **110**, 262001 (2013)
- HBChPT: McGovern et al., EPJA **49**, 12 (2013)

New A2 Measurement of $\vec{\gamma} p \to \gamma p$

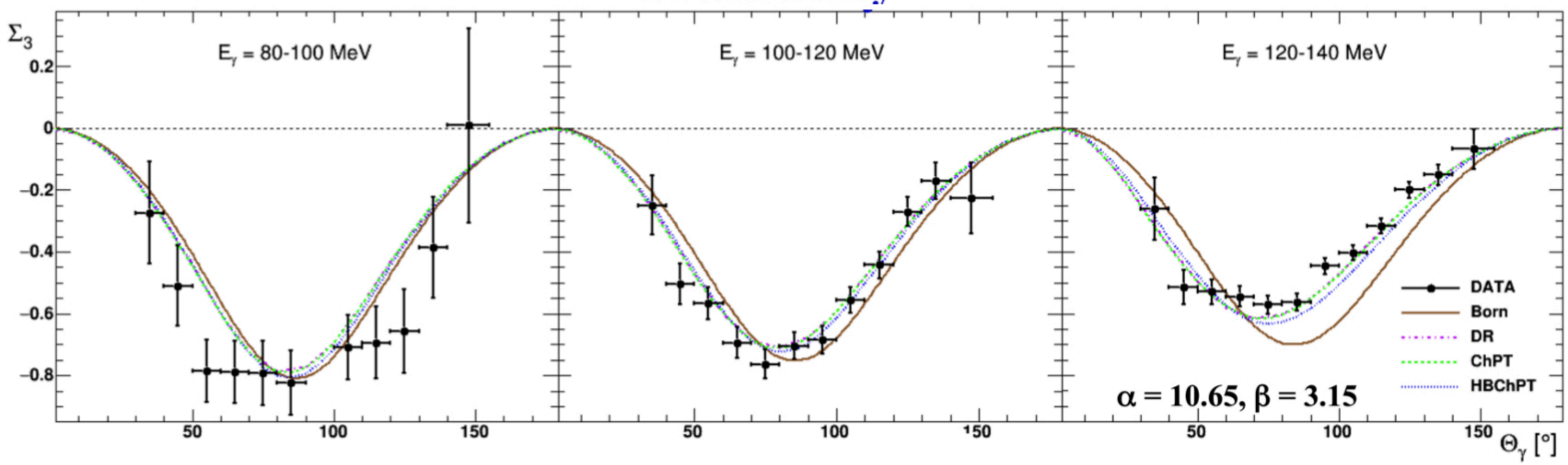
- **Ph.D. work of Edoardo Mornacchi**.
- Data taken in 2017/2018. Similar set up to pilot measurment.
- LH_2 target, CB-TAPS setup, coherent Bremsstrahlung photon beam
- **Upgraded tagger, improved systematic errors:**
    - higher γ-flux with better flux monitoring
    - improved linpol peak stability
    - improved background subtraction
- 1.2×10^6 events, an improvement of $\times 6$ compared to the pilot measurement.
- Approximately $\times 10$ the statistics of the previous world best measurement with TAPS (also A2!) [OdL et al., EPJA **10** 207 (2001)], which makes up of about 50% of the existing world data.

New A2 Measurement of $\vec{\gamma} p \to \gamma p$

$E_\gamma = 120 - 140$ MeV

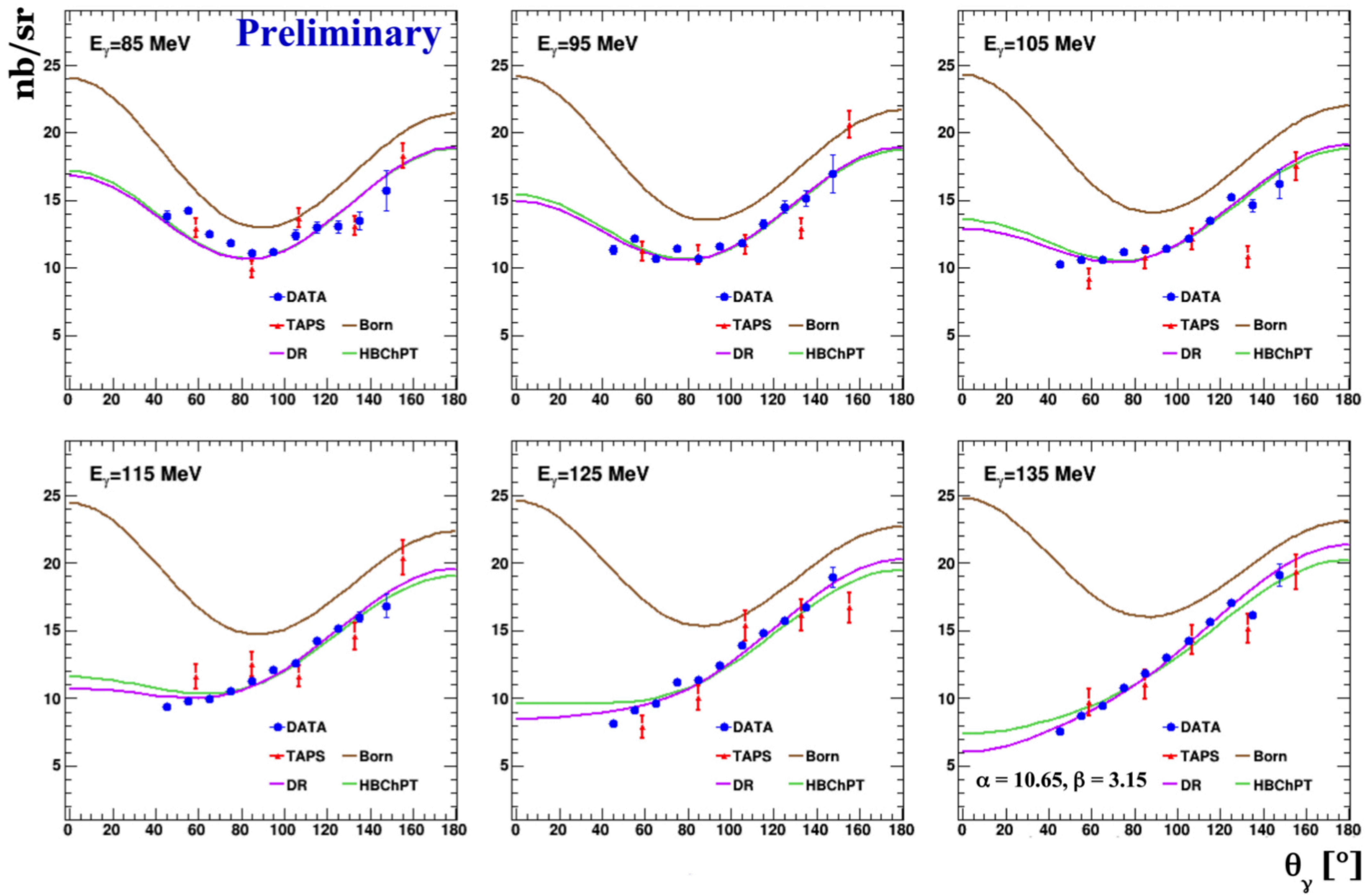


Preliminary



Mornacchi Ph.D.

New A2 Measurement of $\vec{\gamma} p \rightarrow \gamma p$



Mornacchi Ph.D.

α_{E1}, β_{M1} Outlook

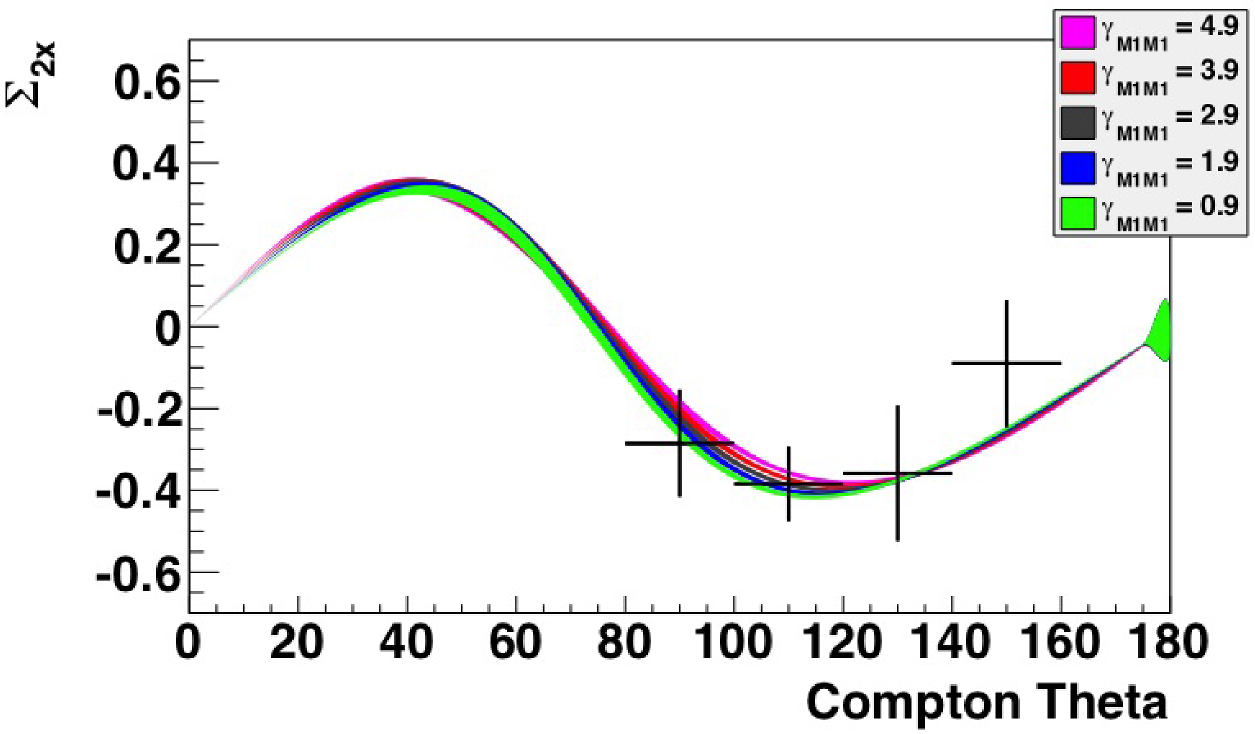
- Finish data analysis
- Use a simultaneous fit to unpolarized cross sections AND asymmetries to achieve precision on β_{M1} comparable to that of the current PDG value!

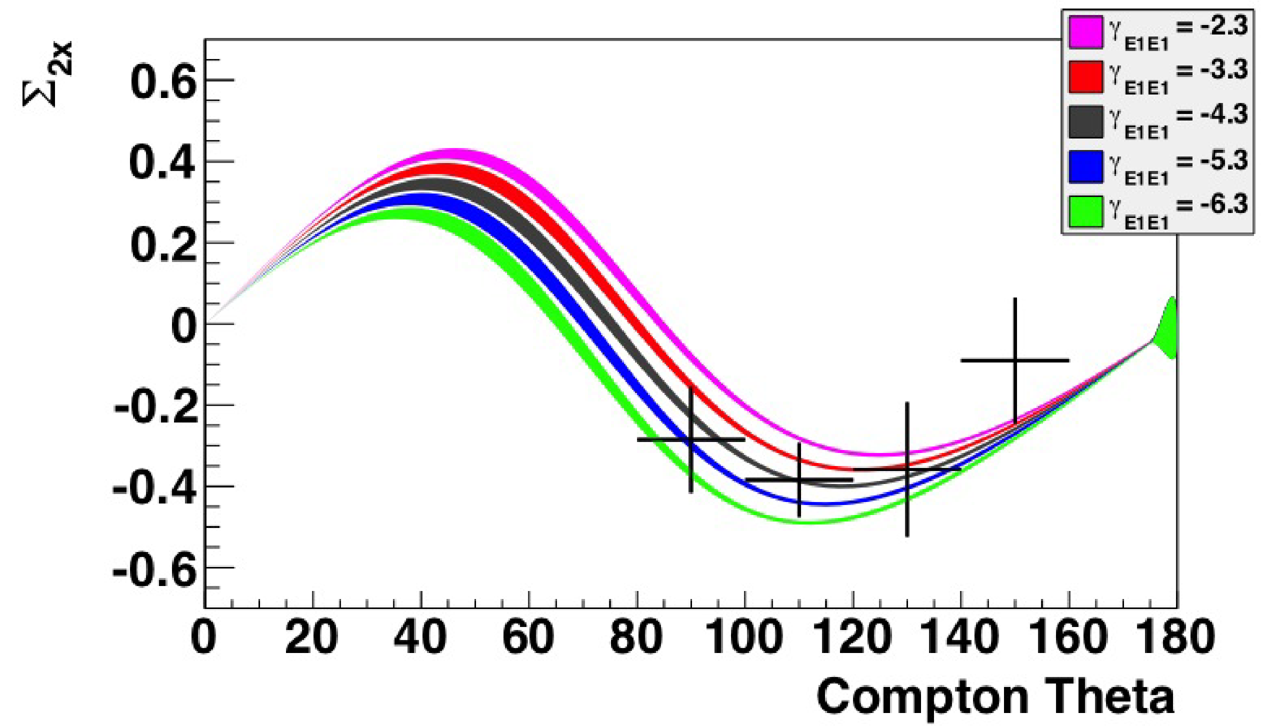
Σ_{2x}/Σ_{2z} Asymmetries - Experimental Challenges

- A source or polarized protons is not easy to come by (nor to operate).
- Small Compton scattering cross sections
- Large background cross sections
  - π^0 photoproduction cross section is about *100 times* larger than that for Compton scattering
  - Coherent and incoherent reactions of C, O, and He
- Proton tracks are required to supress backgrounds, but energy losses in the frozen-spin cryostat (and CB-TAPS) are considerable.

Results Σ_{2x} - Martel et al., PRL **114** 12501 (2015)

E_γ = 273 - 303 MeV





- First measurement of a double-polarized Compton scattering asymmetry on the nucleon.
- Curves are from the DR calculation of Pasquini et al.
- Data resulted in the first extraction of the proton's spin pols in the multipole basis:

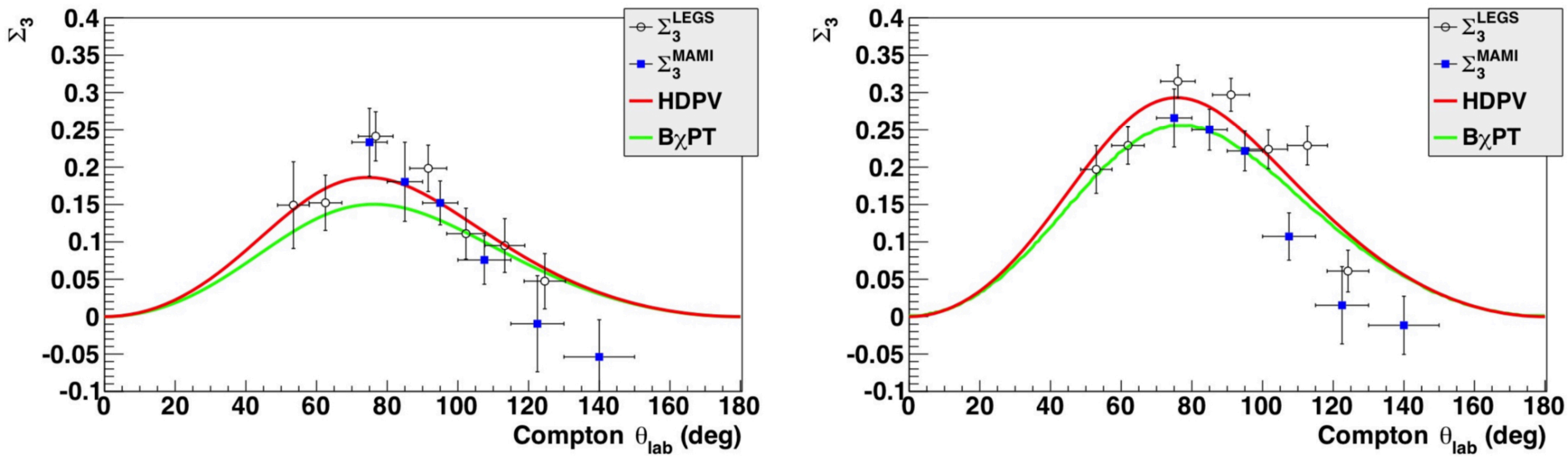
γ_{E1E1}	-3.5 ± 1.2
γ_{M1M1}	3.16 ± 0.85
γ_{E1M2}	-0.7 ± 1.2
γ_{M1E2}	1.99 ± 0.29

$\times\, 10^{-4}\ \text{fm}^4$

Σ_3 Results

PhD work of C. Collicott

$E_\gamma = 267 - 282\,\text{MeV}$ $\quad$ $E_\gamma = 286 - 307\,\text{MeV}$



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

Σ_{2z} Results

- PhD work of both D. Paudyal (Regina) and A. Rajabi (UMass).
- Data have been taken and analysis is done.
- There were some background issues, but we are more or less ready to publish.
- Do global fit, extract spin polarizabilities.

The "Other" Nucleon - The Neutron

The situation is considerably worse for the neutron:

- No free-neutron target
- Neutron is uncharged
- Small data set

Techniques:

- Low-energy neutron scattering
- Elastic Compton scattering from deuterium
- QF Compton scattering from deuterium
- Compton scattering from heavier nuclei

Nuclear Effects are NOT negligible!

Elastic Compton Scattering from ^{3}He

Relatively new idea for extraction of scalar polarizabilities for the neutron.

Shukla, Nogga, and Phillips, NPA **819**, 98 (2009).

Theory is promising, but still needs some work to extend it to higher energies. . .

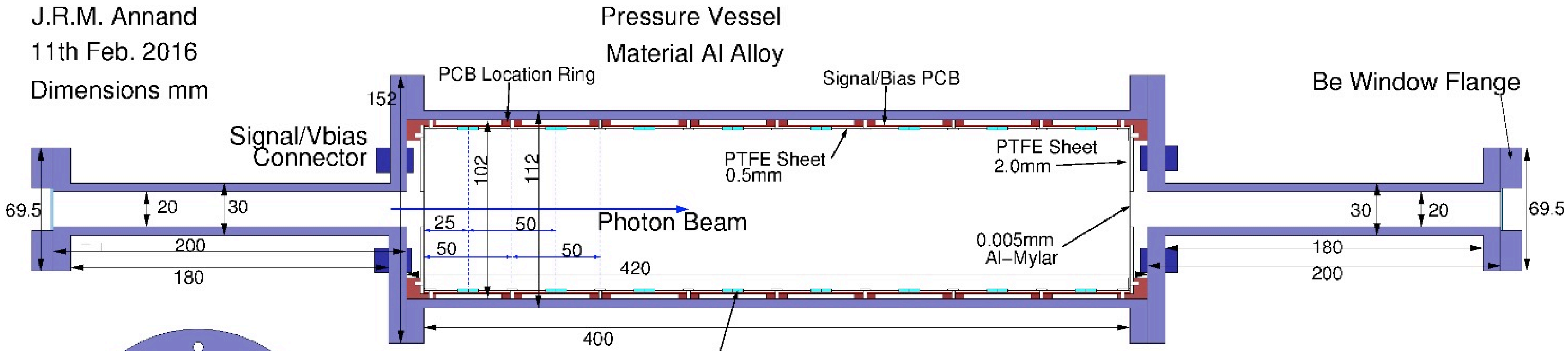
Proposal A2-01-2013 using a high-pressure active helium target (both ^{3}He and ^{4}He).

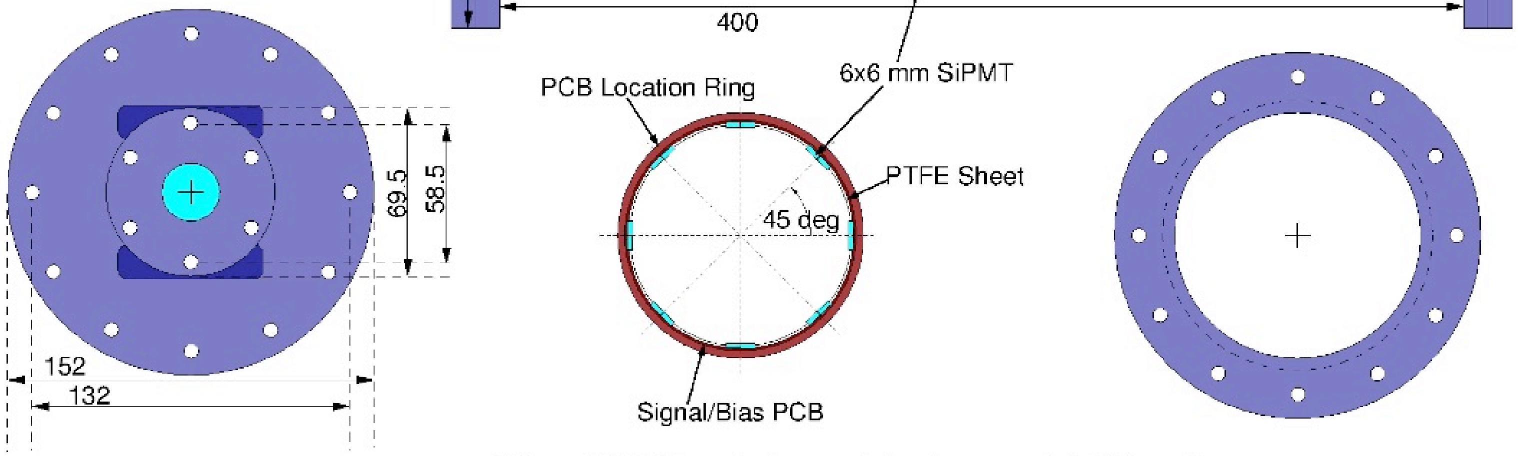
Given a rating of A by the PAC!

Will hopefully run in the next year.

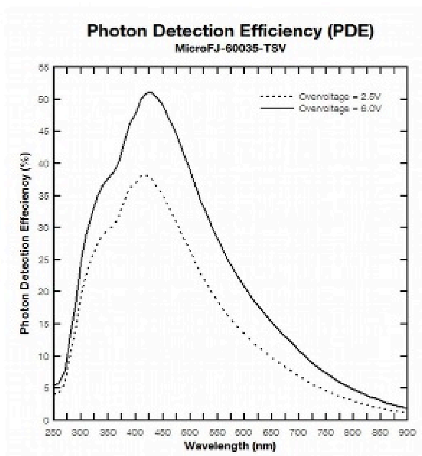
The New Active Target

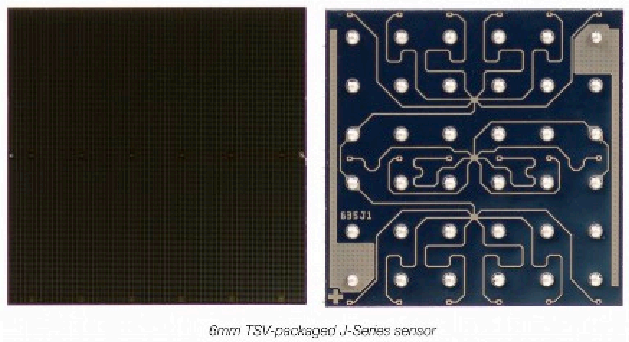
Active Target
J.R.M. Annand
11th Feb. 2016
Dimensions mm





8 rings of SiPMT, each ring consisting 8 groups of 4 6x6mm tiles.
Total number of SiPMT 8x8x4 = 256.
Readout in groups of 16, each group connected to an op–amp.
16 signal outputs
2 vias–voltage inputs





6 x 6mm J-Series SiPMT

- Al pressure vessel, no welds
- Reuse Be outer windows from original Active Target
- PTFE sheet covers printed circuit board, windows cut for SiPMT

Outlook

1. Publish high-energy Σ_3 results.
2. Publish Σ_{2z} results.
3. Complete global fit and extraction of the proton spin polarizabilities.
4. Finish analysis for α_{E1}, β_{M1}.
5. Complementary measurements at HIGS on the proton, deuteron, and helium.
6. An active polarized target is being developed, and we plan to use it for improved measurements of the asymmetries.
7. An active, high-pressure helium target for approved neutron polarizability (and threshold pion) experiments at MAMI.

Summary

1. Important tool for *testing* QCD via ChPT & DRs in the non-perturbative regime.
2. Both theory and experiment are very active at the moment.
3. We can expect lots of new results in the near future.

Special thanks to Edoardo Mornacchi and Vahe Sokhoyan for slides and input.