Compton Scattering and the Nucleon Polarizabilities

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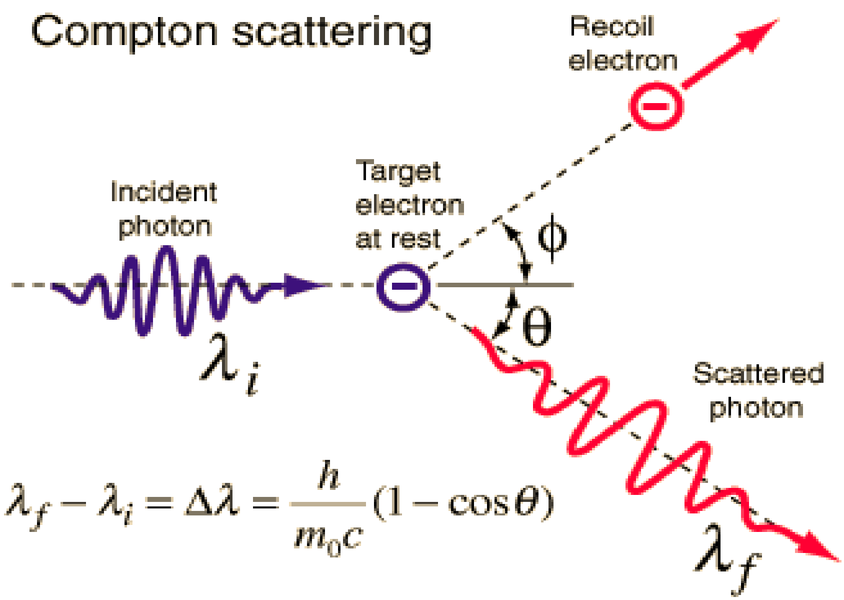
Chiral Dynamics 2015, Pisa, Italy

Awards PHY-1309130 & IIA-1358175

THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

Compton Scattering



- 1892 – 1962 Arthur Holly Compton
- 1922: Theory of Compton Scattering
- No classical explanation
- Required quantization & relativity
- Evidence of the particle-like nature of the photon

Photo: http://www.aip.org/history/gap/Compton/Compton.html

Compton Scattering

- 1927 Nobel Prize for Physics

Photo: http://www.aip.org/history/gap/Compton/Compton.html

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THE

PHYSICAL REVIEW

A QUANTUM THEORY OF THE SCATTERING OF X-RAYS BY LIGHT ELEMENTS

By Arthur H. Compton

Abstract

A quantum theory of the scattering of X-rays and γ-rays by light elements. The hypothesis is suggested that when an X-ray quantum is scattered it spends all of its energy and momentum upon some particular electron. This electron in turn scatters the ray in some definite direction. The change in momentum of the X-ray quantum due to the change in its direction of propagation results in a recoil of the scattering electron. The energy in the scattered quantum is thus less than the energy in the primary quantum by the kinetic energy of recoil of the scattering electron. The corresponding *increase in the wave-length of the scattered beam* is $\lambda_\theta - \lambda_0 = (2h/mc)\sin^2\frac{1}{2}\theta = 0.0484\sin^2\frac{1}{2}\theta$, where h is the Planck constant, m is the mass of the scattering electron, c is the velocity of light, and θ is the angle between the incident and the scattered ray. Hence the increase is independent of the wave-length. *The distribution of the scattered radiation* is found, by an indirect and not quite rigid method, to be concentrated in the forward direction according to a definite law (Eq. 27). The total energy removed from the primary beam comes out less than that given by the classical Thomson theory in the ratio $1/(1+2\alpha)$, where $\alpha = h/mc\lambda_0 = 0.0242/\lambda_0$. Of this energy a fraction $(1+\alpha)/(1+2\alpha)$ reappears as scattered radiation, while the remainder is truly absorbed and transformed into kinetic energy of recoil of the scattering electrons. Hence, if σ_0 is the *scattering absorption coefficient* according to the classical theory, the coefficient according to this theory is $\sigma = \sigma_0/(1+2\alpha) = \sigma_s + \sigma_a$, where σ_s is the true scattering coefficient $[(1+\alpha)\sigma/(1+2\alpha)^2]$, and σ_a is the coefficient of absorption due to scattering $[\alpha\sigma/(1+2\alpha)^2]$. Unpublished experimental results are

Compton Scattering

- 1927 Nobel Prize for Physics
- We started in 1927 and we're not finished yet?

Photo:
http://www.aip.org/history/gap/Compton/Compton.html

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Compton Scattering

- 1927 Nobel Prize for Physics
- We started in 1927 and we're not finished yet?
- Why?
- Compton Scattering on the nucleon simple to picture, not easy to measure
  - ➔ Small cross section
  - ➔ Large backgrounds
  - ➔ Polarization observables need *dirty* targets
  - ➔ Little to cut on!
- Compton Scattering is used to extract the nucleon polarizabilities

Why Measure the Polarizabilities?

- Polarizabilities fundamental constants that describe the nucleon
- Limit precision in many areas of physics: Lamb Shift, neutron stars, EM contribution to p-n mass difference

THE NUCLEON ELECTROMAGNETIC POLARIZABILITIES

J. BERNABEU*, T.E.O. ERICSON and C. FERRO FONTAN**

CERN, Geneva, Switzerland

Received 16 January 1974

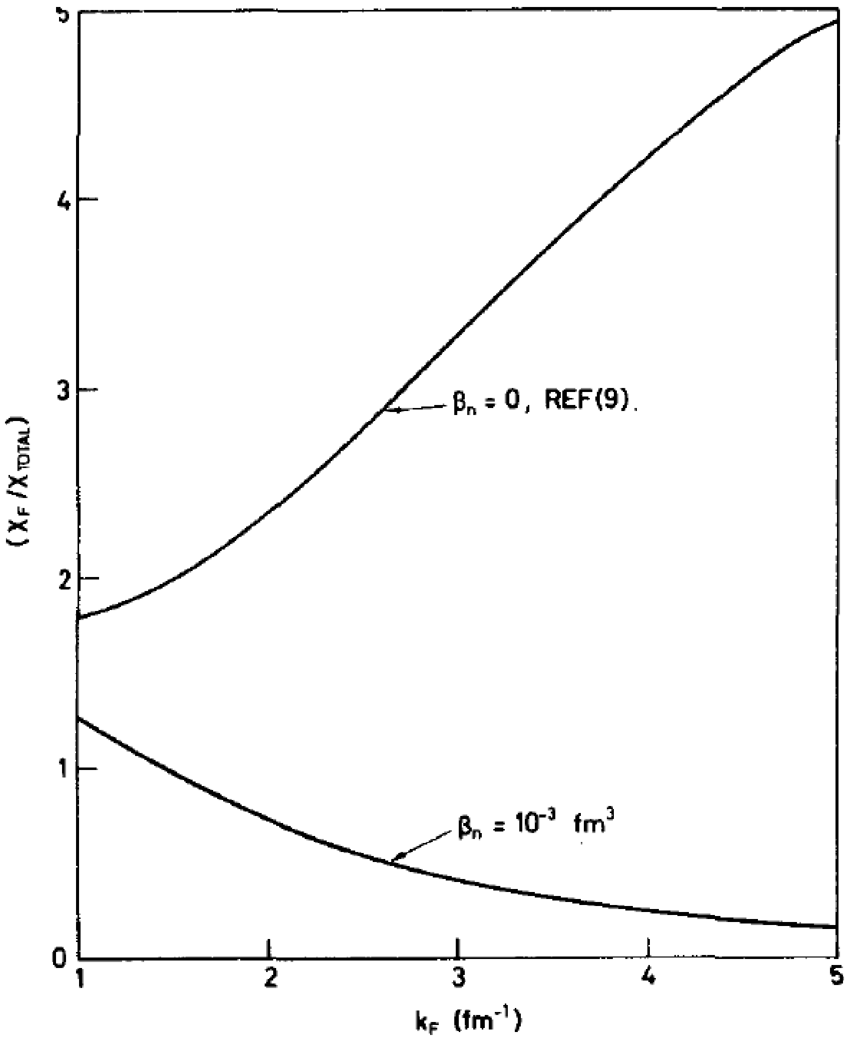

Fig. 2. Effect of the intrinsic magnetic polarizability β_n on a recent calculation of the paramagnetic susceptibility of dense neutron matter, adapted from ref. [9].

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PRL **108,** 232301 (2012) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2012

Electromagnetic Self-Energy Contribution to $M_p - M_n$ and the Isovector Nucleon Magnetic Polarizability

André Walker-Loud,[1,2] Carl E. Carlson,[3] and Gerald A. Miller[1,4]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
[3]*Department of Physics, College of William and Mary, Williamsburg, Virginia 23187-8795, USA*
[4]*Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA*

(Received 7 March 2012; published 7 June 2012)

We update the determination of the isovector nucleon electromagnetic self-energy, valid to leading order in QED. A technical oversight in the literature concerning the elastic contribution to Cottingham's formula is corrected, and modern knowledge of the structure functions is used to precisely determine the inelastic contribution. We find $\delta M^{\gamma}_{p\text{-}n} = 1.30(03)(47)$ MeV. The largest uncertainty arises from a subtraction term required in the dispersive analysis, which can be related to the isovector magnetic polarizability. With plausible model assumptions, we can combine our calculation with additional input from lattice QCD to constrain this polarizability as: $\beta_{p-n} = -0.87(85) \times 10^{-4}$ fm^3.

DOI: 10.1103/PhysRevLett.108.232301 PACS numbers: 13.40.Dk, 13.40.Ks, 13.60.Fz, 14.20.Dh

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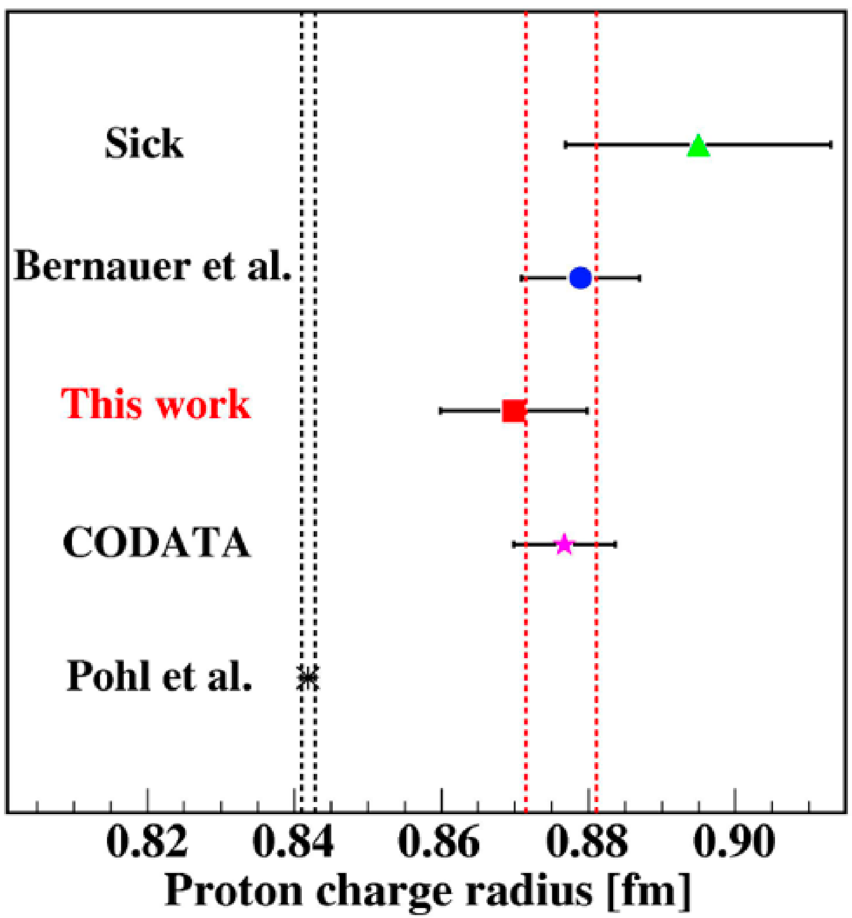

X. Zhan et al., PLB705, 59 (2011)
G. Ron et al., PRC84, 055204(2011)

• Statistics	
Center position uncertainty ($\sim 4\%$ of Γ)	700 MHz
• Systematics	
Laser frequency (H_20 calibration)	300 MHz
AC and DC stark shift	< 1 MHz
Zeeman shift (5 Tesla)	< 30 MHz
Doppler shift	< 1 MHz
Collisional shift	2 MHz
• Total uncertainty of the line determination	760 MHz
• Theory: proton polarizability	1200 MHz
• Discrepancy with CODATA prediction	75 300 MHz

Systematic effects are small since they scale like $1/m$

Finite size effect scales like m^3

Source: R. Pohl

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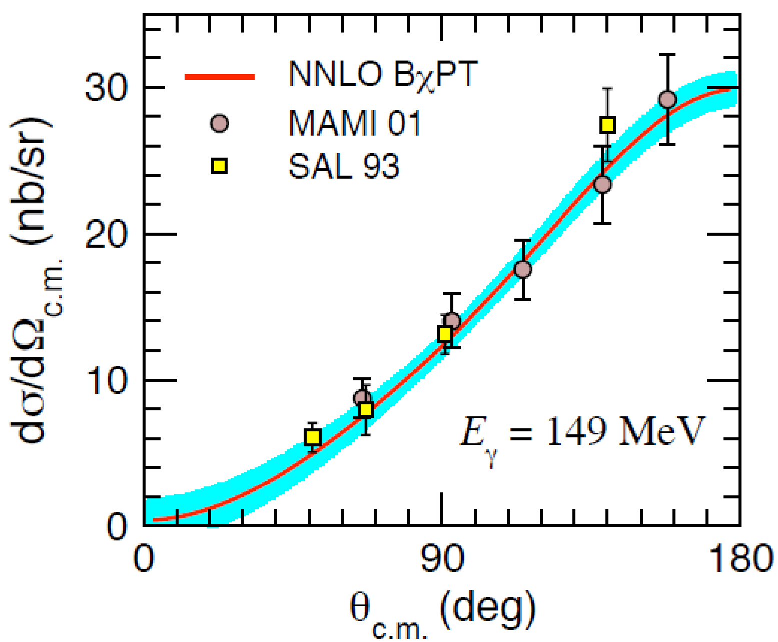
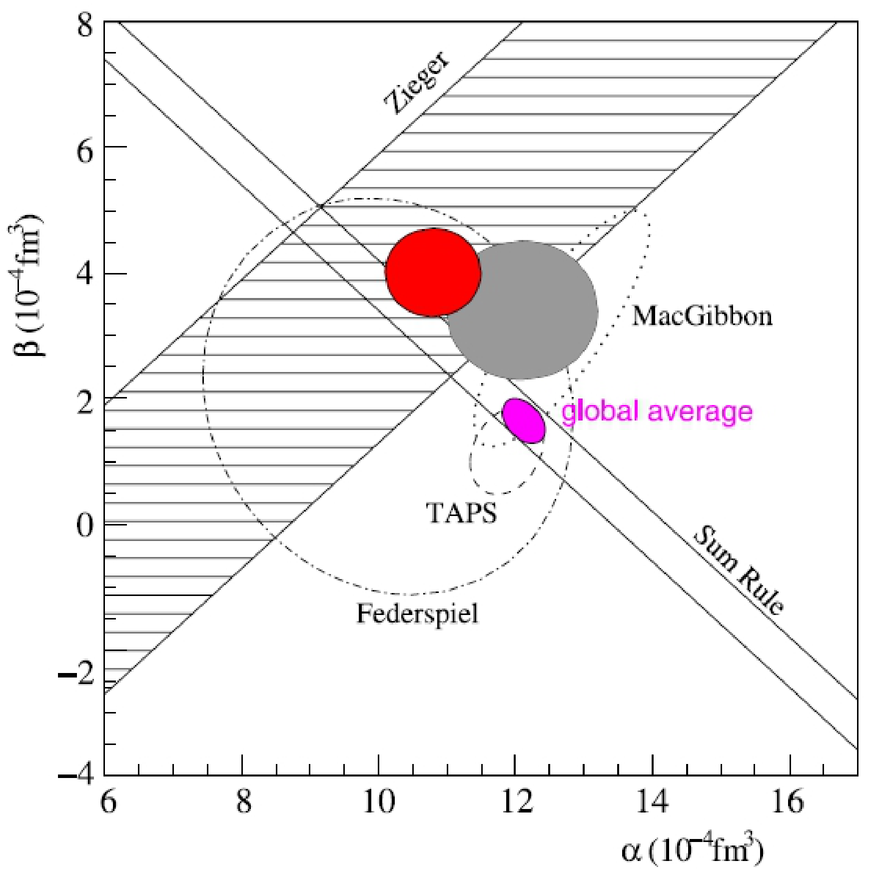
- ChiPT prediction of β, double 2012 CODATA value, but describes data as well as L'vov DR





- BχPT V. Lensky & V. Pascalutsa Eur. Phys. J C (2010) 65:195
  - HBχPT - Beane et. Al Nucl. Phys. A **747** 311 (2005)

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- Meta-analysis (Griesshammer, McGovern, Phillips & Feldman, Prog. In Part. Nuc. Phys. **67** (2012) 841 arXiv:1203.6834v2 [nucl-th]) suggested:

$$\boxed{\begin{array}{l}\alpha = [10.7 \pm 0.3(stat) \pm 0.2(Baldin) \pm 0.8(theory)] \times 10^{-4} fm^3 \\ \beta = [3.1 \pm 0.3(stat) \pm 0.2(Baldin) \pm 0.8(theory)] \times 10^{-4} fm^3\end{array}}$$

Why Measure the Polarizabilities?

- Later analysis from McGovern, Phillips & Griesshammer, EPJA (2013) 49 12:

$$\boxed{\begin{aligned}\alpha &= [10.65 \pm 0.35(stat) \pm 0.2(Baldin) \pm 0.3(theory)] \times 10^{-4} fm^3 \\ \beta &= [3.15 \mp 0.35(stat) \pm 0.2(Baldin) \mp 0.3(theory)] \times 10^{-4} fm^3\end{aligned}}$$

- PDG have taken note:

$$\boxed{\begin{aligned}\alpha &= (12.0 \pm 0.6) \times 10^{-4} fm^3 \\ \beta &= (1.9 \pm 0.5) \times 10^{-4} fm^3\end{aligned}}$$

PDG 2012

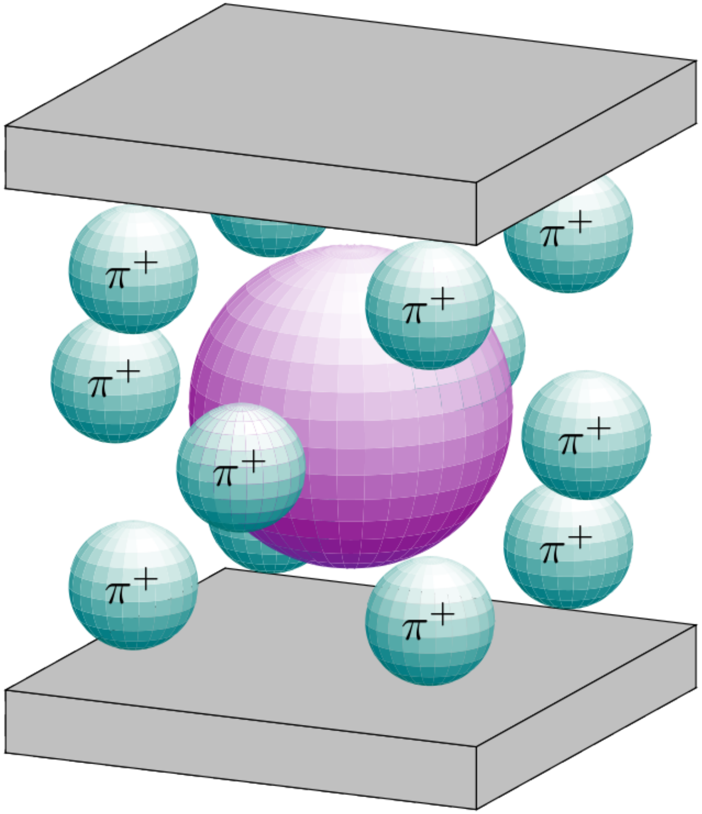
$$\downarrow$$

$$\boxed{\begin{aligned}\alpha &= (11.2 \pm 0.4) \times 10^{-4} fm^3 \\ \beta &= (2.5 \pm 0.4) \times 10^{-4} fm^3\end{aligned}}$$

PDG 2013

- **If, between reviews, with no new experimental data, β can jump by more than its uncertainty, we need new data!**

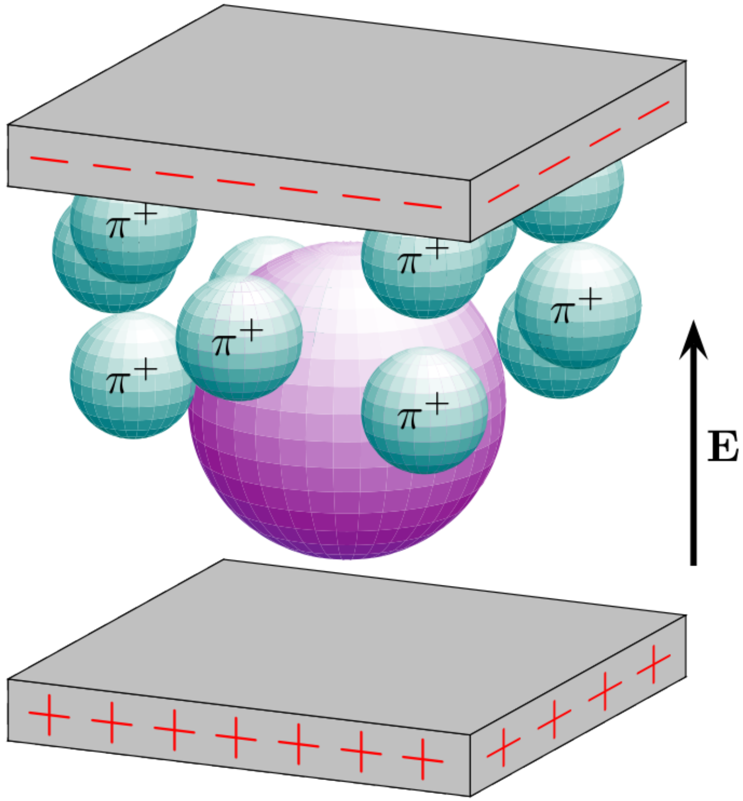
The Electric Polarizability



- α is the electric polarisability
- Putting a proton in a parallel plate capacitor!
- The response of the pion cloud

Picture: P. Martel

The Electric Polarizability



- α is the electric polarisability
- Putting a proton in a parallel plate capacitor!
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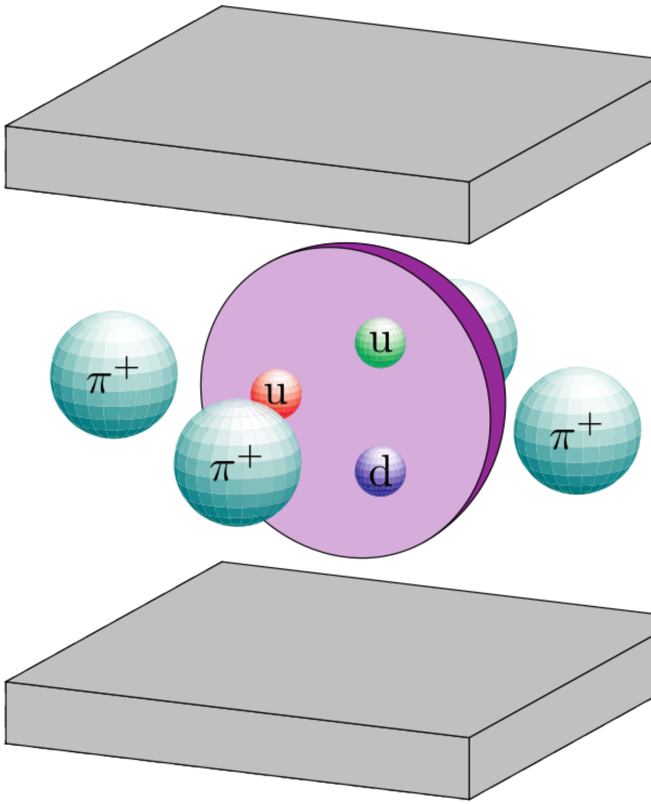
$$\vec{d}_{ind} = 4\pi\alpha\vec{E}$$

Picture: P. Martel

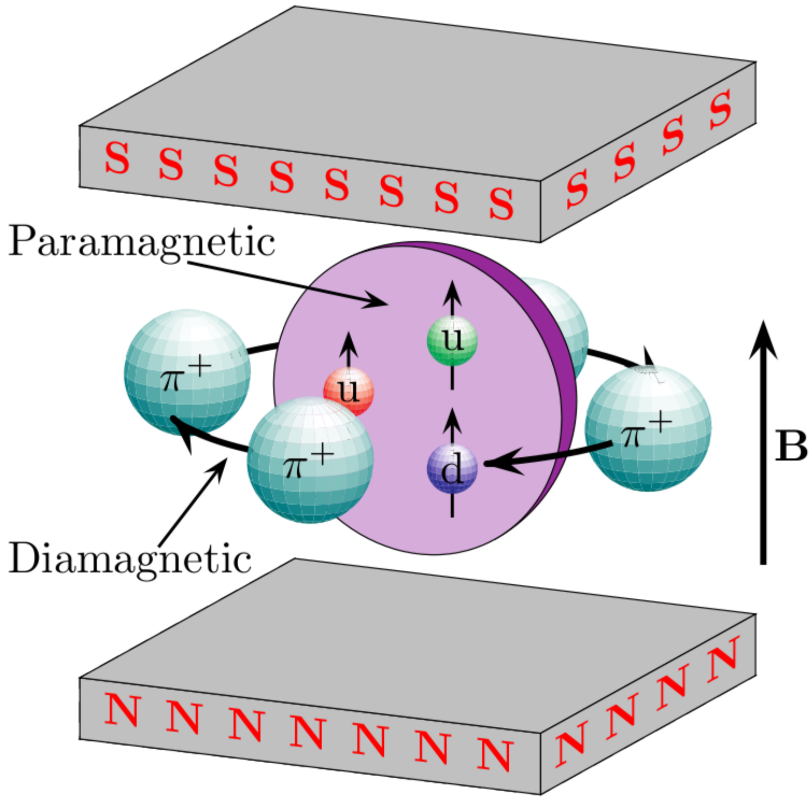
The Magnetic Polarizability



- β is the magnetic polarizability
- Like putting the proton in a magnetic field
- Both diamagnetic and paramagnetic components to the response

Picture: P. Martel

The Magnetic Polarizability



- β is the magnetic polarizability
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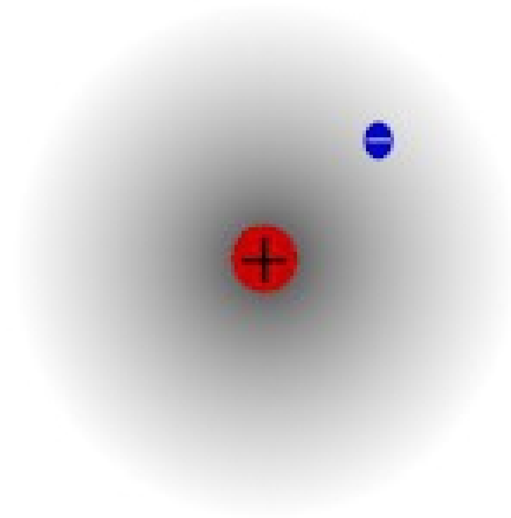
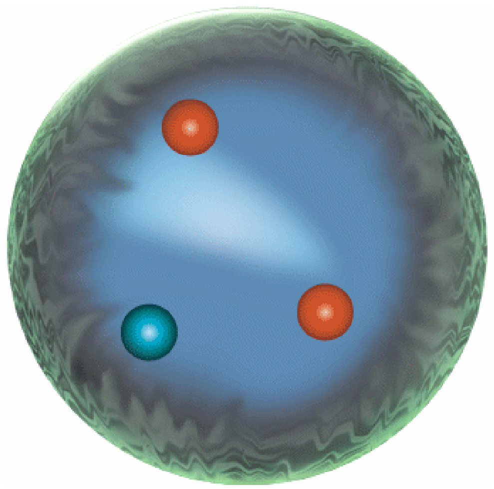
- Both diamagnetic and paramagnetic components to the response

$$\vec{m}_{ind} = 4\pi\beta\vec{B}$$

Picture: P. Martel

Measurement of Polarizabilities

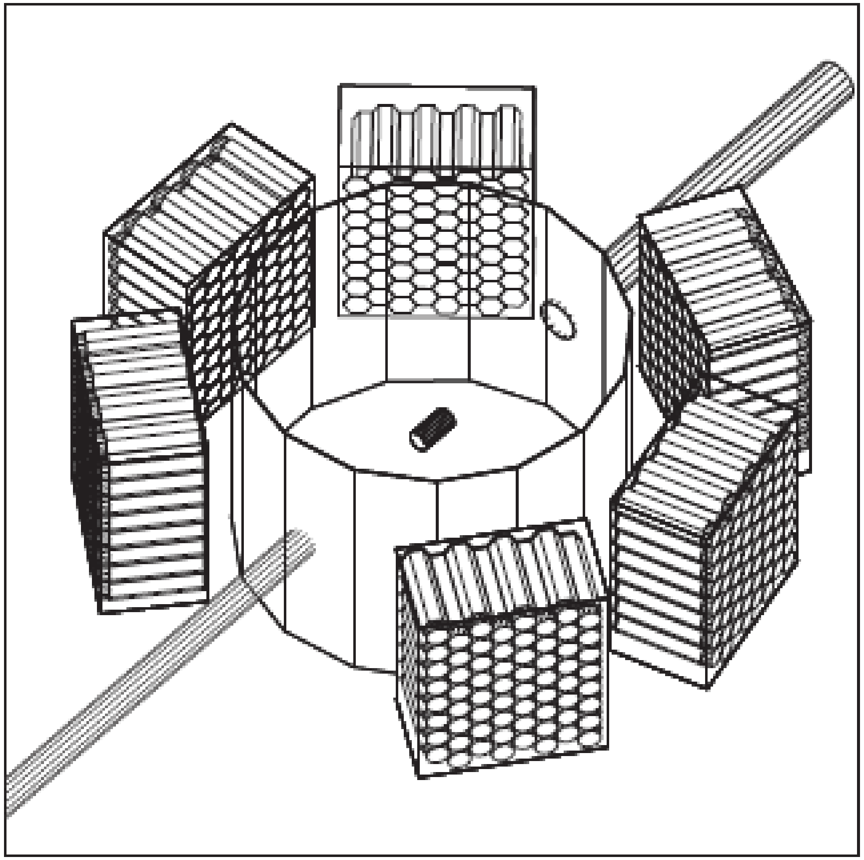
  

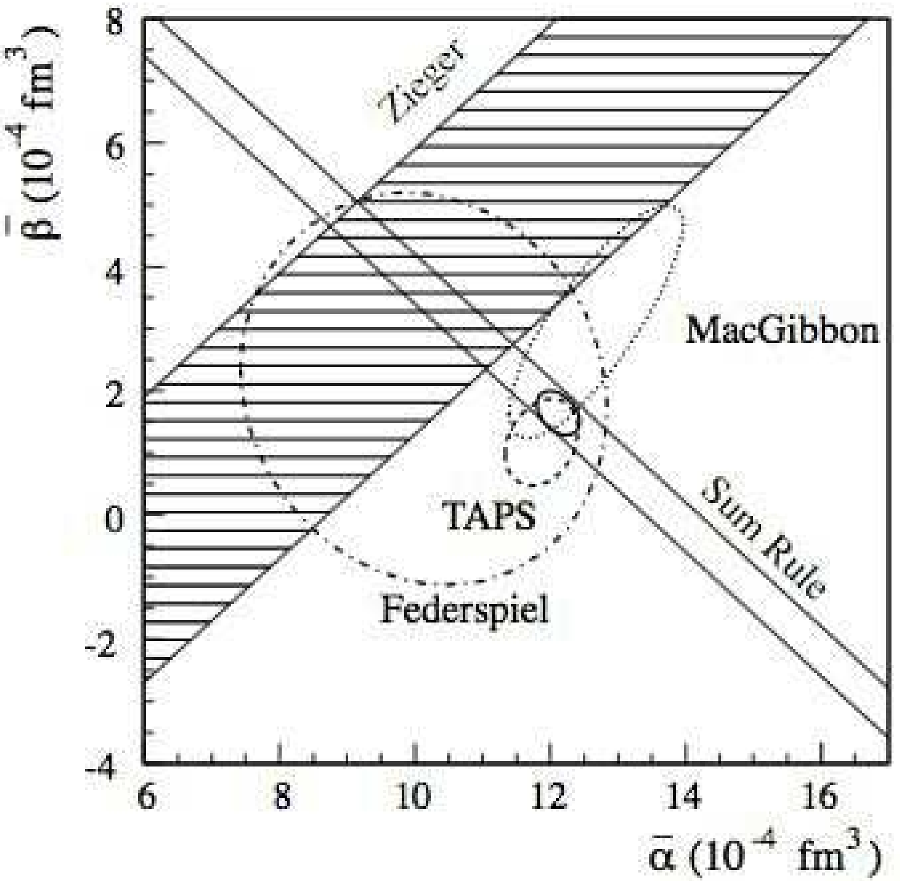
- Scalar polarizability values:

$$\boxed{\begin{aligned} \alpha &= (11.2 \pm 0.4) \times 10^{-4} fm^3 \\ \beta &= (2.5 \pm 0.4) \times 10^{-4} fm^3 \end{aligned}}$$

- Polarizabilities of a perfectly conducting sphere ~ ¼ volume
- Polarizability of a Hydrogen atom ~1/10 volume
- Proton polarizabilities extremely small
- Proton very stiff and strongly bound

Measurement of Polarizabilities





- V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001)
- TAPS setup at MAMI with Liquid H target
- Unpolarized photon beam
- 55 < Eγ < 165 MeV
- Polarizabilities extracted using DR Code of L'vov [PRC 55, 359 (1997)]

Measurement of Polarizabilities

$$\frac{d\sigma}{d\Omega}(\omega,\theta) = \frac{d\sigma}{d\Omega}^{B}(\omega,\theta) - \frac{e^2}{4\pi M}\left(\frac{\omega'}{\omega}\right)^2(\omega\omega')\left[\frac{\alpha+\beta}{2}(1+\cos\theta)^2 + \frac{\alpha-\beta}{2}(1-\cos\theta)^2\right]$$

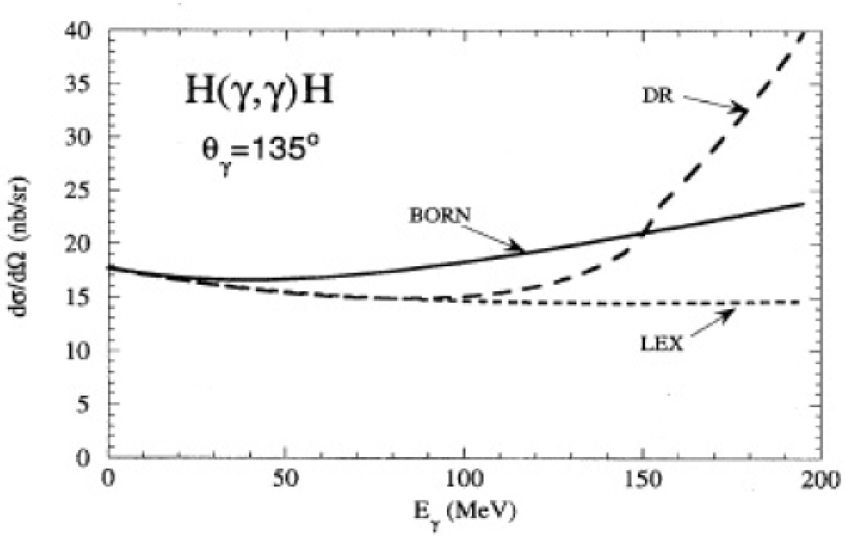
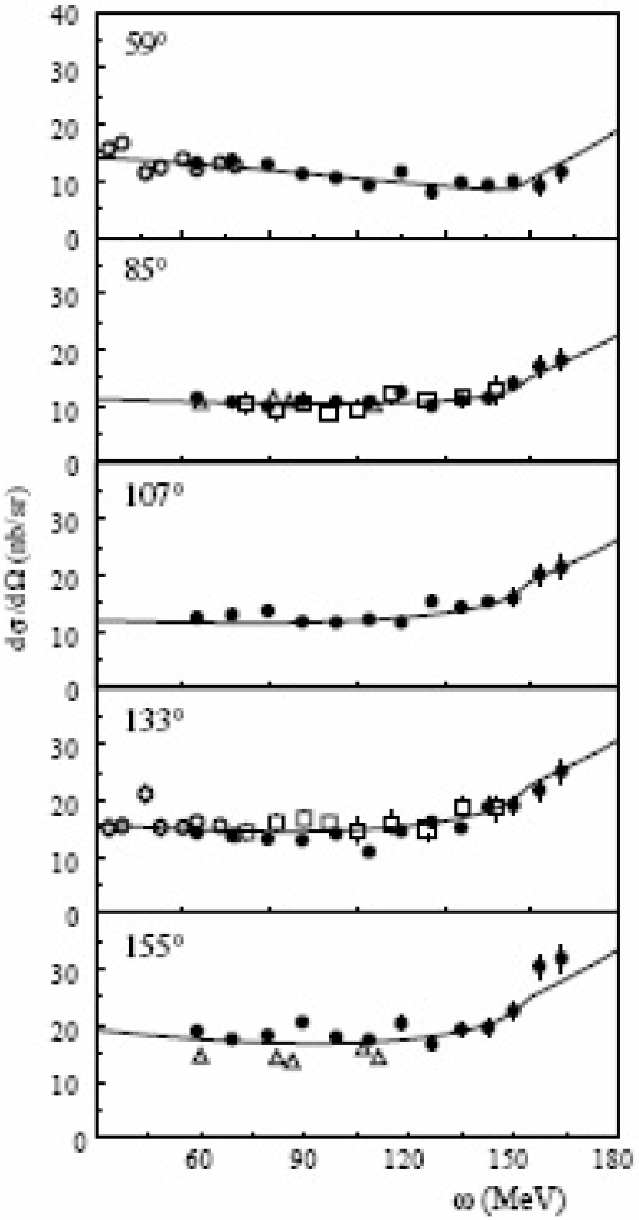
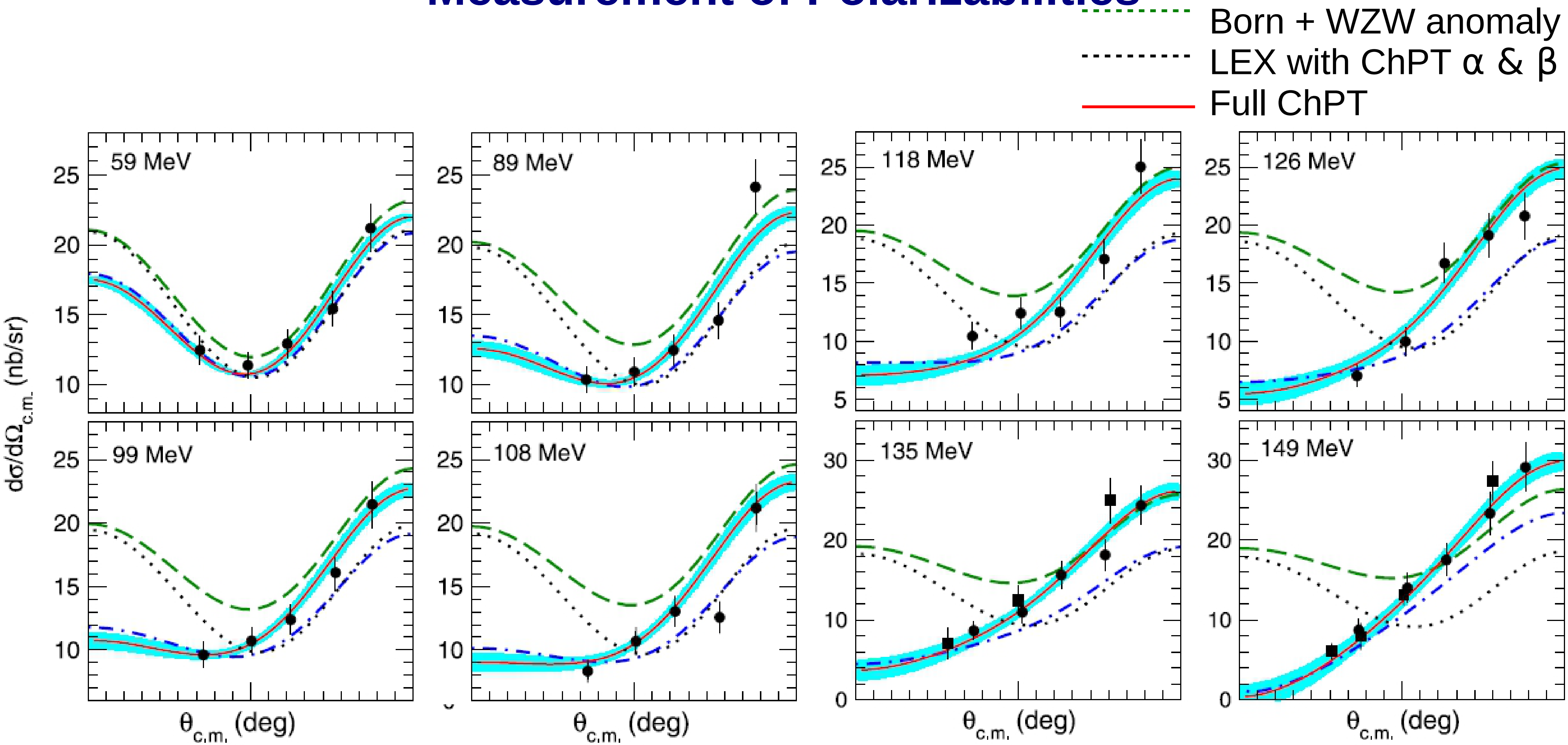


FIG. 1. Calculations of the Compton scattering cross section from the proton, showing the cross section for the point proton (Born), the LEX, and the fixed-t dispersion relations (DR). The calculations assume that $\bar{\alpha}+\bar{\beta}=14.2$ and $\bar{\alpha}-\bar{\beta}=9.0$.

V. Olmos de Leon et al.
Eur. Phys. J. A 10,
207–215 (2001)



Measurement of Polarizabilities



- Chiral perturbation theory predicts different alpha and beta values
- Describes the data well
- Polarized measurements → independent extraction of α, β, other systematics
- V. Lensky & V. Pascalutsa Eur Phys J. C65:195-209

What Exactly Do We Measure?

- Originally suggested measurement: cross section difference between lin. pol. photons parallel and perp. to reaction plane
  - $\boxed{\frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega}}$ proportional to α
  - $\boxed{\frac{(\cos^2\theta)\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega}}$ proportional to β
- At selected kinematics, **independent** extraction of α & β possible

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- At selected kinematics, **independent** extraction of α & β possible
- Later work by Krupina and Pascalutsa [PRL 110, 262001 (2013)]

➔At low energies, the beam asymmetry, Σ_3, is the best way to extract β

$$\boxed{\Sigma_3 \equiv \frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\sigma^{\perp} + d\sigma^{\parallel}}}$$

What Exactly Do We Measure?

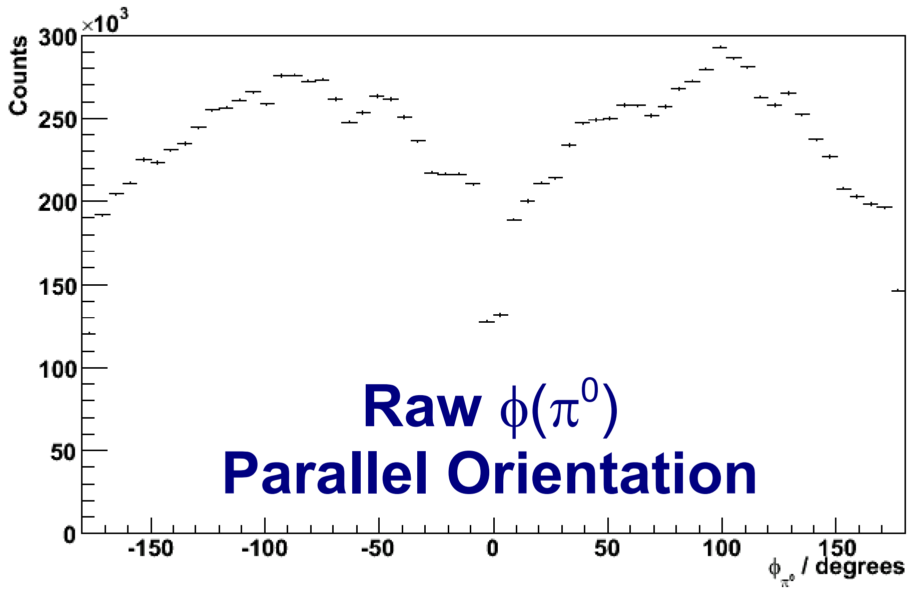
- Differential cross section of RCS for parallel polarized photons ($\sigma_{||}$)
- Differential cross section of RCS for perp. polarized cross sections ($\sigma_{\perp}$)
- Differential cross section of RCS for unpolarized data (σ_u)
- Linear polarization peak at 150 MeV (~100 < $E_{\gamma pol}$ < 150 MeV)

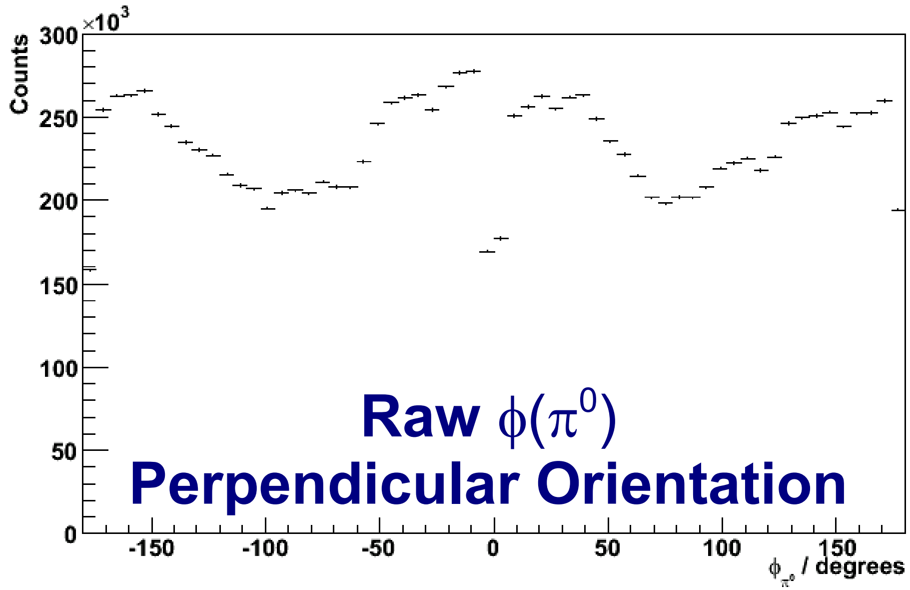
What Exactly Do We Measure?

- This will allow us to reconstruct:

➔ The cross section difference using $(\sigma_{\perp} - \sigma_{\parallel})$

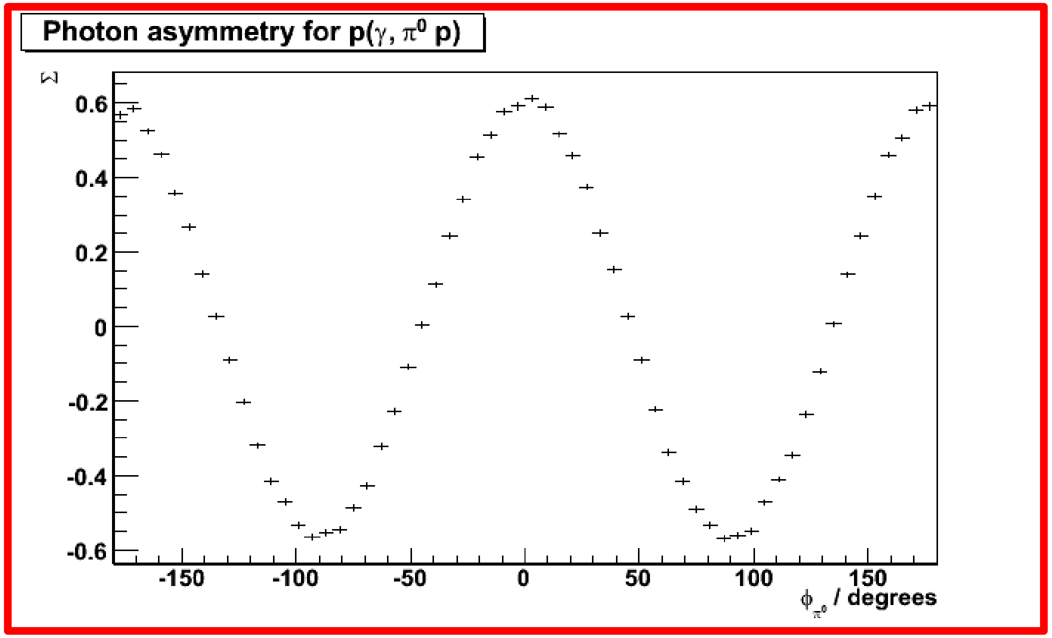
What Exactly Do We Measure?





- This will allow us to reconstruct:
  - ➔The cross section difference using $(\sigma_\perp - \sigma_\parallel)$
  - ➔Independent asymmetries using $(\sigma_\parallel/\sigma_u)$ & $(\sigma_\perp/\sigma_u)$ separately
  - ➔Asymmetry using $(\sigma_\perp - \sigma_\parallel)/(\sigma_\perp + \sigma_\parallel)$
  - ➔The cross section difference using $2\Sigma\sigma_u$
- Can use the full phi distribution to extract Σ
- Can measure cross sections more accurately with unpol. data
- Many systematic checks!

What Exactly Do We Measure?



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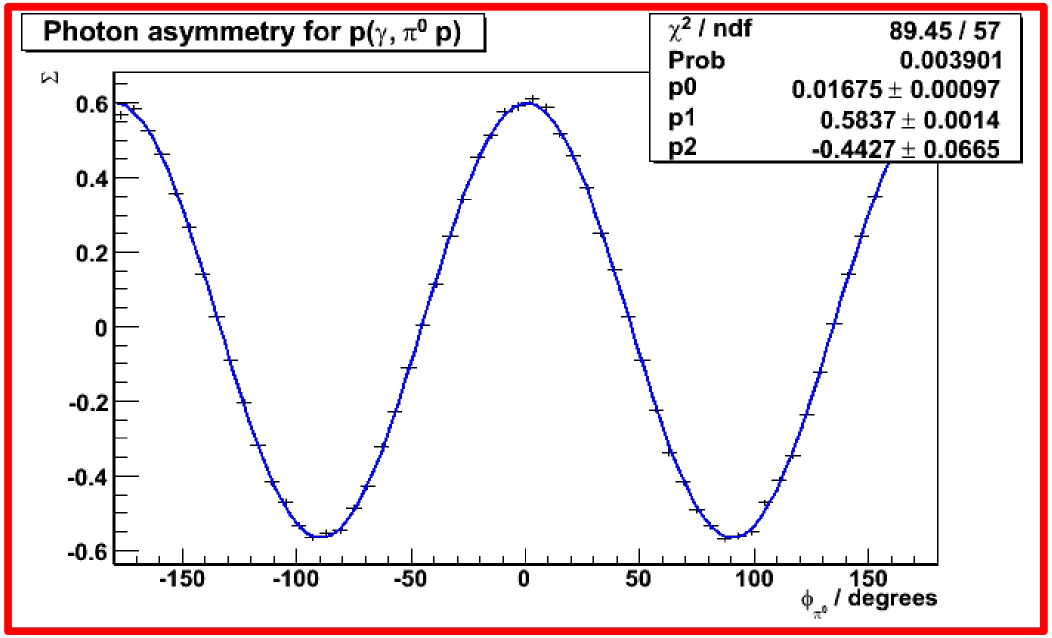

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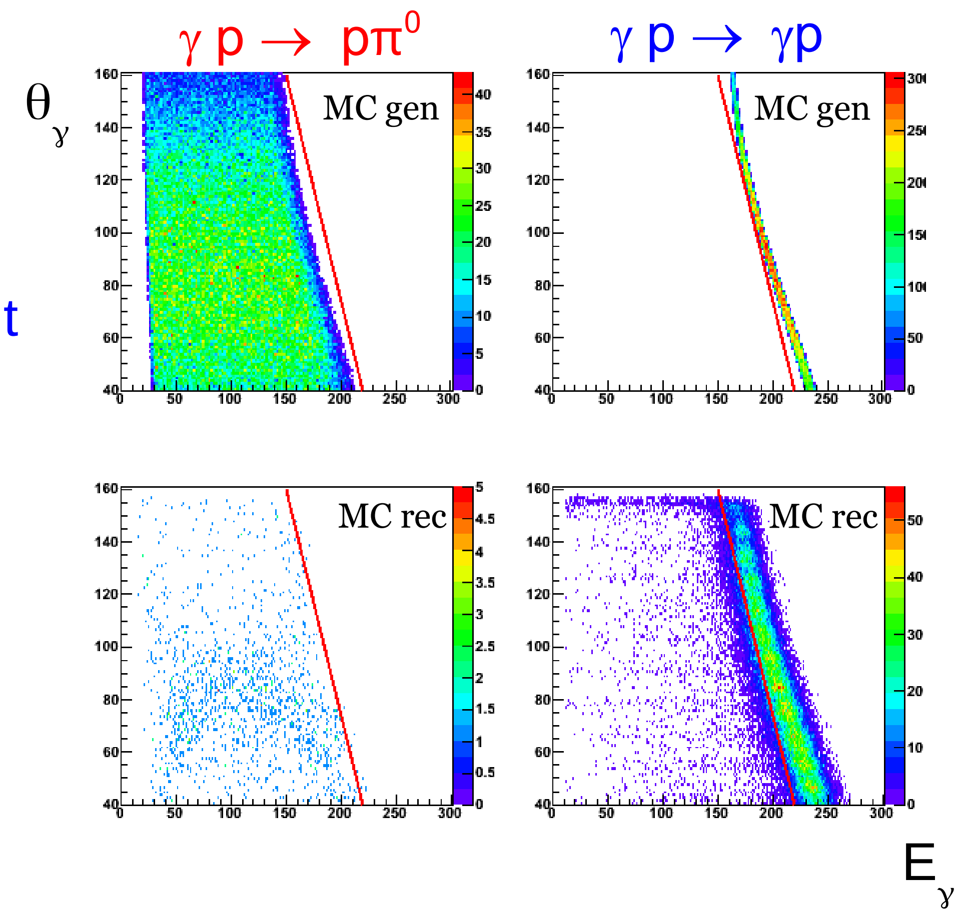
Scalar Polarizability Measurement Status

Up to 250 MeV: 2D (E, θ) cut

Eγ = 245-255 MeV



- 750 hours approved by MAMI PAC in Dec 2012 with an A!
- EJD, D. J. Hornidge, J. R. M. Annand, R. Miskimen

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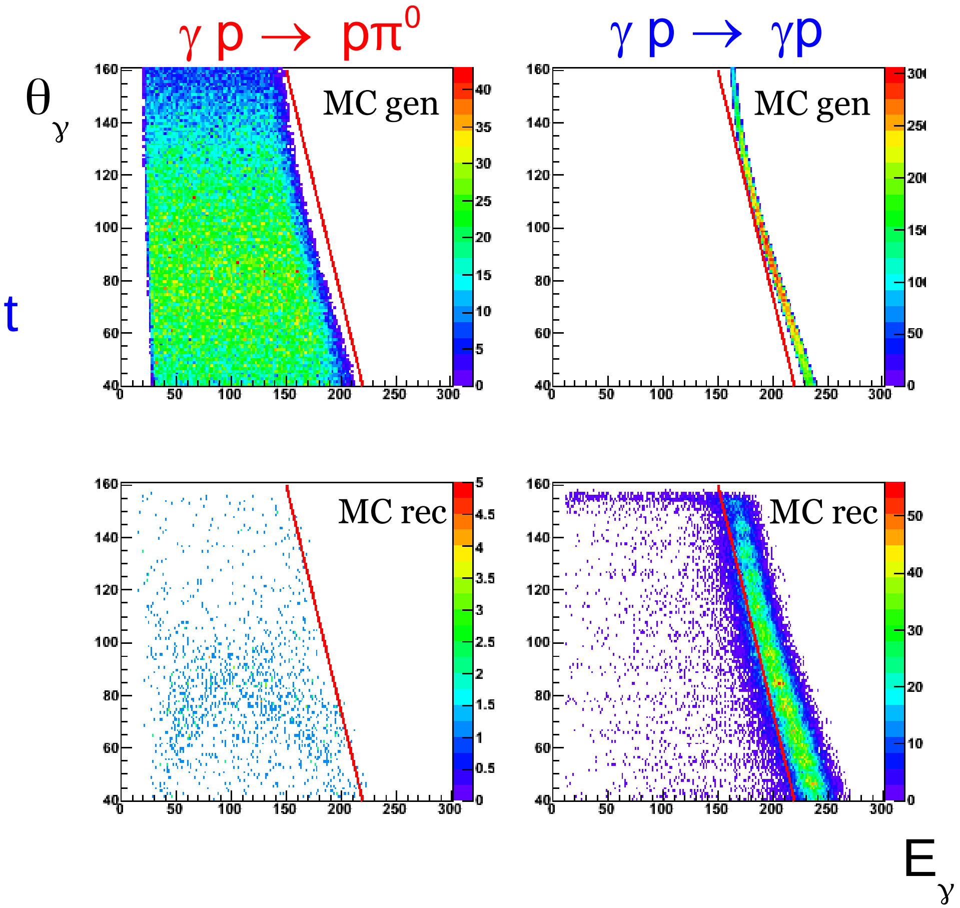
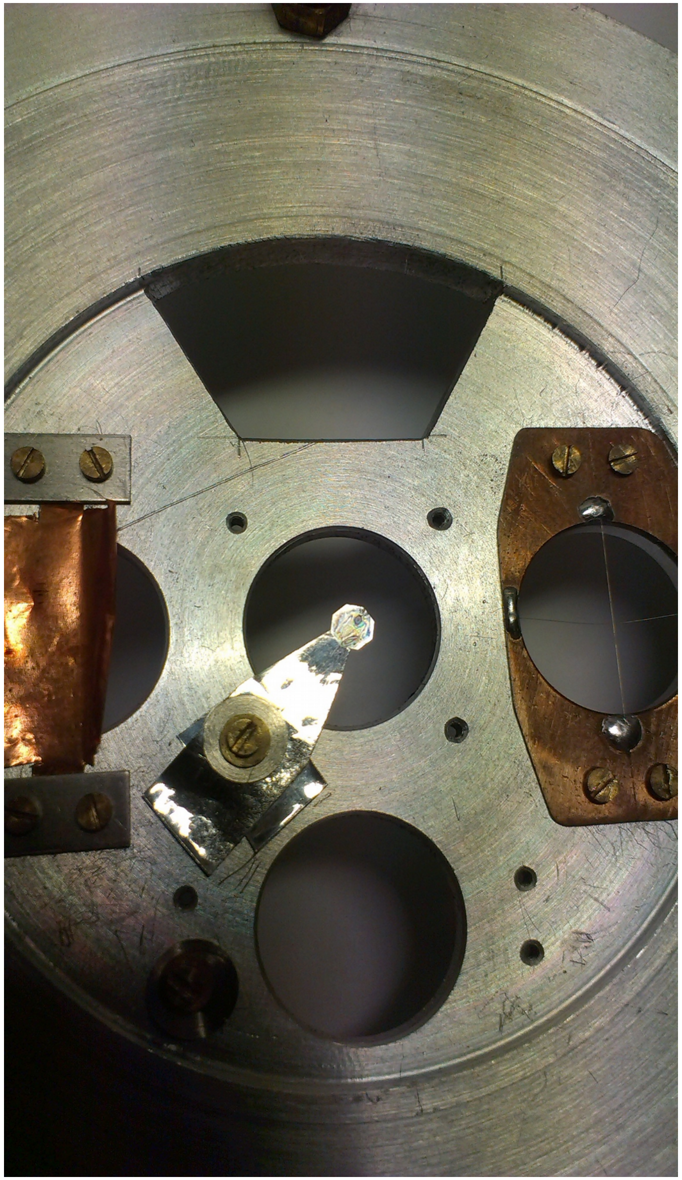
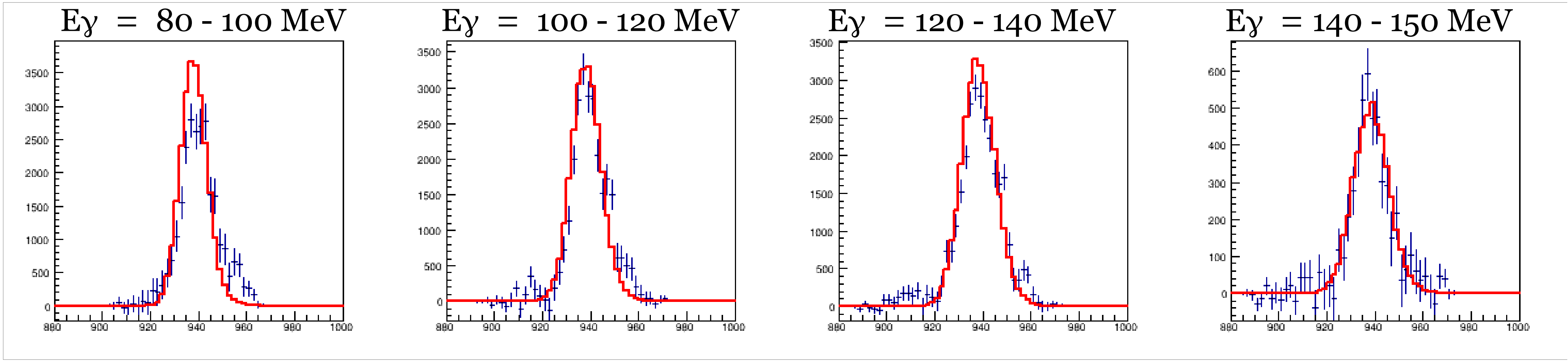


- 750 hours approved by MAMI PAC in Dec 2012 with an A!
- EJD, D. J. Hornidge, J. R. M. Annand, R. Miskimen
- First three-week MAMI run was in May 2013 (< ½ approved beam)
- V. Sokhoyan (GWU)

Scalar Polarizability Measurement Status



Missing Mass Distributions



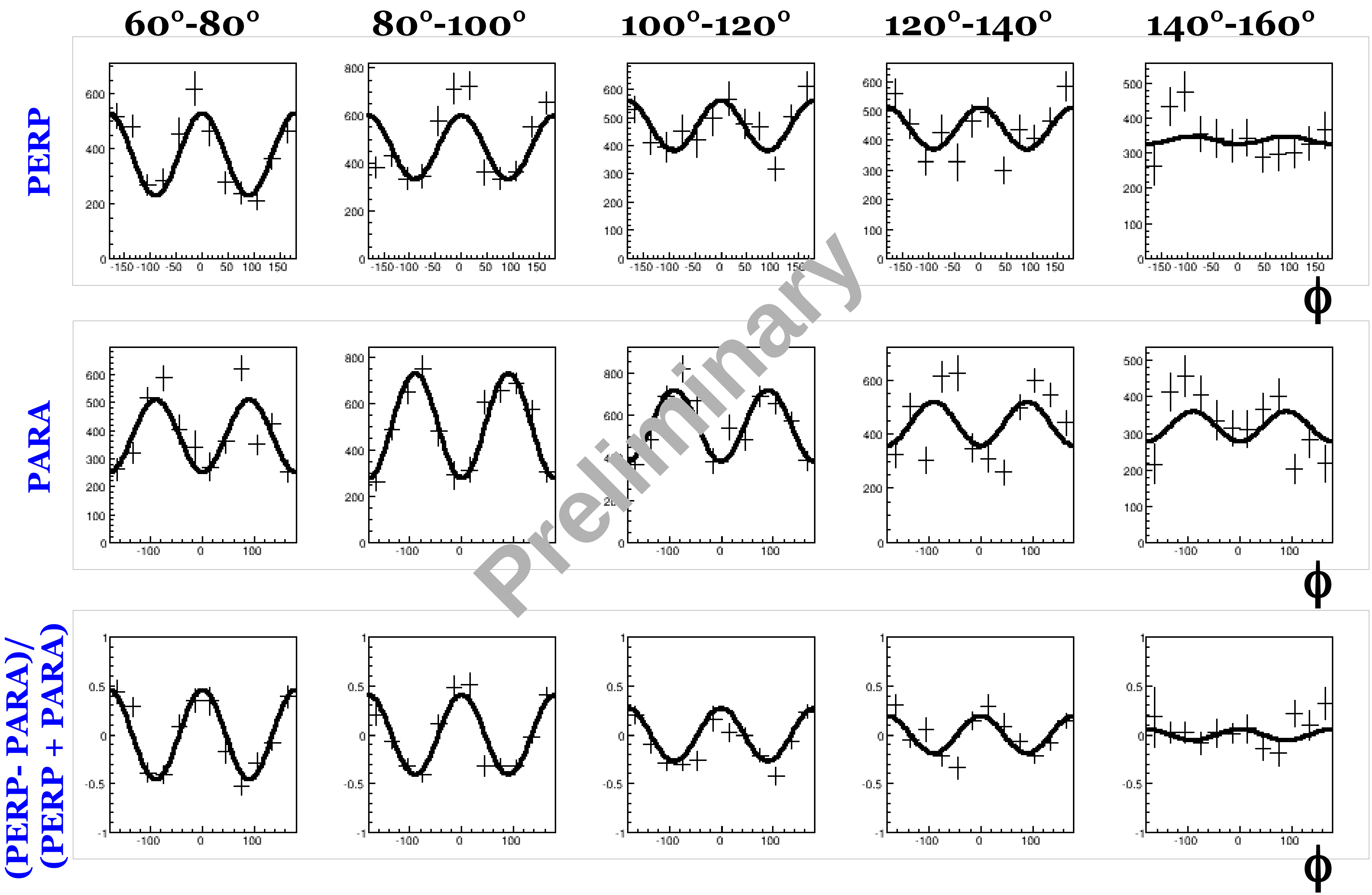
Red: Monte Carlo, Blue: Data

Θ_γ = 60° - 160°

- Good agreement between data and Monte Carlo
- Low background contamination in all energy bins

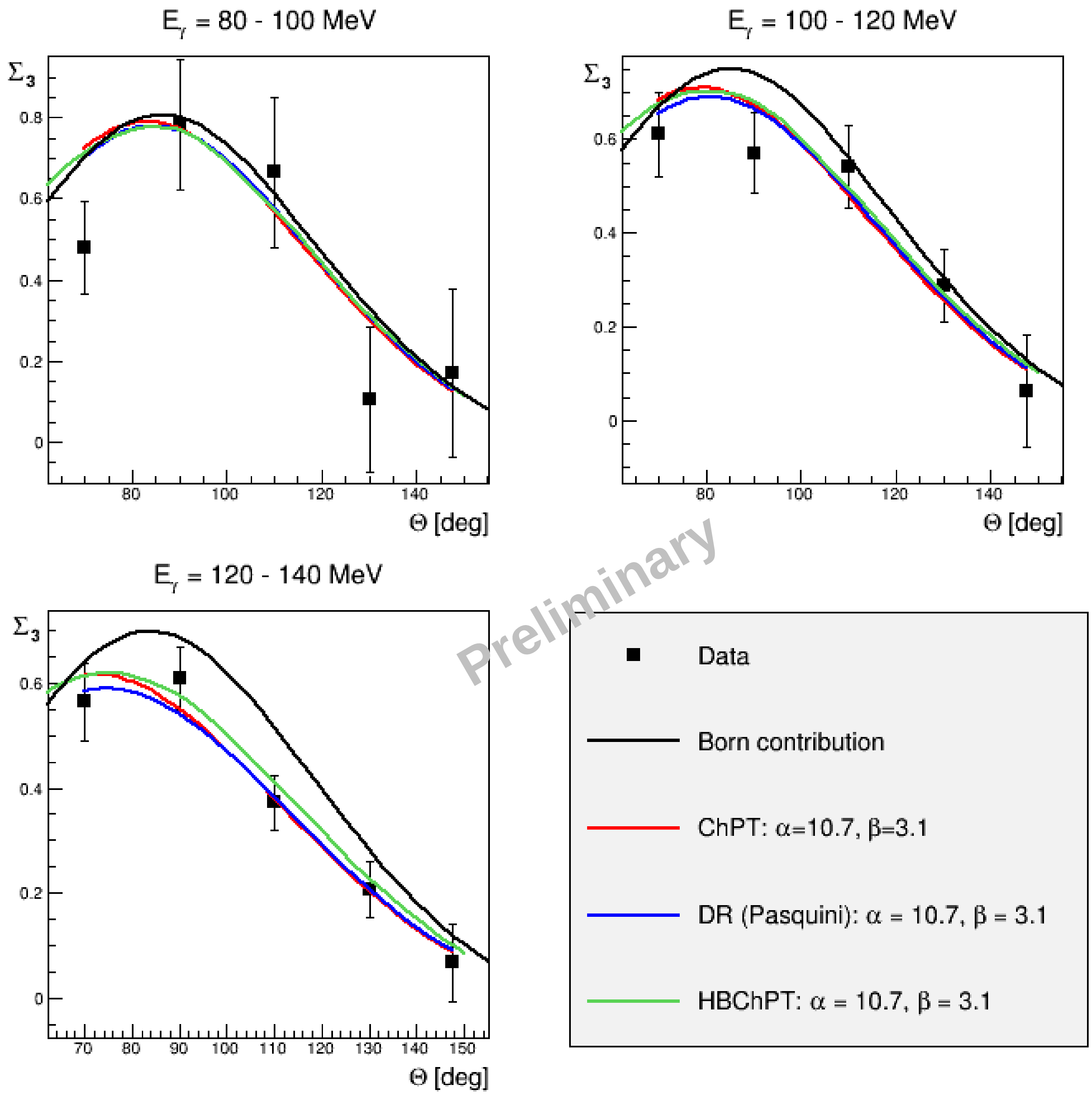
PRELIMINARY

ϕ Distributions Eγ = (120 – 140) MeV



Binning in Θ_γ

Beam Asymmetry Σ_3 : Preliminary Results



Curves:

ChPT: Krupina and Pascalutsa, PRL 110, 262001 (2013),

HB ChPT: J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)

Spin Polarizabilities

- Spin polarizabilities describe spin response to a changing EM field
  - Four vector pol. (γ_{E1E1} γ_{M1M1} γ_{E1M2} γ_{M1E2})
  - Subscript gives multipole of incoming & outgoing photon
  - Appear at 3rd order in eff. Hamiltonian of Compton scattering
  - Need to know nucleon spin → polarized target
  - Known field behavior → polarized photon beam

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

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

Nucleon Spin Polarizabilities – Theory & Experiment

- Previously only two linear combinations of vector polarizabilities measured:

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2} = -1.01 \pm 0.08 \pm 0.10 \times 10^{-4} fm^4$$
$$\gamma_\pi = -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2} = 8.0 \pm 1.8 \times 10^{-4} fm^4$$

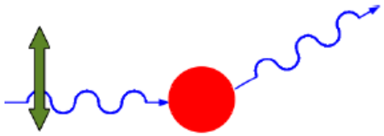
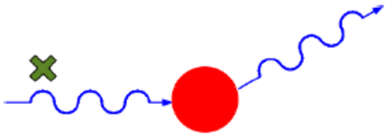
	K-mat.	HDPV	DPV	L_χ	HBχPT	BχPT
γ_{E1E1}	-4.8	-4.3	-3.8	-3.7	-1.1 ± 1.8 (th)	-3.3
γ_{M1M1}	3.5	2.9	2.9	2.5	2.2 ± 0.5 (st) ± 0.7 (th)	3.0
γ_{E1M2}	-1.8	-0.02	0.5	1.2	-0.4 ± 0.4 (th)	0.2
γ_{M1E2}	1.1	2.2	1.6	1.2	1.9 ± 0.4 (th)	1.1
γ_0	2.0	-0.8	-1.1	-1.2	-2.6	-1.0
γ_π	11.2	9.4	7.8	6.1	5.6	7.2

- Spin polarizabilities in units of 10^{-4}fm^4
- **K-matrix:** calculation from Kondratyuk et al., Phys. Rev. C 64, 024005 (2001)
- **HDPV, DPV:** dispersion relation calculations, B.R. Holstein et al., Phys. Rev. C 61, 034316 (2000) and B. Pasquini et al., Phys. Rev. C 76, 015203 (2007), D. Drechsel etal., Phys. Rep. 378, 99 (2003)
- **LC**: chiral lagrangian calculation, A.M. Gasparyan et al., Nucl. Phys. A 866, 79 (2011)
- **HBPT and BPT** are heavy baryon and covariant, respectively, chiral perturbation theory calculations, J.A. McGovern et al., Eur. Phys. J. A 49, 12 (2013), V. Lensky et al., Phys. Rev. C 89, 032202 (2014)).

RCS Asymmetries

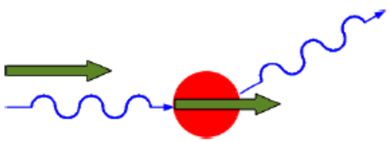
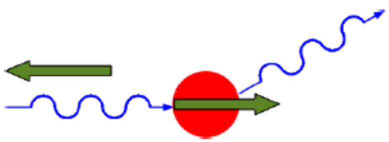
- Linearly polarized photons, parallel and perpendicular to the scattering plane, unpolarized target

$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

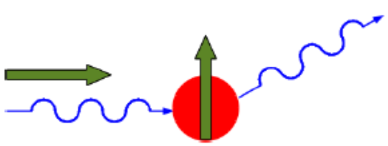
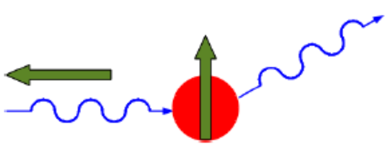
- Circularly polarized photons (left-handed (L) and right-handed (R)), longitudinally polarized target

$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} = \frac{\sigma^R_{+z} - \sigma^R_{-z}}{\sigma^R_{+z} + \sigma^R_{-z}}$$

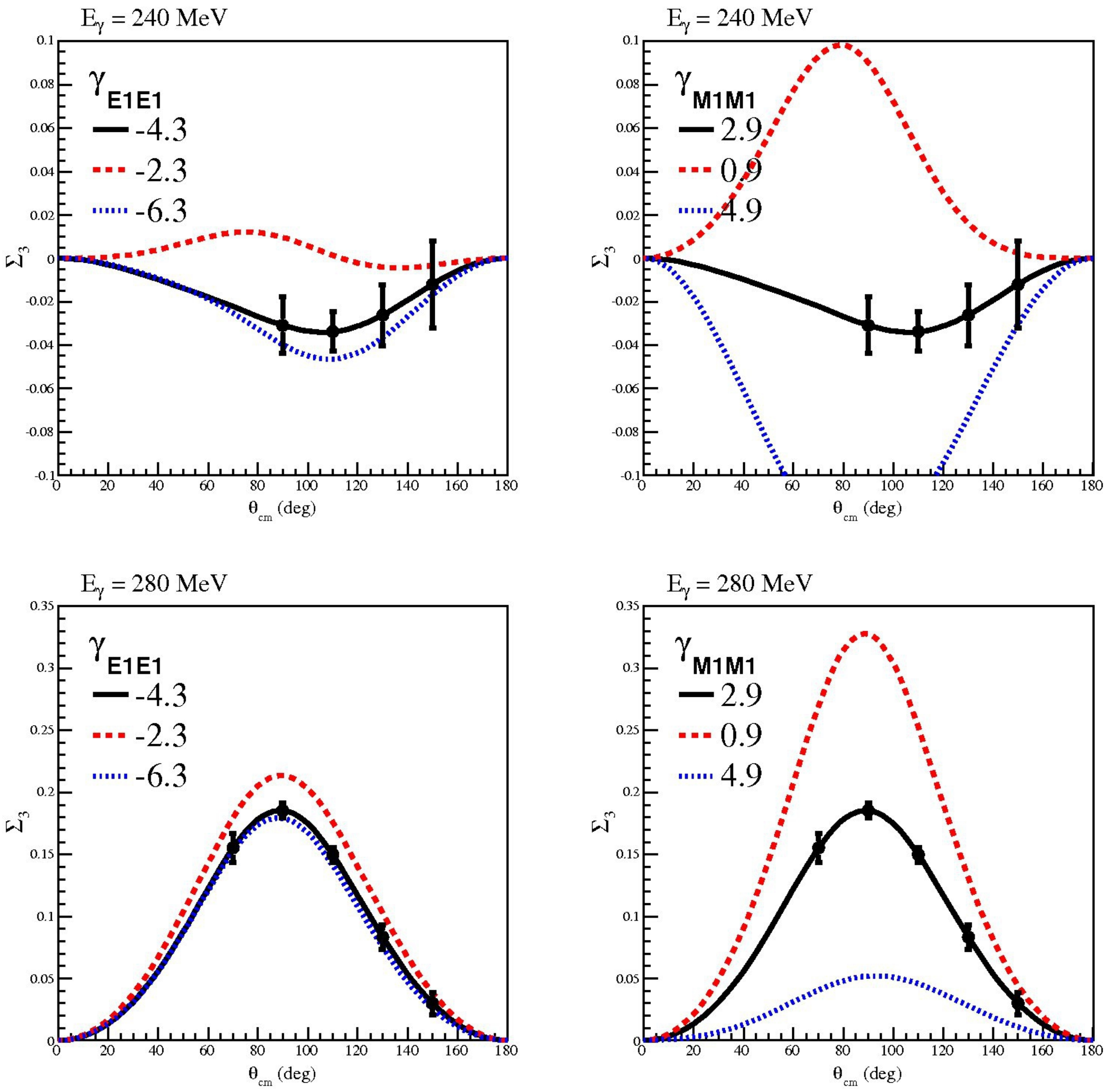



- Circularly polarized photons (left-handed (L) and right-handed (R)), transversely polarized target

$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}}$$

Predicted Polarizability Sensitivities - Σ_3

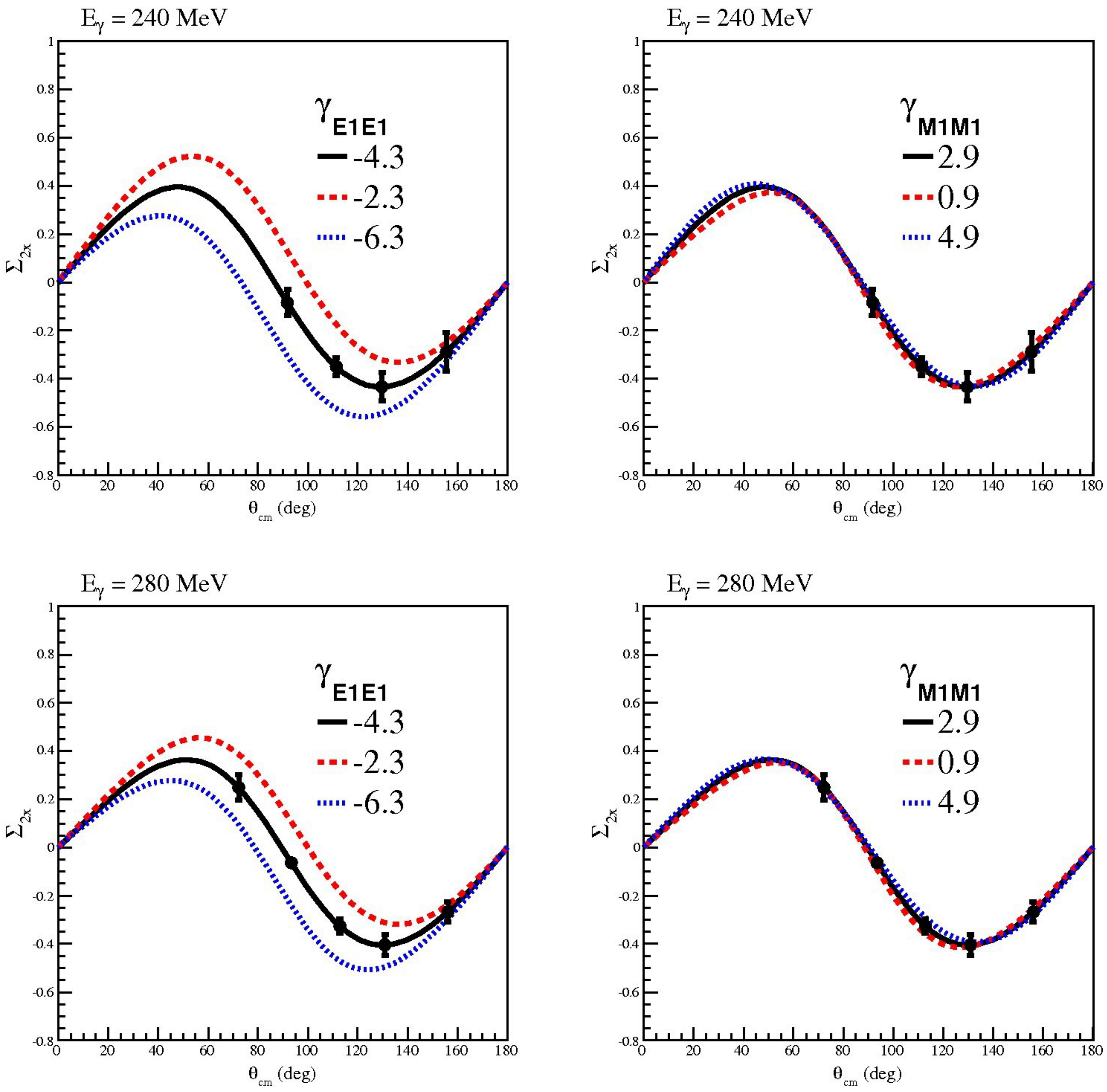


- 100 hours measurement
- Curves from:-

B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rev. C **76** 015203 (2007)

B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rept. **378** 99 (2003)

Predicted Polarizability Sensitivities - Σ_{2x}



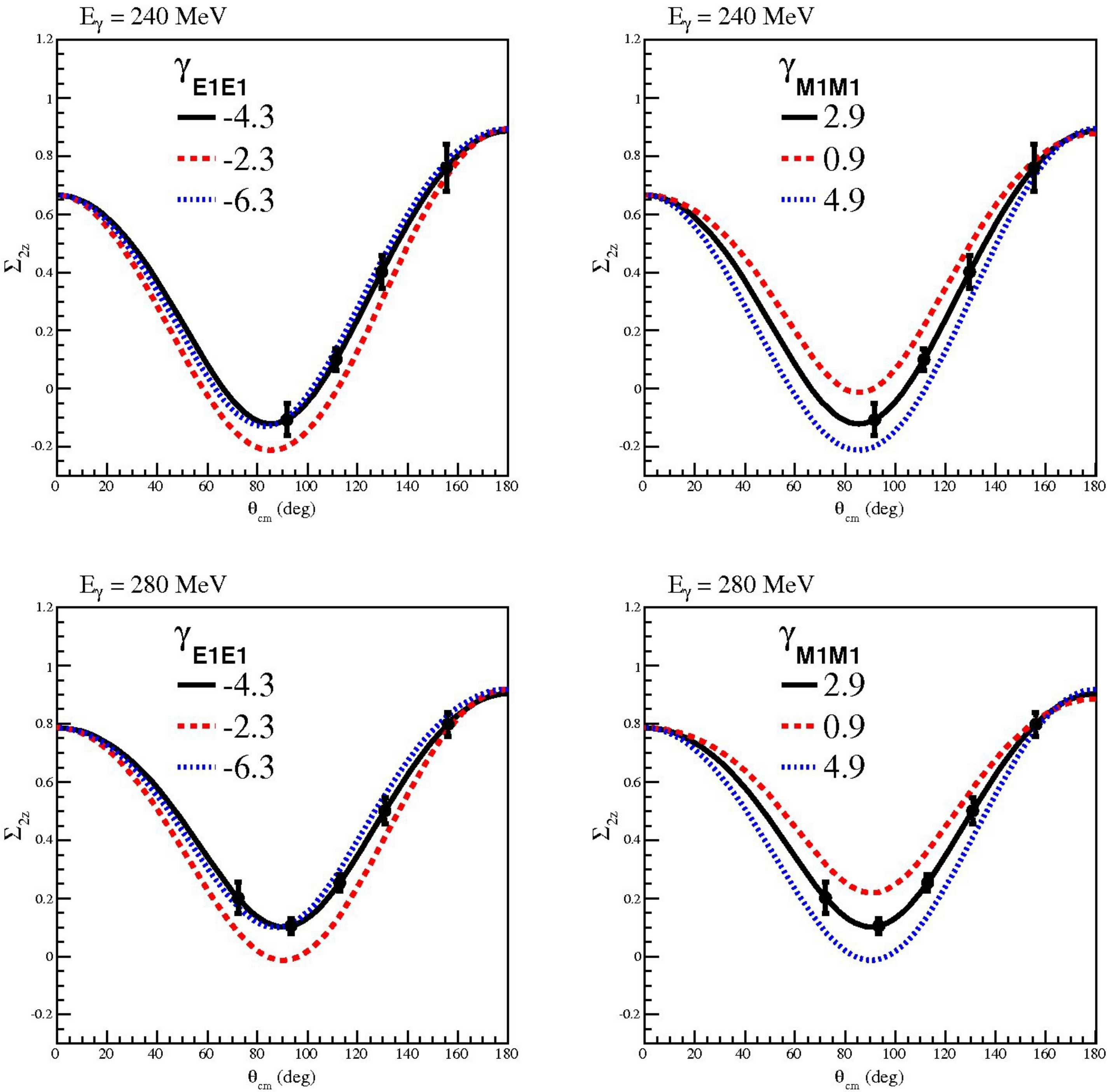
- 300 hours measurement

- Curves from:-

B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rev. C **76** 015203 (2007)

B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rept. **378** 99 (2003)

Predicted Polarizability Sensitivities - Σ_{2z}



- 300 hours measurement

- Curves from:-

B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rev. C **76** 015203 (2007)

B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rept. **378** 99 (2003)

Extracting the Polarizabilities

- Simultaneously fit theoretical curves to data
- Want to minimize model dependence:
  - ➔ Try several different theories / theory types
  - ➔ Fit over as wide a kinematic range as possible

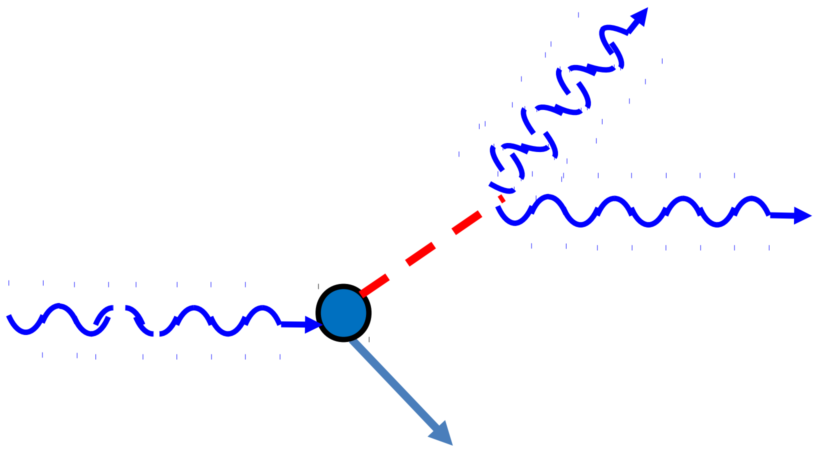
- **Multiple theoretical models:**
  - ➔ Dispersion relations (B. Pasquini)
  - ➔ Chiral coupled channel effective field theory (M. Lutz)
  - ➔ Chiral perturbation theory with delta expansion (V. Pascalutsa)
  - ➔ Chiral effective field theory including baryons (H. Griesshammer)
  - ➔ Dispersion relations (L'vov)
  - ➔ Lattice calculations (Alexandru / Hall)

Extracting the Polarizabilities

- Simultaneously fit theoretical curves to data
- Want to minimize model dependence:
  - Try several different theories / theory types
  - Fit over as wide a kinematic range as possible

- **Measure at multiple laboratories:**
  - A2 Collaboration, MAMI in Mainz
  - MAX Lab in Lund, Sweden
  - HIγS at Triangle Universities Nuclear Laboratory, Durham, NC

Measurement over a large kinematic region



- Largest problem in measurement of Compton scattering: **Pion production**

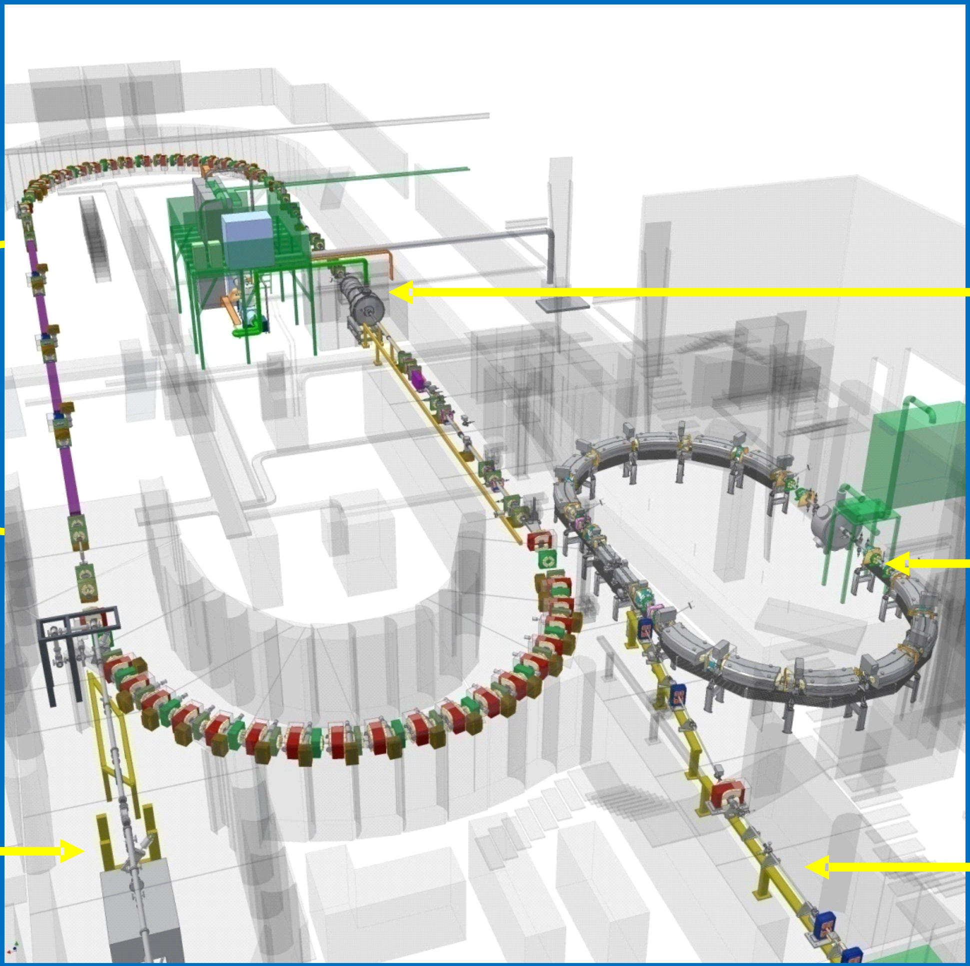
Below Pion Threshold	Above Pion Threshold
Lower sensitivity	Much larger sensitivity
Lower background	XS for π^0 production 100 times greater than RCS
Low energy expansion valid	Larger model dependence

Measurement over a large kinematic region

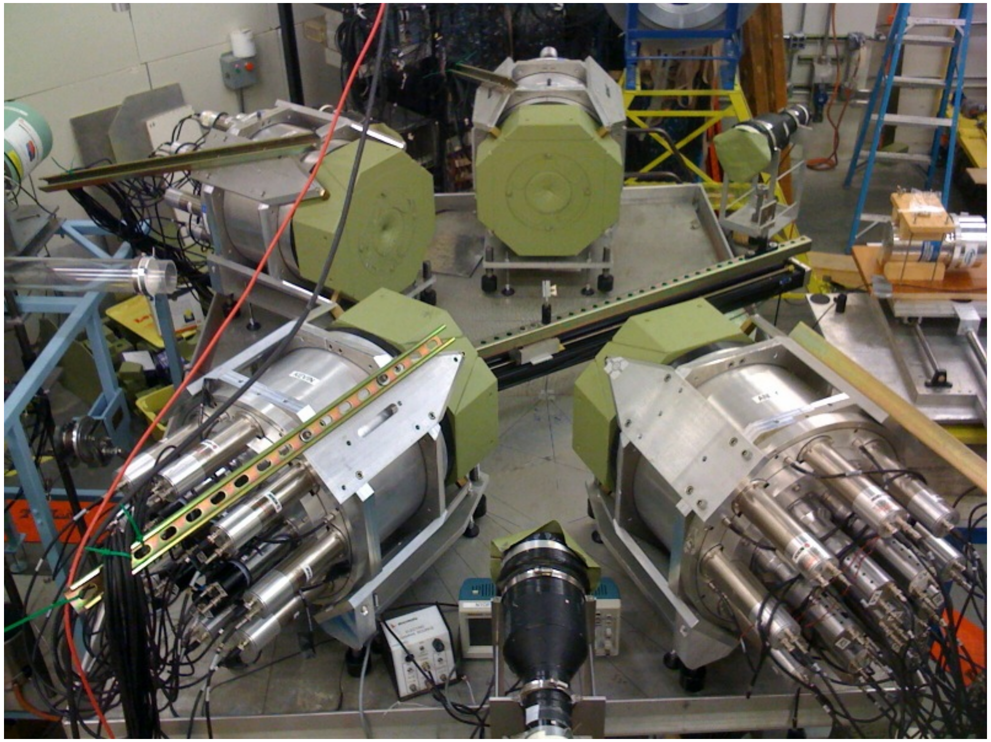
- Largest problem in measurement of Compton scattering: **Pion production**
- **HIγS (The High Intensity Gamma Source)**: low energy, high polarization, single energy photon source
- **MAMI:** higher energy, continuous energy spectrum above pion threshold, lower polarization
- **Lund:** above pion threshold, mainly focused on neutron measurements
- Energy region determines the detector requirements

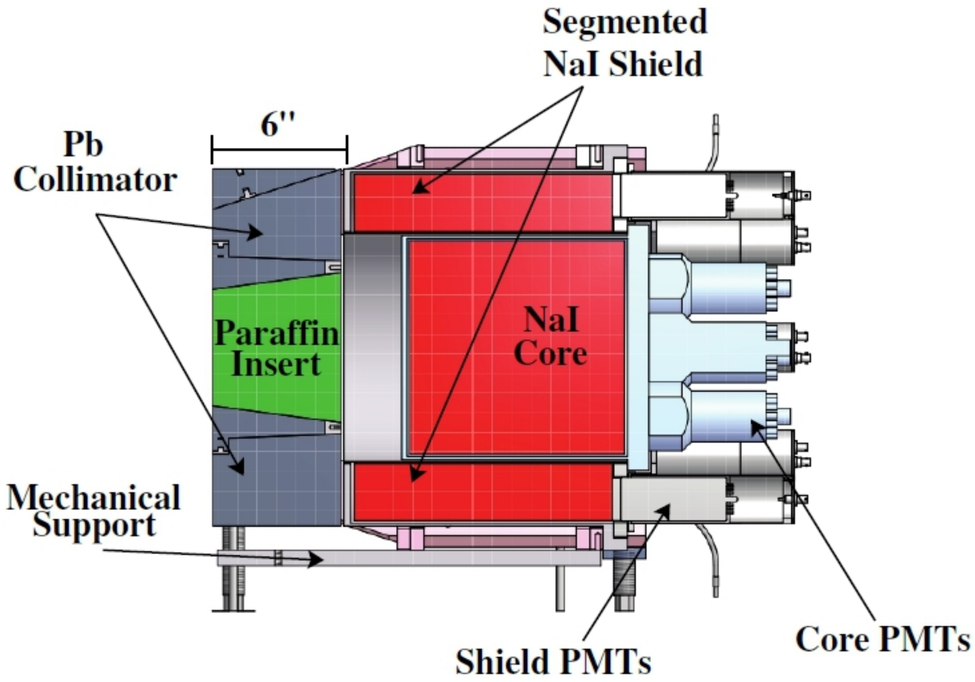
HIγS γ-ray beam generation

- Circularly and linearly polarized, nearly monoenergetic γ–rays from 2 to 100 MeV
- Utilizes Compton backscattering of FEL light to generate γ–rays



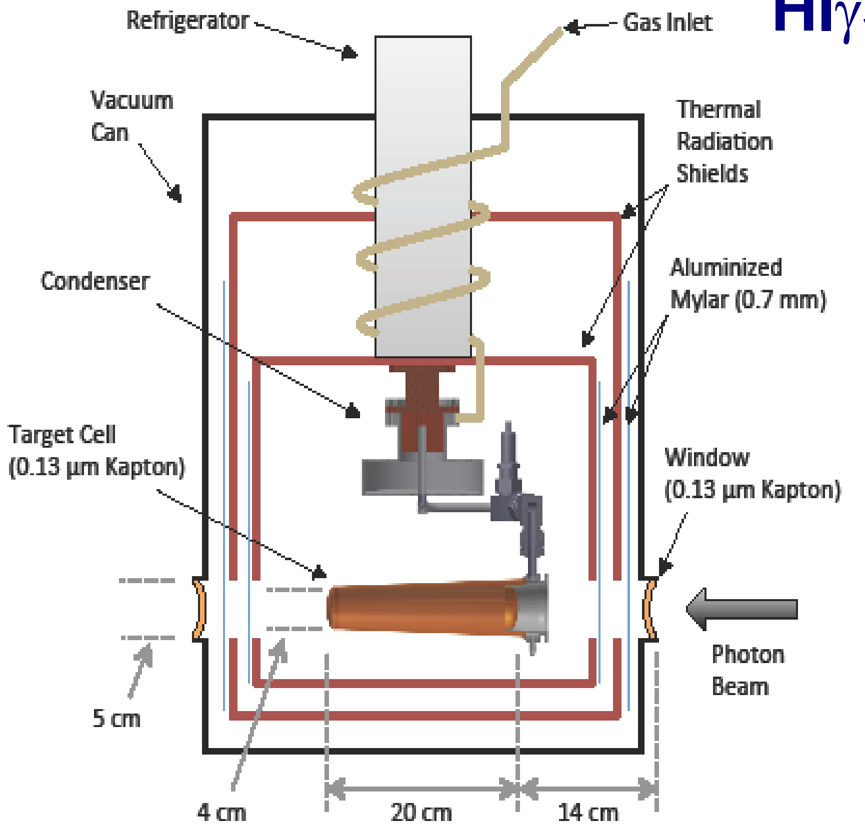
HIγS Programme

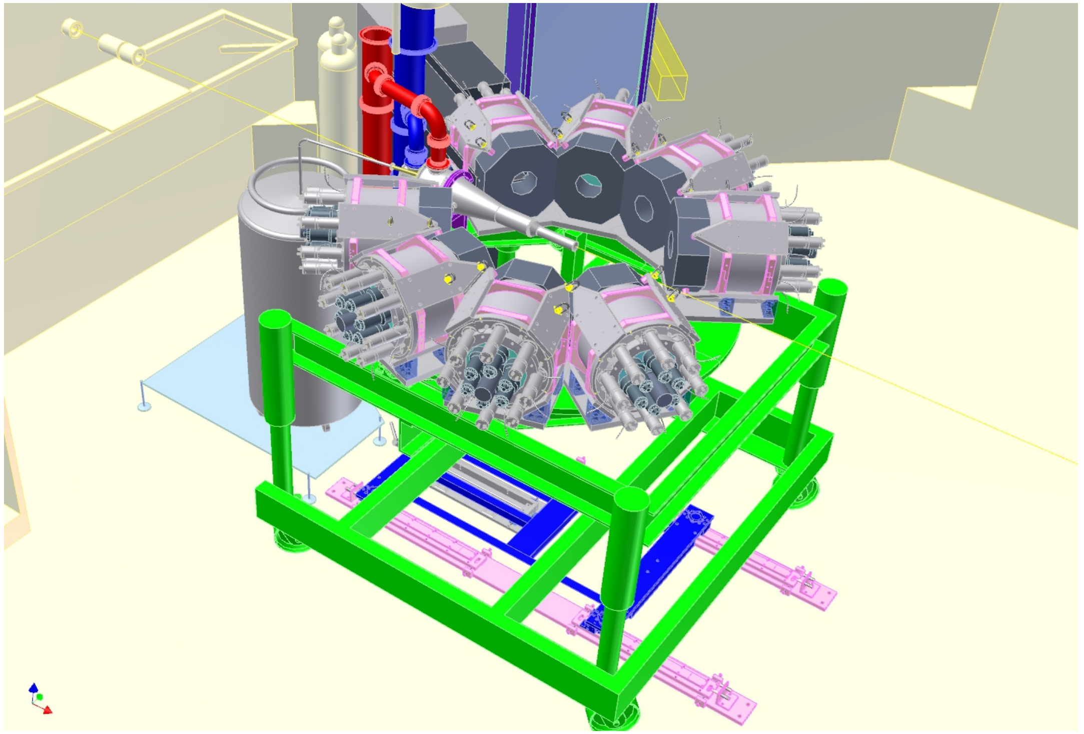




- Uses HINDA Array: eight large volume NaI detectors
- Small solid angle
- Large flux and polarization through Compton backscattering
- Very accurate measurements at few kinematic points
- Lower sensitivity to polarizabilities
- Overlapping energy range with MAMI – systematic checks

HIγS Program





- HINDA Array: all eight detectors are ready
- New H / D target (with G. Feldman (GWU))
- Polarized Target: passed cold tests, transported to HIgS
- Planned measurements:

→ 2016: reduce error by 50% on neutron magnetic dipole polarizability

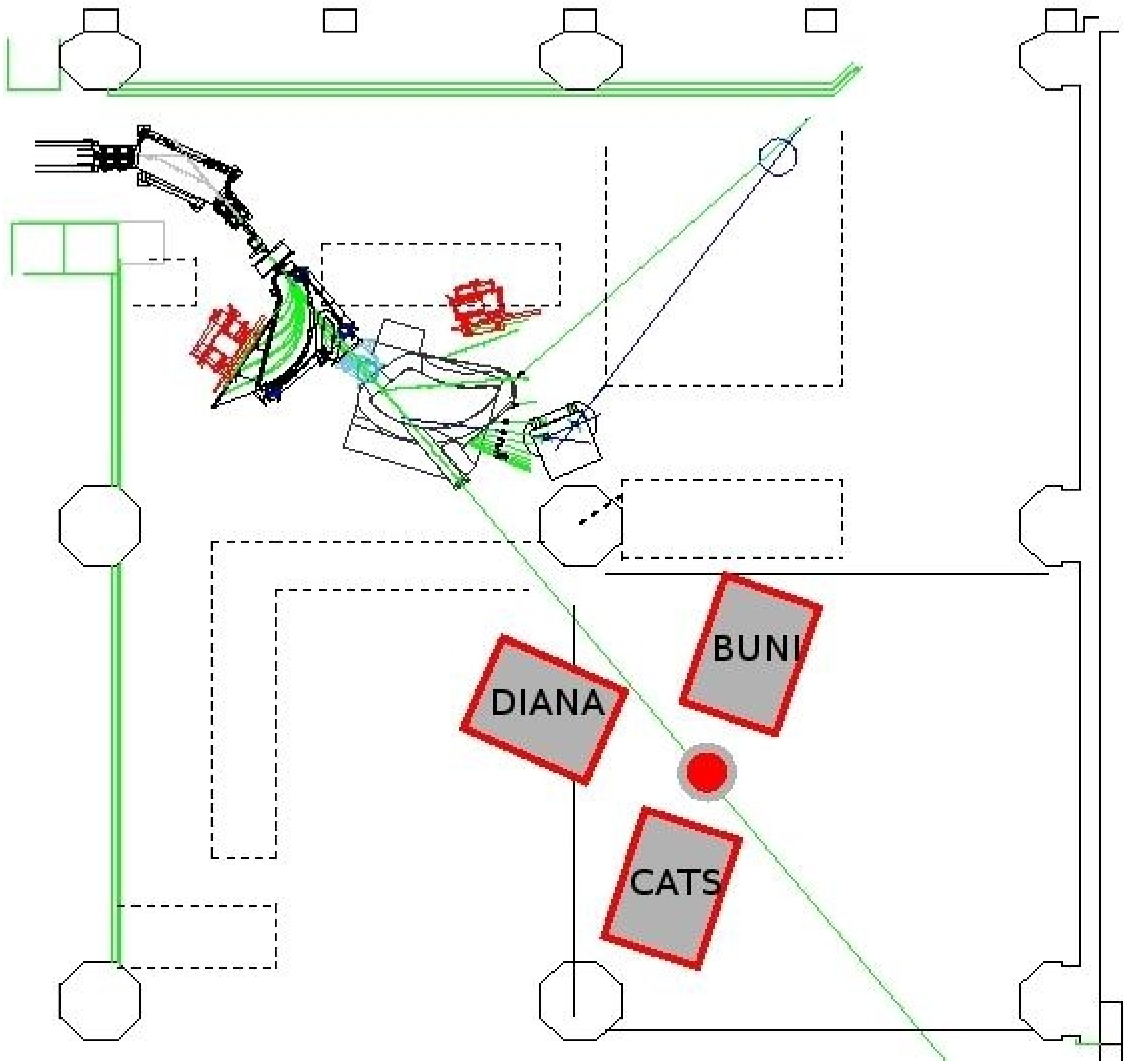
→ 2017: Model independent determination of proton scalar polarizablities

→ 2019: First direct measurement of electric dipole spin polarizability

Goals: H. R. Weller, Hadron 2014

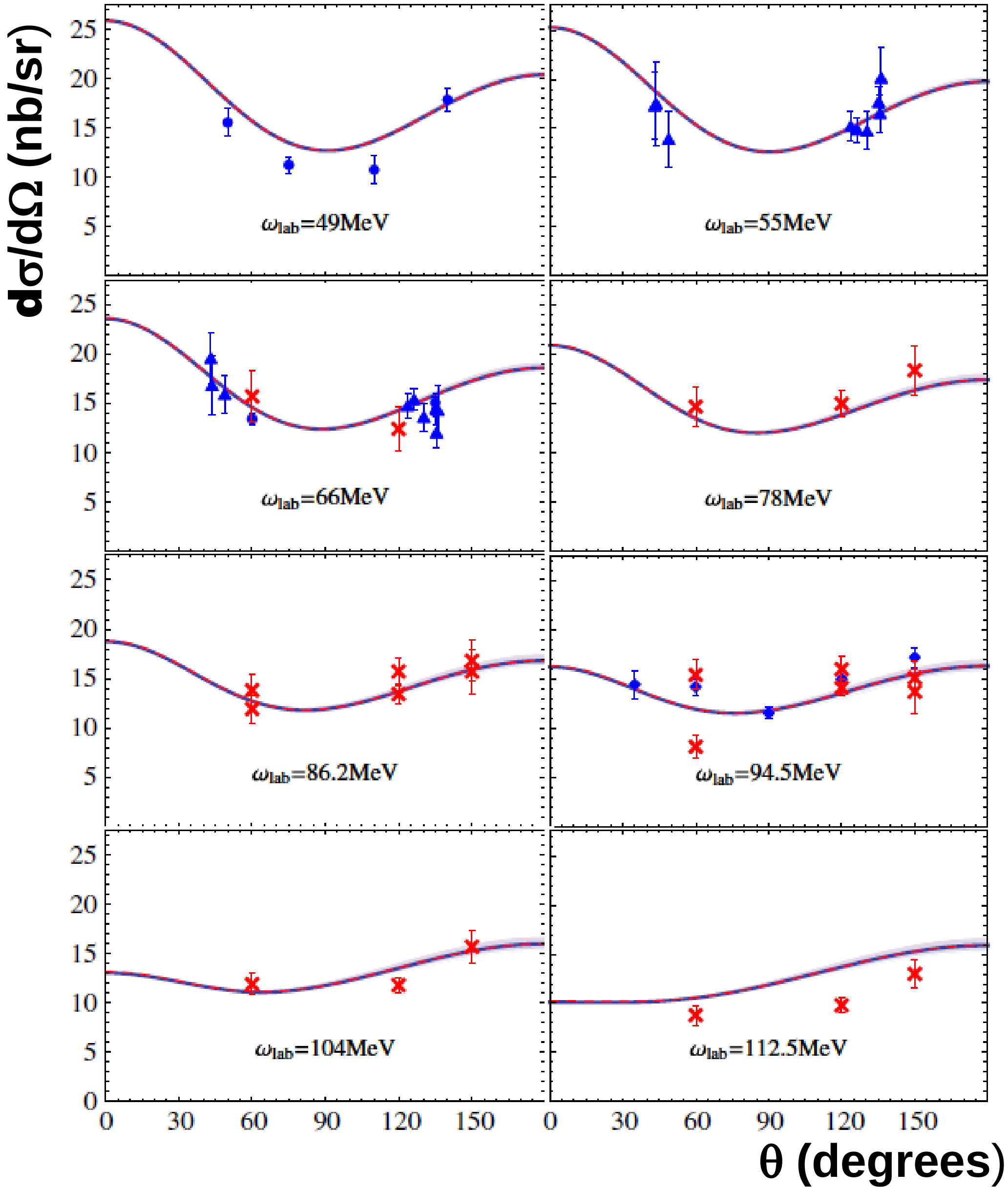
LUND Program

- Three large-volume NaI detectors (CUNI, CATS, LARA)
- Tagged photon beam



L. Myers

LUND Program



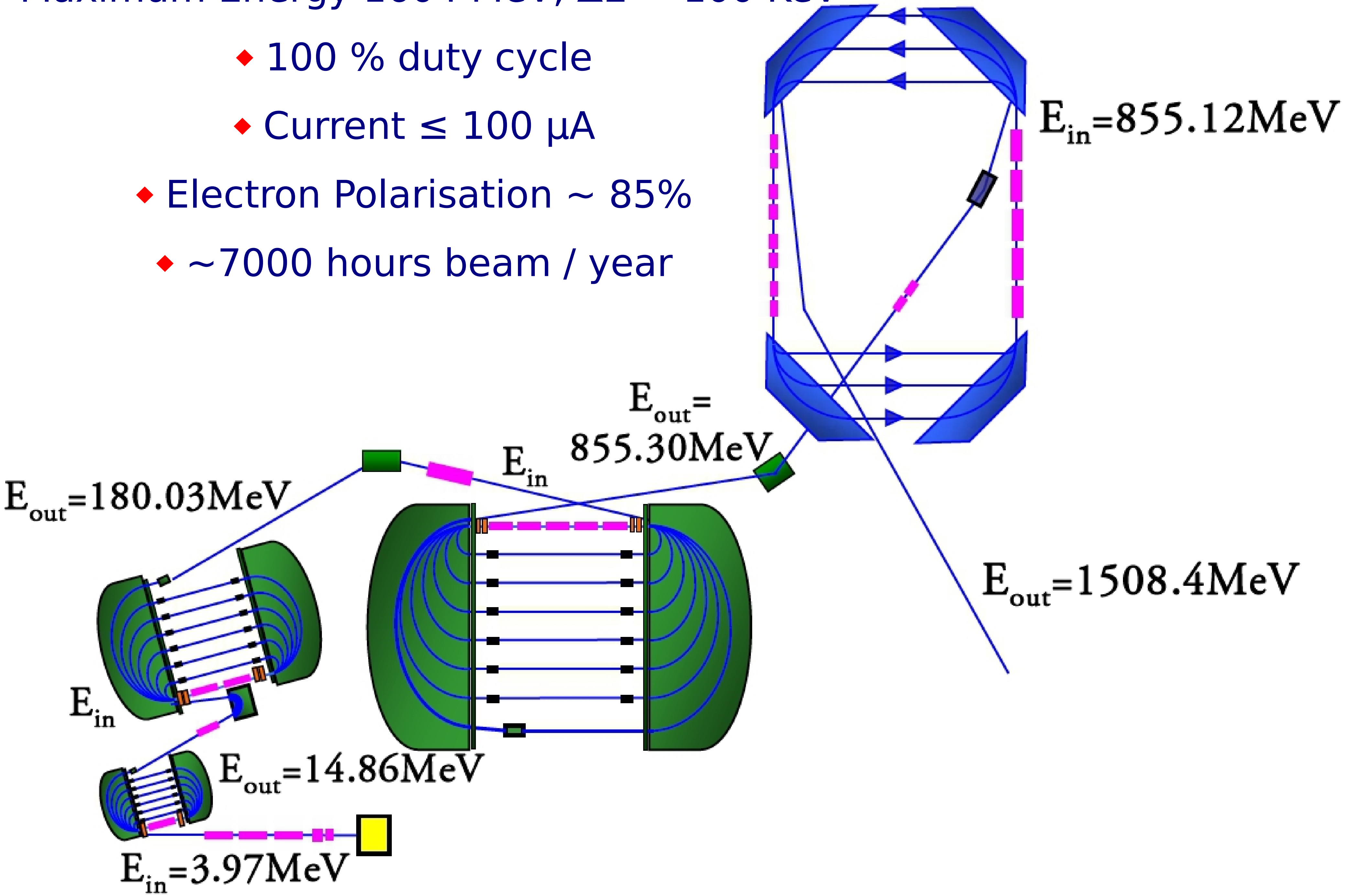
- Three large-volume NaI detectors
- BUNI, CATS, DIANA
- Tagged photon beam
- COMPTON@MAX-lab collaboration
- MAX IV Laboratory
- Extractions: Griesshammer, McGovern and Phillips
- First new Deuteron Compton data in 10+ years
- Doubles the world data set for DCS
- Phys. Rev. Lett. **113** 262506 (2014)
- New measurement under analysis

$$\alpha_n = 11.7 \pm 1.3(stat.) \pm 0.2(BSR) \pm 0.8(th.)$$
$$\beta_n = 3.6 \pm 1.3(stat.) \pm 0.2(BSR) \pm 0.8(th.)$$

L. Myers

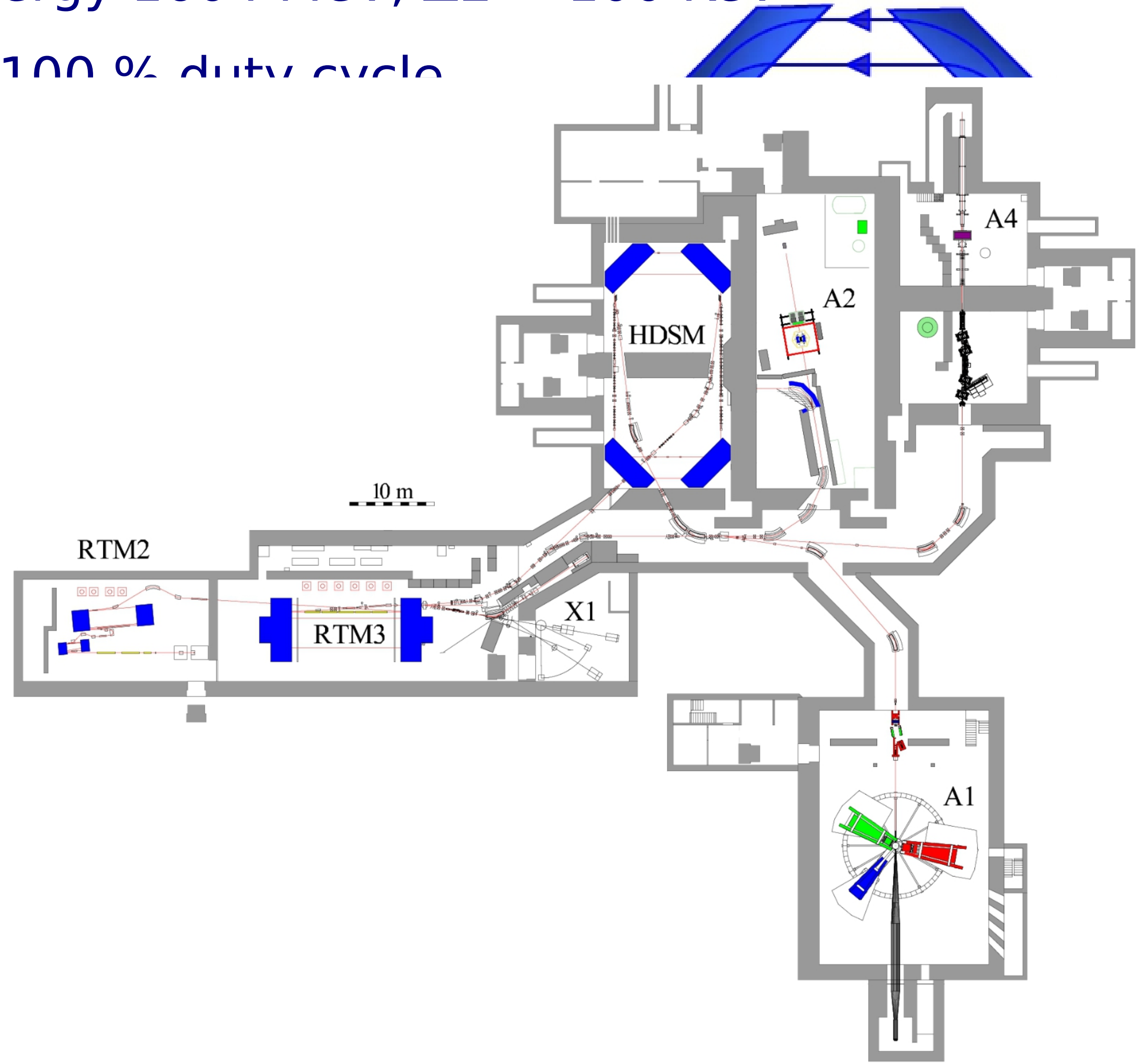
MAMI

- Maximum Energy 1604 MeV, ΔE = 100 KeV
- 100 % duty cycle
- Current ≤ 100 μA
- Electron Polarisation ~ 85%
- ~7000 hours beam / year



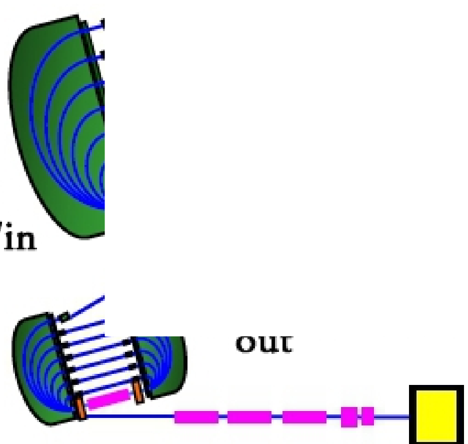
MAMI

- Maximum Energy 1604 MeV, ΔE = 100 KeV
  - 100 % duty cycle



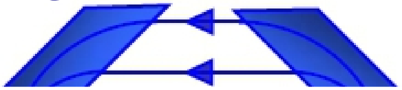
.12MeV

4MeV

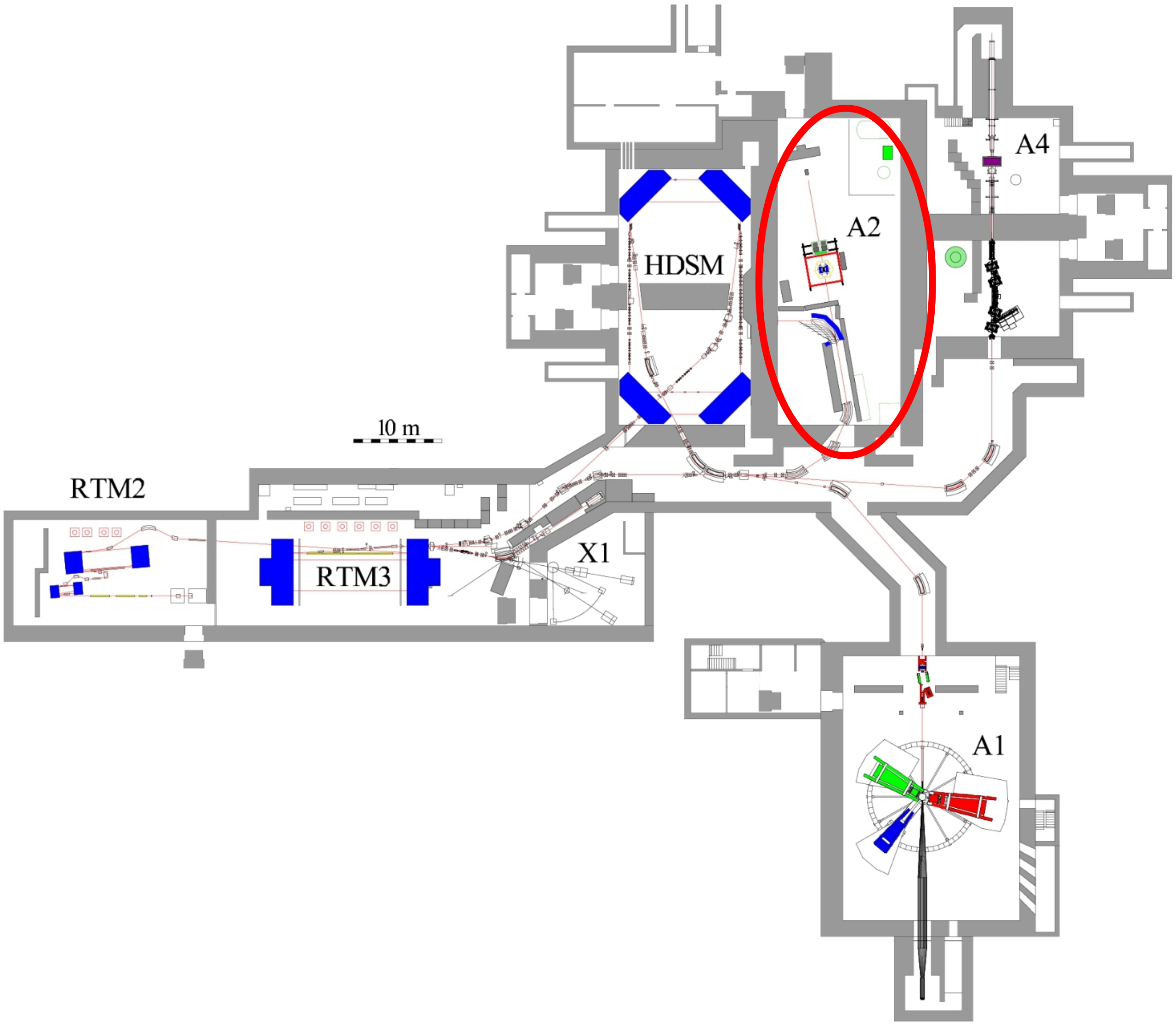


MAMI

- Maximum Energy 1604 MeV, ΔE = 100 KeV



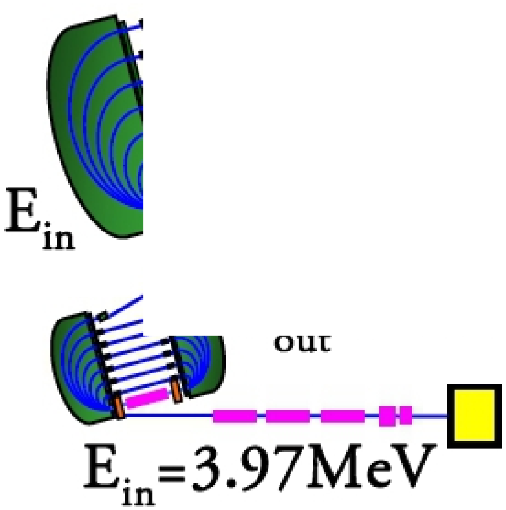
- 100 % duty cycle



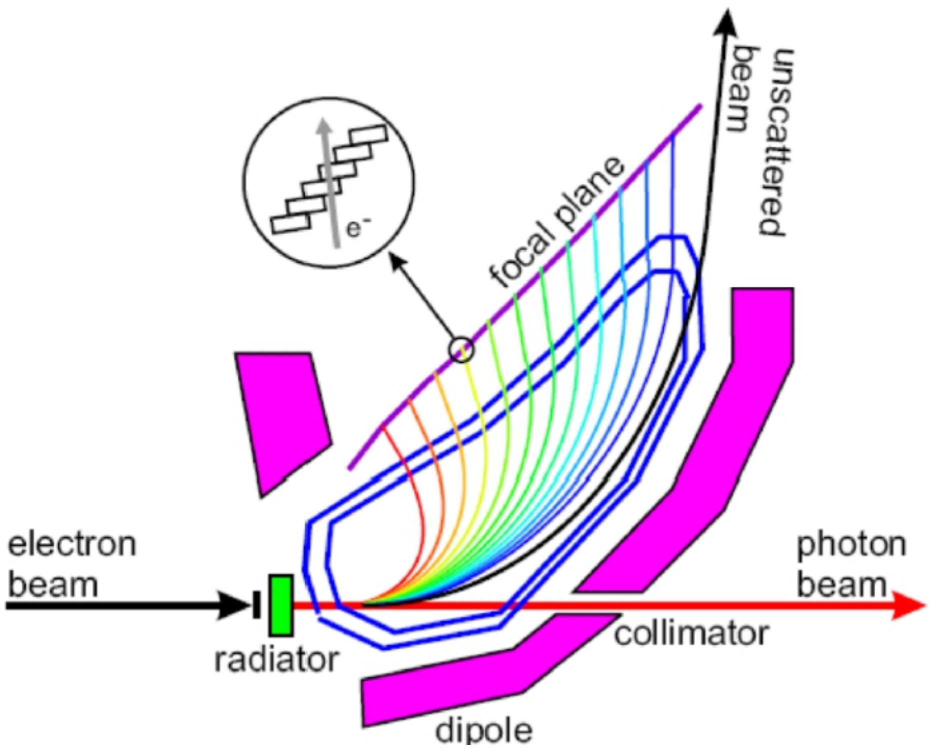
.12MeV

4MeV

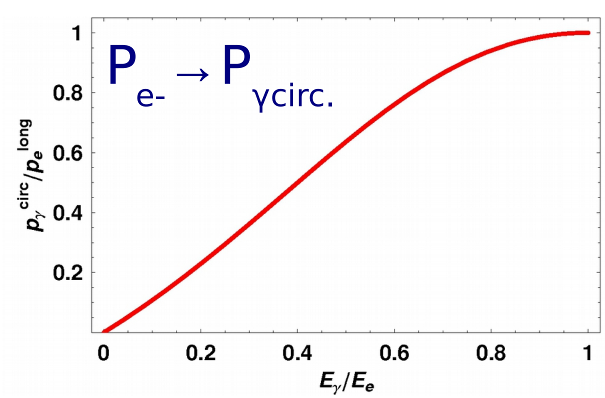
E_{out}=180.

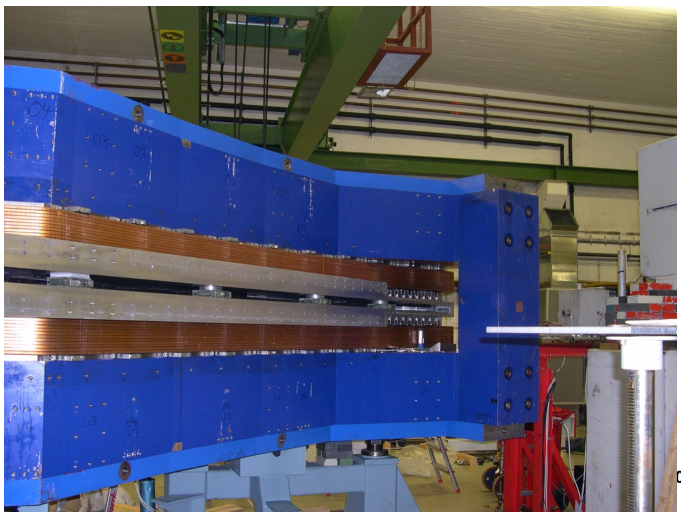


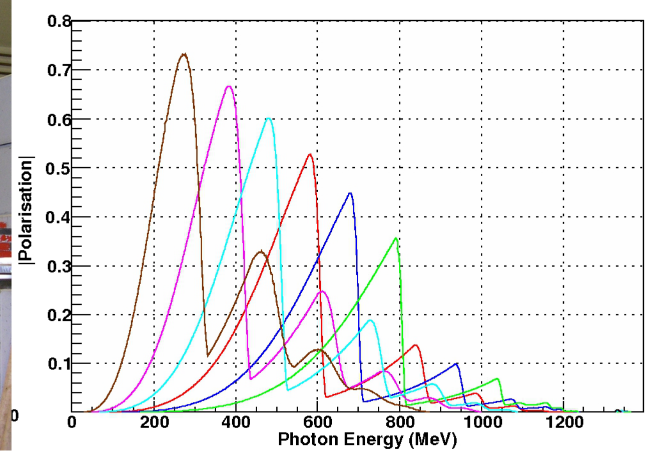
Glasgow Photon Tagger



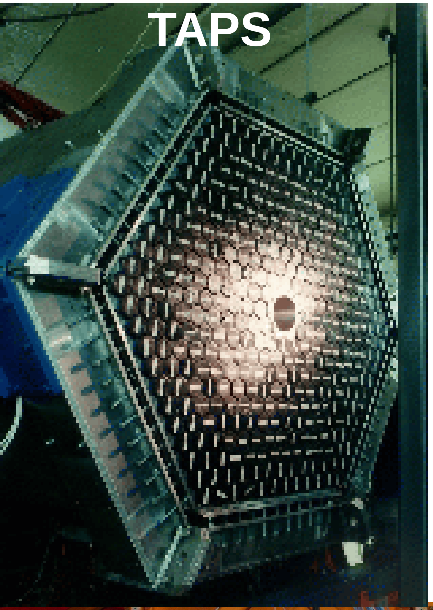
- Detection of radiating electrons:
  - ➔ $E_\gamma = E_0 - E_e'$
- Tagged range: 4.7 – 93% E_0
- Energy resolution ~1 - 4 MeV
- Circularly pol. γ from e^- pol, upto 85%
- Linearly pol. γ from crystal. rad., upto 70%
- 1 MHz / channel e- rate, 352 chans
- EPJ A 37, 129 (2008)

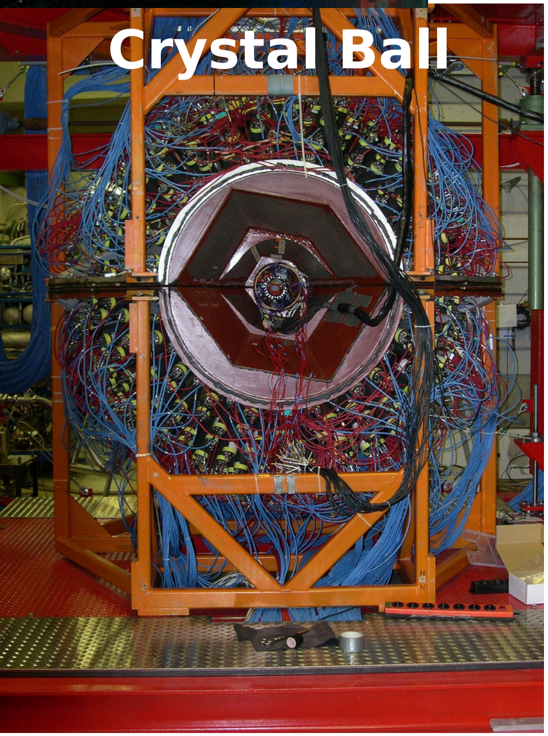


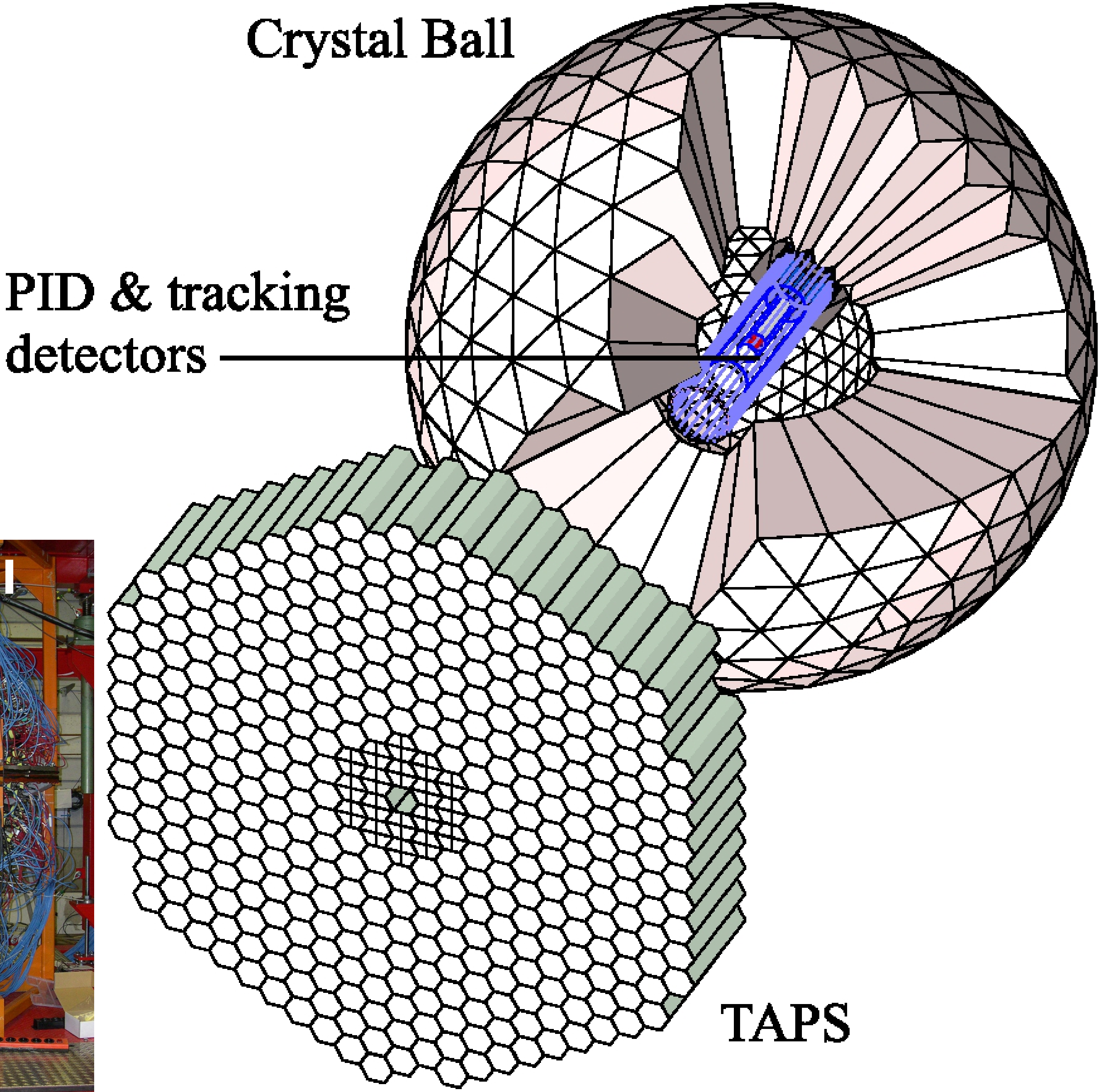




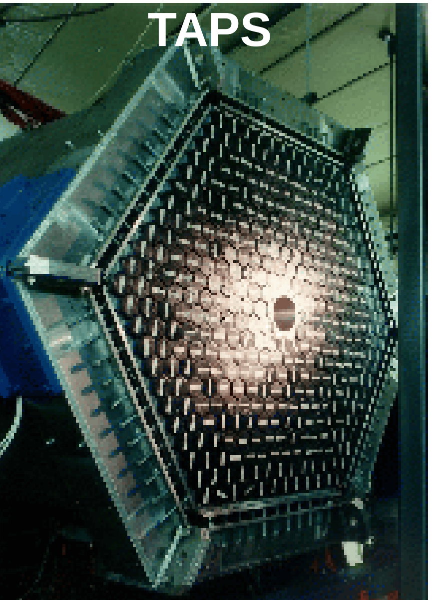
CB@MAMI Detector System

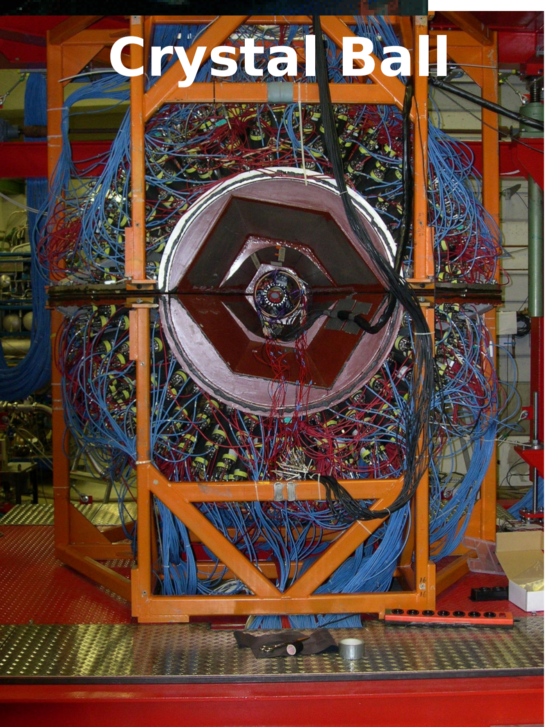


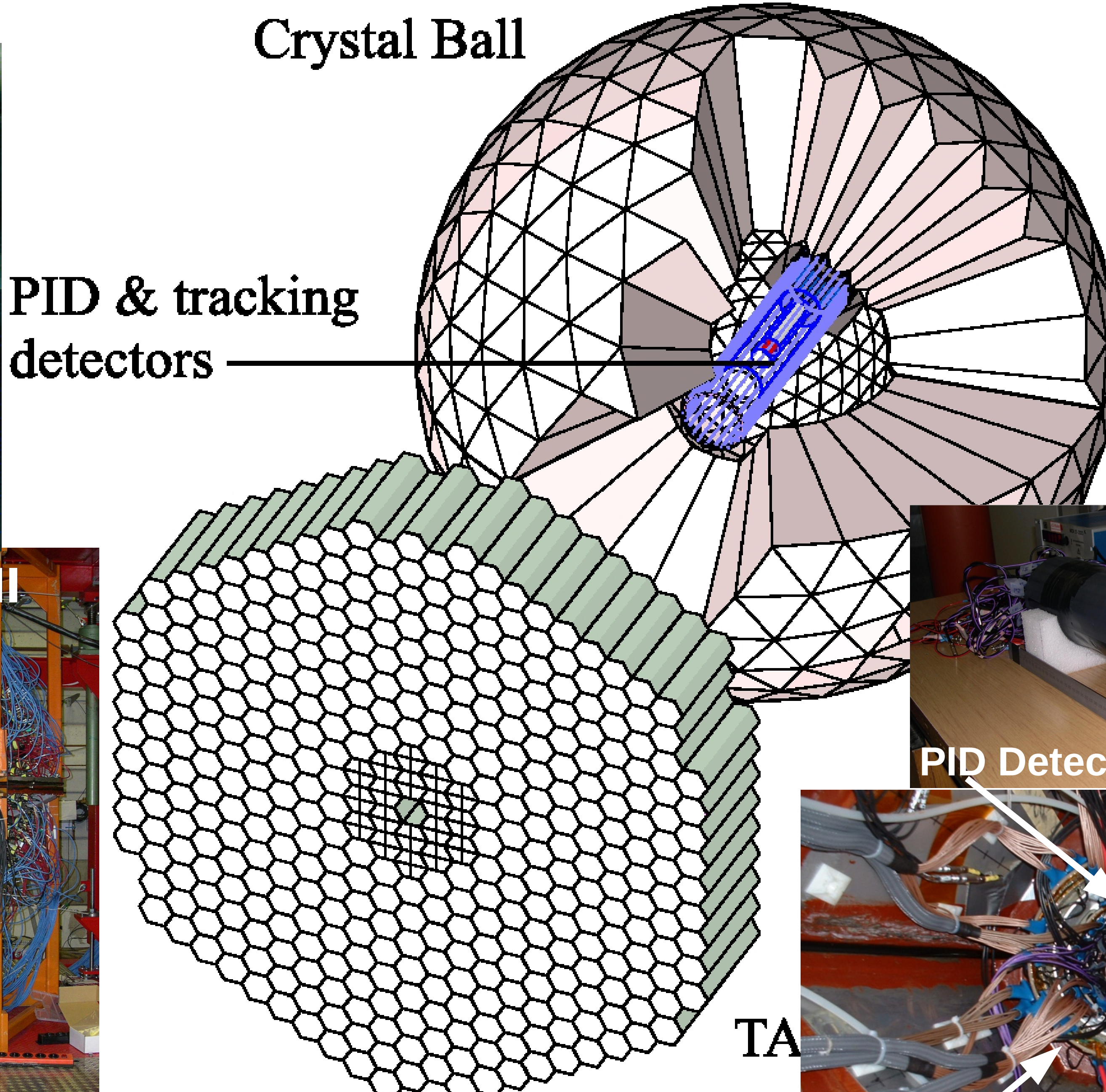


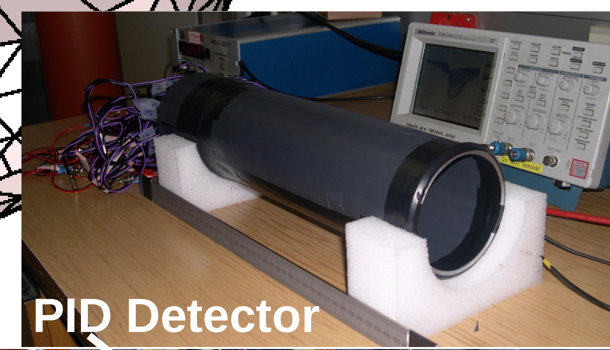


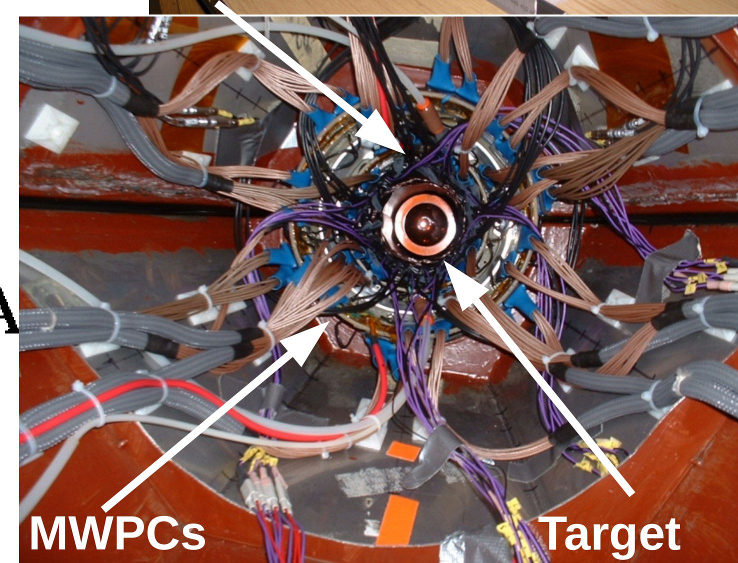
CB@MAMI Detector System

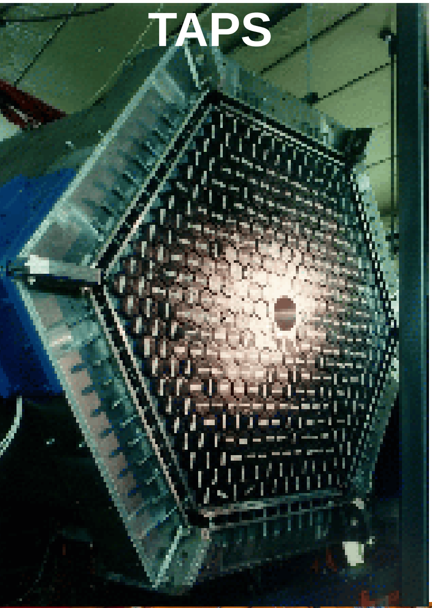


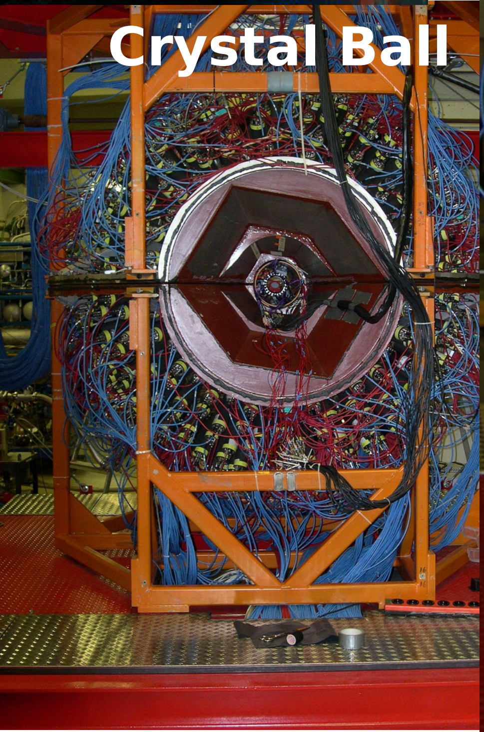


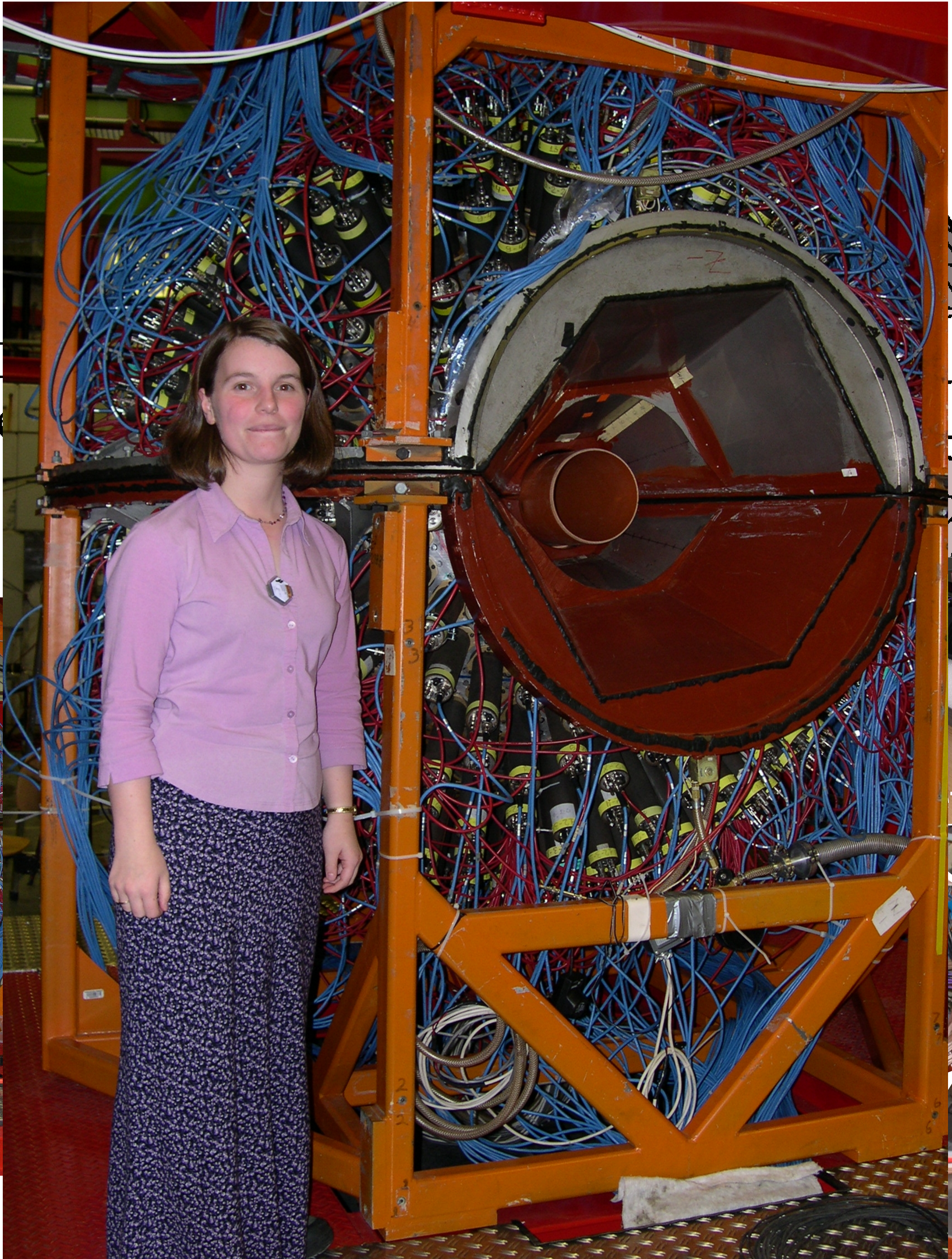


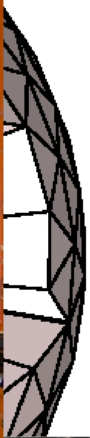


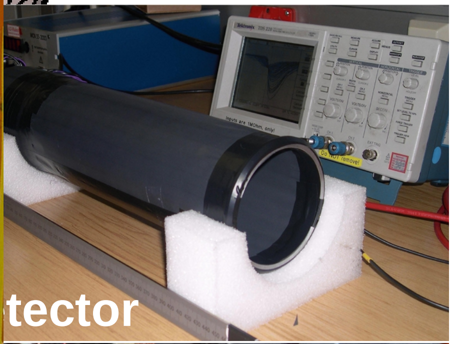


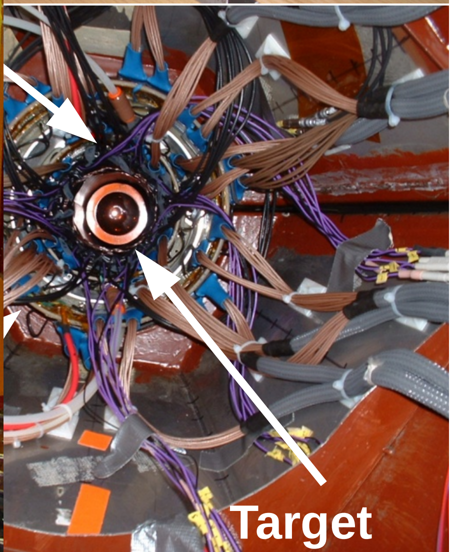

TAPS


Crystal Ball

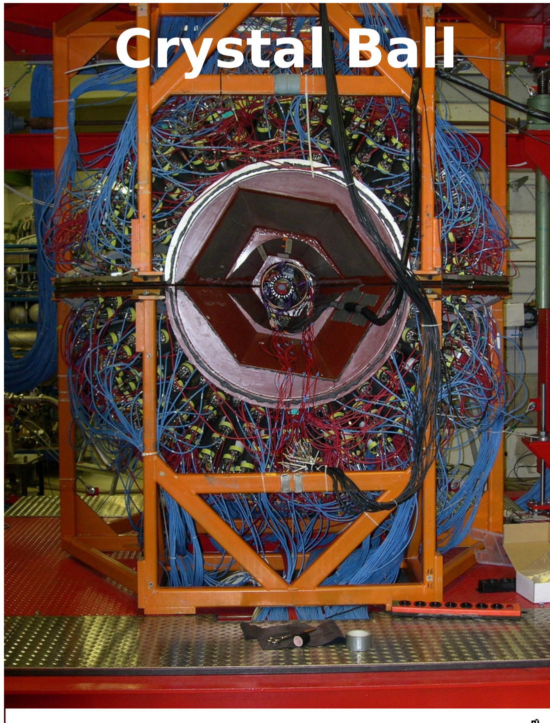


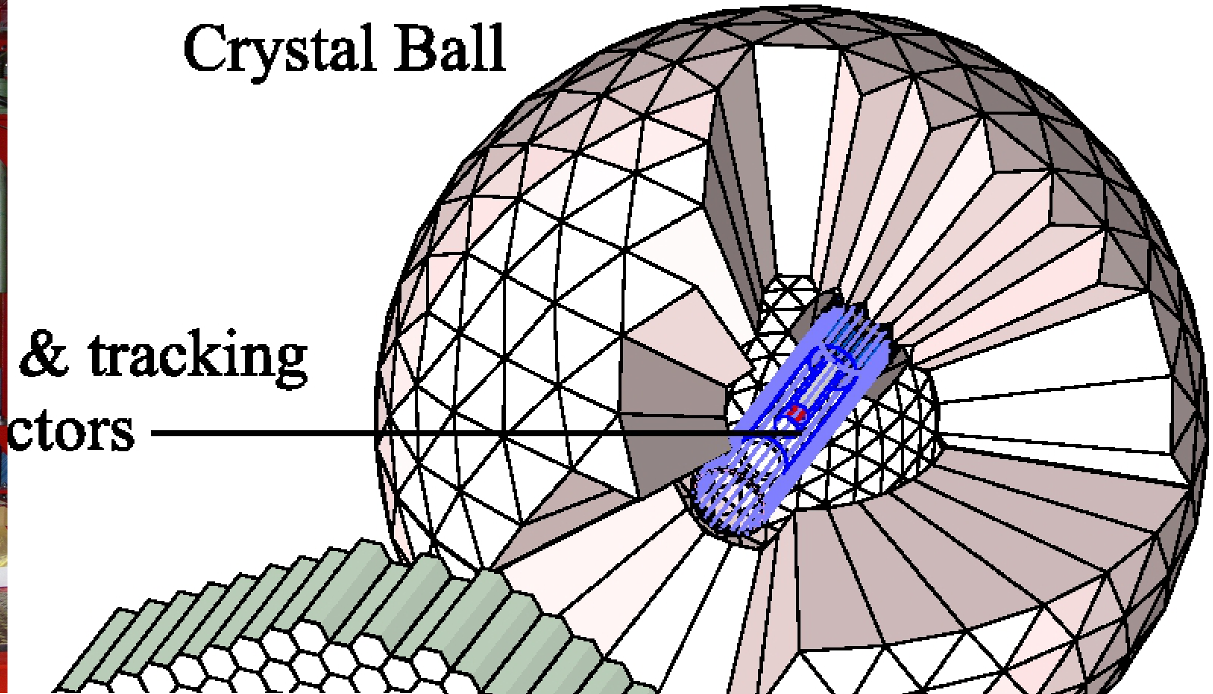


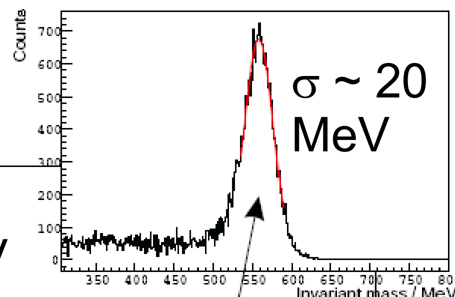

tector

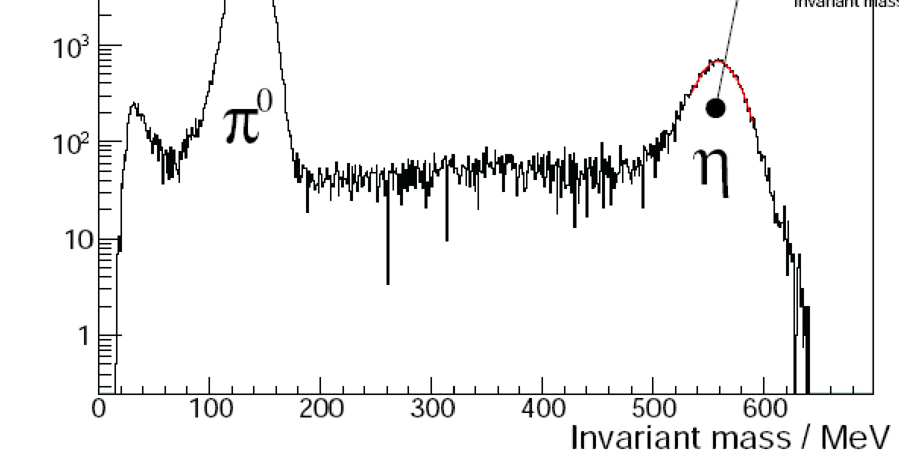

Target

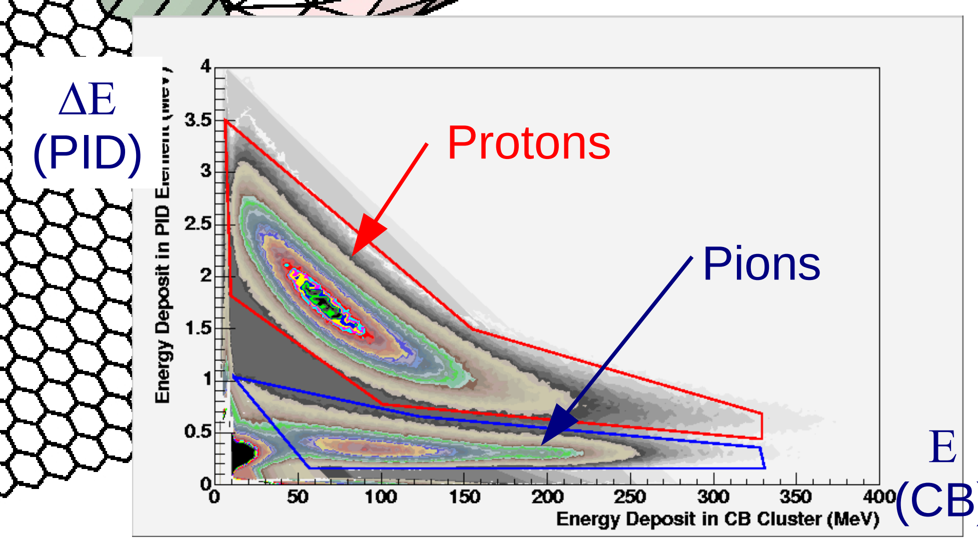
CB@MAMI Detector System



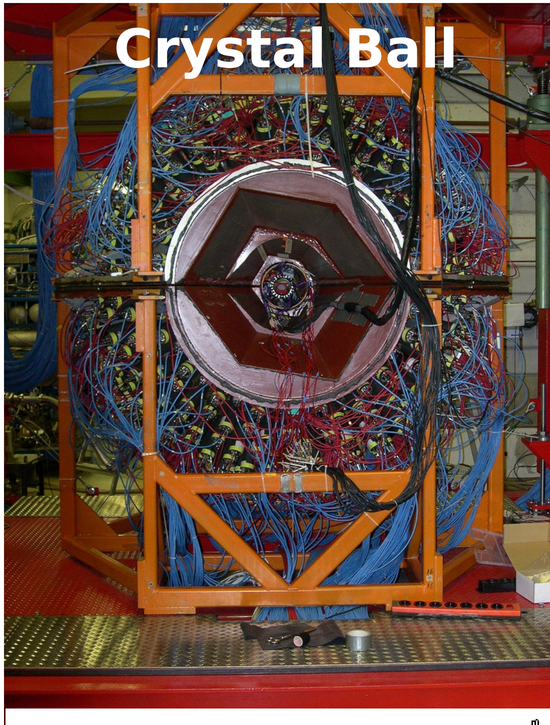


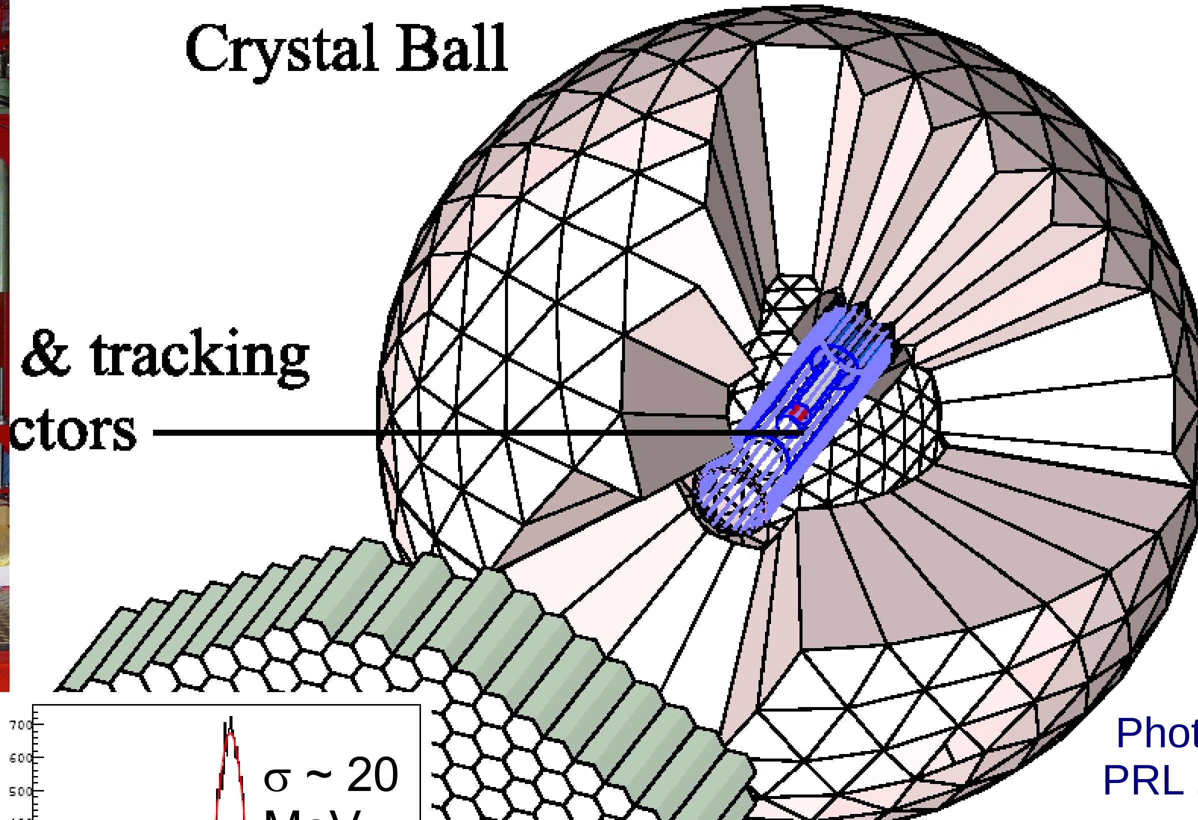


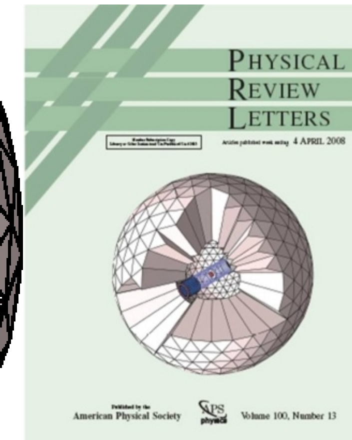




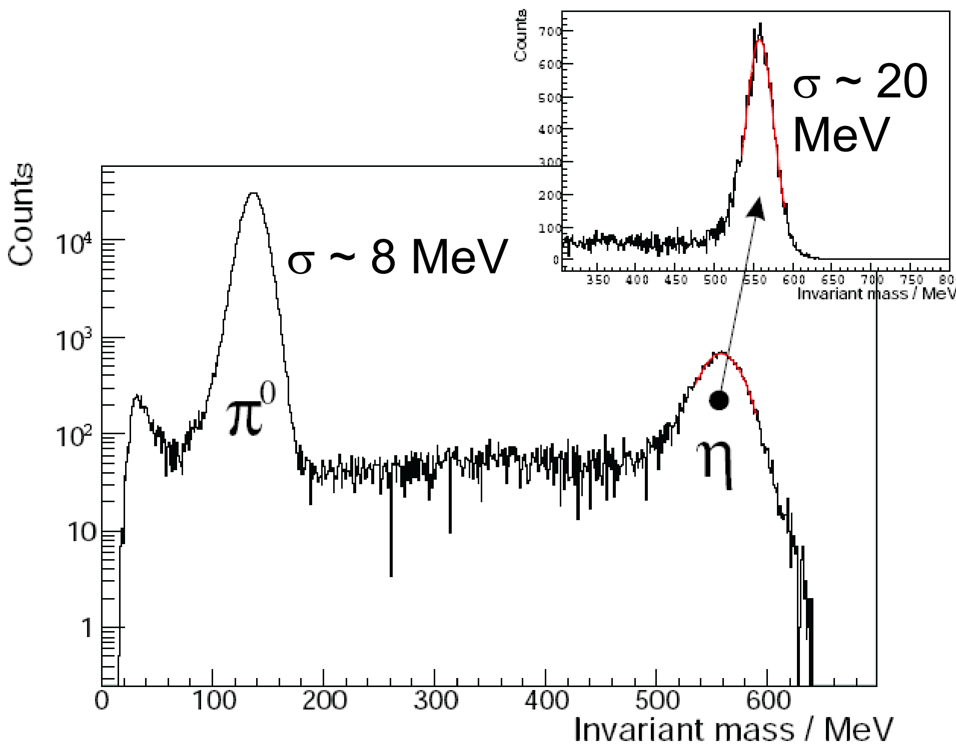
CB@MAMI Detector System

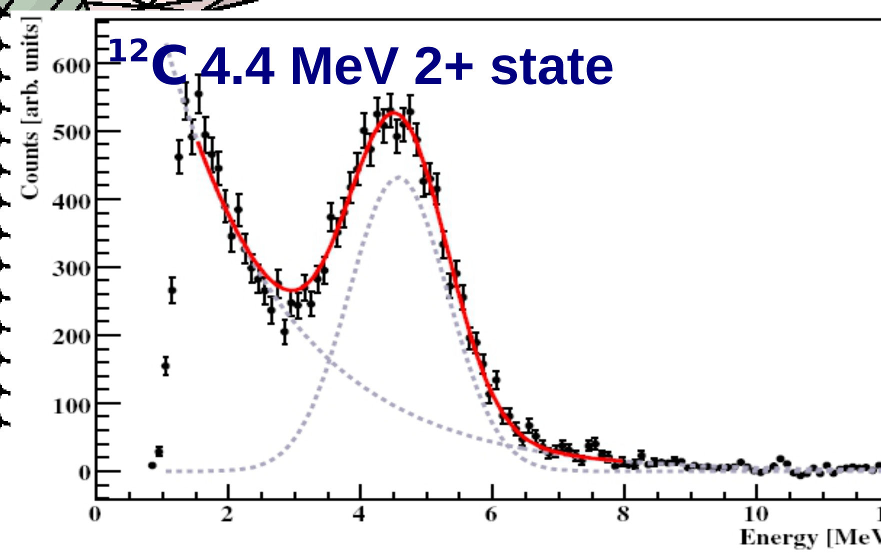




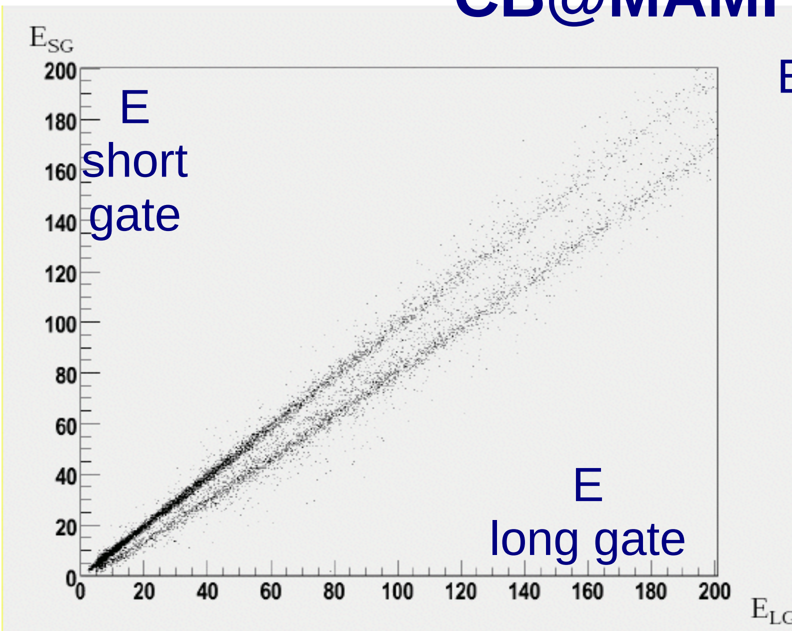


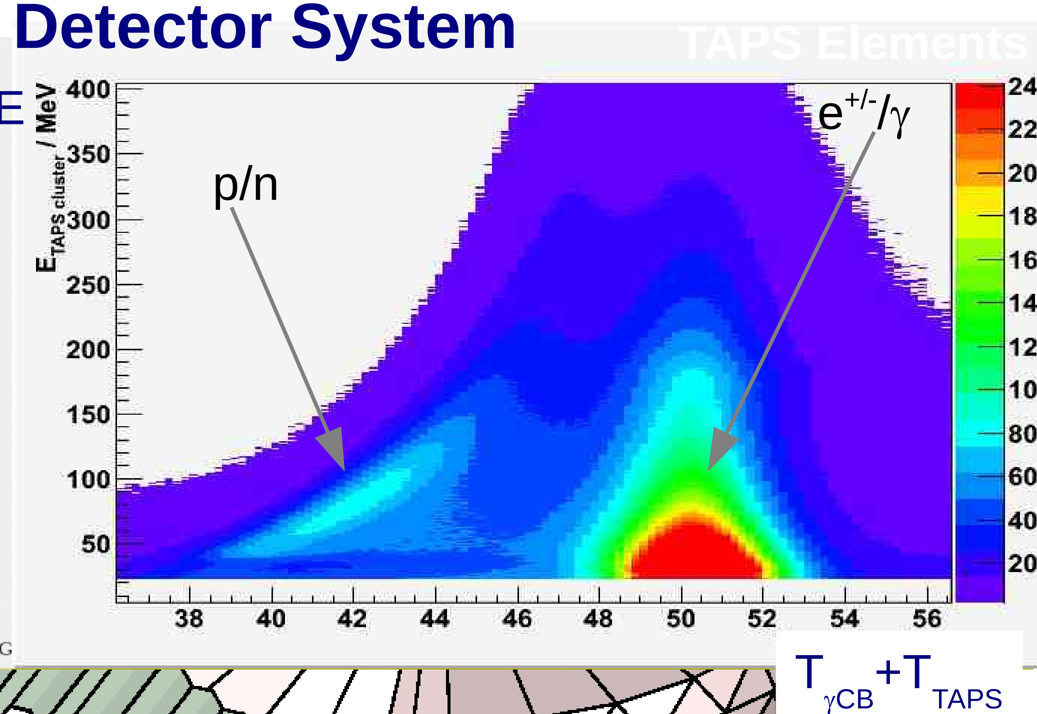
Incoherent pion
Photoproduction on ^{12}C
PRL **100** 132301 (2008)

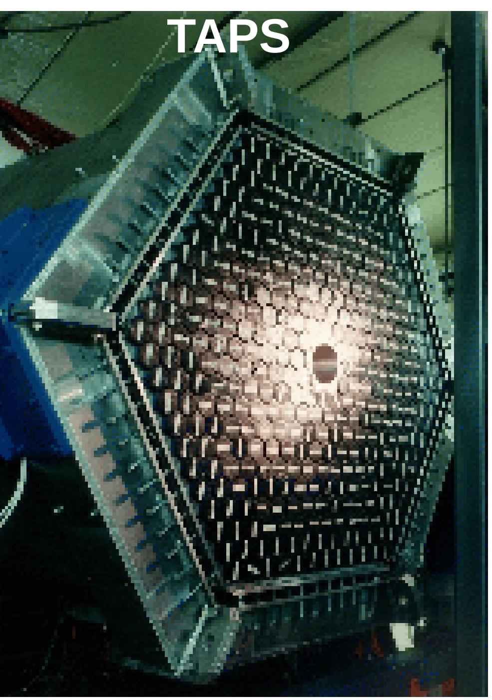


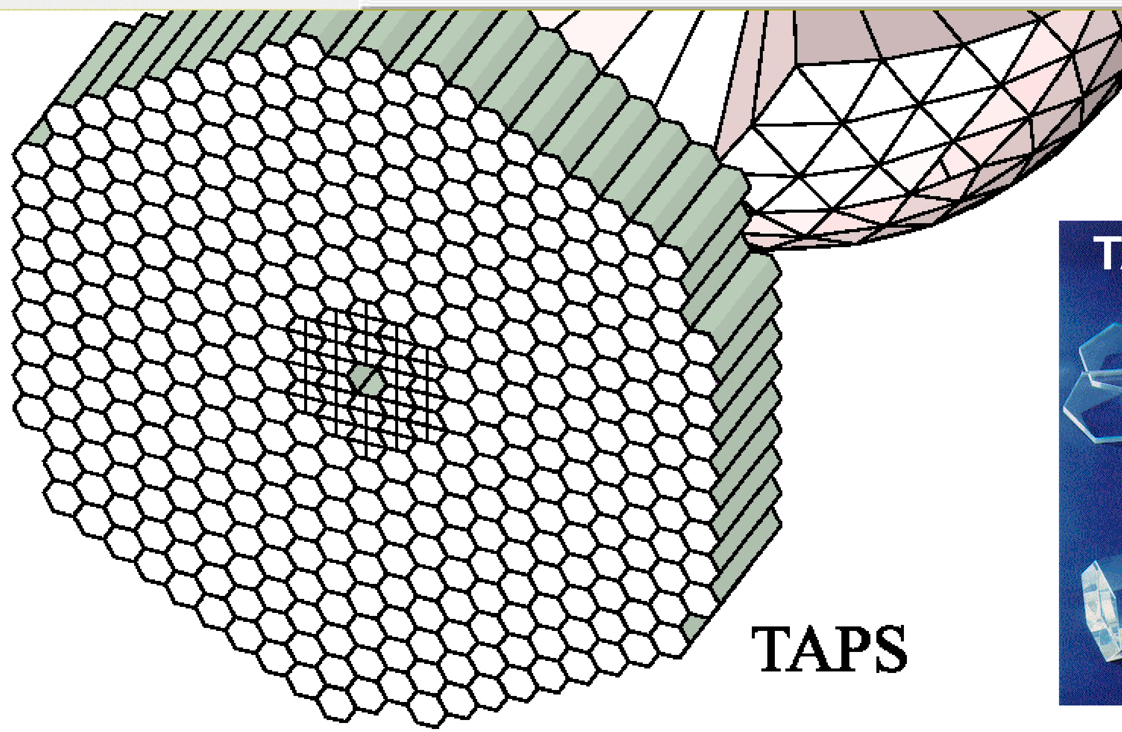


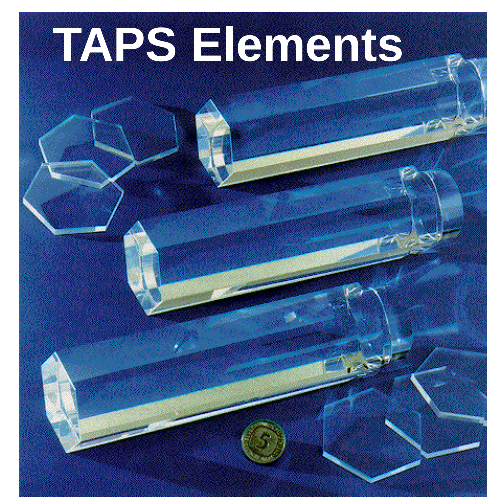
CB@MAMI Detector System



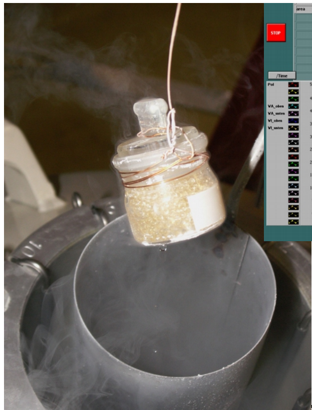


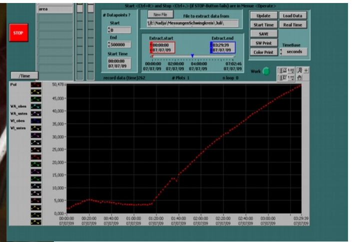


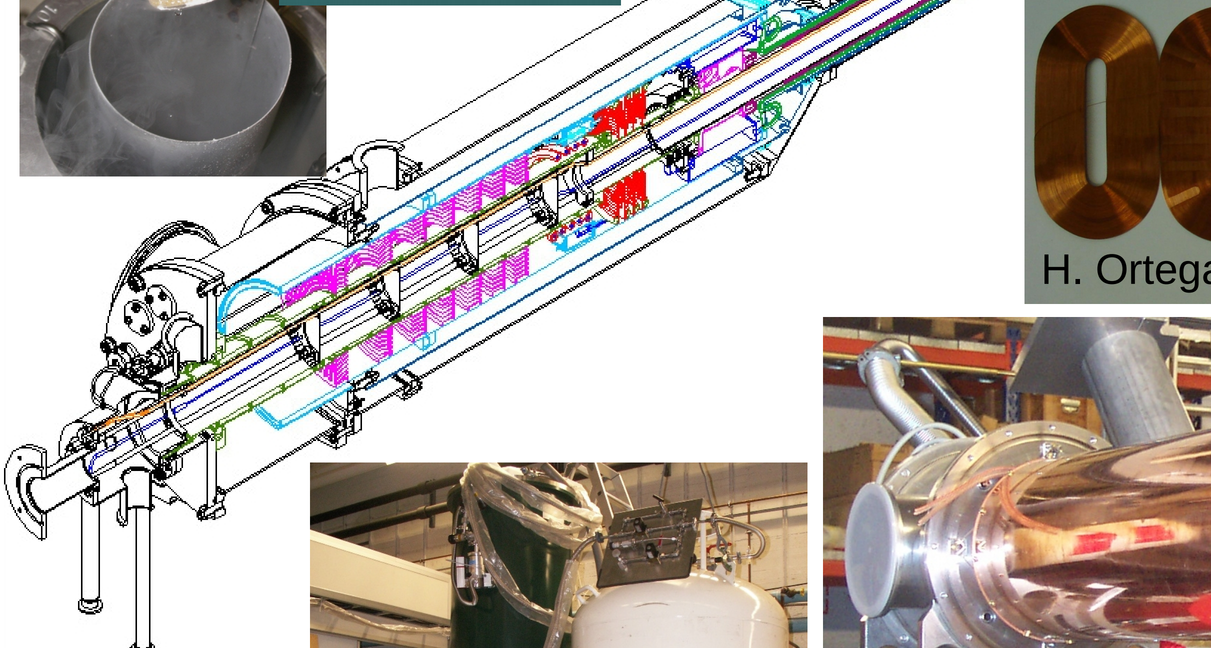


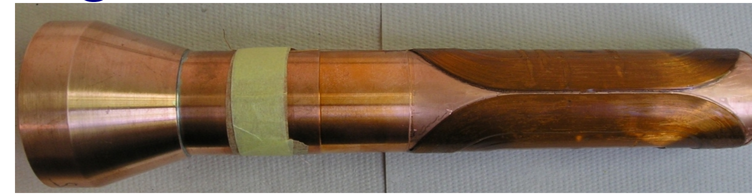


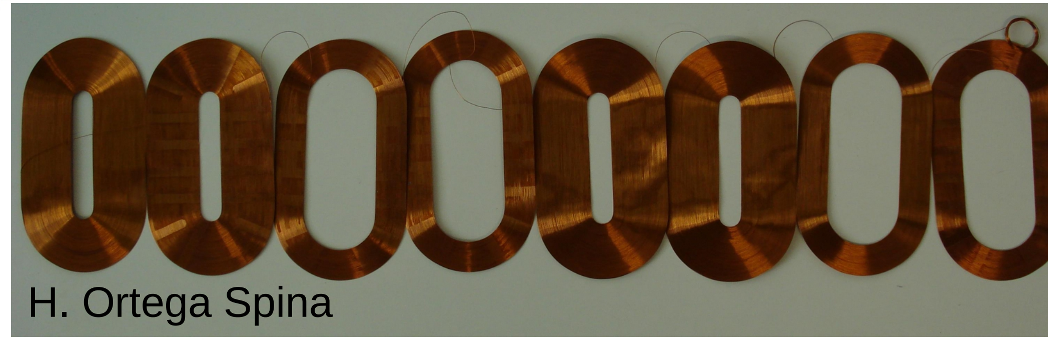
Polarized Frozen Spin Target

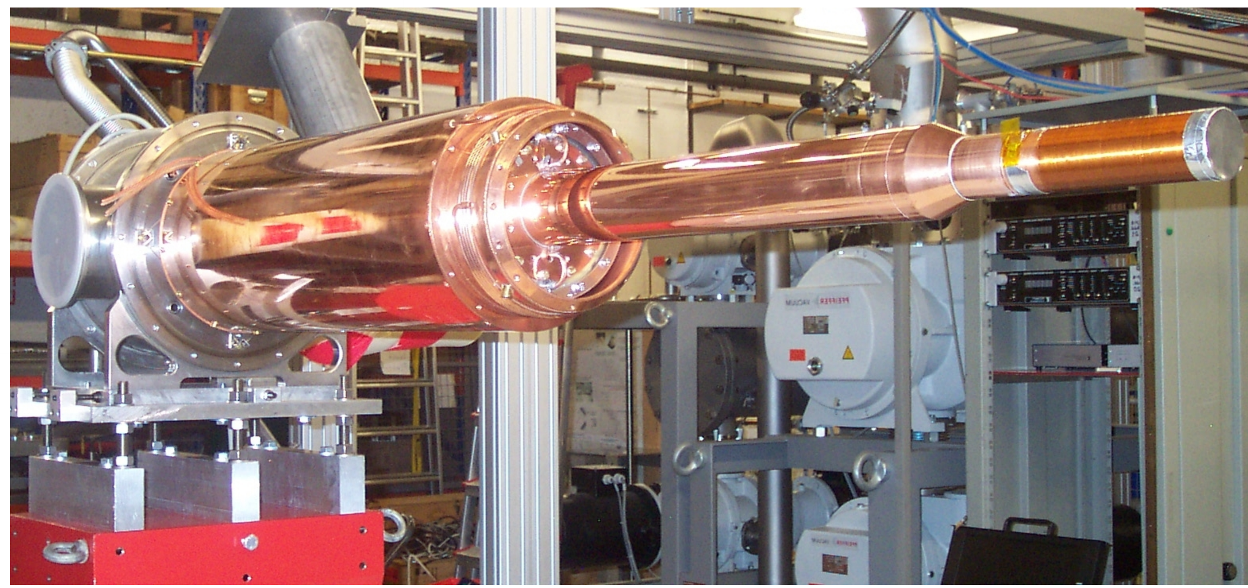










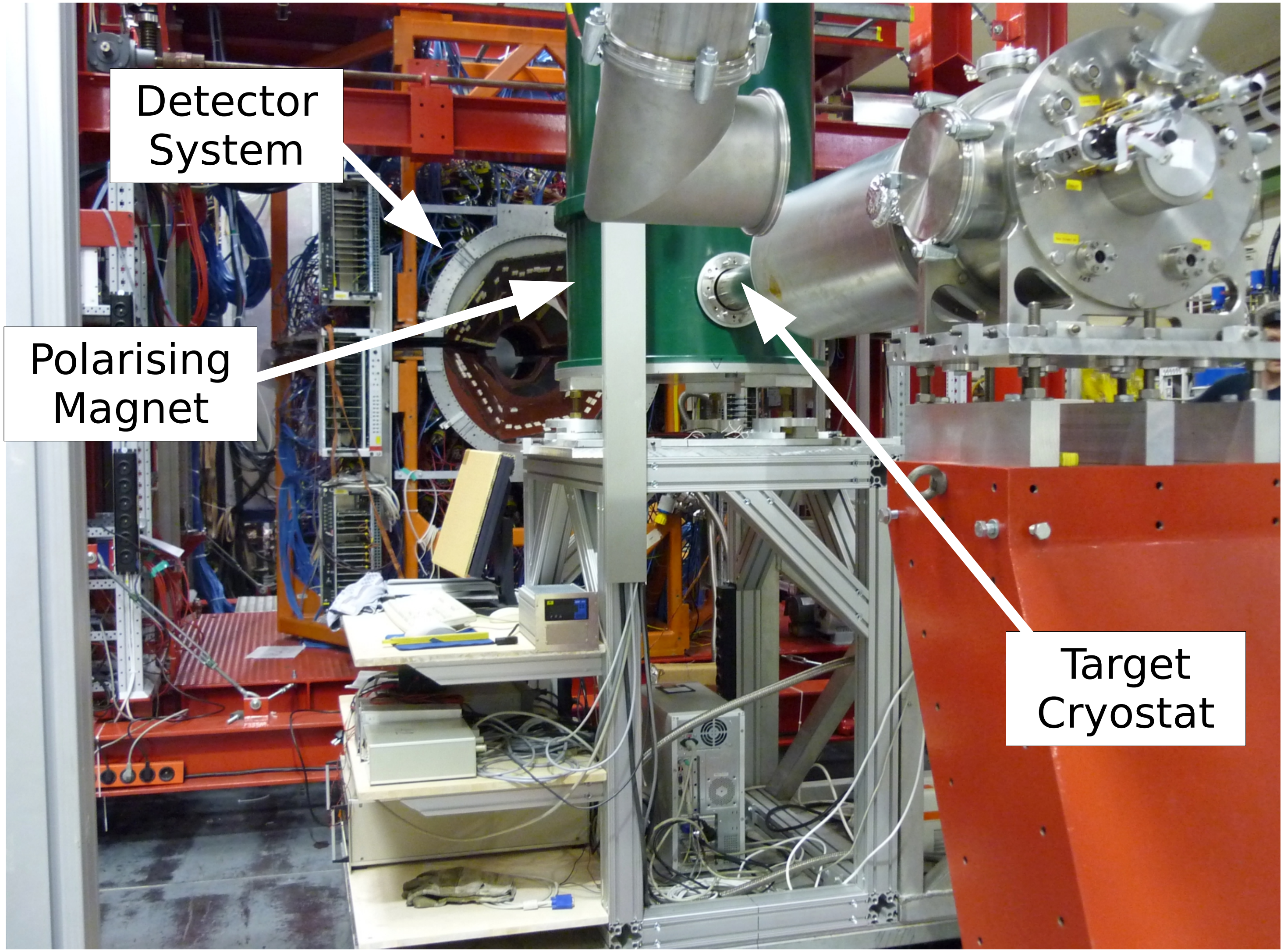


- Uses DNP to achieve ~ 90 % proton, 80 % deuteron
- Needs: Horiz. dilution cryostat, polarizing magnet, microwave, NMR
- Two holding coils: solenoid → longitudinal, saddle coil → transverse

Polarized Frozen Spin Target

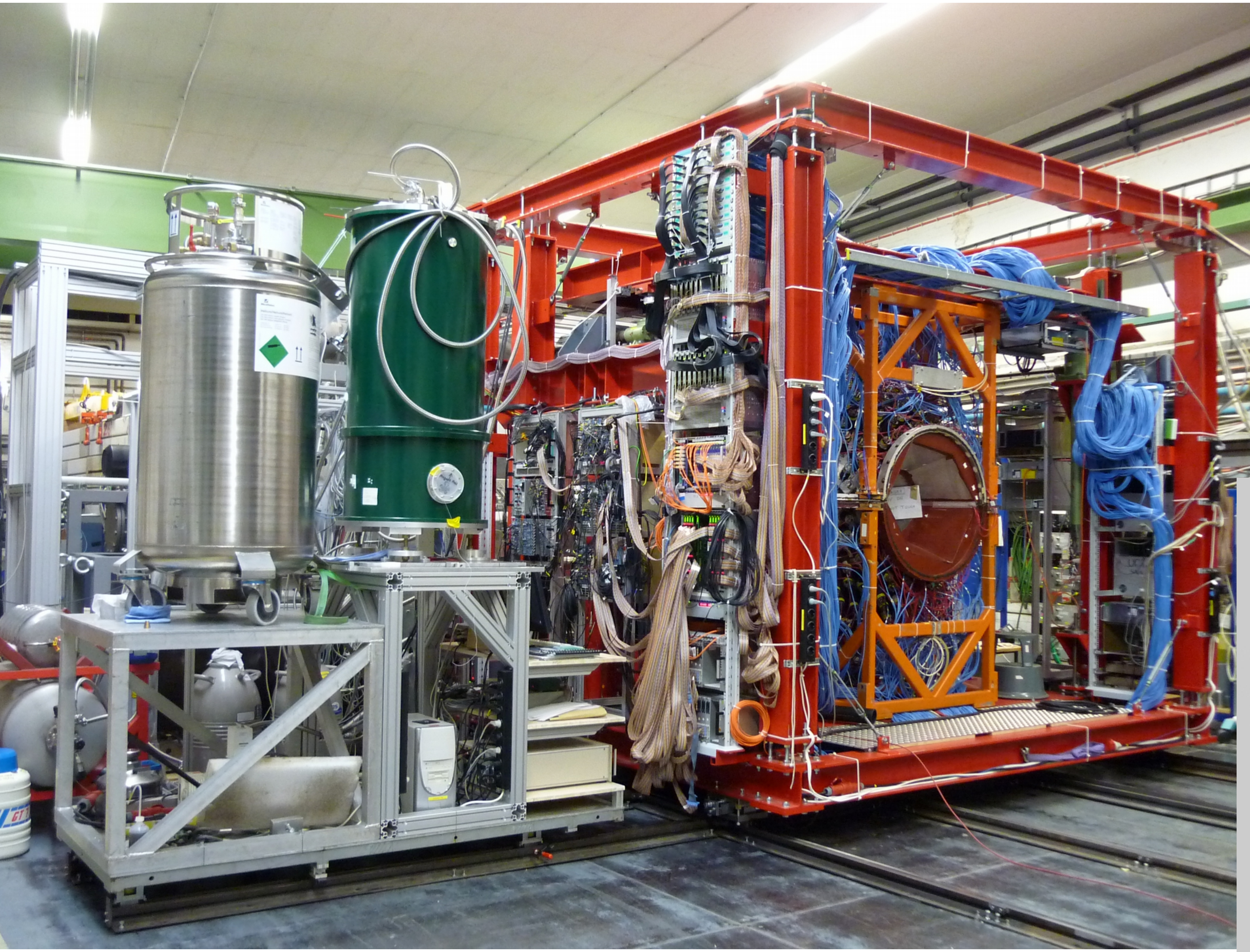
- Uses DNP to achieve ~ 90 % proton, 80 % deuteron
- Needs: Horiz. dilution cryostat, polarizing magnet, microwave, NMR
- Two holding coils: solenoid → longitudinal, saddle coil → transverse

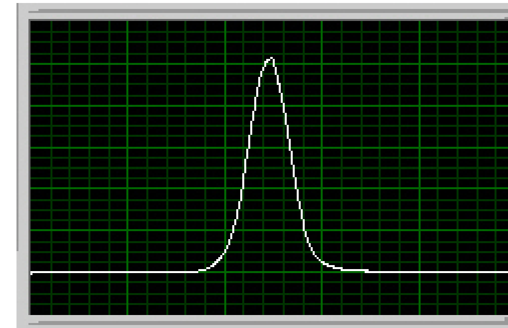
Polarized Frozen Spin Target



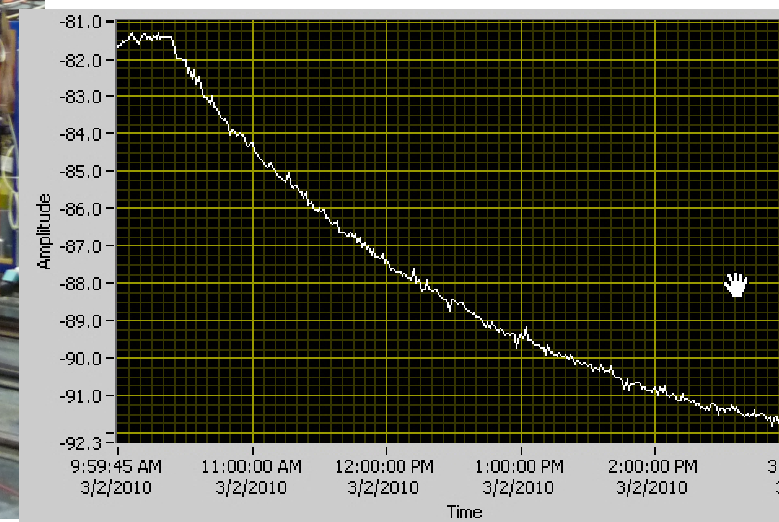
- Uses DNP to achieve ~ 90 % proton, 80 % deuteron
- Needs: Horiz. Dilution cryostat, polarizing magnet, microwave, NMR
- Two holding coils: solenoid → longitudinal, saddle coil → transverse
- Polarization "waltz" – polarize, measure pol., take data, measure pol., repol.

Polarised Frozen Spin Target



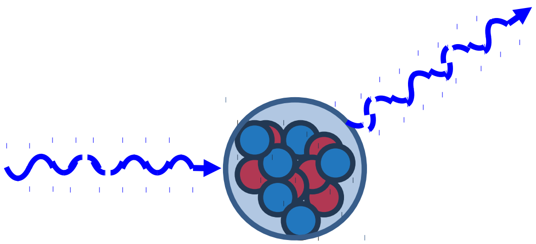


$$P=P_0\exp(t/\tau)$$

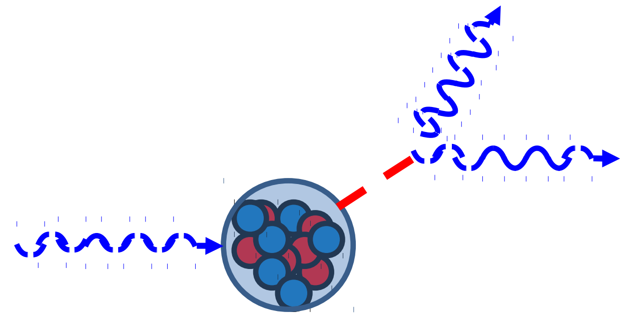


- Frozen spin target in operation since Dec. '09 – **average pol. ~75%**
- **Relaxation time ~1500 hours** & low He usage → long measurement time!
- Ran with **transverse** polarized proton & deuteron target >4500 hours cold
- Running with longitudinal (solenoid) field now

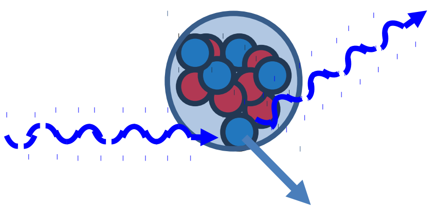
Background Reactions



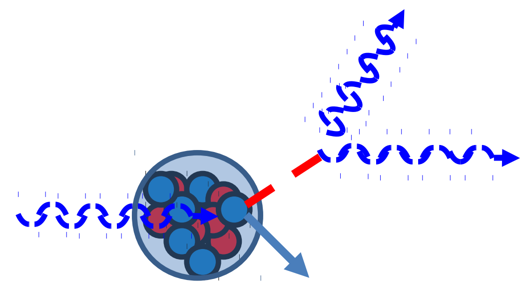
Coherent Compton
on ^{12}C / $^{3/4}He$ / ^{16}O



Coherent π^0 on ^{12}C

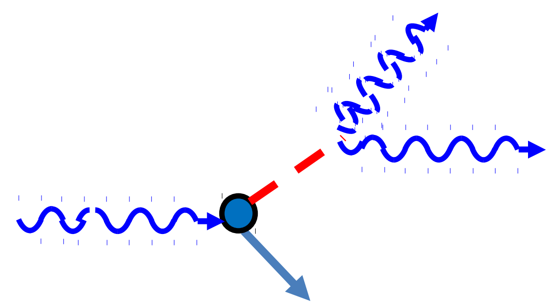


Incoherent Compton on ^{12}C



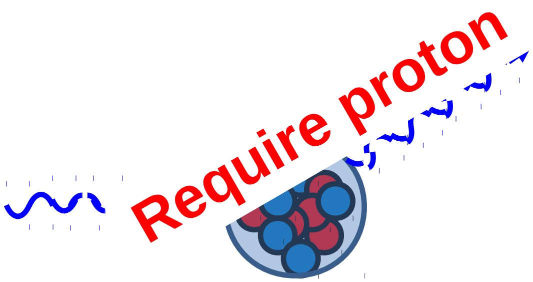
Incoherent π^0 on ^{12}C

Cross sections are orders of magnitude larger than Compton.



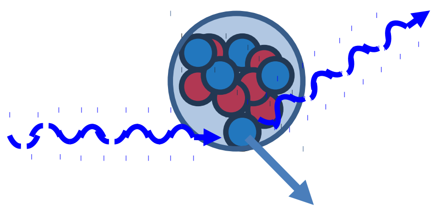
π^0 on proton

Background Reactions

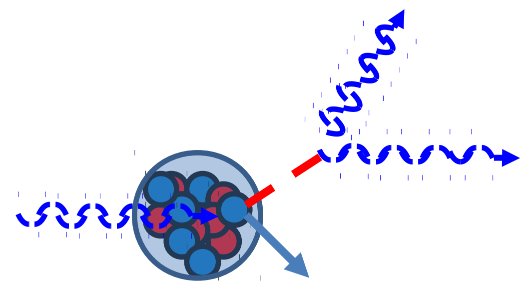


Coherent Compton
on ^{12}C / $^{3/4}He$ / ^{16}O

Coherent π^0 on ^{12}C



Incoherent Compton on ^{12}C



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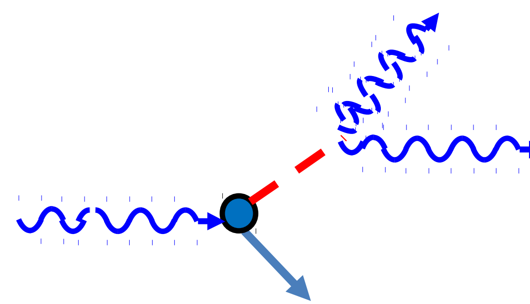
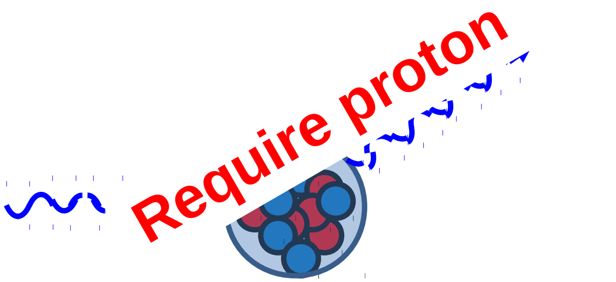


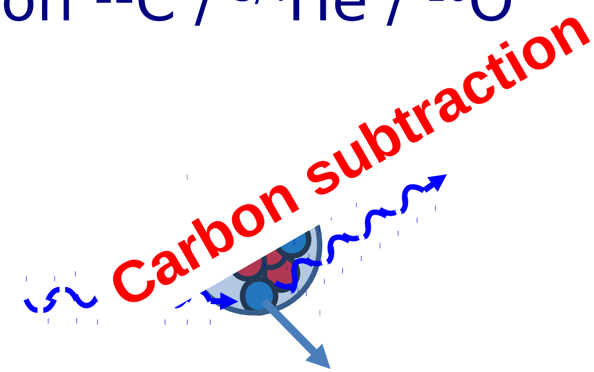
π^0 on proton

Background Reactions

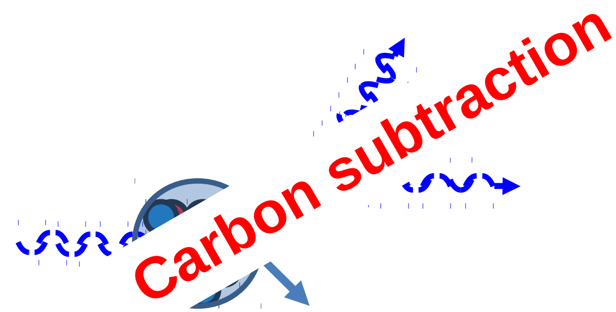


Coherent Compton
on ^{12}C / $^{3/4}$He / ^{16}O

Coherent π^0 on ^{12}C

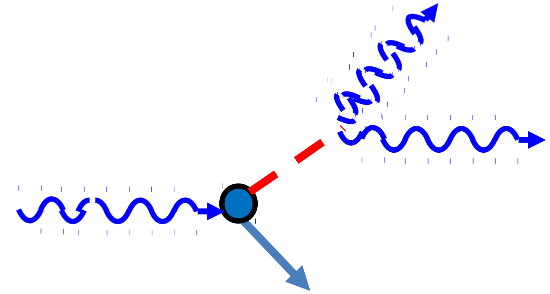


Incoherent Compton on ^{12}C



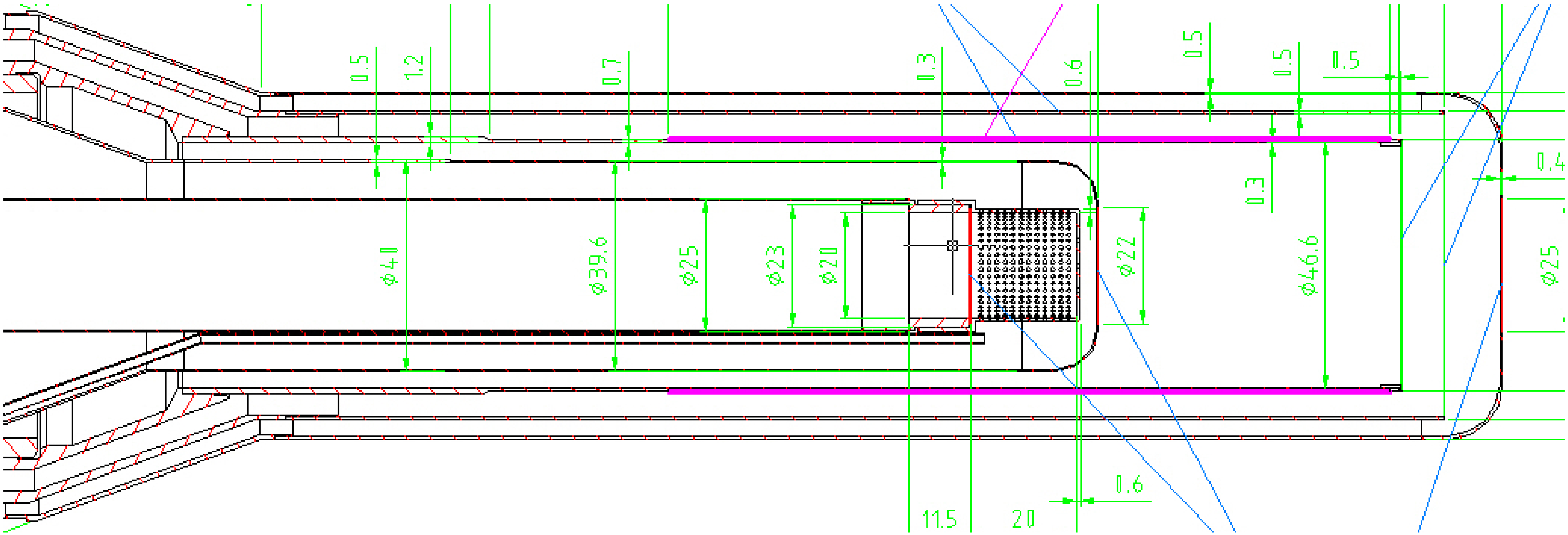
Incoherent π^0 on ^{12}C

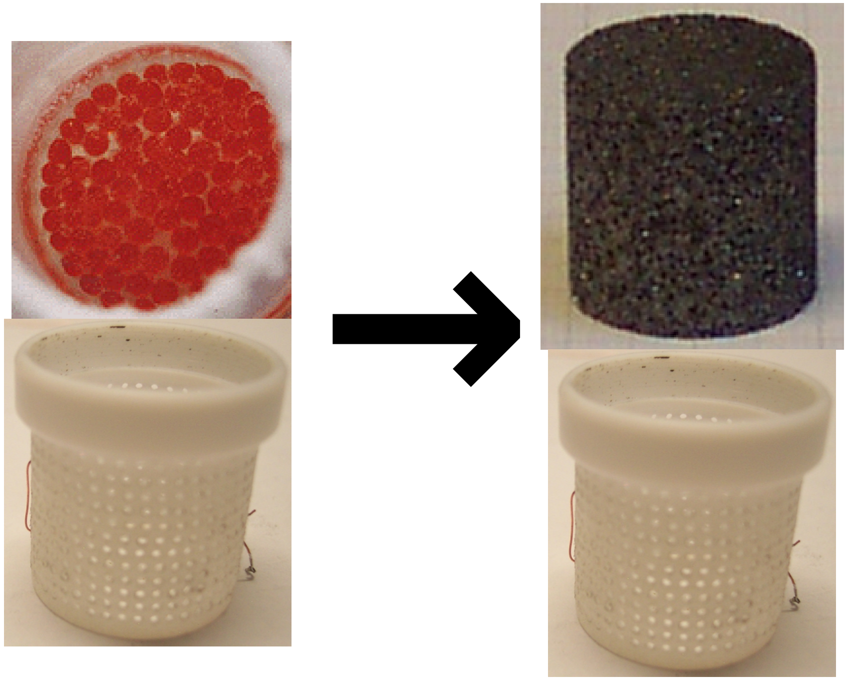
Cross sections are orders of magnitude larger than Compton.



π^0 on proton

Carbon Subtraction & Simulation





- Butanol beads → carbon foam
- $N_{nucleii} = 12N_C + 16N_O + 4N_{He4} + 3N_{He3}$
- Simultaneously subtracts empty target

Background Subtraction

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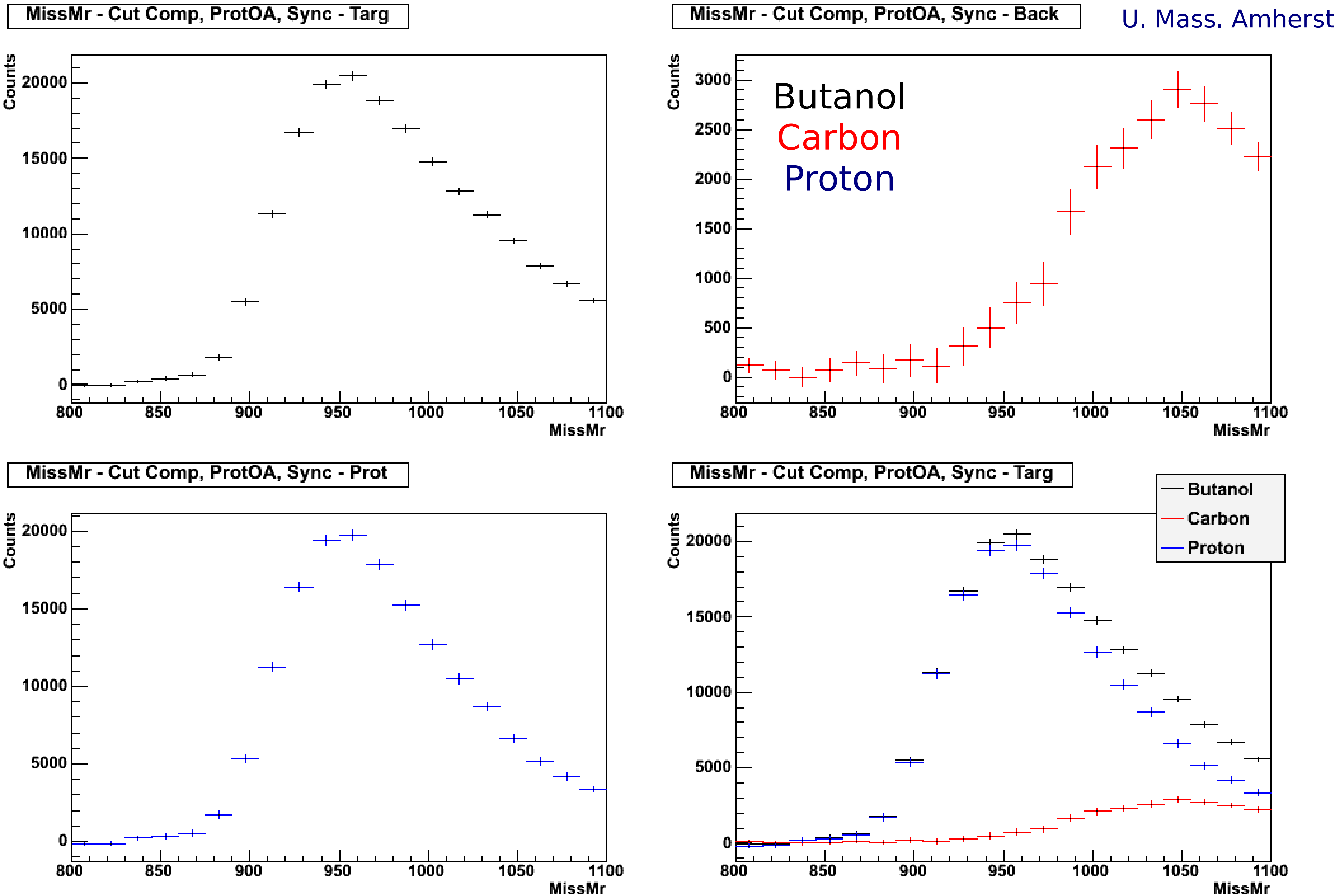
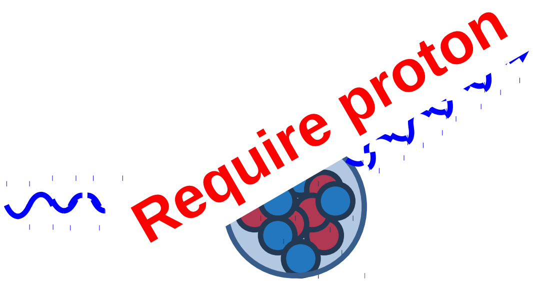
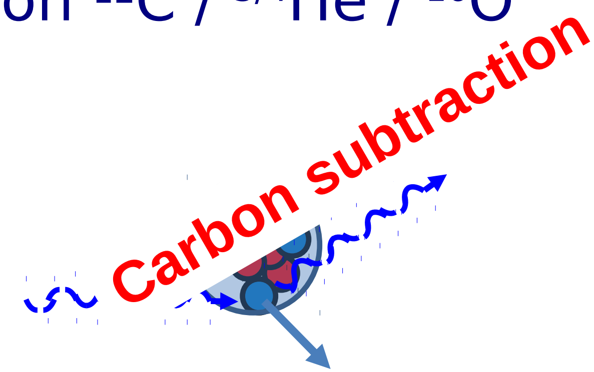


Background Reactions

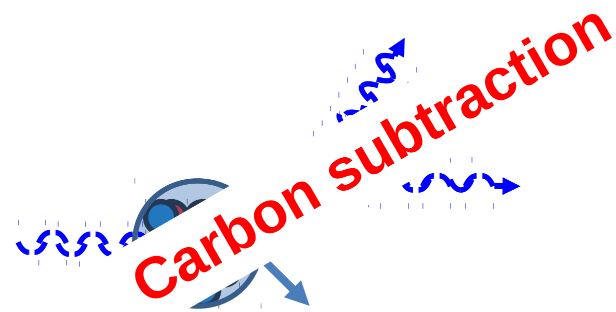


Coherent Compton
on ^{12}C / $^{3/4}He$ / ^{16}O

Coherent π^0 on ^{12}C

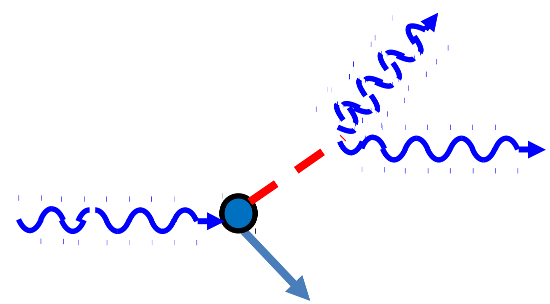


Incoherent Compton on ^{12}C



Incoherent π^0 on ^{12}C

Cross sections are orders of magnitude larger than Compton.



π^0 on proton

RCS Signal Separation & Background Processes

Sim. MM(γ') on Butanol – showing π^0 and Compton contributions

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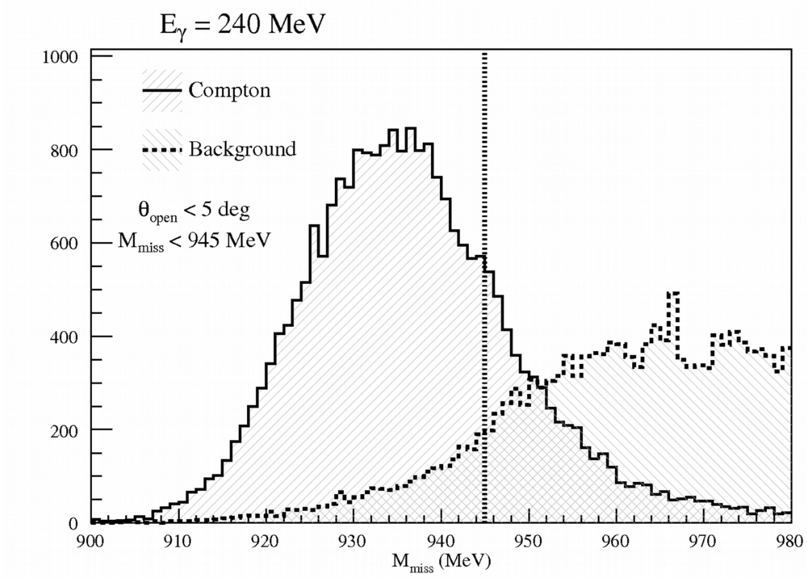
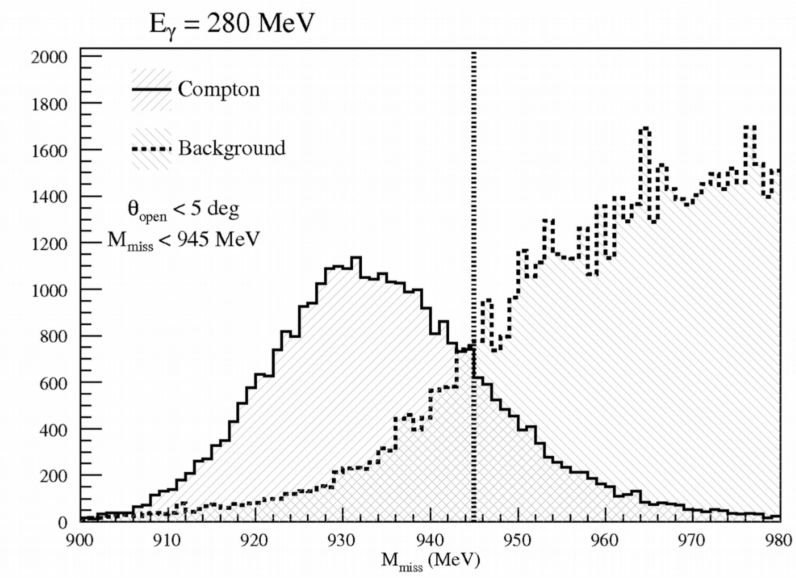
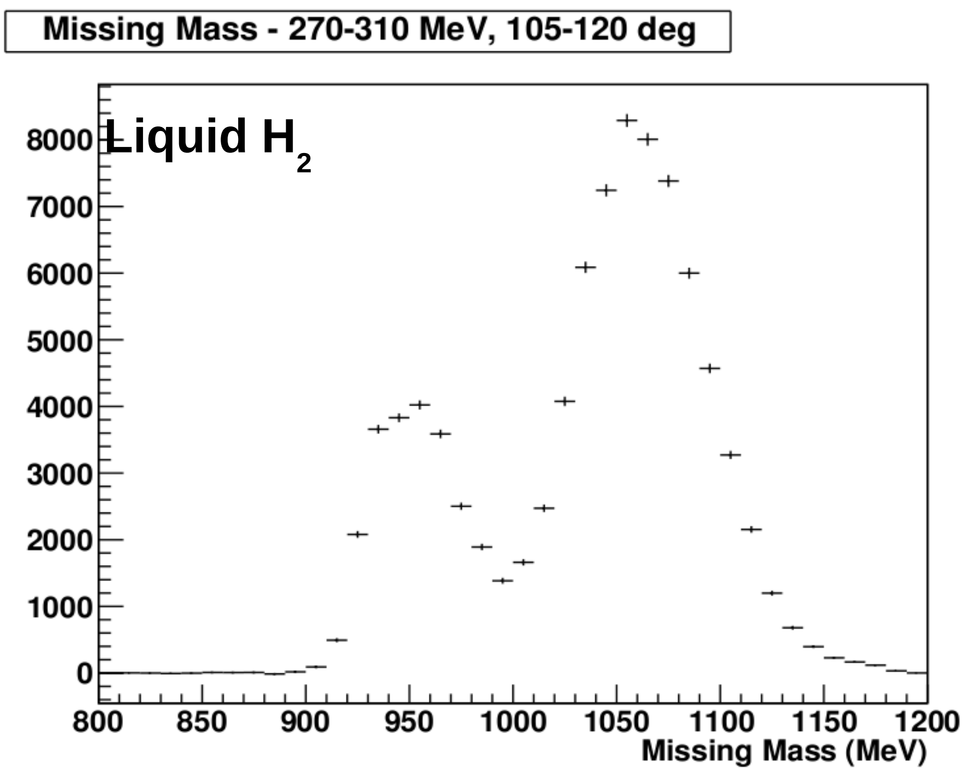
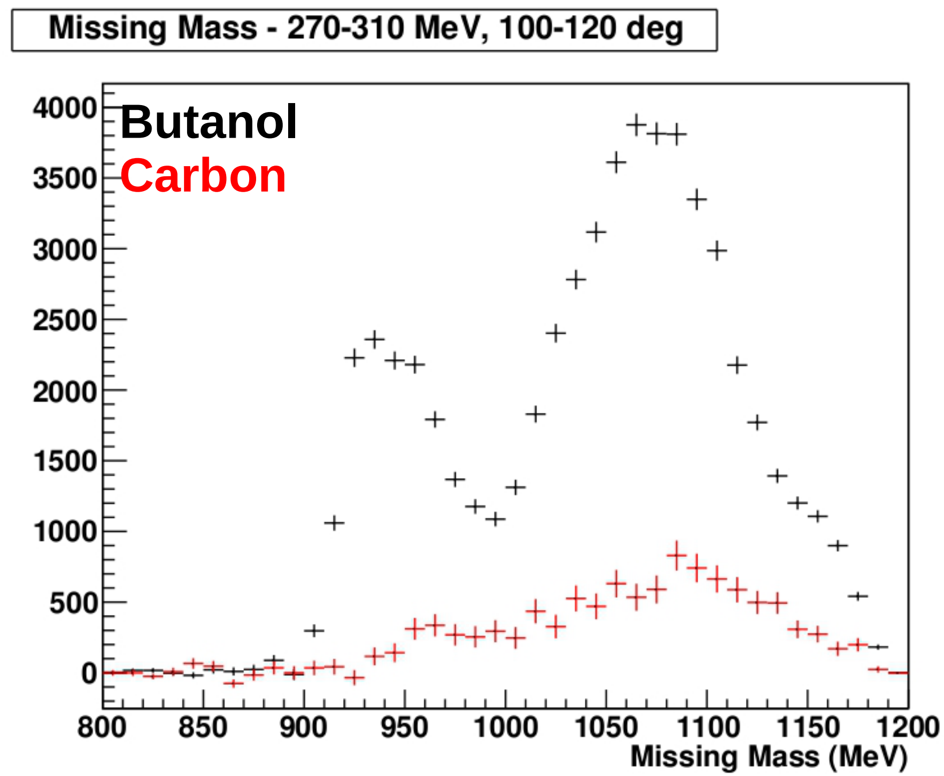
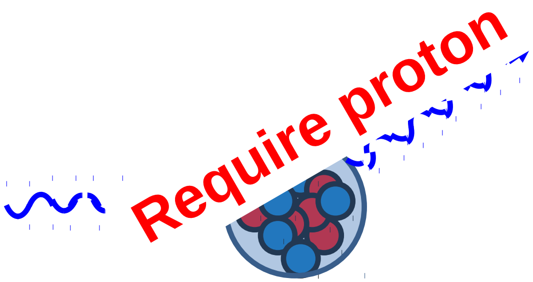






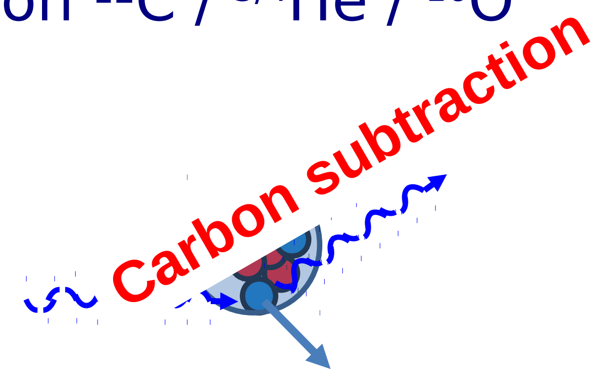


Background Reactions

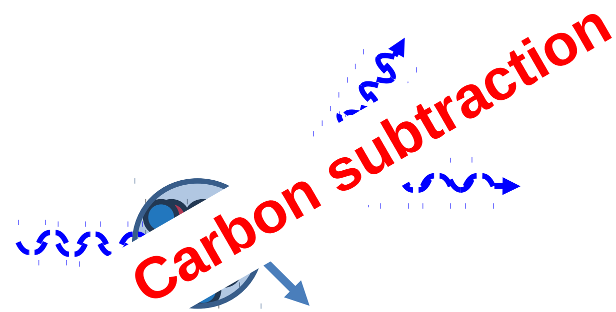


Coherent Compton
on ^{12}C / $^{3/4}He$ / ^{16}O

Coherent π^0 on ^{12}C

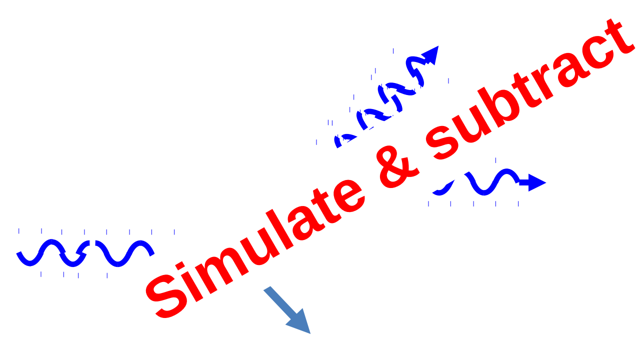


Incoherent Compton on ^{12}C



Incoherent π^0 on ^{12}C

Cross sections are orders of magnitude larger than Compton.



π^0 on proton

RCS Signal Separation & Background Processes

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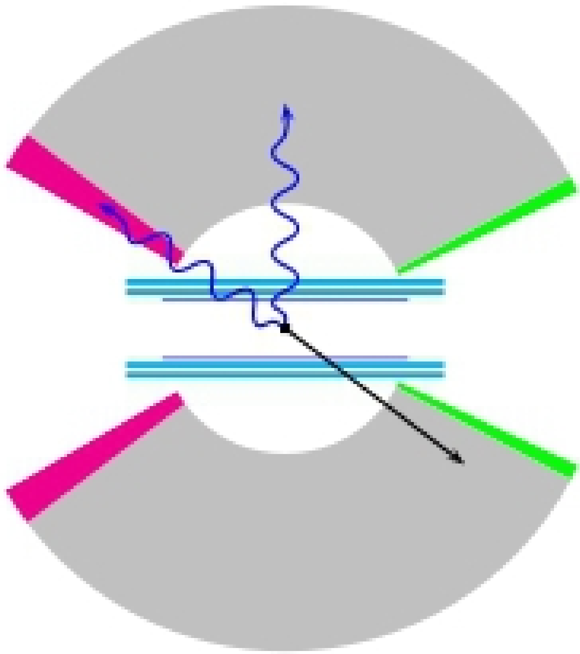

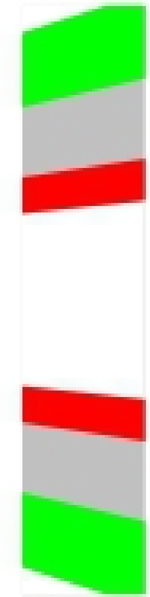

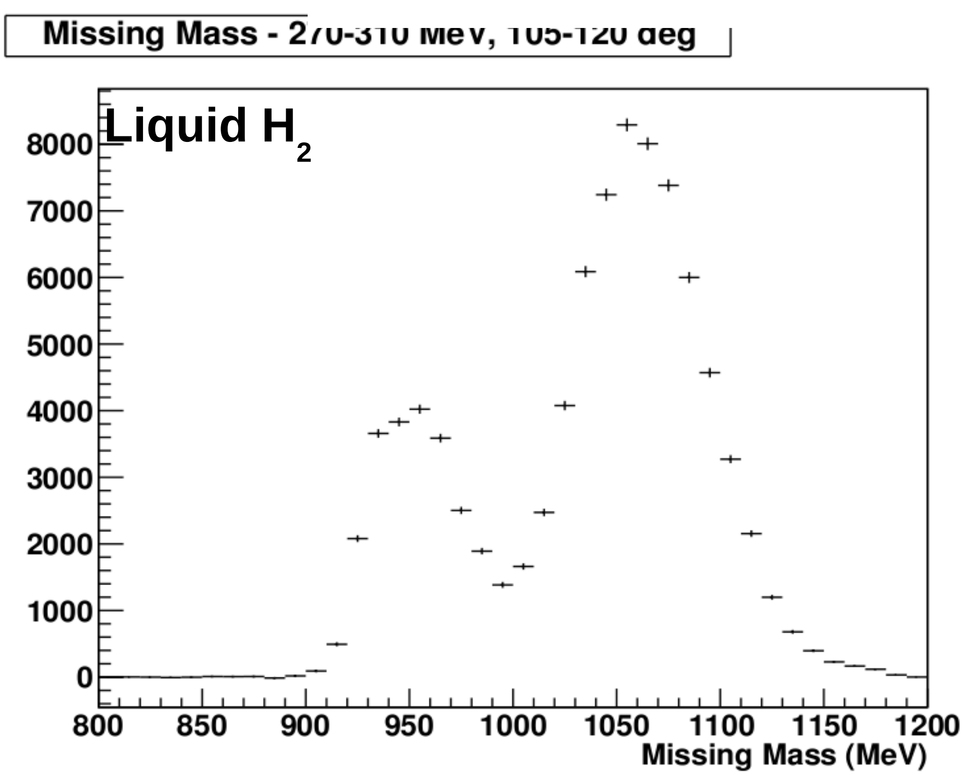

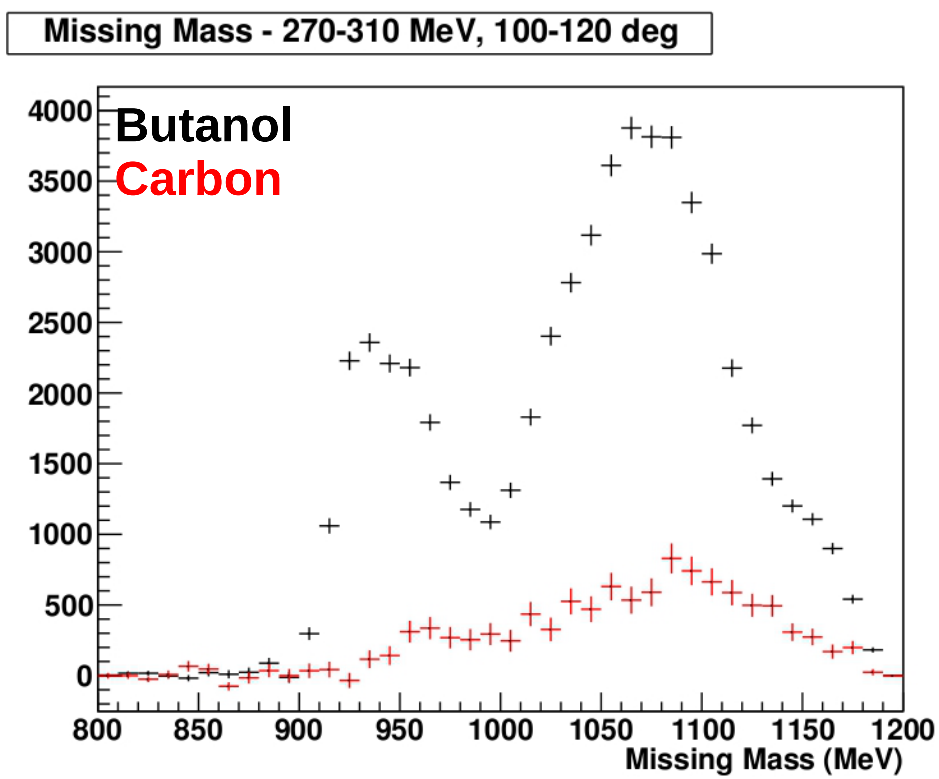

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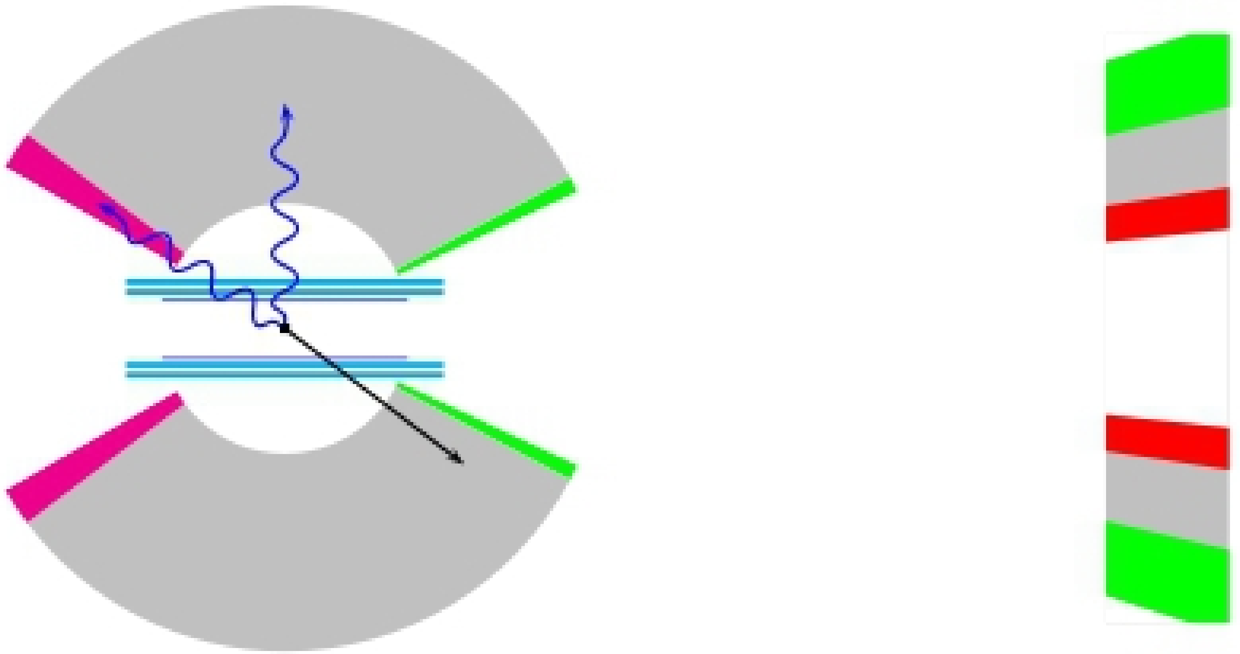
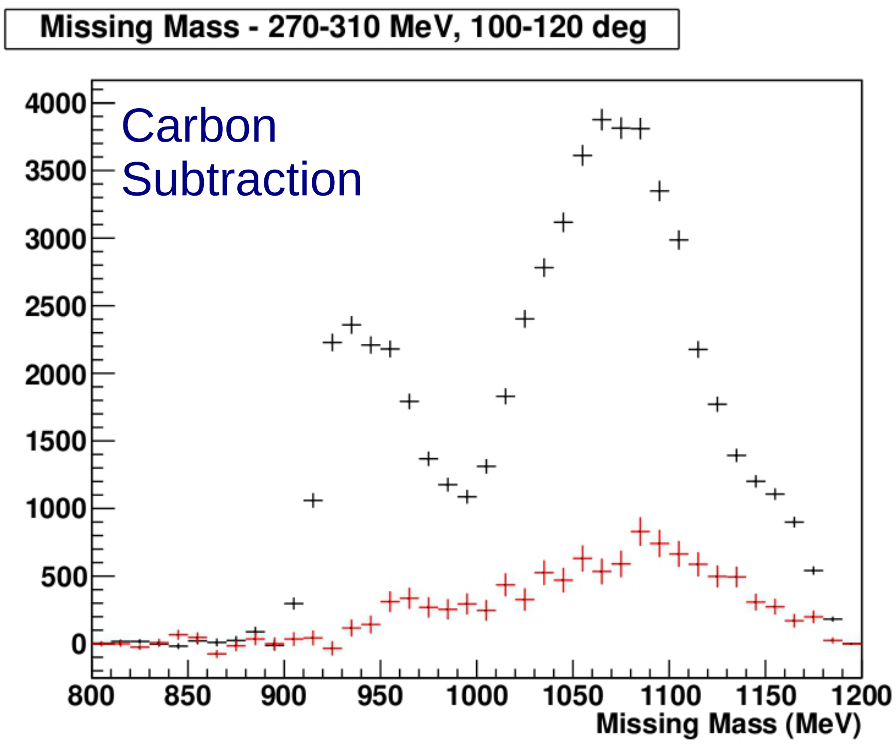
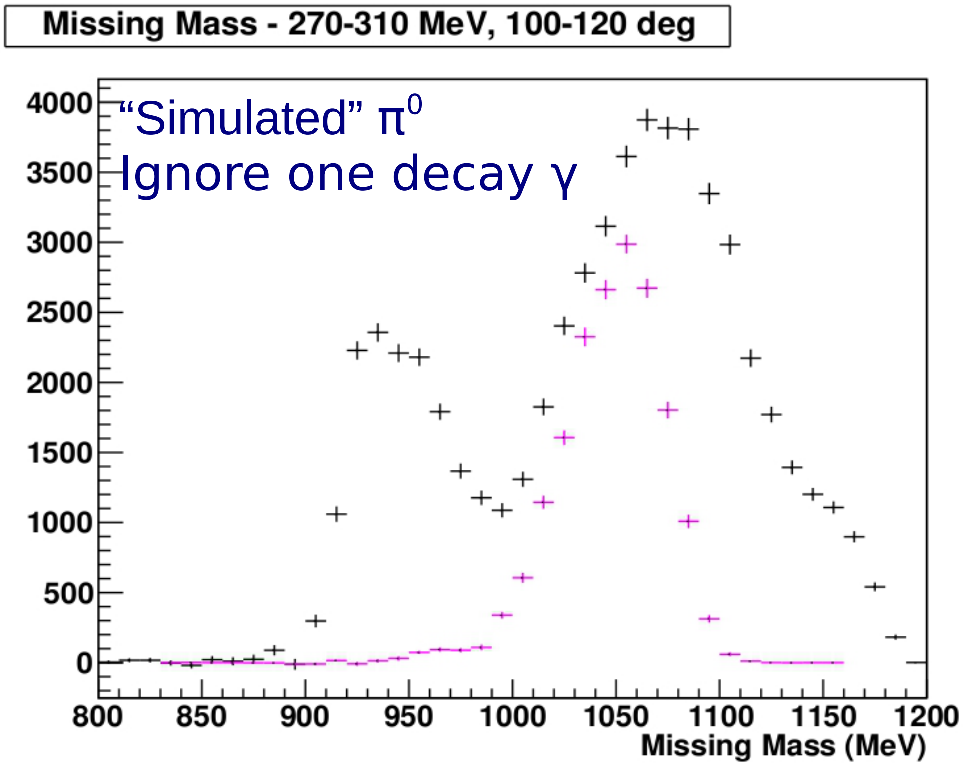
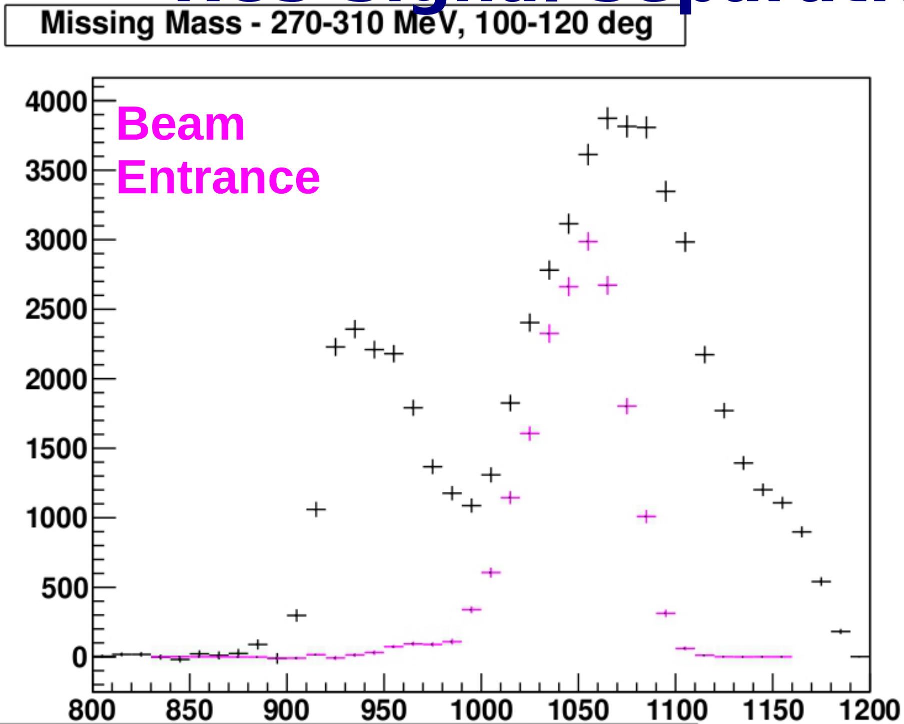
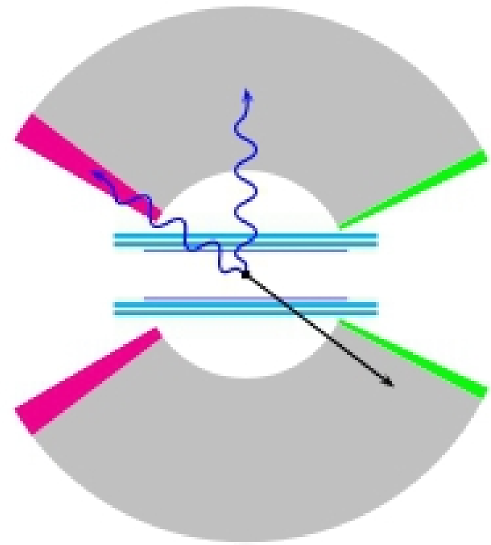


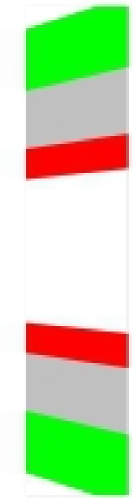




RCS Signal Separation & Background Processes







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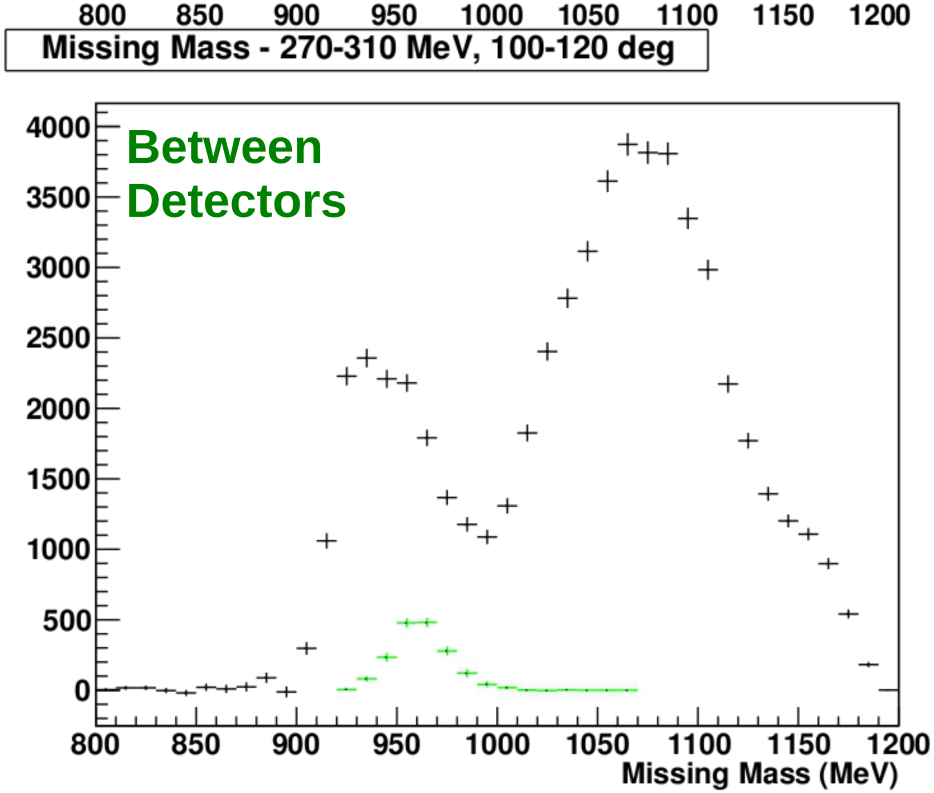

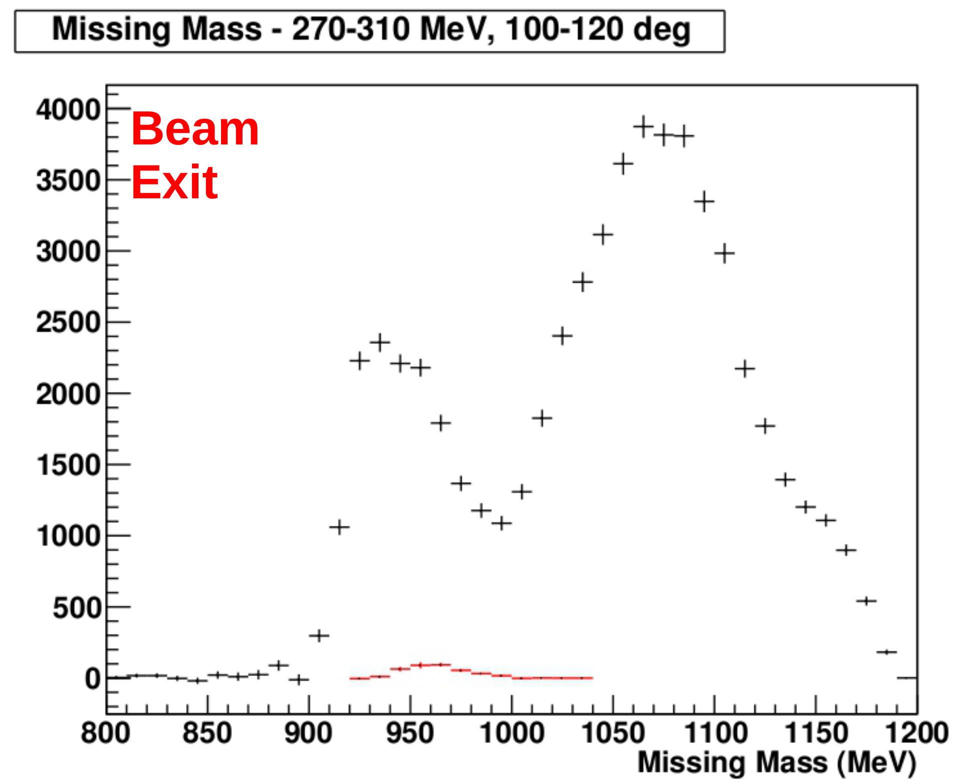

RCS Signal Separation & Background Processes

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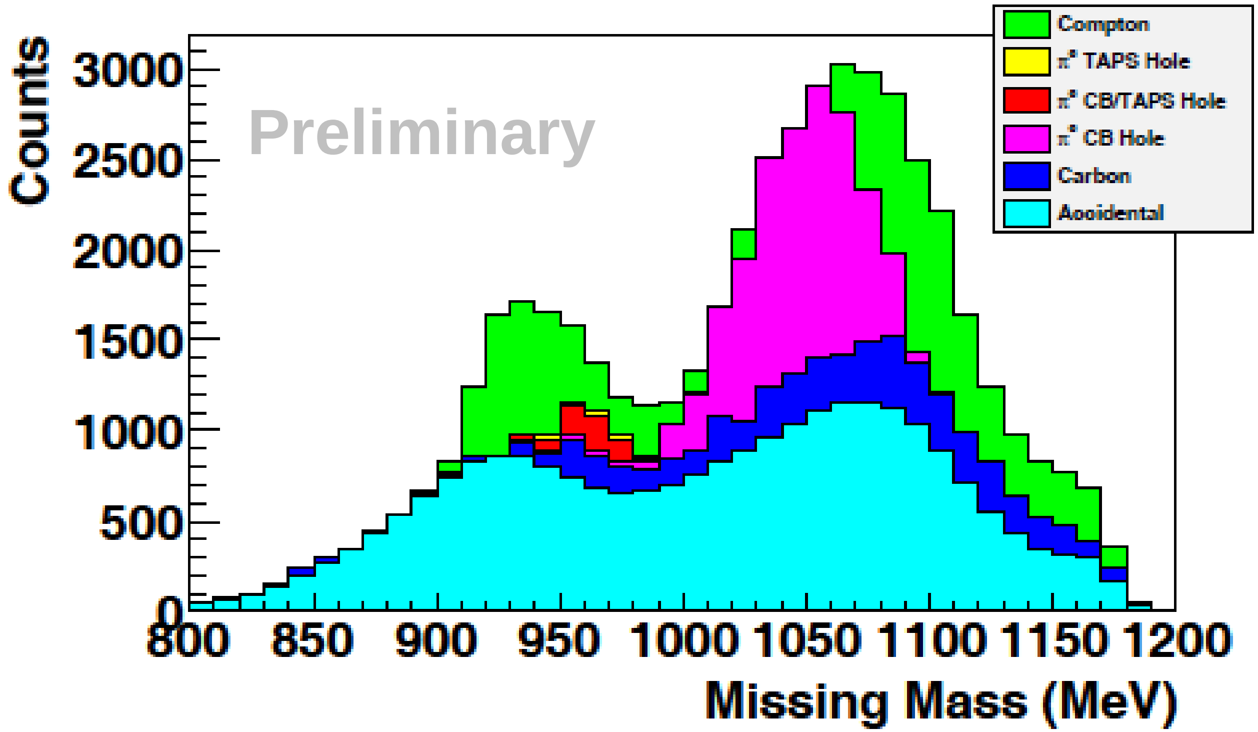

FIG. 1. Missing mass for 273-303 MeV, and 100-120 deg. Light blue is for tagger accidentals. Blue is for carbon/cryostat background. Magenta, red, and yellow are for a π^0 decay photon lost in the upstream CB hole, the region between CB and TAPS, and the downstream TAPS hole, respectively. Green shows the final Compton result.

RCS Signal Separation & Background Processes

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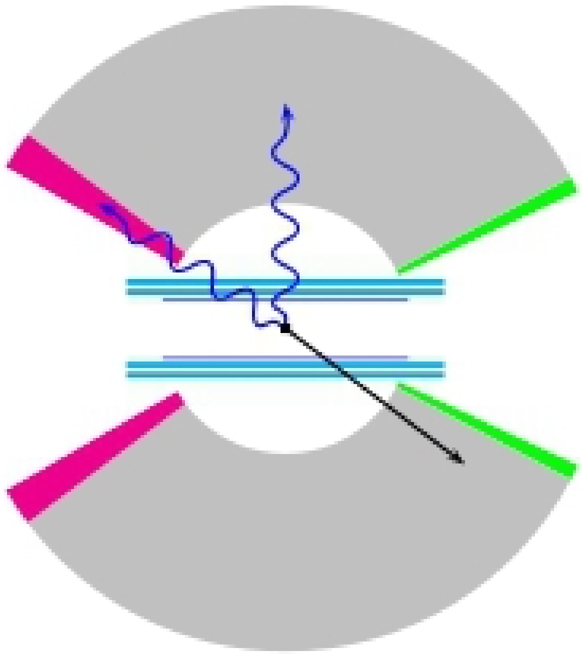

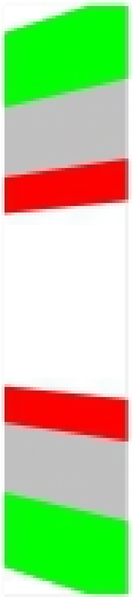

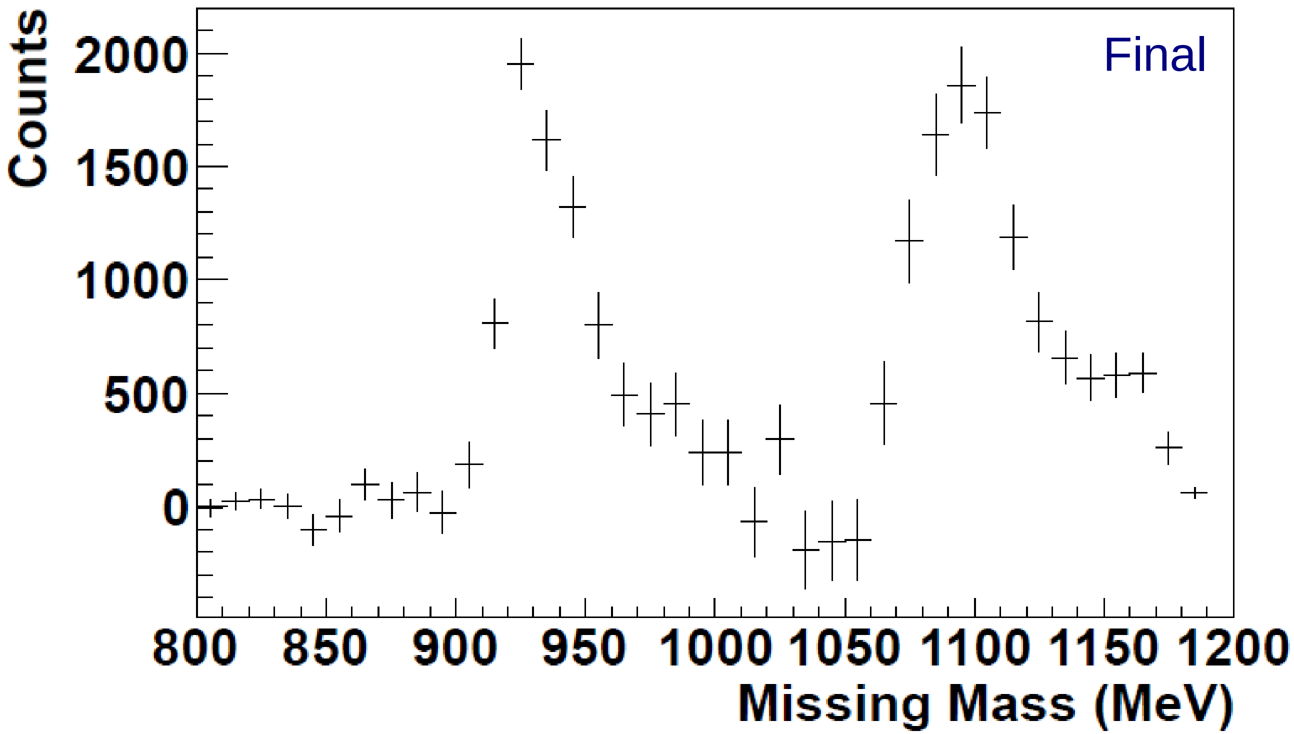

RCS Signal Separation & Background Processes

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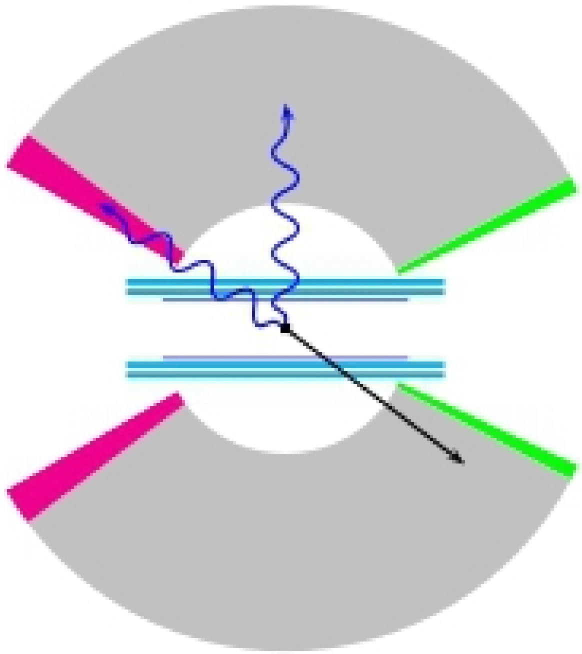

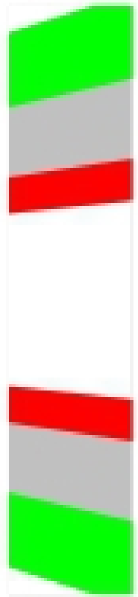

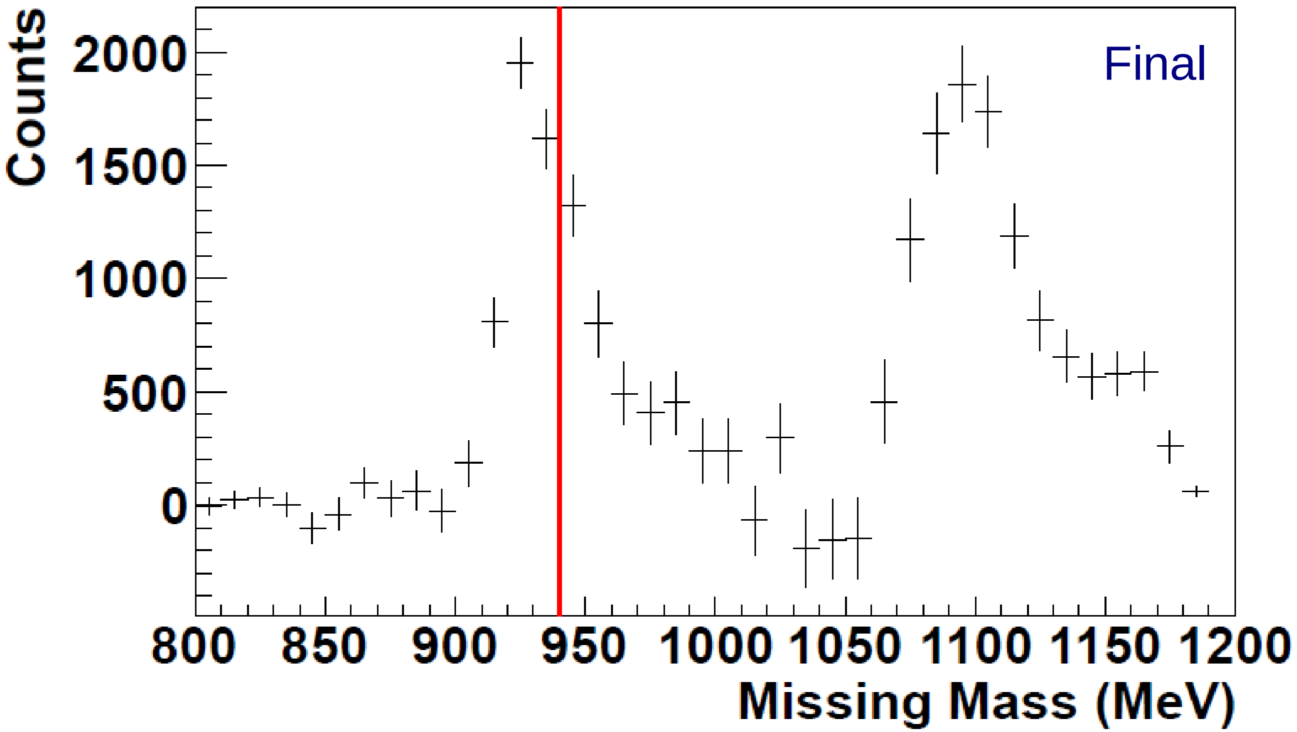

RCS Signal Separation & Background Processes

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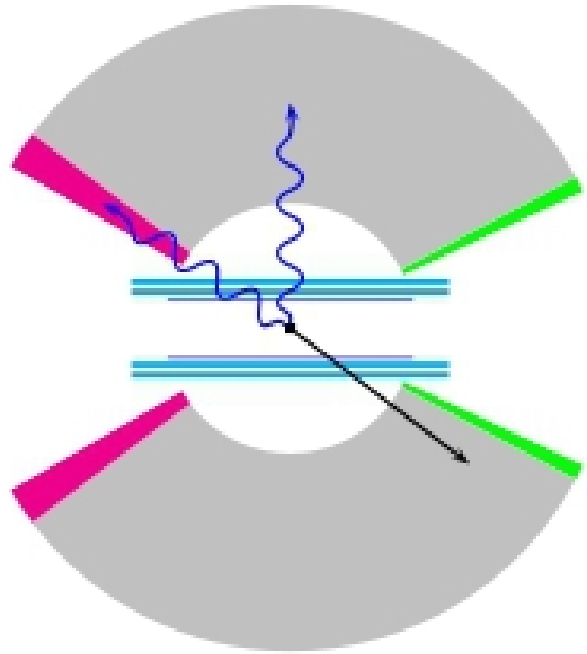
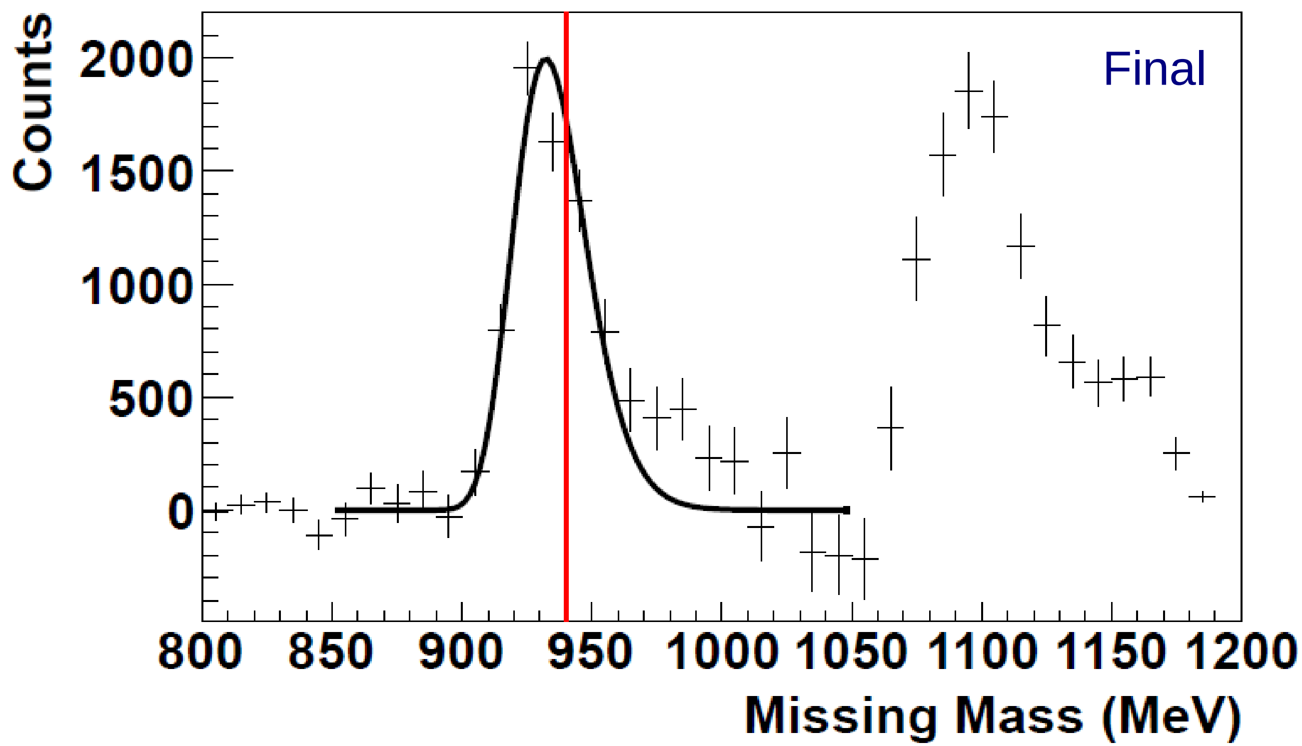
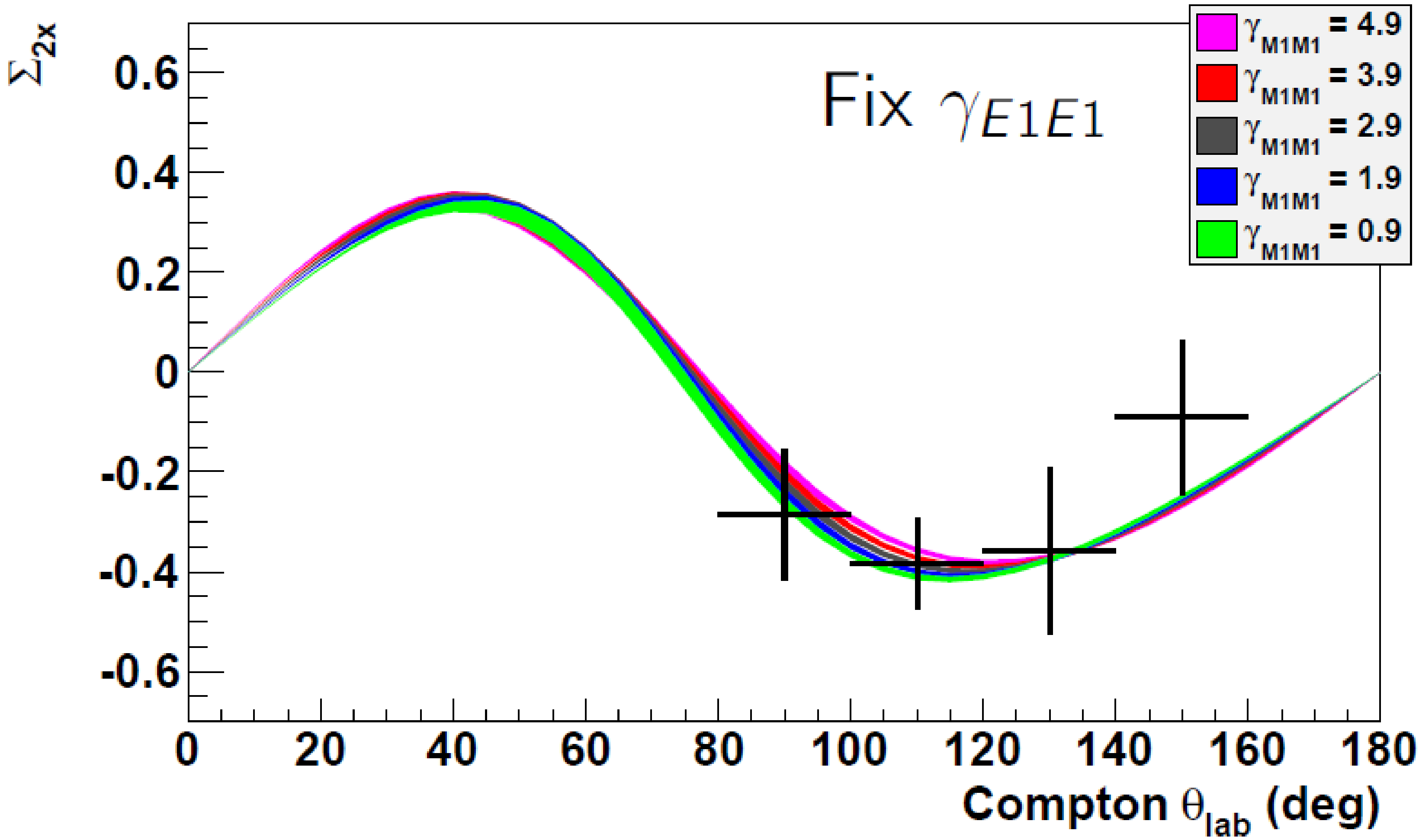


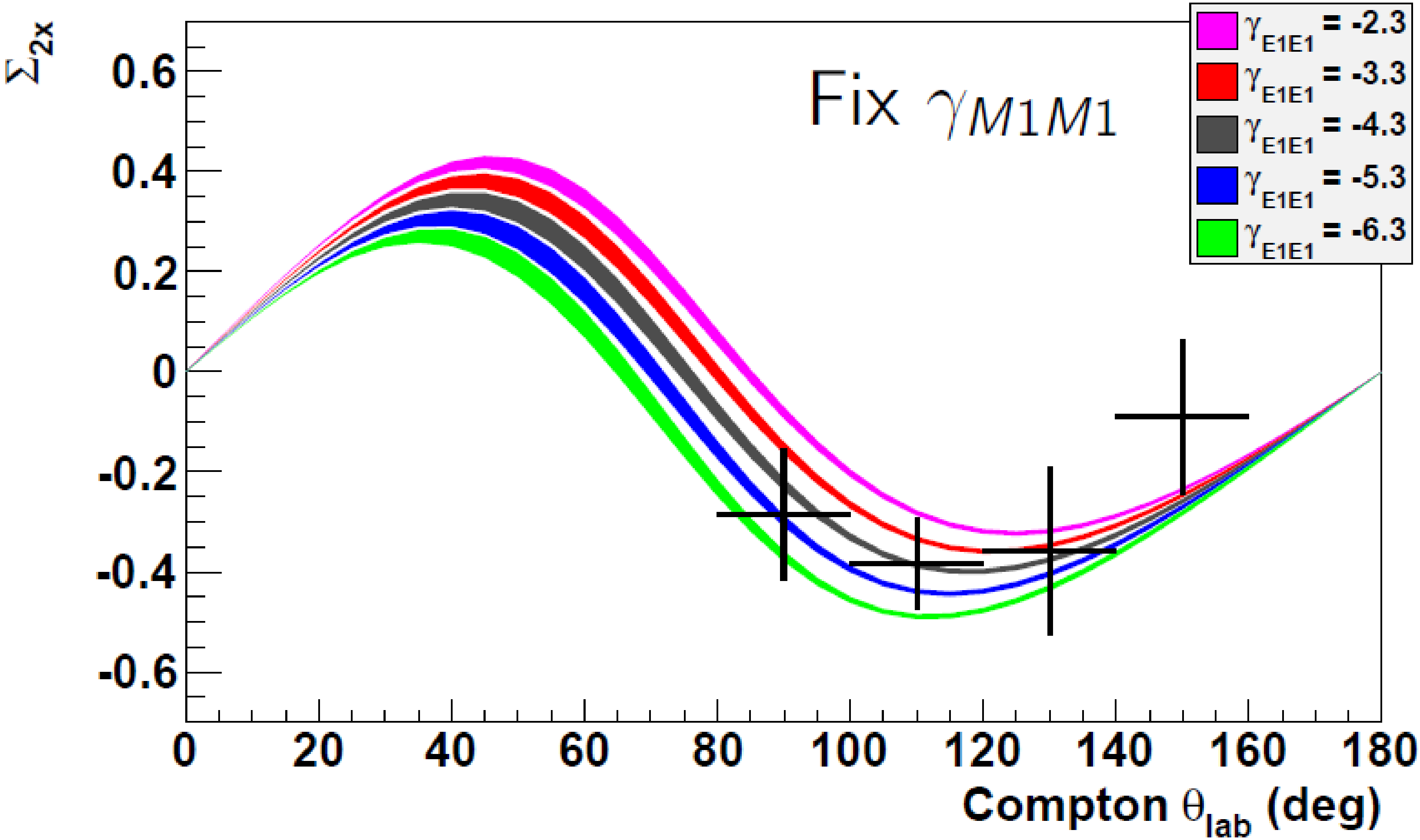


RCS Asymmetries: Σ2x



- Determine the other two using γ_0 and γ_π, while allowing γ_0, γ_π, α and β to vary by their experimental errors.

RCS Asymmetries: Σ2x

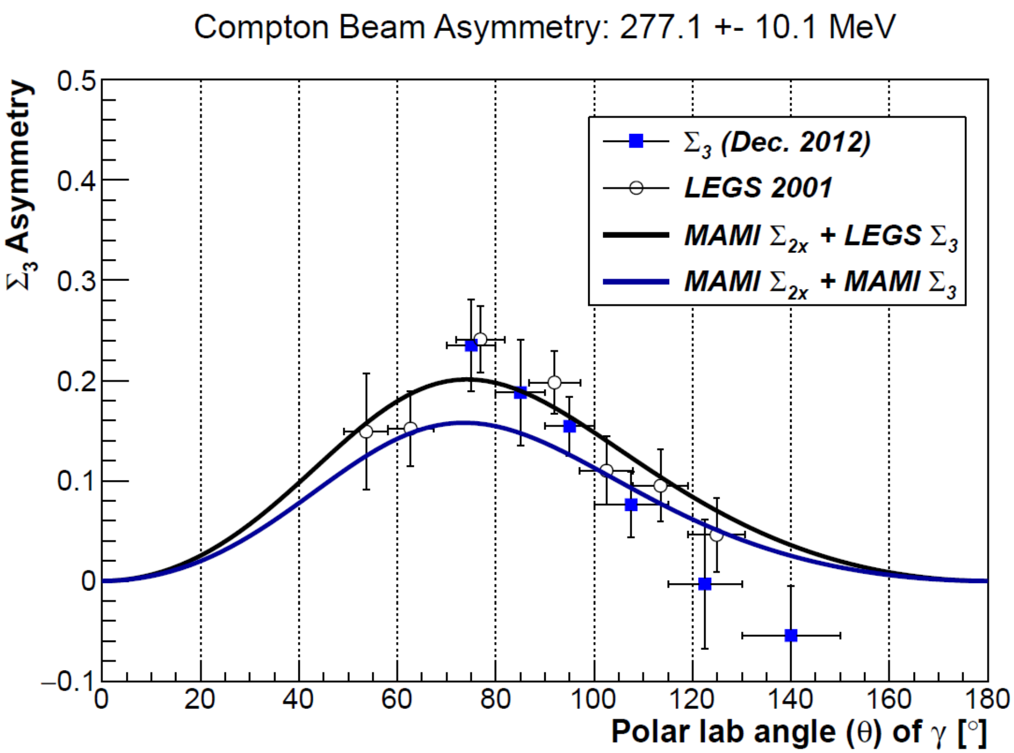


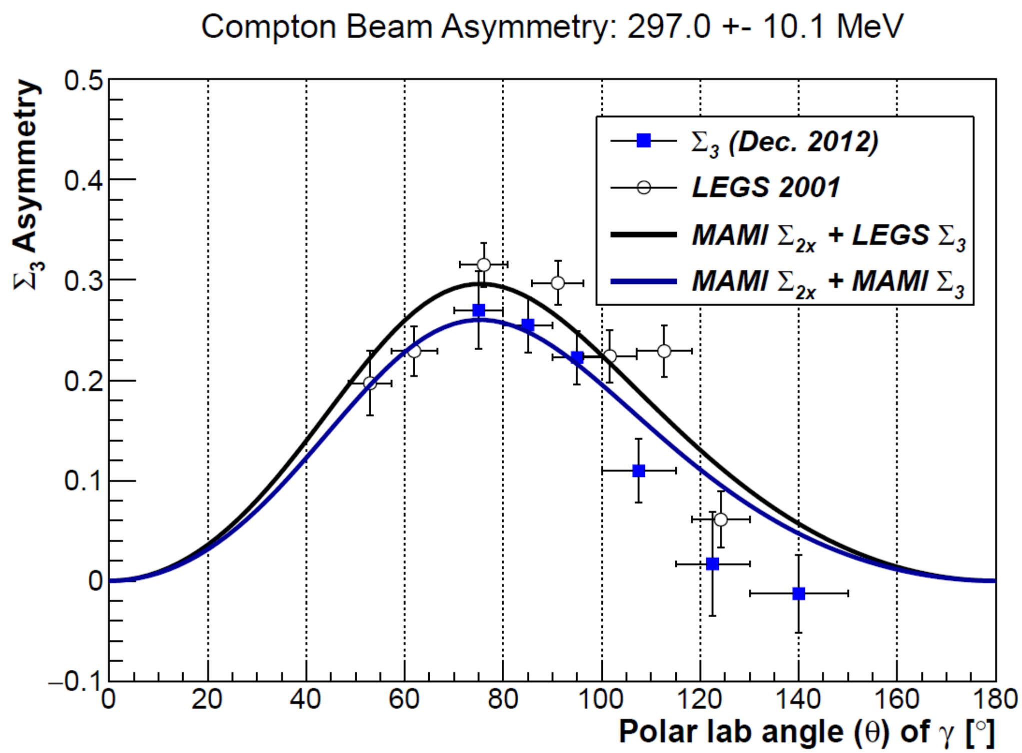
- Determine the other two using γ_0 and γ_π, while allowing γ_0, γ_π, α and β to vary by their experimental errors
- Martel *et al.* (A2) Phys. Rev. Lett. **114**, 112501 (2015)

RCS Asymmetries: Σ2z

- Second round of measurement currently underway in Mainz
- First measurement in Spring 2014
- Data calibrated
- Physics analysis underway
- Preliminary analysis agrees with theory

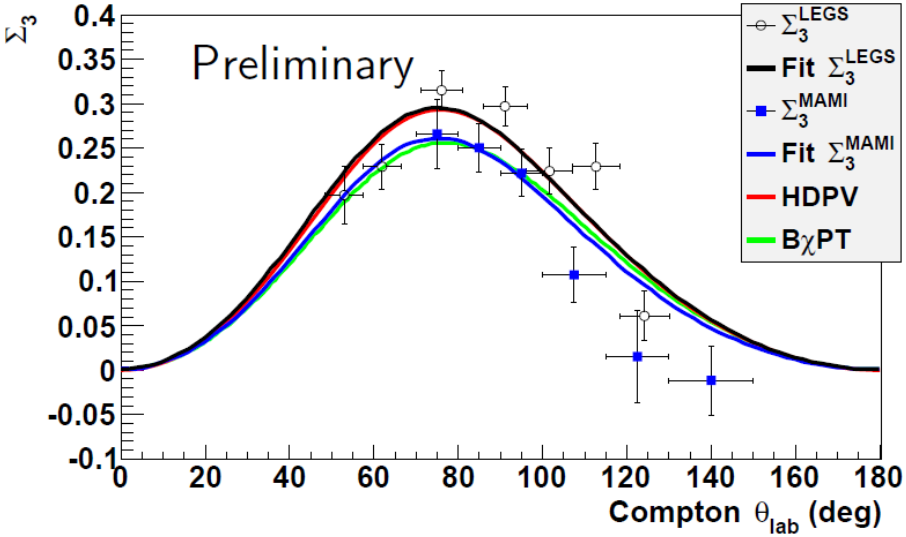
RCS Asymmetries: Σ3

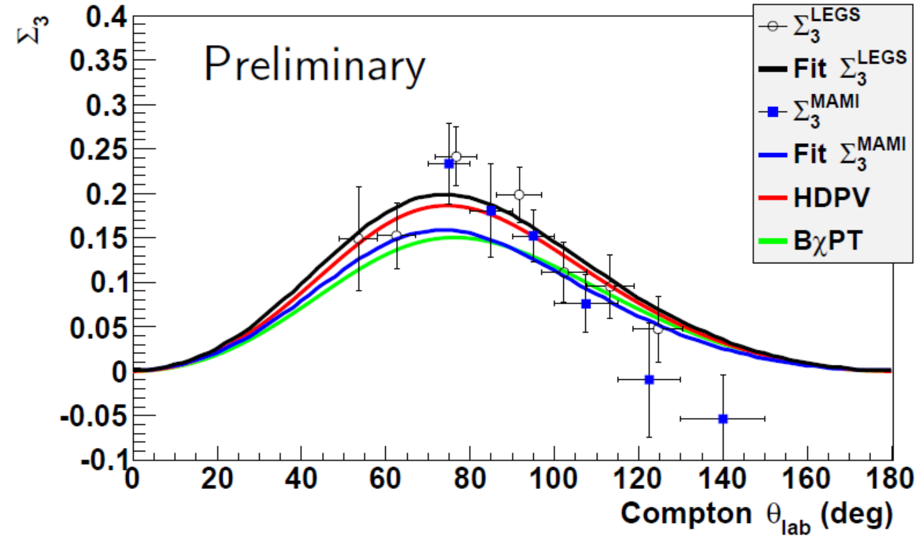




- December 2012 – two weeks of data
- Photon energy 267 – 287.2 MeV
- The recent (MAMI) and older (LEGS) Σ_3 measurements give different results
- LEGS: G. Blanpied *et al.*, Phys. Rev. C 64, 025203 (2001)
- C. Collicott PhD thesis (Dalhousie, 2015), publication in preparation

RCS Asymmetries: Σ2z & Fits

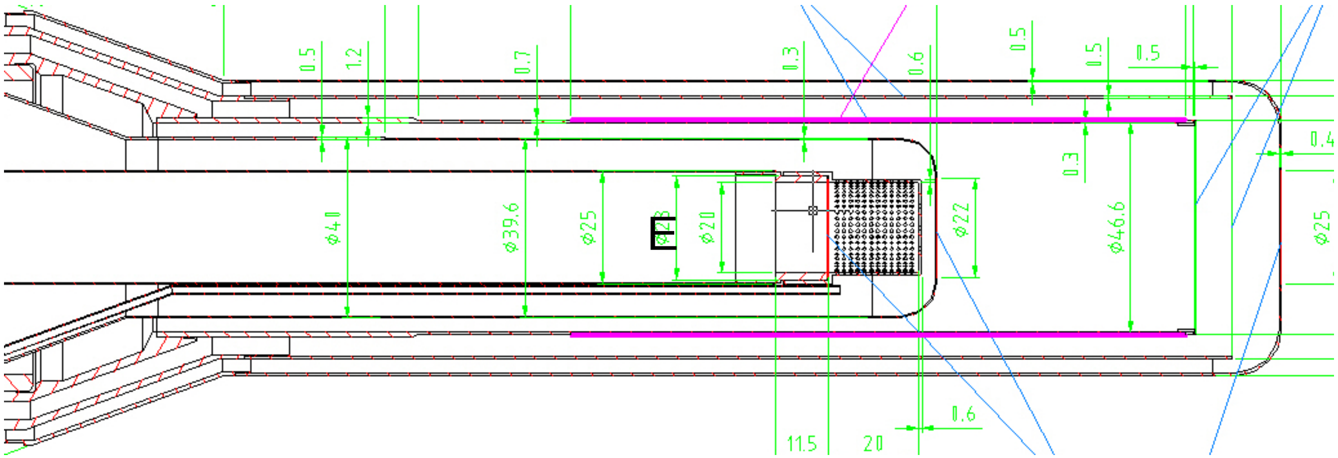


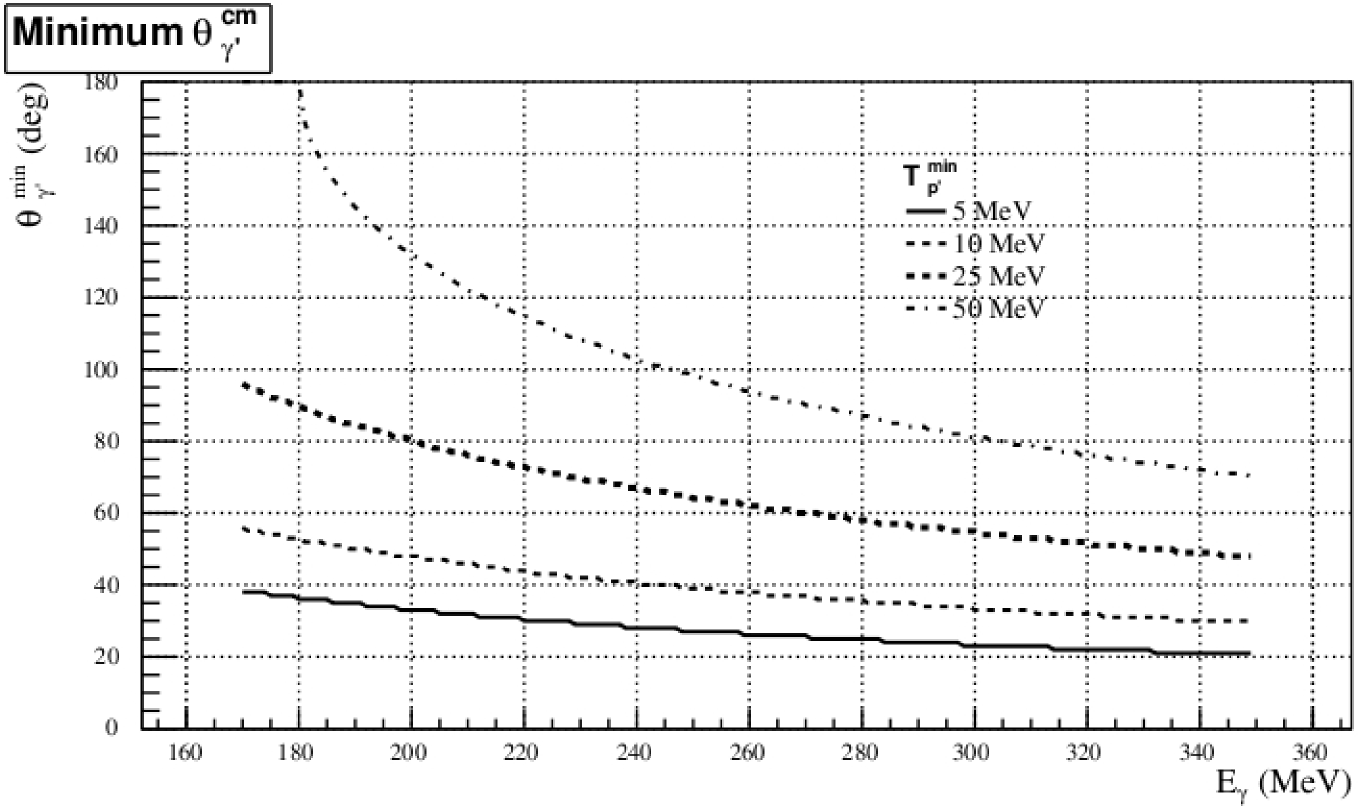


	LEGS + Martel	Collicott + Martel
$\bar{\gamma}_{E1E1}$	-3.5 ± 1.2	-5.0 ± 1.5
$\bar{\gamma}_{M1M1}$	3.16 ± 0.85	3.13 ± 0.88
$\bar{\gamma}_{E1M2}$	-0.7 ± 1.2	1.7 ± 1.7
$\bar{\gamma}_{M1E2}$	1.99 ± 0.29	1.26 ± 0.43
γ_0	-1.03 ± 0.18	-1.00 ± 0.18
γ_π	9.3 ± 1.6	7.8 ± 1.8

- Fitting is underway! Preliminary just now...
- First Σ2z measurements have been made, more data taking just now
- Scalar polarizabiliy data to be added
- Proton work ongoing...

Improving the Kinematic Range





Problem 1:

- Target composite material → need nucleon to identify signal cleanly

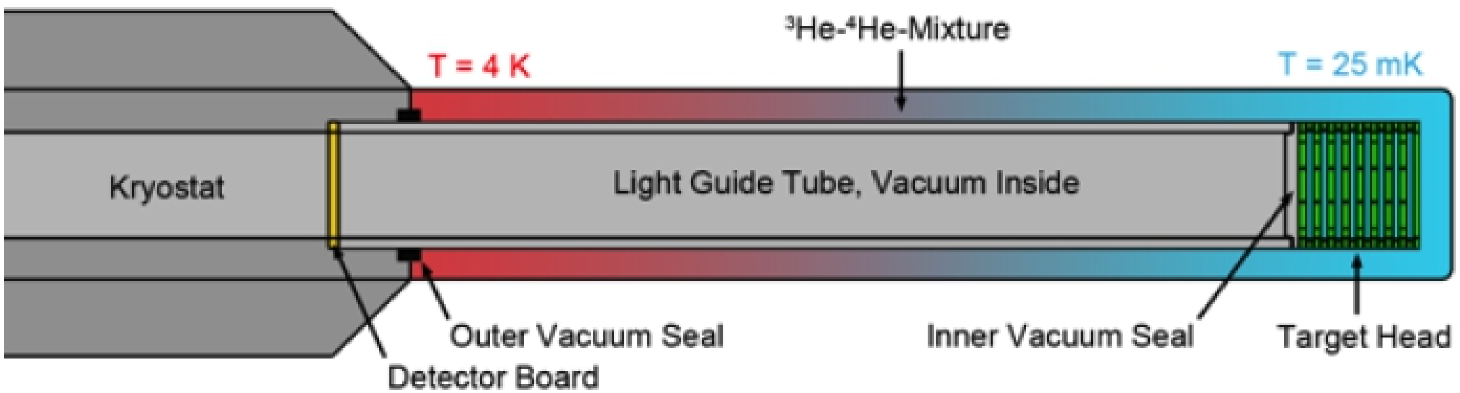
Problem 2:

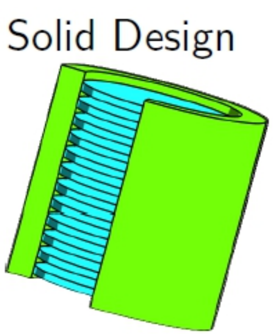
- Cooling & magnetic infrastructure cause high outgoing proton energy threshold

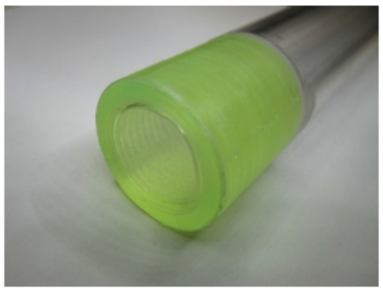
Solution:

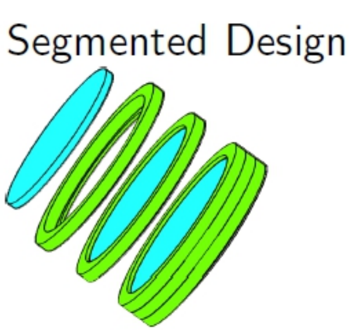
- **Active Polarised Target**

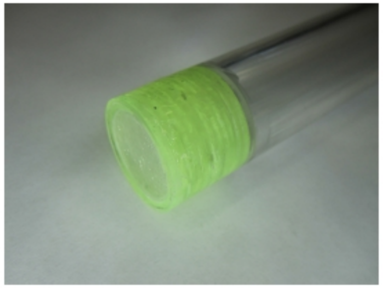
Active Polarized Target











- Polarizable scintillator: 70% polarization 200 mK, 2.5 T, Tested at MAMI, D. Von Maluski and R. Miskimen UMass Amherst
- Light readout and electronics tested by Maik Biroth (Mainz), Laura Lai (GWU)
- Challenging readout at 4K!
- Limited geometry

Active Polarised Target

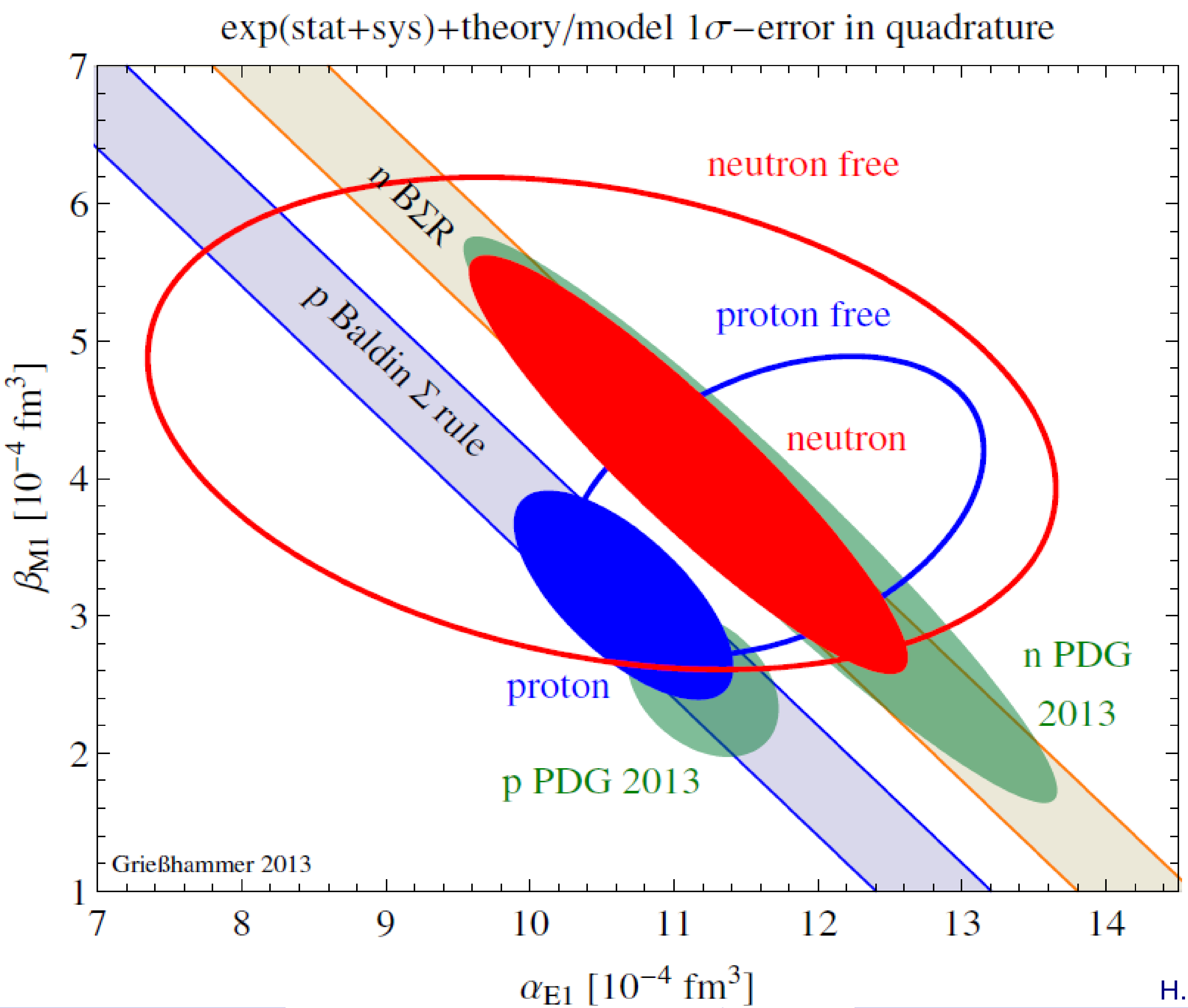
- Cryogenic development:

  Thomas (Mainz),
  Downie (GWU), Borrissov & Usov (JINR)

Carl Zeiss Stiftung

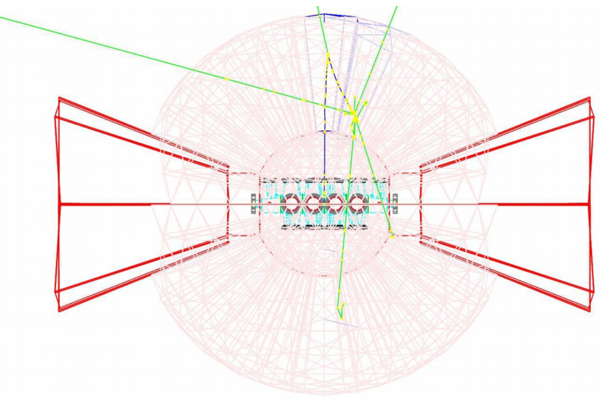
Neutron Data

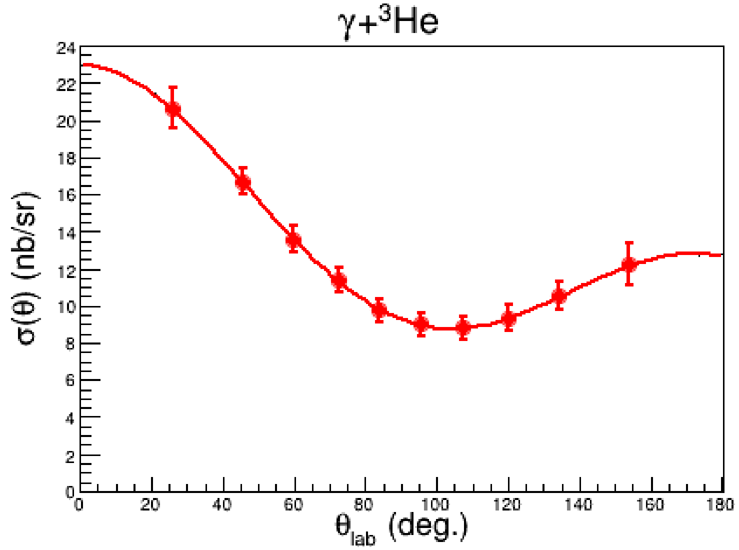
Need better neutron data: proton-neutron differences test χSB in pion cloud.

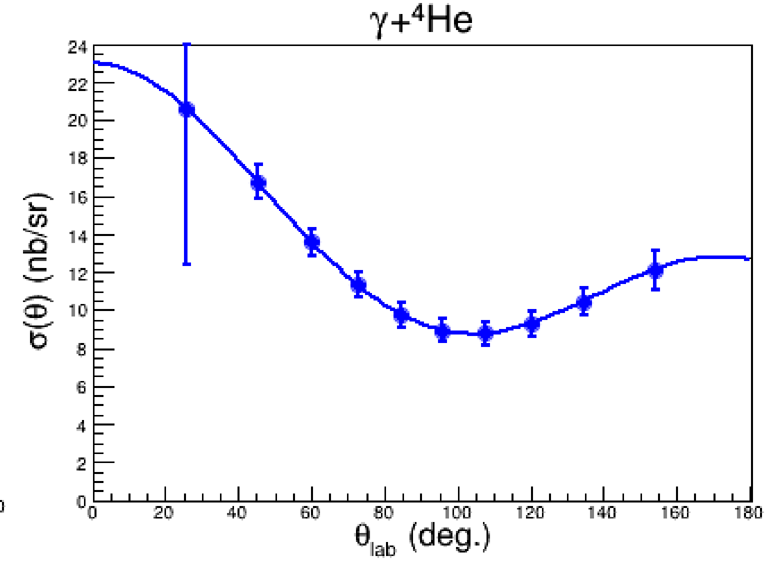


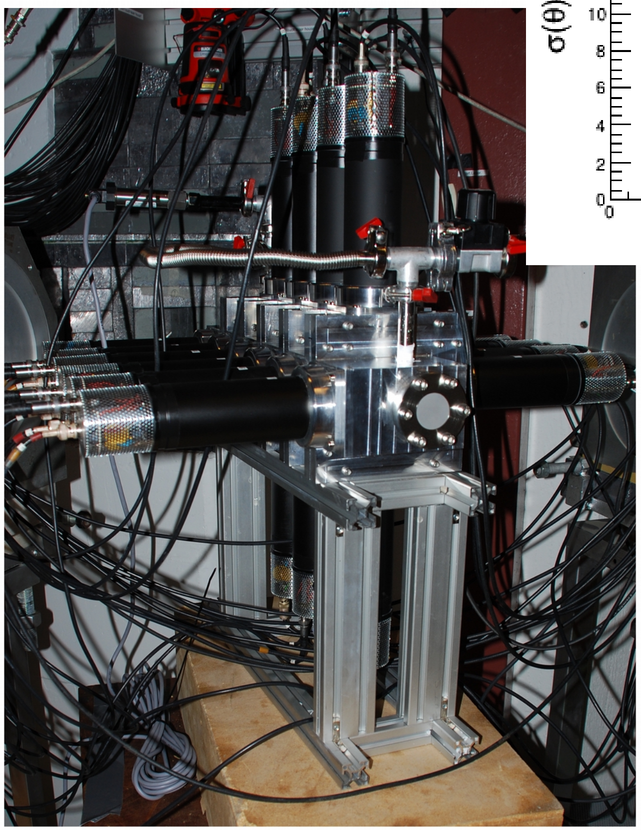
H. Grießhammer

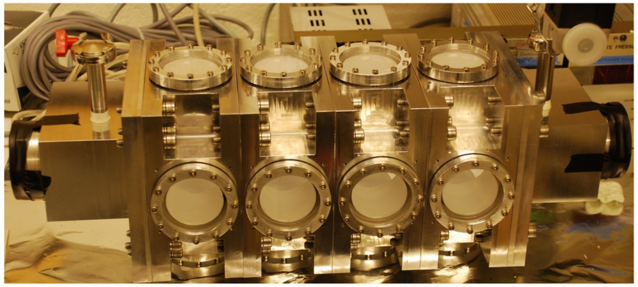
MAMI Neutron Program











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Pictures: J. R. M. Annand

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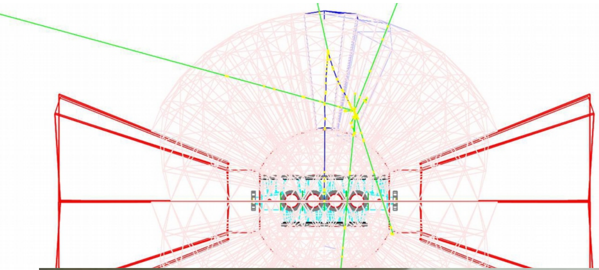
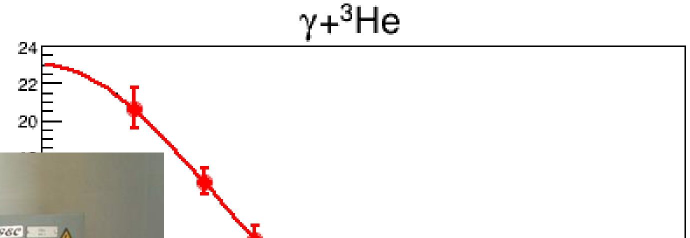
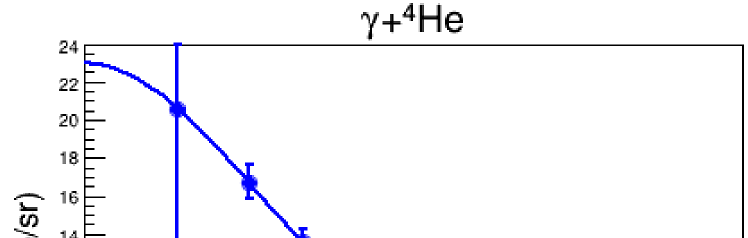
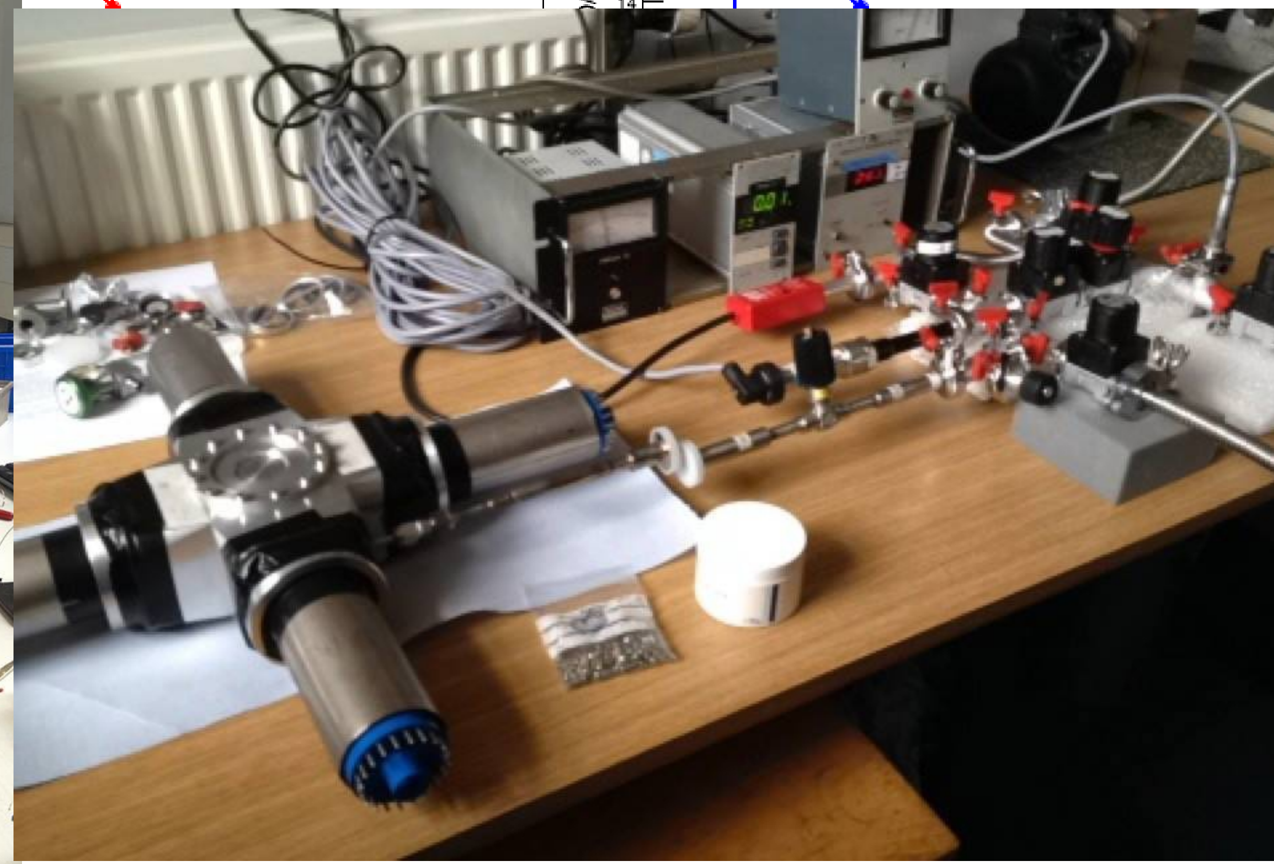
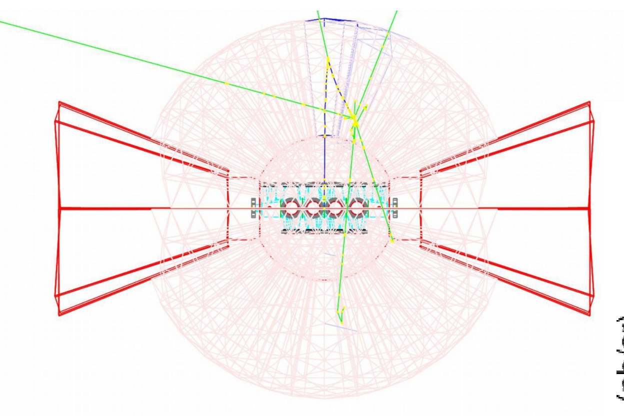








Pictures: J. R. M. Annand



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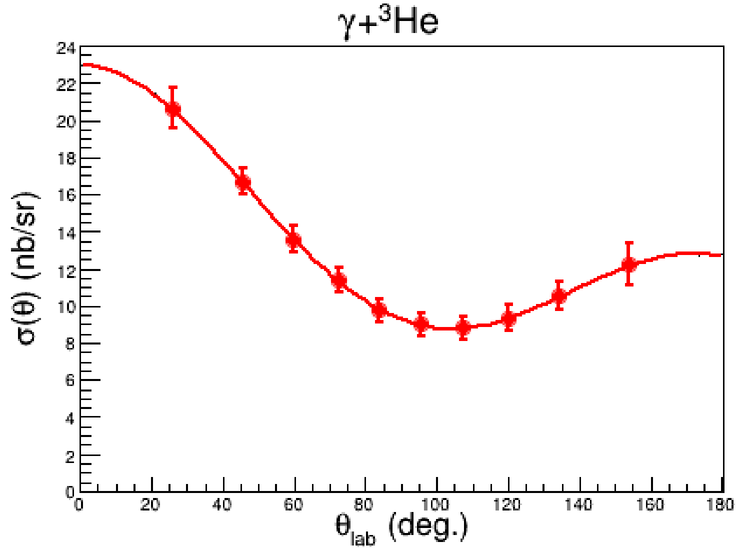

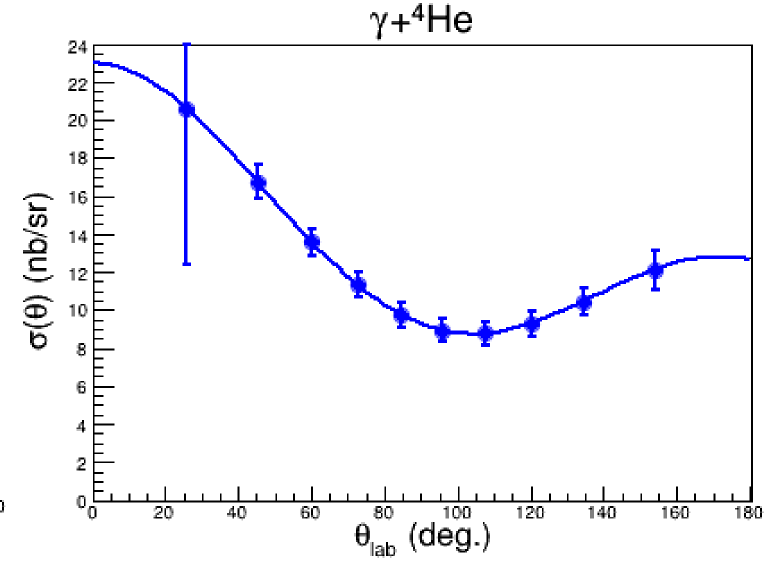

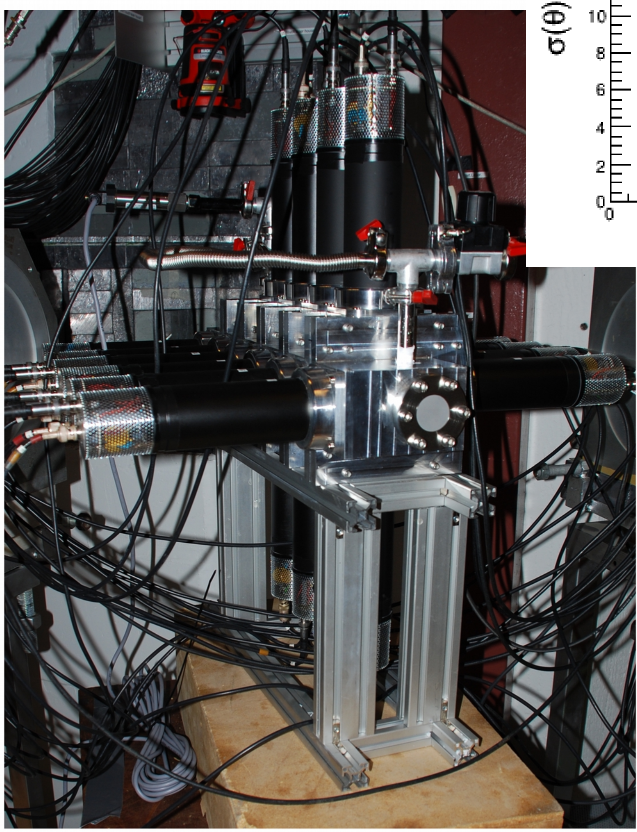

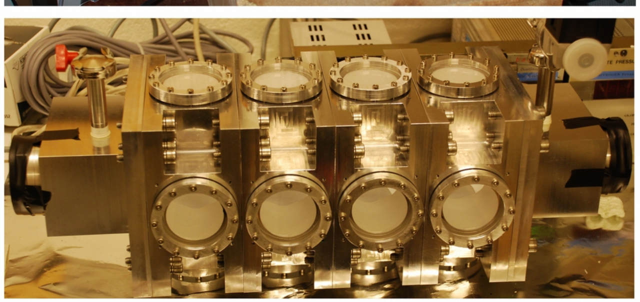

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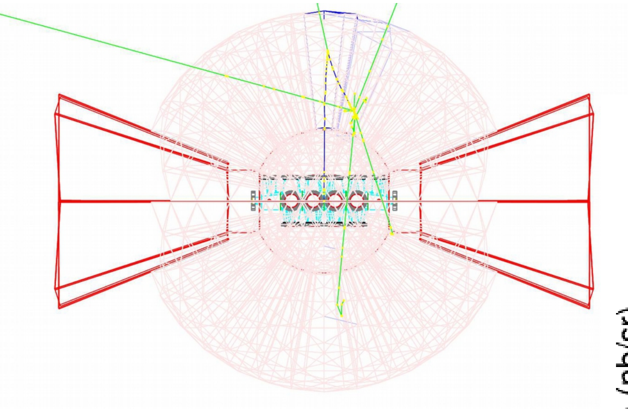

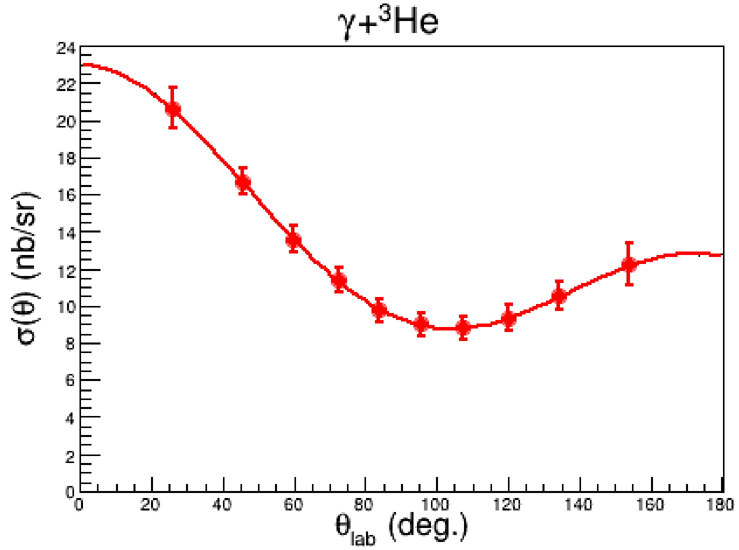

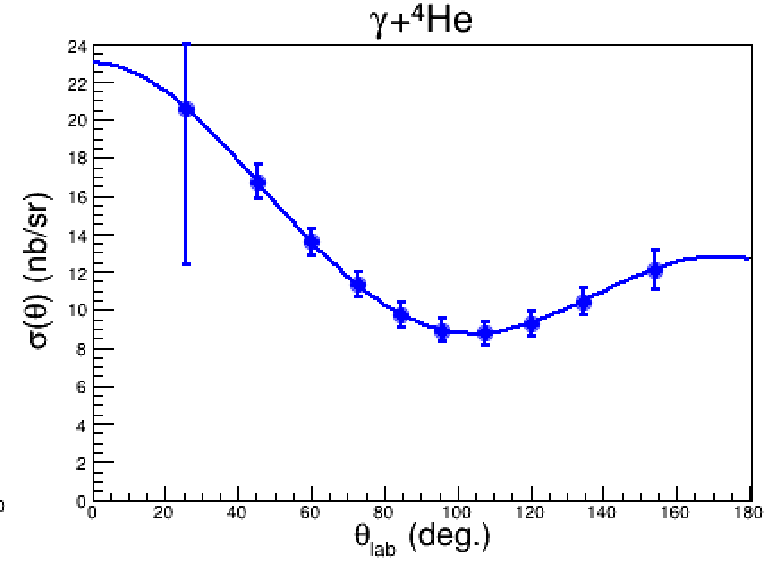

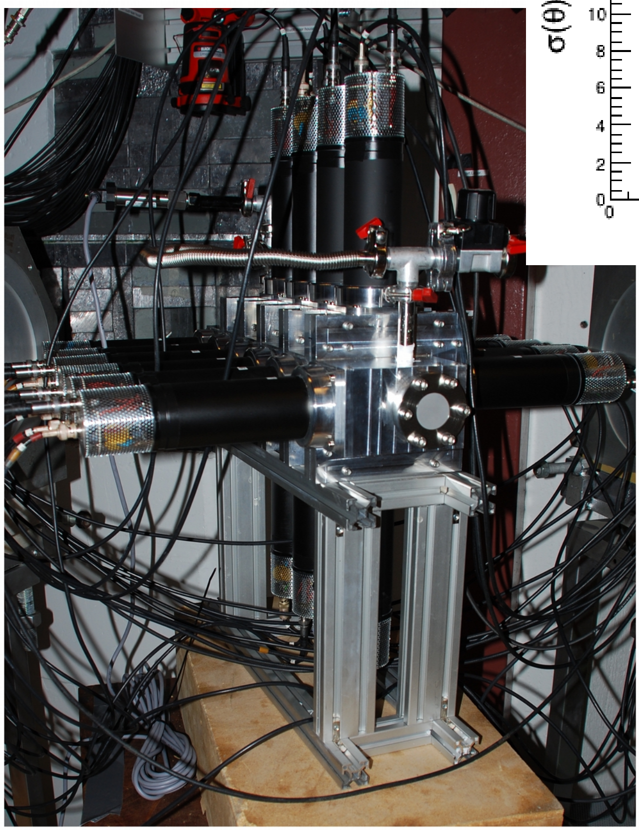

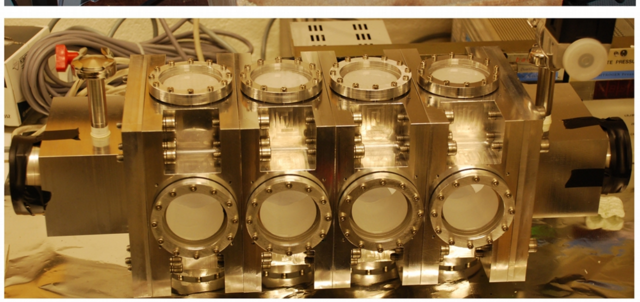

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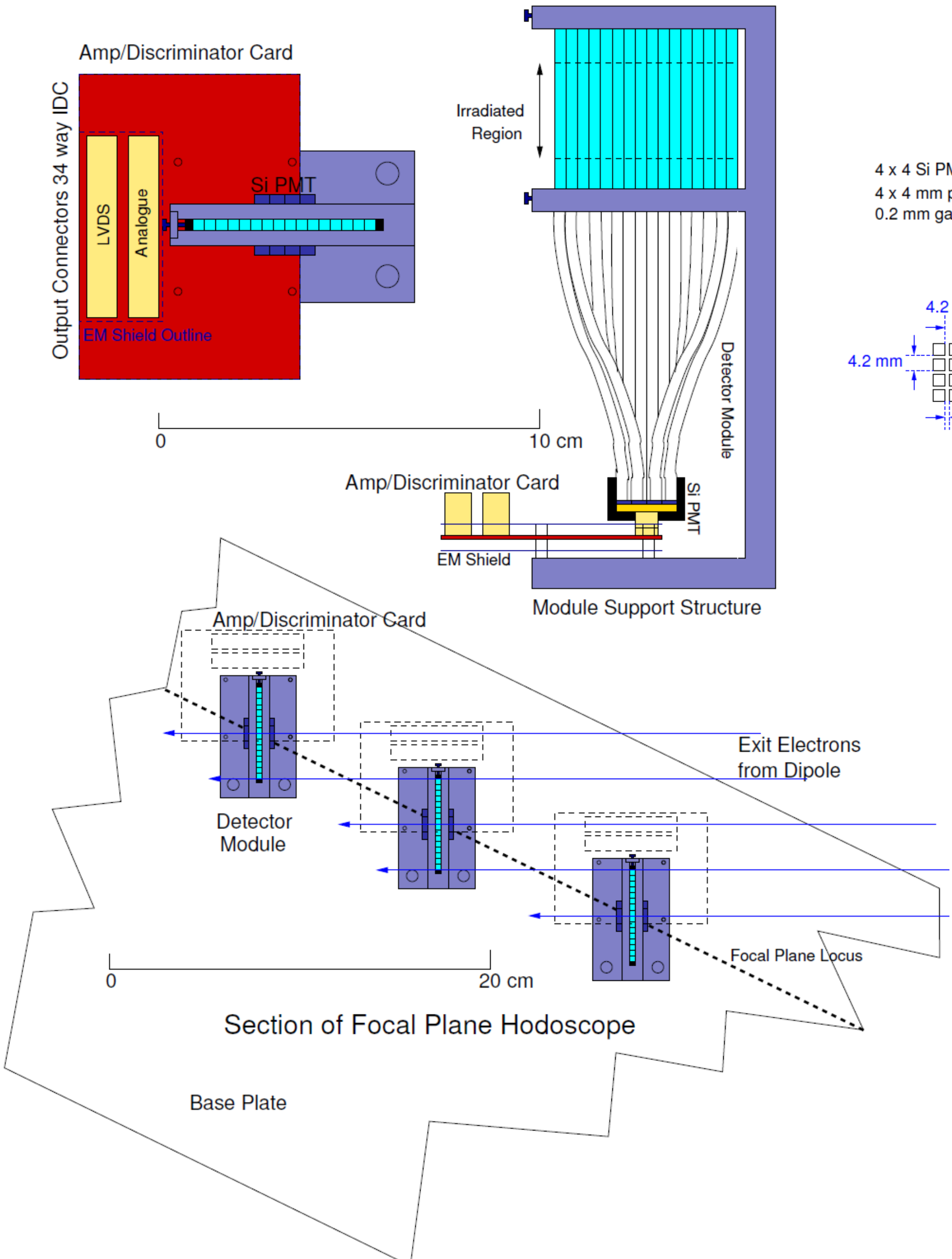
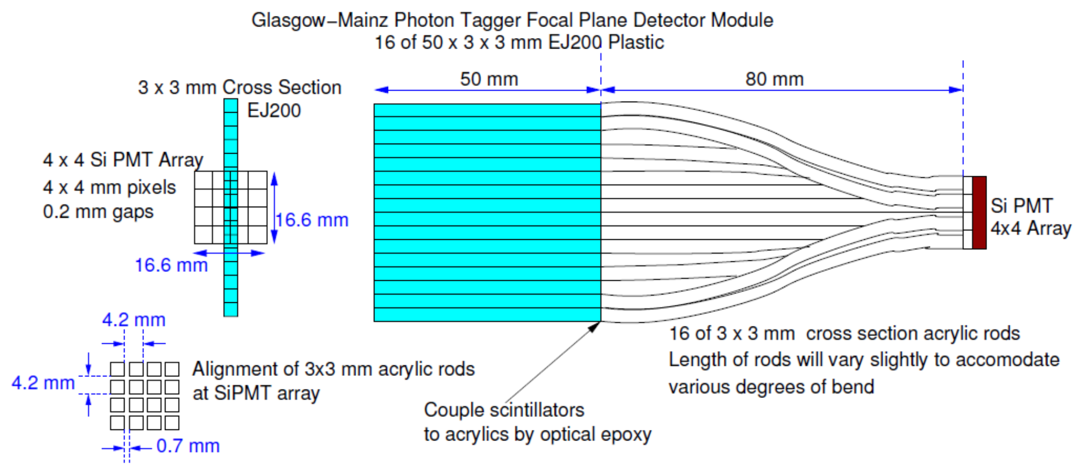
- B. Strandberg (Glasgow) working with H. Grießhammer, & D. Phillips on extending*: D.Shulka, A. Nogga & D. Phillips Nucl. Phys, A819 (2009),98*

Pictures: J. R. M. Annand

Upgraded Glasow Mainz Photon Tagger Focal Plane





- Current Compton experiments are "Tagger limited"
- New, more finely segmented, Tagger Focal Plane detector
- Greater rate capability
- To make progess in RCS, need technological developments in target and beam

Polarizability Status

- HIGS polarized target is in assembly at HIgS
- Cryotarget will run soon for unpolarised deuterium
- Measuring P & N scalar polarizabilities & P spin pol.

- Deuteron analysis complete! New data coming.
- Doubled data base, improved n scalar pol.

- First low energy data for pol α & β measurement
- Σ_{2x}, Σ_{2z}, Σ_3 already measured (fits underway)
- More statistics necessary!
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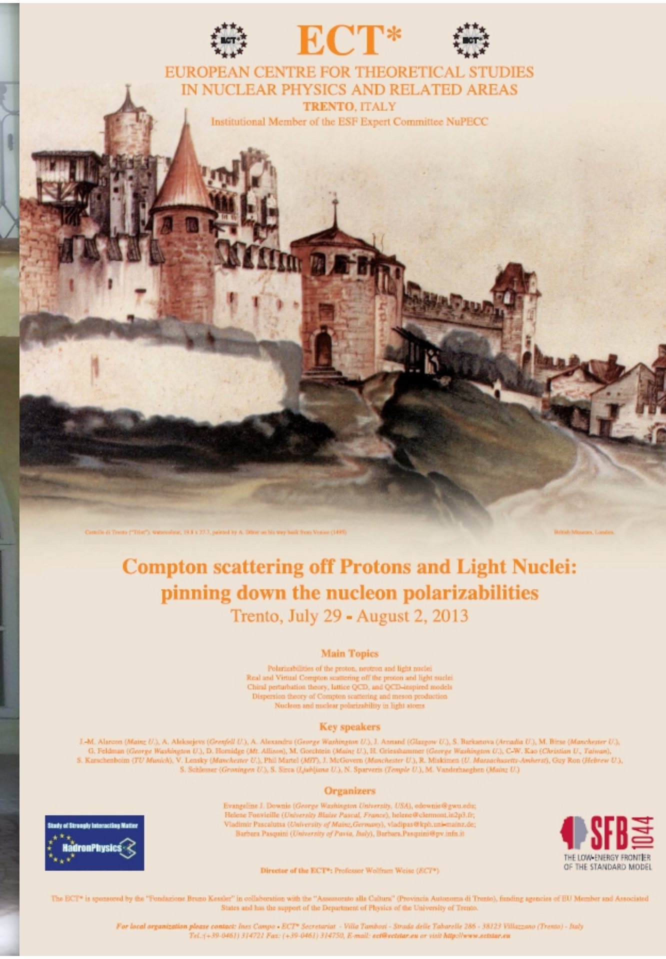
Outlook



- Polarizabilities important – we need to improve their uncertainties!
- Lots of new data planned, on tape, and being published soon!
- Approved experiments across three labs to access scalar & spin pols
- Large kinematic range & multiple theory flavors necessary
- Overlapping data from MAMI & HIGS ideal for systematic constraint
- Close work between theory & experiment essential for success

Outlook

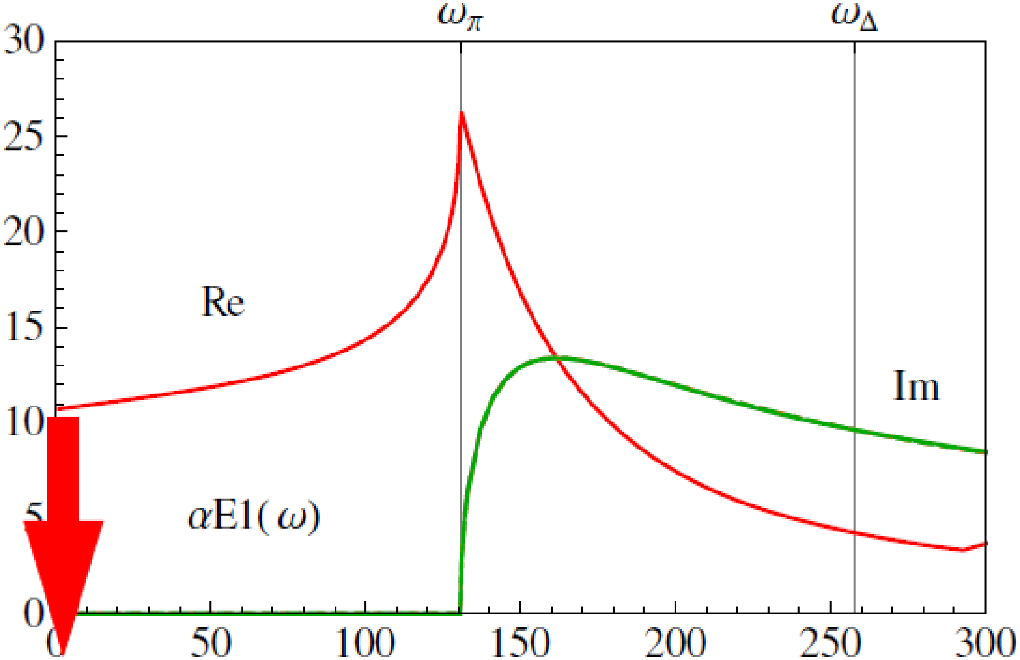
***Dynamical Polarisabilities*: Multipoles of real Compton scattering at fixed energy.**

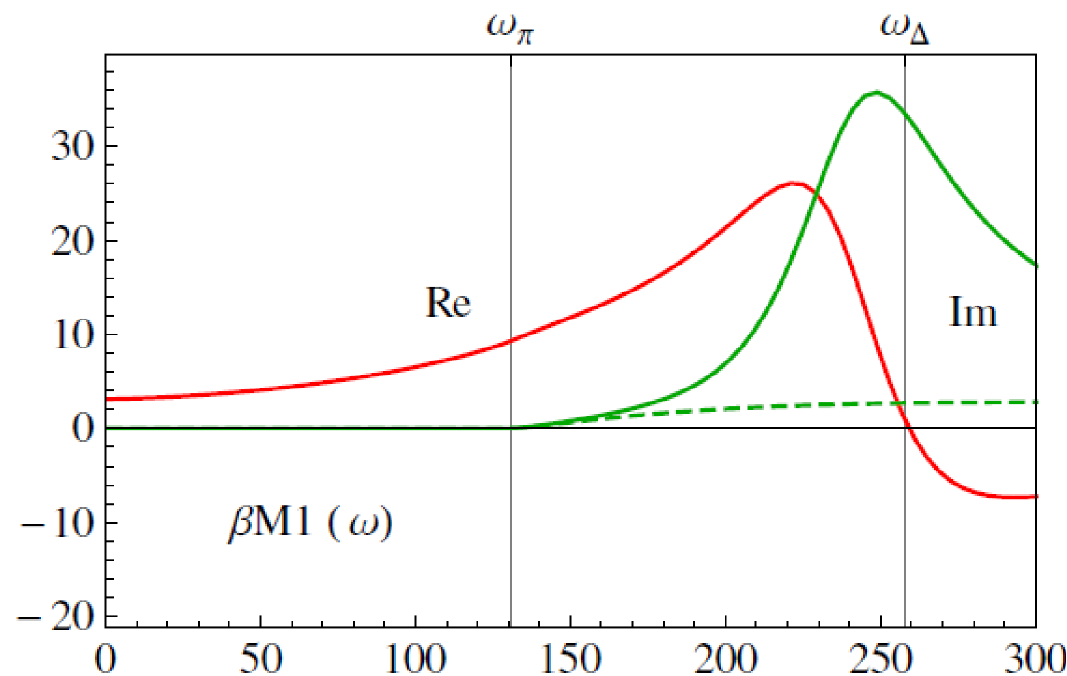
$$2\pi\left[\alpha_{E1}(\omega)\vec{E}^2+\beta_{M1}(\omega)\vec{B}^2+\gamma_{E1E1}(\omega)\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}})+\gamma_{M1M1}(\omega)\vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}})+\dots\right]$$

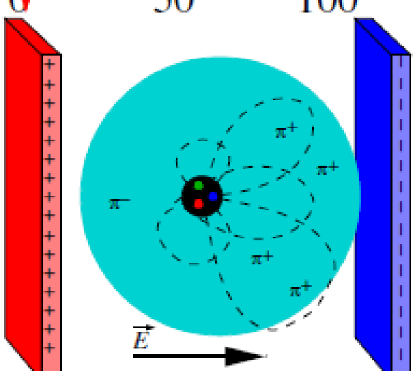
Neither more nor less information about response of constituents, but **more readily accessible.**

$\alpha_{E1}(\omega)$: χiral symmetry & its breaking in pion cloud.

$\beta_{M1}(\omega)$: para-magnetic N-to-Δ $M1$-transition.







Re: **refraction**; Im: **absorption**

For $\omega \not\ll m_\pi$ more than "static+slope"! $\Longrightarrow$ Need to understand *dynamics!*

H. Grießhammer

Thank you for your attention!

Thank you to:

J. R. M. Annand
C. Collicott
H. Grießhammer
D. Hornidge
P. Martel
L. Myers
V. Sokhoyan
H. Weller

for their contributions!

See http://www.facebook.com/SummerResearchInMainz for IRES opportunities for your undergrads!