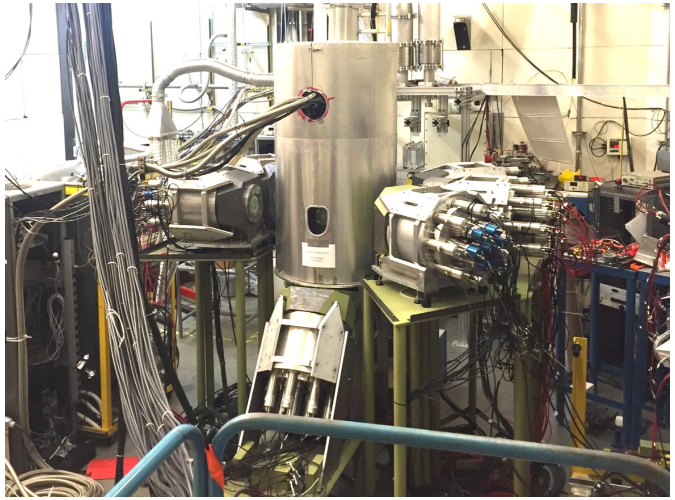
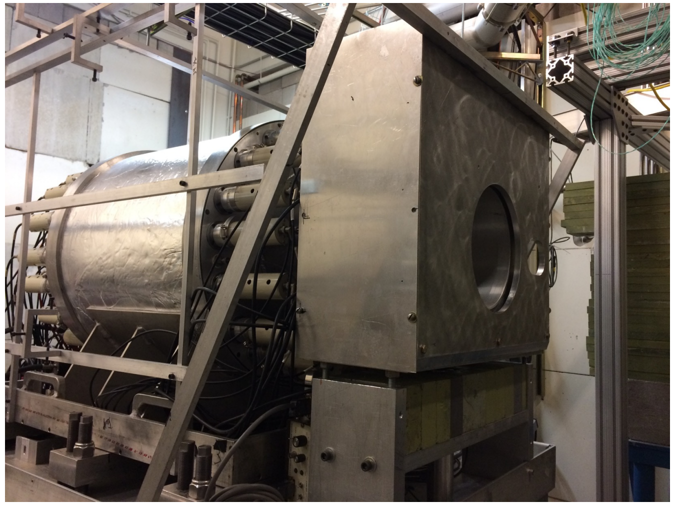
Compton Scattering at HIGS: *from the Proton and Light Nuclei*

TUNL





HIGS Compton Collaboration

Groups from 13 institutions: 10 USA + 3 international

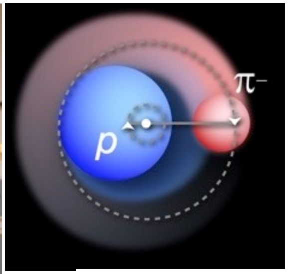
1) **Duke Univ.:** H. Gao, C.R. Howell
2) **GWU:** E. Downie, J. Feldman, H. Griesshammer
3) **James Madison Univ.:** A. Banu and S. Whisant
4) **Montclair State University:** K. Leung
5) **Mount Alison Univ.**, David Hornidge
6) **NC Central Univ.:** M.W. Ahmed, B. Crowe, D. Markoff
7) **North Georgia State Univ.:** M. Spraker
8) **Ohio Univ.:** D. Phillips
9) **Univ. Kentucky:** M. Kovash
10) **Univ. Manchester:** J.A. McGovern
11) **UNC-Chapel Hill:** H. Karwowski
12) **Univ. Mass. - Amherst:** R. Miskimen
13) **Univ. Saskatchewan:** R. Pywell

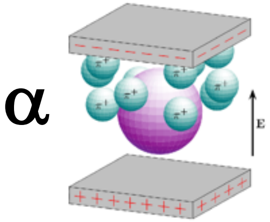
By: Calvin R. Howell, Duke University

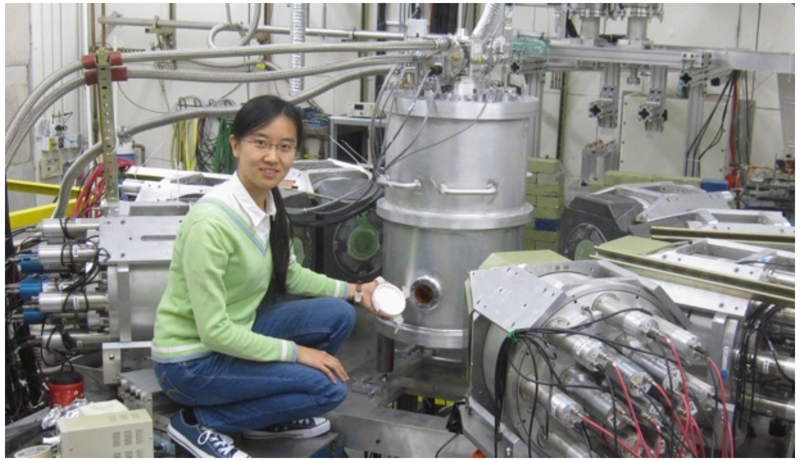
Key:

Blue font = TUNL consortium institution

Red font = Theorist

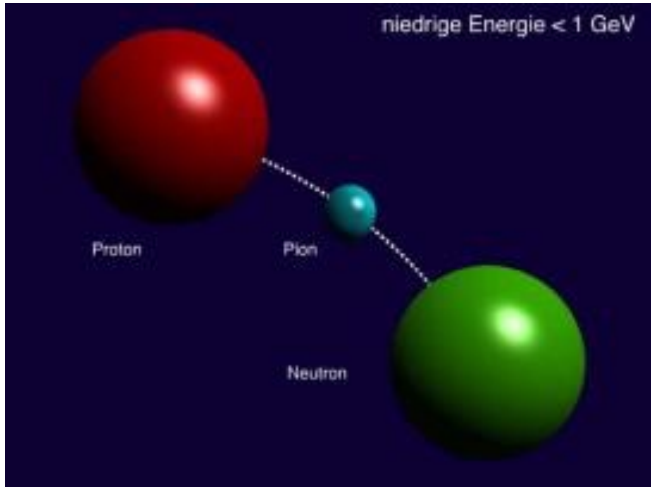






Outline

- Yesterday (activities during last 3 years)
- Today (current activities)
- Tomorrow (next 3 to 5 years)



Work supported in part by:

U.S. Department of Energy grants: DE-FG02-03ER41231, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-FG02-97ER41046, DE-FG02-97ER41042, DESC0005367, DE-SC0015393, DE-SC0016581, DE-SC0016656

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Natural Sciences and Engineering Research Council of Canada

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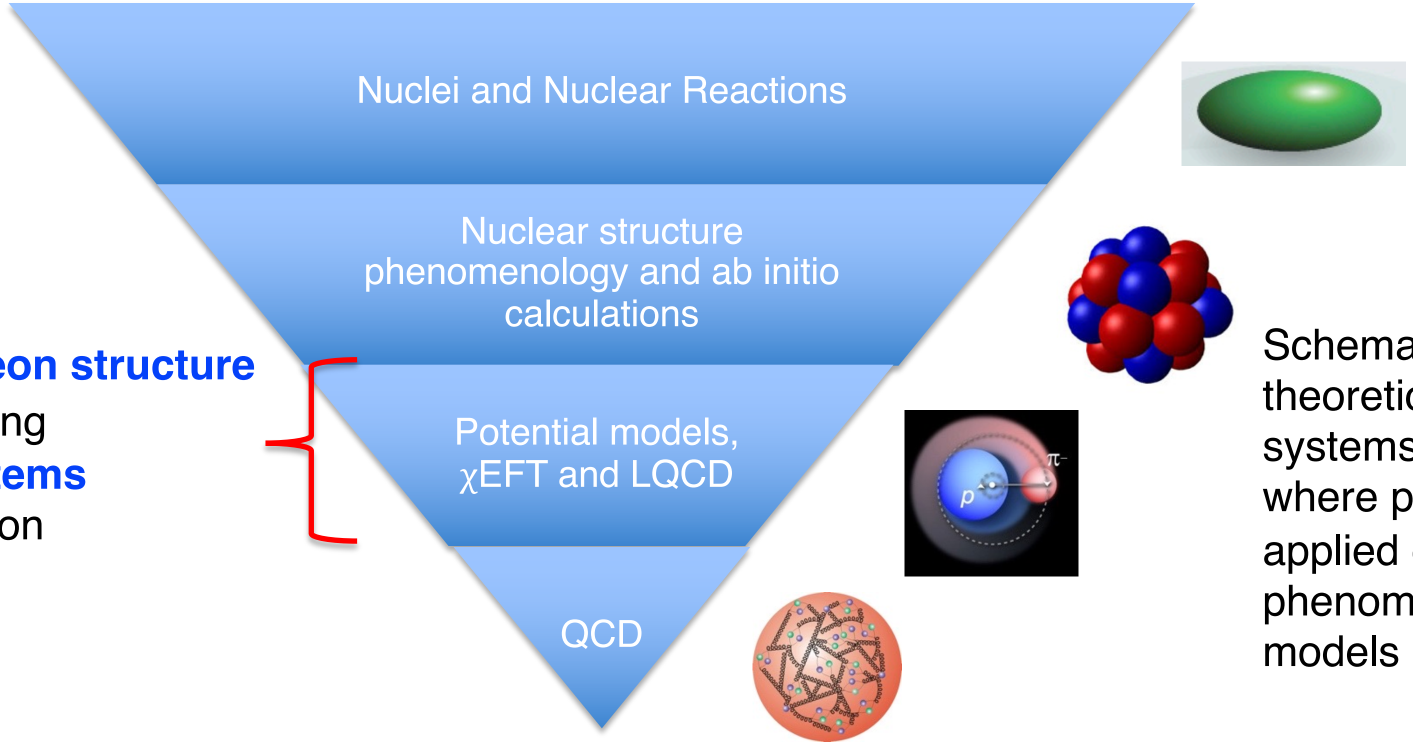
US 2015 Nuclear Science LRP: Organizing Themes

- **May the strong force be with you:** Emergence of the nuclear strong force from QCD
- **Theory of nuclei: to explain, predict and use:** ab-initio calculations (few-nucleon systems and light nuclei), nuclear density functional theory for heavy nuclei

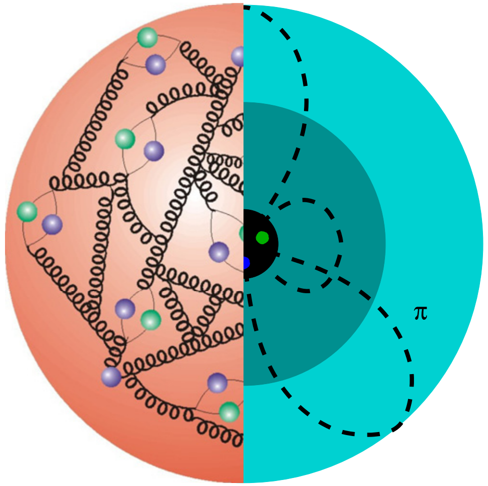
Hierarchy of theoretical treatments of nuclear systems

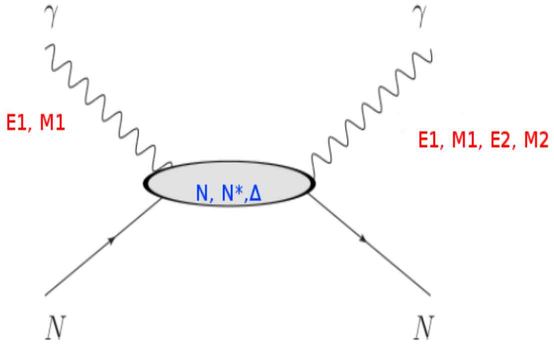


- **Low-energy nucleon structure**
  Compton scattering
- **Few-nucleon systems**
  Photodisintegration

Schematic diagram for coherent theoretical treatment of nuclear systems starting from high energies where perturbative QCD can be applied going to low-energy nuclear phenomena where mean-field potential models are most efficient.

Low-Energy Nucleon Structure: effective degrees of freedom





$$\frac{d\sigma}{d\Omega} = \Phi^2 |T|^2$$

$$T(\omega, z) = A_1(\omega, z)\, \vec{\epsilon}\,'^* \cdot \vec{\epsilon} + A_2(\omega, z)\, \vec{\epsilon}\,'^* \cdot \hat{\vec{k}}\, \vec{\epsilon} \cdot \hat{\vec{k}}'$$
$$+ i\, A_3(\omega, z)\, \vec{\sigma} \cdot (\vec{\epsilon}\,'^* \times \vec{\epsilon}) + i\, A_4(\omega, z)\, \vec{\sigma} \cdot \left(\hat{\vec{k}}' \times \hat{\vec{k}}\right) \vec{\epsilon}\,'^* \cdot \vec{\epsilon}$$
$$+ i\, A_5(\omega, z)\, \vec{\sigma} \cdot \left[\left(\vec{\epsilon}\,'^* \times \hat{\vec{k}}\right) \vec{\epsilon} \cdot \hat{\vec{k}}' - \left(\vec{\epsilon} \times \hat{\vec{k}}'\right) \vec{\epsilon}\,'^* \cdot \hat{\vec{k}}\right]$$
$$+ i\, A_6(\omega, z)\, \vec{\sigma} \cdot \left[\left(\vec{\epsilon}\,'^* \times \hat{\vec{k}}'\right) \vec{\epsilon} \cdot \hat{\vec{k}}' - \left(\vec{\epsilon} \times \hat{\vec{k}}\right) \vec{\epsilon}\,'^* \cdot \hat{\vec{k}}\right]$$

- The non-pole parts of the amplitudes contain internal structure information on the dynamical response of the nucleon to EM fields
- The amplitudes factor into 6 response functions (or polarizabilities): 2 spin independent and 4 spin dependent
- Measurements of the nucleon polarizabilities test chiral dynamics inside the nucleon at energies of $\omega < m_\pi$

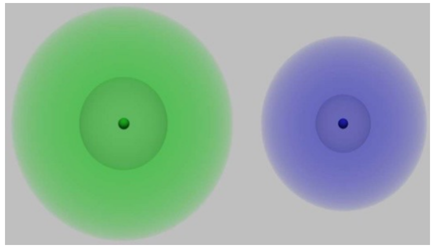
Separate A's into pole and non-pole parts

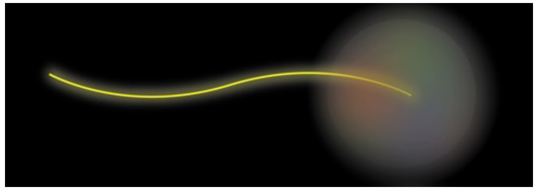
$$A_i(\omega, z) = A_i^{Born}(\omega, z) + \bar{A}_i(\omega, z)$$

($\ell = 1$)

$$\bar{A}_1(\omega,\, z) = \frac{4\pi\, W}{M}\, [\alpha_{E1}(\omega) + z\, \beta_{M1}(\omega)]\, \omega^2 + \mathcal{O}(l = 2),$$
$$\bar{A}_2(\omega,\, z) = -\frac{4\pi\, W}{M}\, \beta_{M1}(\omega)\, \omega^2 + \mathcal{O}(l = 2),$$
$$\bar{A}_3(\omega,\, z) = -\frac{4\pi\, W}{M} \Big[\gamma_{E1E1}(\omega) + z\, \gamma_{M1M1}(\omega) + \gamma_{E1M2}(\omega) + z\, \gamma_{M1E2}(\omega)\Big]\, \omega^3 + \mathcal{O}(l = 2),$$

$$\bar{A}_4(\omega,\, z) = \frac{4\pi\, W}{M} \Big[-\gamma_{M1M1}(\omega) + \gamma_{M1E2}(\omega)\Big]\, \omega^3 + \mathcal{O}(l = 2),$$
$$\bar{A}_5(\omega,\, z) = \frac{4\pi\, W}{M}\, \gamma_{M1M1}(\omega)\, \omega^3 + \mathcal{O}(l = 2),$$
$$\bar{A}_6(\omega,\, z) = \frac{4\pi\, W}{M}\, \gamma_{E1M2}(\omega)\, \omega^3 + \mathcal{O}(l = 2).$$





R. P. Hildebrandt, H.W. Griesshammer, T.R. Hemmert and B. Pasquini, Eur. Phys. J. A **20**, 329 (2004).

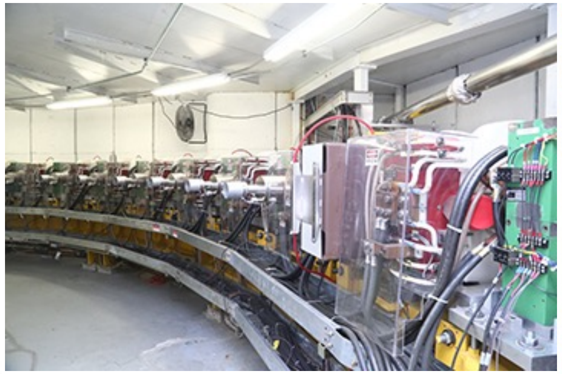
High Intensity Gamma-ray Source (HIGS)

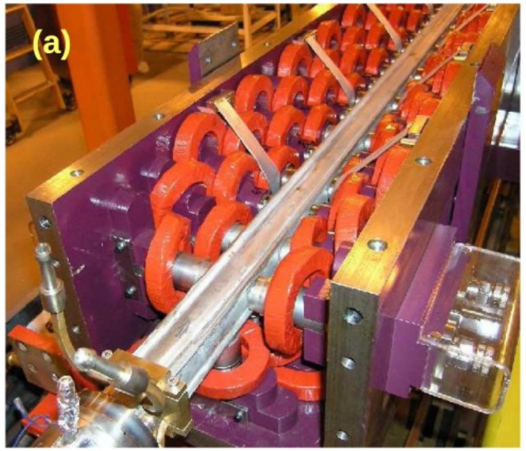
TUNL

Most intense Compton γ-ray source in the world

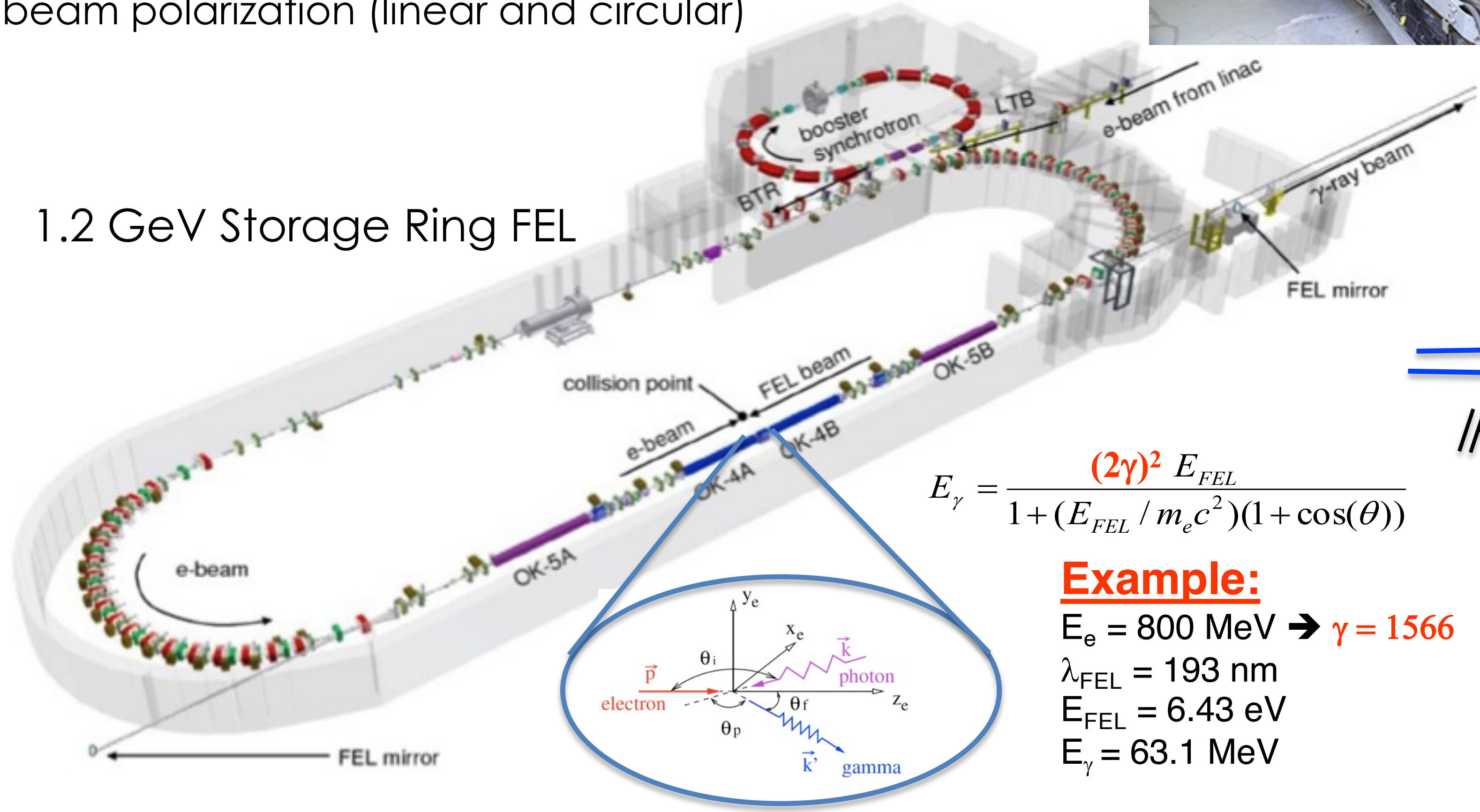
Features that enable basic and applied research

- Wide beam energy range: 1 to 120 MeV
- Selectable beam energy spread (by collimation)
- High beam intensity on target ($>10^7$ γ/s @ ΔE/E = 5%)
- >95% beam polarization (linear and circular)



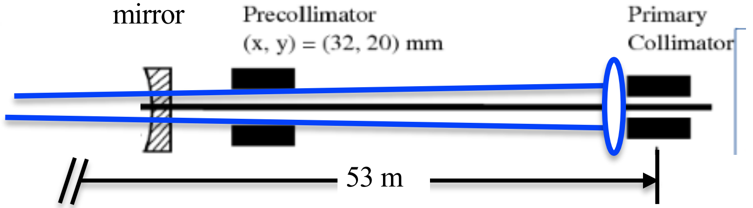


1.2 GeV Storage Ring FEL



Total γ-ray flux → $I_e * P_{oc}$

Energy resolution by collimation



$$E_\gamma = \frac{(2\gamma)^2 E_{FEL}}{1+(E_{FEL}/m_e c^2)(1+\cos(\theta))}$$

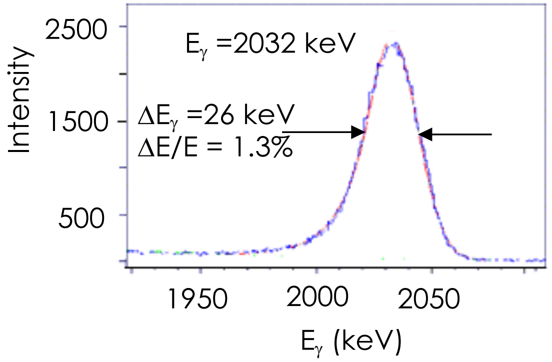
Example:

E_e = 800 MeV → γ = 1566

λ_{FEL} = 193 nm

E_{FEL} = 6.43 eV

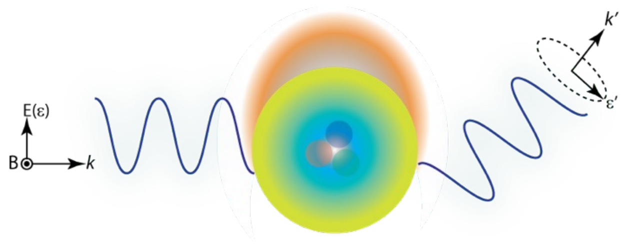
E_γ = 63.1 MeV

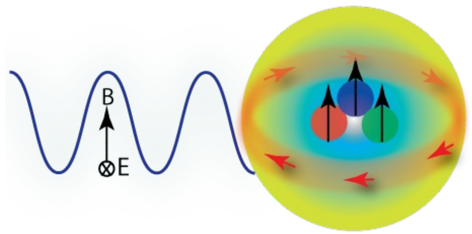


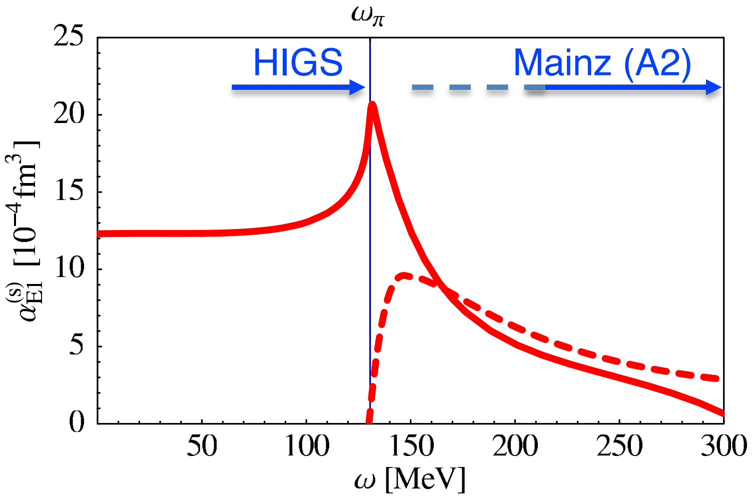
Low-Energy Nucleon Structure: Scalar Polarizabilities

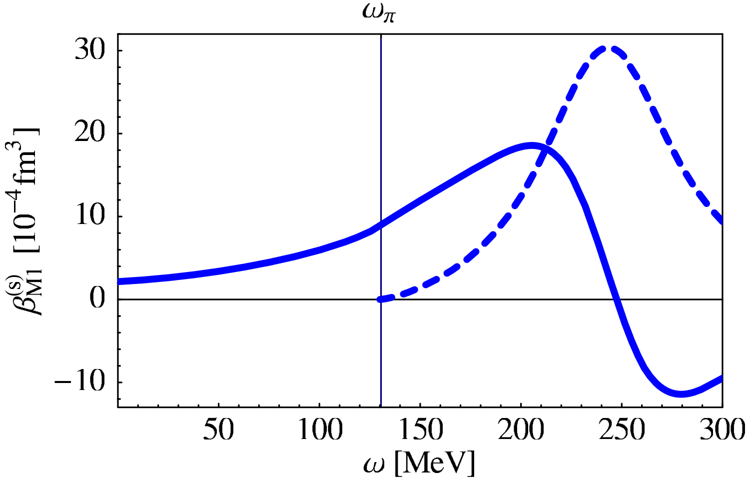
$$\bar{A}_1(\omega, z) = \frac{4\pi W}{M}\left[\alpha_{E1}(\omega) + z\,\beta_{M1}(\omega)\right]\omega^2 + \mathcal{O}(l=2),$$

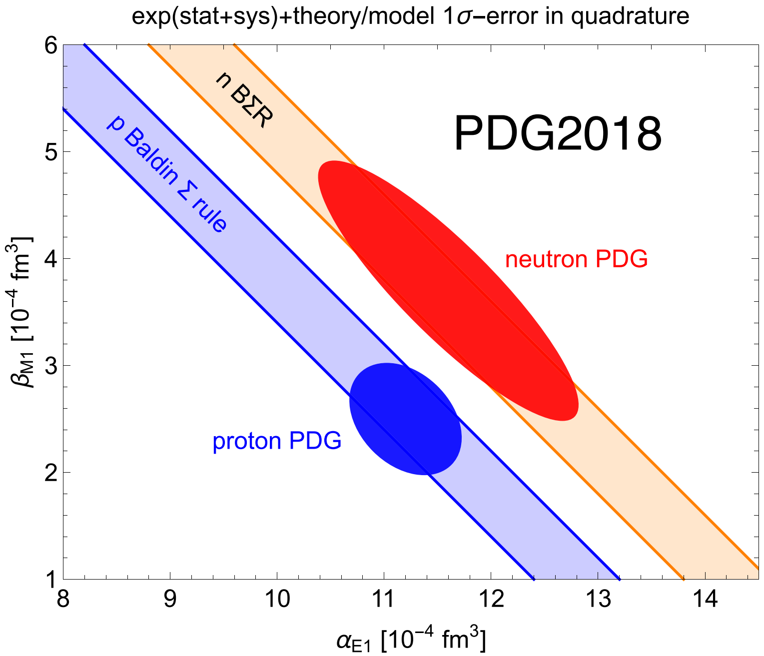
$$\bar{A}_2(\omega, z) = -\frac{4\pi W}{M}\beta_{M1}(\omega)\,\omega^2 + \mathcal{O}(l=2),$$











- α_{E1}: charged pion-cloud dynamics
- β_{M1}: diamagnetic pion charge current dynamics + diamagnetic constituent quarks

Baldin sum rule

$$\alpha_{E1} + \beta_{M1} = \frac{1}{2\pi^2}\int_{\nu_0}^{\infty}\frac{\sigma_T}{\nu^2}d\nu$$

Baldin sum rule

$$\alpha_{E1}^{(p)} + \beta_{M1}^{(p)} = 13.8 \pm 0.4$$

$$\alpha_{E1}^{(n)} + \beta_{M1}^{(n)} = 15.2 \pm 0.4$$

$$\alpha_{E1}^{(p)} = 11.2 \pm 0.4 \quad \beta_{M1}^{(p)} = 2.5 \pm 0.4$$

$$\alpha_{E1}^{(n)} = 11.8 \pm 1.1 \quad \beta_{M1}^{(n)} = 3.7 \pm 1.2$$

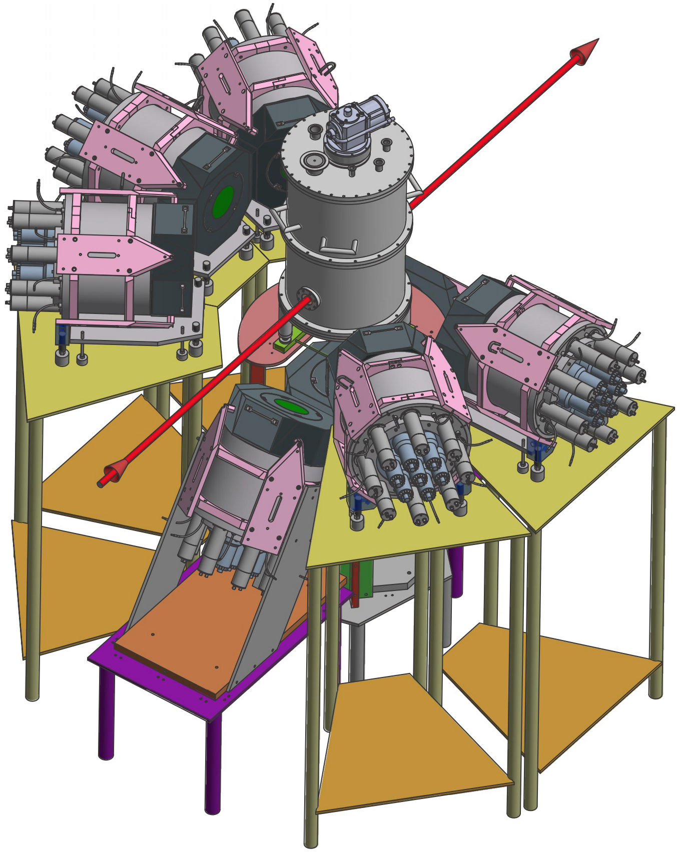
R. P. Hildebrandt, H.W. Griesshammer, T.R. Hemmert and B. Pasquini, Eur. Phys. J. A **20**, 293 (2004).

HIGS: Proton scalar polarizabilities – experiment setup

PHYSICAL REVIEW LETTERS **128,** 132502 (2022)

Proton Compton Scattering from Linearly Polarized Gamma Rays

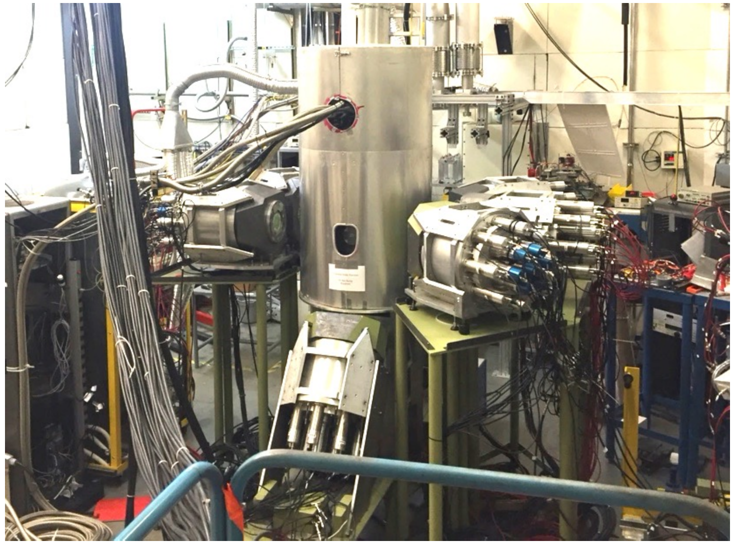
X. Li,[1,2,*] M. W. Ahmed,[2,3] A. Banu,[4] C. Bartram,[2,5] B. Crowe,[2,3] E. J. Downie,[6] M. Emamian,[2] G. Feldman,[6] H. Gao,[1,2] D. Godagama,[7] H. W. Grießhammer,[6,1] C. R. Howell,[1,2] H. J. Karwowski,[2,5] D. P. Kendellen,[1,2] M. A. Kovash,[7] K. K. H. Leung,[1,2,8] D. M. Markoff,[2,3] J. A. McGovern,[9] S. Mikhailov,[2] R. E. Pywell,[10] M. H. Sikora,[6,2] J. A. Silano,[2,5] R. S. Sosa,[3] M. C. Spraker,[11] G. Swift,[2] P. Wallace,[2] H. R. Weller,[1,2] C. S. Whisnant,[4] Y. K. Wu,[1,2] and Z. W. Zhao[1,2]

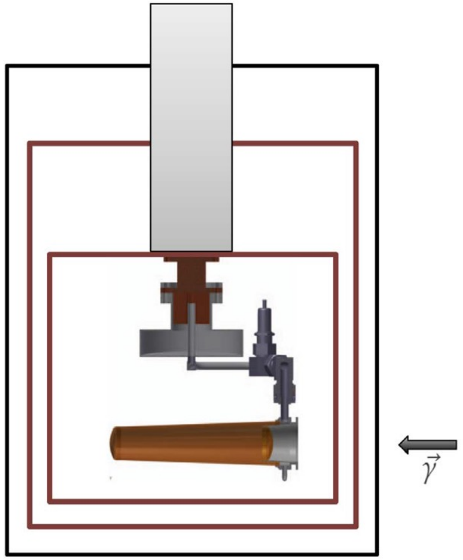


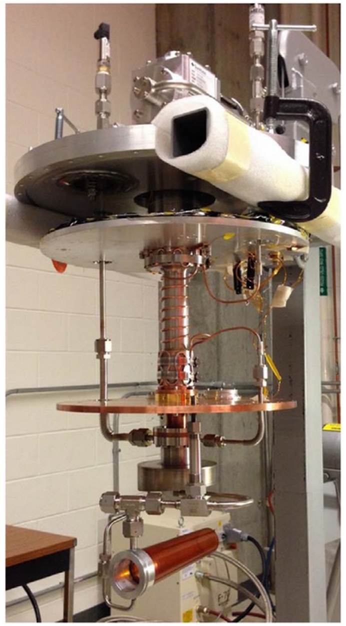
Circular pol.: E_γ = 81.3 MeV; $\frac{d\sigma(\theta)}{d\Omega}$

Linear pol.: E_γ = 83.4 MeV; $\Sigma_3(\theta)$

θ = 55°, 90°, and 125°





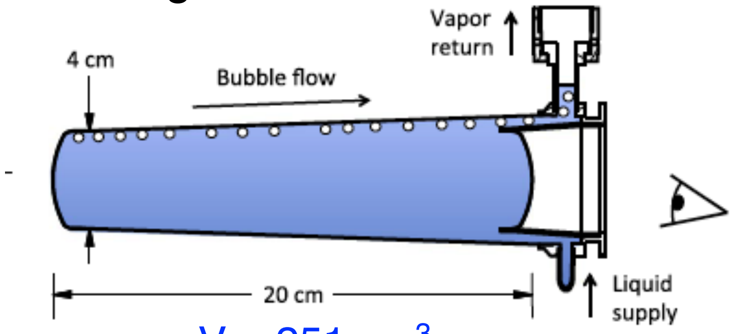


Coll. dia. = 25 mm

$I_\gamma = 10^7\ \gamma$/s

Liquid H Target

Kendellen et al., NIMA 840 (2016) 174



V = 251 cm^3

HIGS: Proton scalar polarizabilities - $d\sigma/d\Omega$ and Σ_3 measurements

TUNL

PHYSICAL REVIEW LETTERS **128,** 132502 (2022)

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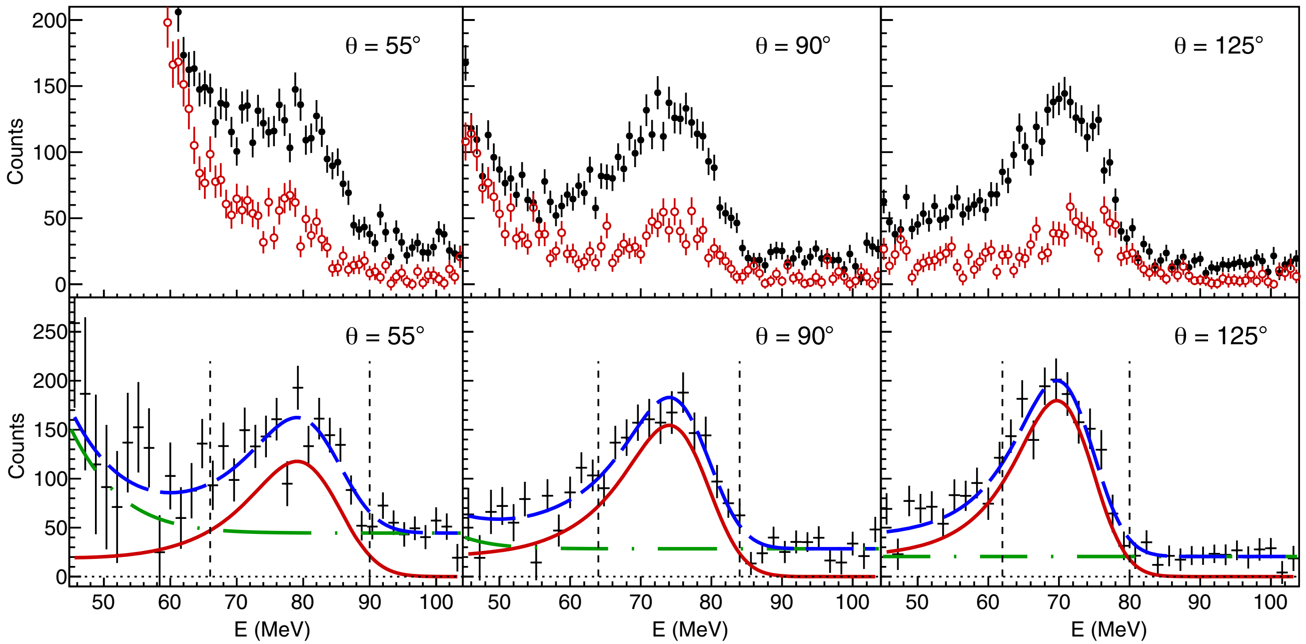

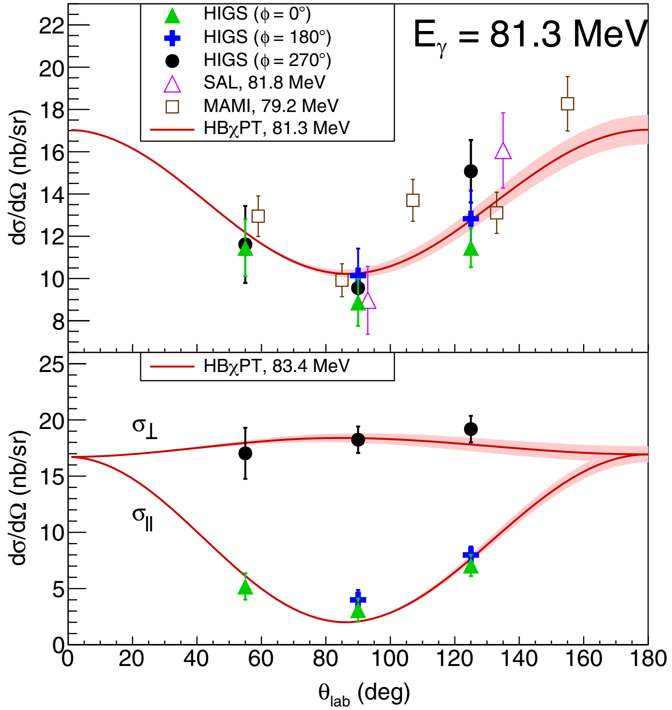

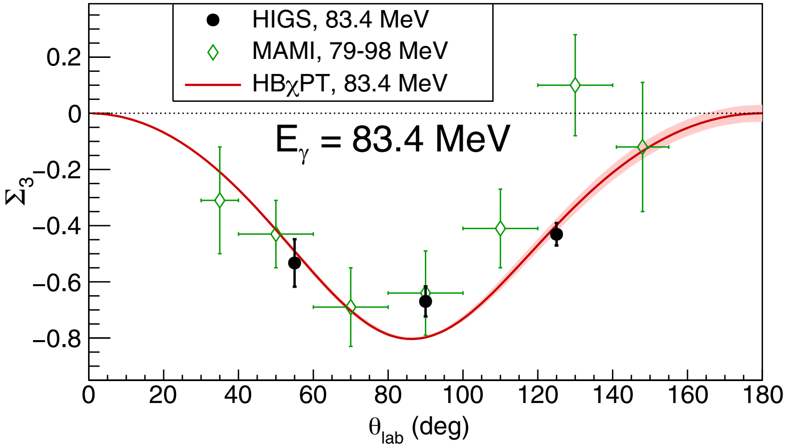

$$\Sigma_3 = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$$

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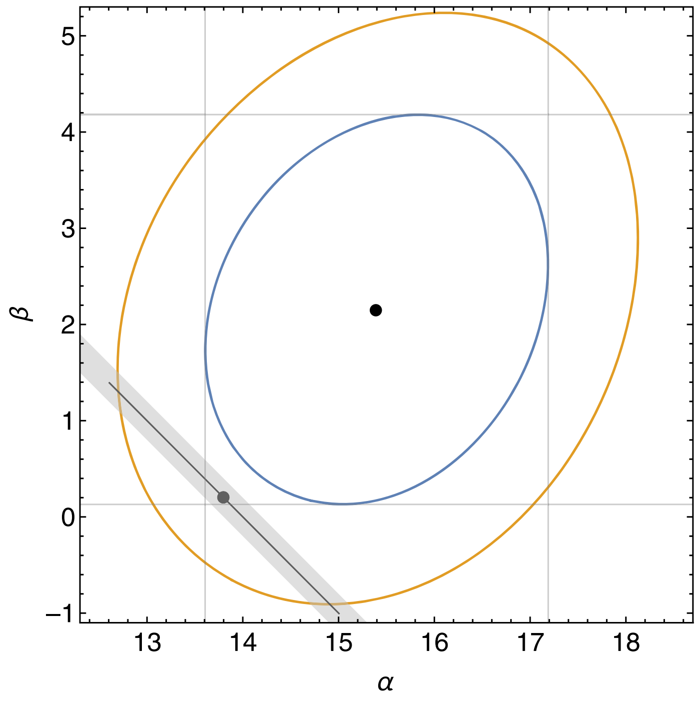


Without BSR applied

$$\alpha^p_{E1} = 15.4 \pm 1.8_{\text{stat}},$$
$$\beta^p_{M1} = 2.1 \pm 2.0_{\text{stat}},$$

With BSR applied

$$\alpha^p_{E1} = 13.8 \pm 1.2_{\text{stat}} \pm 0.1_{\text{BSR}} \pm 0.3_{\text{theo}},$$
$$\beta^p_{M1} = 0.2 \mp 1.2_{\text{stat}} \pm 0.1_{\text{BSR}} \mp 0.3_{\text{theo}},$$

PDG2018 values

$$\alpha^{(p)}_{E1} = 11.2 \pm 0.4$$
$$\beta^{(p)}_{M1} = 2.5 \pm 0.4$$

HIGS: Neutron scalar polarizabilities, dσ/dΩ measurements on ^{2}H

PRELIMINARY

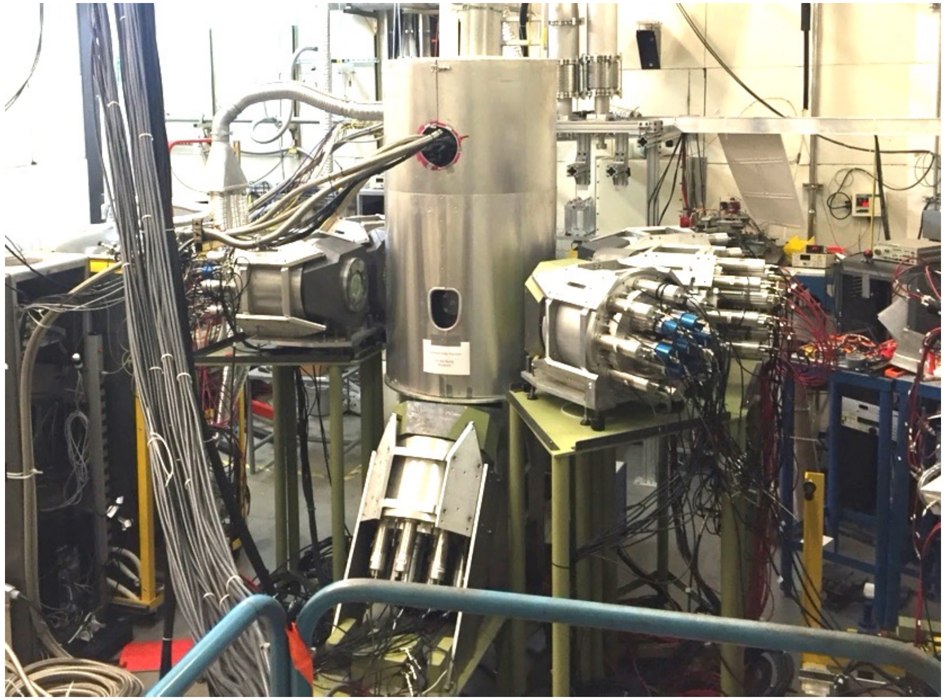
Elastic and Inelastic Compton Scattering from Deuterium at 65 and 85 MeV

Mohammad Ahmed (Spokesperson)
Department of Mathematics and Physics, North Carolina Central University, Durham, NC 27707, 919-530-6100, ahmed2@nccu.edu

Michael A. Kovash (Spokesperson)
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-005.
859-257-1150, kovash@pa.uky.edu

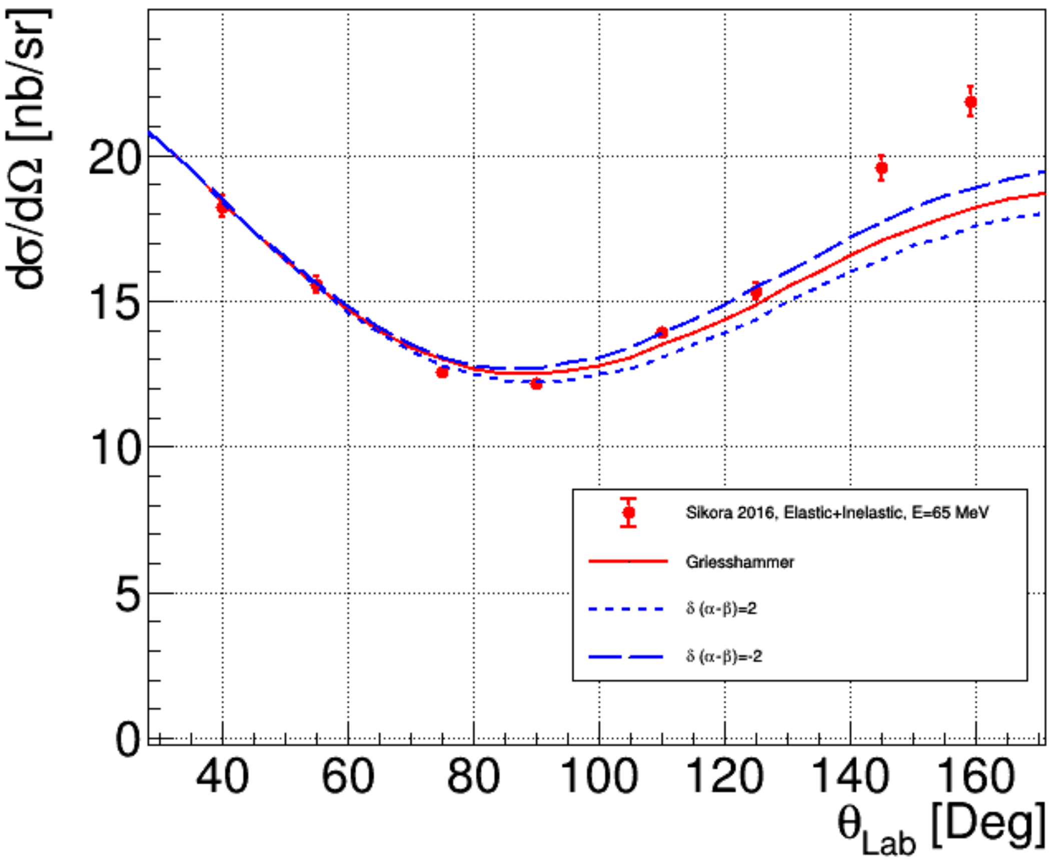
Compton@HIγS Collaboration

June 23, 2017



HIGS expt. P-13-17

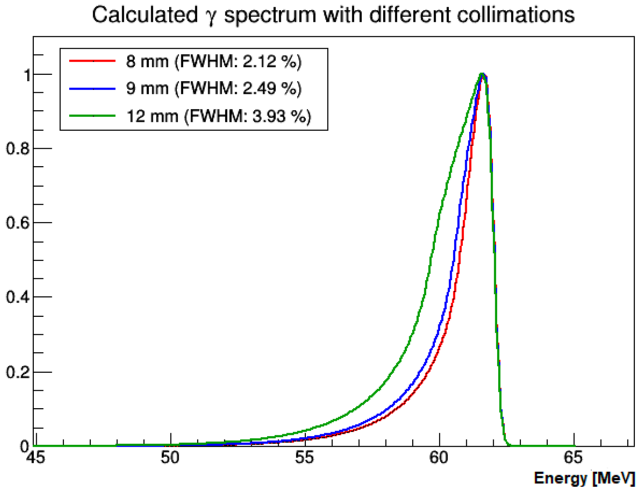
E_γ = 65 MeV

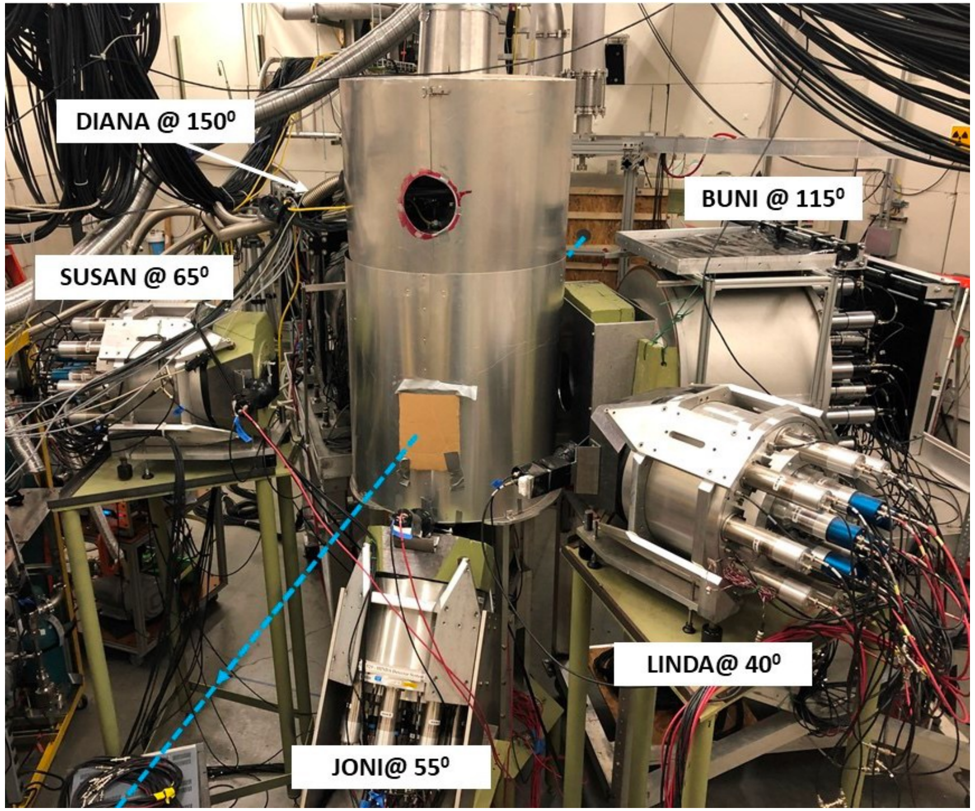


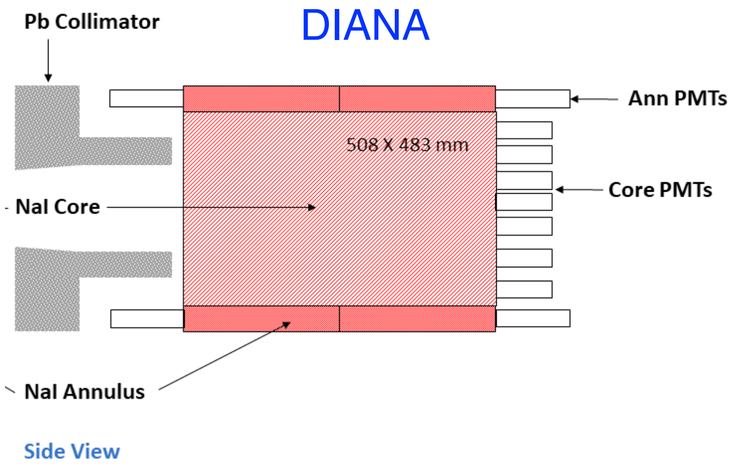
Elastic and Inelastic Compton Scattering from Deuterium at 61 MeV

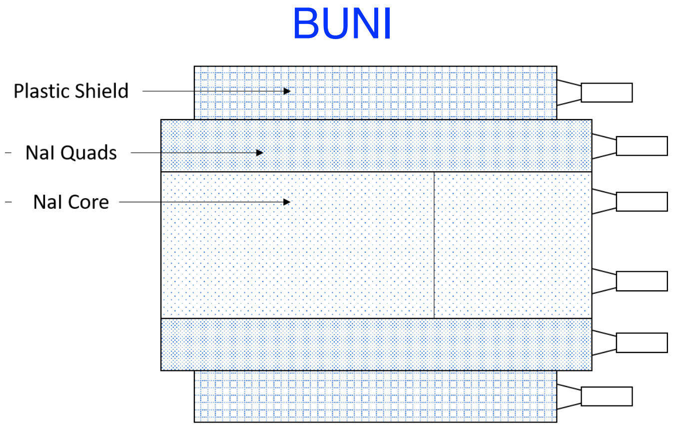
Ph.D Thesis

Danula Godagama, University of Kentucky



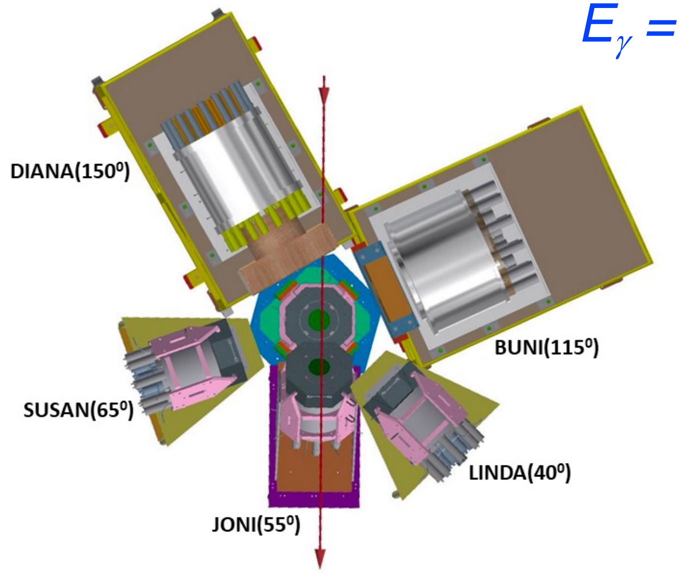


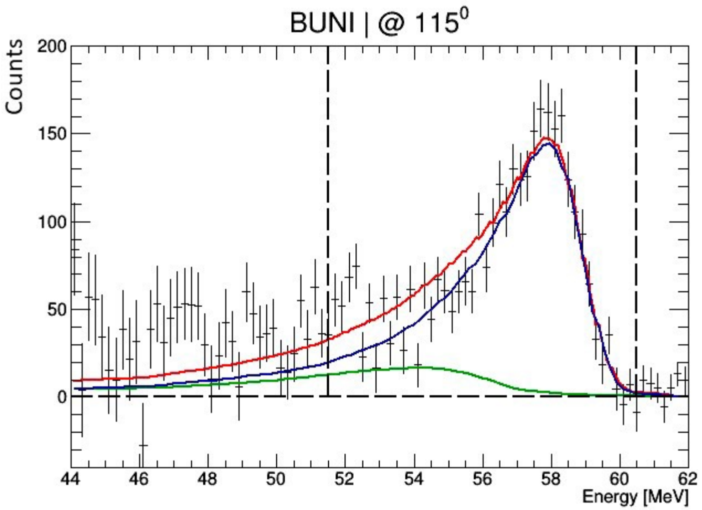


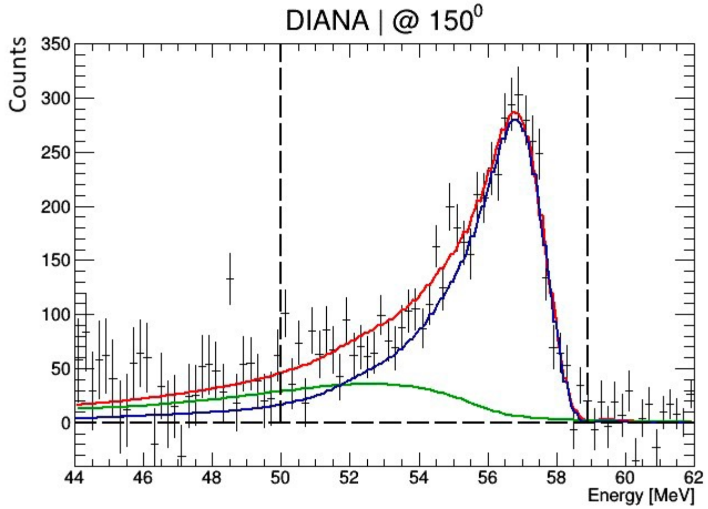


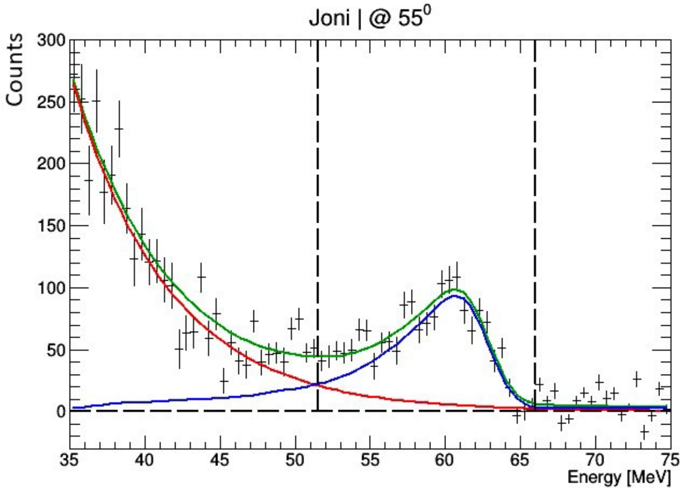
HIGS: Neutron scalar polarizabilities, dσ/dΩ measurements on ^2H

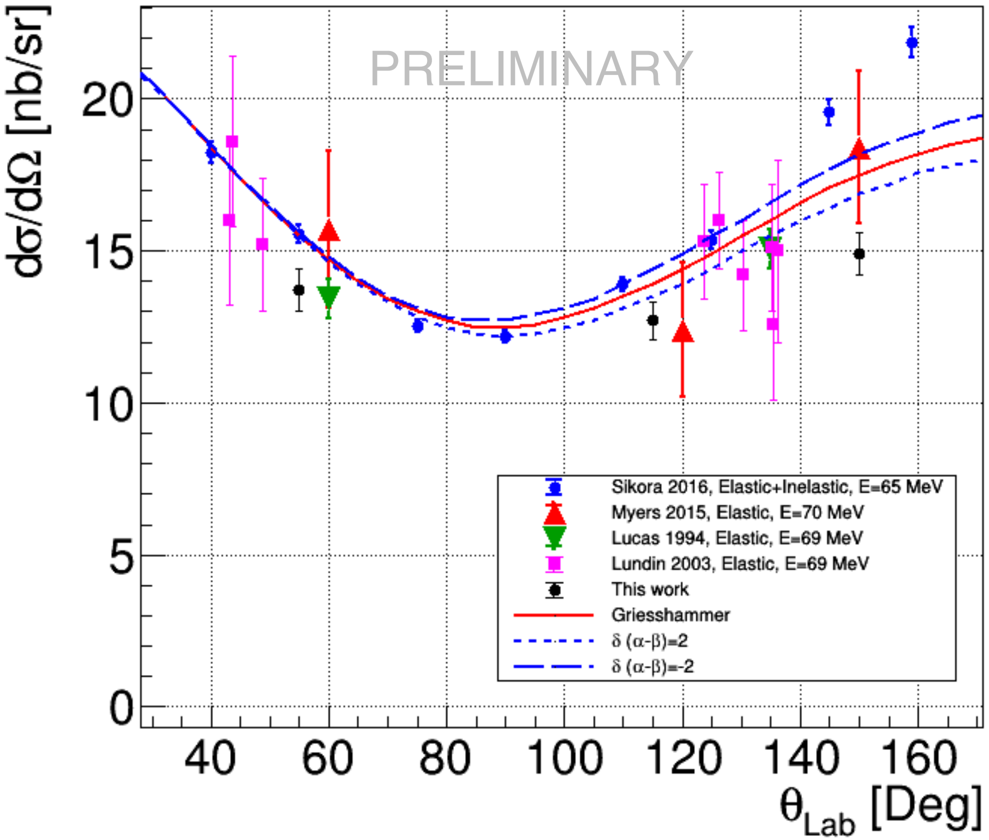
$E_\gamma = 61$ MeV



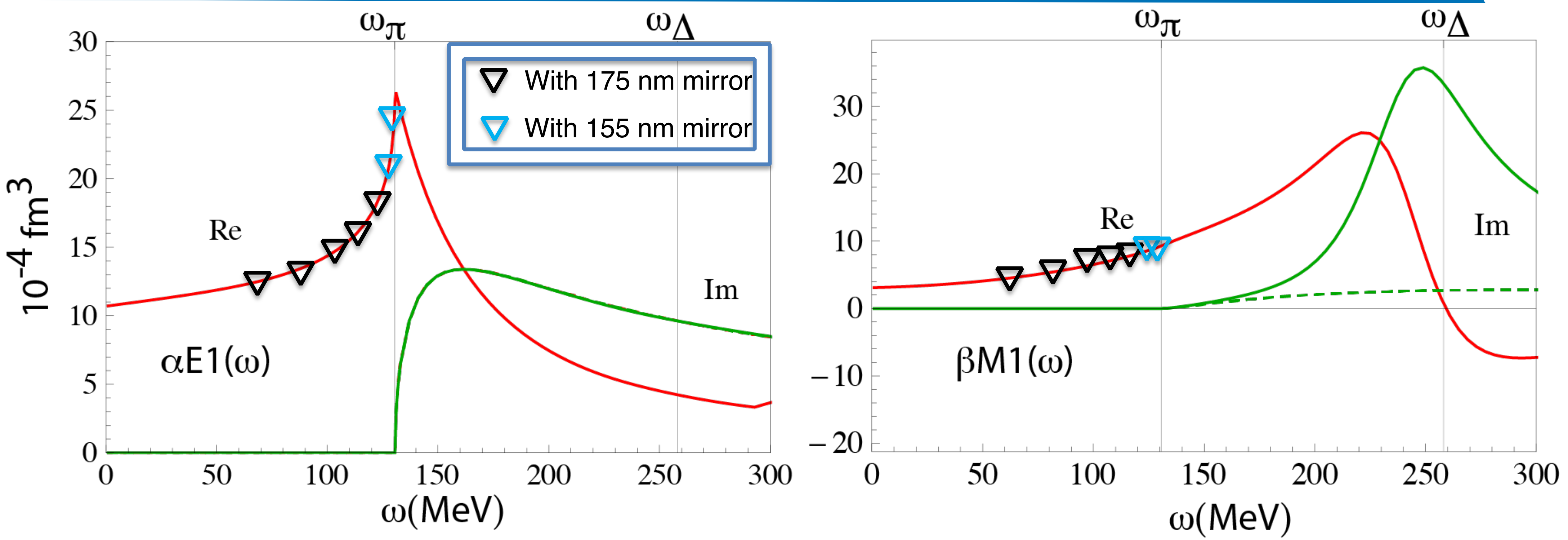








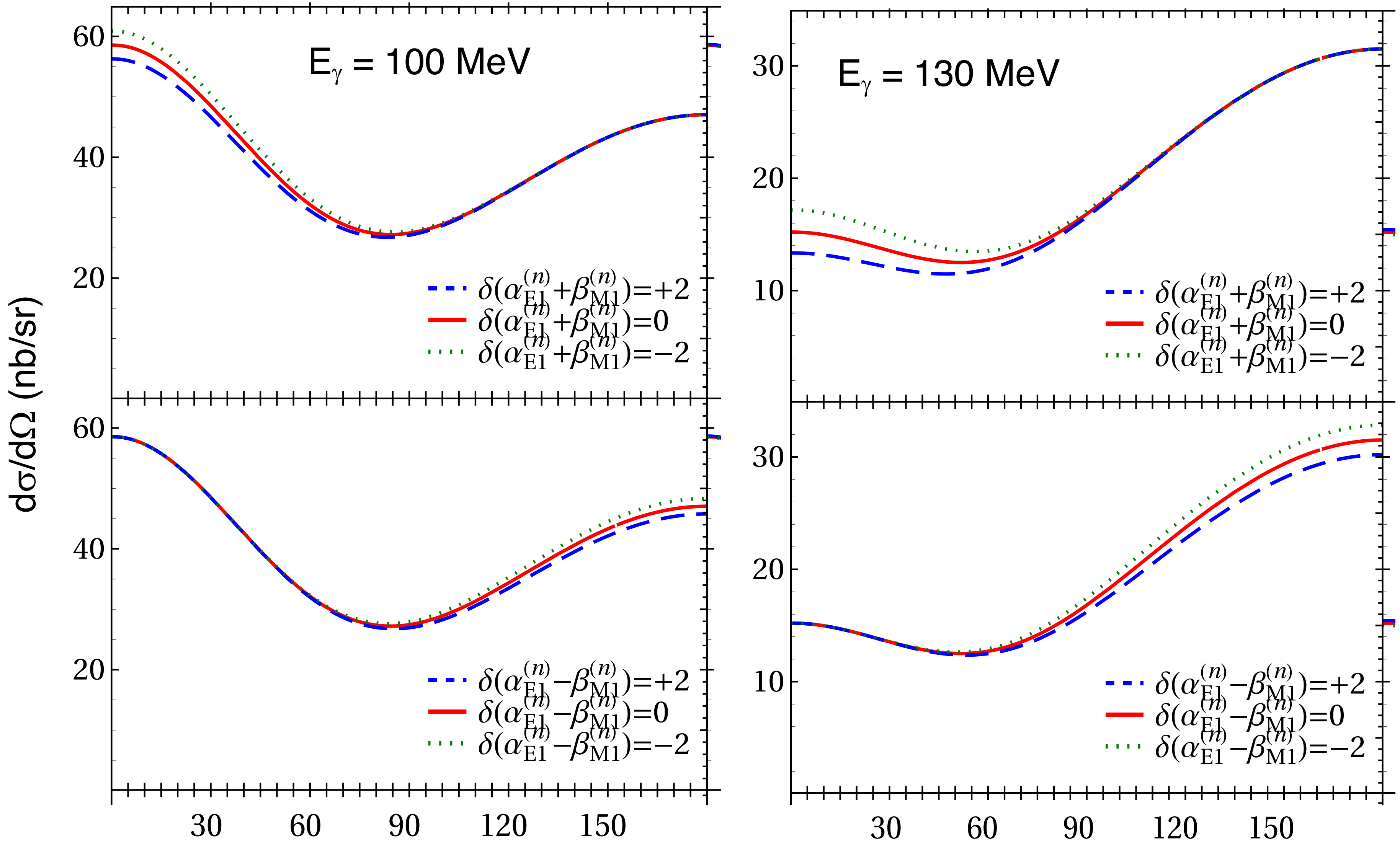
HIGS: R&D of FEL optical cavity mirrors for Compton Scattering



- **Major focus on measurements of neutron EM polarizabilities**
  - Compton scattering from liquid H,D,^{3}He, and ^{4}He targets at E_γ = 65 - 130 MeV
  - E_γ = 65 - 100 MeV made possible through development of 193-nm cavity mirrors
  - E_γ = 100 - 120 MeV made possible through development of 175-nm cavity mirrors by collaboration of TUNL-Laser Zentrum Hannover (LZH)
  - E_γ = 120 - 150 MeV with 155-nm mirrors, R&D underway with TUNL-LZH collaboration

HIGS Compton Scattering: ^{3}He as target for neutron

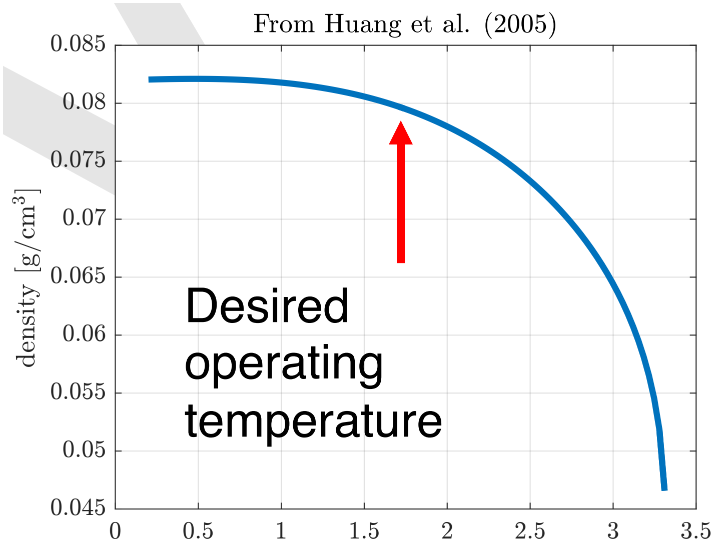
Potential: Nogga-IdahoN3LO+3NIb

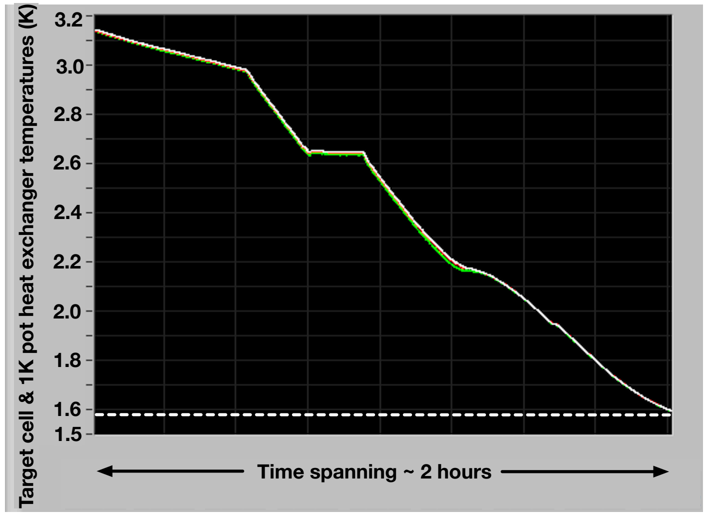


HIGS: Development of cryogenic liquid ^{3}He target for Compton scattering

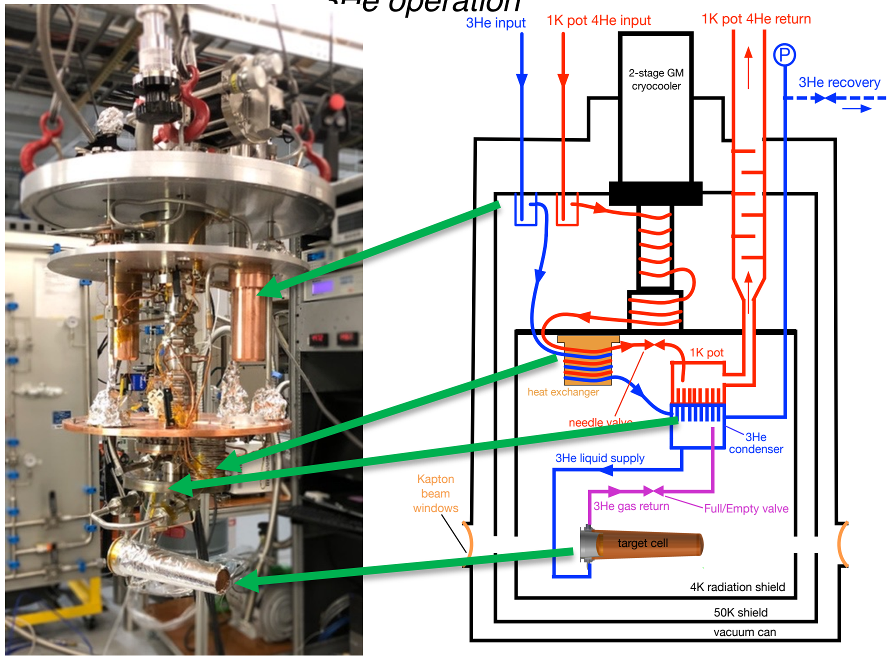
- The desired operating temperature of 0.3 L liquid ^{3}He target cell is 1.7 K. Compared to normal boiling point of 3.2 K, this increases density, reduces dρ/dT , and increases the latent heat of vaporization.
- The upgrade (addition of recirculating dry 1K pot) of the HIGS cryotarget's internal components has been completed.
- Cool-down test with liquid ^{4}He in cryotarget in final experiment location and conditions reached < 1.6 K.
- Inventory (350 bar-liters) of ^{3}He gas now on hand at TUNL
- Developing the gas handling systems and procedures for safely operating and managing this large ^{3}He inventory

Task leader: Kent Leung, Montclair State Univ.





Left: photo of inside cryotarget after internal components upgrade. Right: schematic of cryotarget for 1.7K liquid ^{3}He operation



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https://doi.org/10.1140/epja/s10050-021-00382-2

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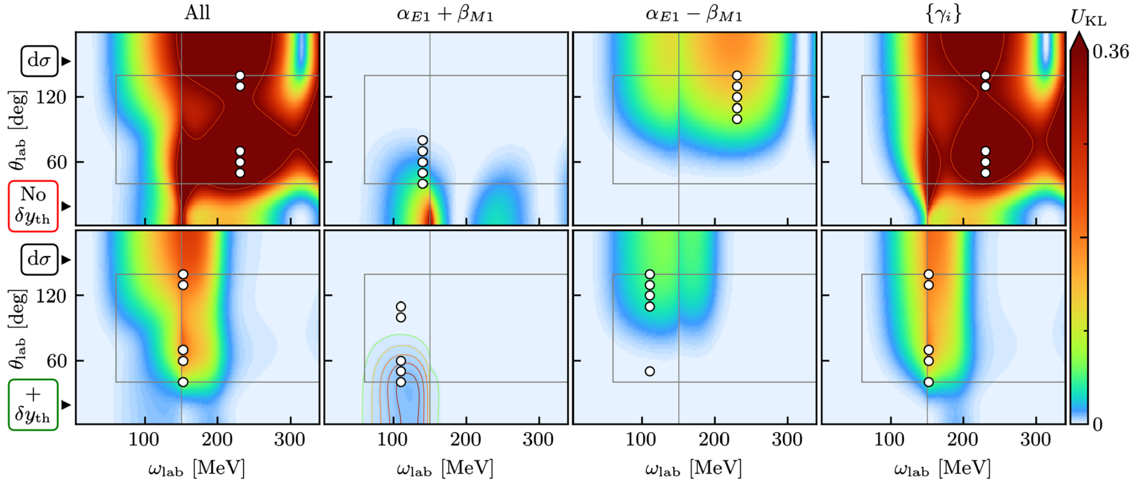
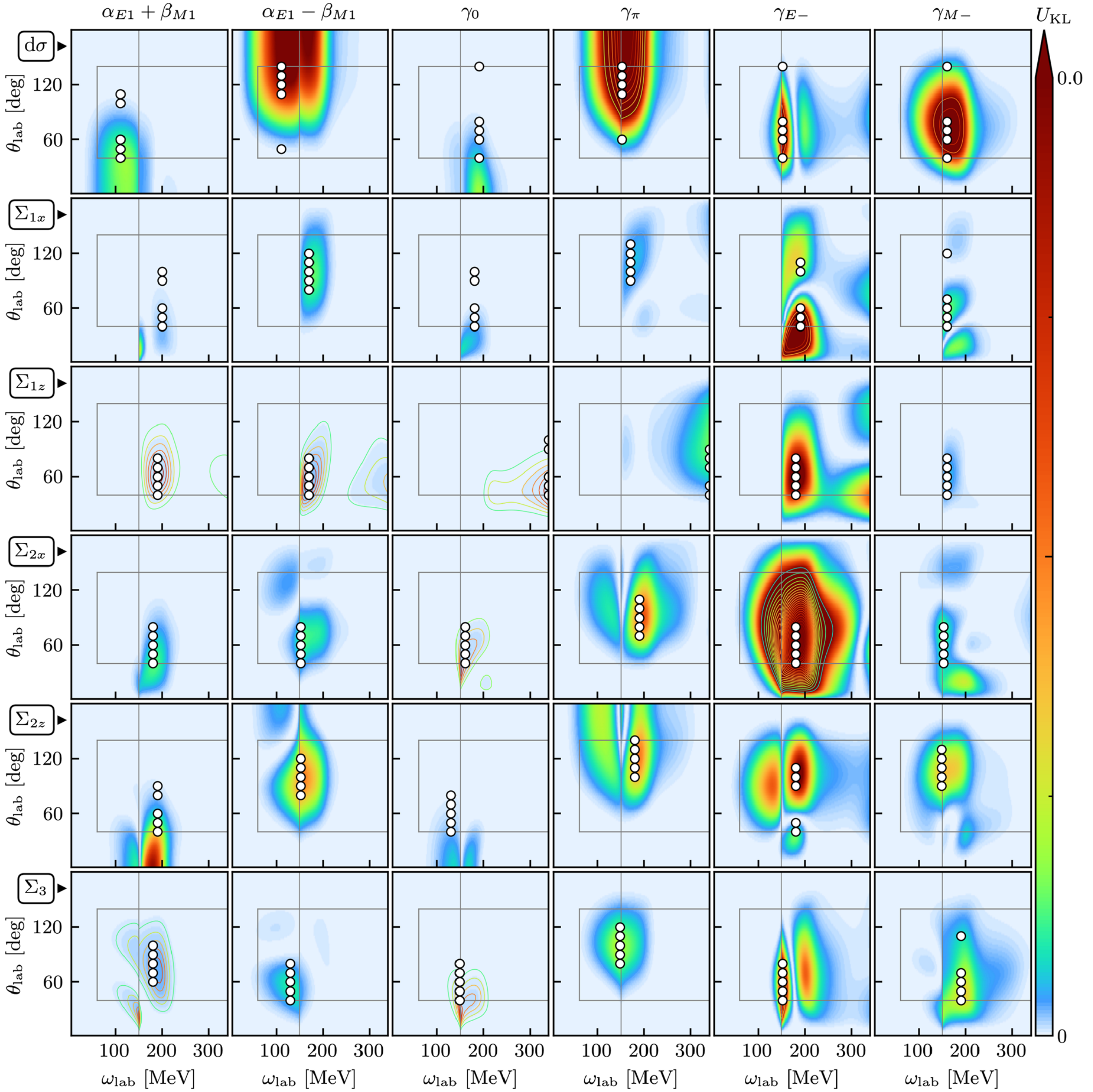
Designing optimal experiments: an application to proton Compton scattering

J.A. Melendez, R.J. Furnstahl, H.W. Grießhammer,
J.A. McGovern, D.R. Phillips, M.T. Pratola

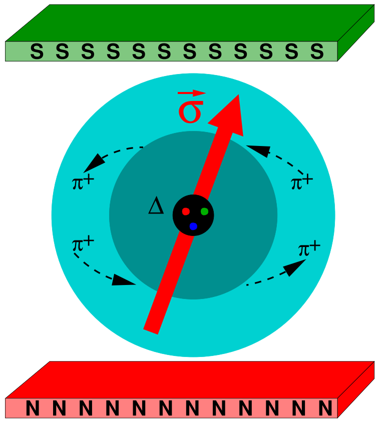


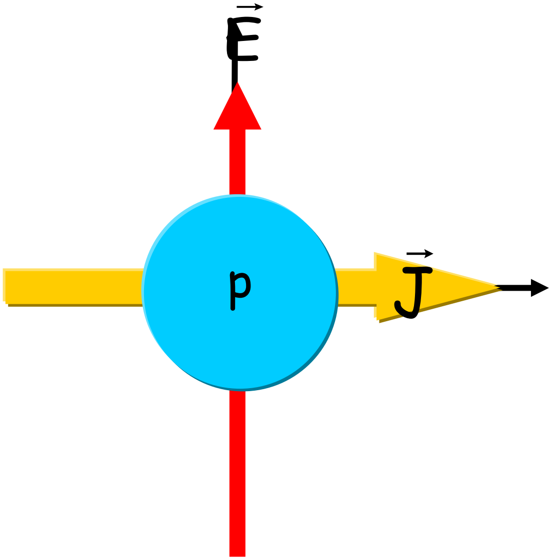
$$\gamma_{E-} = \gamma_{E1E1} - \gamma_{E1M2}$$
$$\gamma_{M-} = \gamma_{M1M1} - \gamma_{M1E2}$$

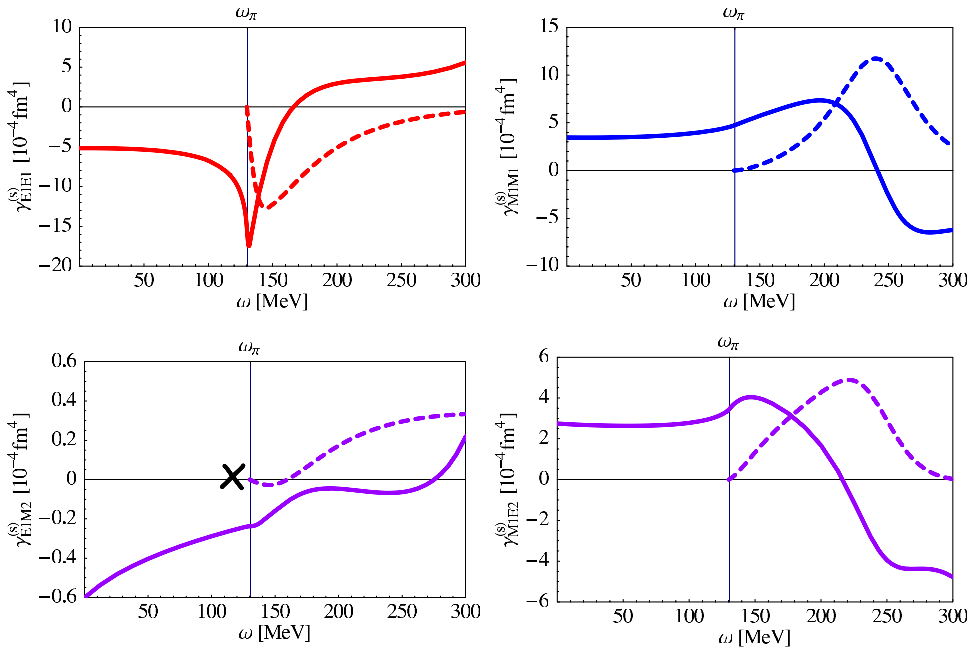


TUNL

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







- The spin-dependent polarizabilities enter the Hamiltonian in terms that involve spin-flip operators
- A rotating E-field or B-field will induce a precession of the nucleon spin axis around the momentum direction of the circularly polarized photon with a rate proportional to the magnitude of the associated spin polarizability.
- Energy dependence of the spin polarizabilities indicates interplay of pion and Delta dynamics in the low-energy response of nucleons: test of chiral dynamics

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2}$$

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2}$$

$$\gamma_0 = -\frac{1}{4\pi^2}\int_{\omega_{th}}^{\infty}\frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega^3}d\omega$$

R. P. Hildebrandt, H.W. Griesshammer, T.R. Hemmert and B. Pasquini, Eur. Phys. J. A **20**, 329 (2004).
D.R. Paudyal, PhD Thesis, Univ. Regina (2017).

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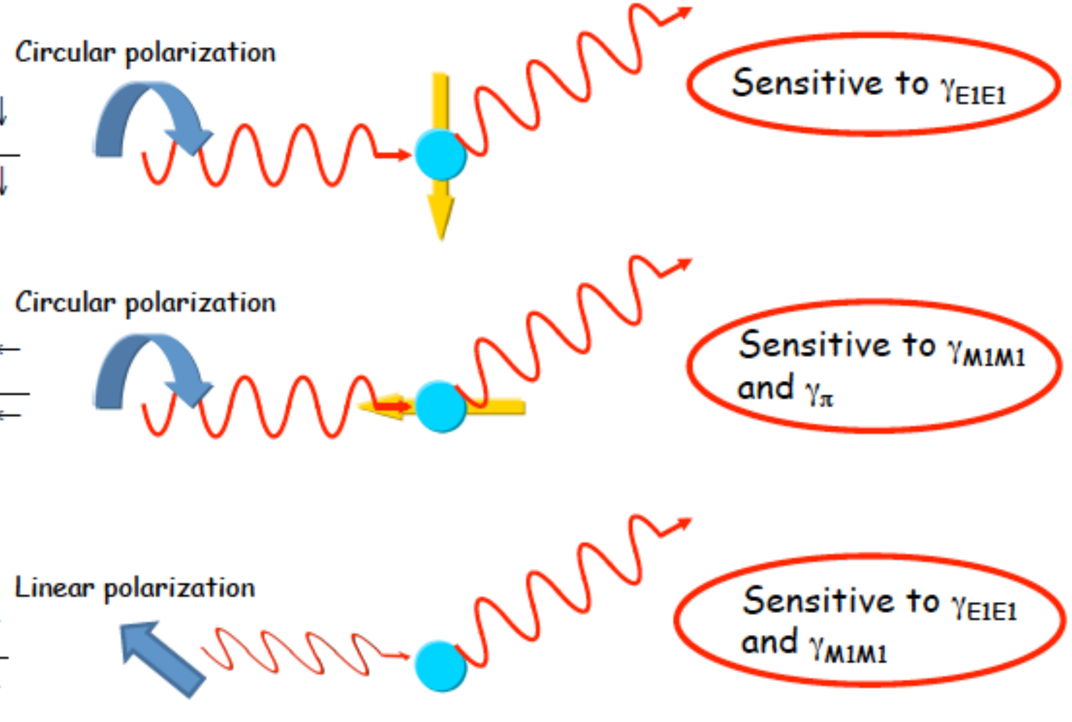
HIGS Scientific Program: Determination of the spin-dependent polarizabilities

Polarized photon beam and polarized target required

$$\Sigma_{2x} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$\Sigma_{2z} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$

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



$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2}$$
$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2}$$

$\gamma_0 = (-1.00 \pm 0.13) \times 10^{-4}\ \text{fm}^4$ J. Ahrens *et al.* (GDH/A2), PRL **87**, 022003 (2001); H. Dutz et al. (GDH), PRL **91**, 192001 (2003).

Recent result from MAMI

$\gamma_\pi = (-38.7 \pm 1.8) \times 10^{-4}\ \text{fm}^4$ M. Camen *et al.*, PRC **65**, 032202(R) (2022).

Beam Polarization

i = 1: unpolarized
i = 2: circular polarization
i = 3: linear polarization

Recent Measurements:

Observable	Proton	Neutron: ^{2}H	Neutron: ^{3}He	Neutron: ^{4}He
$d\sigma/d\Omega$	MAMI/ **HIGS**	**HIGS**	**HIGS**	**HIGS**
Σ_3	MAMI/ **HIGS**			
Σ_{2x}	MAMI **HIGS**	**HIGS**		
Σ_{2z}	MAMI **HIGS**	**HIGS**		

HIGS unpolarized targets
HIGS liquid ^{3}He target
HIGS with polarized target capability

Compton scattering at HIGS: Tomorrow

TUNL

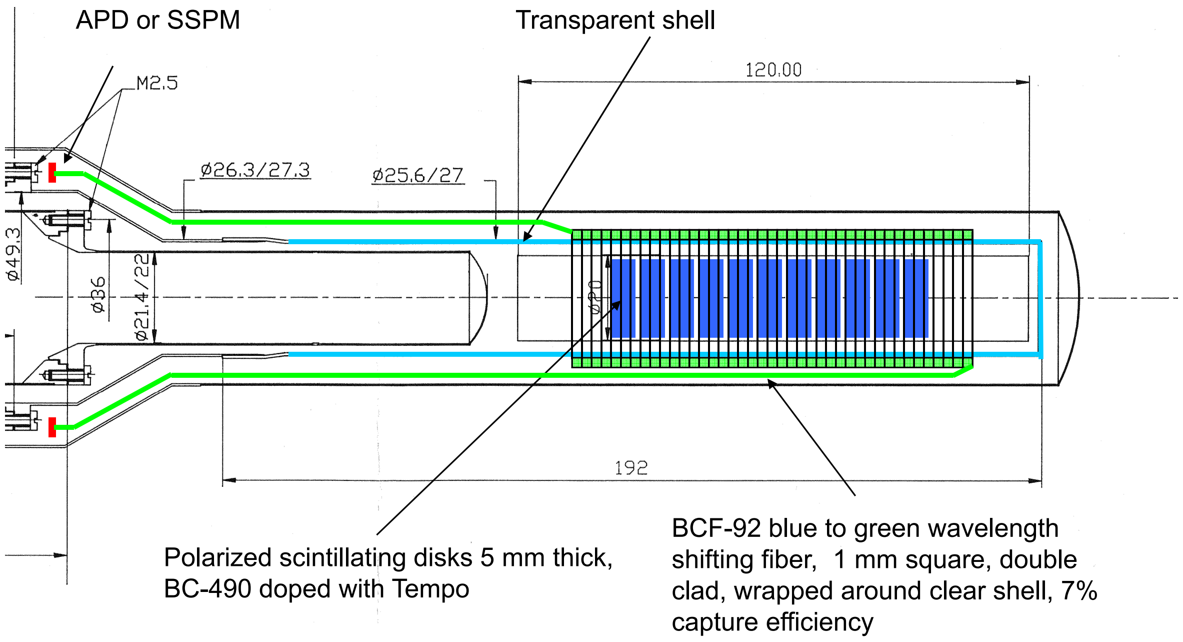
- **Reduce uncertainty in the neutron scalar polarizabilities**
  - The goal is to reduce the uncertainties to be on par with the proton
  - Perform high-precision cross-section and Σ_3 Compton-scattering measurements on ^{2}H, ^{3}He and ^{4}He at E_γ = 100 to 130 MeV (e.g., map out $\alpha^n(\omega)$ over the π production threshold cusp)
- **Map out proton scalar polarizabilities over the unitary cusp**
  - Perform cross-section and Σ_3 Compton-scattering cross-section measurements on the proton at E_γ = 100 to 150 MeV
- **Determine proton spin polarizabilities up to pion-production threshold**
  - Measure asymmetry data (Σ_3, Σ_{2z} and Σ_{2x}) at energies E_γ = 100 to 130 MeV; complement data from Mainz
  - Use several χEFT calculations for reliable assessment of model dependence
- **Determine the neutron spin polarizabilities**
  - Measure asymmetry data (Σ_{2z} and Σ_{2x}) at energies E_γ = 100 to 300 MeV for Compton-scattering on polarized ^{2}H and ^{3}He targets; E_γ = 100 – 150 MeV at HIGS and E_γ = 250 – 300 MeV at Mainz

Compton scattering at HIGS: Goals for next 3 years and beyond

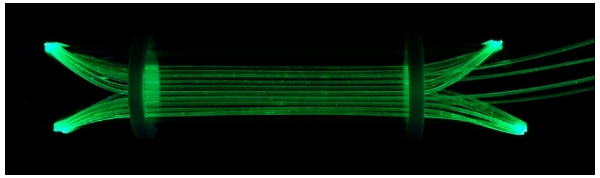
- **Reduce uncertainty in the neutron scalar polarizabilities**
  - The goal is to reduce the uncertainties to be on par with the proton
  - Perform high-precision cross-section and Σ_3 Compton-scattering measurements on ^2H, ^3He and ^4He at E_γ = 100 to 130 MeV (e.g., map out $\alpha^n(\omega)$ up to the π production threshold cusp)
- **Map out proton scalar polarizabilities over the unitary cusp**
  - Perform cross-section and Σ_3 Compton-scattering cross-section measurements on the proton at E_γ = 100 to 130 MeV
- **Establish a Cryogenic Polarized Proton Program**
  - Obtain funding for a TUNL staff position in low-temperature physics to lead polarized target R&D program
  - Obtain funding to build polarized target technical infrastructure
- **Improve determination of proton spin polarizabilities**
  - Measure asymmetry data (Σ_{2z} and Σ_{2x}) at energies E_γ = 100 to 130 MeV; complement data from Mainz at E_γ = 260 - 310 MeV
  - Use several χEFT calculations for reliable assessment of model dependence
- **Determine the neutron spin polarizabilities**
  - Measure asymmetry data (Σ_{2z} and Σ_{2x}) at energies E_γ = 100 to 130 MeV for Compton-scattering on polarized ^2H at E_γ = 100 – 130 MeV

HIGS Scientific Program: Polarized Target Capabilities at TUNL

Scintillating polarized target



Polarizable scintillators in prototype quartz target cell



Wave shifting fiber readout for the HIGS target cell, illumination in blue light for fluorescence

Scintillating Polarized Proton Target at MAMI

M. Biroth et al. (A2), PoS PSTP 2015, 005 (2015).

- Proton polarization ≈ 70%
- Relaxation time ≈ 22 hours
- MAMI group has identified commercial SiPM that operates at 5 K
- Light output ≈ 30% of standard plastic scintillator

Effort limited funding profile

FY	Amount (F23$)	Description
26	2,300,000	Dry dilution refrig. + 5T SC magnet + low-temp target infrastructure
27	500,000	(proton) Specialized electronics
28	500,000	(proton) complete systems for polarizing and measuring target polarization
29	100,000	(proton) Installation in target room, commissioning and operation
30	100,000	(proton) Operation
31	500,000	(deuteron) target development
32	250,000	(deuteron) target development
33	150,000	(deuteron) Install in target room and commission
Total	**4,400,000**	