Low-Energy QCD Research at *HIGS*:

Nucleon Structure and *Strong Nuclear Force in Few-Nucleon Systems*

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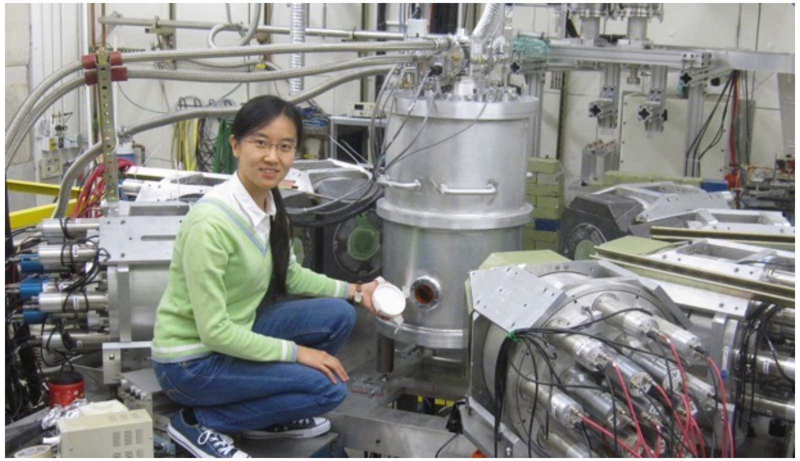

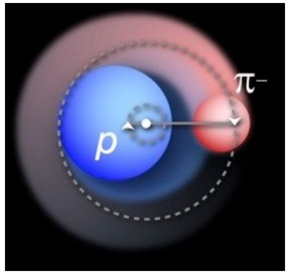

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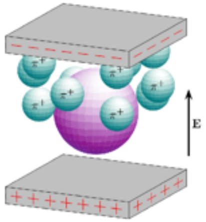
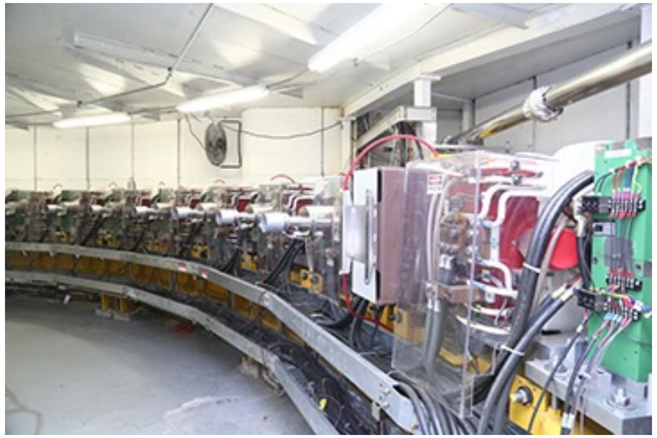
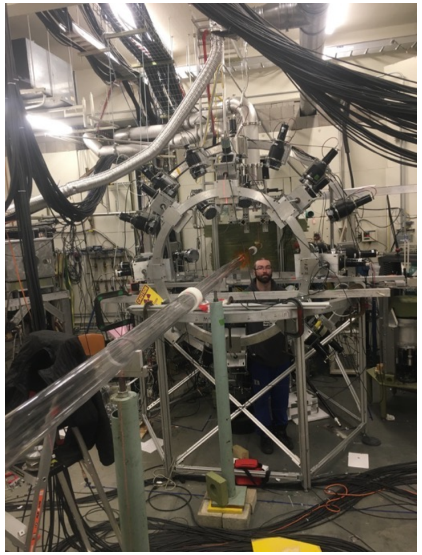
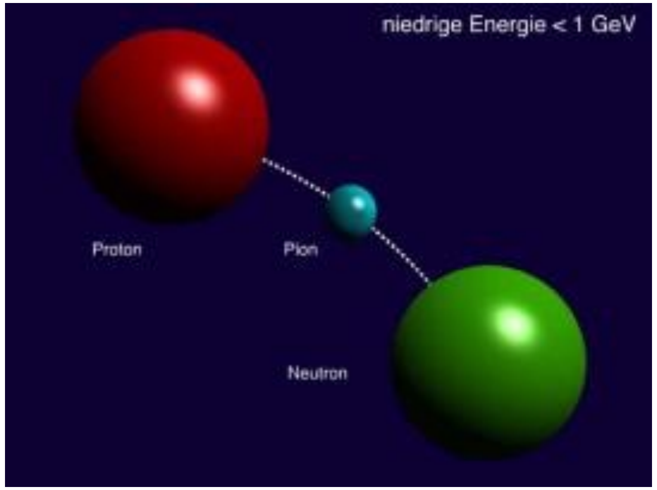


Program Components:

- Nucleon structure in terms of collective degrees of freedom: Compton scattering at E_γ > 60 MeV
- Investigation of the strong nuclear force in the context of few-nucleon systems: *photodisintegration of 3N systems*







High Intensity Gamma-ray Source (HIγS)

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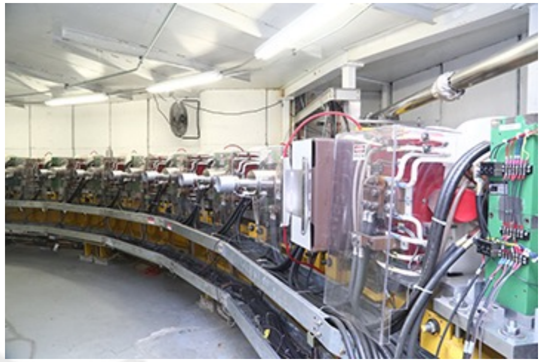
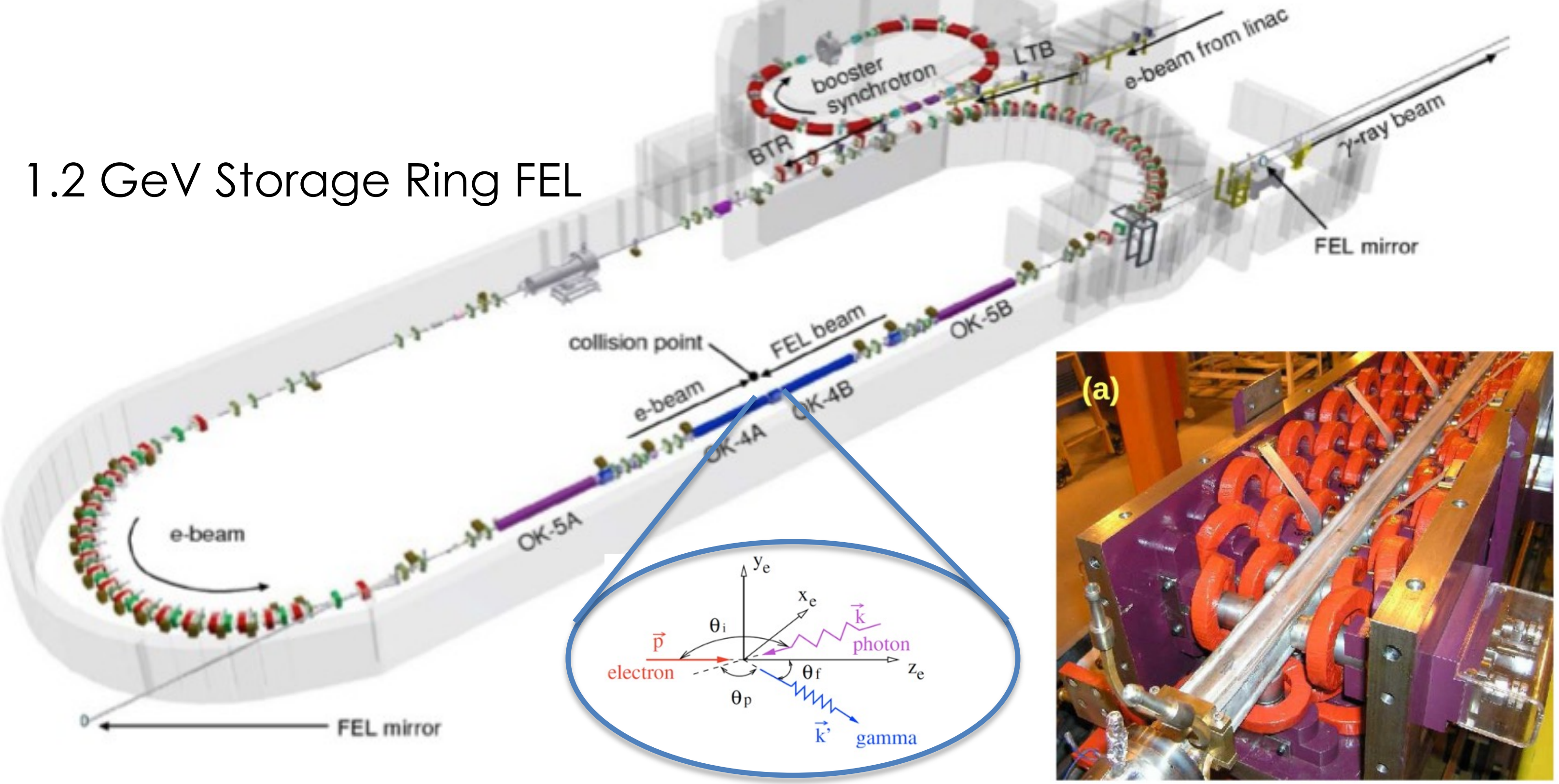
Most intense Compton γ-ray source in the world



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



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Researchers from 19 institutions: 13 USA + 6 international

A. Compton Scattering Collaboration

1) **Duke:** H. Gao, C. Howell, W. Tornow, Y. Wu
2) **NCCU:** M. Ahmed, B. Crowe, D. Markoff
3) **UNC-CH:** H. Karwowski
4) **GWU:** E. Downie, J. Feldman, H. Griesshammer
5) **James Madison Univ.:** A. Banu and S. Whisnant
6) **North Georgia State Univ.:** M. Spraker?
7) **Ohio Univ.:** D. Phillips
8) **Univ. Kentucky:** M. Kovash
9) **Univ. Manchester:** J.A. McGovern
10) **Univ. New Hampshire:** R. Miskimen
11) **Univ. Saskatchewan:** R. Pywell
12) **Mount Alison Uni**, David Hornidge
13) **MontClair State Univ.**, Kent Leung

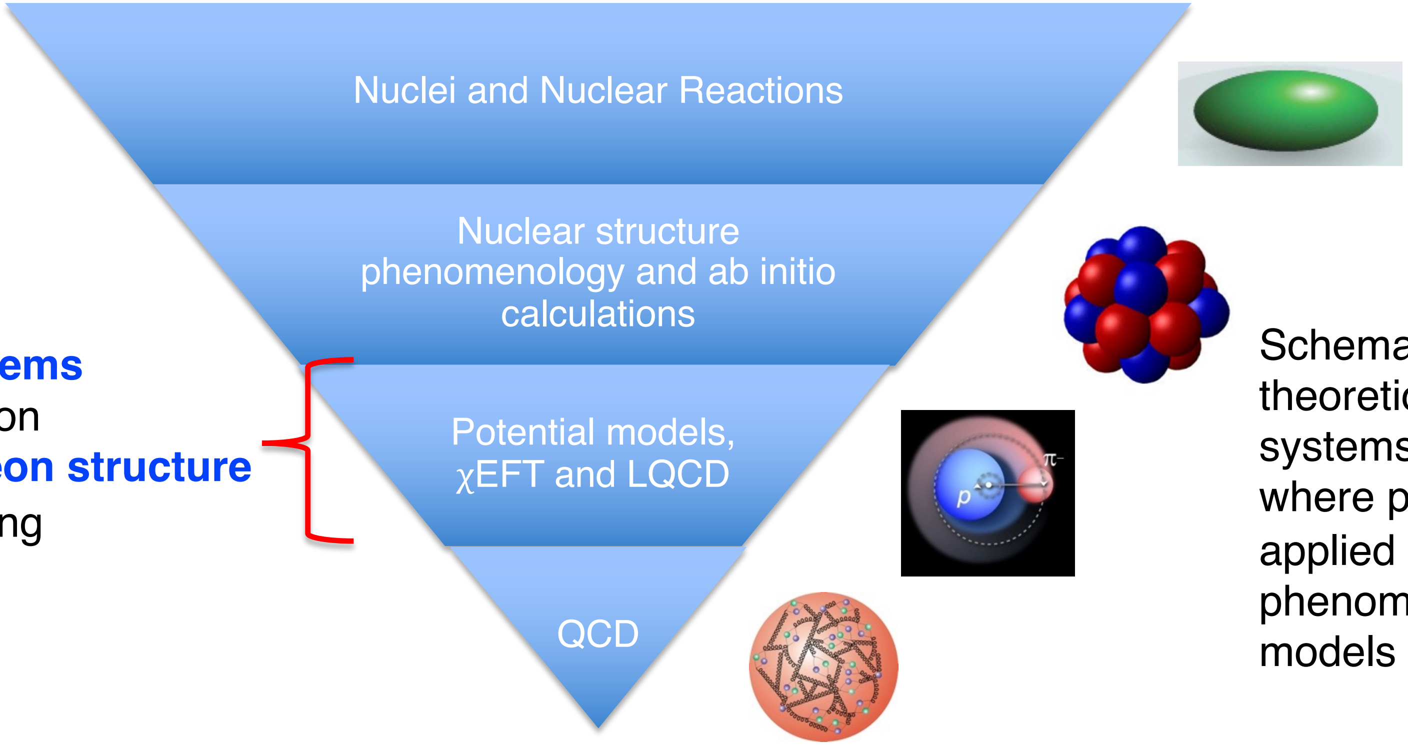
B. Few-Nucleon Systems

1) **Duke:** H. Gao, C. Howell, W. Tornow, Y. Wu
2) **NCCU:** M. Ahmed, B. Crowe, D. Markoff
3) **UNC-CH:** H. Karwowski
4) **Budker Inst. Nucl. Phys., Russia:** R.N. Lee, A.I. Milstein, V.M. Strakhovenko
5) **Jagiellonian Univ.:** H. Witała
6) **JLab:** D.W. Higinbotham, B. Sawatzky
7) **Univ. Rochester:** C.J. Forrest, W. Shmayda
8) **Univ. Saskatchewan:** R. Pywell,
9) **UVA:** B. Norum and D. Crabb
10) **Vilnius Univ., Lithuania:** A. Deltuva

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



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

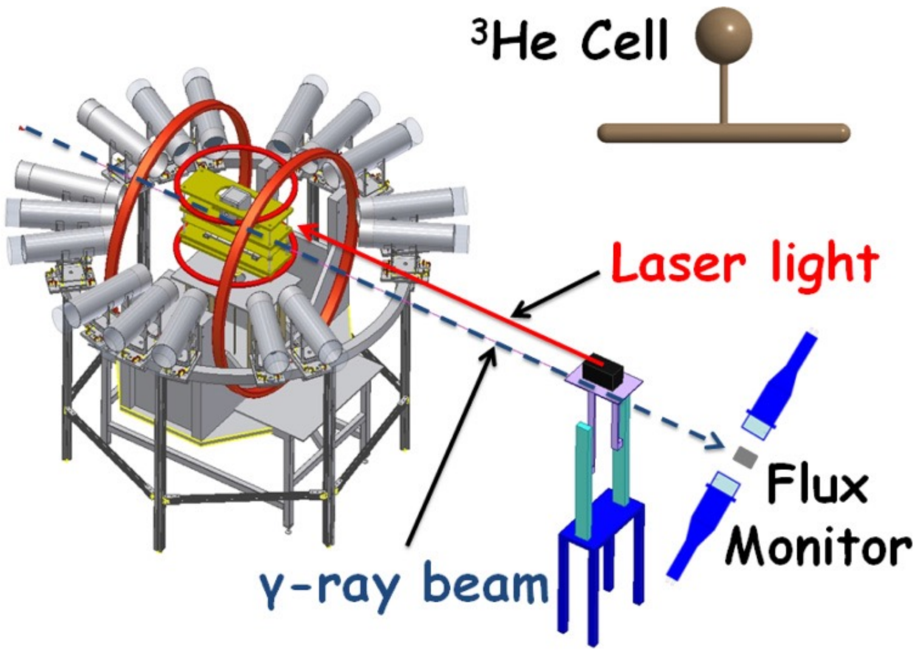
Schematic diagram for coherent theoretical treatment of nuclear systems starting from high energies where perturbative QCD can be applied going to low-energy nuclear phenomena where mean-field potential models are most efficient.

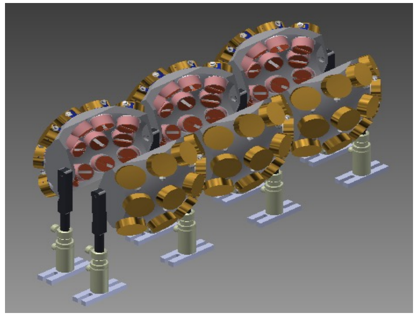
Gerasimov-Drell-Hearn sum rule:

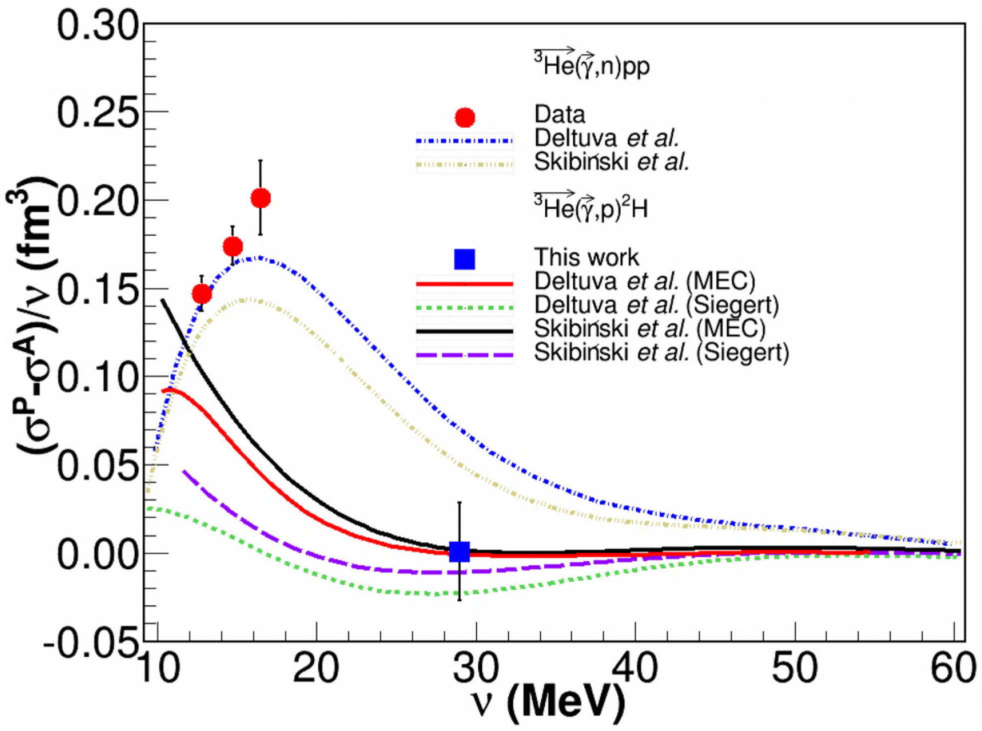
- ^{3}He 3-body and 2-body photodisintegration integrand
- double polarizations

$$I^{GDH} = \int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu}\left[\sigma_N^P(\nu) - \sigma_N^A(\nu)\right] = \frac{4\pi^2\alpha}{M_N^2}\kappa_N^2 I$$

Spokespersons: Haiyan Gao (Duke U.), Georgios Laskaris (, and Mohammad Ahmed (NCCU)



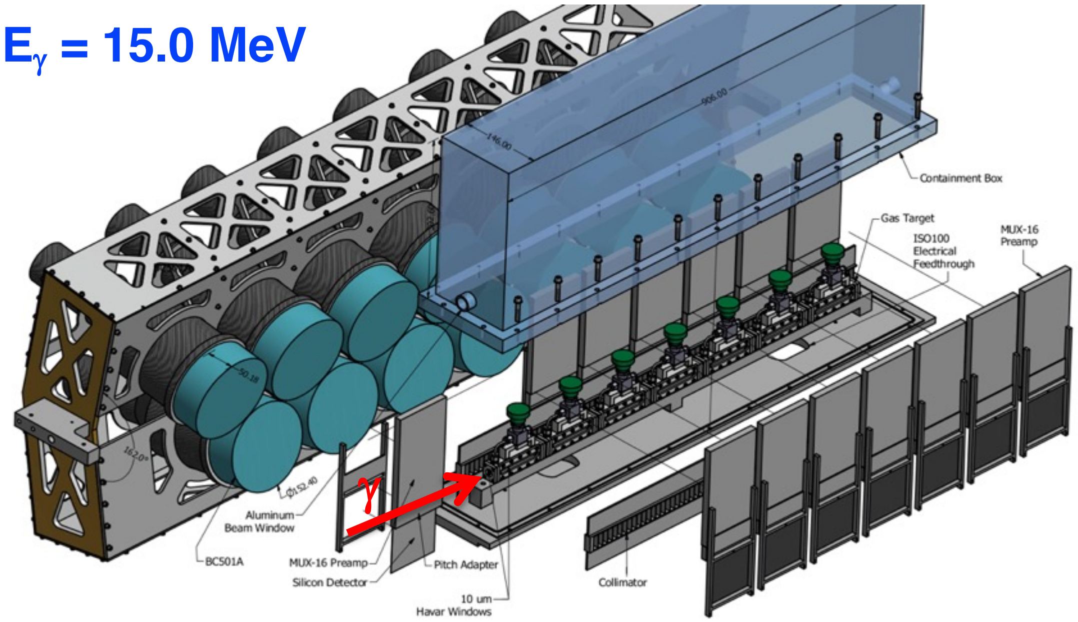


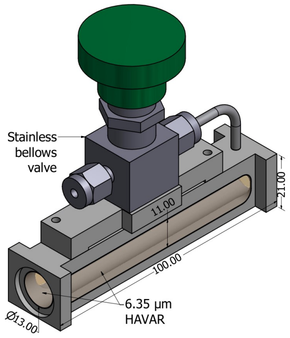


G. Laskaris *et al.*, Phys. Rev. C **103**, 0343311 (2021)
G. Laskaris *et al.*, Phys. Lett. B **750**, 547 (2015)
G. Laskaris *et al.*, Phys. Rev. C **89**, 024002 (2014)
G. Laskaris *et al.*, Phys. Rev. Lett. **110**, 202501 (2013)

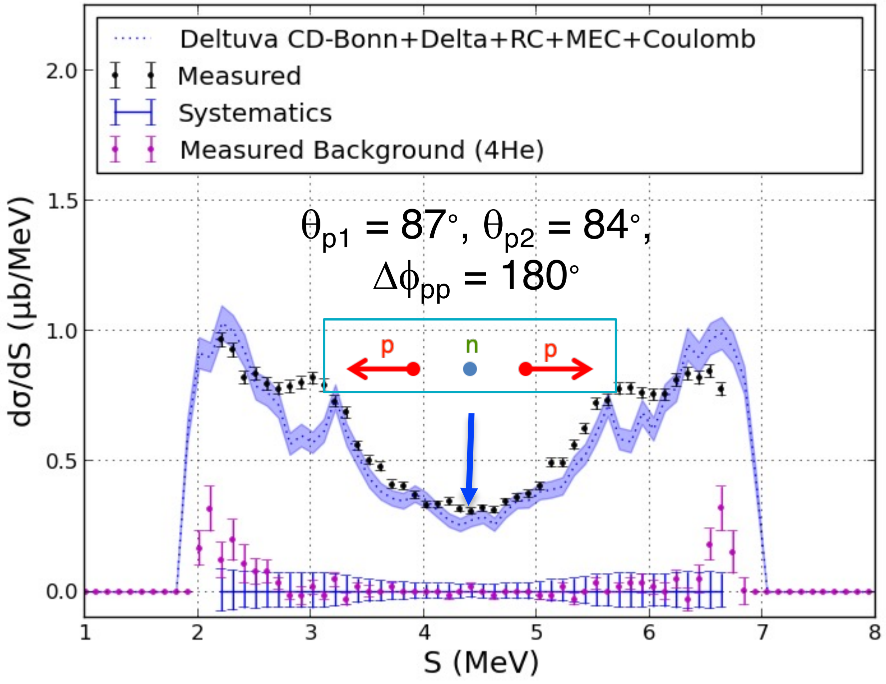
Few-Nucleon Systems: Coming Results – Exclusive ^{3}He photodisintegration

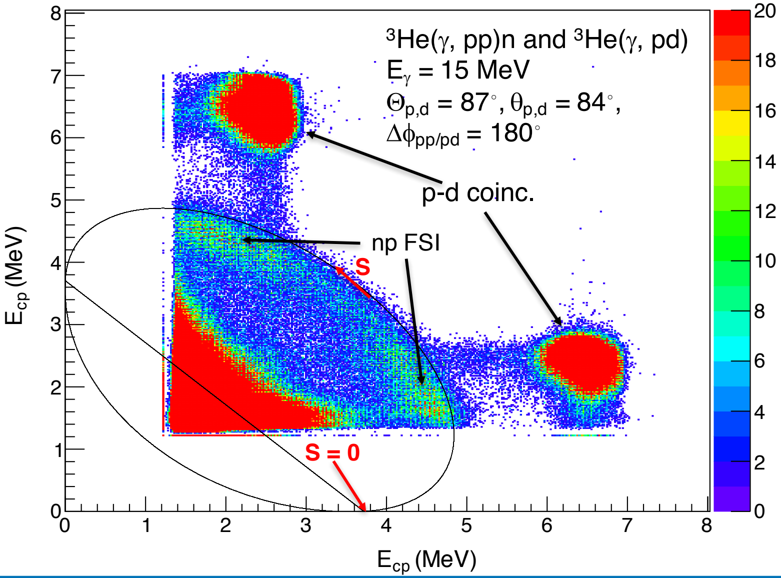
E_γ = 15.0 MeV





Spokespersons: Calvin Howell (Duke U.) and Forrest Friesen (Duke U.)





Status:

- **First exclusive measurements of 3-body photodisintegration of ^{3}He below 200 MeV**
- Forrest Friesen defended thesis in June 2019
- F.Q.L. Friesen and C.R. Howell, NIM A955, 163302 (2020).
- Publication in preparation

Few-Nucleon Systems: Pending – Neutron recoil polarization in ^{2}H photodisintegration

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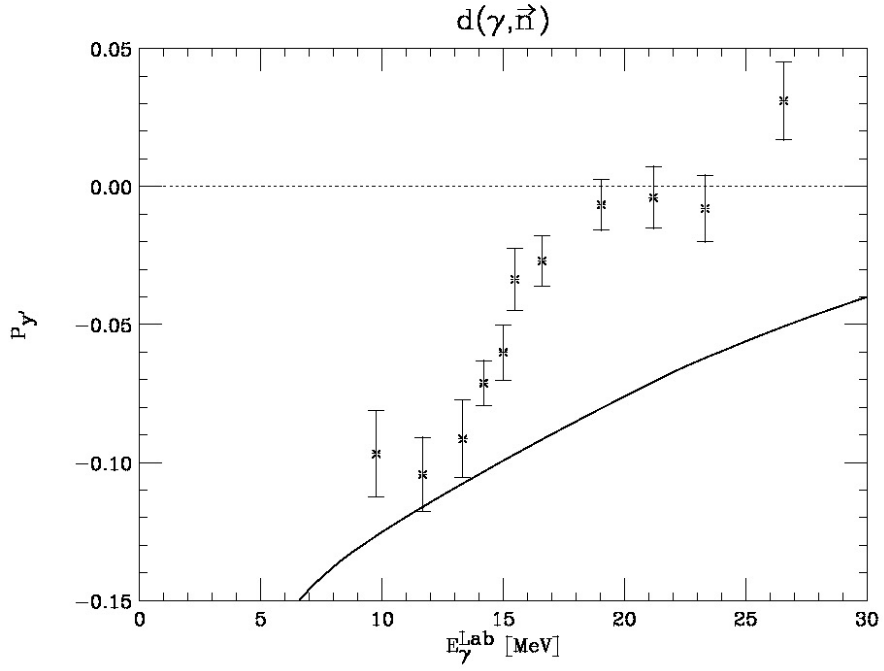
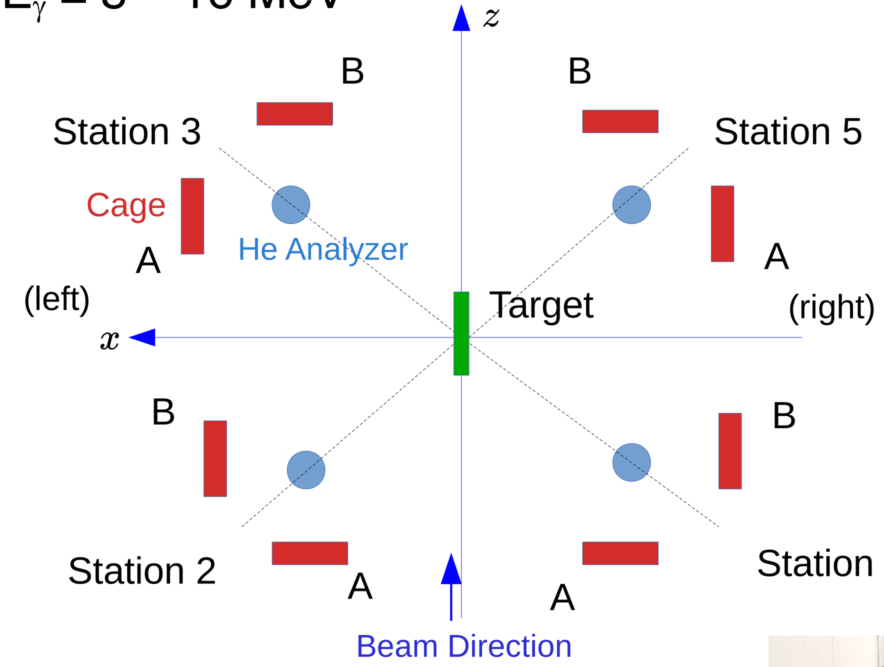
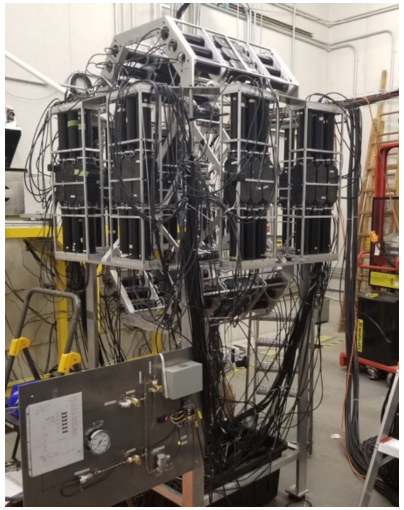
Spokespersons: Blaine Norum (UVA)

$E_\gamma = 8 - 16$ MeV

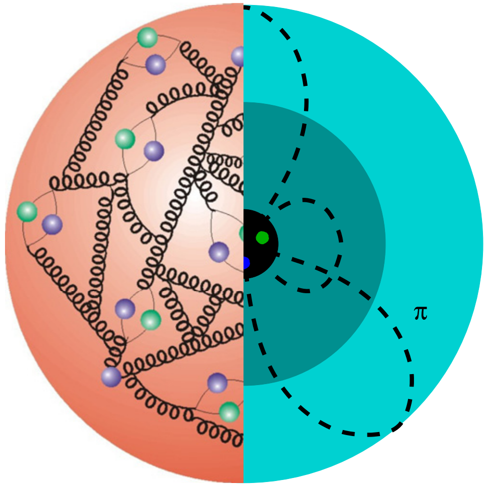


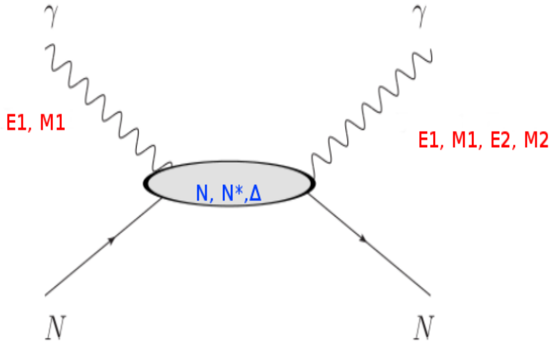




data: R. Nath, F.W.K. Firk, and H.L. Schultz, Nucl. Phys. A**194**, 49 (1972).

Curve: H. Arenhövel and M. Sanzone, Few-body Syst. Suppl. **3**, 1 (1991); private communications





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

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

- 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 $\omega < m_\pi$

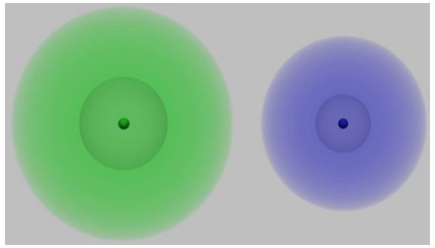
Separate A's into pole and non-pole parts

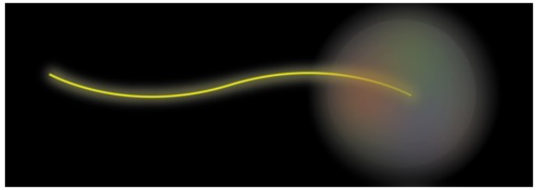
$$A_i(\omega,z) = A_i^{Born}(\omega,z) + \bar{A}_i(\omega,z)$$

(ℓ = 1)

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

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



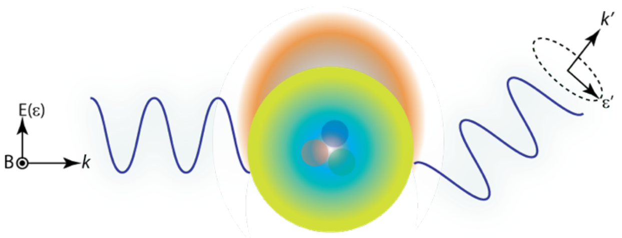


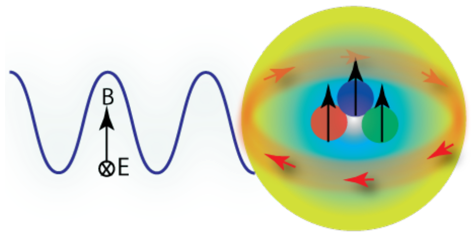
R. P. Hildebrandt, H.W. Griesshammer, T.R. Hemmert and B. Pasquini, Eur. Phys. J. A **20**, 329 (2004).

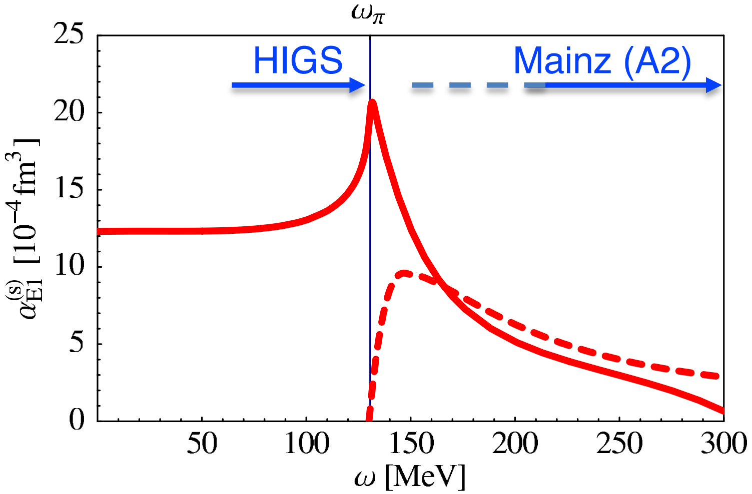
Low-Energy Nucleon Structure: Scalar Polarizabilities

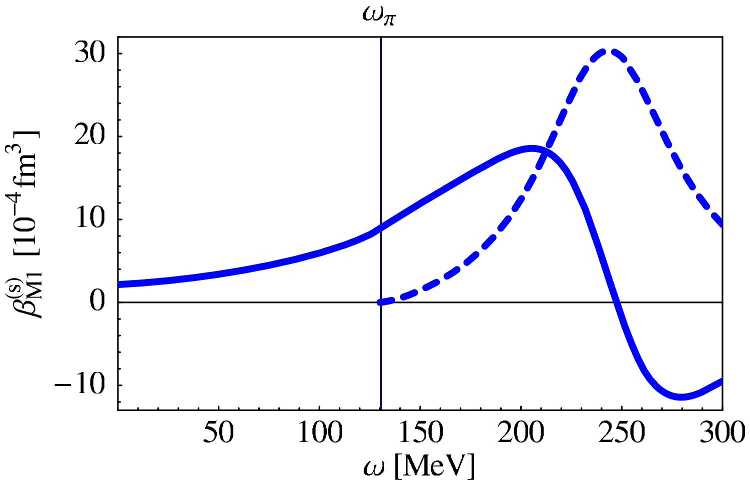
$$\bar{A}_1(\omega,\, z) = \frac{4\pi\, W}{M}\, [\alpha_{E1}(\omega) + z\, \beta_{M1}(\omega)]\; \omega^2 + \mathcal{O}(l=2),$$

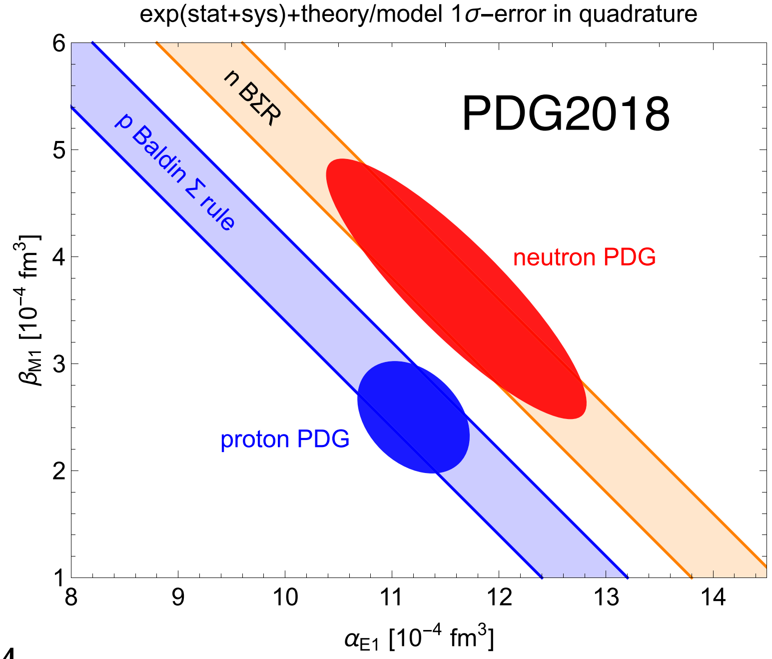
$$\bar{A}_2(\omega,\, z) = -\frac{4\pi\, W}{M}\, \beta_{M1}(\omega)\, \omega^2 + \mathcal{O}(l=2),$$











- α_{E1}: charged pion-cloud dynamics
- β_{M1}: pion charge current dynamical response

Baldin sum rule

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

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

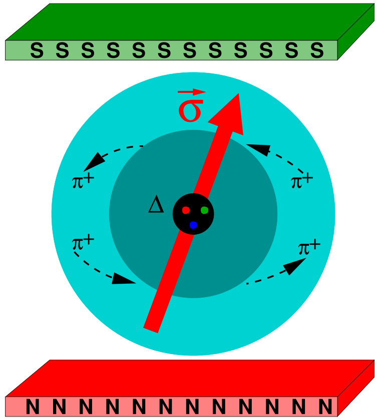
$$\alpha_{E1}^{(p)} = 11.2 \pm 0.4 \quad \beta_{M1}^{(p)} = 2.5 \pm 0.4$$

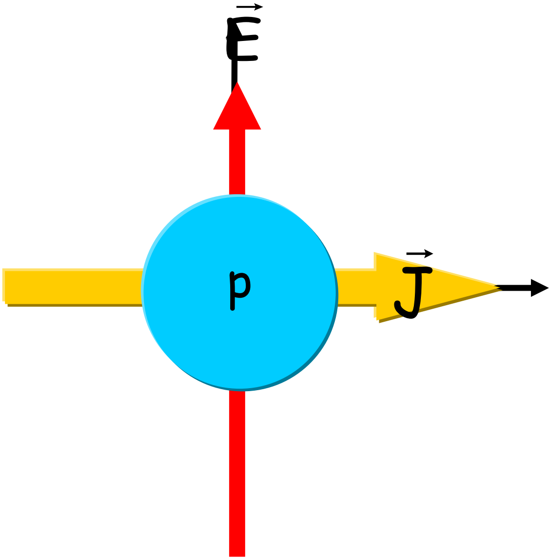
$$\alpha_{E1}^{(n)} = 11.8 \pm 1.1 \quad \beta_{M1}^{(n)} = 3.7 \pm 1.2$$

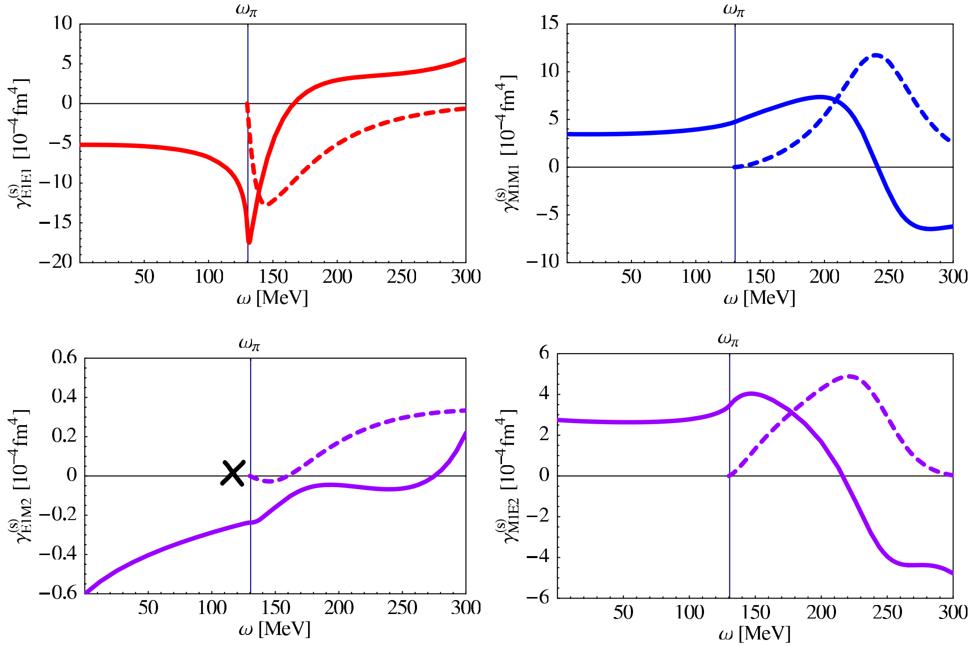
R. P. Hildebrandt, H.W. Griesshammer, T.R. Hemmert and B. Pasquini, Eur. Phys. J. A **20**, 293 (2004).

Low-Energy Nucleon Structure: Spin Polarizabilities

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







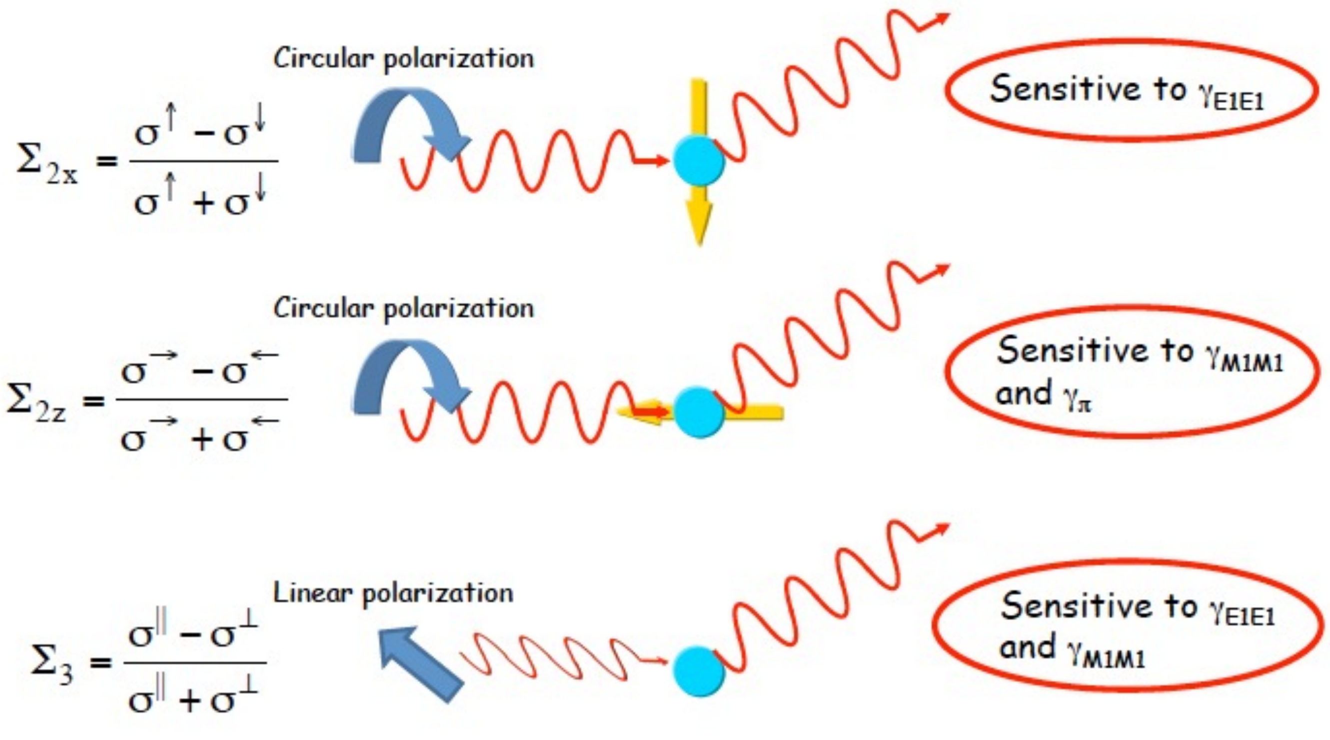
- The spin-dependent polarizabilities enter the Hamiltonian in terms that involve spin-flip operators
- A rotating E-field or B-field will induce a precession of the nucleon spin axis around the momentum direction of the circularly polarized photon with a rate proportional to the magnitude of the associated 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

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

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

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).

Polarized photon beam and polarized target required



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
Σ_3	MAMI/ HIGS			
Σ_{2x}	MAMI			
Σ_{2z}	MAMI			

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

γ_0 = (-1.00 ± 0.13) x 10^{-4} fm^4

γ_π = (-38.7 ± 1.8) x 10^{-4} fm^4

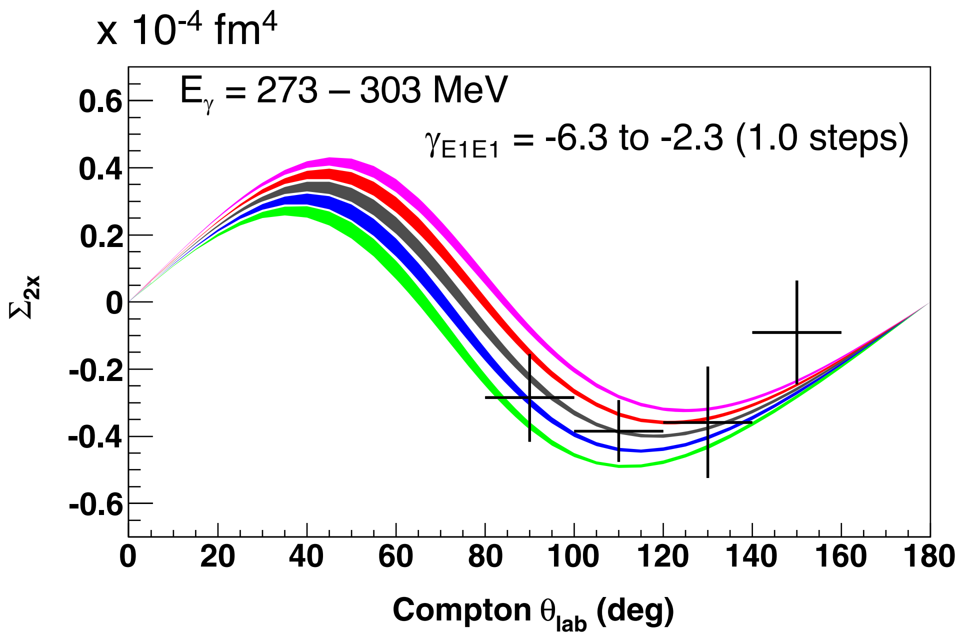
MAMI: Proton spin polarizabilities, Σ_{2x} measurements

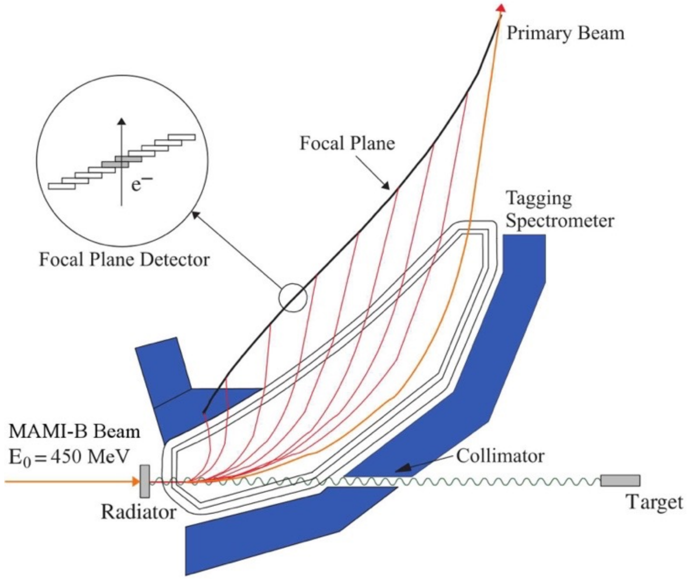
PRL **114**, 112501 (2015) PHYSICAL REVIEW LETTERS

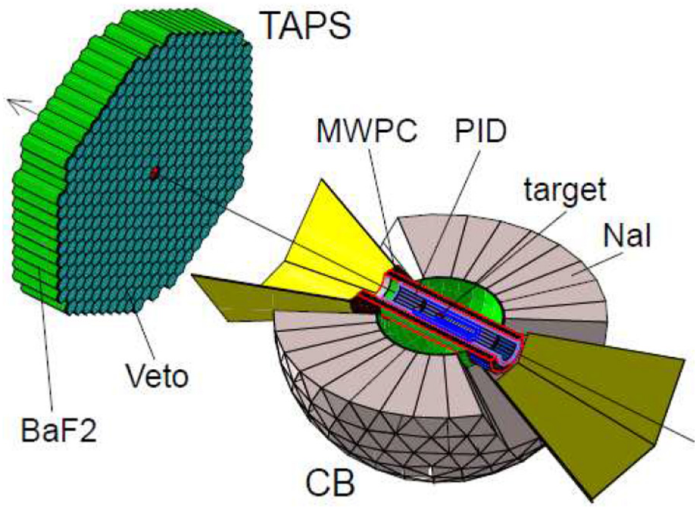
Measurements of Double-Polarized Compton Scattering Asymmetries and Extraction of the Proton Spin Polarizabilities

P. P. Martel,[1,2,3,*] R. Miskimen,[1,†] P. Aguar-Bartolome,[2] J. Ahrens,[2] C. S. Akondi,[4] J. R. M. Annand,[5] H. J. Arends,[2] W. Barnes,[1] R. Beck,[6] A. Bernstein,[7] N. Borisov,[8] A. Braghieri,[9] W. J. Briscoe,[10] S. Cherepnya,[11] C. Collicott,[12,13] S. Costanza,[9] A. Denig,[2] M. Dieterle,[14] E. J. Downie,[2,5,10] L. V. Fil'kov,[11] S. Garni,[14] D. I. Glazier,[5,15] W. Gradl,[2] G. Gurevich,[16] P. Hall Barrientos,[15] D. Hamilton,[5] D. Hornidge,[3] D. Howdle,[5] G. M. Huber,[17] T. C. Jude,[15] A. Kaeser,[14] V. L. Kashevarov,[11] I. Keshelashvili,[14] R. Kondratiev,[16] M. Korolija,[18] B. Krusche,[14] A. Lazarev,[8] V. Lisin,[16] K. Livingston,[5] I. J. D. MacGregor,[5] J. Mancell,[5] D. M. Manley,[4] W. Meyer,[19] D. G. Middleton,[2,3] A. Mushkarenkov,[1] B. M. K. Nefkens,[20,‡] A. Neganov,[8] A. Nikolaev,[6] M. Oberle,[14] H. Ortega Spina,[2] M. Ostrick,[2] P. Ott,[2] P. B. Otte,[2] B. Oussena,[2] P. Pedroni,[9] A. Polonski,[16] V. Polyansky,[11] S. Prakhov,[2,10,20] A. Rajabi,[1] G. Reicherz,[19] T. Rostomyan,[14] A. Sarty,[13] S. Schrauf,[2] S. Schumann,[2] M. H. Sikora,[15] A. Starostin,[20] O. Steffen,[2] I. I. Strakovsky,[10] T. Strub,[14] I. Supek,[18] M. Thiel,[21] L. Tiator,[2] A. Thomas,[2] M. Unverzagt,[2,6] Y. Usov,[8] D. P. Watts,[15] L. Witthauer,[14] D. Werthmüller,[14] and M. Wolfes[2]

(A2 Collaboration at MAMI)







x 10^{-4} fm^4

Data fit	Model	γ_{E1E1}	γ_{M1M1}
Σ_{2x}	Disp	-4.6 ± 1.6	-7 ± 11
Σ_3	Disp	-1.4 ± 1.7	3.20 ± 0.85
Σ_{2x} and Σ_3	Disp	-3.5 ± 1.2	3.16 ± 0.85
Σ_{2x} and Σ_3	$B\chi$PT	-2.6 ± 0.8	2.7 ± 0.5

MAMI: Proton spin polarizabilities, Σ_{2z} measurements

PHYSICAL REVIEW C **102**, 035205 (2020)

Extracting the spin polarizabilities of the proton by measurement of Compton double-polarization observables

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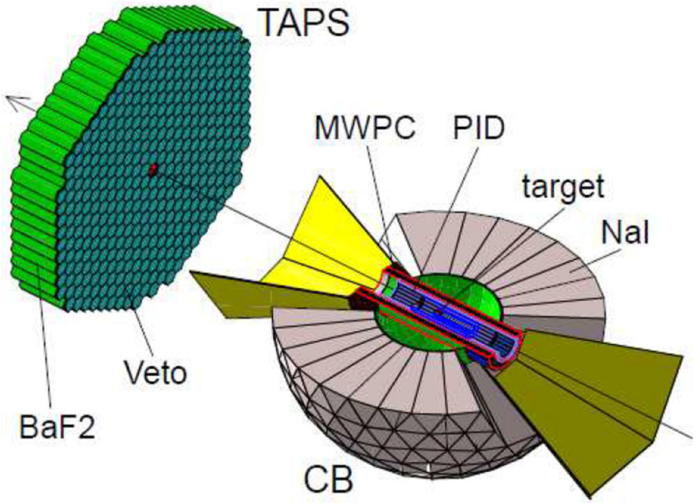
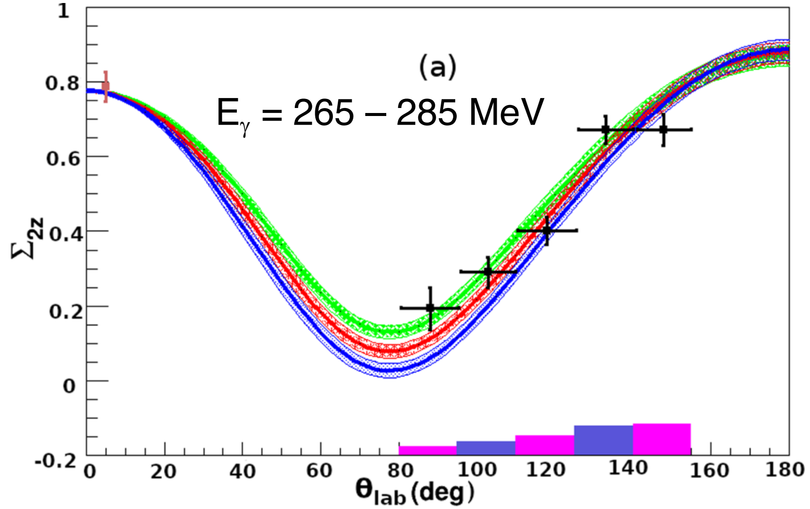
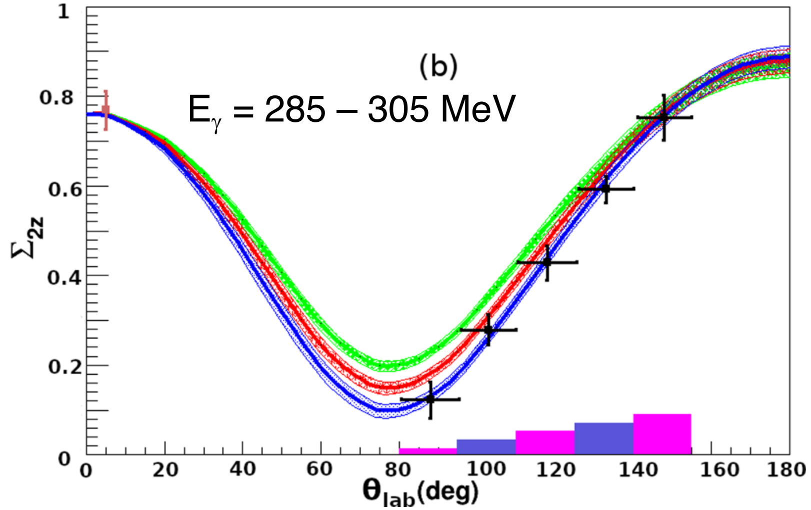
(A2 Collaboration)



	Σ_{2z}, Σ_{2x}, and Σ_3^{LEGS} data fits		
	HDPV	BχPT	Weighted average
γ_{E1E1}	-3.18 ± 0.52	-2.65 ± 0.43	-2.87 ± 0.52
γ_{M1M1}	2.98 ± 0.43	2.43 ± 0.42	2.70 ± 0.43
γ_{E1M2}	-0.44 ± 0.67	-1.32 ± 0.72	-0.85 ± 0.72
γ_{M1E2}	1.58 ± 0.43	2.47 ± 0.42	2.04 ± 0.43
χ^2/dof	1.14	1.36	





TUNL

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

Proton Compton Scattering from Linearly Polarized Gamma Rays

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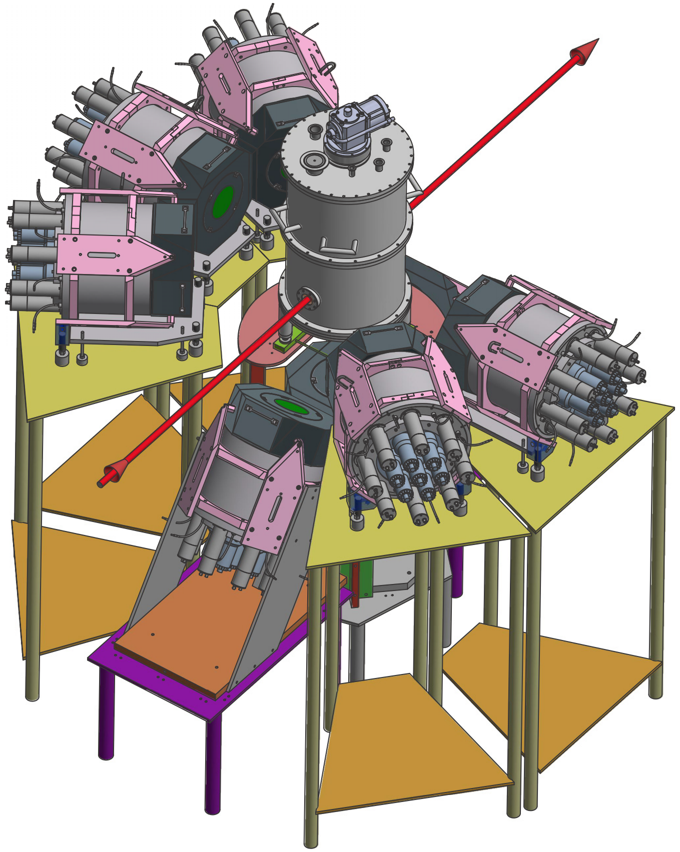

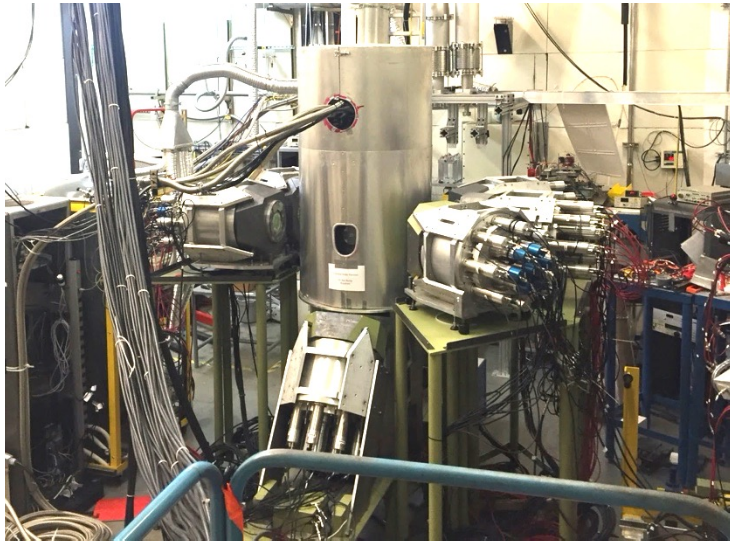

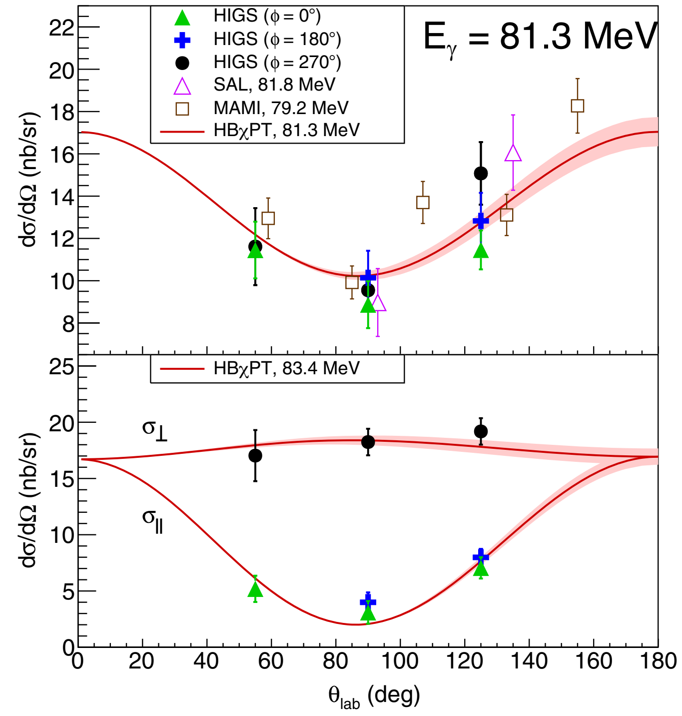

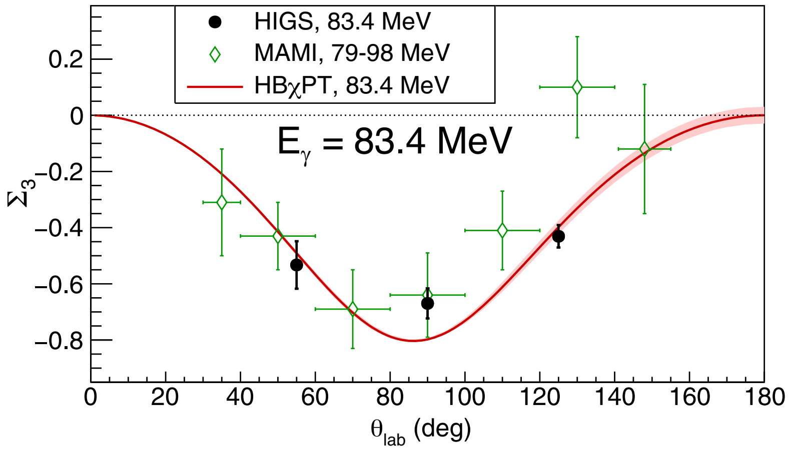

$$\alpha^p_{E1} = 13.8 \pm 1.2_{\rm stat} \pm 0.1_{\rm BSR} \pm 0.3_{\rm theo},$$

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

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

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

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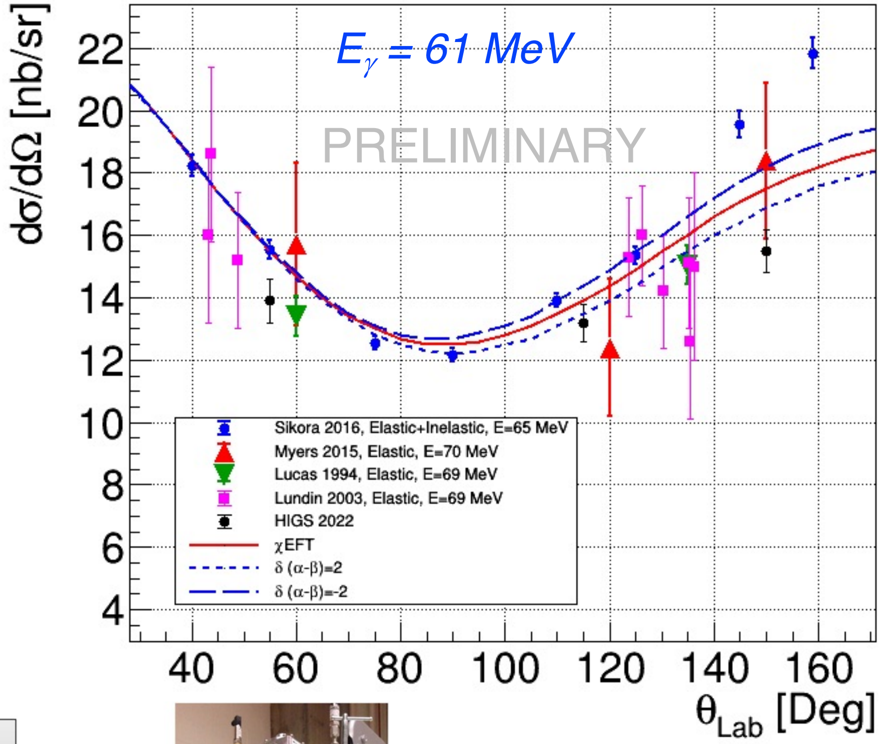
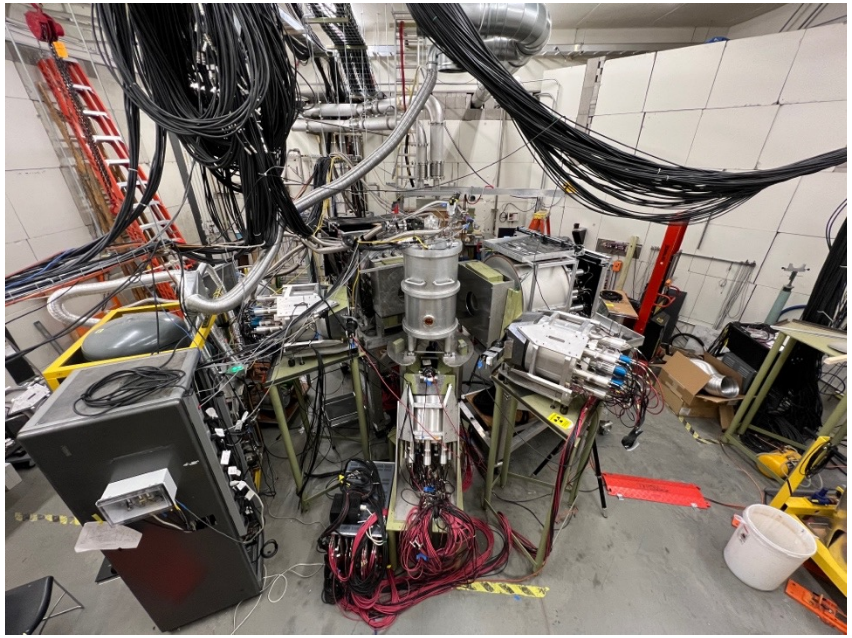
Compton@HIγS Collaboration

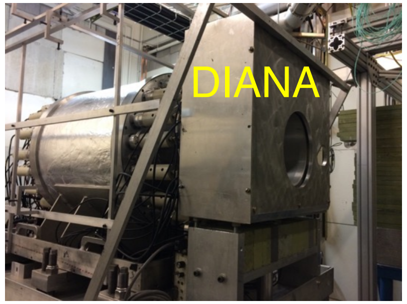
June 23, 2017

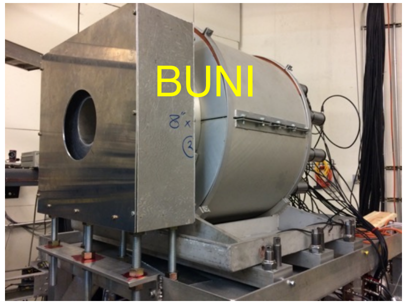
HIGS expt. P-13-17

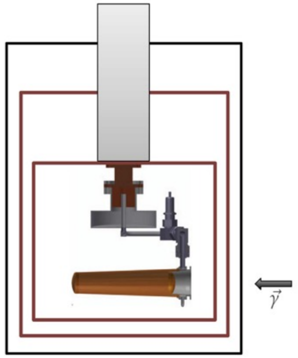


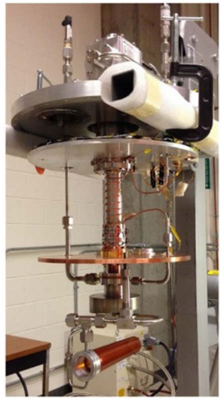
High-energy resolution











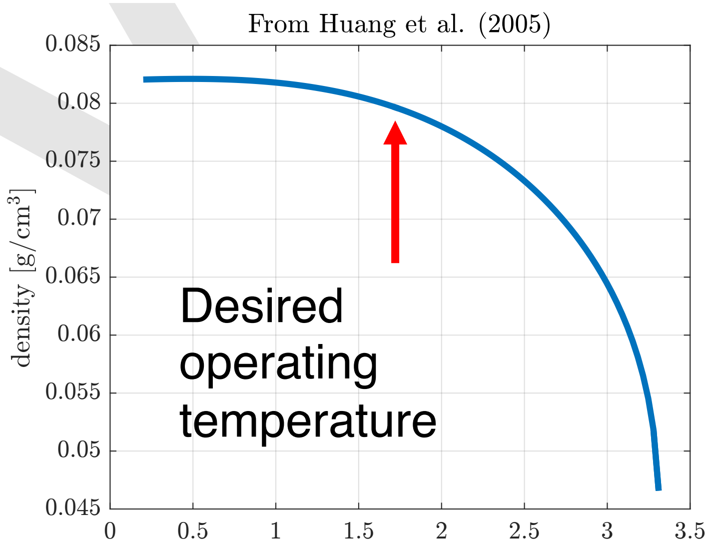
Cryogenic liquid target
Kendellen et al., NIMA 840 (2016) 174

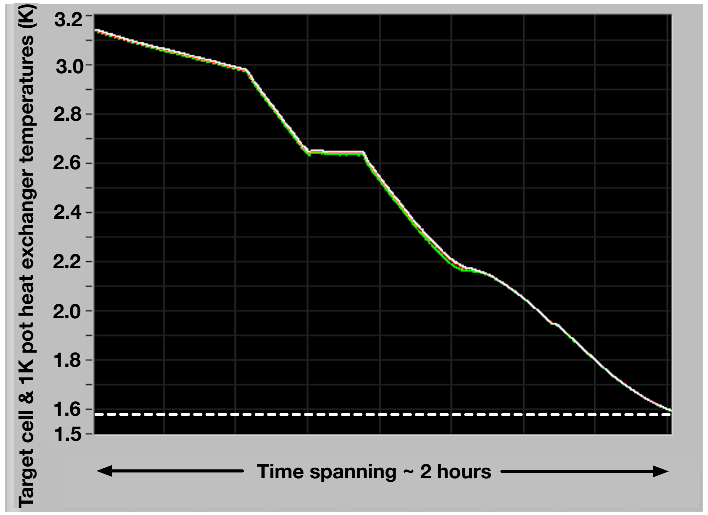
HIGS: Development of cryogenic liquid ^{3}He target for Compton scattering

TUNL

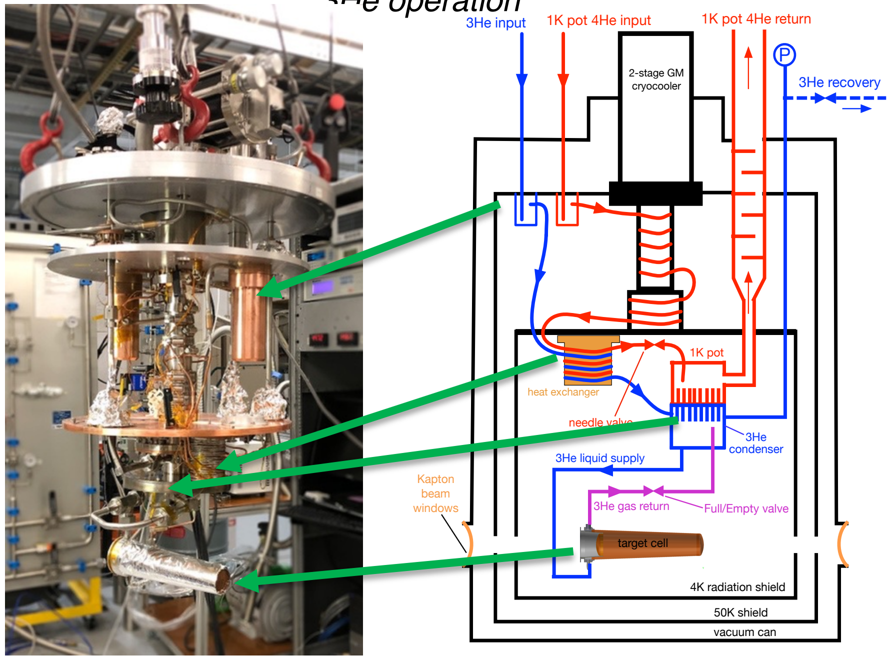
- The desired operating temperature of 0.3 L liquid 3He target cell is 1.7 K. Compared to normal boiling point of 3.2 K, this increases density, reduces dρ/dT , and increases the latent heat of vaporization.
- The upgrade (addition of recirculating dry 1K pot) of the HIGS cryotarget's internal components has been completed.
- Cooldown 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.

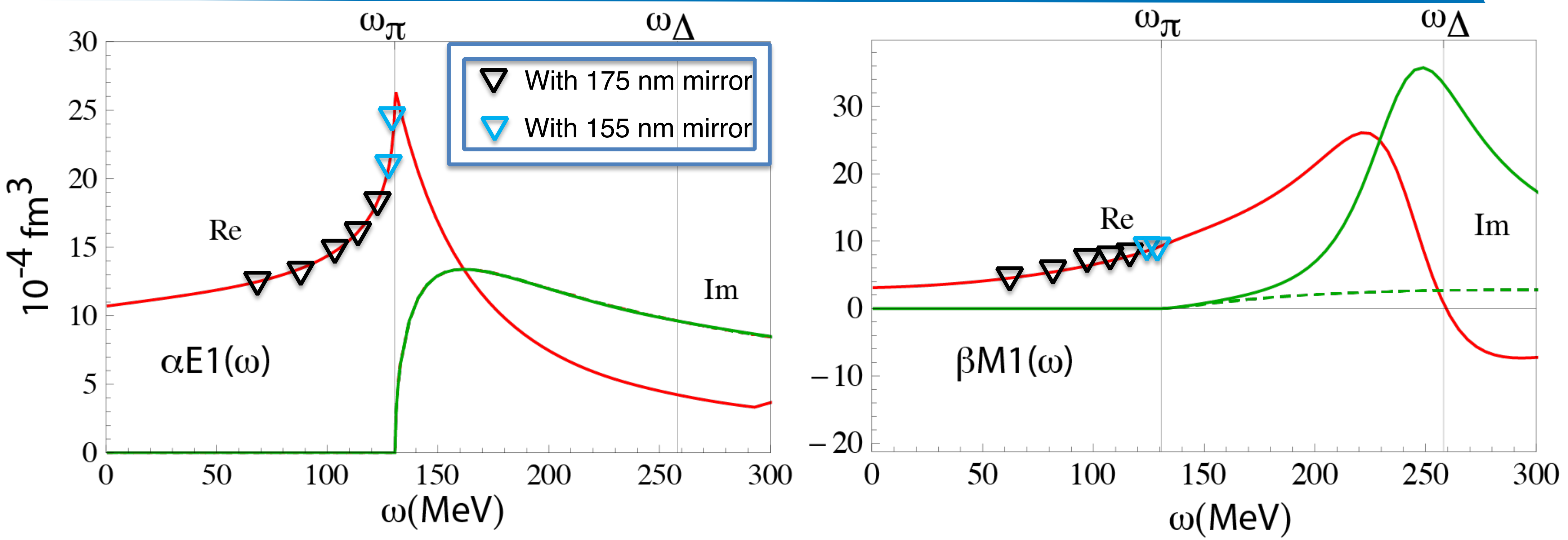




Left: photo of inside cryotarget after internal components upgrade. Right: schematic of cryotarget for 1.7K liquid ^{3}He operation



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



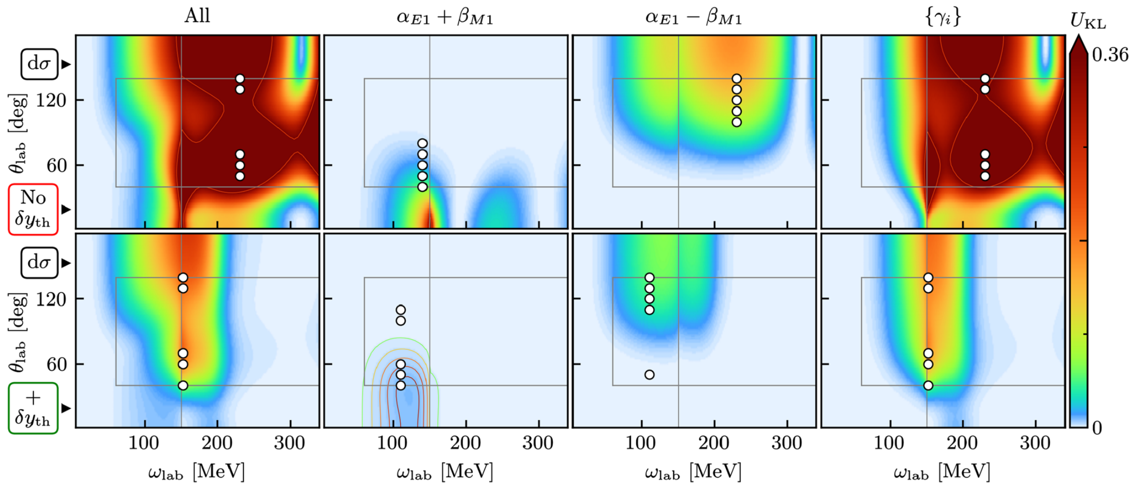
- **Major focus on measurements of neutron EM polarizabilities**
  - Compton scattering from liquid H,D,^{3}He, and ^{4}He targets at E_γ = 65 - 120 MeV
  - E_γ = 100 - 120 MeV made possible through development of 175-nm cavity mirrors by collaboration of TUNL-Laser Zentrum Hannover (LZH)
  - E_γ = 130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

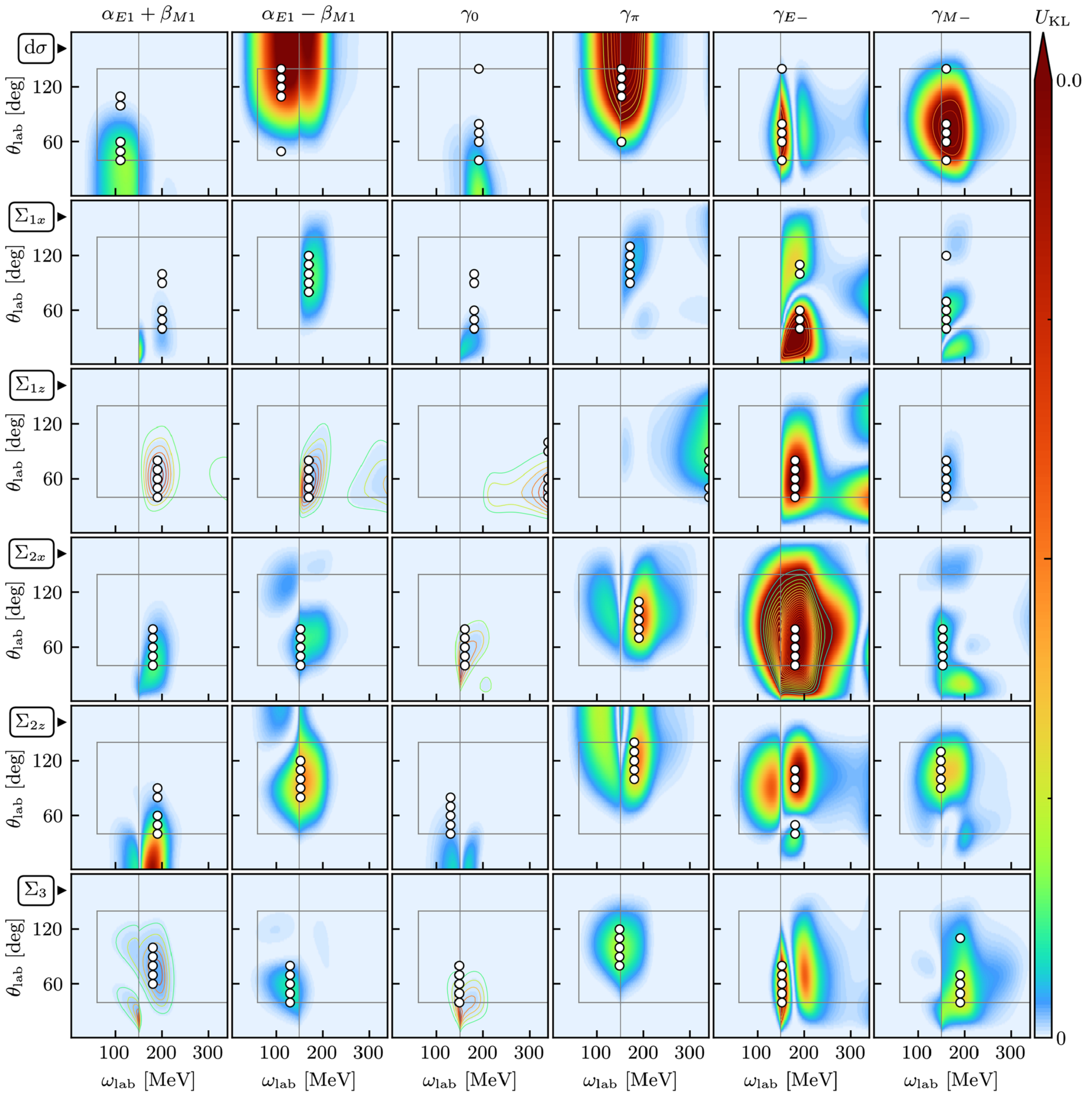
Theory: Global sensitivity survey

Eur. Phys. J. A (2021) 57:81
https://doi.org/10.1140/epja/s10050-021-00382-2
THE EUROPEAN PHYSICAL JOURNAL A

Designing optimal experiments: an application to proton Compton scattering

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





LE Nucleon Structure: Summary (Compton scattering)

- **Substantial progress on determination of proton spin polarizabilities**
  - Recent asymmetry data (Σ_3, Σ_{2z} and Σ_{2x}) from MAMI (A2 coll.); range of E_γ = 265 – 305 MeV
  - New and high precision Σ_3 data from HIGS at E_γ = 83 MeV
  - Convergence of χEFT calculations can be used to assess model uncertainty => crisp test of chiral dynamics of QCD at energies below pion production threshold
- **Progress on reducing uncertainty in the neutron scalar polarizabilities**
  - New high-resolution elastic Compton-scattering cross-section measurements performed on the deuteron at HIGS; E_γ = 61 and 81 MeV
  - χEFT calculations enable determination of α^n and β^n from the unpolarized cross-section data for Compton scattering from the deuteron
- **Development of theory calculations that provide a global sensitivity study for optimizing Compton-scattering measurements for determining nucleon polarizabilities**
- **Technical and methods accomplishments at HIGS enable new measurements important for reducing the uncertainties in α^n and β^n**
  - Installed two large NaI detectors (DIANA and BUNI): $\Delta E/E \sim 3.0\%$ (fwhm) at $E_\gamma > 60$ MeV
  - Developed 175-nm FEL cavity mirrors; enables E_γ = 100 – 120 MeV
  - Developed a liquid ^3He cryogenic target for Compton scattering

- **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 150 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
- **Improve determination of proton spin polarizabilities**
  - Measure asymmetry data (Σ_3, Σ_{2z} and Σ_{2x}) at energies E_γ = 100 to 150 MeV; complement data from Mainz at E_γ = 260 - 310 MeV
  - Use several χEFT calculations for reliable assessment of model uncertainty
- **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

LE Nucleon Structure: Support and Investments for optimum science pursuit

TUNL

- **Optimum operation of HIGS, including FEL mirror R&D for improving mirror lifetime and increasing the energy reach of the facility.** *The research described here will require an average minimum of over 1000 hours of beam time per year.*
- **Upgrade of the electron injector system at HIGS for reliable stable operation.** *Operating HIGS at the upper end of the facility's energy reach for long periods, as is required to achieve the scientific goals outlined here, can not be sustained with the current beam injector system at HIGS. This system is far beyond the average expected service life.*
- **Polarized target R&D program at HIGS with emphasis on scintillating targets for use in Compton-scattering measurements.** *Polarized targets are essential for continued progress on reducing uncertainties of the nucleon spin polarizabilities.*
- **Support for theory efforts relevant to studying low-energy nucleon structure.** *The main advances made during the last two decades in quantifying the low-energy nucleon structure parameters have resulted from progress made in both experiment and theory and through their close collaboration.*
- **Support for research in low-energy nucleon structure at Mainz.** *Sustaining the energy and techniques complementarity of the Compton-scattering programs at Mainz and HIGS is important for continued advancement of this low-energy QCD research area.*