Nucleon Electromagnetic and Spin Structure: Real photons at long wavelengths

Mohammad Waseem Ahmed

North Carolina Central University &
Triangle Universities Nuclear Laboratory

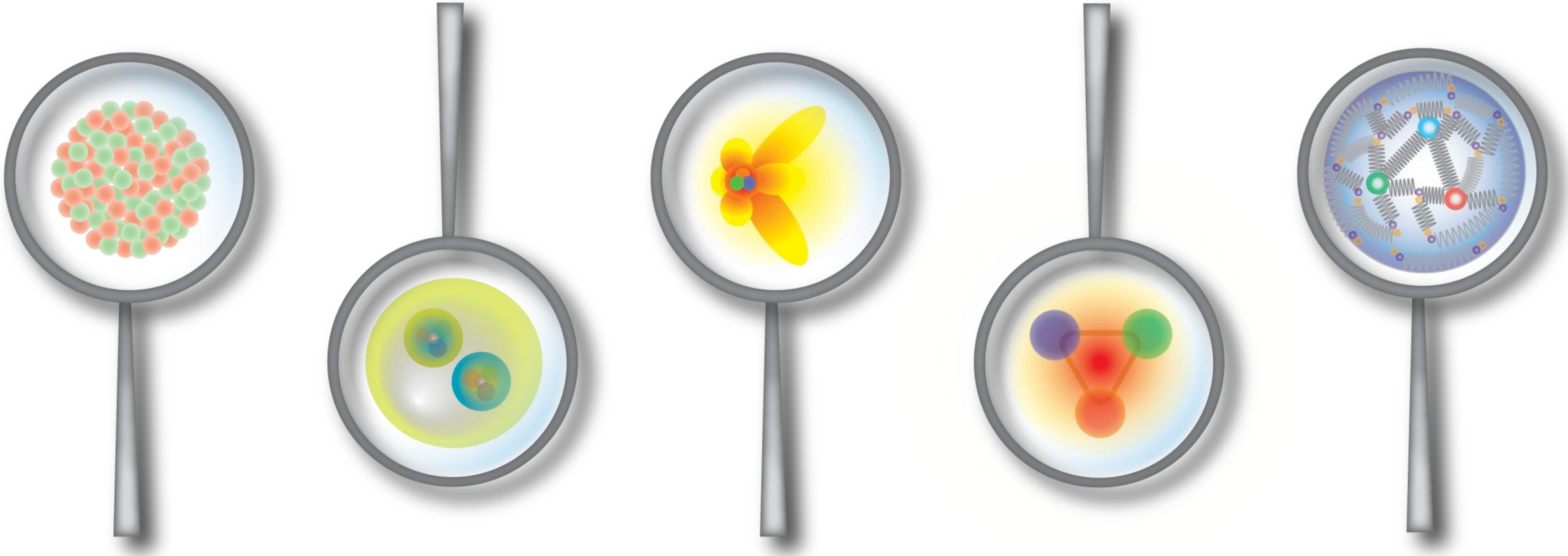
Nucleon Electromagnetic and Spin Structure: Real photons at long wavelengths

Faculty	Ahmed[1], Crowe, Gao, Howell, Karwowski[2], Markoff, Wu
Graduate Students	C. Bartram, X. Li, S. Meadows, X. Yan
Post-docs/Research Scientists	M. Sikora (TUNL & GWU), D. Kendellen
External Collaborators	Evie Downie, Jerry Feldman, Harald Griesshammer (GWU), Mike Kovash (Uky), Rob Pywell (USask), Mark Spraker (UNG), Blaine Norum, Don Crabb (UVa), Steve Whisant, Adriana Banu (JMU)
Facility	HIGS, Cryogenic and Polarized Target

[1]TUNL-NCCU Joint Appointment, [2]Faculty Emeritus as of 7/2018

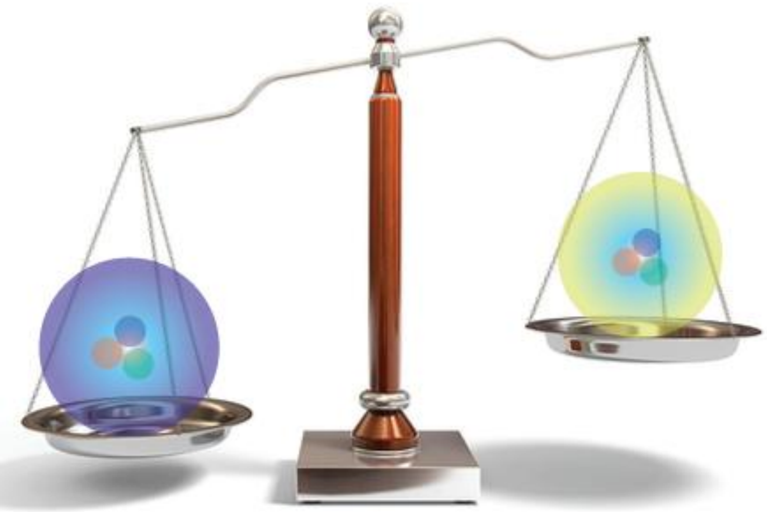
Motivation

Understanding the structure of nucleons in terms of effective degrees of freedom that are relevant at low energies and confinement distances is key to bridging the theory gap between QCD and nuclear phenomenology



How nucleons combine to make a nucleus? Nuclear description transitions from Meson/Nucleon to Quark/Gluon

Why polarizabilities matter?

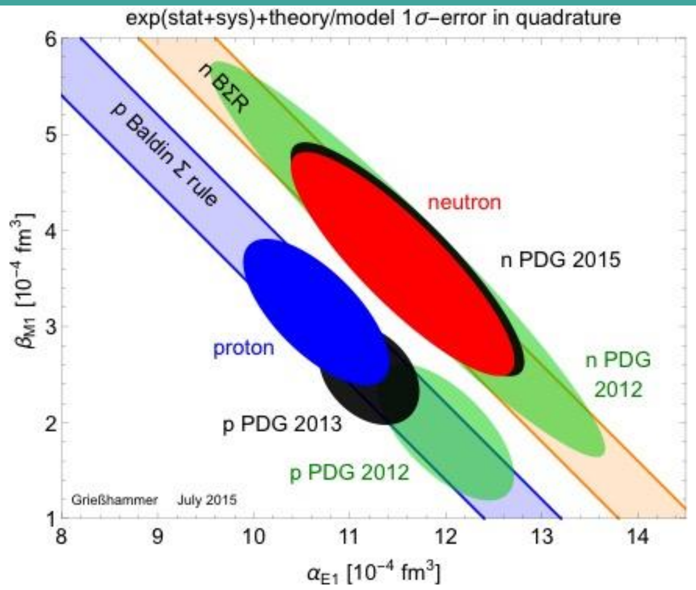


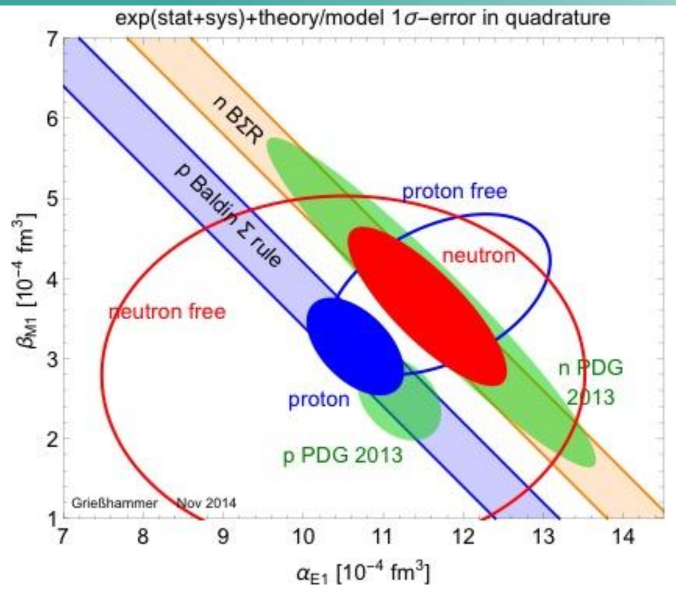
- The net effect of u-d quark mass difference and electromagnetic contributions is known (to 0.000032 % precision) ;
- How to disentangle the two contributions? (LQCD), EM is the issue!
- The EM self-energy of the nucleon can be related to the measured elastic/inelastic cross sections;
- Largest source of error is from $\beta_p - \beta_n$ (where error from neutron dominates)

Cottingham : Ann Phys (NY) 25, 424 (1963), AW-L, CEC, GAM, PRL, 108, 232301 (2012)

- **Test our understanding of interplay between EM and SNF**, theoretical determination of proton – neutron mass difference, and two-photon exchange contribution to the Lamb shift in muonic hydrogen (JAM, Eur. Phys. J. A (2012) 48: 120, H.WG, JAM, and DR, arXiv:1511.01952)
- Insight into the binding in nuclear force due to photon coupling to charged pion-exchange currents;
- Fundamental structure functions of the nucleons, Input to the extraction of spin polarizabilties

Plans for next thee years: Impact





$\alpha_{E1}^{s} = 11.1 \pm 0.6$ $\quad\quad$ $\beta_{M1}^{s} = 3.4 \mp 0.6$

$\alpha_{E1}^{p} = 10.65 \pm 0.35\ (3.28\%)_{stat} \pm 0.2_{Baldin} \pm 0.3_{th}$ $\quad\quad$ $\beta_{M1}^{p} = 3.15 \mp 0.35\ (11.1\%)_{stat} \pm 0.2_{Baldin} \pm 0.3_{th}$

$\alpha_{E1}^{n} = 11.55 \pm 1.25\ (10.8\%)_{stat} \pm 0.2_{Baldin} \pm 0.3_{th}$ $\quad\quad$ $\beta_{M1}^{n} = 3.65 \mp 1.25\ (34.0\%)_{stat} \pm 0.2_{Baldin} \pm 0.3_{th}$

1. J.A. McGovern, D.R. Phillips, and H.W. Grieshammer, Compton scattering from the proton in an effective field theory with explicit Delta degrees of freedom, Eur. Phys. J. A (2013) 49: 12
2. H.W. Grieshammer, J.A. McGovern, D.R. Phillips, G. Feldman, Using Effective Field Theory to analyse low-energy Compton scattering data from protons and light nuclei, Progress in Particle and Nuclear Physics 67 (2012) 841–897
3. Harald W. Grießhammer, Judith A. McGovern, and Daniel R. Phillips, News on Compton Scattering γX → γX in Chiral EFT, EPJ Web of Conferences, 113, 04006 (2016)
4. Harald W. Grießhammer, Dissecting Deuteron Compton Scattering I: The Observables with Polarised Initial States, arXiv:1304.6594 [nucl-th], INT-PUB-13-014
5. Vadim Lensky and Judith McGovern, Proton polarizabilities from Compton data using covariant chiral effective field theory, PHYSICAL REVIEW C 89, 032202(R) (2014)

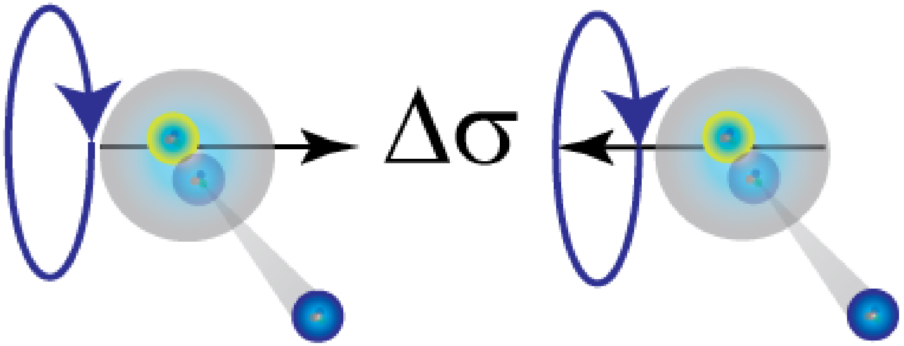
Global Efforts and the TUNL Program

- Characterization of the internal structure of the nucleon by mapping the charge and current distributions inside the nucleon;
- Spin Sum Rule Physics at Intermediate Energies

- Response of nucleons to quasi-static electromagnetic fields in terms of polarizabilities and their spatial distribution
- Spin Sum Rules with real photons

- Internal structure of the nucleons at large distance scales: electromagnetic and spin polarizabilities
- Spin Sum Rules with real photons below pion production threshold

Why spin sum rules matter?



$$I(D)_{GDH} = \int_{\omega_{th}}^{\infty} \frac{\Delta\sigma}{\omega} d\omega = \frac{2\pi^2\alpha}{m^2}\kappa^2$$

- Understanding the spin structure of the nucleon is at the heart of present nuclear and particle physics activities.
- **Sum rules connect information from all energies to fundamentals of our current view of nature's laws and are consequences of general principles**
- They can be used to test these fundamental principles and provide a method to access new experimental observables and to study the physics of strongly interacting systems in refined detail.

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0.65 μb

$$I(D)_{GDH} = \int_{\omega_{th}}^{\infty} \frac{\Delta\sigma}{\omega} d\omega = \int_{2.2}^{\omega_\pi} \frac{\Delta\sigma}{\omega} d\omega + \int_{\omega_\pi}^{\omega_{max}} \frac{\Delta\sigma}{\omega} d\omega + \int_{\omega_{max}}^{\infty} \frac{\Delta\sigma}{\omega}$$

HIGS

437 μb

305 μb

MAMI (Mainz), ELSA (Bonn), LEGS, and Q^2 dep by JLab

496 μb

$$I(^3He)_{GDH} = \int_{\omega_{th}}^{\infty} \frac{\Delta\sigma}{\omega} d\omega = \int_{5.5}^{\omega_\pi} \frac{\Delta\sigma}{\omega} d\omega + \int_{\omega_\pi}^{\omega_{max}} \frac{\Delta\sigma}{\omega} d\omega + \int_{\omega_{max}}^{\infty} \frac{\Delta\sigma}{\omega} d\omega$$

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Compton Scattering Program Accomplishments

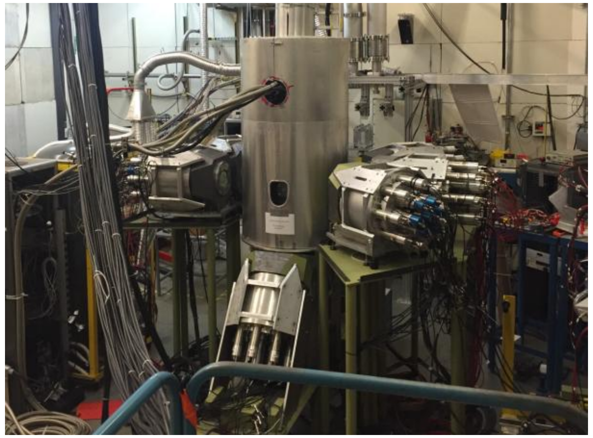
Experiment	Accomplishment
^{4}He @ 61 & 85 MeV	Most precise data on ^{4}He Compton scattering to-date – Theoretical calculations underway to extract nucleon polarizabilities (published)
Deuteron at 65 & 85 MeV	Most precise (statistical & systematic) data with large angular coverage on total deuteron CS. Upon extraction of the elastic cross sections, these data will nearly double the deuteron CS database for the extraction of neutron polarizabilities
Proton at 85 MeV	Most precise proton CS data on Beam Asymmetry (Σ_3) at low energies. Analysis underway to extract new proton polarizabilities using Low-Energy Expansion (LEX) as well as proton spin polarizabilities

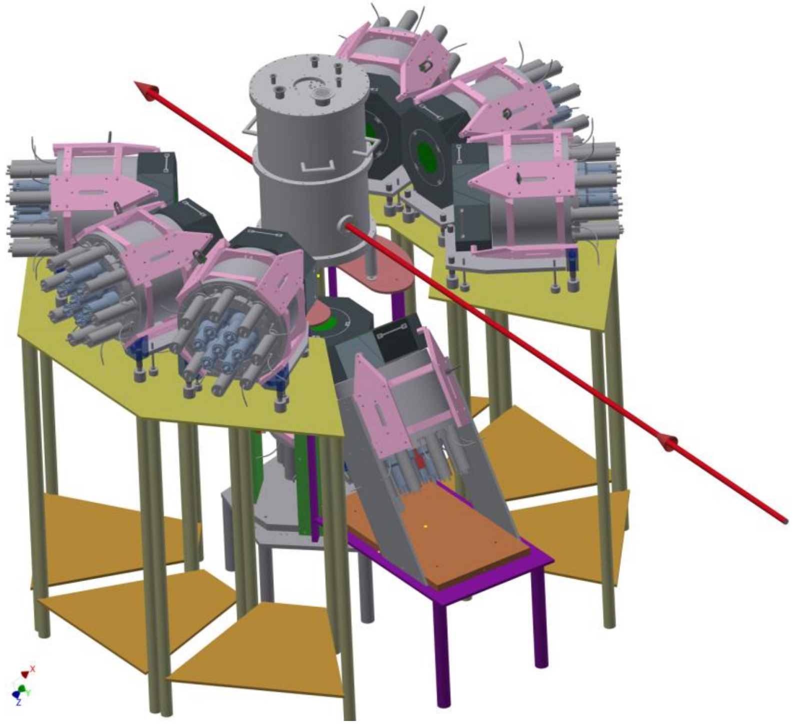
New capabilities at HIGS for LEQCD

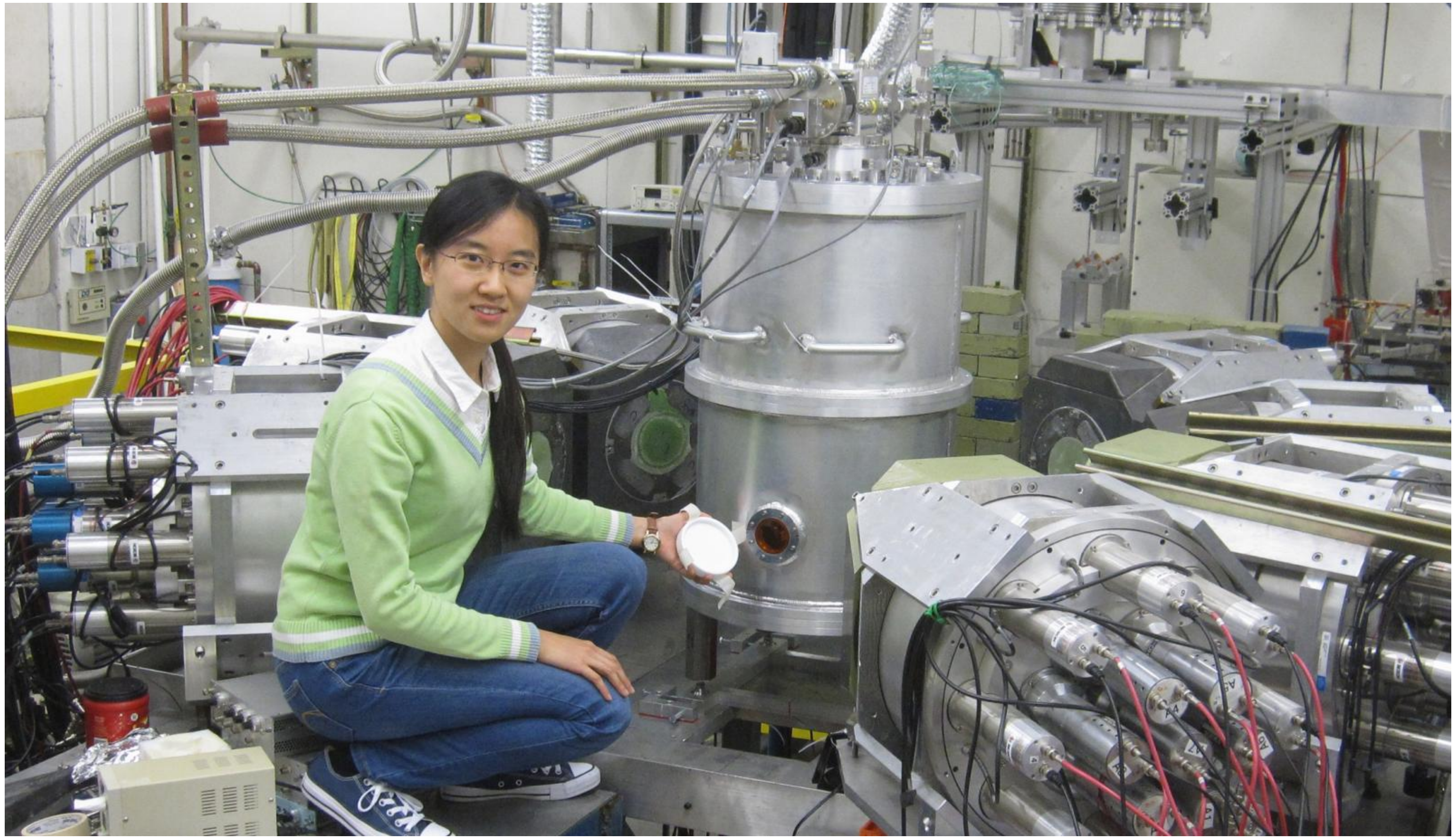
Experiment	Accomplishment
[1]Cryogenic Target	Reached 1000 hours of operation at HIGS with LHe, LD, and LH targets
HINDA + DIANA + BUNI	New Infrastructure for Polarized and High-Resolution Measurements
Fully Digitized DAQ	1200 hours, and 30 TB of data

The Compton Scattering Setup

- Circular or Linear polarized gamma-ray beams
- 65 – 100 MeV
- LH, LD, LHe Cryogenic Target
- Large NaI Array (HINDA) with various angles
- In-plane and out-of-plane detectors for polarization studies

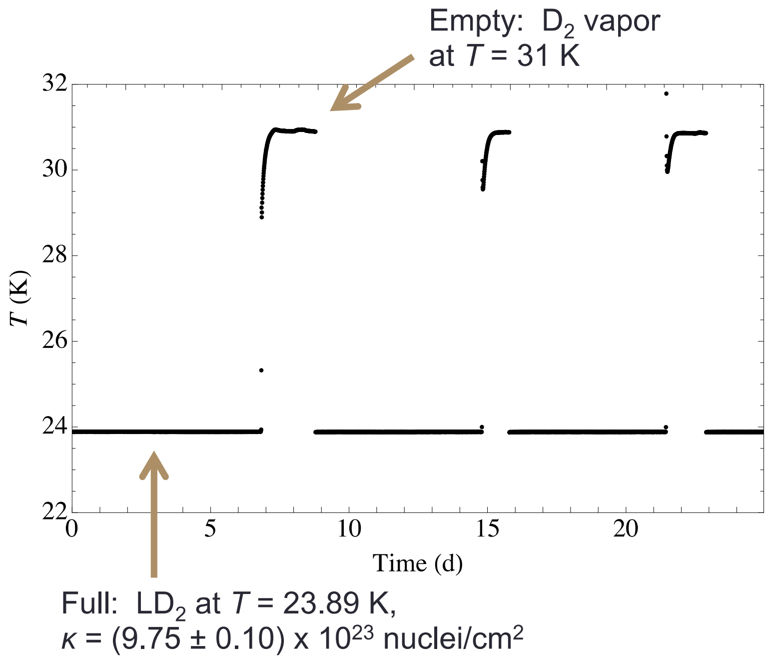






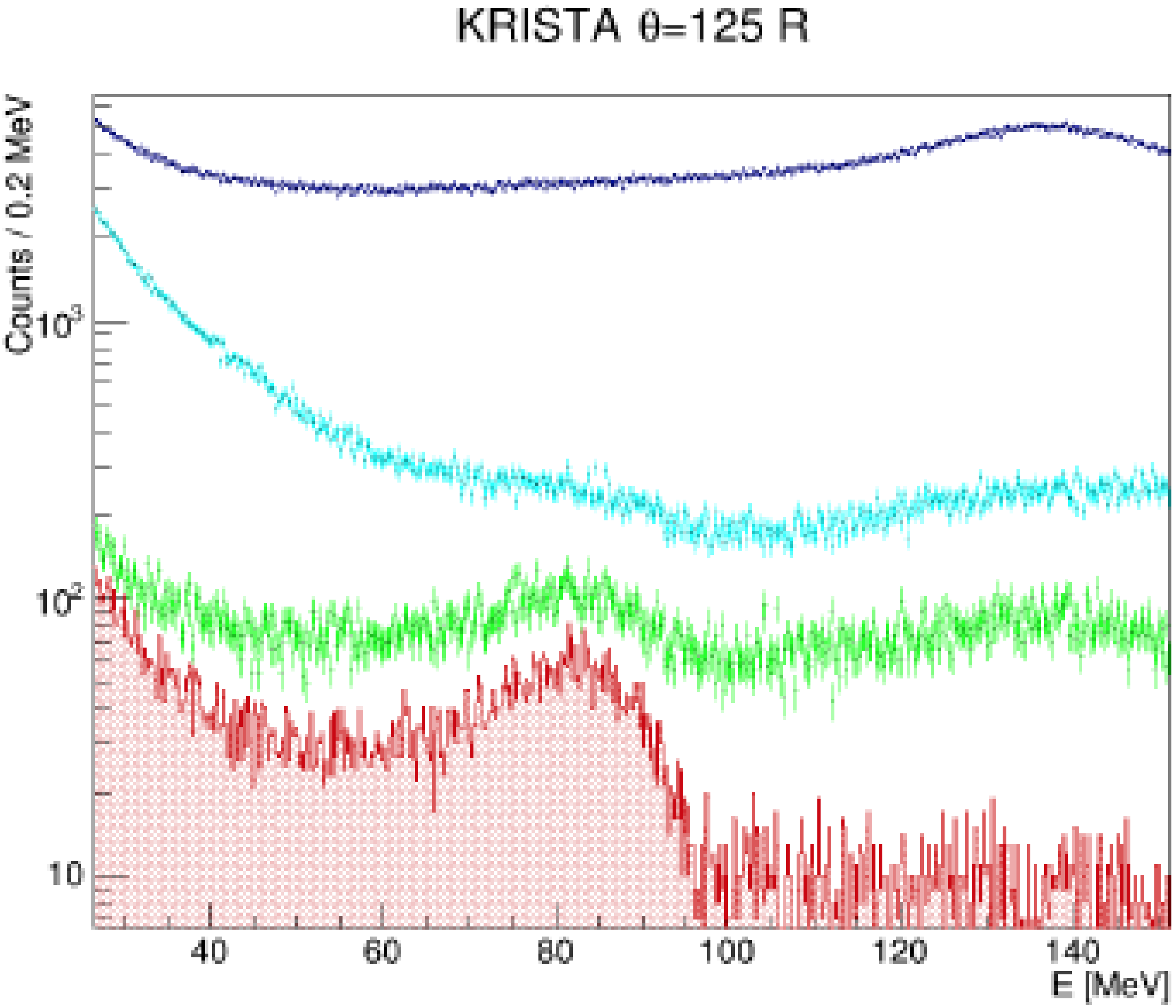
Duke Graduate student Xiaqing Li poses in front of the target and the HINDA

June 2016 LD_2 production run:



Target temperature over a month of running time. It takes less than 15 minutes to empty and few minutes to refill

Kendellen et al., NIMA 840 (2016) 174



No Cuts

Cosmic Shield Cut

Time-of-Flight Cut

Shield + ToF Cut

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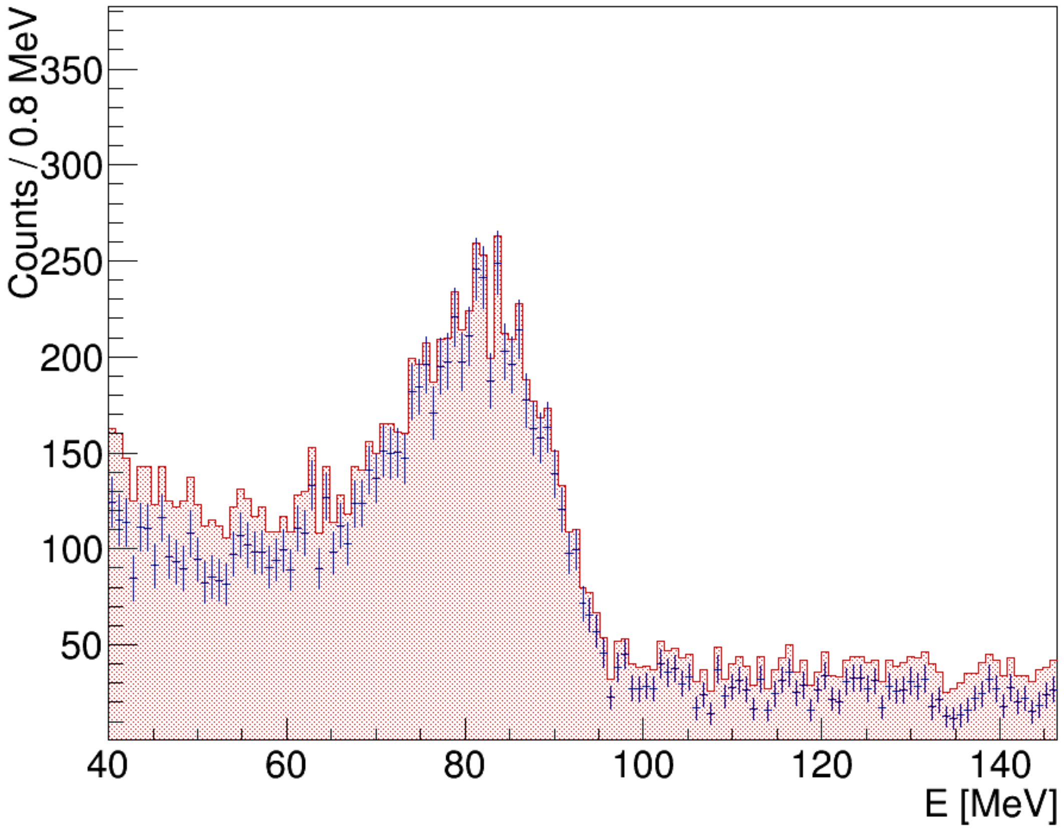
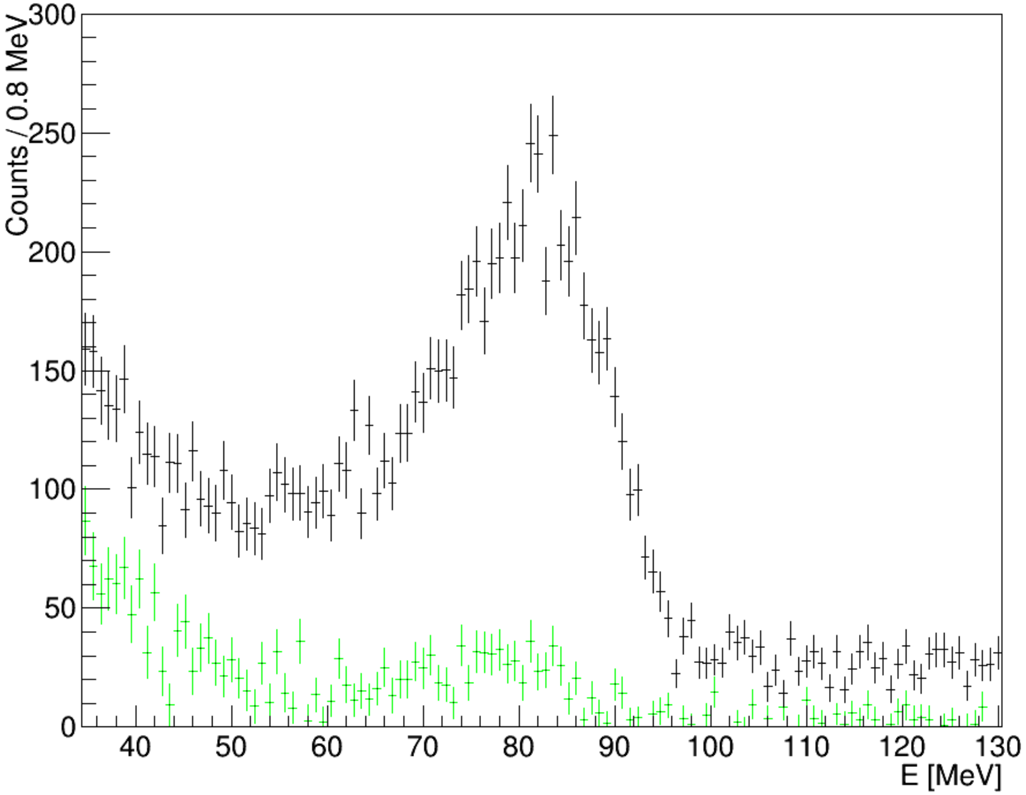
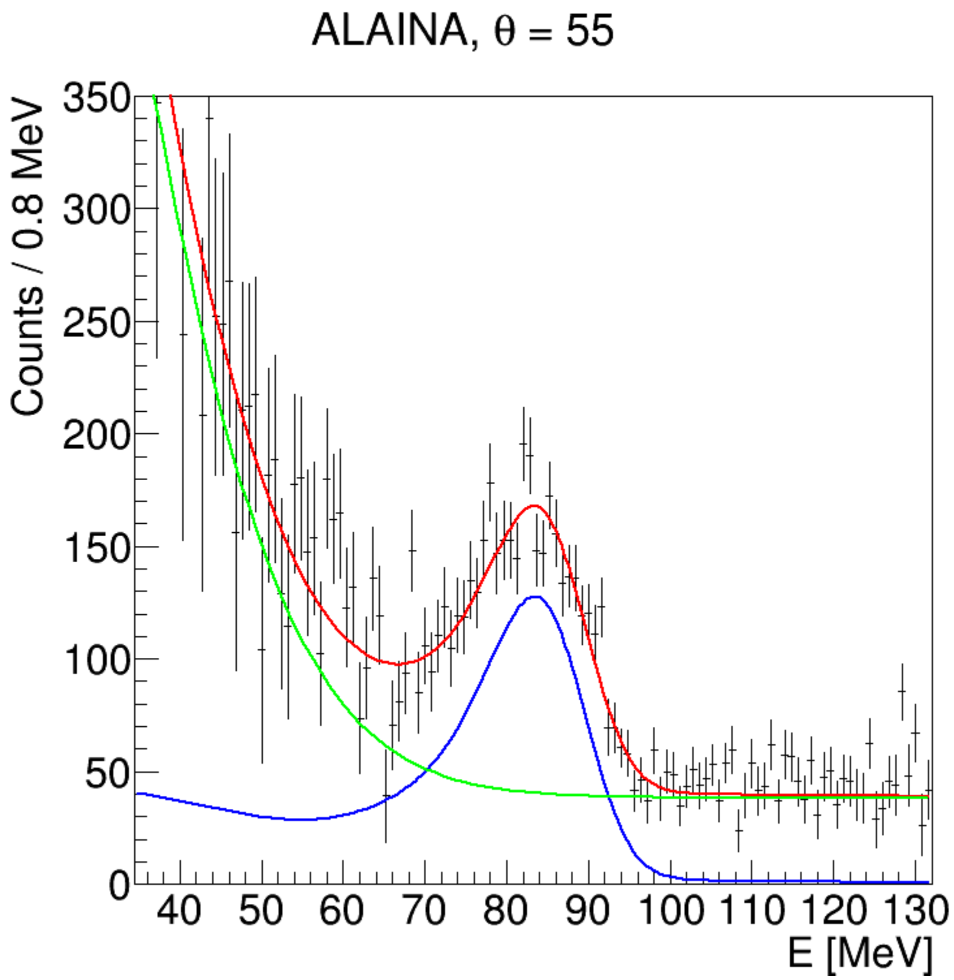
Random Subtraction

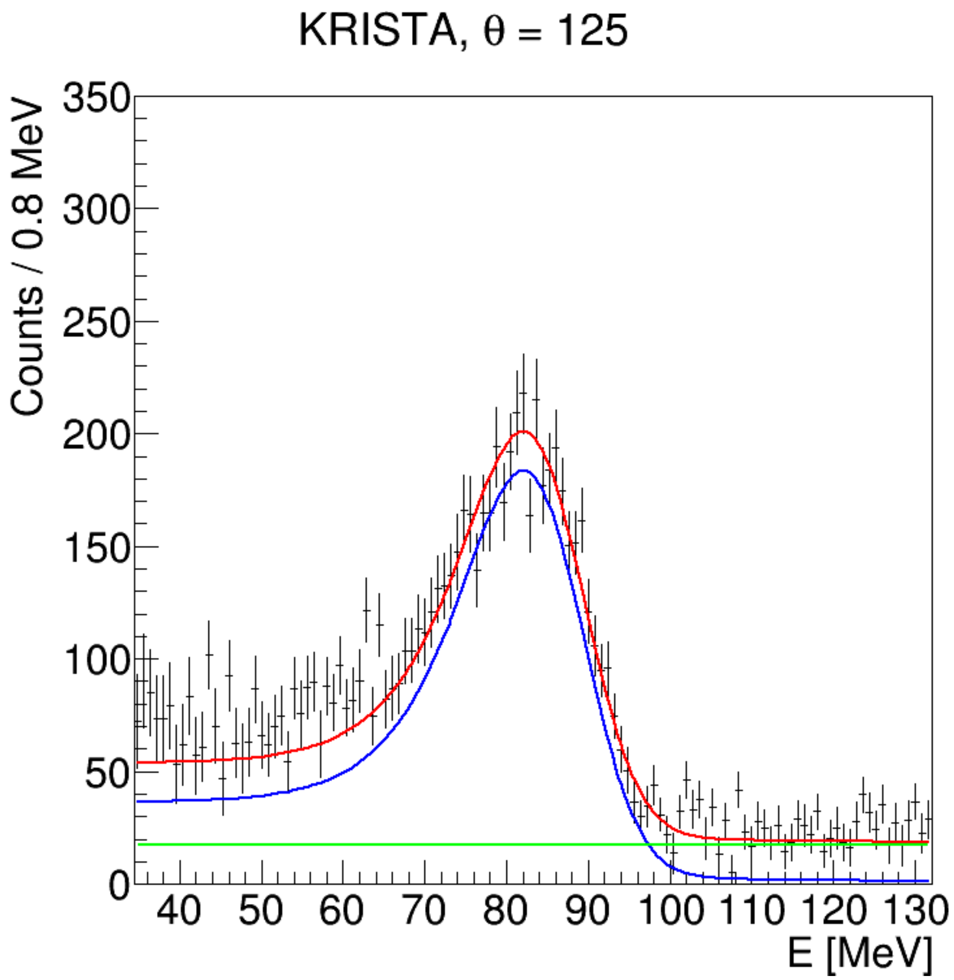


Empty-Target Subtraction

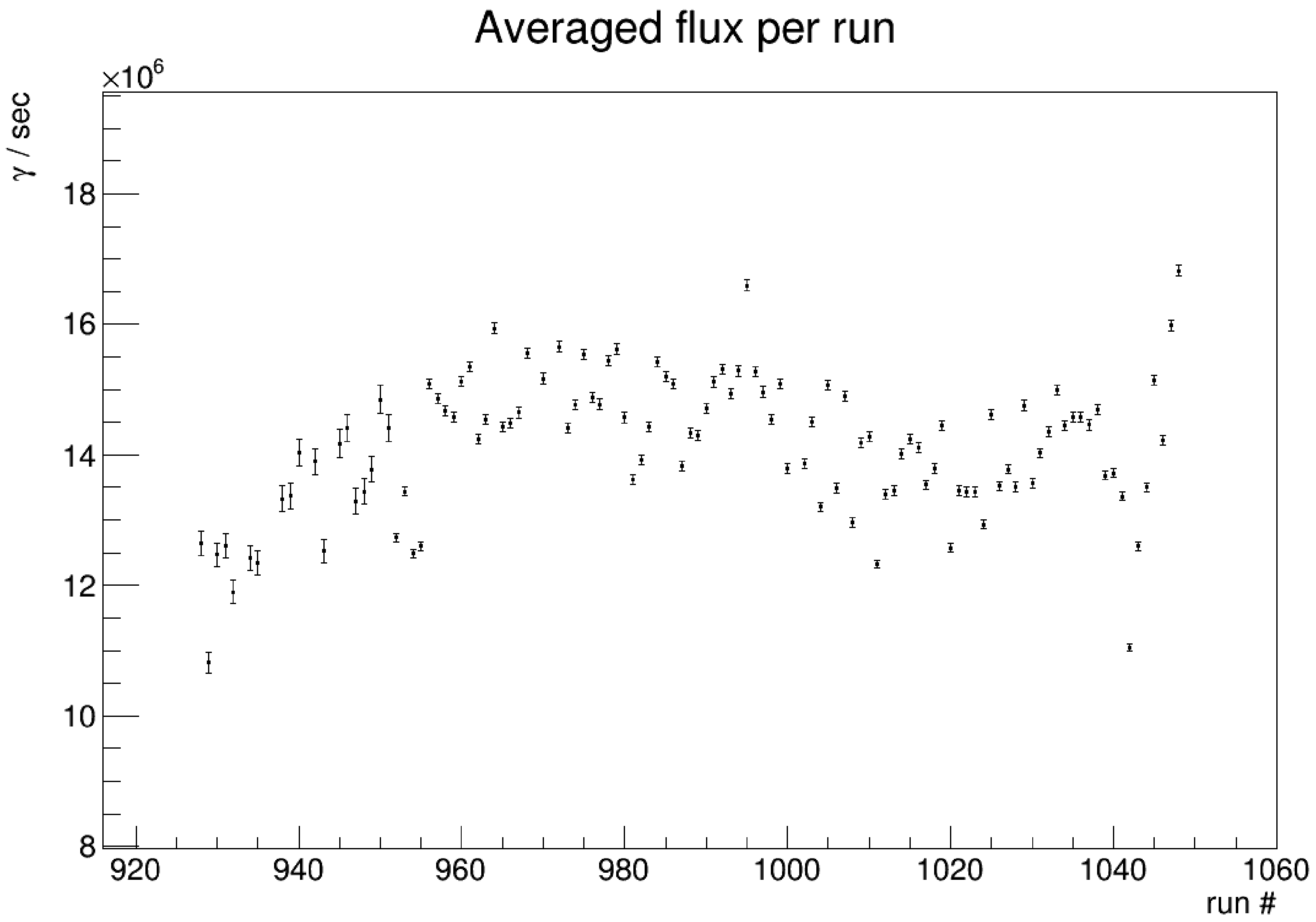


Final Spectra and Line-shape fitting

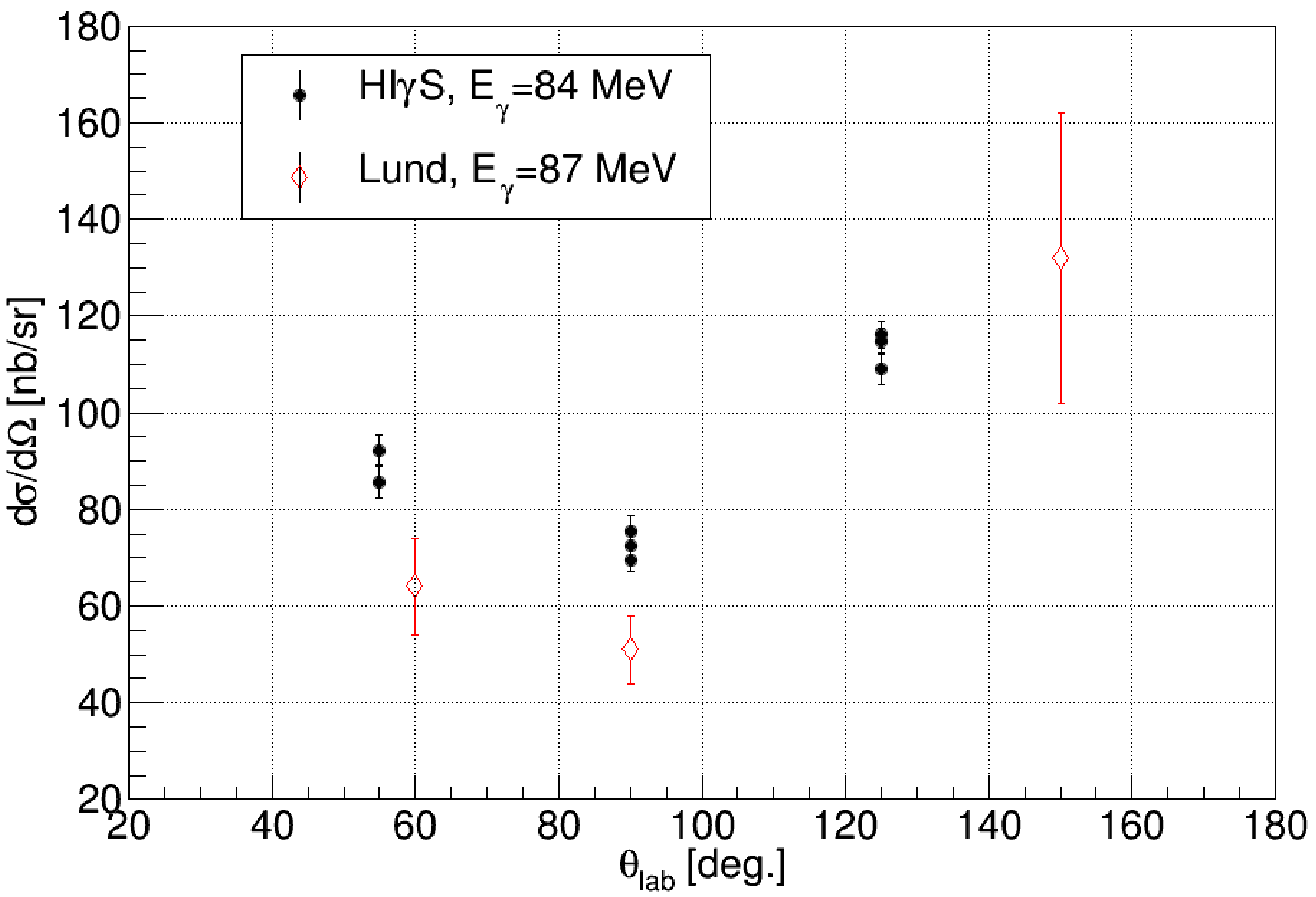




Flux in circular polarization mode



Results from 4He Compton at 84 MeV



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^{4}He Compton Scattering Experiment at 61 and 85 MeV

PHYSICAL REVIEW C

covering nuclear physics

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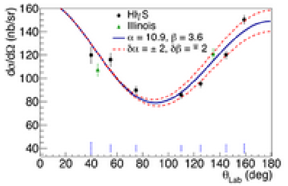


61 MeV

EDITORS' SUGGESTION

Compton scattering from ^{4}He at 61 MeV

Compton scattering, where the electromagnetic field of a real photon induces radiation multipoles by displacing charges and currents inside the nucleon, is an important probe of both the structure of light nuclei and the nucleon polarizabilities. This paper presents the first extensive and precise measurements of elastic Compton scattering on ^{4}He. These results should allow precision comparisons with new calculations expected from both lattice gauge and effective field theories.

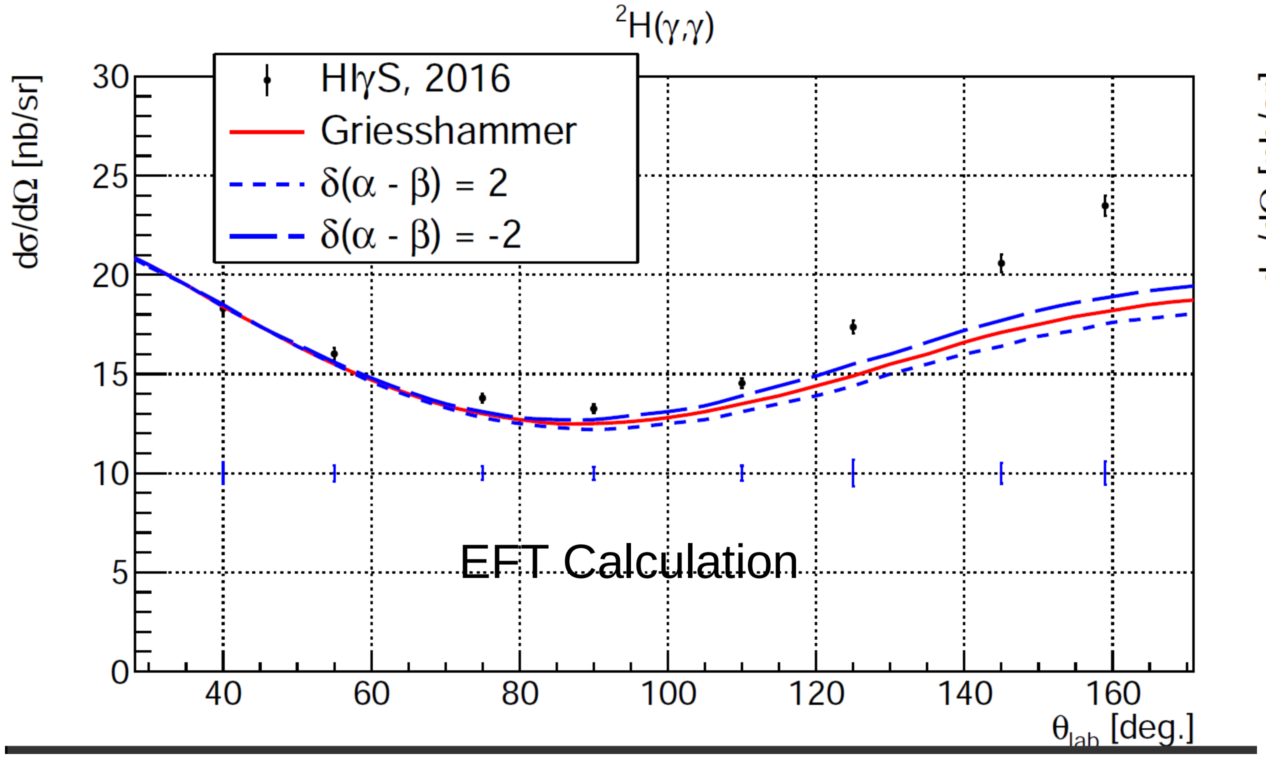
M. H. Sikora *et al.*

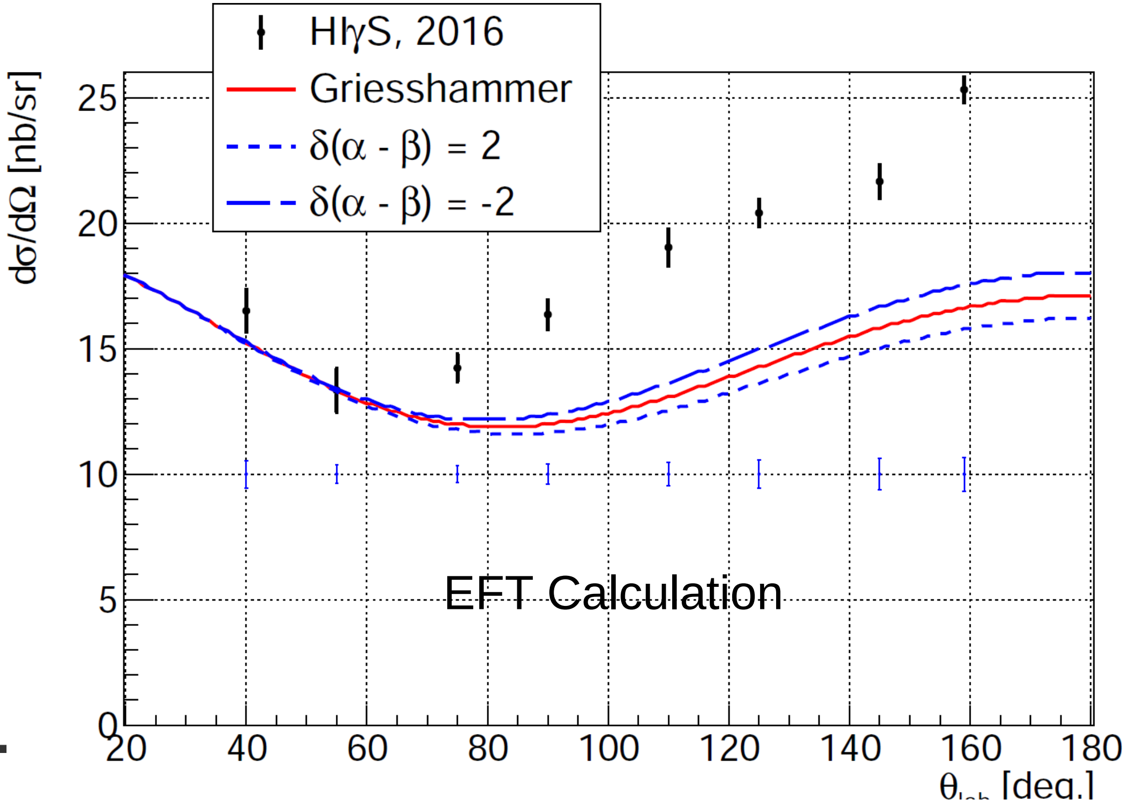
Phys. Rev. C **96**, 055209 (2017)

The curves for the 61 MeV data were calculated using a phenomenological model. **These data have inspired *ab inito* calculations of ^{4}He Compton scattering for the extraction of EM nucleon polarizabilities.**

PRC: DOI: 10.1103/PhysRevC.96.055209

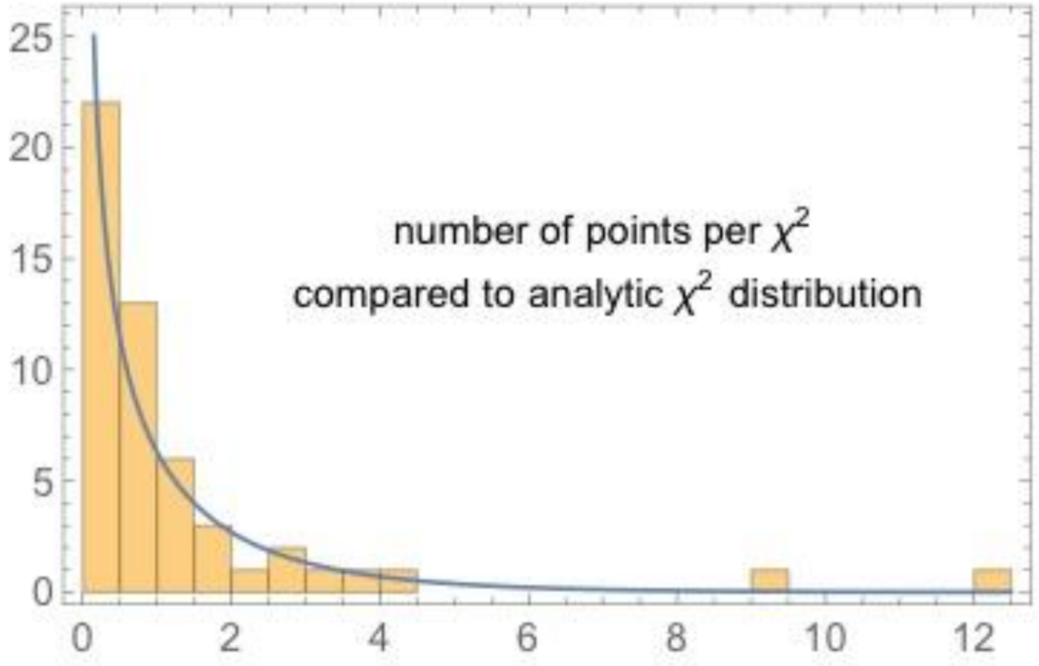
Deuteron Compton Scattering total cross sections at 65 and 85 MeV



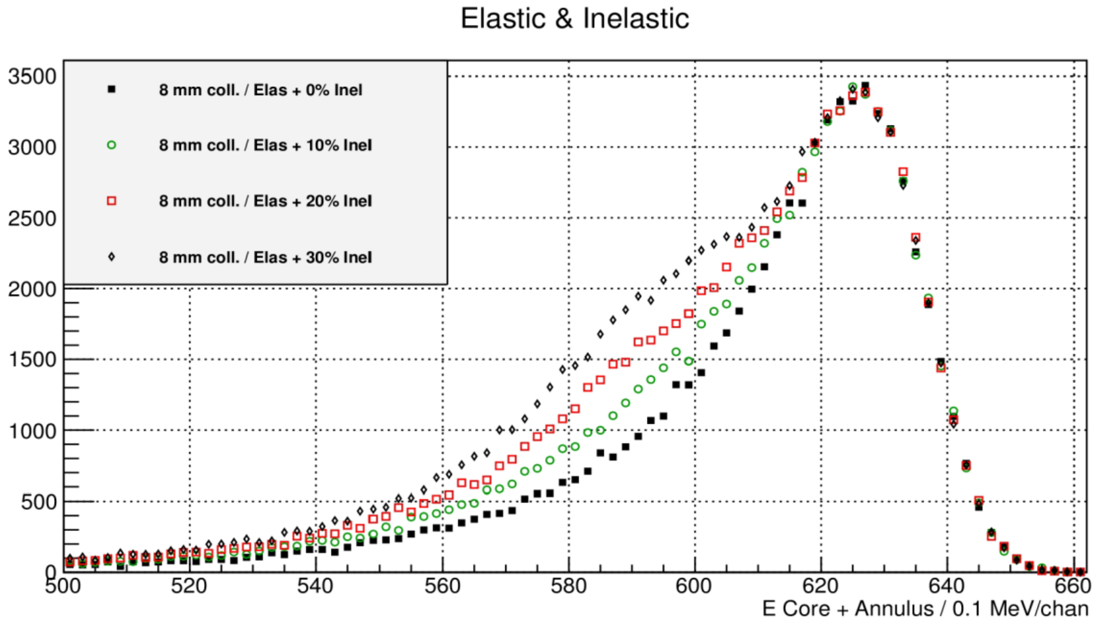


The data include both elastic and inelastic channels. The curves are EFT calculation for purely elastic Compton scattering cross section.

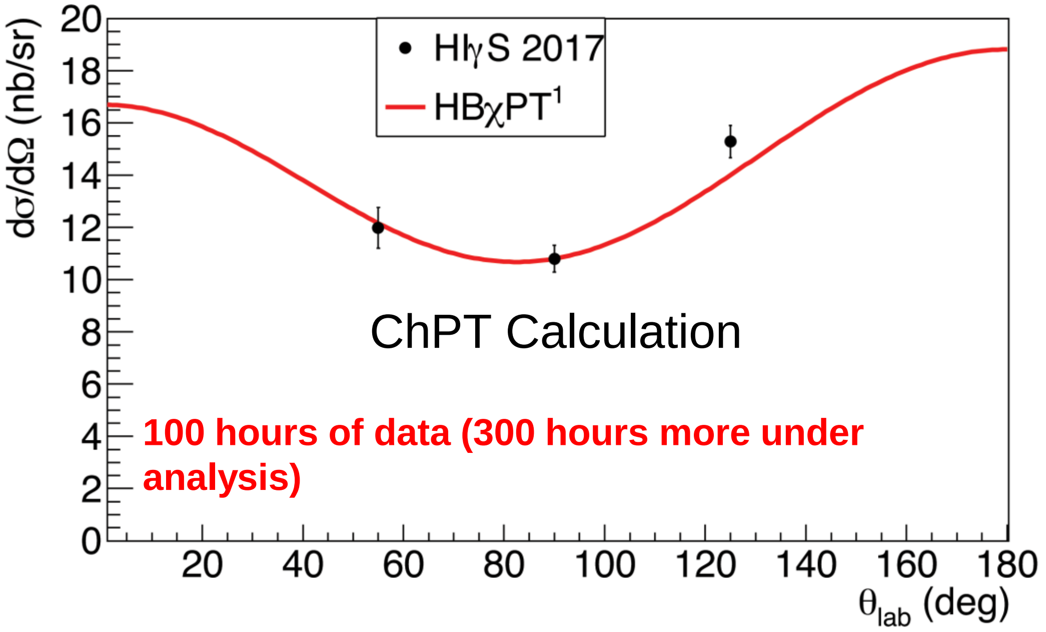
Deuteron World Data

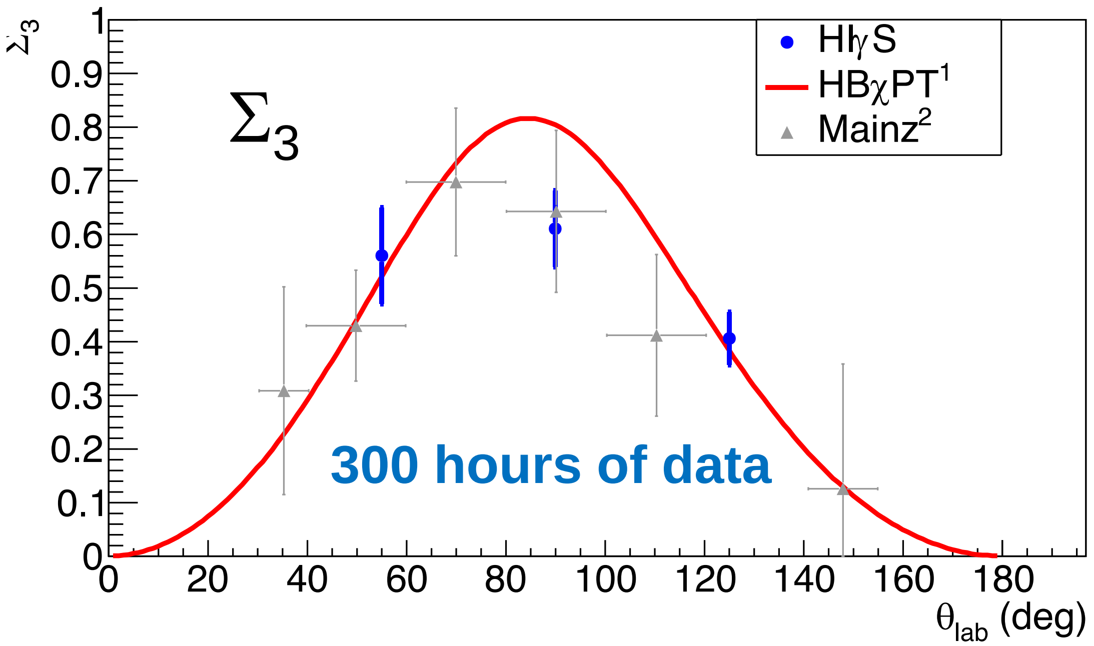


Getting ready to do high energy-resolution deuteron measurement



Proton Compton Scattering at 85 MeV with Circular & **Linear** Polarization





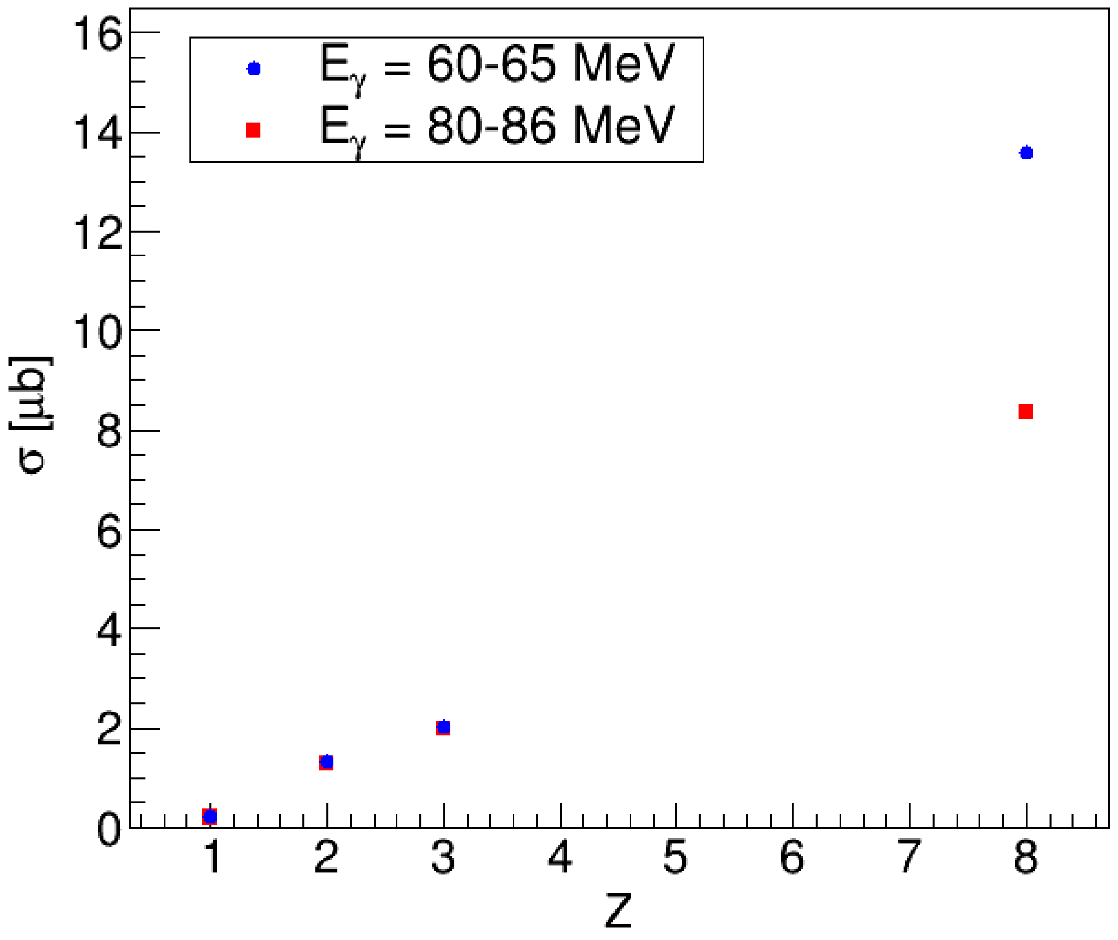
These data will allow for the extraction of the proton polarizabilities using LEX. Along with the Σ_3 measurement, a new extraction of the proton EM polarizabilities will be available soon.

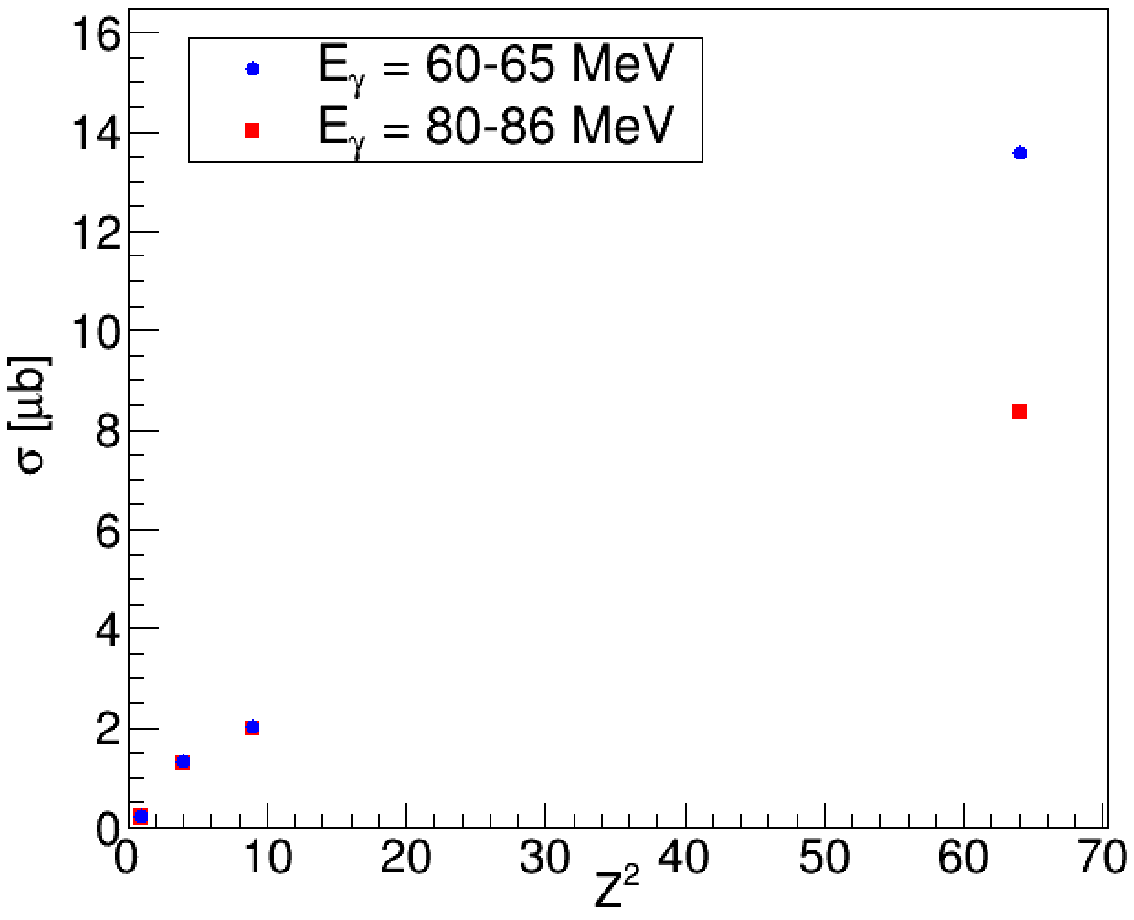
Theory by: J.A McGovern, D.R. Phillips, H.W. Grießhammer, Eur. Phys. J. A, 49, 12 (2013)

Compton Scattering data collected at HIGS to-date

Target	Z	A	E_γ[MeV]	40°	55°	75°	90°	110°	125°	145°	159°
Hydrogen	1	1	84		X		X		X		
Deuterium	1	2	65	X	X	X	X	X	X	X	X
			85	X	X	X	X	X	X	X	X
Helium-4	2	4	61	X	X	X		X	X	X	X
			84		X		X		X		
Lithium-6	3	6	60	X	X	X	X	X	X	X	X
			86	X	X	X	X	X		X	X
Oxygen-16	8	16	60	X	X	X	X	X	X	X	X
			86	X	X	X	X	X		X	X

What is the dependence (Z, Z^2, A) of the Compton cross section for light nuclei?





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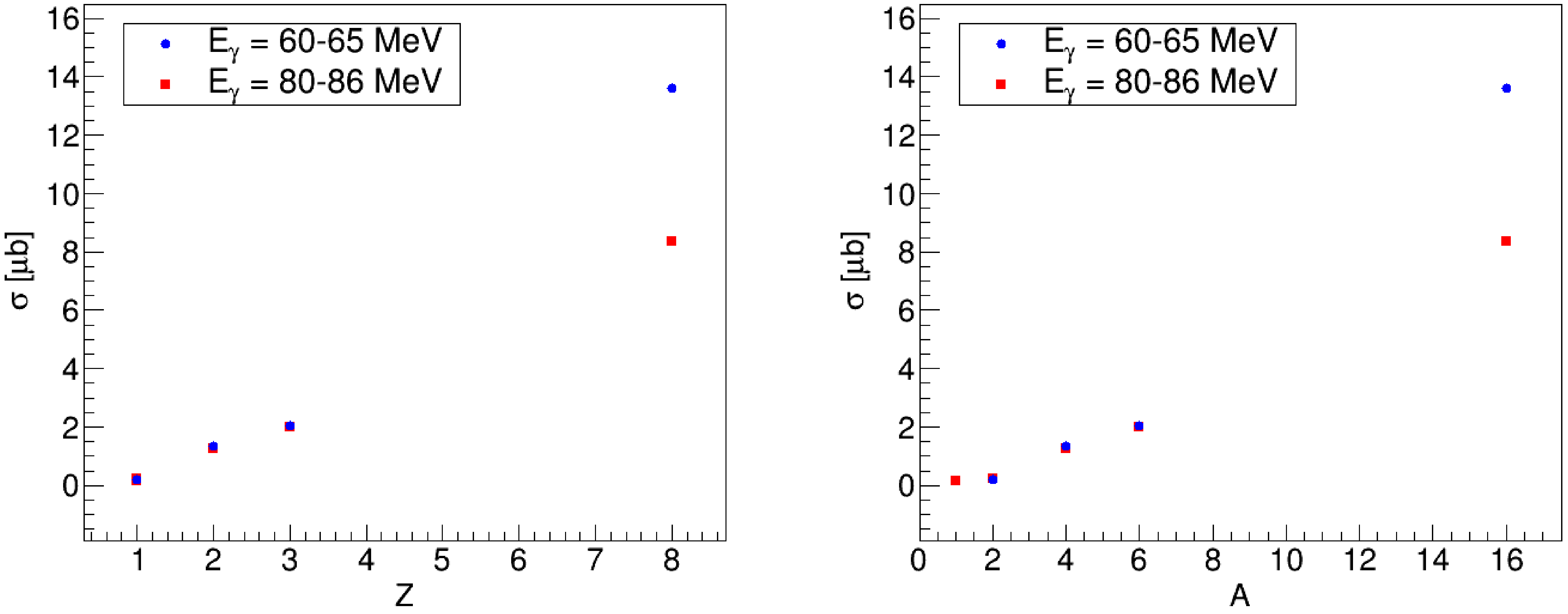
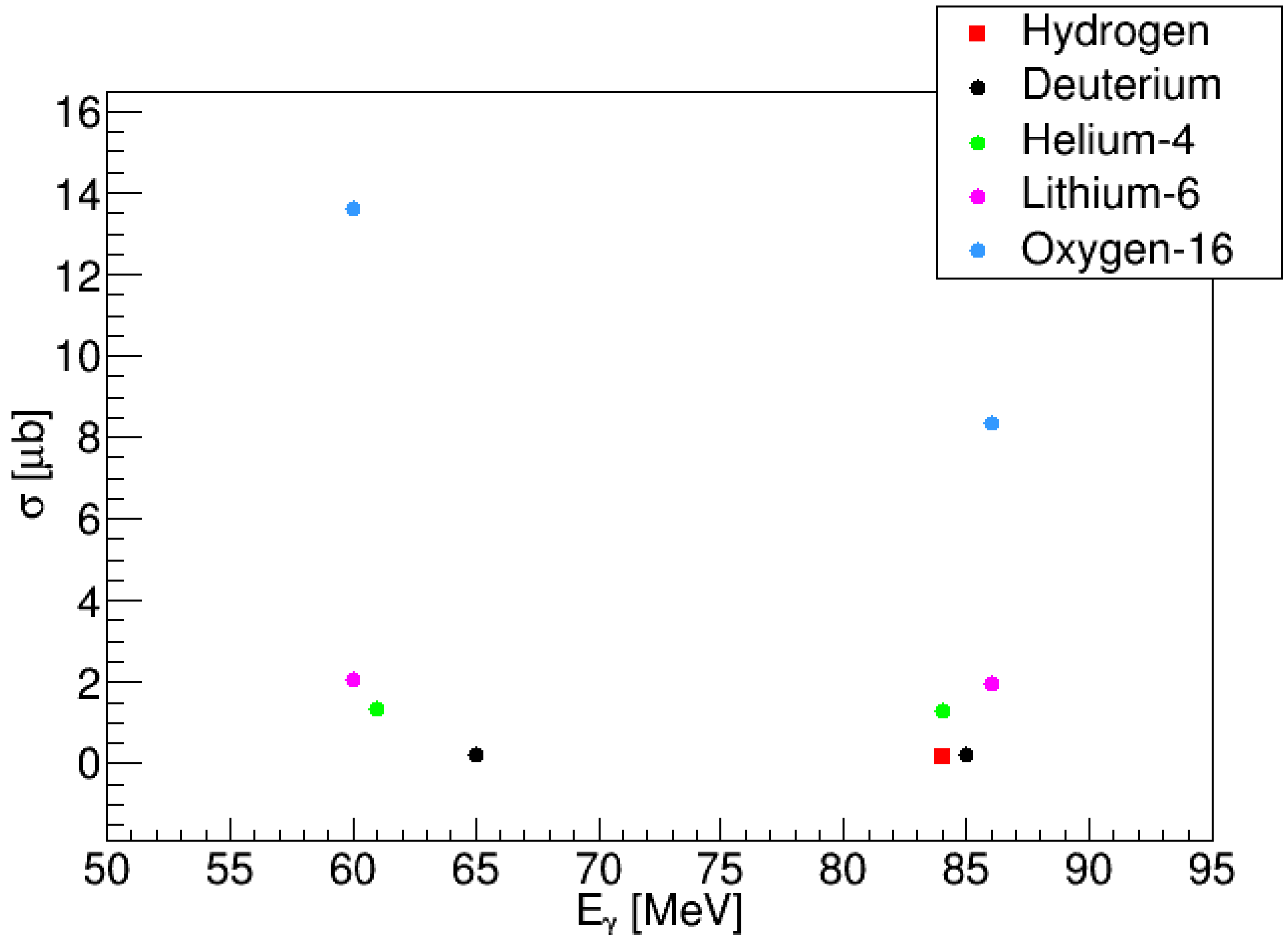


Holistic view of the HIGS Compton scattering program

What is the angular and energy dependence of the Compton cross section for light nuclei?



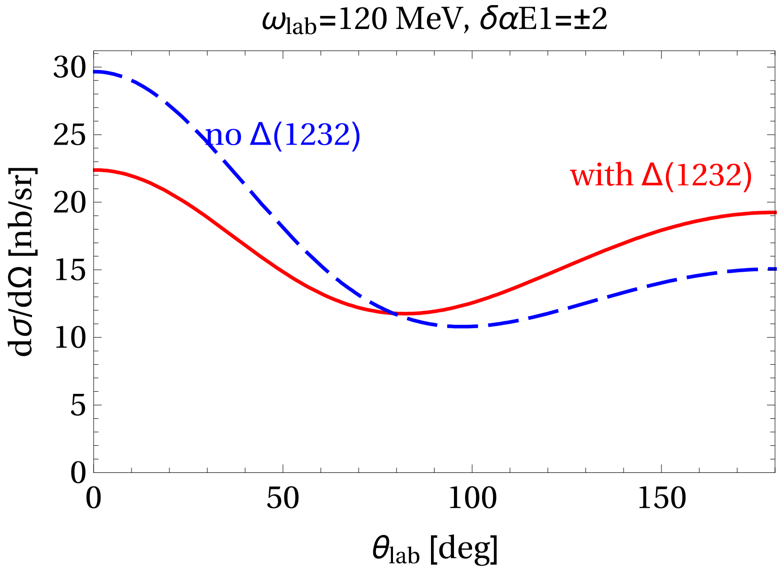
Plans for Next Three Years – Compton Scattering Summary

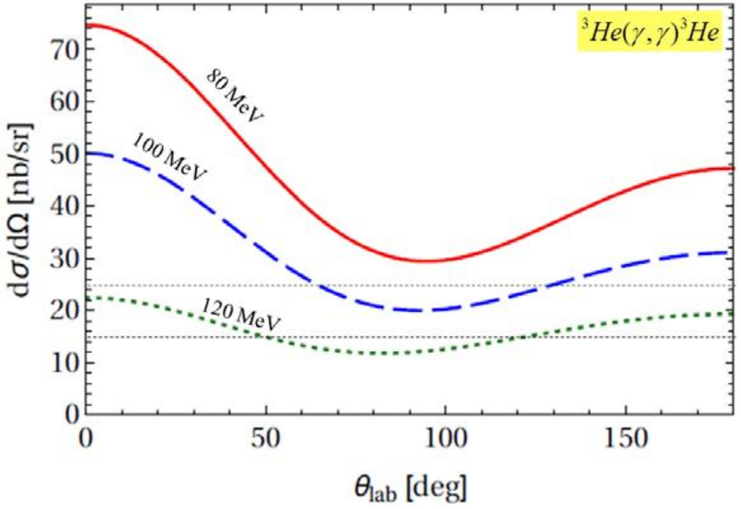
- The overarching goal of the proposed Compton scattering program is to provide a new and much improved extraction of neutron EM polarizabilities
- The forthcoming extractions of the nucleon EM polarizabilities from HIGS will also allow for the extraction of new and improved values for the proton spin polarizabilities

Experiment	Projected Accomplishment
High-Resolution Compton Scattering on ^{2}H @ 65 - 85 MeV	Combined with the existing HIGS data and with the extraction of the elastic cross sections, these data will double the deuteron Compton scattering database for the extraction of the neutron polarizabilities.
Compton Scattering on ^{3}He at 100 - 115 MeV	First world data on Compton scattering on ^{3}He for the extraction of nucleon polarizabilities.

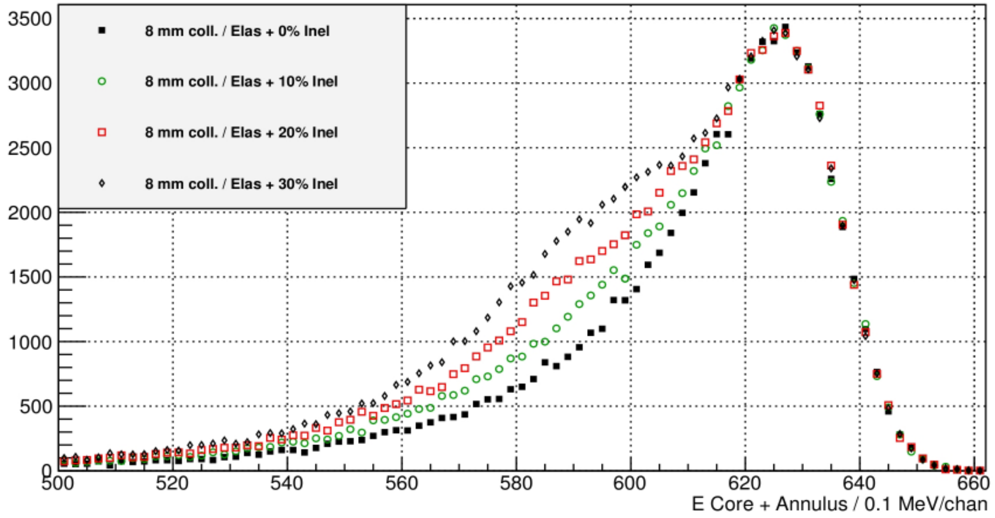
Plans for Next Three Years – ^{3}He/D Compton Scattering Summary

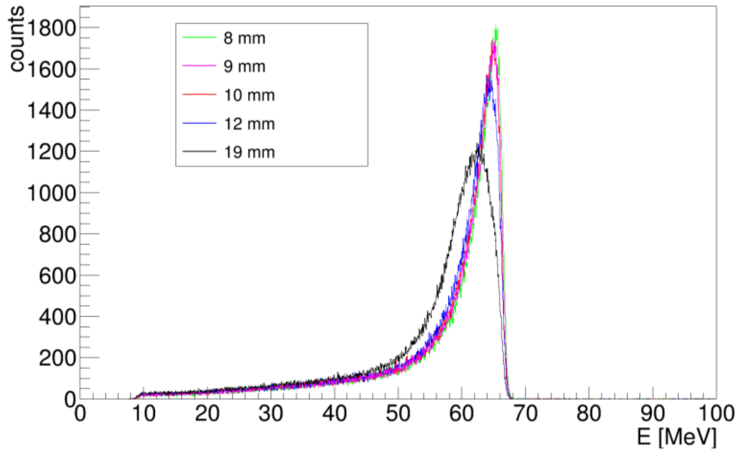
^{3}He Compton Scattering EFT Calculations

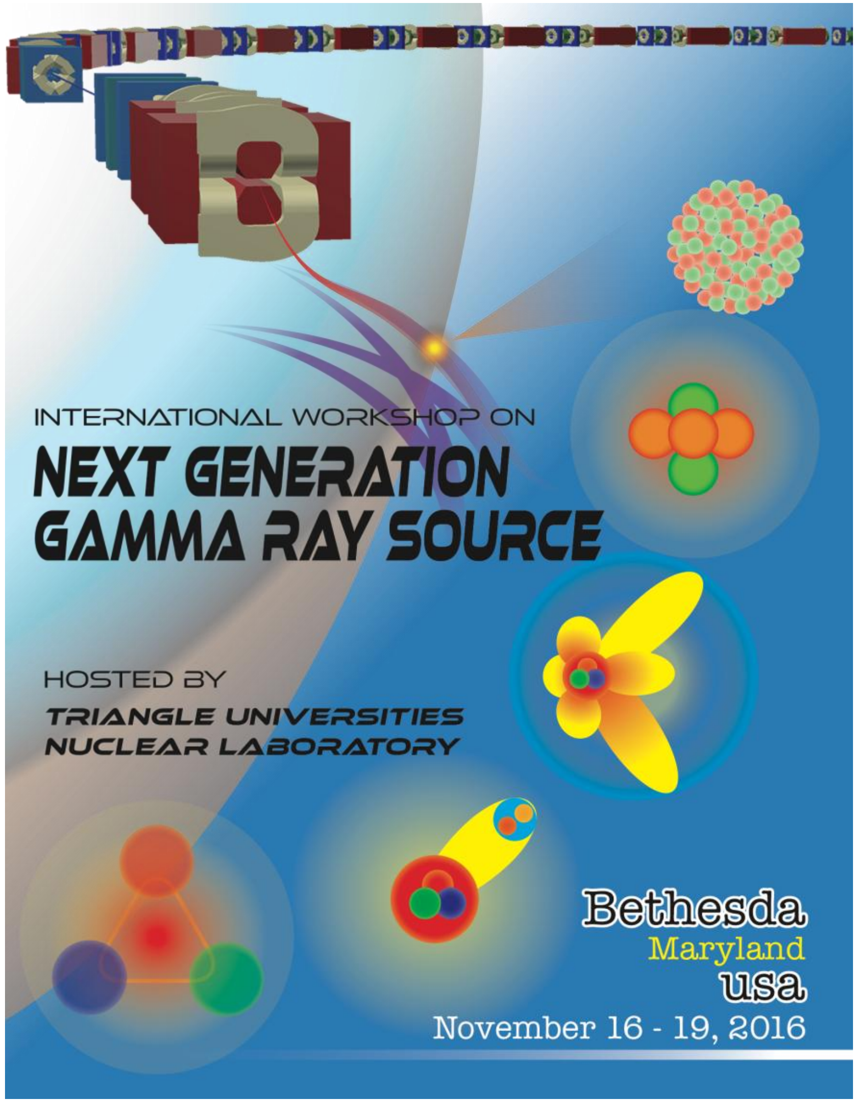




^{2}H Compton Scattering High Resolution Beam measurement and Detector Response







International Workshop on Next Generation Gamma Ray Source, Funded by DOE, Office of Science → Whitepaper

Chiral Dynamics 2018 (www.cd18.org)

Ninth International Workshop on Chiral Dynamics

September 17 – 21st, 2018
Durham, NC