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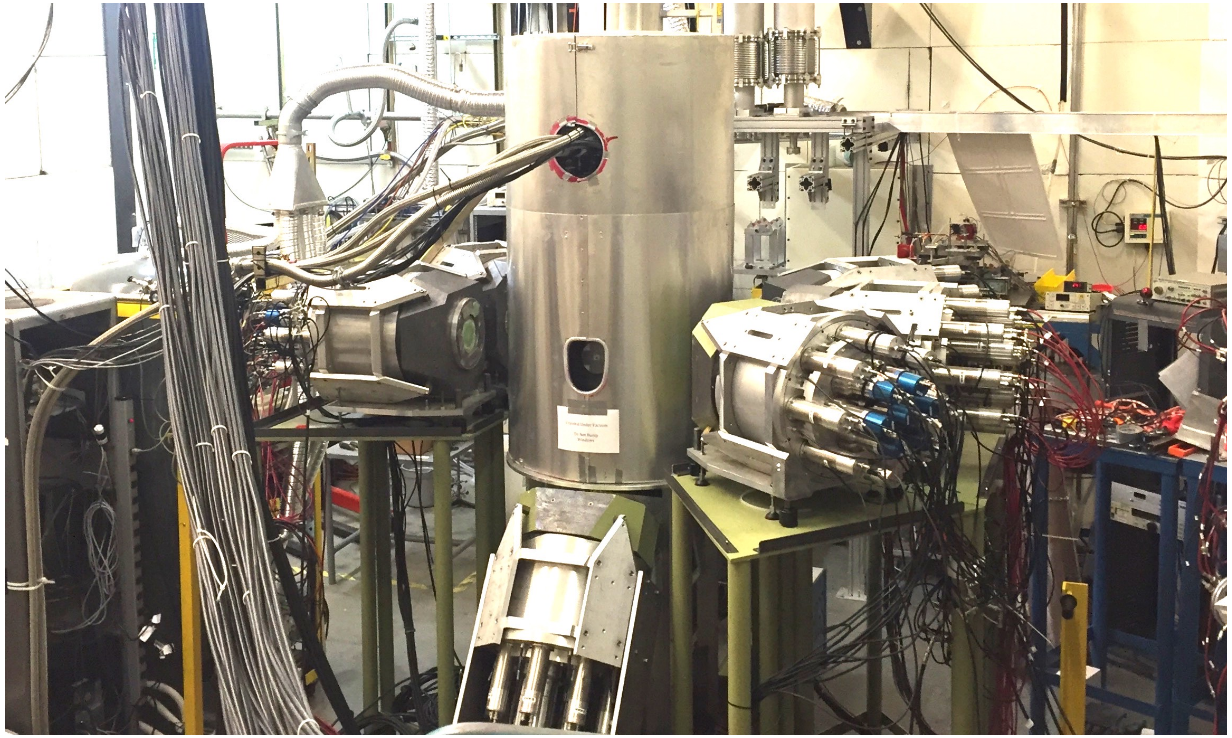
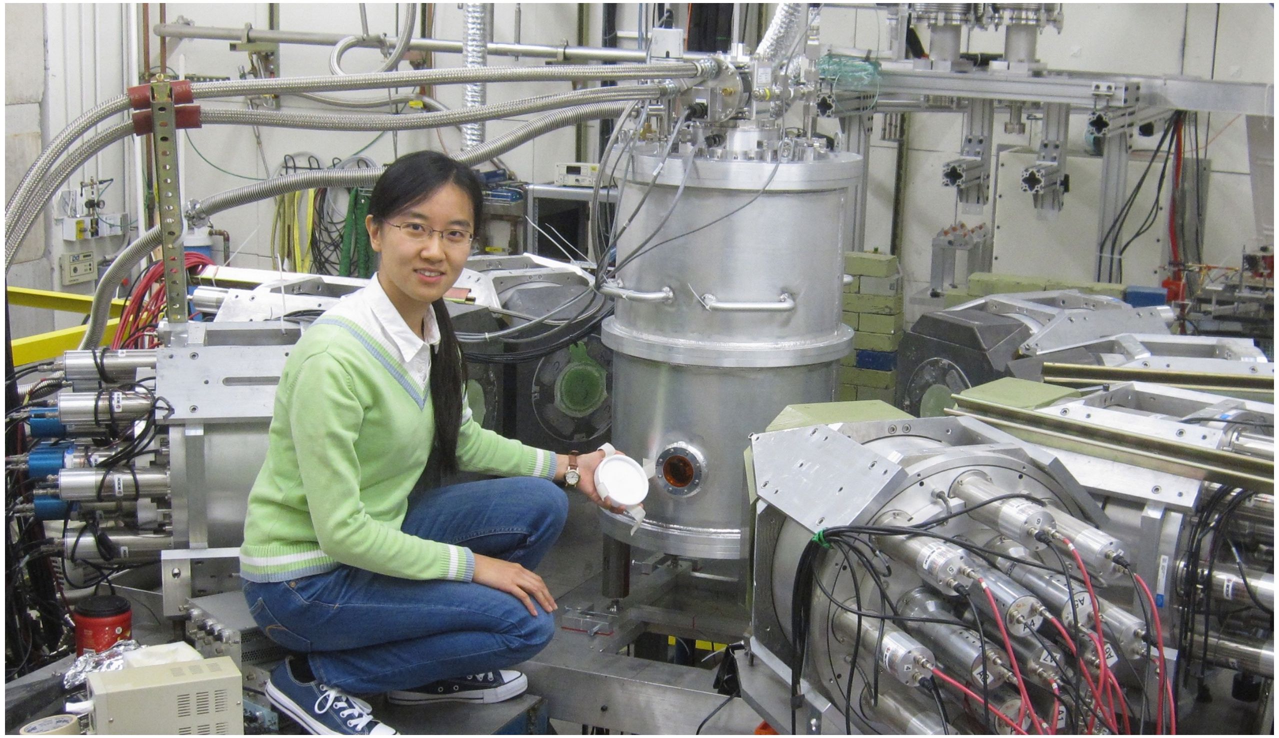
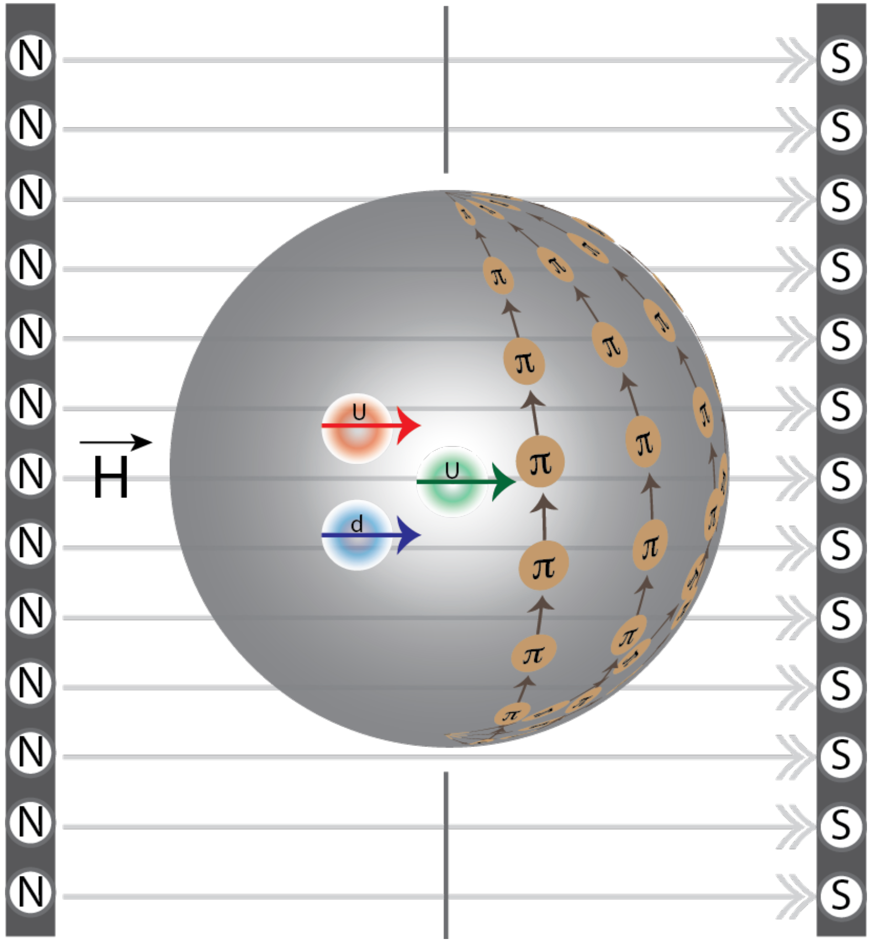
Compton Scattering

Polarized & Unpolarized





Scientific Merit: Polarizabilities in Nucleons



- Nucleon POLARIZABILITIES characterize the response of the nucleon to low-frequency light: Structure Functions
- e.g., the β_M (magnetic polarizability) of a nucleon is an interplay between diamagnetic charged pion currents and paramagnetic Δ resonance
- Polarizabilities have been parameterized in various frameworks[1]:
  - Low-Energy Expansion (LEX)[2] $\omega < 70\ \mathrm{MeV}$
  - Dispersion Relations (DR)[3]
  - Chiral Effective Field Theories (χEFT)[4] ($\omega < \Lambda_b \sim 650\ \mathrm{MeV}$)
  - Lattice QCD (L-QCD)[5]

[1] F. Hagelstein, R. Miskimen, V. Pascalutsa arXiv:1512.03765v3 [nucl-th] (2016)
[2] B. E. MacGibbon, et al., Phys. Rev. C 52 (1995) 2097–2109
[3] B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rev. C 76 (2007) 015203.
[4] H. W. Griesshammer, J. A. McGovern, and D. R. Phillips, Eur. Phys. J. A 52, 139 (2016), arXiv:1511.01952 [nucl-th].
[5] NPLQCD, GW group, Adelaide group, …
[6] R. P. Hildebrandt, Griesshammer, Hemmert, Pasquini, Eur, Phys. J, A 20, 293-315 (2004)

Polarizabilities in the χEFT framework

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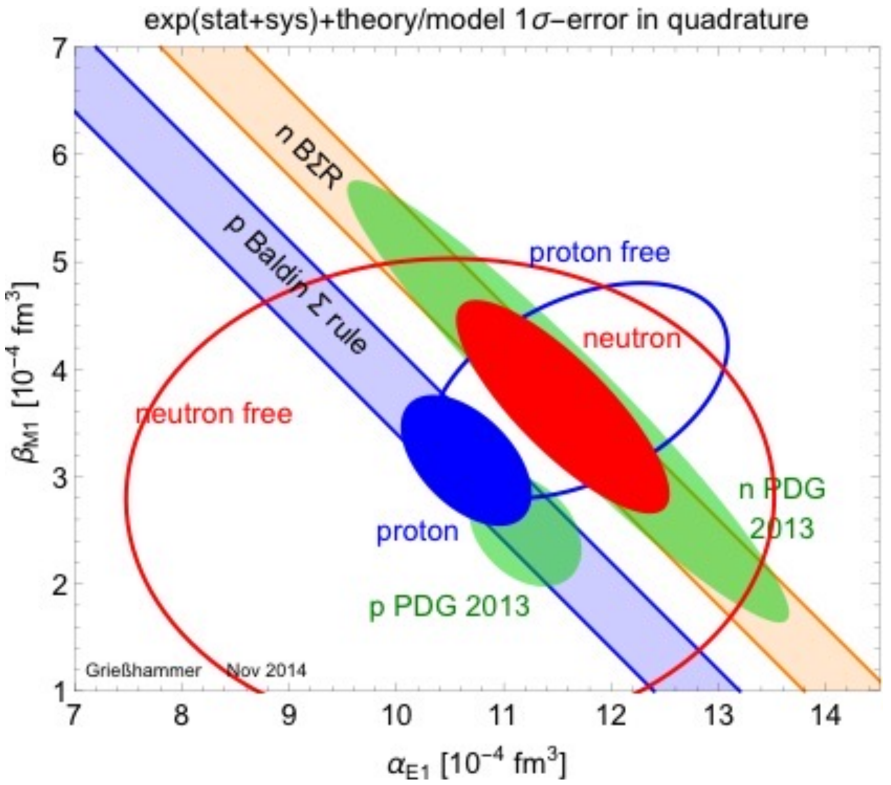
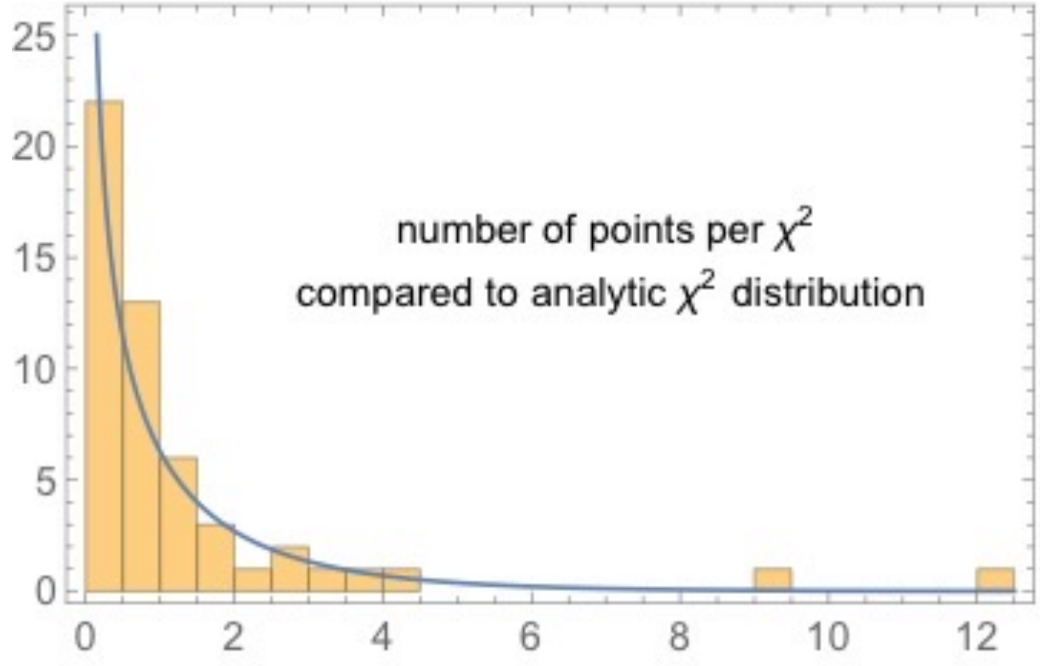
- Polarizabilities have been characterized in the framework of Elastic Compton scattering in χEFT as six low-energy parameters[1]:
  - Consider the case for Coherent scattering from a single nucleon (e.g., proton), in the region $\omega \lesssim m_\pi$:
    - LO: the Born terms (point-like nucleon with κ), plus the π^0 t-channel coupling, no NLO
    - N^2LO: pion cloud (this is where polarizabilities enter)
    - N^3LO: Δ and its pion cloud
    - N^4LO: Corrections to pion-cloud effects
  - For the case of neutron, since there are no free neutron targets, light-nuclei are considered
    - (e.g. Deuteron and 3He) two-body currents
    - Nucleon polarizabilities as linear combinations (^{3}He: $2\alpha_p+\alpha_n$, ^{2}H: $\alpha_p+\alpha_n$)

1. H. W. Griesshammer, J. A. McGovern, and D. R. Phillips, Eur. Phys. J. A54, 37 (2018), arXiv:1711.11546
2. H. W. Griesshammer, J. A. McGovern, and D. R. Phillips, Eur. Phys. J. A 52, 139 (2016), arXiv:1511.01952 [nucl-th].
3. H.W. Griesshammer, 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, doi:10.1016/j.ppnp.2012.04.003

Deuteron World Data





Plots courtesy of Harald Grießhammer

[1] H. W. Griesshammer, J. A. McGovern, and D. R. Phillips, Eur. Phys. J. A54, 37 (2018), arXiv:1711.11546.
H. W. Griesshammer, J. A. McGovern, and D. R. Phillips, Eur. Phys. J. A 52, 139 (2016), arXiv:1511.01952 [nucl-th].

The current status of polarizabilities

- χEFT extraction of polarizabilities based upon fit to the world data[1]. Spin polarizabilities are not discussed in detail in this proposal. However, it must be noted that the EM polarizabilities are inputs to the extraction of spin polarizabilities

α_{E1}	**Electric Dipole**	(p) $10.65\ \pm 3.2\%\ (stat) \pm 0.2\ (Baldin) \pm 0.3\ (theory)$ (n) $11.55\ \pm 10.8\%\ (stat) \pm 0.2\%\ (Baldin) \pm 0.8\ (theory)$
β_{M1}	**Magnetic Dipole**	(p) $3.15\ \mp 11.1\%\ (stat) \pm 0.2\ (Baldin) \pm 0.3\ (theory)$ (n) $3.65\ \mp 34.2\%\ (stat) \pm 0.2\ (Baldin) \pm 0.8\ (theory)$
	Spin Polarizabilities	They have been calculated for proton and neutron in various theoretical frameworks, data only exists for proton spin polarizabilities [2]. See Ref [3] for a detailed overview of spin polarizabilities
γ_{E-}	$\gamma_{E1E1} - \gamma_{E1M2}$	
γ_{M-}	$\gamma_{M1M1} - \gamma_{M1E2}$	
γ_0	$-\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2}$	
γ_π	$-\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2}$	

[1] H. W. Griesshammer, J. A. McGovern, and D. R. Phillips, Eur. Phys. J. A54, 37 (2018), arXiv:1711.11546.
H. W. Griesshammer, J. A. McGovern, and D. R. Phillips, Eur. Phys. J. A 52, 139 (2016), arXiv:1511.01952 [nucl-th].
[2] P. P. Martel, et al., Phys. Rev. Lett. 114 (2015) 112501.
[3] F. Hagelstein, R. Miskimen, V. Pascalutsa arXiv:1512.03765v3 [nucl-th] (2016)

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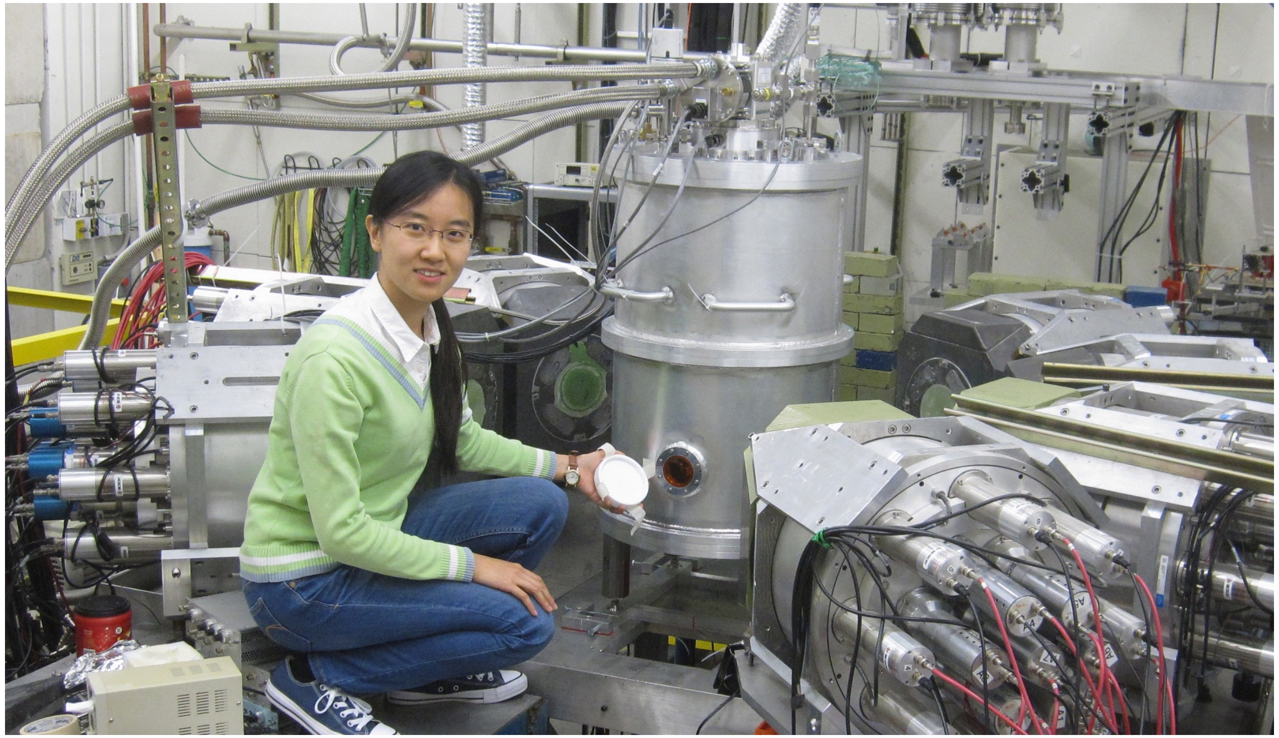
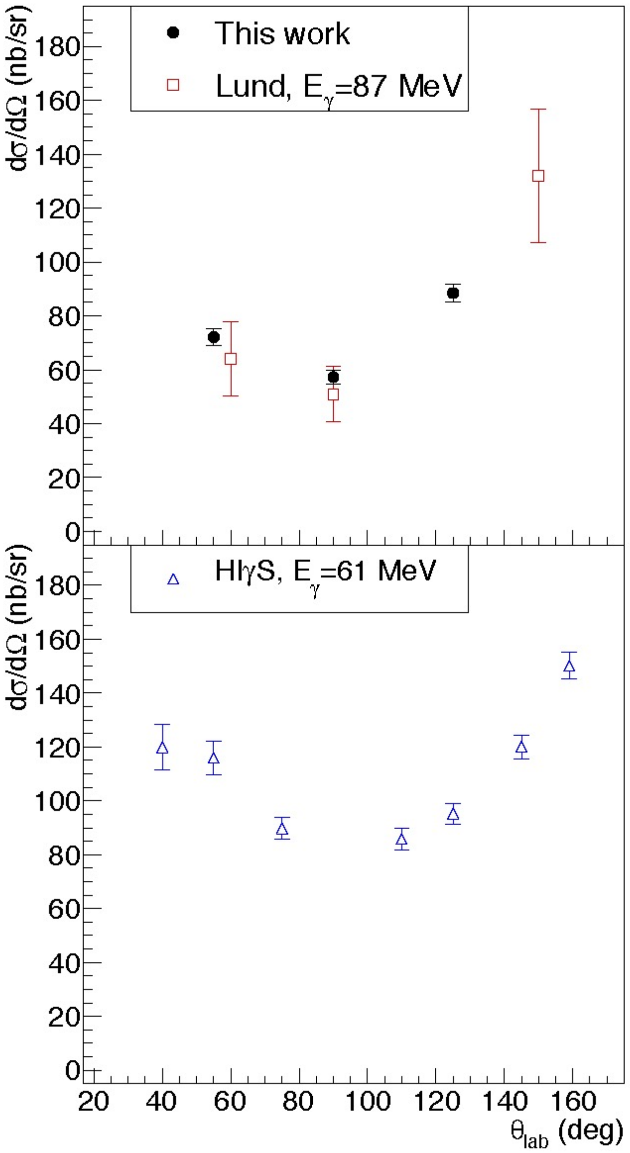
Start of the Compton Program at HIGS (the last three years)

Experiment	Status - Outcome
Proton Compton Scattering with Linear and Circularly Polarized Beams (81 MeV)	Manuscript submitted to PRL, new Chiral EFT extraction of proton EM polarizabilities
Deuteron Compton scattering (65 and 85 MeV) – high statistics / low-energy resolution	Manuscript in preparation, adds 16 more data points to the deuteron Compton scattering database – calculations are underway to extract EM polarizability sensitivity to the total cross section
^{4}He Compton scattering at 81 MeV	Phys. Rev. C Published March 2020 – new Chiral EFT calculation to extract nucleon polarizabilities from 4He Compton scattering expected soon (HG- GWU)
^{2}H Compton scattering at 65 and 85 MeV with high energy-resolution	DIANA and BUNI detectors commissioned. First data collected at 61 MeV
^{3}He Compton Scattering at 110 MeV Using Cryogenic Target	^{3}He target modified for 2K operations. Awaiting delivery of 3He from UVa

Compton Scattering – ^{4}He





^{4}He CS

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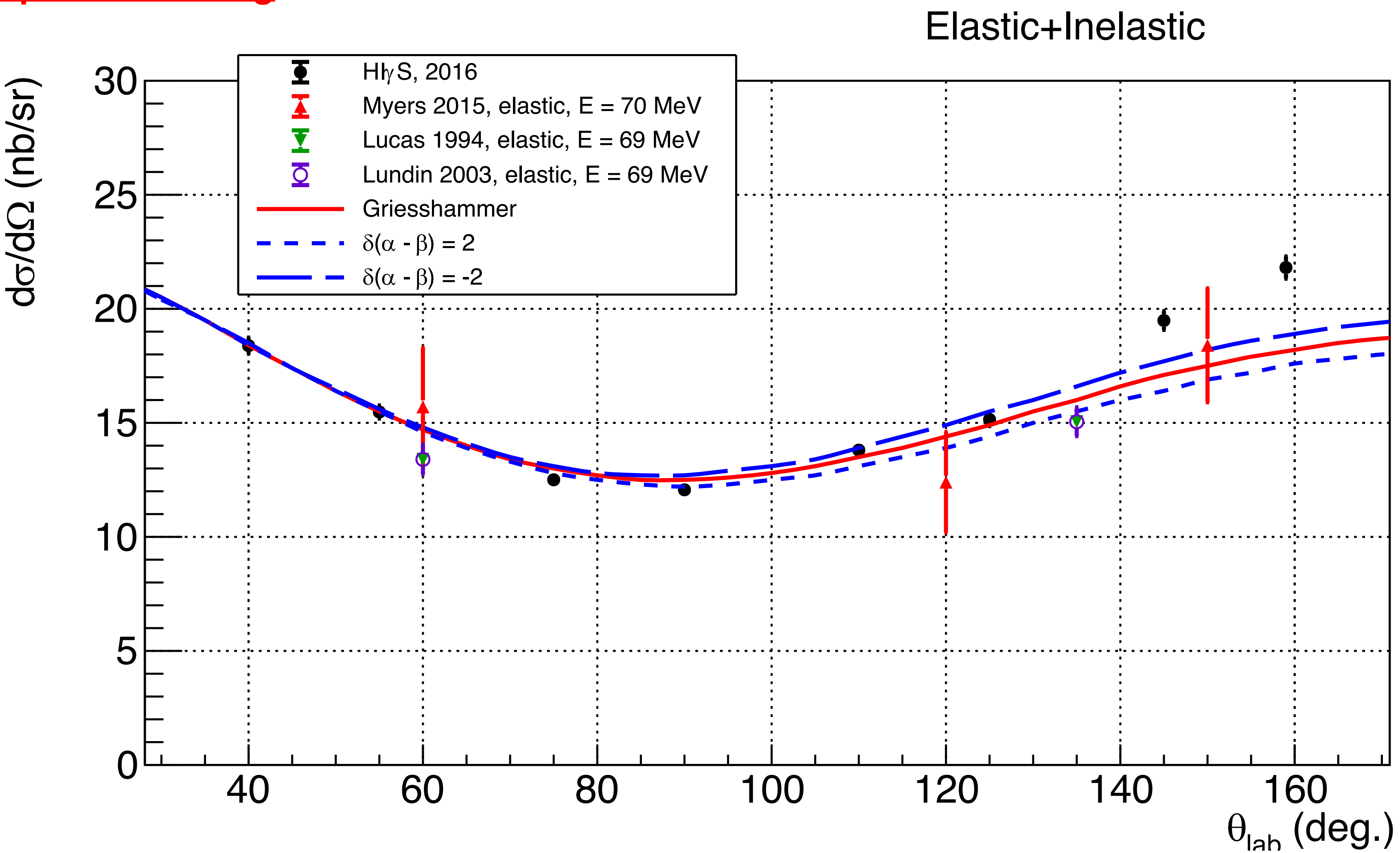
Deuteron Compton Scattering



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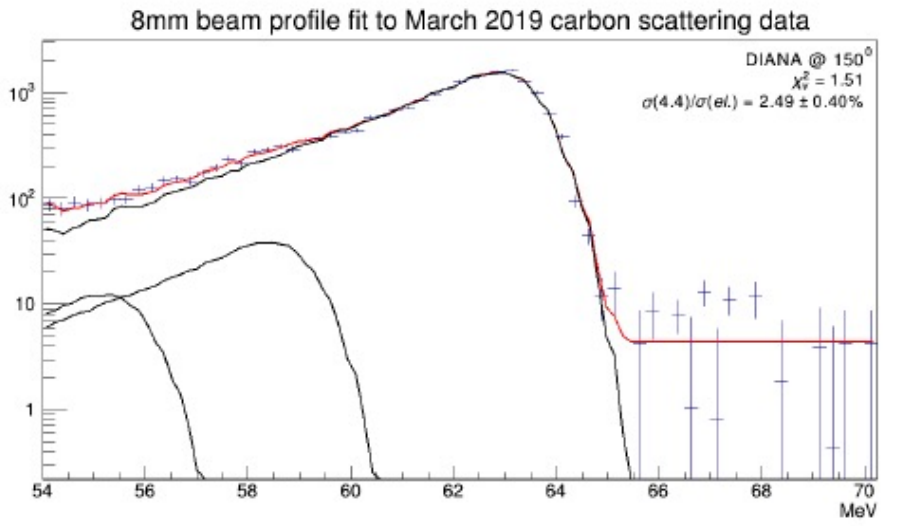
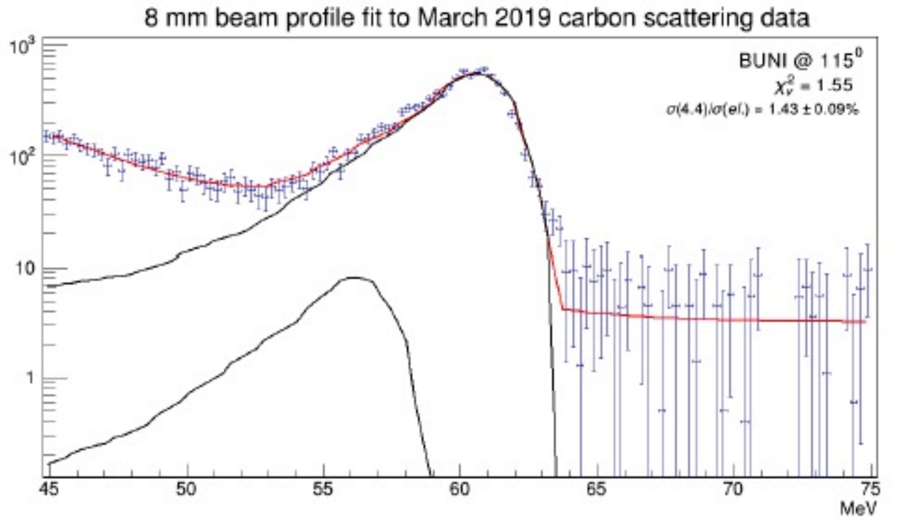
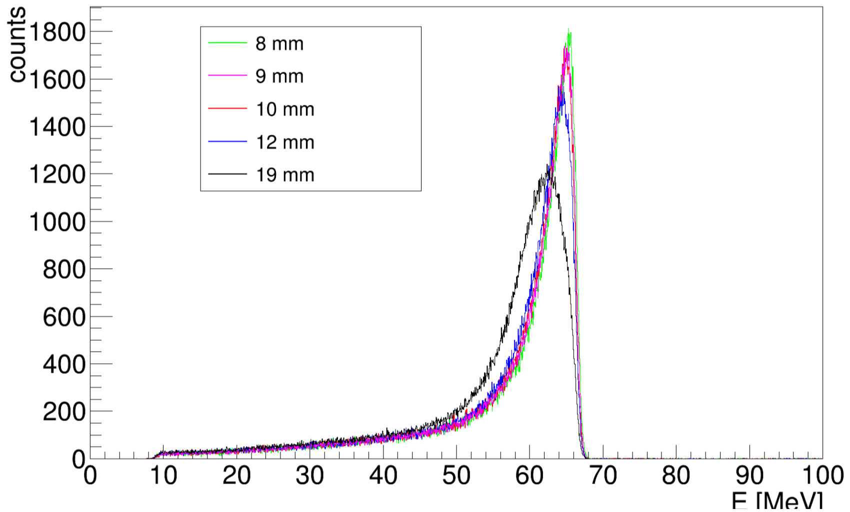
Proof of Principle – ^{12}C Compton scattering with high energy-resolution beam

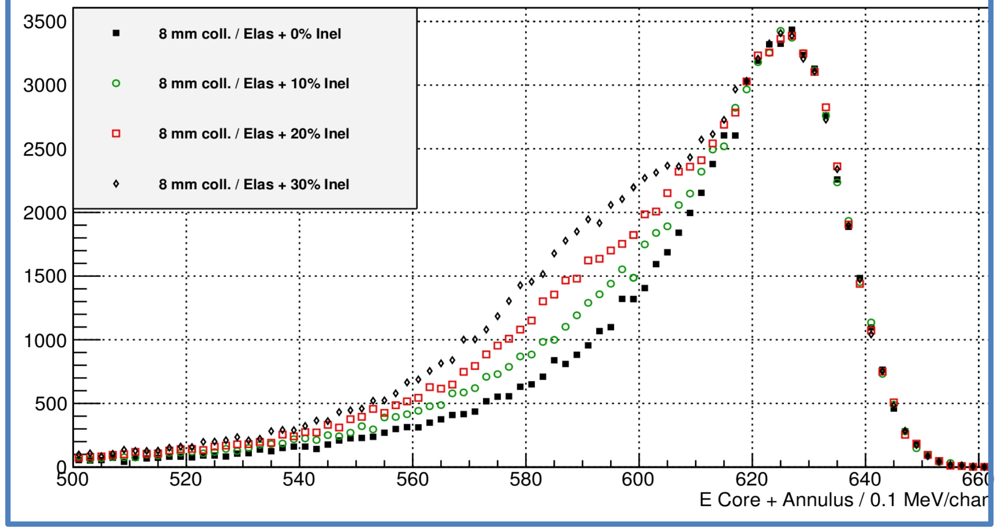




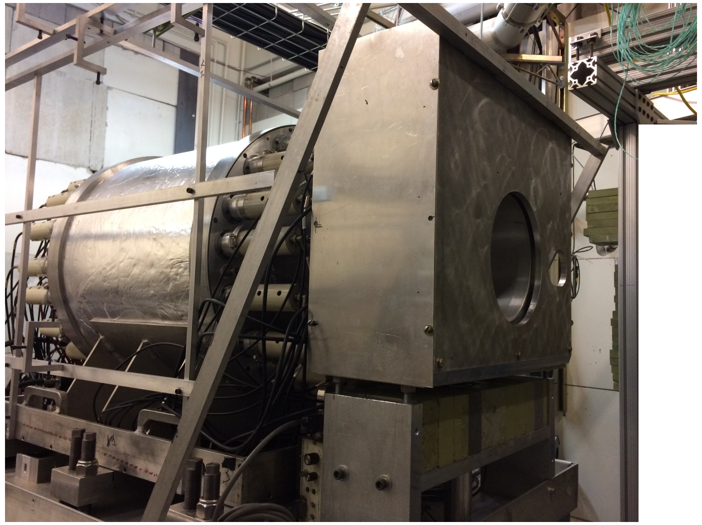
Fitted Spectra to elastic + inelastic channel in CS

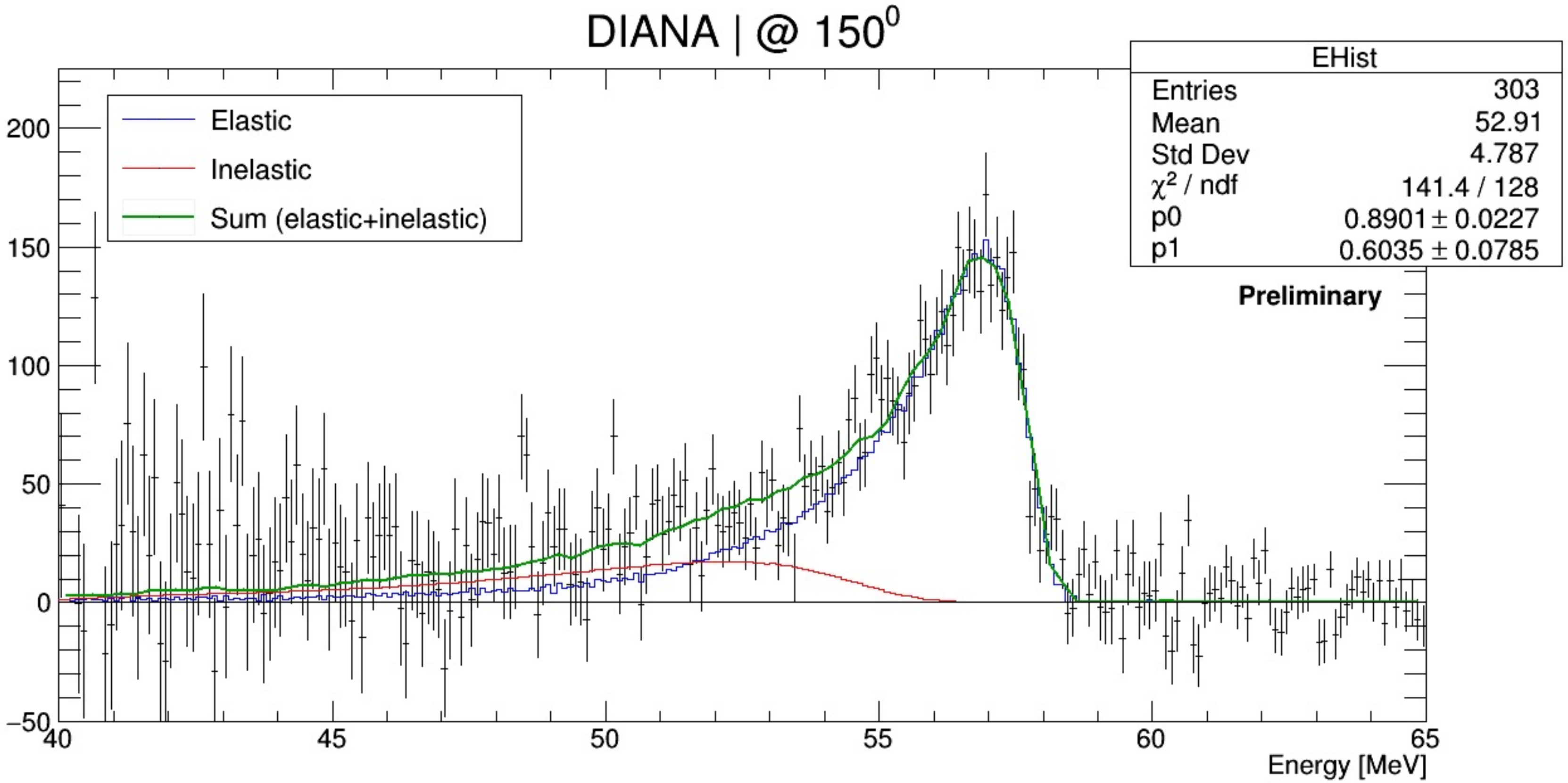
Test of beam resolution and simulation of detector response





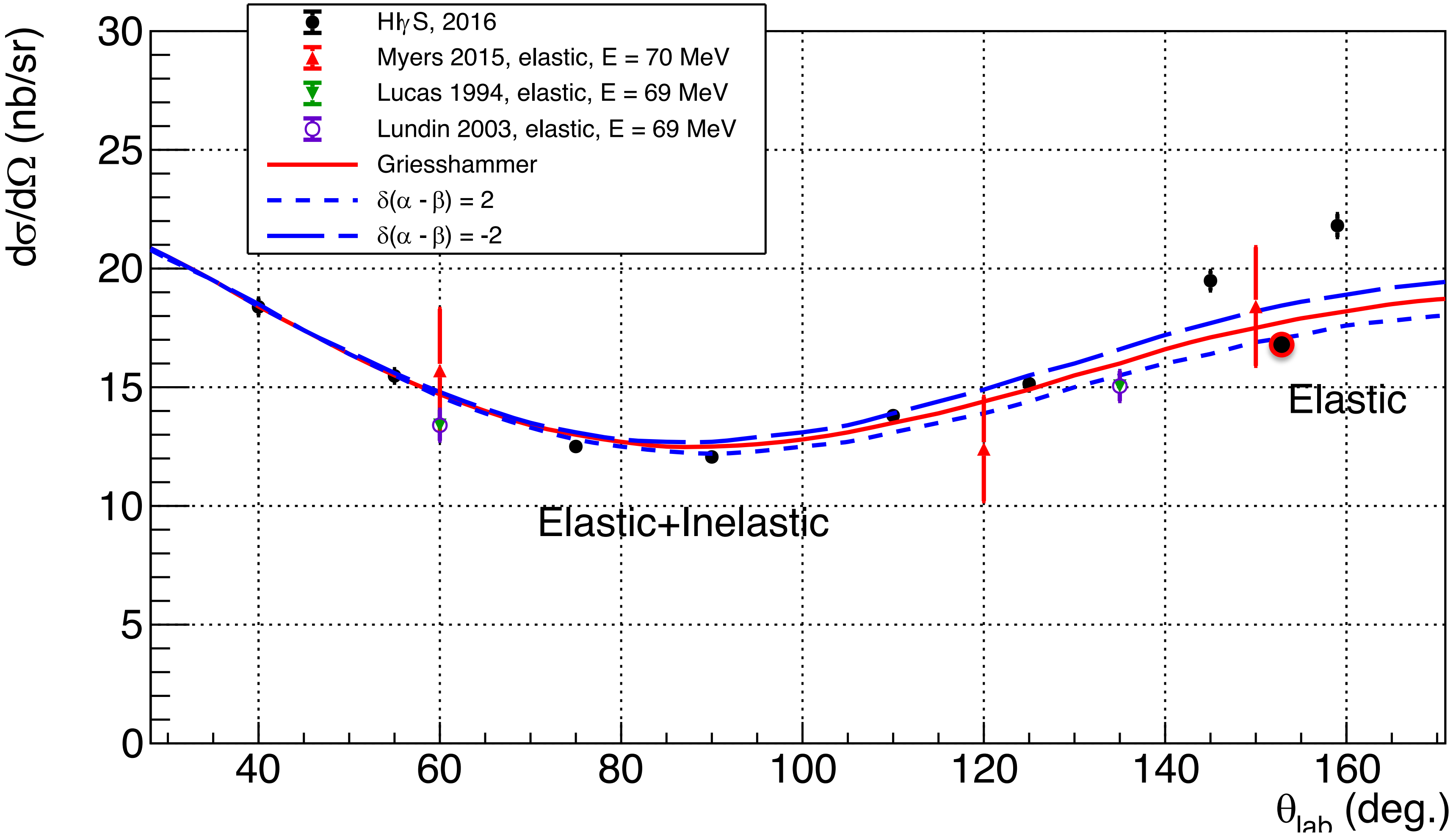
Compton Scattering – ^{2}H, High Resolution



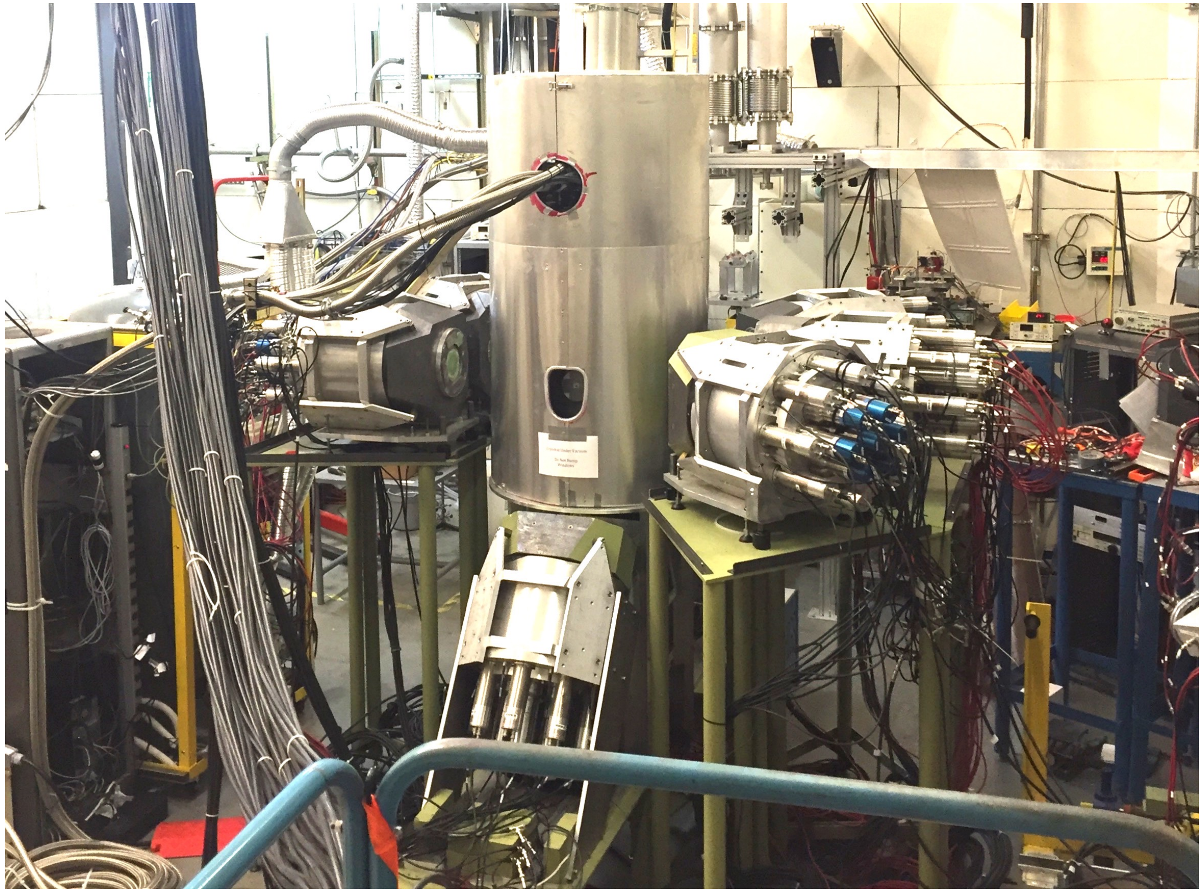


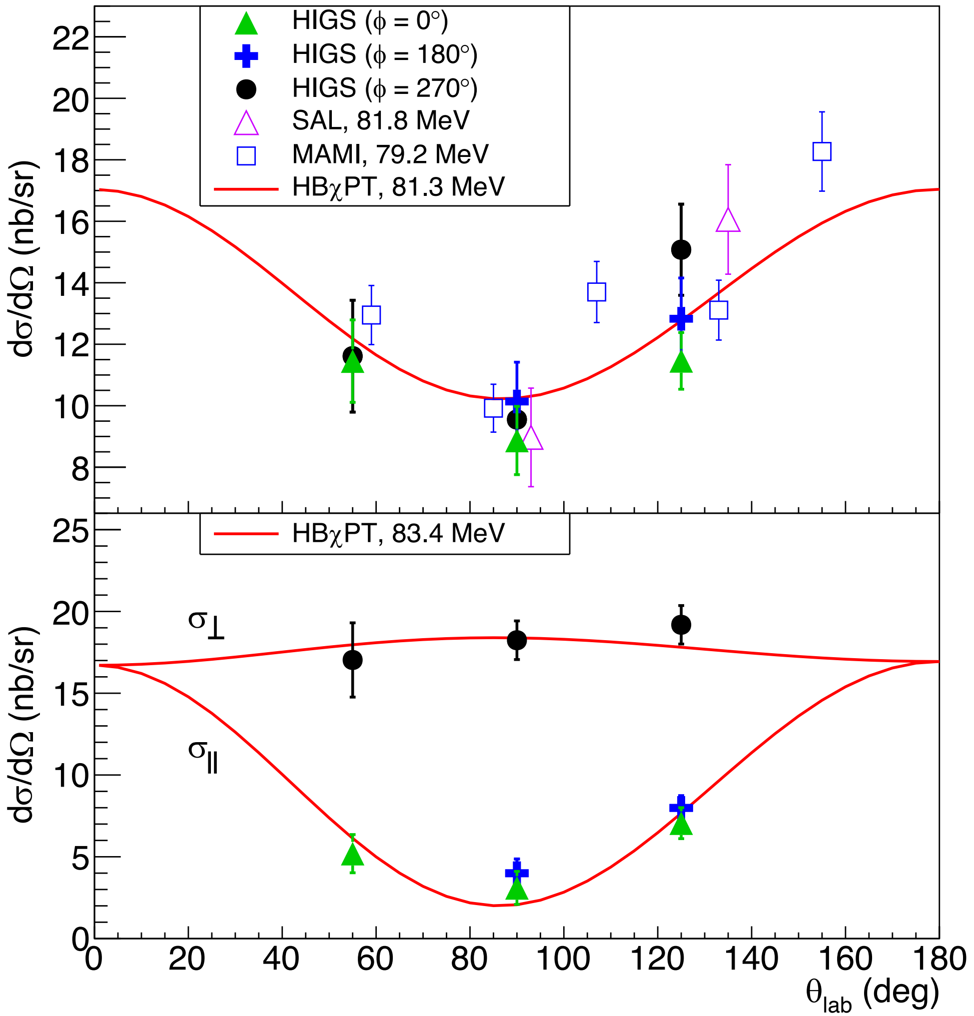
Inelastic contribution to the total cross section is approximately 23.9%

Deuteron Compton Scattering – Scaling our earlier measurement to the newly found inelastic contribution

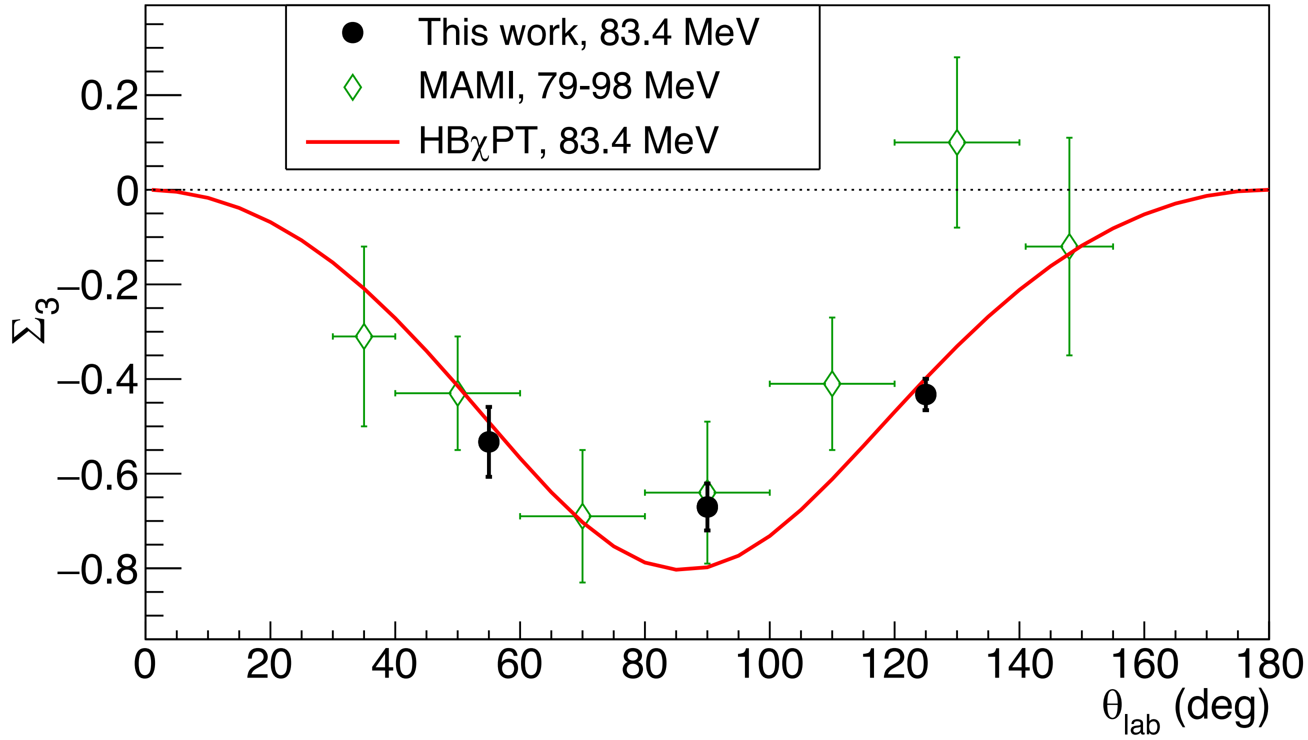


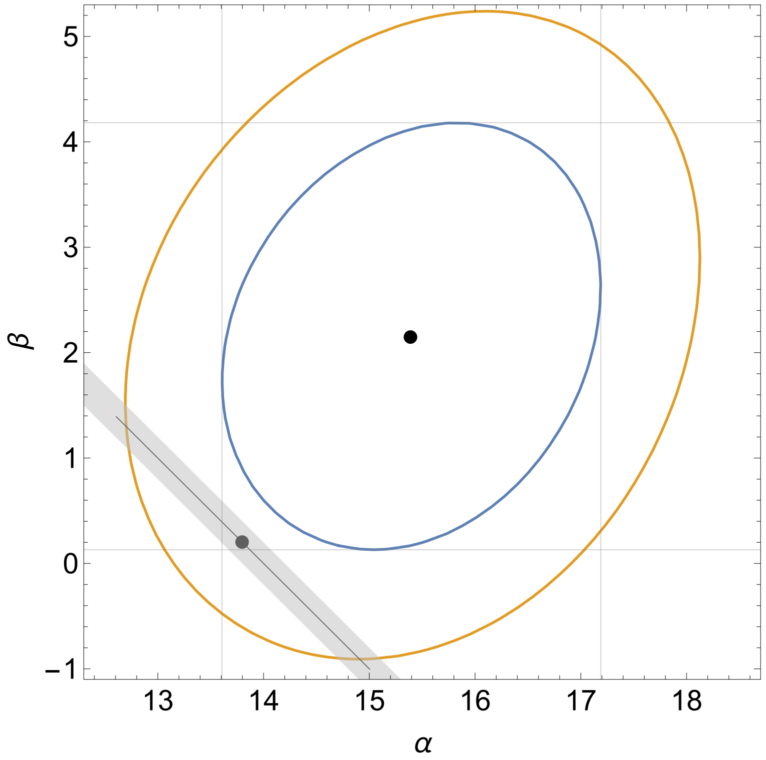
Polarized Compton Scattering – ^{1}H





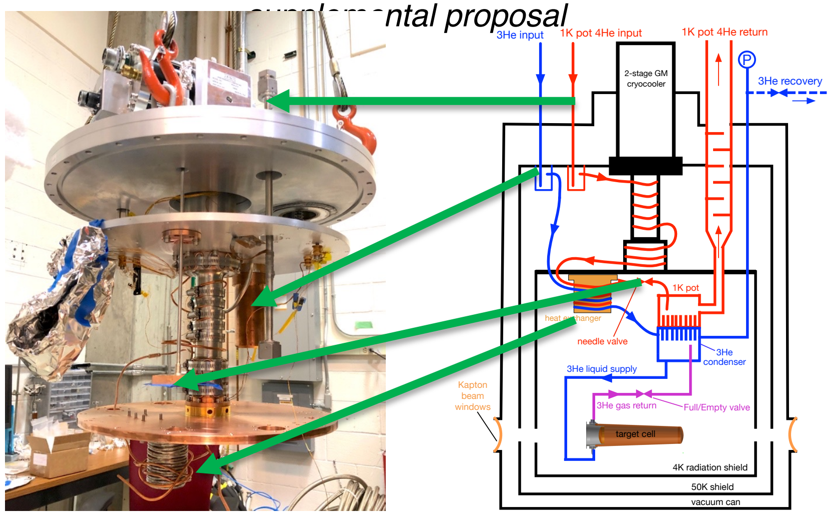
Polarized Compton Scattering – ^{1}H



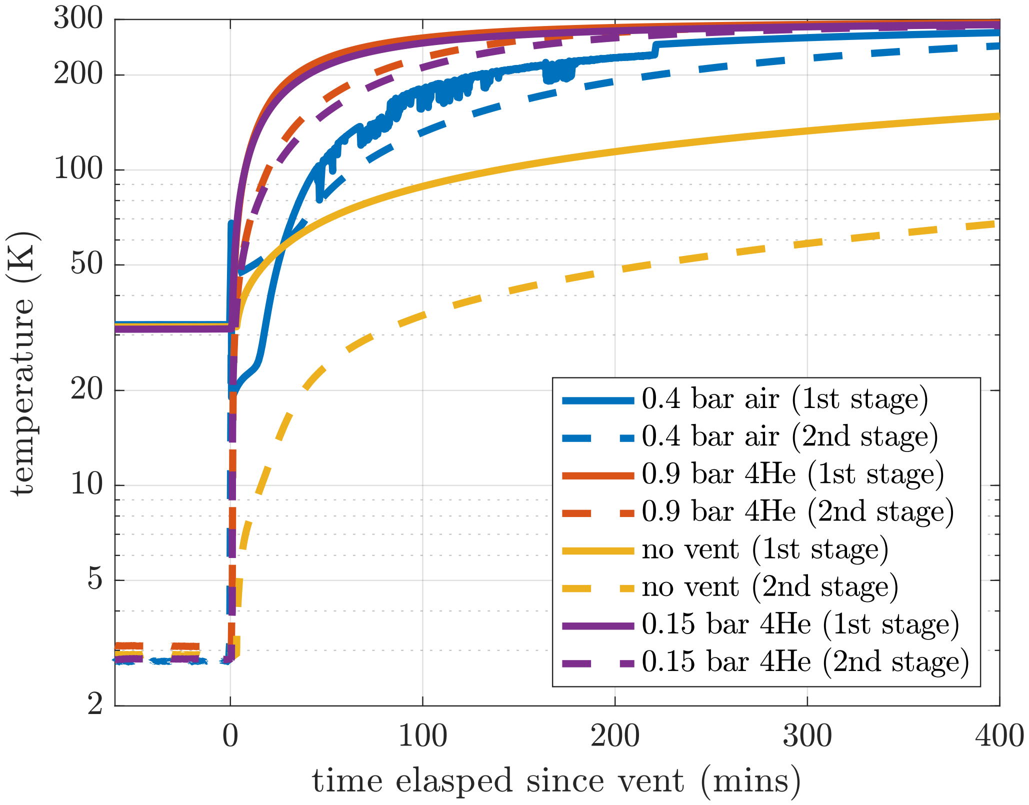


Preparation for 3He Compton scattering

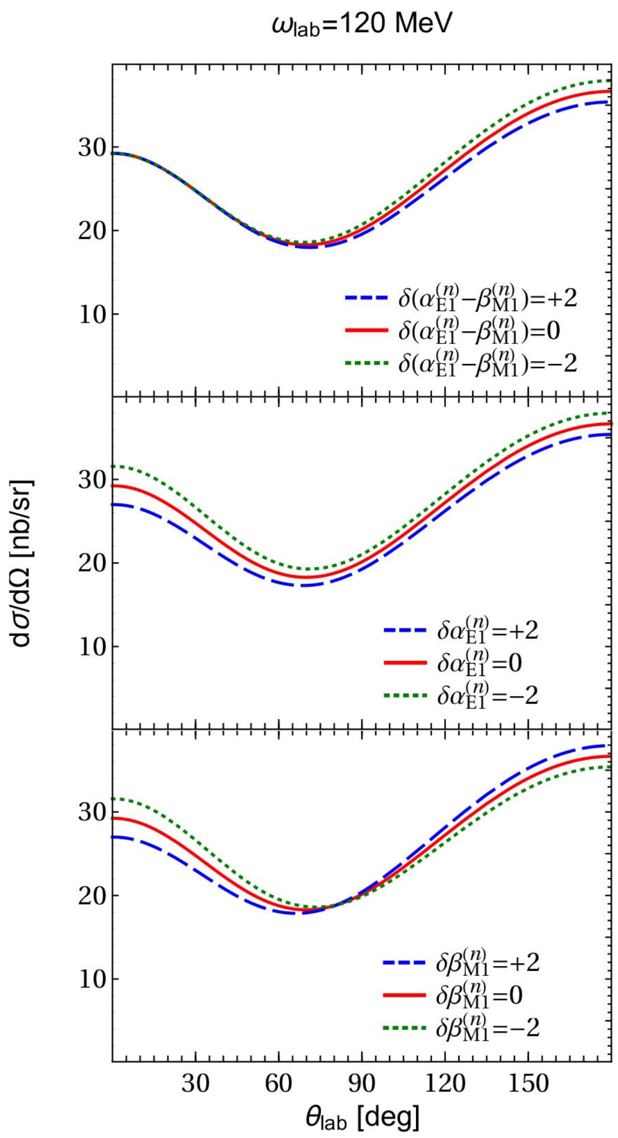
Left: photo of inside cryotarget during upgrade. Right: schematic of cryotarget for 2K liquid 3He operation from supplemental proposal



Left: the cryotarget with fragile components (Kapton windows and cell) removed for vent test cooldowns. Right: The temperature rise after venting. Occurs on ~ 1 min time-scale. This determines the ^{3}He gas recovery needs.



Neutron Polarizabilities from 3He Compton Scattering



- Perform a differential cross section measurement at 120 MeV or higher;
- Measure 8 angles between 55° and 155° ;
- For neutron $\alpha_n - \beta_n$known to ± 3 (canonical units);
- Polarizabilities show $\pm 5\%$variation at 120 MeV when $\alpha - \beta$ is varied by ± 2;
- To be better than the collective neutron error bar, we have to measure the cross sections at 110 MeV with $\pm 7\%$ accuracy at the back angles[2]
- If the UVU mirror development is successful, we maybe able to do $120 < \omega < 140$ MeV

1. H. W. Griesshammer, J. A. McGovern, and D. R. Phillips, Eur. Phys. J. A54, 37 (2018), arXiv:1711.11546.
2. Harald Griesshammer, D R. Phillips, and J. McGovern, private communication

Continuing the Deuteron and 4He Compton scattering

2H Compton Scattering

- Perform a differential cross section measurement at 65 and 85 MeV;
- Measure 6 angles between 55^o and 155^o ;
- Six angles at two energy would add twelve (12) data points to the world data set for the extraction of polarizabilities from deuteron CS

4He Compton Scattering

- As part of commissioning the cryogenic target for ANY Compton scattering run, we always first take date with ^{4}He filled target;
- This exercise will provide us ^{4}He CS cross section data at 8 angles for 120 MeV run with ^{3}He;
- The nucleon polarizability extractions using xEFT are expected soon[1]

1. Harald Griesshammer, private communication

TUNL Role: Leadership & the Team

TUNL Faculty	Ahmed, Crowe, Gao, Howell, Karwowski, Markoff, Wu
Graduate Students	Xiaqing Li (TUNL), J. Zhou, Danula Godagama (Uky), + 1 Ph.D students (TUNL) + 1 M.S. and 4 Undergraduate Students
Post-docs/Research Scientists	M. Sikora (TUNL & GWU), Kent Leung (Cryogenic Expert)
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), Dave Hornidge (MAU)
Theory Support	Harald Grießhammer (GWU), D. R. Phillips (Ohio), and J. A. McGovern (Manchester)

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Extra Slides

Why do/should we care about polarizabilities?

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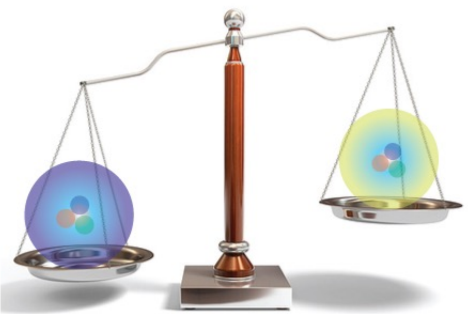
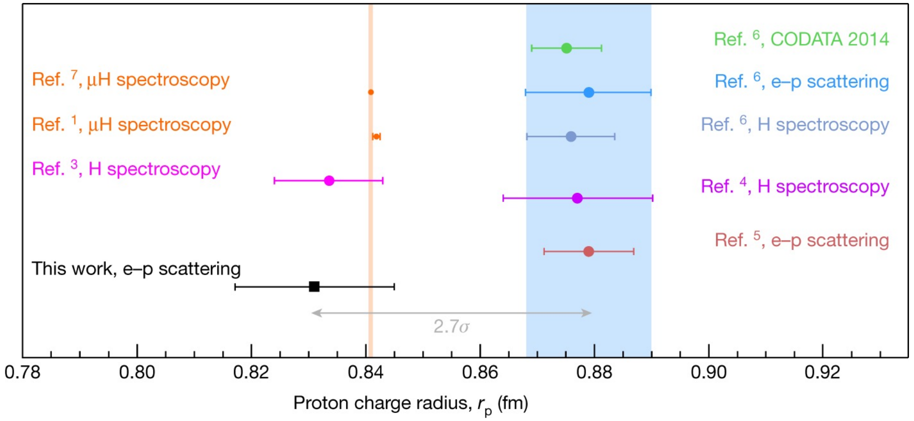
Nucleon Self-Energy



- $M_n - M_p = 1.29333217(42)$ MeV
- 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 the neutron dominates)

Proton Radius Puzzle



$$r^p = 0.84184(36{:}\,exp)(56{:}\,theory)fm$$

Proton polarizability comes as an input to the theoretical treatment

Themes from the LRP 2015

- **Expressions of chiral dynamics in hadrons:** Pion-cloud physics
- **A new era in the theory of hadron structure:** Low-energy effective field theories and Lattice QCD
- **Theory of nuclei: to explain, predict and use:** ab-initio calculations (few-nucleon systems and light nuclei
- Long-distance […] effective theory, as well as emerging LQCD calculations, can provide **benchmark predictions for so-called polarizabilities that parameterize the deformation of hadrons due to electromagnetic fields, spin fields, or even internal color fields**.

  - Insight into the binding in nuclear force due to photon coupling to charged pion-exchange currents;

1. Miller, G. A. Proton polarizability contribution: muonic hydrogen Lamb shift and elastic scattering. Phys. Lett. B 718, 1078–1082 (2013).
2. Xiong, W., Gasparian, A., Gao, H. *et al.* A small proton charge radius from an electron–proton scattering experiment. *Nature* **575,** 147–150 (2019)
3. R. Pohl, et al., Nature 466 (2010) 213–216
4. E. Borie, Lamb Shift in Muonic Hydrogen, arXiv:Physics/04100513v3
5. J. C. Bernauer, R. Pohl, Sci. Am. 310 (2014) 18–25.
6. Cottingham : Ann Phys (NY) 25, 424 (1963),
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8. J. Gasser, M. Hoferichter, H. Leutwyler, A. Rusetsky, Cottingham formula and nucleon polarisabilities, Eur. Phys. J. C (2015) 75:375
9. J. A. McGovern, Eur. Phys. J. A (2012) 48: 120, H.WG, JAM, and D. R. Phillips, arXiv:1511.01952)