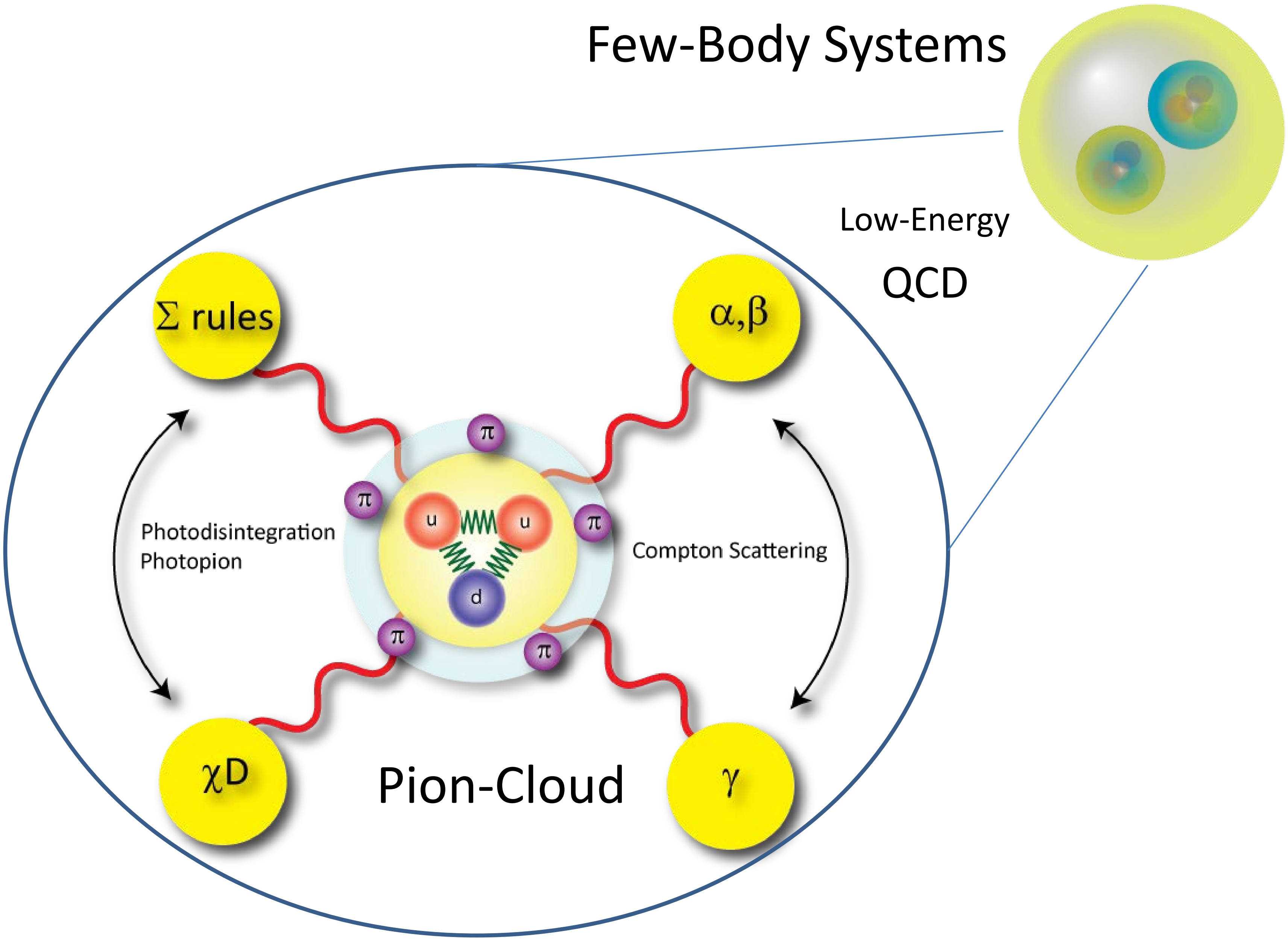
Low-Energy Description of the Hadron Structure With Few-Body Systems

James E. Shepard, Founder

Mohammad Ahmed

High Intensity Gamma Ray Source: Physics @ Various Scales



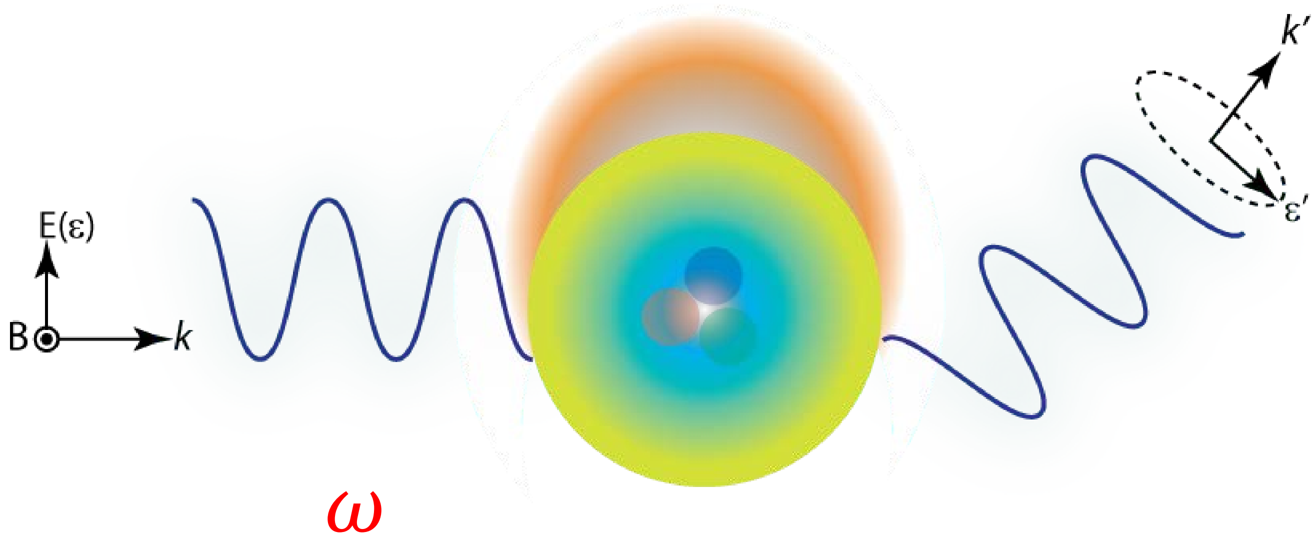
Two examples: Compton Scattering & Photodisintegration

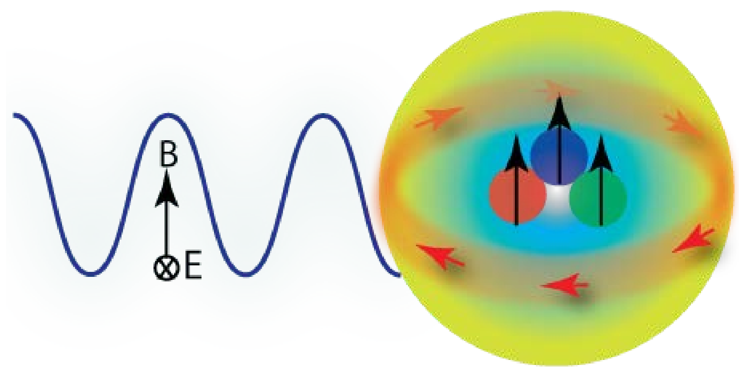
- **Measurement of polarizabilities via Compton Scattering *provide stringent test of calculations that link the effective low-energy description of nucleons to QCD, and Lattice QCD predictions*;**

- ***The spin sum rules provide a model-independent tool to investigate underlying theories which connect* the static properties of a system to a weighted sum of its dynamical excitation spectrum.**

Dipole Response of the Nucleon to a Polarized Photon

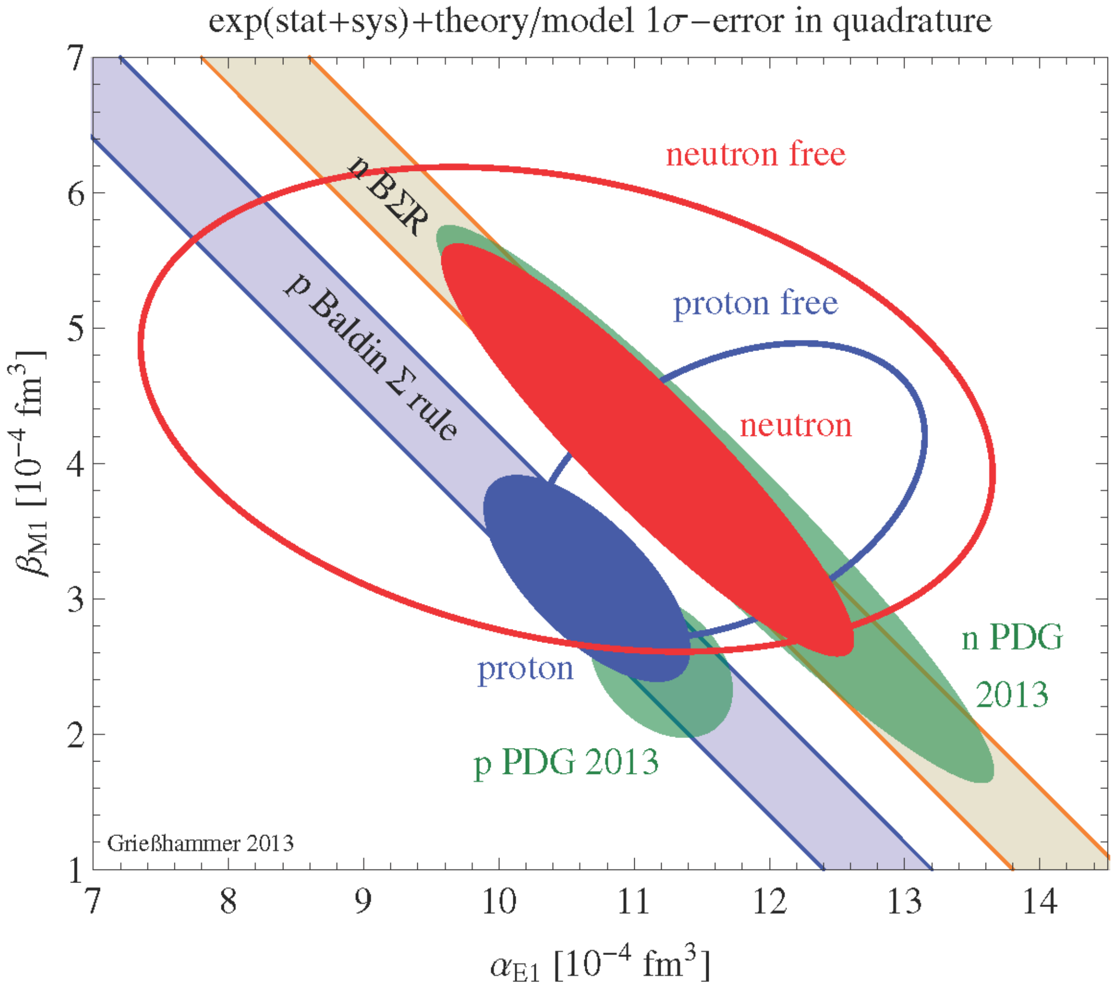
$$\vec{d} = 4\pi\alpha_{E1}(\omega)\vec{E}(\omega)$$





$$\vec{m} = 4\pi\beta_{M1}(\omega)\vec{B}(\omega)$$

The current picture of the EM Polarizabilities (Image Courtesy of HWG)



EFT Extractions – HWG, JAMcG, DRP, GF

PDG - 2013

HWG, JAM, DRP, GF, PPNP, 67 (2012) 841-897

JAM, DRP, HWG, EJP, A 49 (2013) 12

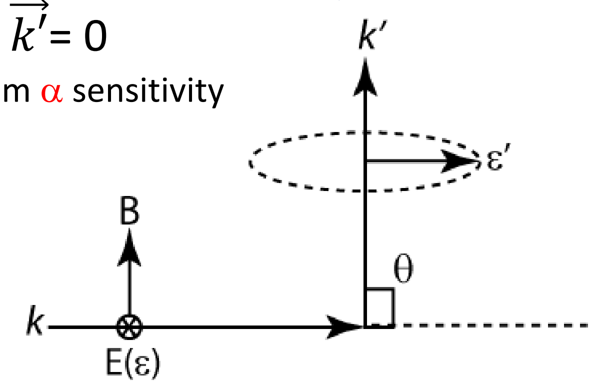
Compton Scattering, Making use of the Polarization

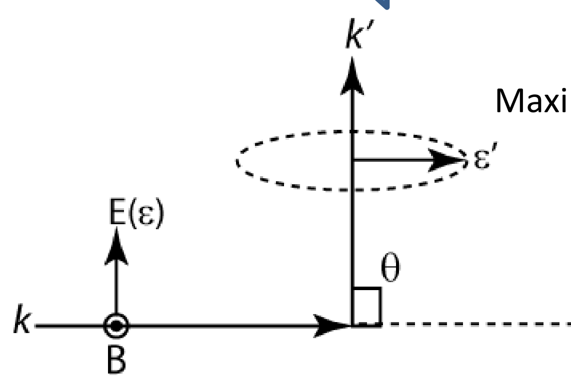
The T-matrix for the Compton scattering of incoming photon of energy ω with a spin (σ) ½ target is described by six structure functions. ε = photon polarization, *k* is the momentum

$$T(\omega, z) = \overbrace{4\pi(\alpha_{E1} + \beta_{M1} cos\theta)\omega^2}^{A_1}(\vec{\epsilon'}^{*} \cdot \vec{\epsilon}) + \overbrace{4\pi\beta_{M1}\omega^2}^{A_2}(\vec{\epsilon'}^{*} \cdot \hat{\vec{k}})(\vec{\epsilon} \cdot \hat{\vec{k'}}) + \mathcal{O}(\omega^3)A^{\gamma}_{3,4,5}$$

$\vec{\varepsilon} \cdot \vec{k'} = 0$

Maximum α sensitivity





$\vec{\varepsilon} \cdot \vec{\varepsilon'} = 0$

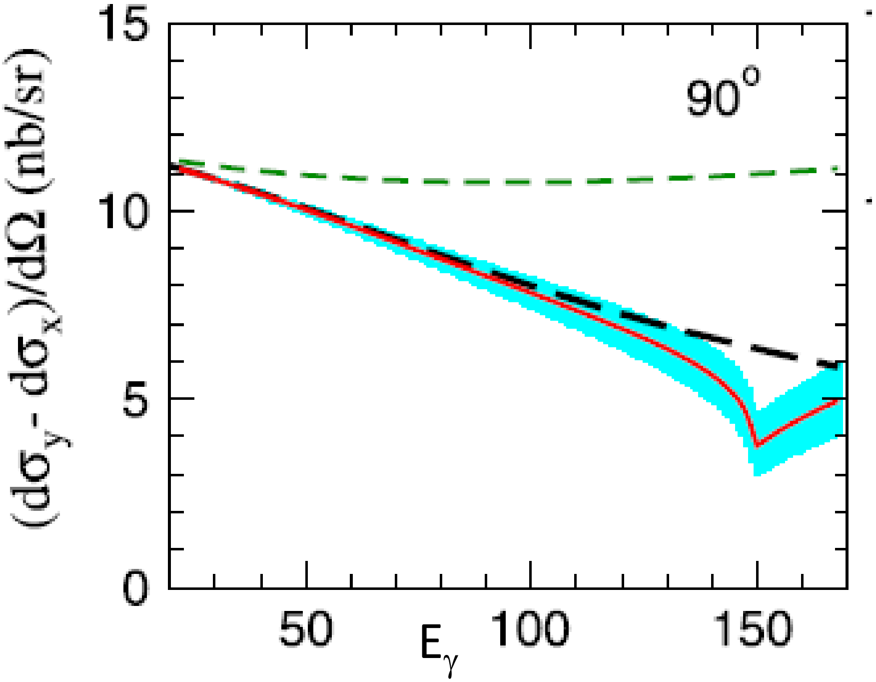
Maximum β sensitivity

H.W. Grießhammer, et al., Progress in Particle and Nuclear Physics (2012), doi:10.1016/j.ppnp.2012.04.003

HIGS: Linearly polarized gamma ray measurement

Eur. Phys. J. C (2010) 65: 195–209
DOI 10.1140/epjc/s10052-009-1183-z

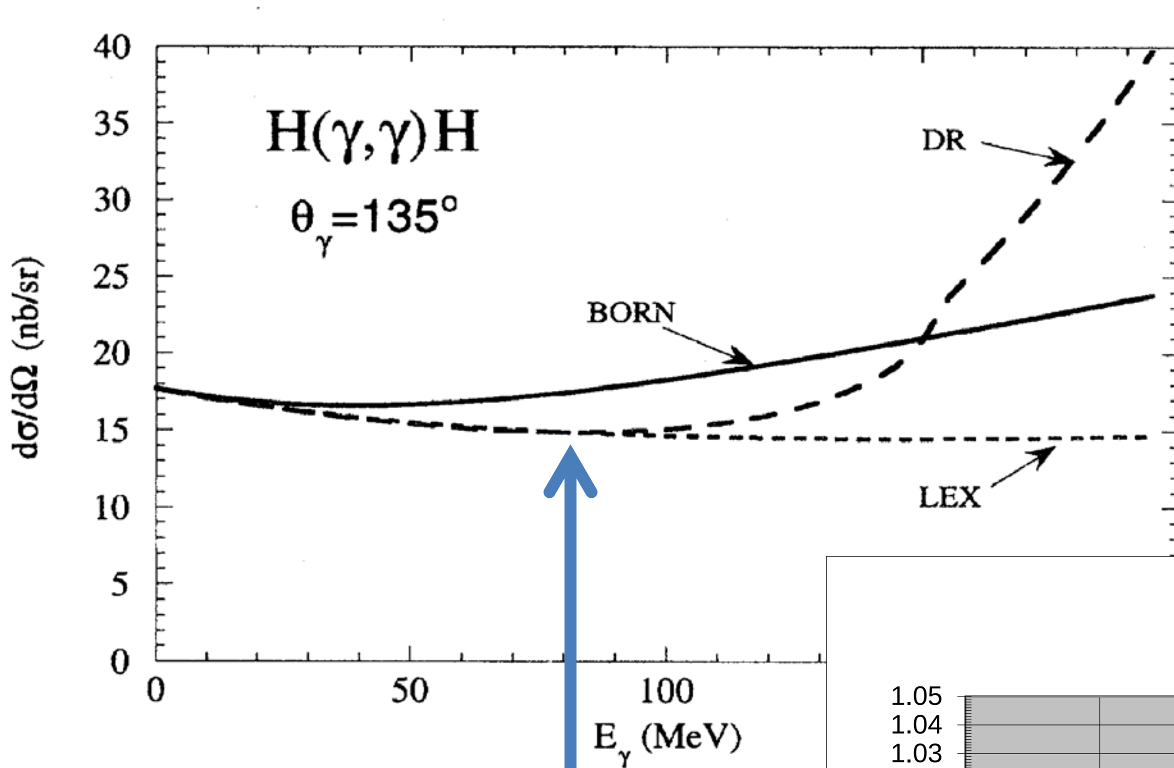
BχPT with Δ

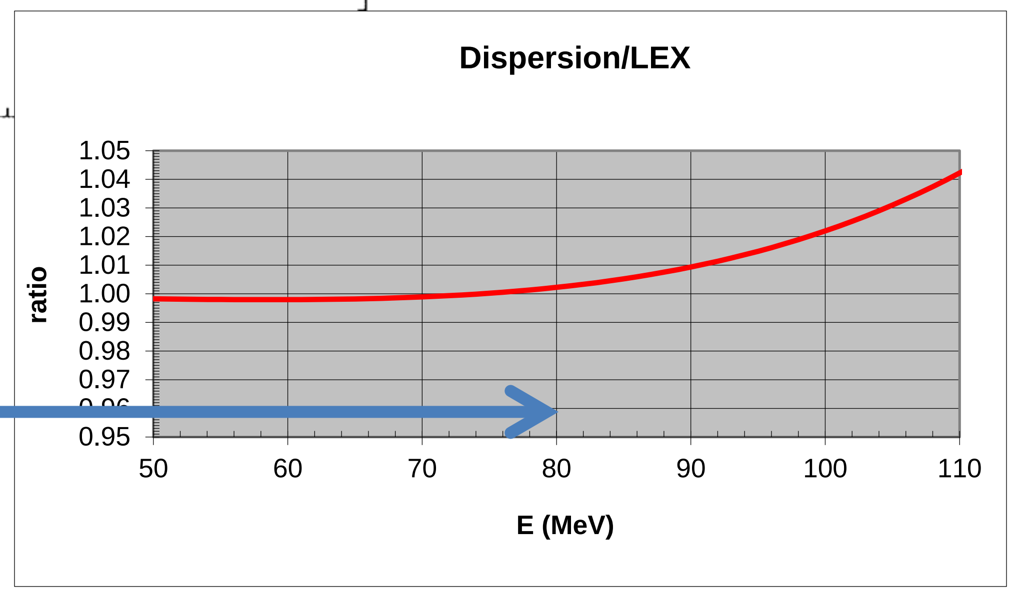


$$\frac{d\sigma_x}{d\Omega} - \frac{d\sigma_x}{d\Omega}^{(\mathrm{Born})} = -8(e^2/4\pi)\,\Phi\,\nu\nu'\boxed{(\alpha\cos\theta+\beta)\cos\theta} + \mathcal{O}(\nu^3)$$

$$\frac{d\sigma_y}{d\Omega} - \frac{d\sigma_y}{d\Omega}^{(\mathrm{Born})} = -8(e^2/4\pi)\,\Phi\,\nu\nu'\boxed{(\alpha+\beta\cos\theta)} + \mathcal{O}(\nu^3),$$

A sum-rule independent measurement of the polarizabilities





A sweet region (80 -90 MeV) where LEX is valid (few %) and there is sensitivity to the polarizability

EM Self-Energy Contribution to $M_p - M_n$ and the β_n

$M_n > M_p$

The net effect of isospin breaking from u- and d-quark mass difference and the electromagnetic interactions is precisely known. The difference of proton and neutron masses is known at a level of 0.000032 %

How to disentangle the two sources ? (LQCD) : $m_d - m_u$ effects are robust, EM is the issue

$\Delta M = \Delta M^{EL} + \Delta M^{INEL}$ (Cottingham : Ann Phys (NY) 25, 424 (1963)

The EM self-energy of the nucleon can be related to the measured elastic and inelastic cross sections

$\delta M_{inel-sub} \propto \beta$, the error from this contribution to self-energy is 36%

Largest source of error is from β_{p-n} (where error from neutron dominates). The error is 100%

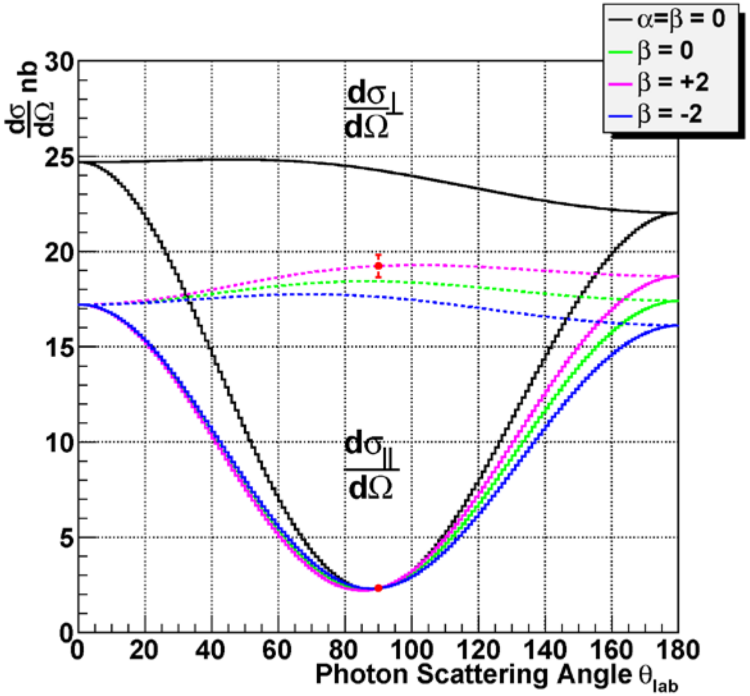
$$\delta M\Big|_{p-n} = 1.30(03)(47)MeV$$

AW-L, CEC, GAM, PRL, 108, 232301 (2012)

HIGS measurement of β_n will reduce the error on the EM self-energy contribution to the mass difference

Measurements at HIGS (Proton)
Similar measurements have also started at Mainz

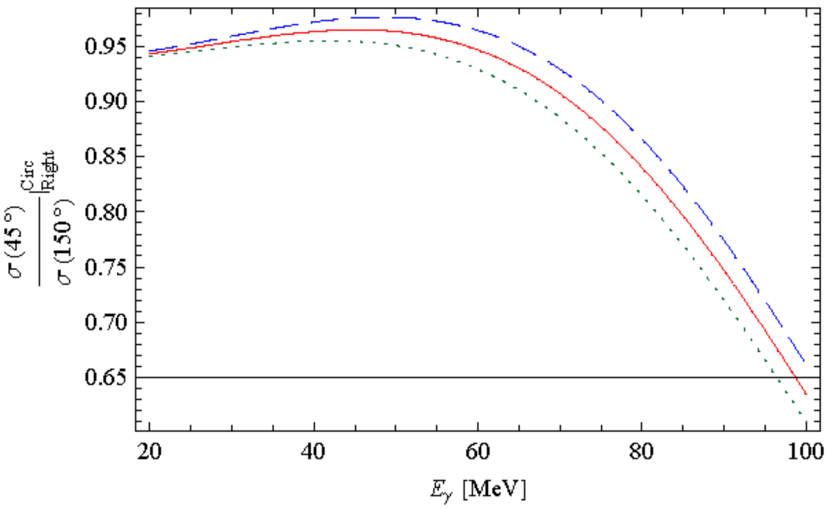
- ❑ Eγ = 85 MeV, Linearly Polarized
- ❑ Unpolarized LH Target
- ❑ Eight (8) 10 x 10 NaI with Active Shields (HINDA)
- ❑ Measure differential cross section and Asymmetry at 90°



Quantity	Polarization	Eγ	% Err
α_p	Linear	85 MeV	2.5 %
β_p	Linear	85 MeV	<10%

Measurements at HIGS (Deuteron)

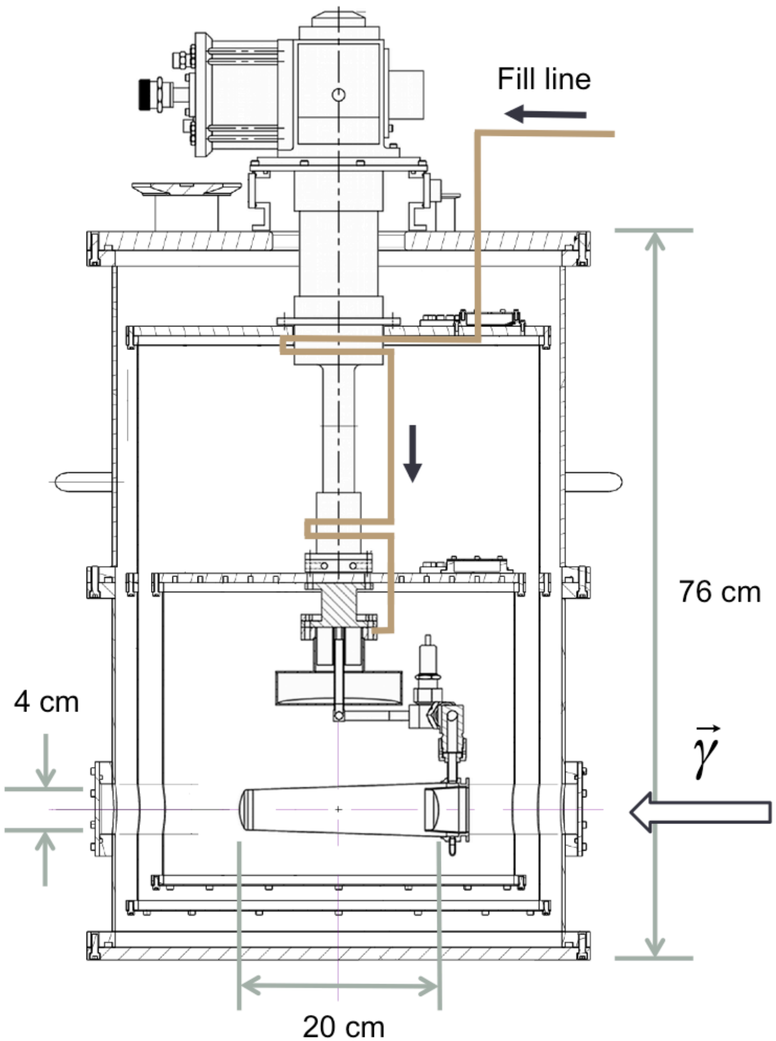
- Eγ = 65, 100 MeV, Circular
- Unpolarized LD Target
- HINDA
- Measure Full angular distribution

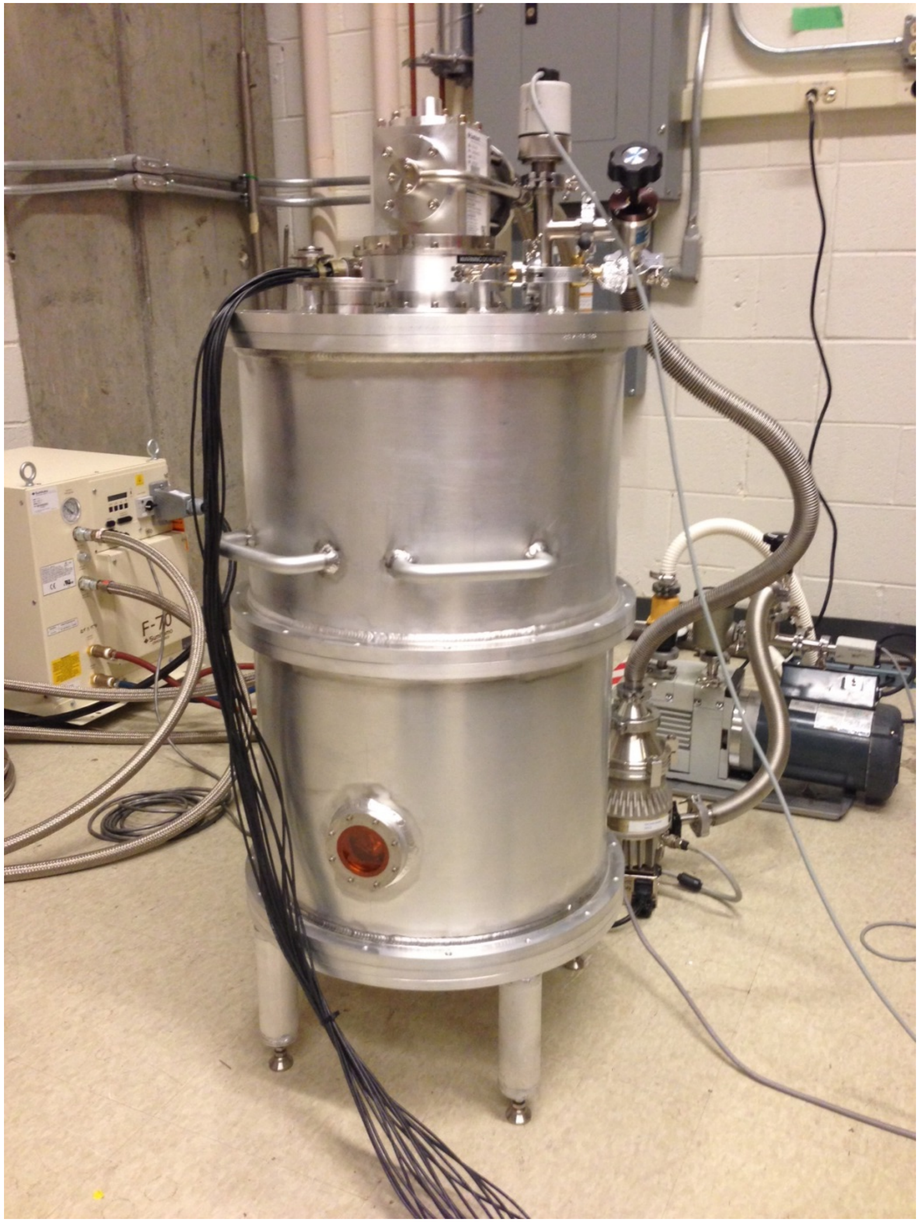


The 65 and 100 MeV measurements will reduce the error in βn from ~ 50% to ~27 %

Energy (MeV)	Angle	Cross Section (nb/sr)	Rate (counts/hour)	Time (hours)	%Err (stat)
65	45	16.5	47	300	0.84%
65	80	12.4	36	300	0.96%
65	115	13.7	40	300	0.91%
65	150	17.8	52	300	0.80%

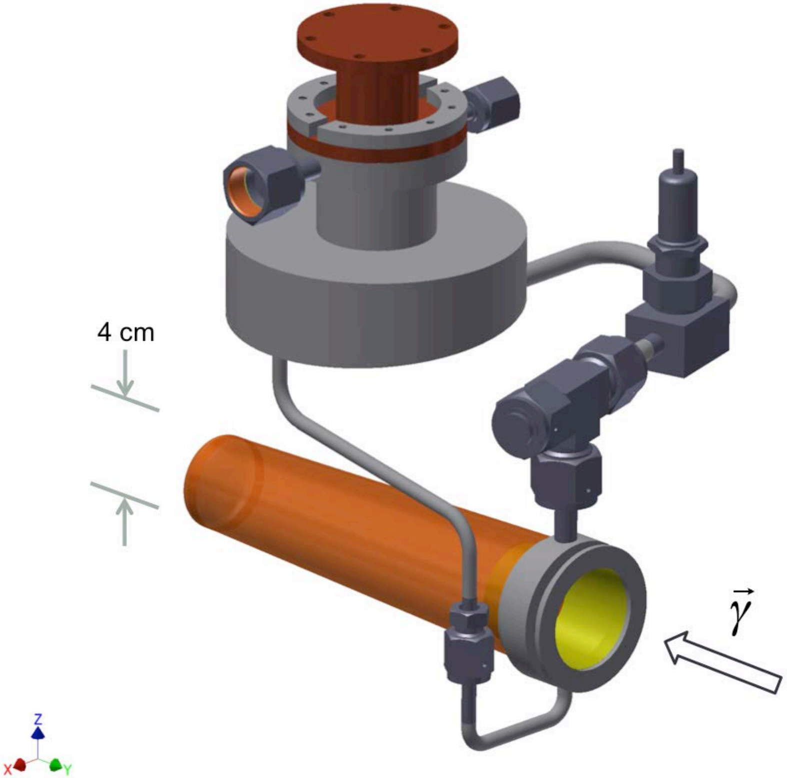
HIGS Cryogenic Target (TUNL + GWU Joint Effort)

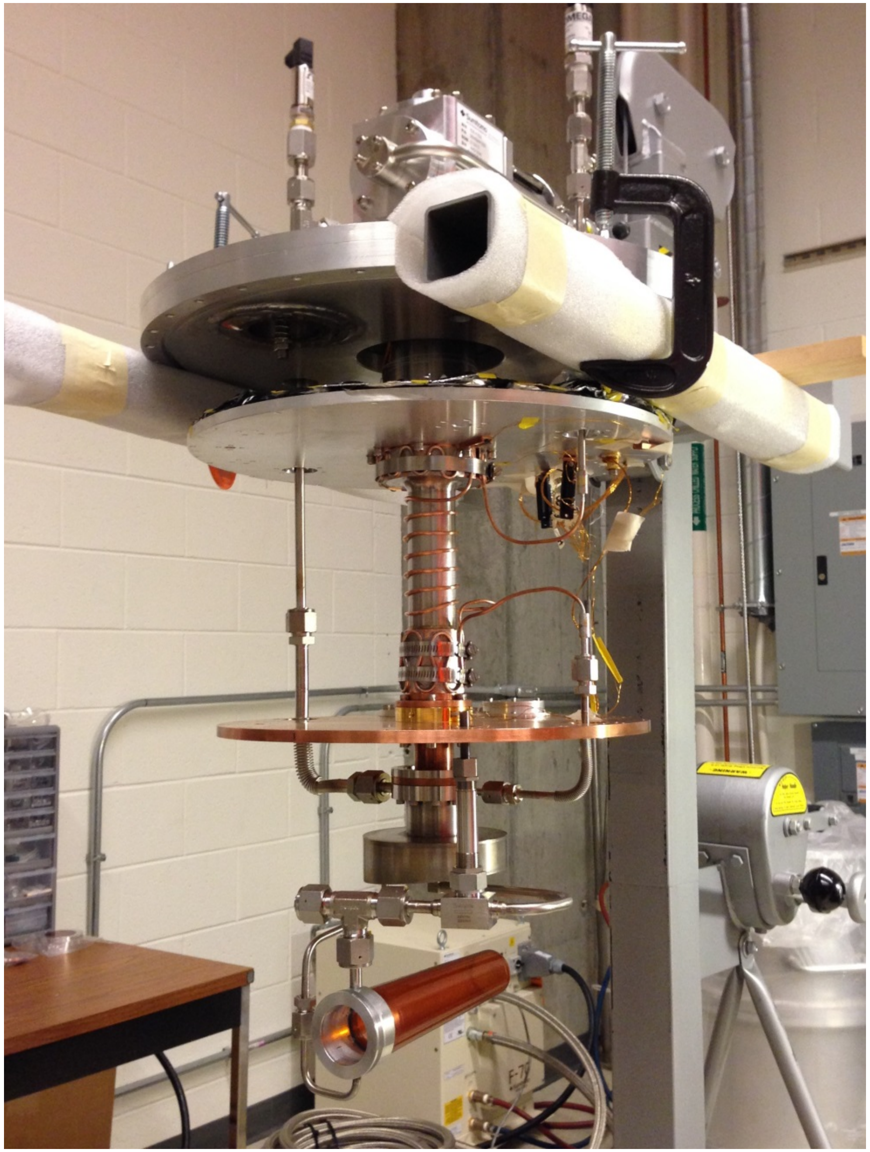




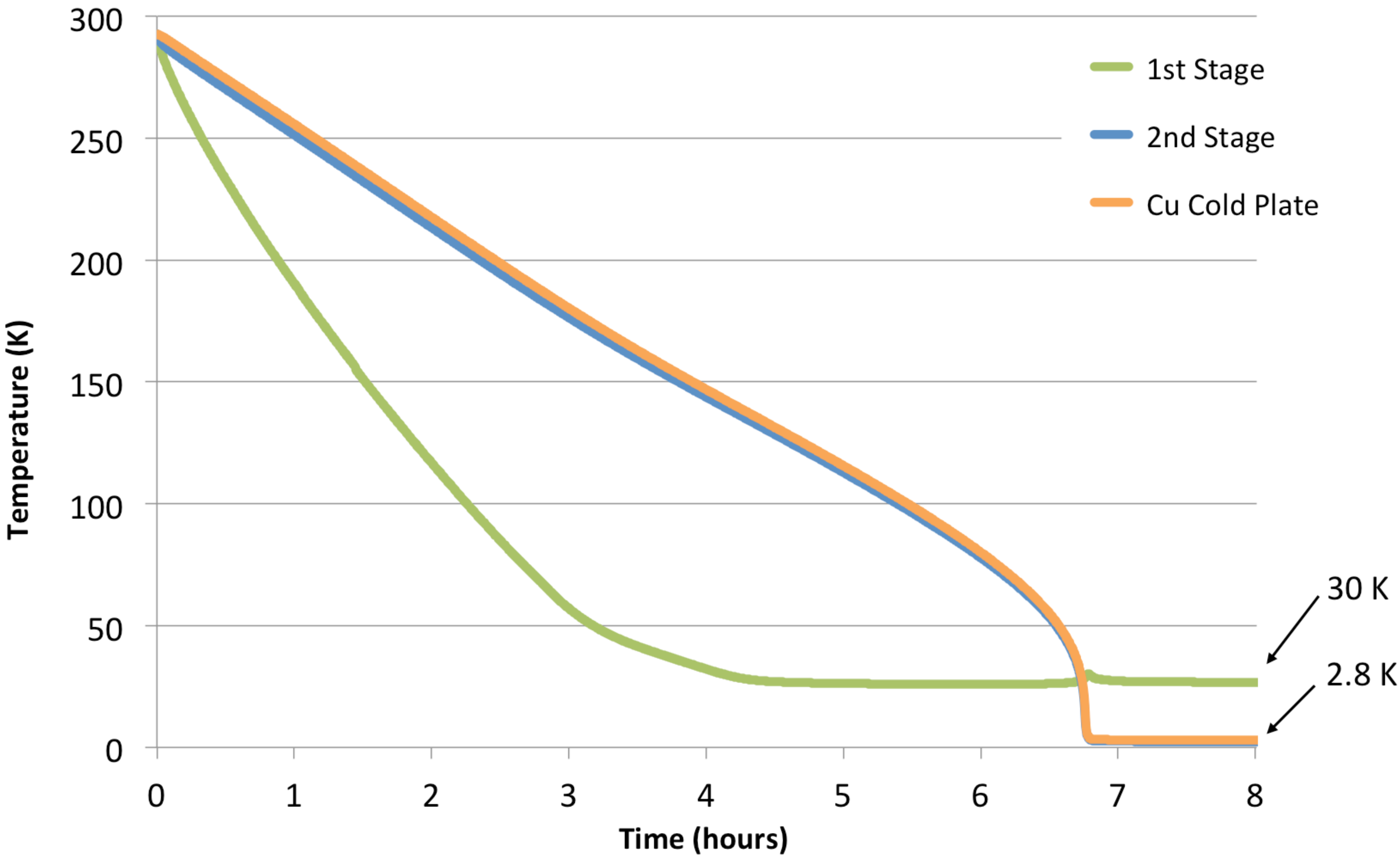
HIGS Cryogenic Target

- Cryo-Cooler
- Cooling Power: 1.5 W @ 4.2 K
- Base T = 3.5 K
- L = 20 cm, V = 0.24 Lit
- $D/H/cm^2 = 10^{24}$

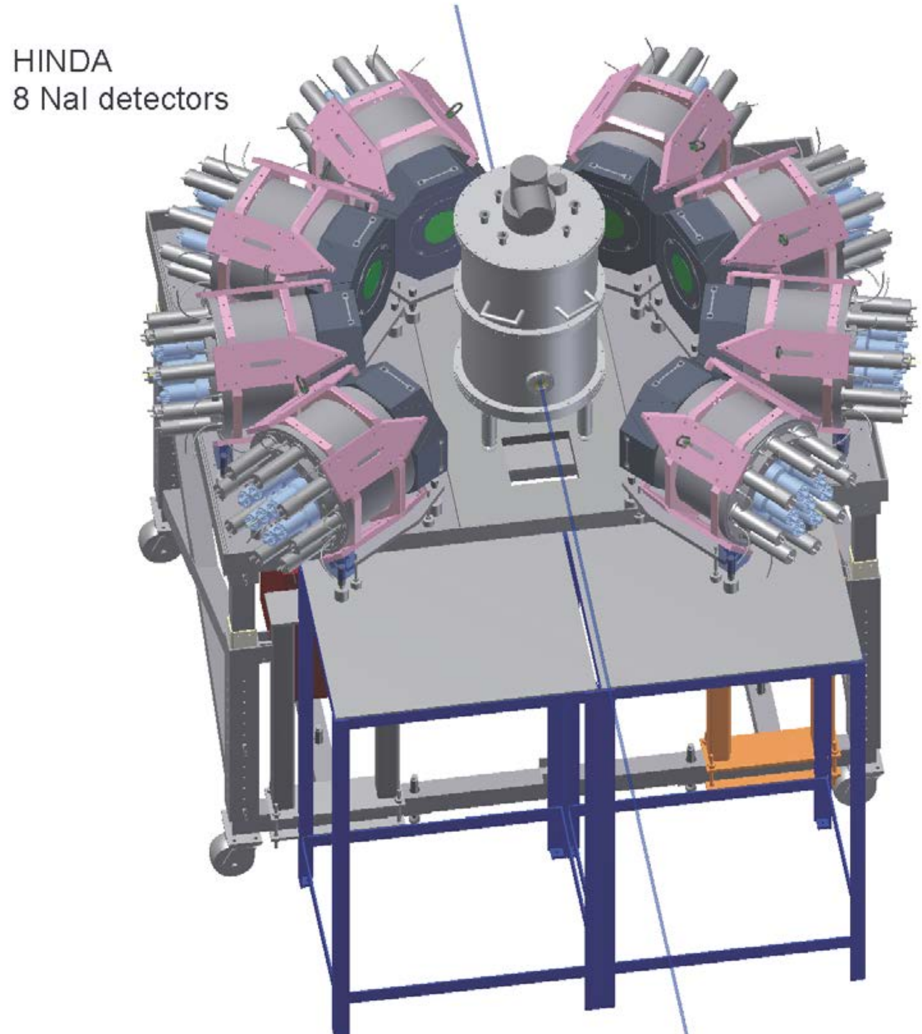




HIGS Cryogenic Target - Performance



The Target and the HINDA for Compton Scattering Experiments

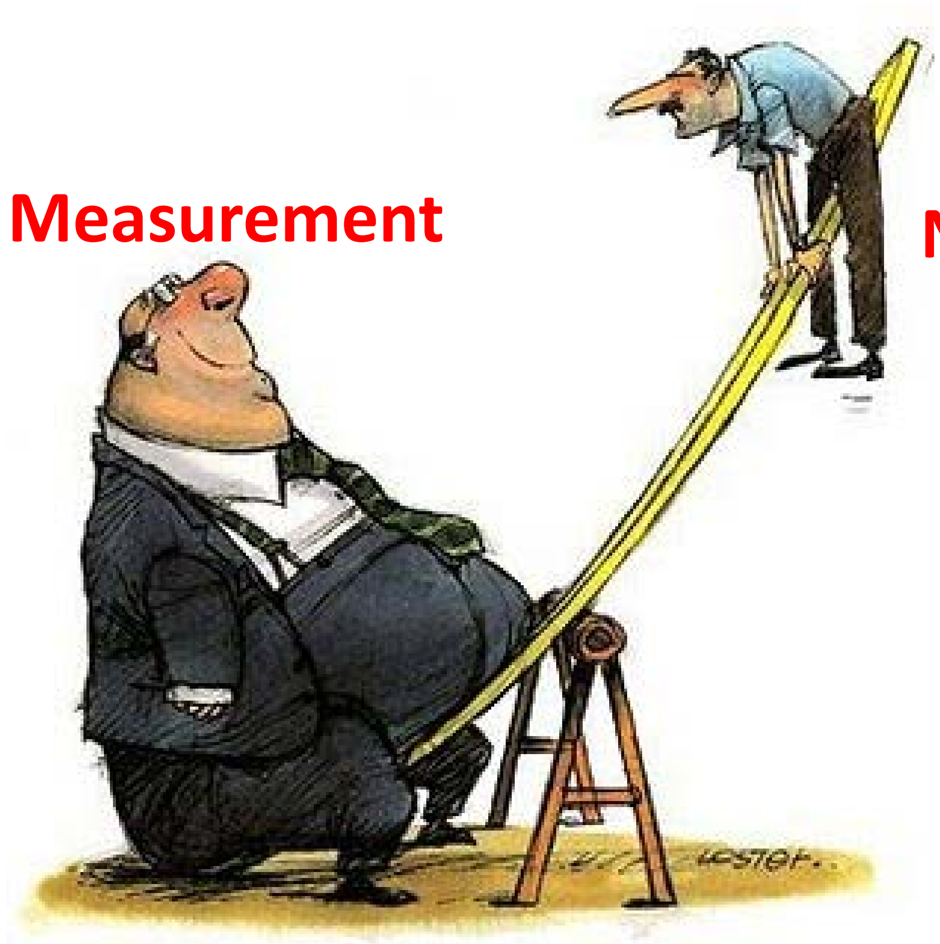


Scattered photons attenuated < 5%

Nucleon Compton Scattering

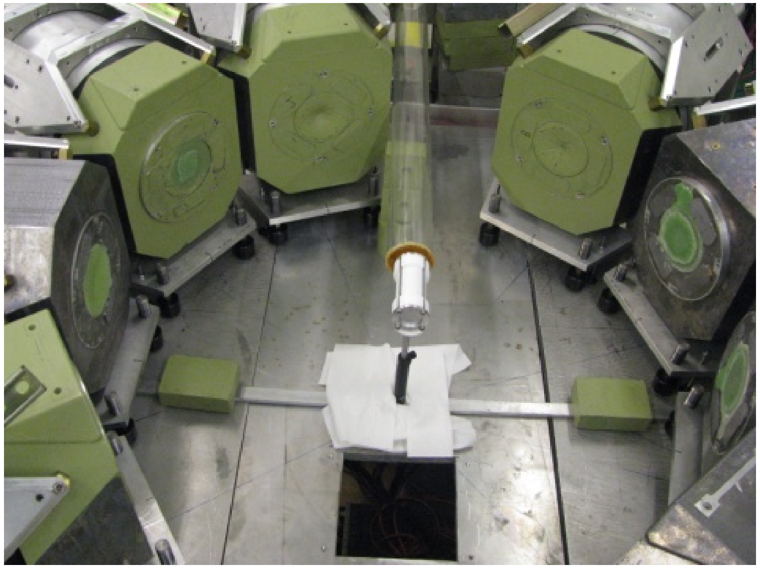
The Measurement

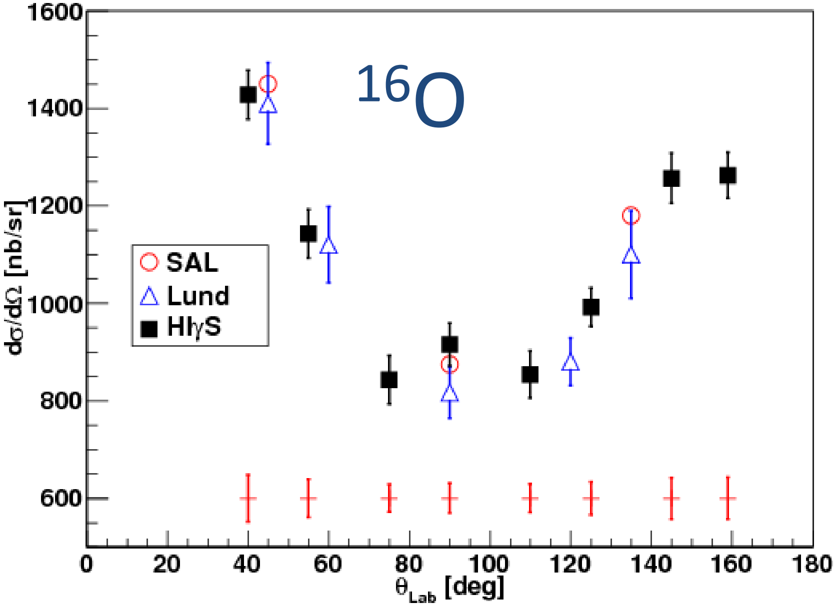
Nucleon

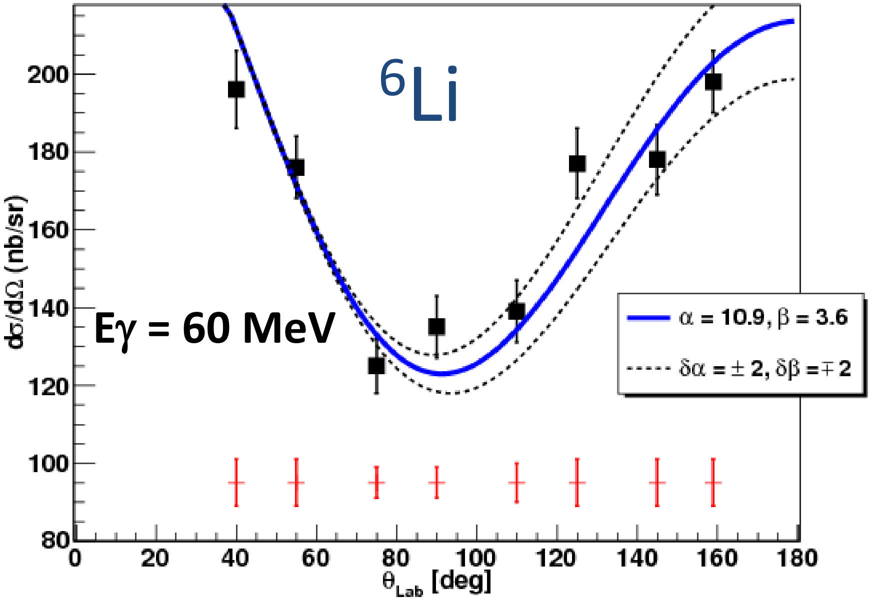


You do not want to start the game like this !

HIGS Results on ^{16}O and ^{6}Li Compton Scattering







Phenomenological Model

- Giant Resonances
- Quasi-Deuteron
- Modified Thompson

Phys. Rev. C 86, 044614 (2012)

Spin Sum Rules: The GDH Sum rule on ^{2}H and ^{3}He

World Data

0.65 μb **436 μb**

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

437 μb

HIGS

305 μb

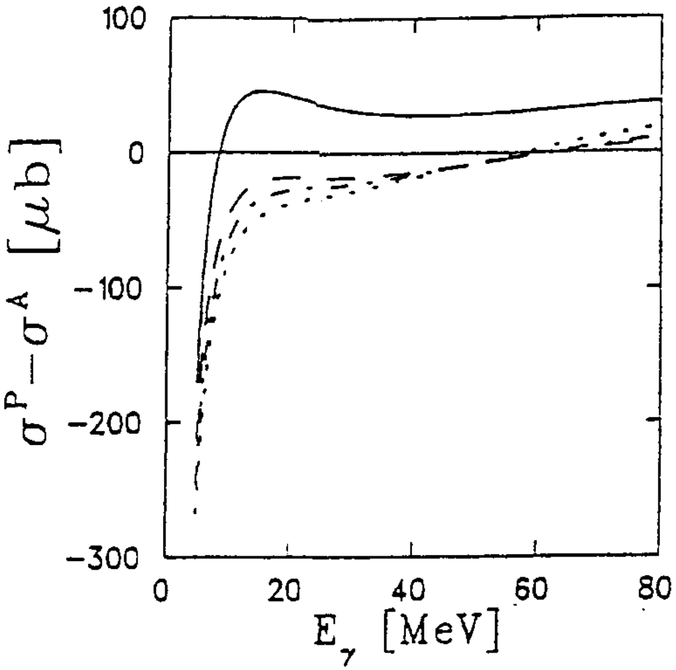
$$I(^3He)_{GDH} = \int_{\omega_{th}}^{\infty} \frac{\Delta\sigma}{\omega} d\omega = \int_{5.5}^{\omega_\pi} \frac{\Delta\sigma}{\omega} d\omega + \int_{\omega_\pi}^{\omega_{max}} \frac{\Delta\sigma}{\omega} d\omega + \int_{\omega_{max}}^{\infty} \frac{\Delta\sigma}{\omega} d\omega$$

496 μb **191 μb**

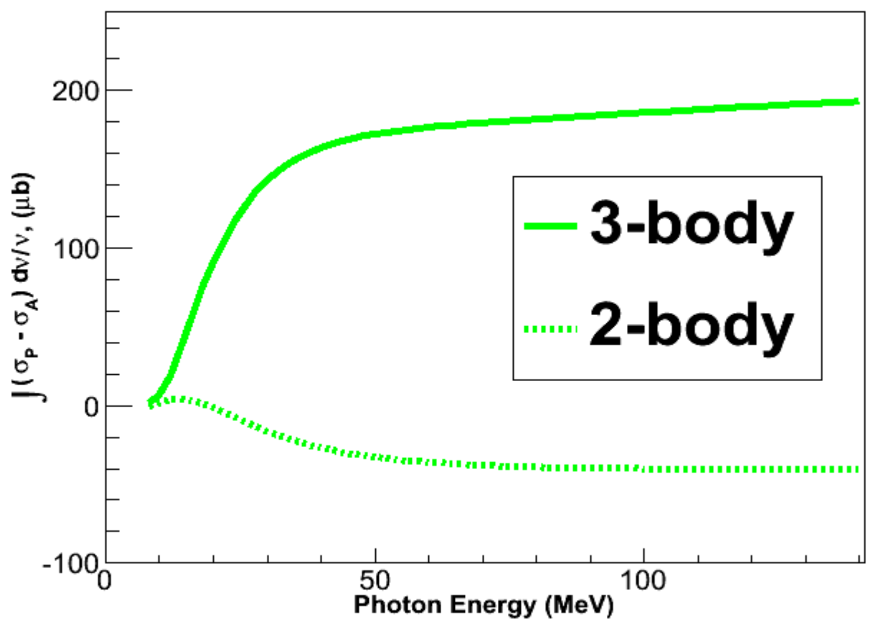
World Data

Spin Sum Rules: The GDH Sum rule on ^{2}H and ^{3}He

Deuteron Prediction (Ahrenhovel)



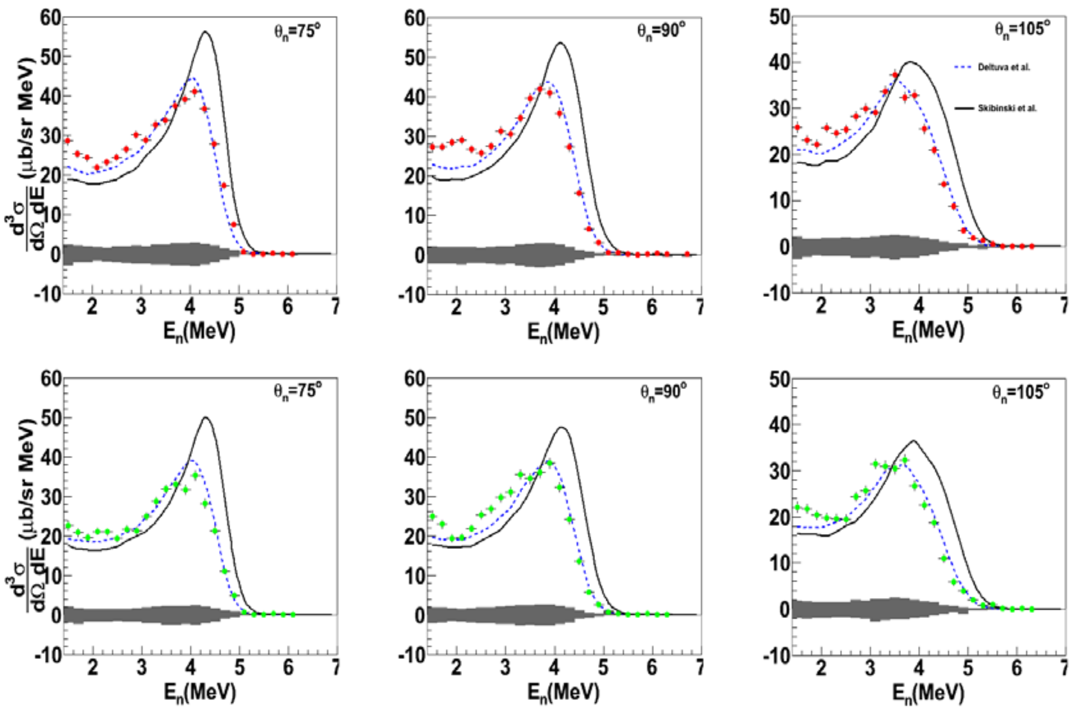
^{3}He Prediction (Deltuva)

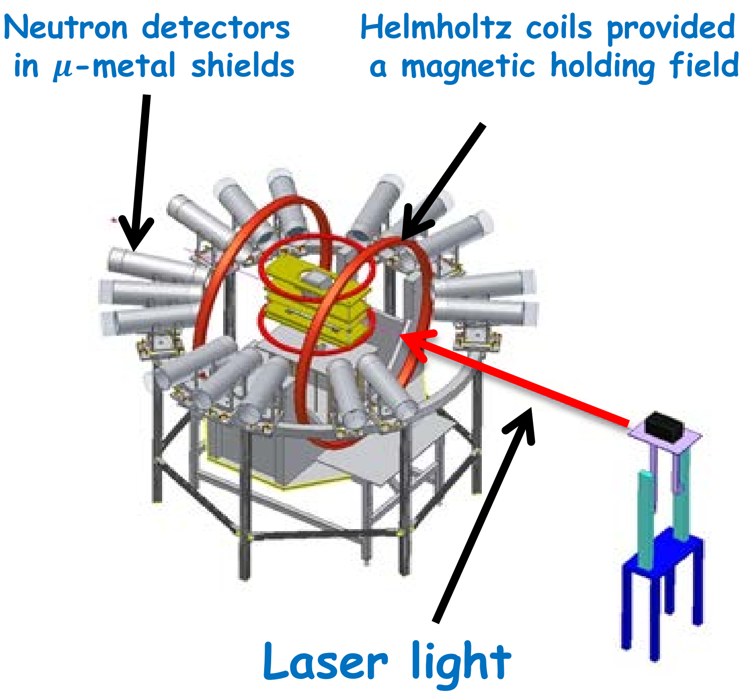


Alt-Grassberger-Sandhas equations – the charge-dependent Bonn potential with the corresponding single-baryon and meson-exchange electromagnetic currents plus relativistic single-nucleon charge corrections.The proton-proton Coulomb force is included using the method of screening and renormalization

GDH on ^{3}He – three body channel

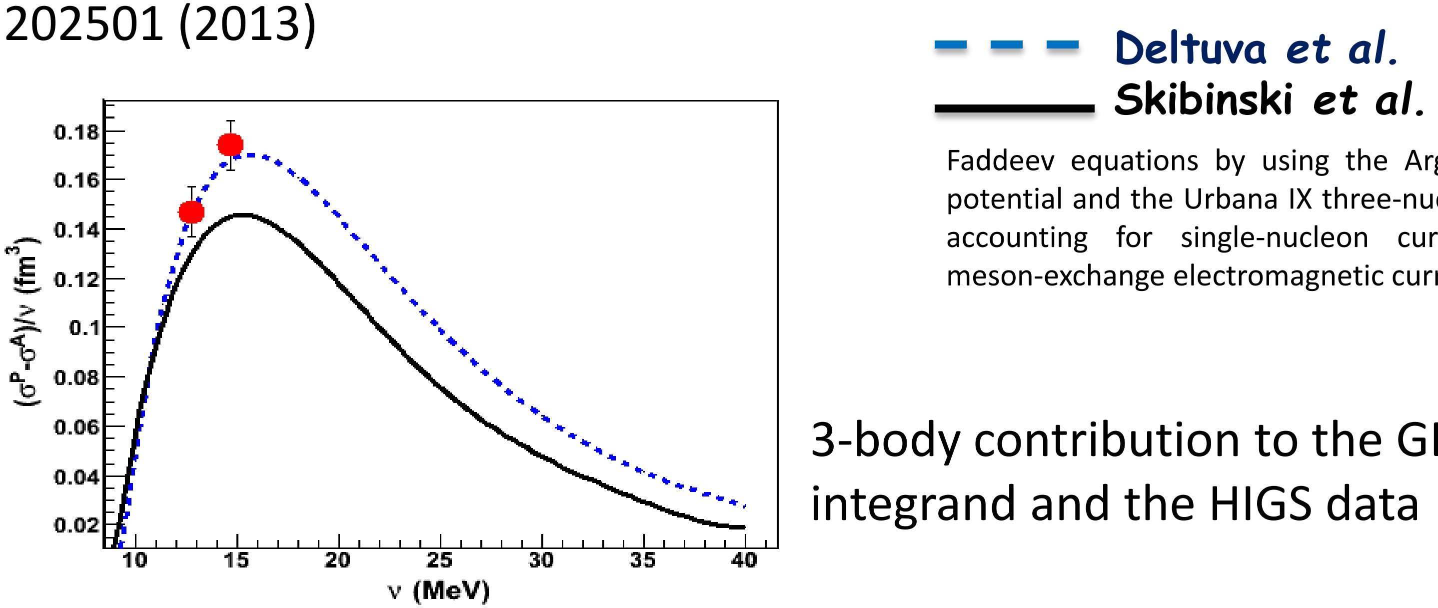
- ~100% circularly polarized γ-ray beam at 12.8 and 14.7 MeV
- Neutrons detected with 16 neutron detectors at different angles
- High pressure hybrid ^{3}He target (~7amgs) polarized longitudinally using Spin Exchange Optical Pumping





GDH on ^{3}He – three body channel

- Spin-dependent cross sections from the three-body photodisintegration of ^{3}He at incident energies of 12.8 and 14.7 MeV, G. Laskaris et al., **Phys. Rev. C** 89, 024002 (2014)
- First Measurements of Spin-Dependent Double-Differential Cross Sections and the Gerasimov-Drell-Hearn Integrand from ^{3}He(γ,n)pp at Incident Photon Energies of 12.8 and 14.7 MeV, G. Laskaris et al., , **Phys. Rev. Lett**. **110**, 202501 (2013)



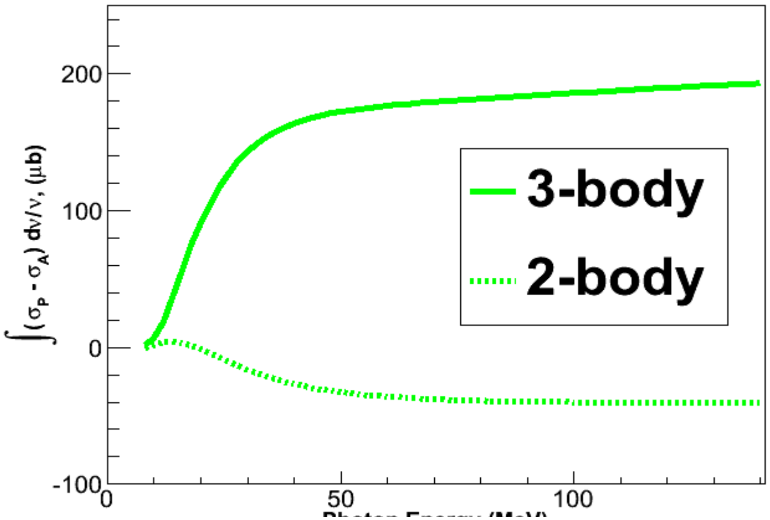
Faddeev equations by using the Argonne V18 potential and the Urbana IX three-nucleon force accounting for single-nucleon currents and meson-exchange electromagnetic currents

3-body contribution to the GDH integrand and the HIGS data

More data has been acquired for the 3- and 2-body channels to fulfill a comprehensive study of the GDH Sum Rule integrand

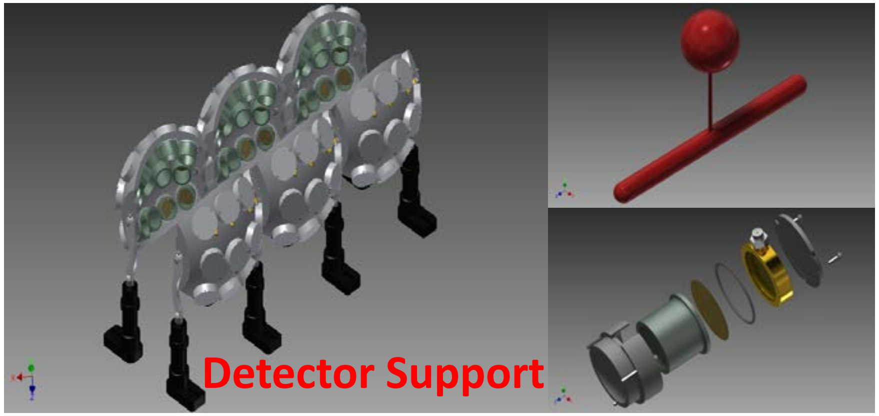
GDH on ^{3}He – three body channel

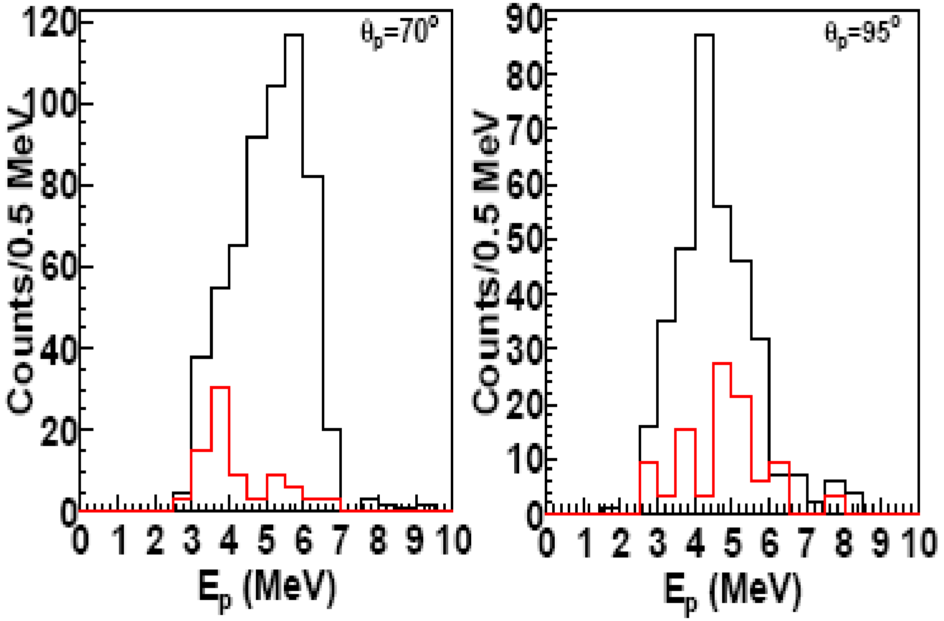
- Test state-of-the-art three-body calculations including future EFT calculations
- Investigate the GDH integral for ^{3}He from breakup to pion production threshold



Two-body photodisintegration of ^{3}He

- ~100% circularly polarized γ-ray beam
- High pressure polarized thin-walled (~700 μm) ^{3}He target
- Protons from two-body breakup detected using 72 fully-depleted SSB detectors

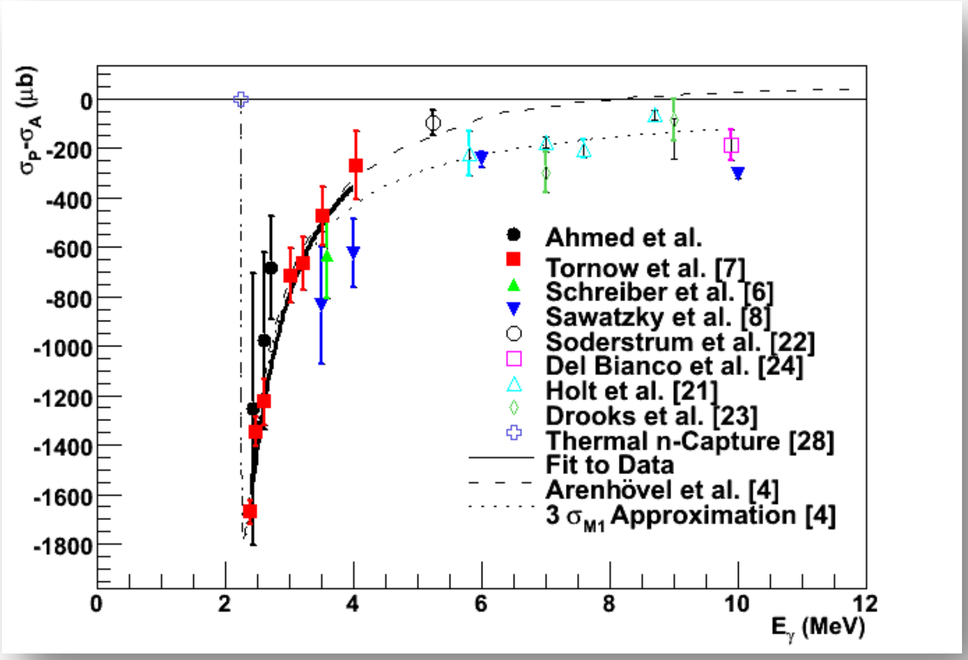


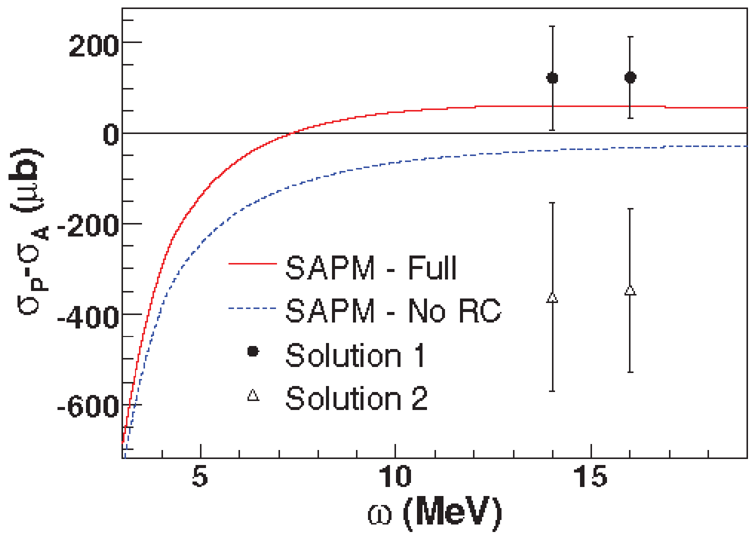


GDH on ^2H – below pion threshold

- HIGS is mounting the GDH experiment on the deuteron
- HIGS Frozen Spin Target (HIFROST)

Previous Measurements without Polarized Target Using Multipole Analysis





Phys. Rev. C78, 034003 (2008)

Phys. Rev. C77, 044005 (2008)

GDH on ^2H – below pion threshold

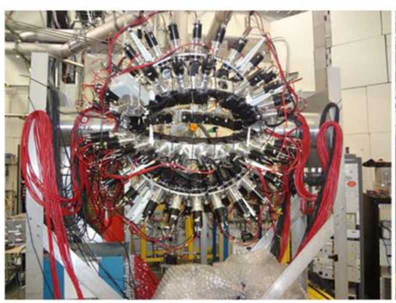
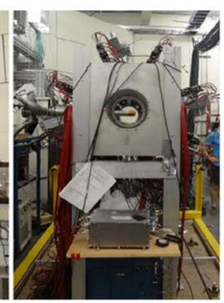
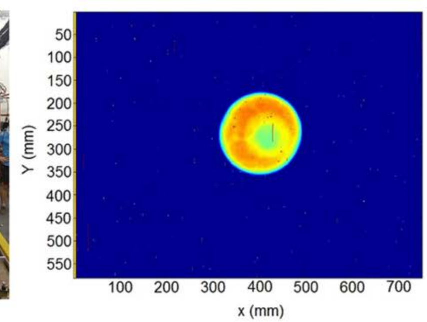
- HIGS Frozen Spin Target – HIFROST, Scientific Team: Don Crabb, P.-N. Seo, R. Duve, Gary Swift, David Kendellen

HIFROST is now fully installed at HIGS and commissioning cool-downs have started

GDH on ^2H – below pion threshold

- 3He Dilution test : 200 mK reached (without optimization)
- 50 mK Butanol target, more than 85% polarization, 10^{23} d/cm^2



In Summary

- Upcoming measurements at HIGS of the EM polarizabilities
- GDH Sum Rule measurements on the Deuteron
- Results from the GDH measurement on ^3He

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