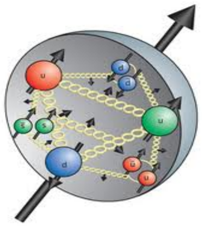
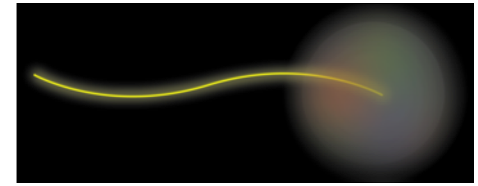
Probing Hadron Structure with Photons



Calvin R. Howell

Duke University and
Triangle Universities Nuclear Laboratory



- Spin-dependent photo absorption, GDH sum rule on ^{2}H and ^{3}He
- Compton Scattering
  - o Electric and Magnetic Polarizabilities
  - o Spin-Dependent Polarizabilities
- Near threshold photo-pion production; weighing the quarks
- Probing Hadronic Parity Violation with Low-Energy Photons (parity violating photodisintegration of ^{2}H)

Pictures from: https://drupal.star.bnl.gov/STAR/pwg/spin and J. Arrington, arXiv:1208.4047v1[nucle-ex]

Acknowledgements

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M.W. Ahmed, NCCU and TUNL
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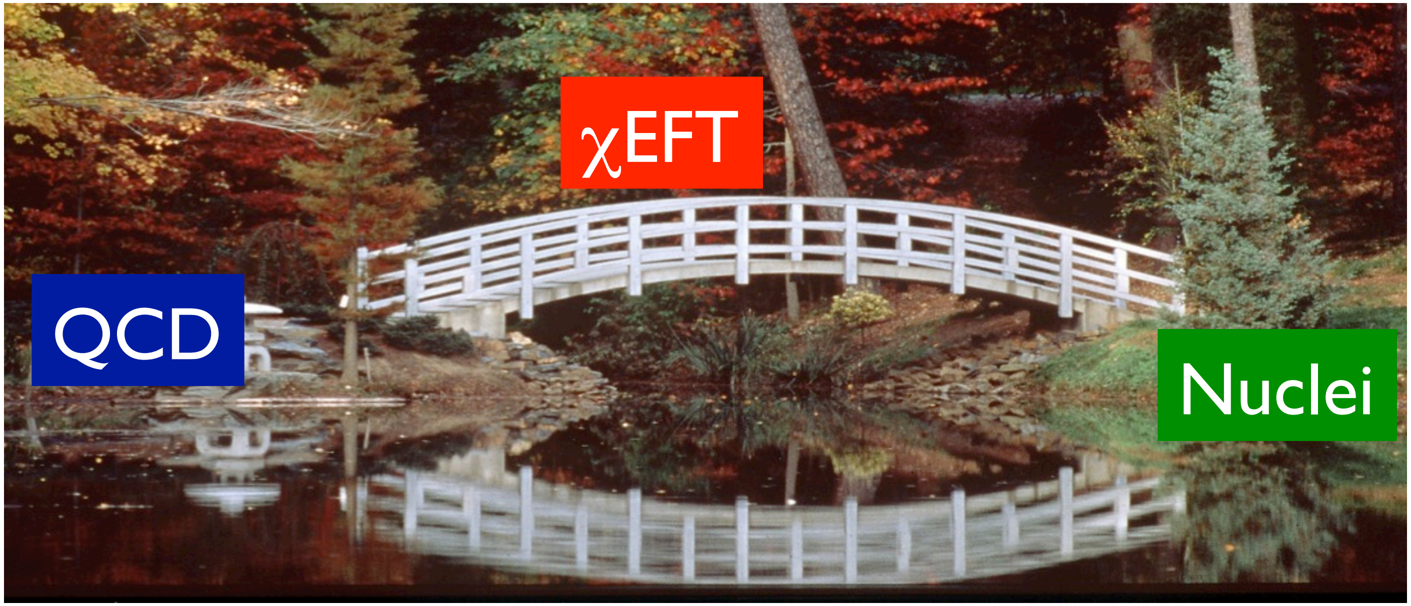
Low-energy QCD: Overarching theme



Measure/determine quantities that are connected to χEFT and Lattice QCD that help build a bridge between QCD and nuclear phenomena

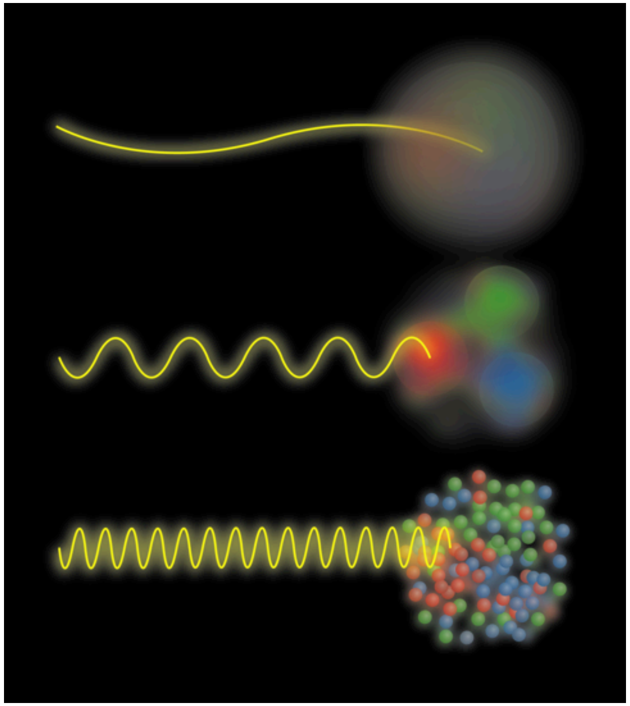
Substantial accomplishments have been made in both theory and experiment since the 2007 LRP. Continued progress requires:

- Building on advances made over the last decade;
- Making optimum use of investments in both experiment and theory; and
- Continued coordination between experiment and theory.

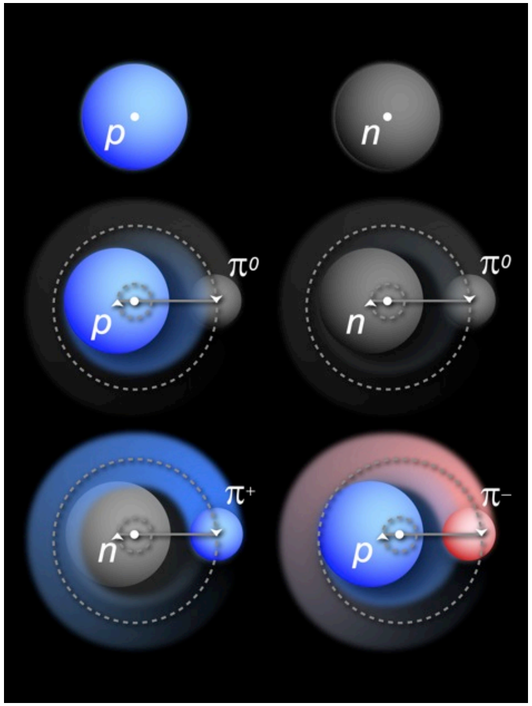
Probing with long wavelength photons

Focus is on at $E_\gamma < 500$ MeV

$$\lambda = \frac{\hbar c}{E_\gamma} \quad \rightarrow \lambda > 0.4 \text{ fm}$$



Most sensitive to the nucleon-(virtual pion cloud) DoF



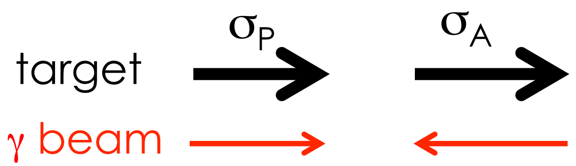
Pion-cloud physics

Pictures from: J. Arrington, arXiv:1208.4047v1[nucle-ex]

GDH (Gerasimov-Drell-Hearn) Sum Rule

Relates the helicity dependence of the photoabsorption cross section of a nucleon/nucleus to its static properties, i.e., magnetic moment, mass and spin: provides opportunities to gain insight about the dynamical response of the internal dof of nucleons to EM impulses over a broad frequency band

$$I_{GDH} = \int_0^\infty \frac{\sigma_P^N - \sigma_A^N}{\omega} d\omega = 4\pi^2 \left(\frac{e}{M}\right)^2 \kappa^2 S$$



Derived by applying dispersive analysis and assuming:

- Lorentz invariance
- Gauge invariance
- Crossing symmetry
- Rotational invariance
- Causality and
- Unitarity

Baldin sum rule:

$$\alpha_E + \beta_M = \frac{1}{2\pi^2} \int_0^\infty \frac{\sigma_P^N - \sigma_A^N}{\omega^2} d\omega$$

Forward spin polarizability:

$$\gamma_0 = -\frac{1}{4\pi^2} \int_0^\infty \frac{\sigma_P^N - \sigma_A^N}{\omega^3} d\omega$$

GDH on the Nucleons

Theoretical predictions for I_{GDH} of p and n

	I_{GDH} proton	I_{GDH} neutron
$\gamma N \to N\pi$	172 [164]	147 [131]
$\gamma N \to N\pi\pi$	94	82
$\gamma N \to N\rho$	-8	-6
$\gamma N \to K\Lambda(\Sigma)$	-4	2
$\gamma N \to N\rho(\omega)$	0	2
Regge contribution ($E_\gamma > 2$ GeV)	-14	20
TOTAL	∼ 239 [231]	∼ 247 [231]
GDH sum rule	204	233

S. Costanza, JP conf. 349, 012011 (2012)

ELSA@Bonn and MAMI@Mainz

$$I^p_{GDH} = 211 \pm 5(stat) \pm 12(stat)\mu b$$

GDH Coll., J. Ahrens et al, PRL **87**, 022003 (2001).
GDH Coll., H. Dutz et al, PRL **91**, 192001 (2003).
GDH Coll., H. Dutz et al, PRL **93**, 032003 (2004).

$$\int_{\omega_{0.2}}^{\omega_{1.8}} \frac{\sigma^d_P - \sigma^d_A}{\omega} d\omega = 452 \pm 9(stat) \pm 24(sys)\mu b$$

$$I^n_{GDH} = 275 \pm 6(stat) \pm 21(sys)\mu b$$

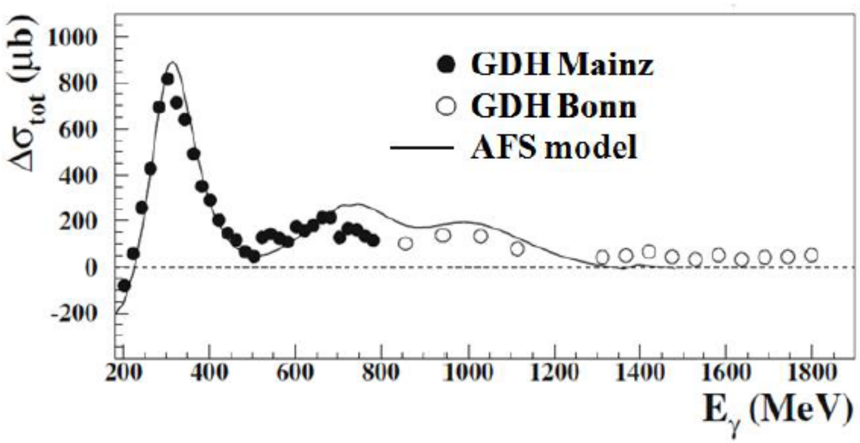
Determine GDH on n from double polarization measurements on ^{2}H and ^{3}He targets

$$\int_{m_\pi}^{\omega_{\max}} \frac{\sigma^d_P - \sigma^d_A}{\omega} d\omega \approx p^d_p \cdot I^p_{GDH} + p^d_n \cdot I^n_{GDH} \qquad p^d_p = p^d_n \approx 0.93$$

$$\int_{m_\pi}^{\omega_{\max}} \frac{\sigma^{^3He}_P - \sigma^{^3He}_A}{\omega} d\omega \approx -2 p^{^3He}_p \cdot I^p_{GDH} + p^{^3He}_n \cdot I^n_{GDH} \qquad p^{^3He}_p \approx -0.026 \quad p^{^3He}_n \approx 0.87$$

Experiment situation with GDH on ^{2}H and ^{3}He prior to 2007:

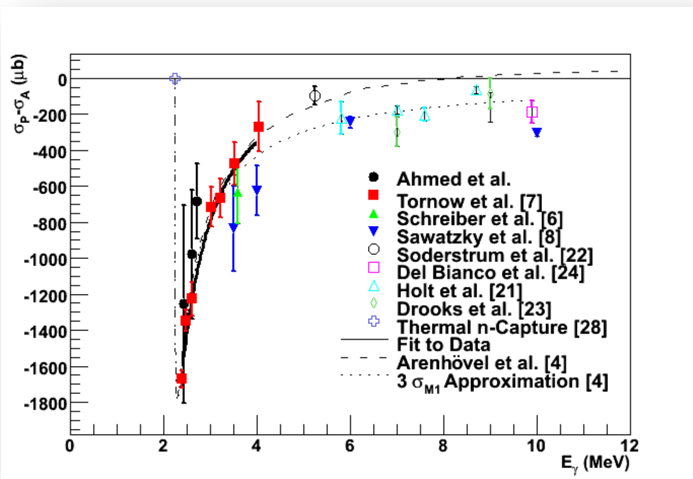
- Measurements on ^{2}H (LEGS, MAMI, ELSA)
- No measurements on ^{3}He

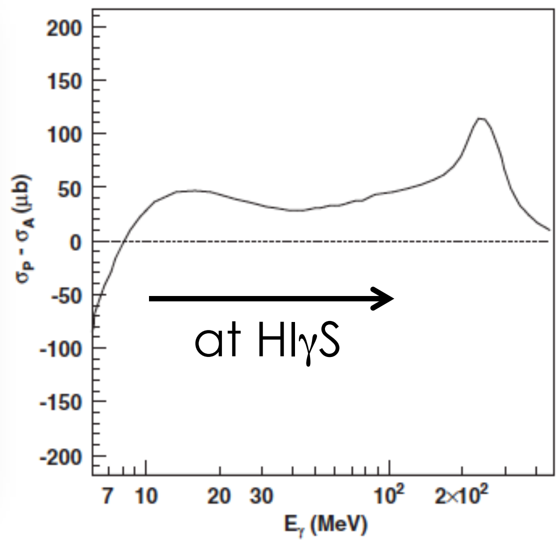


Recent accomplishments and plans for GDH on ^{2}H

$$\int_{\omega_2}^{\infty}\frac{\sigma_P^d-\sigma_A^d}{\omega}\,d\omega=\int_{\omega_2}^{\omega_\pi}\frac{\sigma_P^d-\sigma_A^d}{\omega}\,d\omega+\int_{\omega_\pi}^{\omega_{\max}}\frac{\sigma_P^d-\sigma_A^d}{\omega}\,d\omega+\int_{\omega_{\max}}^{\infty}\frac{\sigma_P^d-\sigma_A^d}{\omega}\,d\omega$$

0.6 μb | **Measured HIGS** | **Measured LEGS, Mainz, ELSA** | **Calculated -14 μb**





Measurements at HIγS:

W. Tornow *et al.*, Phys. Lett. B **574**, 8 (2003).

M.A. Blackston *et al.*, Phys. Rev. C**78**, 034003 (2008)

M.W. Ahmed *et al.*, Phys. Rev. C**77**, 044005 (2008)

Experimental setup for measurement of the GDH Sum Rule on ^2H

***HIFROST* – *HIGS FRO*zen *S*pin *T*arget**

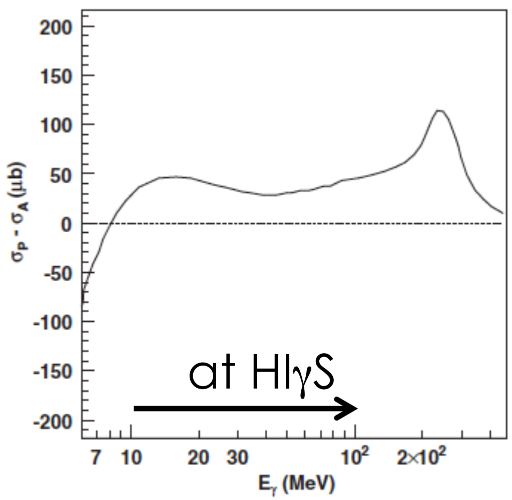
^3He/ ^4He Dilution refrigerator originally obtained from Geesthacht, Germany

d-Butanol 10 cm target

Assembled and initially tested at UVA

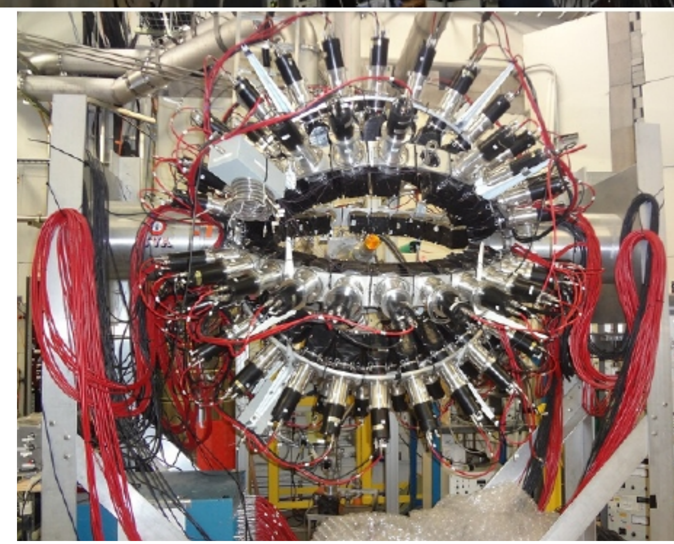
Currently being installed at HIGS

Technical lead – Don Crabb (UVA)

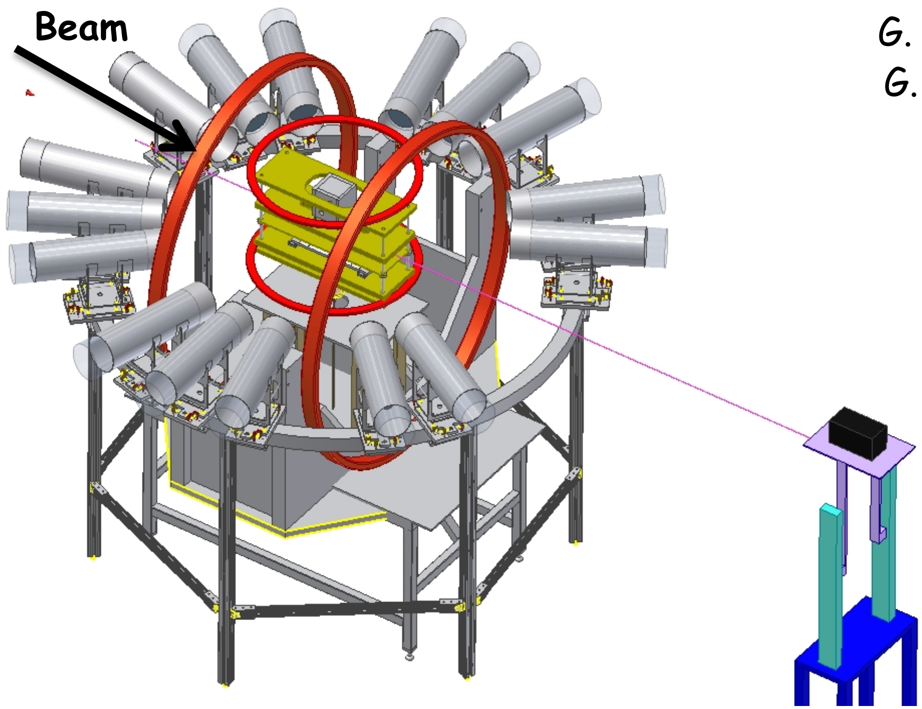


$^2H + \gamma \rightarrow n + p$

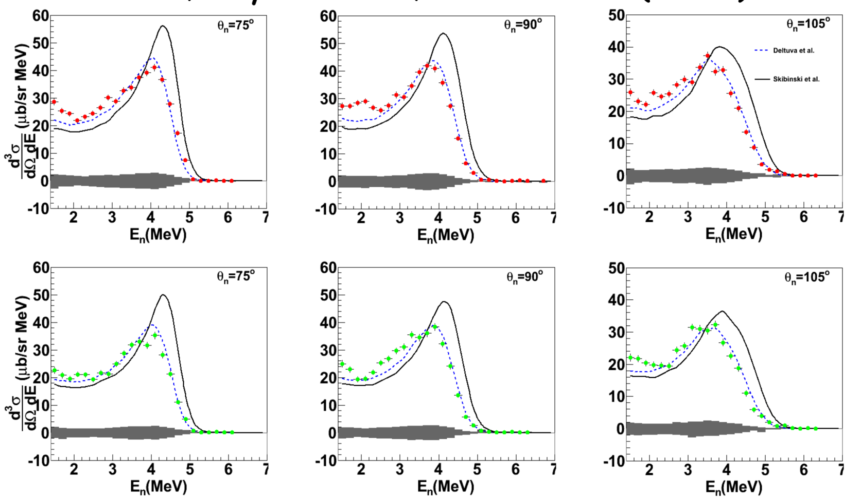
$10 < E_\gamma < 100$ MeV



Recent accomplishments and plans for GDH on ^{3}He

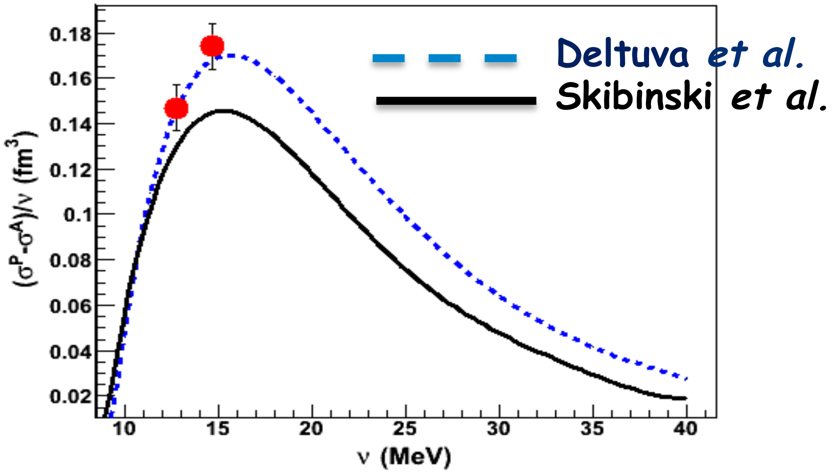


G. Laskaris *et al.*, Phys. Rev. Lett. **110**, 202501 (2013)
G. Laskaris *et al.*, Phys. Rev. C, **89** 024002 (2014).



^{3}He + γ → n + p + p (3-body channel)

Data taken on 2-body channel;
analysis underway
^{3}He + γ → p + d

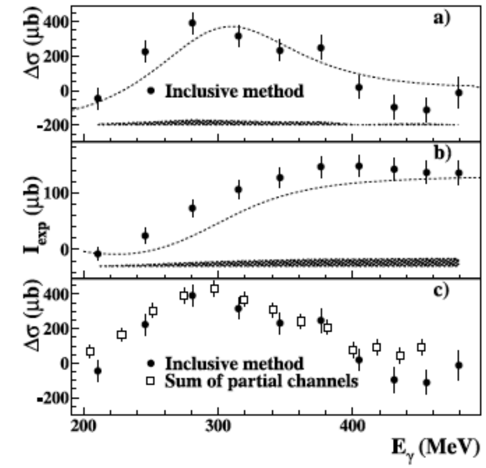


Future: push to higher energies, up to ~50 MeV

Recent accomplishments and plans for for GDH on ^{3}He

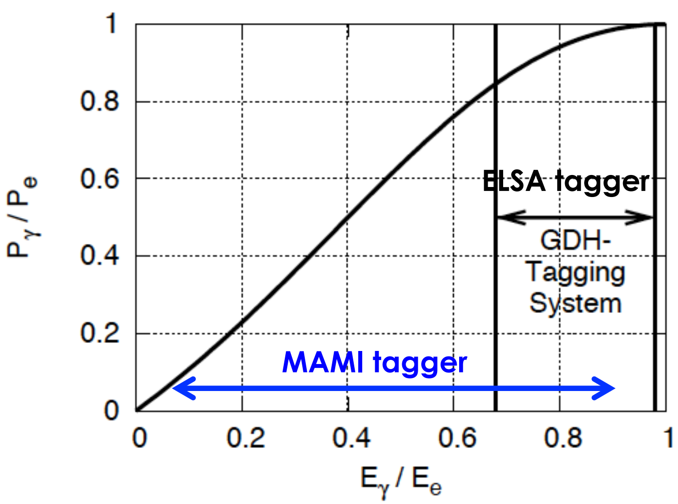
High-energy measurements at MAMI:

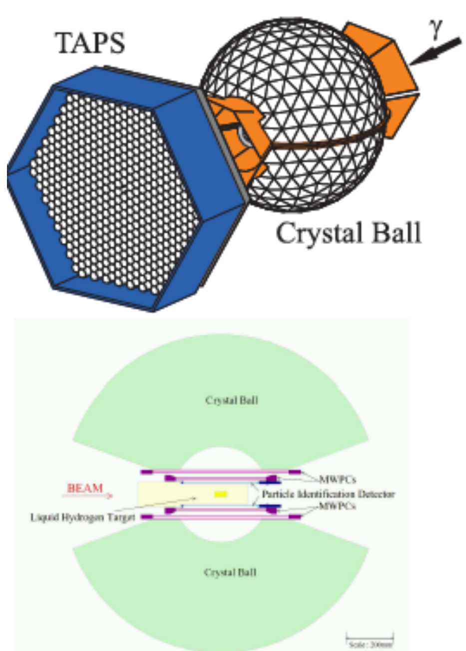
First measurement of the helicity dependence of ^{3}He photoreactions in the Δ (1232)resonance region ($150 < E_\gamma < 500$ MeV)
P. Aguar Bartolomé *et al.*, Phys. Lett. B **723**, 71 (2013).

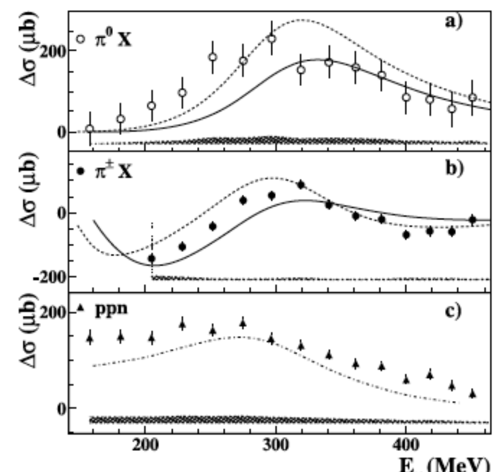


Experiment Setup

- Coherent bremsstrahlung γ-ray beam
- Tagged photons







Compton Scattering: Nucleon Polarizabilities

$$T_{fi} = \frac{4\pi W}{M} \sum_{i=1}^{6} \rho_i \, R_i(\omega, z) \, .$$

z = cos(θ)

$$\rho_1 = \vec{\epsilon}^{\,\prime *} \cdot \vec{\epsilon}, \qquad \rho_2 = \vec{s}^{\,\prime *} \cdot \vec{s},$$
$$\rho_3 = i\,\vec{\sigma} \cdot (\vec{\epsilon}^{\,\prime *} \times \vec{\epsilon}) \, , \qquad \rho_4 = i\,\vec{\sigma} \cdot (\vec{s}^{\,\prime *} \times \vec{s}) \, ,$$
$$\rho_5 = i \left(\left(\vec{\sigma} \cdot \hat{\vec{k}} \right) (\vec{s}^{\,\prime *} \cdot \vec{\epsilon}) - \left(\vec{\sigma} \cdot \hat{\vec{k}}' \right) (\vec{\epsilon}^{\,\prime *} \cdot \vec{s}) \right) ,$$
$$\rho_6 = i \left(\left(\vec{\sigma} \cdot \hat{\vec{k}}' \right) (\vec{s}^{\,\prime *} \cdot \vec{\epsilon}) - \left(\vec{\sigma} \cdot \hat{\vec{k}} \right) (\vec{\epsilon}^{\,\prime *} \cdot \vec{s}) \right)$$

with $\vec{s} = \hat{\vec{k}} \times \vec{\epsilon}$, $\vec{s}^{\,\prime *} = \hat{\vec{k}}' \times \vec{\epsilon}^{\,\prime *}$ and $\vec{\sigma}$ the vector of the Pauli spin matrices. Furthermore, $\hat{\vec{k}} = \vec{k}/\omega$ ($\hat{\vec{k}}' = \vec{k}'/\omega$) is the unit vector in the direction of the momentum of the incoming (outgoing) photon with polarization $\vec{\epsilon}$ ($\vec{\epsilon}^{\,\prime *}$).

$$R_i(\omega, z) = R_i^{\text{pole}}(\omega, z) + R_i(\omega, z)$$

Multipole expansion

T = E or M

Scalar polarizabilities

$$\alpha_{E1}(\omega) = \left[2\, f_{EE}^{1+}(\omega) + f_{EE}^{1-}(\omega)\right] / \omega^2 \, ,$$
$$\beta_{M1}(\omega) = \left[2\, f_{MM}^{1+}(\omega) + f_{MM}^{1-}(\omega)\right] / \omega^2 \, ,$$
$$\alpha_{E2}(\omega) = 36 \left[3\, f_{EE}^{2+}(\omega) + 2\, f_{EE}^{2-}(\omega)\right] / \omega^4 \, ,$$
$$\beta_{M2}(\omega) = 36 \left[3\, f_{MM}^{2+}(\omega) + 2\, f_{MM}^{2-}(\omega)\right] / \omega^4$$

Spin-dependent polarizabilities

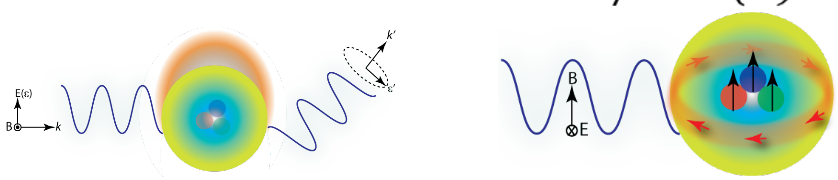
$$\gamma_{E1E1}(\omega) = \left[f_{EE}^{1+}(\omega) - f_{EE}^{1-}(\omega)\right] / \omega^3 \quad (E1 \rightarrow E1) \, ,$$
$$\gamma_{M1M1}(\omega) = \left[f_{MM}^{1+}(\omega) - f_{MM}^{1-}(\omega)\right] / \omega^3 \quad (M1 \rightarrow M1) \, ,$$
$$\gamma_{E1M2}(\omega) = 6\, f_{EM}^{1+}(\omega) / \omega^3 \quad (E1 \rightarrow M2) \, ,$$
$$\gamma_{M1E2}(\omega) = 6\, f_{ME}^{1+}(\omega) / \omega^3 \quad (M1 \rightarrow E2) \, .$$

$$\gamma_0 = -\bar{\gamma}_{E1E1} - \bar{\gamma}_{E1M2} - \bar{\gamma}_{M1M1} - \bar{\gamma}_{M1E2} \, ,$$
$$\gamma_\pi = -\bar{\gamma}_{E1E1} - \bar{\gamma}_{E1M2} + \bar{\gamma}_{M1M1} + \bar{\gamma}_{M1E2} \, ,$$

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

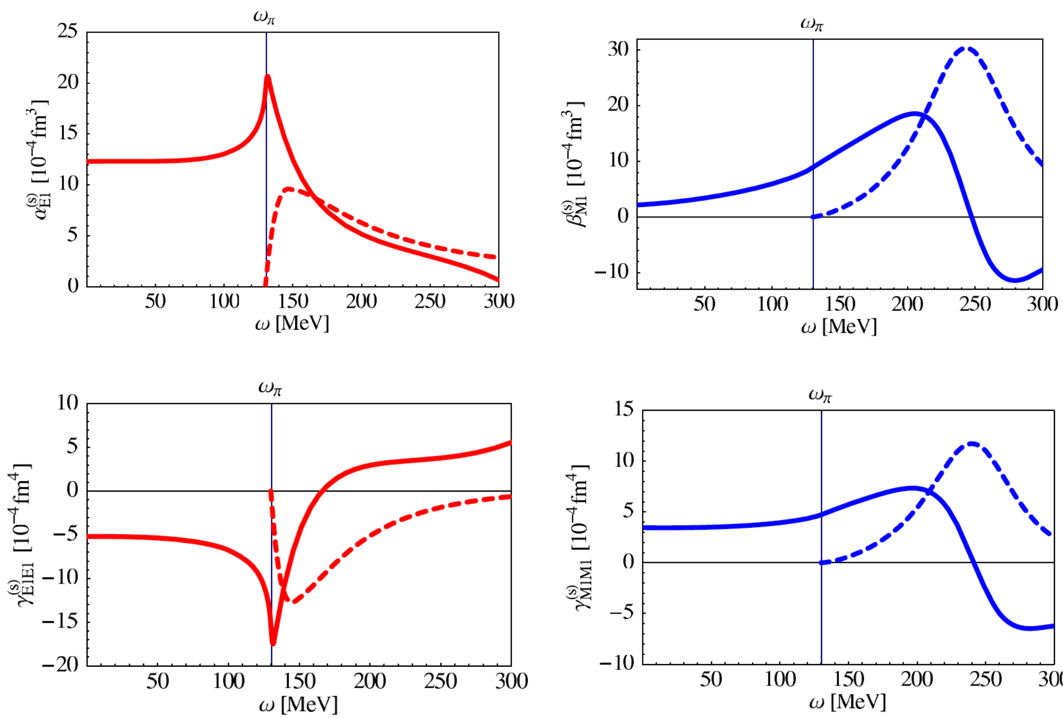
Compton Scattering: Nucleon Polarizabilities

$$d = 4\pi\alpha_{E1}(\omega)E(\omega) \qquad m = 4\pi\beta_{M1}(\omega)B(\omega)$$



Provides insights about:

- Freq. response of system
- Binding energy of charged constituents
- Confinement volume of charged constituents
- $\Delta\beta_n$ causes a significant uncertainty in calc. m_n-m_p
- β_p input to Lamb-shift corr. In μH atoms
- Collective response of internal spin dof to em pulse

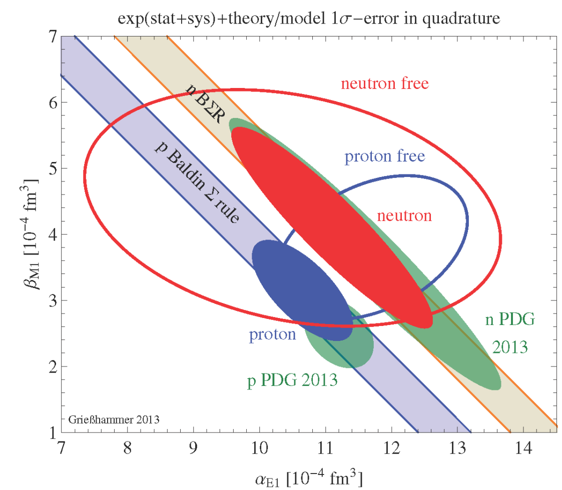


EFT Extractions – HWG, JAMcG, DRP, GF

PDG - 2013

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

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



Expt. goals:

- sum-rule independent meas. of β_p
- reduce $\Delta\beta_n$ by ~ factor of 2

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

Determination of β_p independent of the Baldin sum rule

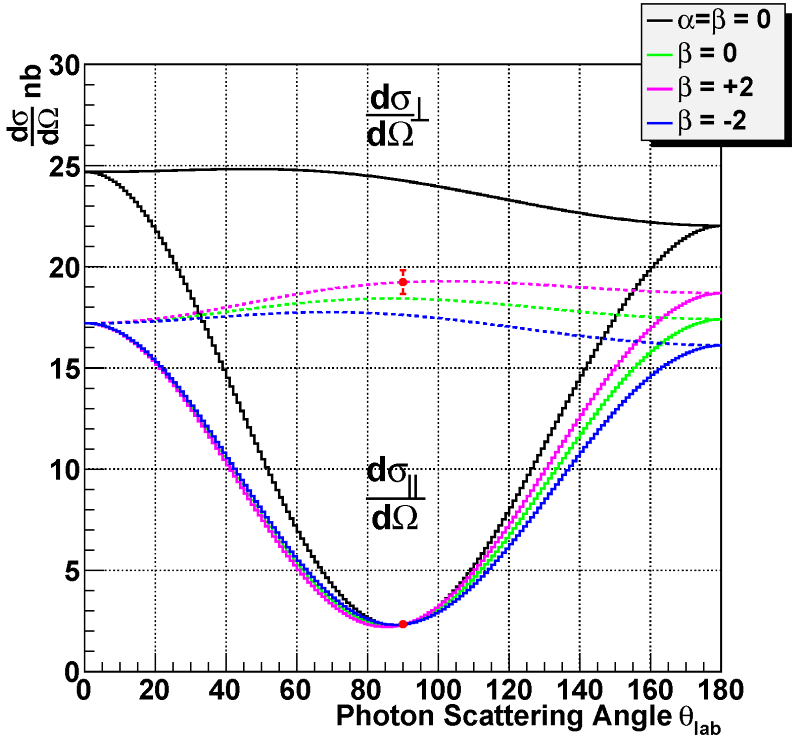
Experiment Features:

- ❑ Linear γ-ray beam polarization
- ❑ Unpolarized LH Target
- ❑ High efficiency γ-ray detection
- ❑ Measure differential cross section and asymmetry at 90° and a backward θ

$$\frac{d\sigma_\perp}{d\Omega} = \overbrace{\frac{1}{2}\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2\left[\begin{array}{c}\left[\frac{\omega'}{\omega}+\frac{\omega}{\omega'}\right]\\ +\frac{\omega\omega'}{M^2}\left[\begin{array}{c}2\kappa(1-\cos\theta)^2\\ +\kappa^2[5(1-\cos\theta)+\frac{1}{2}\sin^2\theta]\\ +\kappa^3[2(1-\cos\theta)+2\sin^2\theta]\\ +\frac{1}{2}\kappa^4(1+\sin^2\theta)\end{array}\right]\end{array}\right]}^{d\sigma_\perp^{point}} - \underbrace{\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2\omega\omega'(2\bar{\alpha}+\cancel{2\bar{\beta}\cos\theta})}$$

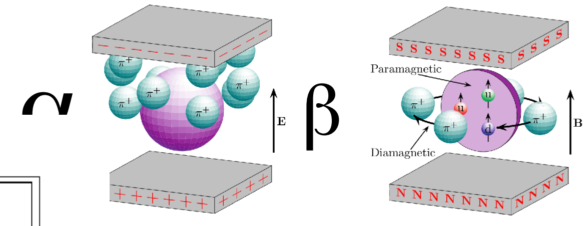
θ = 90°

$$\frac{d\sigma_\parallel}{d\Omega} = \overbrace{\frac{1}{2}\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2\left[\begin{array}{c}\left[\frac{\omega'}{\omega}+\frac{\omega}{\omega'}-2\sin^2\theta\right]\\ +\frac{\omega\omega'}{M^2}\left[\begin{array}{c}2\kappa(1-\cos\theta)^2\\ +\kappa^2[5(1-\cos\theta)-\frac{3}{2}\sin^2\theta]\\ +\kappa^3[2(1-\cos\theta)]\\ +\frac{1}{2}\kappa^4\end{array}\right]\end{array}\right]}^{d\sigma_\parallel^{point}} - \underbrace{\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2\omega\omega'(2\bar{\alpha}\cancel{\cos^2\theta}+\cancel{2\bar{\beta}\cos\theta})}_{d\sigma_\parallel^{dipole}}$$



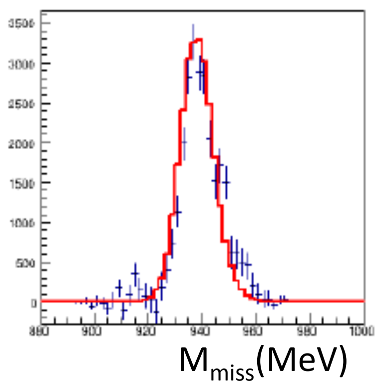
$$\Sigma_3(\theta) = \frac{\frac{d\sigma_\perp(\theta)}{d\Omega} - \frac{d\sigma_\parallel(\theta)}{d\Omega}}{\frac{d\sigma_\perp(\theta)}{d\Omega} + \frac{d\sigma_\parallel(\theta)}{d\Omega}}$$

First determination of bp independent of the Baldin sum-rule at MAMI



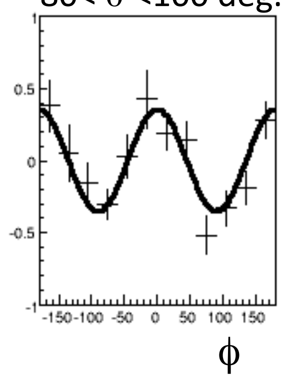
80 MeV < E_γ < 150 MeV

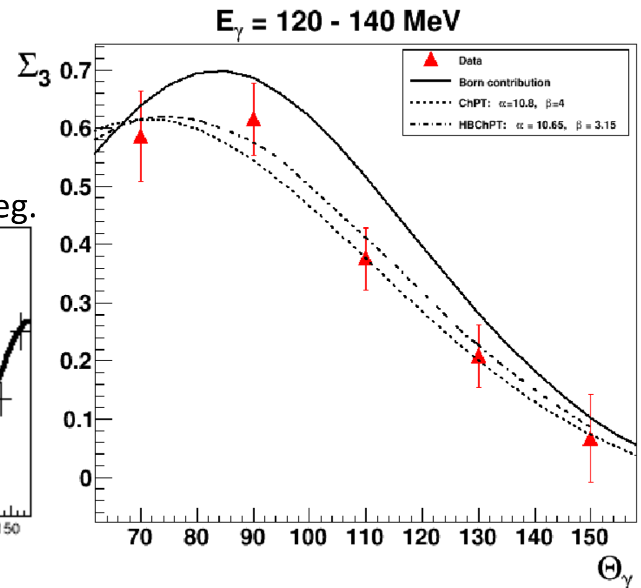
60< θ <160 deg.



100 -120 MeV

80< θ <100 deg.





Data:
V. Sokhoyan, E.J. Downie
Curves:
ChPT: Krupina and Pascalutsa, PRL 110, 262001 (2013),
HB ChPT: J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)

Status

- Accumulated 300 hours of data
- Background level relative to sign acceptable
- Analysis underway
- Data accumulation for another 550 hours planned

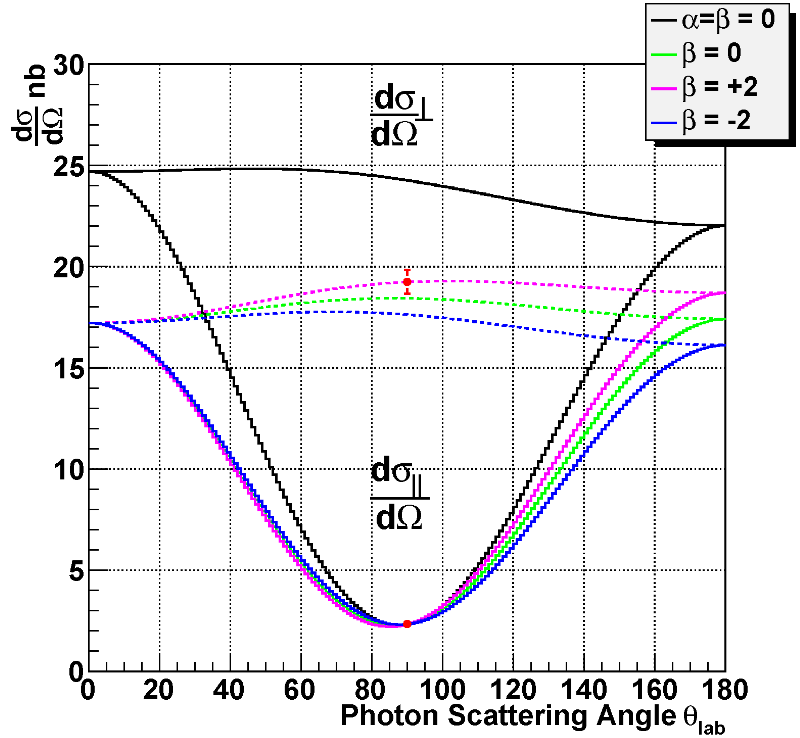
Planned: α_p and β_p measurements at HIγS

- 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° and a backward θ

$$\frac{d\sigma_\perp}{d\Omega} = \overbrace{\frac{1}{2}\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2\left[\begin{array}{c}\left[\frac{\omega'}{\omega}+\frac{\omega}{\omega'}\right] \\ +\frac{\omega\omega'}{M^2}\left[\begin{array}{c}2\kappa(1-\cos\theta)^2 \\ +\kappa^2[5(1-\cos\theta)+\frac{1}{2}\sin^2\theta] \\ +\kappa^3[2(1-\cos\theta)+2\sin^2\theta] \\ +\frac{1}{2}\kappa^4(1+\sin^2\theta)\end{array}\right]\end{array}\right]}^{d\sigma_\perp^{point}}$$
$$\underbrace{-\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2\omega\omega'(2\bar{\alpha}+\cancel{2\bar{\beta}\cos\theta})}$$

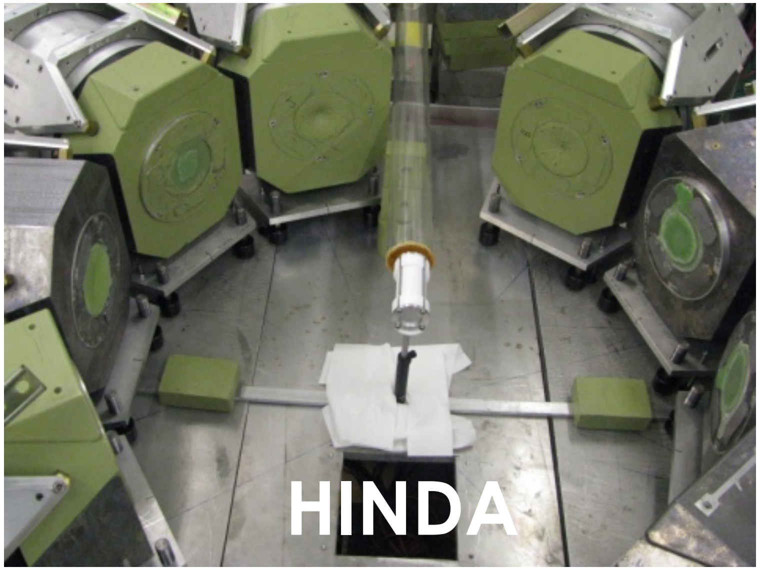
θ = 90°

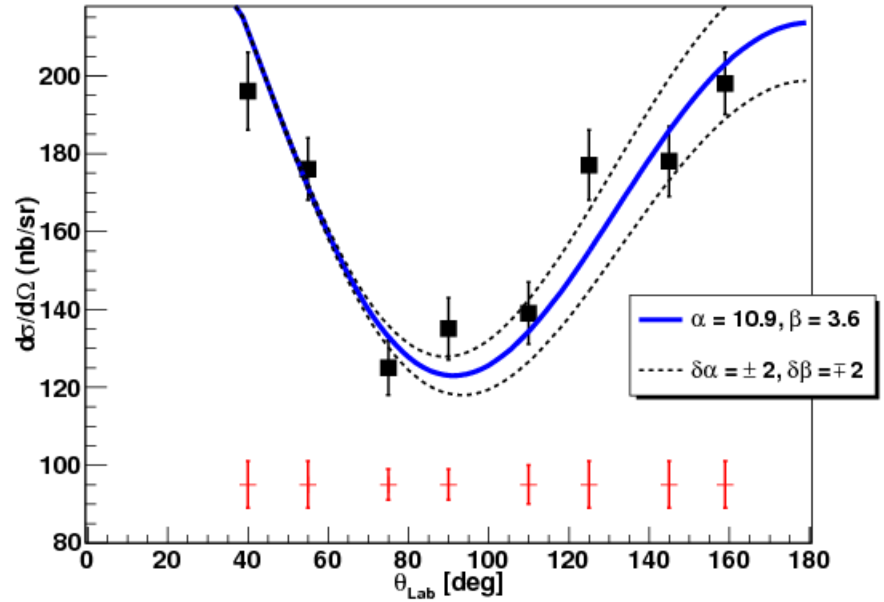
$$\frac{d\sigma_\parallel}{d\Omega} = \overbrace{\frac{1}{2}\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2\left[\begin{array}{c}\left[\frac{\omega'}{\omega}+\frac{\omega}{\omega'}-2\sin^2\theta\right] \\ +\frac{\omega\omega'}{M^2}\left[\begin{array}{c}2\kappa(1-\cos\theta)^2 \\ +\kappa^2[5(1-\cos\theta)-\frac{3}{2}\sin^2\theta] \\ +\kappa^3[2(1-\cos\theta)] \\ +\frac{1}{2}\kappa^4\end{array}\right]\end{array}\right]}^{d\sigma_\parallel^{point}}$$
$$\underbrace{-\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2\omega\omega'(2\bar{\alpha}\cancel{\cos^2\theta}+\cancel{2\bar{\beta}\cos\theta})}_{d\sigma_\parallel^{dipole}}$$



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

Method for determining isoscalar nucleon polarizabilities





For Compton scattering:

$$\frac{d\sigma}{d\Omega} \propto Z^2$$

L.S. Meyers *et al.*, Phys. Rev. C **86**, 044614 (2012)

- Advantage: increased S/N ratio
- Challenge: requires ab initio calculations for light nuclei

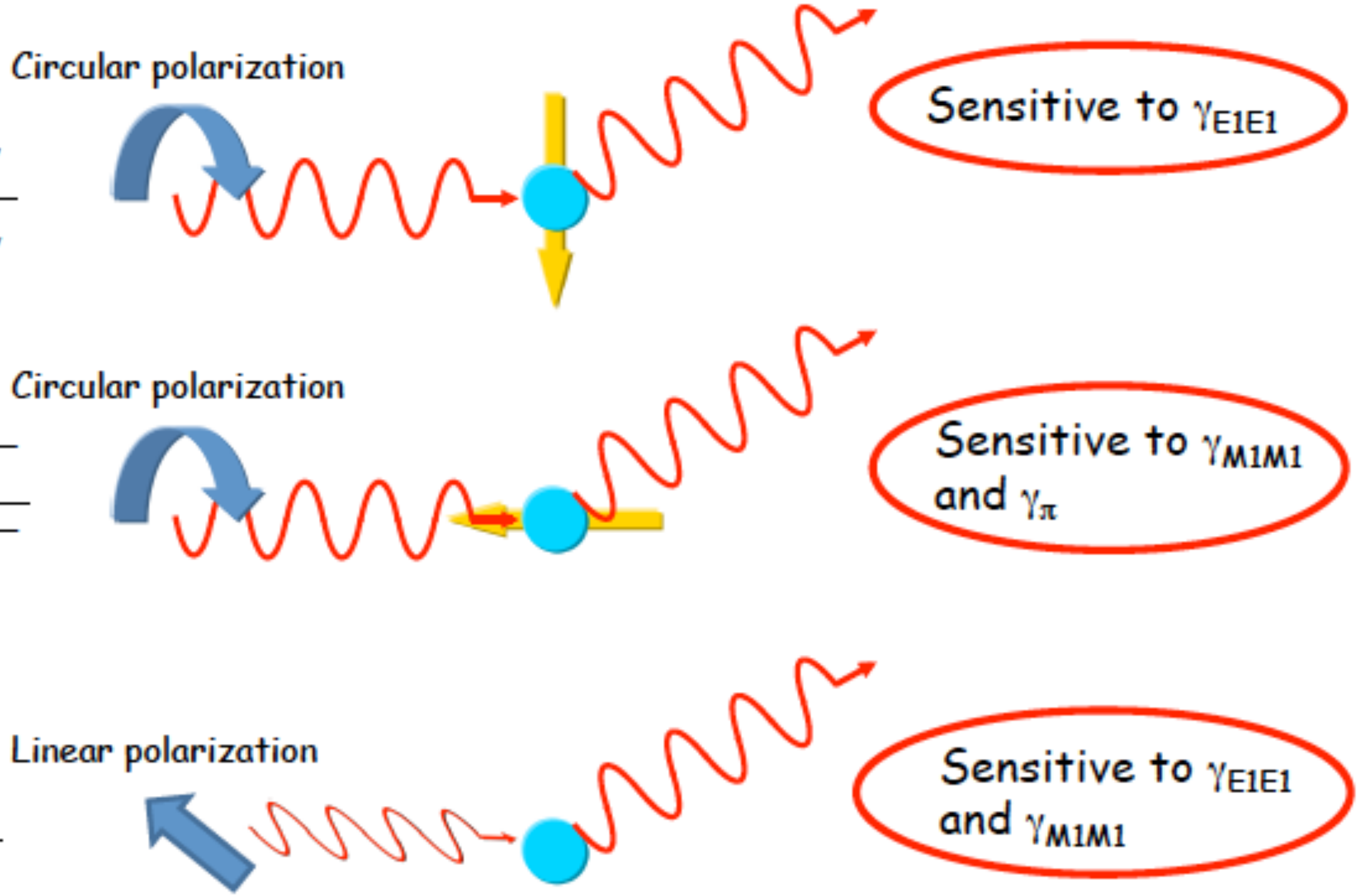
Ab initio calculations enable determination of α_n and β_n with A>1 targets:
HIγS and MAMI: ^2H, ^3He and ^4He

Method for measuring spin polarizabilities

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

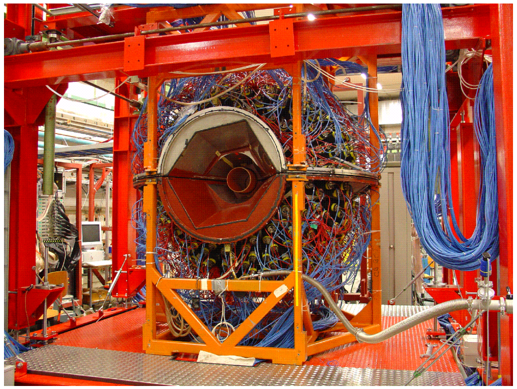
$$\Sigma_{2z} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$

$$\Sigma_{3} = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

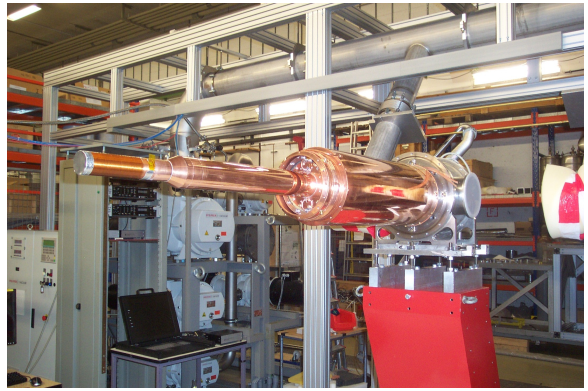


Accomplishments: **Spin-Polarizability Measurements at MAMI (Σ_{2x}) in the Δ region**

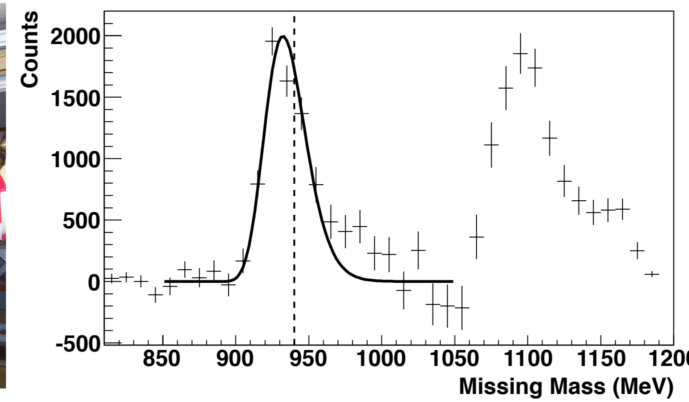
Compton scattering in the Δ region with transverse polarized proton target, Σ_{2x}



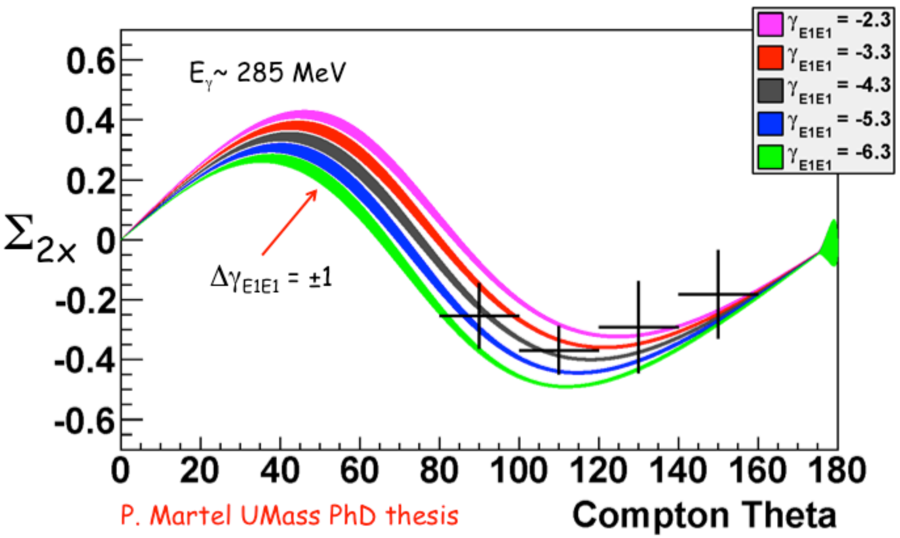
Crystal Ball and TAPS at MAMI



Frozen spin butanol target



Compton scattering missing mass distribution with MC simulation



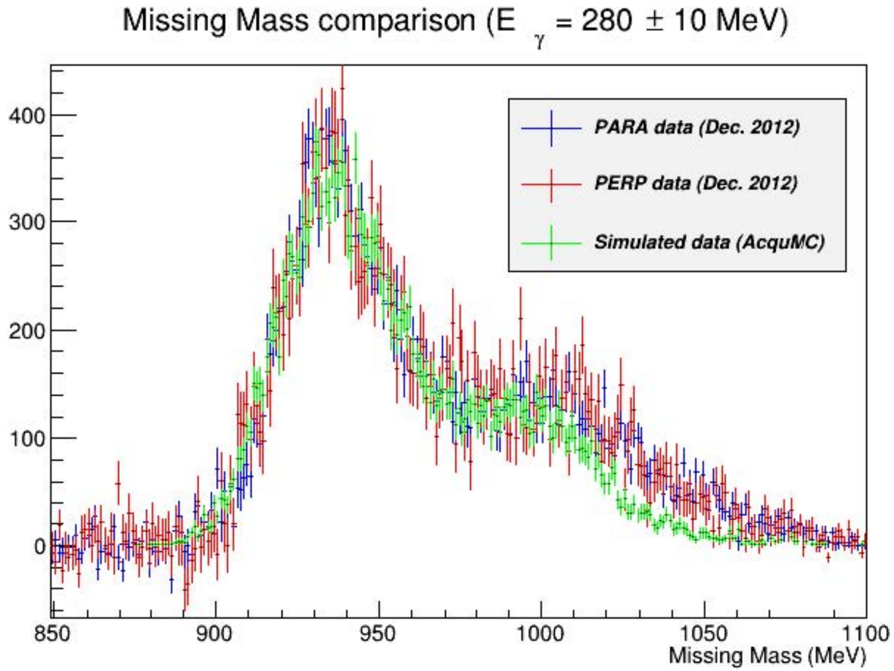
Transverse asymmetry with circularly polarized photons

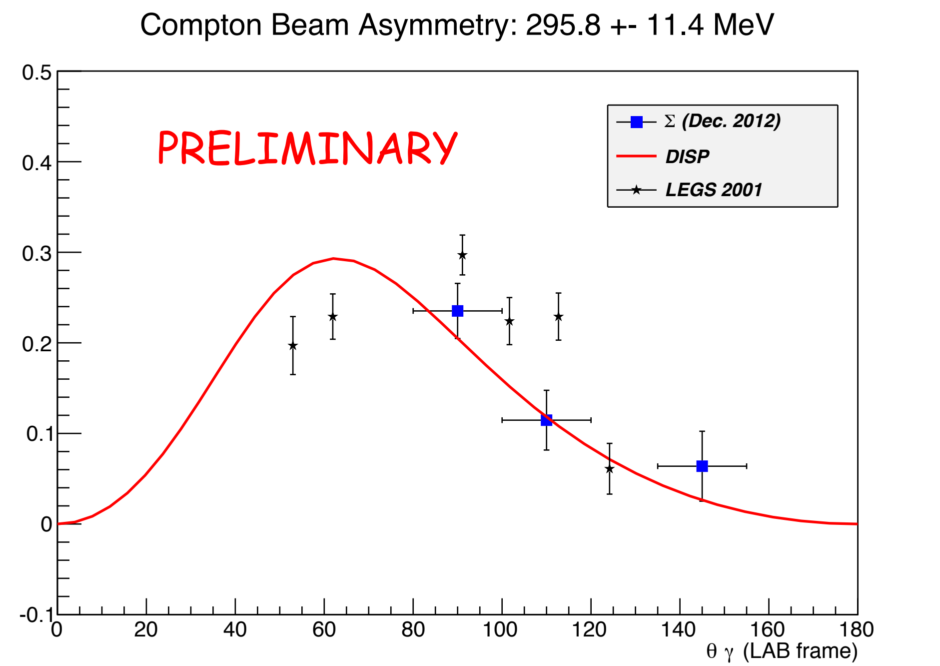
	Disp theory	L_χ	HBχPT	BχPT	This Expt
γ_{E1E1}	-3.8	-3.7	-1.1± 1.8 (th)	-3.3	-3.2± 1.2
γ_{M1M1}	2.9	2.5	2.2±.5 (st) ± .7 (th)	3.0	3.16± .85
γ_{E1M2}	0.5	1.2	-.4± .4 (th)	0.2	-.7± 1.2
γ_{M1E2}	1.6	1.2	1.9± .4 (th)	1.1	1.99± .29

Submitted to PRL, arXiv:1408.1576

Accomplishments: **Spin-Polarizability Measurements at MAMI in the Δ region**

I. Compton scattering in the Δ region with linearly polarized photons and unpolarized proton target, Σ_3





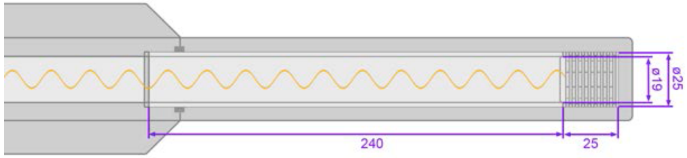
Cristina Collicott, Dalhousie University NS, PhD thesis

II. Compton scattering in the Δ region with longitudinal polarized proton target, Σ_{2z}

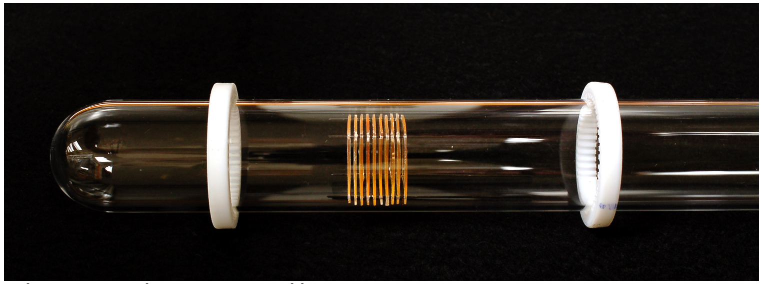
Data taking completed April 2014
PhD theses D. Paudyual U. Regina, and A. Rajabi UMass

Future Spin-Polarizability Measurements at HIγS and MAMI

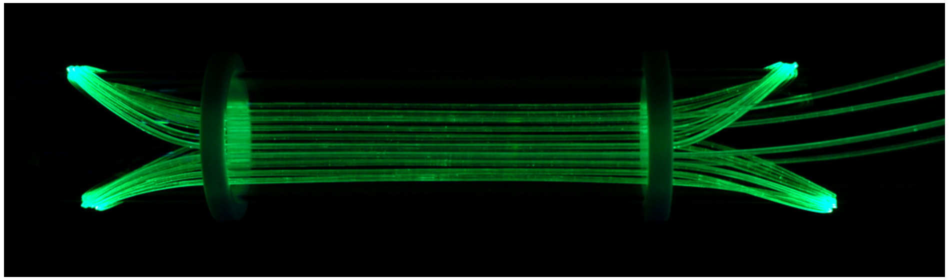
I. Development of a polarized scintillating proton and deuterium target for use in Compton experiments near pion threshold.



- 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



Polarizable scintillators in prototype quartz target cell



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

II. Additional data taking on Σ_3, Σ_{2x} and Σ_{2z} for the proton

III. Measurement of neutron spin-polarizabilities

- Coherent and incoherent Compton scattering on polarized deuterium
- Theoretical guidance and support are critical for this effort, see H. Grieβhammer, Eur. Phys. J. A 49, 100 (2013)

Near threshold photo-pion production

In the Chiral limit $m_u = m_d \rightarrow 0$ ➔ that the S-wave amplitude for $\gamma N \rightarrow \pi N \rightarrow 0$

- Strength of S-wave amplitude for photo-pion production provides insight about the mechanism for spontaneous and explicit chiral symmetry breaking in QCD.
- S-wave amplitude for $\gamma p \rightarrow \pi^0 p$ amplitude very sensitive to $\Delta m = m_d - m_u$ (isospin violation)

$$d\sigma/d\Omega_\pi = (p_\pi^*/k_\gamma^*)\{R_T^{00} + \Pi_T\, {}^cR_{TT}^{00}\cos 2\varphi + P_x\left(-\Pi_T\, {}^s\boldsymbol{R}_{TT}^{0x}\sin 2\varphi + \Pi_\odot R_{TT'}^{0x}\right) + P_y\left(\boldsymbol{R}_T^{0y} + \Pi_T\, {}^c\boldsymbol{R}_{TT}^{0y}\cos 2\varphi\right) + P_z\left(-\Pi_T\, {}^s\boldsymbol{R}_{TT}^{0z}\sin 2\varphi + \Pi_\odot R_{TT'}^{0z}\right)\},$$

Observable	Response function	Name
$\sigma_T(\theta_\pi^*)$	$= (p_\pi^*/p_\gamma^*)R_T^{00}$	Transverse differential cross section
$A(\vec{\gamma}) \equiv \Sigma(\theta)$	$= -R_{TT}^{00}/R_T^{00}$	Polarized photon asymmetry
$\boldsymbol{A(y)} \equiv \boldsymbol{T}(\theta)^b$	$= \boldsymbol{R_T^{0y}}/\boldsymbol{R_T^{00}}$	Polarized target asymmetry
$A(\gamma_c, z) \equiv E(\theta)$	$= -R_{TT'}^{0z}/R_T^{00}$	Circularly polarized photon; longitudinally polarized target
$A(\gamma_c, x) \equiv F(\theta)$	$= R_{TT'}^{0x}/R_T^{00}$	Circularly polarized photon; transversely polarized target
$A(\vec{\gamma}, z) \equiv G(\theta)$	$= -\boldsymbol{R_{TT}^{0z}}/\boldsymbol{R_T^{00}}$	Transversely polarized photon; longitudinally polarized target
$A(\vec{\gamma}, x) \equiv \boldsymbol{H}(\theta)$	$= \boldsymbol{R_{TT}^{0x}}/\boldsymbol{R_T^{00}}$	Transversely polarized photon; transversely polarized target
$A(\vec{\gamma}, y) \equiv \boldsymbol{P}(\theta)$	$= -\boldsymbol{R_{TT}^{0y}}/\boldsymbol{R_T^{00}}$	Transversely polarized photon; normal target

Near threshold photo-pion production

In the Chiral limit $m_u = m_d \rightarrow 0 \Rightarrow$ that the S-wave amplitude for $\gamma N \rightarrow \pi N \rightarrow 0$

- Strength of S-wave amplitude for photo-pion production provides insight about the mechanism for spontaneous and explicit chiral symmetry breaking in QCD.
- S-wave amplitude for $\gamma p \rightarrow \pi^0 p$ amplitude very sensitive to $\Delta m = m_d - m_u$ (isospin violation)

A2 Collaboration at Mainz:

Recent Measurements:

$\vec{\gamma} p \rightarrow \pi^0 p$: PRL 111, 062004 (2013). First measurement of the energy dependence in the beam asymmetry, and corresponding energy dependence in the P-wave multipoles.

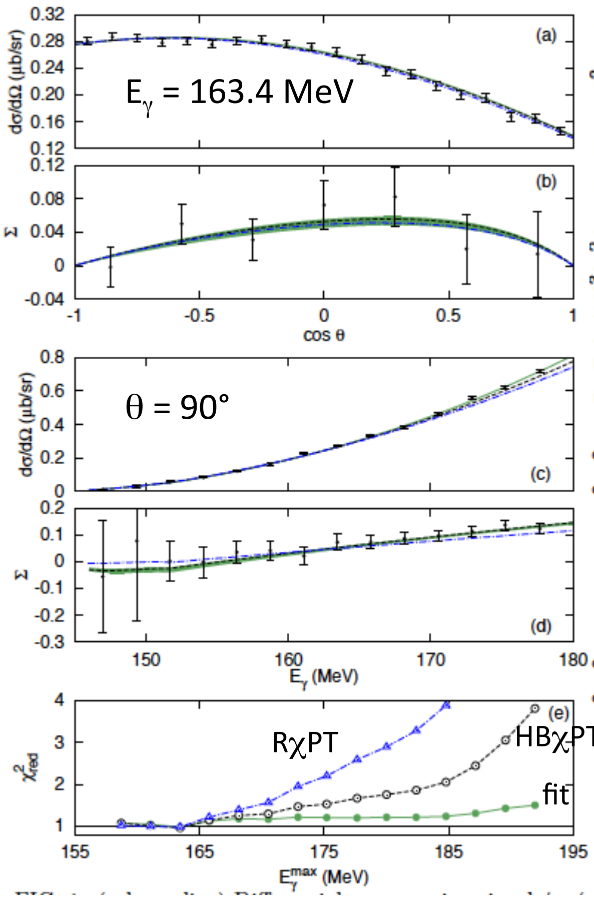
$\vec{\gamma} \vec{p} \rightarrow \pi^0 p$: Analysis underway.

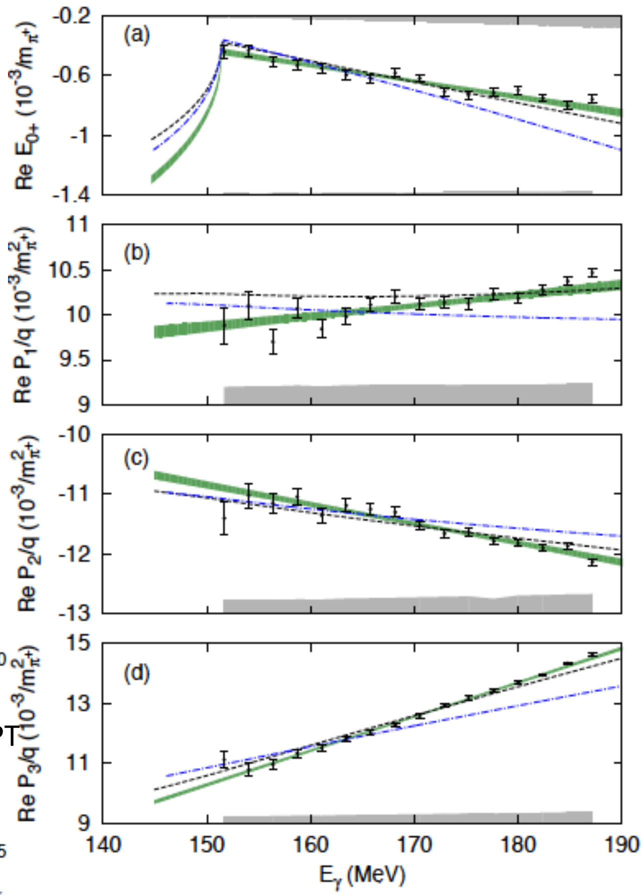
Planned measurements:

Unpolarized photo-pion production on ^{3}He at extract $E_{0^+}^{\pi^0 n}$

Near threshold photopion production: Recent Accomplishments

Results from A2 Coll. Measurements: D. Hornidge et al, PRL 111, 062004 (2013)





$$\frac{d\sigma}{d\Omega}(\theta) = \frac{q}{k}(A + B\cos\theta + C\cos^2\theta),$$

$$A = |E_{0+}|^2 + \frac{1}{2}\left(|P_2|^2 + |P_3|^2\right)$$

$$B = 2\,\mathrm{Re}\left(E_{0+}P_1^*\right)$$

$$C = |P_1|^2 - \frac{1}{2}\left(|P_2|^2 + |P_3|^2\right)$$

$$E_{0+}(W) = E_{0+}^{(0)} + E_{0+}^{(1)}\left(\frac{E_\gamma - E_\gamma^{\mathrm{thr}}}{m_{\pi^+}}\right) + i\beta\frac{q_{\pi^+}}{m_{\pi^+}},$$

$$P_i(W) = \frac{q}{m_{\pi^+}}\left[P_i^{(0)} + P_i^{(1)}\left(\frac{E_\gamma - E_\gamma^{\mathrm{thr}}}{m_{\pi^+}}\right)\right],$$

Low-Energy QCD Experiments: the next decade

HIγS & MAMI γ-ray beam capabilities:

HIγS: Compton scattering – E_γ < 160 MeV, monoenergetic, polarized (linear & circ), high energy resolution via collimation

MAMI: Coherent bremsstrahlung – E_γ > 150 MeV, polarized (linear & circ), high energy resolution via tagging

Research Program:

Gerasimov-Drell-Hearn (GDH) sum rule

- HIγS: on ^2H and ^3He at E_γ < 100 MeV
- MAMI: on ^3He at E_γ > 80 MeV

Nucleon Scalar Polarizabilities

- HIγS: Sum-rule independent determination of β_p (E_γ ~ 90 MeV); α_n and β_n with ^2H, ^3He and ^4He targets
- MAMI: Sum-rule independent determination of β_p (E_γ ~ 90 MeV); α_n and β_n with ^2H, ^3He and ^4He targets

Nucleon Spin-dependent Polarizabilities

- HIγS: $\gamma_{E1E1}(\omega)$, $\gamma_{M1M1}(\omega)$, $\gamma_{E1M2}(\omega)$, $\gamma_{E1M2}(\omega)$ of the proton at E_γ < 120 MeV (requires γ-ray intensity upgrade)
- MAMI: $\gamma_{E1E1}(\omega)$, $\gamma_{M1M1}(\omega)$, $\gamma_{E1M2}(\omega)$, $\gamma_{E1M2}(\omega)$ of the proton at E_γ > 200 MeV

Photo-pion Production near threshold

- HIγS: E_γ < 160 MeV (requires energy upgrade and investment in π spectrometer)
- MAMI: E_γ < 200 MeV

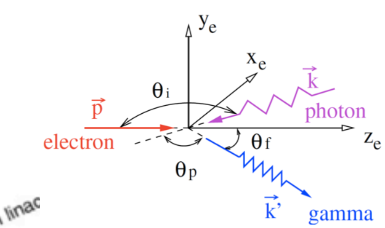
Hadronic Parity Violation (measurement of hadronic-weak coupling)

- HIγS **(beyond next 7 years):** PV photodisintragration of ^2H at threshold (requires upgrade to HIγS2)

High Intensity Gamma-ray Source (HIγS)

HIγS is the most intense accelerator-driven γ -ray source in the world

Produces γ-rays by Compton backscattering
E_γ = 1 – 100 MeV; Mono-energetic beam; Intensity = 10^3 γ /s/eV on target
Linear and circular polarized beams

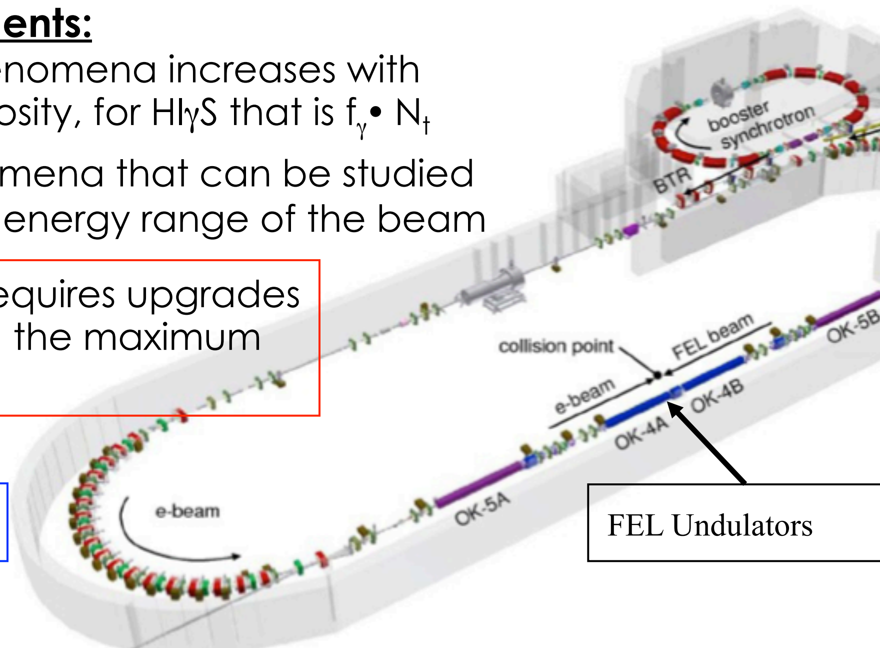


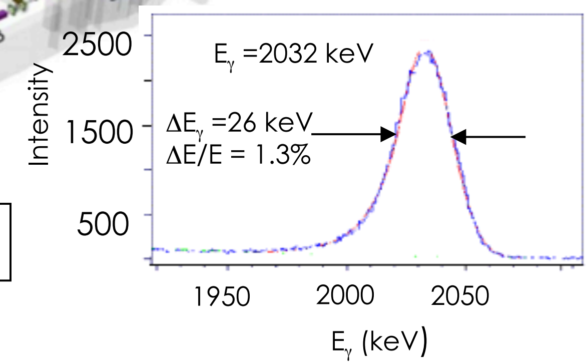
<u>For beam experiments:</u>

- Sensitivity to phenomena increases with increasing luminosity, for HIγS that is $f_\gamma \bullet N_t$
- Scope of phenomena that can be studied depends on the energy range of the beam

Planned research requires upgrades of both the flux and the maximum energy γ-ray beam.

$$f_\gamma \propto I_e \bullet P_{oc}$$





Mode	γ-ray Energy	γ-ray flux limited by
Electron loss	> 20 MeV	(1) Mirror max. power limit (2) Electron injector current capability
No loss	< 20 MeV	Storage-ring max. charge/bunch stability

HIγS2 Concept (Compton backscattering γ-ray source)

Projected Performance

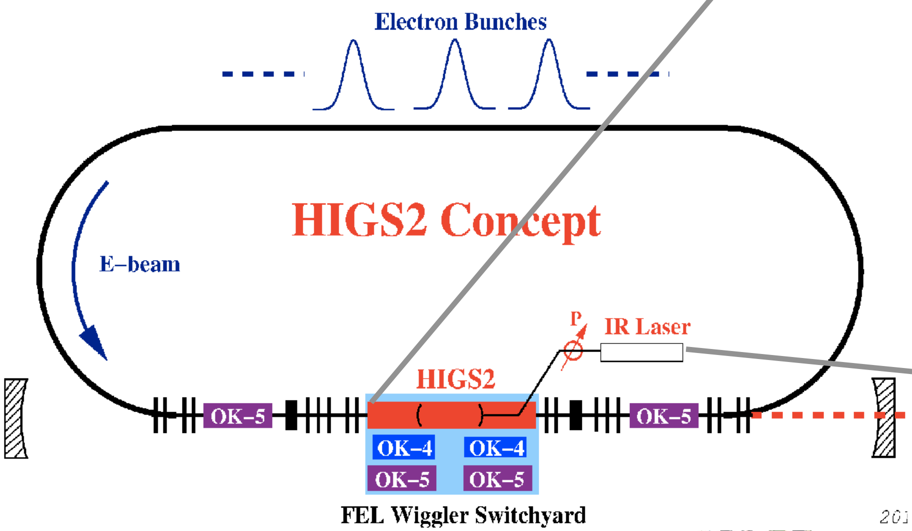
~2 μm FP cavity

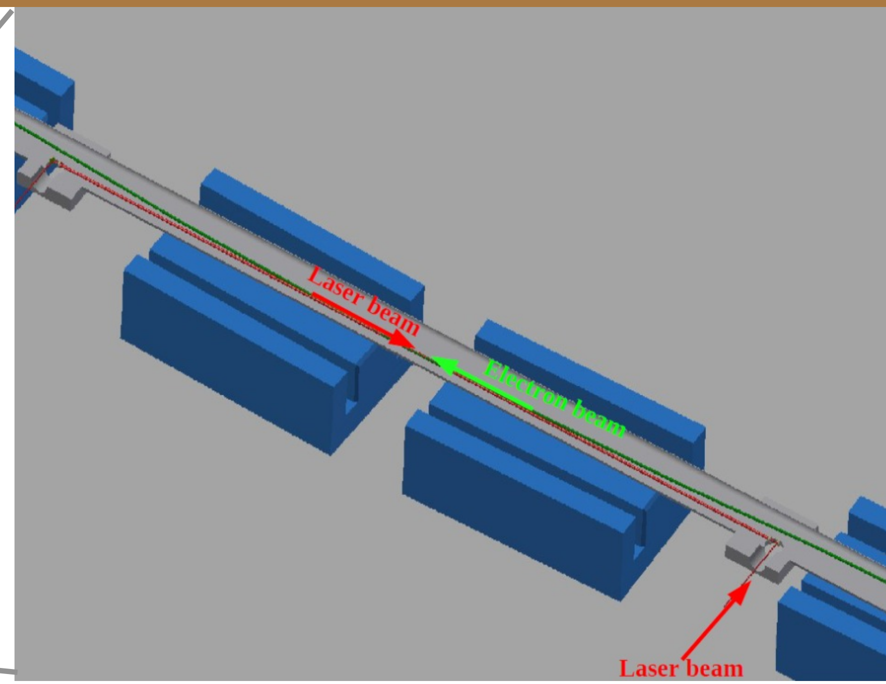
E_γ = 2 – 12 MeV

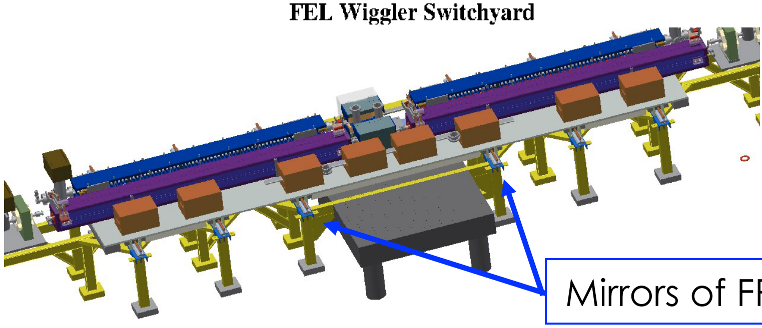
Total flux = $10^{11} – 10^{12}$ γ/s

Polarization: linear or circular (rapid switch)

Energy resolution (FWHM) < 0.5%







HIγS: Summary of Upgrades

Starting Year	Amount	Description
2018	\$3.5 M	Upgrade electron injector system (\$2.5M) New helical FEL wigglers (\$1.0M)?
2019	\$1.0 M	π^0 detector, scint. pol. hydogen target, and equipment for Compton-scattering program
2021	\$1.5 M	HIγS2 upgrade (optical cavity pumped by external laser)
2021	\$0.6 M	Target-room equipment for hadronic parity violation experiment

HIγS: Upgrades for LE QCD Program

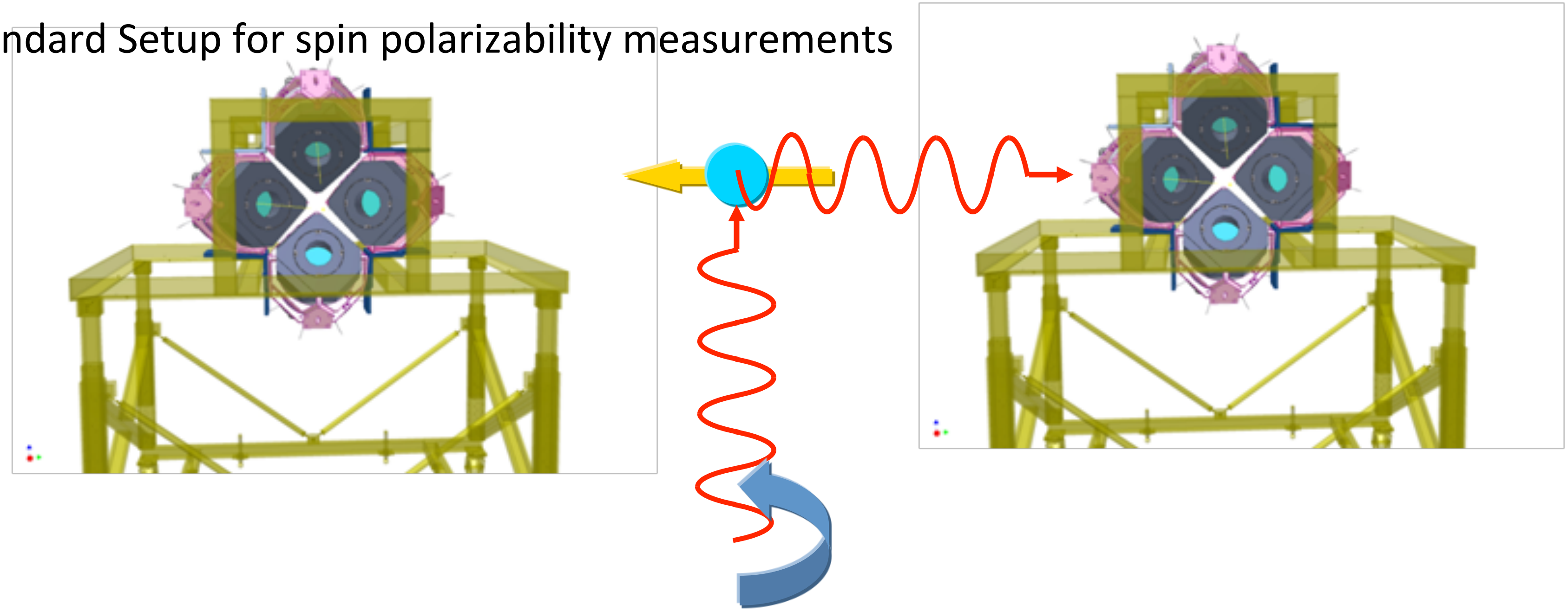
Approx. Timeline	Research	Equipment	γ-ray beam
Sep 2014 – Jun 2016	GDH on ^2H (part 1)	HIFROST pol. target	3.5 – 18 MeV, circ. pol.
Dec 2014 – Jun 2017	β_n (deuteron)	LD target	60 – 100 MeV, circ. pol.
Dec 2015 – Dec 2017	α_p, β_p (proton)	LH target	80 MeV, lin. pol. (rotate)
Jan 2018 -	Proton spin pol.	St-HIFROST	>110 MeV, circ. pol.
Beyond 2020	π^0 production	π^0 spectrometer	>158 MeV, circ. pol.
Beyond 2021	Hadronic Parity Violation	Parity violation expt.	HIGS2

- Can be carried with current capabilities and planned enhancements
- Require accelerator upgrades and new target room equipment

Extra Slides

Compton-scattering: Spin polarizabilities

Standard Setup for spin polarizability measurements



- photon helicity

$$\Sigma_{2x}^{+} = \frac{1}{P_B P_T} \frac{N_R^+ - N_L^+}{N_R^+ + N_L^+}$$

$$\Sigma_{2x}^{-} = \frac{1}{P_B P_T} \frac{N_L^- - N_R^-}{N_L^- + N_R^-}$$

$$\Sigma_{2x} \cong \frac{1}{2}\left(\Sigma_{2x}^{+} + \Sigma_{2x}^{-}\right)$$

Assuming HINDA left-right acceptance matching at the level of 10%, the resulting error in Σ_{2x} is at the level of 0.001

Recent accomplishments and plans for GDH on ^{3}He

Low-energy measurements at HIγS:

$$\int_{\nu_{thr}}^{\infty} GDH_{^3He} \rightarrow 496\,\mu b$$

$$\parallel$$

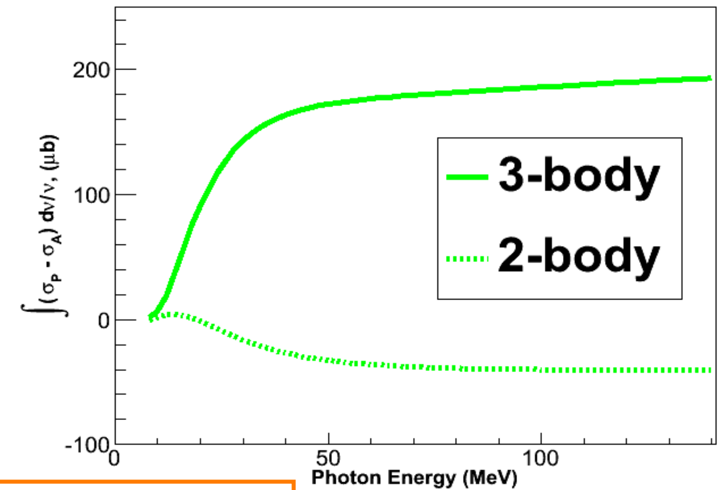
$$\int_{\nu_{thr}}^{\nu_\pi} GDH_{^3He} \rightarrow 217 \pm 39\,\mu b$$?? HIγS @ DUKE

$$+$$

$$\int_{\nu_\pi}^{2-3GeV} GDH_{^3He} \rightarrow \approx 247 \pm 38\,\mu b$$

$$+$$

$$\int_{2-3GeV}^{\infty} GDH_{^3He} \rightarrow \approx 31.9 \pm 9.6\,\mu b$$



Extrapolated from low Q^2 ^{3}He GDH (E94-010) measurement @ JLab, **(E97-110 much lower Q^2)**

Q^2 (GeV^2)	I_{GDH} (μb)	Statistical (μb)	Systematic (μb)
0.10	187.50	5.23	28.43
0.26	109.92	2.04	13.77
0.42	53.51	1.21	5.48
0.58	31.68	0.74	3.72
0.74	18.27	0.64	2.42
0.90	10.47	0.46	1.52

$$\int_{2-3GeV}^{\infty} GDH_{^3He} = P_n \times \int_{2-3GeV}^{\infty} GDH_n + 2 \times P_p \times \int_{2-3GeV}^{\infty} GDH_p$$
$$= 0.87 \times 35 + 2 \times (-0.027) \times (-26)$$

M. Amarian, PRL 89, 242301(2002) J.L. Friar et al. PRC 42, 2310 (1990) N. Bianchi, et al. PLB 450, 439 (1999)