Compton Scattering at HIGS:
from Giant Resonances to Spin Polarizabilities

Compton@HIGS Collaboration

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  - Mark Sikora
- Duke University/TUNL
  - Luke Myers
  - Henry Weller
  - Mohammad Ahmed
  - Jonathan Mueller
  - Seth Henshaw
- University of Kentucky
  - Mike Kovash

Outline

- **What (and where) is HIGS?**
- **What have we done so far at HIGS?**
  - polarized Compton scattering study of IVGQR
  - elastic Compton scattering on ^{6}Li
- **What are we planning to do at HIGS?**
  - elastic Compton scattering on deuterium
    - neutron polarizability
  - polarized Compton scattering on proton
    - proton electric polarizability
  - double-polarized Compton scattering on proton
    - proton spin polarizability
  - double-polarized Compton scattering on ^{3}He
    - neutron spin polarizability

Background Information on HIGS

United States

North Carolina

Duke University

TUNL

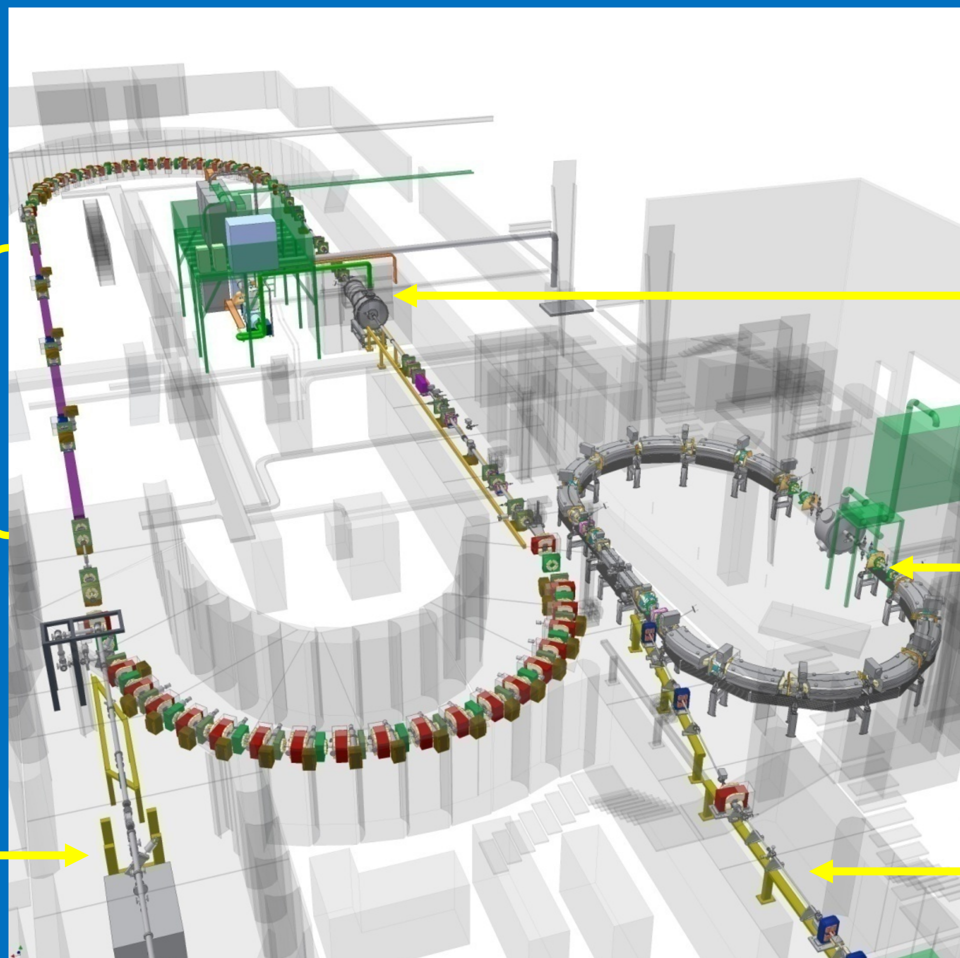
Triangle Universities Nuclear Laboratory

Duke Free-Electron Laser Lab

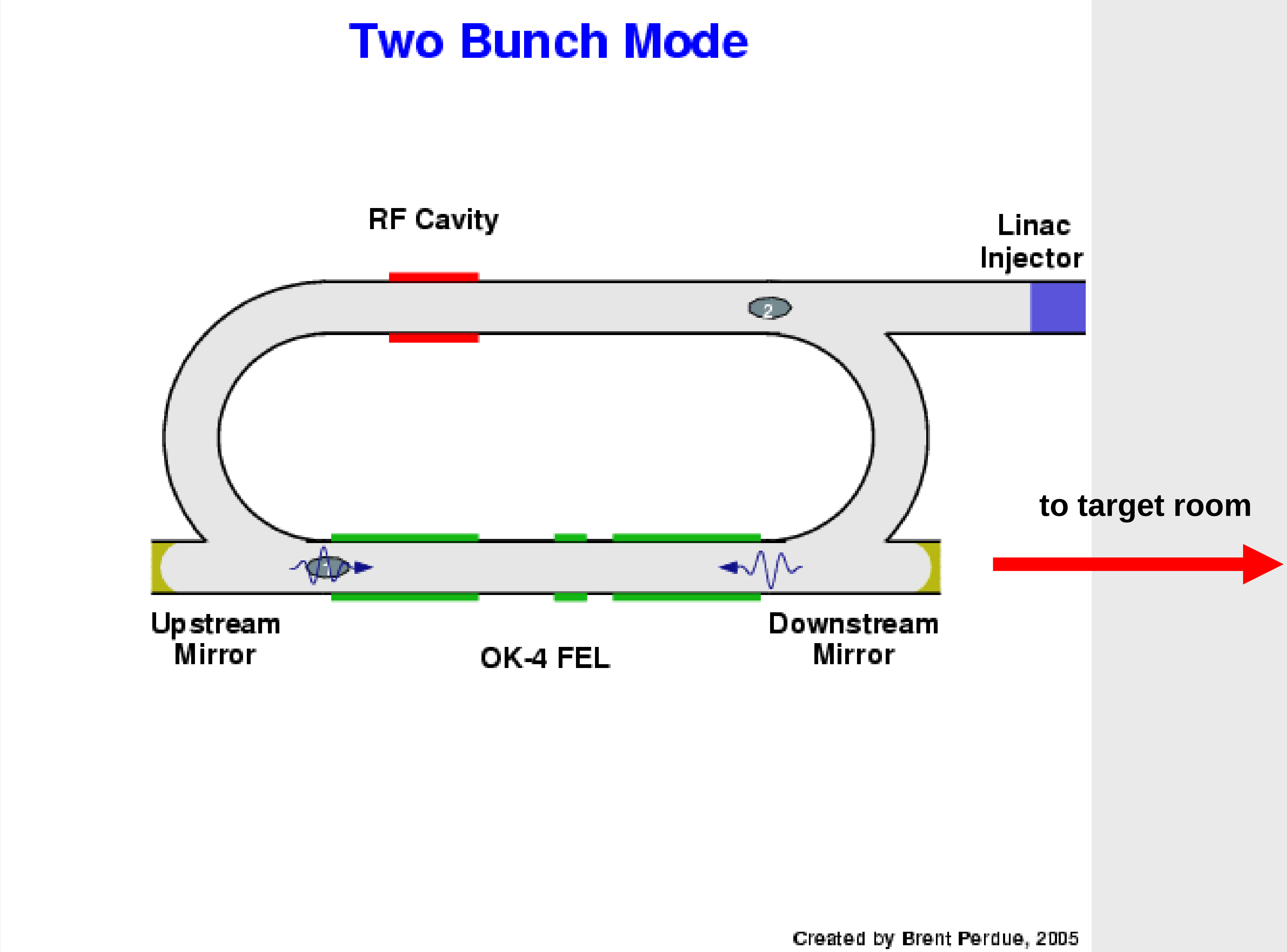
Storage Ring and Booster

Circularly and linearly polarized γ rays, nearly **monoenergetic** (E_{γ} = 2–90 MeV)

Utilizes Compton backscattering to generate γ rays



HIGS Photon Beam



HIGS Photon Beam

- monoenergetic photons up to ~90 MeV
  - energy will reach ~160 MeV by 2015
- 100% linear or circular polarization
- high photon beam intensity
  - ~10^7 Hz at 20-60 MeV
  - ~10^8 Hz below 15 MeV
- low beam-related background
  - no bremsstrahlung typical of tagged photons

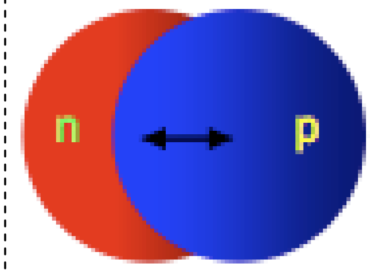
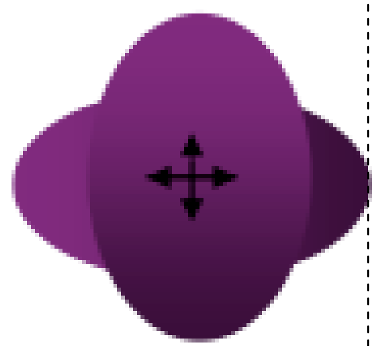
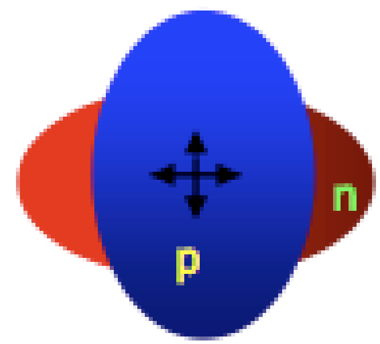
Polarized Compton Scattering

for IVGQR Systematics

Giant Resonances

- collective nuclear excitations
- GDR and ISGQR well known
- **IVGQR poorly known**
- photon as **isovector** probe

- use pol. photons for IVGQR
- map systematics vs. A
- nuclear symmetry energy
  - neutron star eqn. of state

	ΔT = 0	ΔT = 1
L = 1		
L = 2		

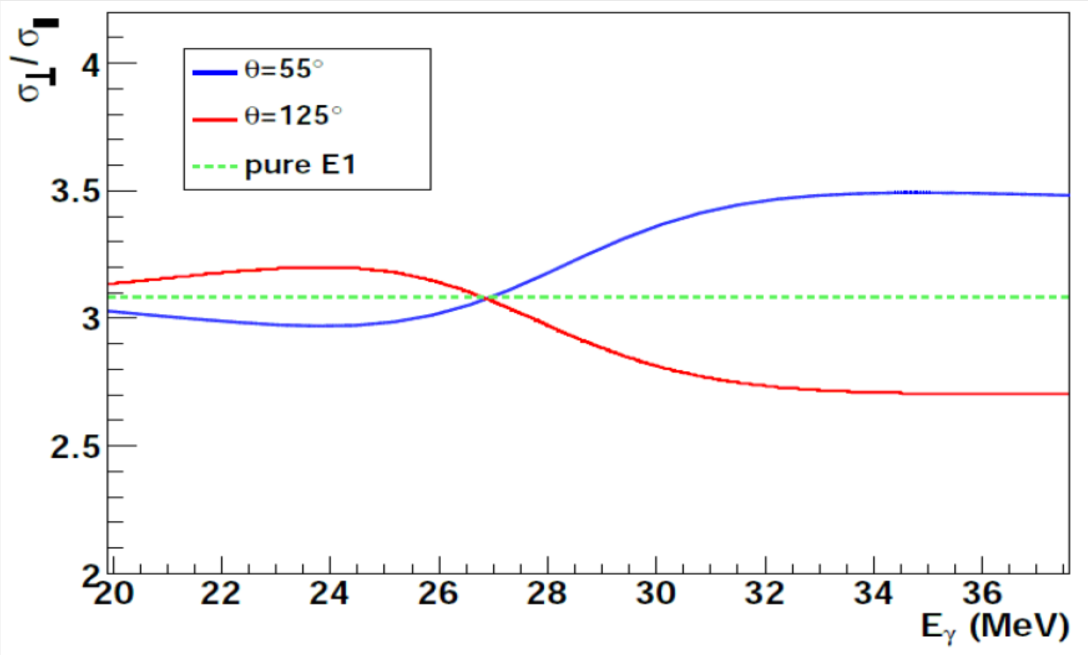
- ratio of H/V scattered photons is sensitive to E1/E2 interference
- sign difference in interference term at forward/backward angles

Photon Asymmetry in IVGQR

$$\frac{\sigma_{\parallel}}{\sigma_{\perp}} = \cos^2\theta + \frac{2|C^{E2}|}{|C^{E1}|}\cos(\phi_{E2}-\phi_{E1})\left[\cos^3\theta - \cos\theta\right]$$

pure E1

E1 / E2 interference



$$\cos(\phi_{E2}-\phi_{E1})\begin{cases} < 0, & E < E_{res} \\ > 0, & E > E_{res} \end{cases}$$

θ	$\cos^2\theta$	$\cos^3\theta - \cos\theta$
125°	0.33	0.38
55°	0.33	-0.38

Phenomenological Formalism

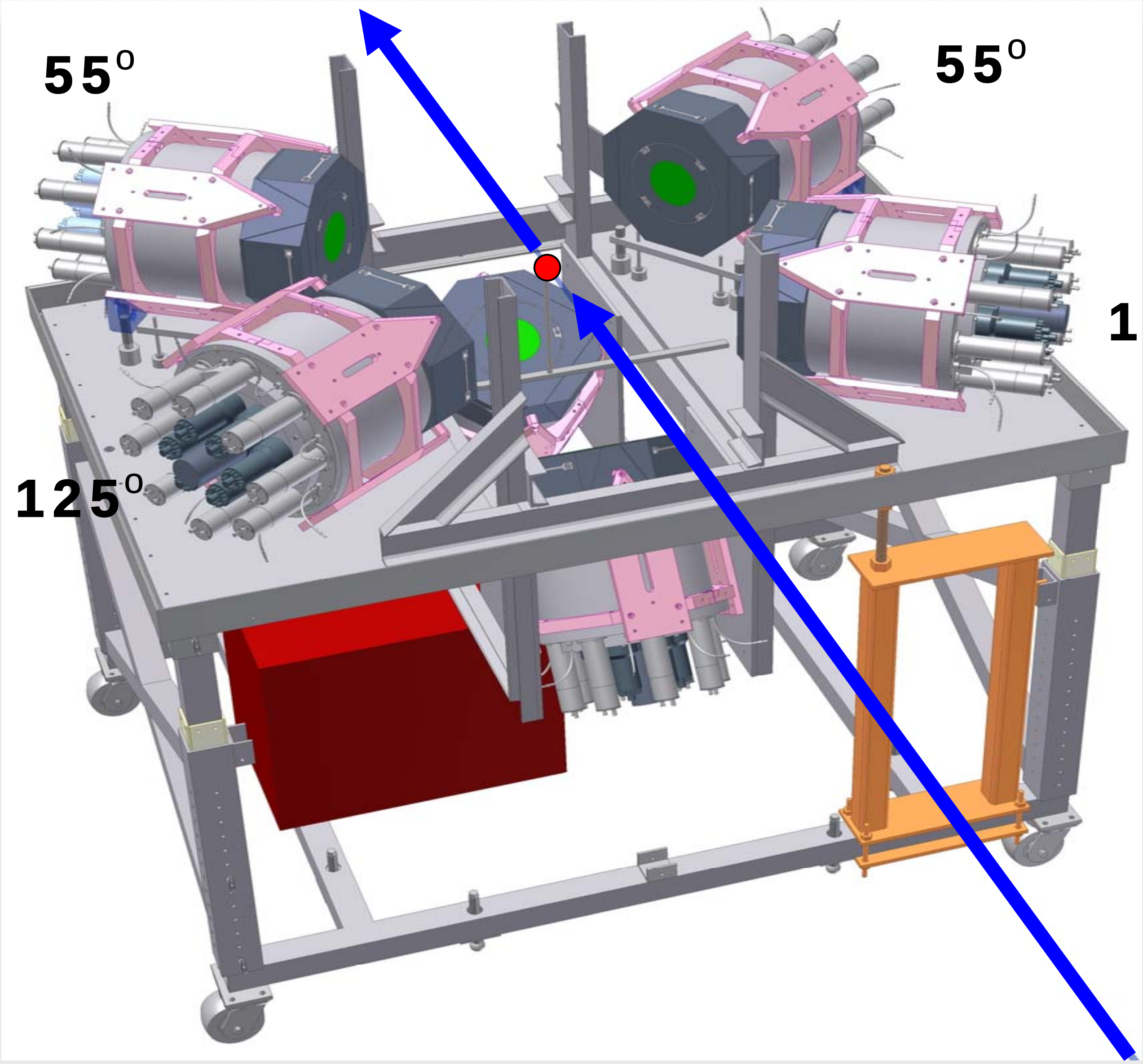
$$R(E,\theta) = R^{GR}(E,\theta) + R^{QD}(E,\theta) + R_1^{SG}(E,\theta) + R_2^{SG}(E,\theta)$$

$$\begin{cases} R^{GR}(E,\theta) = f_{E1}(E)g_{E1}(\theta) + f_{E2}(E)g_{E2}(\theta) + \dfrac{NZ}{A} r_0 [1+\kappa_{GR}] g_{E1}(\theta) \\ R^{QD}(E,\theta) = \left[f_{QD}(E) + \dfrac{NZ}{A} r_0 \kappa_{QD} \right] F_2(q) g_{E1}(\theta) \end{cases}$$

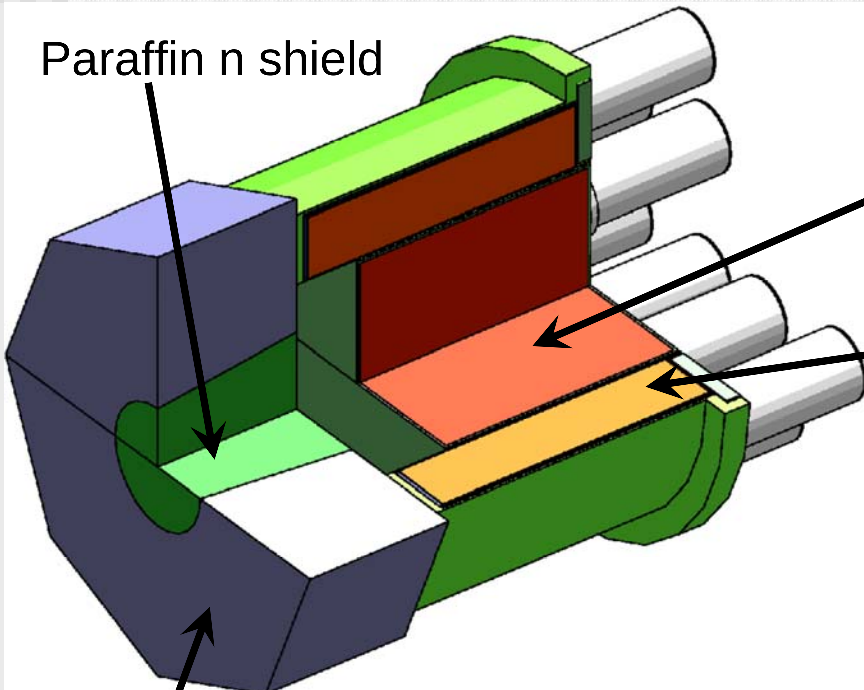
$$\begin{cases} R_1^{SG}(E,\theta) = -F_1(q)\left\{ \left[Zr_0 - \left(\dfrac{E}{\hbar c}\right)^2 A\overline{\alpha} \right] g_{E1}(\theta) - \left[\left(\dfrac{E}{\hbar c}\right)^2 A\overline{\beta} \right] g_{M1}(\theta) + O(E^4) \right\} \\ R_2^{SG}(E,\theta) = -F_2(q) \dfrac{NZ}{A} r_0 (\kappa_{GR} + \kappa_{QD}) \end{cases}$$

HINDA Array

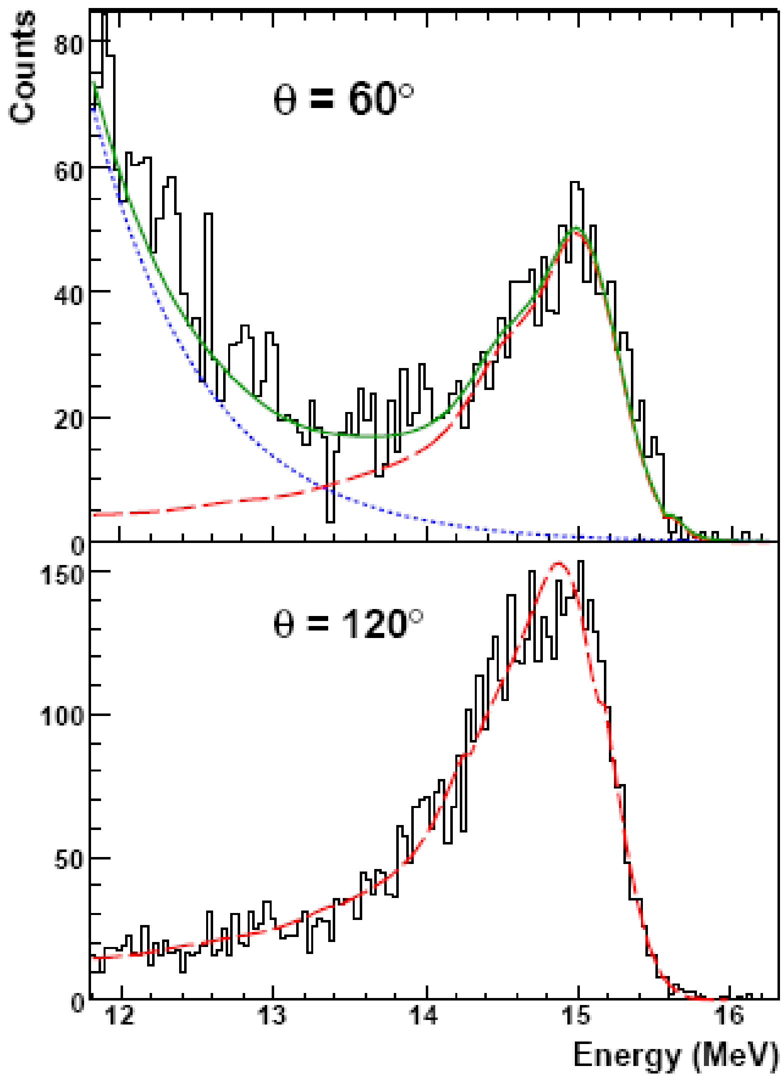
HIGS NaI Detector Array

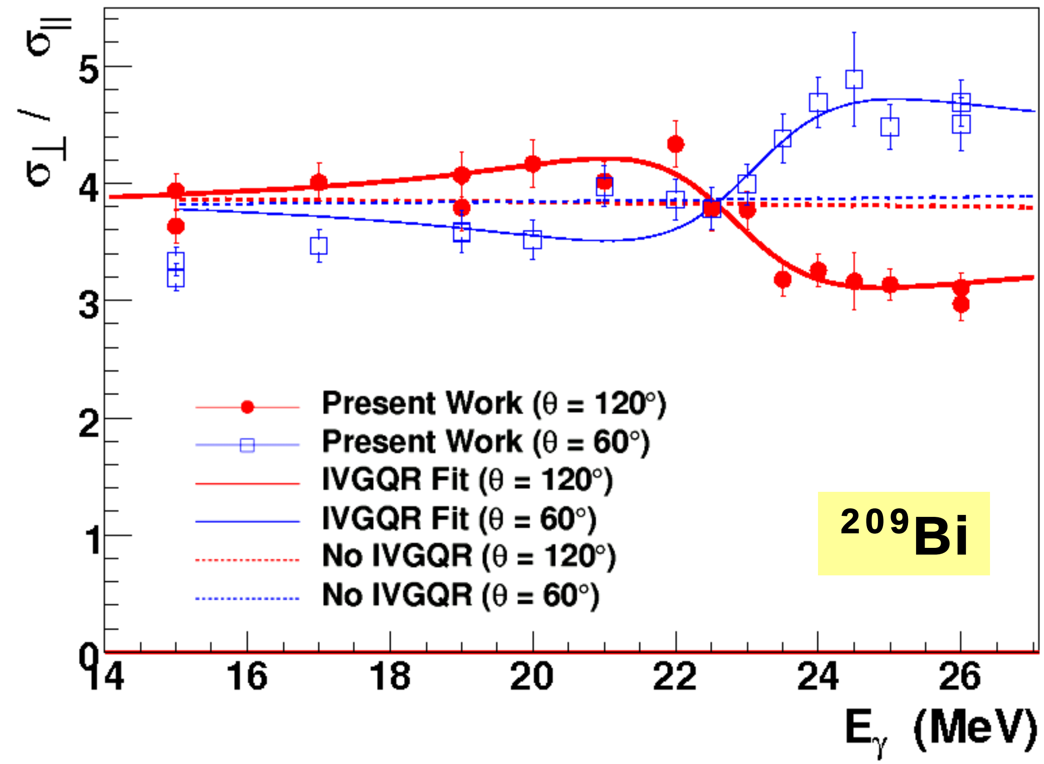


NaI Detectors



Results for ^{209}Bi





E_{res} (MeV)	Width (MeV)	Strength (IVQEWSRs)
$23.0^{\pm 0.13(stat)}_{\pm 0.18(sys)}$	$3.9^{\pm 0.7(stat)}_{\pm 0.6(sys)}$	$0.56^{\pm 0.04(stat)}_{\pm 0.05(sys)}$

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New Method for Precise Determination of the Isovector Giant Quadrupole Resonances in Nuclei

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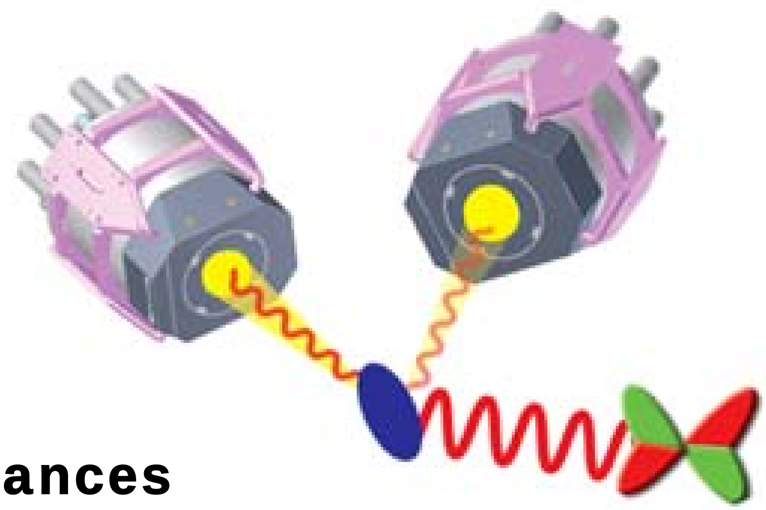
Physics spotlighting exceptional research

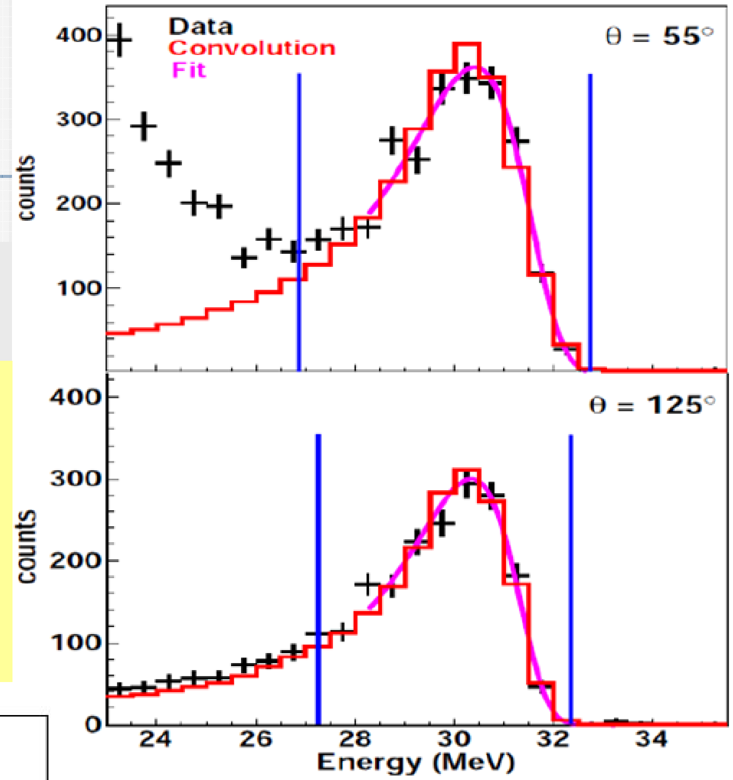


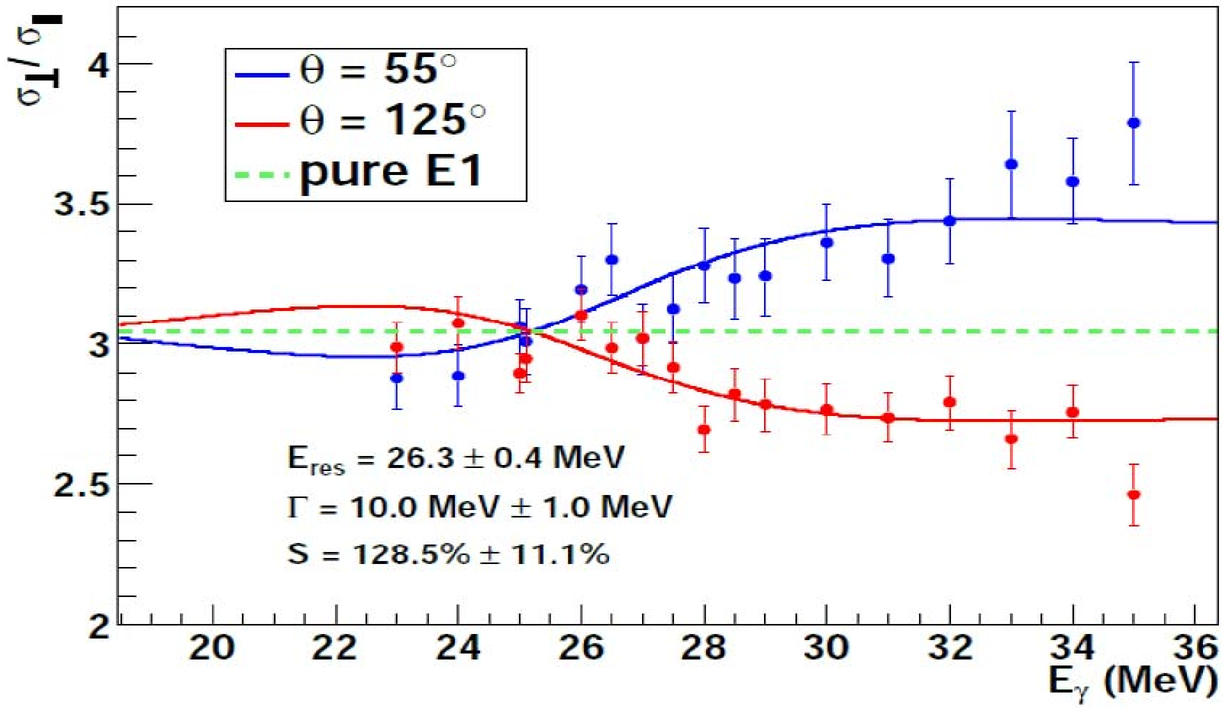
Synopsis: Ringing Nuclear Resonances

Courtesy Seth Henshaw, Duke University

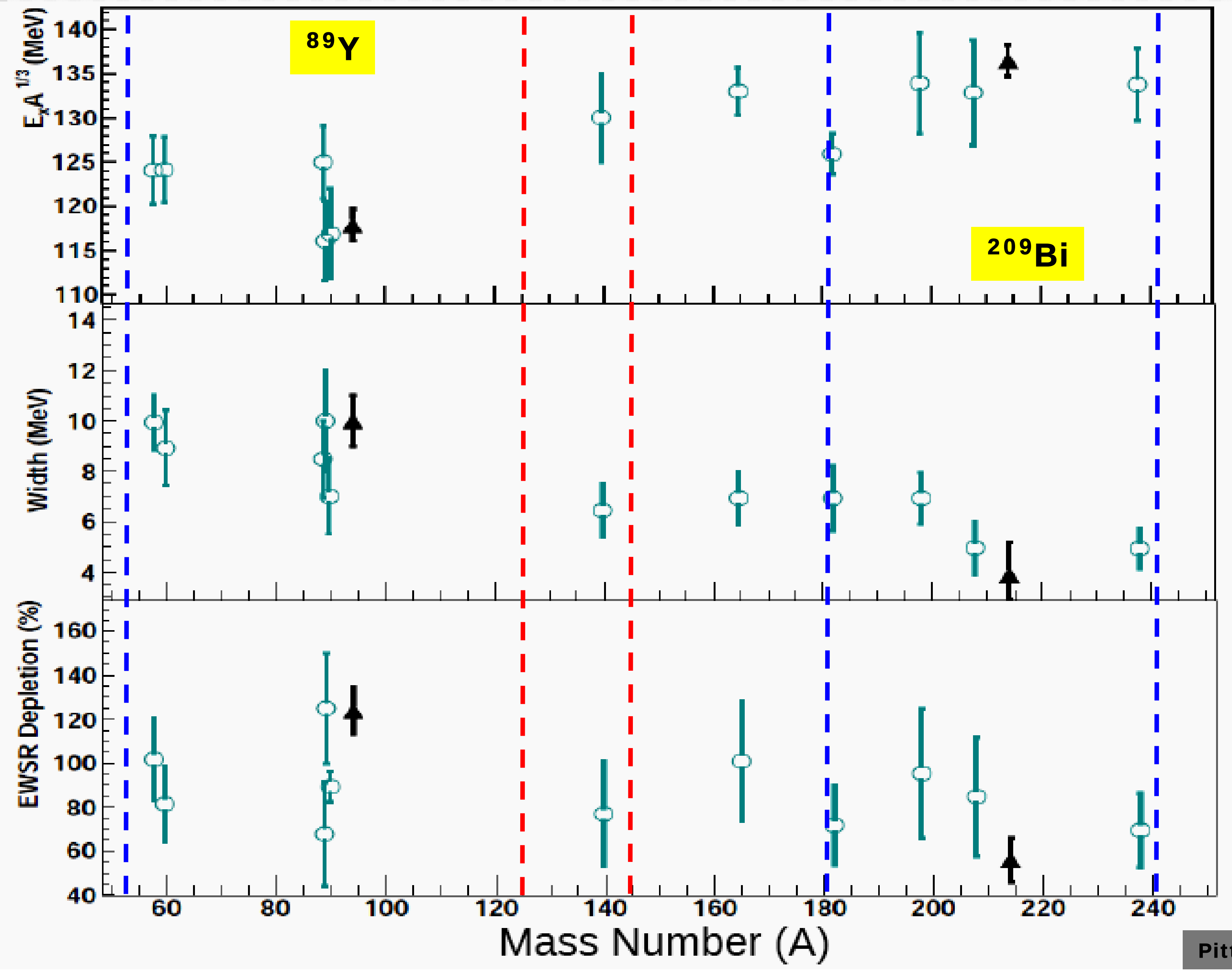
Results for ^{89}Y

- extend measurements to ^{89}Y
- measure ^{124}Sn early next year
- lease ^{142}Nd target from ORNL for $15k
- other tgts include A = 51, 181, 238





IVGQR Systematics



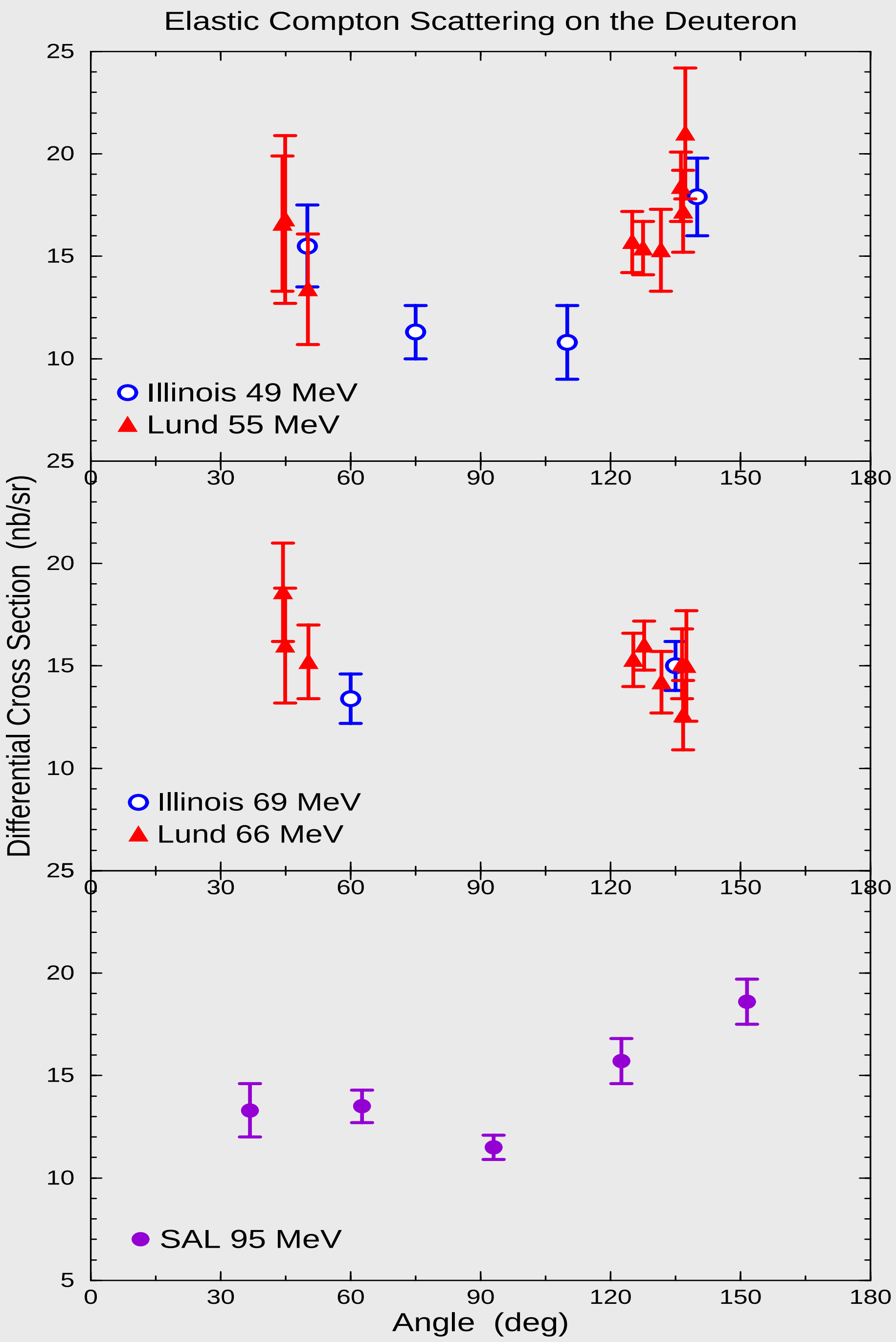
Pitthan 1980

Compton Scattering on ^6Li

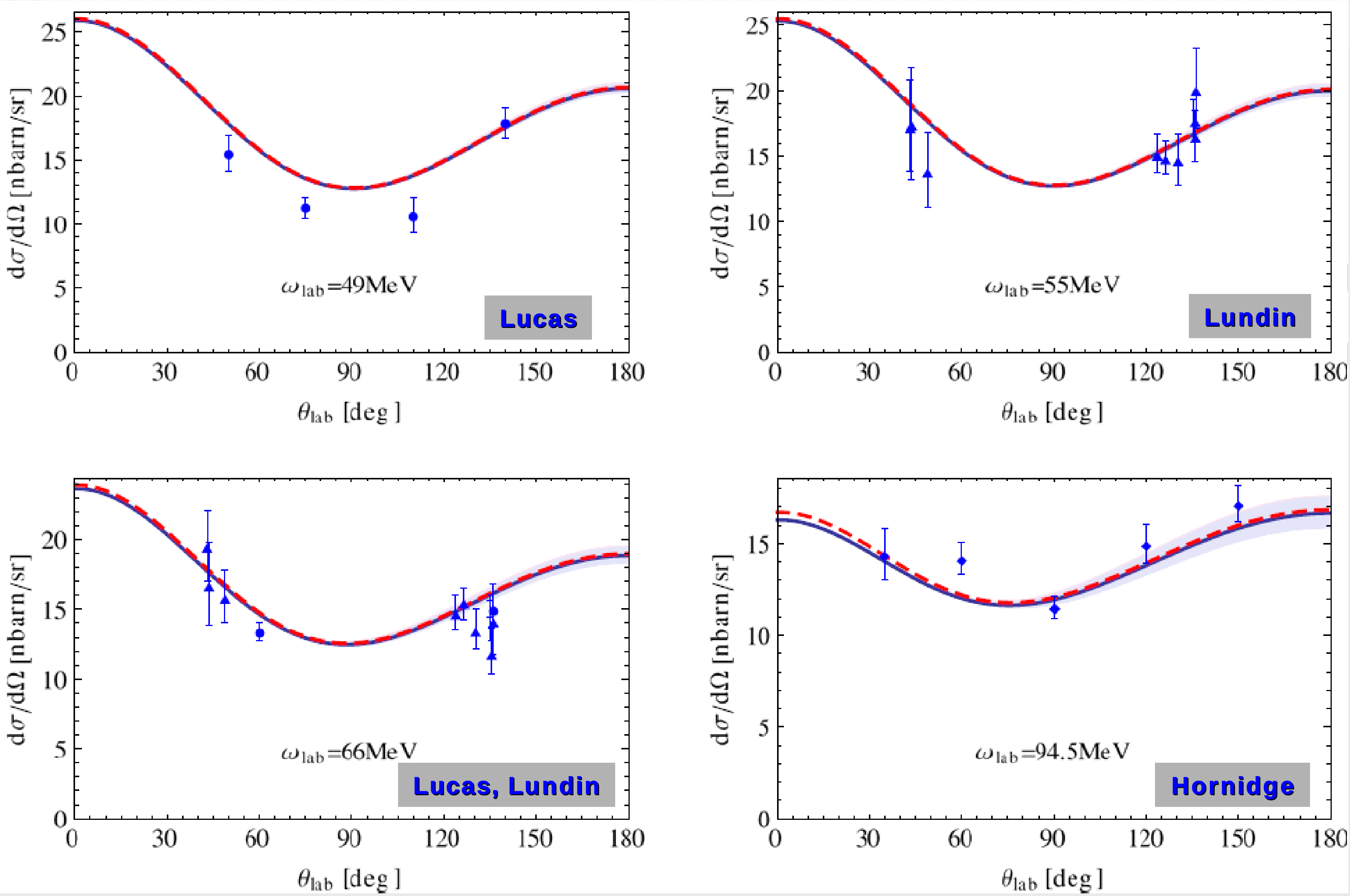
World Data Set

D(γ,γ)D

- **Lucas – Illinois (1994)**
  E_γ = 49, 69 MeV
- **Hornidge – SAL (2000)**
  E_γ = 85-105 MeV
- **Lundin – Lund (2003)**
  E_γ = 55, 66 MeV
- **Myers and Shonyozov (coming 2012)**
  Illinois, GW, UK, Lund
  E_γ = 58-115 MeV



EFT Fits to Deuteron Data



Griesshammer 2012

Summary of Neutron Results

- Neutron scattering
  - Schmiedmayer (91)

$$\alpha_n = 12.6 \pm 1.5(\text{stat}) \pm 2.0(\text{syst})$$

- Quasi-free Compton scattering
  - Kossert (03)

$$\alpha_n = 12.5 \pm 1.8(\text{stat})\ {}^{+1.1}_{-0.6}(\text{syst}) \pm 1.1(\text{model})$$

$$\beta_n = 2.7 \mp 1.8(\text{stat})\ {}^{+0.6}_{-1.1}(\text{syst}) \mp 1.1(\text{model})$$

- Elastic Compton scattering
  - data from Lucas (94), Hornidge (00), Lundin (03)

$$\alpha_n = 11.6 \pm 1.5\ (\text{stat}) \pm 0.6\ (\text{Baldin})$$

$$\beta_n = 3.6 \mp 1.5\ (\text{stat}) \pm 0.6\ (\text{Baldin})$$

Hildebrandt 05

$$\alpha_n = 11.1 \pm 1.8\ (\text{stat}) \pm 0.4\ (\text{Baldin}) \pm 0.8\ (\text{theory})$$

$$\beta_n = 4.1 \mp 1.8\ (\text{stat}) \pm 0.4\ (\text{Baldin}) \pm (0.8\ (\text{theory})$$

Griesshammer 12

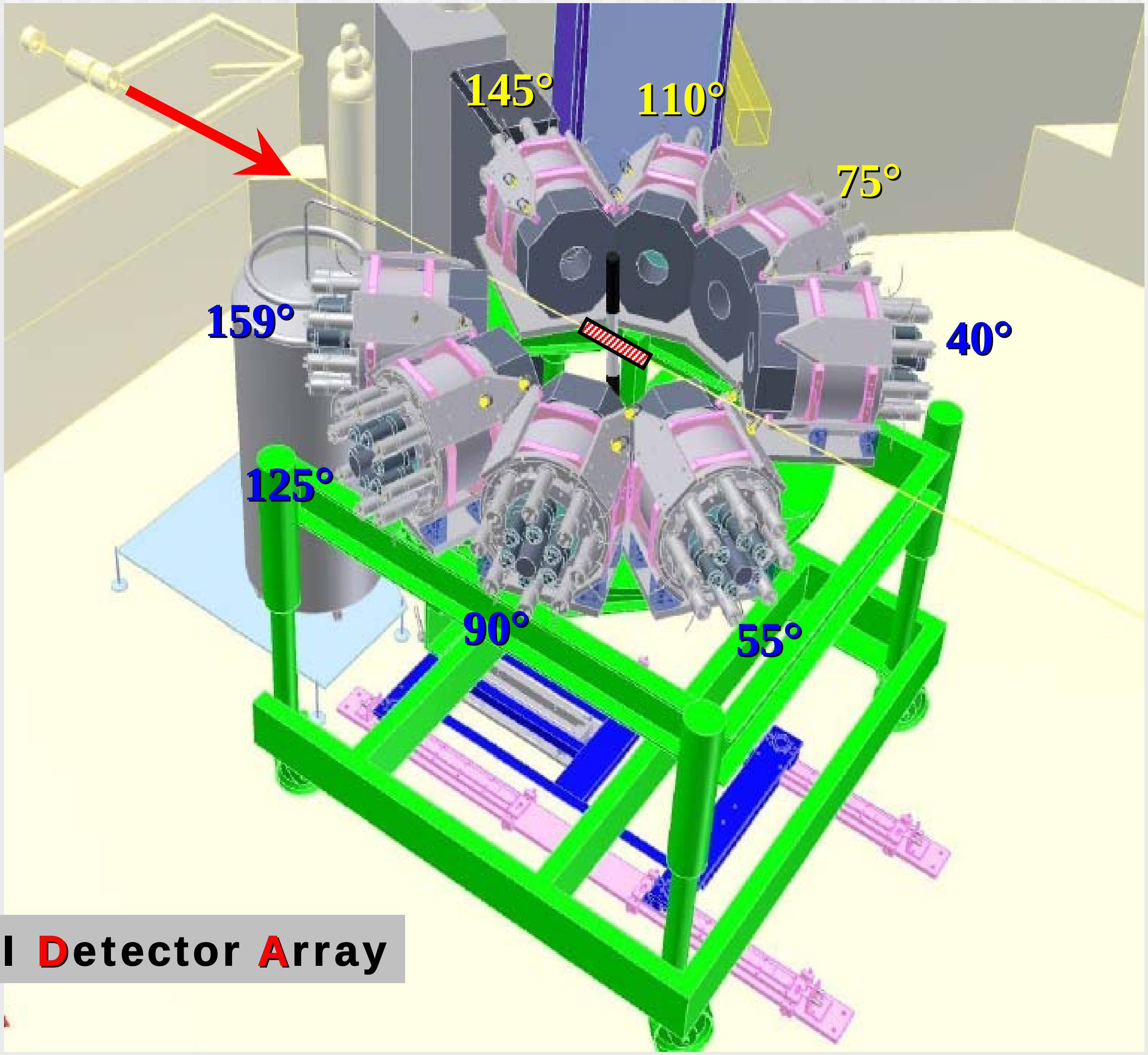
Nucleus	Energy (MeV)	Angles	Reference
D	49, 69	50°-140°	Lucas 1994
D	85-105	35°-150°	Hornidge 2000
D	55, 66	45°, 135°	Lundin 2003
D	60-115	60°, 90°, 120°, 150°	Myers, Shonyozov 2012
^{4}He	23-70	45°, 135°	Wells 1990
^{4}He	61	45°-150°	Proff 1999
^{12}C	19-52	45°, 90°, 135°	Wright 1985
^{12}C	58, 75	45°-135°	Hager 1995
^{12}C	85-105	35°-150°	Warkentin 2001
^{16}O	58, 75	45°-150°	Hager 1995
^{16}O	61	50°, 135°	Proff 1999
^{16}O	27-108	45°, 90°, 135°	Feldman 1996
^{40}Ca	19-52	45°, 90°, 135°	Wright 1985
^{40}Ca	58, 74	45°-150°	Proff 1999

Experiment on ^{6}Li at HIGS

- experiment motivation
  - exploit higher nuclear cross section to measure α and β
    - cross section scales as Z^2, so factor of 9x higher than ^{2}H
  - solid ^{6}Li target is simple
    - provided by Univ. of Saskatchewan
  - no previous Compton data on ^{6}Li exists (except Pugh 1957)

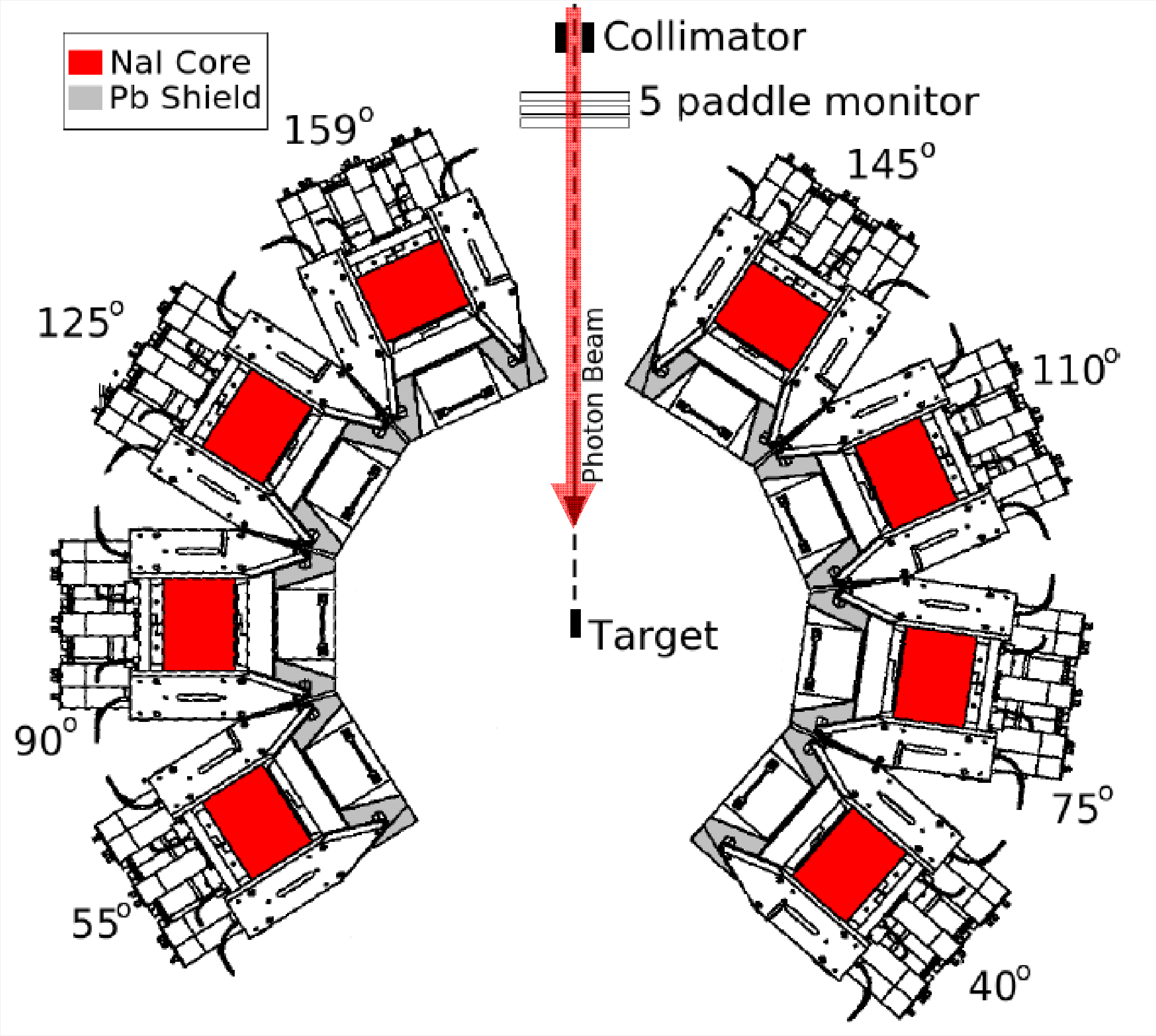
- energies: **E_γ = 60, 80 MeV**
- angles: **θ_γ = 40°-160°** ($\Delta\theta$ = 17°)
- target: solid **12.7 cm long ^{6}Li** cylinder (plus empty)
- detectors: **eight 10”×12” NaI’s** (HINDA array)
  - good photon energy resolution ($\Delta E_\gamma / E_\gamma$ < 5%)

HINDA Array



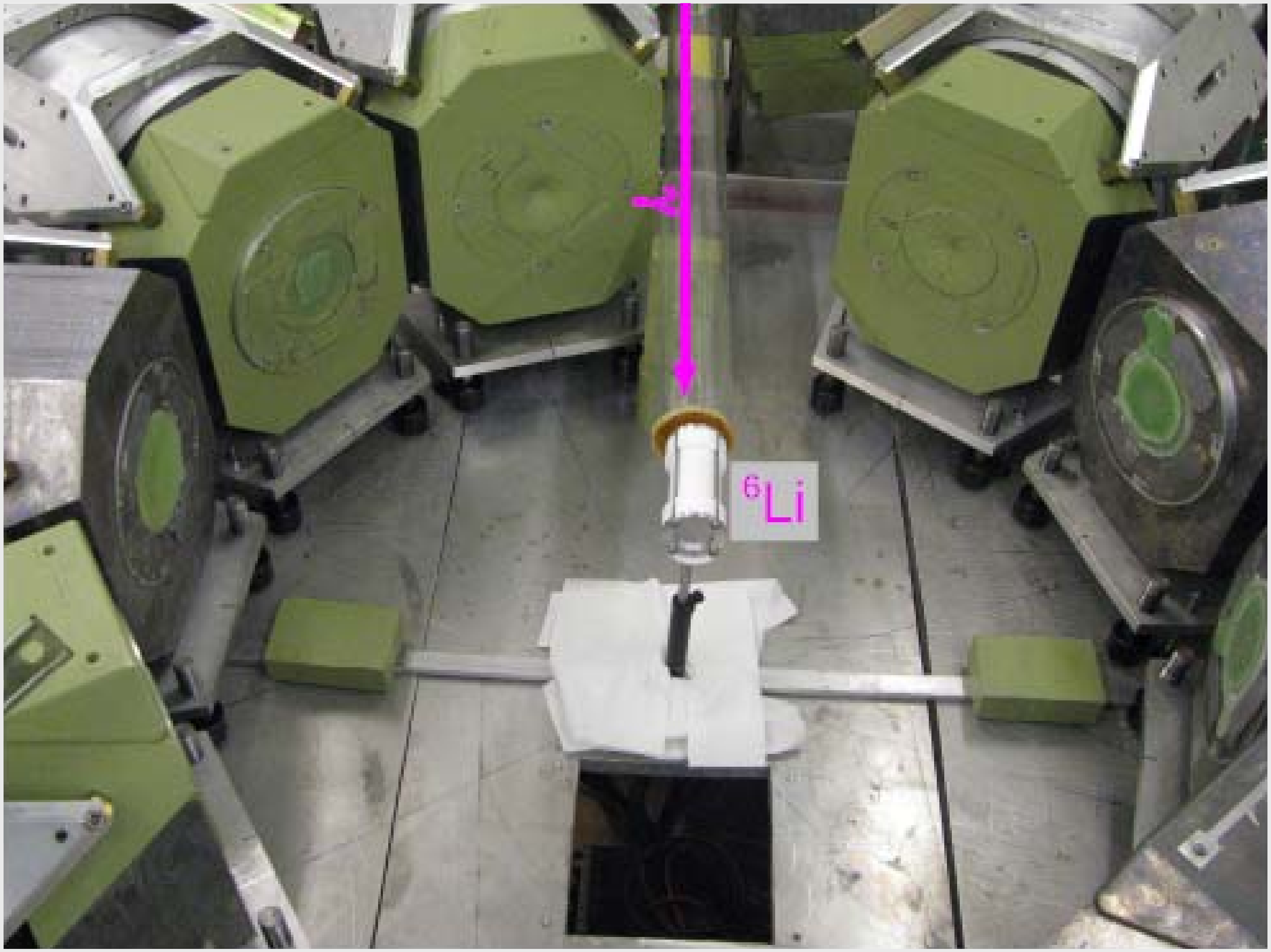
HIGS NaI Detector Array

HINDA Array



NaI Core
Pb Shield
Collimator
5 paddle monitor
Photon Beam
Target
159°
145°
125°
110°
90°
75°
55°
40°

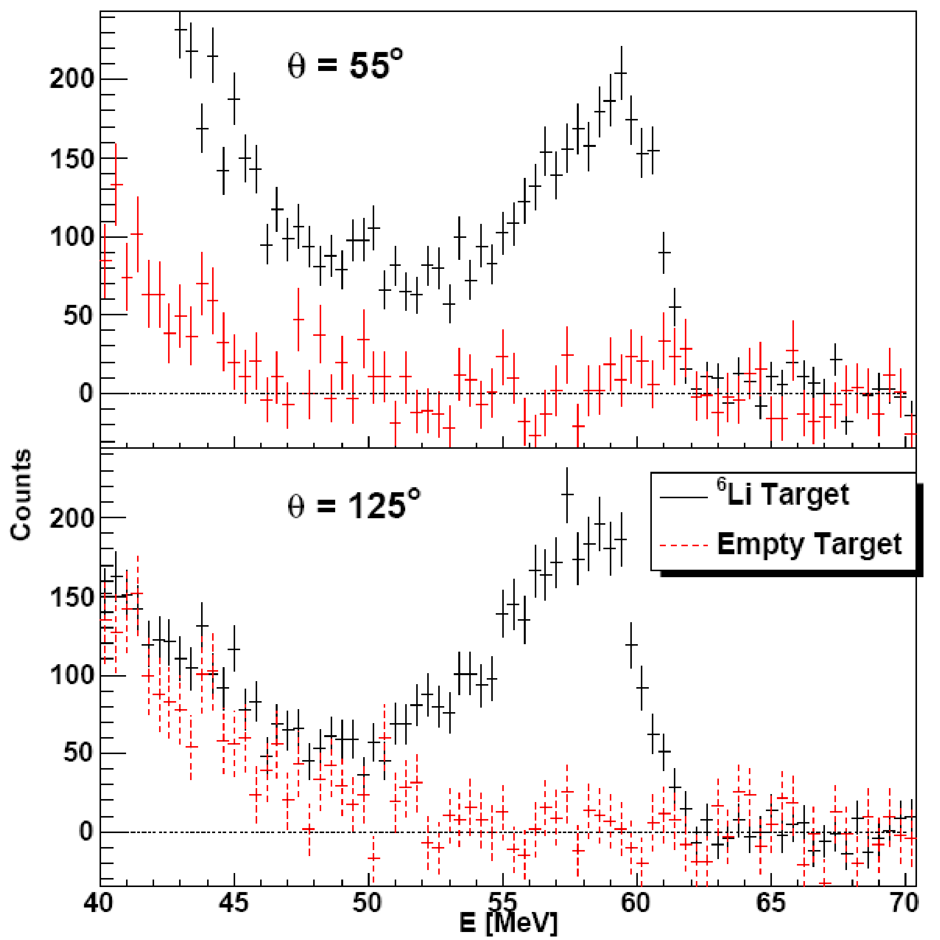
Experimental Setup

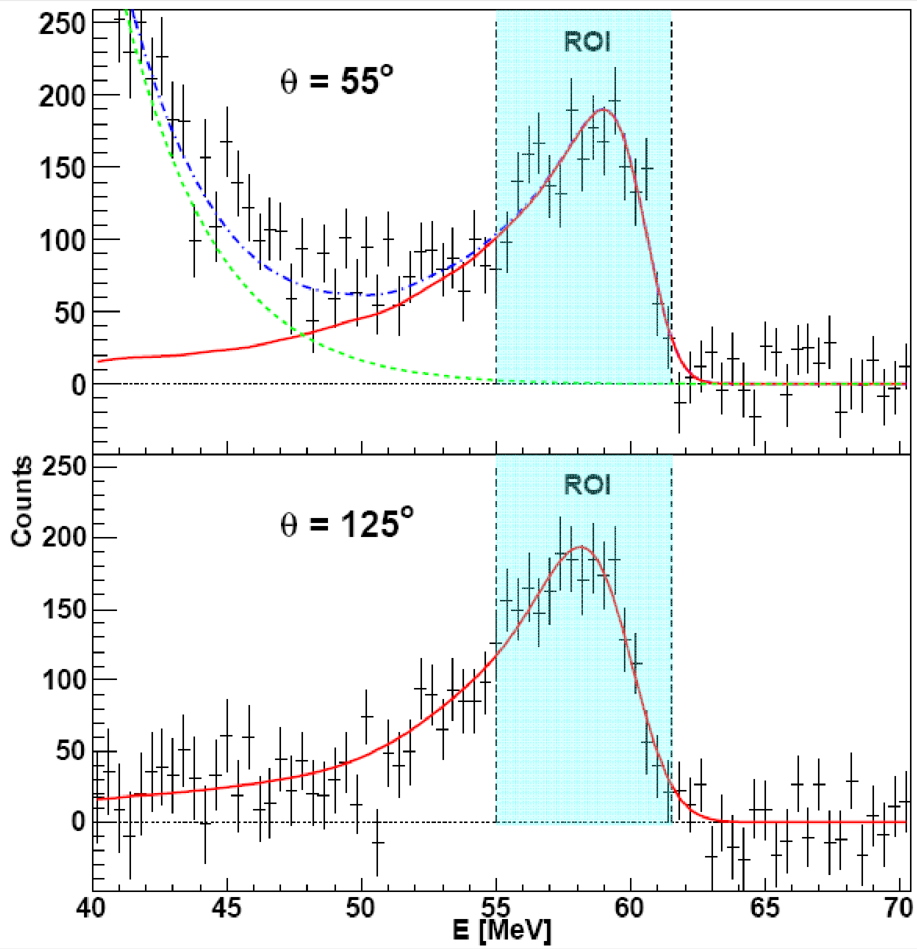


Sample Spectra

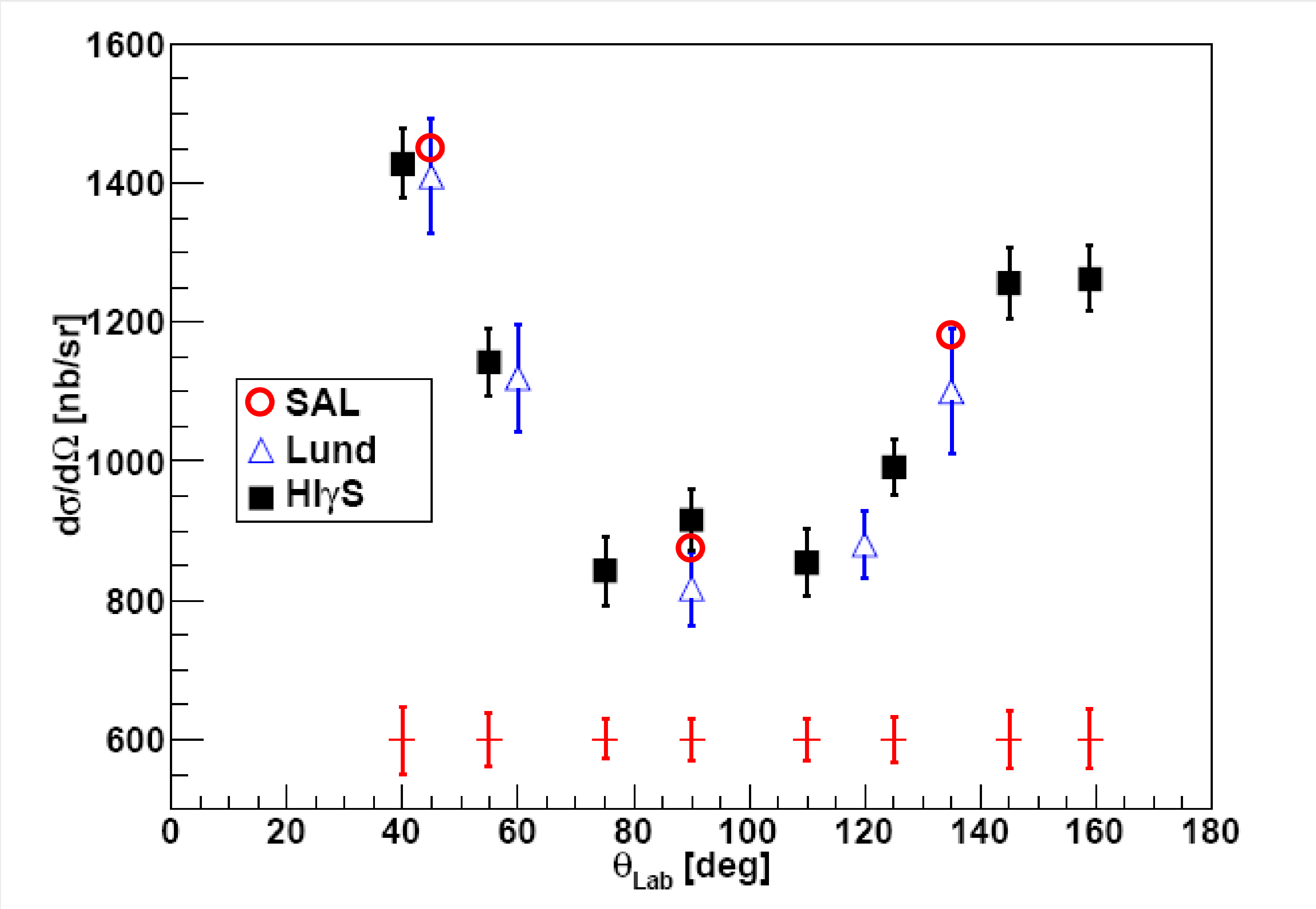
$^{6}Li(\gamma,\gamma)^{6}Li$

E_{γ} = 60 MeV



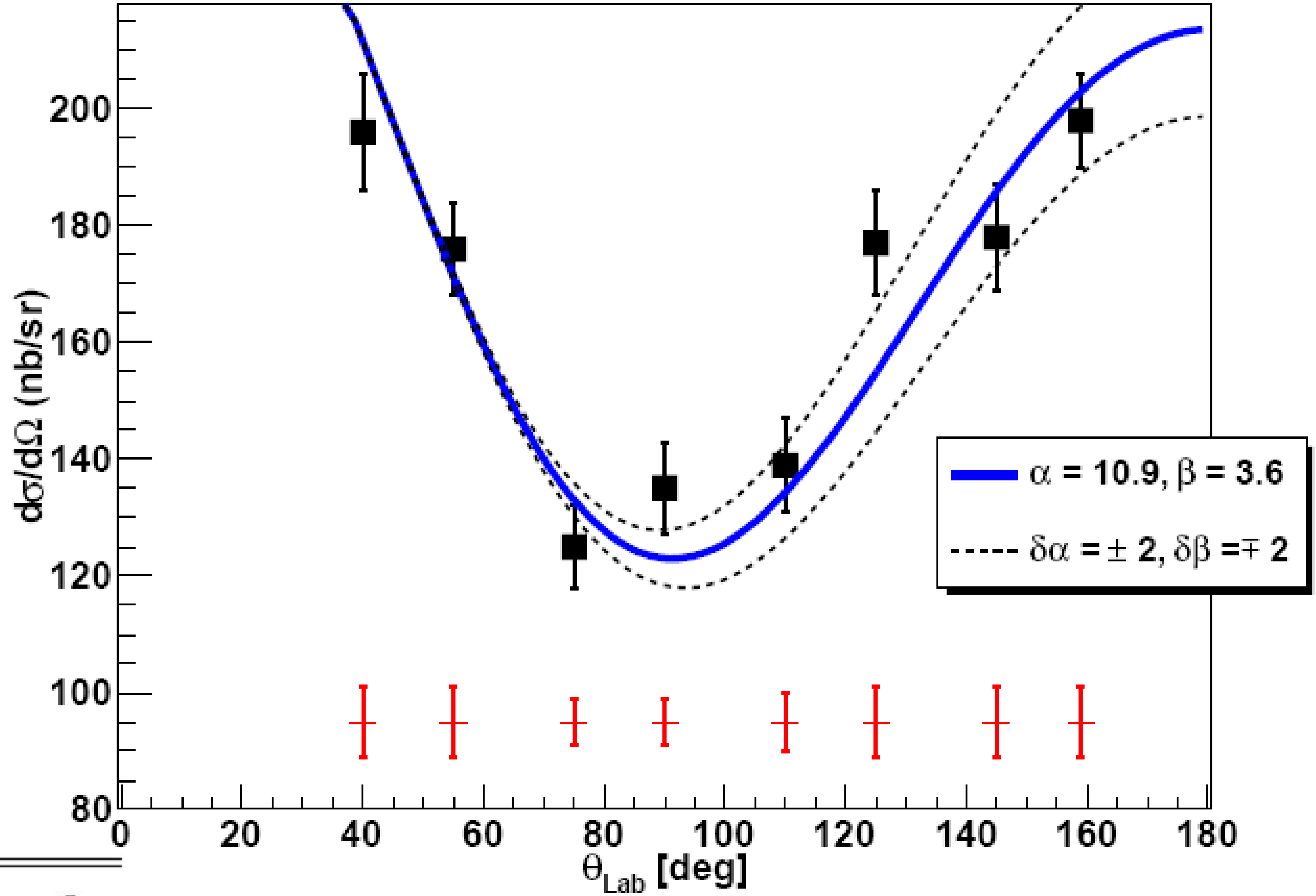


Cross Section for $^{16}O(\gamma,\gamma)^{16}O$



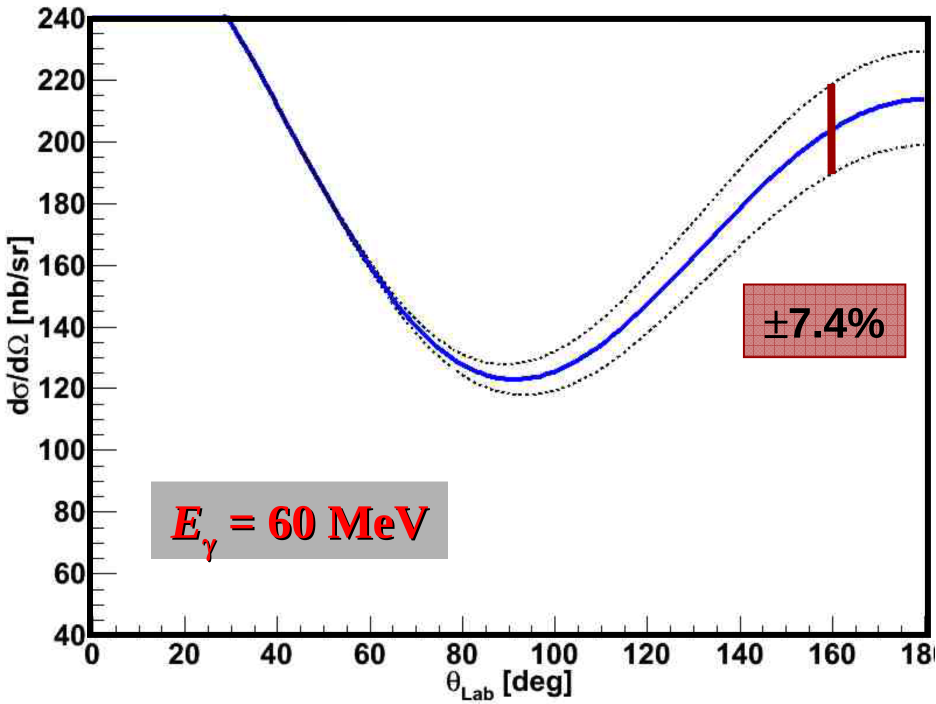
Cross Section for $^6Li(\gamma,\gamma)^6Li$

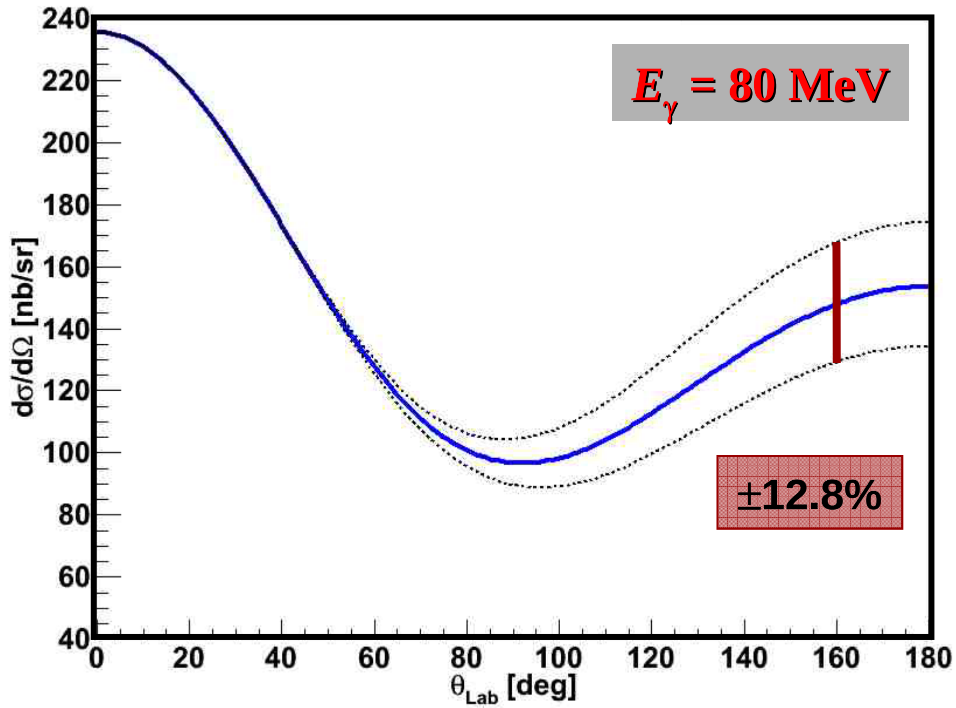
L. Myers *et al.*
Phys. Rev. C86 (2012)



Resonance	E_{res} (MeV)	Γ_{res} (MeV)	σ_{res} (mb)
$E1$	25.0	6.0	7.2
$E2$	34.0	8.0	0.14
QD	40.0	100	1.1

sum rule: $\alpha + \beta$ = 14.5



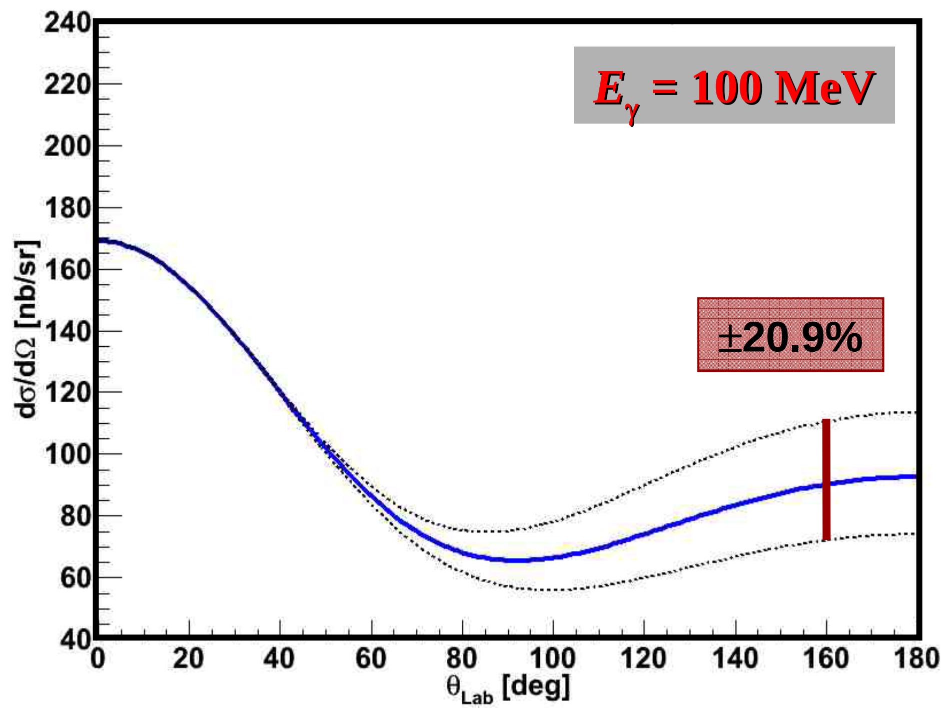


$(\alpha, \beta) = (10.9, 3.6)$

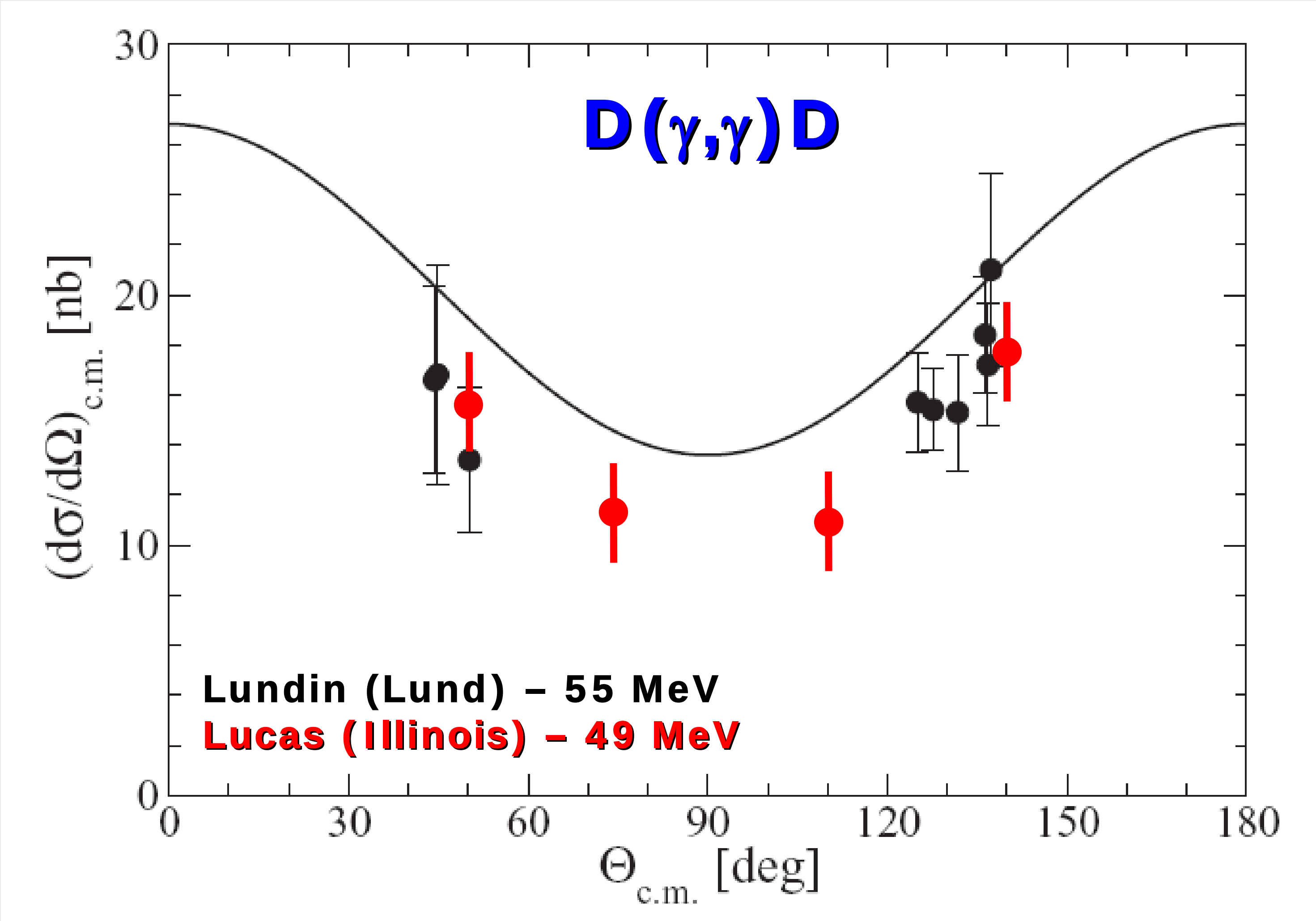
$\Delta\alpha = \pm 2$

$\Delta\beta = \mp 2$

sum rule: $\alpha + \beta = 14.5$



LIT Method for Compton Scattering

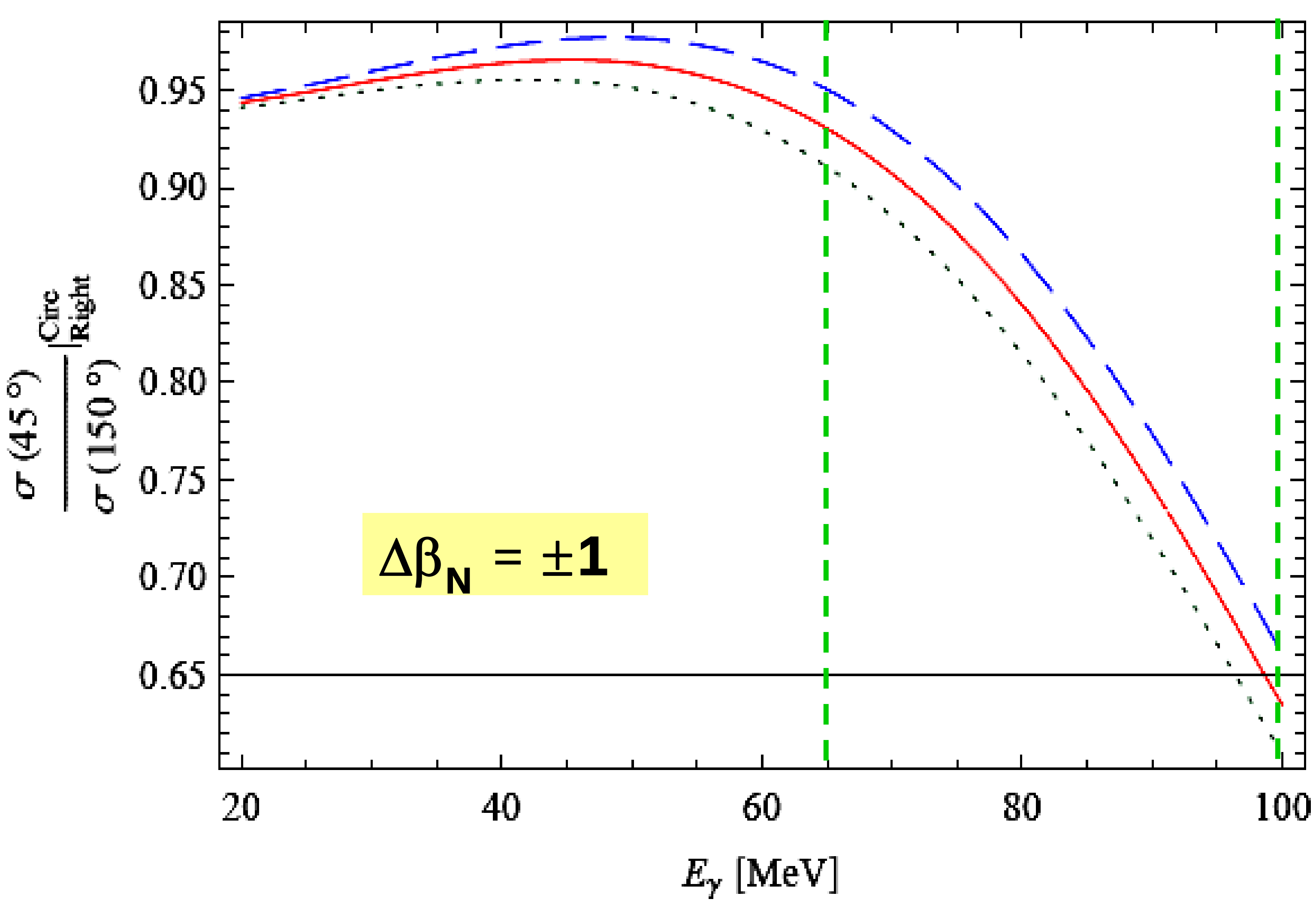


Compton Scattering on the Proton and Deuteron

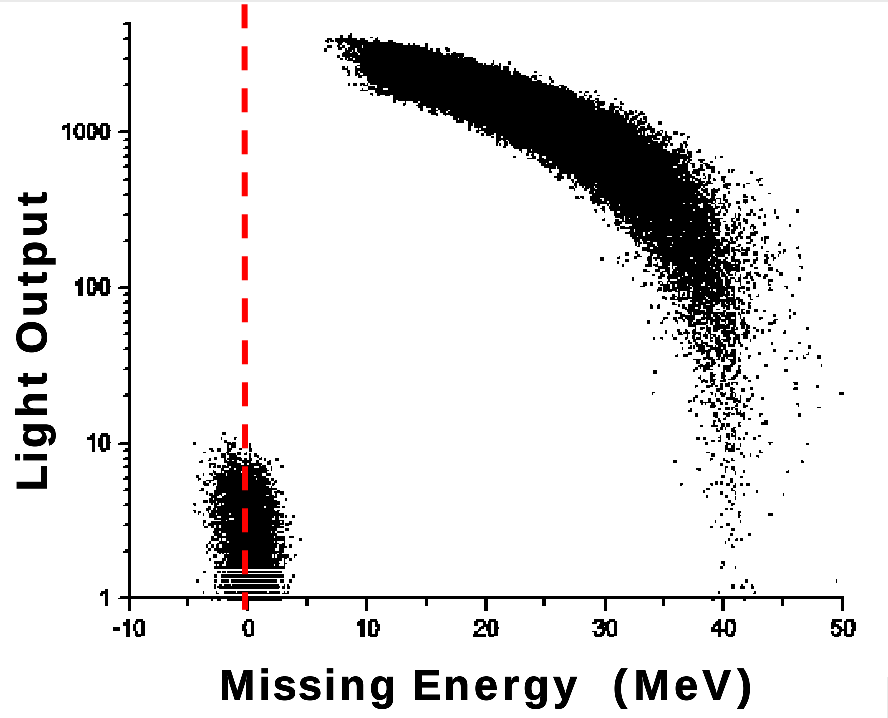
Cross-Section Ratios for Deuterium

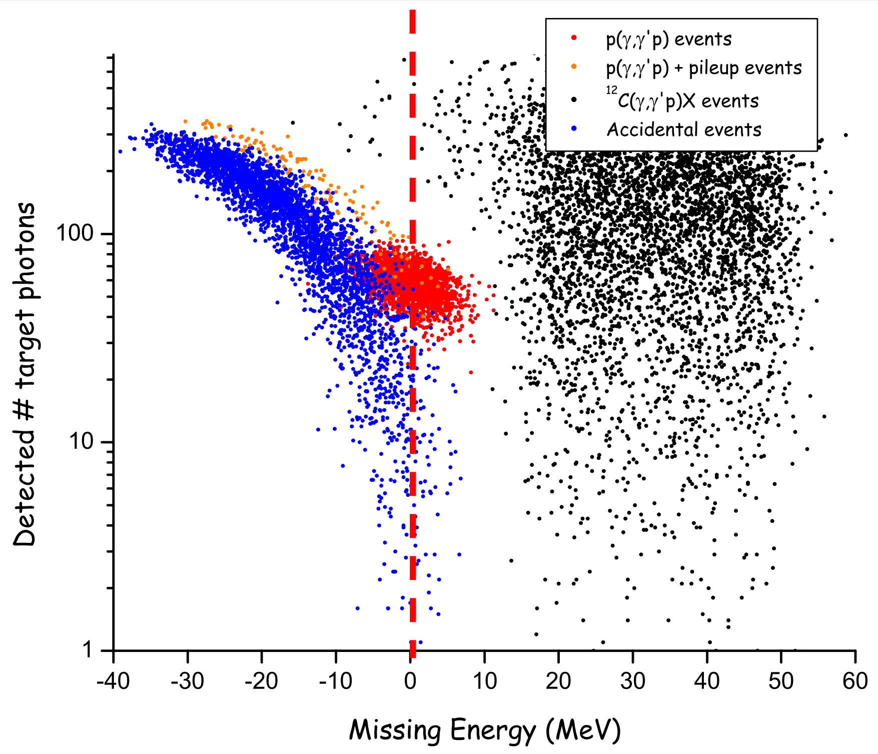
- **proposal by Henry Weller**
- unpolarized photon beam and unpolarized deuterium tgt
  - scintillating active target (detect recoils in coincidence)
- scattering angles 45^o, 80^o, 115^o, 150^o (E_γ = 65, 100 MeV)
- requires 300 hrs (65 MeV) + 100 hrs (100 MeV)
- detectors: eight 10”×12” NaI’s
  - arranged symmetrically left/right

Cross-Section Ratios for Deuterium



Compton Scattering with scintillating target





deuteron

proton

simulations: R. Miskimen

Sum-Rule-Independent Measurement of α_p

- **proposal by Mohammad Ahmed**
- linearly polarized photon beam (unpolarized target)
  - scintillating active target (detect recoils in coincidence)
- measure scattered photons at 90^o (E_γ = 82 MeV)
  - scattering cross section is independent of β_p
  - extraction of α_p is independent of the Baldin sum rule
  - extraction of α_p is model-independent
- requires 300 hrs for 5% uncertainty in α_p
- detectors: four 10”×12” NaI’s (HINDA array)
  - located left, right, up, down

Sum-Rule-Independent Measurement of α_p

$$\begin{cases} \dfrac{d\sigma_\perp}{d\Omega} = \dfrac{d\sigma_\perp}{d\Omega}(point) - \underbrace{\left[\dfrac{e^2}{Mc^2}\right]\left[\dfrac{\omega'}{\omega}\right]^2 \omega\omega'(2\bar{\alpha} + 2\bar{\beta}\cos\theta)}_{d\sigma_\perp^{dipole}} \\ \dfrac{d\sigma_\parallel}{d\Omega} = \dfrac{d\sigma_\parallel}{d\Omega}(point) - \underbrace{\left[\dfrac{e^2}{Mc^2}\right]\left[\dfrac{\omega'}{\omega}\right]^2 \omega\omega'(2\bar{\alpha}\cos^2\theta + 2\bar{\beta}\cos\theta)}_{d\sigma_\parallel^{dipole}} \end{cases}$$

- The 90° parallel cross section is independent of $\bar{\alpha}$ and $\bar{\beta}$: $\dfrac{d\sigma_\parallel}{d\Omega}(90^\circ) = \left(\dfrac{d\sigma_\parallel}{d\Omega}(90^\circ)\right)_{point}$
- The cross section asymmetry $A(\omega,\theta) = \dfrac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$

$$A(\omega, 90^\circ) = \frac{C_1(\omega) - C_2(\omega)\bar{\alpha}}{C_3(\omega) + C_2(\omega)\bar{\alpha}}$$

Nucleon Spin Polarizability

$$\mathcal{L}_{\rm pol} = 2\pi\, N^\dagger \big[\alpha_{E1}(\omega)\, \vec{E}^2 + \beta_{M1}(\omega)\, \vec{B}^2 +$$

$$+\, \gamma_{E1E1}(\omega)\, \vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \gamma_{M1M1}(\omega)\, \vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}})$$

$$-\, 2\gamma_{M1E2}(\omega)\, \sigma_i\, B_j\, E_{ij} + 2\gamma_{E1M2}(\omega)\, \sigma_i\, E_j\, B_{ij} + \ldots \big]\, N$$

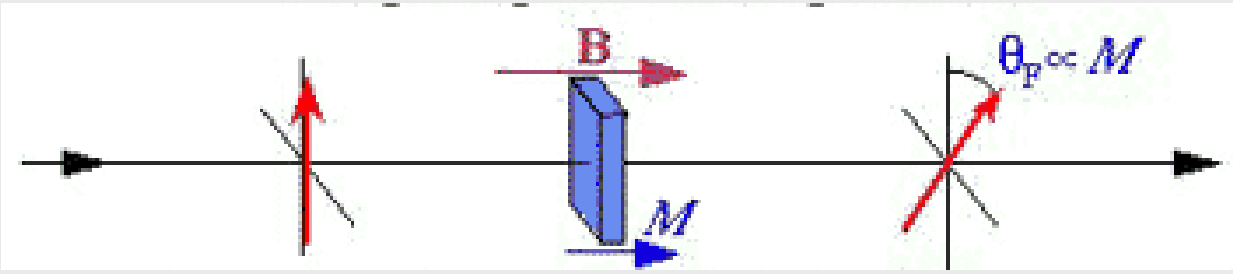
$$\gamma_0(\omega) = -\gamma_{E1E1}(\omega) - \gamma_{M1M1}(\omega) - \gamma_{E1M2}(\omega) - \gamma_{M1E2}(\omega)$$

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

forward and backward spin polarizabilities

Nucleon Spin Polarizability

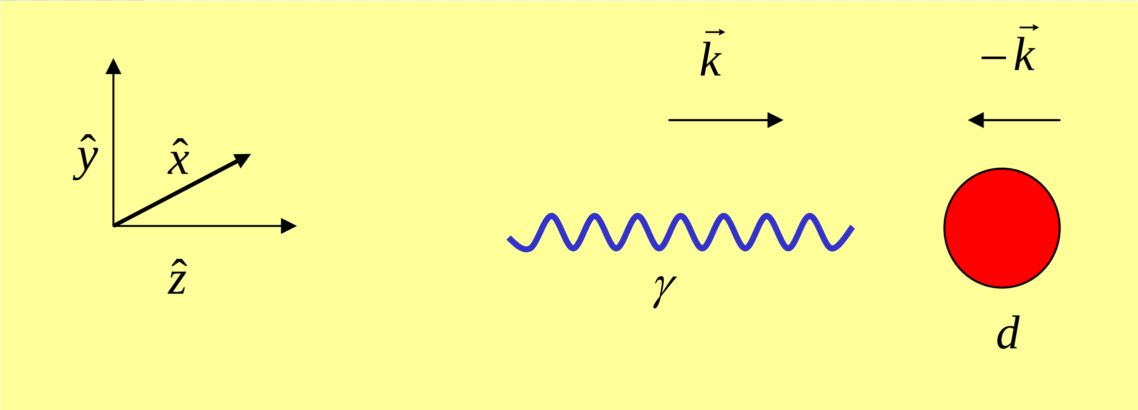
- classical analogy: Faraday rotation of linearly polarized light in a spin-polarized medium

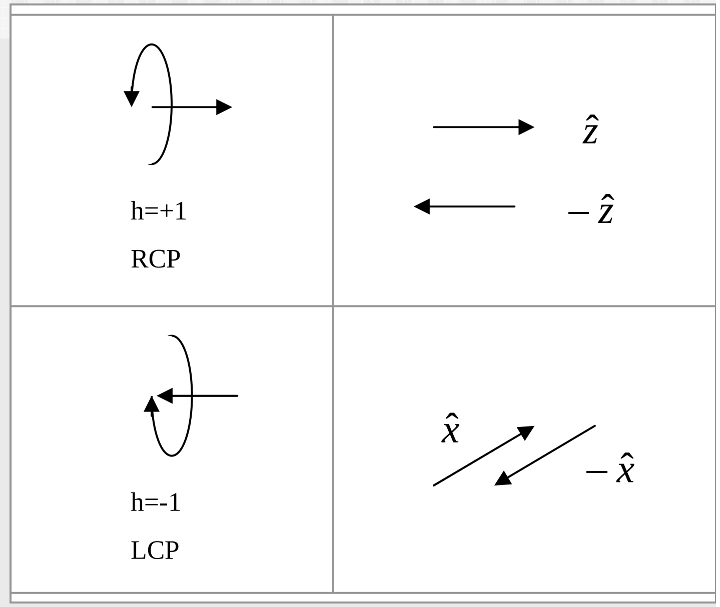


- four spin polarizabilities: $\gamma_1, \ldots, \gamma_4$
  - forward spin polarizability: $\gamma_0 = \gamma_1 - \gamma_2 - 2\gamma_4$
  - backward spin polarizability: $\gamma_\pi = \gamma_1 + \gamma_2 + 2\gamma_4$

- expt. asymmetries with circularly polarized photons
  - Σ_x : target spin $\perp$ photon helicity (in reaction plane)
  - Σ_z : target spin parallel to photon helicity

Double Polarization Observables





$$\left[\Sigma_z = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\uparrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\downarrow}}{Sum} \right]_{h=\pm1}$$

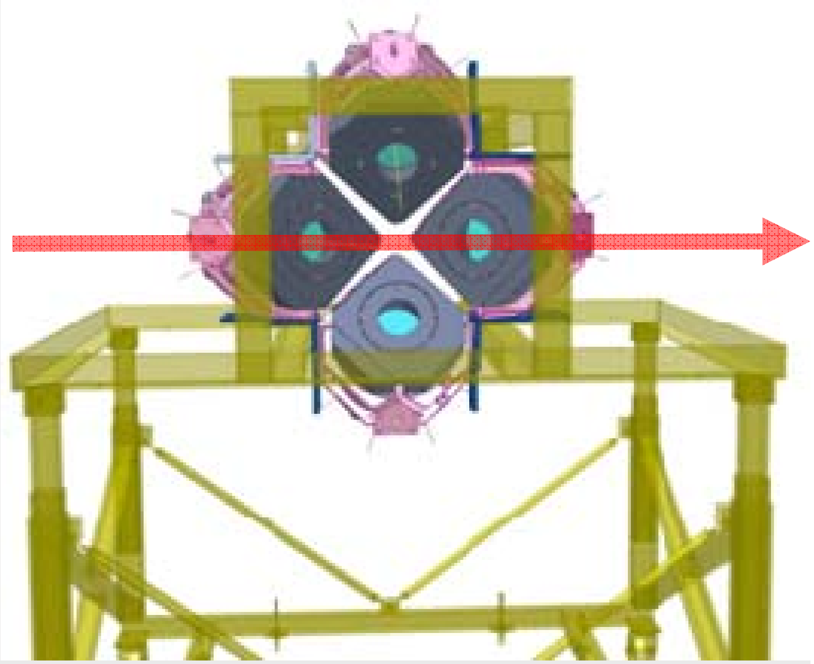
$$\left[\Sigma_x = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\rightarrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\leftarrow}}{Sum} \right]_{h=\pm1}$$

circularly polarized beam

vector polarized target

Spin Polarizabilities of the Proton

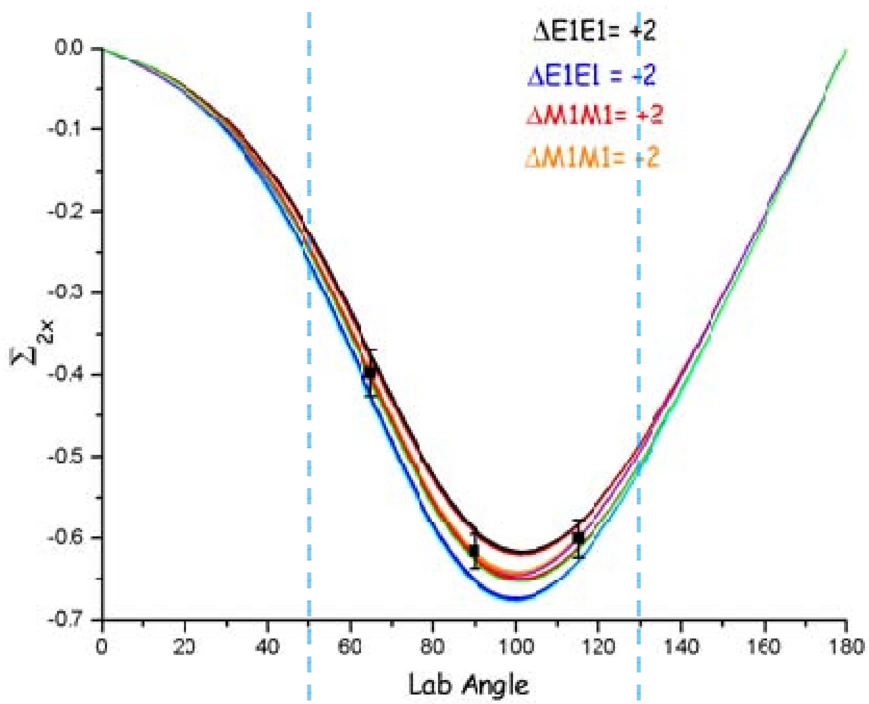
- **proposal by Rory Miskimen**
- first measurement of proton γ_{E1E1}
- circularly polarized photon beam
  - scintillating active ***transverse*** *polarized* target (P ~ 80%)
- scattering angles 65°, 90°, 115° (E_γ = 100 MeV)
- requires 800 hrs for $\Delta\gamma_{E1E1} = \pm 1$
- detectors: eight 10”×12” NaI’s
  - 4 in plane, 4 out of plane

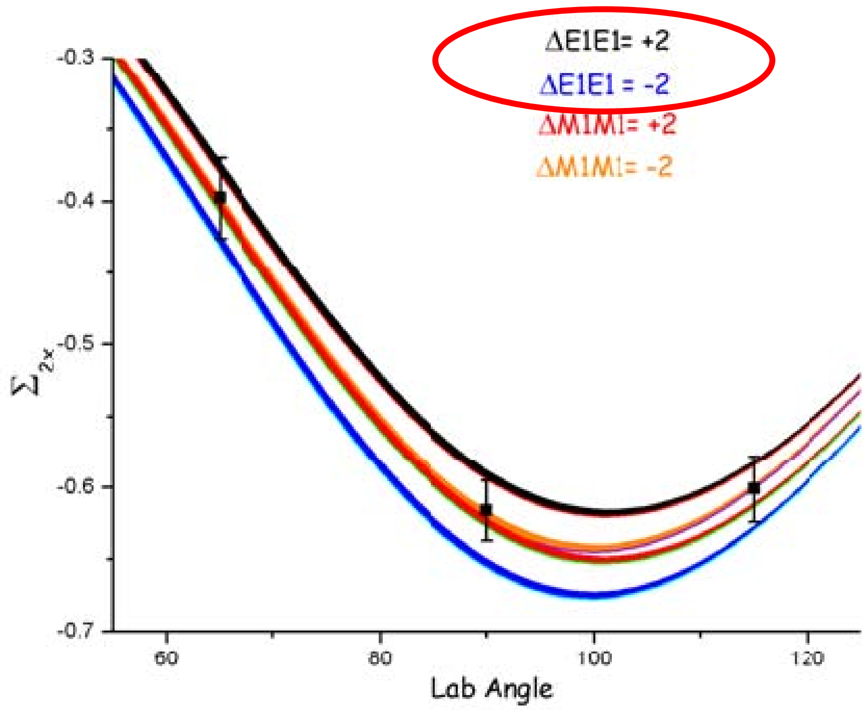


Spin Polarizabilities of the Proton

expand

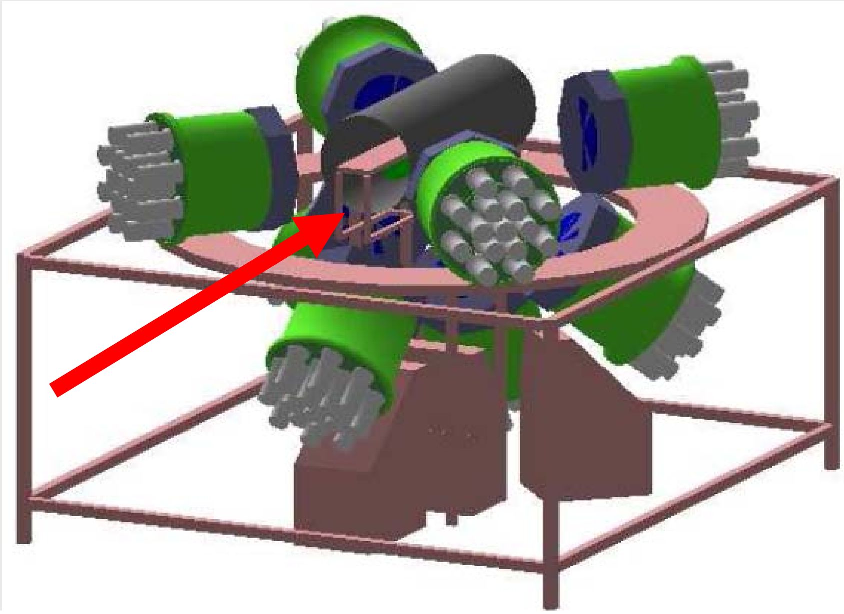
expanded view



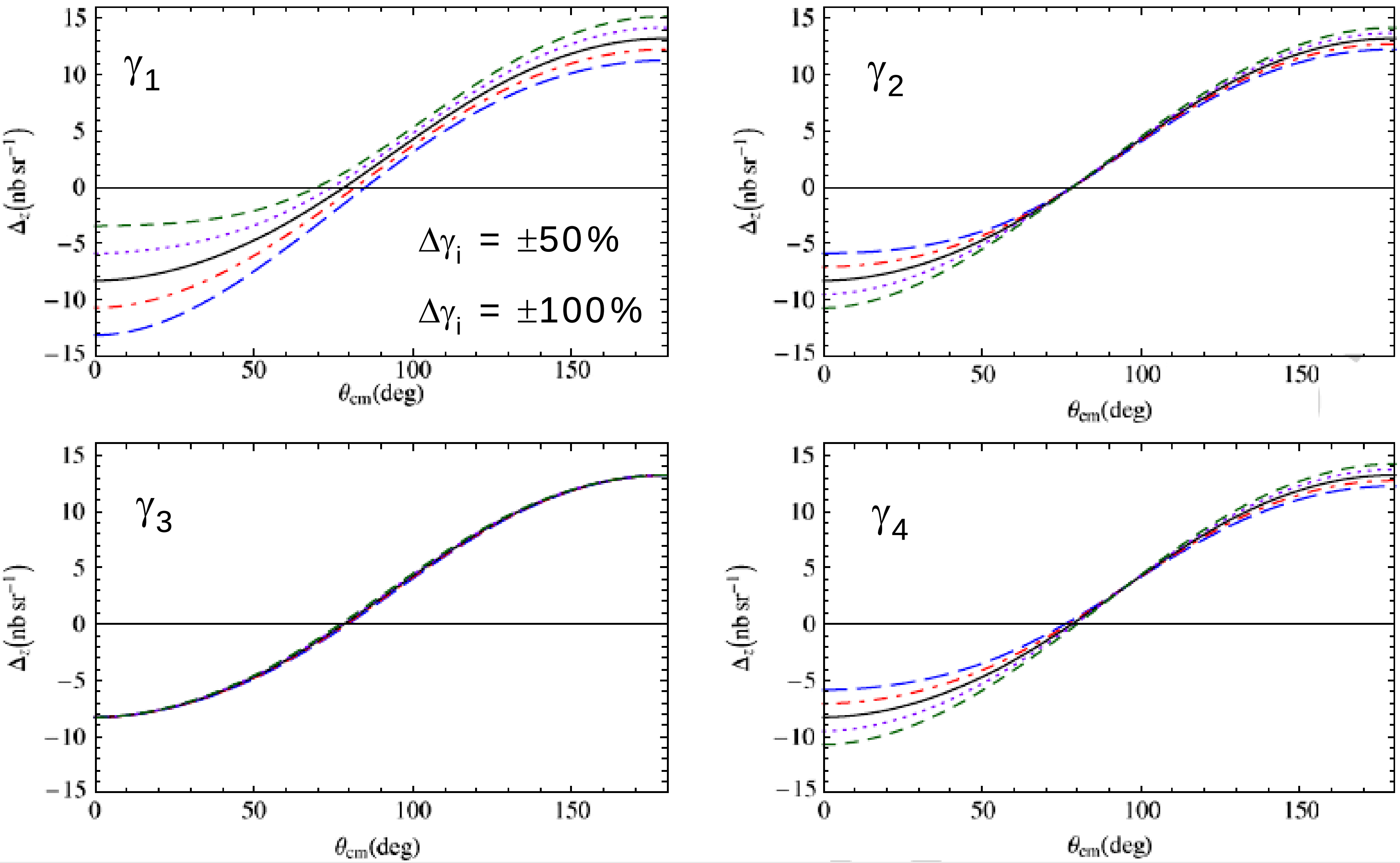


Polarized Compton Scattering from ^{3}He

- **proposal by Haiyan Gao**
- first measurement of neutron spin polarizabilities
- circularly polarized photon beam
  - **longitudinally** polarized high-pressure ^{3}He target (P ~ 50%)
- scattering angles 40°, 60°, 140° (E_γ = 125 MeV)
- requires 1200 hrs for ~20% uncertainty in γ_1, γ_2, γ_4
- detectors: eight 10”×12” NaI’s
  - 4 in plane, 4 out of plane



Polarized Compton Scattering from ^{3}He



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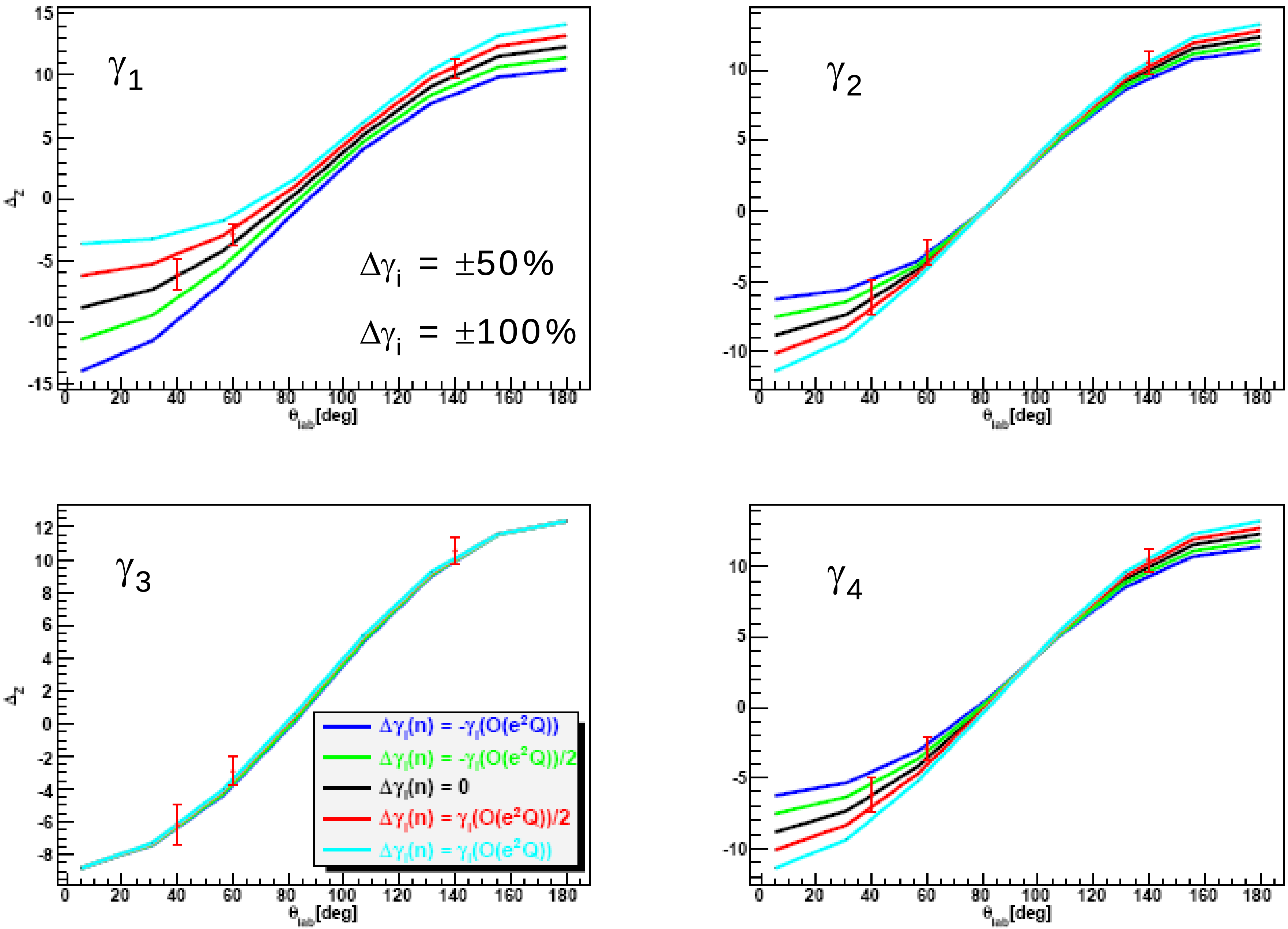
Polarized Compton Scattering from ^{3}He



HIGS Capabilities for User Programs in 2012

Parameter	Value		Comments
E-beam Configuration E-beam current [mA]	Symmetric two-bunch beam 50 - 120		High flux configuration
Gamma-ray Energy [MeV]	1 – 100		with mirrors 1064 to 190 nm Available with existing hardware Extending wiggler current to 3.5 kA
(a) No-loss mode	Total flux [γ/s]	Collimated flux (ΔE/E~5%) [γ/s]	Both Horizontal and Circular Polarizations
1 – 3 MeV[a]	$1 \times 10^8 – 1 \times 10^9$	$6 \times 10^6 – 6 \times 10^7$	
3 – 5 MeV	$6 \times 10^8 – 2 \times 10^9$	$3.6 \times 10^7 – 1.2 \times 10^8$	
5 – 13 MeV	$4 \times 10^8 – 4 \times 10^9$	$2.4 \times 10^7 – 2.4 \times 10^8$	
13 – 20 MeV	$1 \times 10^9 – 2 \times 10^9$	$6 \times 10^7 – 1.2 \times 10^8$	
(b) Loss mode	Total flux [γ/s]	Collimated flux (ΔE/E~5%) [γ/s]	To extend mirror lifetime, circular polarization is preferred
21 – 54 MeV	$> 2 \times 10^8$ [b]	$> 1 \times 10^7$	
55 – 65 MeV	$\sim 2 \times 10^8$ [b]	$\sim 1 \times 10^7$	1st user experiment: March, 2011
66 – 100 MeV	1×10^8 [b] [c]	$\sim 5 \times 10^6$	190 nm, 1st user experiment in 2013

[a] With present configuration of OK-5 wigglers separated by 21 m, the circular polarization is about ½ the values here.
[b] The flux in loss mode is mainly limited by injection rate.
[c] Thermal stability of FEL mirror may limit the maximum amount of current can be used in producing FEL lasing, thus flux.

Highest Total Flux (2010): $>2\times 10^{10}$ γ/s @ 9 – 11 MeV

Projected energy upgrades above 100 MeV (circular pol)

2014: 110 – 120 MeV, ~1x 10^8 g/s (total)

- **After 2015: 150+ MeV, ~1x 10^8 g/s (total)**

Summary

- **Early measurements of Compton scattering at HIGS**
  - unpolarized expt. on ^{6}Li
  - polarized expts. on A = 89-238 for IVGQR studies
  - new proposal: low-energy (3-15 MeV) for ^{6}Li nuclear pol.
- **Next generation of expts. on proton and deuteron**
  - electric and magnetic polarizability
    - ✓ unpolarized expt. on deuterium
    - ✓ **polarized** expt. on proton
  - spin polarizability
    - ✓ **double-polarized** expt. on proton
    - ✓ **double-polarized** expt. on ^{3}He
- **HIGS can contribute high-quality polarized data!**
  - stay tuned for further developments in the future…