

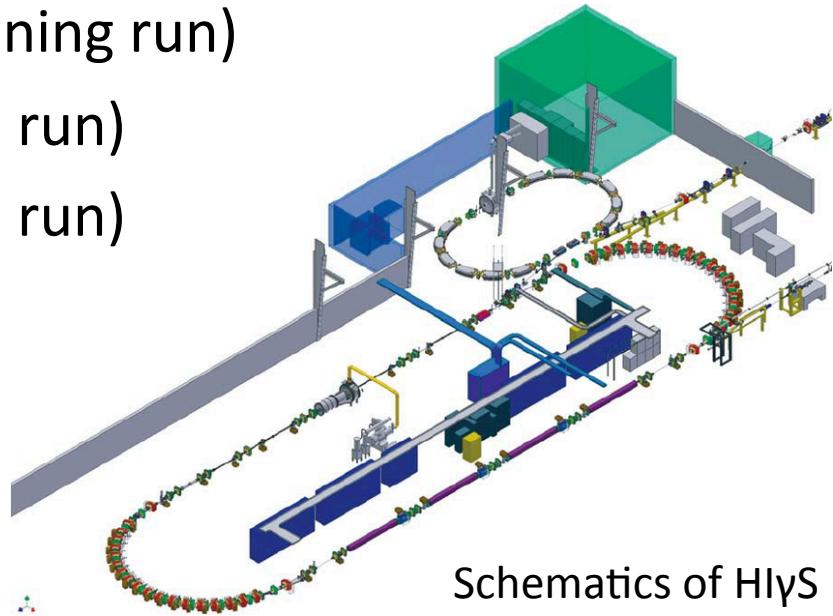
Compton scattering and nucleon polarizabilities at the High Intensity γ -Ray Source (HI γ S)



Xiaqing Li
For the Compton @ HI γ S collaboration
Duke University / TUNL

Outline

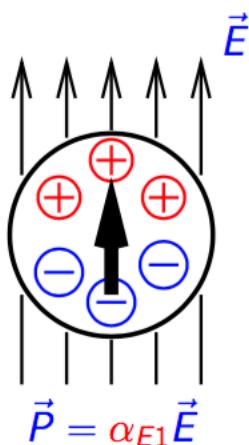
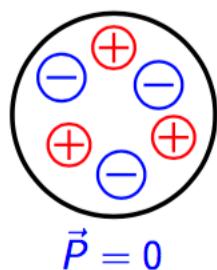
- Nucleon EM polarizabilities
- Compton scattering at HI γ S
- Data analysis and preliminary results
 - LHe (61 MeV, commissioning run)
 - LD₂ (65 MeV, production run)
 - LD₂ (85 MeV, production run)
- Summary



Polarizabilities and nucleon structure

Electric polarizability (α_E)

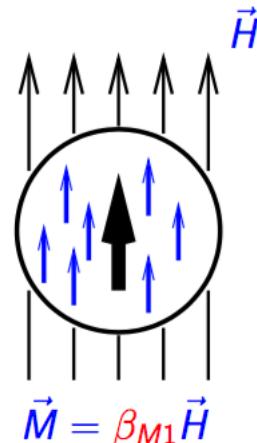
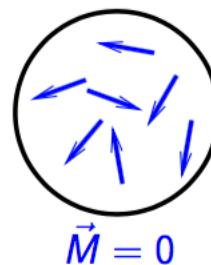
$$\vec{P} = \alpha_E \vec{E}$$



“Stretchability”

Magnetic polarizability (β_M)

$$\vec{M} = \beta_M \vec{H}$$

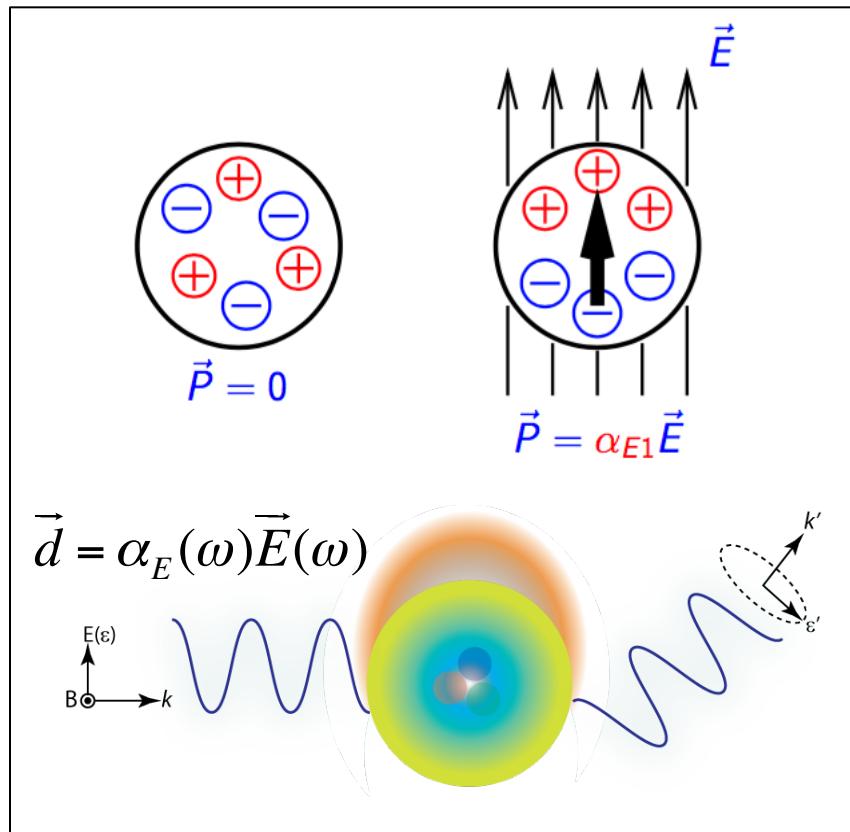


“Alignability”

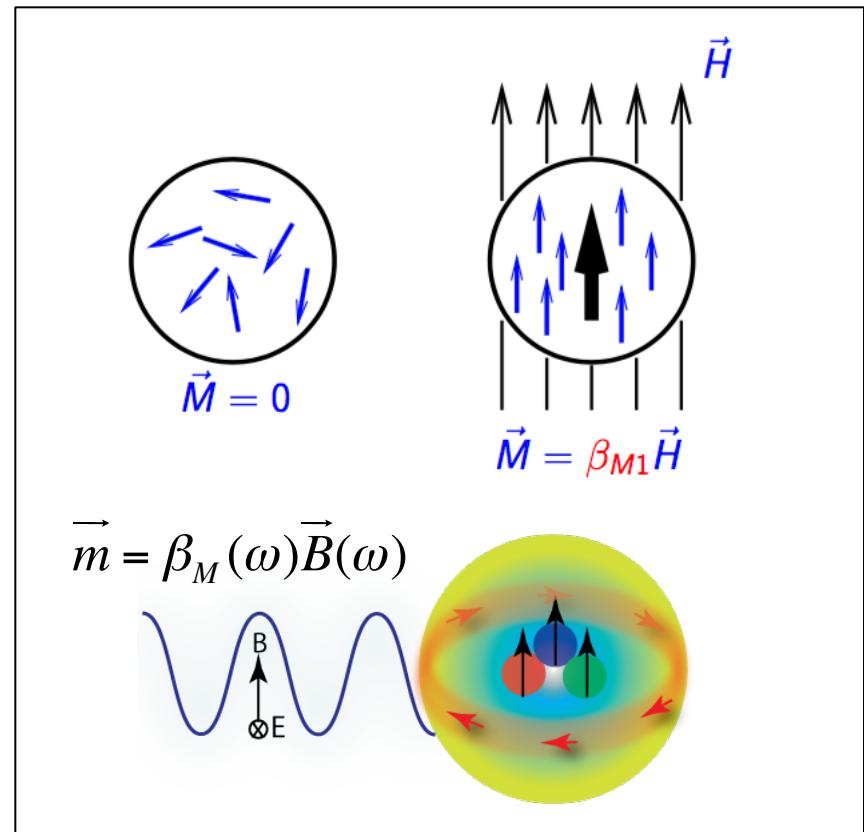
Both are **fundamental structure constants of nucleons**.

Polarizabilities and nucleon structure

Electric polarizability (α_E)



Magnetic polarizability (β_M)



In Compton scattering, the incident photon acts as an applied EM field to the constituents in a nucleon.

Amplitude of Compton scattering

- Incoming photon of energy ω scattered from a spin-1/2 target:

$$\begin{aligned}
 T(\omega, z) = & A_1(\omega, z) (\vec{\epsilon}'^* \cdot \vec{\epsilon}) + A_2(\omega, z) (\vec{\epsilon}'^* \cdot \hat{\vec{k}}) (\vec{\epsilon} \cdot \hat{\vec{k}}') \\
 & + iA_3(\omega, z) \vec{\sigma} \cdot (\vec{\epsilon}'^* \times \vec{\epsilon}) + iA_4(\omega, z) \vec{\sigma} \cdot (\hat{\vec{k}}' \times \hat{\vec{k}}) (\vec{\epsilon}'^* \cdot \vec{\epsilon}) \\
 & + iA_5(\omega, z) \vec{\sigma} \cdot \left[(\vec{\epsilon}'^* \times \hat{\vec{k}}) (\vec{\epsilon} \cdot \hat{\vec{k}}') - (\vec{\epsilon} \times \hat{\vec{k}}') (\vec{\epsilon}'^* \cdot \hat{\vec{k}}) \right] \\
 & + iA_6(\omega, z) \vec{\sigma} \cdot \left[(\vec{\epsilon}'^* \times \hat{\vec{k}}') (\vec{\epsilon} \cdot \hat{\vec{k}}') - (\vec{\epsilon} \times \hat{\vec{k}}) (\vec{\epsilon}'^* \cdot \hat{\vec{k}}) \right]
 \end{aligned}$$

$$A_1(\omega, z) = -\frac{Q^2 e^2}{M_N} + \frac{e^2 \omega^2}{4M_N^3} ((Q + \kappa)^2(1 + z) - Q^2)(1 - z) + 4\pi\omega^2(\alpha_{E1} + z\beta_{M1}) + \mathcal{O}(\omega^4)$$

$$A_2(\omega, z) = \frac{e^2 \omega^2}{4M_N^3} \kappa(2Q + \kappa)z - 4\pi\omega^2\beta_{M1} + \mathcal{O}(\omega^4)$$

$A_3 - A_6$: related to spin polarizabilities, order of ω^3

Differential cross section of Compton scattering $N(\gamma, \gamma') N$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{Born}}{d\Omega}$$

$$-\left(\frac{e^2 Q^2}{4\pi M_N}\right) \left(\frac{\omega'}{\omega}\right)^2 (\omega\omega') \left[\underbrace{\frac{1}{2}(\alpha + \beta)(1 + \cos\theta)^2}_{+ higher\ order\ terms} + \underbrace{\frac{1}{2}(\alpha - \beta)(1 - \cos\theta)^2}_{\text{higher order terms}} \right]$$

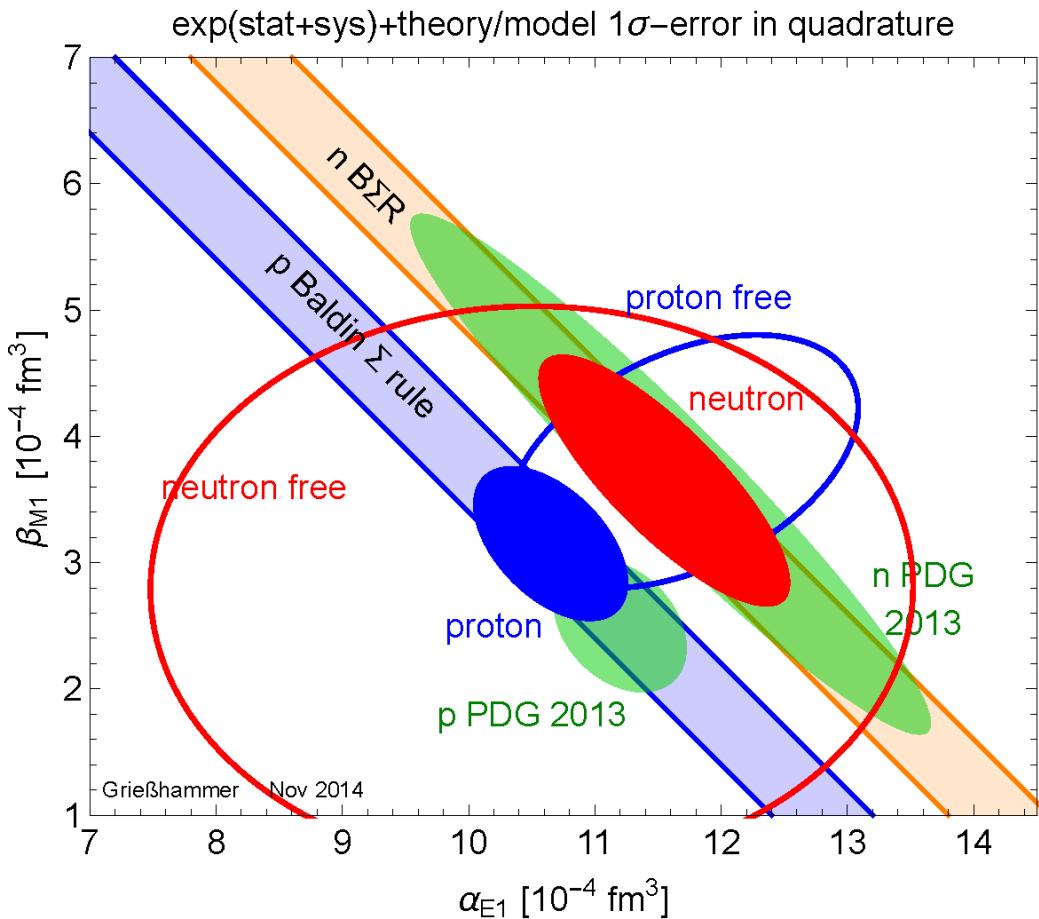
+ higher order terms

dominant in
forward-angle
cross section

dominant in
backward-angle
cross section

- $-eQ$: nucleon charge
- M_N : nucleon mass
- ω : incident photon energy
- ω' : scattered photon energy

The state of nucleon polarizabilities



$$\alpha_n = 11.55 \pm 1.25(\text{stat}) \pm 0.2(\Sigma) \pm 0.8(\text{theory})$$

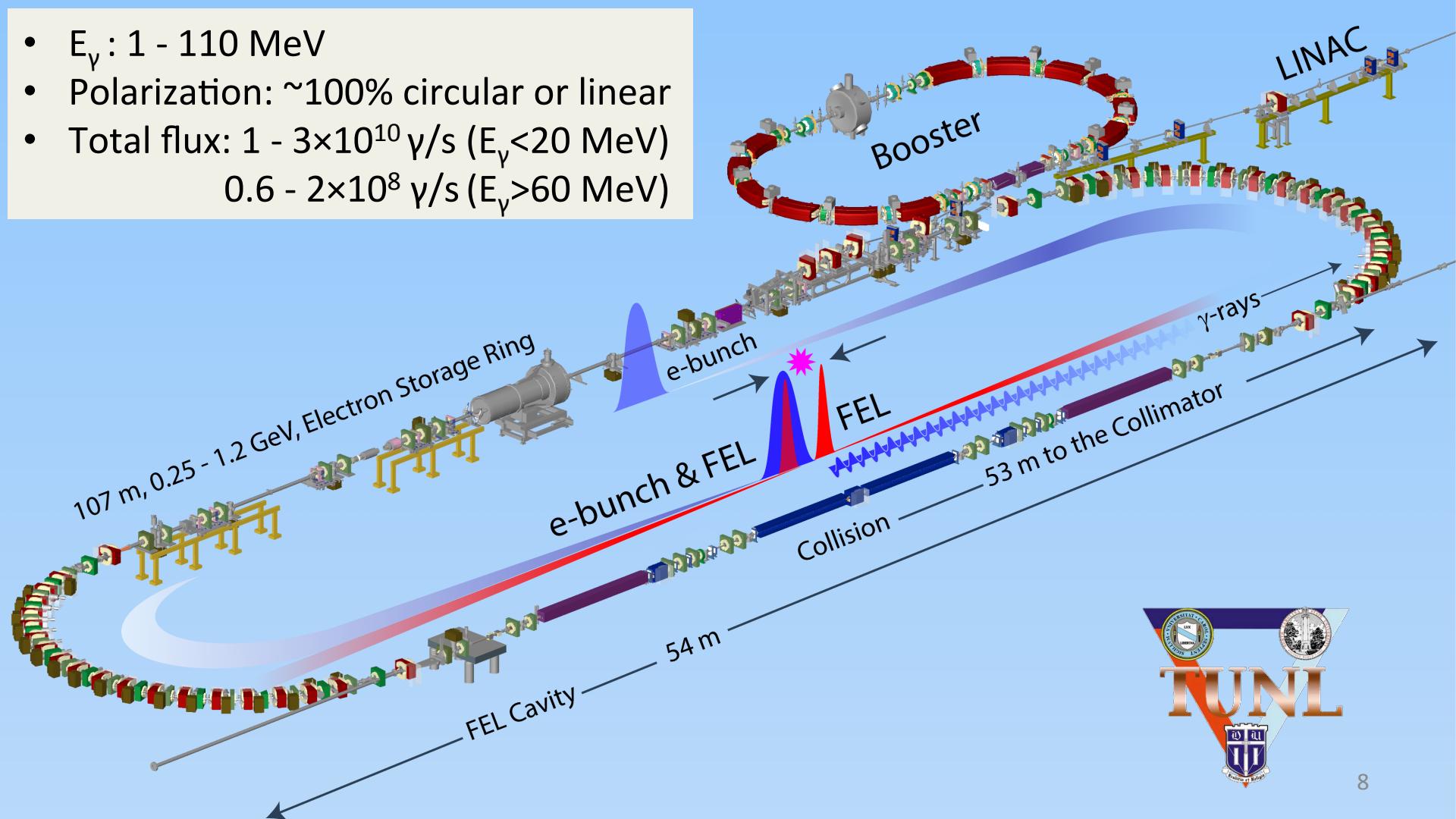
$$\beta_n = 3.65 \mp 1.25(\text{stat}) \pm 0.2(\Sigma) \pm 0.8(\text{theory})$$

L. S. Myers, Phys. Rev. Lett. **113**, 262506 (2014)

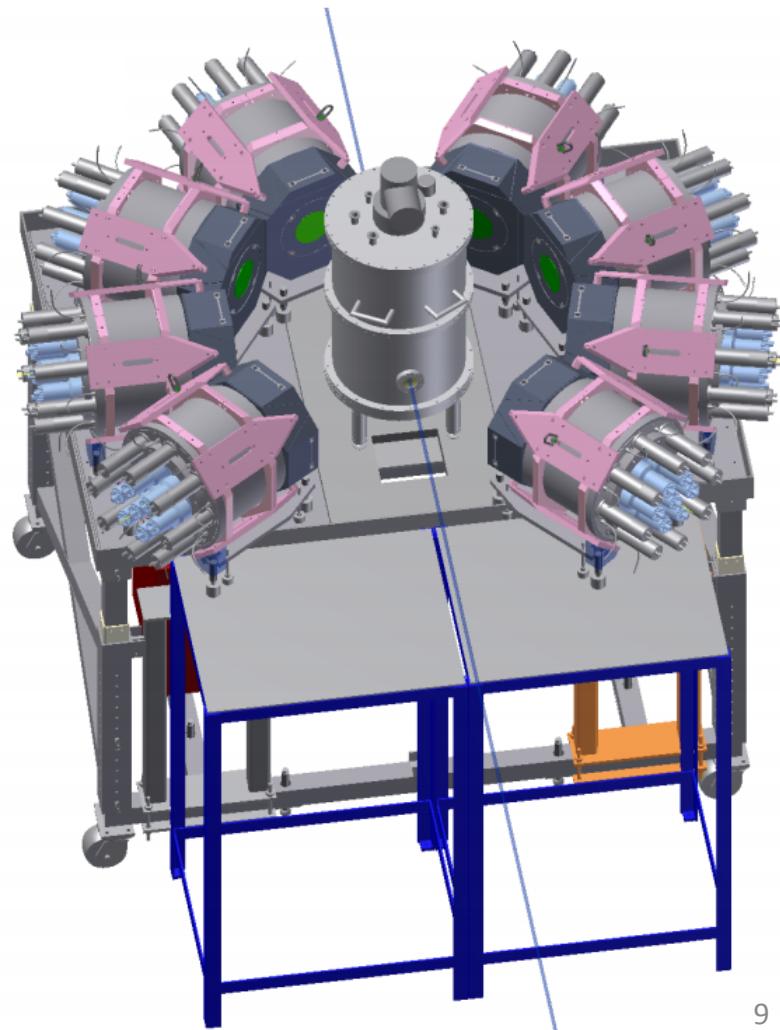
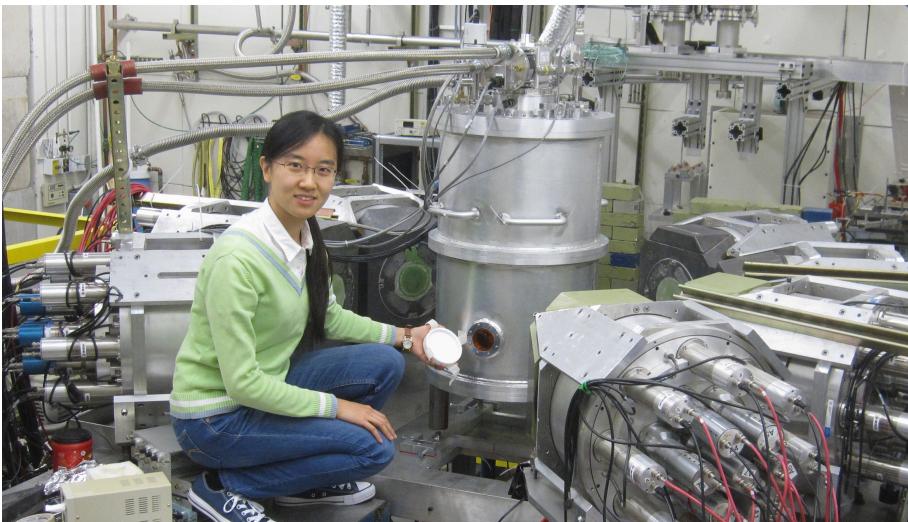
- Neutron data less precise than proton data
- No stable free neutron target
- Effective neutron targets: Deuterium and ${}^3\text{He}$

The High Intensity γ -Ray Source (HI γ S)

- $E_\gamma : 1 - 110 \text{ MeV}$
- Polarization: $\sim 100\%$ circular or linear
- Total flux: $1 - 3 \times 10^{10} \text{ } \gamma/\text{s}$ ($E_\gamma < 20 \text{ MeV}$)
 $0.6 - 2 \times 10^8 \text{ } \gamma/\text{s}$ ($E_\gamma > 60 \text{ MeV}$)

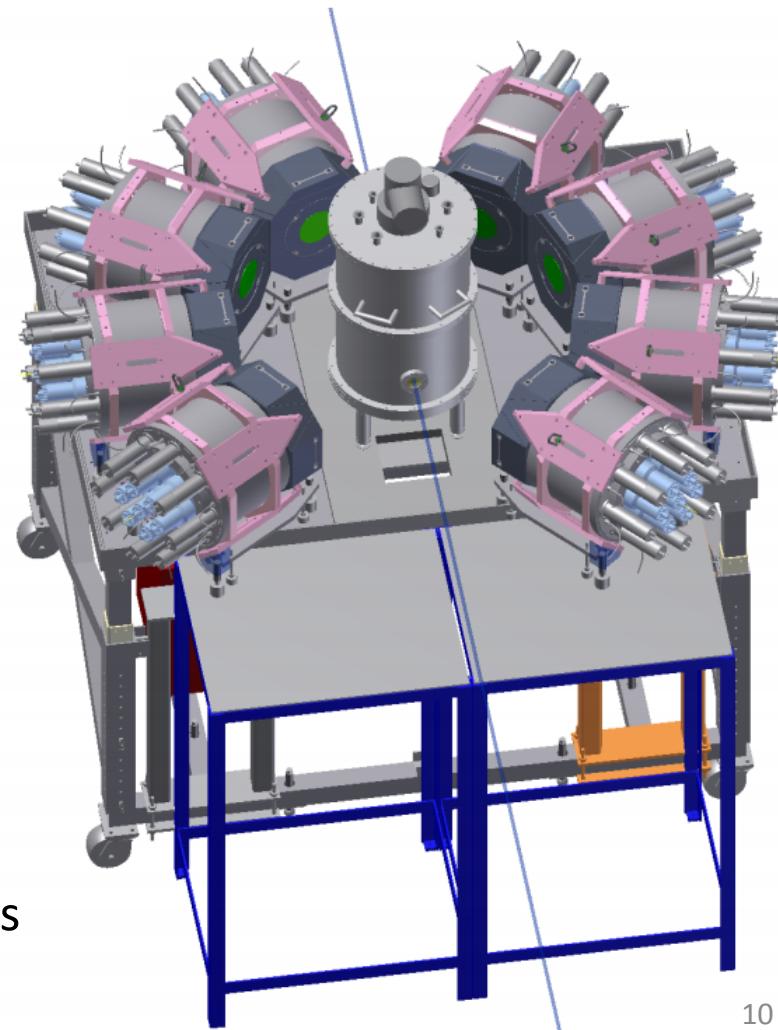
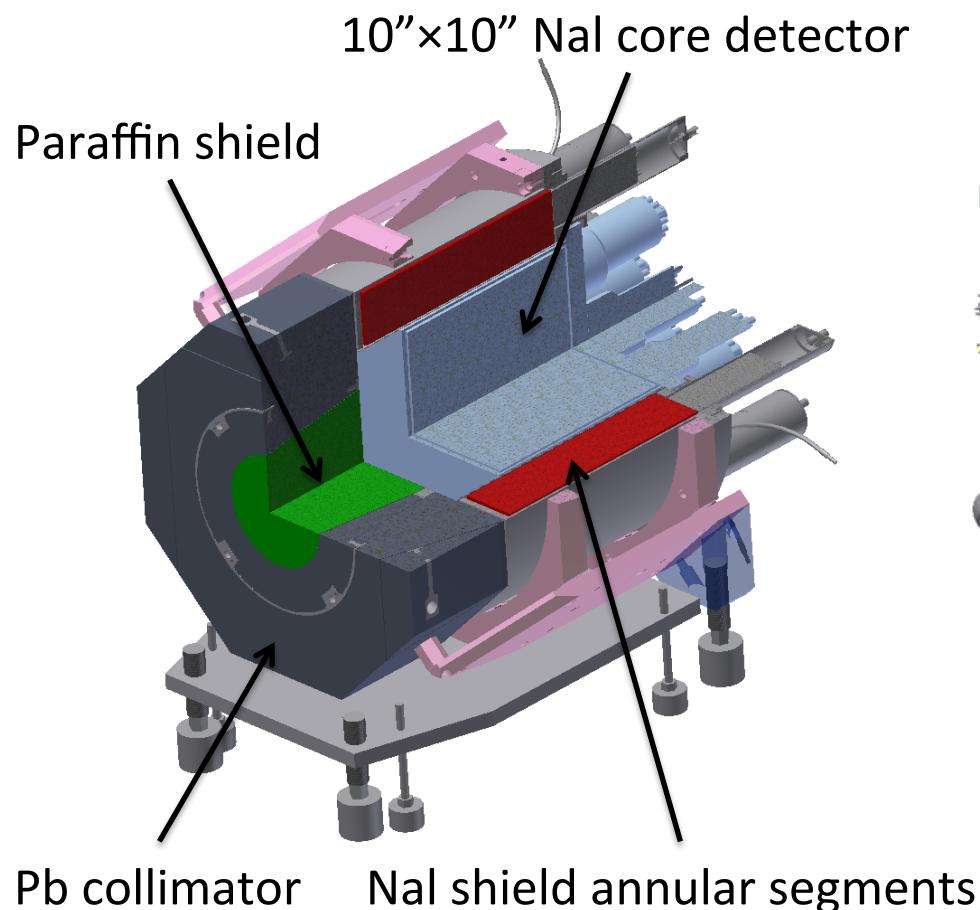


Compton experiment apparatus

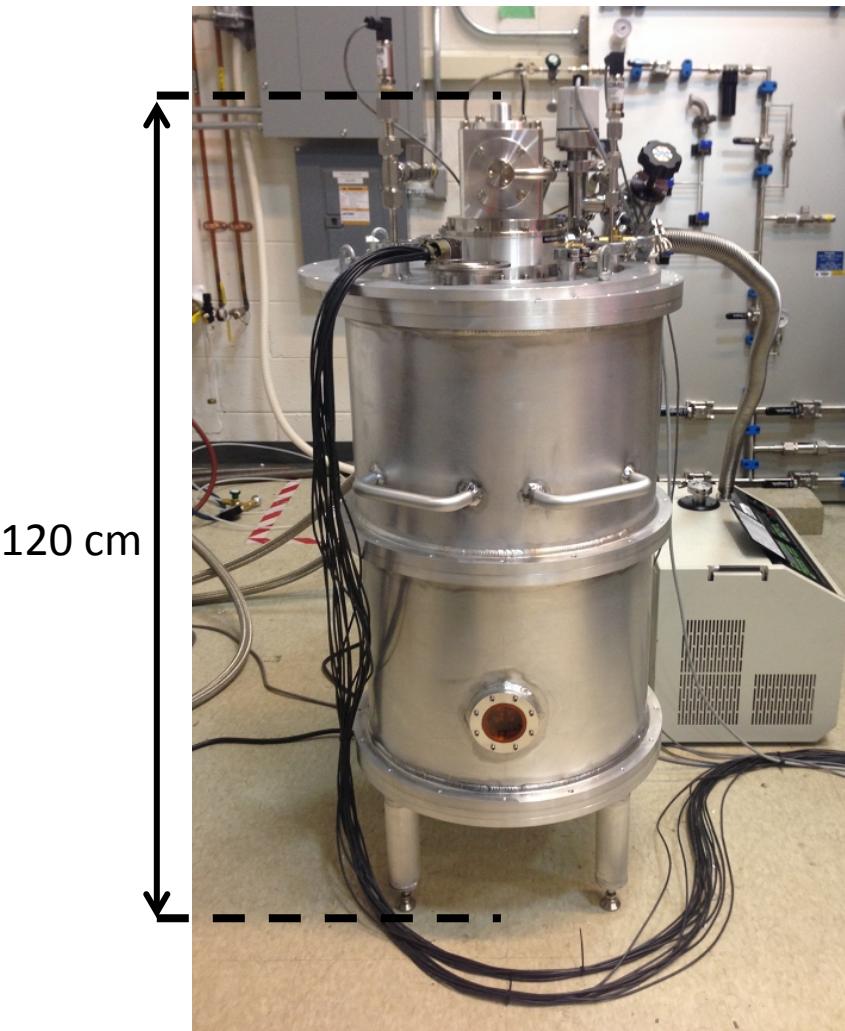


- Detector array:
 - Eight (8) 10" × 10" NaI
 - θ from 40° to 159°
 - Active shield structure
- Cryogenic target

HI γ S NaI Detector Array (HINDA)

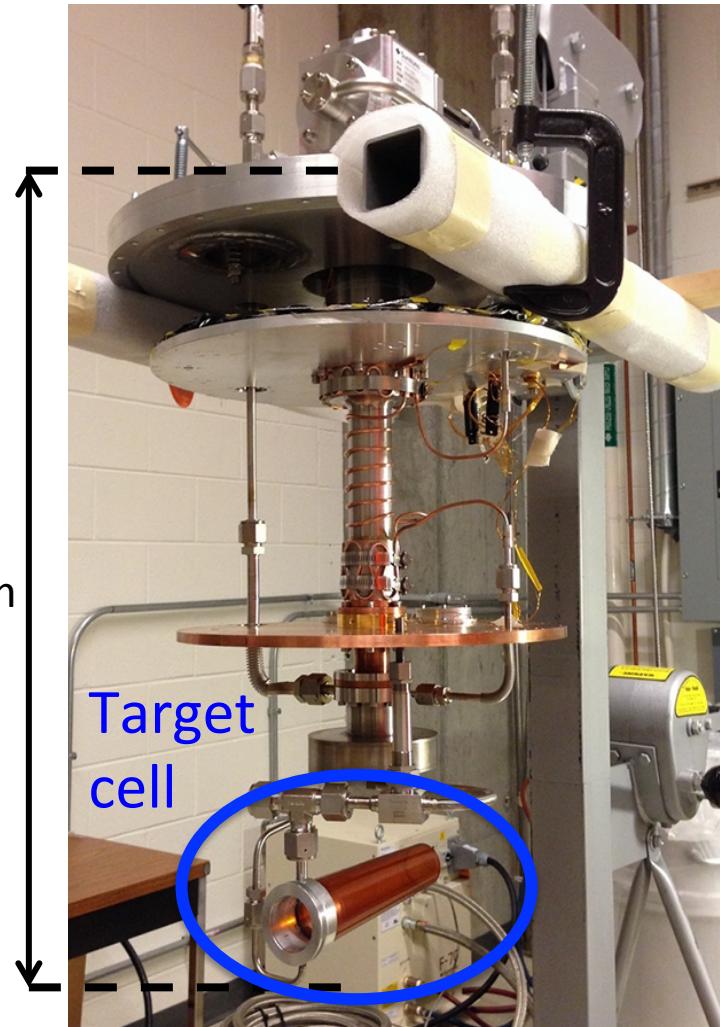


Cryogenic target



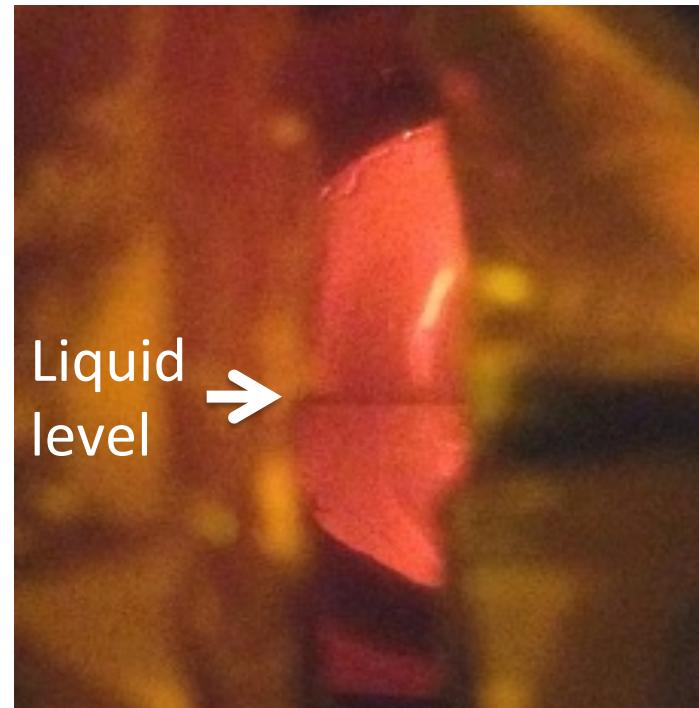
- Capable of liquefying helium (LHe), hydrogen (LH₂), or deuterium (LD₂)
- Base temperature ~ 3.2 K
- 0.125 mm thick Kapton windows

Cryogenic target



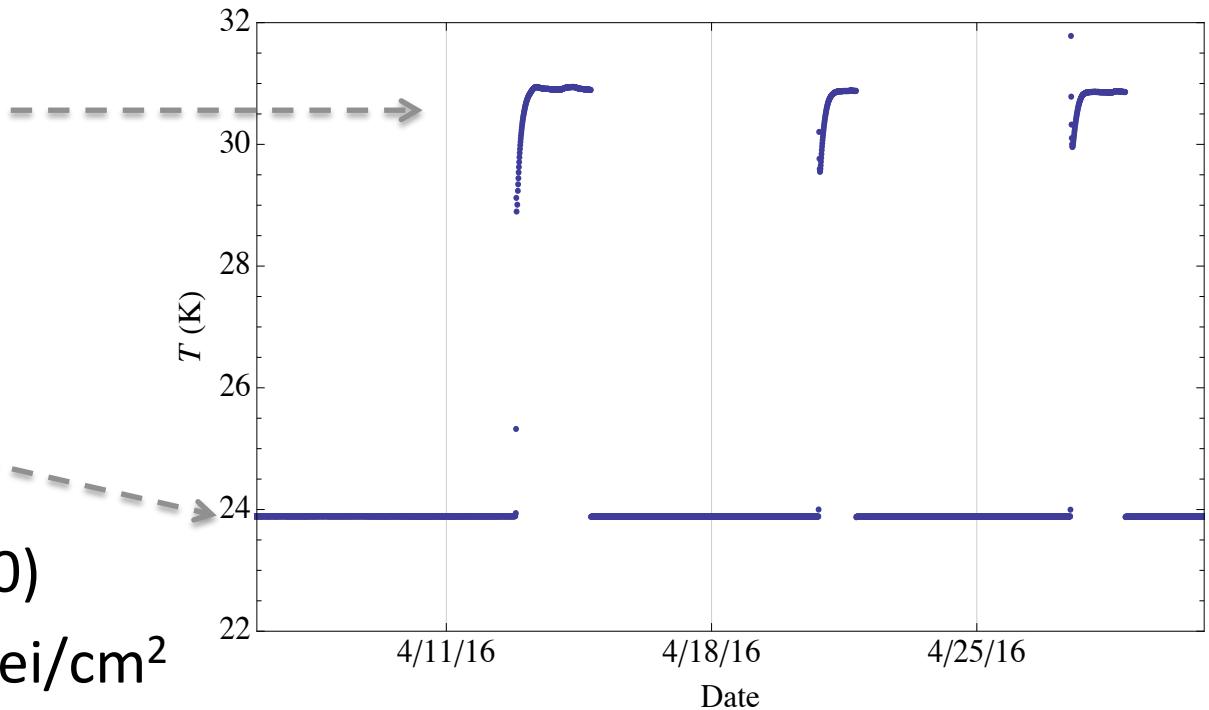
- 0.125 mm Kapton film cell:
 $d = 4 \text{ cm}$, $L = 20 \text{ cm}$, $V \approx 0.25 \text{ L}$

Half-full LD_2 target cell



Cryogenic target

- Empty: D_2 gas
 - $T = 31 \text{ K}$

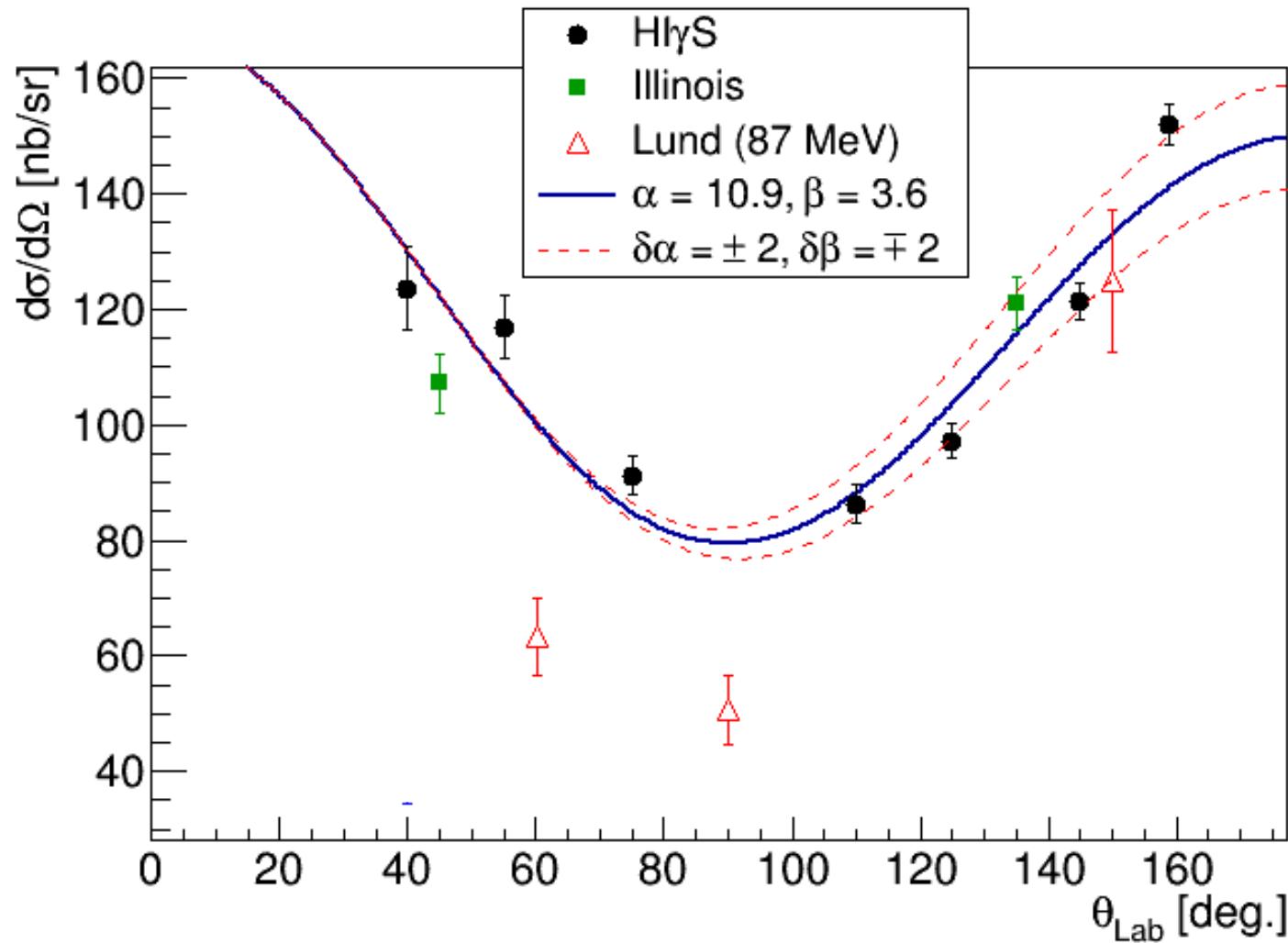


- Fast empty and refill cycle:
 - Empty in $\sim 15 \text{ min}$, refill in seconds

Data taking summary

Date	Sep., 2015	April, 2016	June, 2016
Purpose	commission	production	production
Target	LHe	LD ₂	LD ₂
Beam energy [MeV]	61	65	85
Beam flux [γ/s] (with 1" collimator)	$1\text{-}2 \times 10^7$	3.65×10^7	2×10^7
Total run time [hrs]	54	304	268
Full-target time [hrs]	45	209	181
Empty-target time [hrs]	9	95	87

Target commissioning run: Compton scattering from ${}^4\text{He}$, 61 MeV

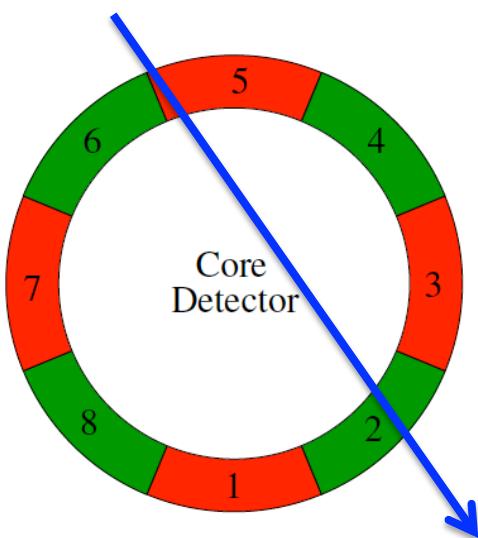


Compton scattering from ^2H , 65 MeV

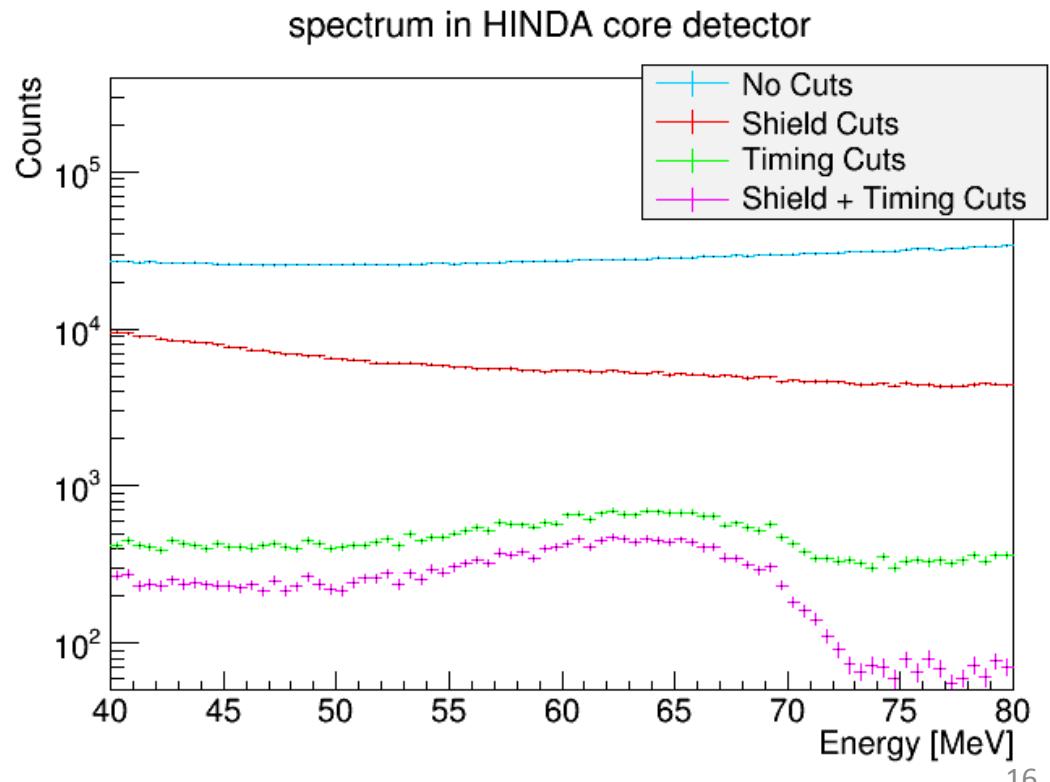
To suppress cosmic muon backgrounds:

- 1) Shield cuts (remove $\sim 93\%$ cosmic events by G4 simulation)

A cosmic muon event



One (1) NaI core detector
surrounded by eight (8) annular
segments of NaI shield detector

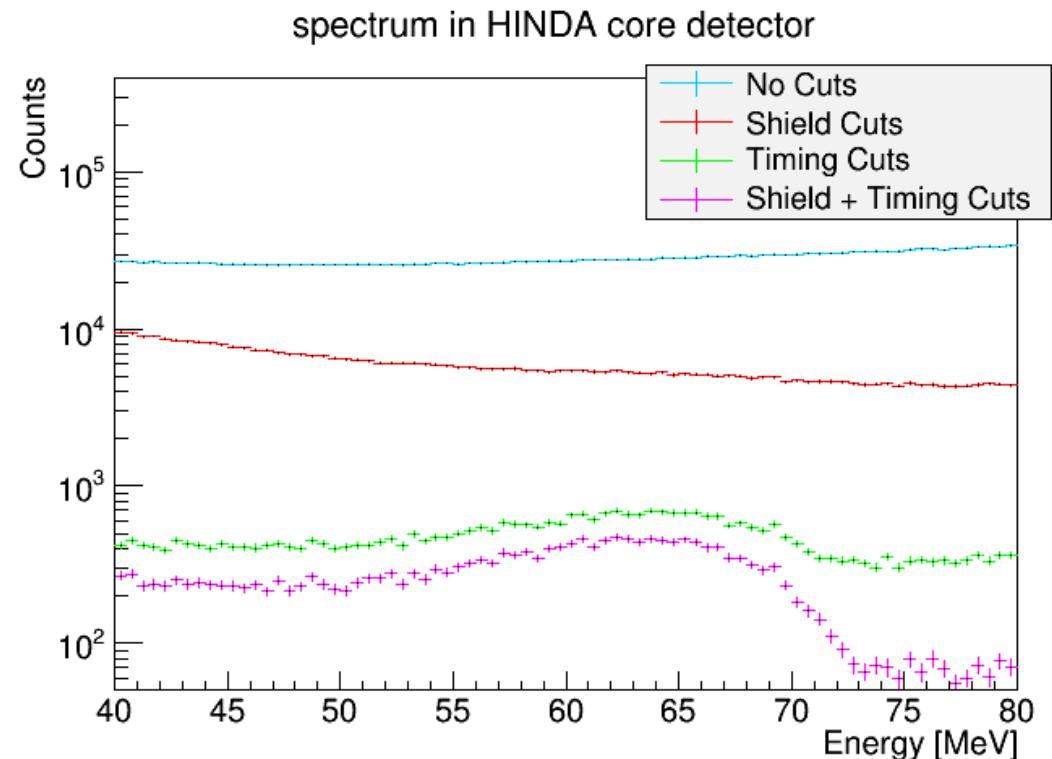


Compton scattering from ^2H , 65 MeV

To suppress cosmic muon backgrounds:

- 1) Shield cuts (remove $\sim 93\%$ cosmic events by G4 simulation)
- 2) Timing cuts (remove extra $\sim 6.7\%$ cosmic events)

Beam time structure
= 4 ns / 180 ns
= 1 / 45

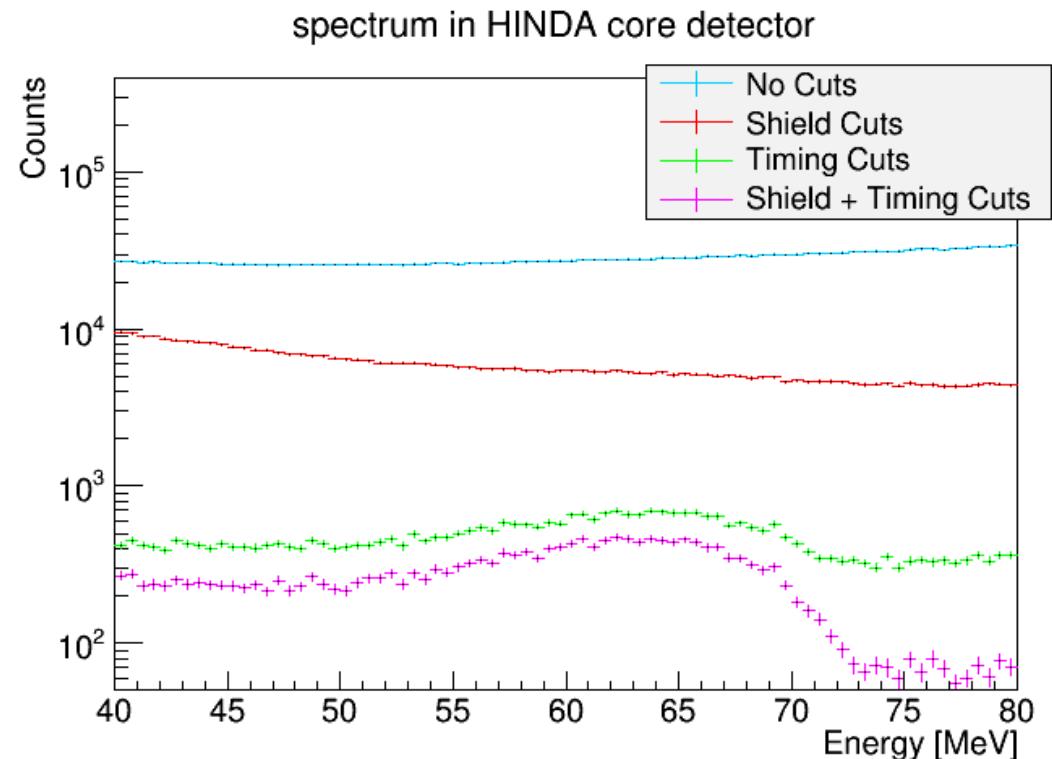


Compton scattering from ^2H , 65 MeV

To suppress cosmic muon backgrounds:

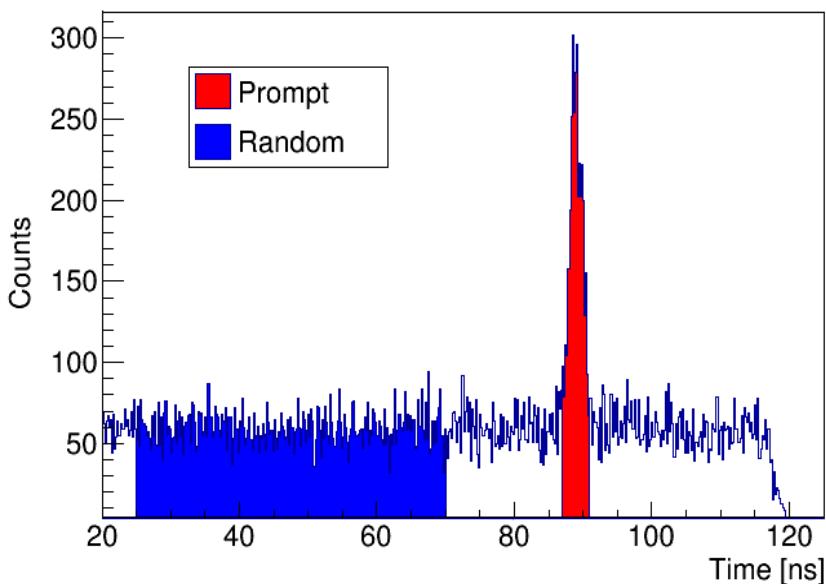
- 1) Shield cuts (remove $\sim 93\%$ cosmic events by G4 simulation)
- 2) Timing cuts (remove extra $\sim 6.7\%$ cosmic events)

- Shield + timing cuts:
Remove $> 99\%$ cosmic events in total

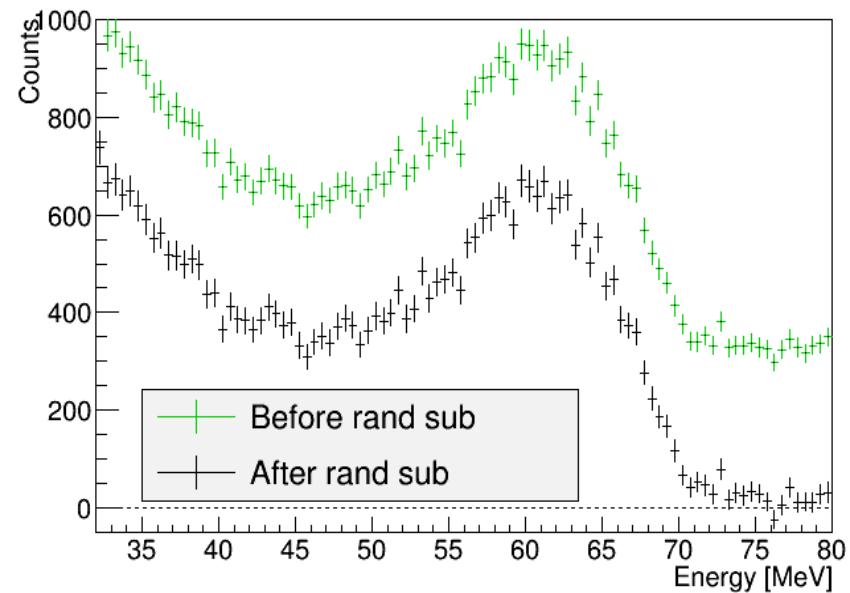


3) Random-event subtraction

What is random subtraction



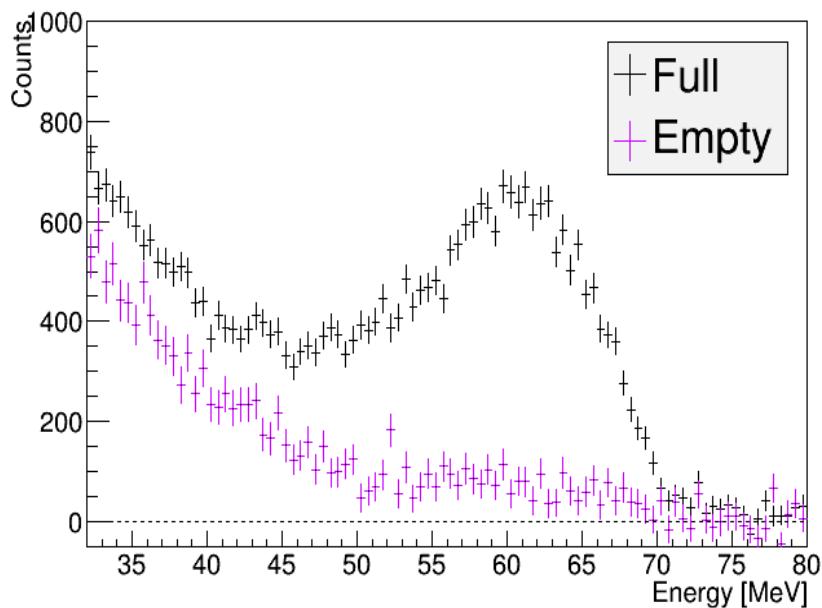
Effect of random subtraction



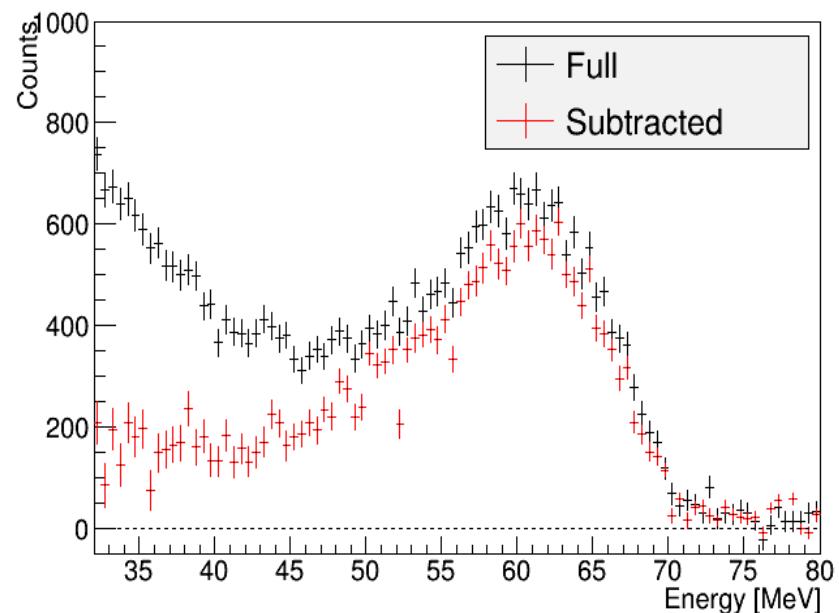
- **Prompt events:** events within the timing cut windows (in-time events)
- **Random events:** time-independent background (out-of-time events)
- **Prompt – Random (time scaled)** → **net spectrum** for full target runs

4) Empty-target subtraction

Full & empty target spectra



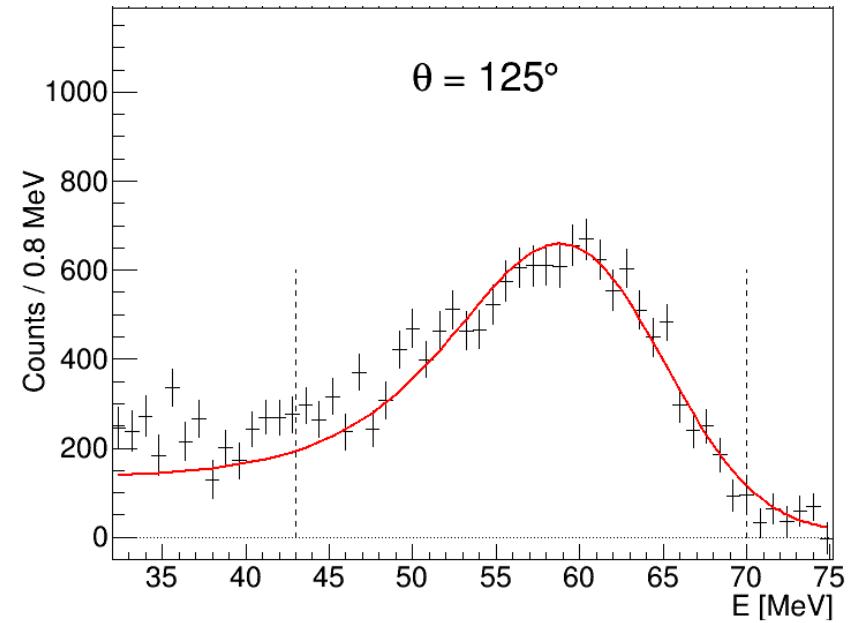
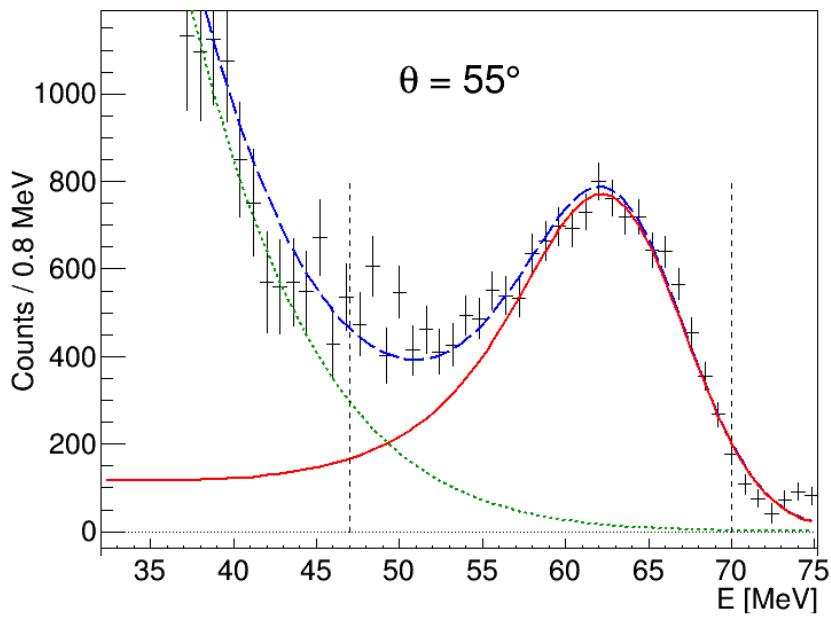
Effect of empty subtraction



- Empty target spectrum: target-related background
- The empty subtracted lineshapes are used in the yield extraction fitting

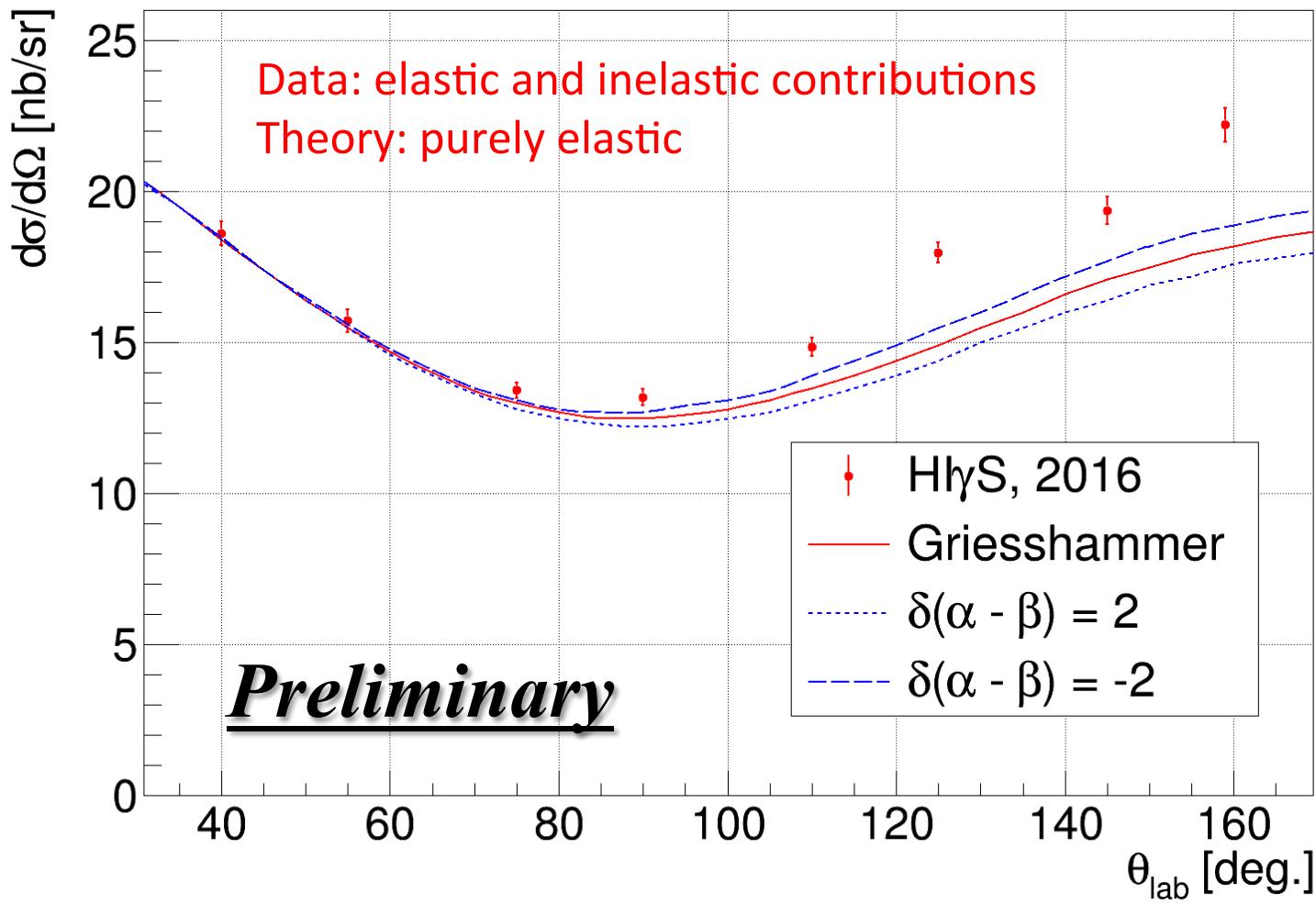
Compton scattering from ^2H , 65 MeV

- Typical forward and backward angle spectra



Total fit = Compton peak fit + Exponential background fit
(forward-angle detectors)

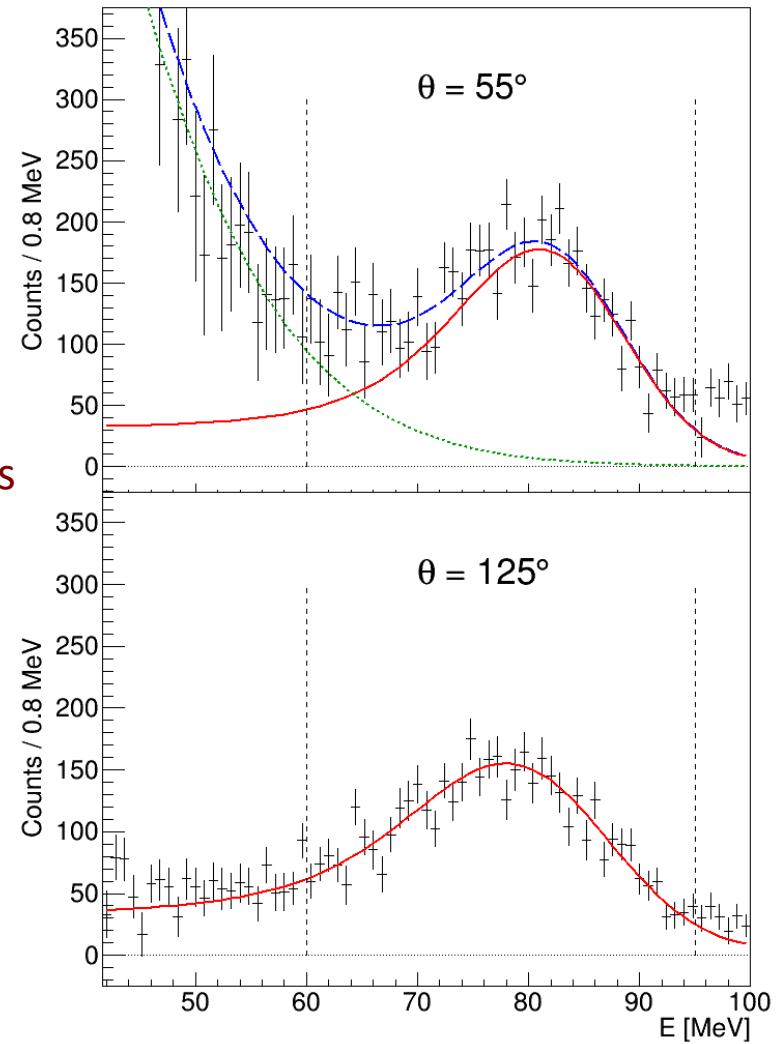
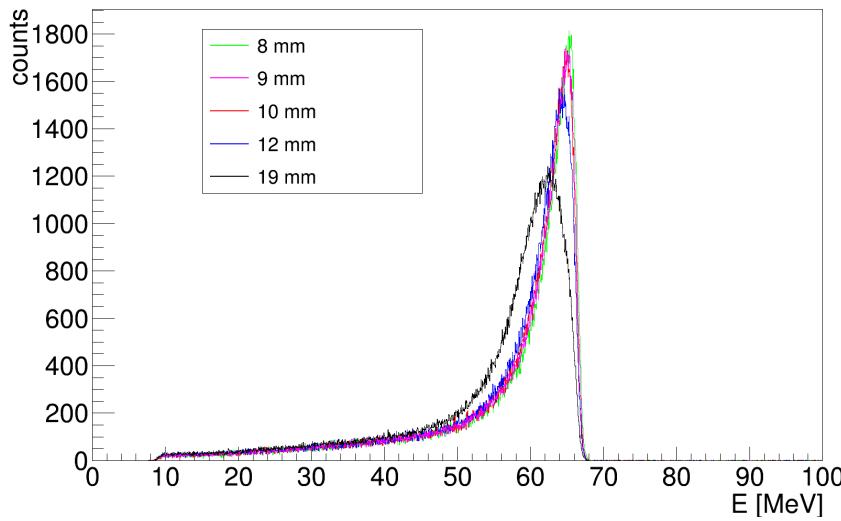
Compton scattering from ^2H , 65 MeV



Compton scattering from ^2H , 85 MeV

- To resolve the elastic and inelastic channels:
 - High resolution detectors
 - High resolution beams

Hi resolution beam test with various collimators



Summary

- EM polarizabilities
 - Fundamental properties of nucleons
 - Neutron data are not very precise
- HIγS: unique facility
 - Monoenergetic 1-110 MeV photon beams
 - high-intensity flux / high resolution
 - ~100% polarizations
- Compton scattering at HIγS
 - HINDA and cryogenic target
 - Provides the most precise extraction of α_n and β_n
 - Analysis ongoing, more data coming in future

Acknowledge:

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- c) Mike Kovash - **UKY** ;
- d) Rob Pywell - **USask**;
- e) Mark Spraker - **NGU**

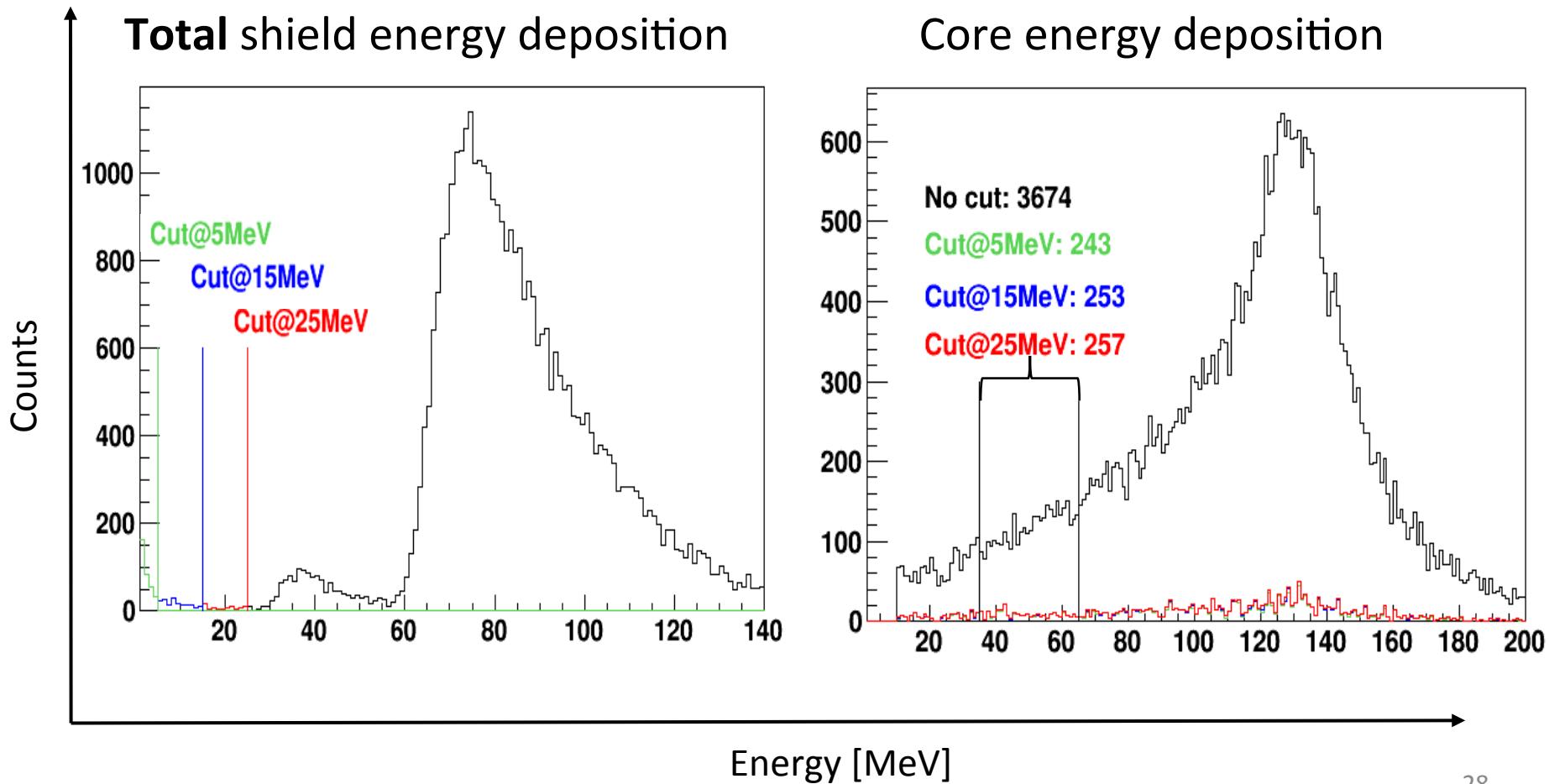
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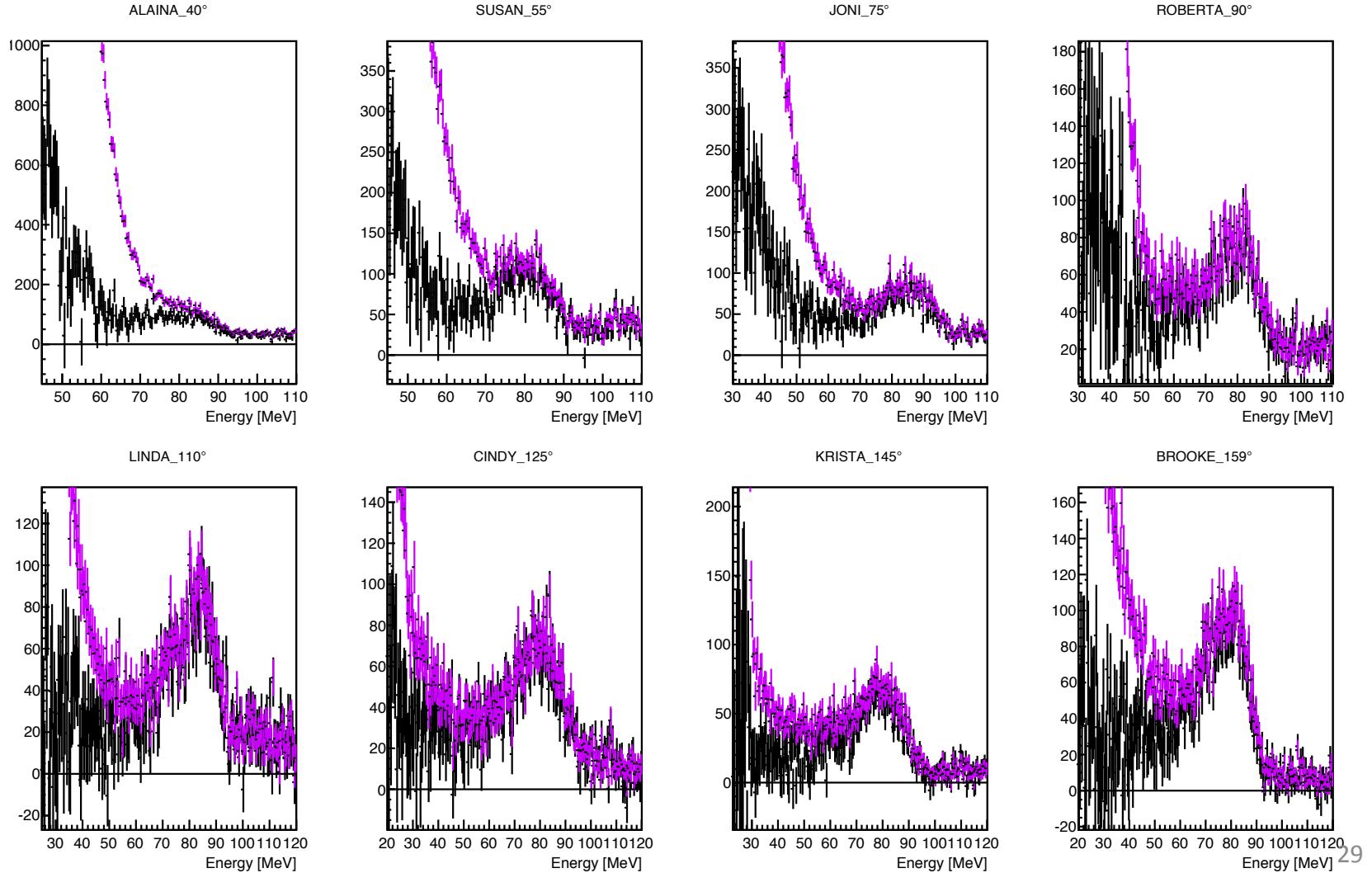
Thank you!
ΤHANK YOU

BACKUP SLIDES

Cosmic background rejection



Empty target subtraction



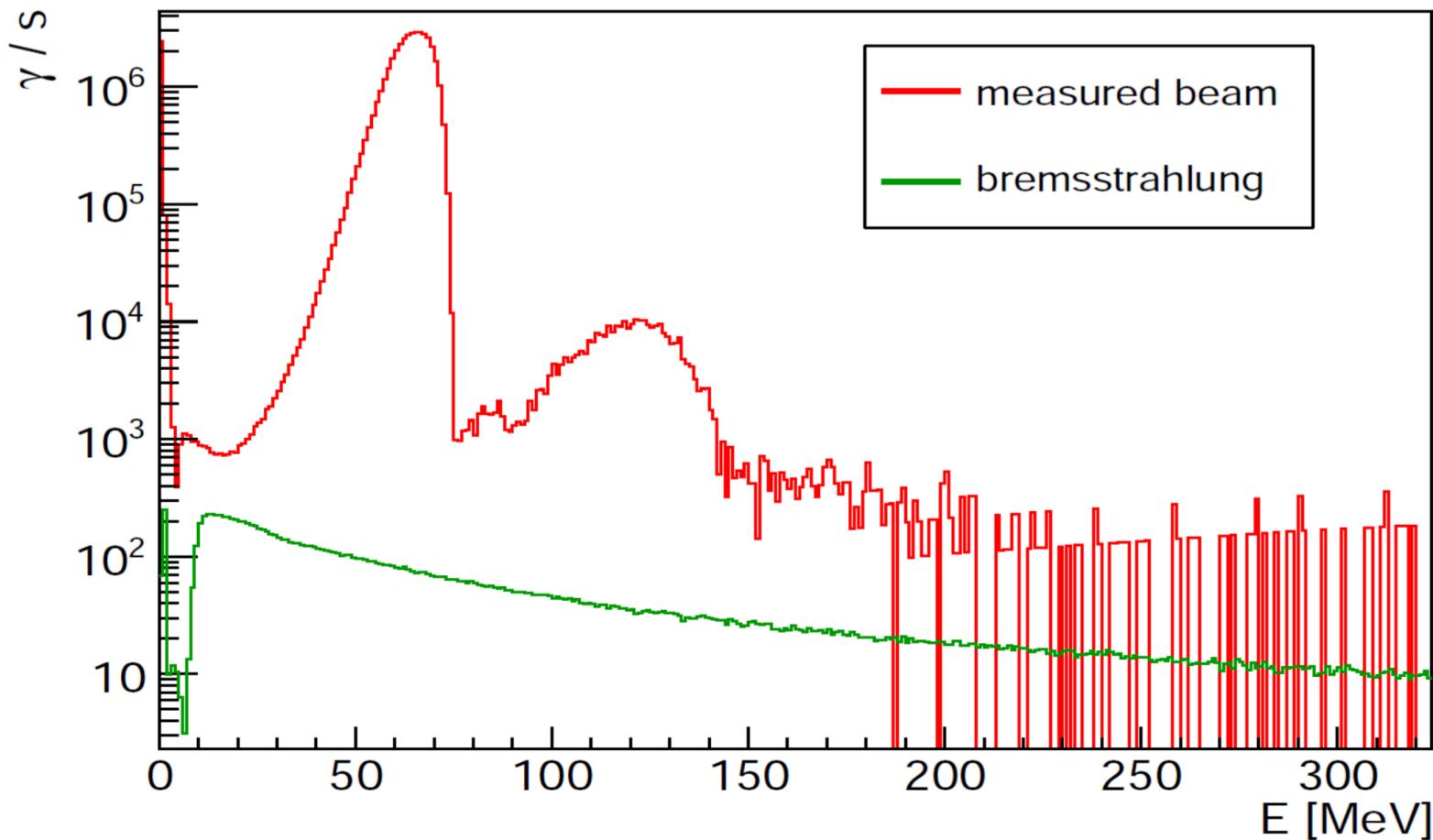
Compton data analysis outline

Formula for the differential cross section extraction:

$$\frac{d\sigma}{d\Omega} = \frac{\chi Y}{f_{abs} N_\gamma \kappa \Omega_{eff}}$$

- χY : **extracted yield**
- f_{abs} : correction factor for target absorption
- N_γ : number of incident photons
- κ : target thickness [nuclei/cm²]
- Ω_{eff} : effective solid angle

Post-production running beam measurements



DAQ electronics

