THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Compton Scattering & Polarizabilities at HIGS

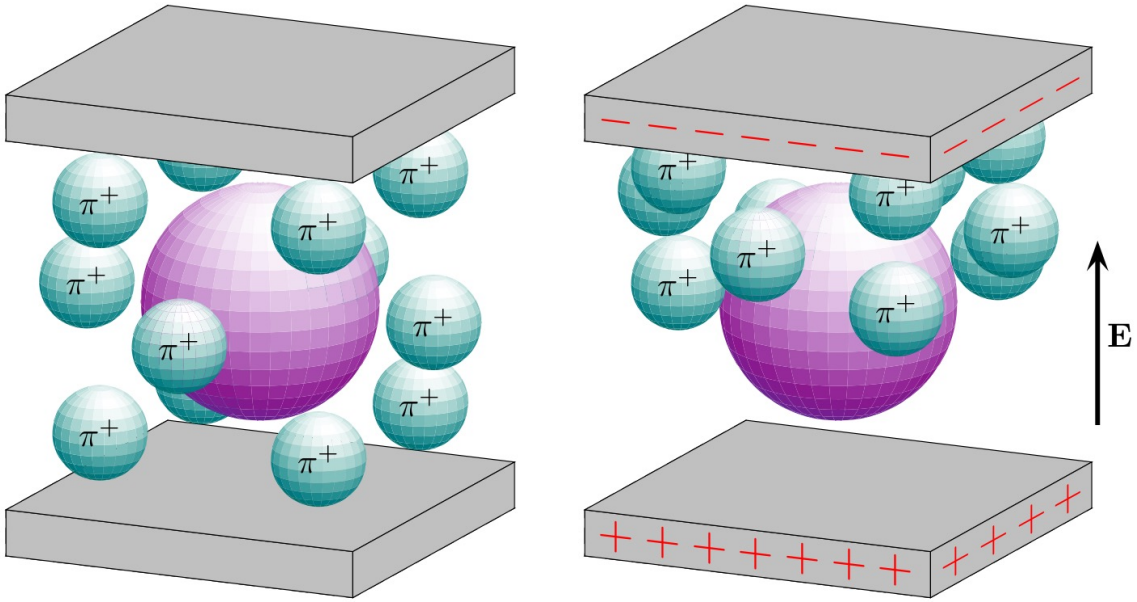
Evangeline J. Downie

TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

NSF
PHY-2012940 (GW)

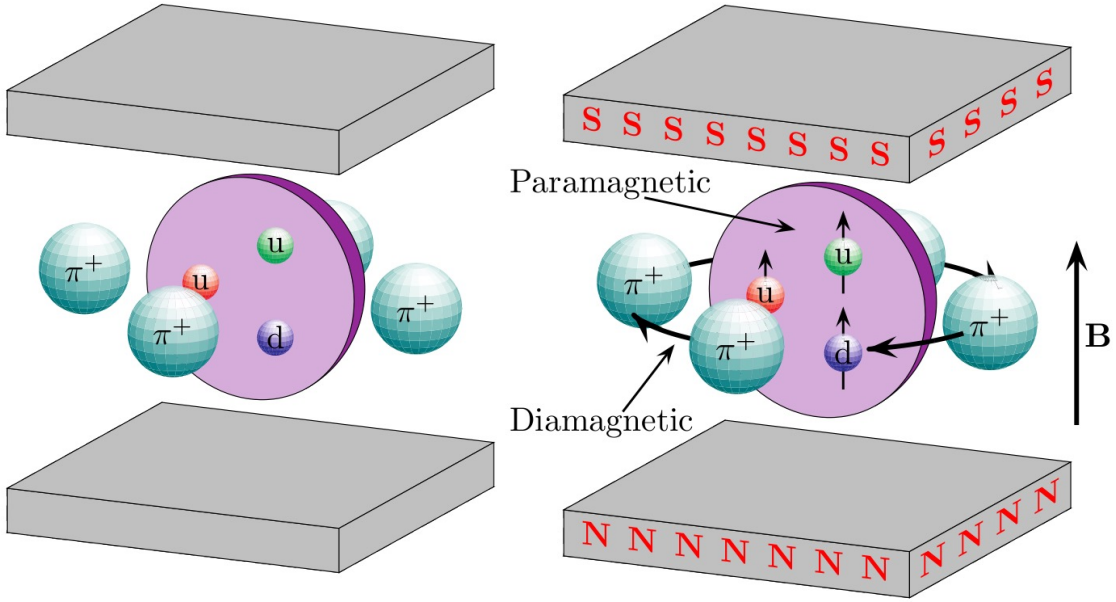
DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA
DE-SC0016581 (GW)
DE-FG02-97ER41033 (TUNL)
DE-SCOO0536 (Ahmed, NCCU)

Electric Polarizability



$$\vec{d}_{ind} = 4\pi\alpha\vec{E}$$

Magnetic Polarizability

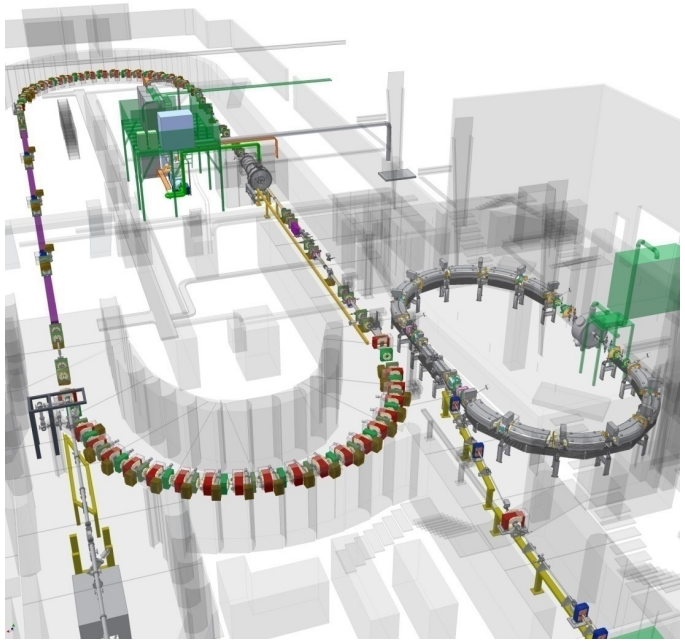


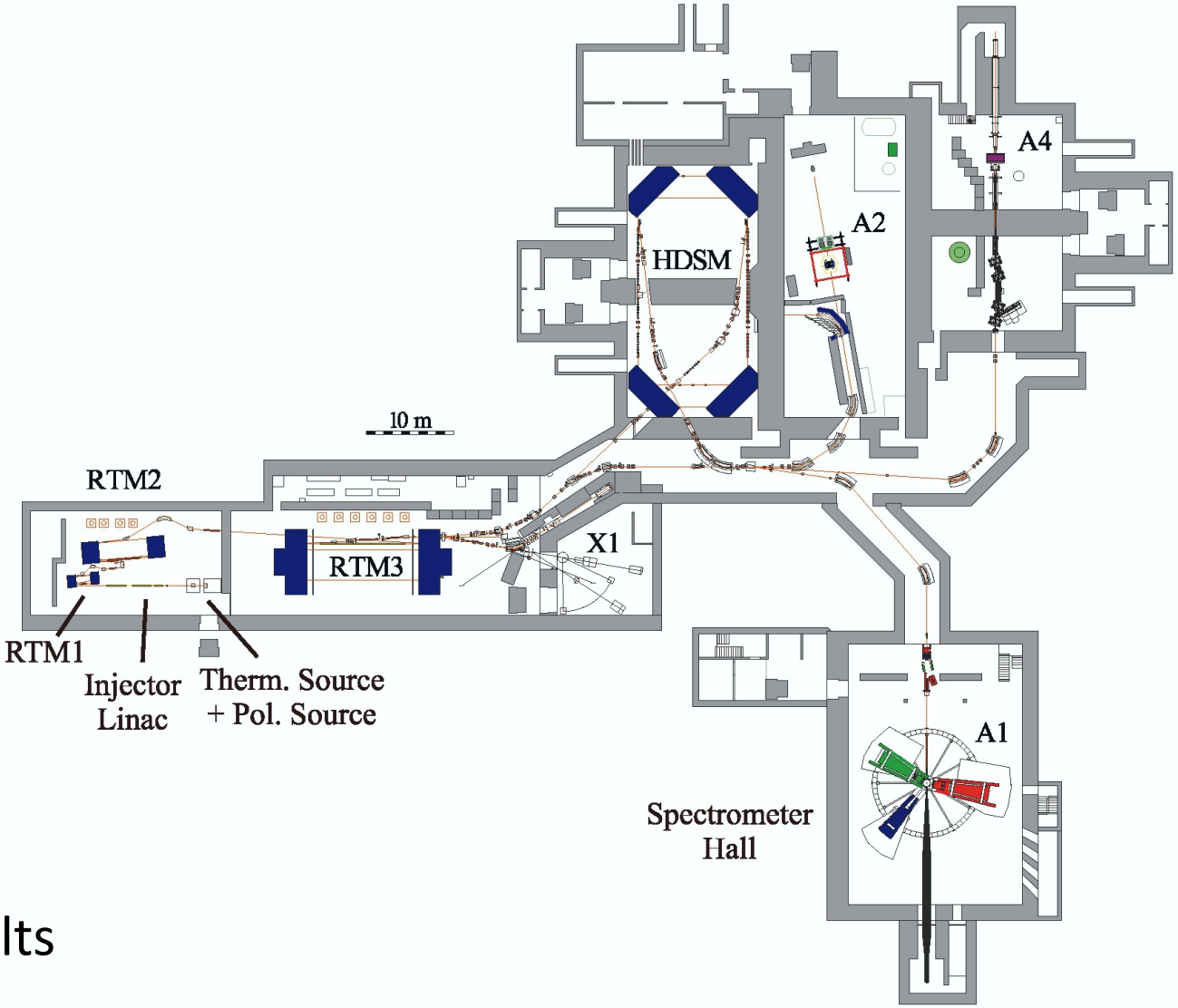
$$\vec{m}_{ind} = 4\pi\beta\vec{B}$$

Images: P. Martel, PhD Thesis (2012)

Compton Scattering & Polarizabilities

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC





- Cross sections small (~nb)
- Backgrounds very large
- Need a thorough systematic check of results

Why two facilities?

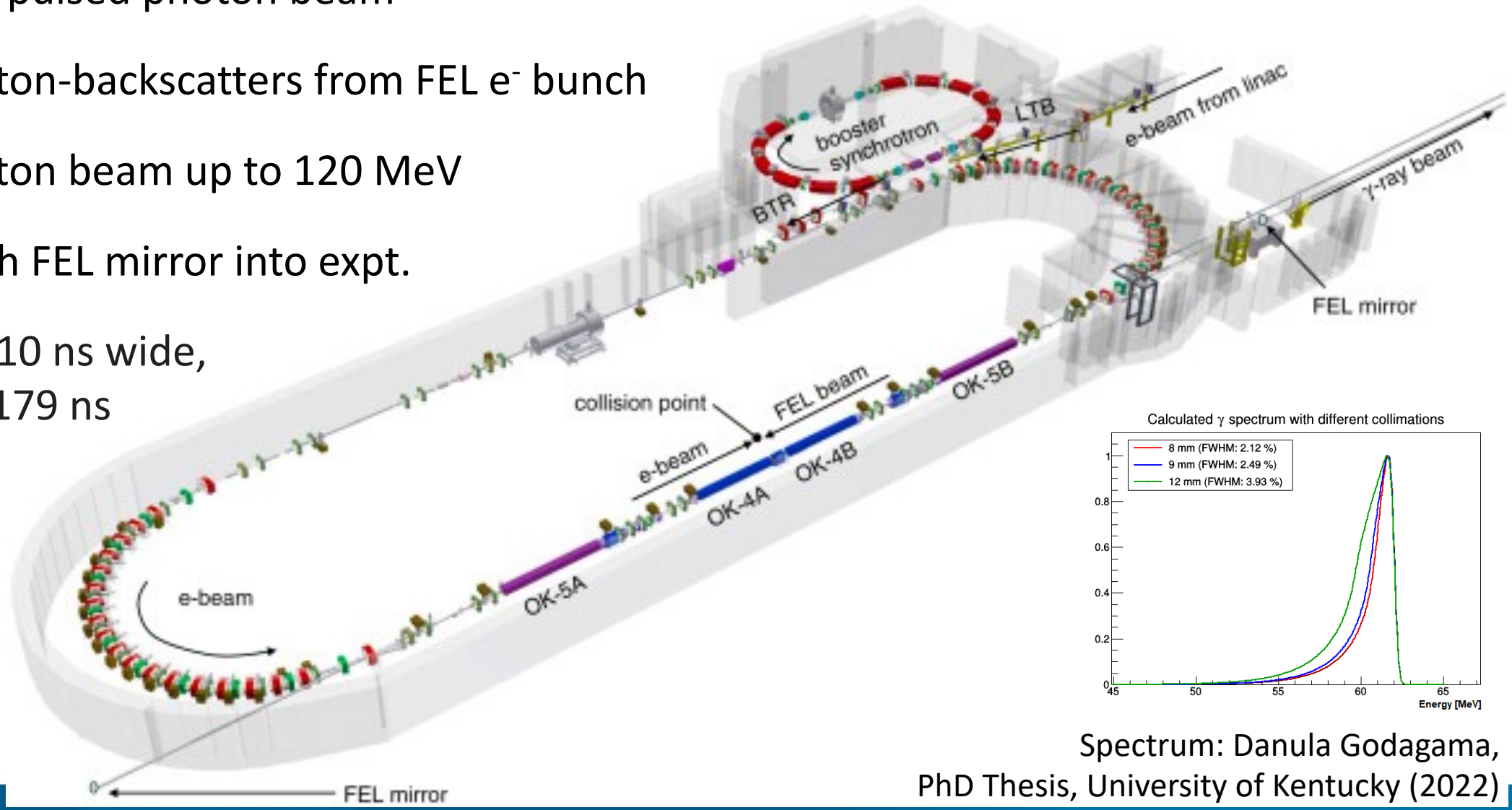
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Property	HIGS	MAMI
Beam Mechanism	Laser Compton Backscattering	Tagged Bremsstrahlung
Beam Energy Distribution	Around a central energy	$1/E_0$ distribution, tagged from ~5% - 92% of E_0
Maximum Energy	120 MeV	1.6 GeV, typically use 883 MeV or 450 MeV for Compton
Photon Flux	Max Flux: 10^7@65MeV, 10^9 at low E	2 x 10^6 rate in max. photon tagger channel
Polarization Mechanism	Wiggler Cavity	Linear: Diamond radiator Circular: e-beam polarization
Polarization	Linear or circular, ~100%	Energy dependent
Backgrounds	Small	Pion Photoproduction
Detector	High resolution, large volume NaI	Large solid angle, segmented NaI, BaF_2, and $PbWO_4$
Polarizability Extraction	Model dependence small, sensitivity small	Model dependence larger, sensitivity higher

Comparison of HIGS & MAMI

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

- FEL generates pulsed photon beam
- Photon Compton-backscatters from FEL e^- bunch
- Produces photon beam up to 120 MeV
- Passes through FEL mirror into expt.
- Photon pulse 10 ns wide, separated by 179 ns

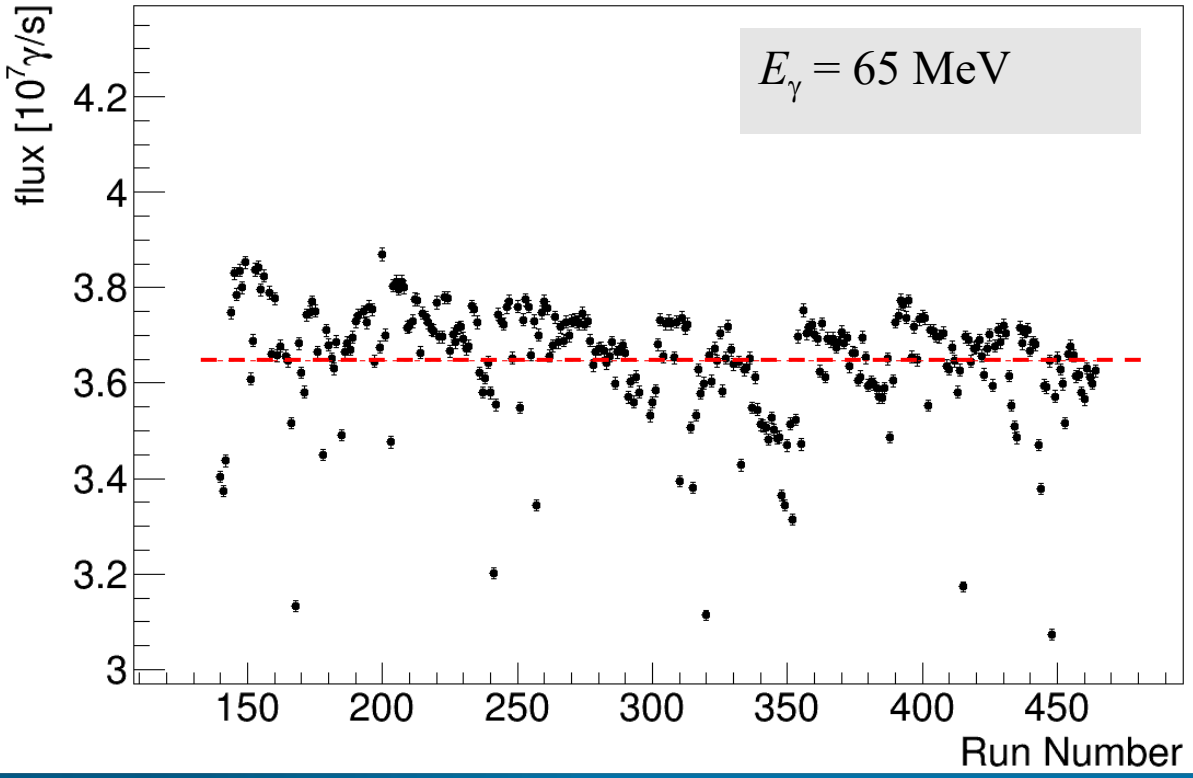


Spectrum: Danula Godagama, PhD Thesis, University of Kentucky (2022)

HIGS Operation

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

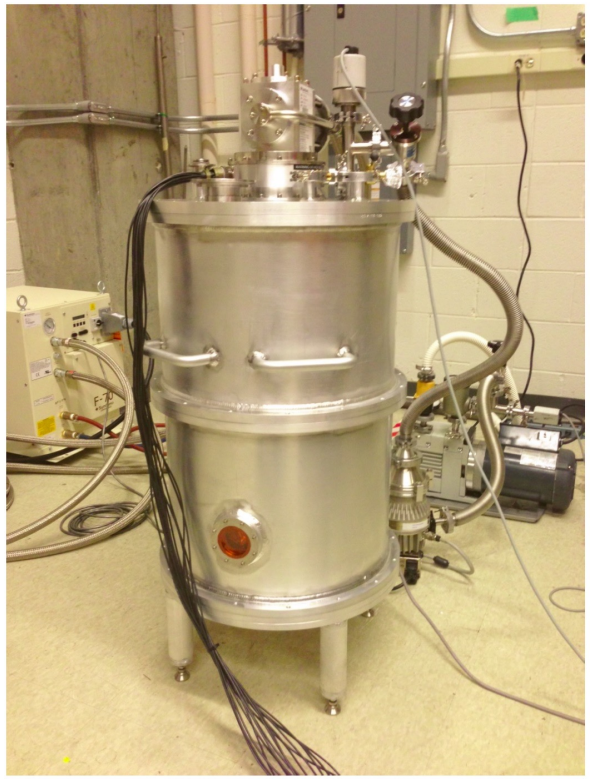
- Monoenergetic photons up to ~120 MeV
  - ✓ beam energy resolution depends on collimation
- Close to 100% linear or circular polarization
- High photon beam intensity
  - ✓ ~5×10^6 Hz above 80 MeV
  - ✓ ~10^7 Hz at 20-80 MeV
  - ✓ ~10^8 Hz below 20 MeV

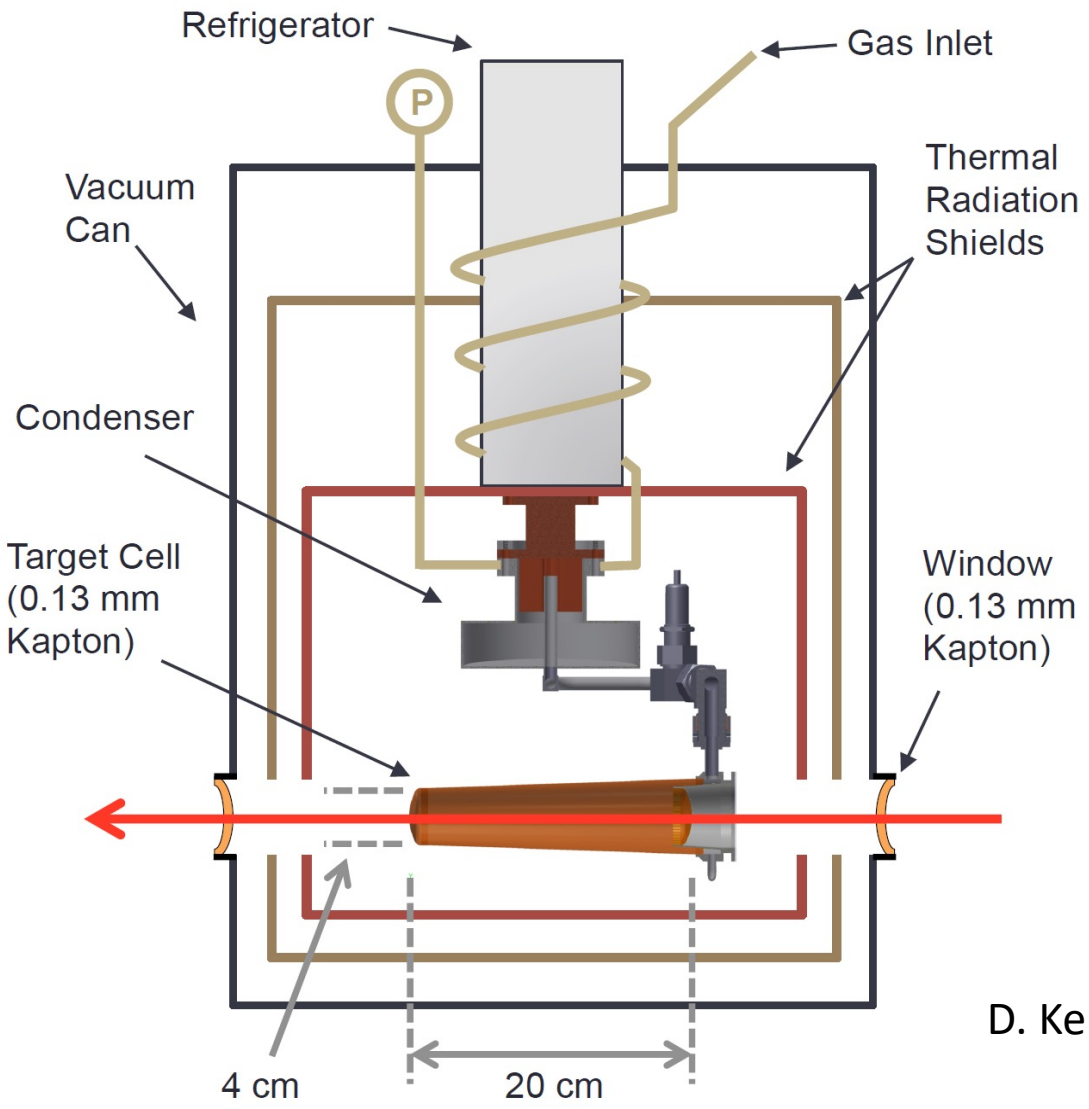


HIGS Facility

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

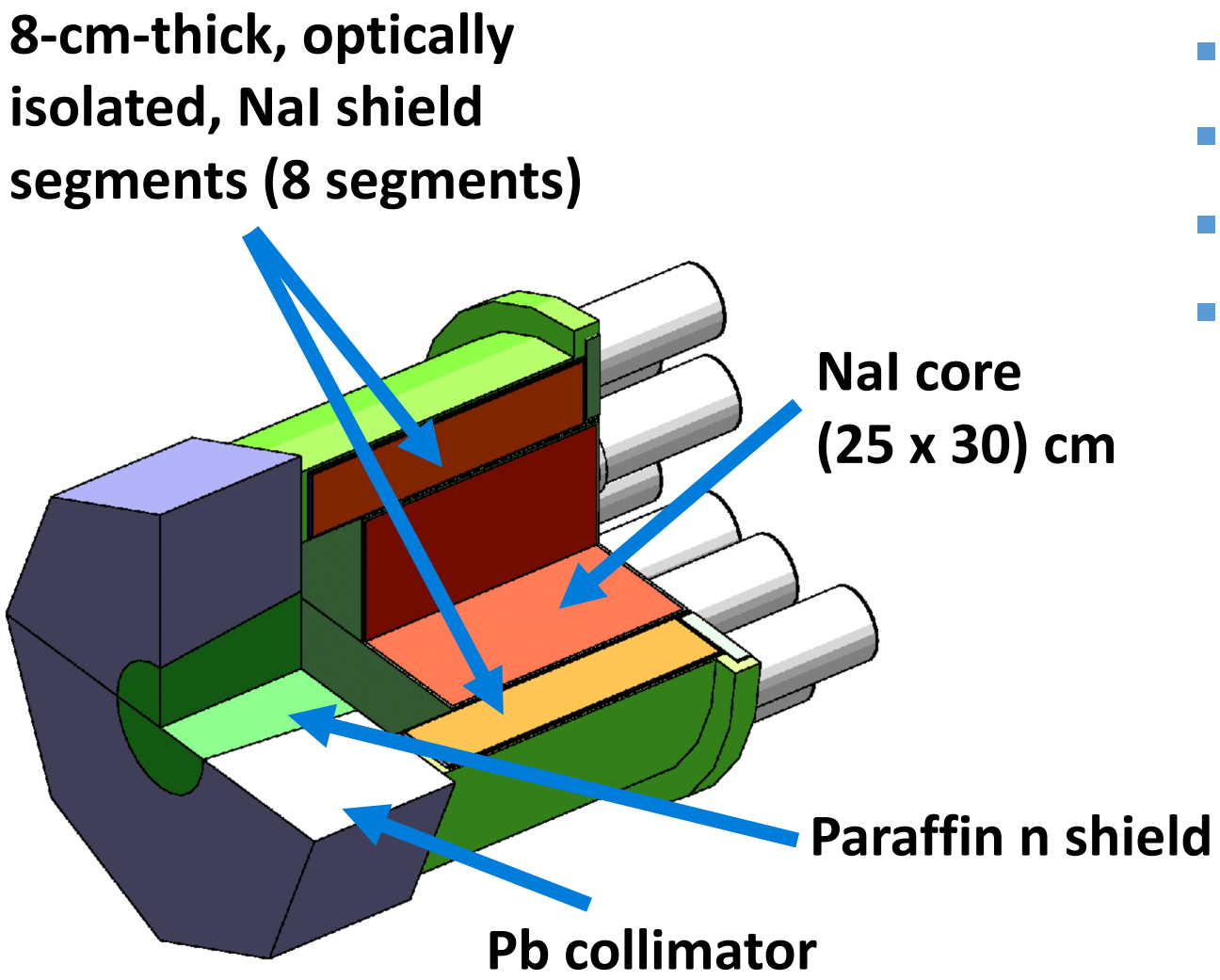
- Allows LH_2 / LD_2 / LHe
- Temperature range: 3.5 K – 24 K
- Working on adjustments to prepare for ^3He





D. Kendellen (2016)

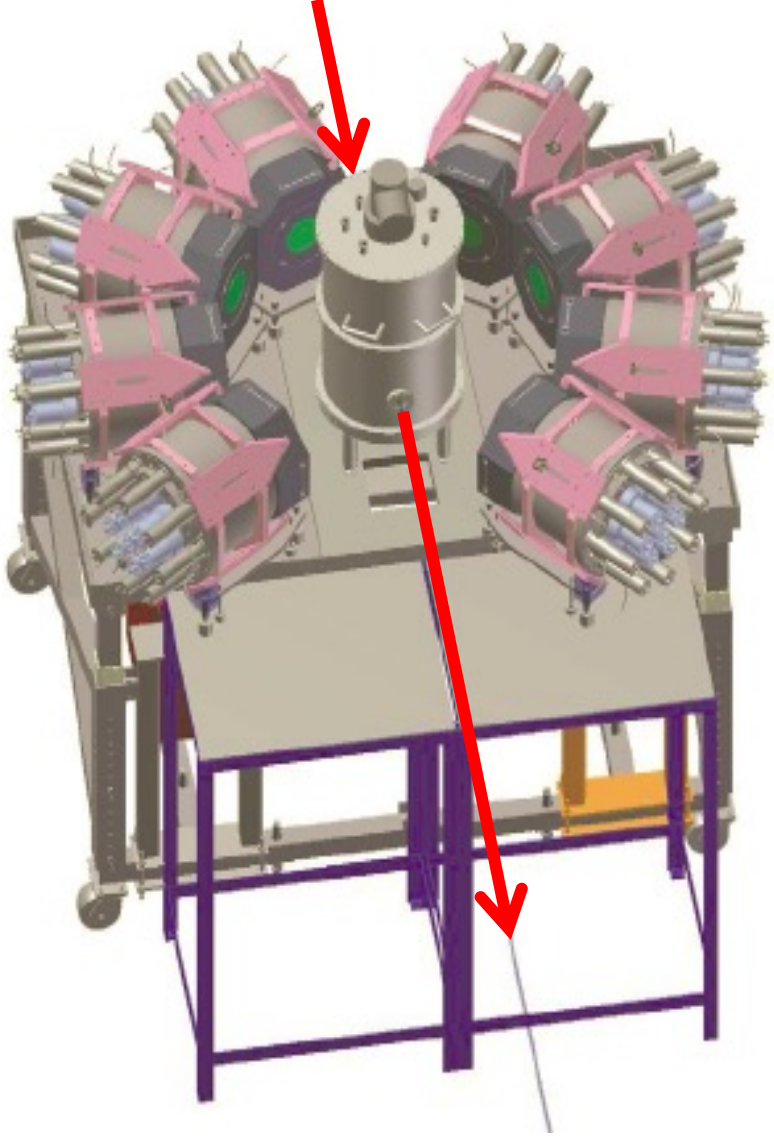
Cryogenic Target

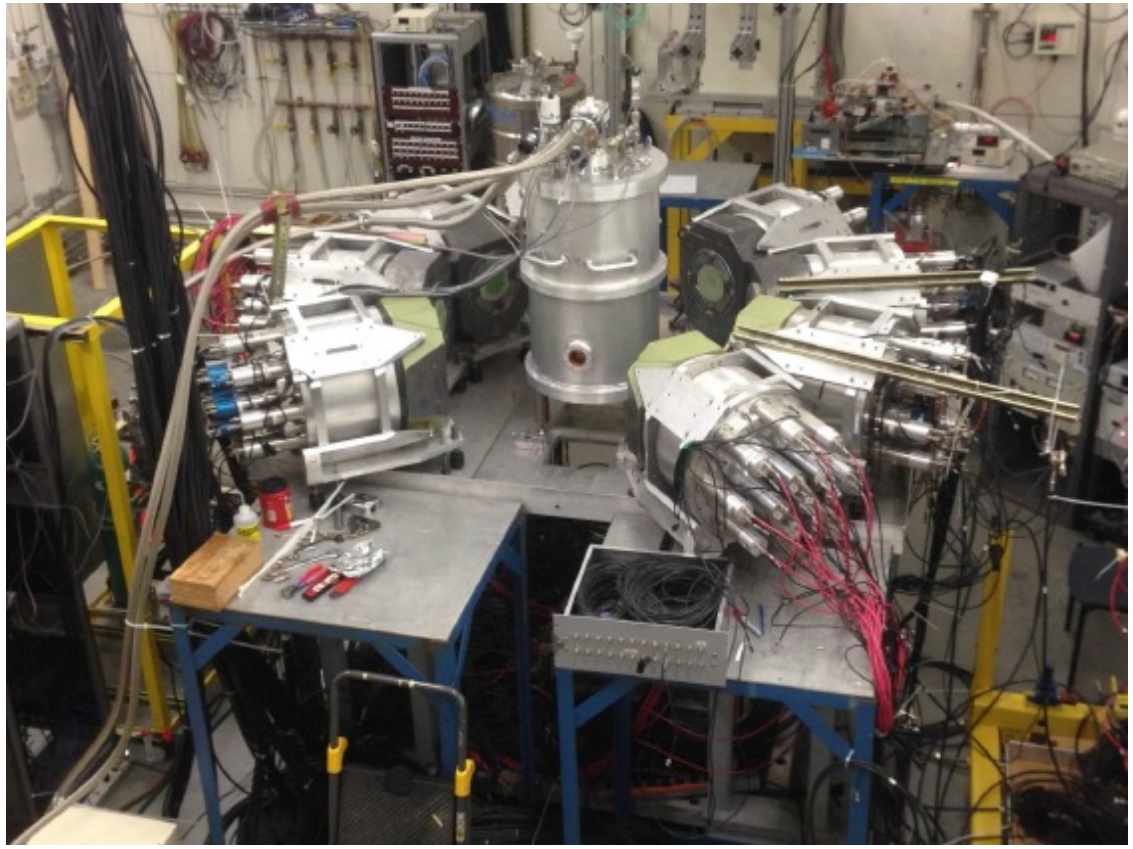


- Array of up to 8 elements
- Can be positioned for optimal coverage
- Both in-plane and out-of-plane
- Shield segments allow cosmic veto

HIGS NaI Detector Array (HINDA)

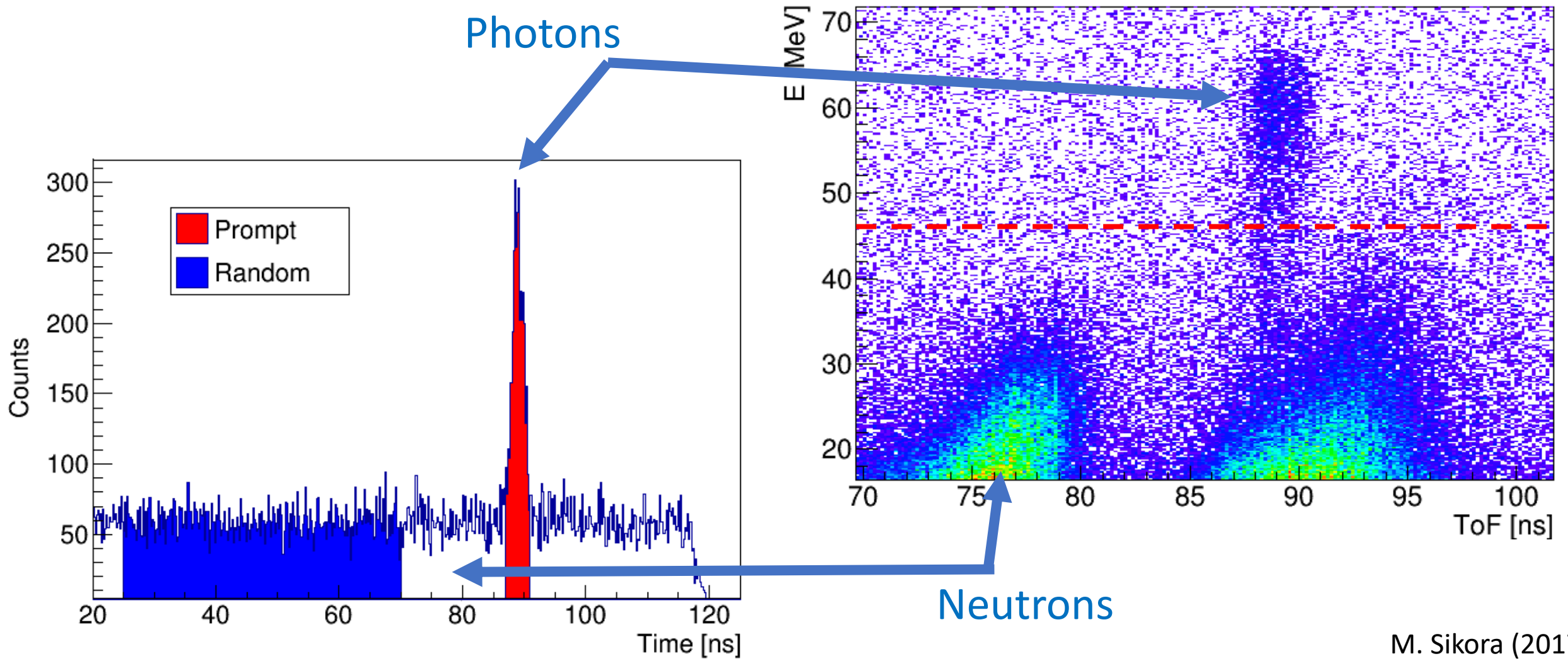
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC





Setup for ^{4}He Experiment

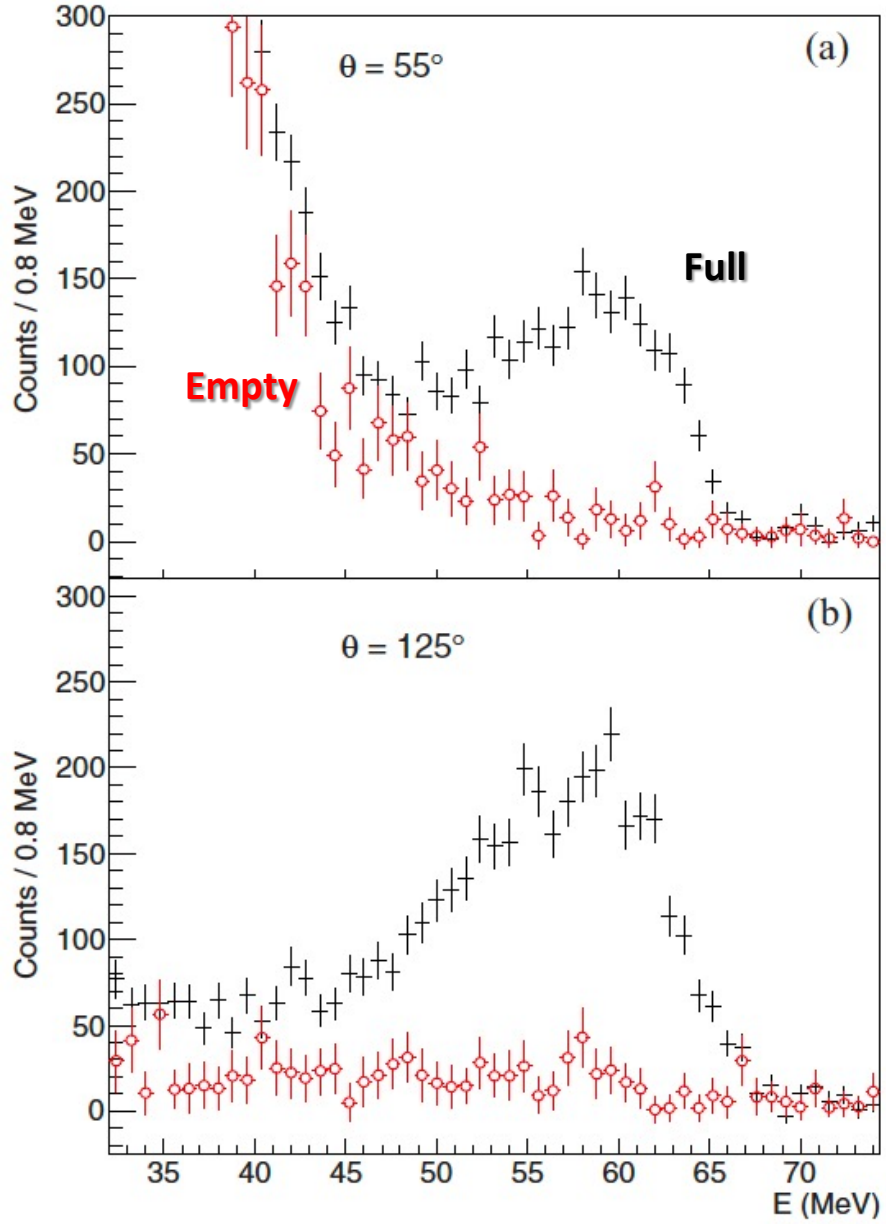
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC



M. Sikora (2017)

Random Subtraction

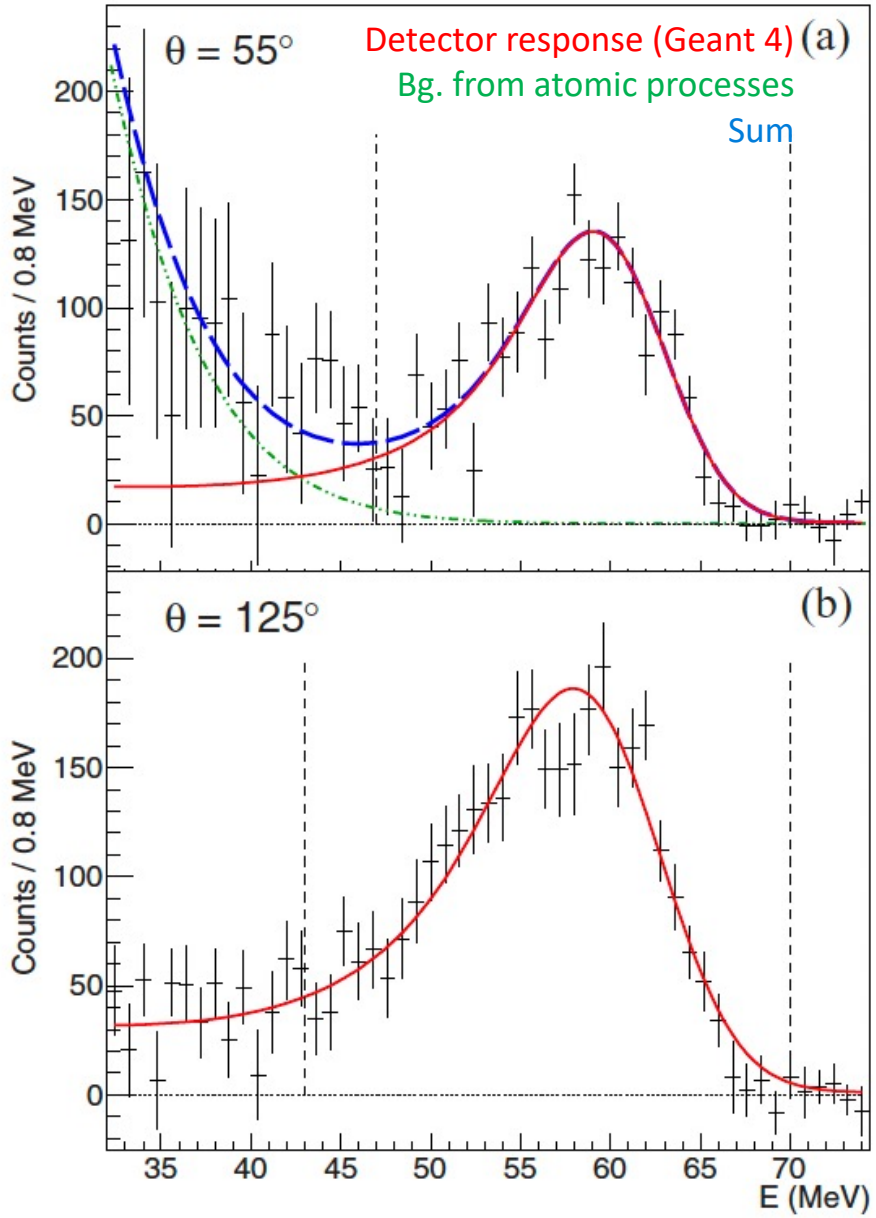
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC



$^4He(\gamma,\gamma)^4He$

E_γ= 61 MeV

M. Sikora *et al.*, PRC 96, 055209 (2017)

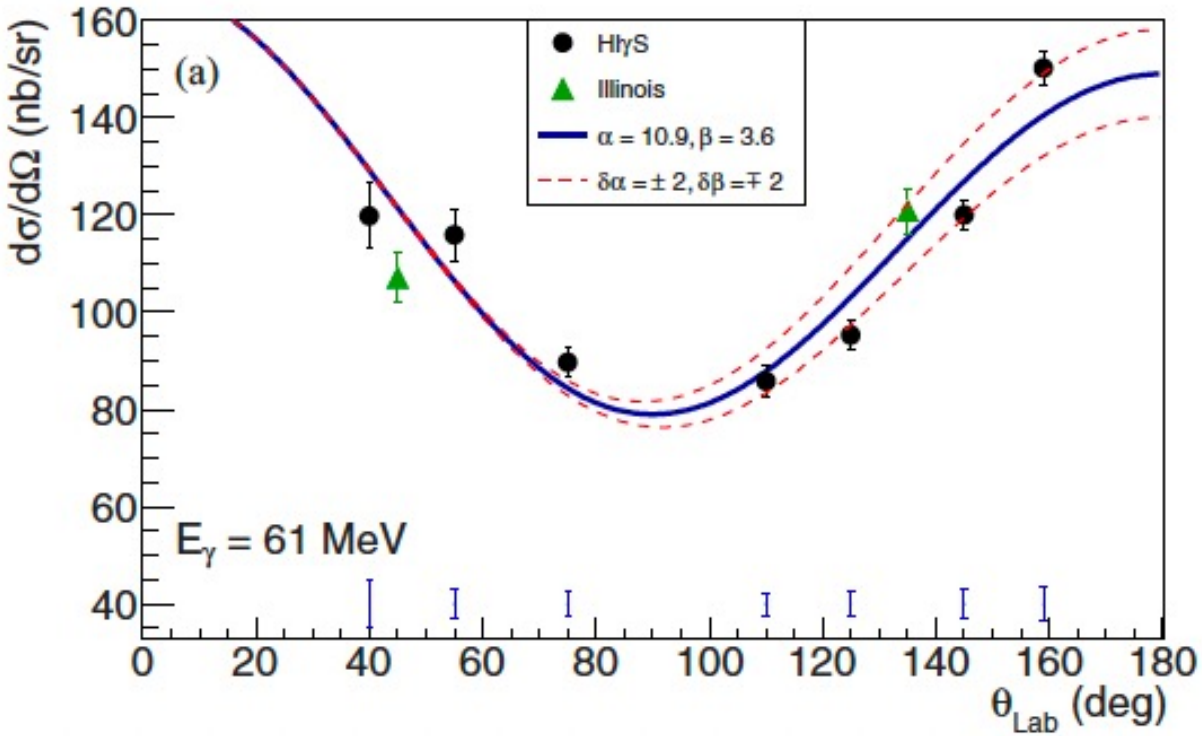


Scattered Photon Spectra

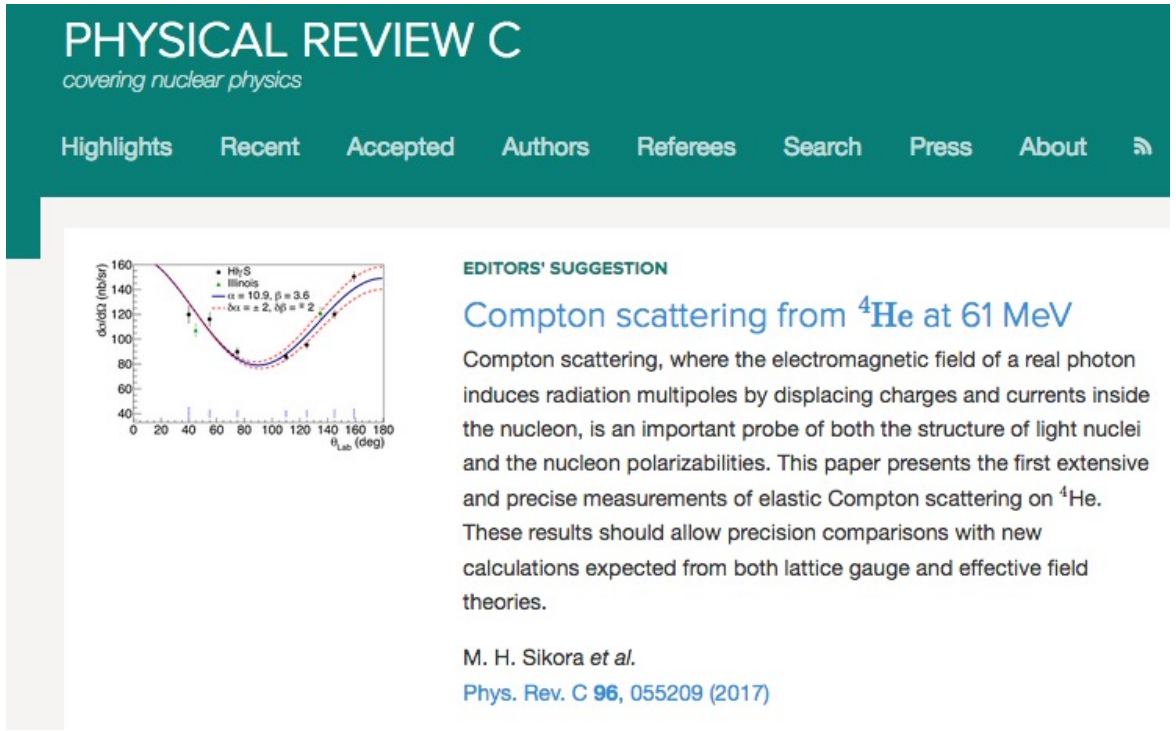
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

$^4He(\gamma,\gamma)^4He$

E_γ= 61 MeV



Illinois: D. Wells, Ph.D. thesis, University of Illinois at Urbana-Champaign, Champaign, IL, 1990



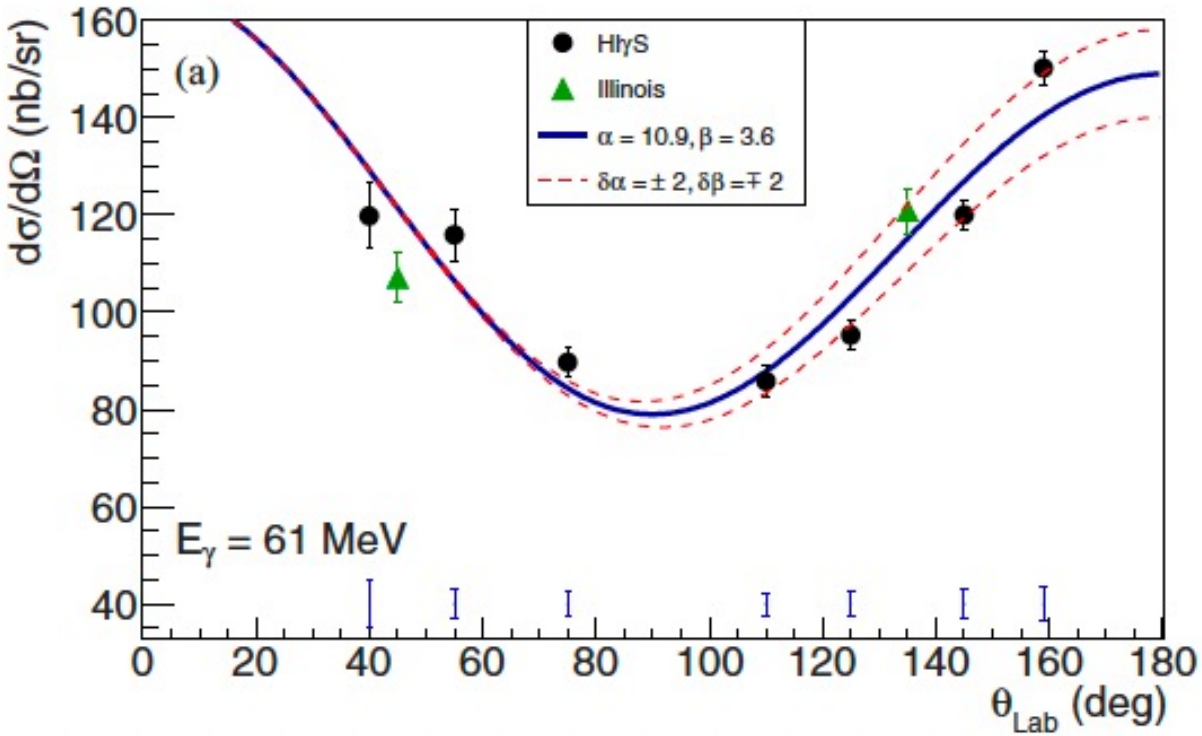
M. Sikora *et al.*, PRC **96**, 055209 (2017)

^{4}He Compton Scattering

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

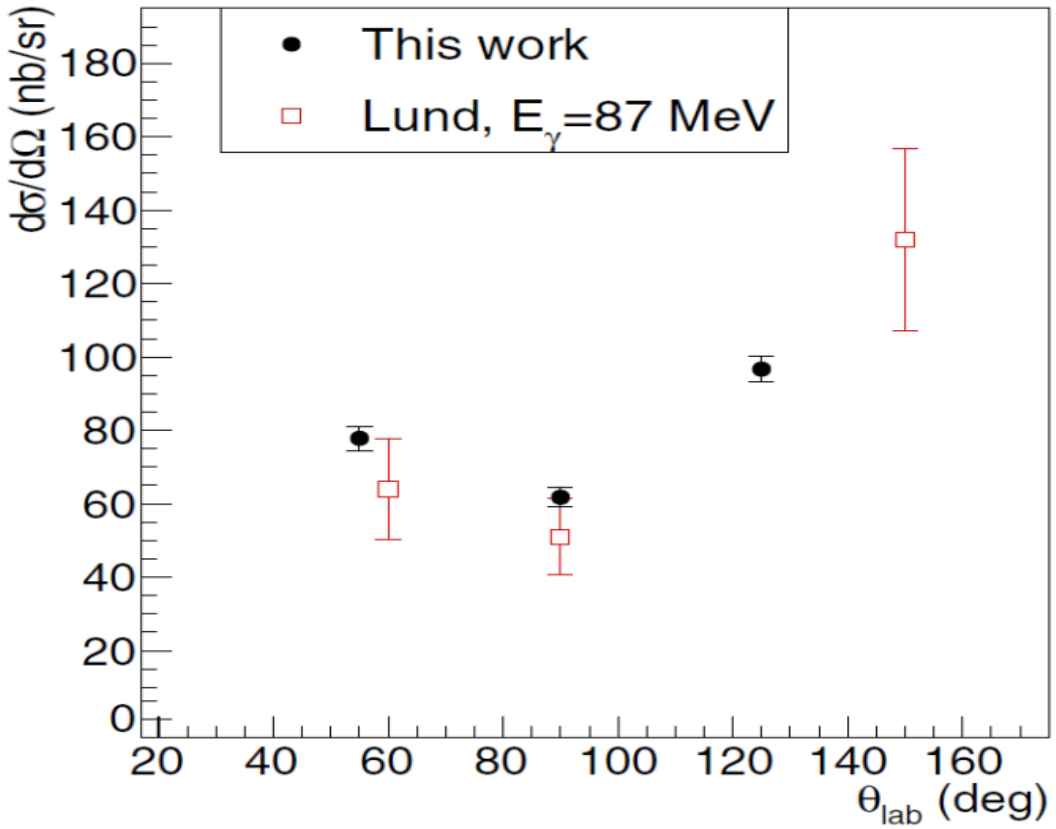
$^4He(\gamma,\gamma)^4He$

E_γ= 61 MeV, 54 hours



M. Sikora *et al.*, PRC **96**, 055209 (2017)

E_γ= 81 MeV, 100 hours

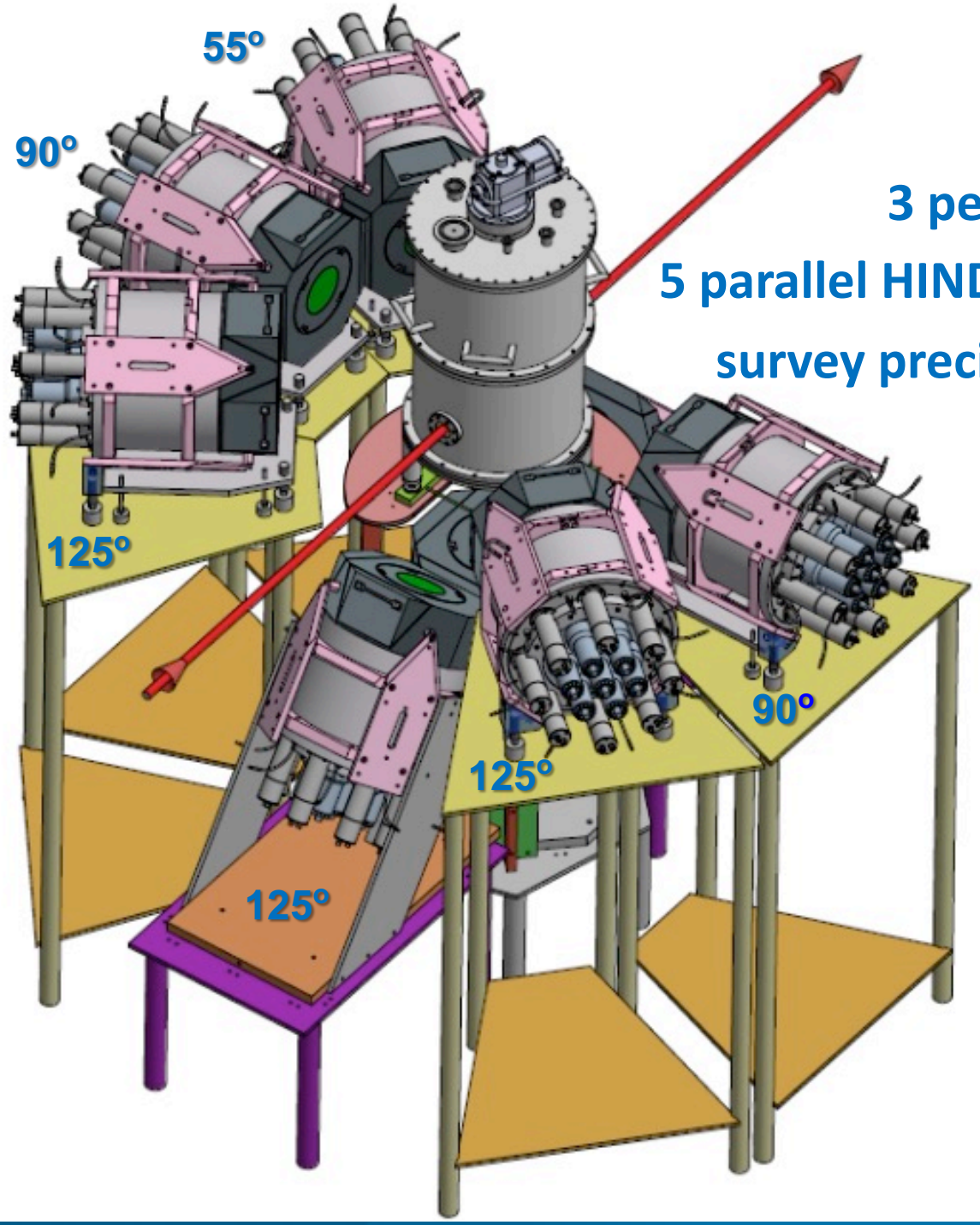


X. Li *et al.*, PRC **101**, 034618 (2020)

^{4}He Compton Scattering

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

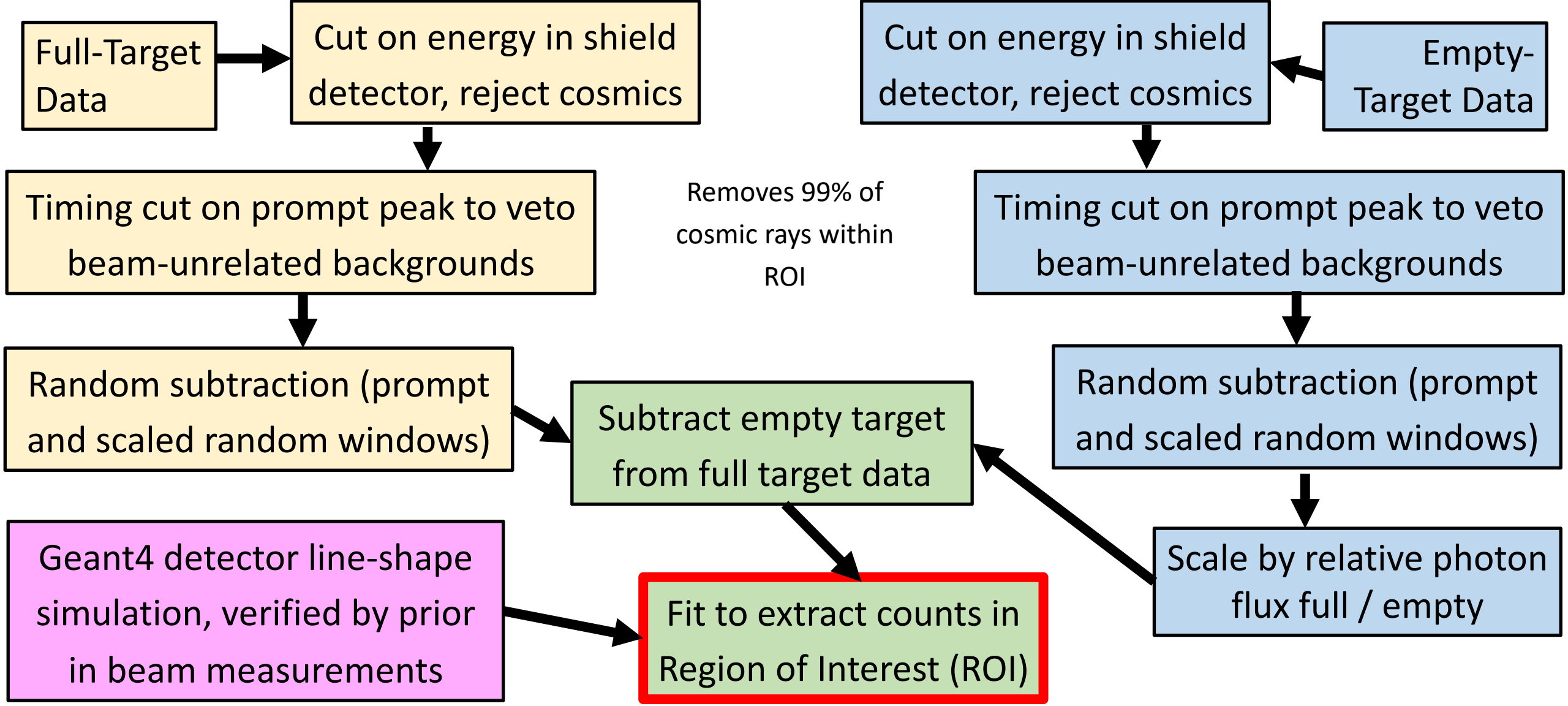
- Polarized Compton scattering on p
- 25.4-mm-diameter lead collimator
- Horizontal Lin. Pol:
  - ✓ 83.4 MeV, 2.7% FWHM
- Circularly pol.
  - ✓ 81.3 MeV, 6.5% FWHM
- On-target intensity ≈10^7 γ/s.



3 perpendicular,
5 parallel HINDA elements
survey precision 0.5mm

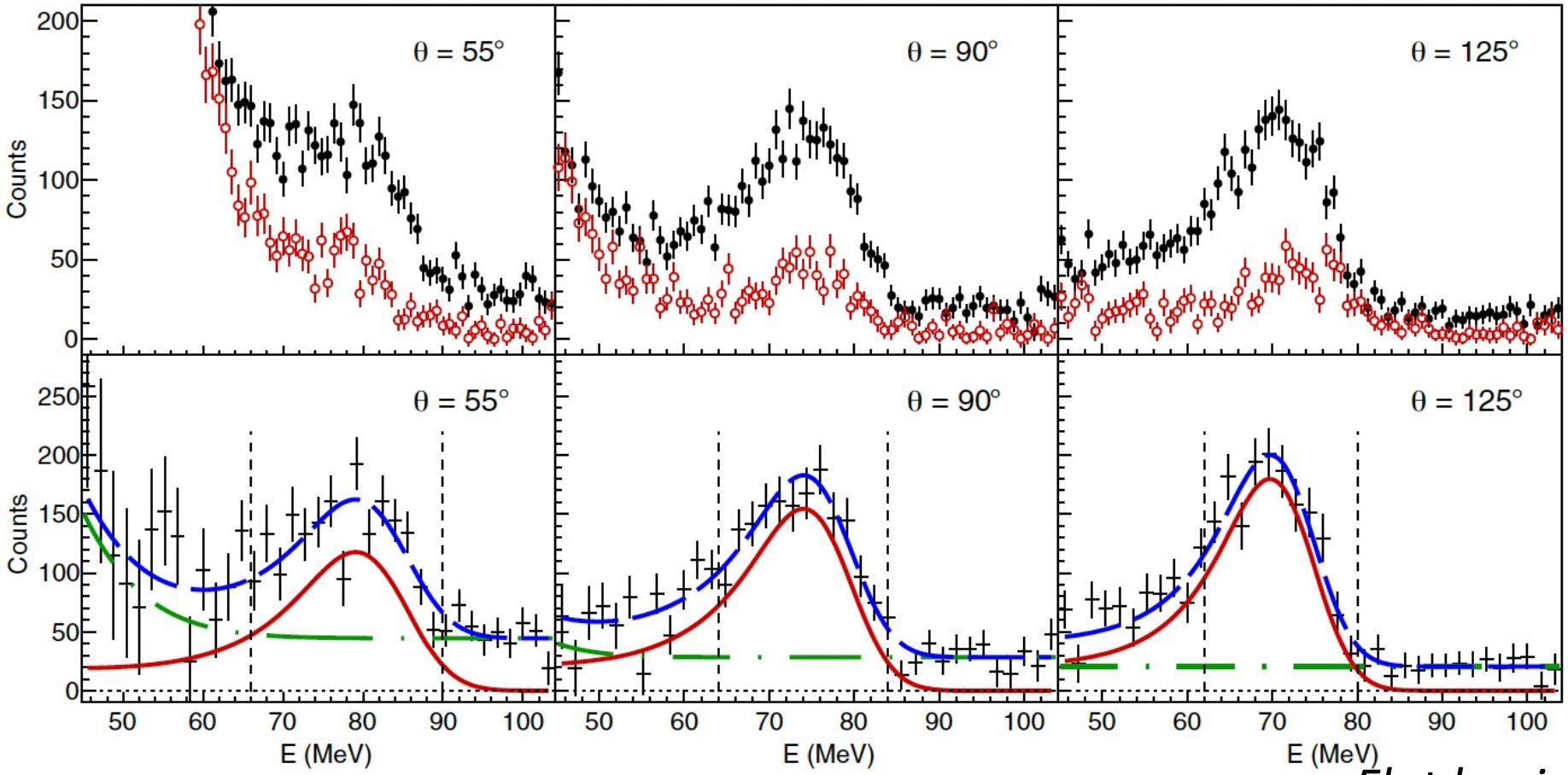
Experimental Setup

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC



Data Analysis

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC



Full Target
Empty Target

Forward region bg. from atomic processes in low E region, fitted with exponential

Sum of simulation and bg.
Simulated detector line-shape
Fitted Background

Flat bg. in all detectors scattering of brems. photons from e^- beam in storage ring

Background Subtraction

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Normalized for:

- Efficiencies
- Target thickness
- Target absorption (incident γ)
- Bin center correction factors
- Effective solid angles

Cross Section Extraction

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Normalized for:

- Efficiencies
- Target thickness
- Target absorption (incident γ)
- Bin center correction factors
- Effective solid angles

Overall Systematic Uncertainty:

- No. of incident γ – 2%
- Target thickness – 1%

Cross Section Extraction

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Normalized for:

- Efficiencies
- Target thickness
- Target absorption (incident γ)
- Bin center correction factors
- Effective solid angles

Point-to-Point Systematics:

- Cuts to timing spectra
- Cuts on shield energy
- ROI boundaries
- Fitting window

Varied by individual detector

Range: 4.5% to 13.8%

Overall Systematic Uncertainty:

- No. of incident γ – 2%
- Target thickness – 1%

Cross Section Extraction

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Normalized for:

- Efficiencies
- Target thickness
- Target absorption (incident γ)
- Bin center correction factors
- Effective solid angles

Point-to-Point Systematics:

- Cuts to timing spectra
- Cuts on shield energy
- ROI boundaries
- Fitting window

Varied by individual detector

Range: 4.5% to 13.8%

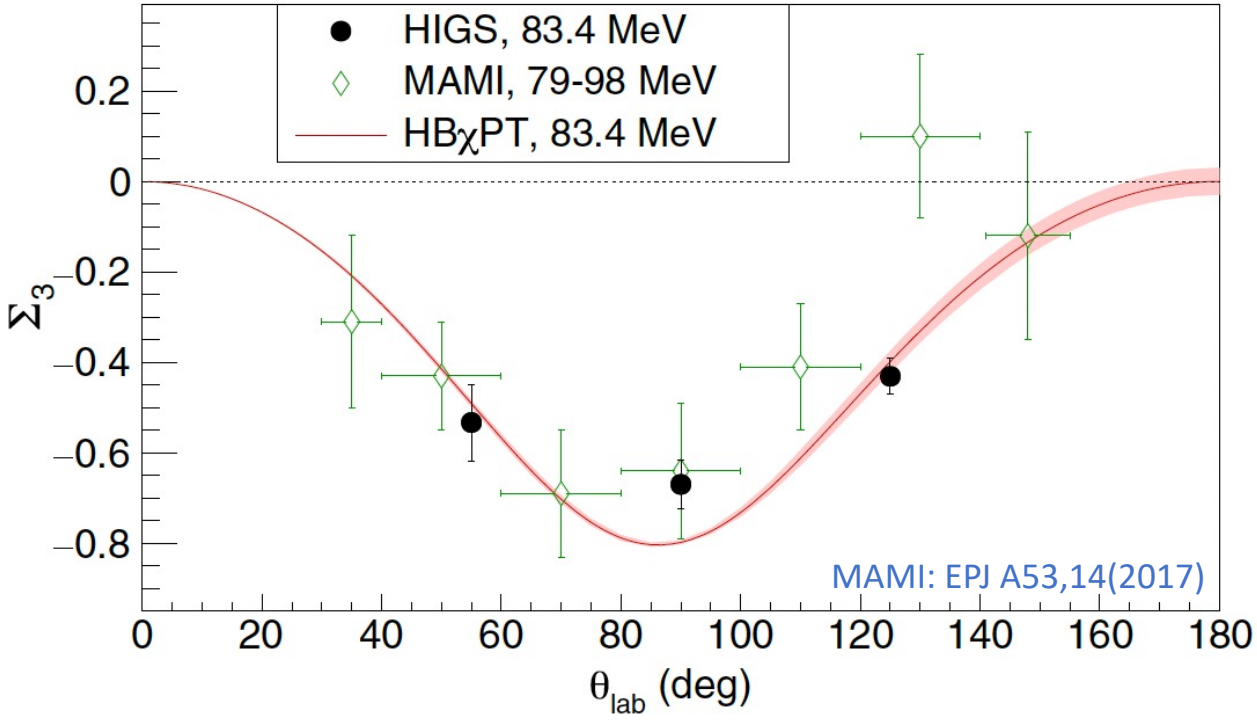
Additional Point-to-Point Systematics for perp. 55° & 125° due to uncertainty in distance to target

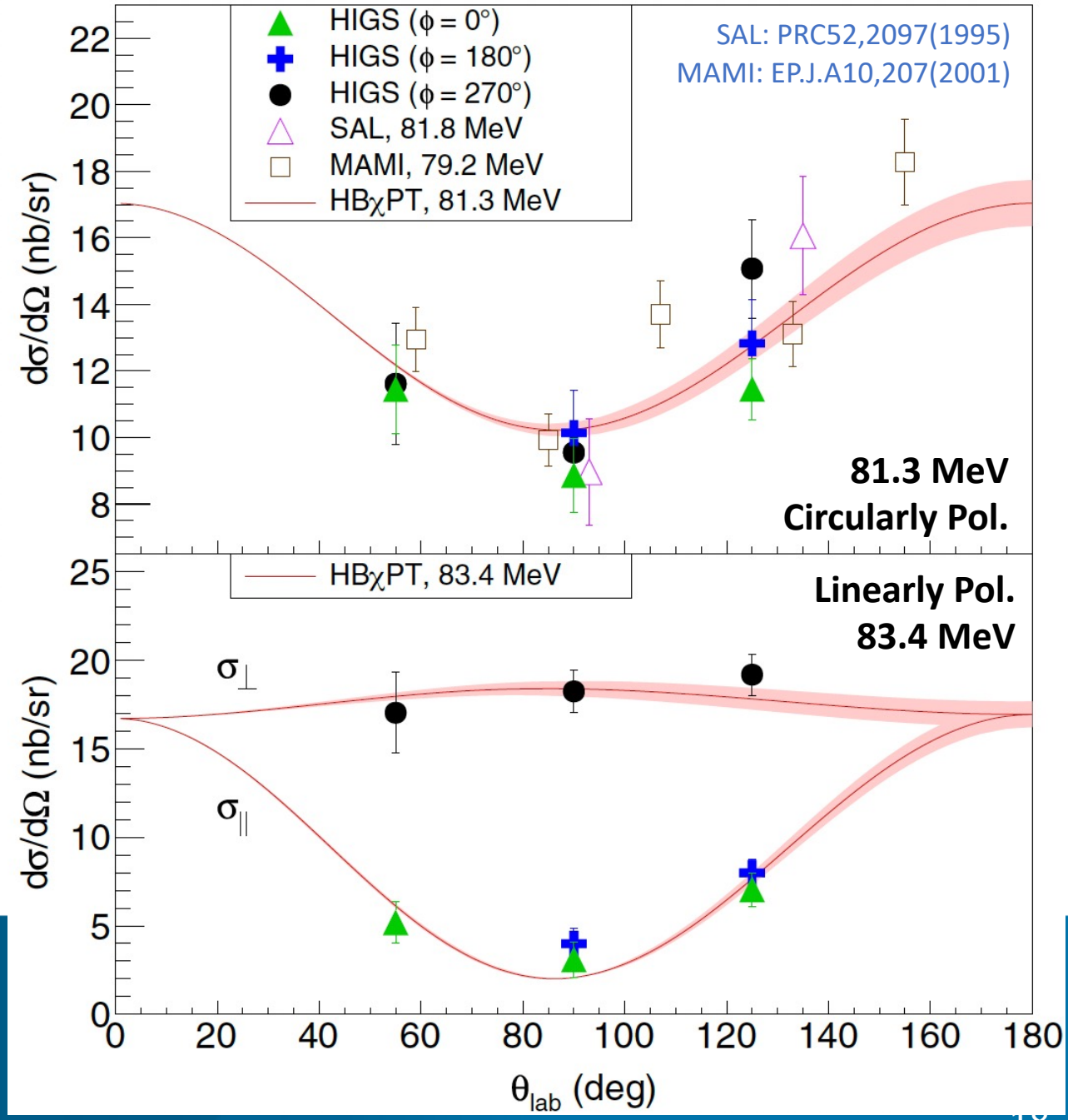
Overall Systematic Uncertainty:

- No. of incident γ – 2%
- Target thickness – 1%

Cross Section Extraction

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC





Curves with 1σ error bands theoretical cross sections implied by measured polarizabilities using the χEFT framework.

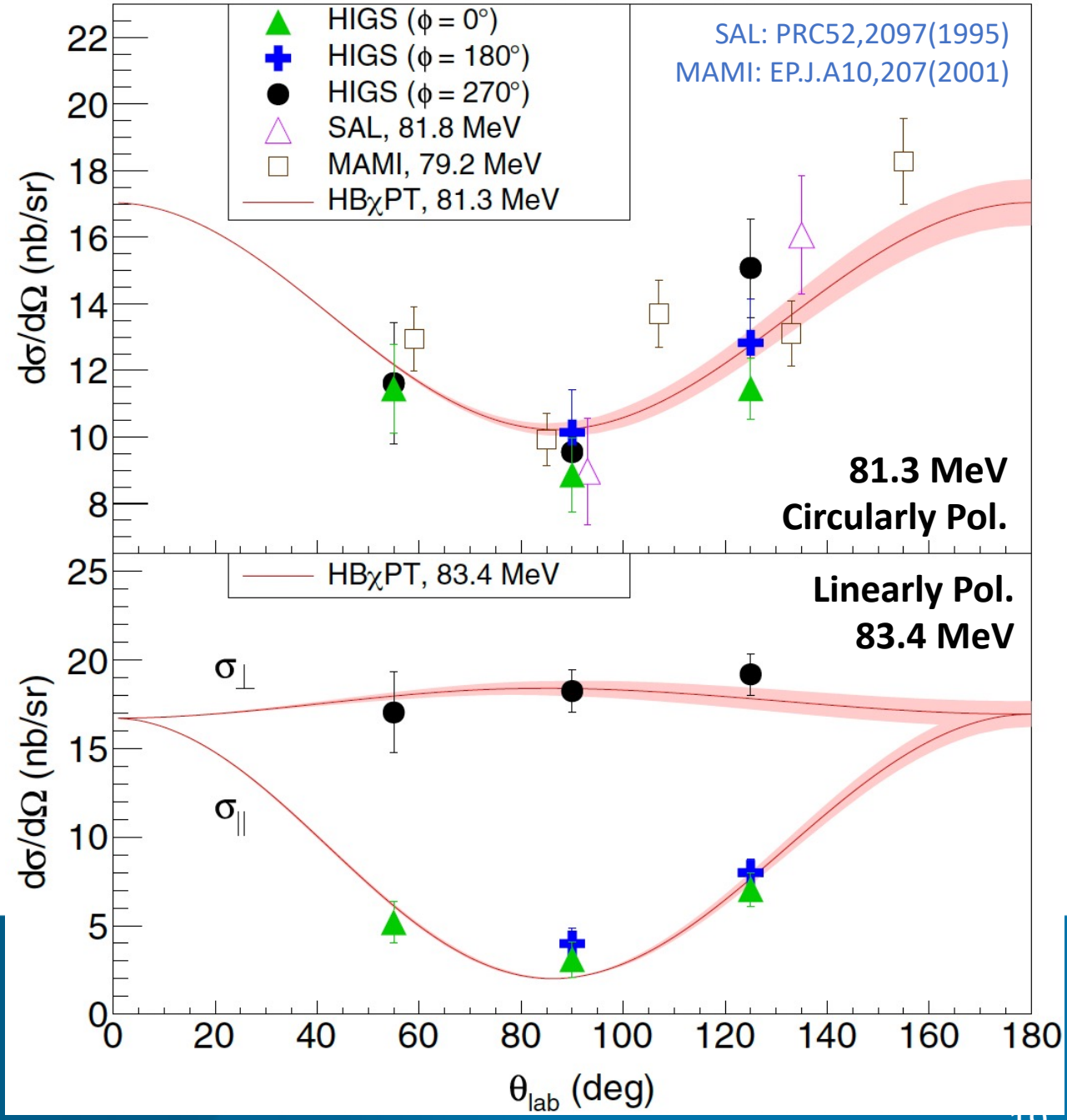
$$\Sigma_3 = \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp}$$

Results

X. Li *et al.*, PRL **128,** 132502 (2022)

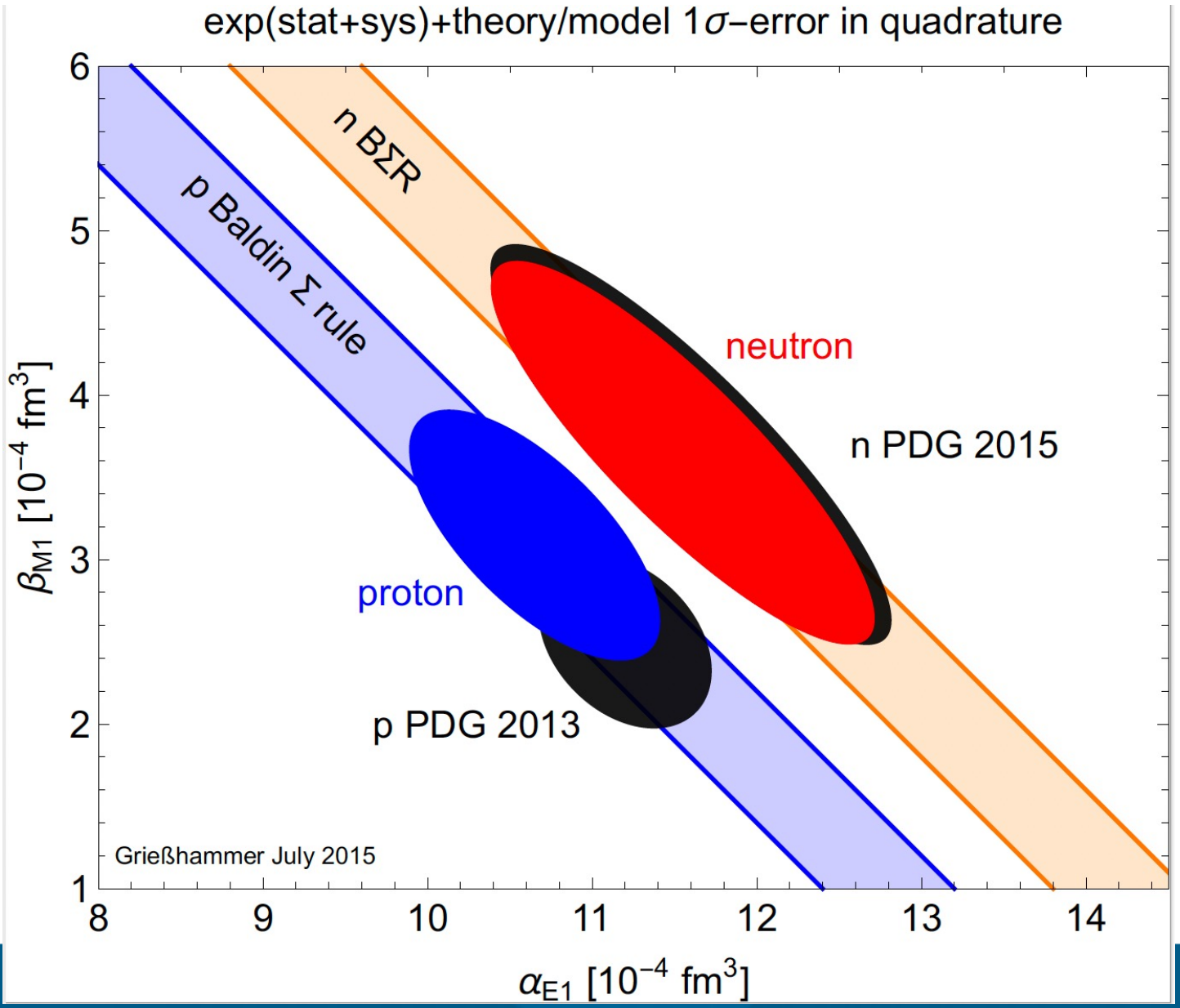
$$\alpha^p_{E1} = 13.8 \pm 1.2_{\text{stat}} \pm 0.1_{\text{BSR}} \pm 0.3_{\text{theo}},$$
$$\beta^p_{M1} = 0.2 \mp 1.2_{\text{stat}} \pm 0.1_{\text{BSR}} \mp 0.3_{\text{theo}},$$

- Fit to 16 σ points with BSR constraint
- Agrees with MAMI within uncertainty
- Best uncertainties with unpol. σ
- Measured in region of minimal theory uncertainty



Results

X. Li *et al.*, PRL **128,** 132502 (2022)



PDG 2022

$$\alpha_p = (11.2 \pm 0.4)\times 10^{-4}\ \mathrm{fm}^3$$
$$\beta_p = (2.5 \pm 0.4)\times 10^{-4}\ \mathrm{fm}^3$$

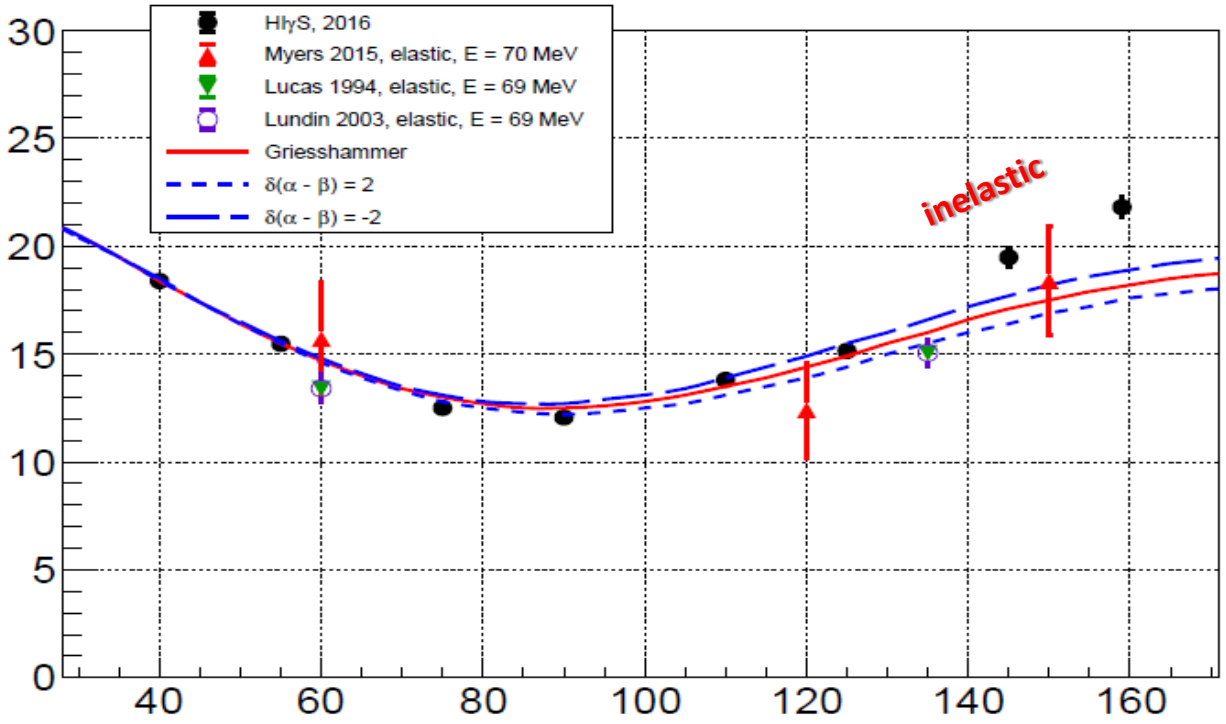
- Lots of effort to extract polarizabilities from data!
- Involves close collaboration with theory
  - ✓ HBχPT: Griesshammer, McGovern, Phillips
  - ✓ χEFT: Pascalutsa, Vanderhaghen
  - ✓ DR: Pasquini
- Thank you to our theory colleagues!

World Data & Theory Efforts

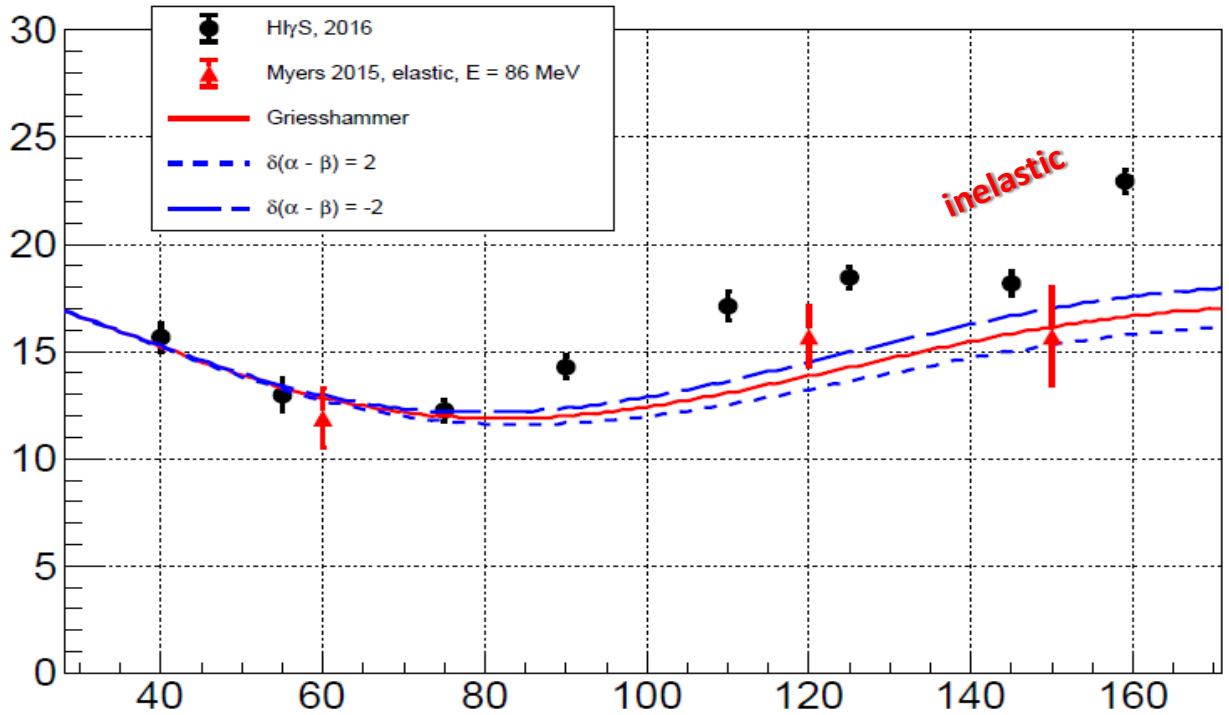
Grießhammer, McGovern and Phillips, EPJ A **52** 139 (2016)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

D(γ,γ)D



E_γ= 65 MeV, 300 hours



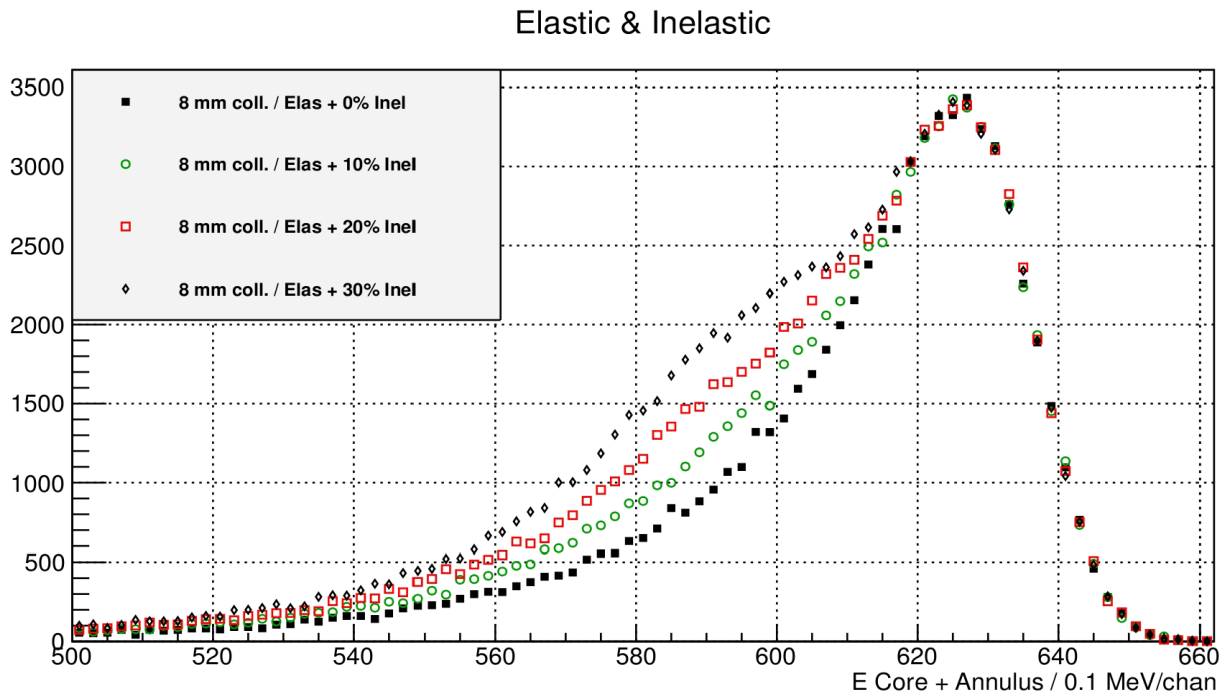
E_γ= 85 MeV, 270 hours

M. Sikora, *PoS* CD2018 (2019) 108
EFT Curves Grießhammer, McGovern, Phillips

Compton Scattering on Deuterium

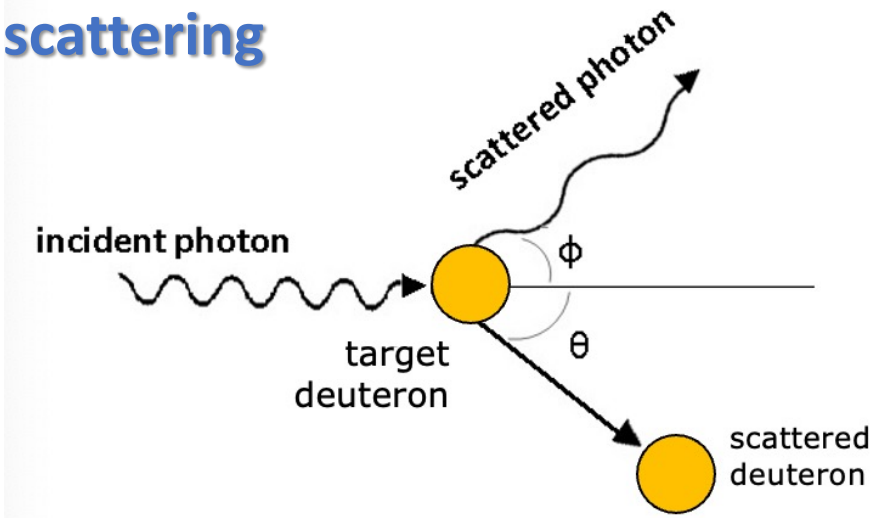
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

E_γ= 62.7 MeV



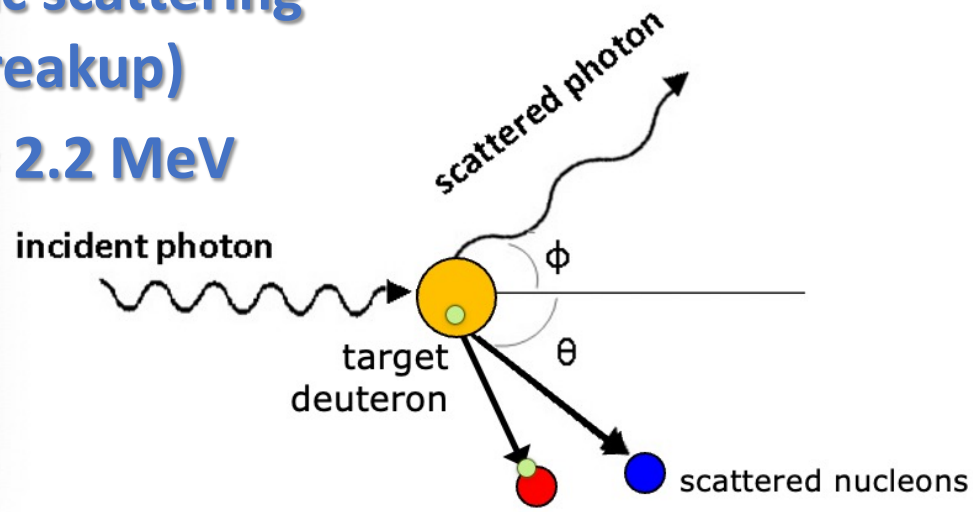
M. Kovash (2018)

elastic scattering



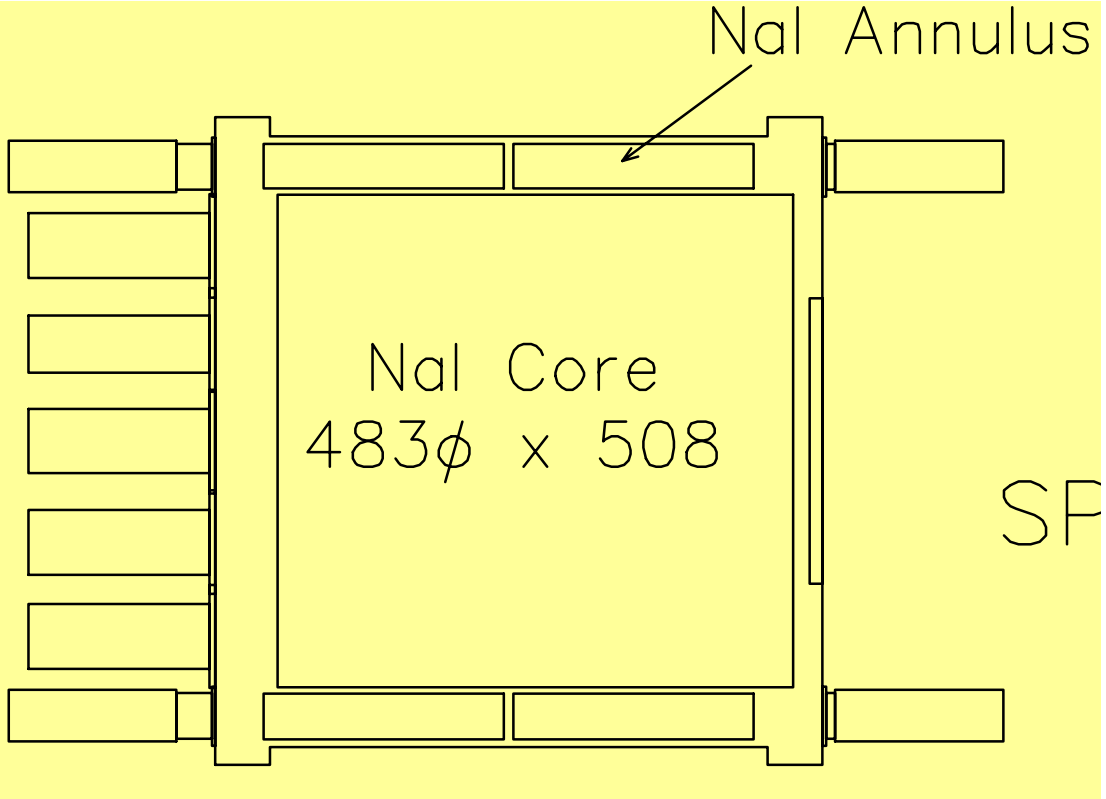
inelastic scattering (breakup)

ΔE = 2.2 MeV



Compton Scattering on Deuterium

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC



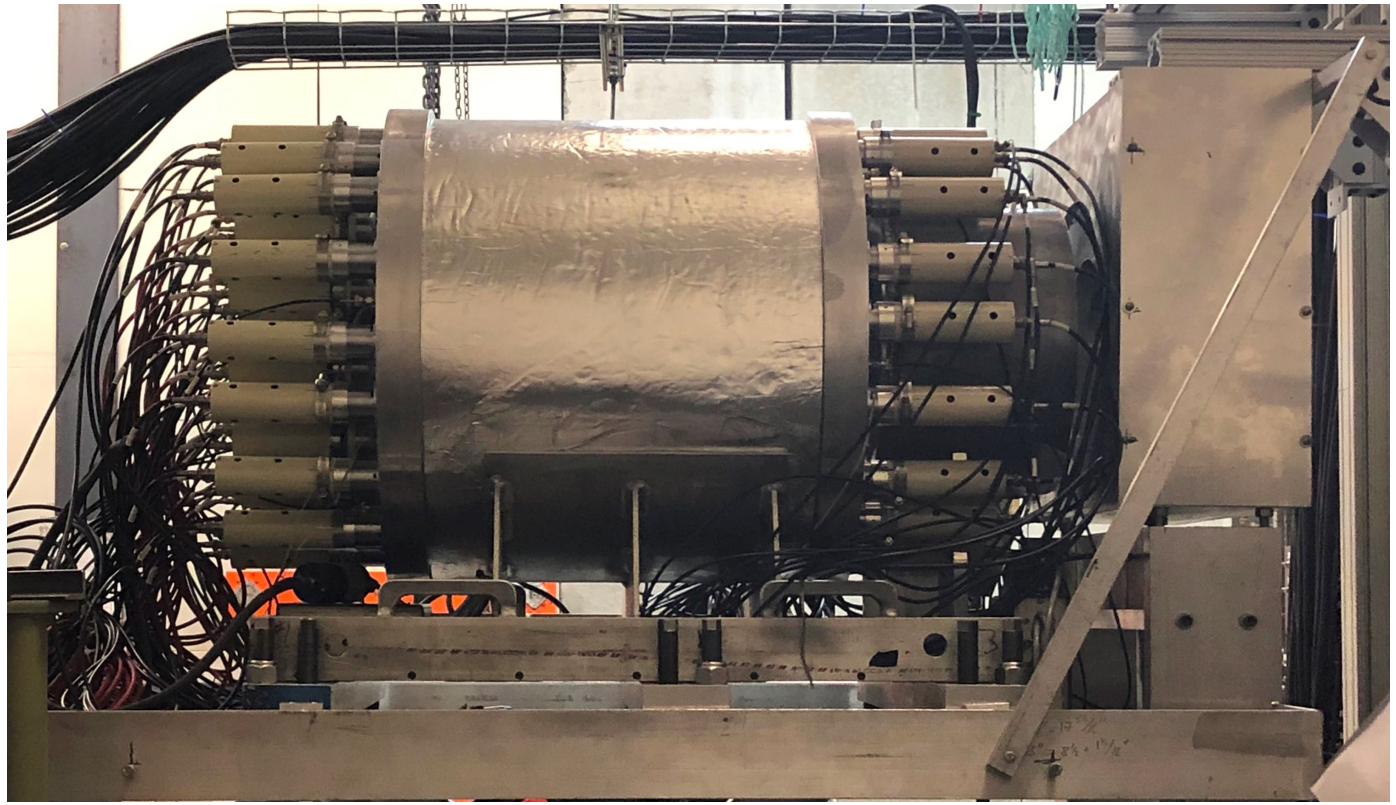
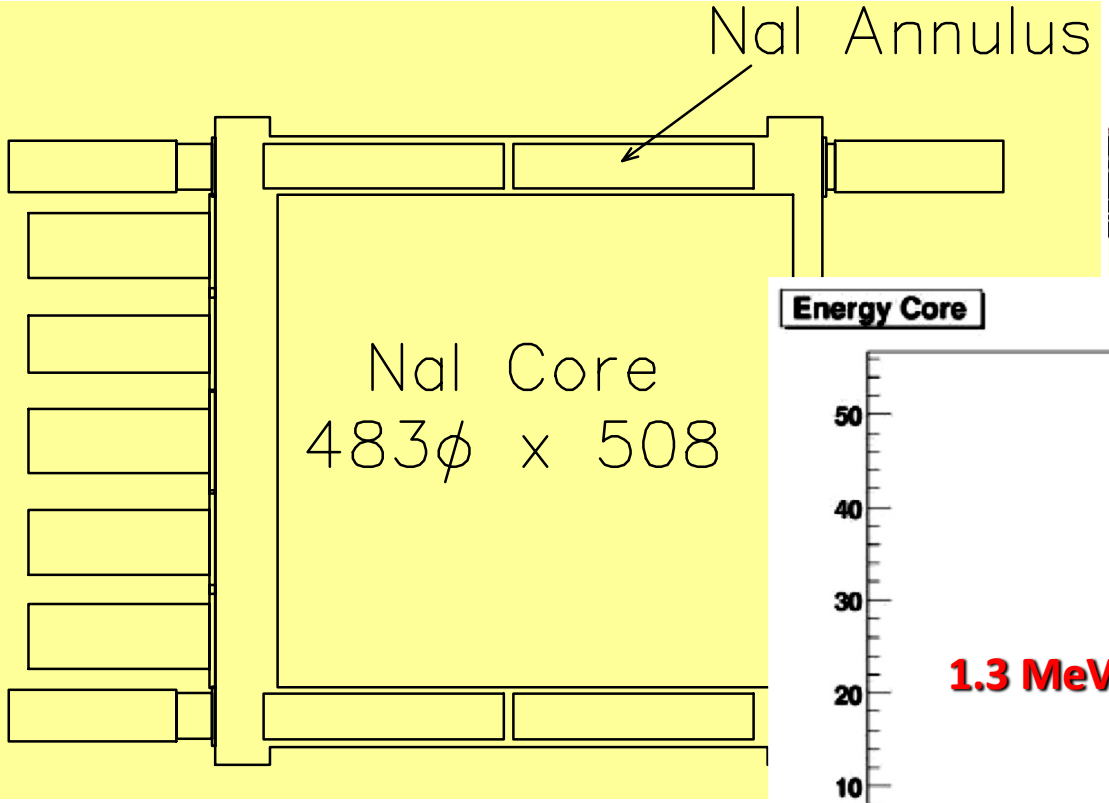
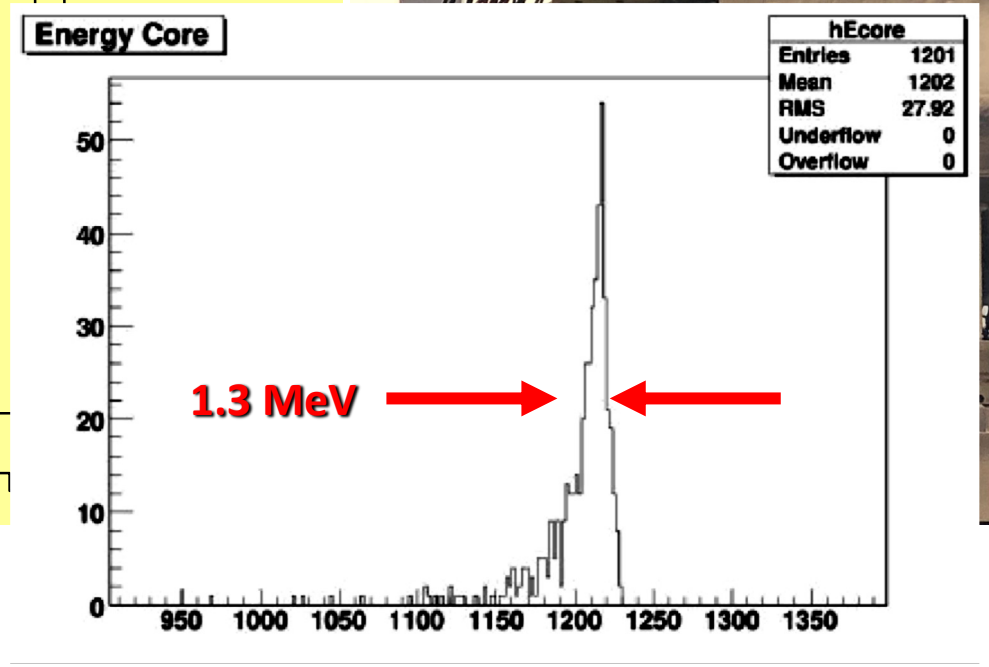


Photo: Danula Godagama,
PhD Thesis (2022)
University of Kentucky

Detector of Iodine and Na (DIANA)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC





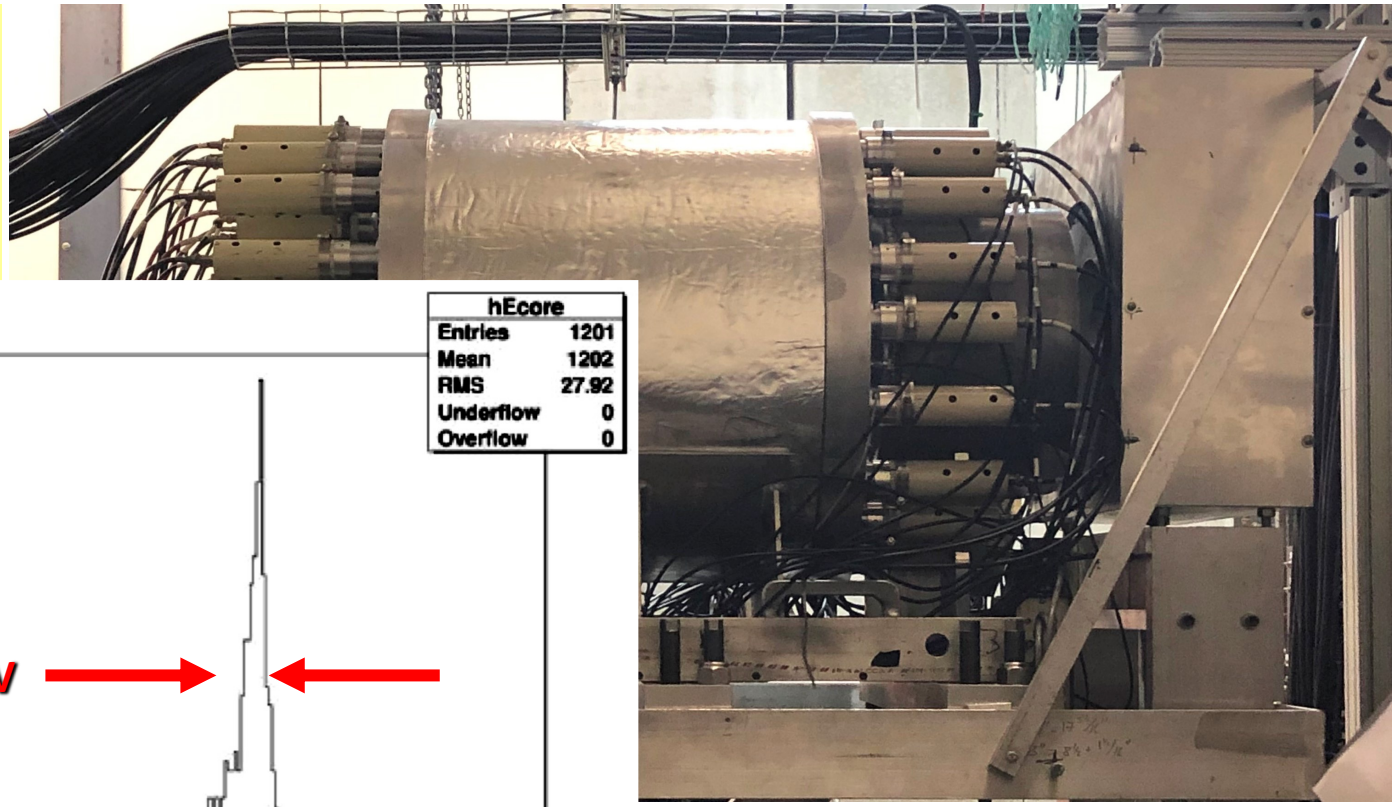
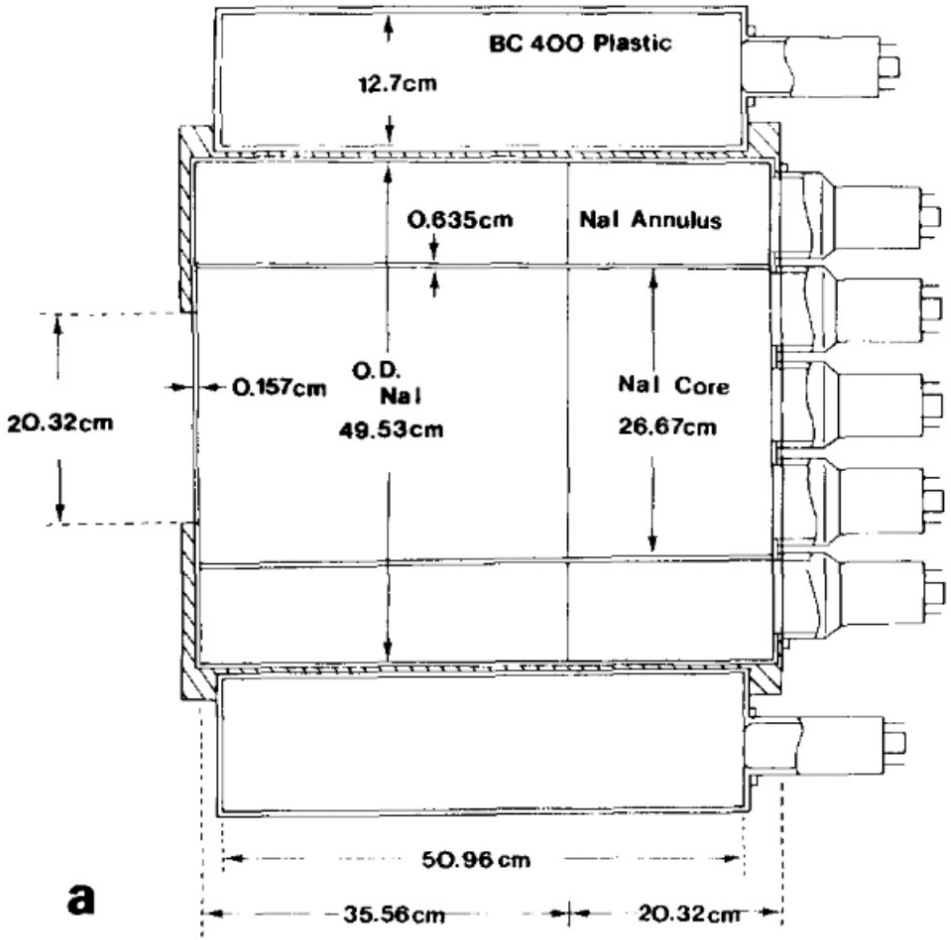
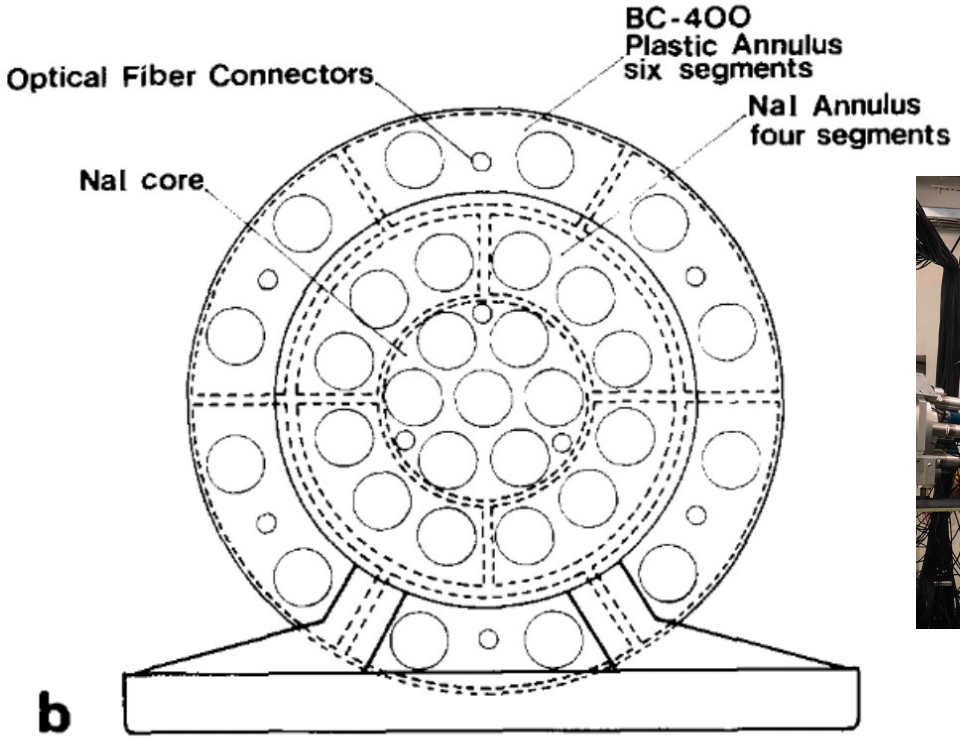


Photo: Danula Godagama, PhD Thesis (2022) University of Kentucky

Detector of Iodine and Na (DIANA)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC





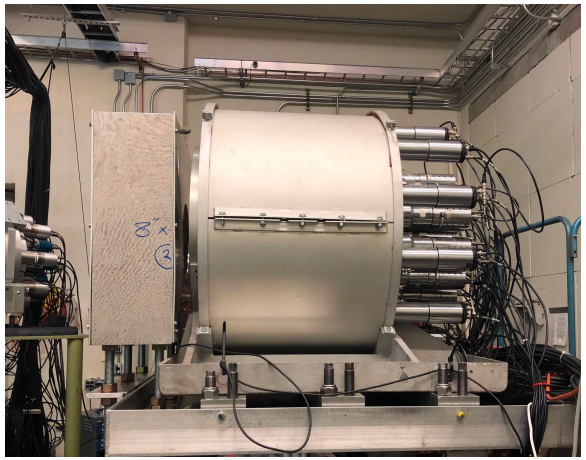
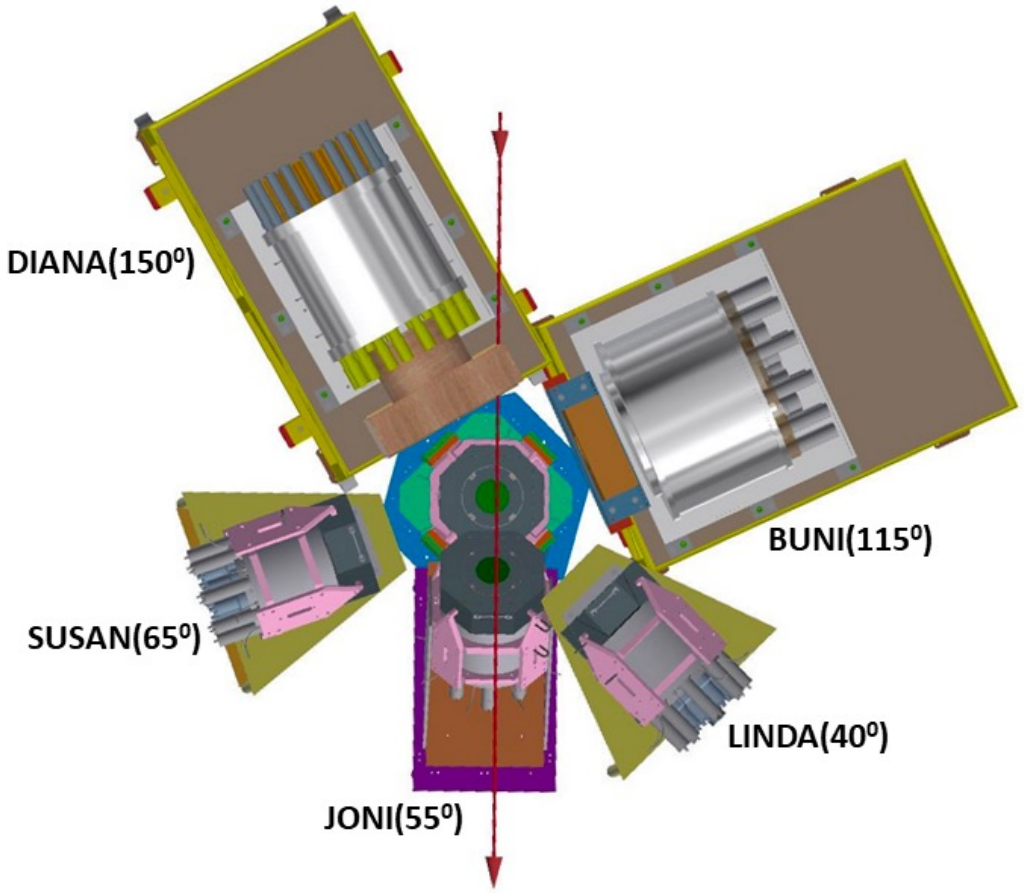


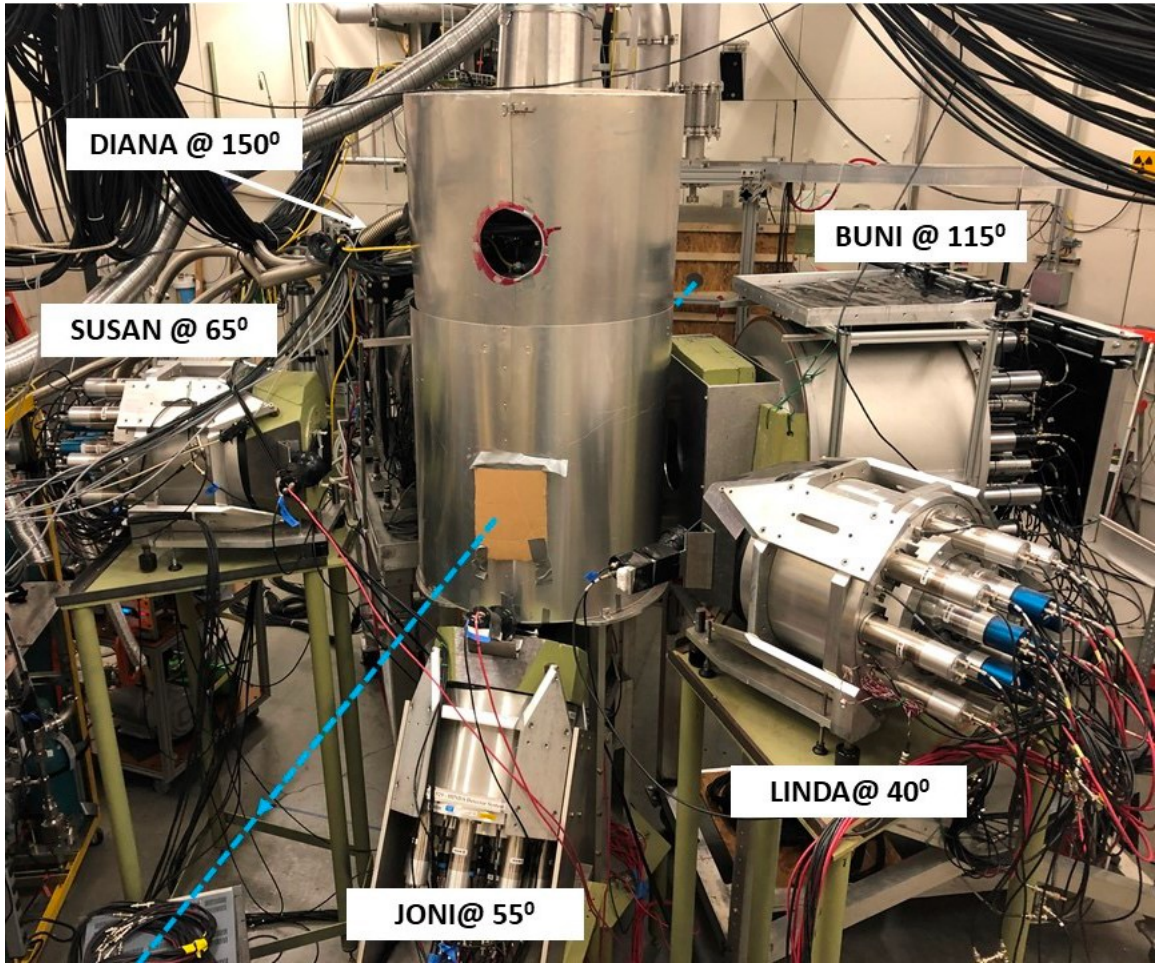
Photo: Danula Godagama, PhD Thesis (2022) University of Kentucky

NIM A270 (1988) 431

Boston University NaI (BUNI)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC





Images: Danula Godagama, PhD Thesis, University of Kentucky (2022)

Boston University NaI (BUNI)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Highlighted HIGS Compton Measurements

- **^{1}H**: E_γ = 83 MeV linearly polarized beam; X. Li *et al.,* PRL **128,** 132502 (2022)
- **^{4}He**: E_γ = 61 MeV M. Sikora *et al.*, PRC **96**, 055209 (2017)
  E_γ = 81 MeV X. Li *et al.*, PRC **101**, 034618 (2020)

Ongoing / Future Measurements

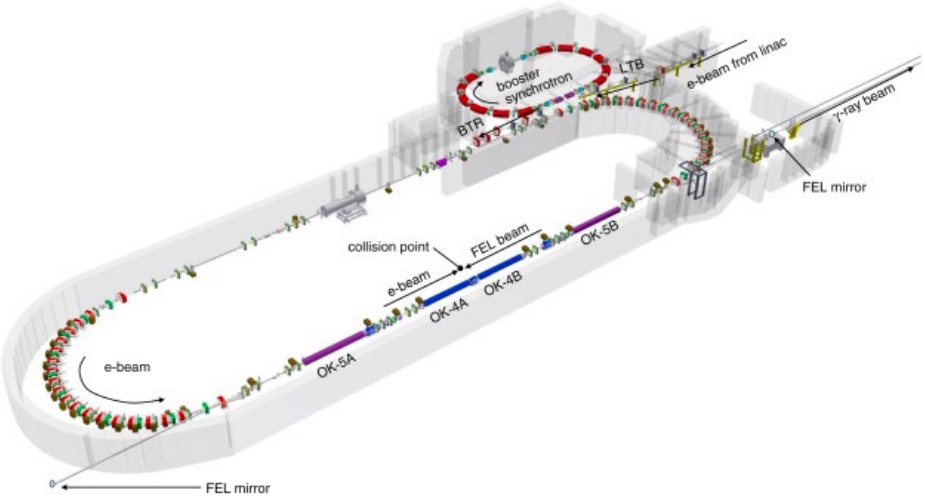
- **^{2}H**: E_γ = 65, 85 MeV; neutron polarizability, data taken 2020 (under analysis)
- **^{3}He**: E_γ = 80, 100, 120 MeV; first Compton on A=3, measurement planned for Summer 2023

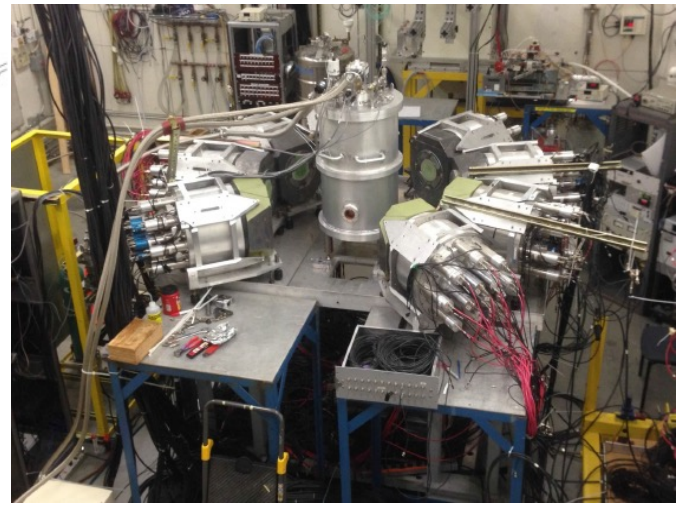
Older Measurements

- **^{6}Li**: E_γ = 60, 86 MeV; L. S. Myers et al., PRC **90**, 027603 (2014)
- **^{16}O**: E_γ = 62, 84 MeV; commissioning of DIANA; L. S. Myers et al., PRC **86**, 044614 (2012)

HIGS Compton Program

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC





- HIGS has the world's highest flux monoenergetic photon beam
- Offers great opportunity to take high statistics Compton scattering data
- Energy region of minimal theoretical uncertainty
- Excellent synergy with Mainz: overlapping E-range, totally different systematics
- None of this would be possible without excellent theory support!

Summary

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Thank you to the conference organizers!

TUNL
Triangle Universities Nuclear Laboratory

University of North Carolina Chapel Hill
LVX
LIBERTAS

University of Saskatchewan

The George Washington University
Washington, DC

North Carolina Central University
Truth 1910 Service
Durham, North Carolina
James E. Shepard, Founder

UK
University of Kentucky

Duke University
Eruditio et Religio

Bluffton University

Compton @ HIGS Collaboration