Recent and Future Measurements of Nucleon Polarizabilities at HIGS

Gerald Feldman

Department of Physics
George Washington University

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON DC

Compton@HIGS Collaboration

TUNL

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON DC

Duke University

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

UK
UNIVERSITY OF KENTUCKY

University of North Carolina Chapel Hill
LVX LIBERTAS

UNIVERSITY OF SASKATCHEWAN

Mount Allison University

Introduction

- polarizability – measure of induced dipole moment in external field

electric

$$\boldsymbol{D} = \alpha \boldsymbol{E}$$

$$\Delta\varepsilon = -\boldsymbol{d}\cdot\boldsymbol{E} - \tfrac{1}{2}\alpha\,|\boldsymbol{E}|^2$$

magnetic

$$\boldsymbol{M} = \beta \boldsymbol{B}$$

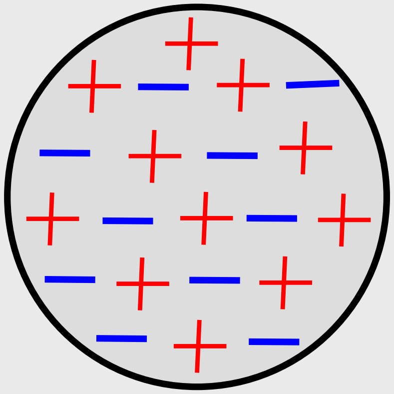
$$\Delta\varepsilon = -\boldsymbol{\mu}\cdot\boldsymbol{B} - \tfrac{1}{2}\beta\,|\boldsymbol{B}|^2$$

q, μ	$\Rightarrow\Rightarrow\Rightarrow\Rightarrow$	**1st order response**
α, β	$\Rightarrow\Rightarrow\Rightarrow\Rightarrow$	**2nd order response**

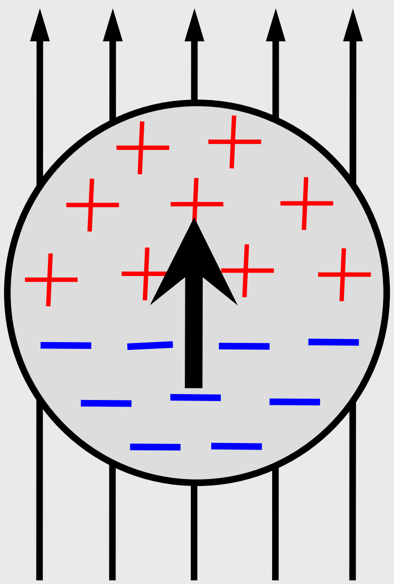
(lowest-order response of *internal* structure)

- for the free nucleon:
  - fundamental structure constants (and not so well known)
  - test of models of nucleon structure

electric polarizability:
separation of charge



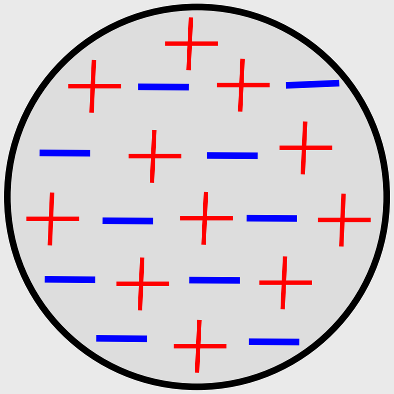
$D = 0$



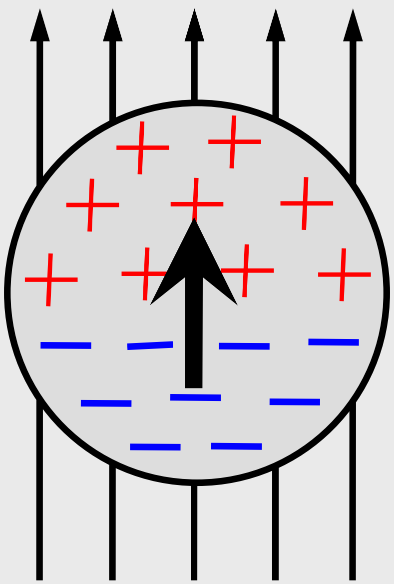
$D = \alpha E$

polarizability: measure of induced dipole moment in external field

electric polarizability:
separation of charge

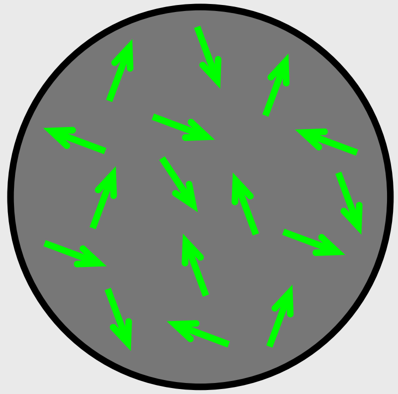


$D = 0$

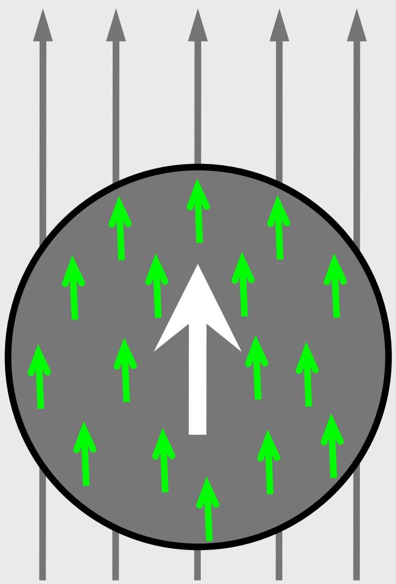


$D = \alpha E$

paramagnetic polarizability:
moments align with *B*

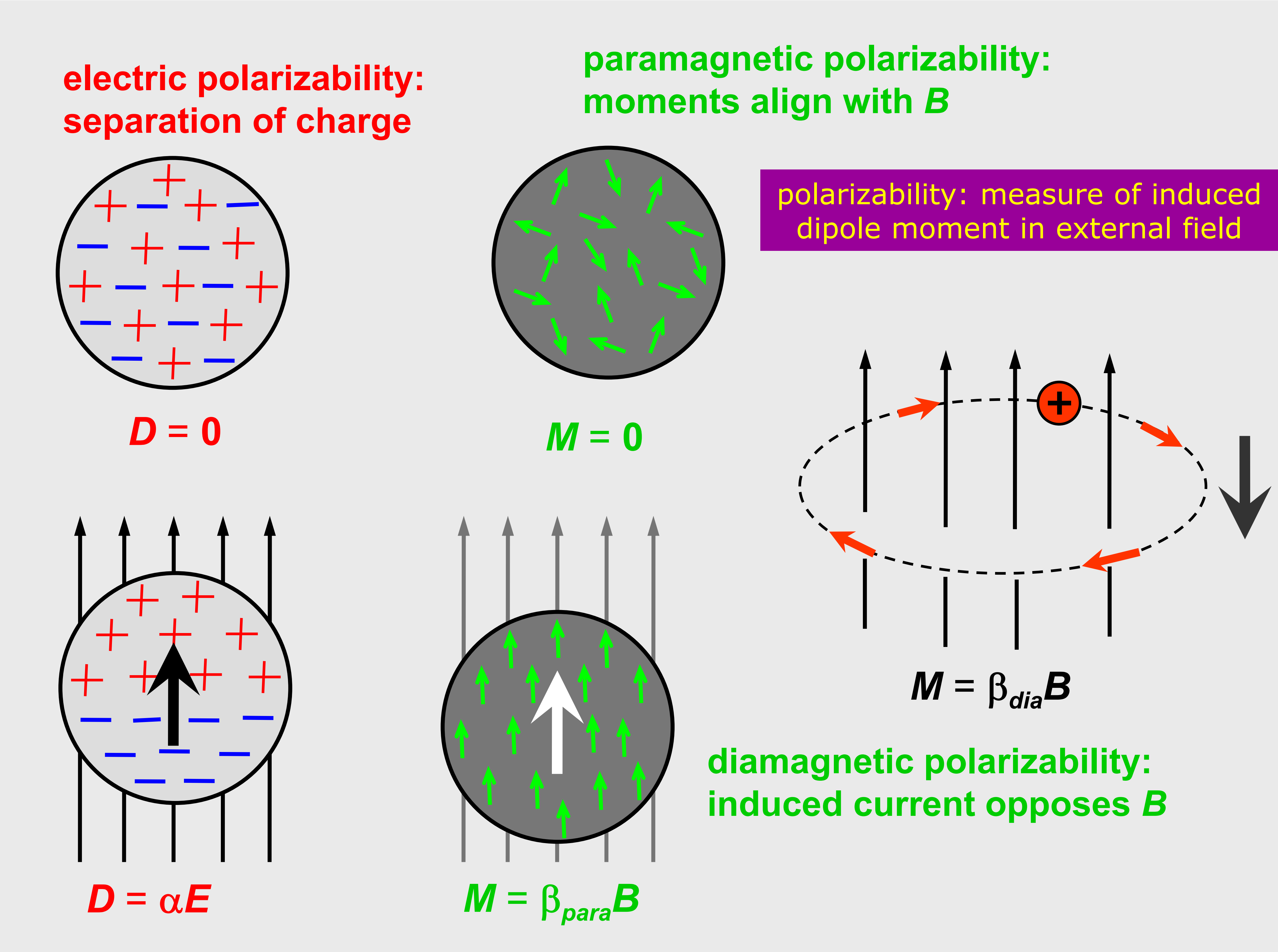


$M = 0$



$M = \beta_{para} B$

polarizability: measure of induced dipole moment in external field


electric polarizability:
separation of charge
paramagnetic polarizability:
moments align with *B*
polarizability: measure of induced dipole moment in external field
$D = 0$
$M = 0$
$M = \beta_{dia} B$
diamagnetic polarizability:
induced current opposes *B*
$D = \alpha E$
$M = \beta_{para} B$

Measuring Nucleon Polarizability

- **Proton**
  - Compton scattering

$$\sigma_p(\omega) \approx r_0^2 - 2\, r_0\, \alpha_p\, \omega^2$$

Measuring Nucleon Polarizability

- **Proton**
  - Compton scattering

$$\sigma_p(\omega) \approx r_0^2 - 2\, r_0\, \alpha_p\, \omega^2$$

- **Neutron**
  - difficulties
    - ✓ no free neutron targets
    - ✓ neutron is uncharged (no Thomson scattering)

$$\sigma_n(\omega) \approx \alpha_n^2\, \omega^4$$

Measuring Nucleon Polarizability

- **Proton**
  - Compton scattering

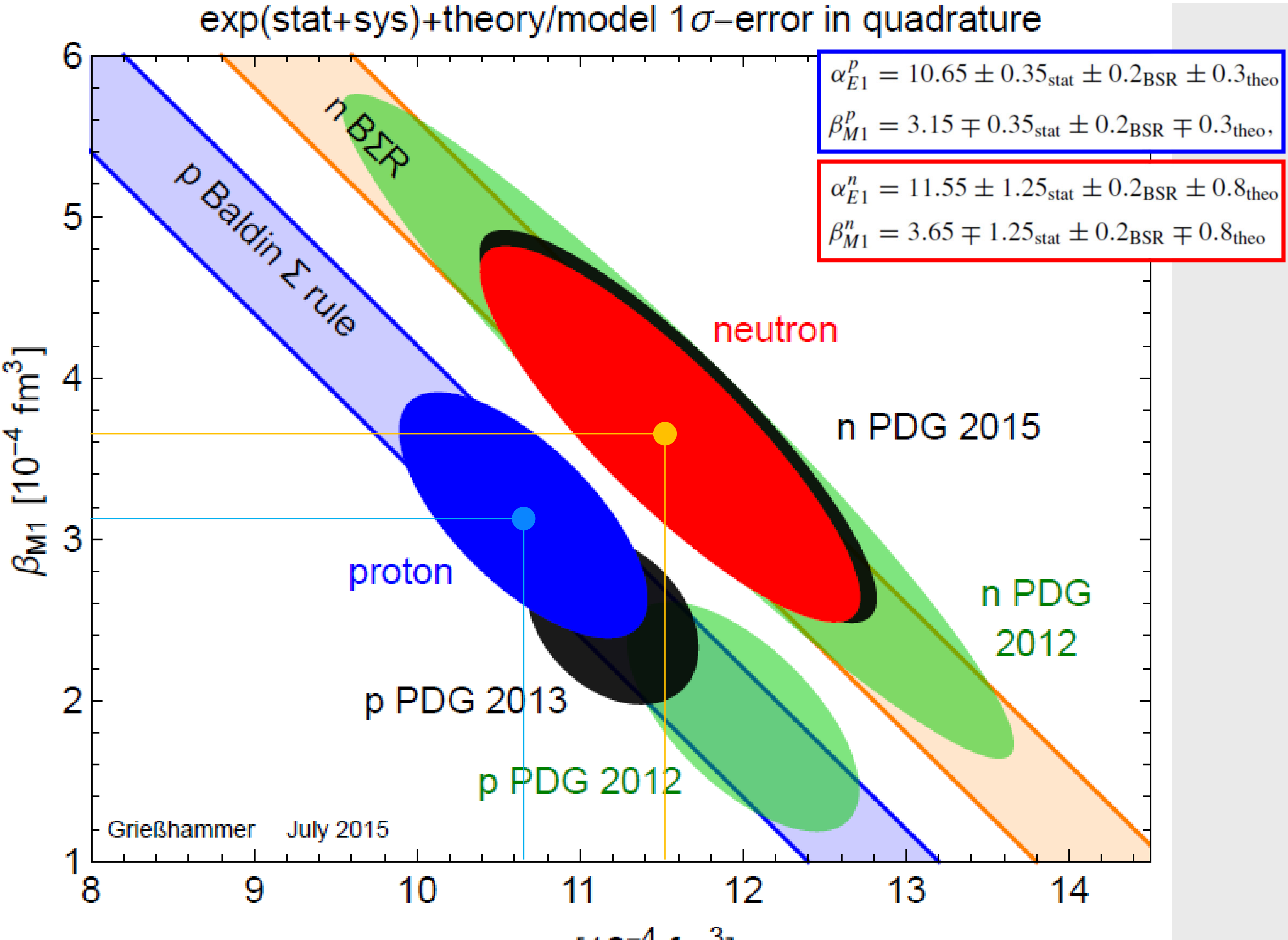
$$\sigma_p(\omega) \approx r_0^2 - 2\, r_0\, \alpha_p\, \omega^2$$

- **Neutron**
  - difficulties
    - no free neutron targets
    - neutron is uncharged (no Thomson scattering)

$$\sigma_n(\omega) \approx \alpha_n^2\, \omega^4$$

  - techniques
    - neutron scattering by heavy nucleus
    - quasi-free Compton scattering: $D(\gamma,\gamma' n)p$
    - elastic Compton scattering: $D(\gamma,\gamma)D$

$$\sigma_D(\omega) \approx r_0^2 - 2\, r_0\, (\alpha_p + \alpha_n)\, \omega^2$$



Griesshammer (2015)

High Intensity Gamma-Ray Source

(HIGS)


Washington
Oregon
California
Nevada
Idaho
Montana
Wyoming
Utah
Arizona
Colorado
New Mexico
North Dakota
South Dakota
Nebraska
Kansas
Oklahoma
Texas
Minnesota
Iowa
Missouri
Arkansas
Louisiana
Wisconsin
Illinois
Michigan
Indiana
Ohio
Kentucky
Tennessee
Mississippi
Alabama
Georgia
Florida
South Carolina
North Carolina
Virginia
Pennsylvania
New York
Maine
New Hampshire
Vermont
Massachusetts
Rhode Island
Connecticut
New Jersey
Delaware
Maryland
Washington, D.C.
West Virginia
Alaska
Hawaii


North Carolina
KENTUCKY
WEST VIRGINIA
VIRGINIA
TENNESSEE
NORTH CAROLINA
GEORGIA
SOUTH CAROLINA
Elizabeth City
36°
Henderson
Rocky Mount
Winston-Salem
Greensboro
Durham
High Point
Chapel Hill
Raleigh
Wilson
Greenville
Goldsboro
Hickory
Kinston
Asheville
Kannapolis
New Bern
Gastonia
Charlotte
Fayetteville
Jacksonville
Wilmington
34°
Columbia
Atlanta
Atlantic Ocean
0 50 100 mi
0 50 100 km

Duke University

TUNL

Triangle Universities Nuclear Laboratory

Duke University
Univ. of North Carolina
NC State University
NC Central University

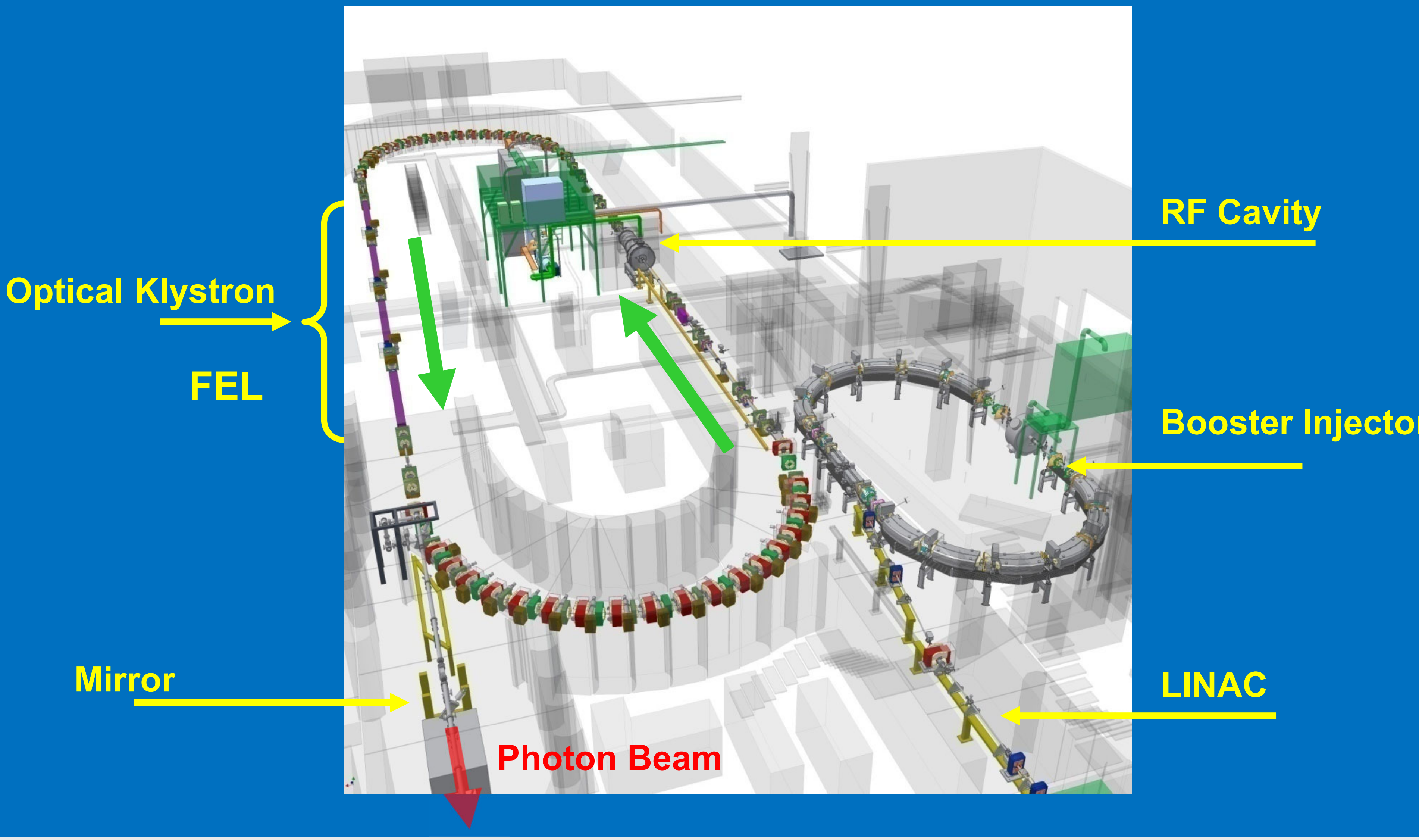
Duke Free-Electron Laser Lab

High Intensity Gamma-Ray Source

Storage Ring and Booster

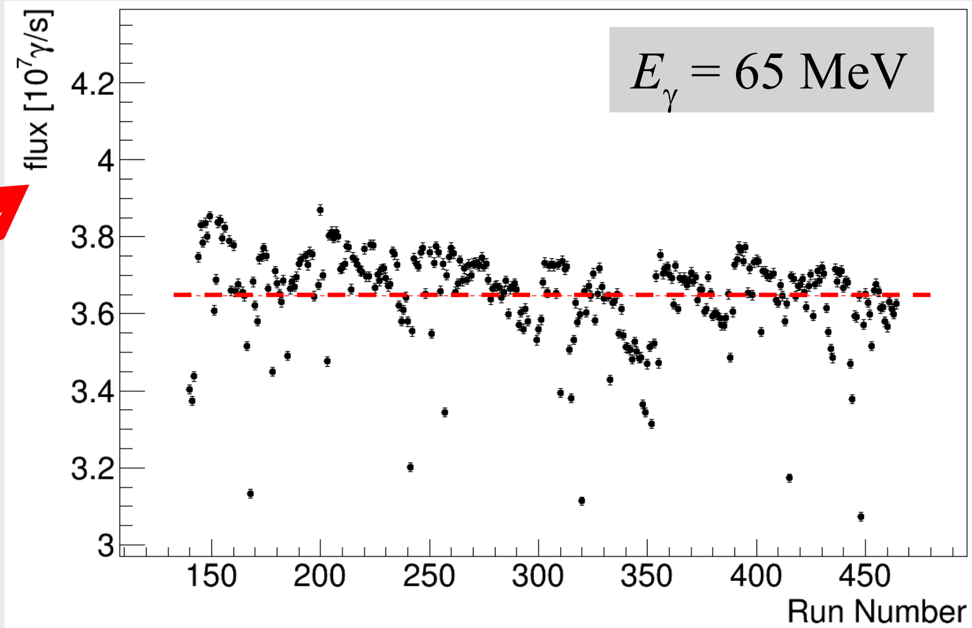
Circularly and linearly polarized γ rays, nearly monoenergetic (E_γ = 1–120 MeV)

Utilizes Compton backscattering to generate γ rays



HIGS Photon Beam

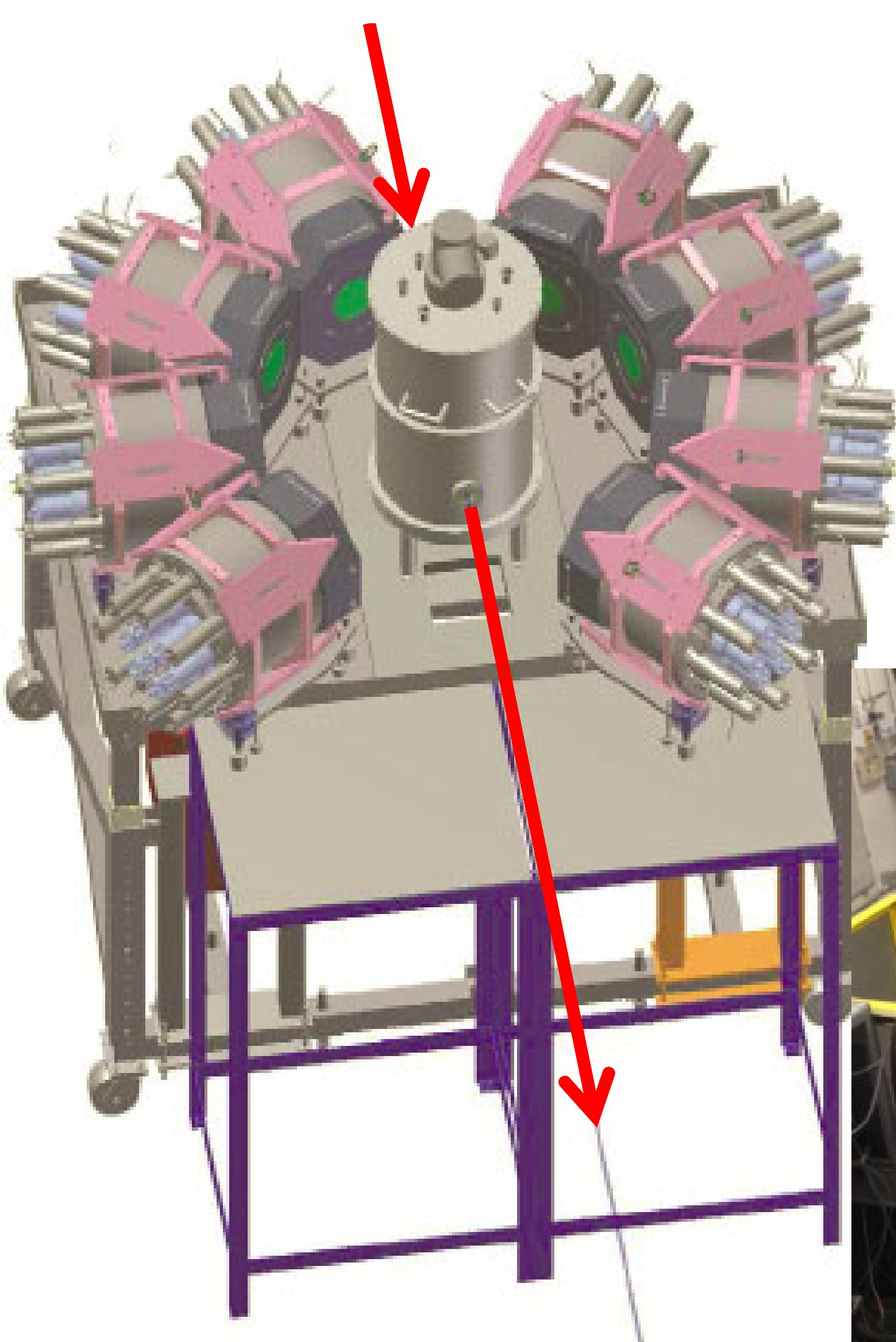
- monoenergetic photons 1 - 100 MeV (soon 120 MeV)
  - beam energy resolution depends on collimation
- nearly 100% linear or circular polarization
- high photon beam intensity
  - ~5×10^{6} Hz above 80 MeV
  - ~10^{7} Hz at 20-80 MeV
  - ~10^{8} Hz below 20 MeV



- low beam-related background
  - no bremsstrahlung typical of tagged photons

Compton Scattering on ^{4}He

Experimental Setup



HINDA detectors

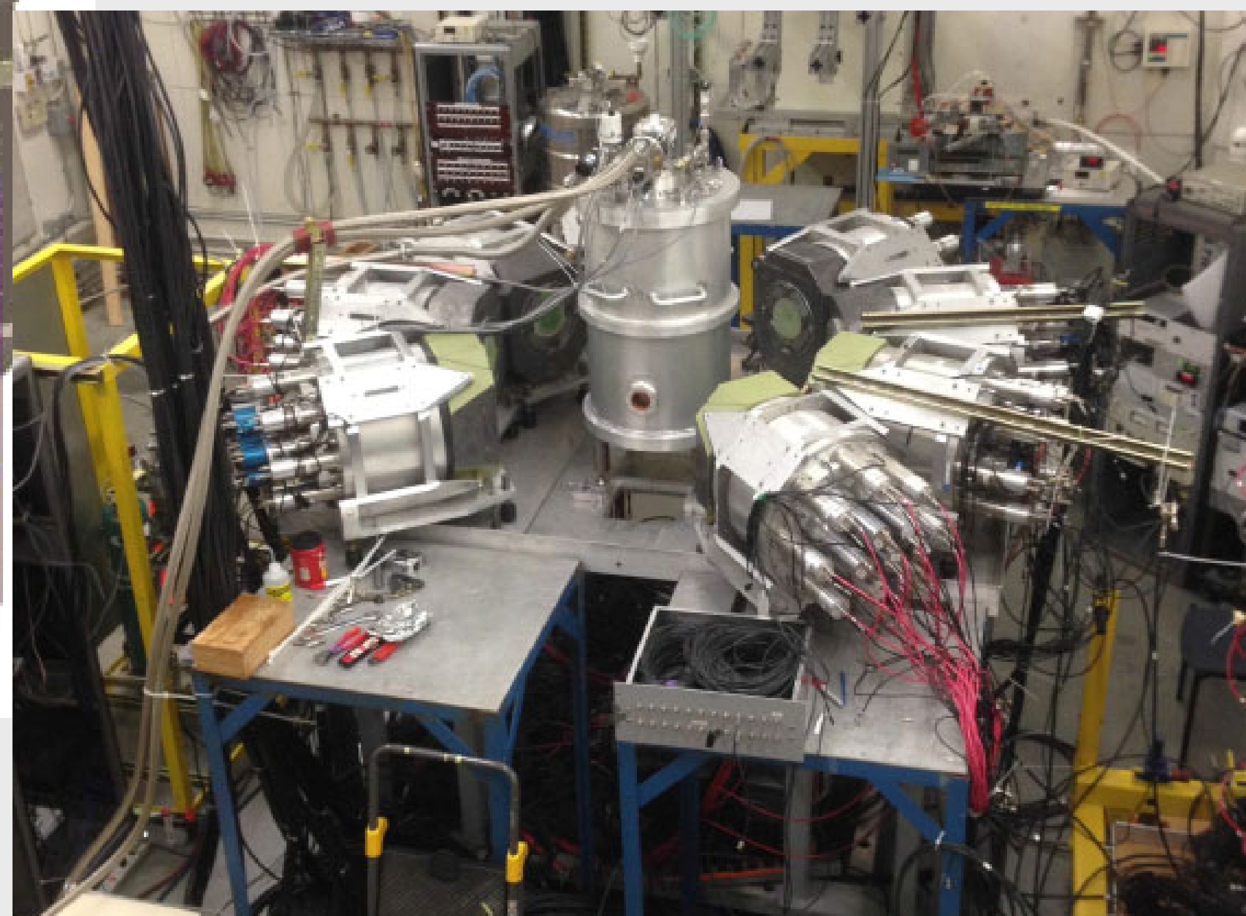
HIGS
NaI
Detector
Array

cryotarget

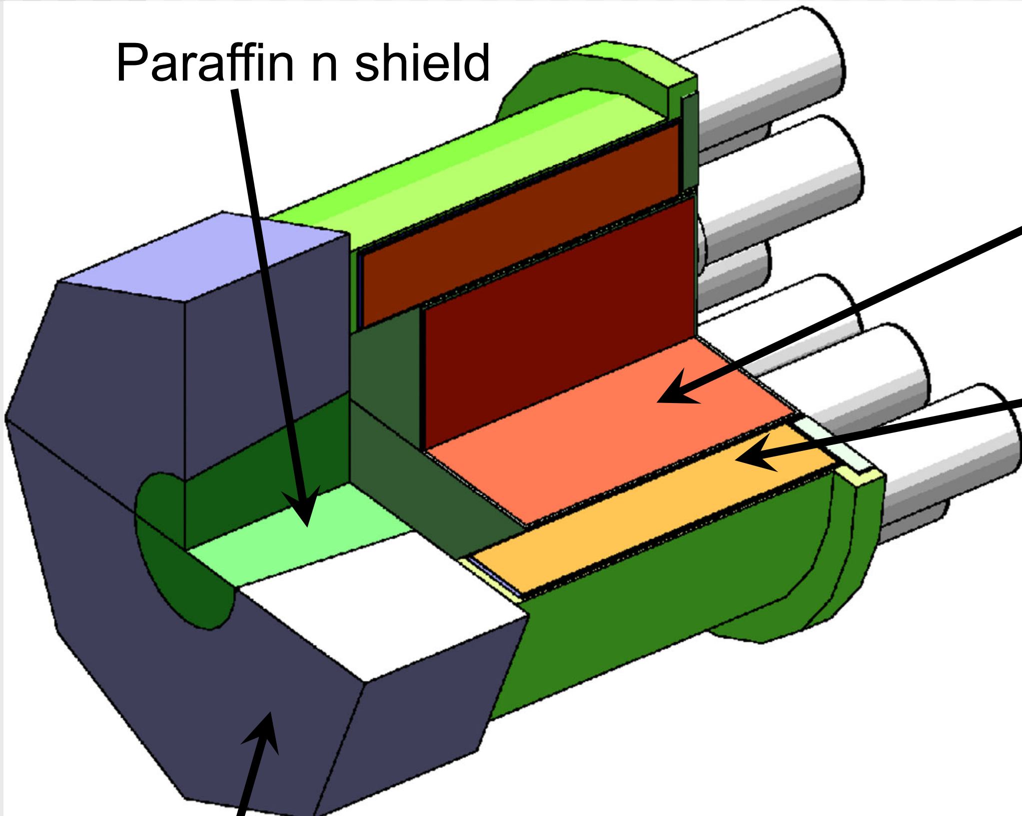
$LH_2/LD_2/LHe$

(3.5 K – 24 K)

upgrade to 1.7 K for ^3He



NaI Detectors

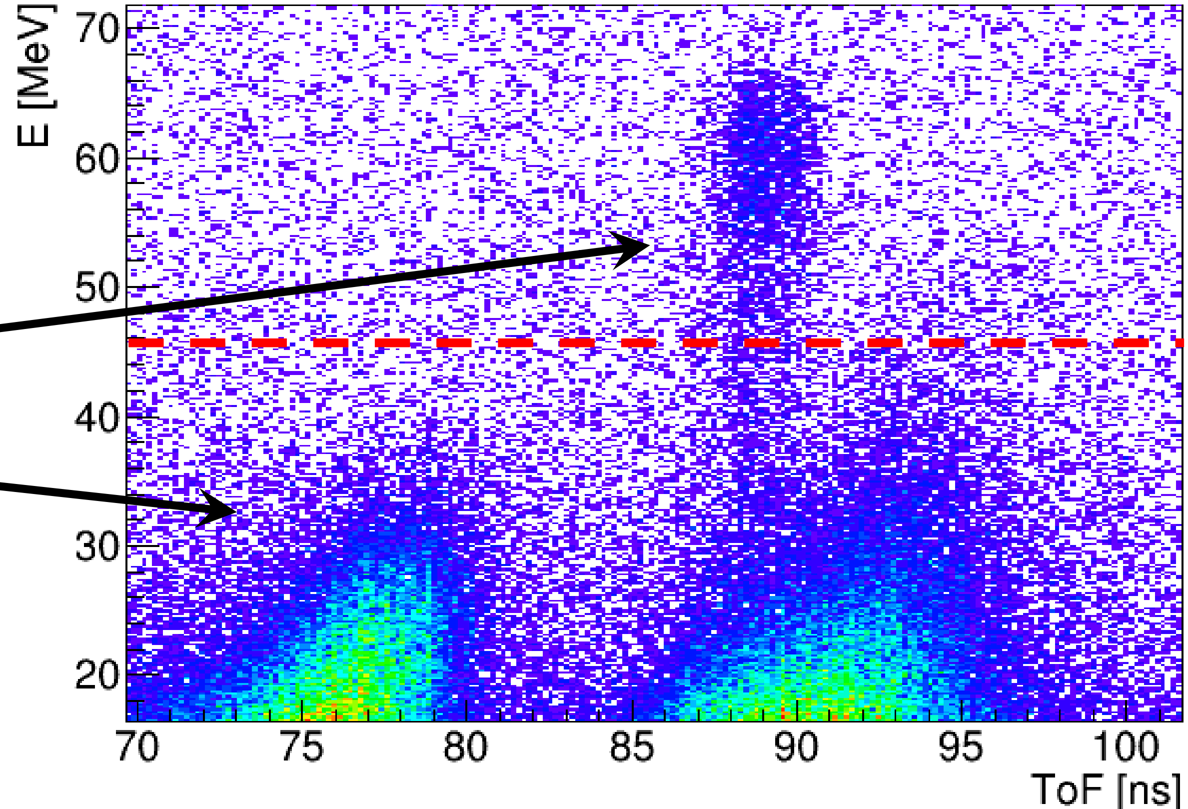


from the detector we obtain energy and timing information

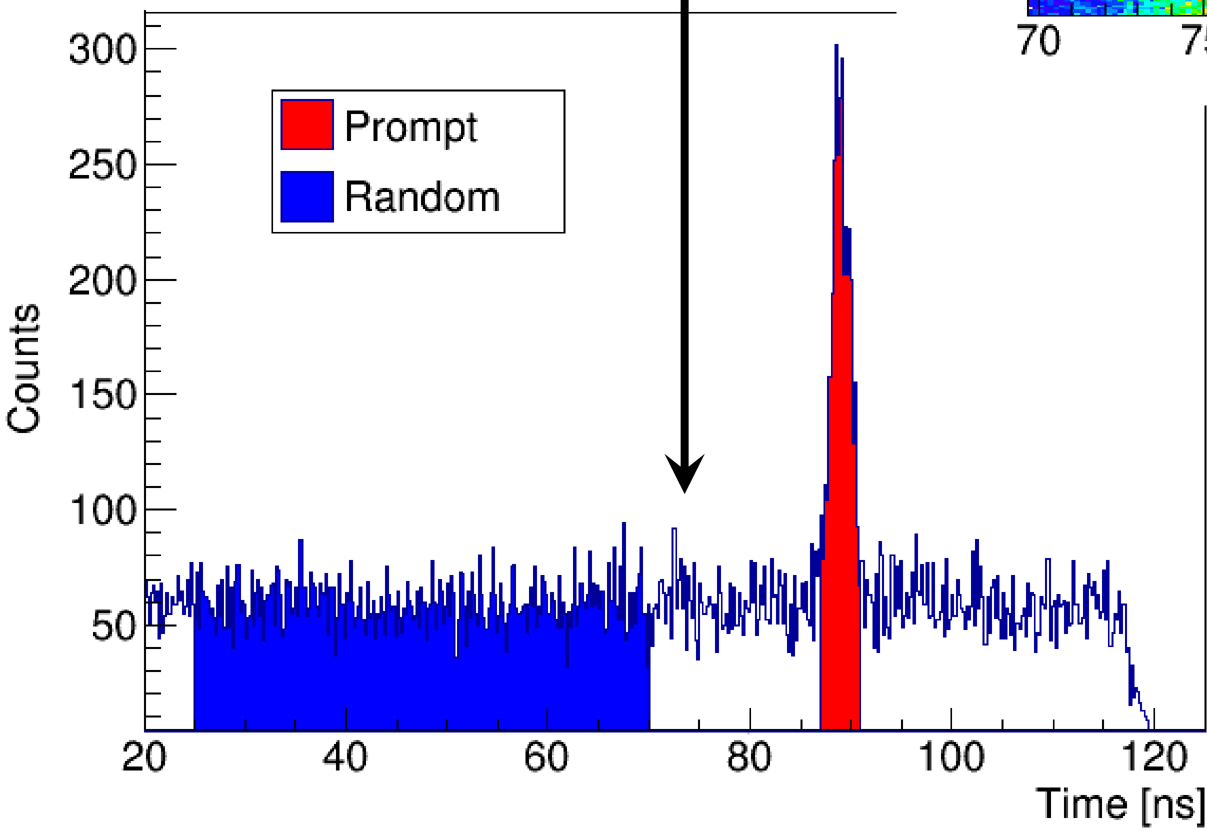
TDC Coincidence Timing

photons

neutrons



energy vs. TOF plot

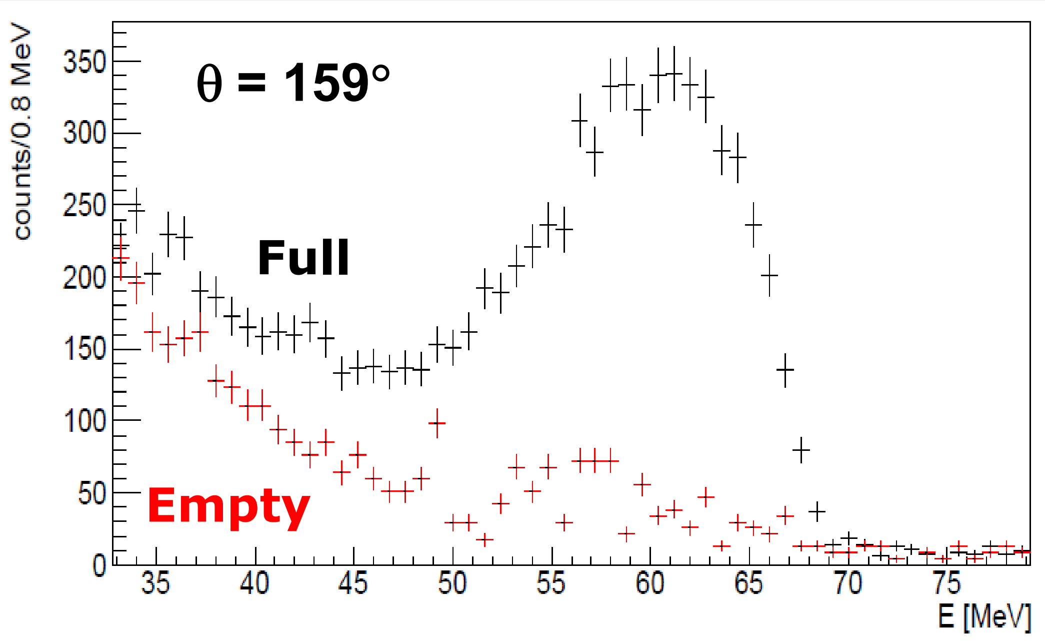


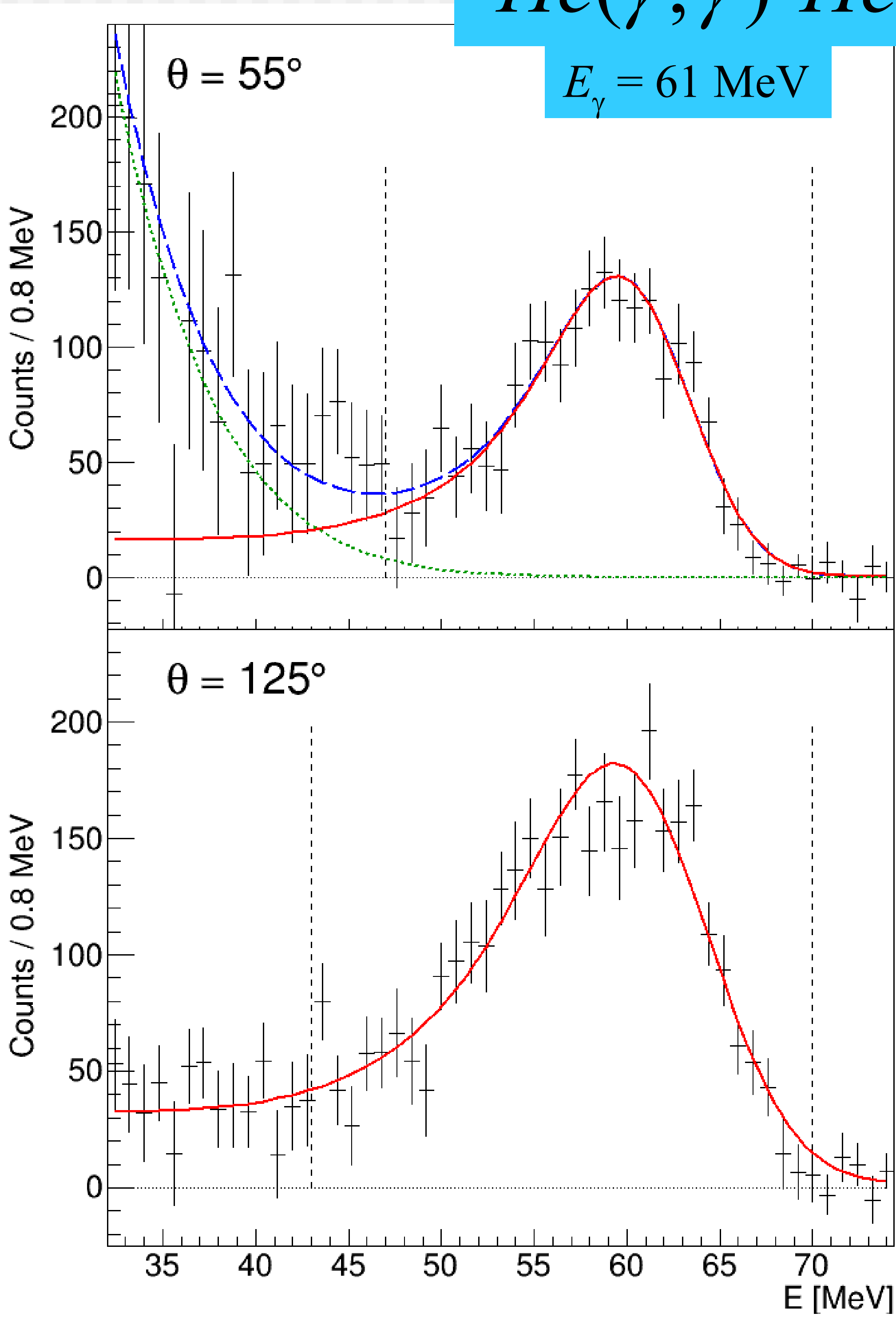
M. Sikora (2017)

Spectra of Scattered Photons

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

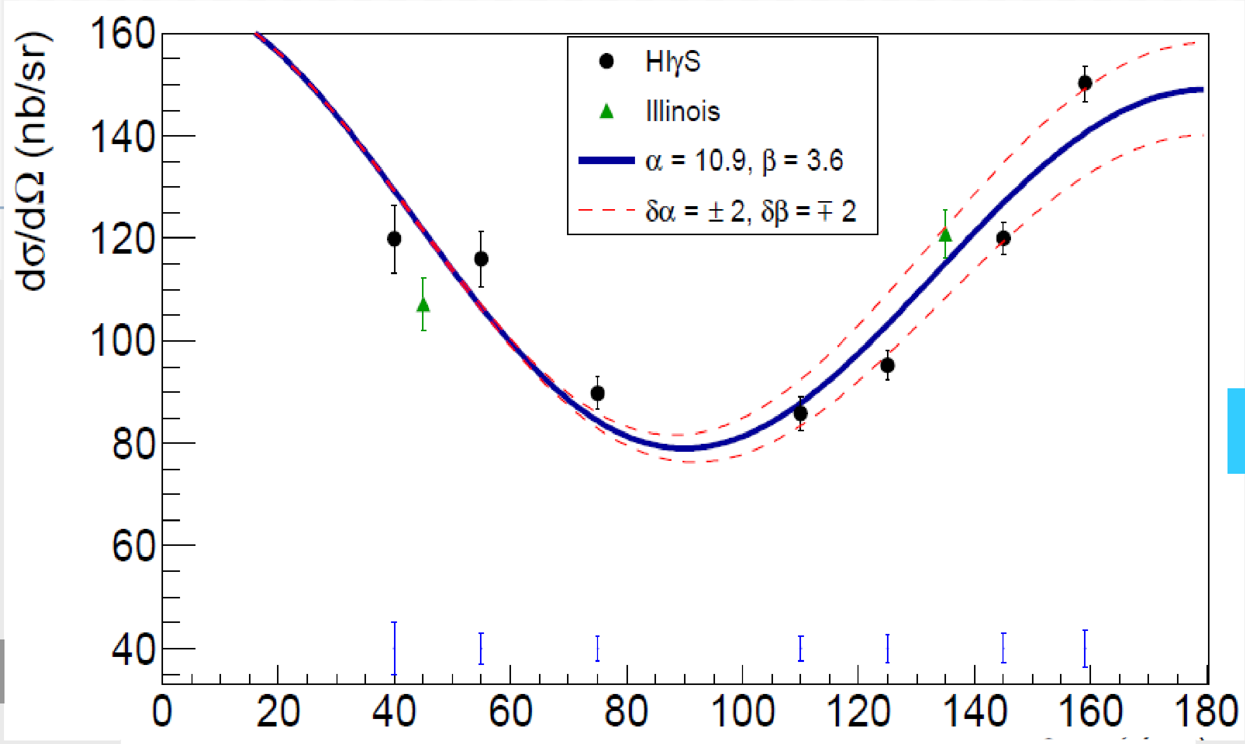
$E_{\gamma} = 61$ MeV





M. Sikora (2017)

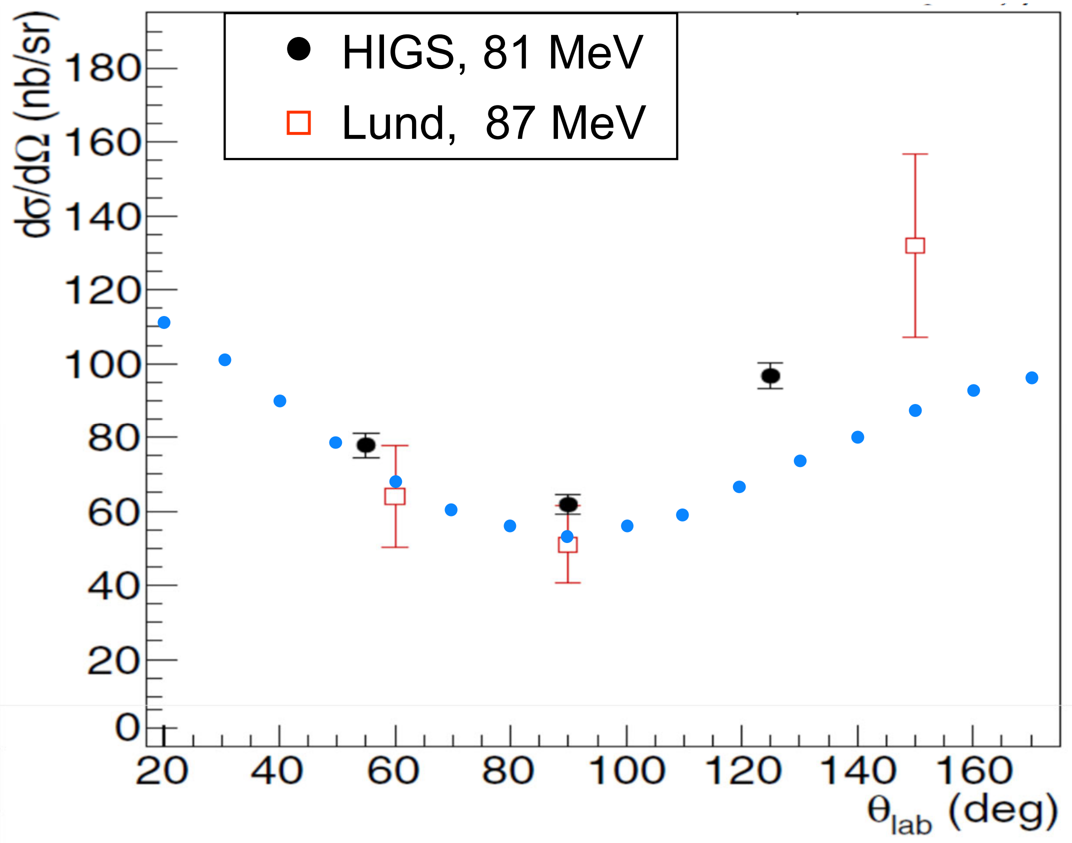
$^4He(\gamma,\gamma)^4He$



M. Sikora (2017)

$E_\gamma = 61$ MeV

(54 hrs)



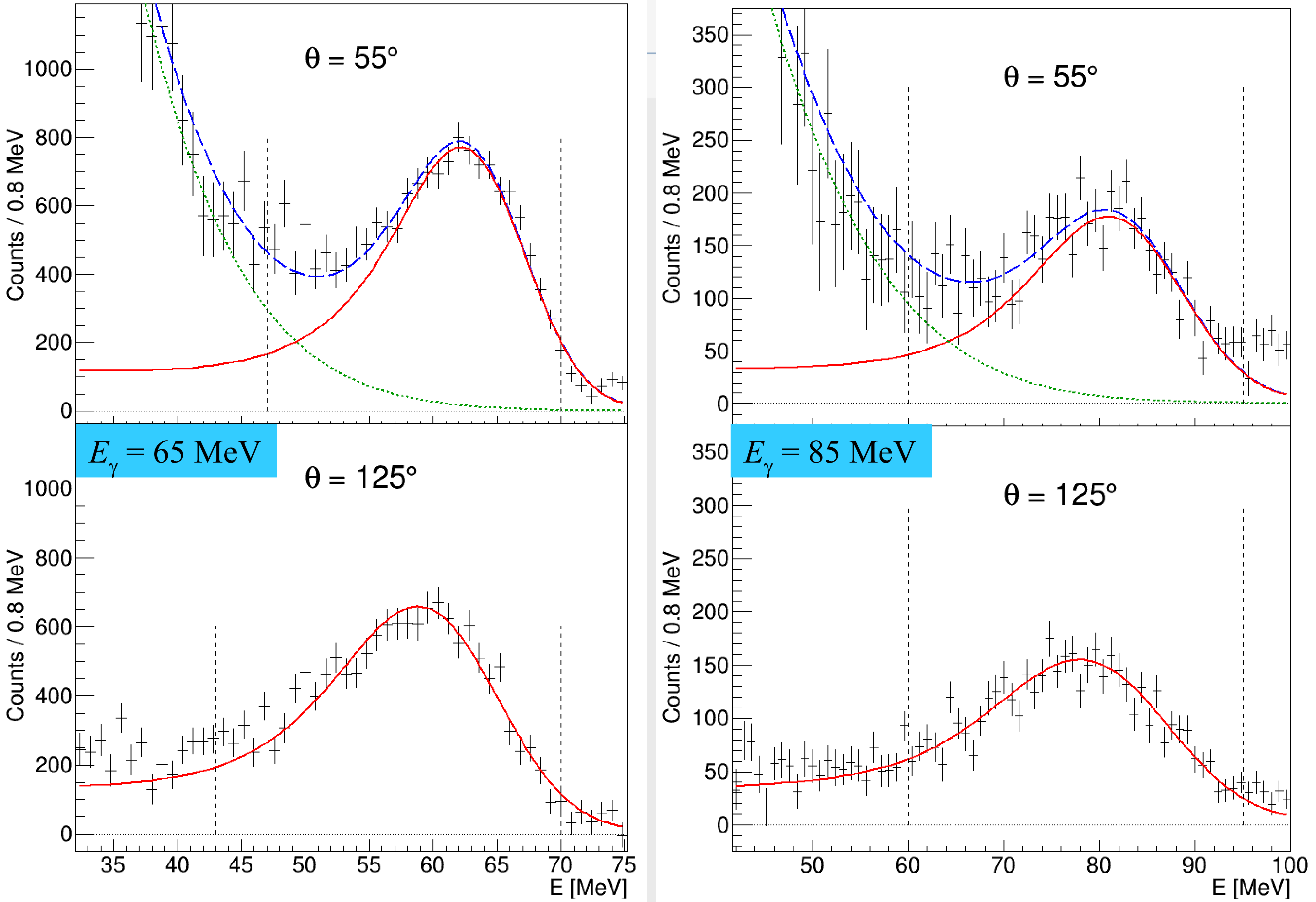
X. Li (2020)

$E_\gamma = 81$ MeV

(100 hrs)

Compton Scattering on Deuterium

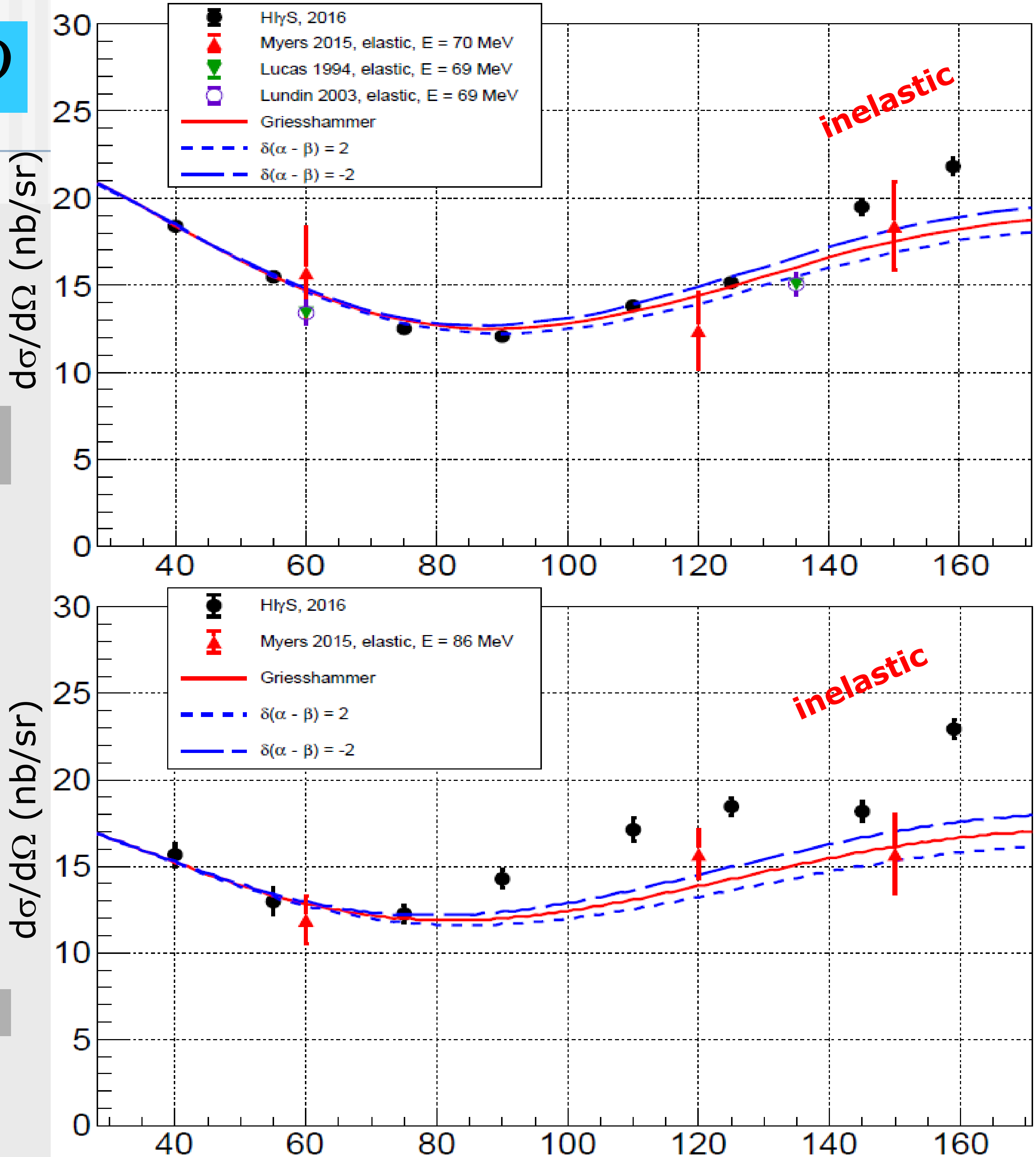
$D(\gamma,\gamma)D$



$D(\gamma,\gamma)D$

EFT curves (Griesshammer)

M. Sikora (2020)



$E_\gamma = 65$ MeV

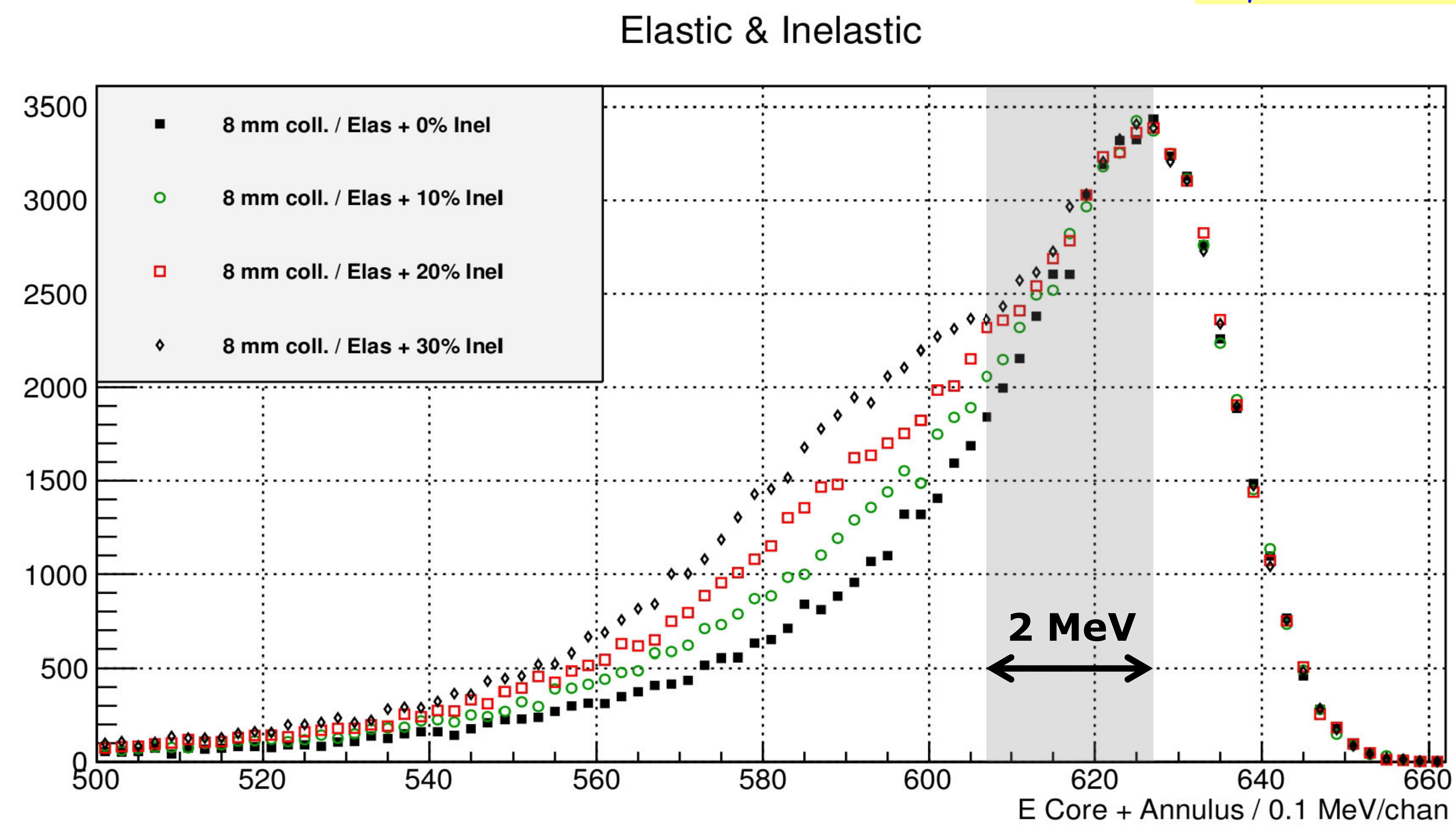
(300 hrs)

$E_\gamma = 85$ MeV

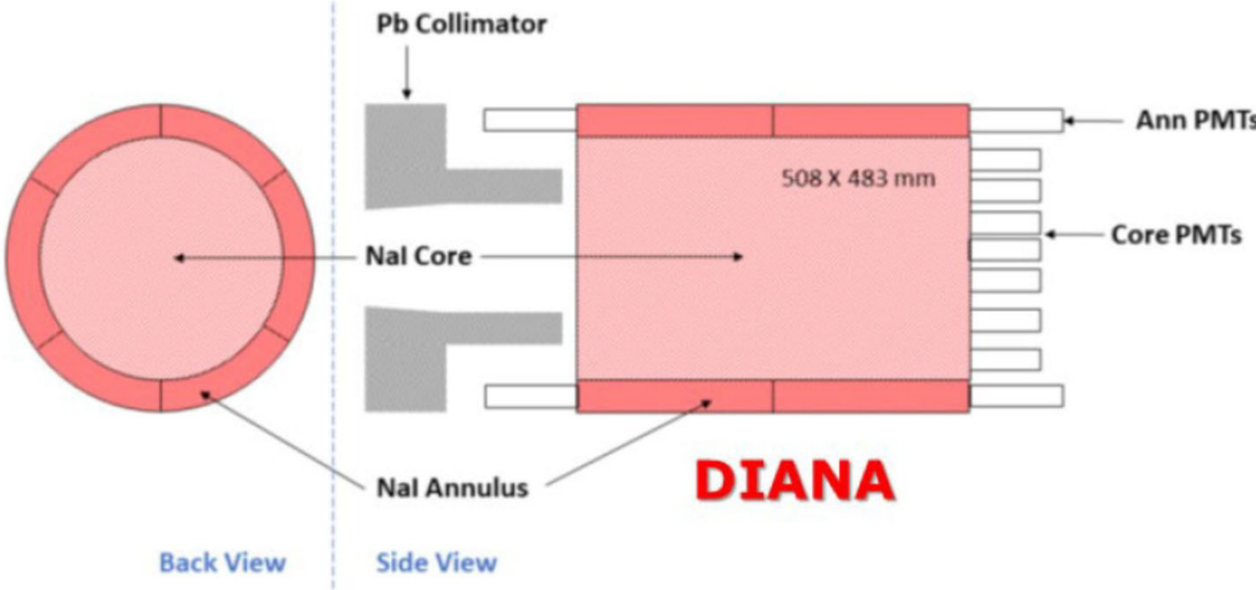
(270 hrs)

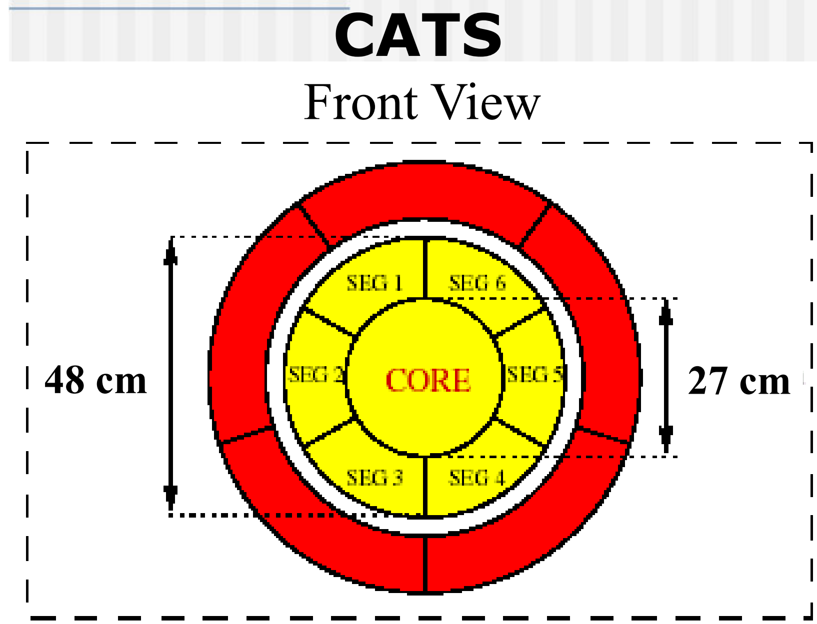
$D(\gamma,\gamma)D$

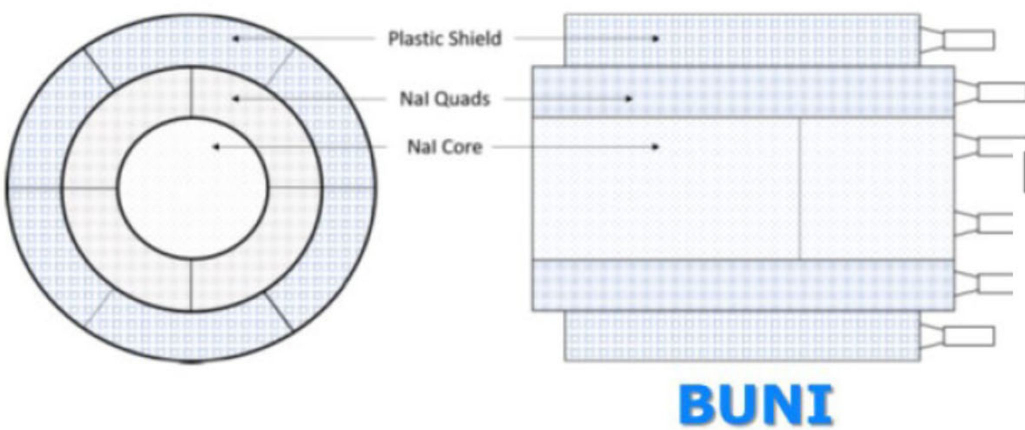
E_γ = 62.7 MeV

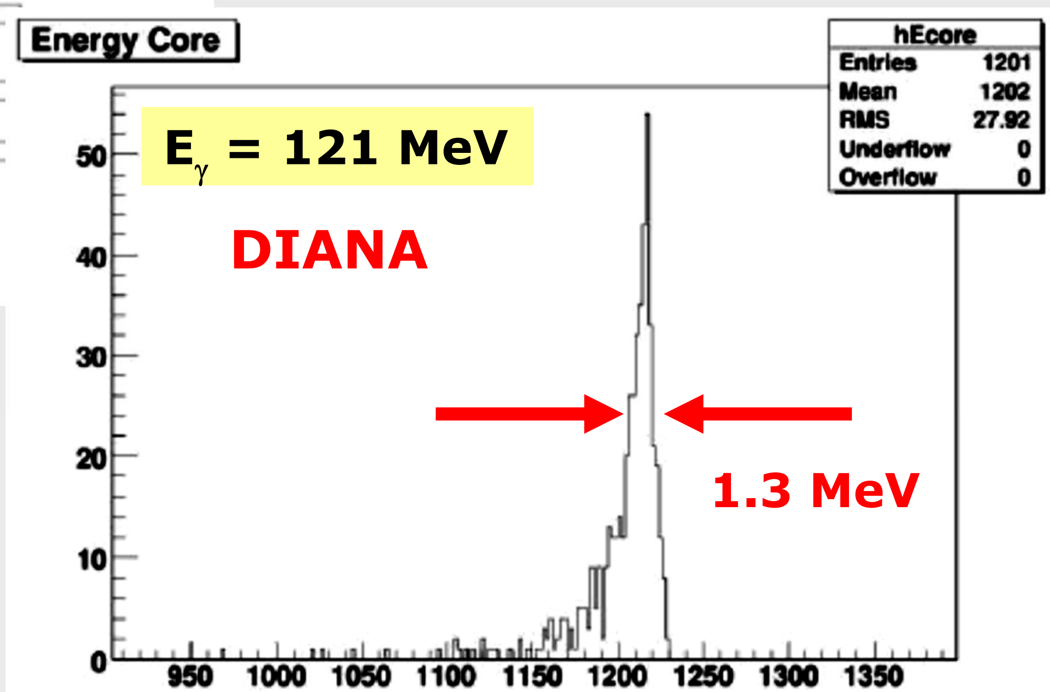


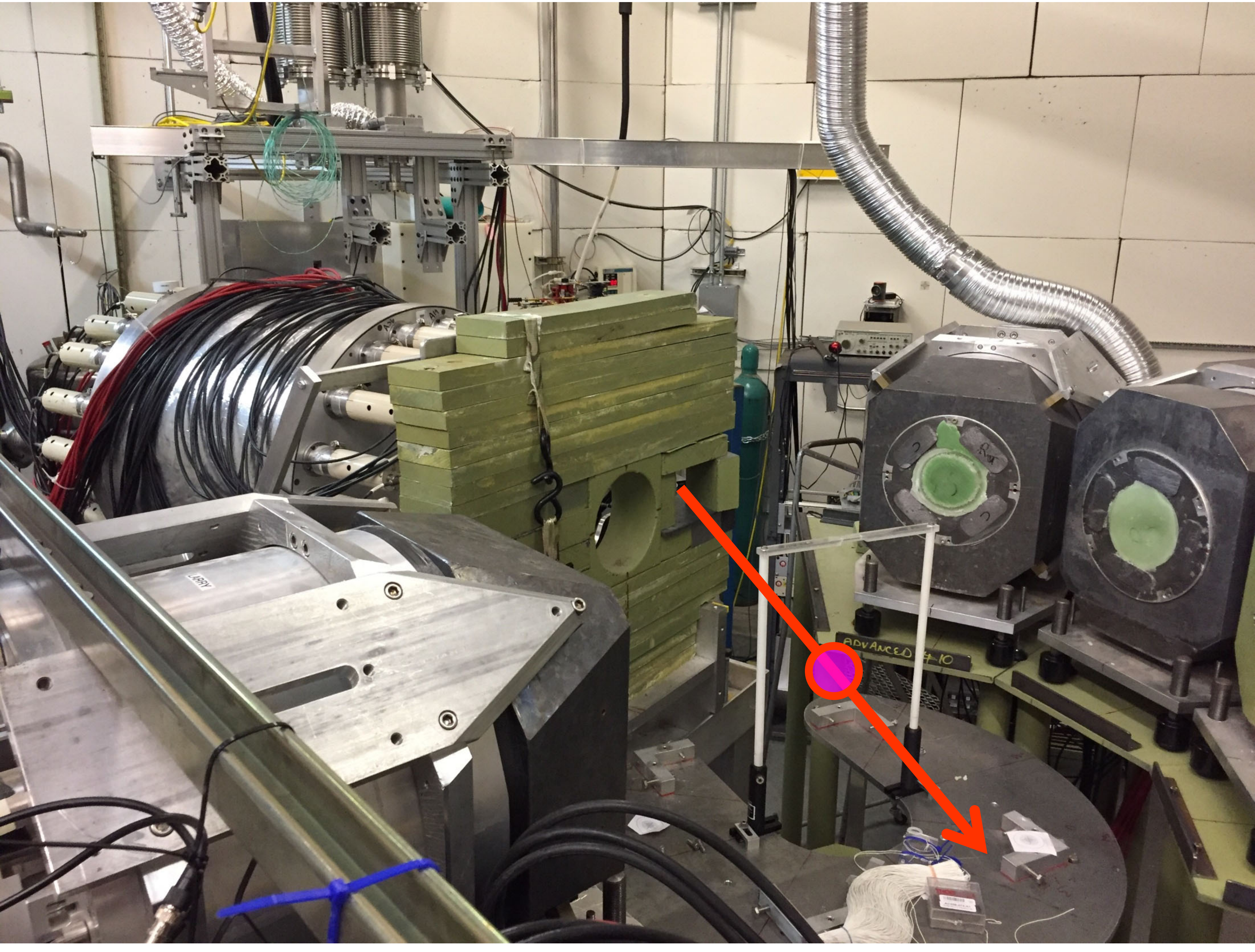
M. Kovash (2018)

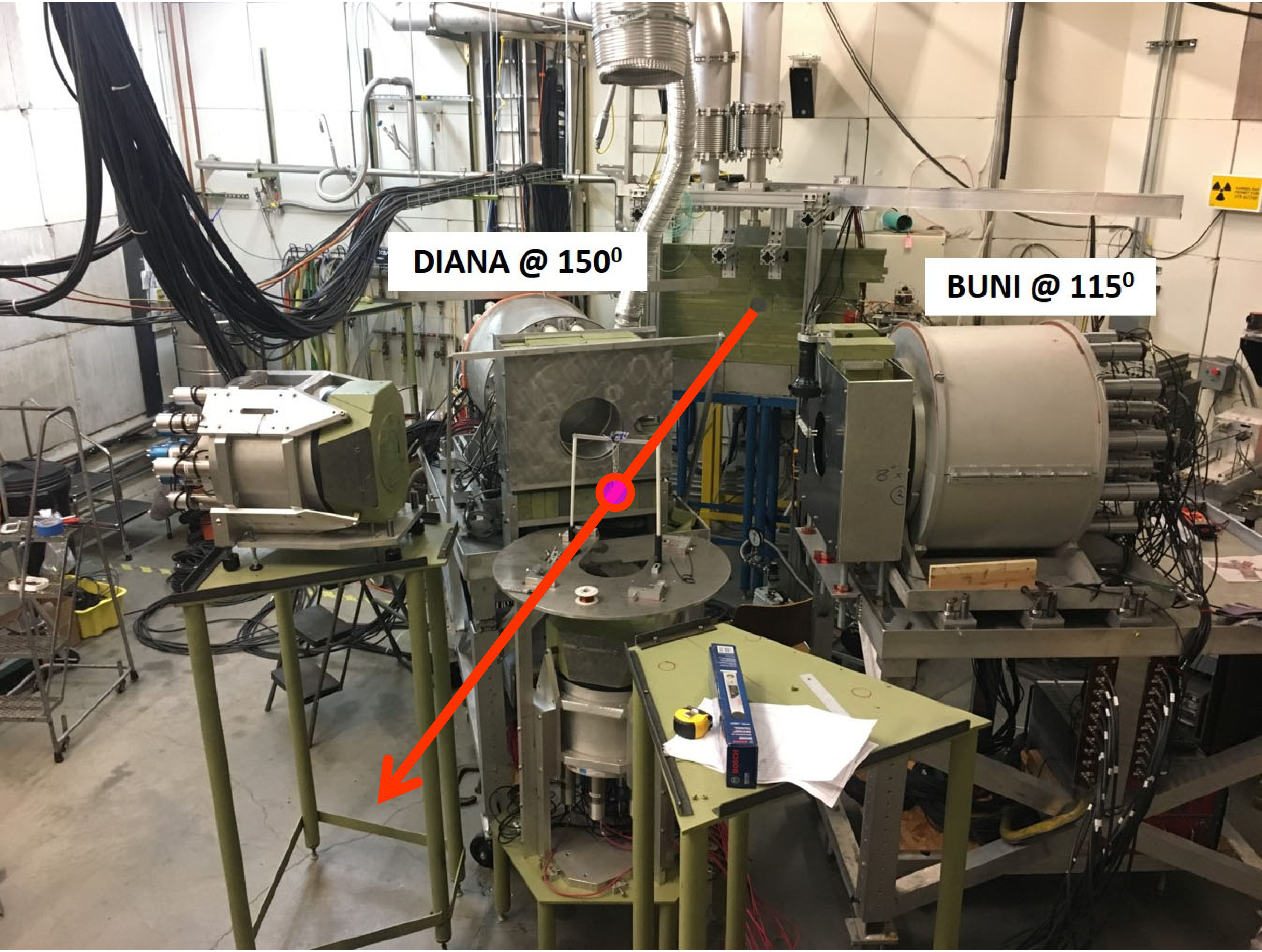

Pb Collimator
Ann PMTs
508 X 483 mm
Core PMTs
NaI Core
NaI Annulus
DIANA
Back View
Side View


CATS
Front View
48 cm
27 cm
SEG 1
SEG 6
SEG 2
CORE
SEG 5
SEG 3
SEG 4


Plastic Shield
NaI Quads
NaI Core
BUNI


Energy Core
hEcore
Entries 1201
Mean 1202
RMS 27.92
Underflow 0
Overflow 0
E$_\gamma$ = 121 MeV
DIANA
1.3 MeV
0
10
20
30
40
50
950 1000 1050 1100 1150 1200 1250 1300 1350

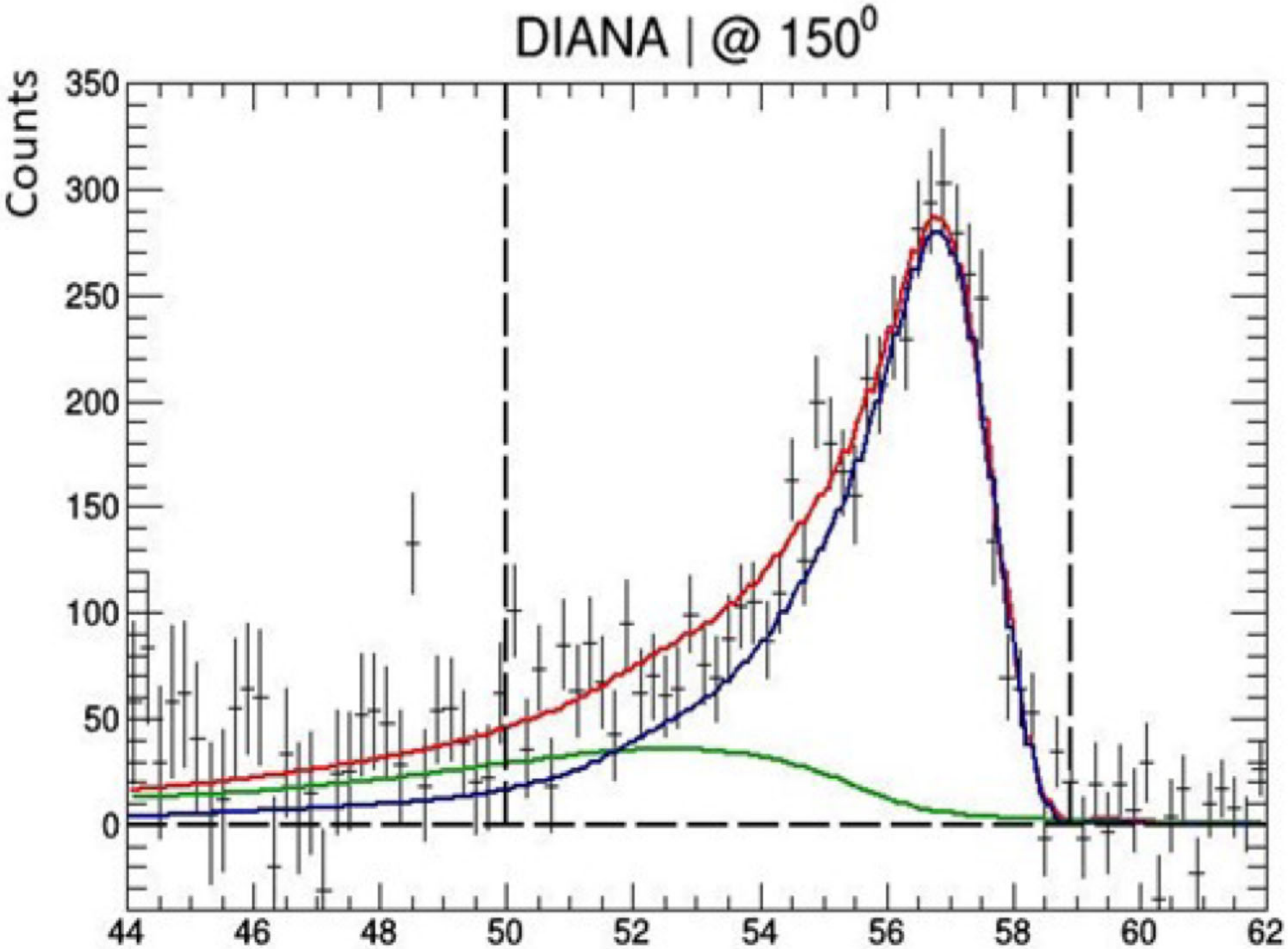

LARRY
ADVANCED

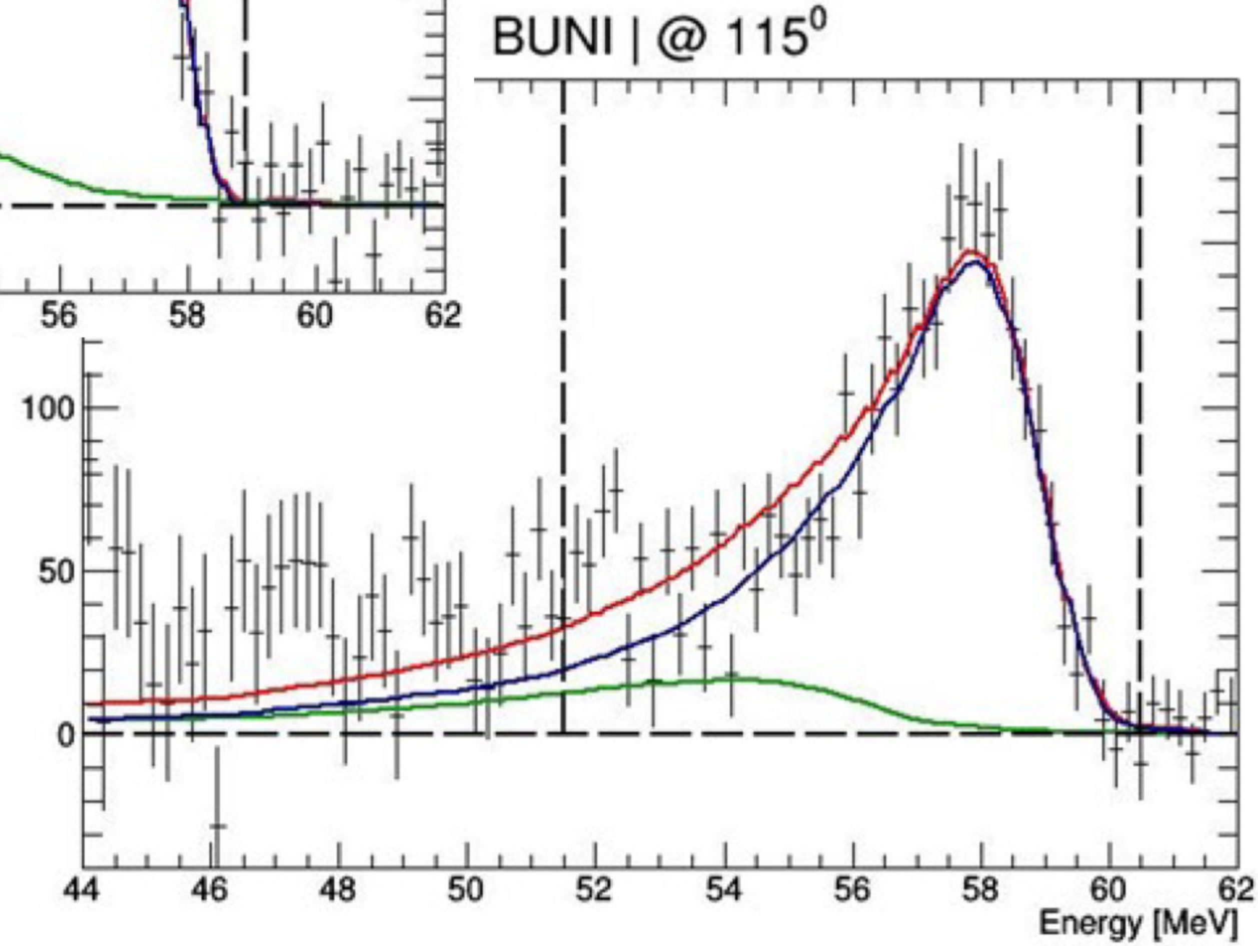


DIANA @ 150^0
BUNI @ 115^0

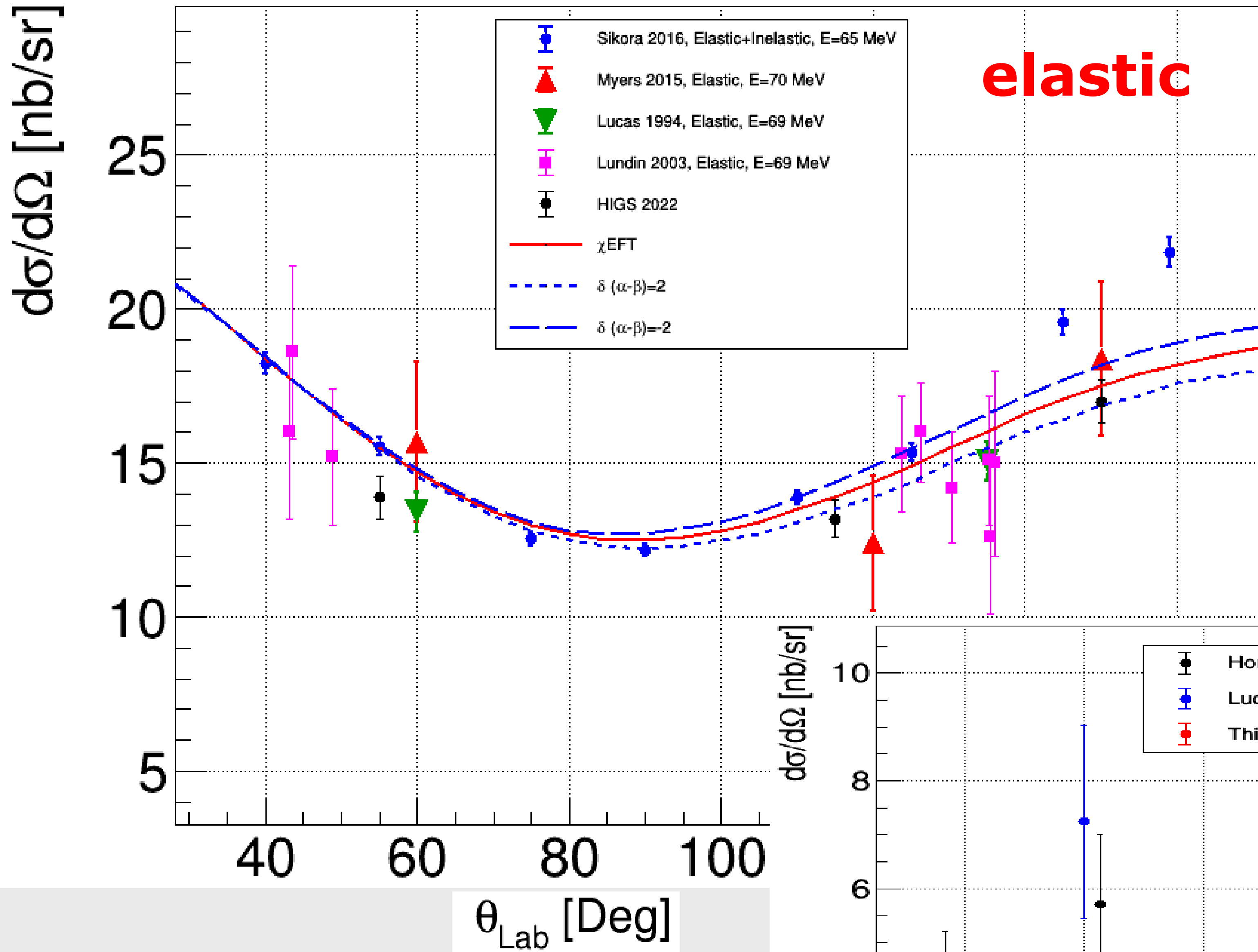
$D(\gamma,\gamma)D$

$E_\gamma = 61$ MeV





D. Godagama (2022)

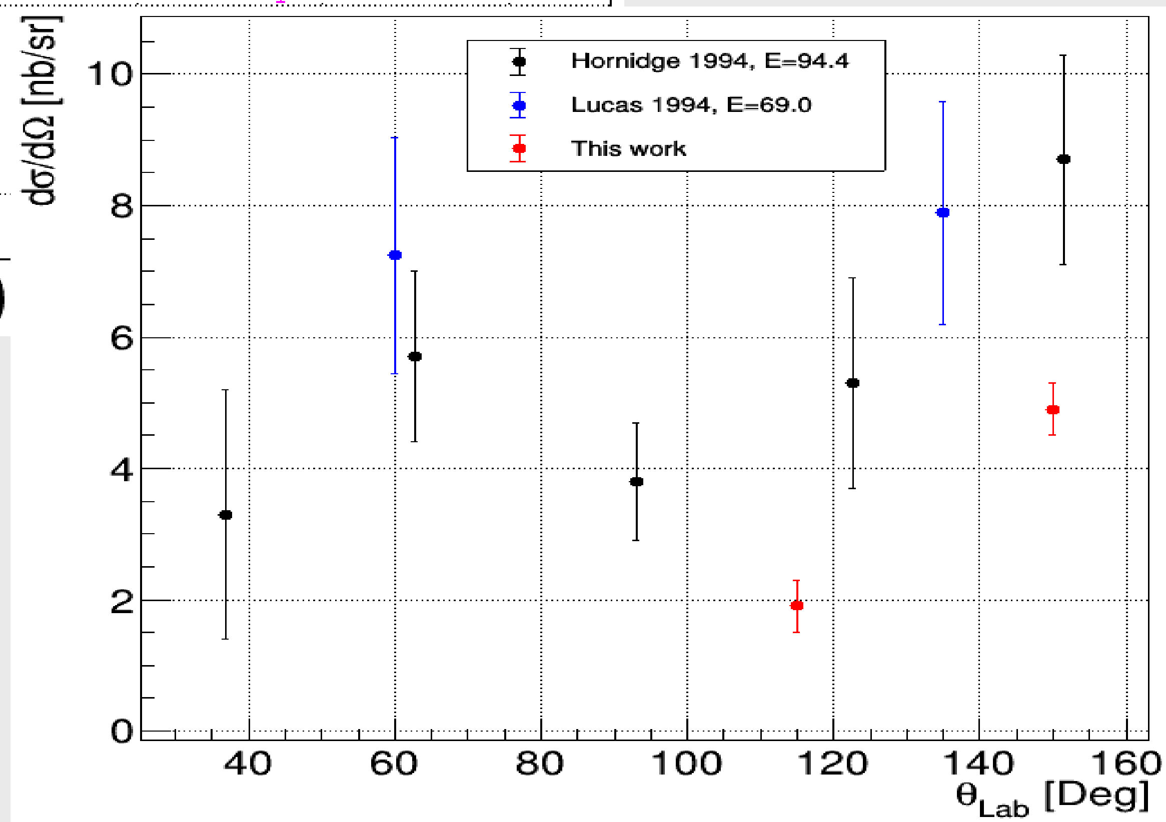


$D(\gamma,\gamma)D$

E_γ = 61-70 MeV

inelastic

E_γ = 61-94 MeV



D. Godagama (2022)

Polarized Compton Scattering on the Proton

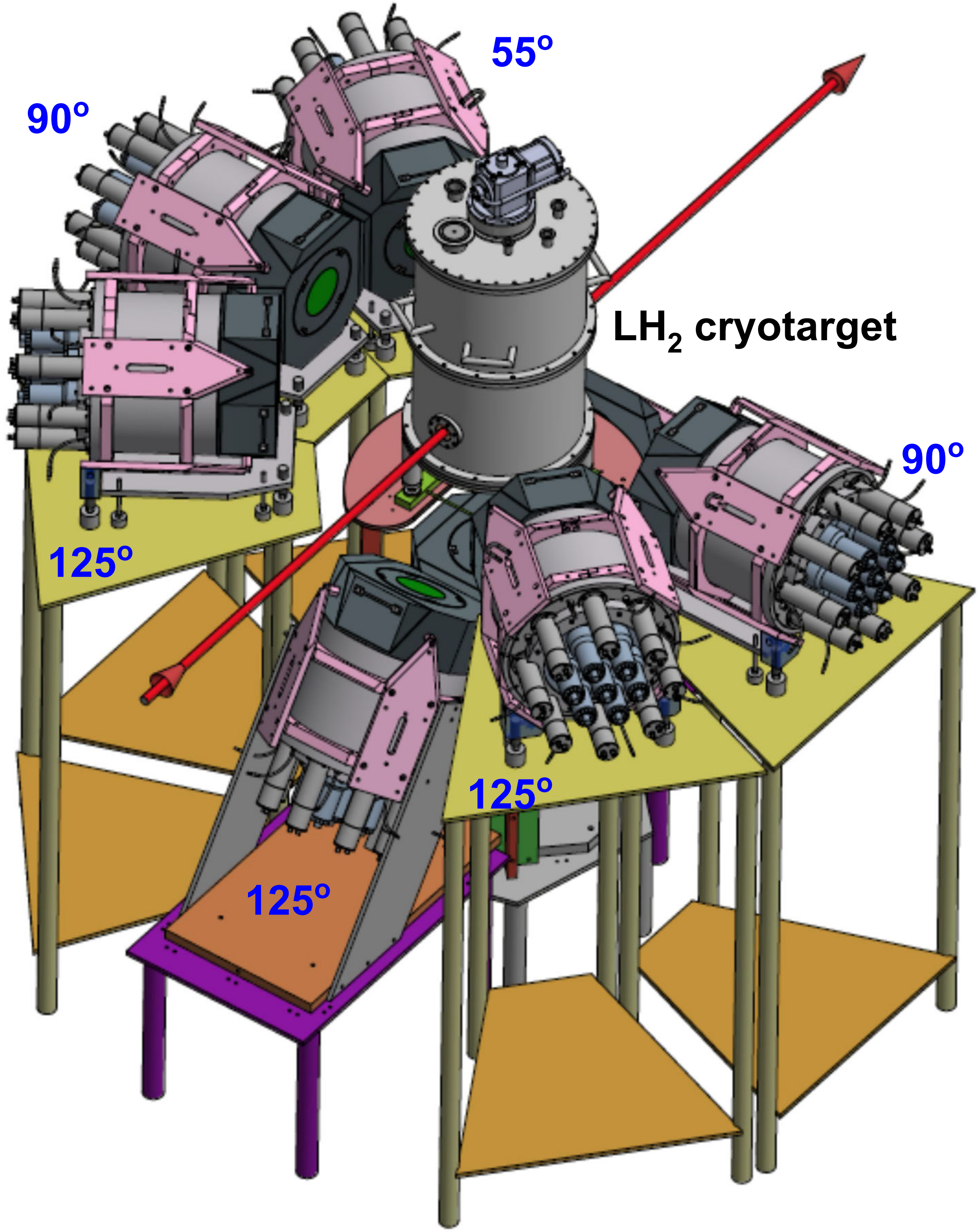
Experimental Setup

polarized Compton scattering on proton

beam polarization in horizontal plane

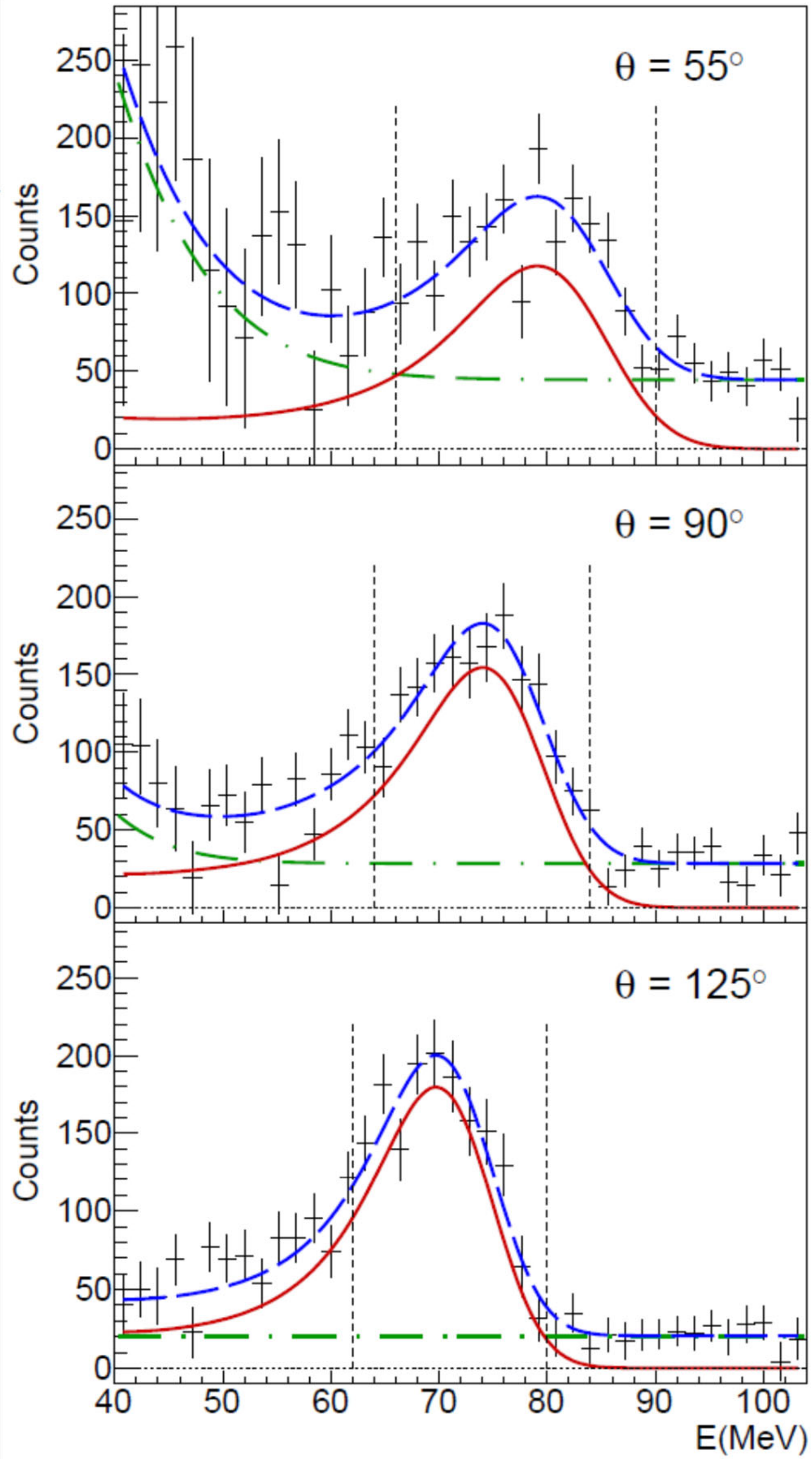
5 parallel NaI's

3 perpendicular



$p(\vec{\gamma},\gamma)p$

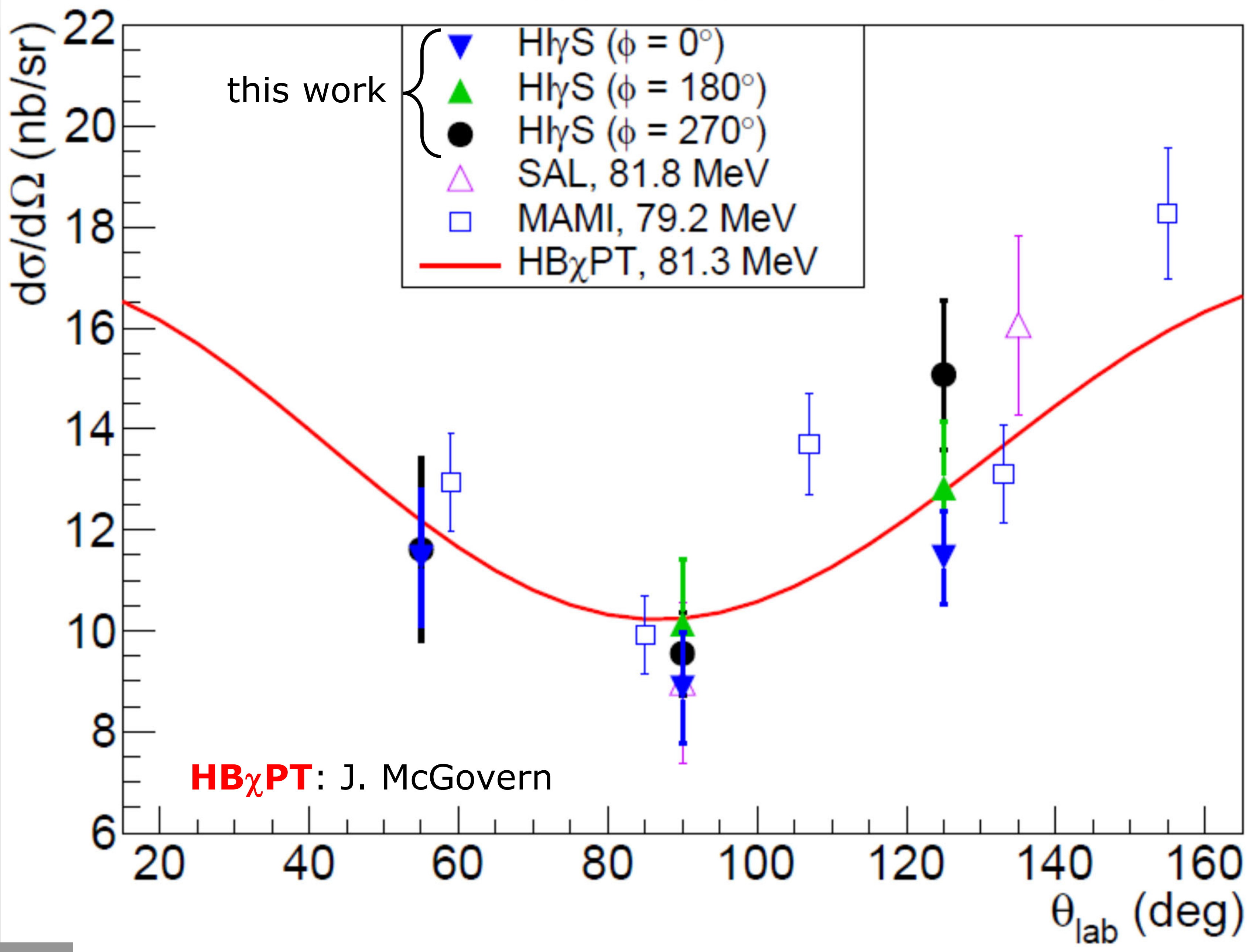
$E_\gamma = 83$ MeV



X. Li (2022)

$p(\gamma,\gamma)p$

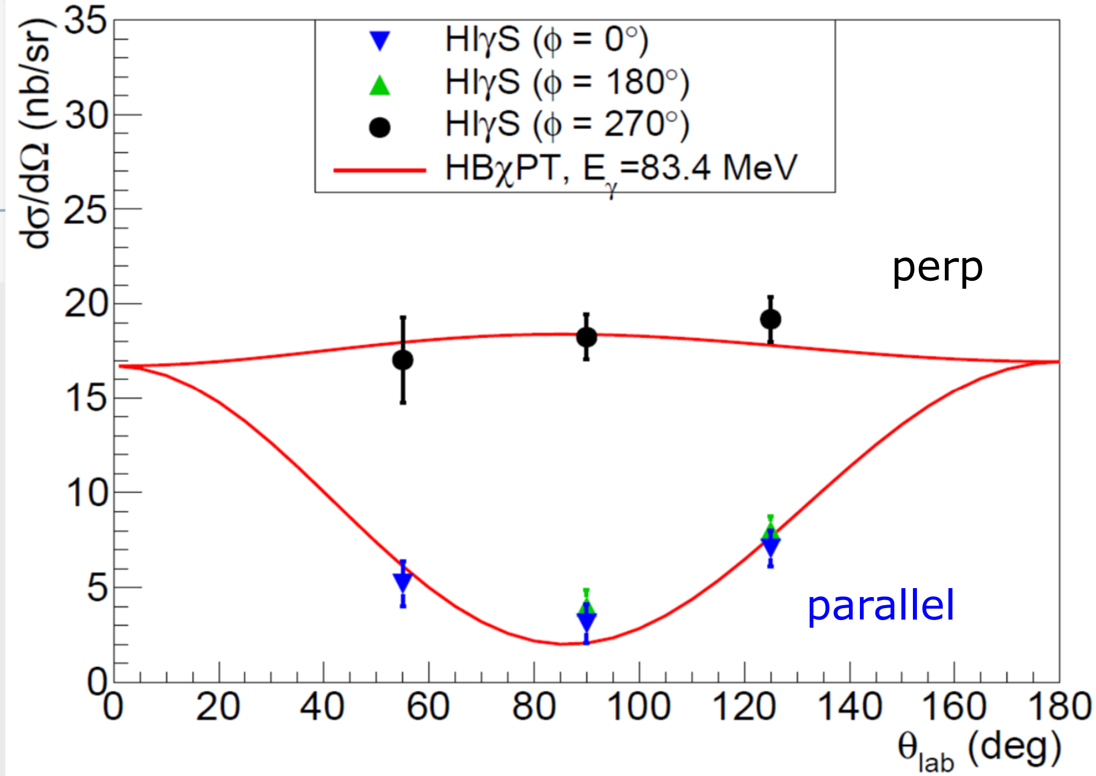
$E_\gamma = 81$ MeV



X. Li (2022)

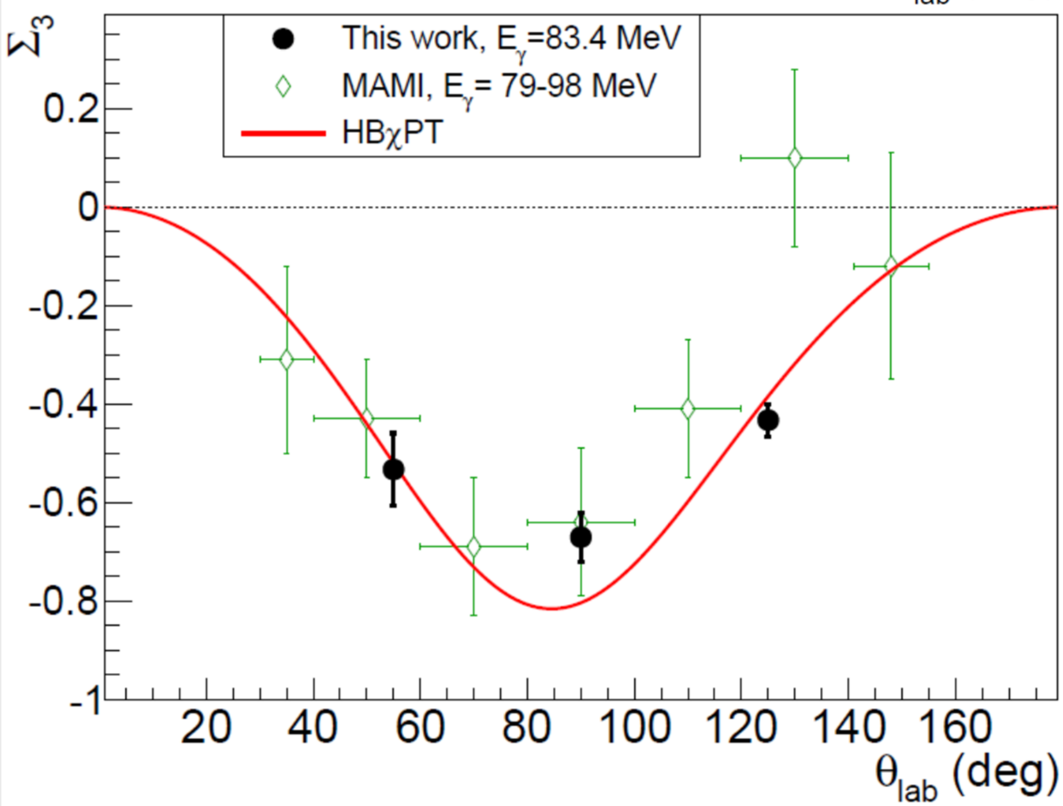
$p(\vec{\gamma},\gamma)p$

$E_\gamma = 83$ MeV



HBχPT: J. McGovern

$$\Sigma_3(\theta) = \frac{\sigma_{\|}(\theta) - \sigma_{\perp}(\theta)}{\sigma_{\|}(\theta) + \sigma_{\perp}(\theta)}$$



X. Li (2022)

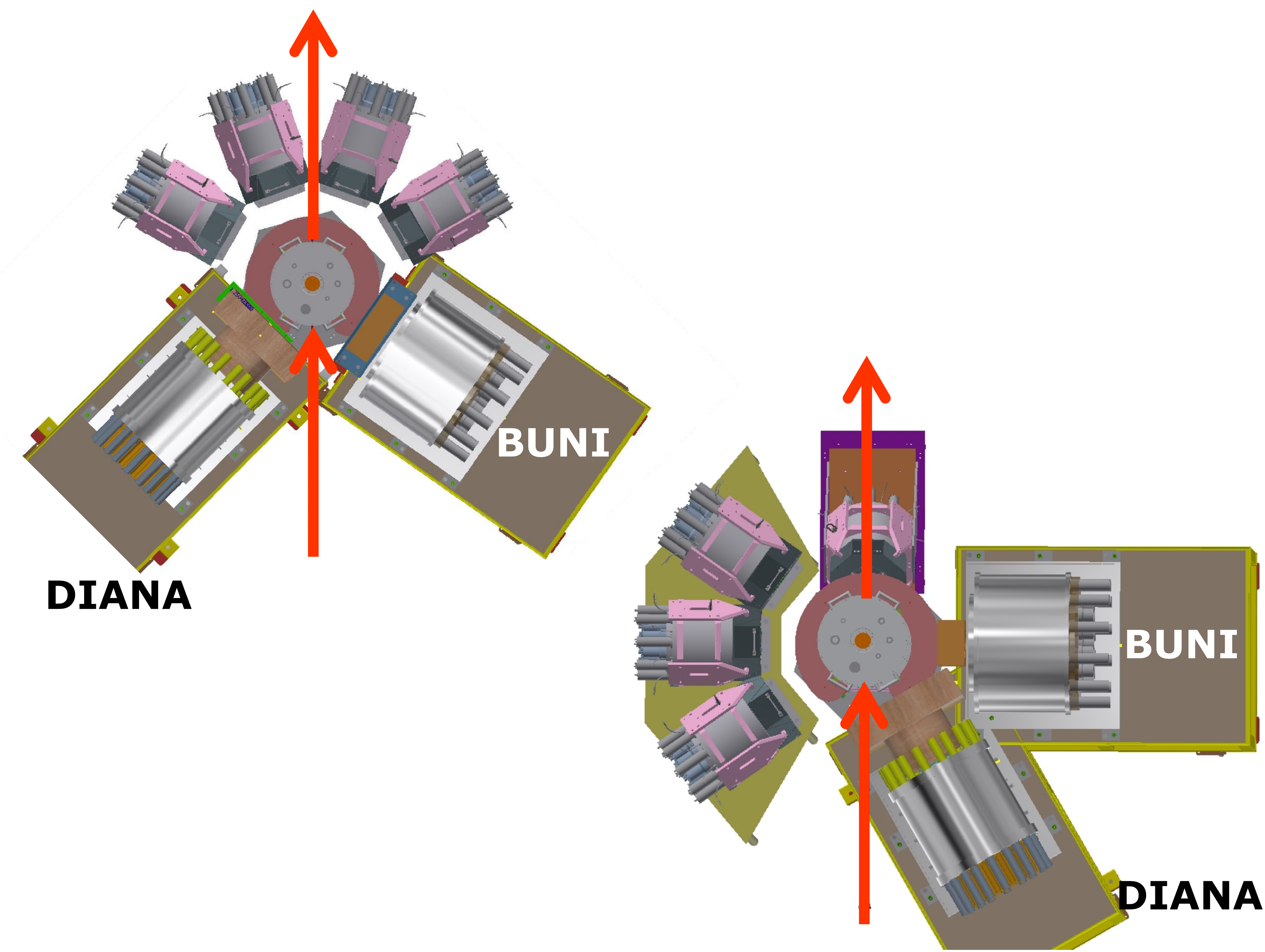
Compton Scattering on ^3He

New Experiment $^3He(\gamma,\gamma)^3He$

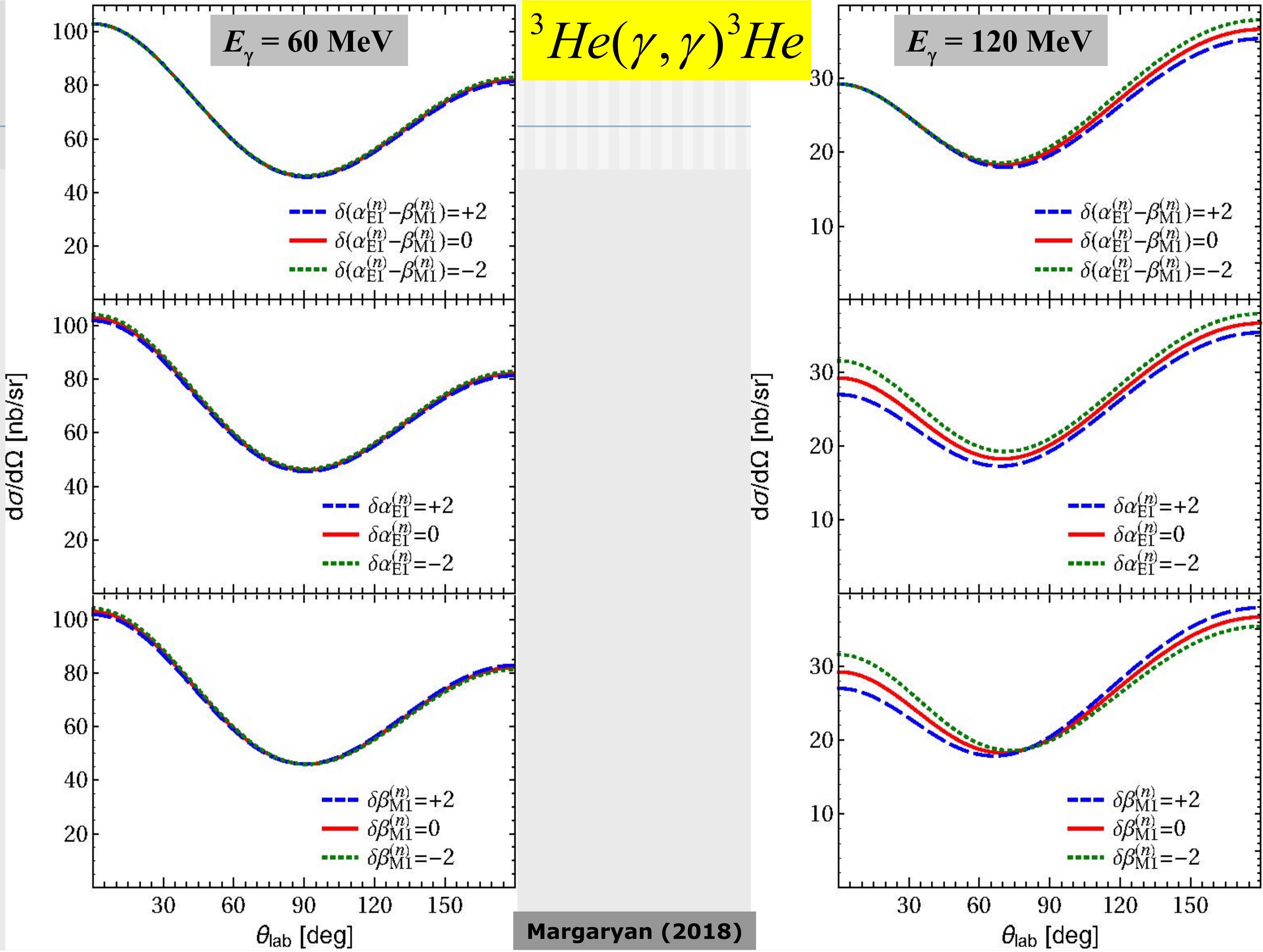
- experiment details
  - higher cross section for **Z = 2** target (compared to ^2H)
  - first breakup channel (***d + p***) at **5.5 MeV** (compared to ^2H)
  - exploit different Compton scattering channel to access α and β
  - no previous Compton data on ^3He exists!
  - modify cryotarget: lower base temperature and ^3He recovery

---

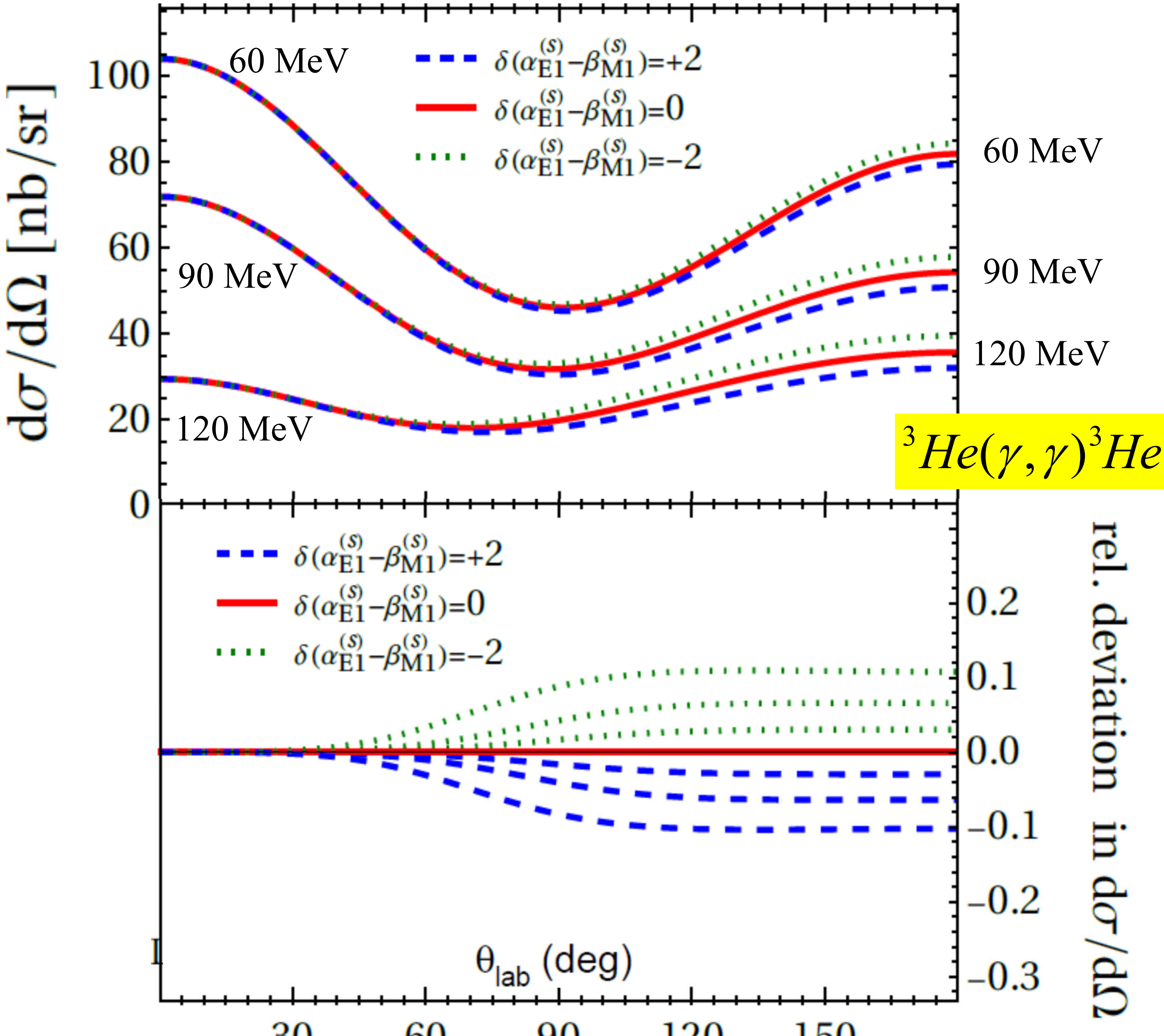
- energies: **E_γ = 60, 80, 100, 120 MeV**
- angles: **θ_γ = 45°-150°**
- target: liquid **^3He** cryogenic target
- detectors: **BUNI, DIANA, and 4 HINDA NaI's**


BUNI
DIANA
BUNI
DIANA

$^3He(\gamma,\gamma)^3He$

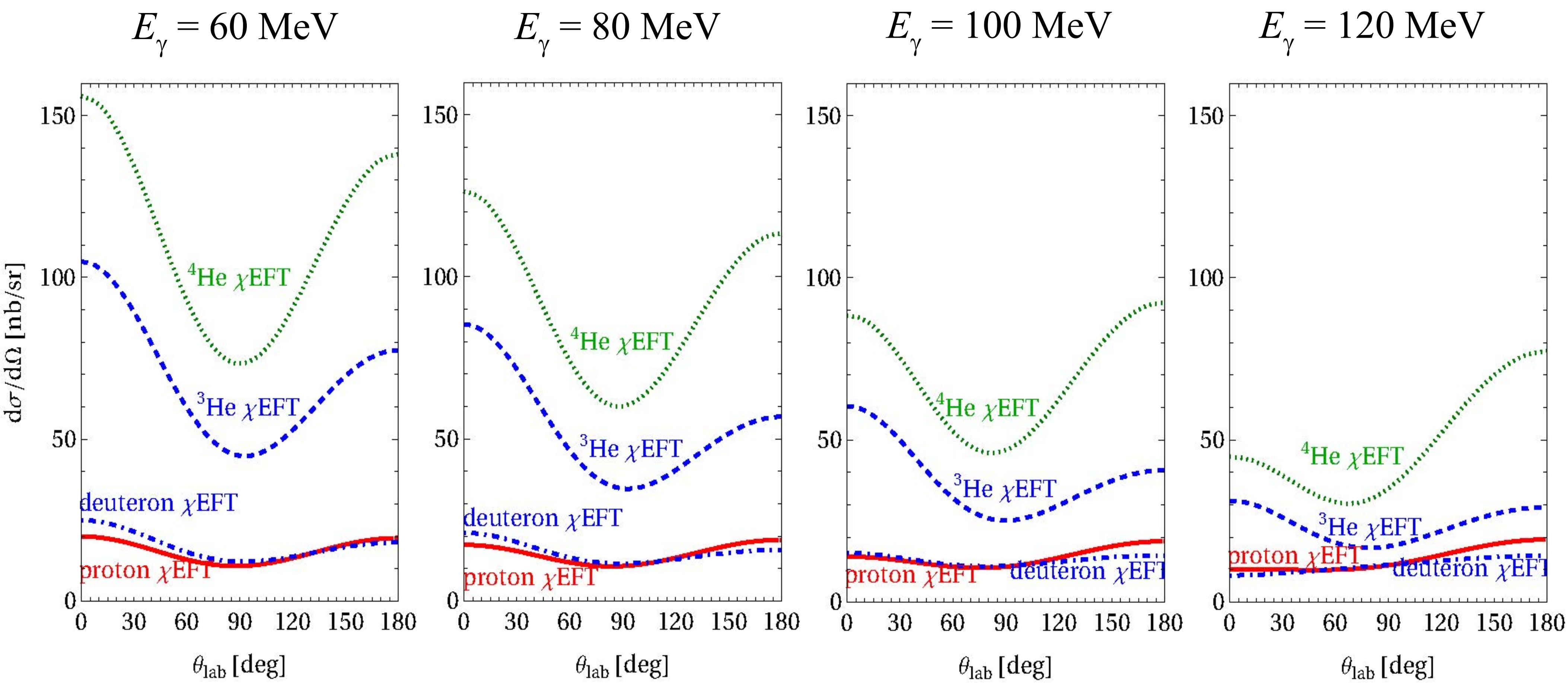


Margaryan (2018)



Margaryan (2018)

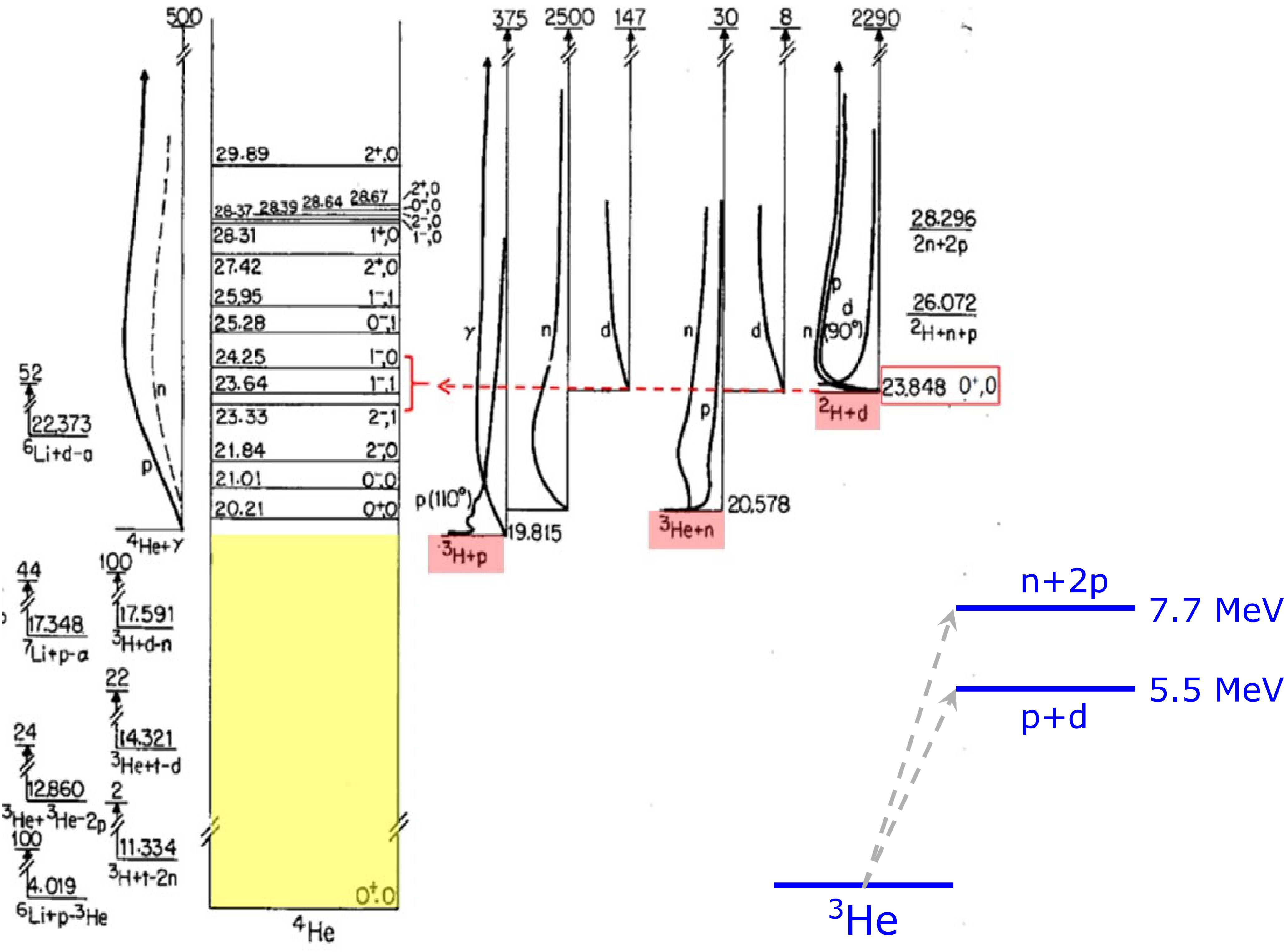
Compton Scattering on ^4He (extended)

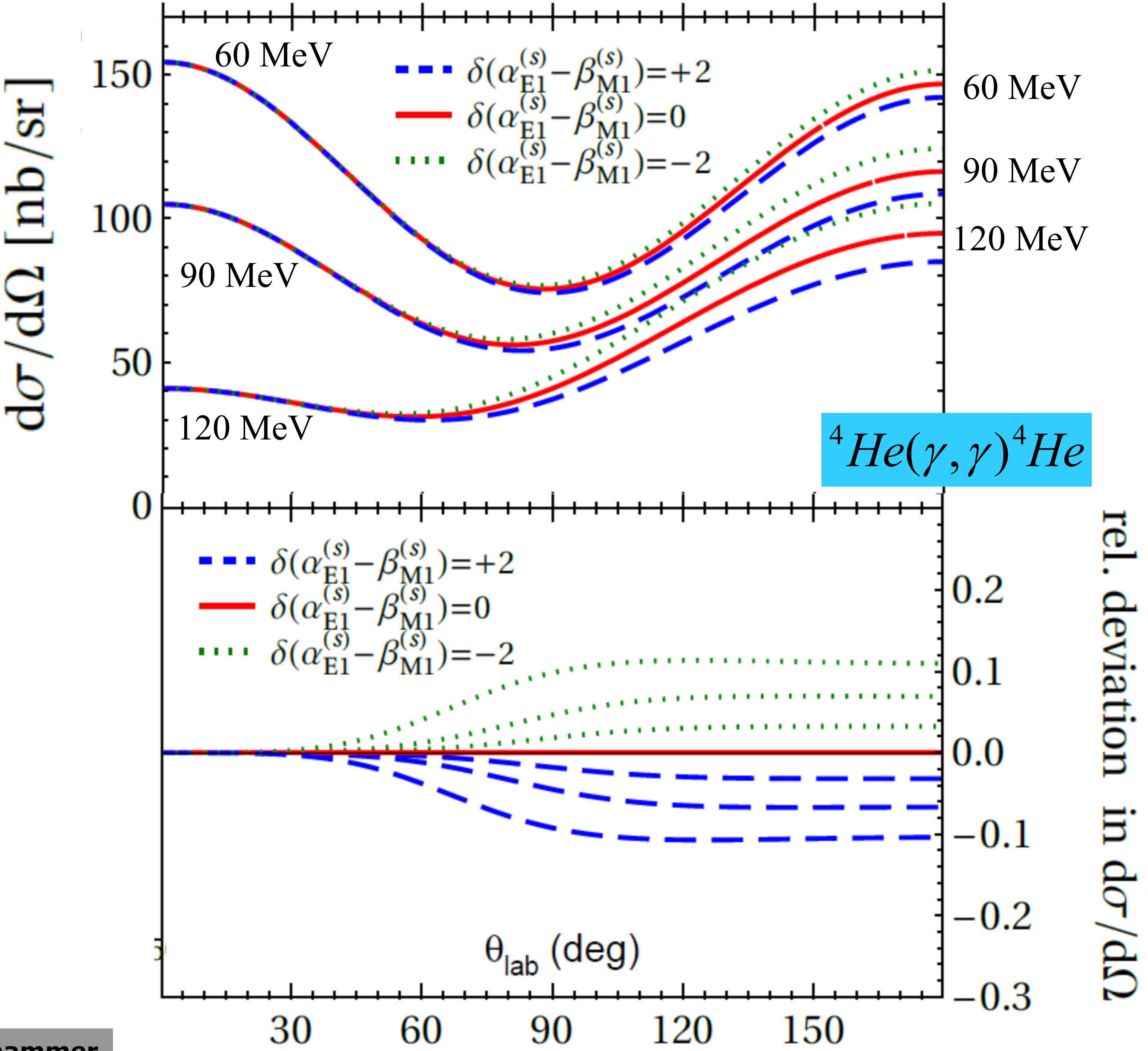


big advantage for ^{4}He over ^{3}He

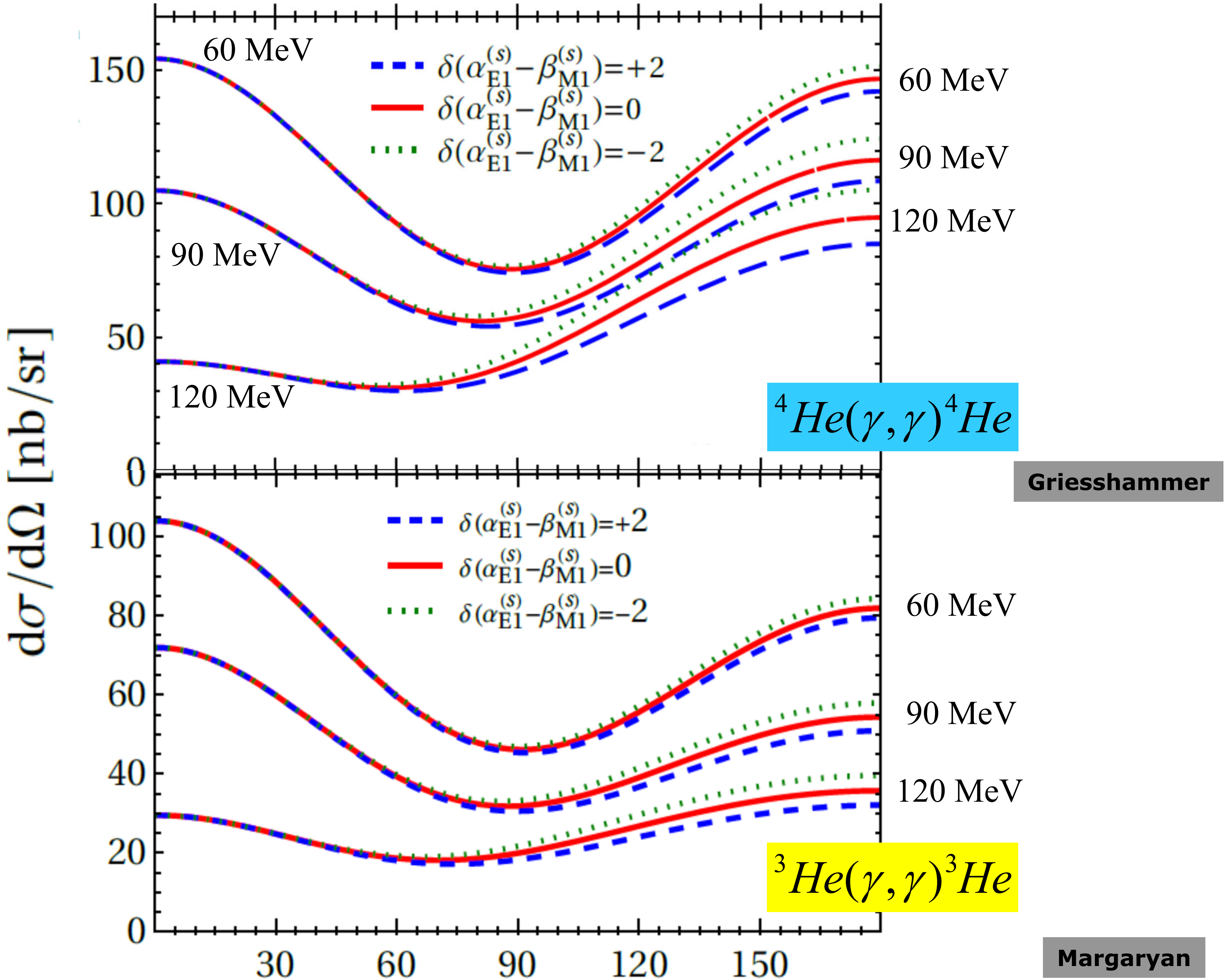
(especially at backward angles!)

Griesshammer


29.89 2+,0
28.37 28.39 28.64 28.67
2+,0
0-,0
2-,0
1-,0
28.31 1+,0
27.42 2+,0
25.95 1-,1
25.28 0-,1
24.25 1-,0
23.64 1-,1
23.33 2-,1
21.84 2-,0
21.01 0-,0
20.21 0+,0
0+,0
4He
500
4He+γ
52
22.373
6Li+d-α
44
17.348
7Li+p-α
100
17.591
3H+d-n
22
14.321
3He+t-d
24
12.860
3He+3He-2p
2
11.334
3H+t-2n
100
4.019
6Li+p-3He
375 2500 147 30 8 2290
p(110°)
19.815
3H+p
20.578
3He+n
23.848 0+,0
2H+d
28.296
2n+2p
26.072
2H+n+p
d(90°)
n+2p
7.7 MeV
5.5 MeV
p+d
3He



Griesshammer



60 MeV
$\delta(\alpha_{E1}^{(s)}-\beta_{M1}^{(s)})=+2$
$\delta(\alpha_{E1}^{(s)}-\beta_{M1}^{(s)})=0$
$\delta(\alpha_{E1}^{(s)}-\beta_{M1}^{(s)})=-2$
60 MeV
90 MeV
120 MeV
90 MeV
120 MeV
$^4He(\gamma,\gamma)^4He$
Griesshammer
$d\sigma/d\Omega$ [nb/sr]
$\delta(\alpha_{E1}^{(s)}-\beta_{M1}^{(s)})=+2$
$\delta(\alpha_{E1}^{(s)}-\beta_{M1}^{(s)})=0$
$\delta(\alpha_{E1}^{(s)}-\beta_{M1}^{(s)})=-2$
60 MeV
90 MeV
120 MeV
$^3He(\gamma,\gamma)^3He$
Margaryan

Summary

- ^{4}He and ^{2}H **unpolarized** data
- proton: photon beam asymmetry with **linearly polarized** beam
- ^{6}Li, ^{12}C and ^{16}O unpolarized data

Summary

- ^{4}He and ^{2}H **unpolarized** data
- proton: photon beam asymmetry with **linearly polarized** beam
- ^{6}Li, ^{12}C and ^{16}O unpolarized data

- ^{2}H: high resolution run (separate elastic/inelastic)
- **^{3}He: first Compton on A = 3 (coming in Spring 2024)**
- ^{4}He: measure energy dependence (60-120 MeV)

Summary

- ^{4}He and ^{2}H **unpolarized** data
- proton: photon beam asymmetry with **linearly polarized** beam
- ^{6}Li, ^{12}C and ^{16}O unpolarized data

- ^{2}H: high resolution run (separate elastic/inelastic)
- **^{3}He: first Compton on A = 3 (coming in Spring 2024)**
- ^{4}He: measure energy dependence (60-120 MeV)

- **Strong EFT support (Griesshammer, McGovern, Phillips)**
  - next milestone – theory framework for A = 4
- **HIGS can contribute high-quality data!**
  - stay tuned for further developments in the future…