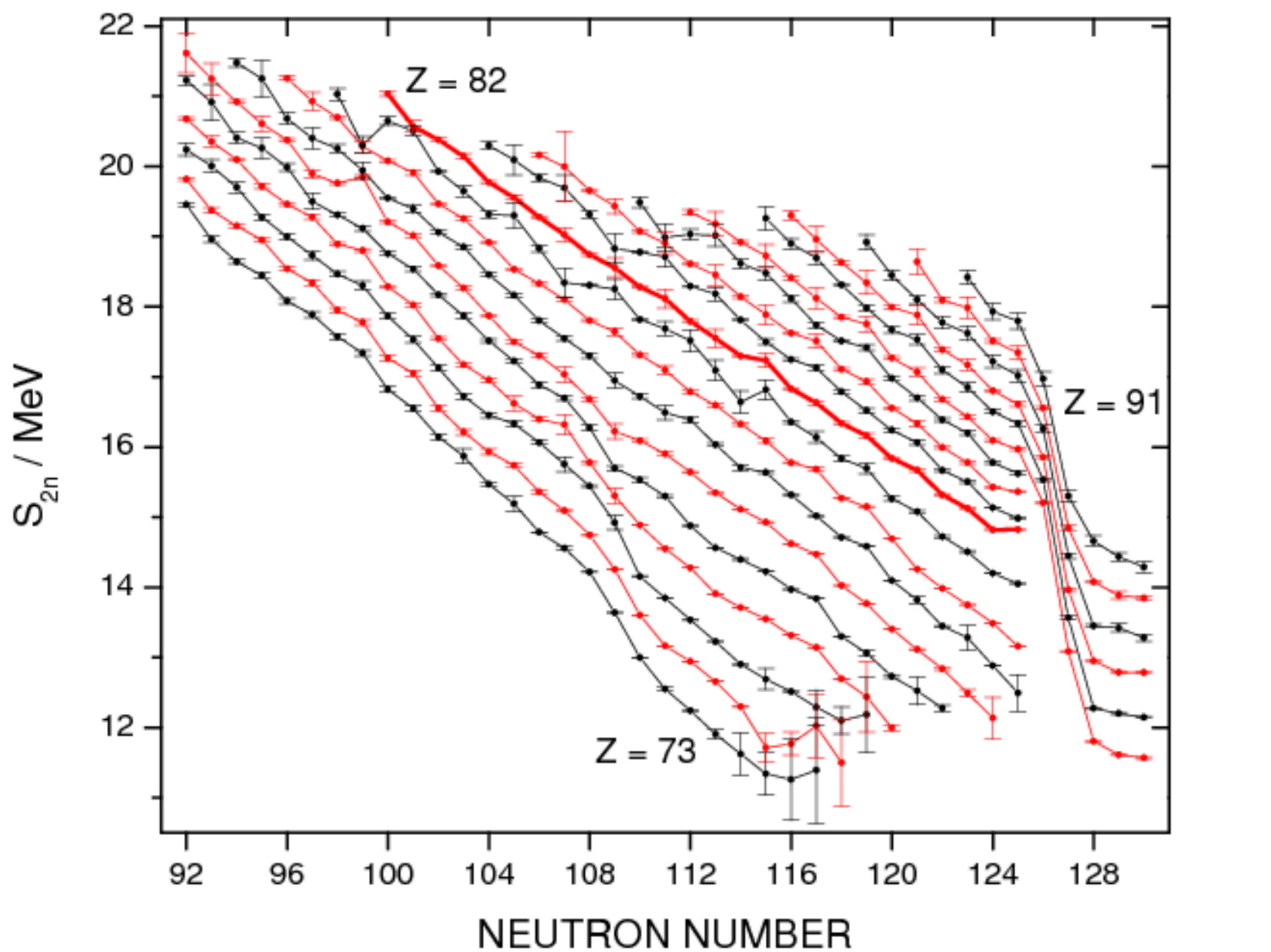
WNPPC 2021

SIMULATING DAEMON (DETECTOR ARRAY FOR ENERGY MEASUREMENTS OF NEUTRONS): A NEW COMPLEMENTARY NEUTRON DETECTOR FOR GRIFFIN

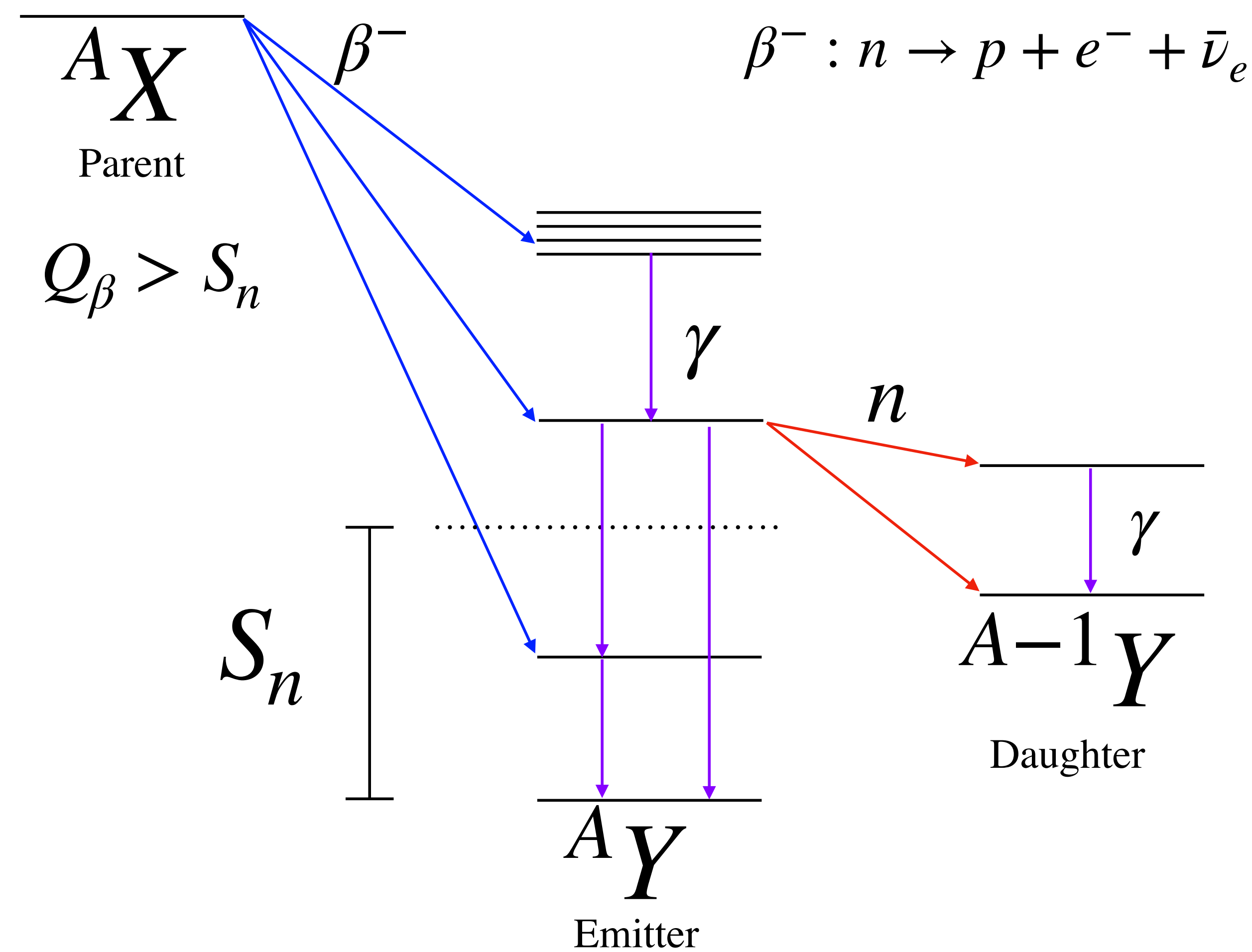
HARRIS BIDAMAN
UNIVERSITY OF GUELPH

BACKGROUND

Beta Delayed Neutron Emission



C. Weber et al., Nuclear Physics A 803, 1 (2008)



- Studying neutron rich nuclei is the at the forefront of nuclear physics research
- As the ratio of neutrons (N) to protons (Z) increases, the valence neutrons become less bound which can give rise to beta delayed neutron emission

BACKGROUND

Astrophysical Processes

Many r-process nuclei are beta delayed neutron emitters

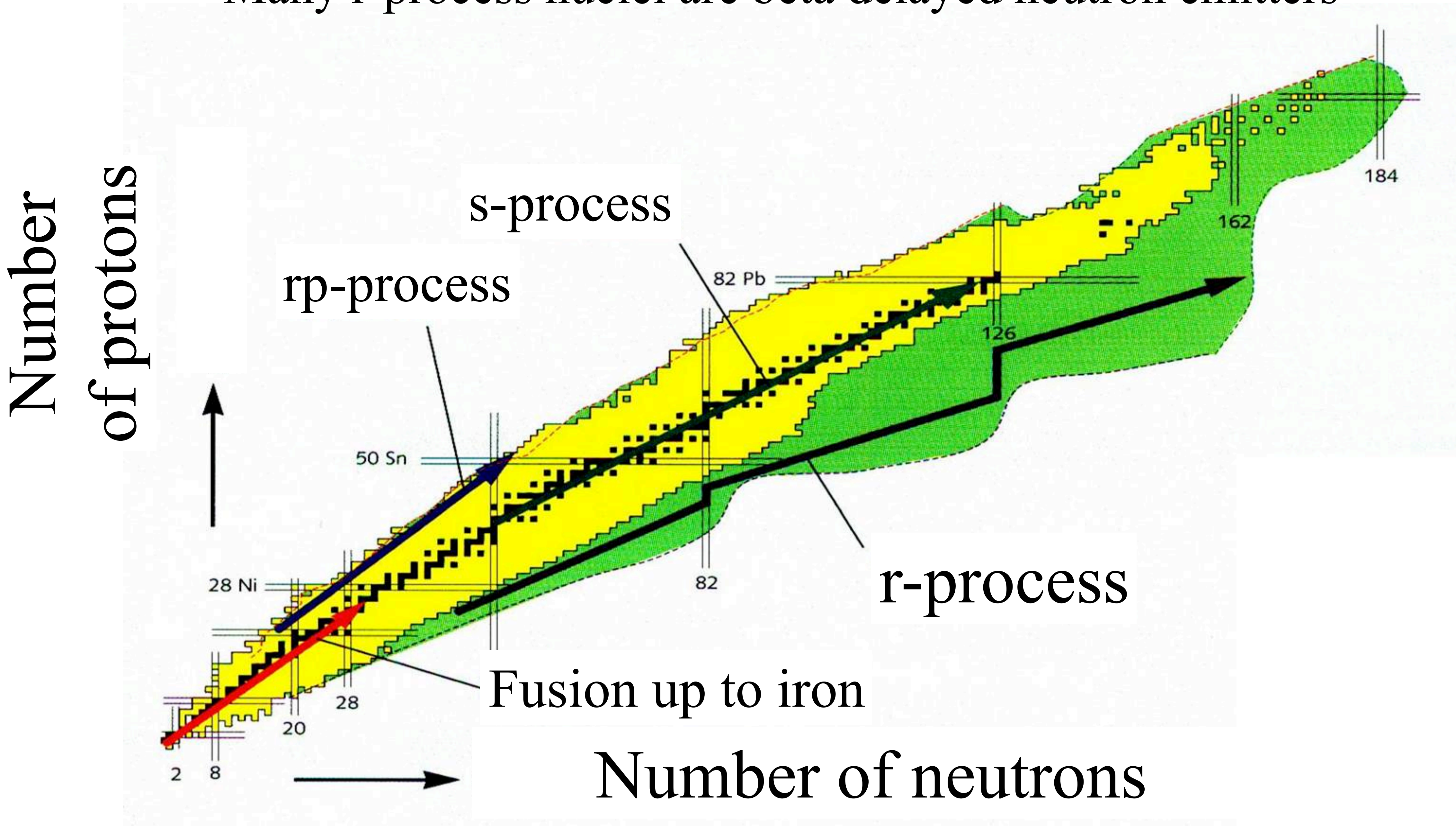
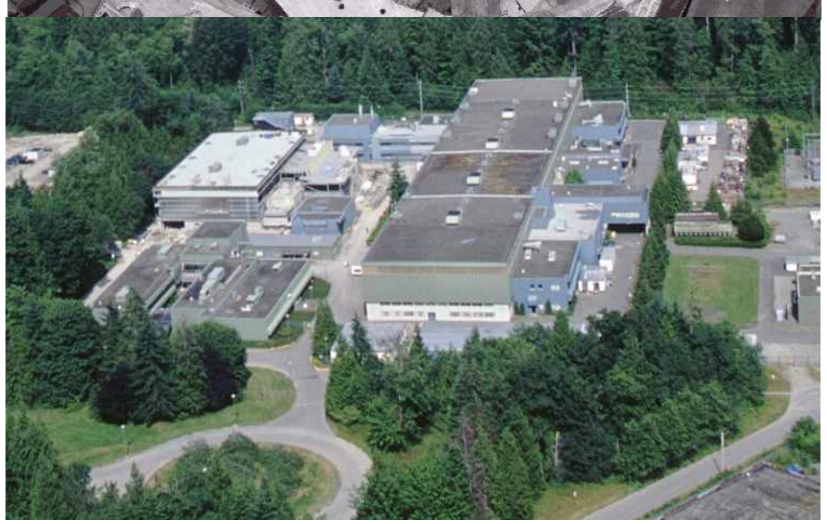
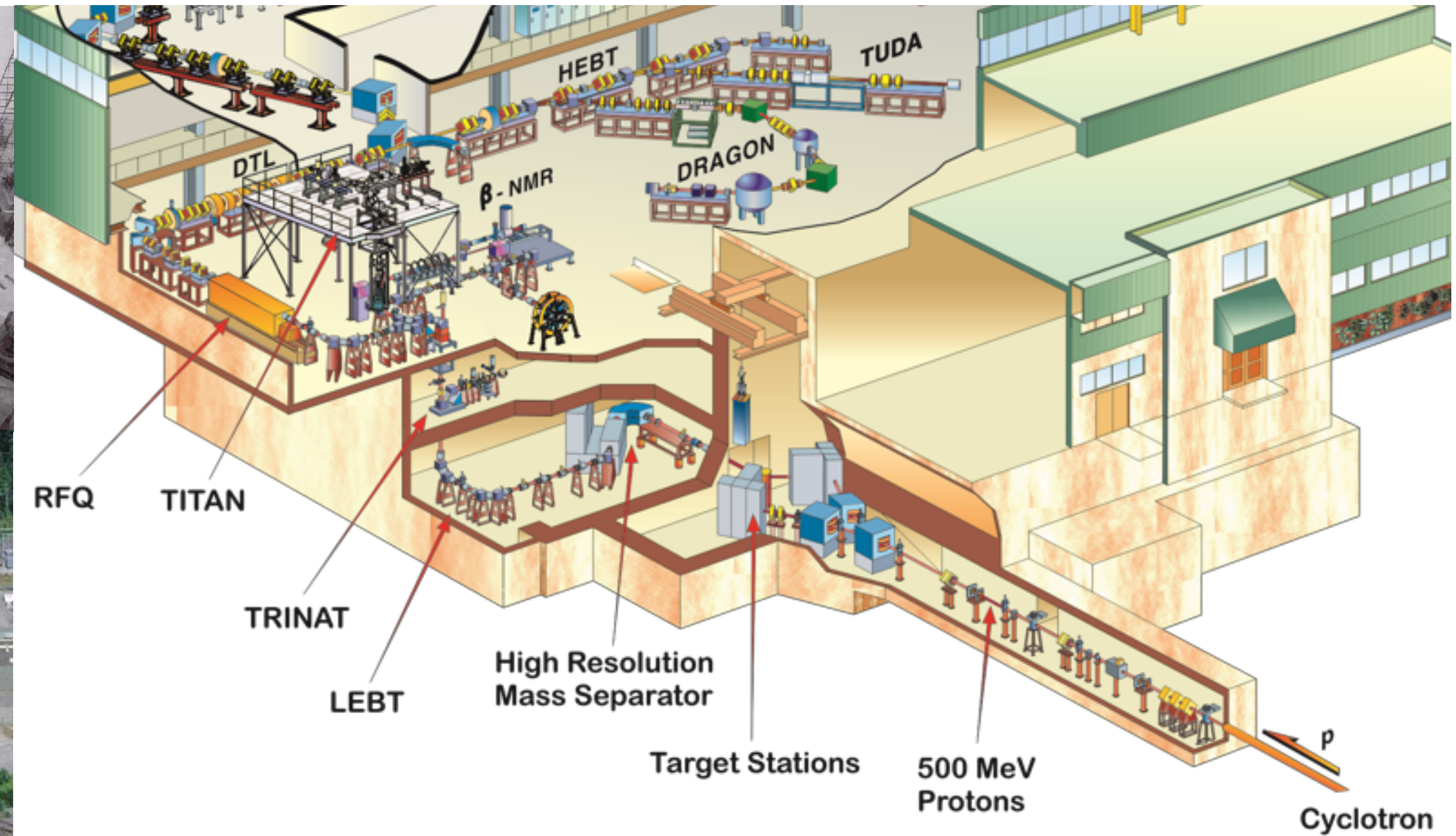


Image from: http://www.phys.utk.edu/expnuclear/nucastro.html

TRIUMF

Canada's particle accelerator centre

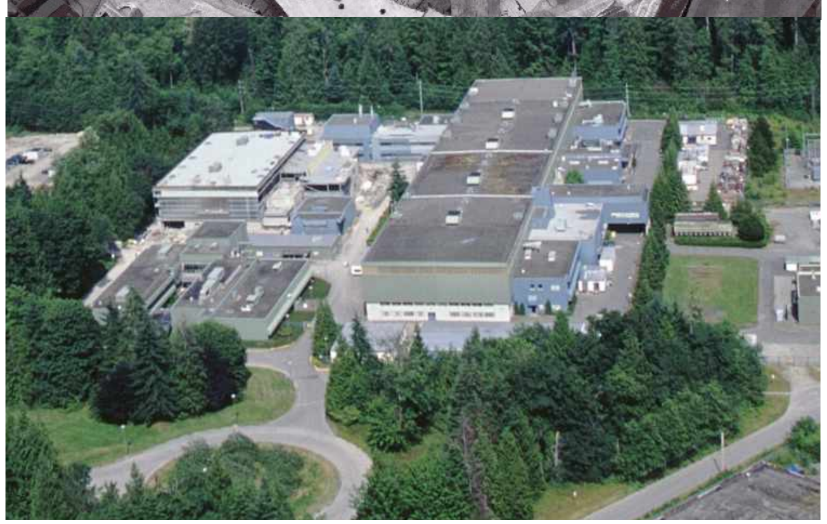


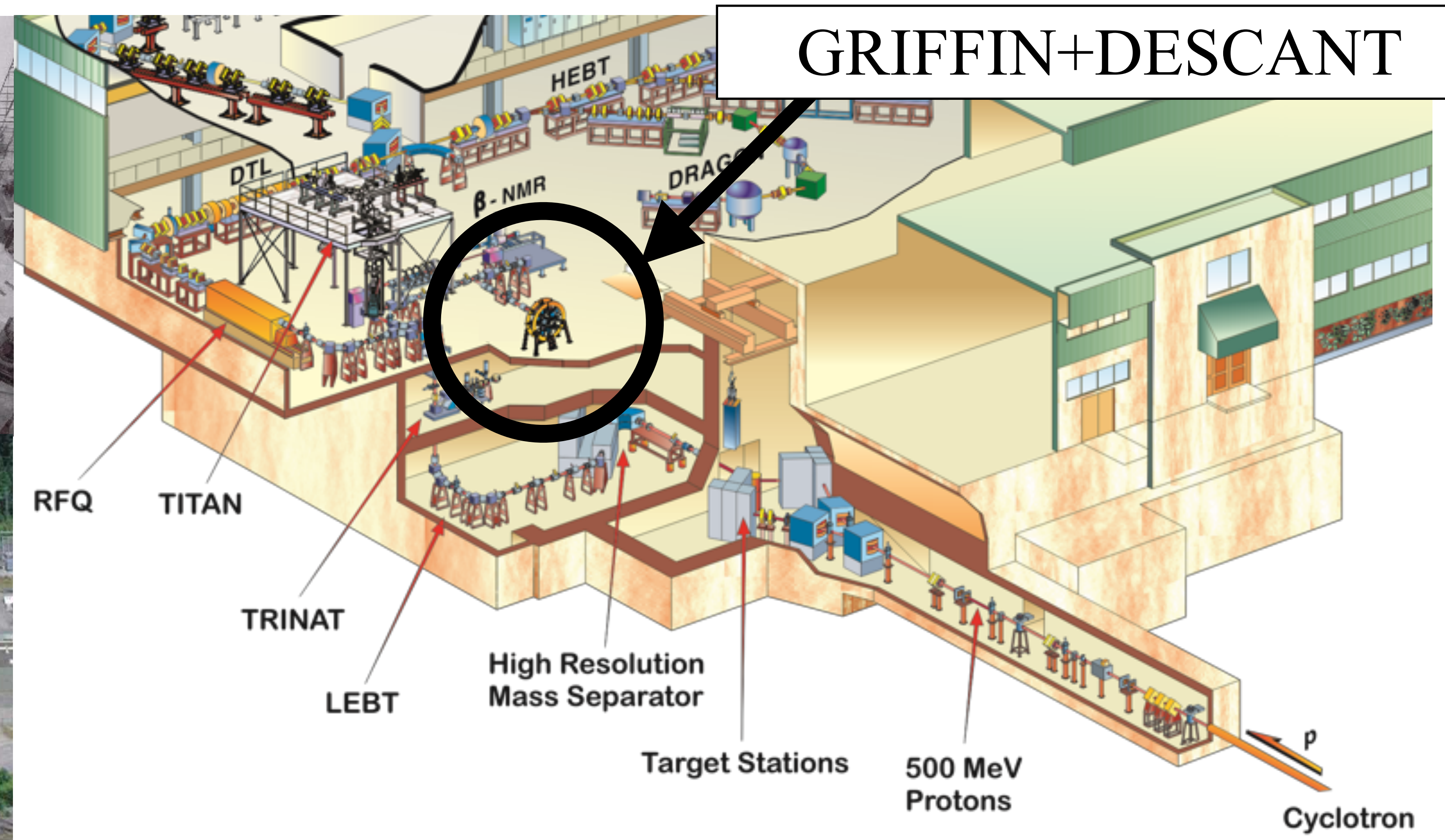


- Strong campaign studying neutron rich nuclei at TRIUMF
  - Via beta decay and beta delayed neutron spectroscopy

TRIUMF

Canada’s particle accelerator centre





- Strong campaign studying neutron rich nuclei at TRIUMF
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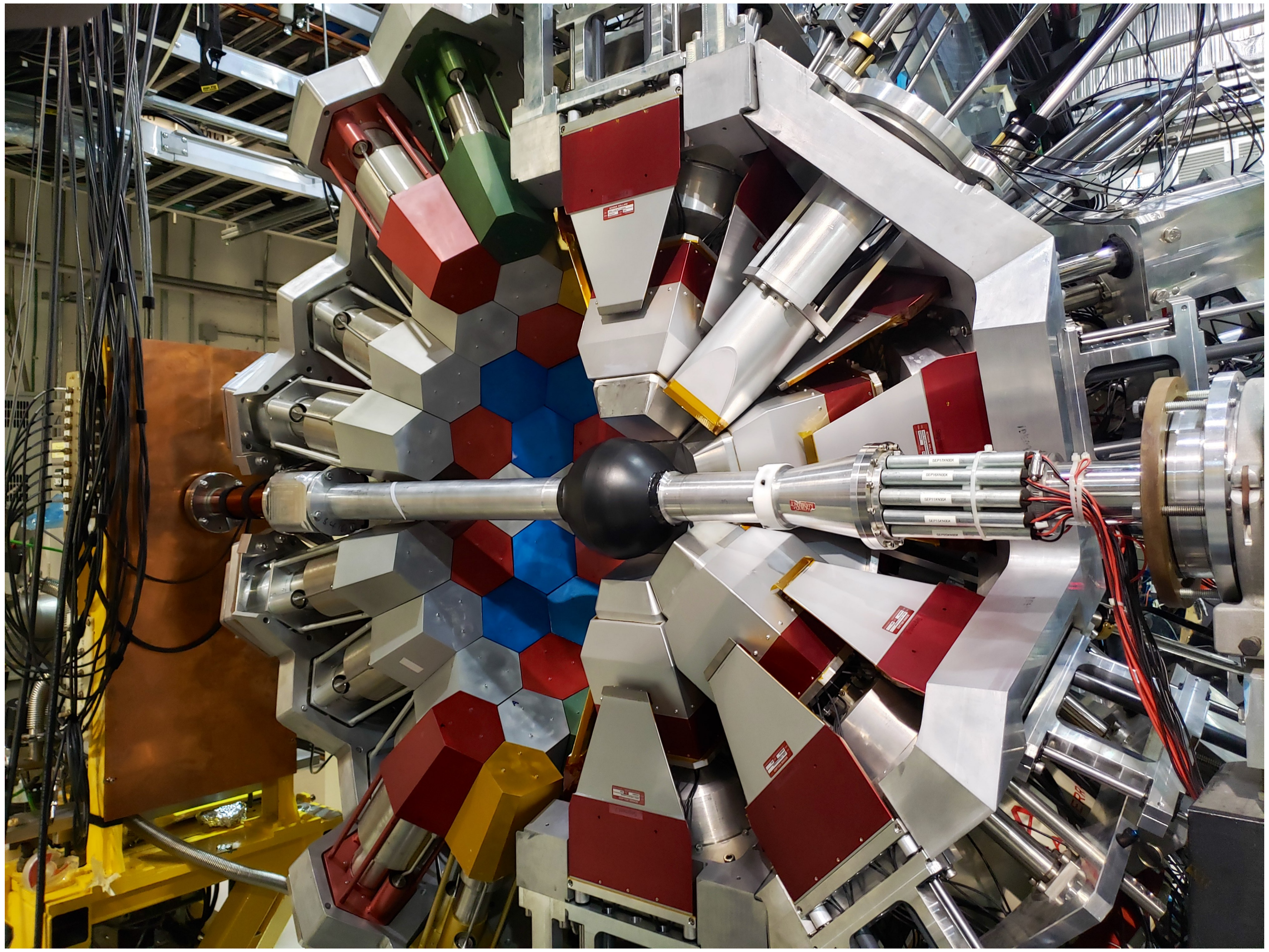
GRIFFIN+DESCANT

Experimental Setup

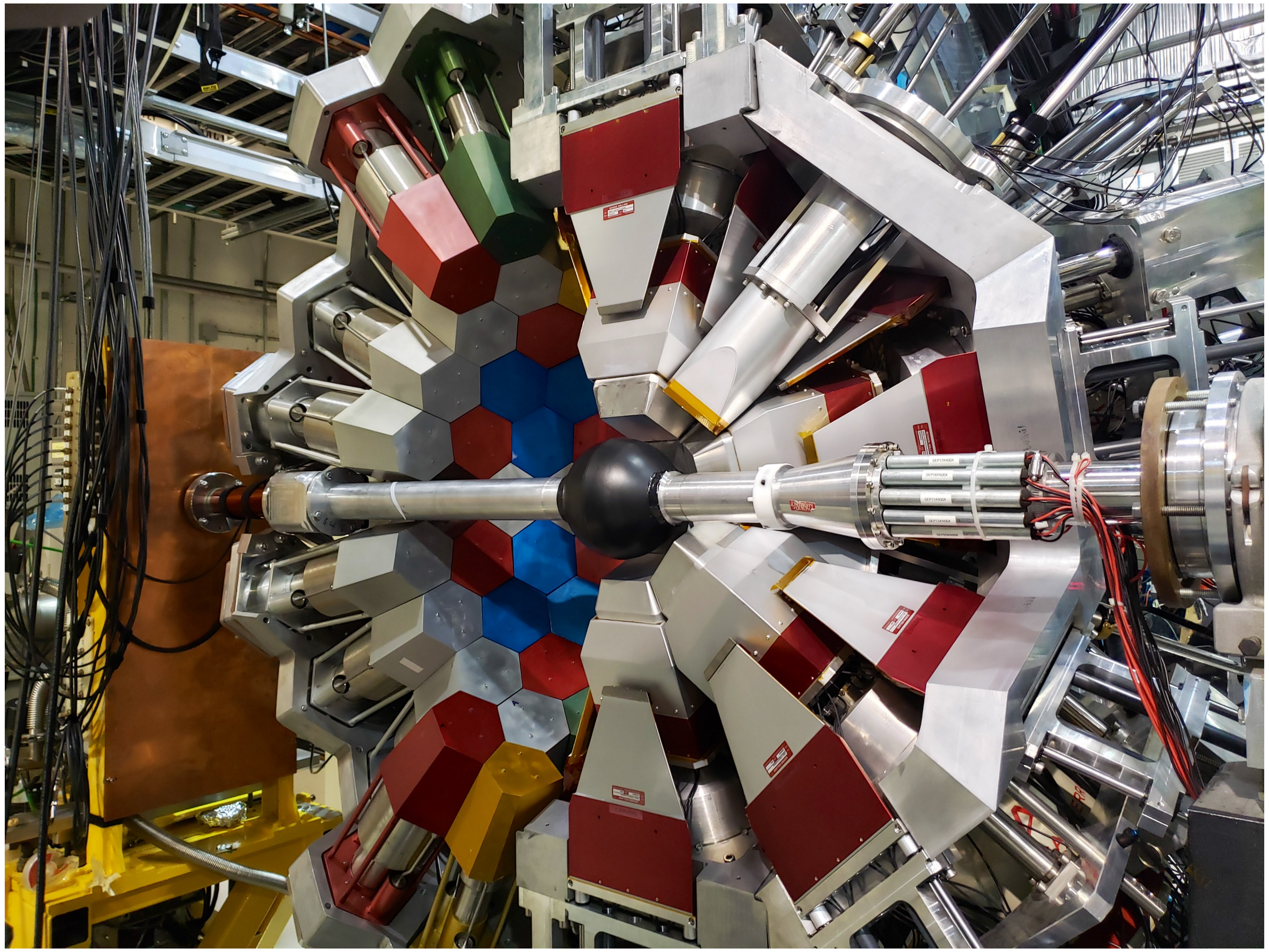
- GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigation of Nuclei)
- DESCANT (DEuterated SCintillator Array for Neutron Tagging)
- In addition there are beta particle detectors and positions for other ancillary devices are available



GRIFFIN+DESCANT

Experimental Setup

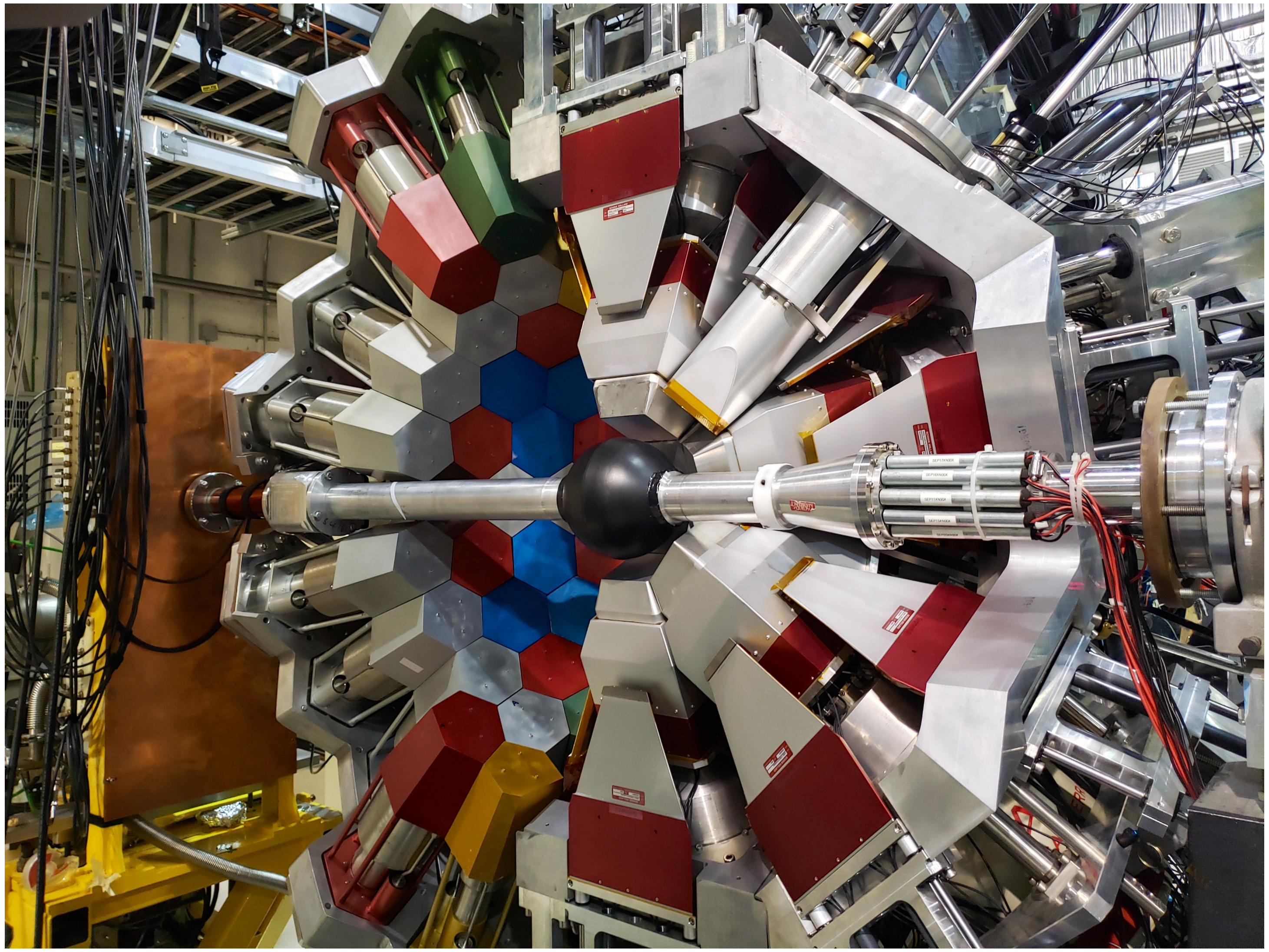
- DESCANT has good neutron detection efficiency, but at the expense of precision on the neutron kinetic energy - an important quantity for beta delayed neutron emitters!
- Want to create a neutron detector array that can measure neutron energy with high precision that would be compatible with GRIFFIN and DESCANT



GRIFFIN+DESCANT

Experimental Setup

- Good neutron energy resolution could be obtained through the addition of an <u>array of plastic scintillators</u> potentially placed in front of DESCANT
  - DAEMON (<u>D</u>etector <u>A</u>rray for <u>E</u>nergy <u>M</u>easurements <u>O</u>f <u>N</u>eutrons)
  - Plastic scintillators have good timing resolution, are inexpensive, and can be customized into nearly any shape
  - Energy can be determined via Time-of-Flight technique



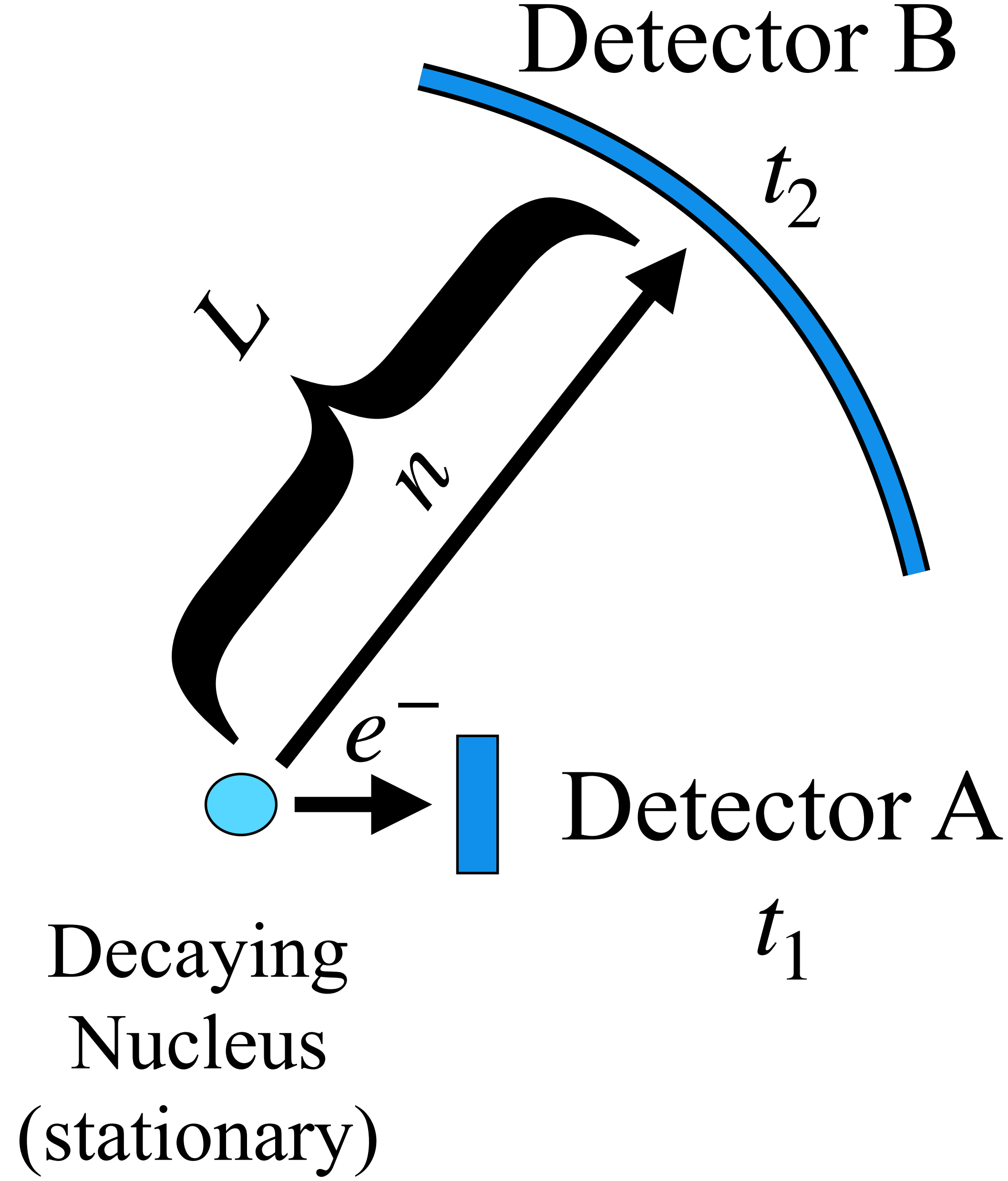
TIME OF FLIGHT TECHNIQUE

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m\frac{L^2}{TOF^2}$$

- Get TOF from 2 separate detectors that act as a stopwatch
- Good TOF energy resolution requires thin detectors
- Good efficiency requires thick detectors
- Detector geometry must be optimized

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{2\Delta L}{L}\right)^2 + \left(\frac{2\Delta TOF}{TOF}\right)^2$$

$$TOF = t_2 - t_1$$



TIME OF FLIGHT TECHNIQUE

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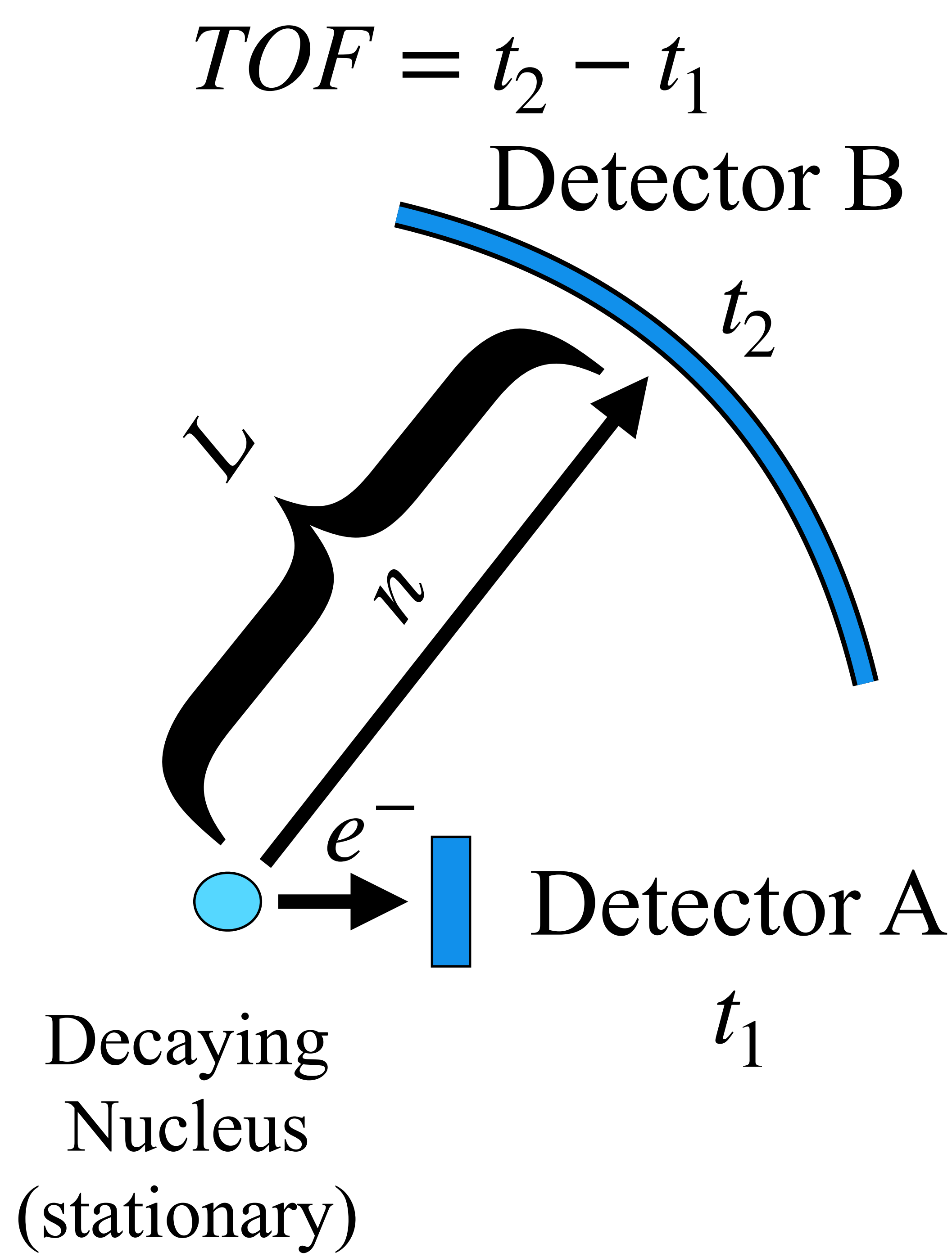


- DESCANT TOF energy resolution dominated by detector thickness

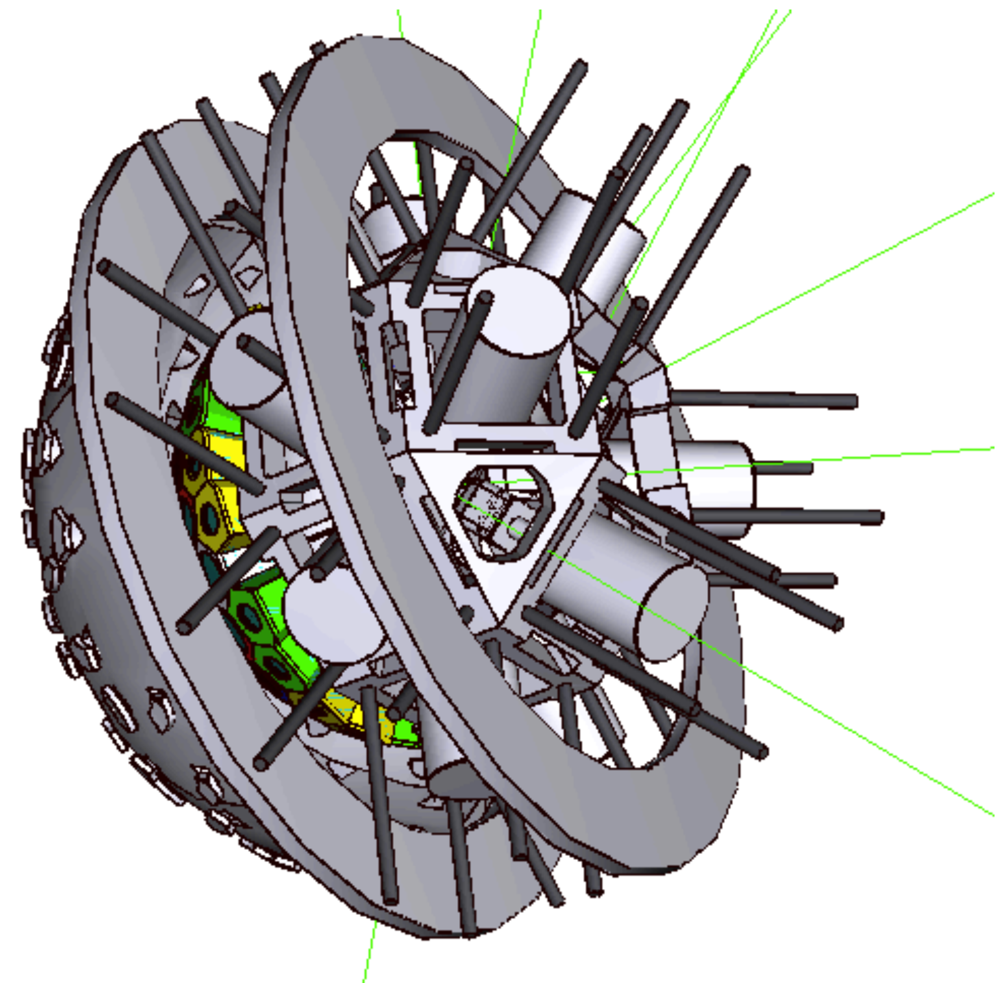
$$\frac{\Delta E}{E} \propto \frac{\Delta L}{L} = \frac{15\ cm}{50\ cm} = 30\ \%$$

- DAEMON energy resolution simulated to be 6.5% at 1 MeV with a the 1.5 cm thick scintillator

GEANT4 SIMULATIONS

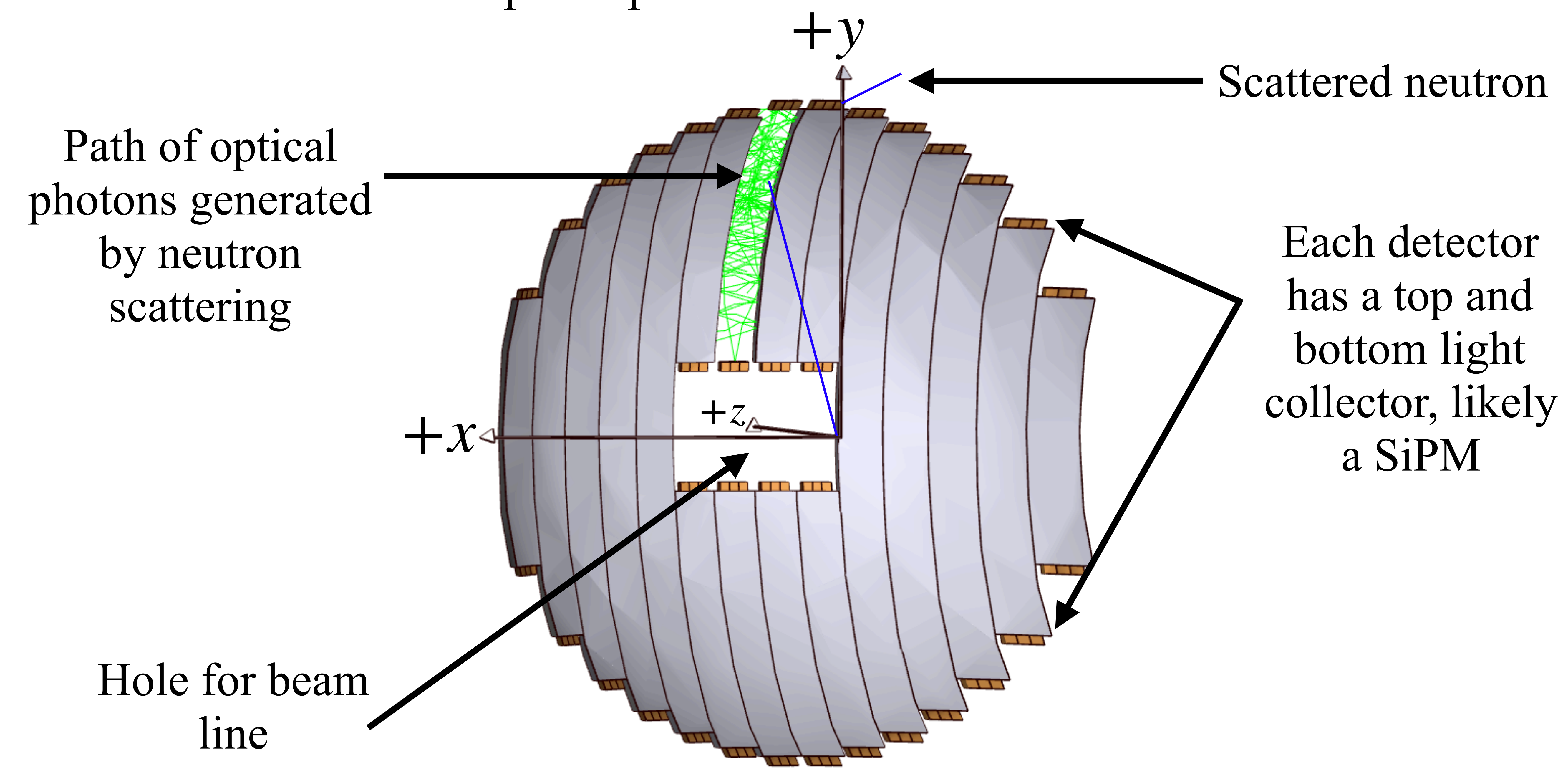
Detector Geometry

- GEANT4 is a toolkit for simulating particles passing through matter
  - Monte-Carlo technique
  - Ideal for designing and optimizing new detector concepts



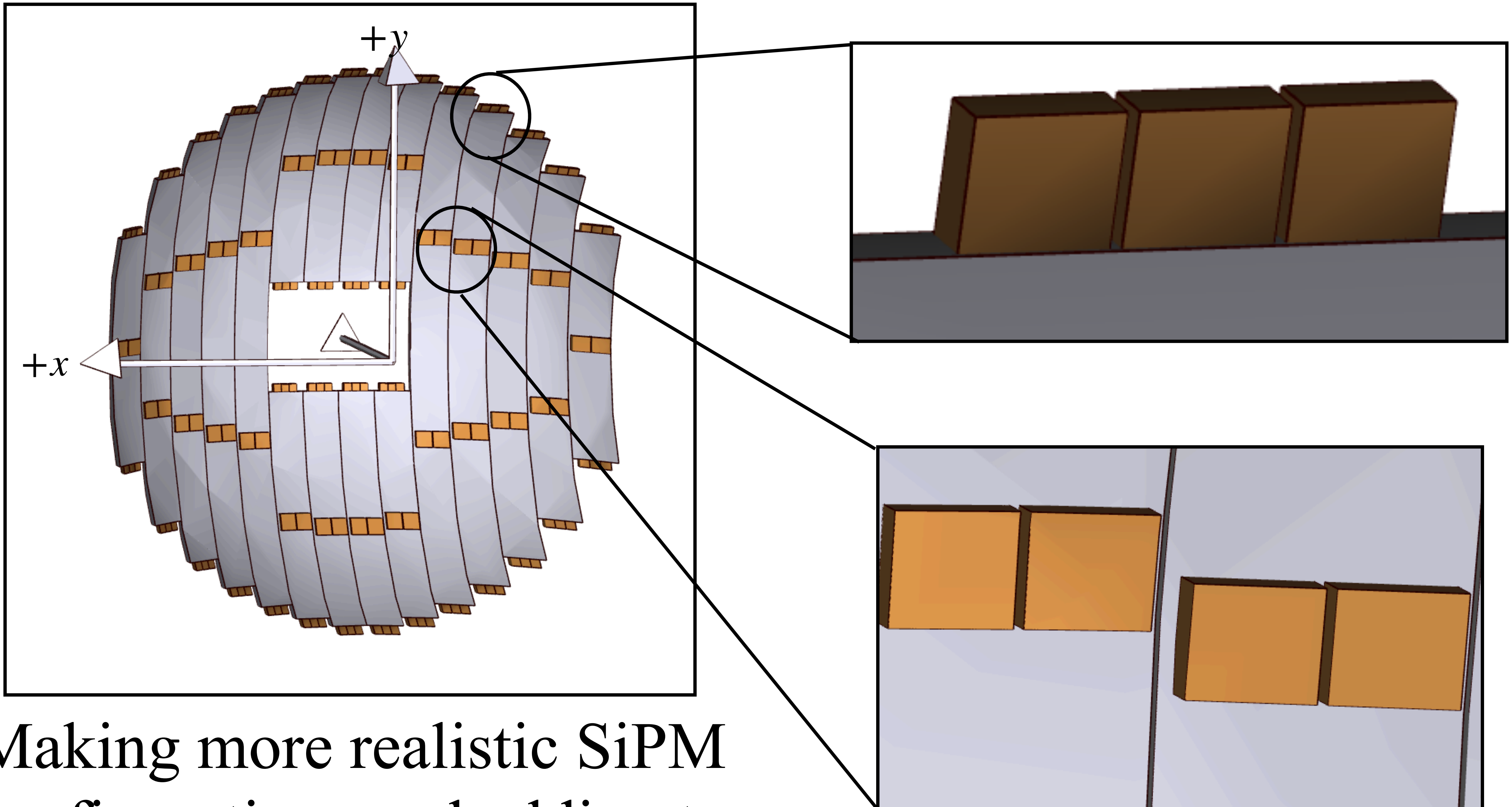
GEANT4 SIMULATIONS

Detector geometry optimized to fit on the inside of DESCANT. Optical physics is incorporated into simulation. **TOF** is then determined by collecting optical photons in both SiPM's



GEANT4 SIMULATIONS

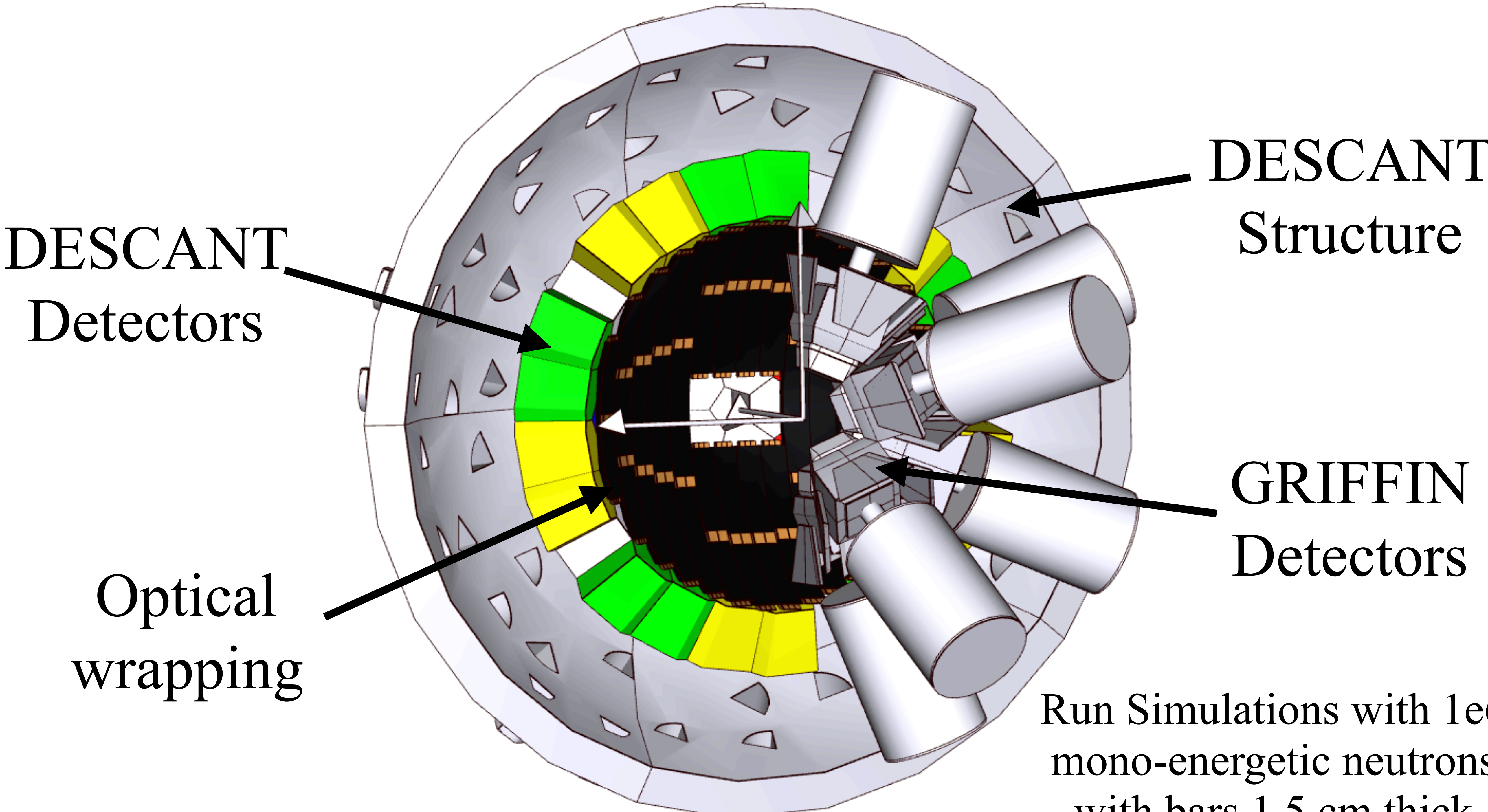
1.5 cm thick and approximately 5.5 cm wide



Making more realistic SiPM configurations and adding to the front face

GEANT4 SIMULATIONS

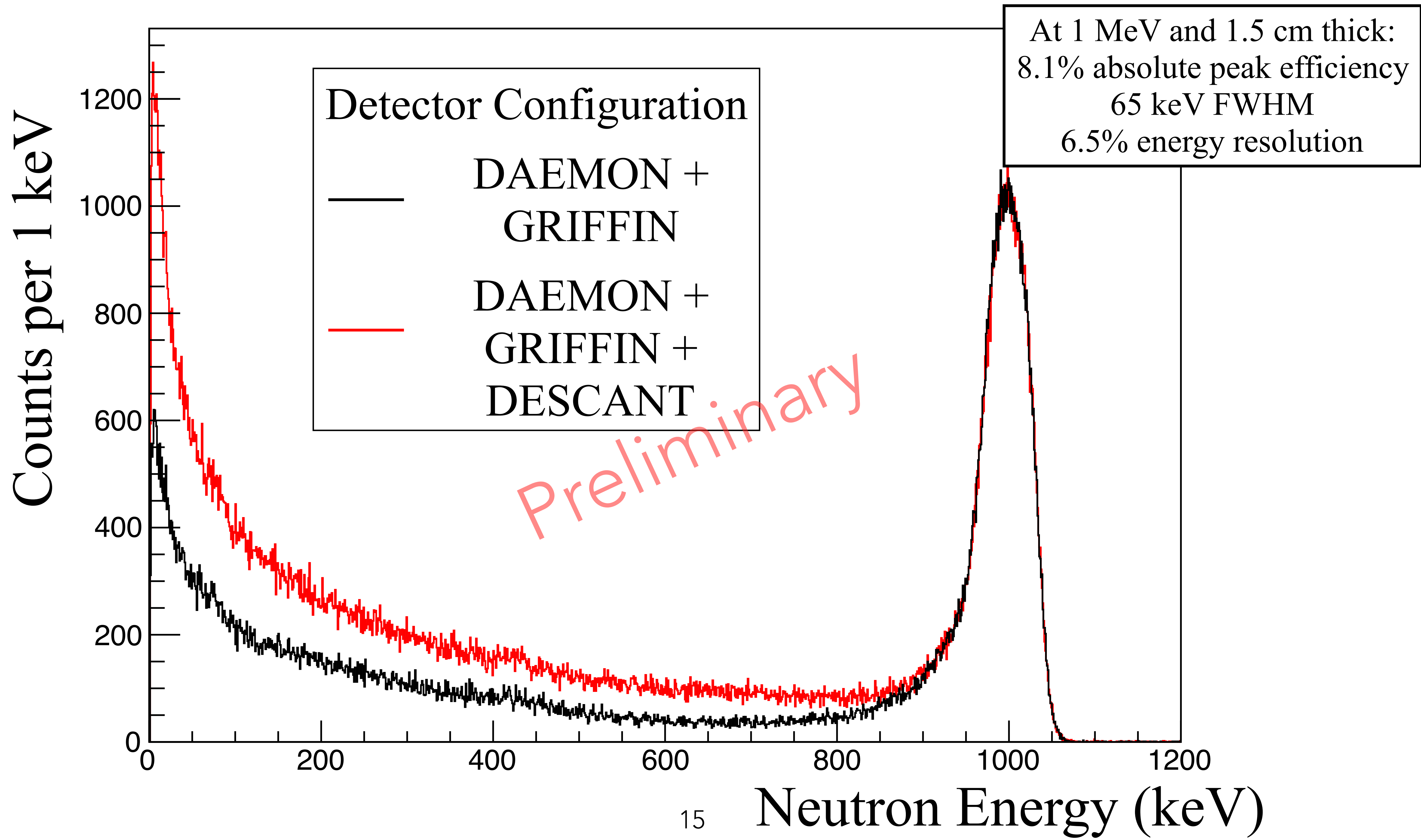
Detector geometry is being optimized to fit on the inside of DESCANT with GRIFFIN.



Run Simulations with 1e6 mono-energetic neutrons with bars 1.5 cm thick and 5.5 cm wide

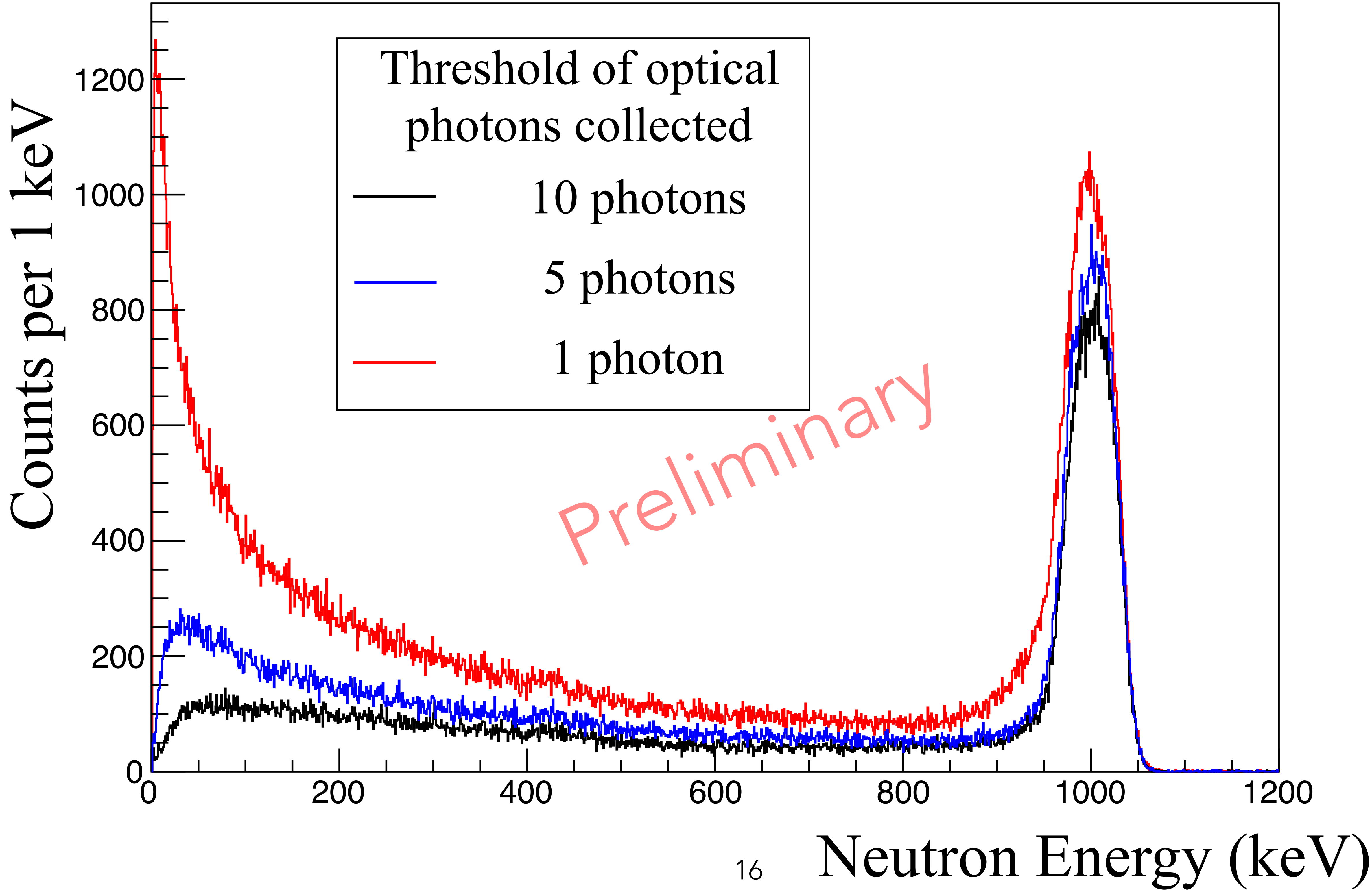
GEANT4 SIMULATIONS

1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event



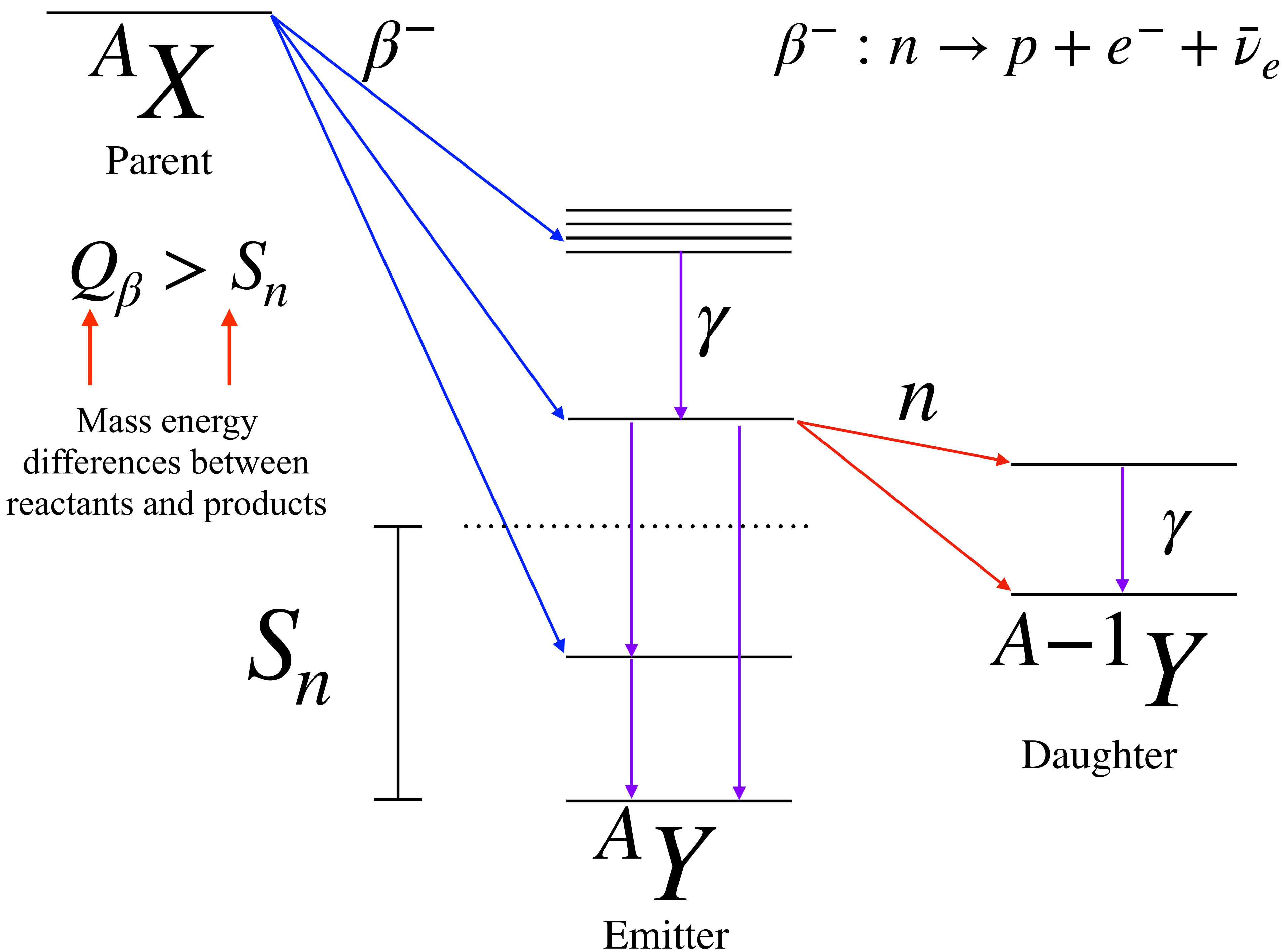
GEANT4 SIMULATIONS

DAEMON +GRIFFIN + DESCANT with condition of 2 different arrays of SiPMs required to fire to register event



GEANT4 SIMULATIONS

Beta Delayed Neutron Emission



GEANT4 SIMULATIONS

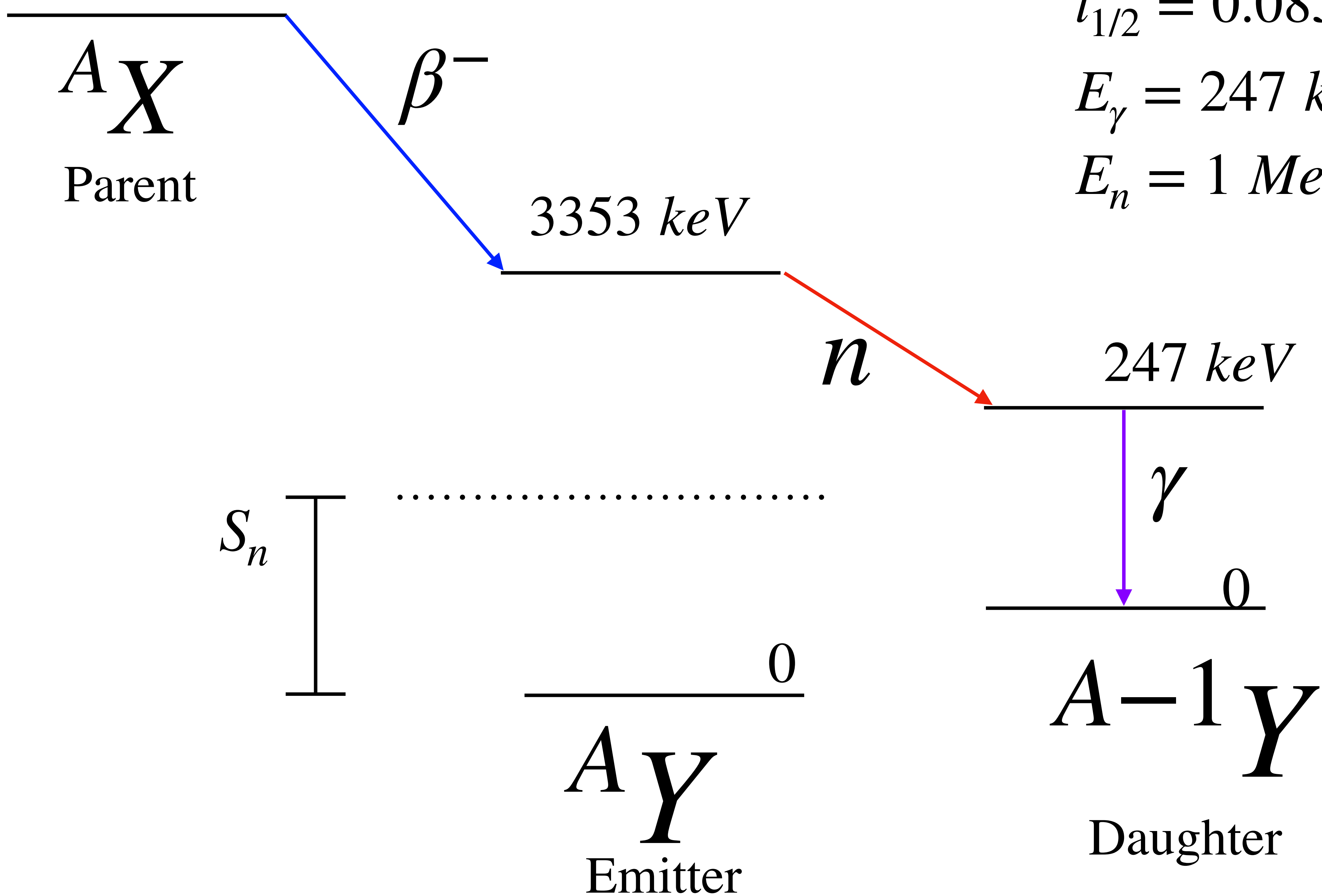
Simplified Decay

$Q_\beta = 5\ MeV$

$t_{1/2} = 0.085\ s$

$E_\gamma = 247\ keV$

$E_n = 1\ MeV$



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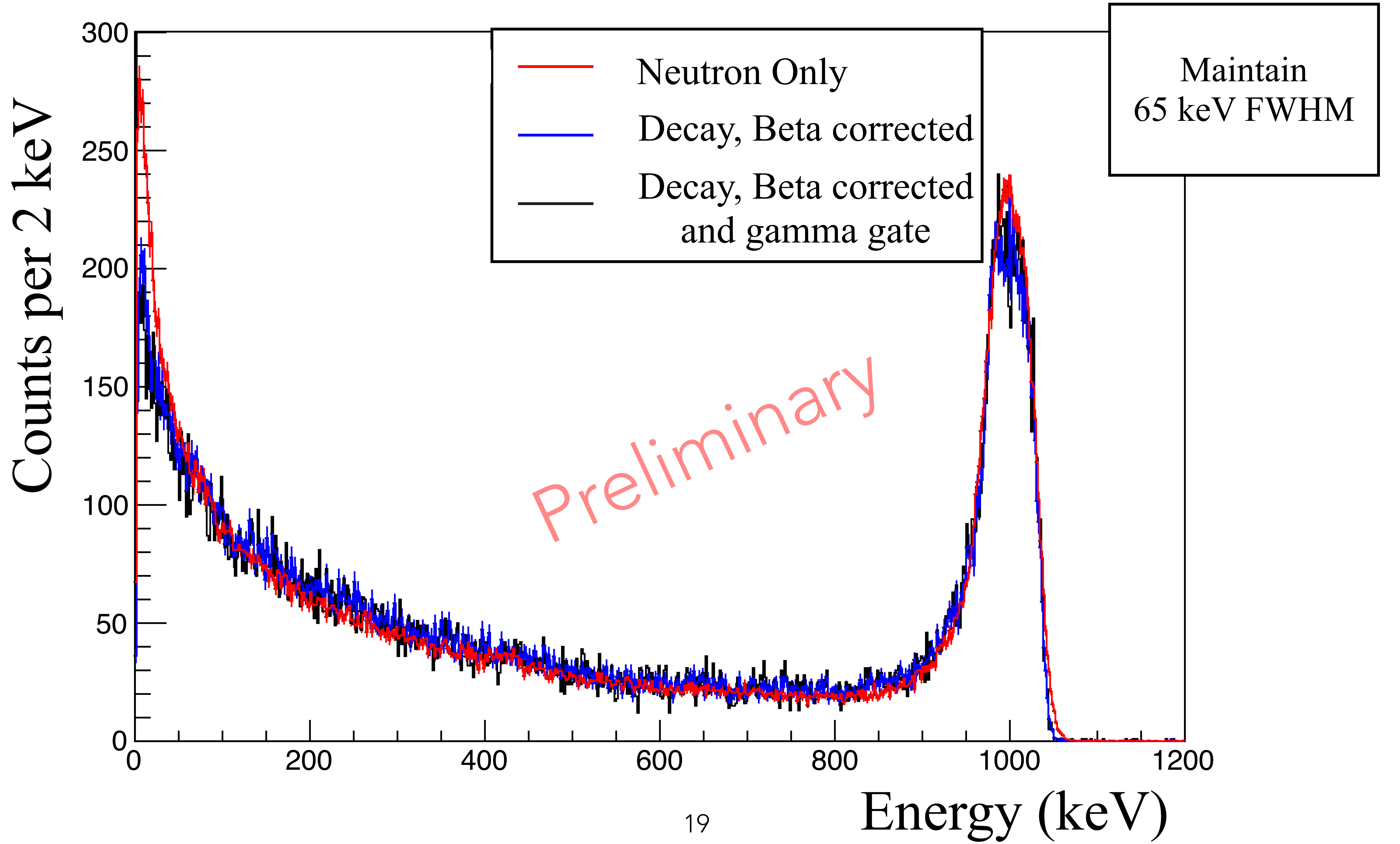

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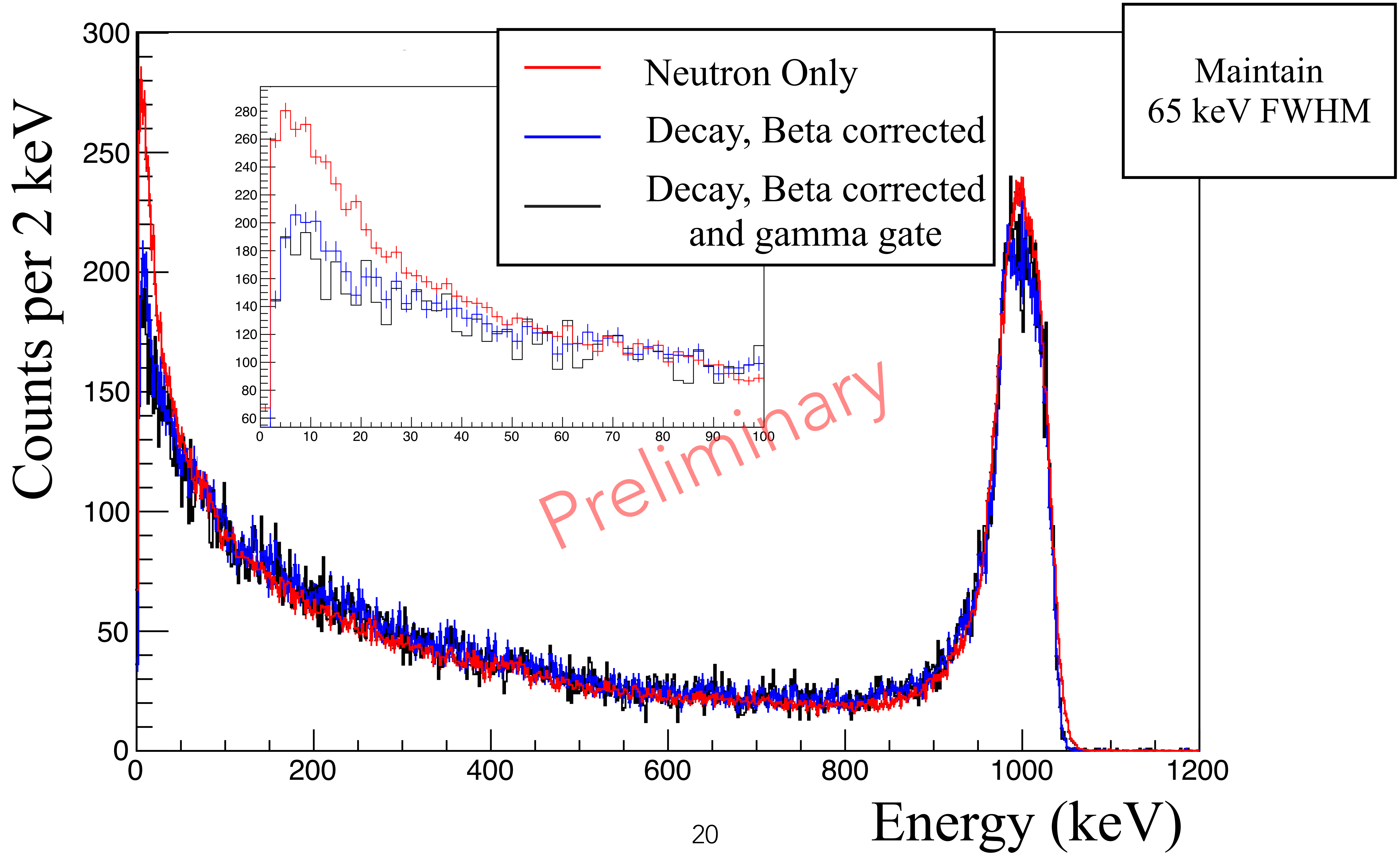
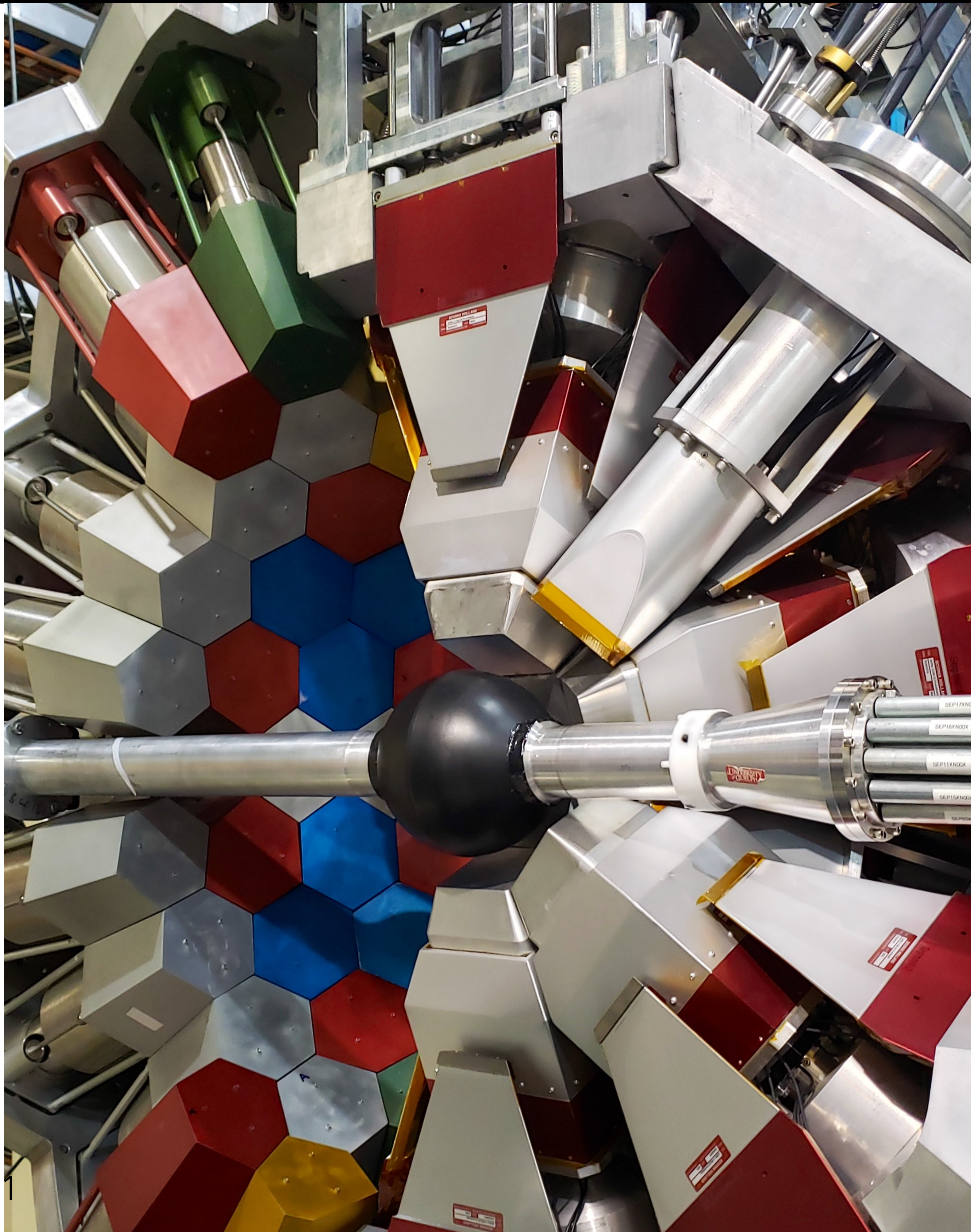


CONCLUSION & NEXT STEPS

- DAEMON is able to increase precision to the neutron kinetic energy in the presence of GRIFFIN and DESCANT compared to the pre-existing setup

- Detector geometry has been designed to maximize performance and minimize cost

- Prototype construction and comparing results to simulation



THANK YOU

Collaborators

University of Guelph

Paul Garrett

Carl Svensson

Vinzenz Bildstein

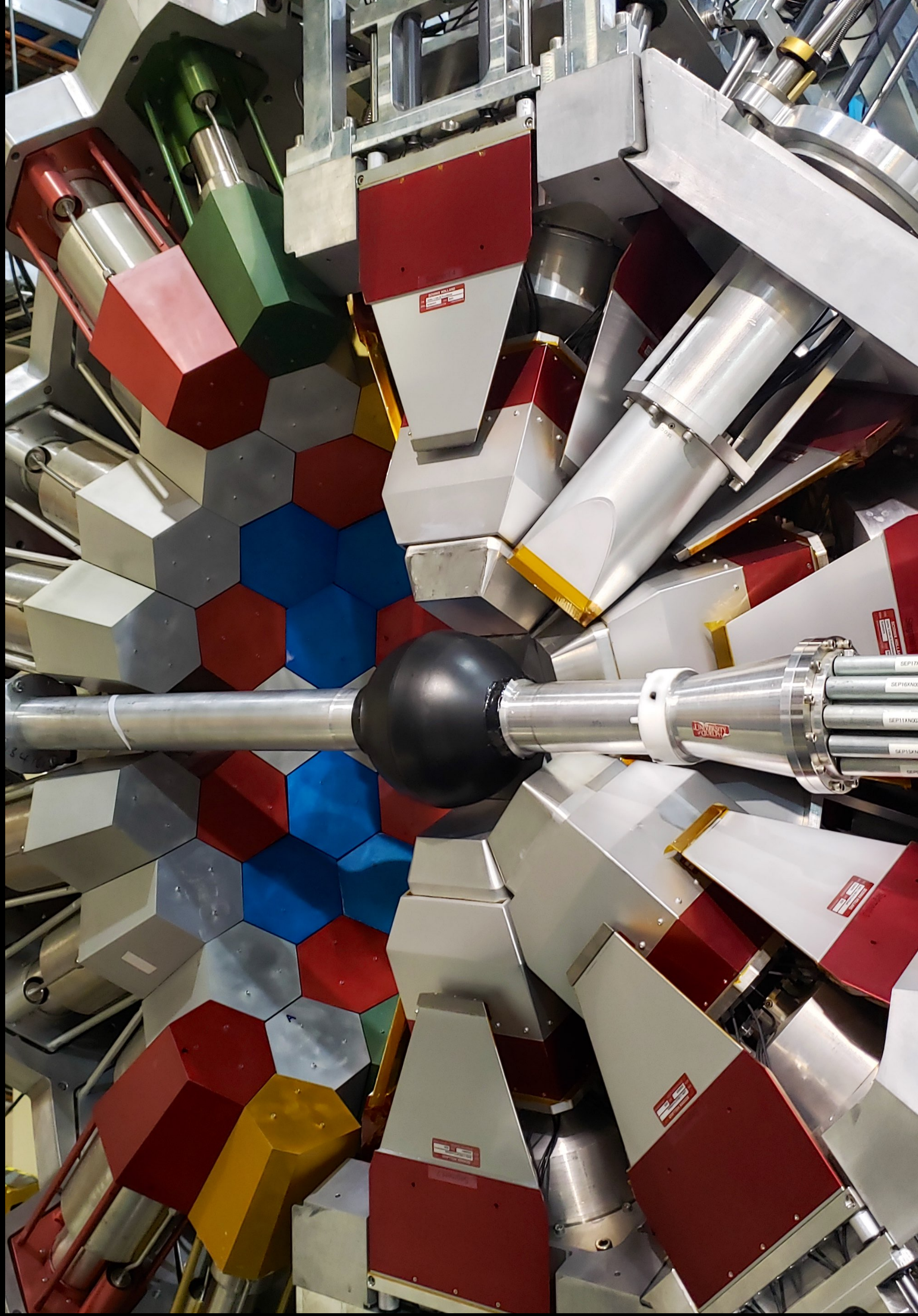
Alex Laffoley

Allison Radich

Colorado School of Mines

Fred Sarazin

Steven Shadrick



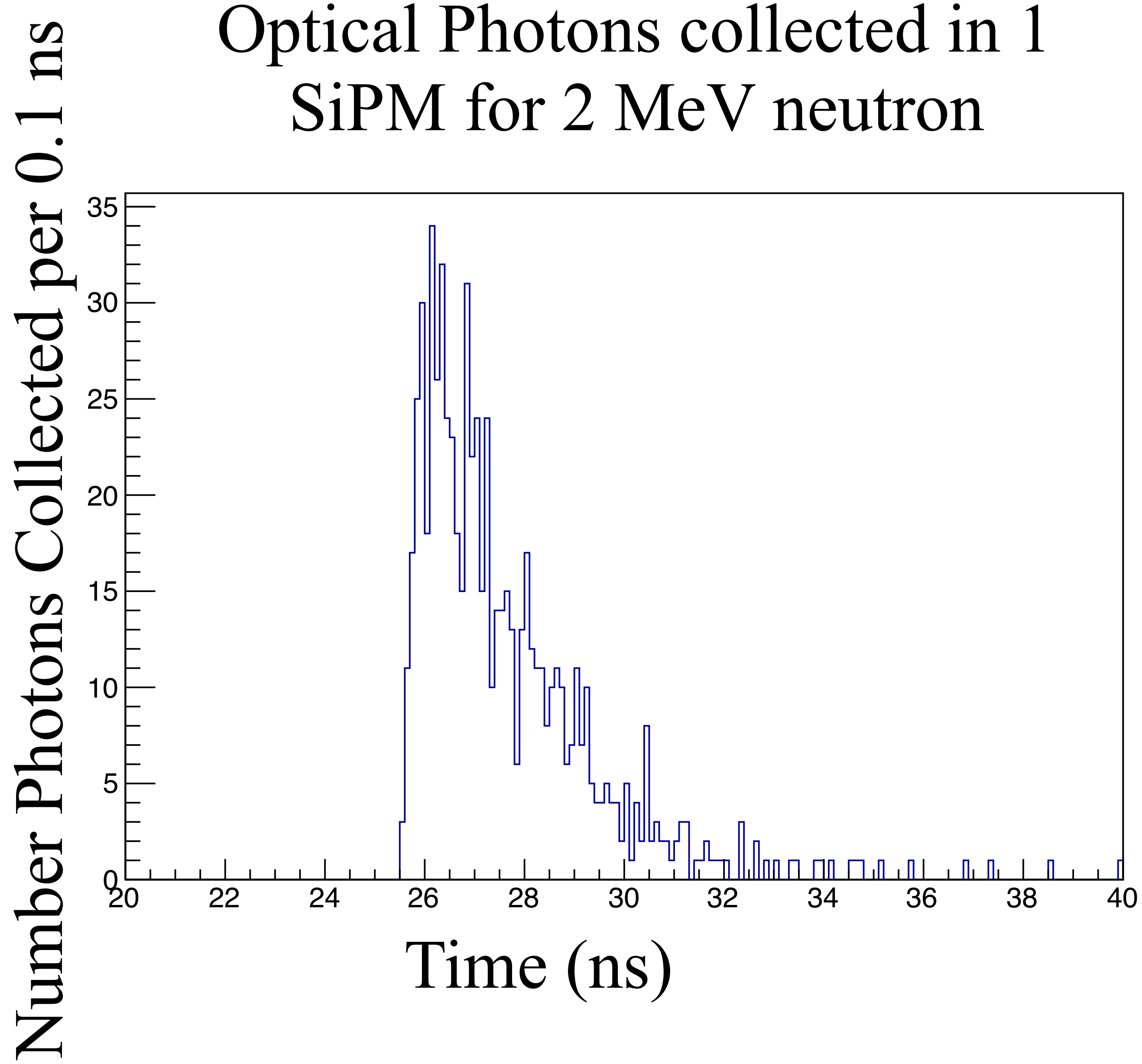
GRIFFIN + DESCANT Collaborations

UNIVERSITY of GUELPH

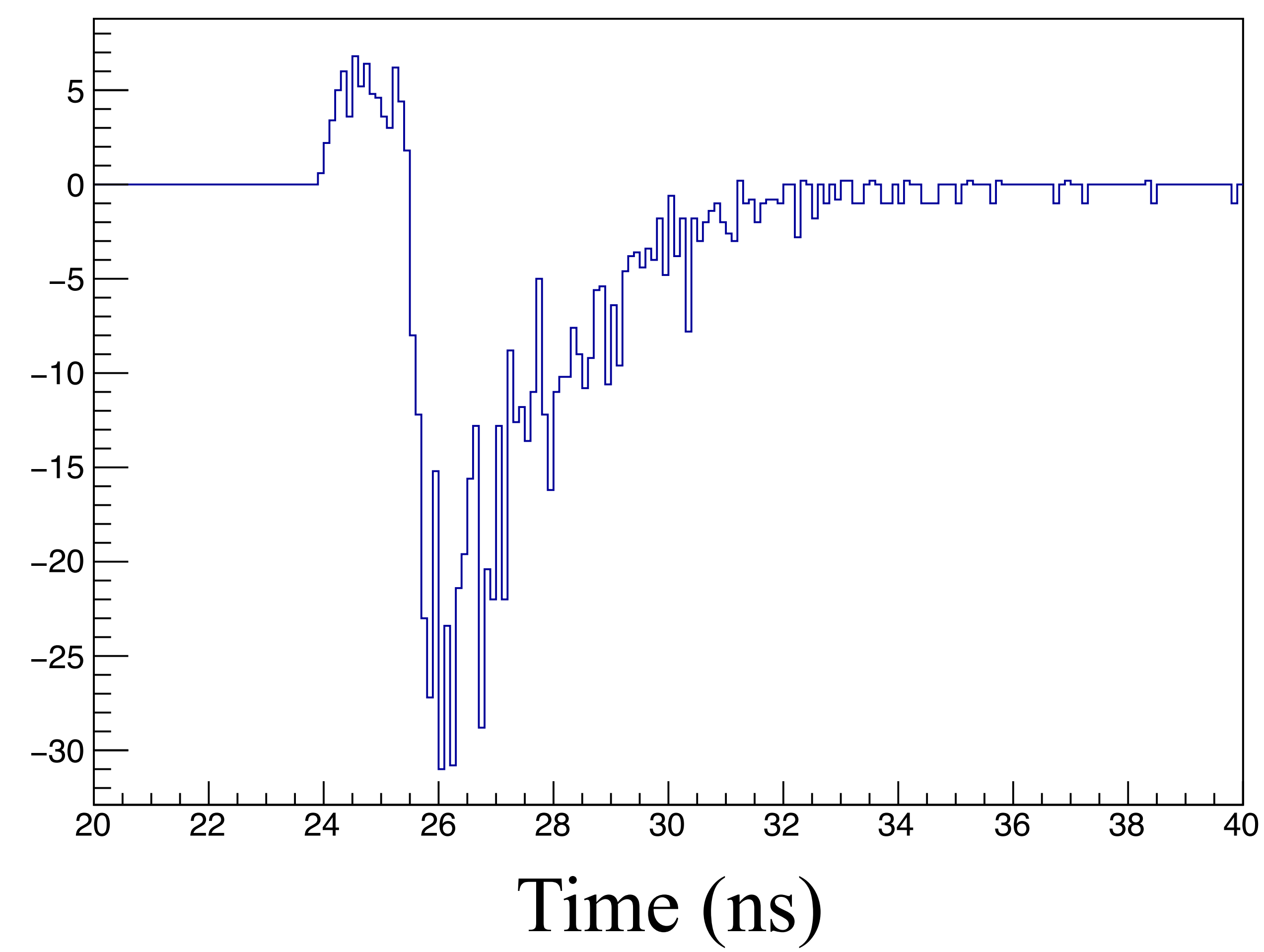
TRIUMF

TOF DETERMINATION

Optical Photons collected in 1 SiPM for 2 MeV neutron



CFD algorithm Monitor Output



Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

$$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$$

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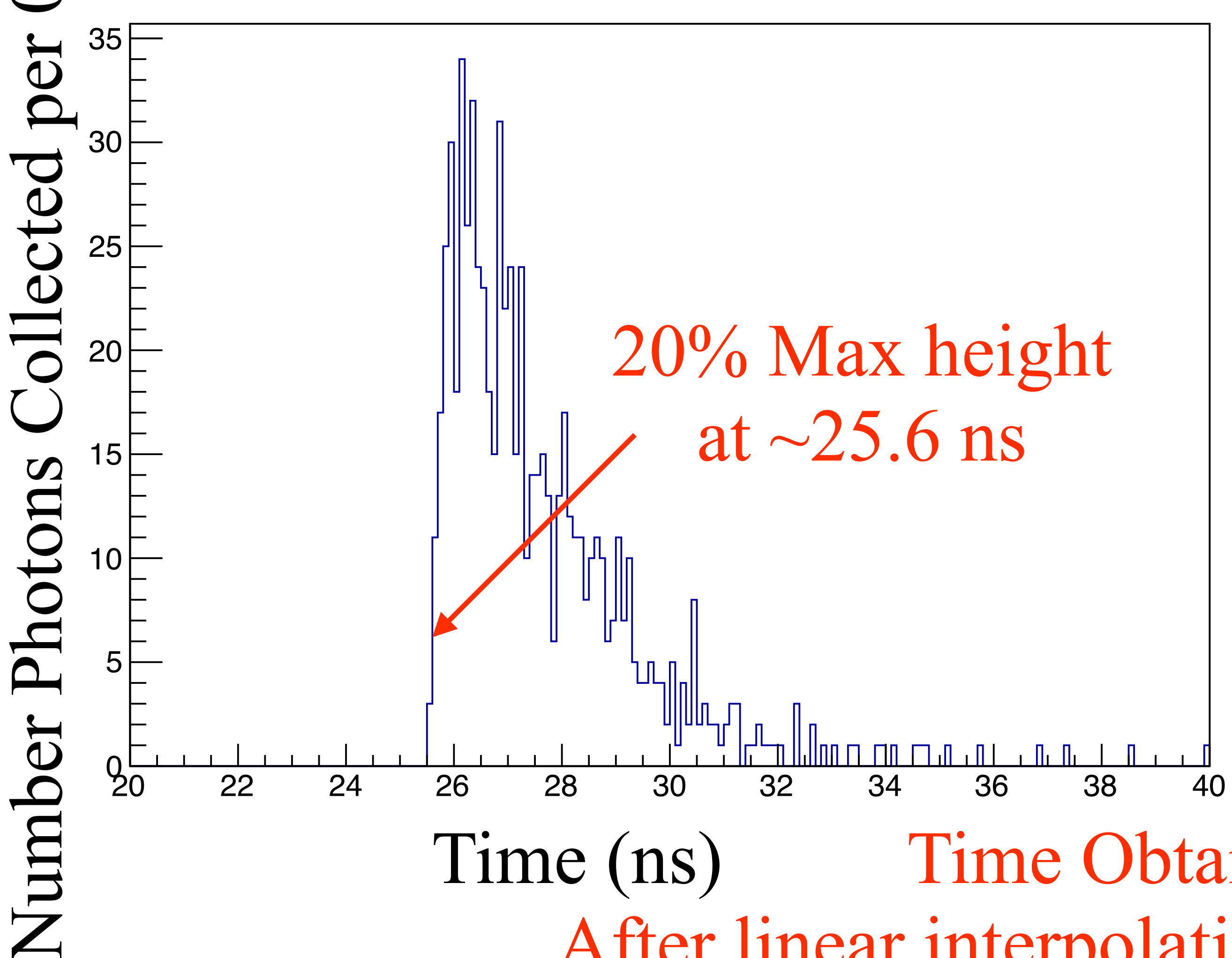
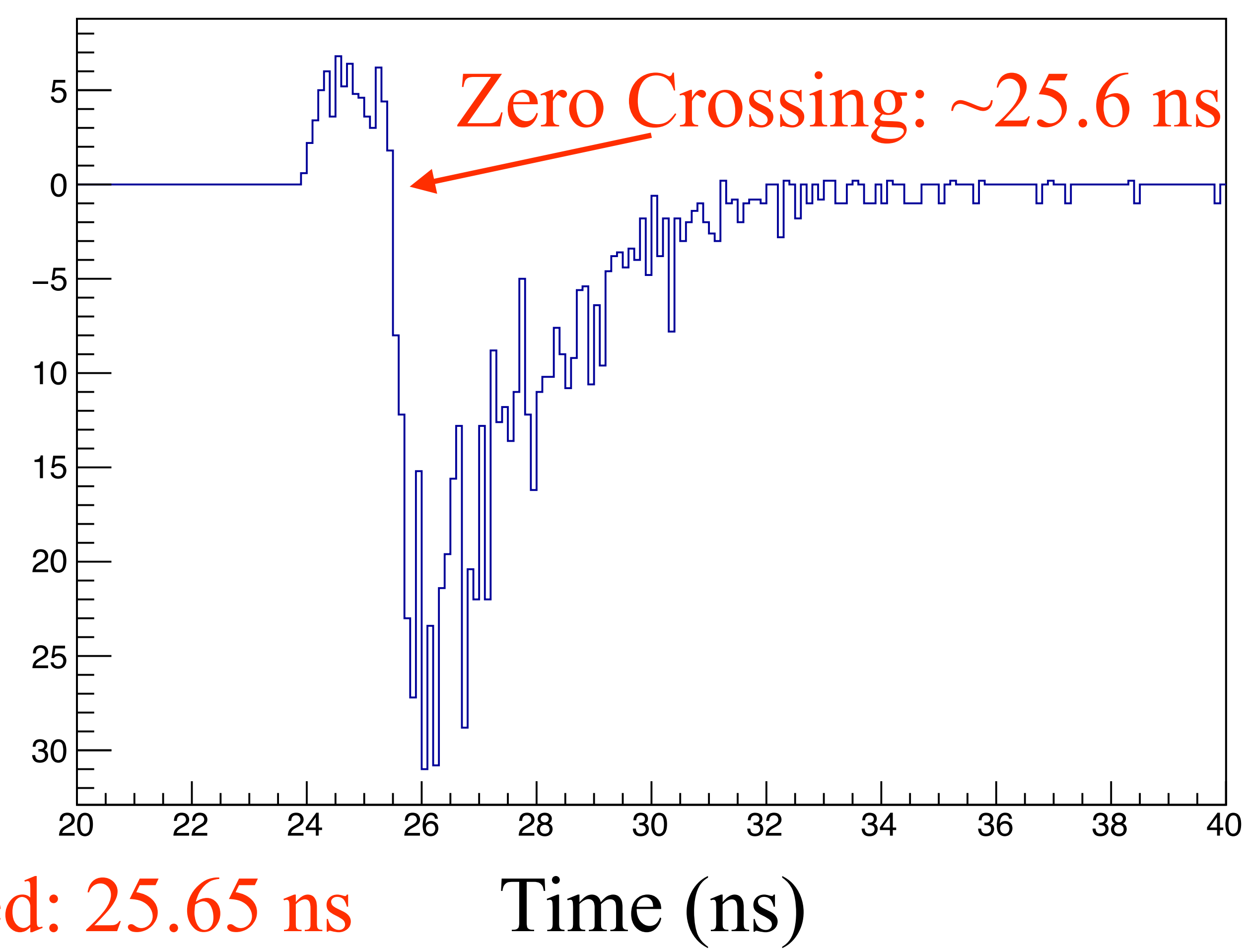


CFD algorithm Monitor Output



Time Obtained: 25.65 ns

After linear interpolation and bin randomization

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DETECTOR THICKNESS

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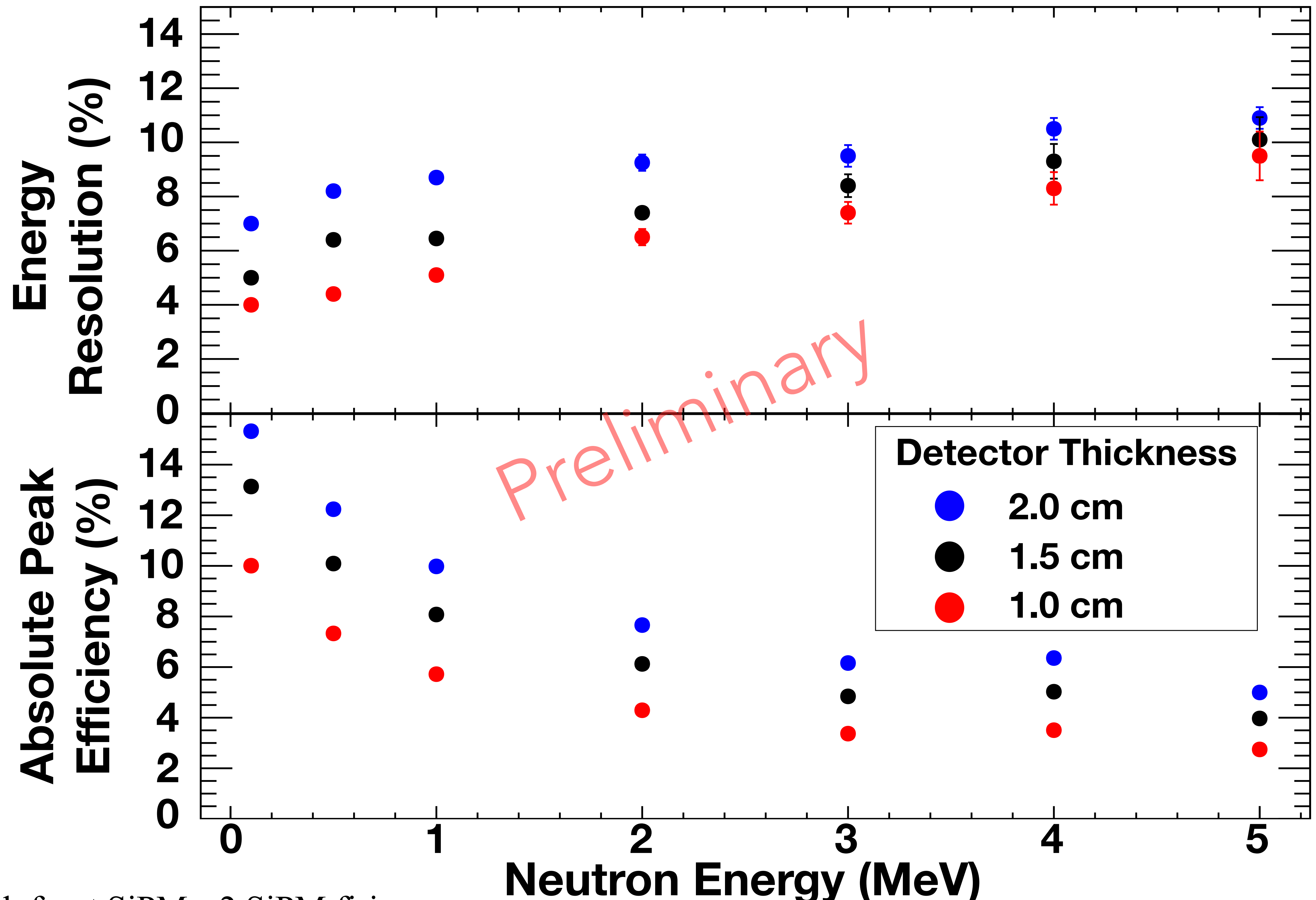
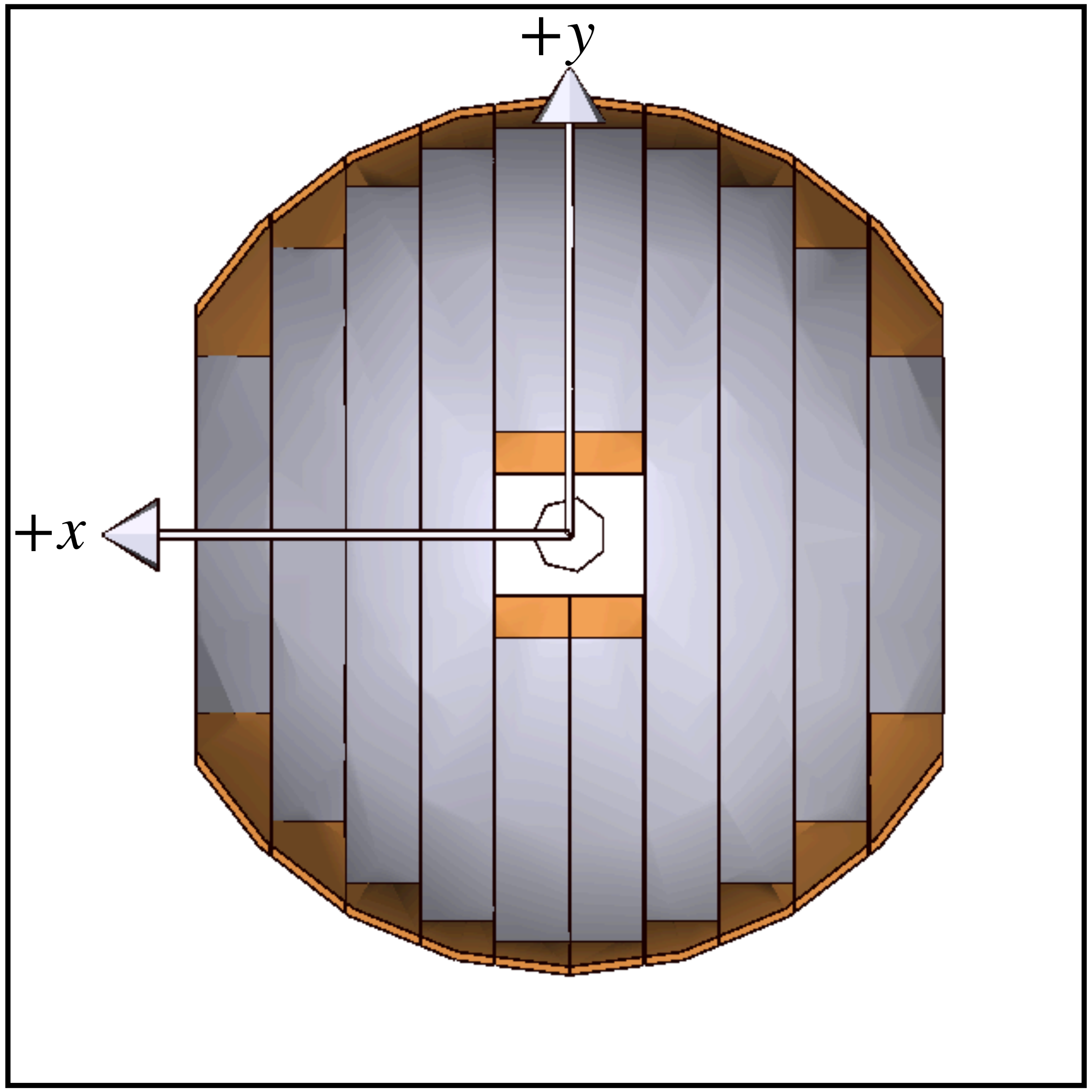


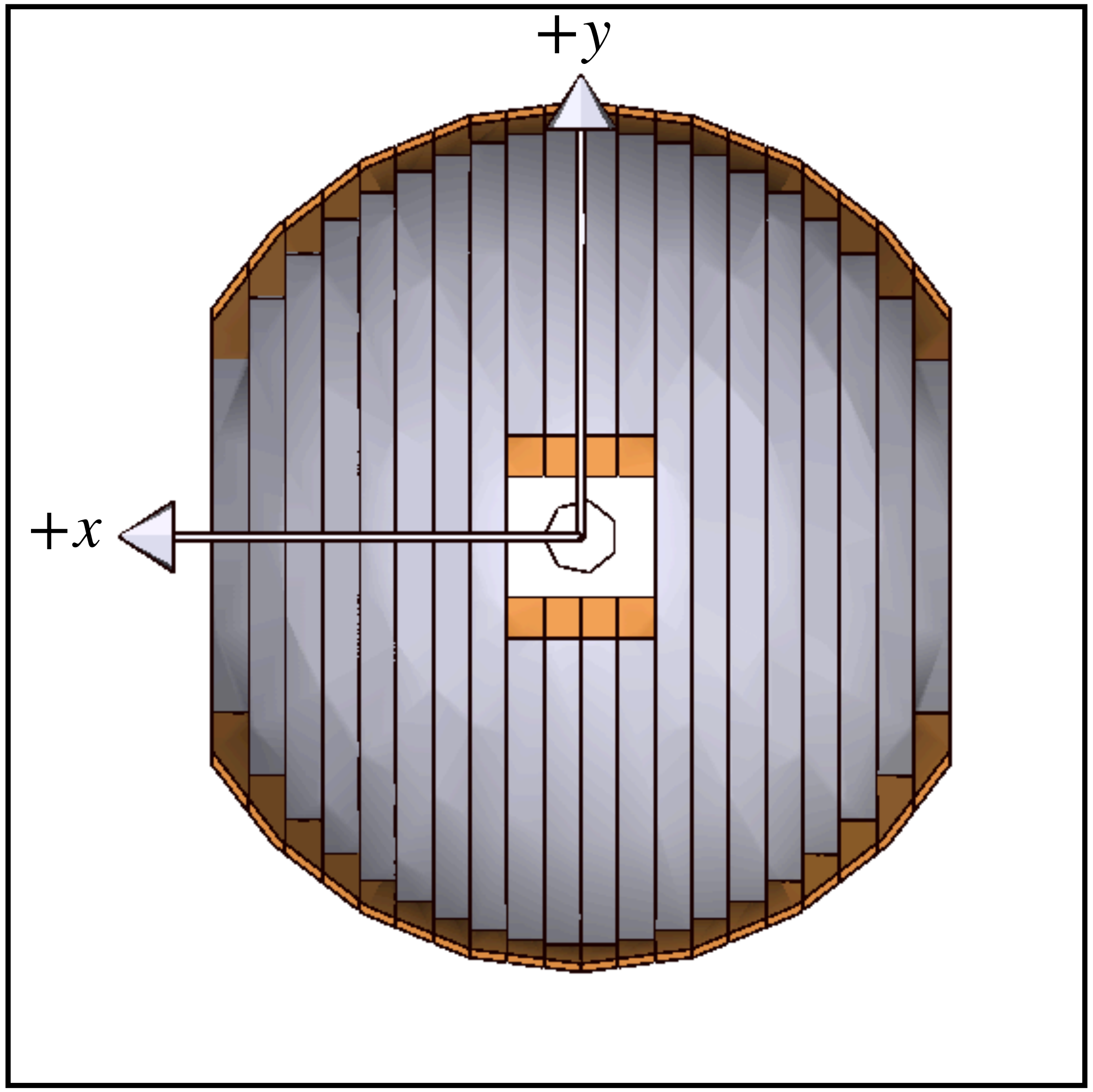
With front SiPMs, 2 SiPM firing condition, 1 optical photon threshold

WIDTH OF BARS

NUMBER OF DETECTORS

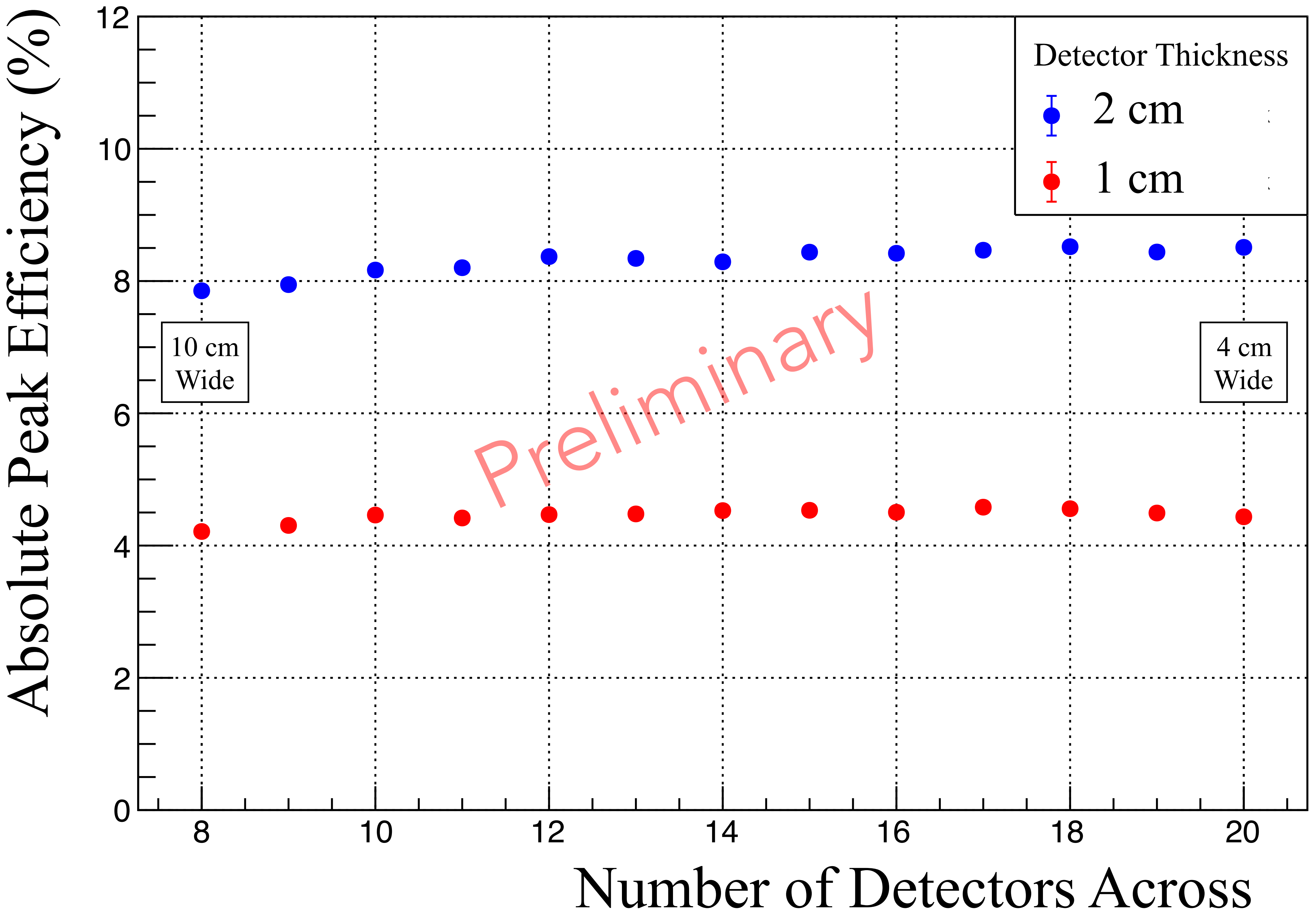


10 Detectors
Across



20 Detectors
Across

NUMBER OF DETECTORS



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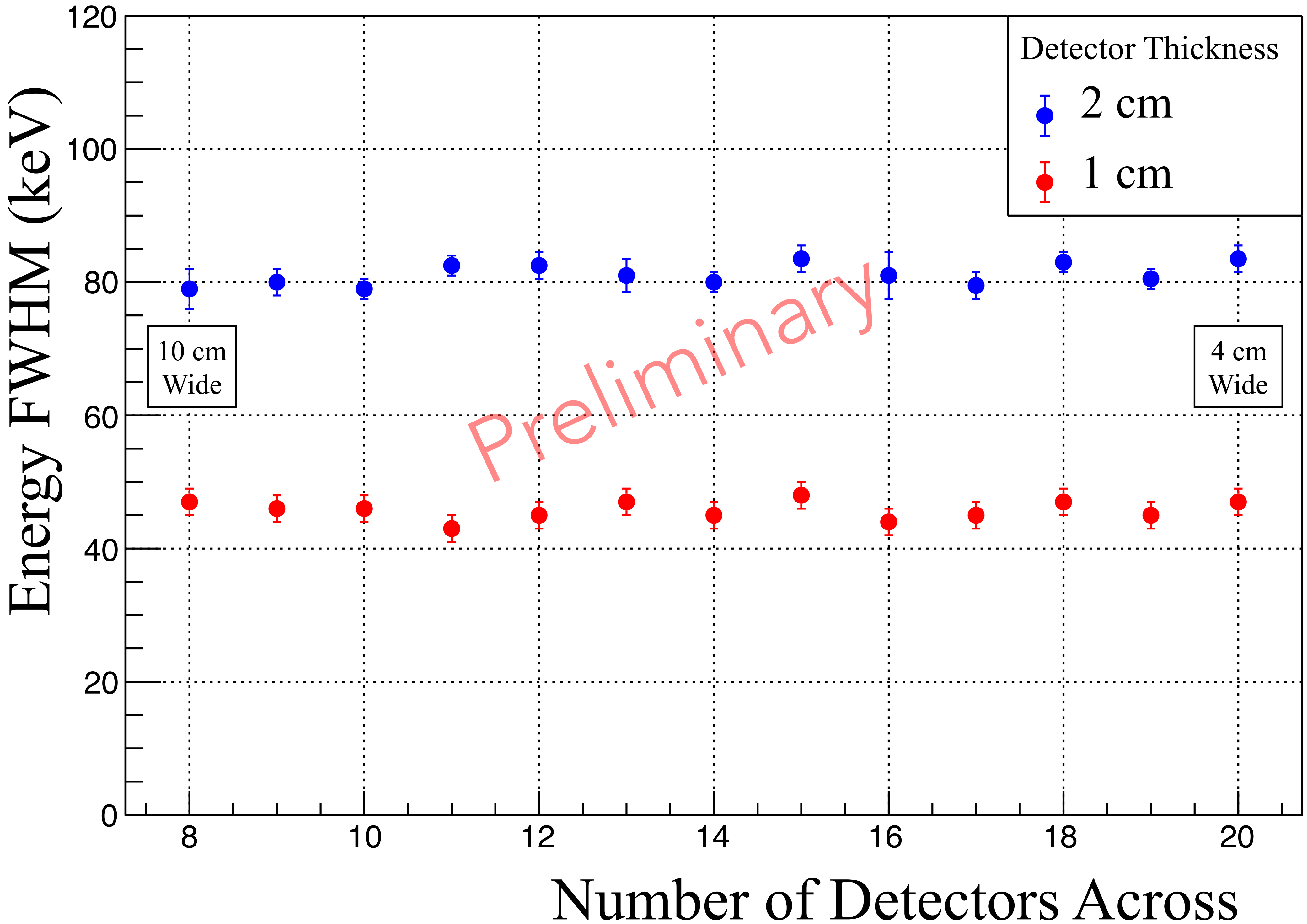
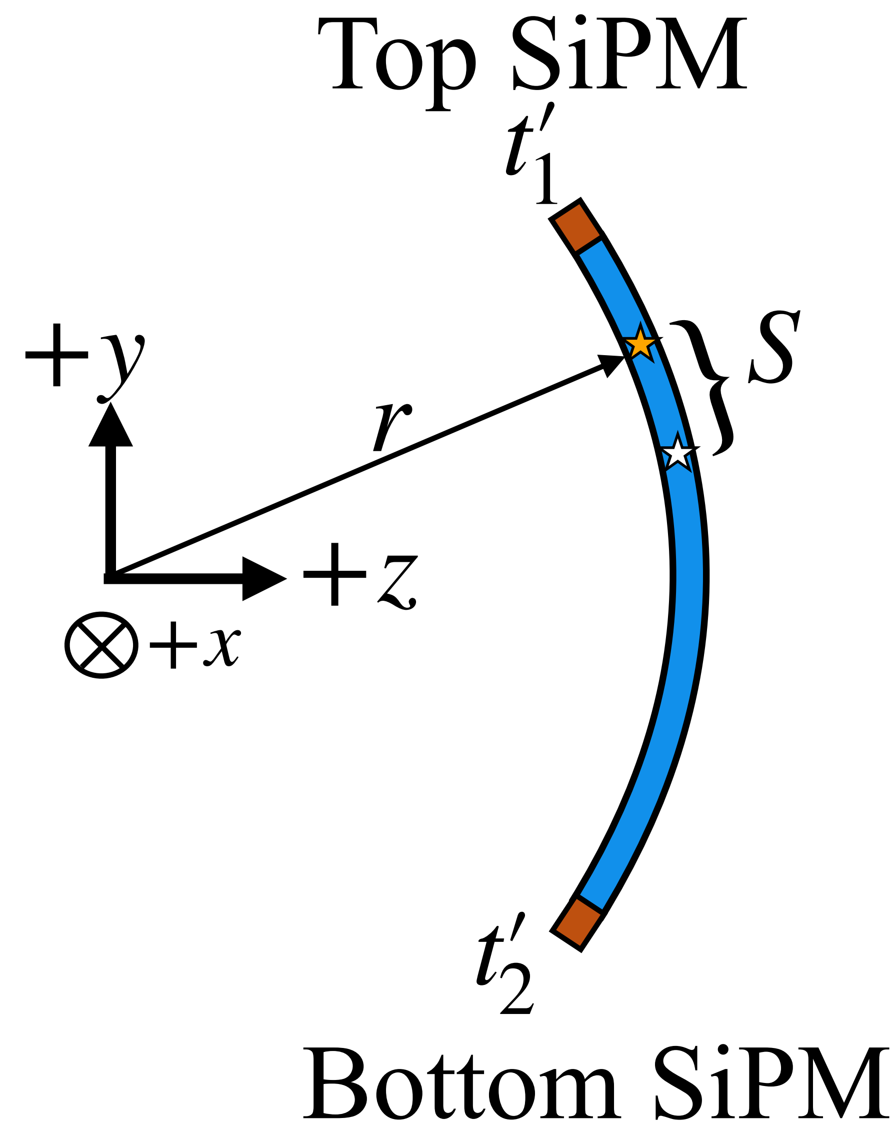


POSITION RESOLUTION

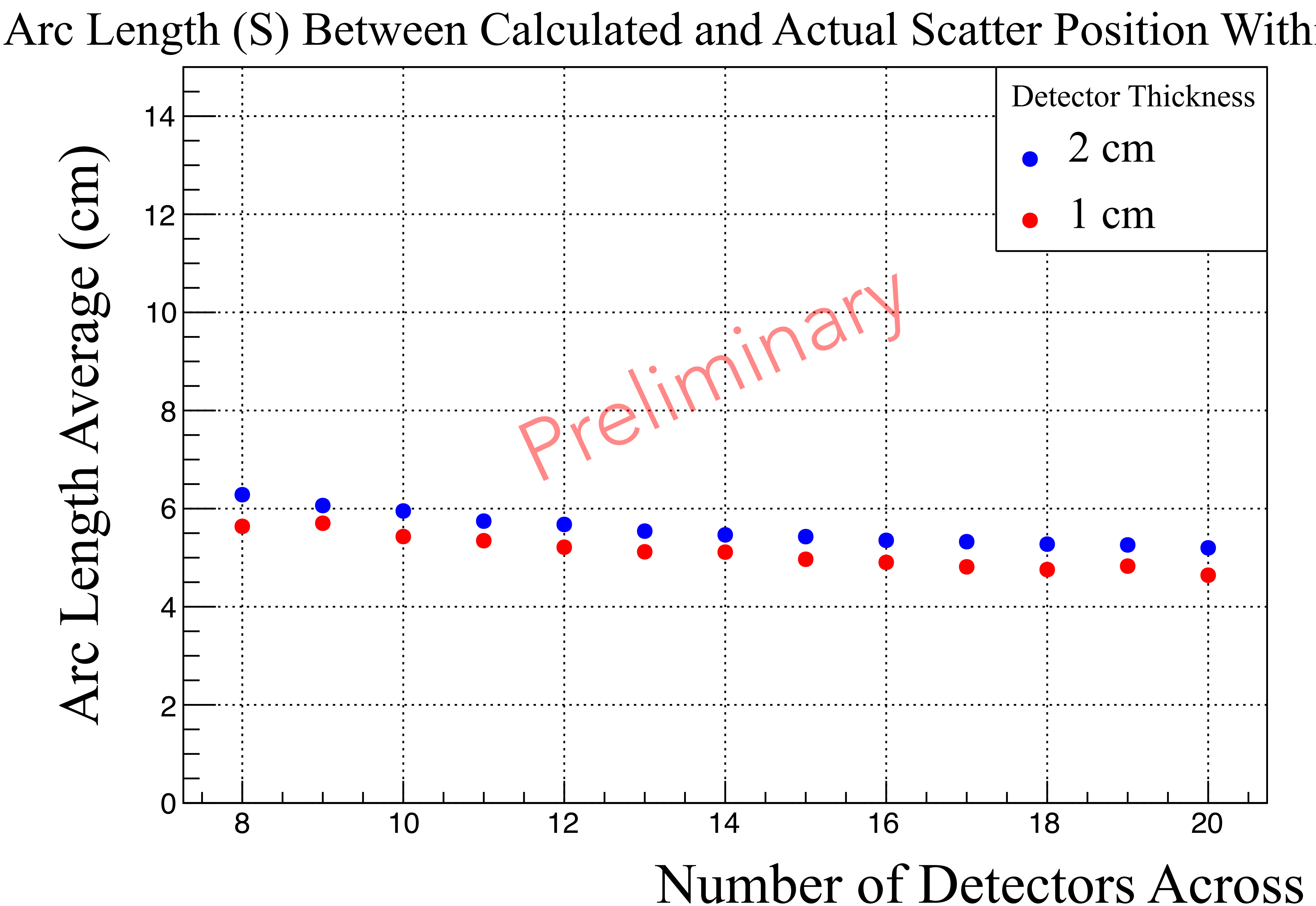
Arc Length (S) Between Calculated and Actual Scatter Position Within Bars

- X is assumed to be centre of detector.
- Y is calculated via SiPM time when both fire.
- Radial distance (r) is assumed to be middle of detector.
- Z is calculated using x, y, and r.



★ Calculated scatter position
☆ Actual scatter position

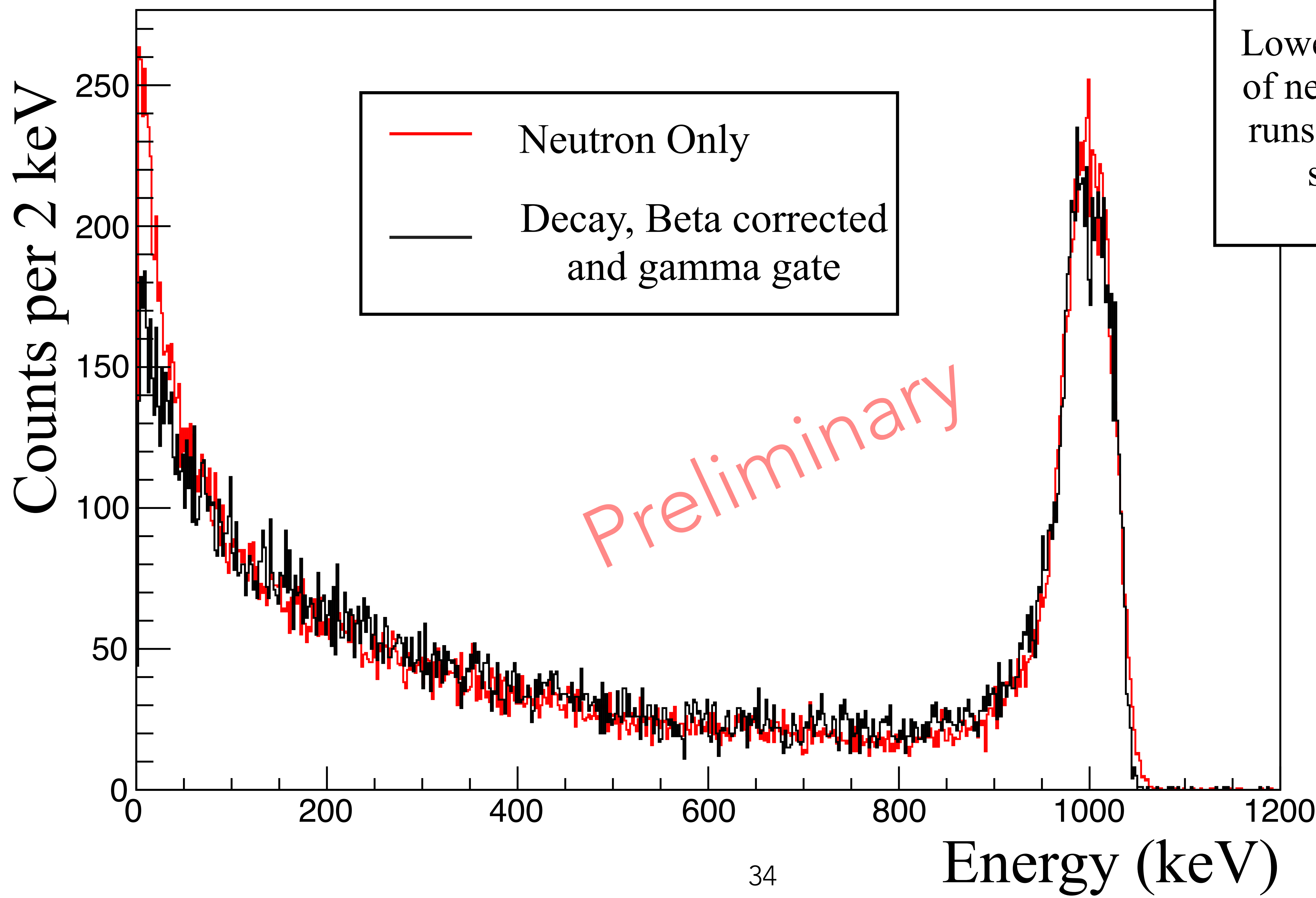
NUMBER OF DETECTORS



ENERGY SPECTRA

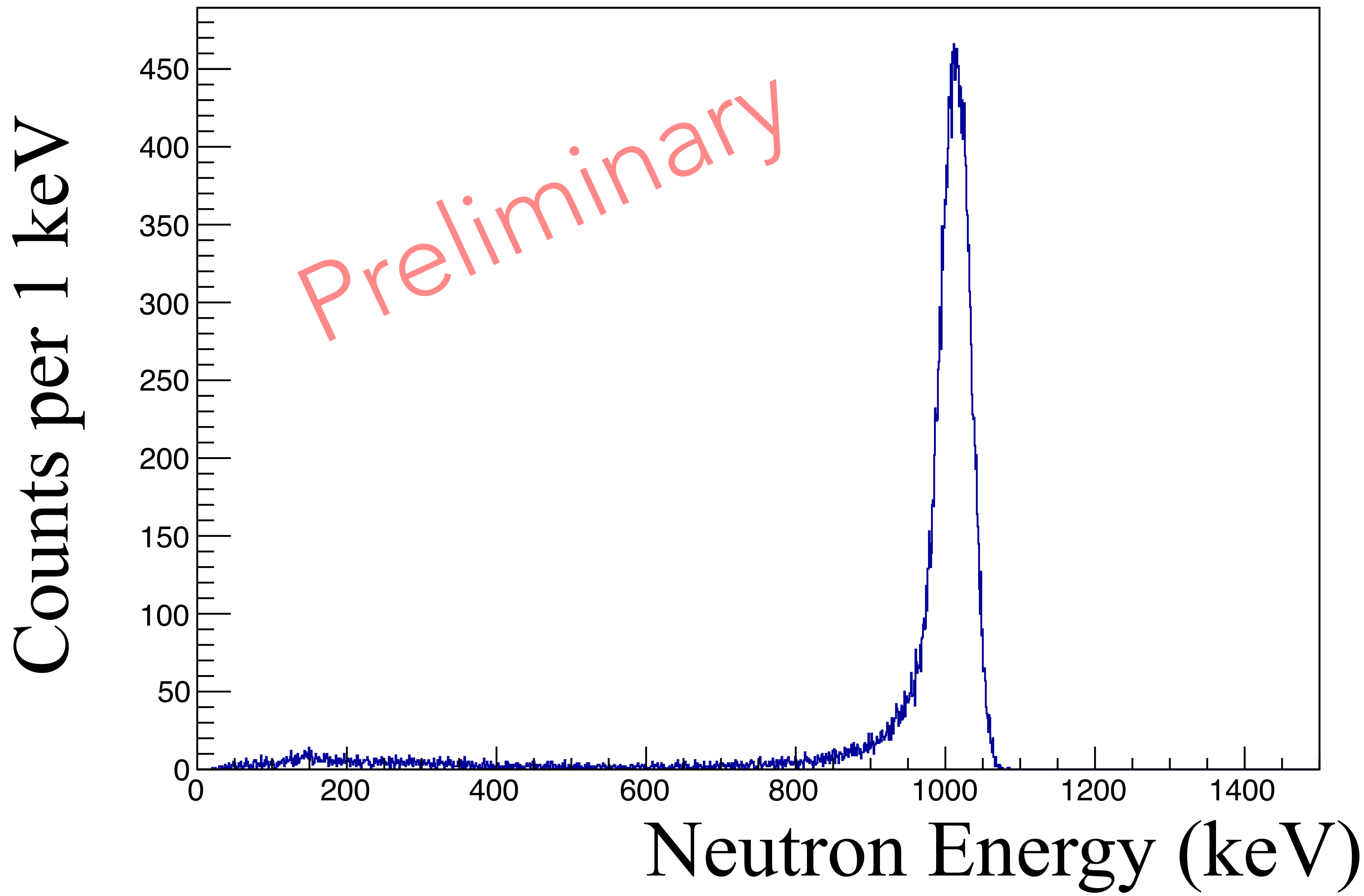
GEANT4 SIMULATIONS

1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event



Lower statistics of neutron only runs instead of scaling

ENERGY SPECTRA

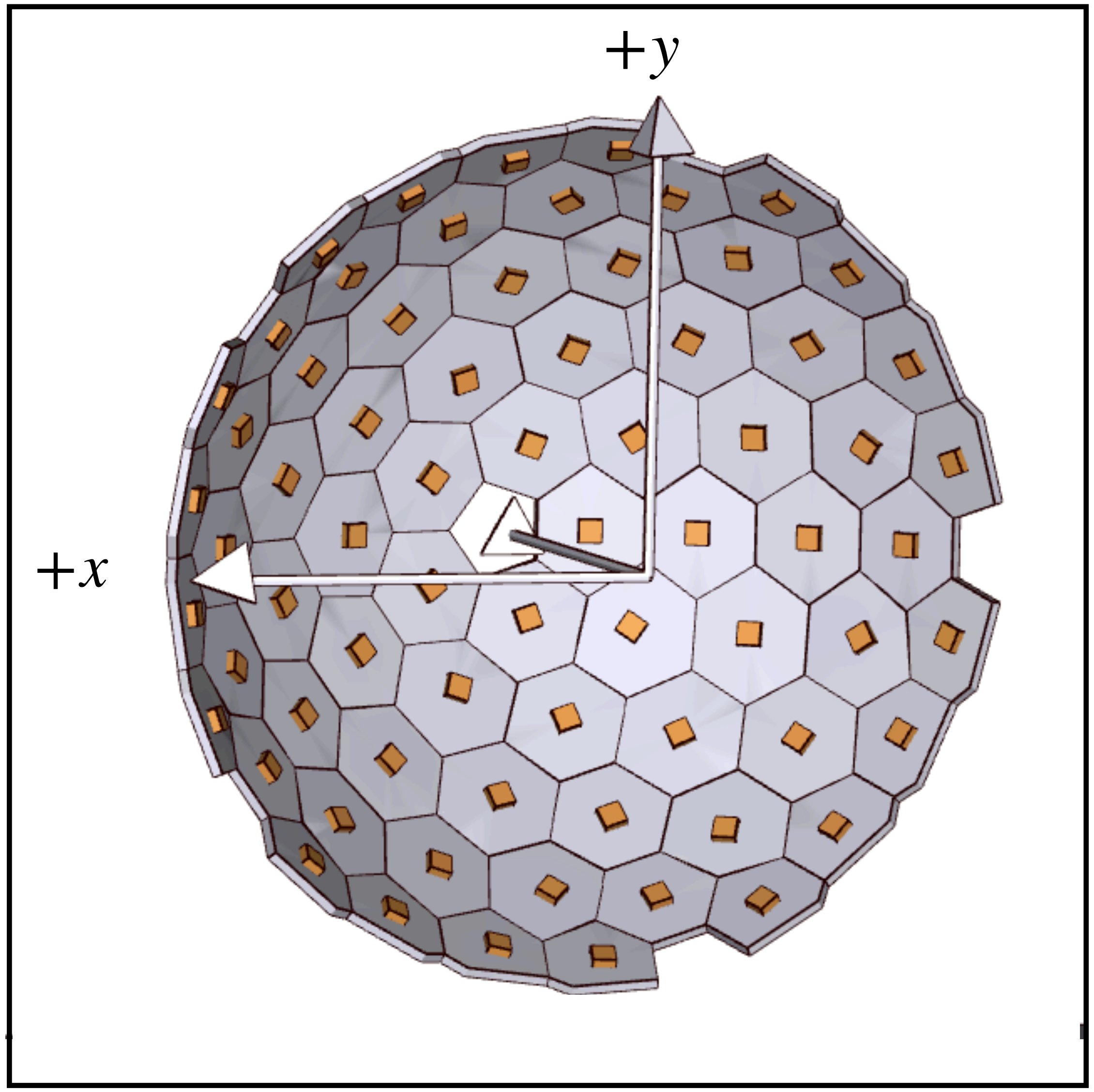


Scintillator in vacuum, neutrons shot at a 1cm thick, 8 cm wide detector, using a threshold of 1 optical photons detected in each SiPM

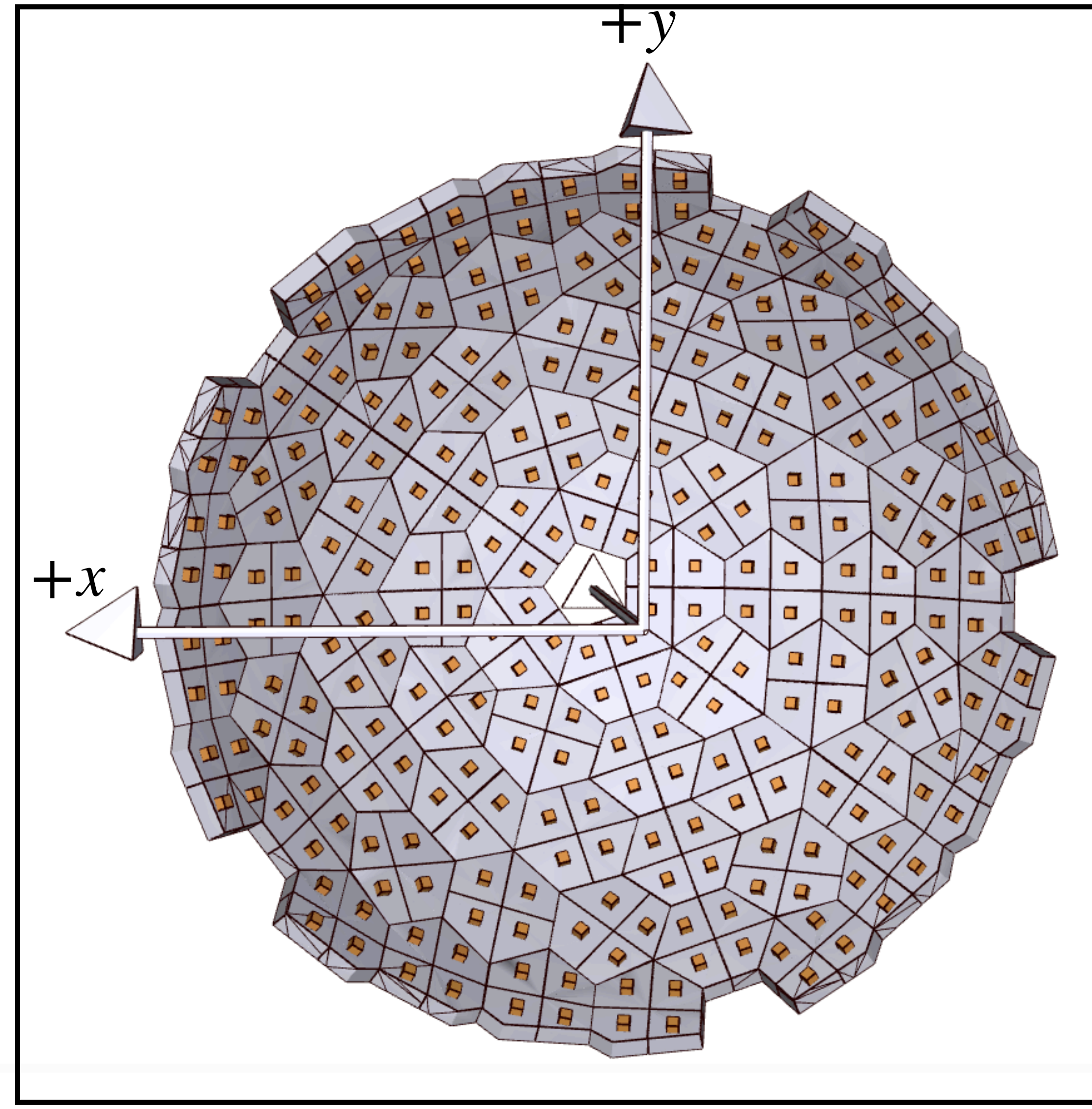
DETECTOR CONFIGURATION COMPARISONS

TILE CONFIGURATIONS

1.5 cm thick



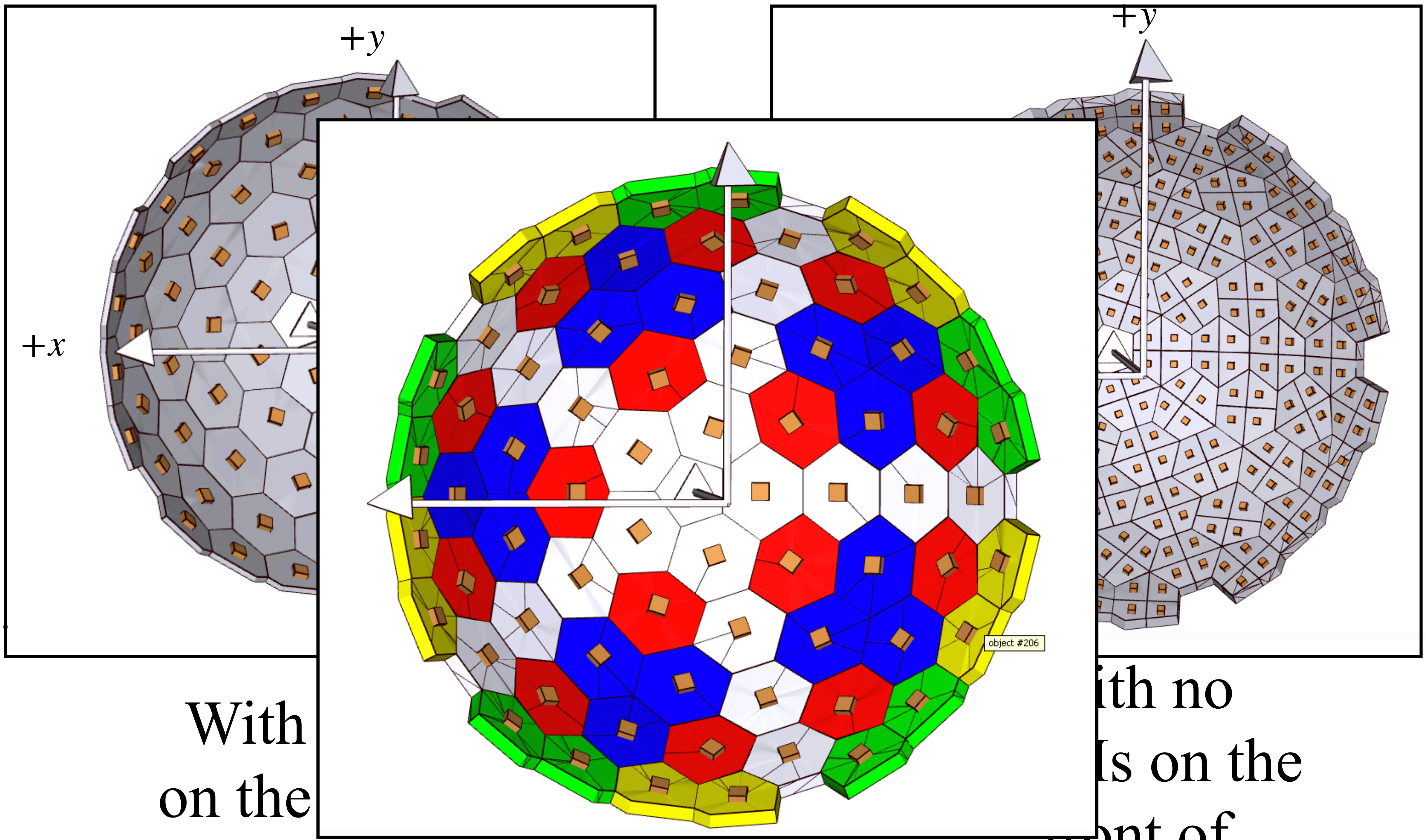
With SiPMs on the front of detector



With no SiPMs on the front of detector

DIFFERENT SIPM CONFIGURATIONS

1.5 cm thick



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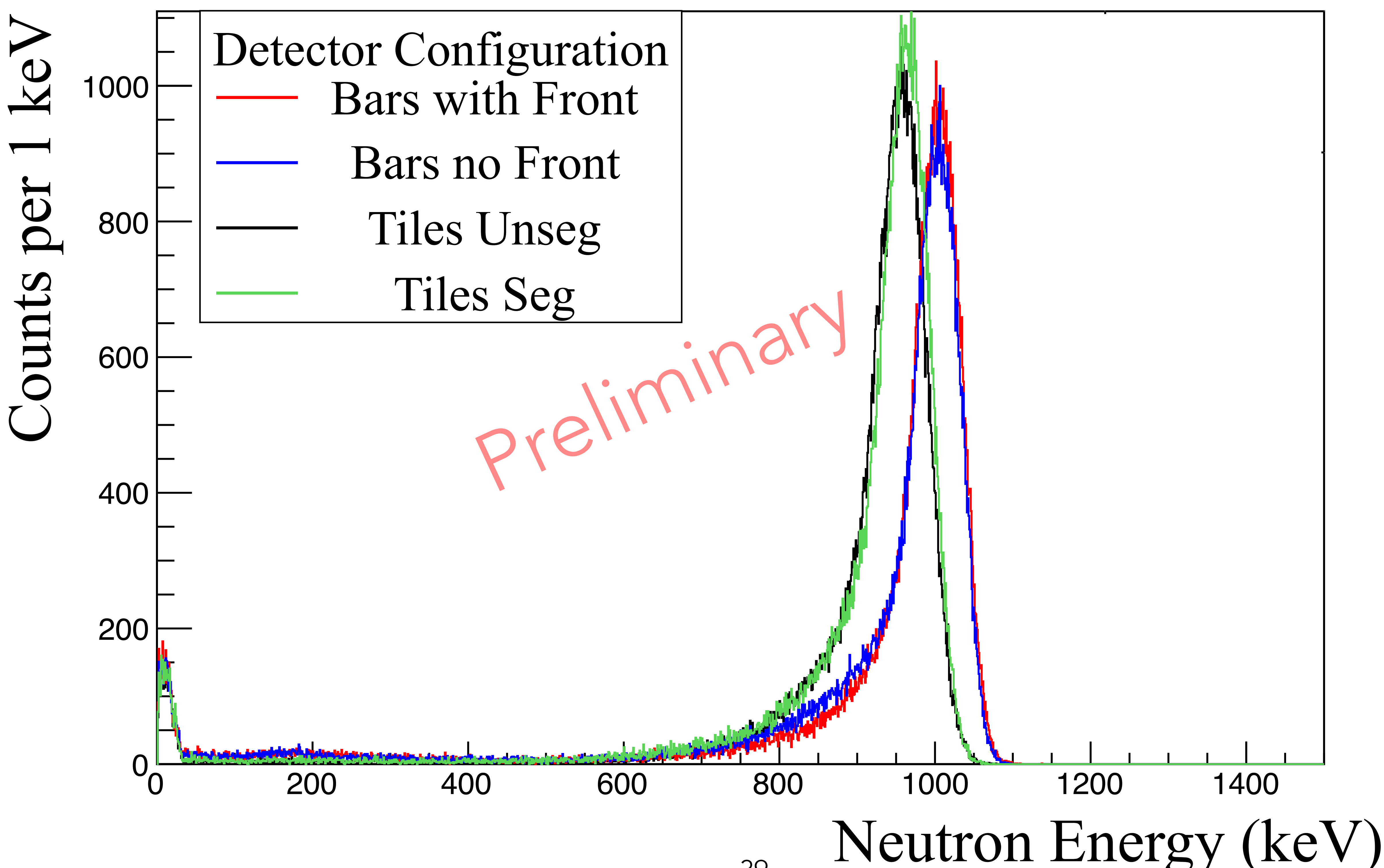
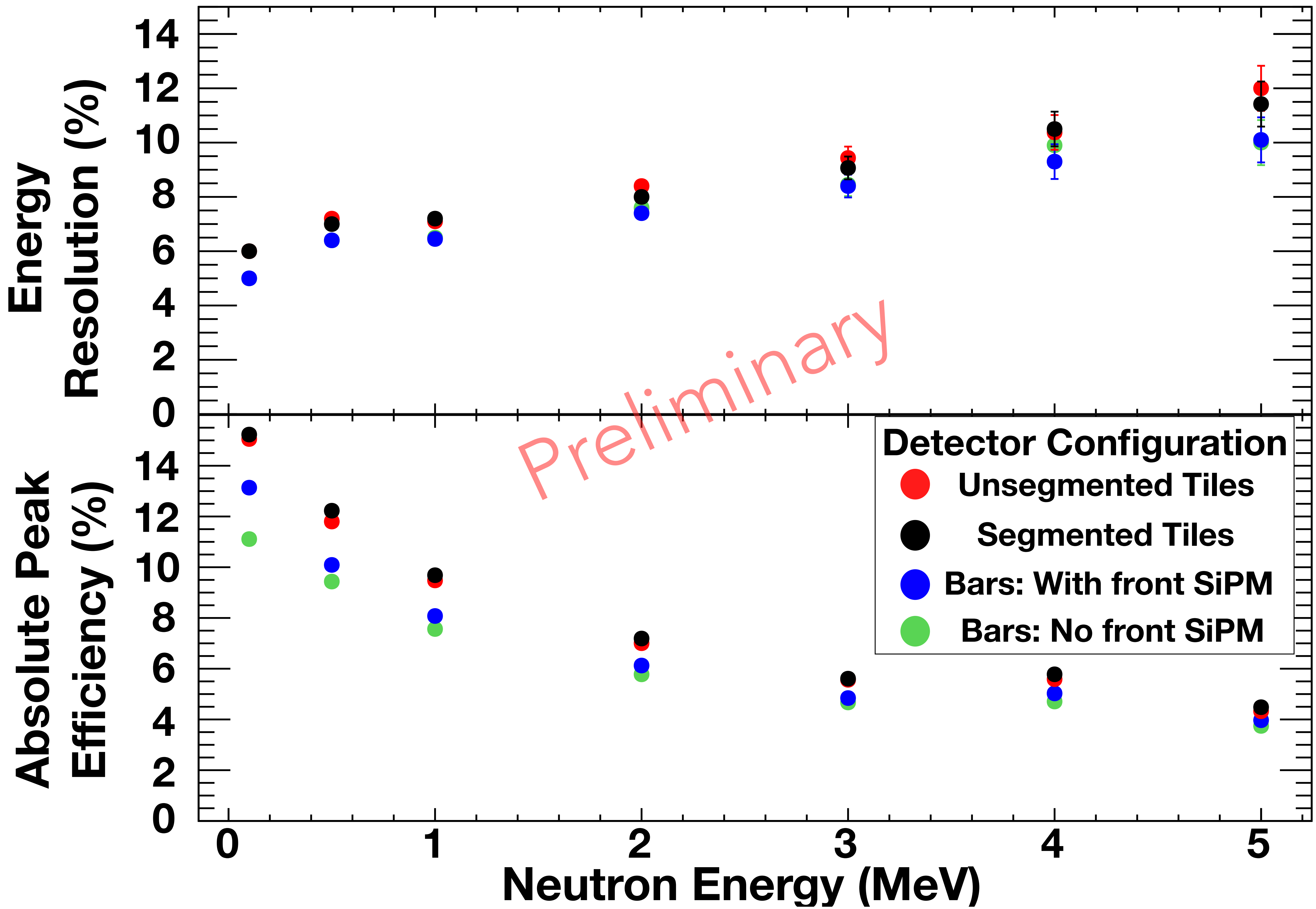
CONFIGURATION COMPARISON



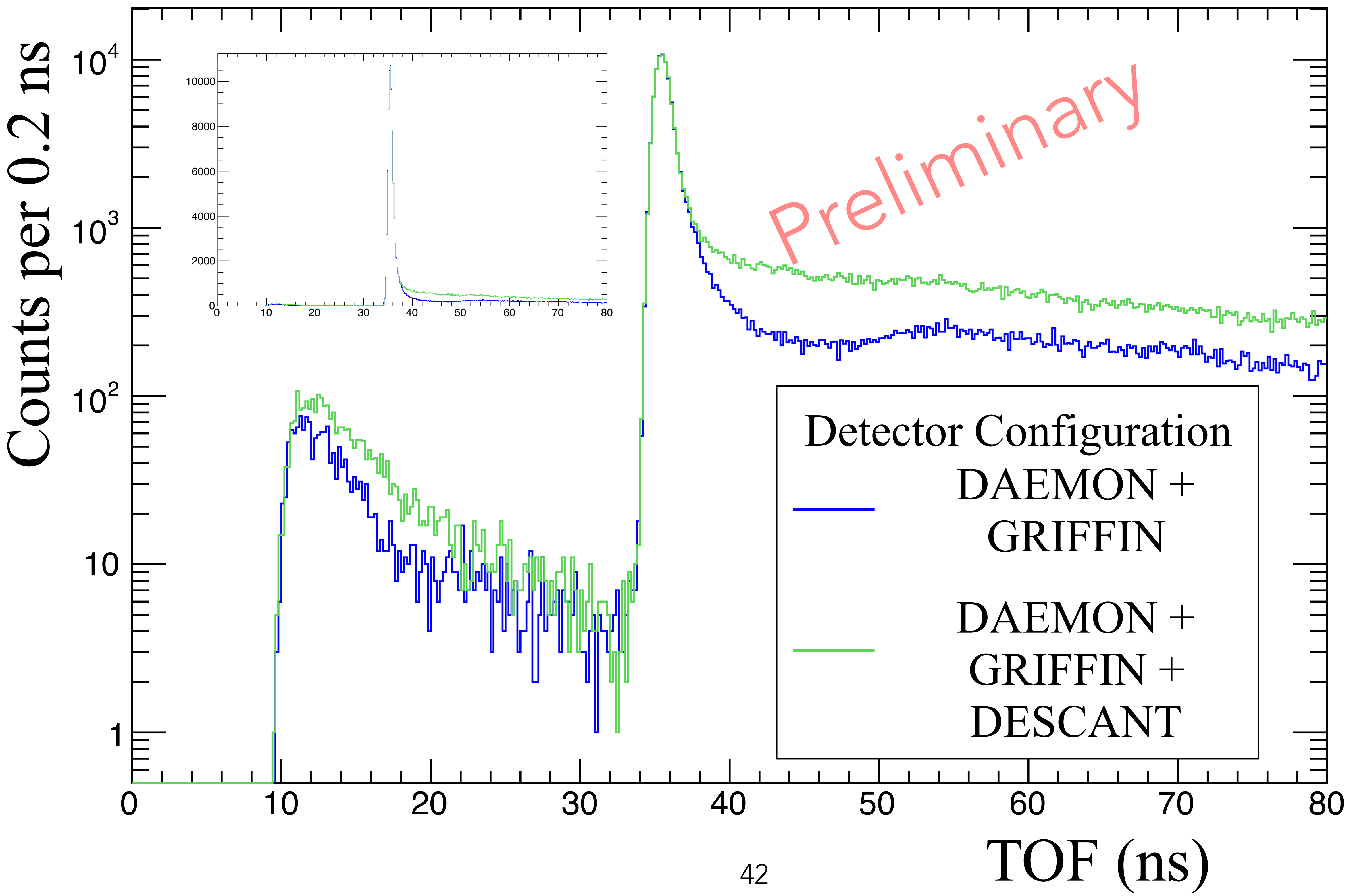
CONFIGURATION COMPARISON



TOF SPECTRA

GEANT4 SIMULATIONS

1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event



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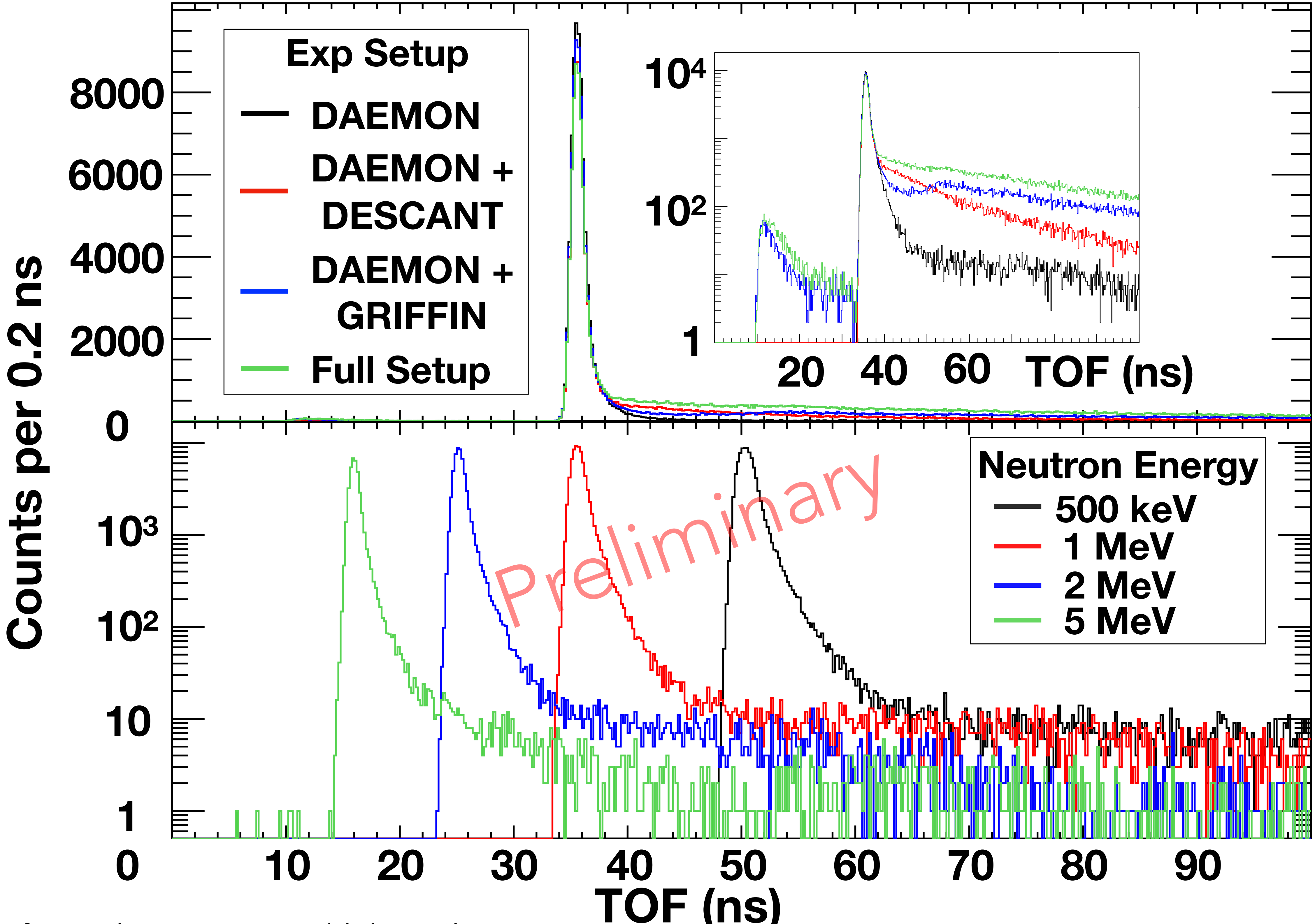
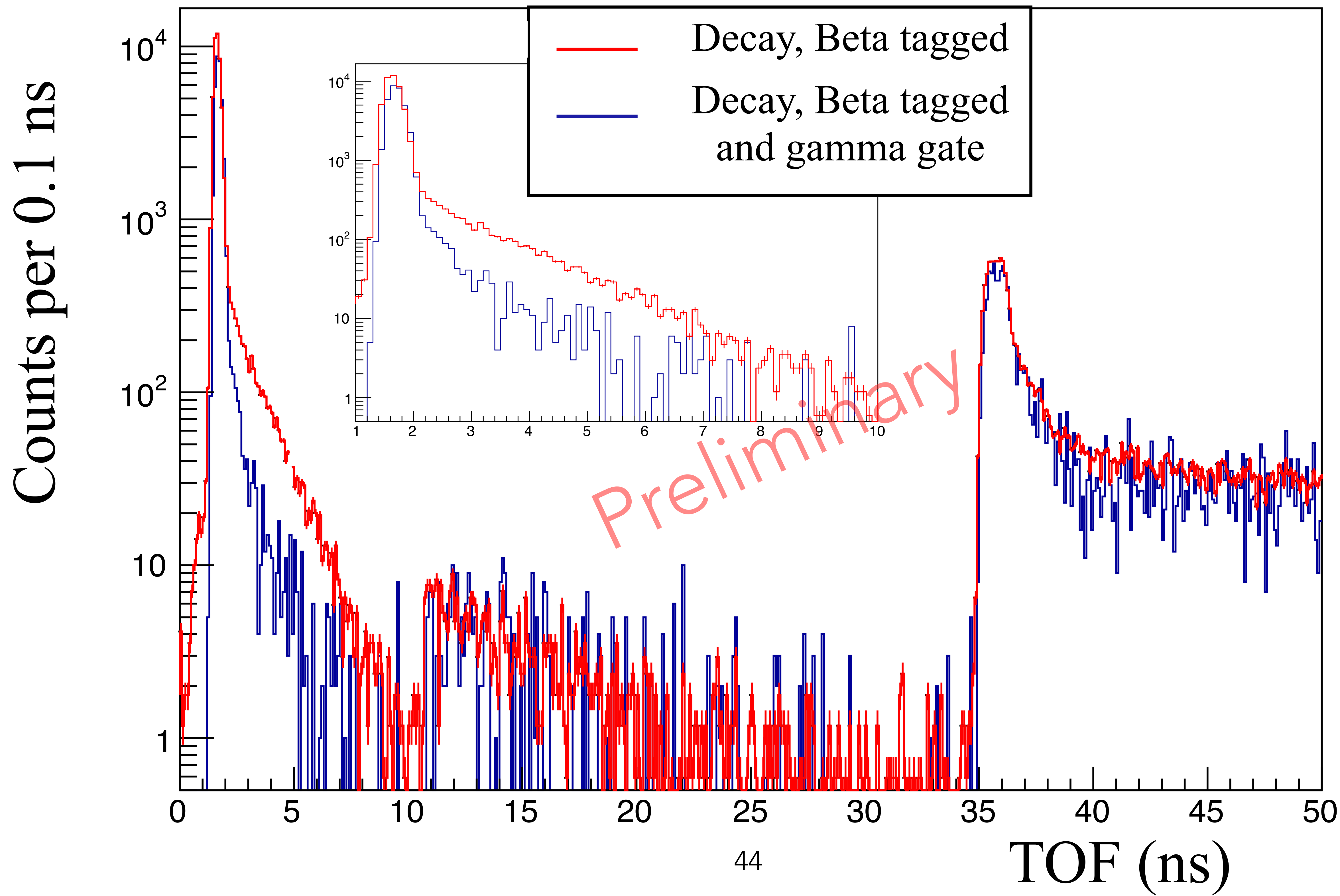


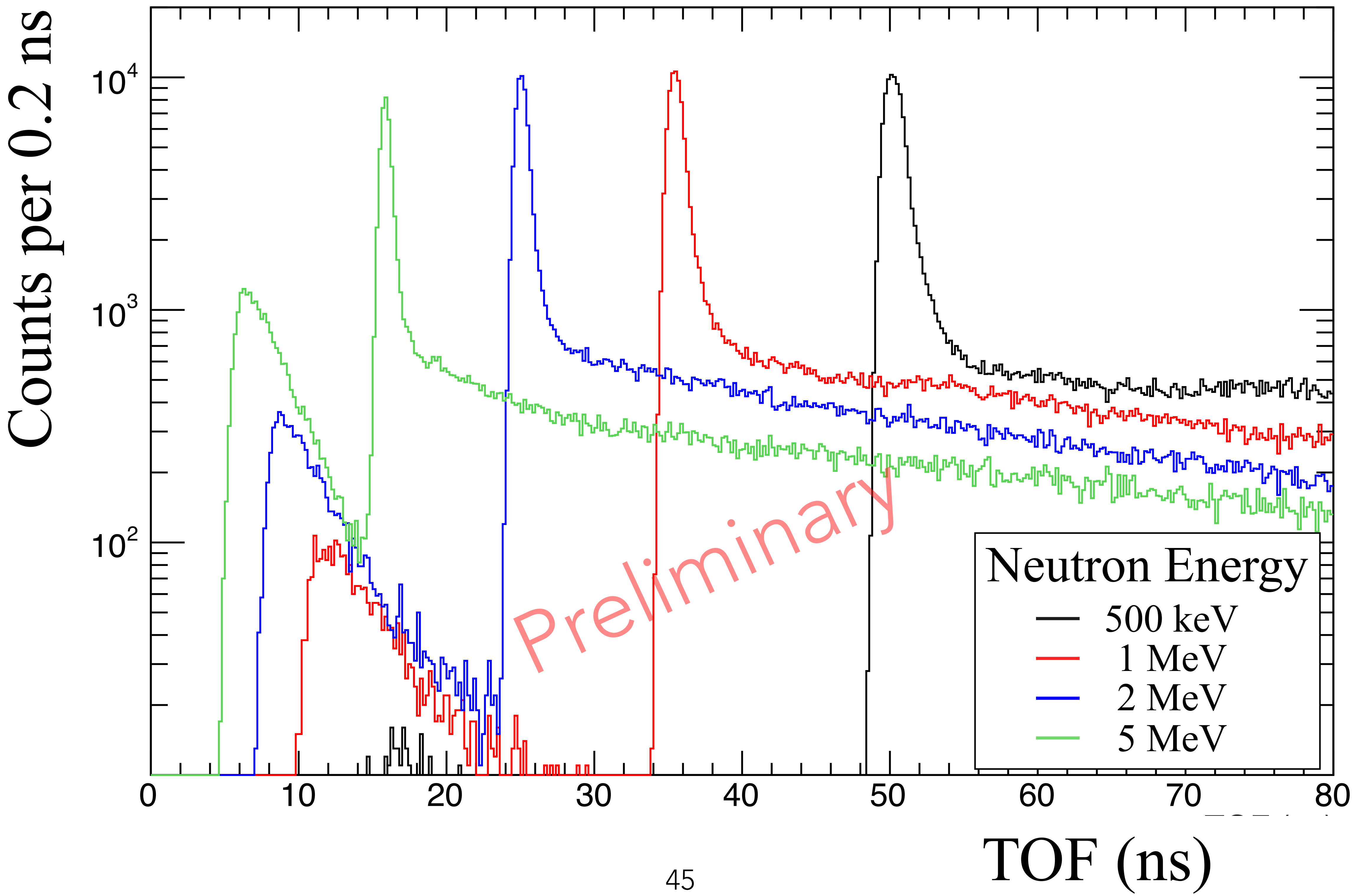
With front SiPMs, 1.5 cm thick, 2 SiPM firing condition, 1 optical photon threshold

GEANT4 SIMULATIONS



GEANT4 SIMULATIONS

Full setup, 1 optical photon threshold and 2 different arrays of SiPMs are required to fire to register event



GEANT4 SIMULATIONS

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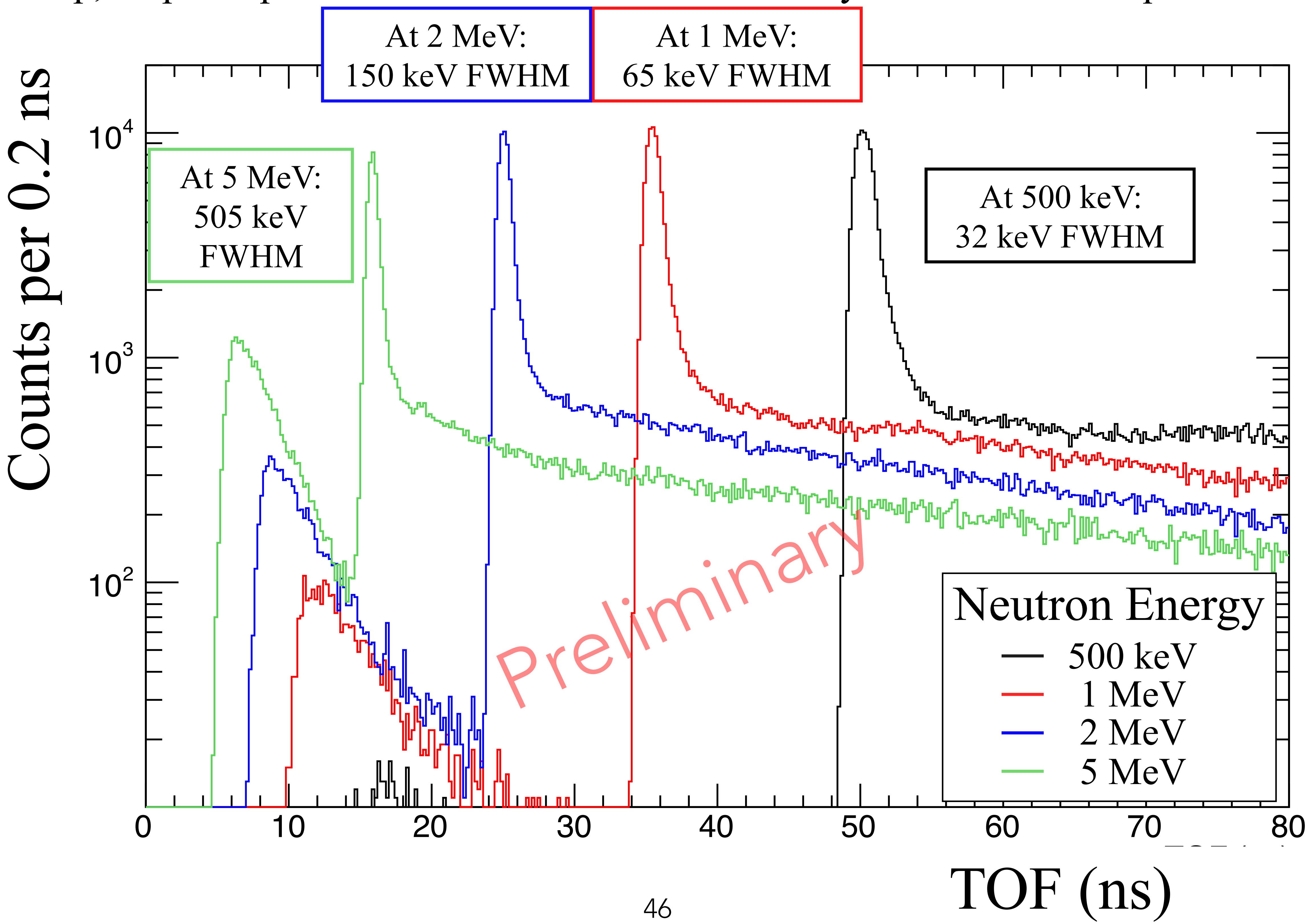
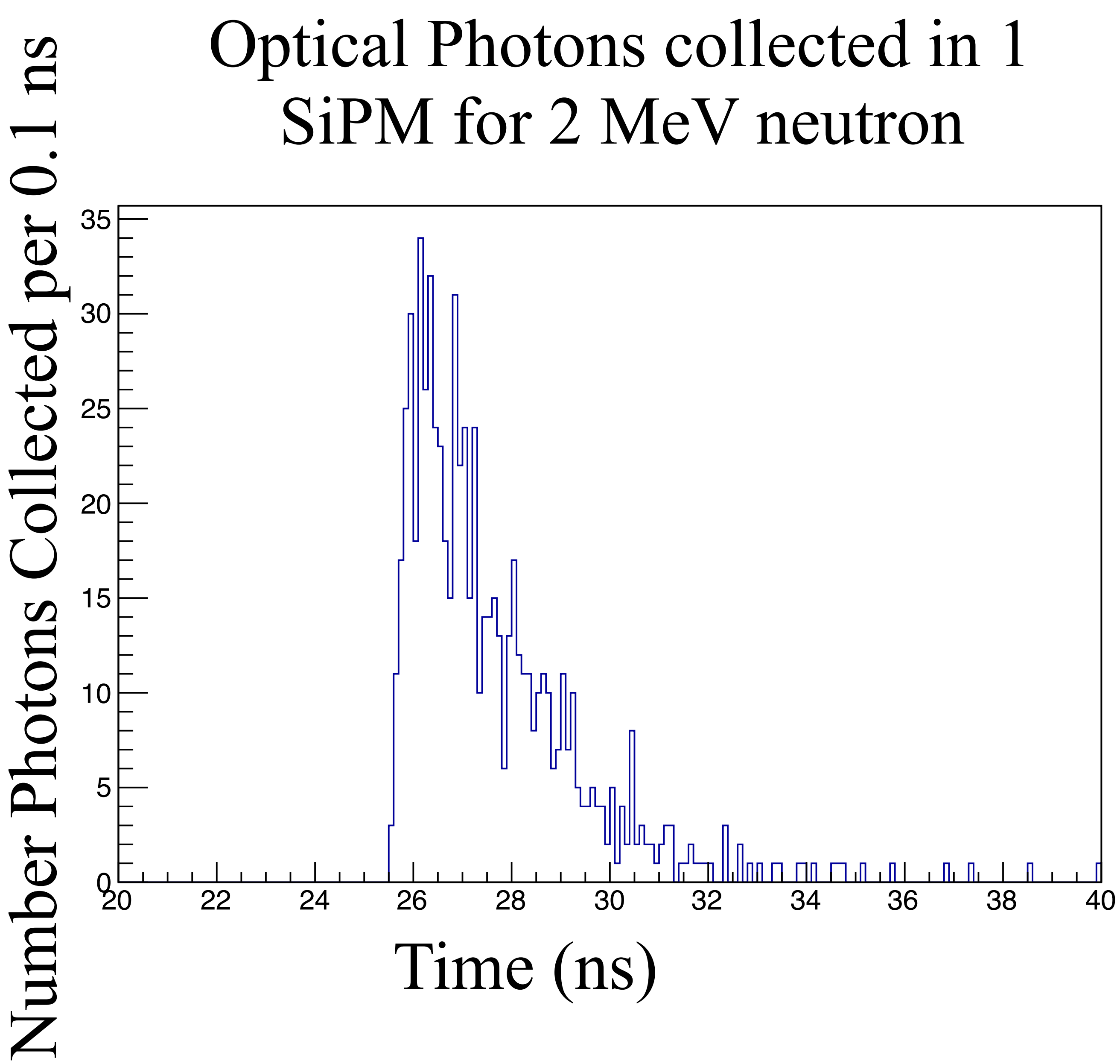
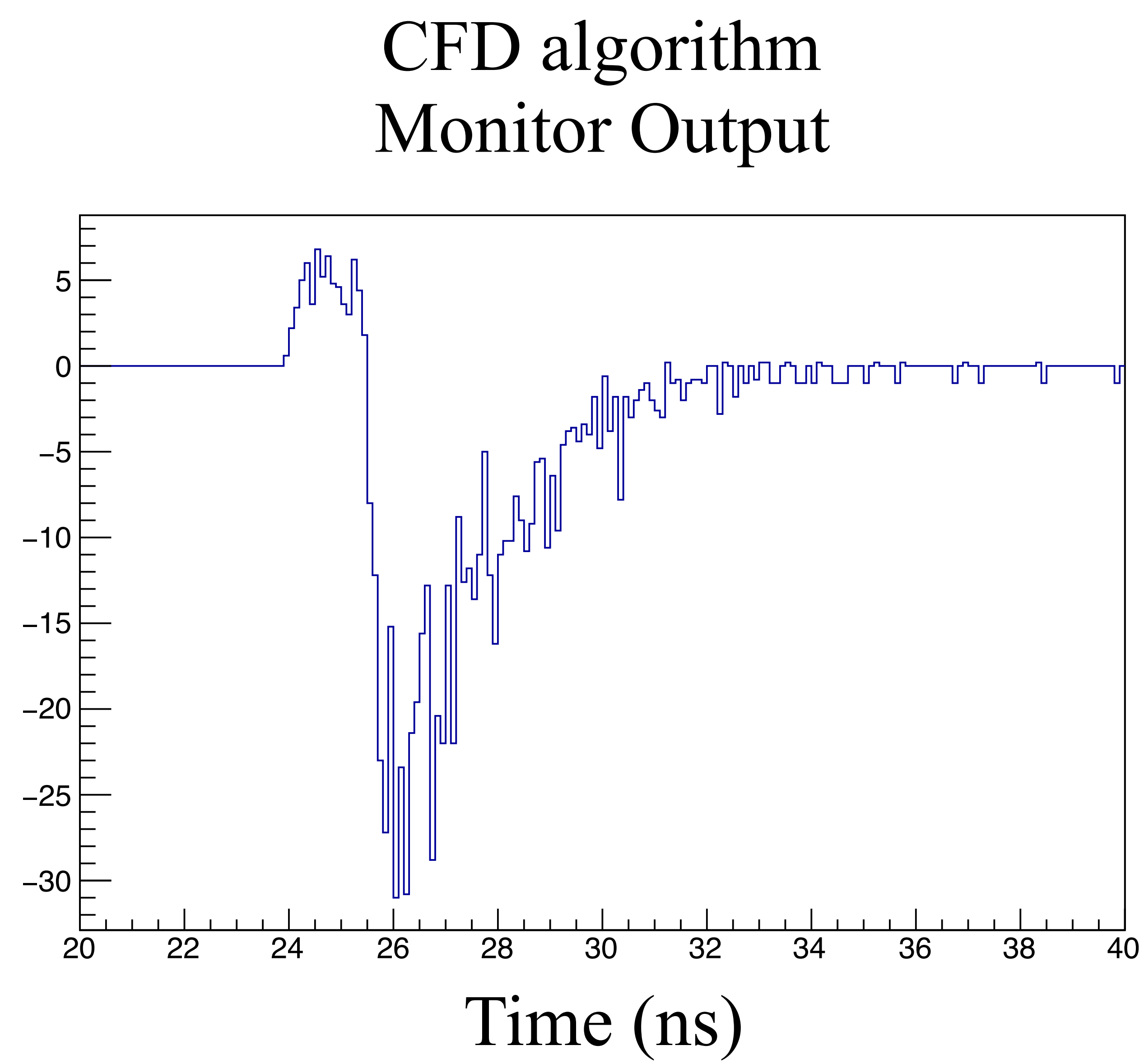


OPTICAL PHYSICS AND MATERIALS

TOF DETERMINATION





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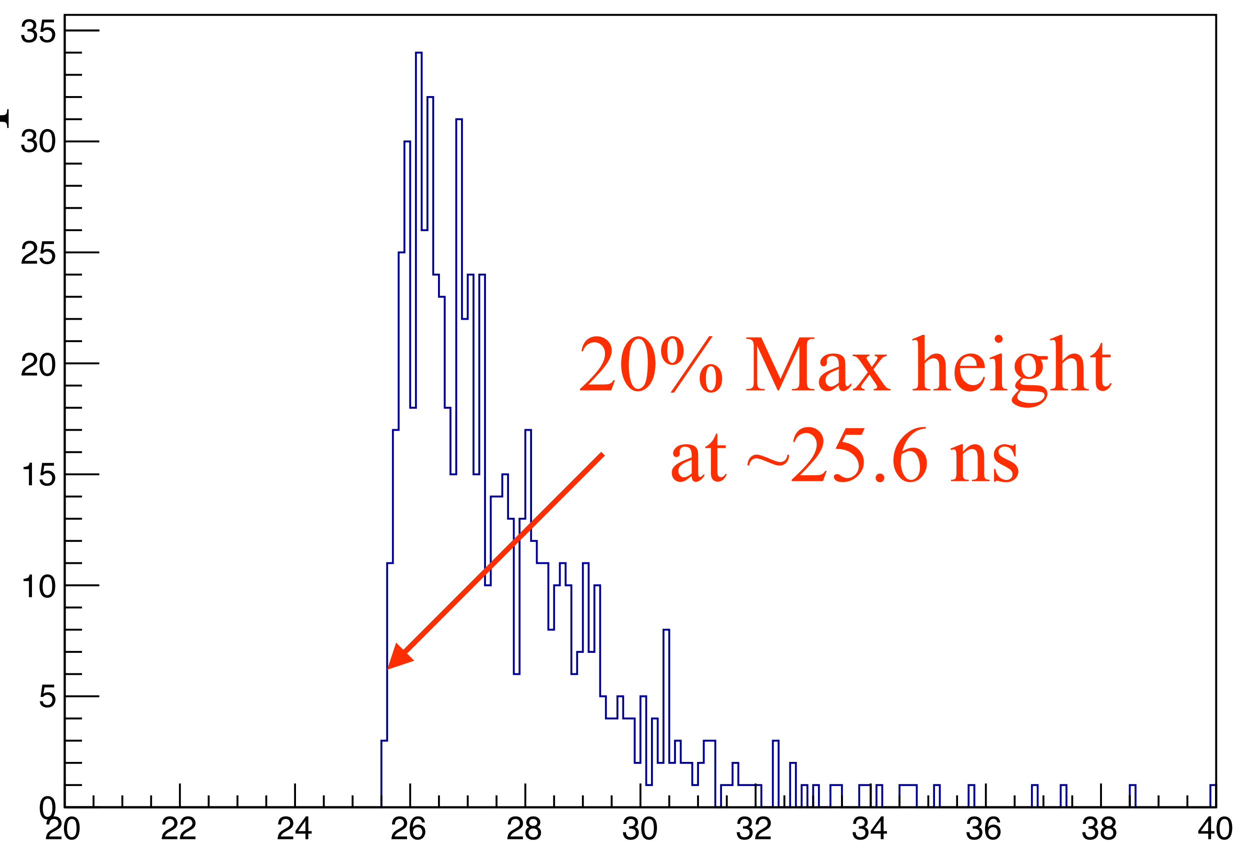
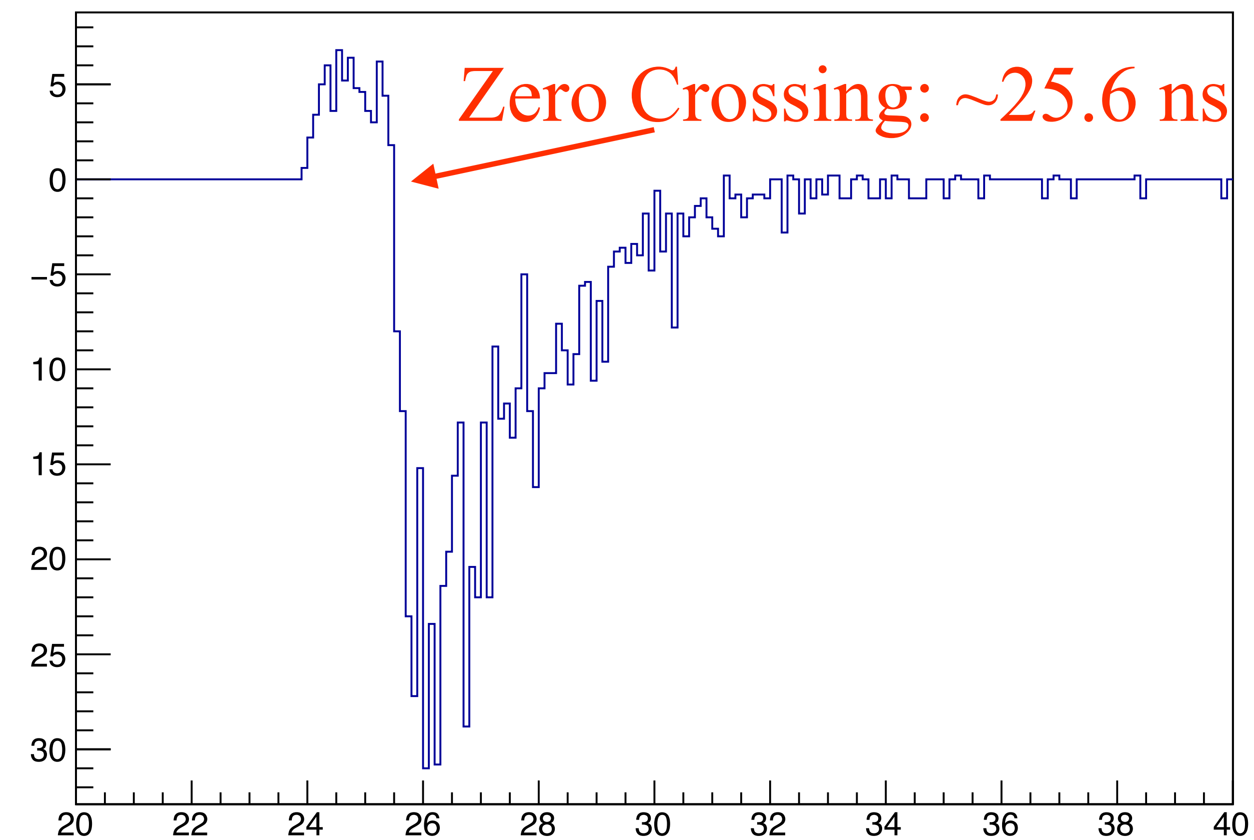
$$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$$

TOF DETERMINATION

Optical Photons collected in 1 SiPM for 2 MeV neutron



CFD algorithm Monitor Output



Time Obtained: 25.65 ns
After linear interpolation and bin randomization

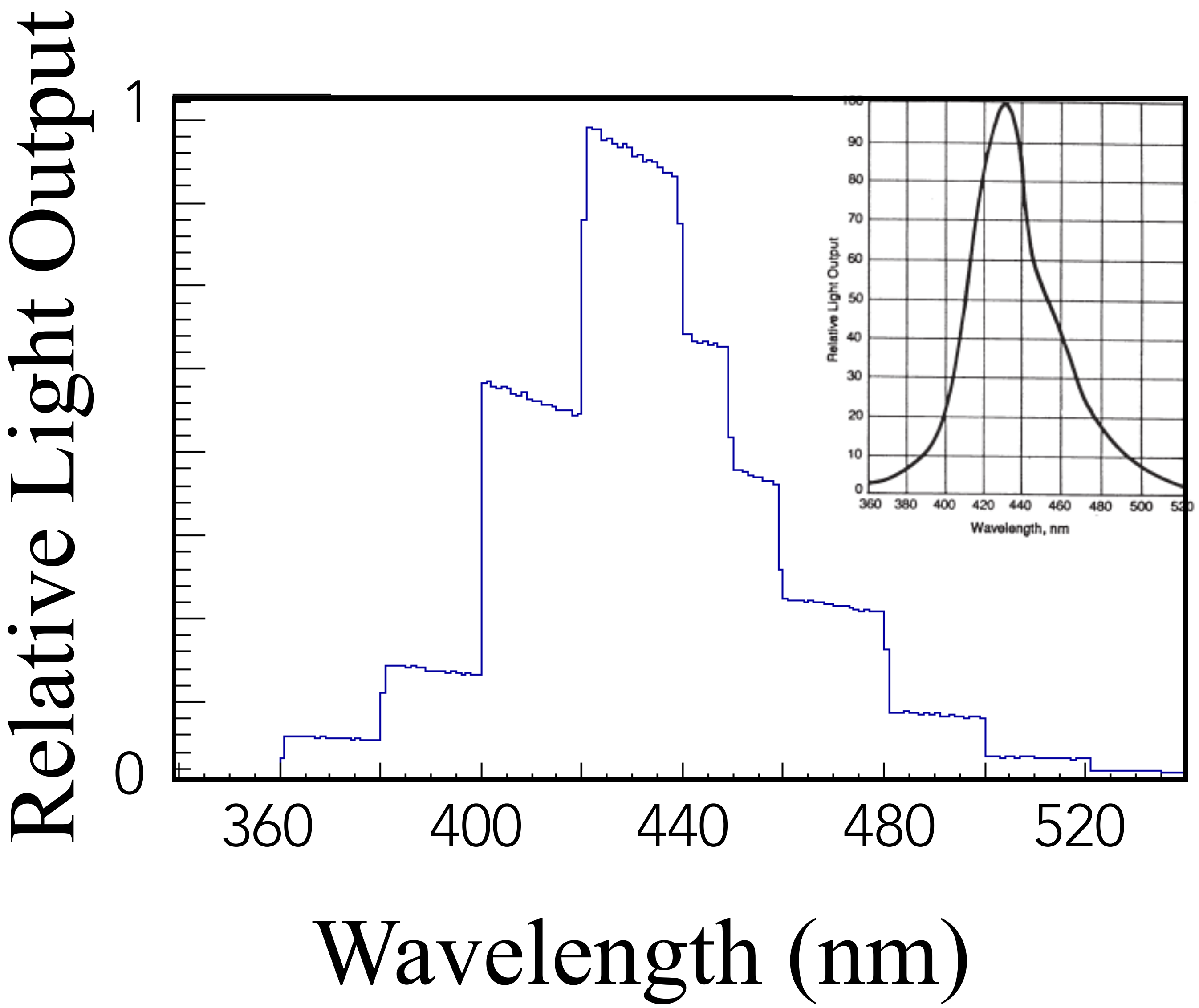
Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

$$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$$

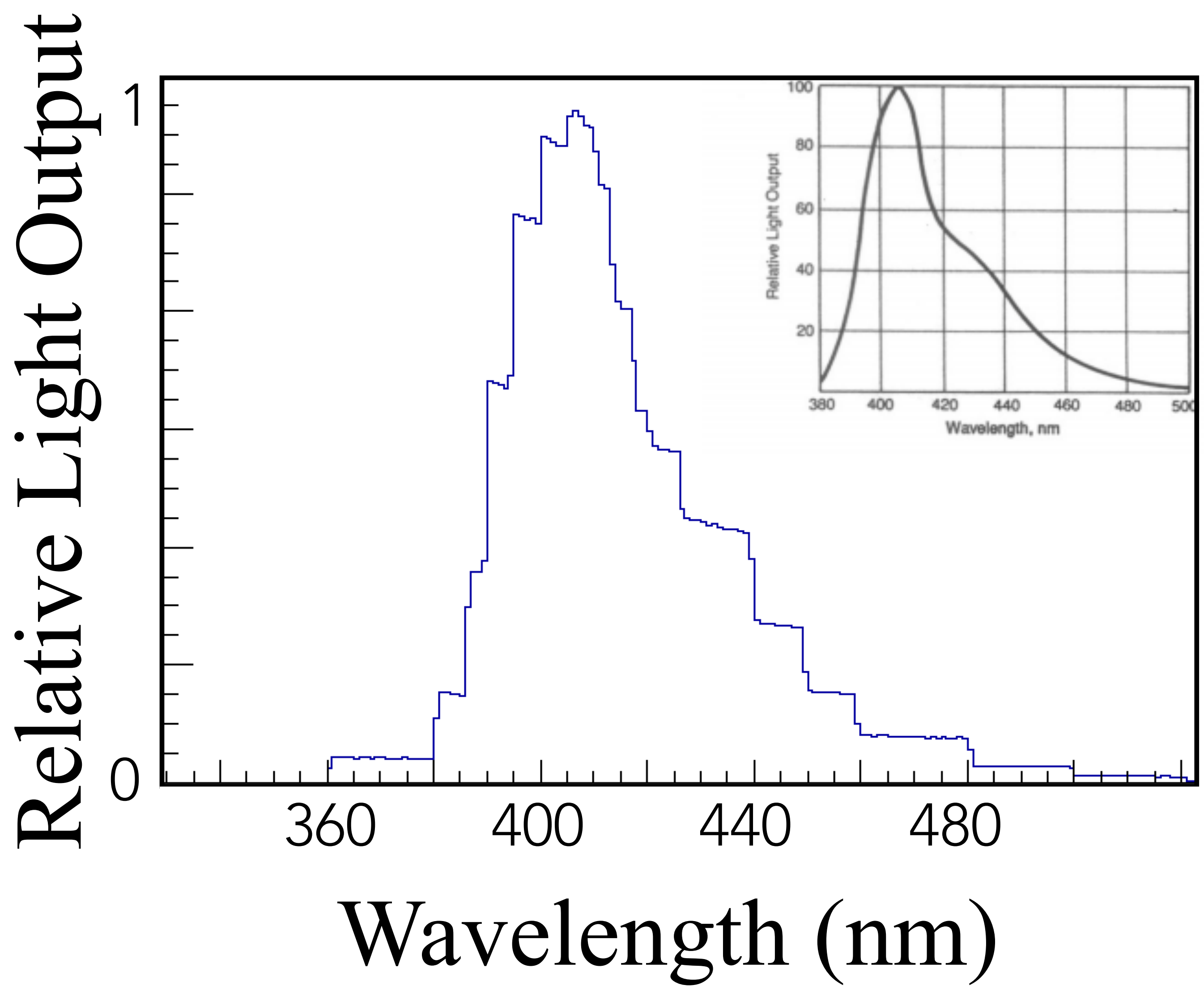
A 600 ps FWHM coincidence timing uncertainty is then applied

EMISSION SPEC

BC408

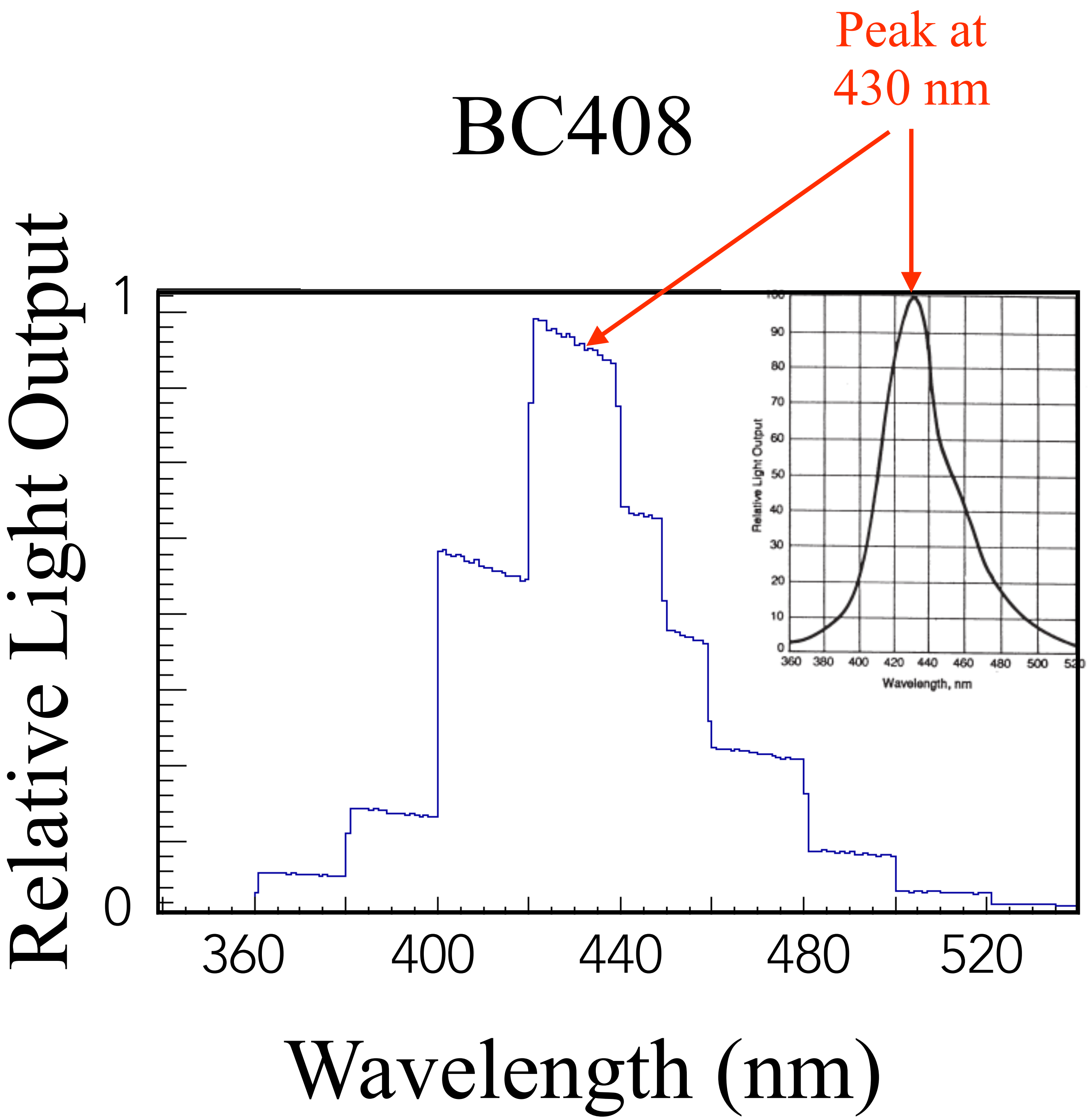


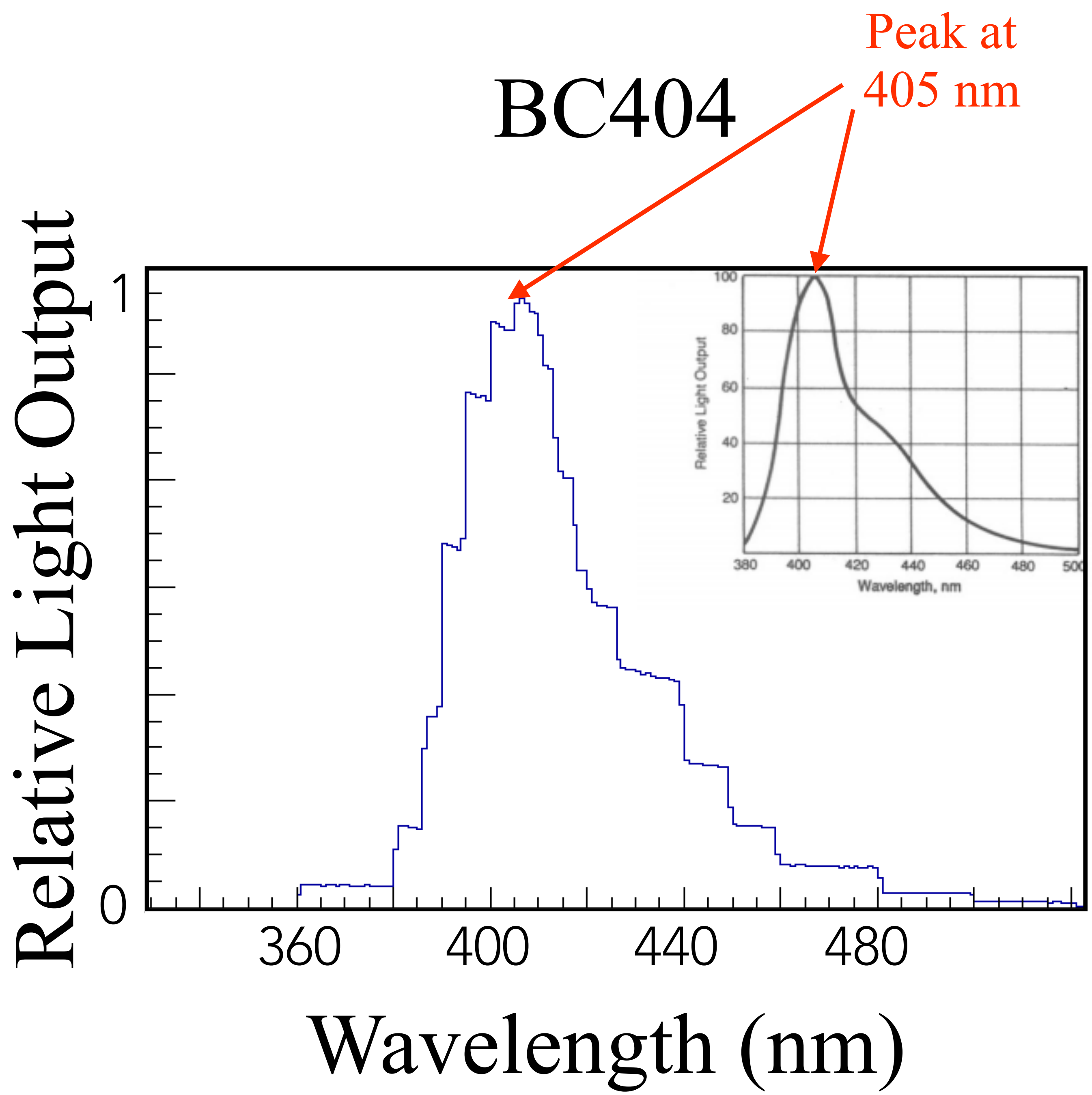
BC404



Saint Gobain data sheets: https://www.crystals.saint-gobain.com/products/bc400-bc404

EMISSION SPEC



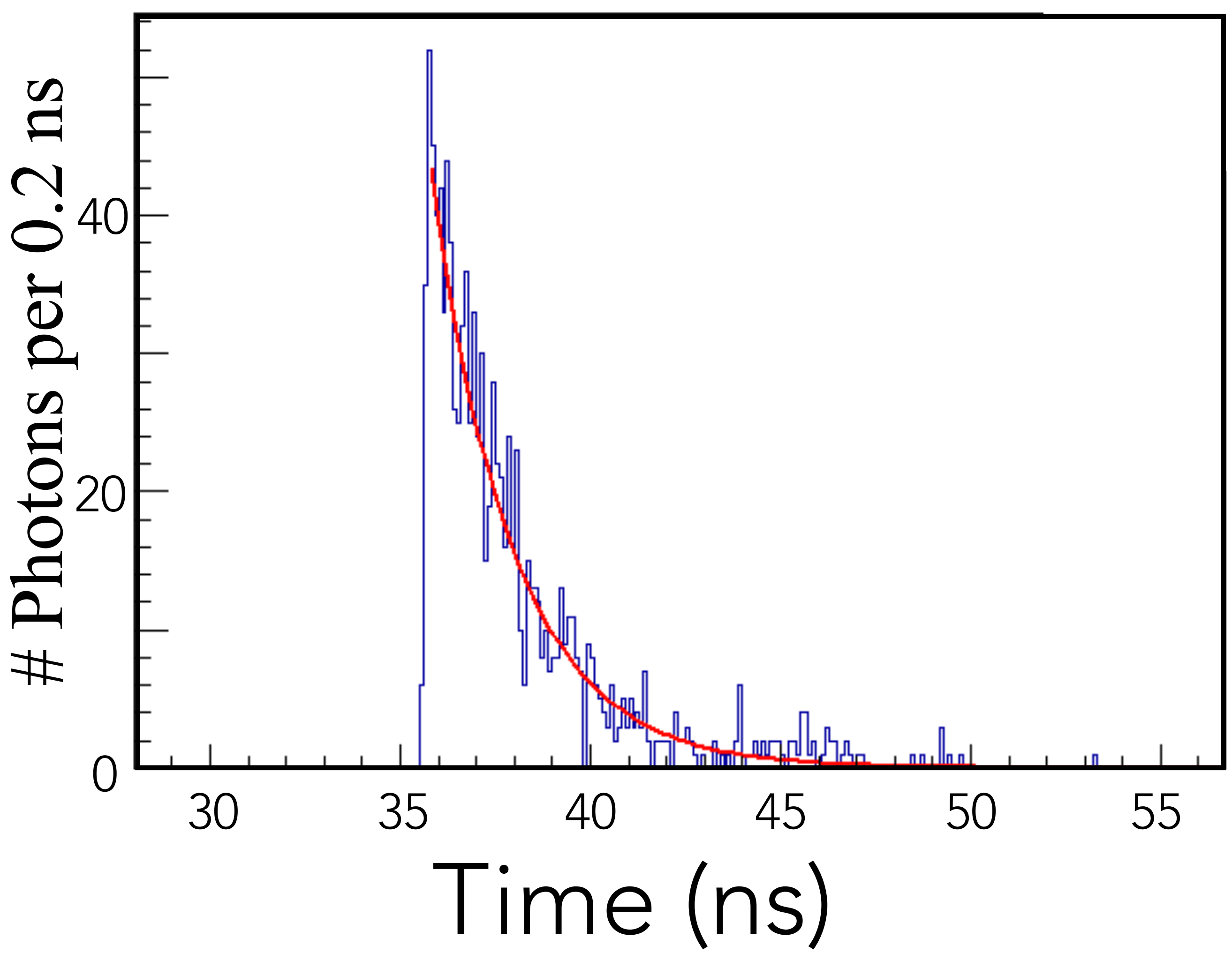


Saint Gobain data sheets: https://www.crystals.saint-gobain.com/products/bc400-bc404

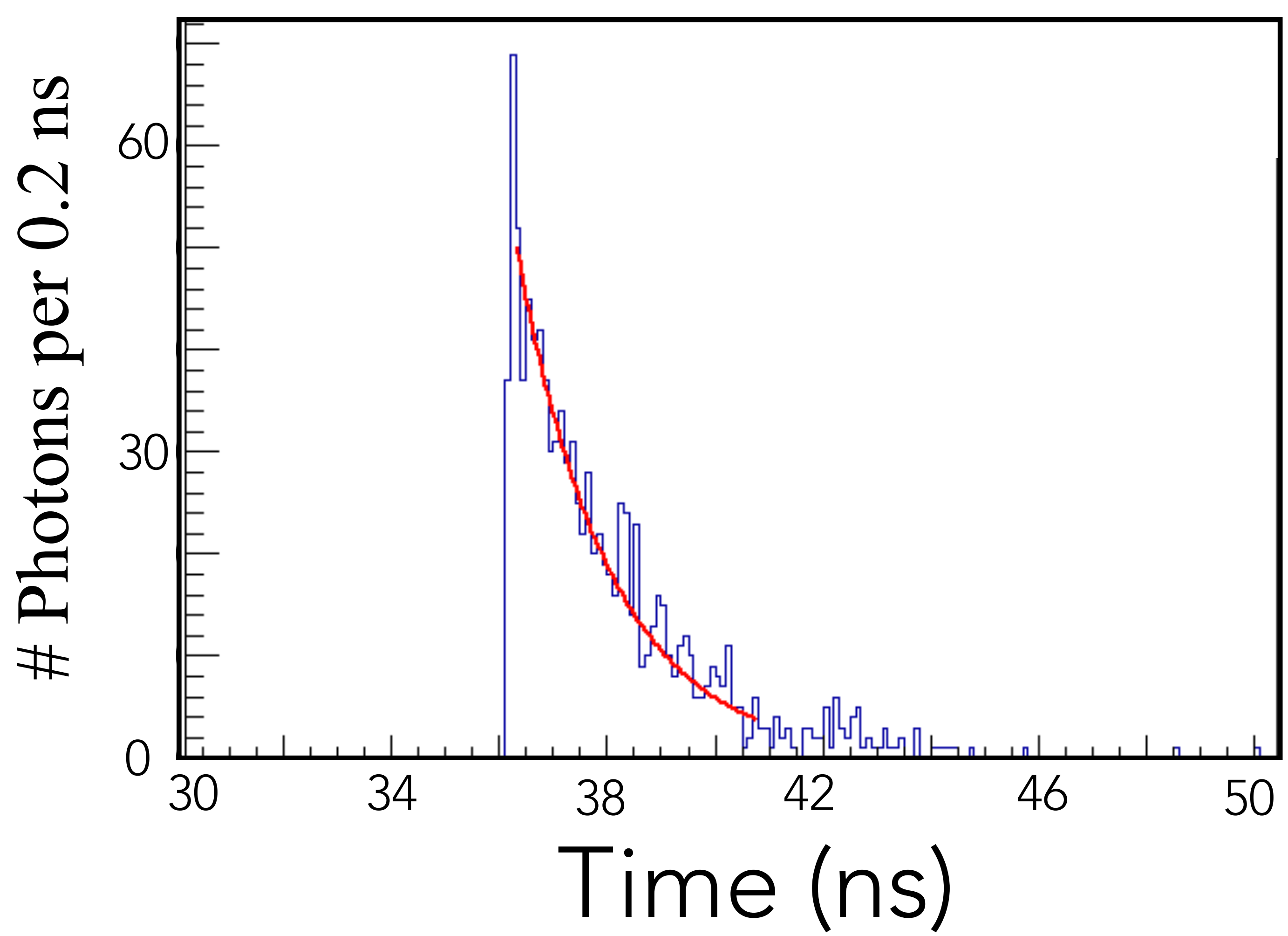
DECAY TIME

Photons generated in plastic scintillator as a function of time

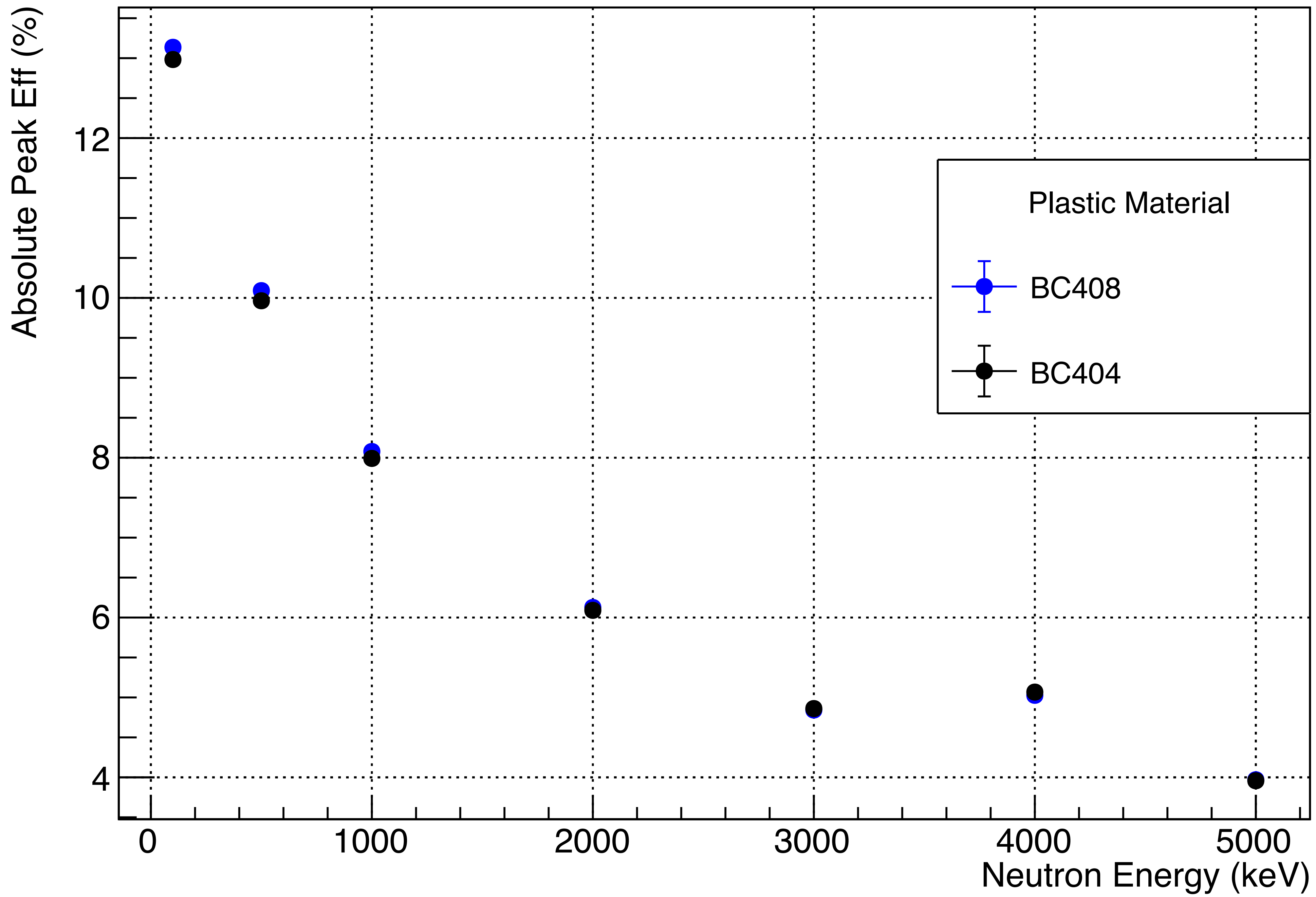
BC408
2.1 ns decay time from data sheets
2.14 ns obtained from fit



BC404
1.8 ns decay time from data sheets
1.77 ns obtained from fit

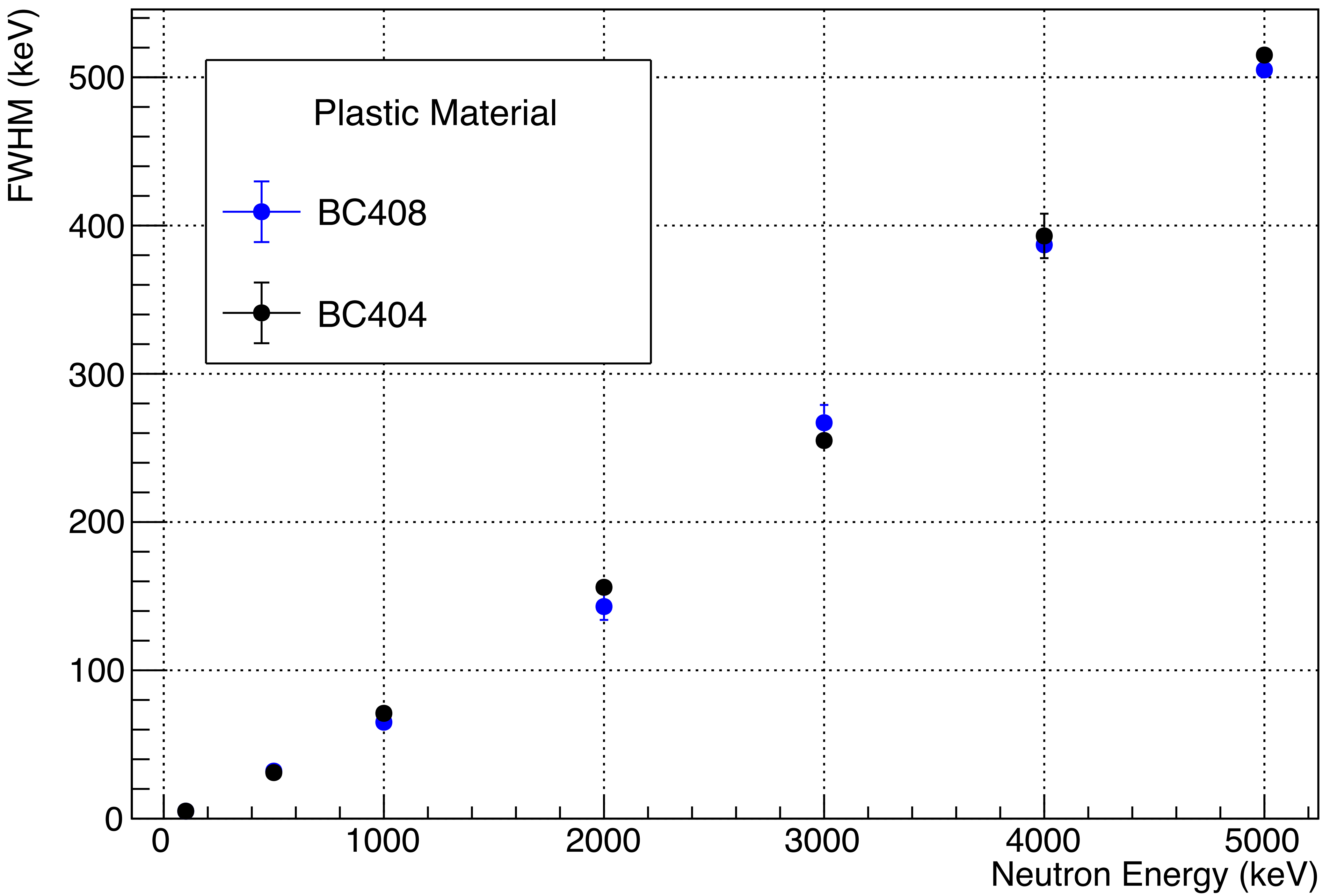


PUT IN BC404 VS 408 COMPARISON



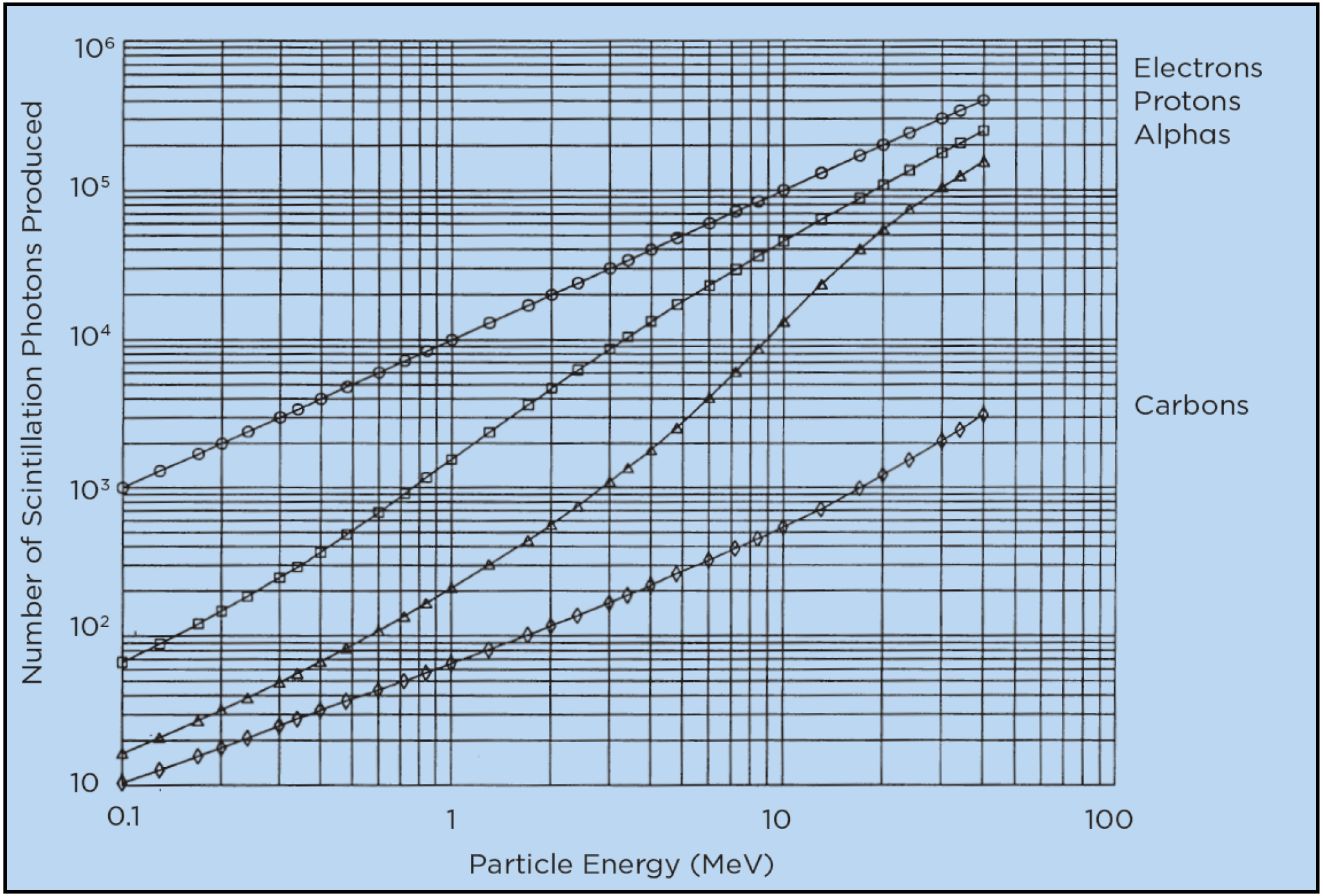
Bars withFront SiPM Configuration, 1.5 cm thick, 5.5cm wide

PUT IN BC404 VS 408 COMPARISON



Bars withFront SiPM Configuration, 1.5 cm thick, 5.5cm wide

PARTICLE BASED LIGHT OUTPUT



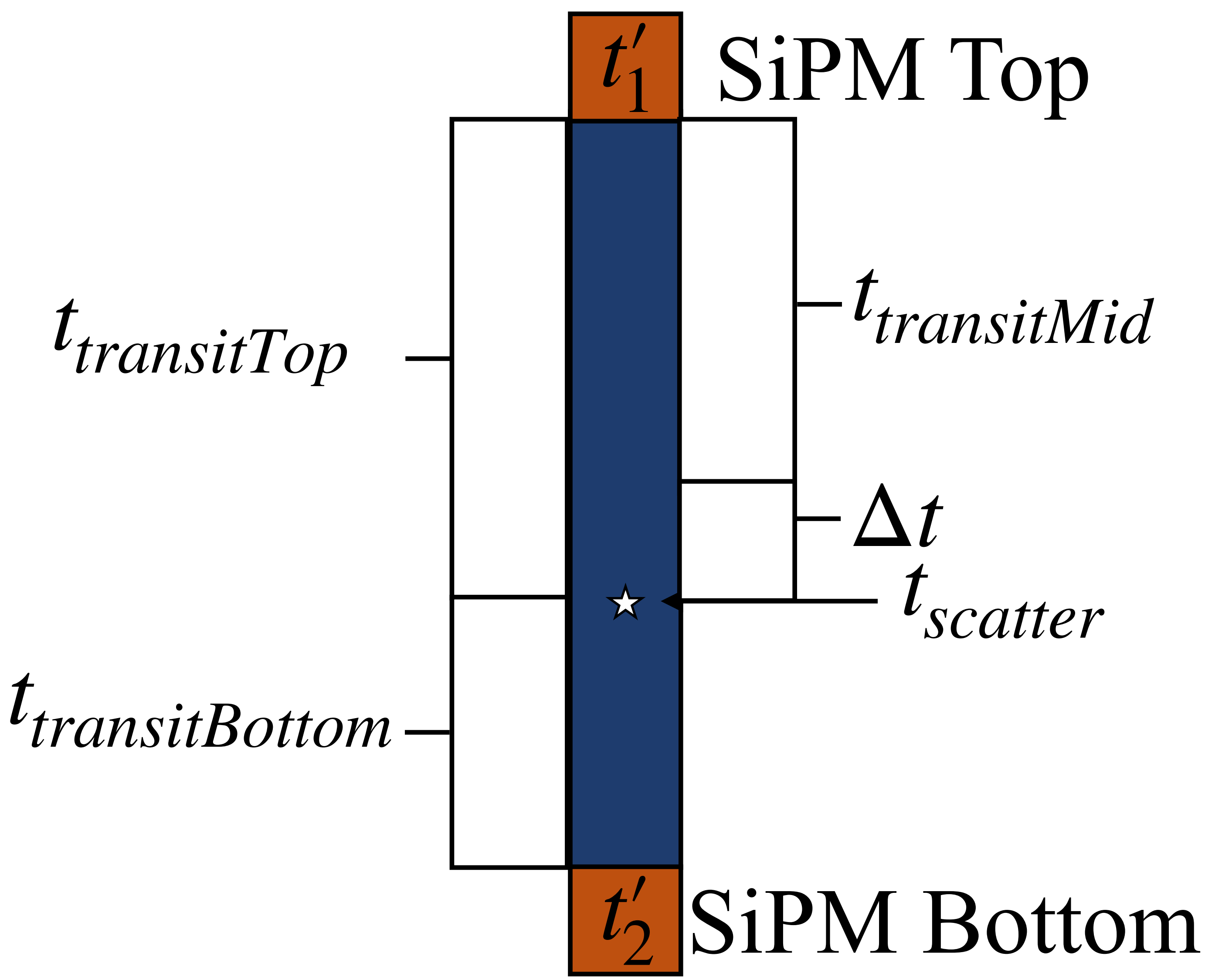
Taken from Saint-Gobain plastic scintillator data sheet

DETERMINING SCATTER TIME AND POSITION

OBTAIN SCATTER TIME

Want to extract $t_{scatter}$ from t'_1 and t'_2

Assume Bottom SiPM fires before Top.
Assume scatter is closer to Bottom



Define

$$\Delta t = t_{scatter} - t_{TransitToMiddle}$$

And

$$t'_1 = t_{scatter} + t_{transitTop}$$

$$t'_2 = t_{scatter} + t_{transitBottom}$$

Therefore

$$t'_1 = t_{scatter} + t_{transitMid} + \Delta t$$

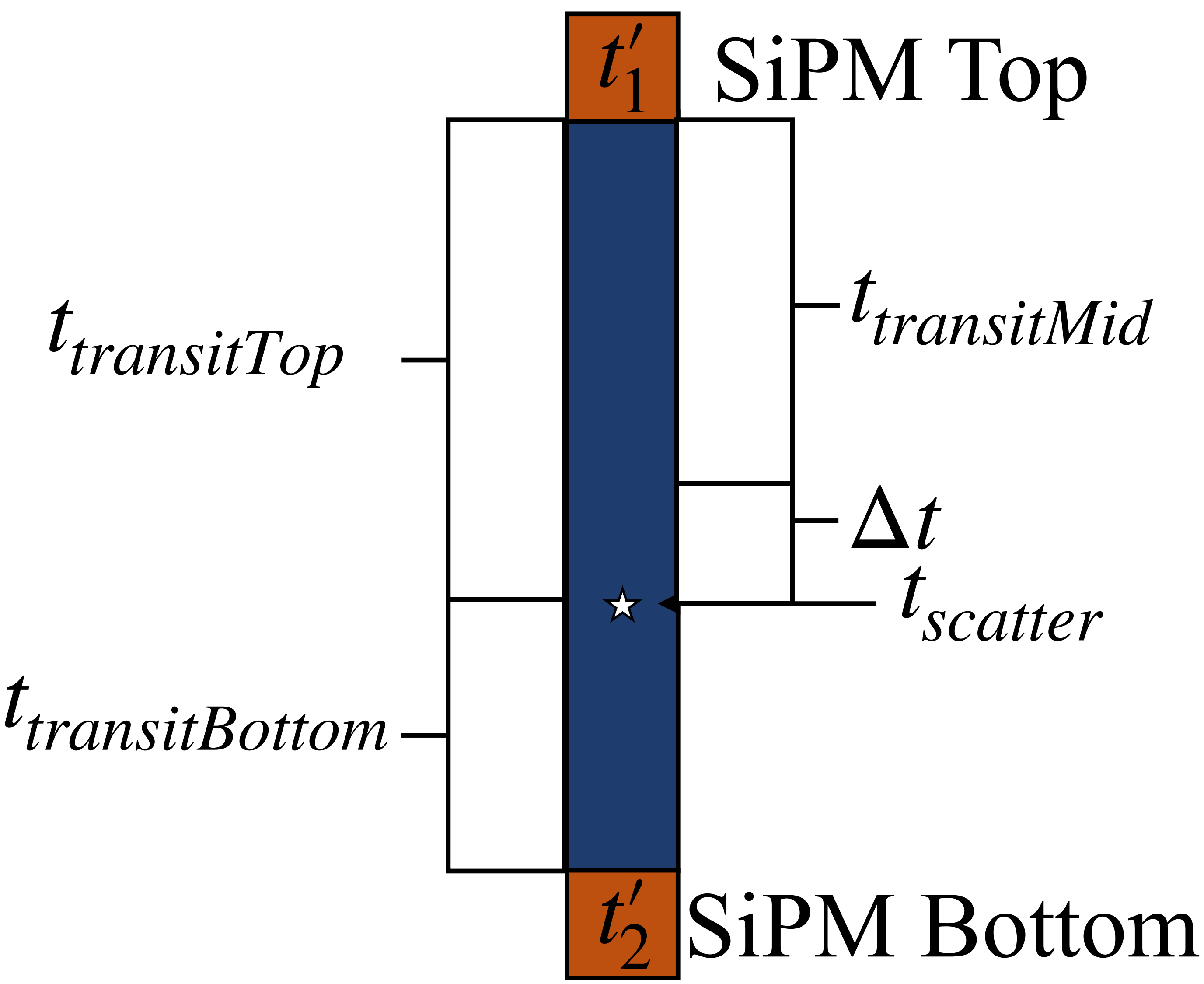
$$t'_2 = t_{scatter} + t_{transitMid} - \Delta t$$

☆ Scatter Location at time $t_{scatter}$

OBTAIN SCATTER TIME

Want to extract $t_{scatter}$ from t'_1 and t'_2

Assume Bottom SiPM fires before Top.
Assume scatter is closer to Bottom



$$\Delta t = t_{scatter} - t_{TransitToMiddle}$$

$$t'_1 = t_{scatter} + t_{transitMid} + \Delta t$$

$$t'_2 = t_{scatter} + t_{transitMid} - \Delta t$$

Define

$$t_{avg} = \frac{t'_1 + t'_2}{2}$$

Therefore

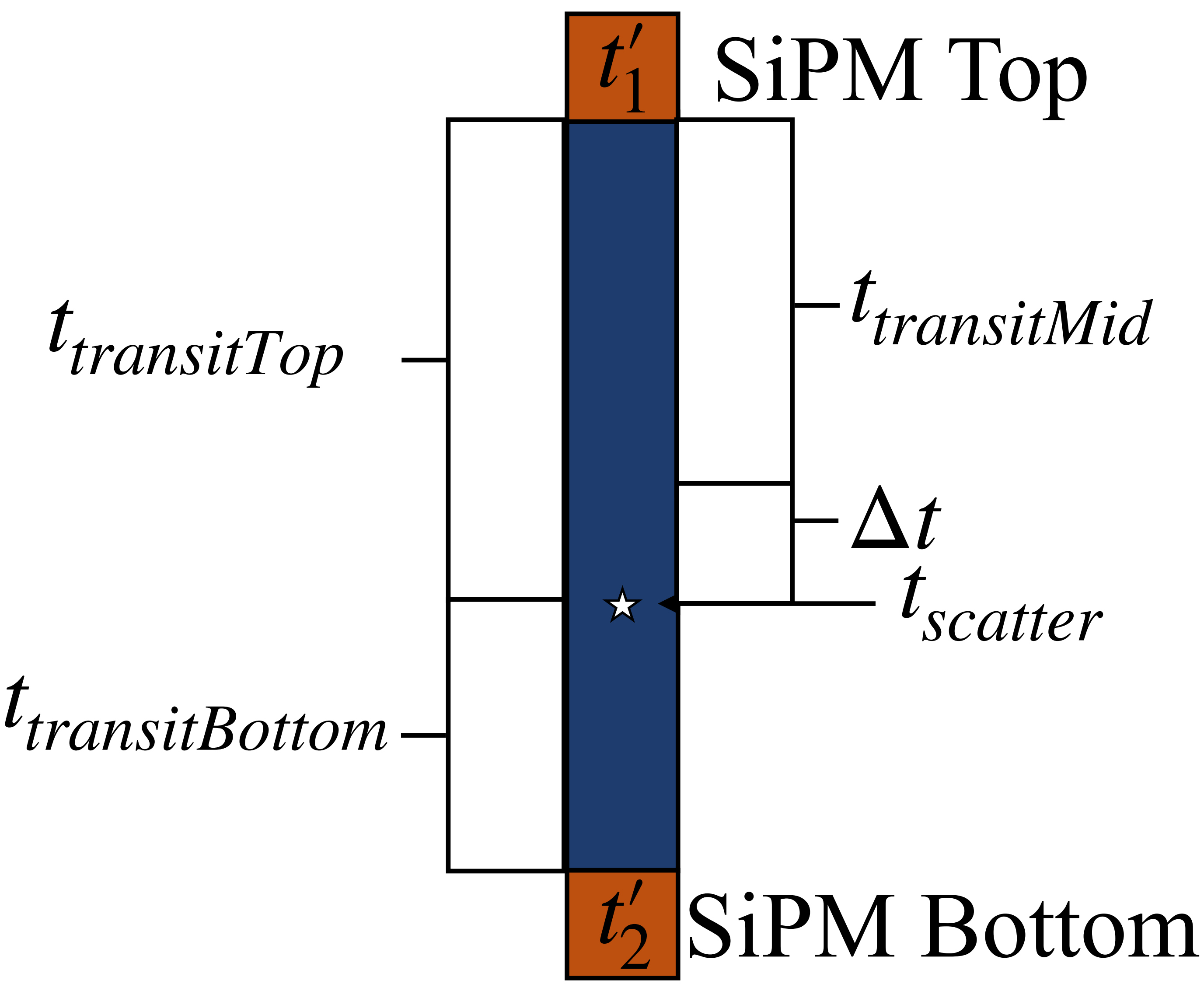
$$t_{avg} = t_{scatter} + t_{transitMid}$$

☆ Scatter Location at time $t_{scatter}$

OBTAIN SCATTER TIME

Want to extract $t_{scatter}$ from t_1' and t_2'

Assume Bottom SiPM fires before Top.
Assume scatter is closer to Bottom



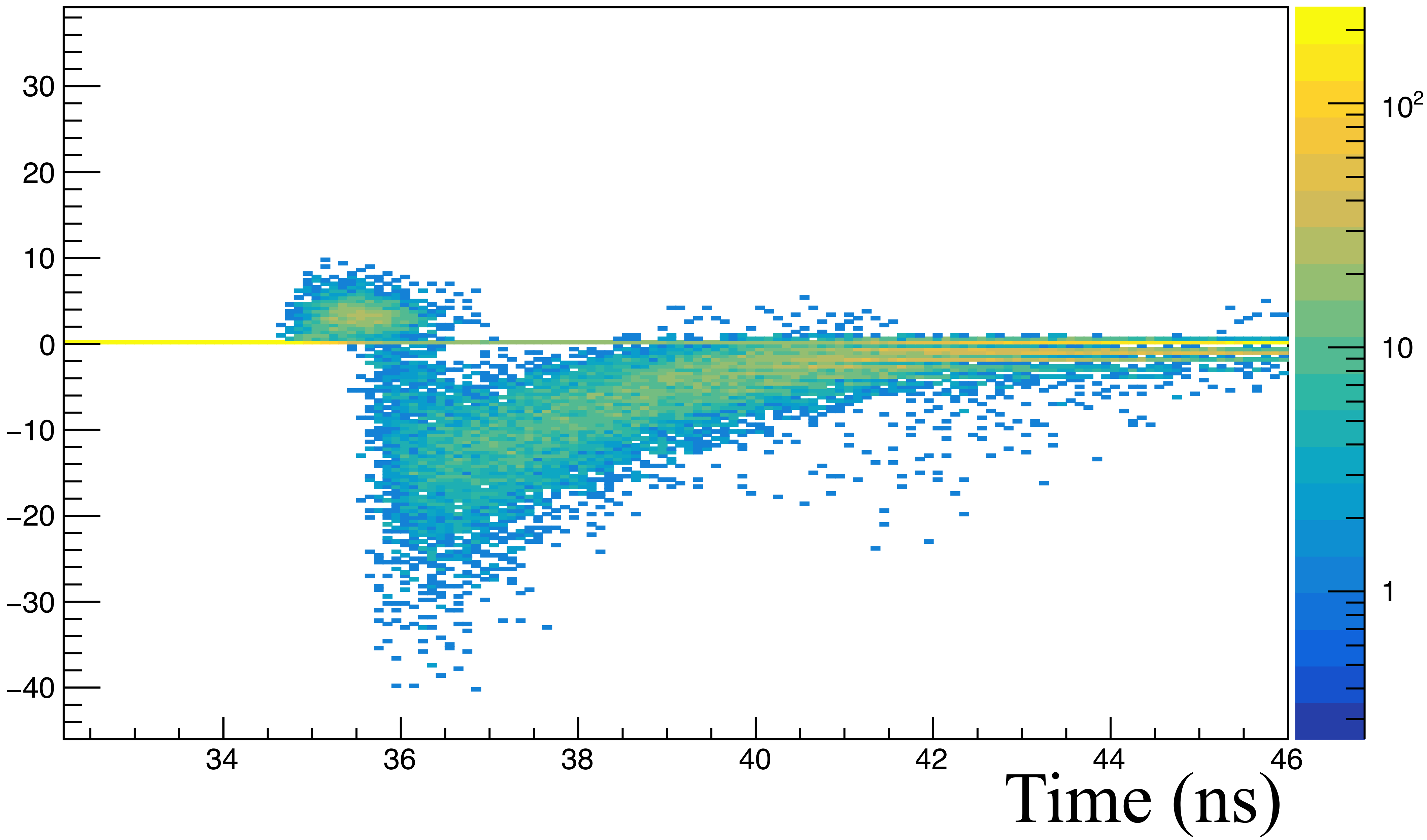
Define $$t_{avg} = \frac{t_1' + t_2'}{2}$$

$$t_{avg} = t_{scatter} + t_{transitMid}$$

Need the effective speed of light in the plastic

$$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$$

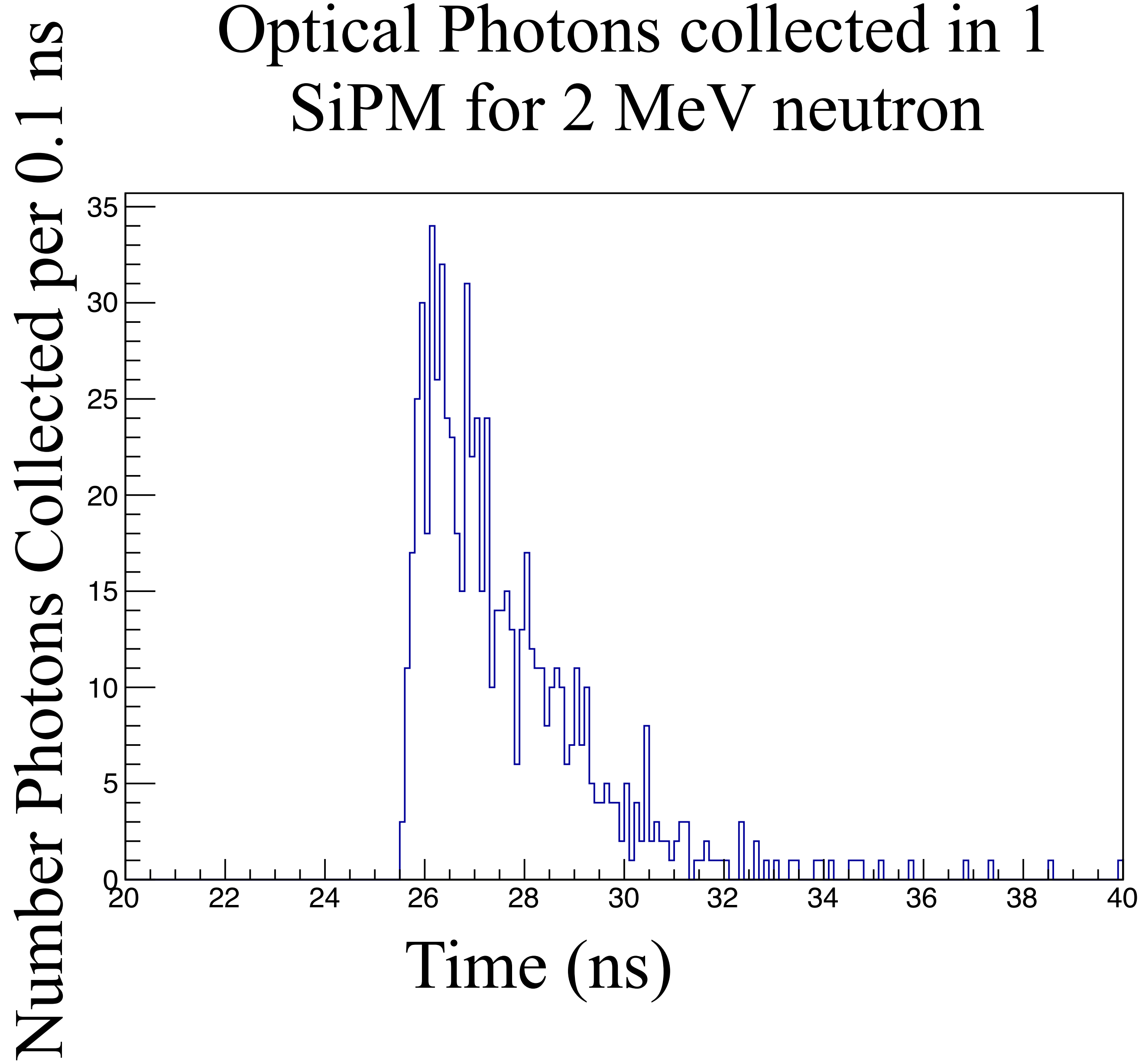
DETERMINING SIPM COLLECTION TIME



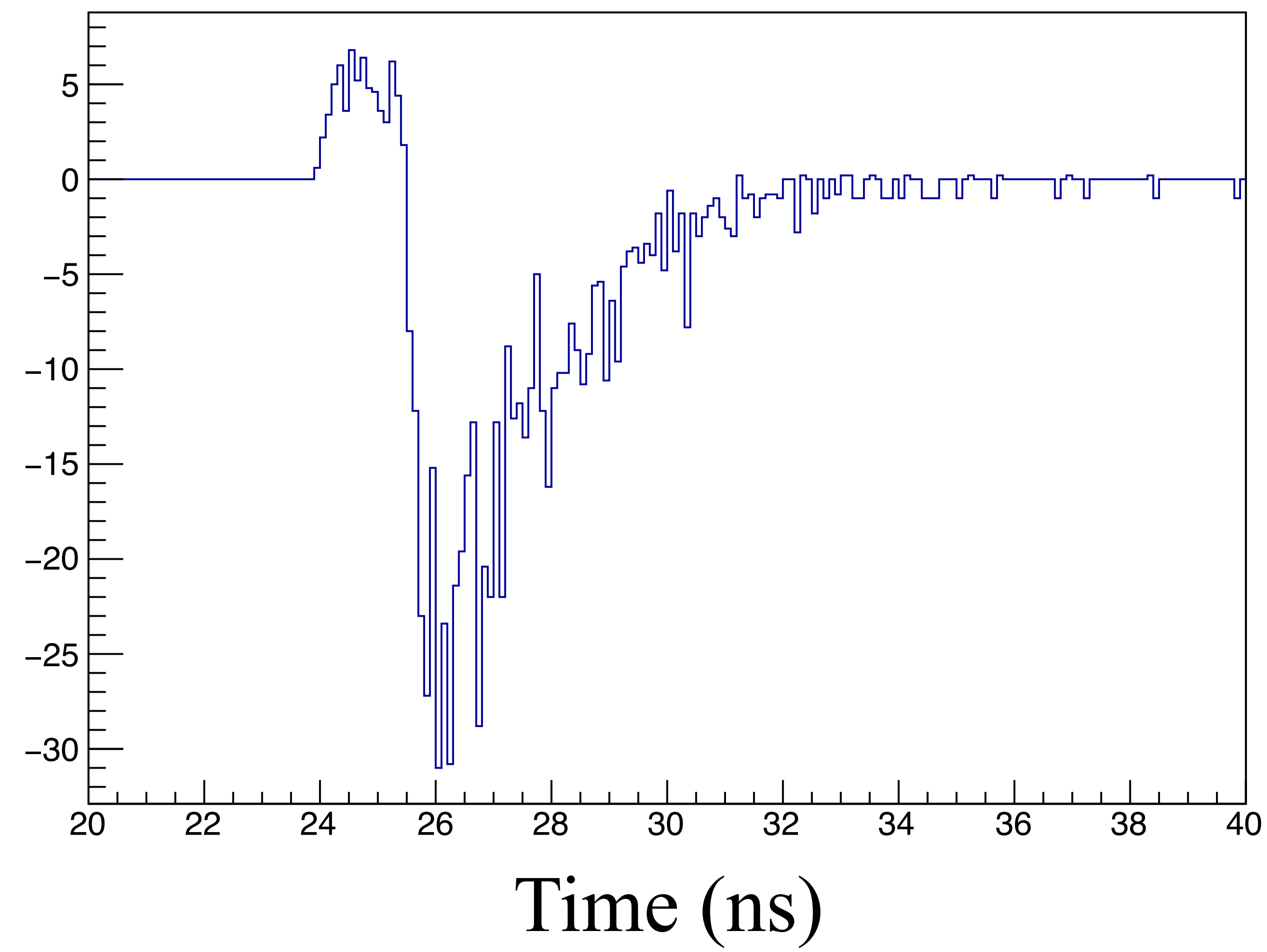
CFD Monitor output. Cross over is the point at which time is taken at signal time

TOF DETERMINATION

Optical Photons collected in 1 SiPM for 2 MeV neutron



CFD algorithm Monitor Output

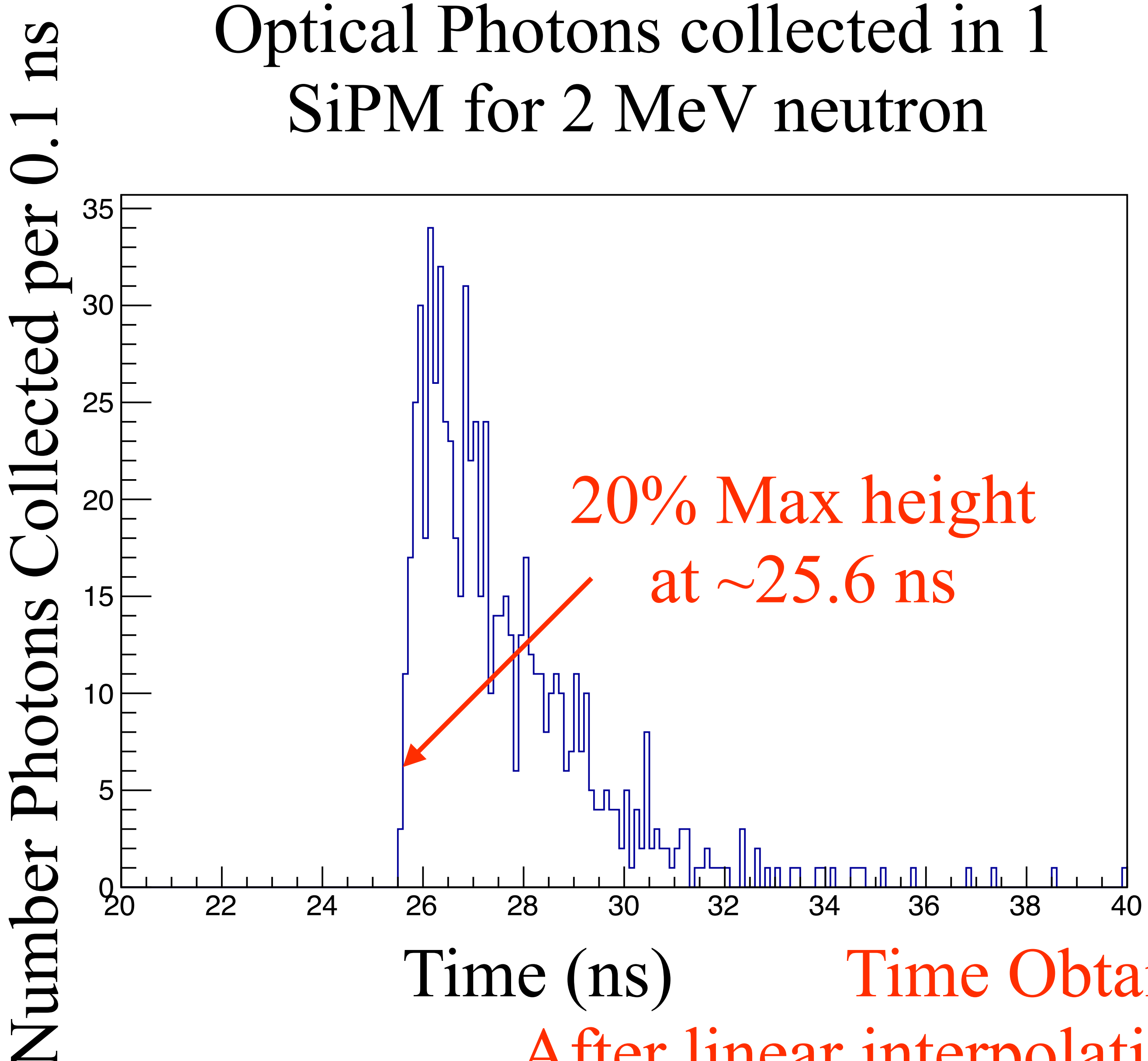


Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

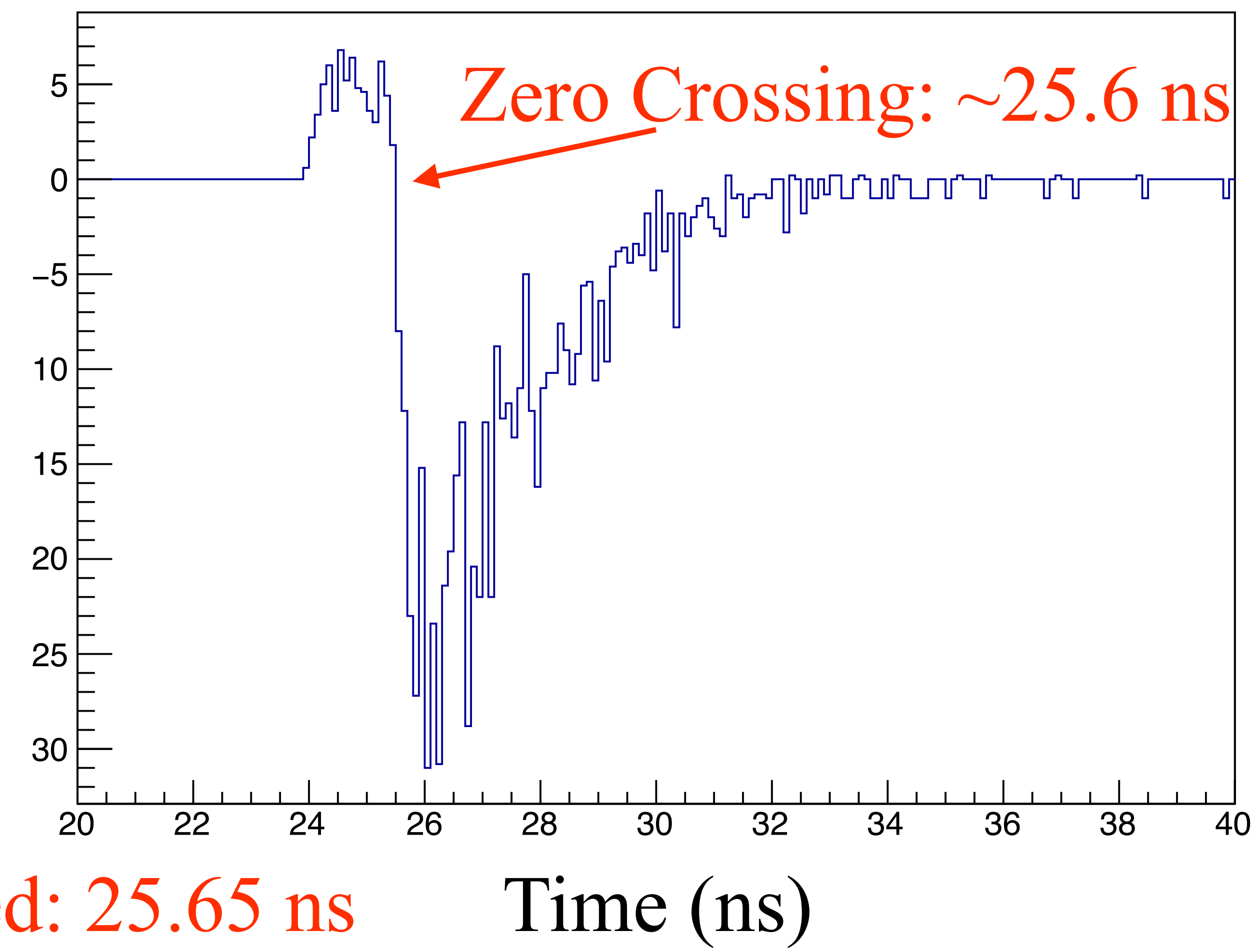
$$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$$

TOF DETERMINATION

Optical Photons collected in 1 SiPM for 2 MeV neutron



CFD algorithm Monitor Output

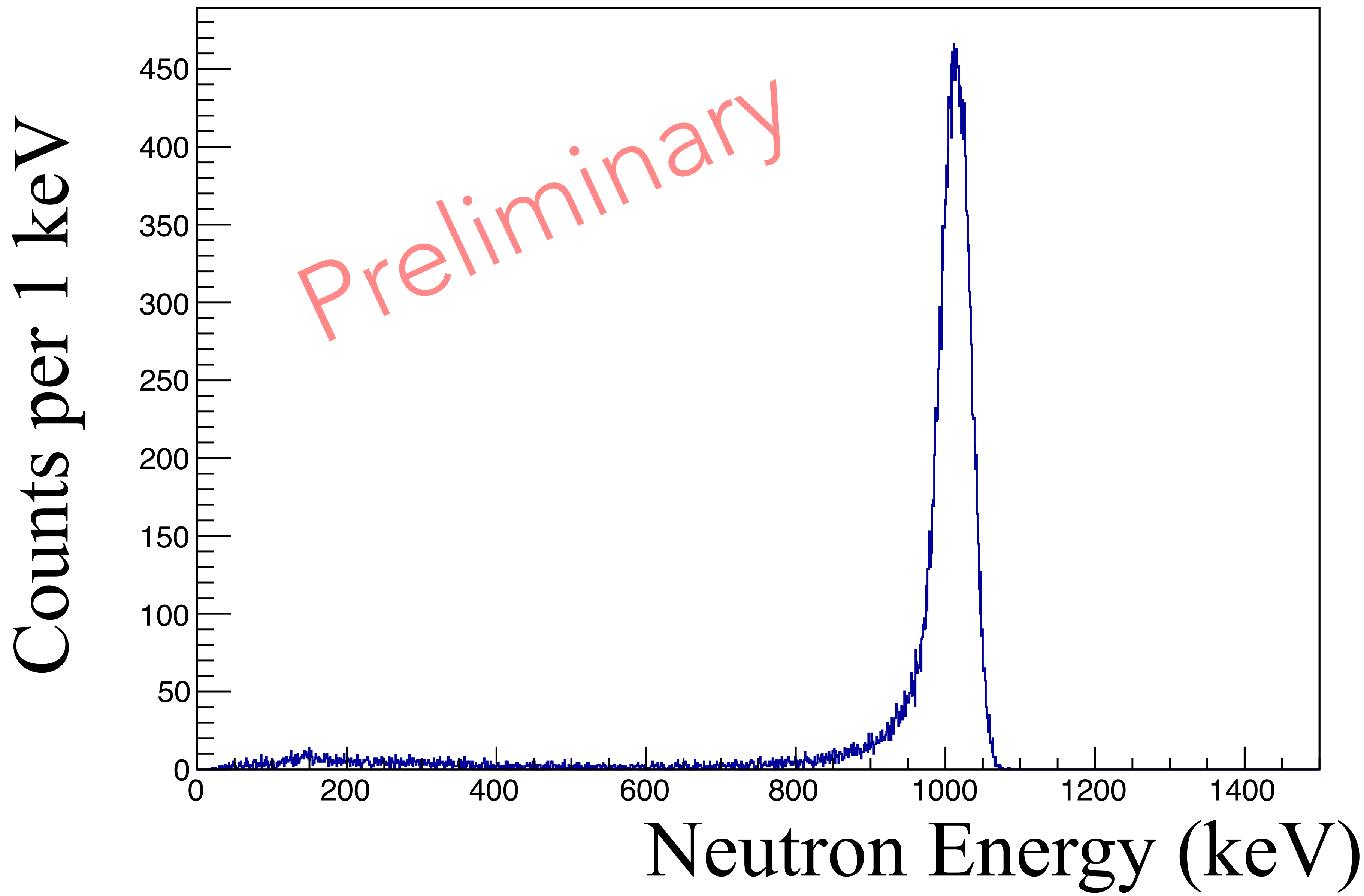


Time Obtained: 25.65 ns
After linear interpolation and bin randomization

Time determined to be 35.3 ns in this case. This is done for both SiPM arrays

$$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$$

ENERGY SPECTRA



Scintillator in vacuum, neutrons shot at a 1cm thick, 8 cm wide detector, using a threshold of 1 optical photons detected in each SiPM

COINCIDENCE TIMING UNCERTAINTY

To make our extracted times from the CFD algorithms and the ZDS more realistic, he timing coincidence uncertainties are approximated to 600 ps fwhm. Applying a 200 ps fwhm for the ZDS we can work out the uncertainties in the CFD algorithms, depending if 1 or 2 SiPMs are involved. Then the times obtained are convoluted with a gaussian with the corresponding FWHM.

$$\delta t^2 = \delta t_{ZDS}^2 + \delta_{DAEMON}^2$$

$$600^2 = 200^2 + \delta_{DAEMON}^2$$

$$\delta_{DAEMON} = 565ps$$

$$\delta_{DAEMON}^2 = \delta t_{CFD1}^2 + \delta t_{CFD2}^2$$

$$565^2 = (2\delta t_{CFD})^2 \qquad \delta t_{CFD} = 400ps$$

OBTAIN Y POSITION

Assume Top SiPM fires before Bottom.
Assume scatter is closer to Top

$$t_{avg} = \frac{t_1' + t_2'}{2}$$

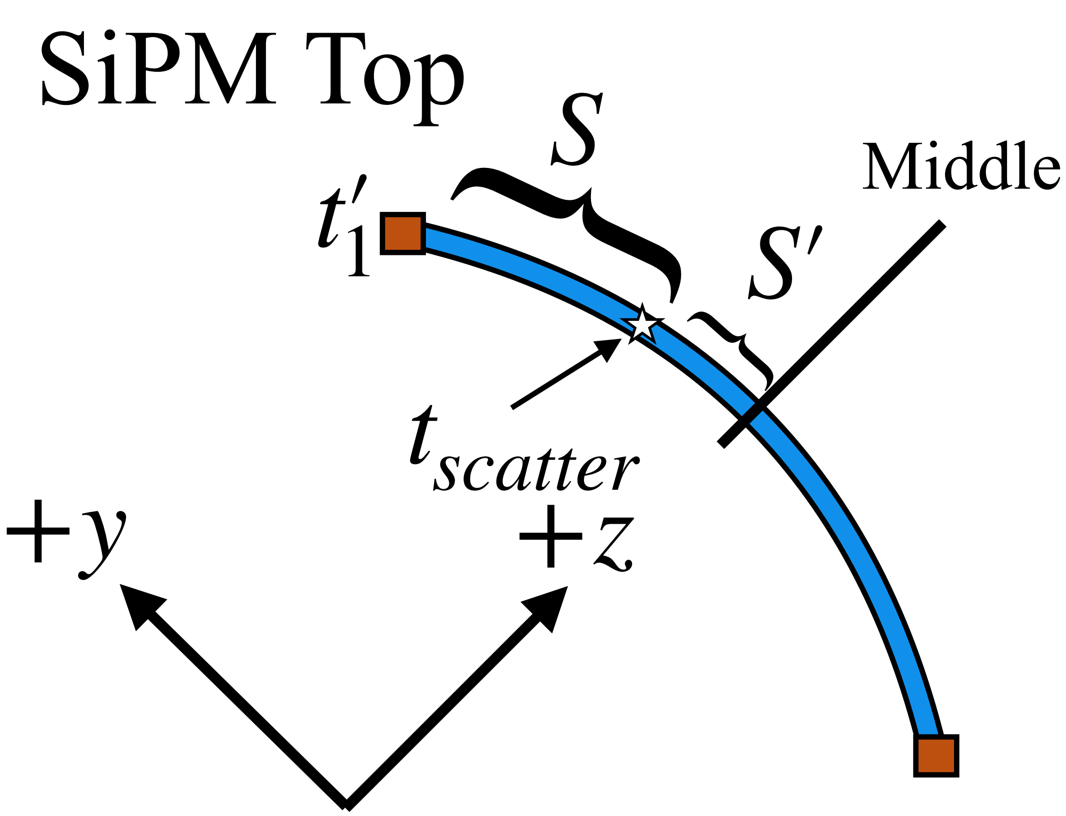
$$t_{avg} = t_{scatter} + t_{transitMid}$$

$$t_{scatter} = t_{avg} - \frac{t_{Max}}{2}$$

$$S = (t_1' - t_{scatter}) * c_{eff}$$

$$S = (t_1' - t_{avg} + \frac{t_{Max}}{2}) * c_{eff}$$

$$S = (\frac{t_1' - t_2'}{2} + \frac{t_{Max}}{2}) * c_{eff}$$



OBTAIN Y POSITION

Assume Top SiPM fires before Bottom.
Assume scatter is closer to Top

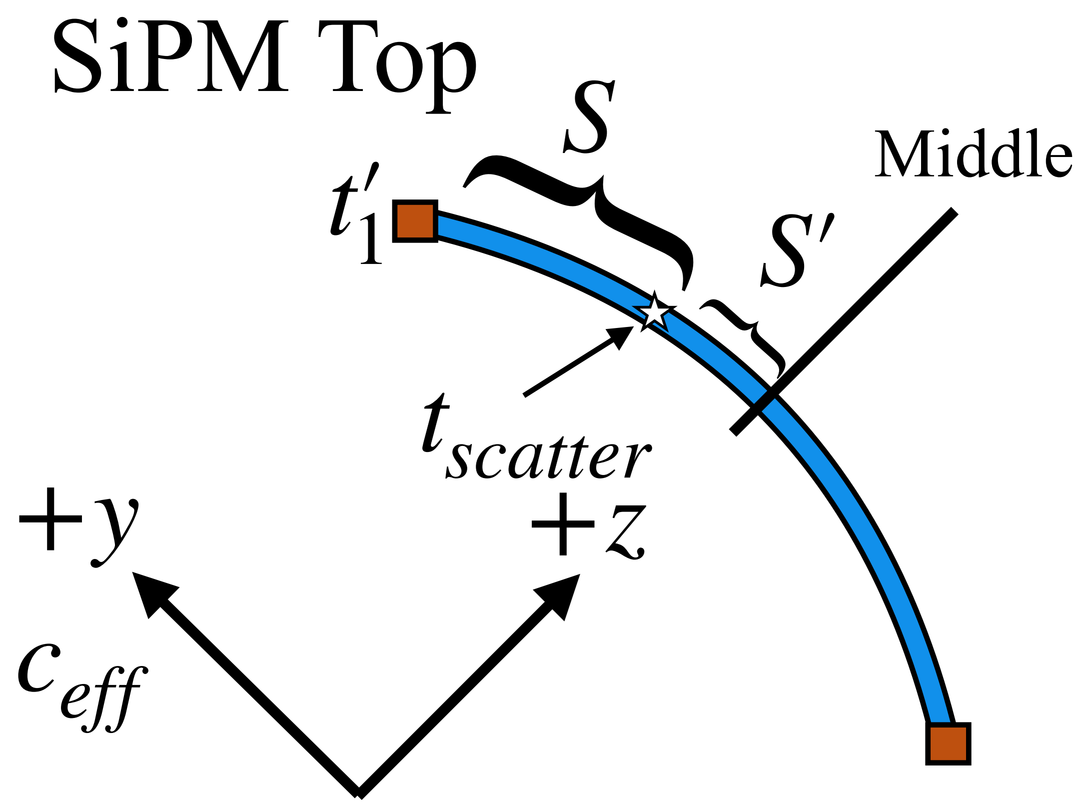
$$S = (\frac{t_1' - t_2'}{2} + \frac{t_{Max}}{2}) * c_{eff}$$

Want S'

$$\frac{Arclength}{2} = S + S'$$

$$S' = \frac{t_{Max}}{2} * c_{eff} - (\frac{t_1' - t_2'}{2} + \frac{t_{Max}}{2}) * c_{eff}$$

$$S' = (\frac{t_2' - t_1'}{2}) * c_{eff}$$



OBTAIN Y POSITION

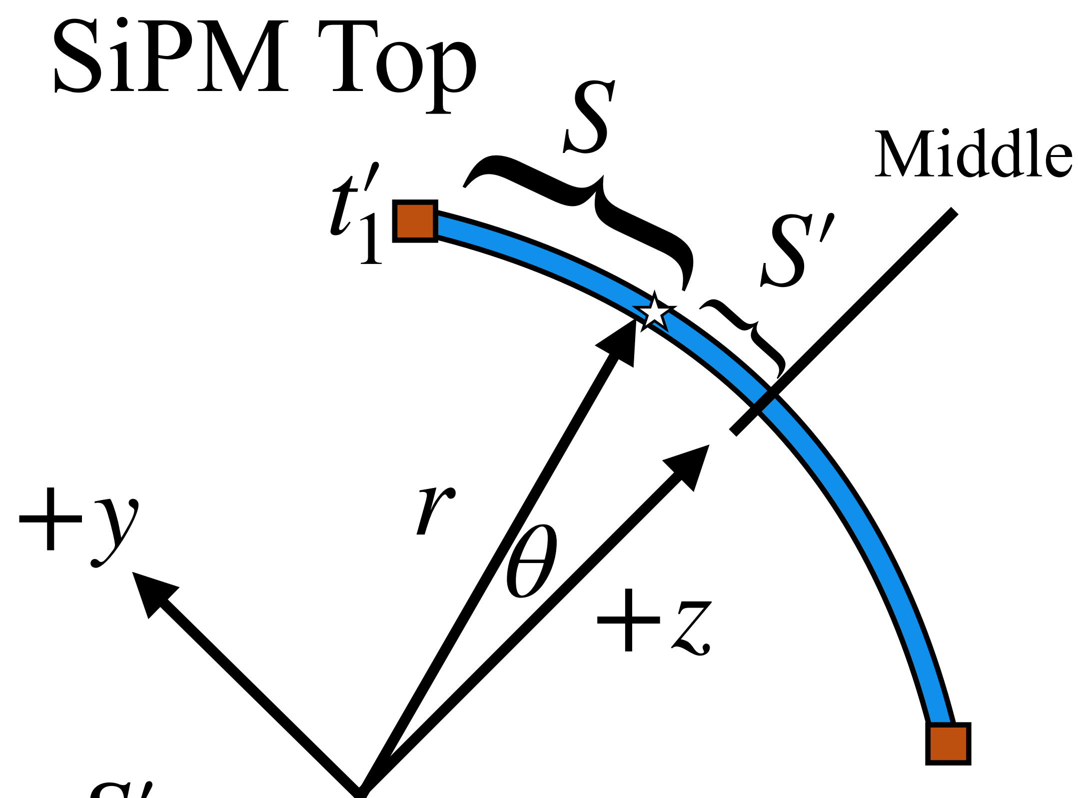
Assume Top SiPM fires before Bottom.
Assume scatter is closer to Top

$$S' = (\frac{t_2' - t_1'}{2}) * c_{eff} \quad \text{For} \quad t_1' < t_2'$$

If S' is negative, the t1' > t2'.
Therefore S' has a negative y component

Shift to Center of Detectors YZ Planes

$$r = \sqrt{(}R^2 - X_{MidDet}^2)$$

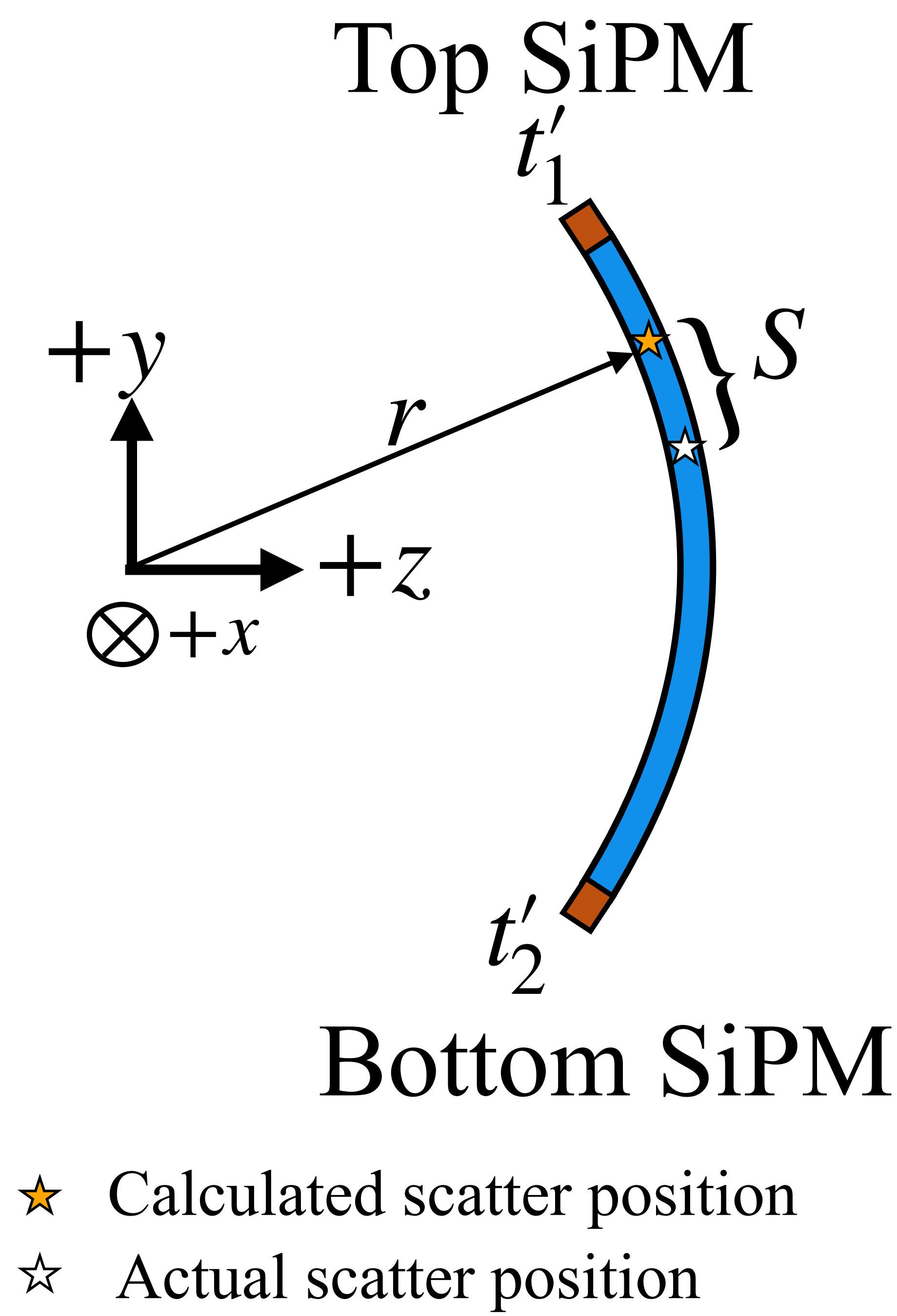


$$Y_{Scatter} = r sin(\frac{S'}{r})$$

POSITION RESOLUTION

Arc Length (S) Between Calculated and Actual Scatter Position Within Bars

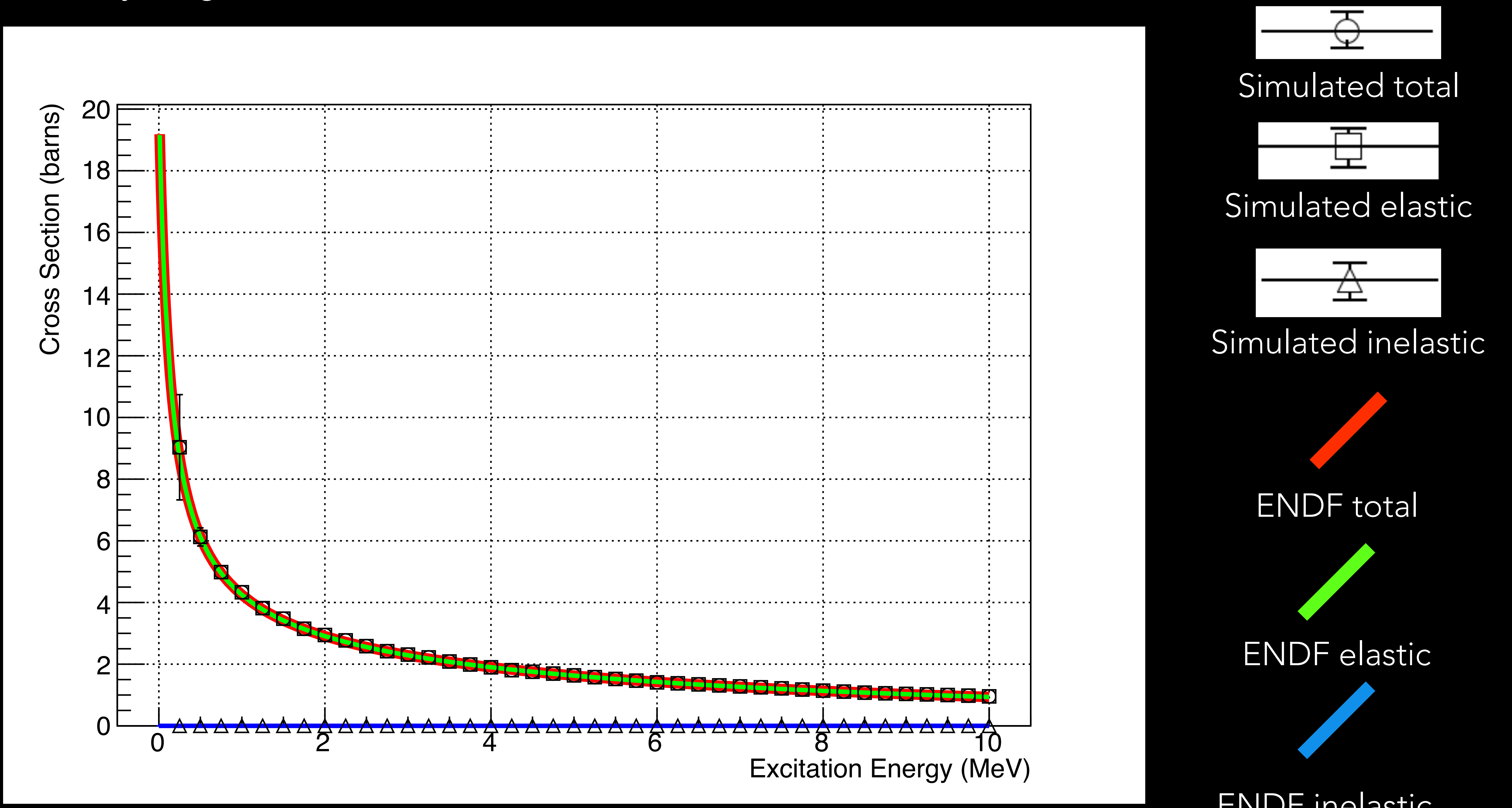
- X is assumed to be centre of detector.
- Y is calculated via SiPM time when both fire.
- Radial distance (r) is assumed to be middle of detector.
- Z is calculated using x, y, and r.



VALIDATING GEANT4 PHYSICS PACKAGES QGSP_BERT_HP

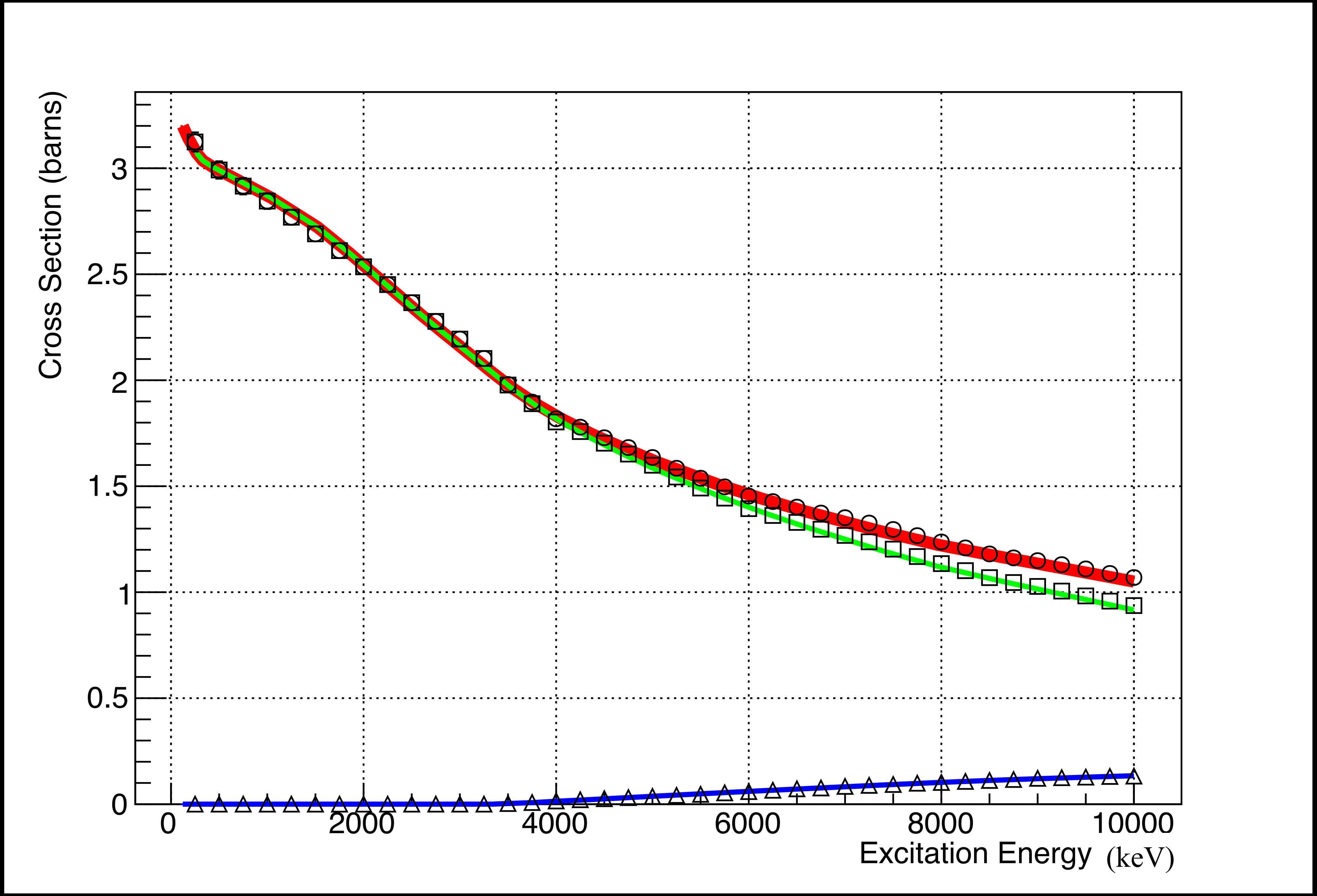
PHYSICS VALIDATION OF GEANT4

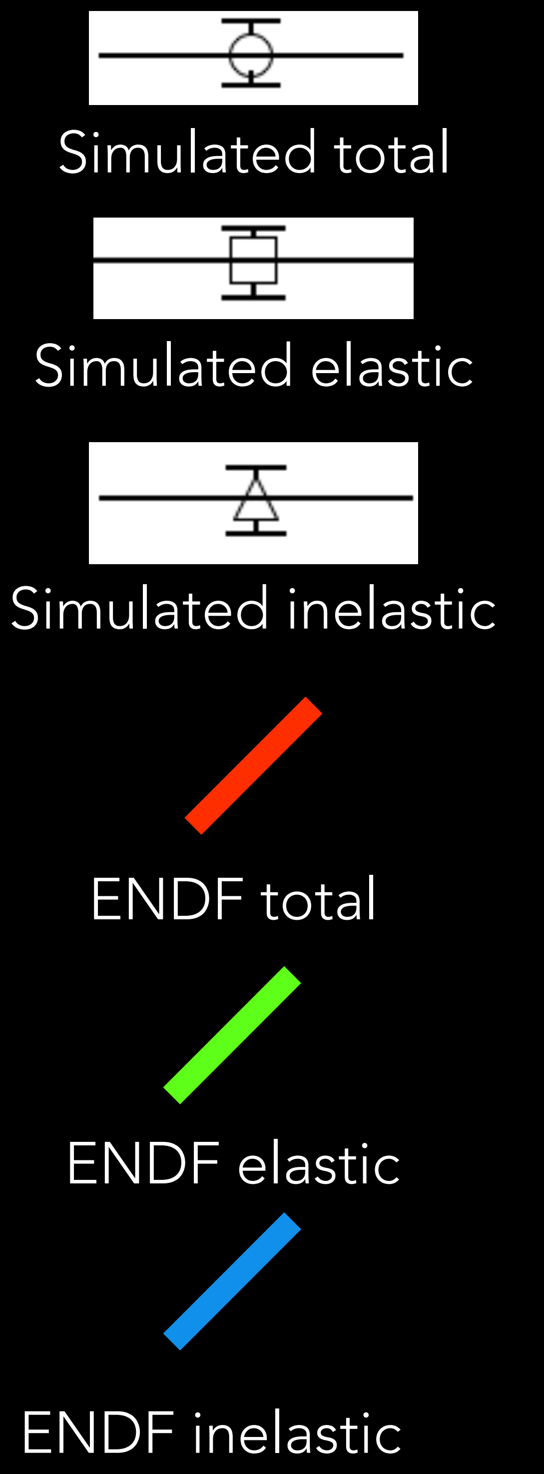
- Hydrogen



PHYSICS VALIDATION

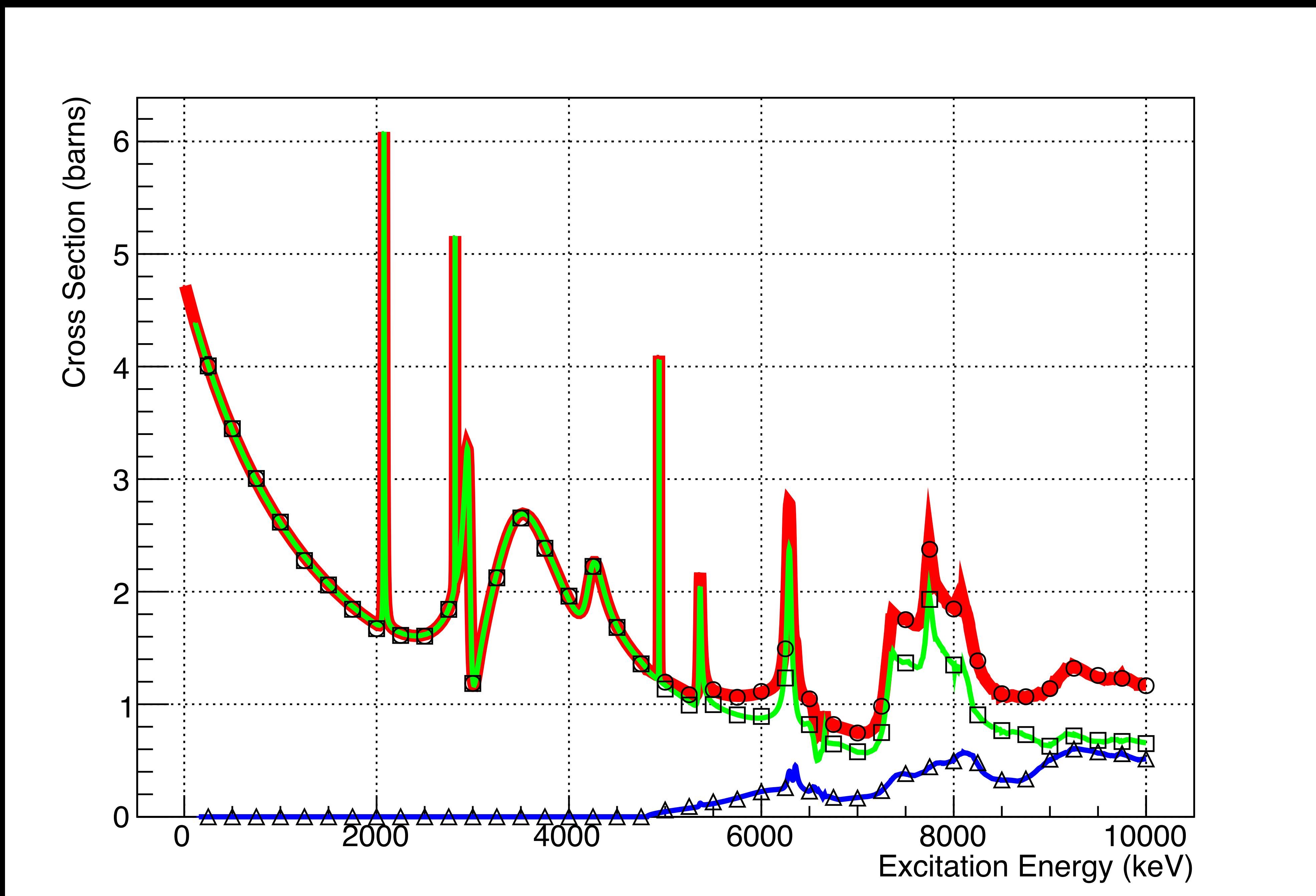
- Deuterium

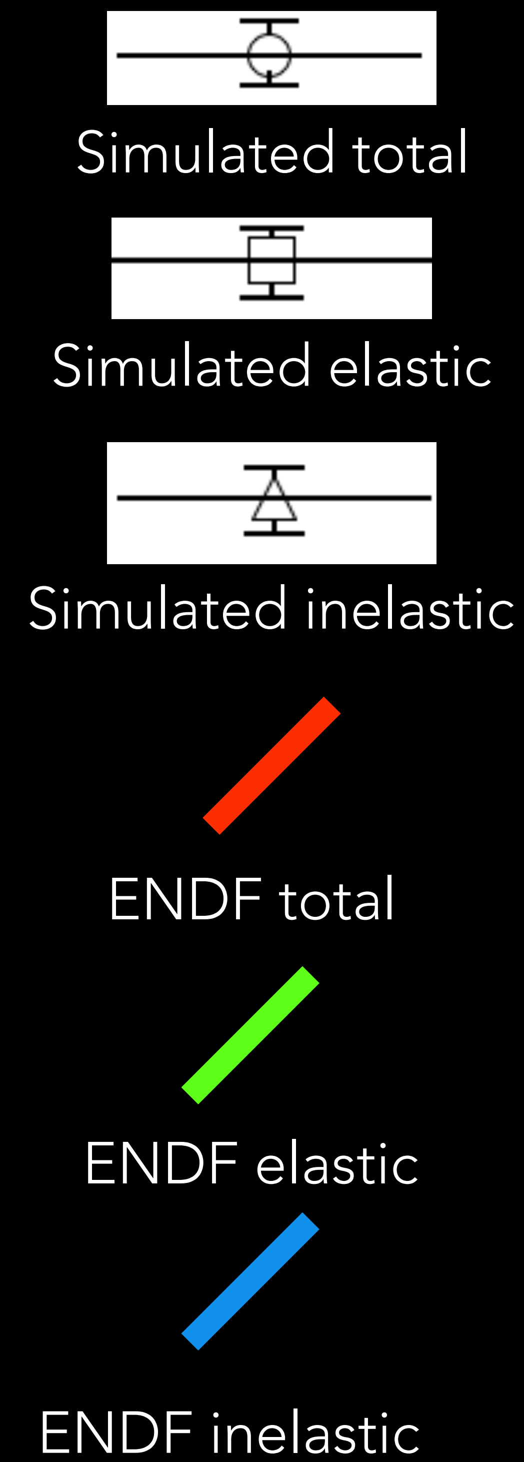




PHYSICS VALIDATION

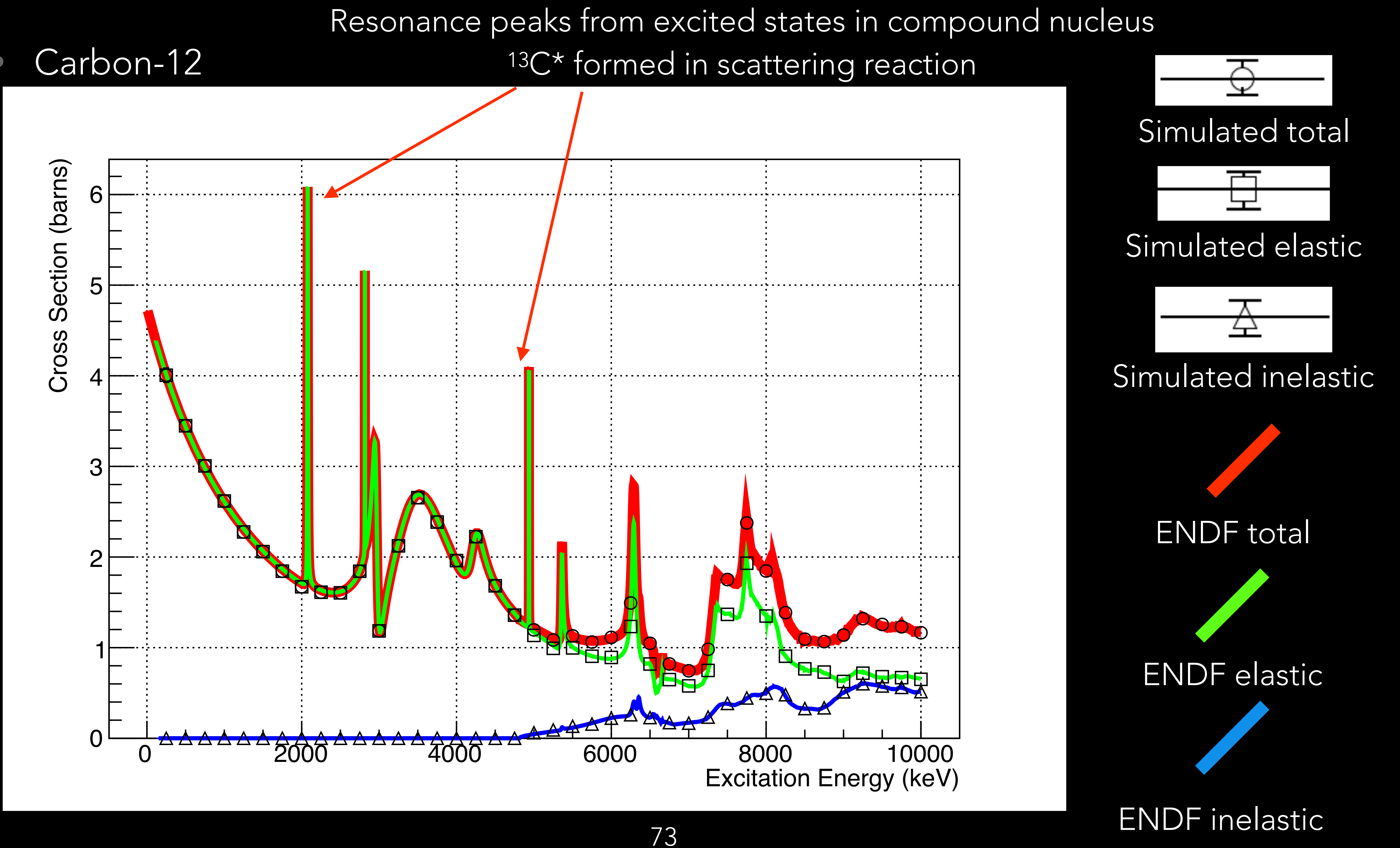
- Carbon-12





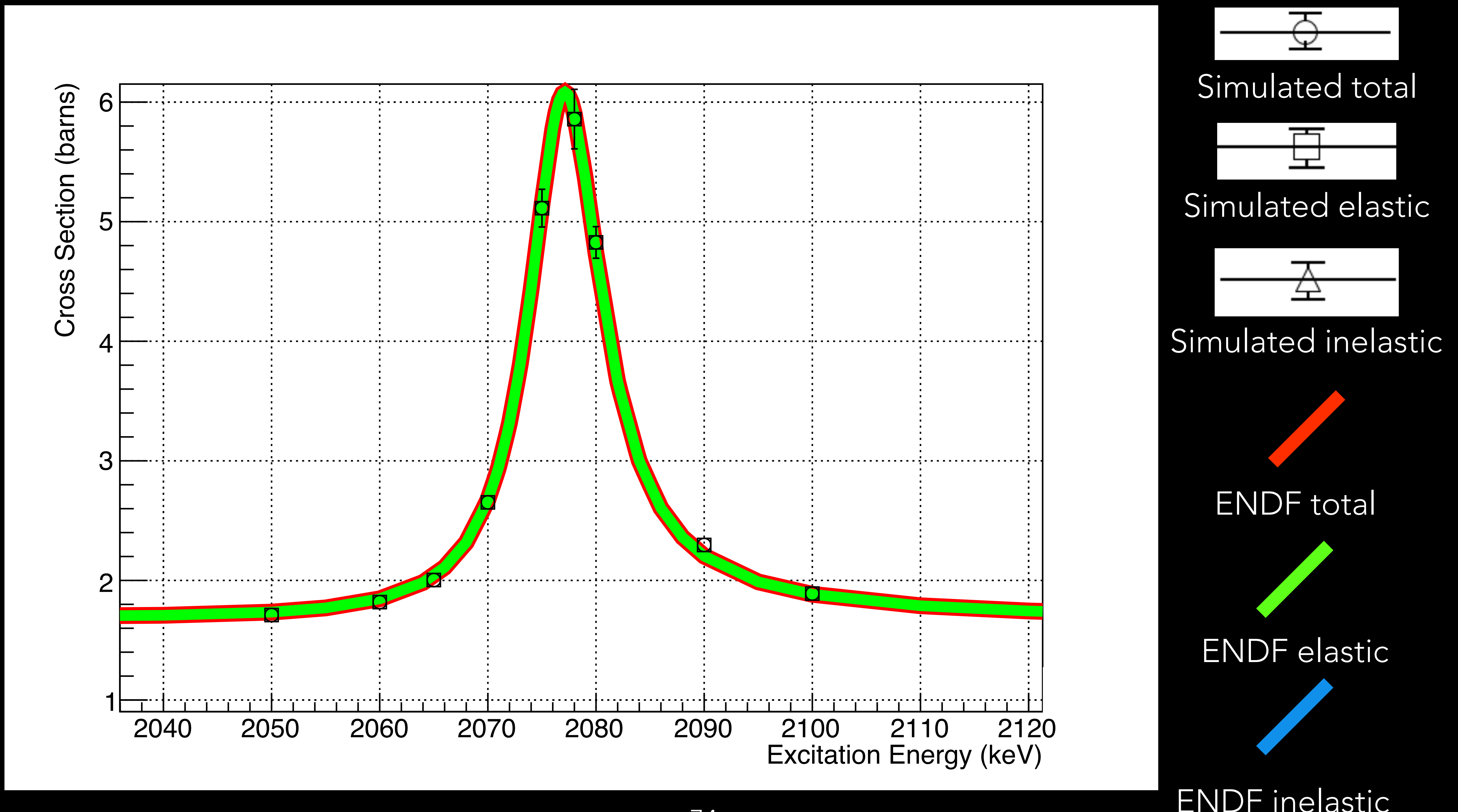
PHYSICS VALIDATION

- Carbon-12



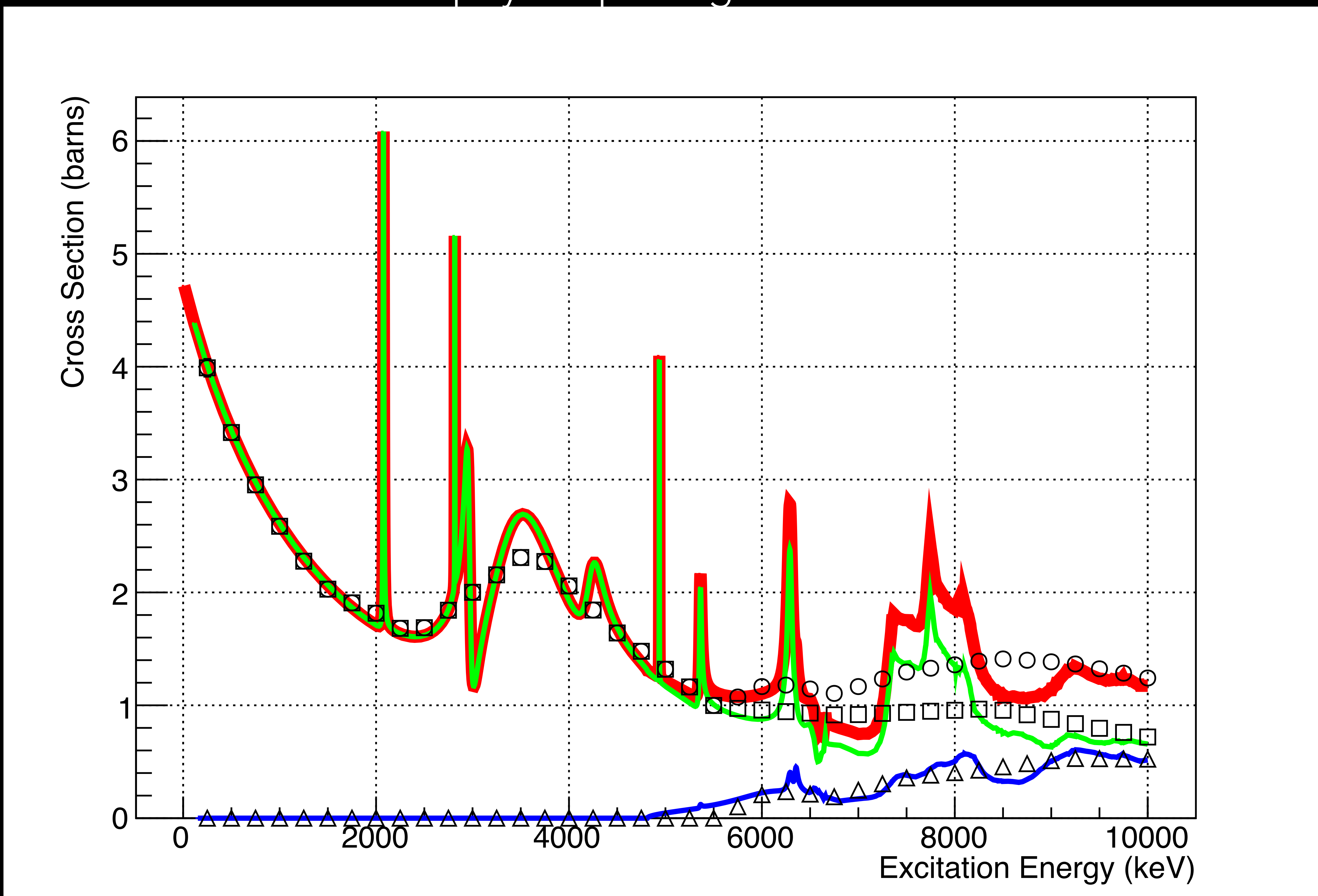
PHYSICS VALIDATION

- Carbon-12



PHYSICS VALIDATION

- Carbon-12: Not HP physics package



Simulated total

Simulated elastic

Simulated inelastic

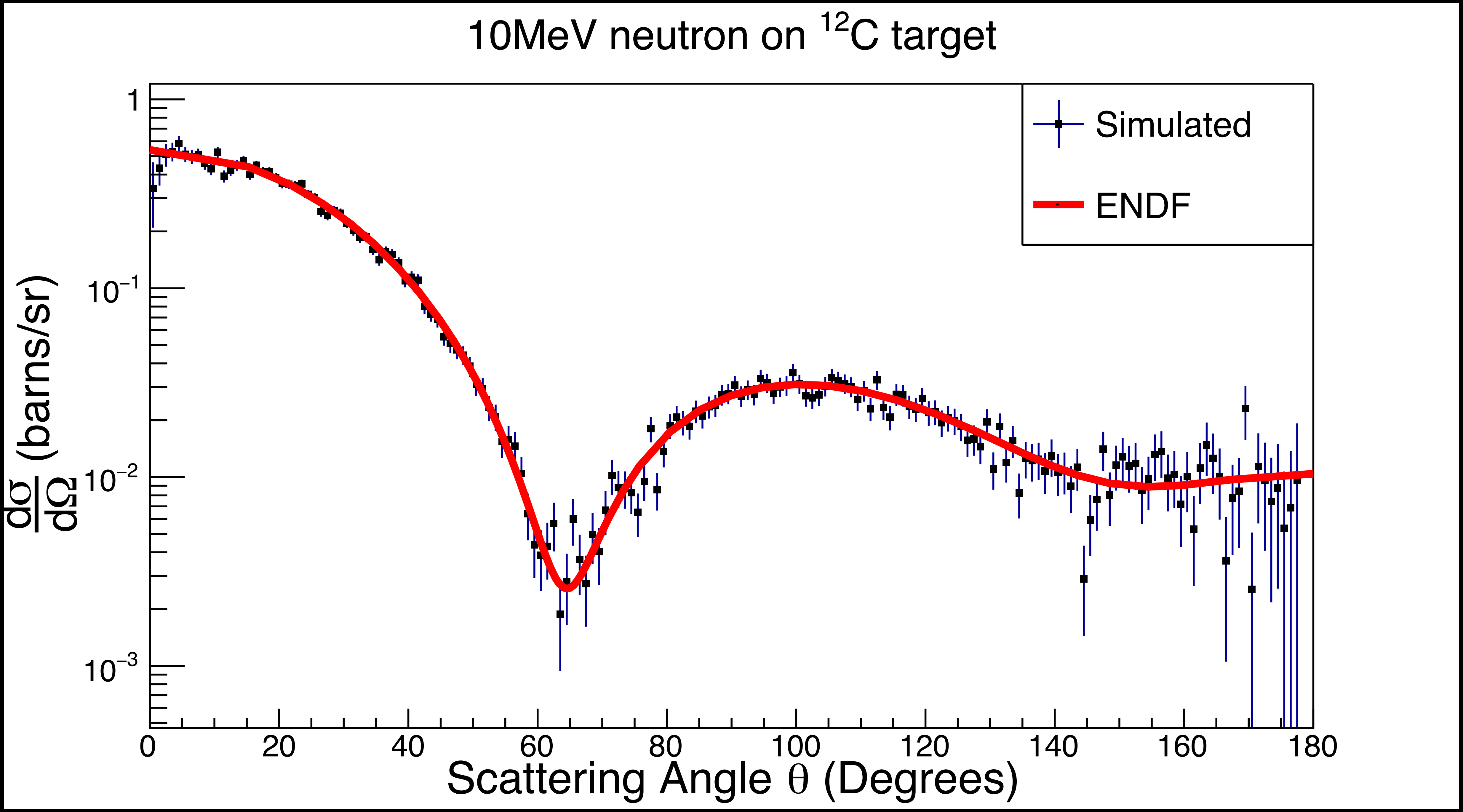
ENDF total

ENDF elastic

ENDF inelastic

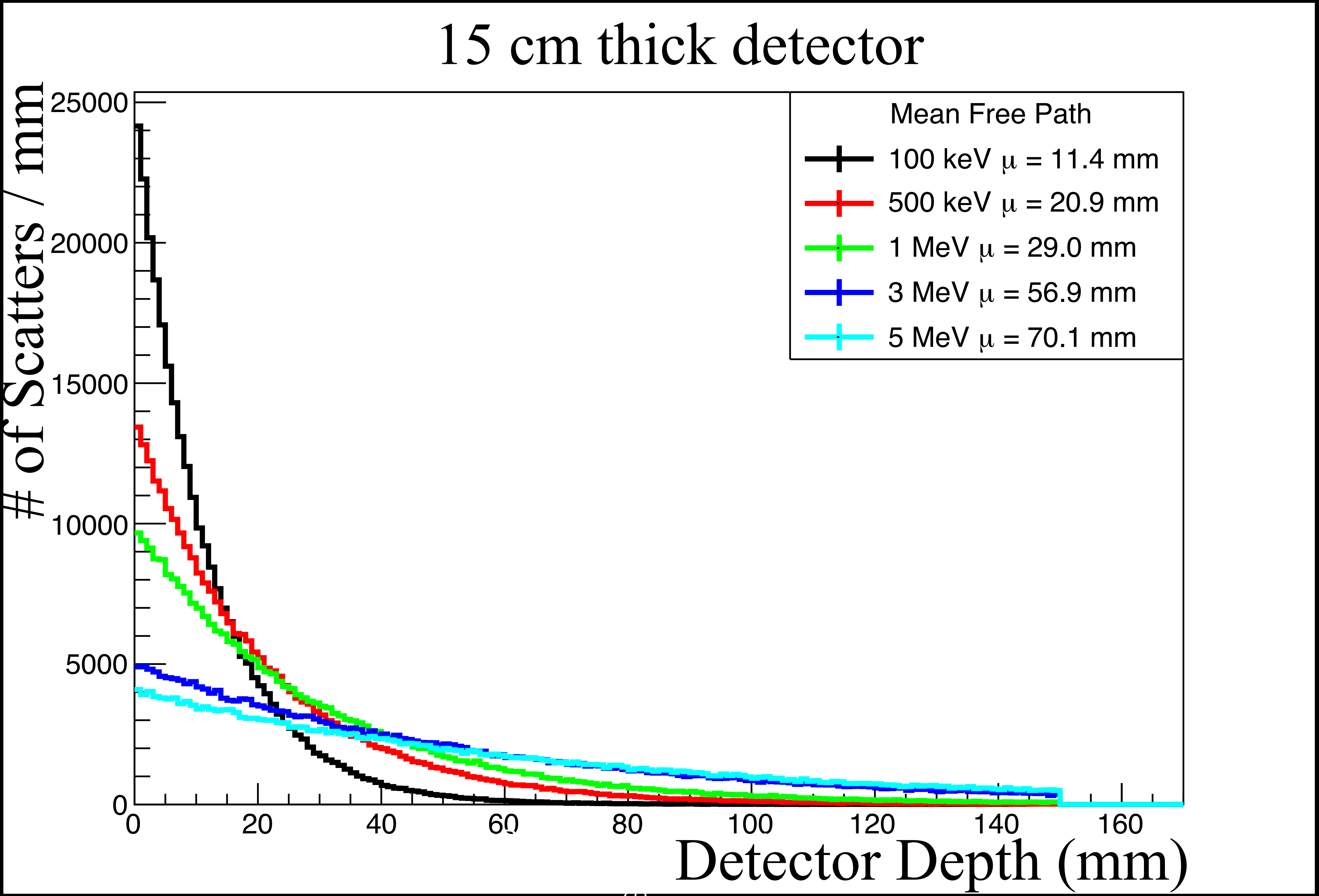
GEANT4 SIMULATIONS PHYSICS VALIDATION

- Carbon-12: HP physics package



MEAN FREE PATH

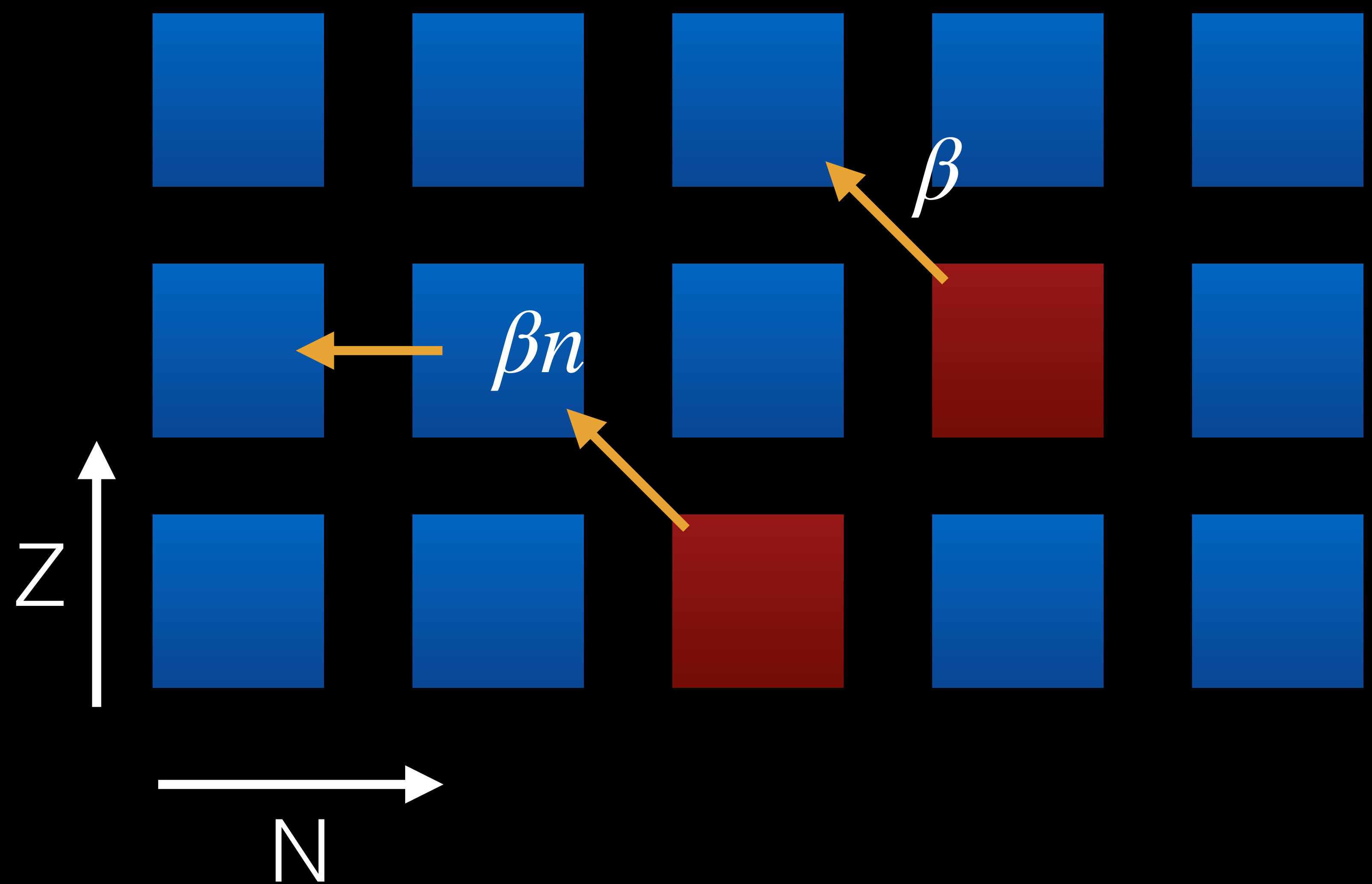
GEANT4 SIMULATIONS
MEAN FREE PATH OF NEUTRONS IN BC408



BACKGROUND

BACKGROUND

- Many of the nuclei found in the astrophysical rapid neutron capture process are beta delayed neutron emitters



BACKGROUND

Start with energy conservation

$$m_{Emitter}c^2 + E_{Emitter} = m_{Daughter}c^2 + E_{Daughter} + m_n c^2 + T_n + T_R$$

Use

$$S_n = m_{Daughter}c^2 + m_n c^2 - m_{Emitter}c^2$$

To get:

$$E_{Emitter} = E_{Daughter} + T_n + T_R + S_n$$

BACKGROUND

- Beta delayed neutron spectroscopy
    - If the following values are measured precisely, information on excited states can be extracted, which has nuclear structure implications.

$$E_{Emitter} = E_{Daughter} + T_n + T_R + S_n$$

$E_{Emitter}$: (Excited) State of Emitter

$E_{Daughter}$: (Excited) State of Daughter

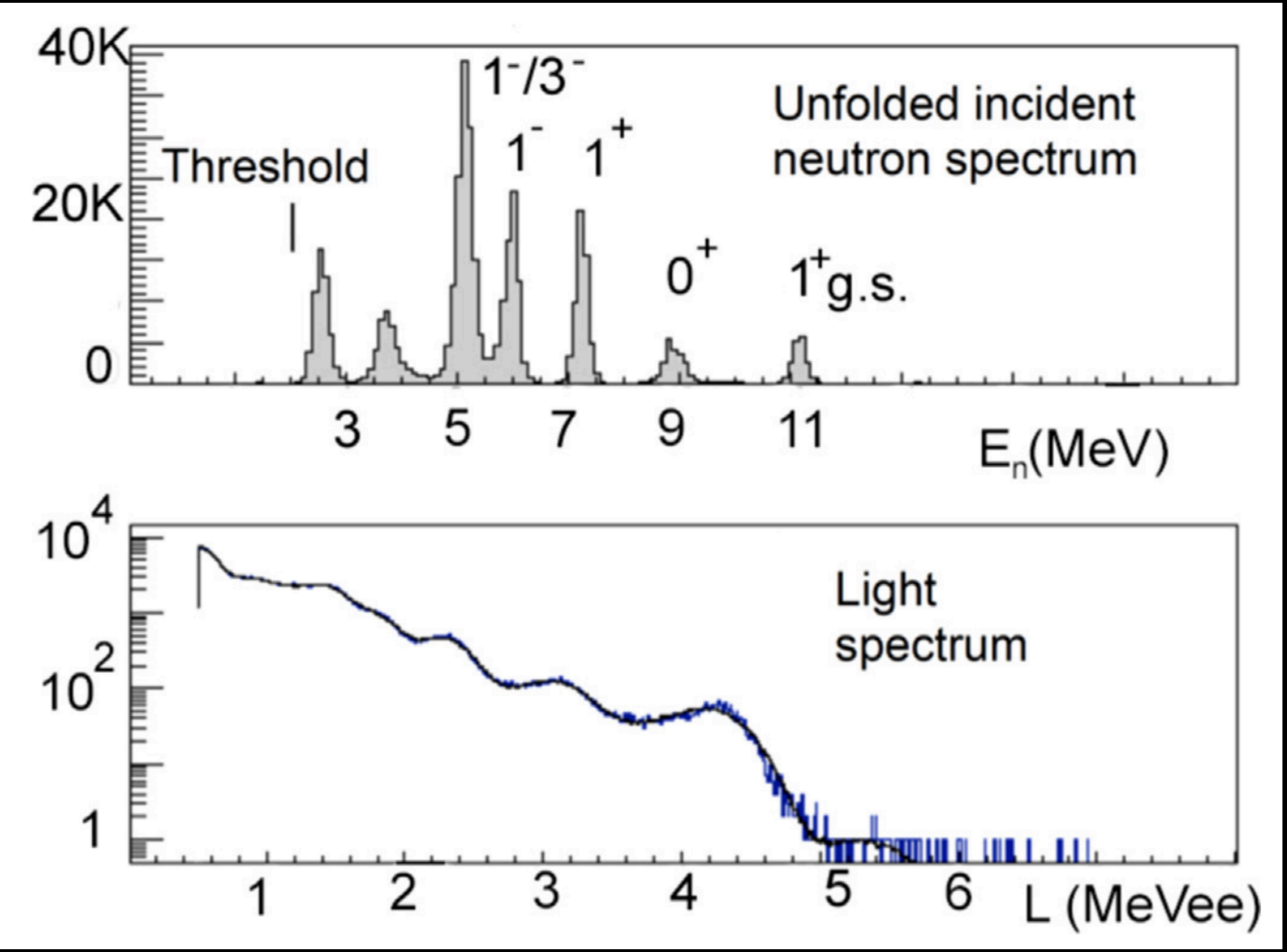
T_n: Kinetic Energy Neutron

T_R: Nucleus Recoil Energy

S_n: Neutron Separation Energy

- Our goal is to measure neutron energy with good resolution!

DEUTERATED SCINTILLATORS



$^{13}CH_2$ Target

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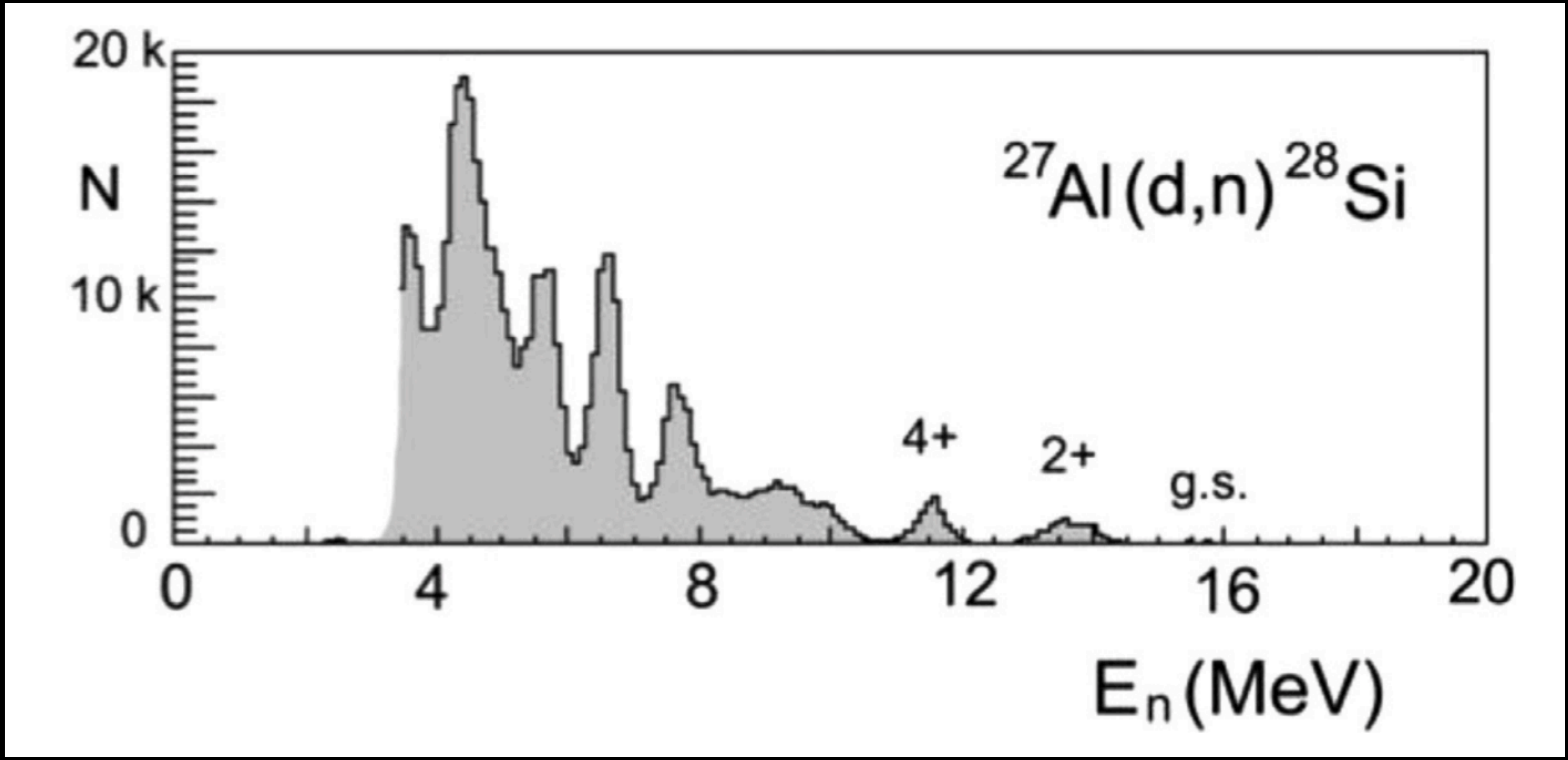
DEUTERATED SCINTILLATORS



Ideal for lighter nuclei close to closed shells with low level density

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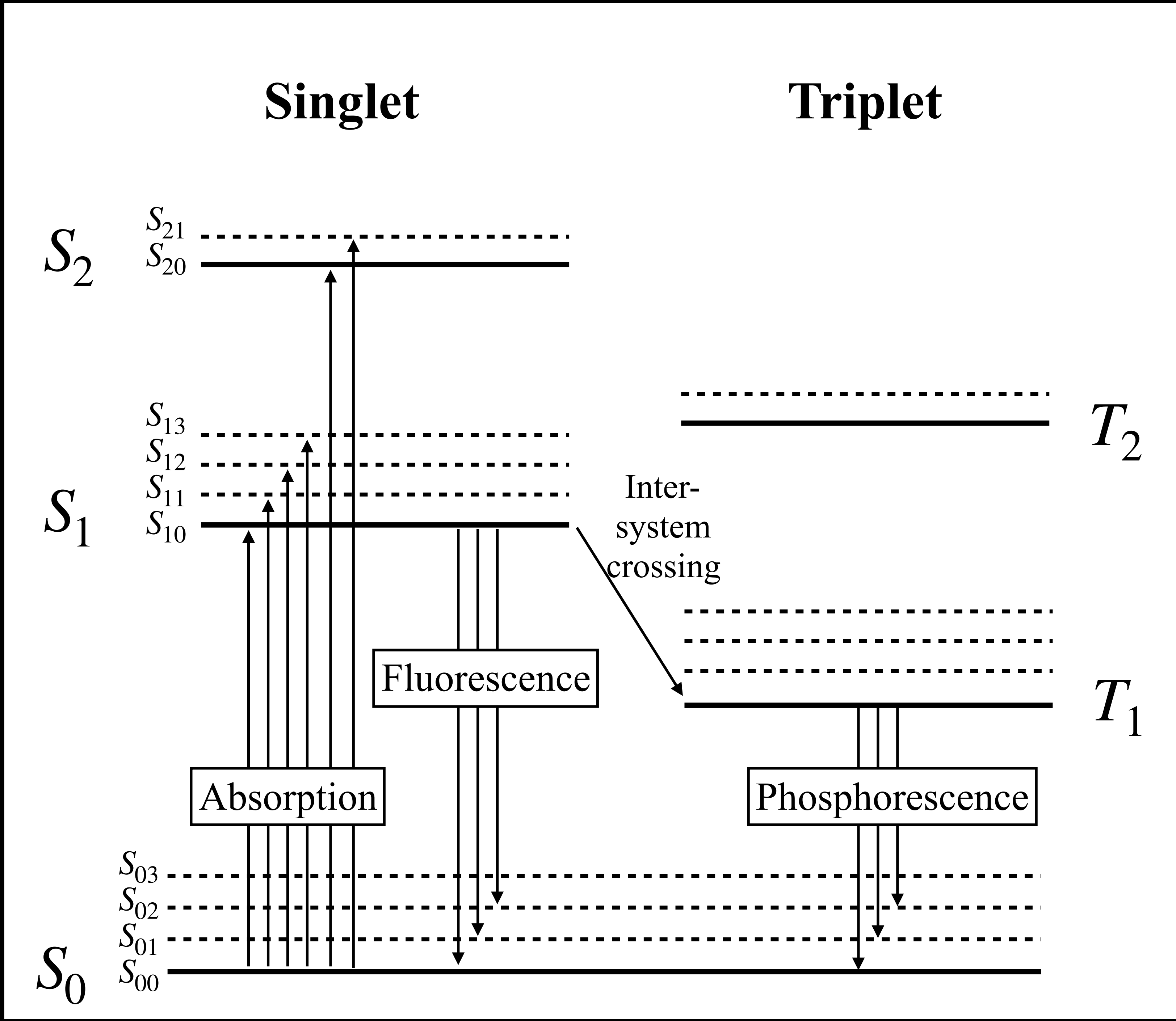
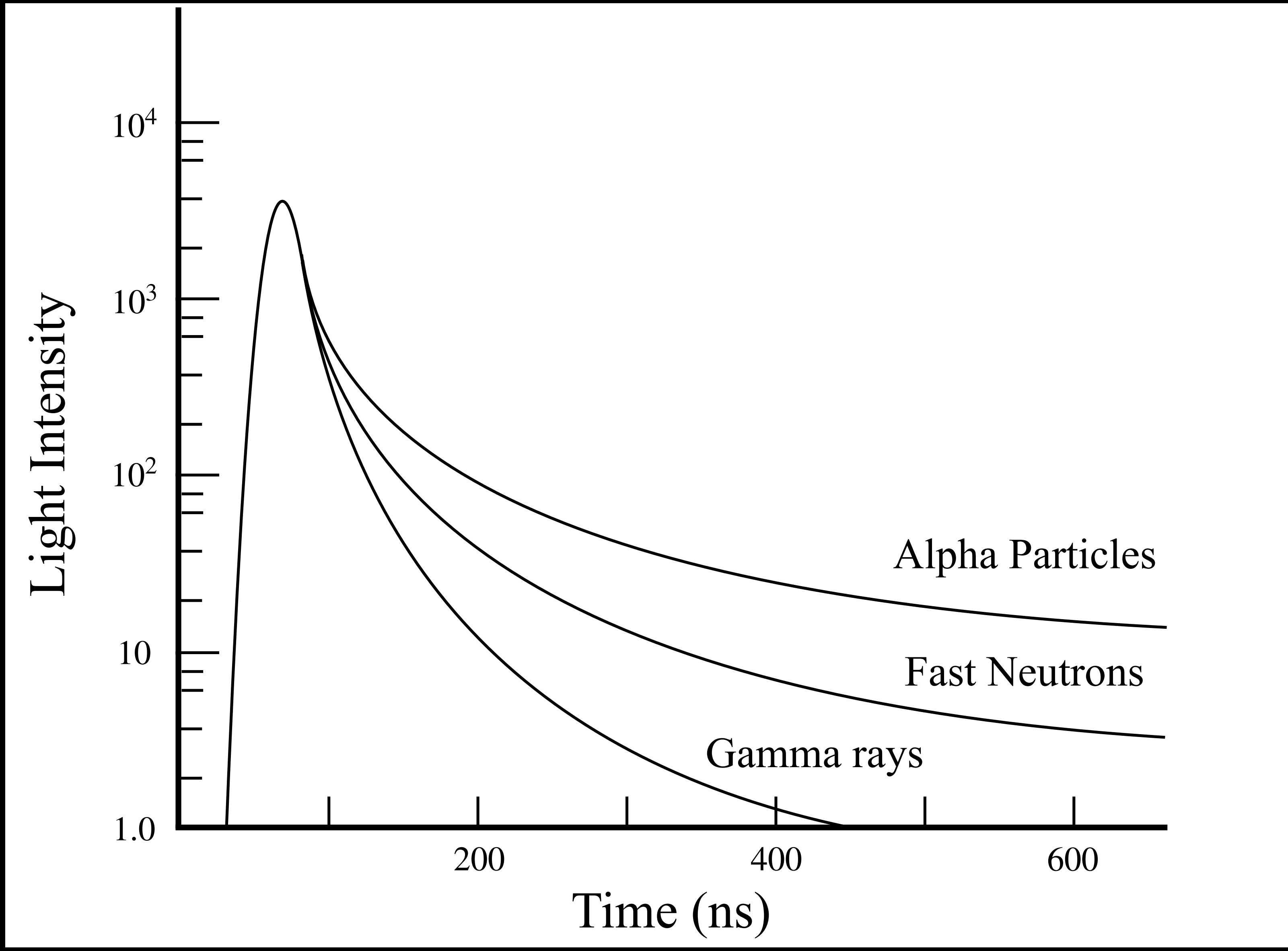
NEUTRON DETECTION SCINTILLATORS

- Extracting neutron energies is slightly more complicated than other radiation due to their lack of charge
- Need special detectors - like scintillators - which can convert kinetic energy of particles into photons for particle detection



NEUTRON DETECTION SCINTILLATORS

- It is possible to determine the type of radiation incident on a scintillator
  - This can be based on the timing profile of the scintillation light emission



Knoll, G. Radiation and Detection Measurement.