CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

INSTITUT DE FÍSICA CORPUSCULAR

EXCELENCIA SEVERO OCHOA

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Proton Range Verification Using a Multidetector Setup: Preliminary Results from the PRIDE Project

Cyclotron Centre Bronowice

CCB

IEM

Carolina Fonseca-Vargas, Enrique Nacher, José A. Briz.

Instituto de Física Corpuscular – CSIC, Valencia (Spain)
Instituto de Estructura de la Materia - CSIC, Madrid (Spain)

Motivation

- Proton Therapy has emerged as a promising technique for cancer treatment.
- There is uncertainty in the proton Range.
- To avoid this, proton treatment plans are designed with safety margins that don’t allow the maximum potential of the technique.

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PRIDE project (Proton Range and Imaging Device)

Solution approaches:

1. Take images with protons: Direct RSP map.
2. Verify the proton range online: Detection of scattered particles (normally gammas) **[1] [2]**

[1] K.S. Ytre-Hauge, et al., Sci Rep 9, 2011 (2019)
[2] F. Hueso-Gonzalez and T. Bortfeld, IEEE Trans Radiat Plasma Med. Sci. 4, p. 170 (2020)

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Nácher, E.; Briz, J. A.; Nerio, A. N.; Perea, A.; Távora, V. G.; Tengblad, O.; Borge, M. J. G. **Characterization of a Novel Proton-CT Scanner Based on Silicon and $LaBr_3$(Ce) Detectors.** *Eur. Phys. J. Plus* **2024**, *139* (5), 404.

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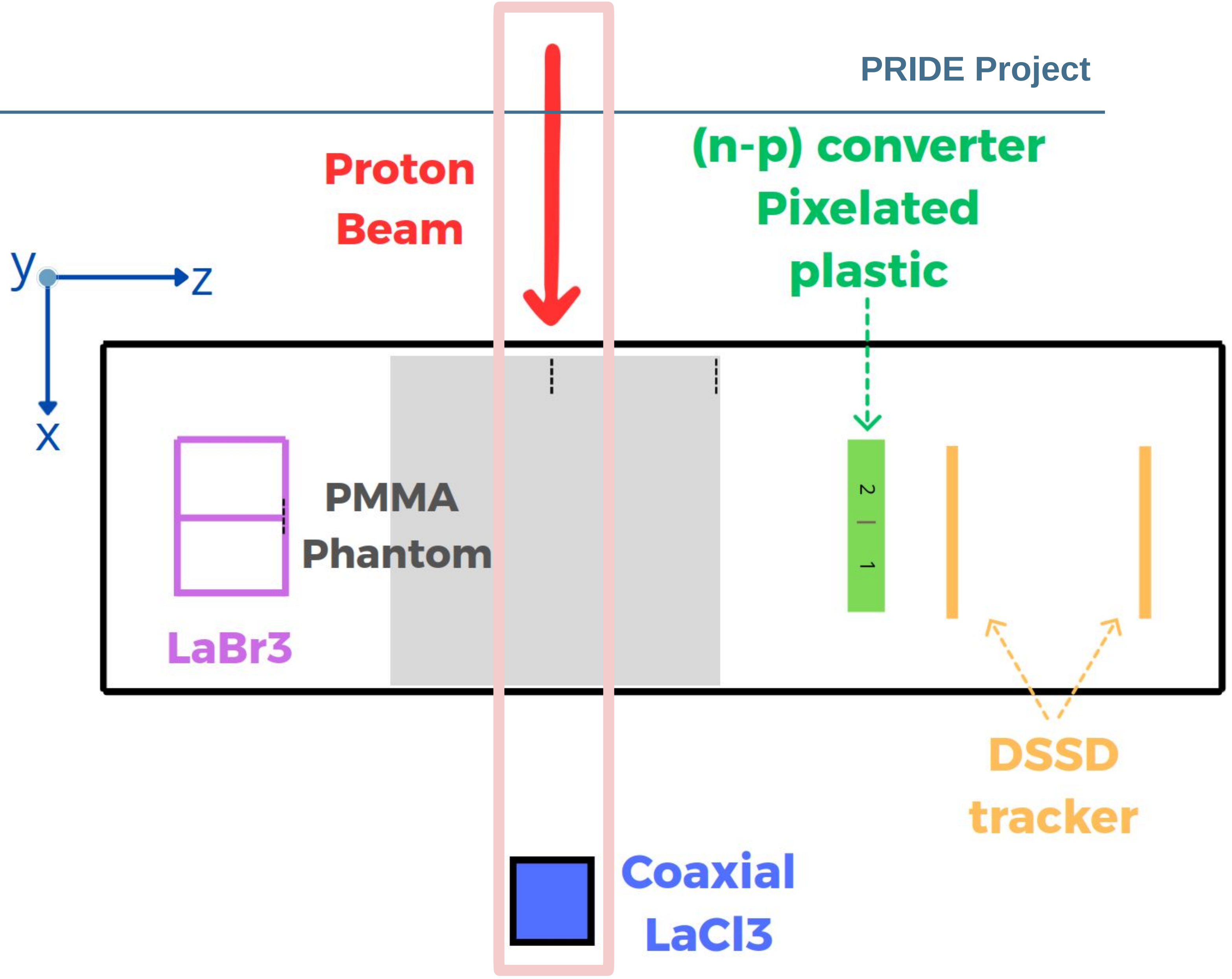
2. Range Verification

What do we want to measure?

Coaxial configuration
Scintillator crystal, with excellent neutron-gamma discrimination.



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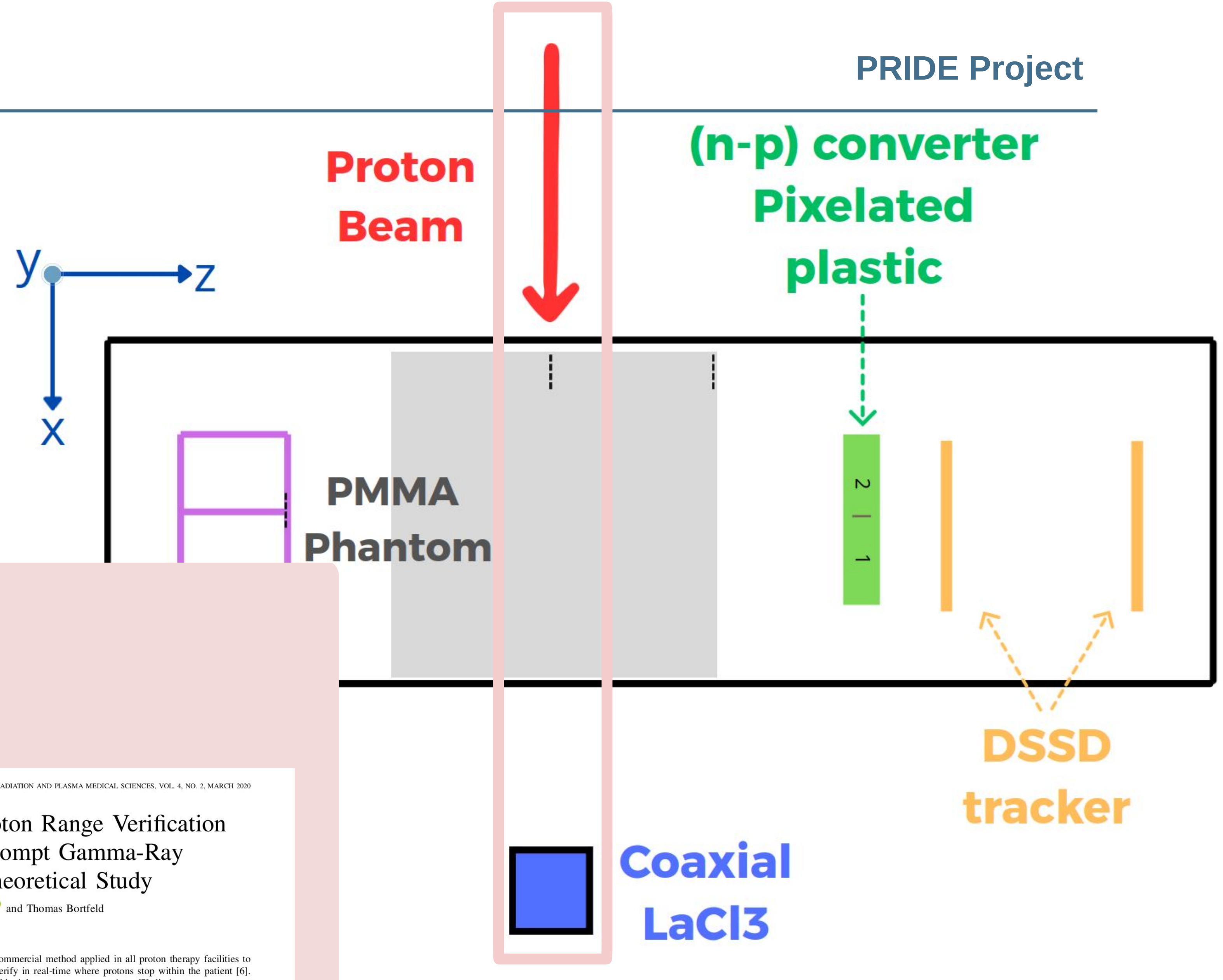
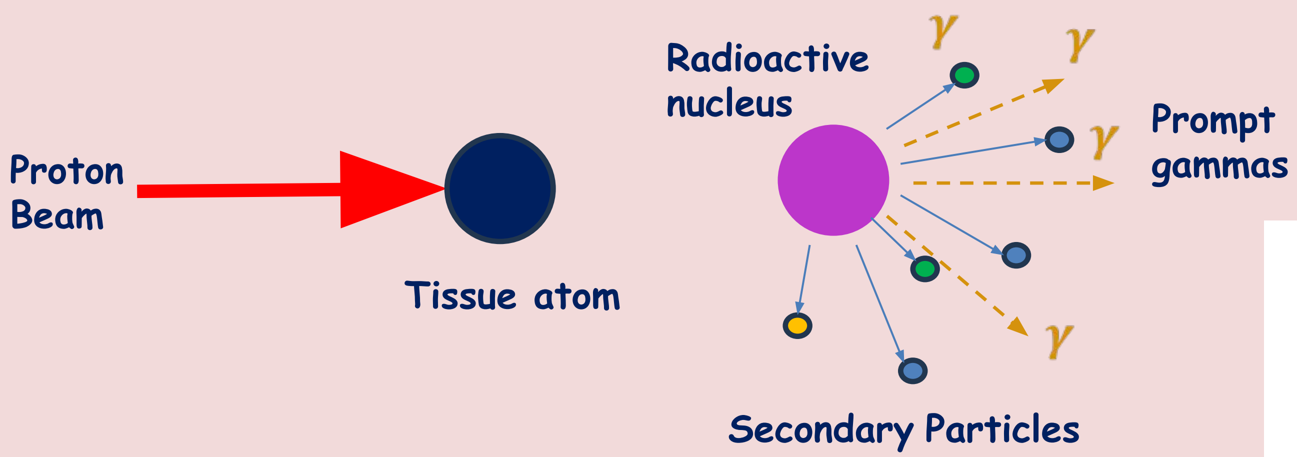
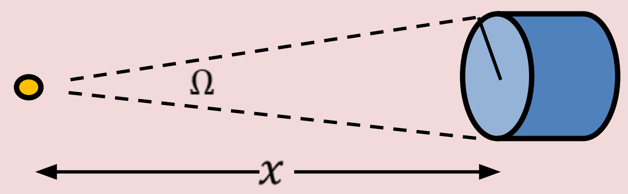
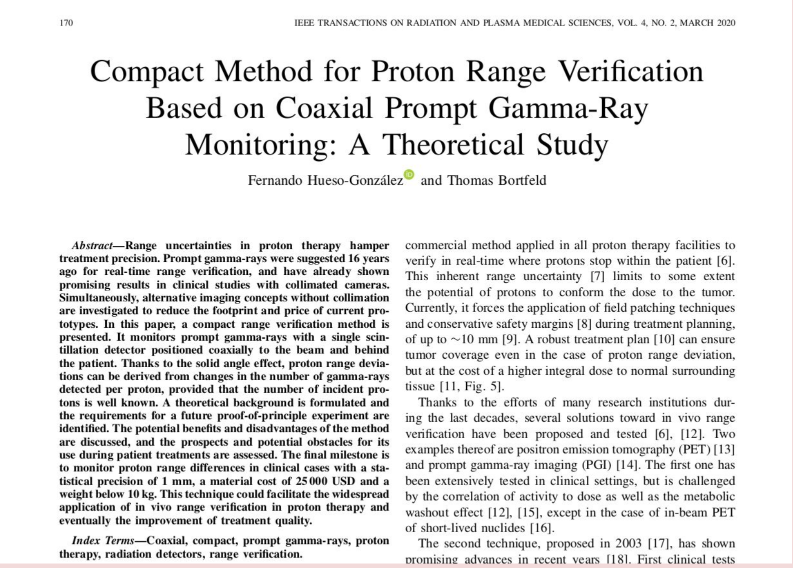







170 IEEE TRANSACTIONS ON RADIATION AND PLASMA MEDICAL SCIENCES, VOL. 4, NO. 2, MARCH 2020

Compact Method for Proton Range Verification Based on Coaxial Prompt Gamma-Ray Monitoring: A Theoretical Study

Fernando Hueso-González and Thomas Bortfeld

Abstract—Range uncertainties in proton therapy hamper treatment precision. Prompt gamma-rays were suggested 16 years ago for real-time range verification, and have already shown promising results in clinical studies with collimated cameras. Simultaneously, alternative imaging concepts without collimation are investigated to reduce the footprint and price of current prototypes. In this paper, a compact range verification method is presented. It monitors prompt gamma-rays with a single scintillation detector positioned coaxially to the beam and behind the patient. Thanks to the solid angle effect, proton range deviations can be derived from changes in the number of gamma-rays detected per proton, provided that the number of incident protons is well known. A theoretical background is formulated and the requirements for a future proof-of-principle experiment are identified. The potential benefits and disadvantages of the method are discussed, and the prospects and potential obstacles for its use during patient treatments are assessed. The final milestone is to monitor proton range differences in clinical cases with a statistical precision of 1 mm, a material cost of 25 000 USD and a weight below 10 kg. This technique could facilitate the widespread application of in vivo range verification in proton therapy and eventually the improvement of treatment quality.

Index Terms—Coaxial, compact, prompt gamma-rays, proton therapy, radiation detectors, range verification.

commercial method applied in all proton therapy facilities to verify in real-time where protons stop within the patient [6]. This inherent range uncertainty [7] limits to some extent the potential of protons to conform the dose to the tumor. Currently, it forces the application of field patching techniques and conservative safety margins [8] during treatment planning, of up to ~10 mm [9]. A robust treatment plan [10] can ensure tumor coverage even in the case of proton range deviation, but at the cost of a higher integral dose to normal surrounding tissue [11, Fig. 5].

Thanks to the efforts of many research institutions during the last decades, several solutions toward in vivo range verification have been proposed and tested [6], [12]. Two examples thereof are positron emission tomography (PET) [13] and prompt gamma-ray imaging (PGI) [14]. The first one has been extensively tested in clinical settings, but is challenged by the correlation of activity to dose as well as the metabolic washout effect [12], [15], except in the case of in-beam PET of short-lived nuclides [16].

The second technique, proposed in 2003 [17], has shown promising advances in recent years [18]. First clinical tests

Thanks to the effect of the solid angle, the change in the range of the protons can generate a variation in the number of gamma rays detected per proton, as long as the number of incident protons is well known.

[2] F. Hueso-Gonzalez and T. Bortfeld, IEEE Trans Radiat Plasma Med. Sci. 4, p. 170 (2020)

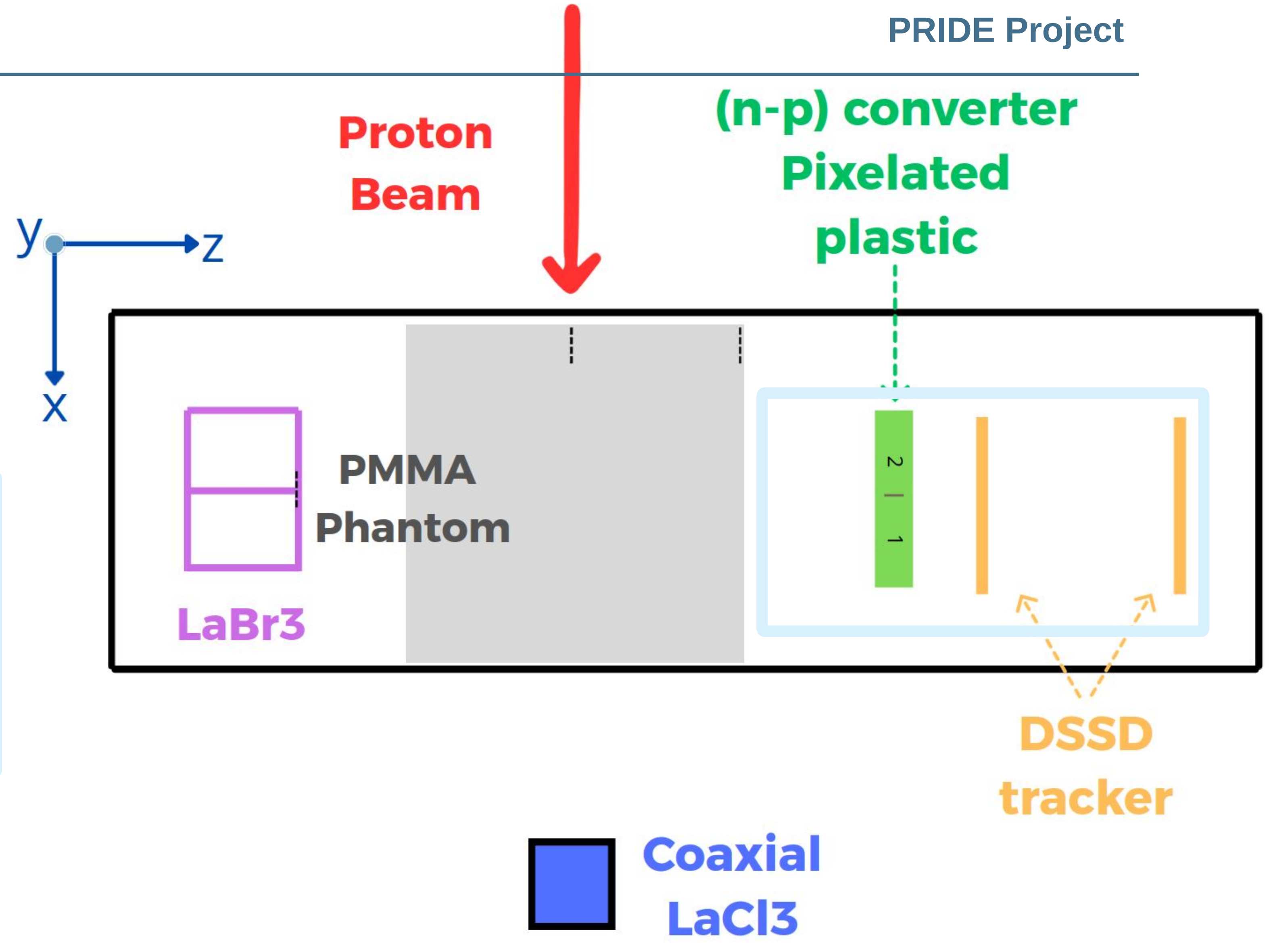
What do we want to measure?

Coaxial configuration

Scintillator crystal, with excellent neutron-gamma discrimination.

Lateral configuration

A position-sensitive plastic scintillator; Two Double-Sided Silicon-Strip Detectors for the detection of lateral scattered neutrons and protons.



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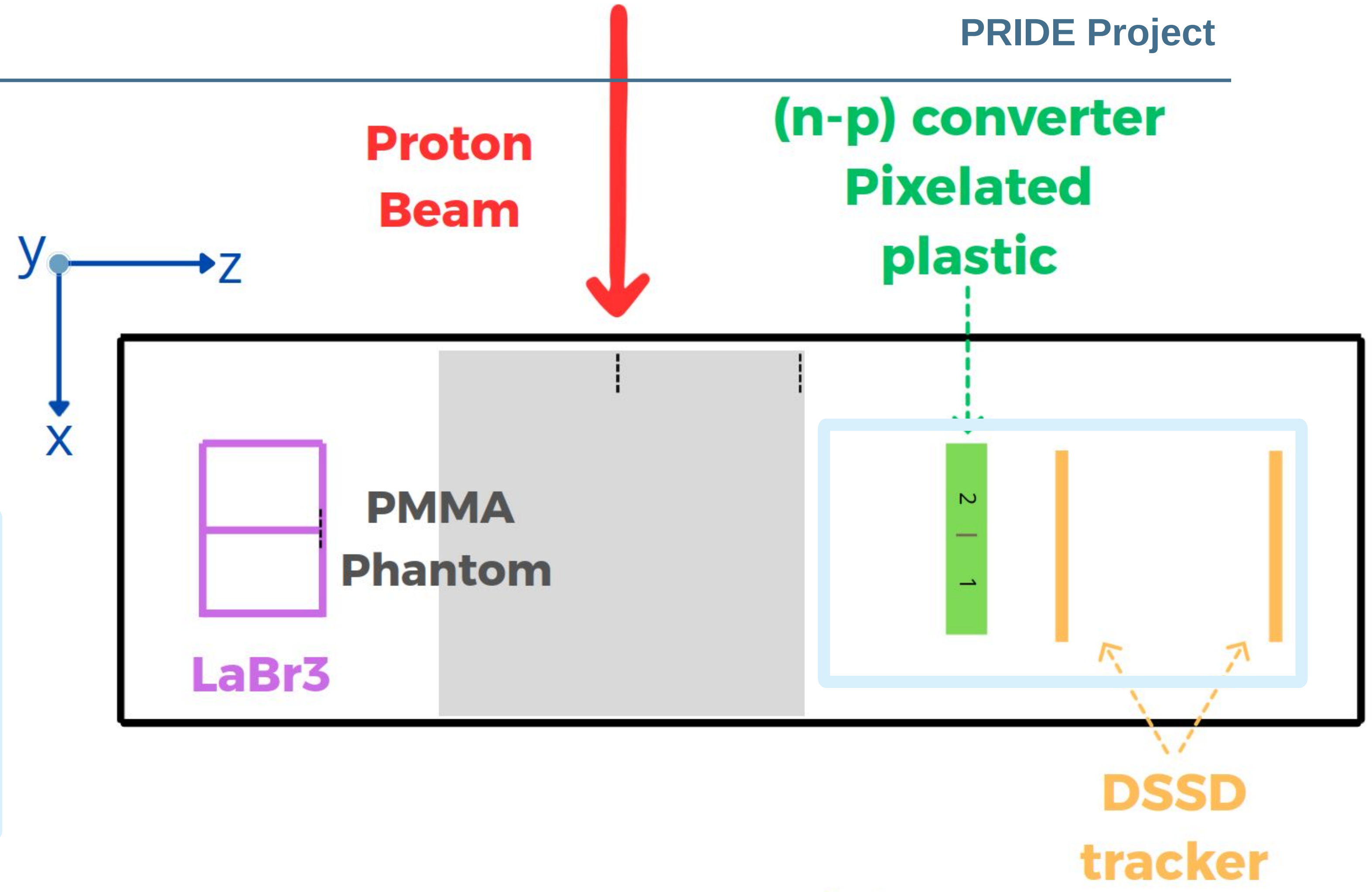

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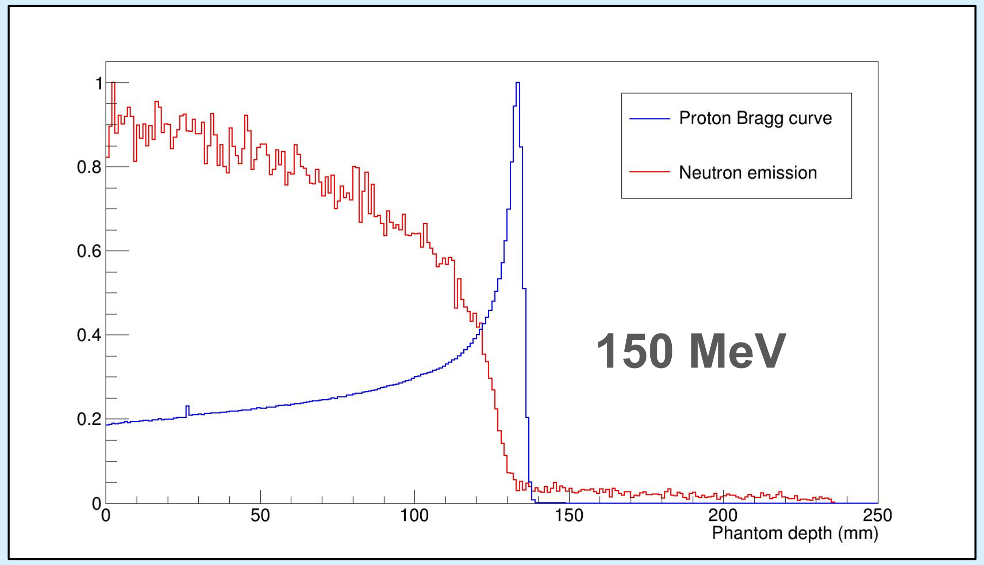

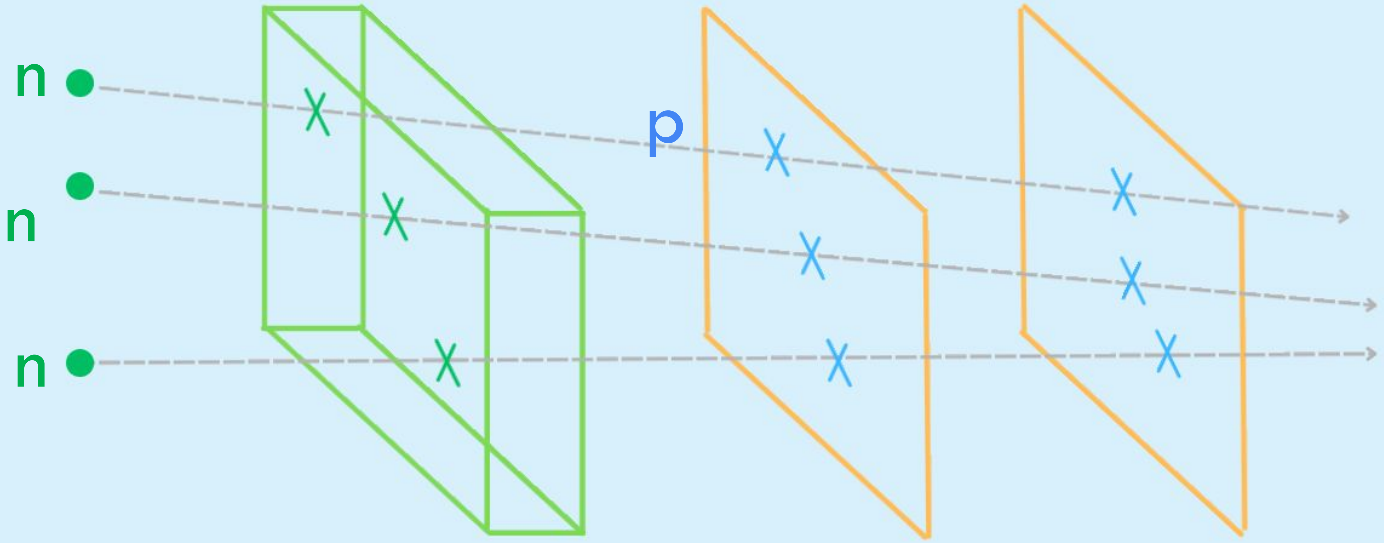

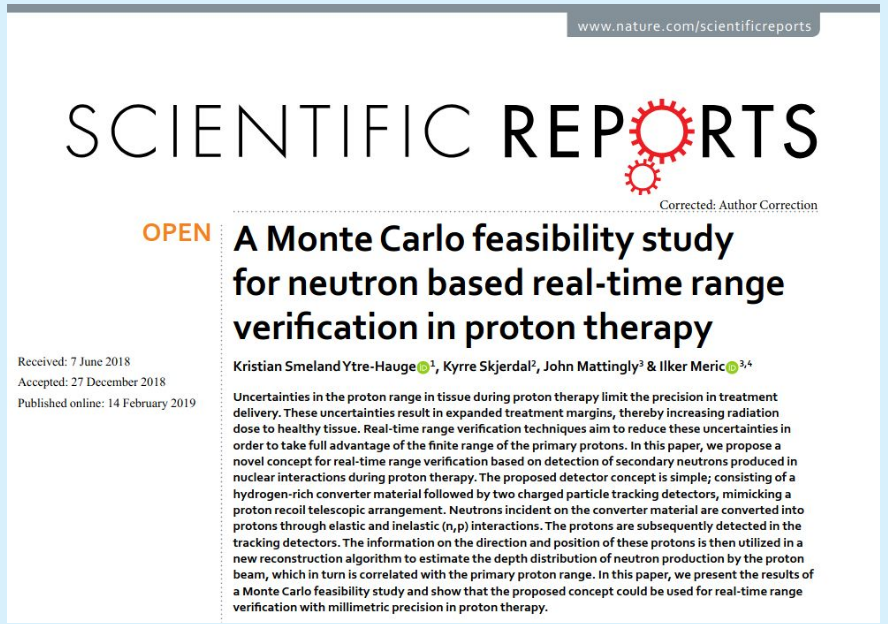

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Corrected: Author Correction

OPEN

A Monte Carlo feasibility study for neutron based real-time range verification in proton therapy

Received: 7 June 2018
Accepted: 27 December 2018
Published online: 14 February 2019

Kristian Smeland Ytre-Hauge[1], Kyrre Skjerdal[2], John Mattingly[3] & Ilker Meric[3,4]

Uncertainties in the proton range in tissue during proton therapy limit the precision in treatment delivery. These uncertainties result in expanded treatment margins, thereby increasing radiation dose to healthy tissue. Real-time range verification techniques aim to reduce these uncertainties in order to take full advantage of the finite range of the primary protons. In this paper, we propose a novel concept for real-time range verification based on detection of secondary neutrons produced in nuclear interactions during proton therapy. The proposed detector concept is simple; consisting of a hydrogen-rich converter material followed by two charged particle tracking detectors, mimicking a proton recoil telescopic arrangement. Neutrons incident on the converter material are converted into protons through elastic and inelastic (n,p) interactions. The protons are subsequently detected in the tracking detectors. The information on the direction and position of these protons is then utilized in a new reconstruction algorithm to estimate the depth distribution of neutron production by the proton beam, which in turn is correlated with the primary proton range. In this paper, we present the results of a Monte Carlo feasibility study and show that the proposed concept could be used for real-time range verification with millimetric precision in proton therapy.

K.S. Ytre-Hauge, et al., Sci Rep 9, 2011 (2019)

PRIDE Project

Experiment

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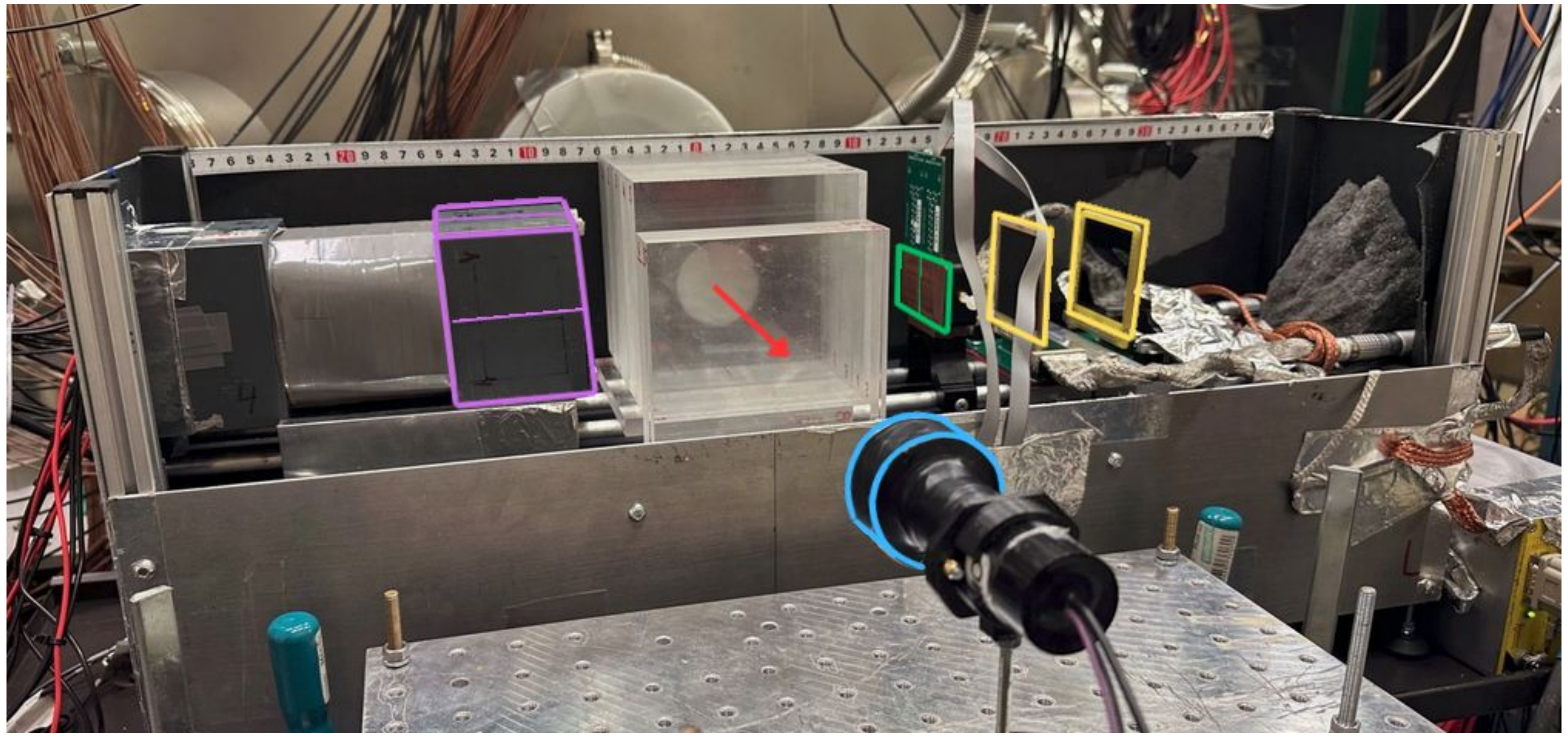
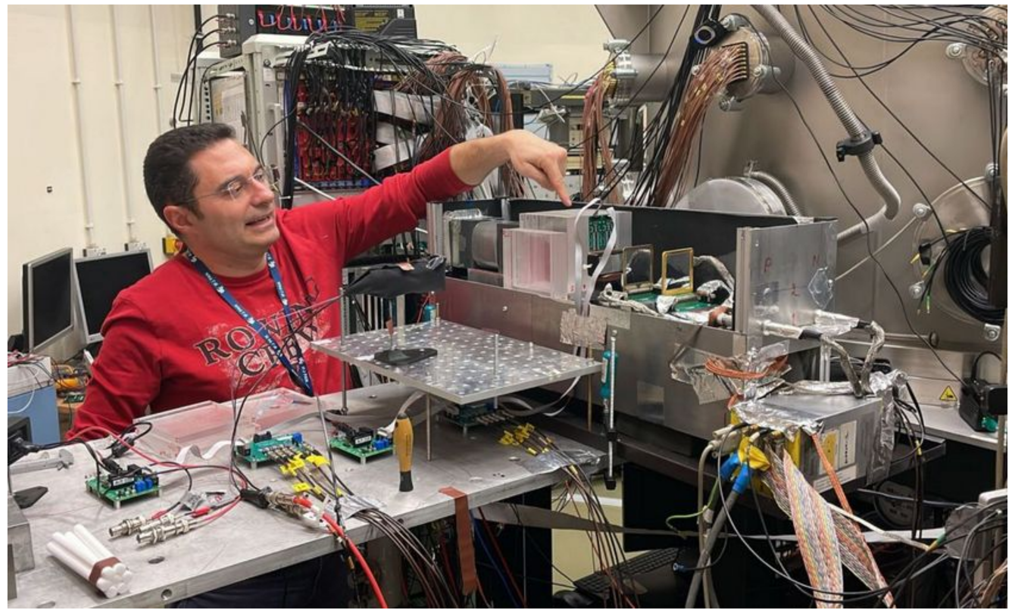
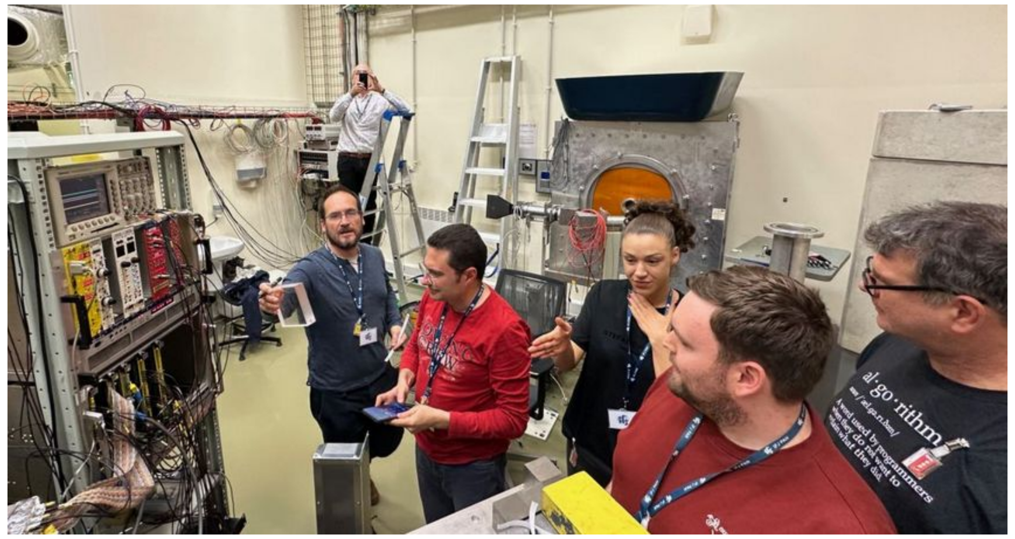
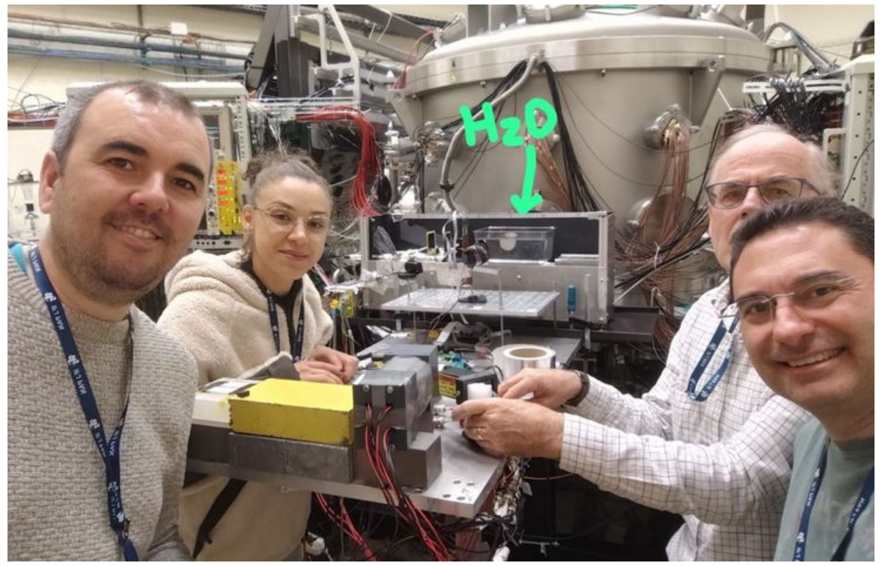
- Sweep PMMA
- Energy from 100 to 160 MeV









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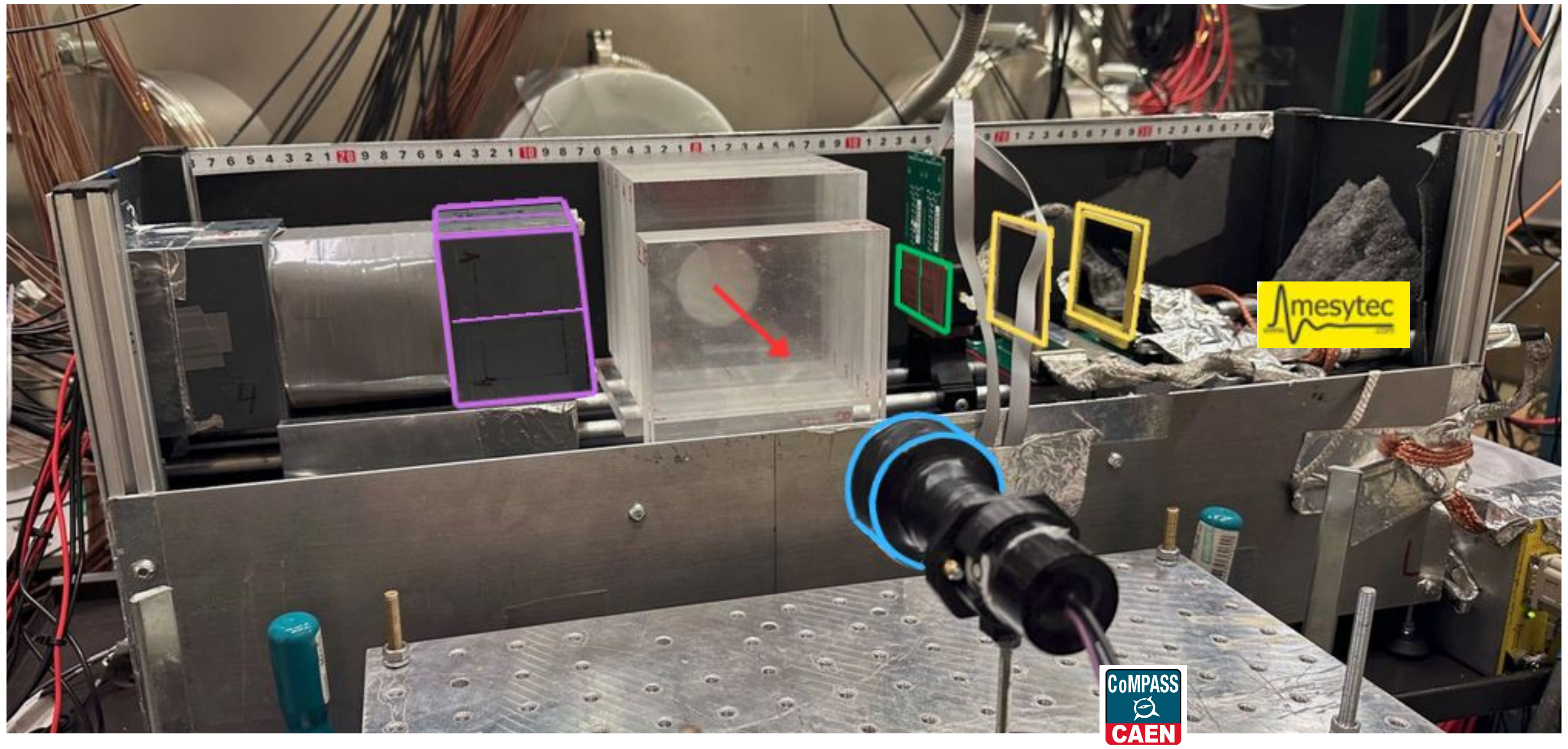
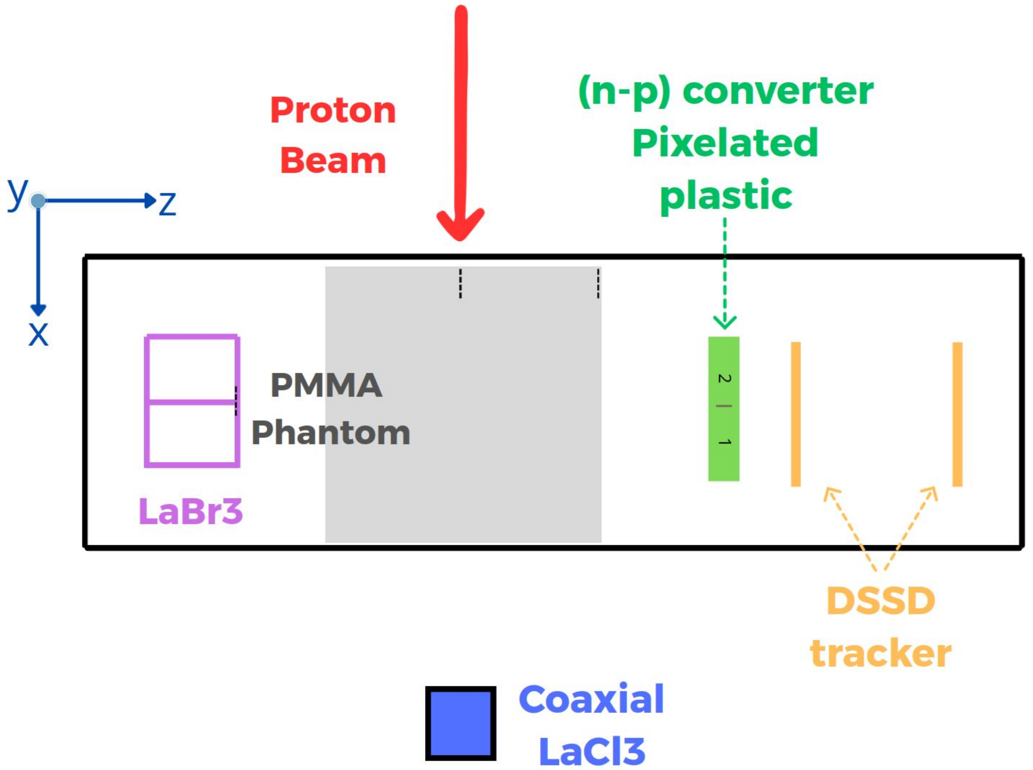
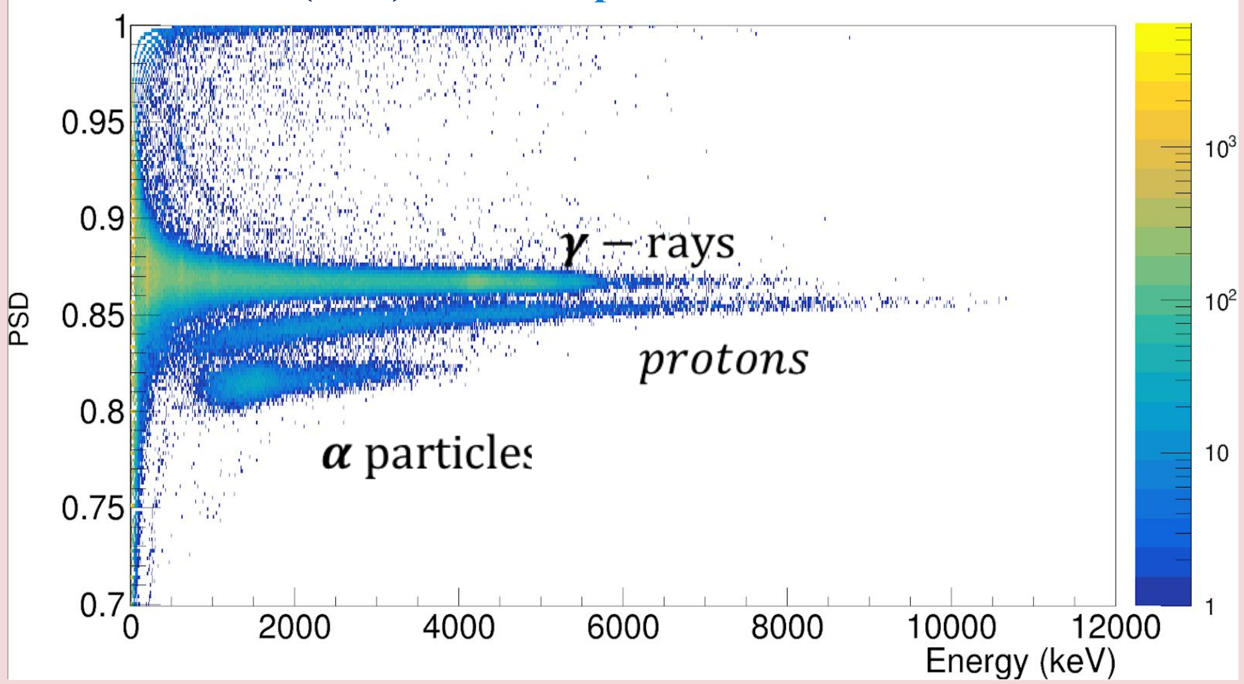




Coaxial configuration

Pure LaCl3

35Cl(n,p)35S
35Cl(n,a)32P



We have used a **non-commercial** pure LaCl3 scintillator with excellent neutron-gamma discrimination, provided by our collaborators Phan Quoc Vuong and Hongjoo Kim from the Department of Physics at Kyungpook National University (South Korea).

P. Vuong, H. Kim et al., Nuclear Engineering and Technology 53, p. 3784 (2021)

Cyclotron Centre Bronowice CCB

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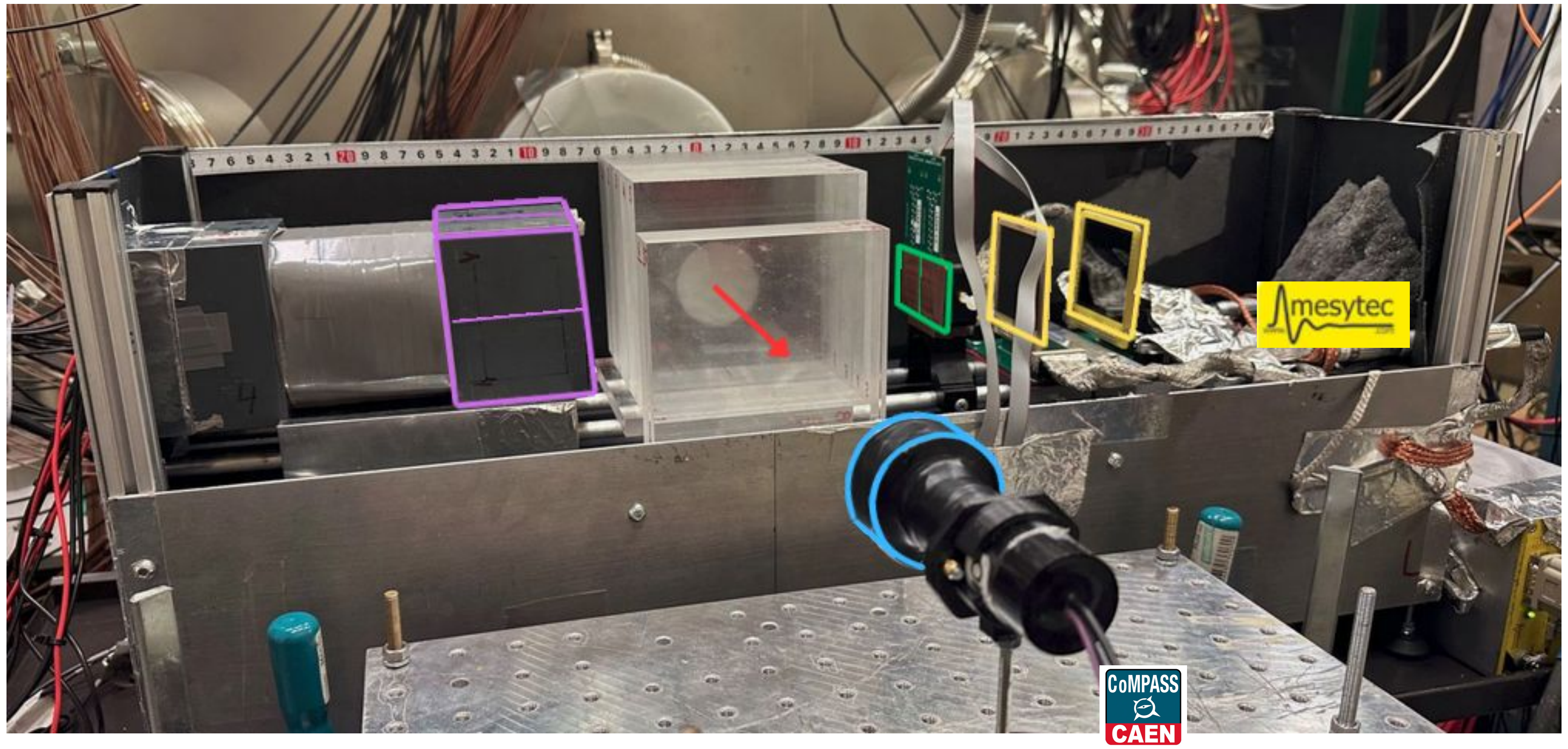
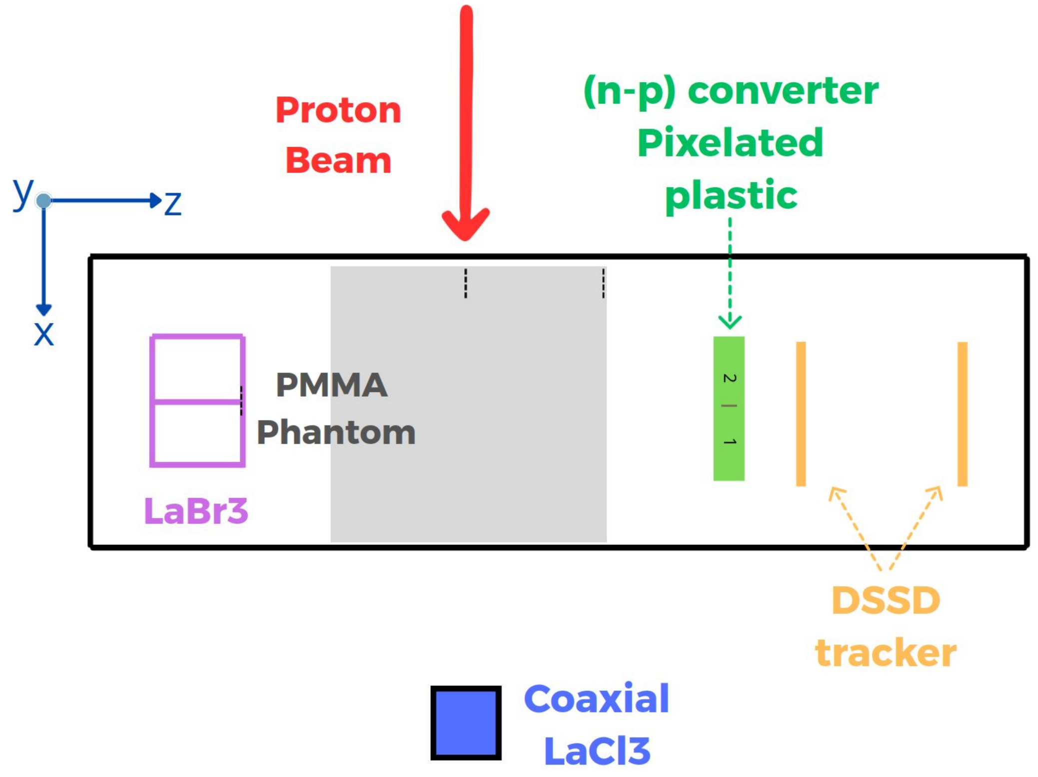
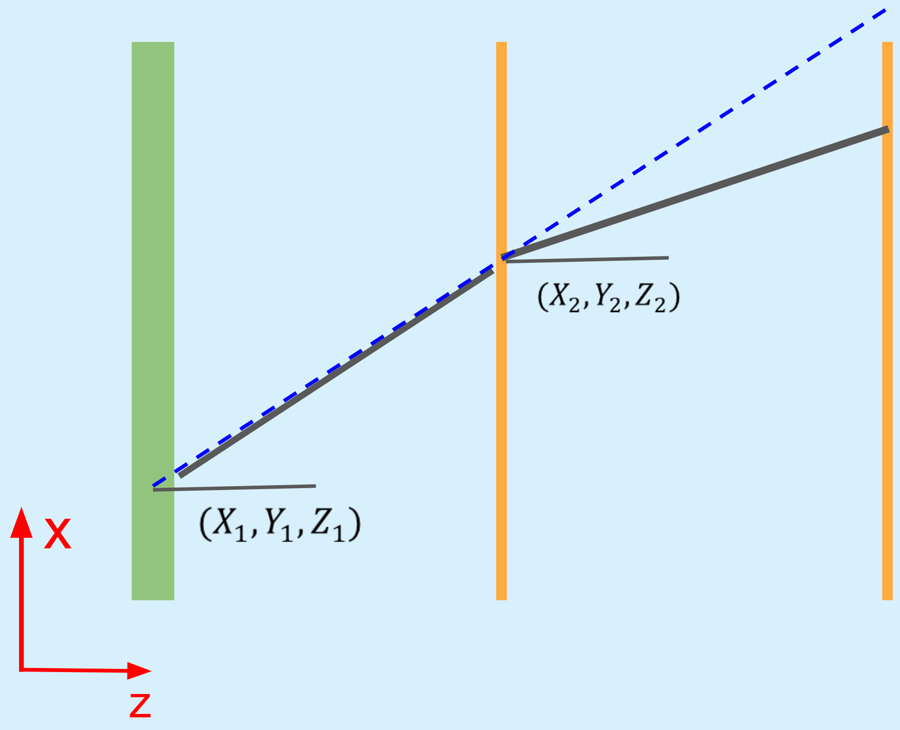




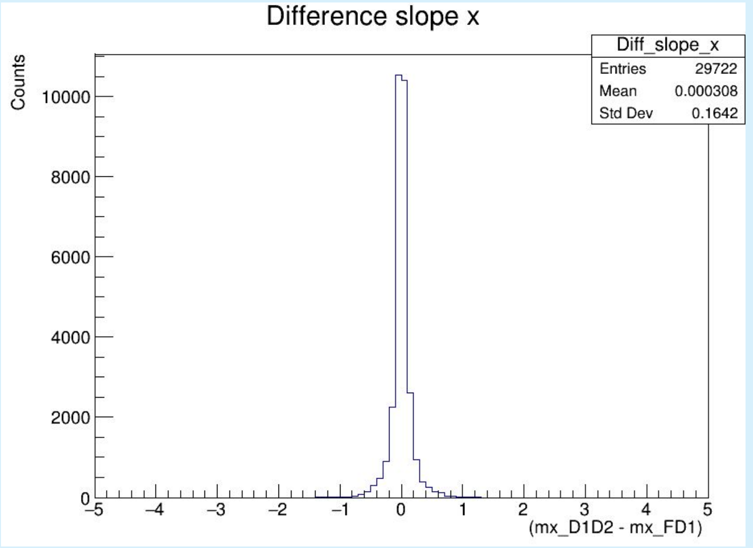
Lateral configuration

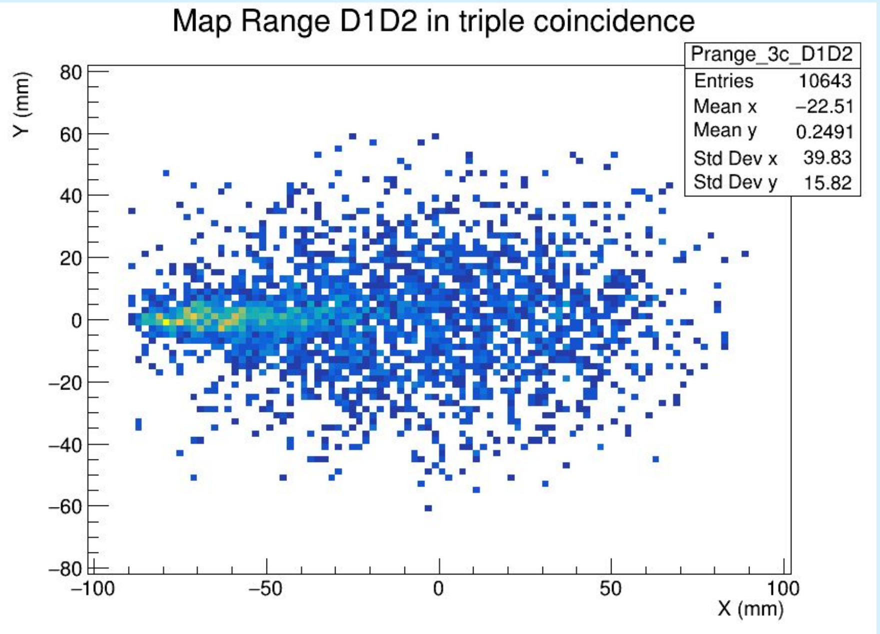


$$m_x = \frac{X_2 - X_1}{Z_2 - Z_1}$$

$$X_0 = X_1 - m_x \cdot (Z_1 - Z_0)$$

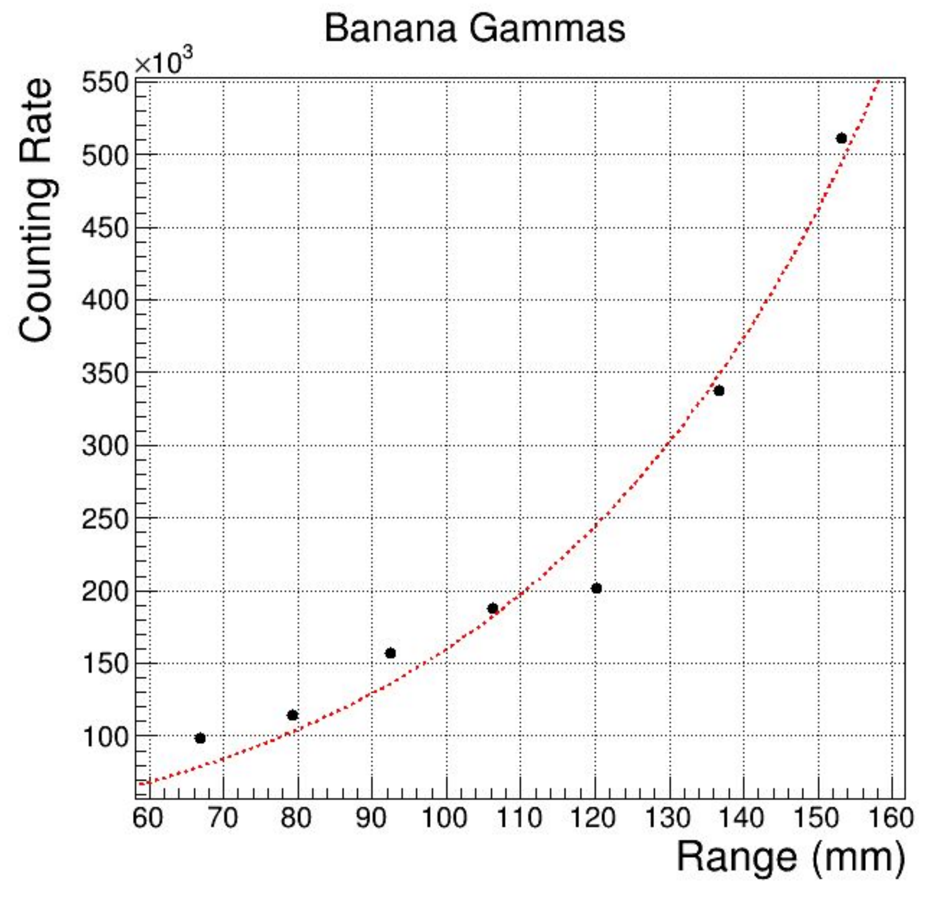
$$X_0 = X_1 - m_x \cdot Z_1$$

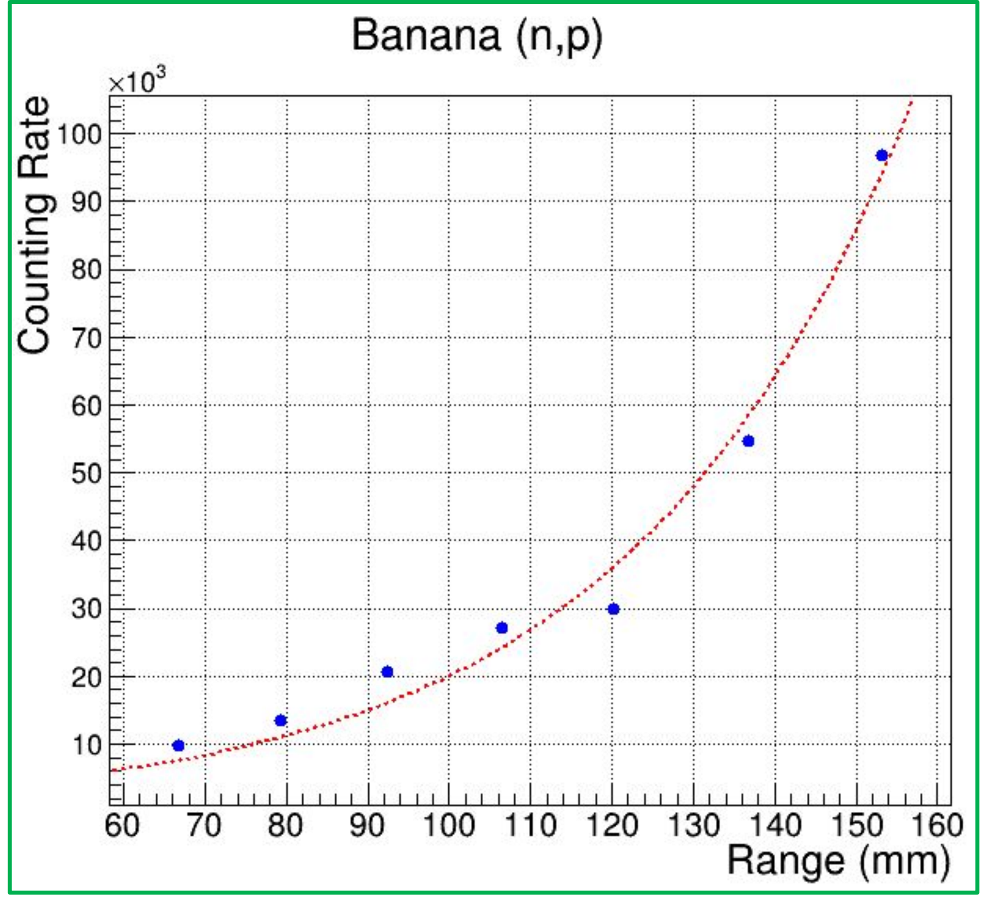


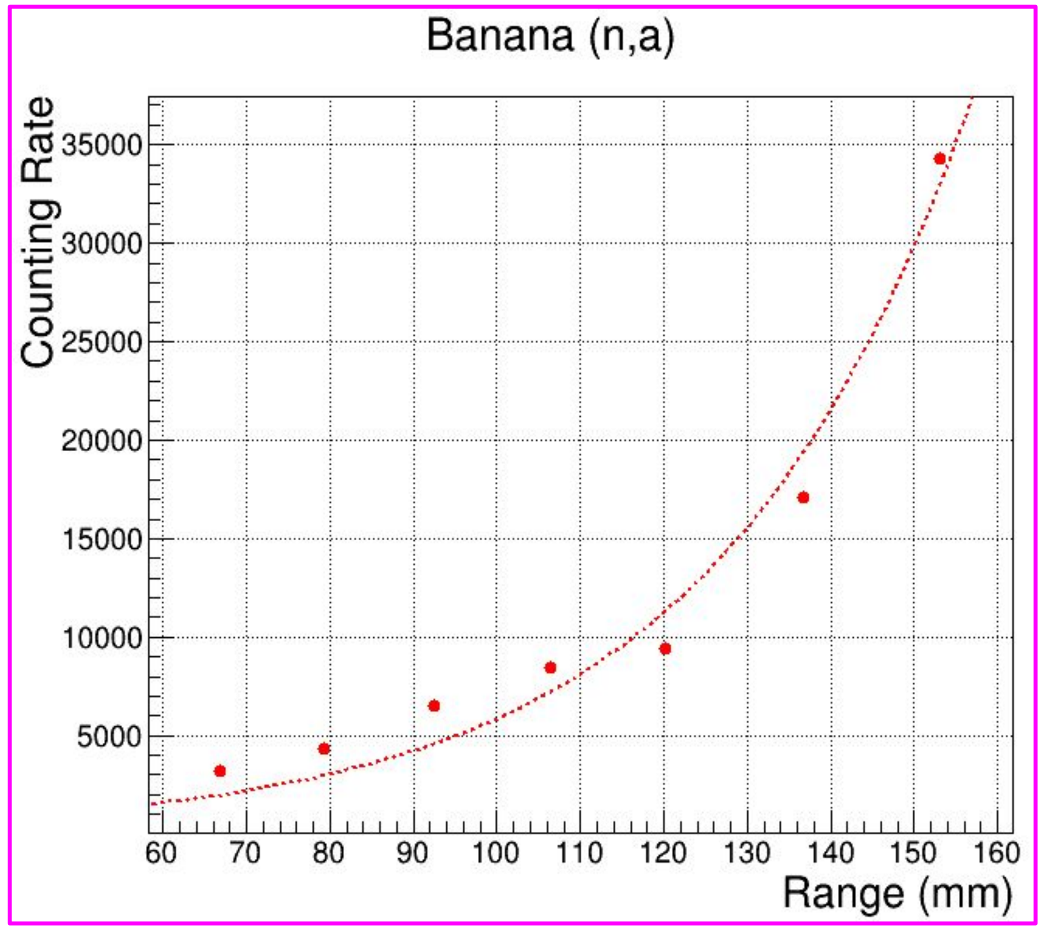


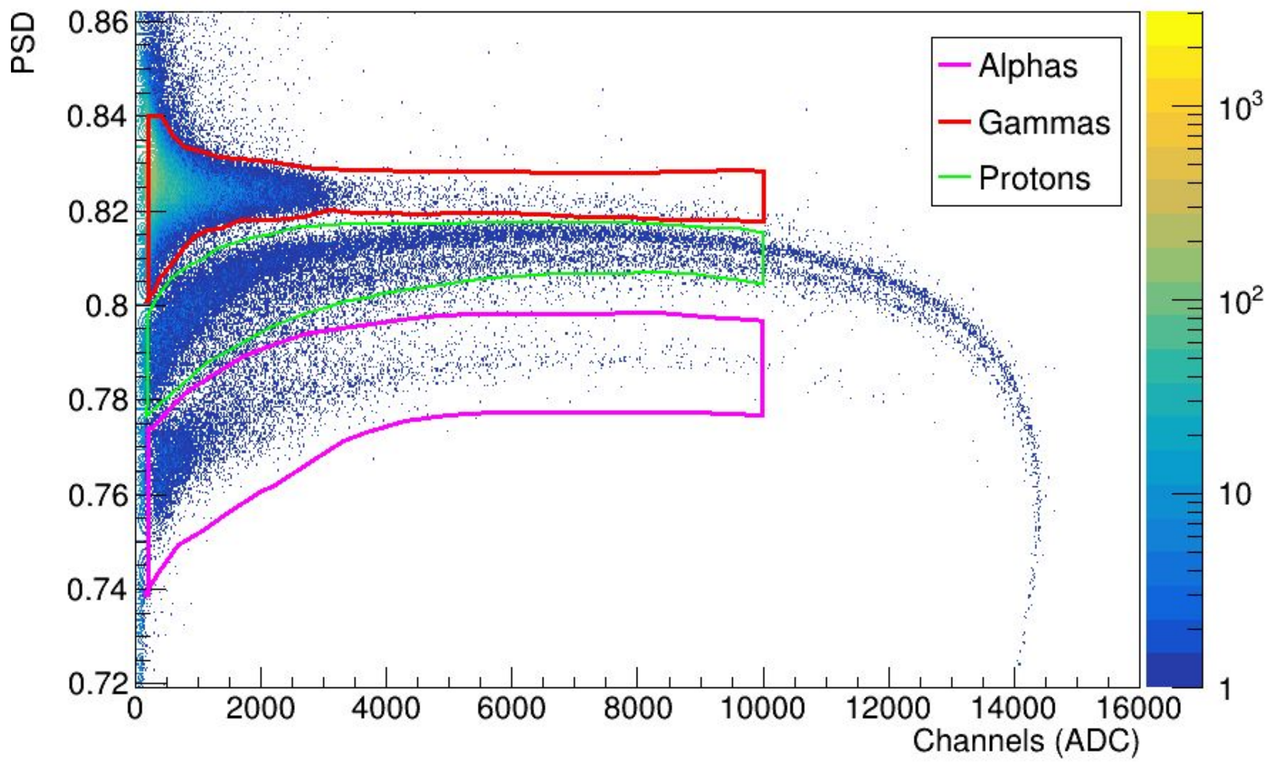
Preliminary Results

Coaxial configuration









$$CR\left(x\right) = e^{(\alpha+\beta x)}$$

Constant	=	9.86031	+/-	0.252947
Slope	=	0.0212279	+/-	0.00182766

Constant	=	7.00686	+/-	0.341066
Slope	=	0.0290337	+/-	0.00238057

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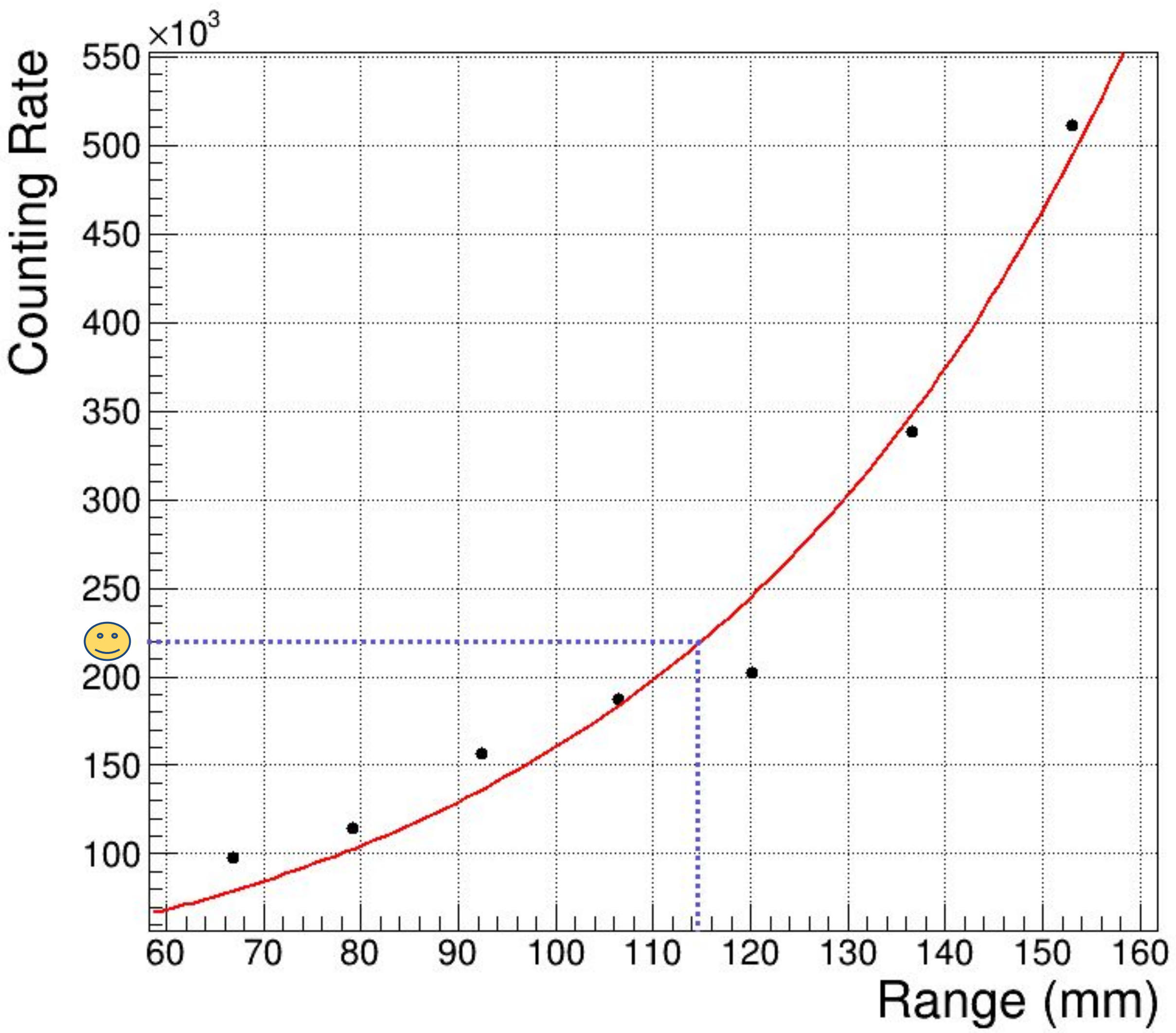
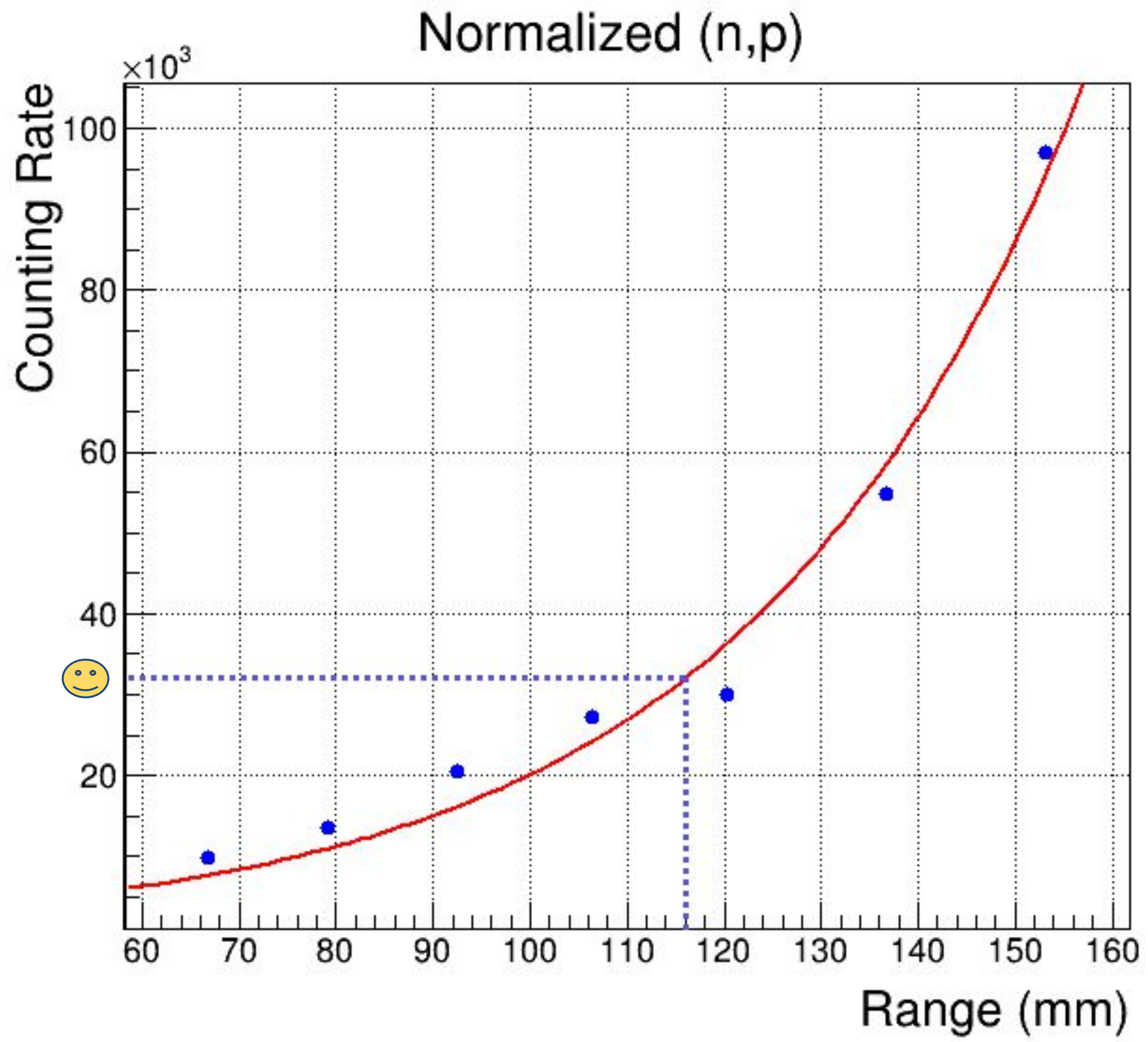
Coaxial configuration

Energy	135 MeV
Counts Gammas	219485
Counts Protons	31787
Counts Alpha	9972





135 MeV

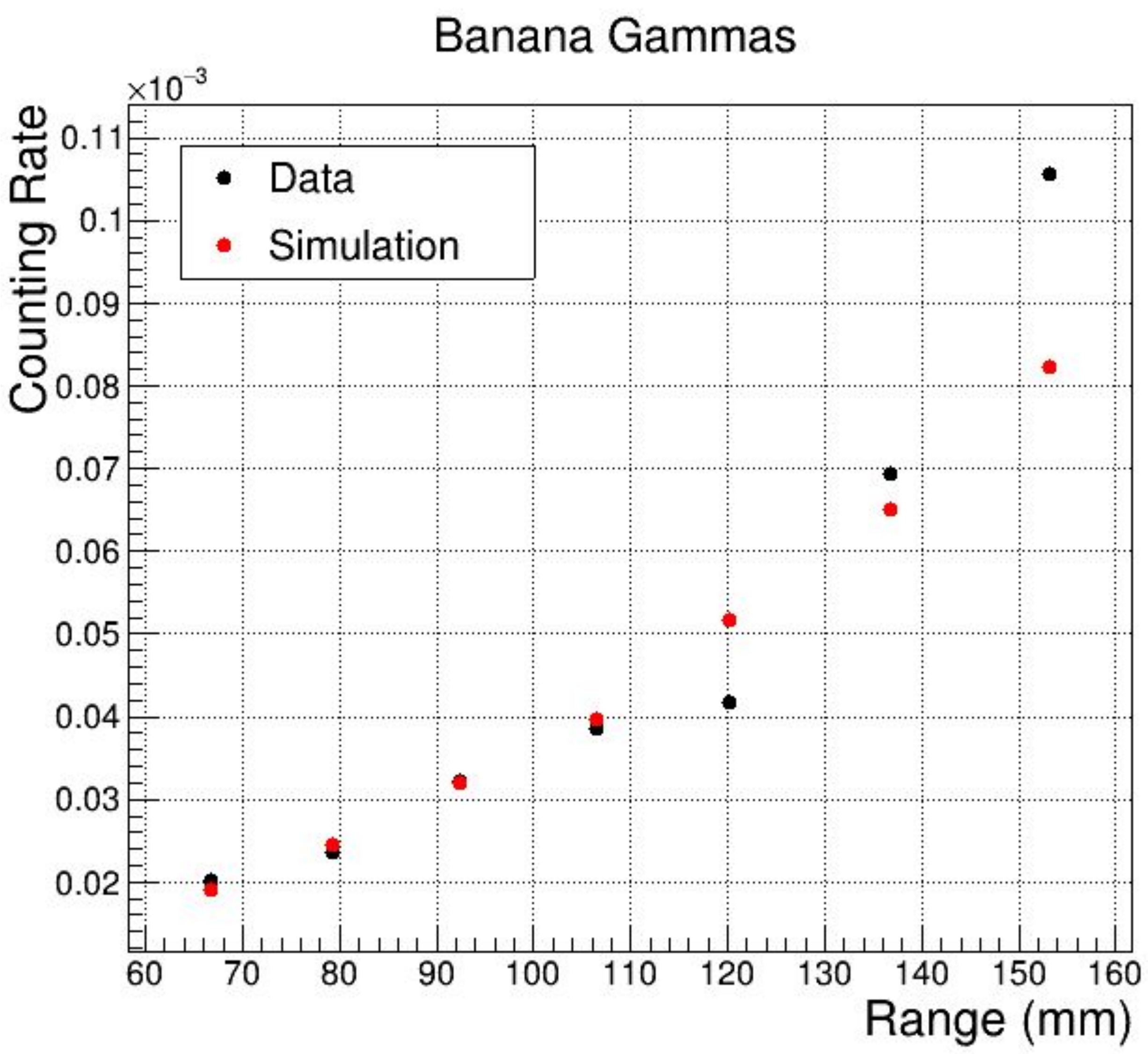
Range:

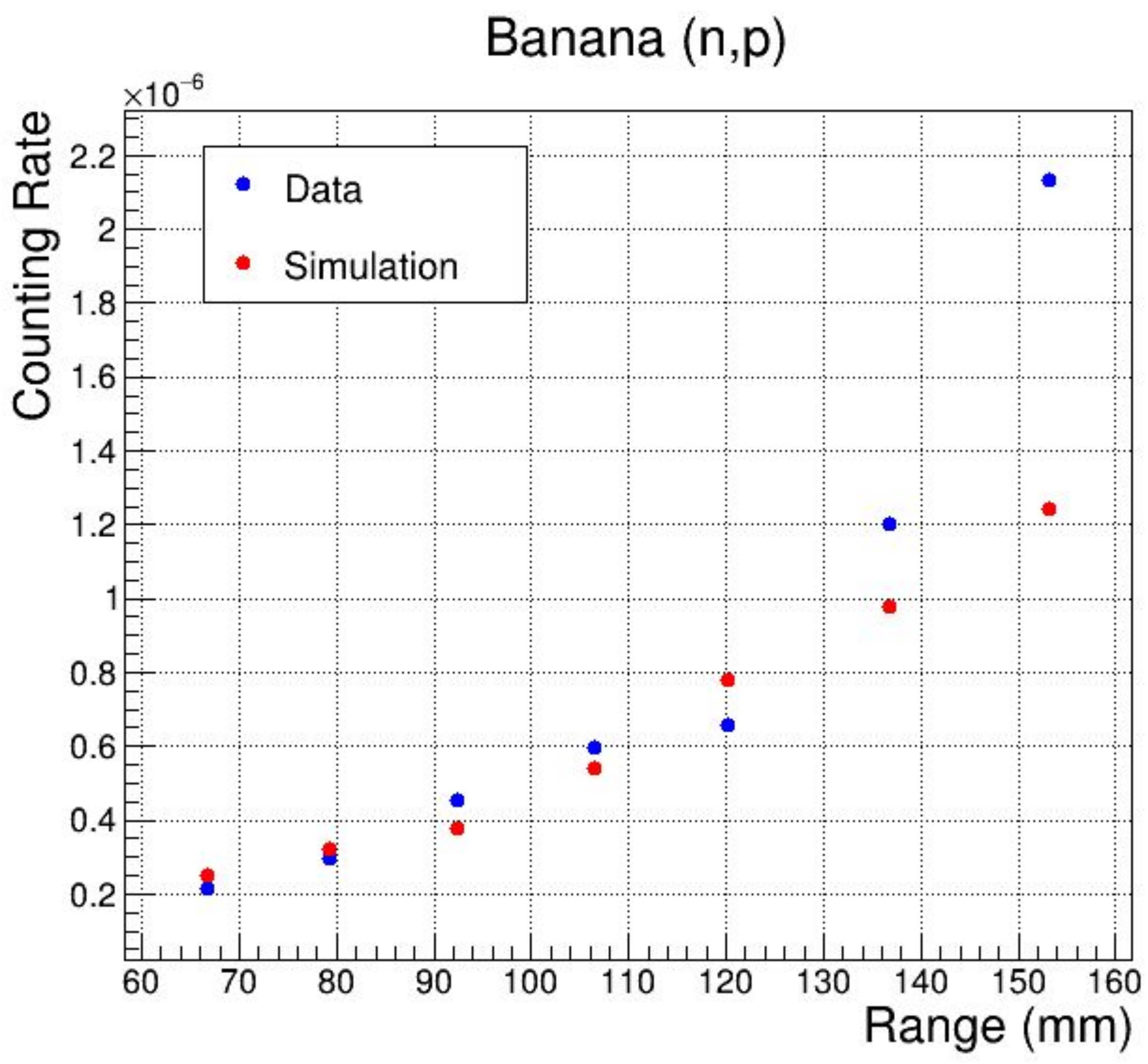
—> 115 mm (Fit gamma)

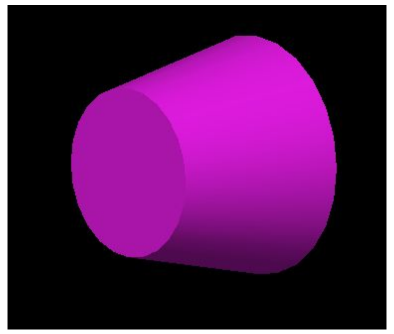
—> 116 mm (Fit (n,p))

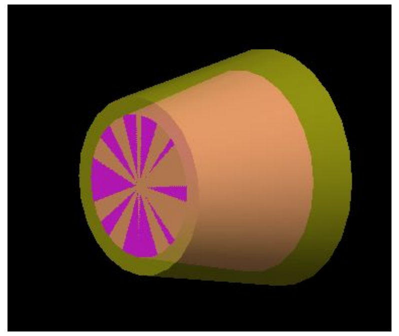
Range (mm,NIST) = 112.8 mm

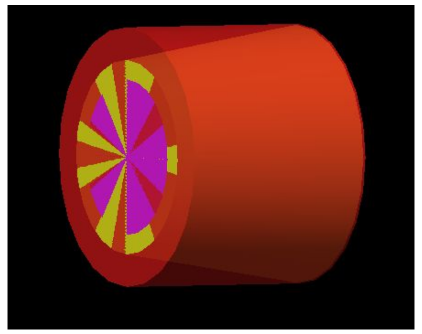
Simulation - Coaxial configuration





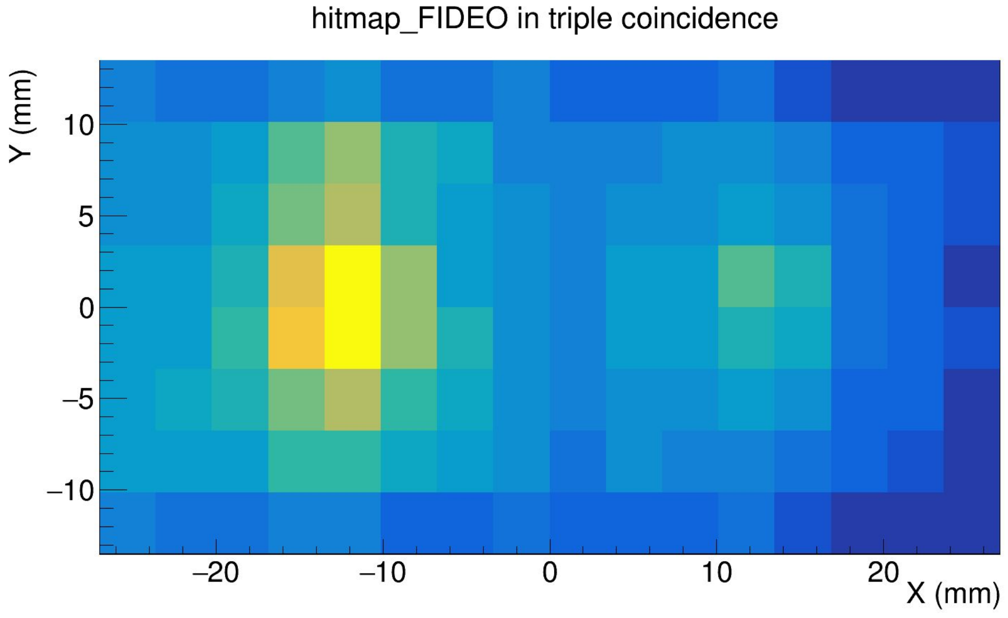


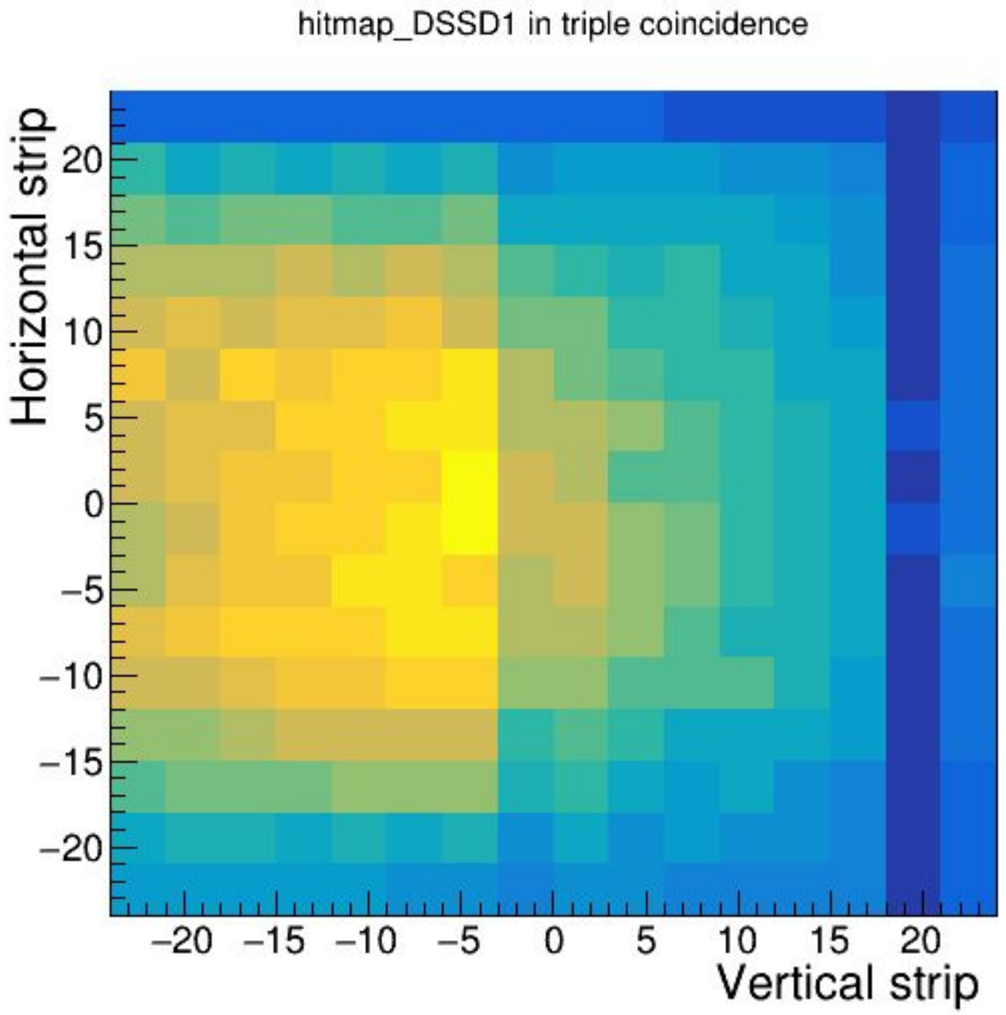


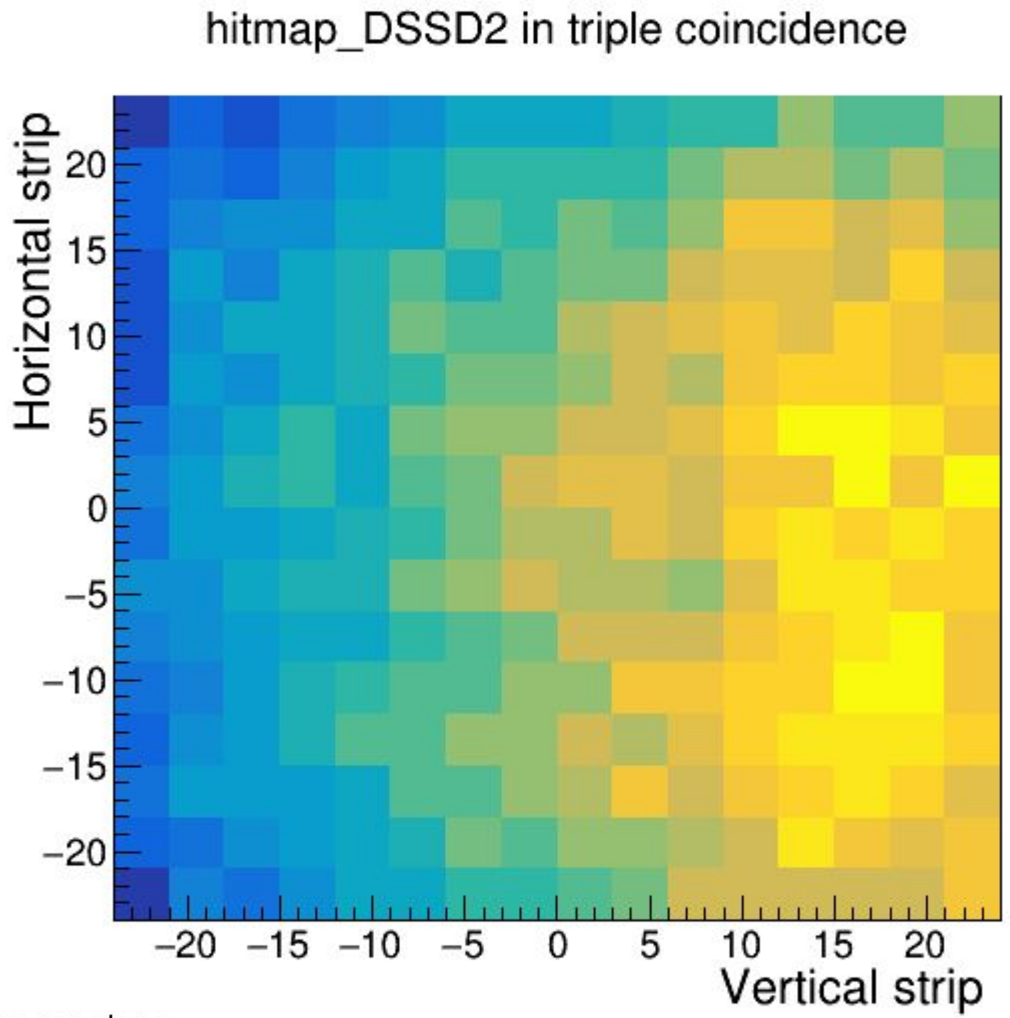


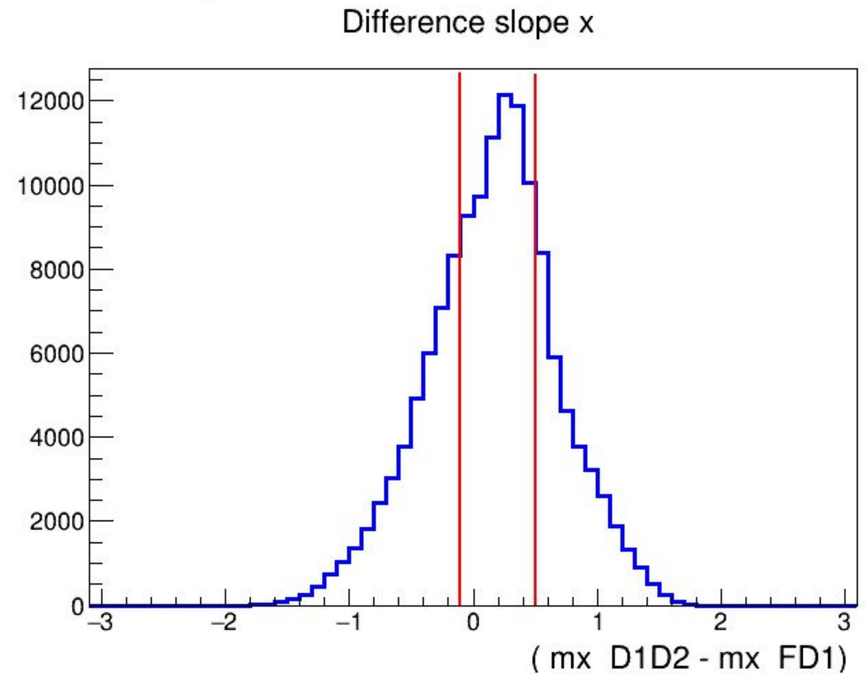
Lateral configuration

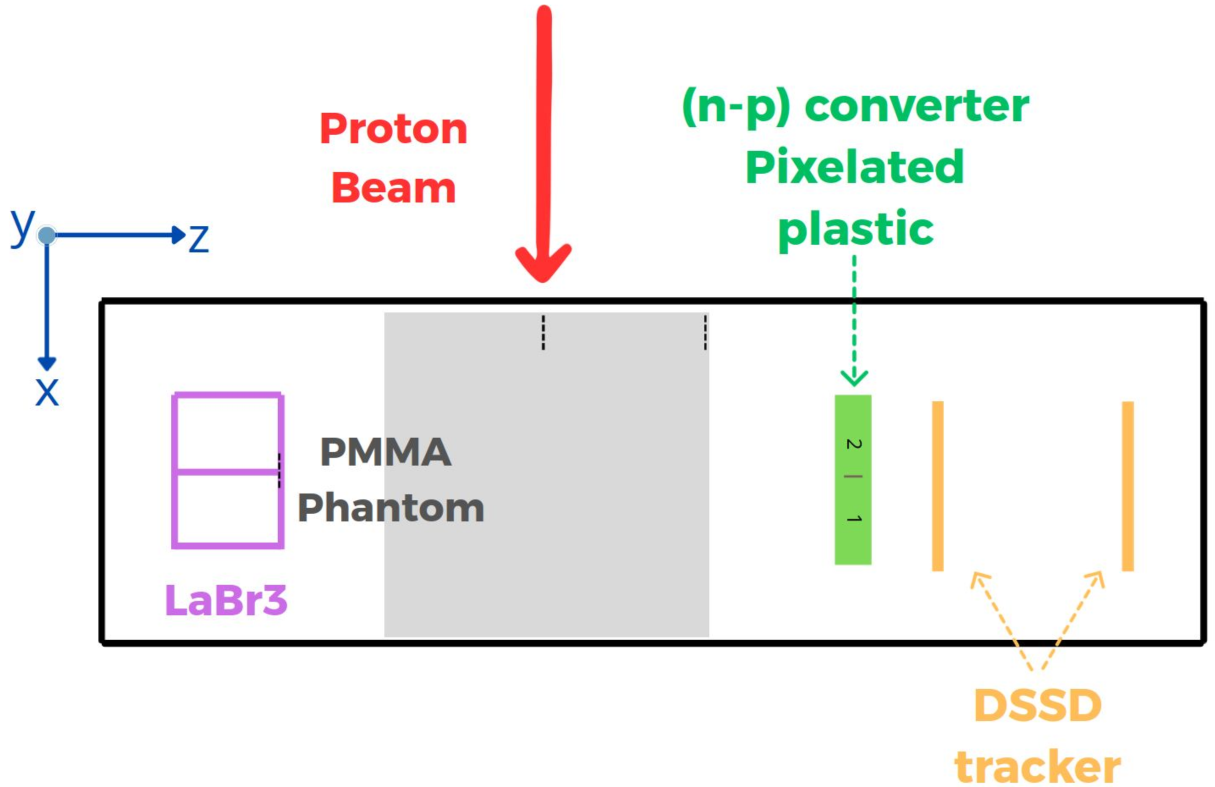
160 MeV





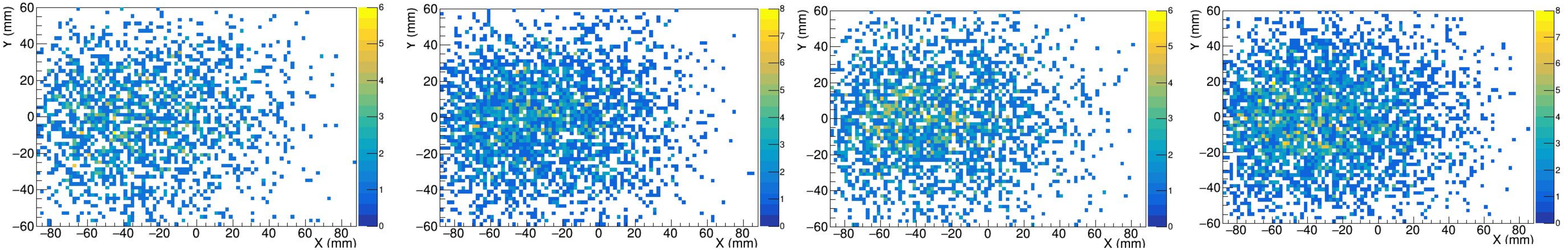




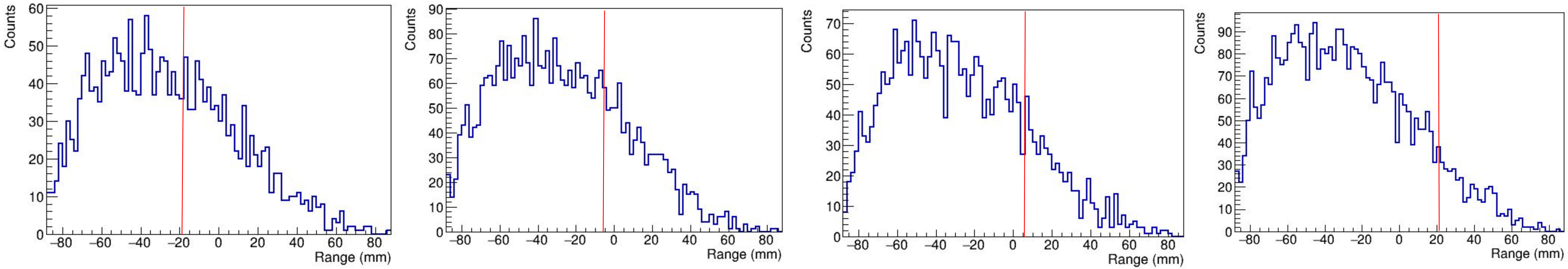


Lateral configuration

100 MeV | 110 MeV | 120 MeV | 130 MeV

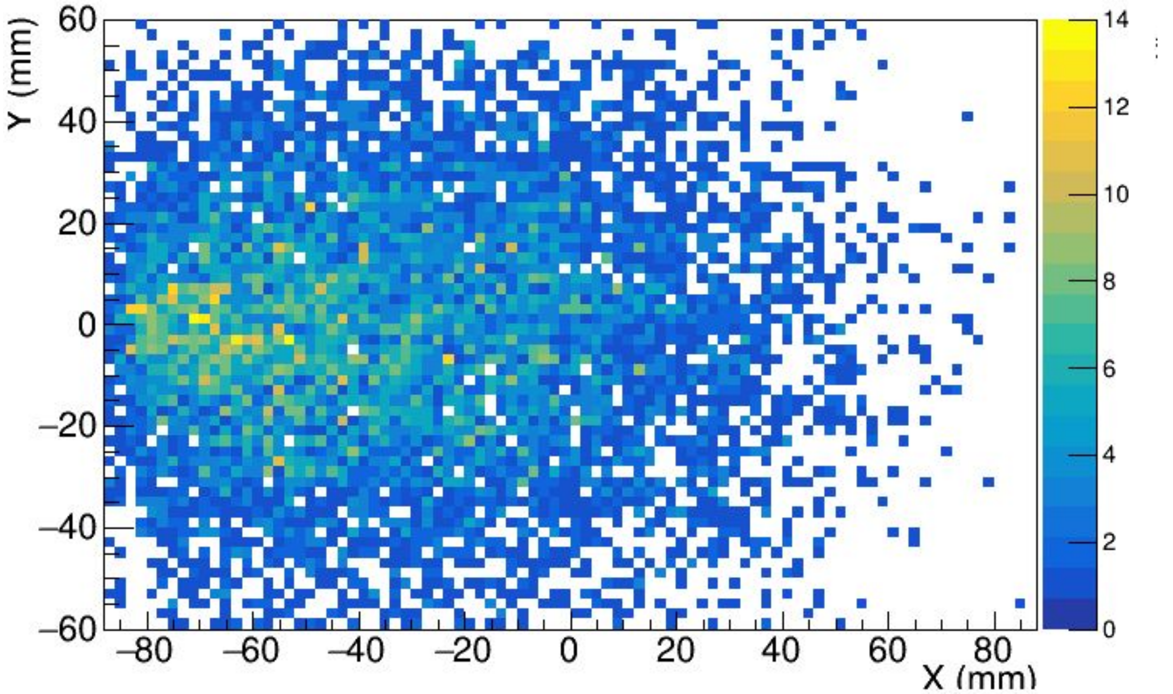


X Projection

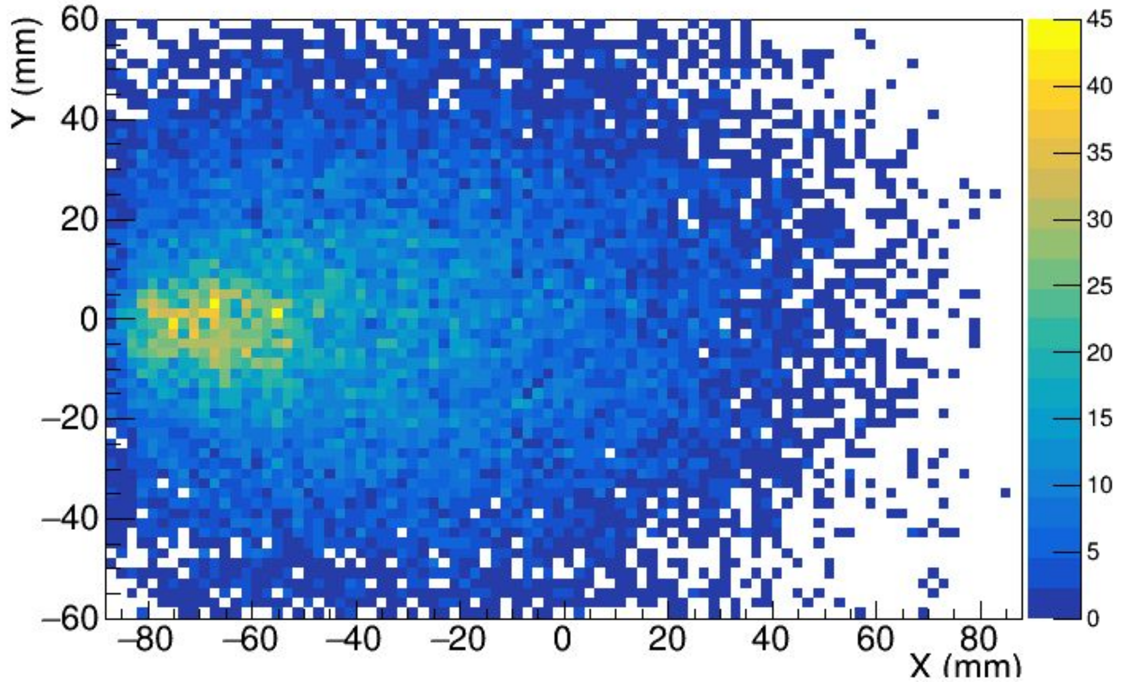


Lateral configuration

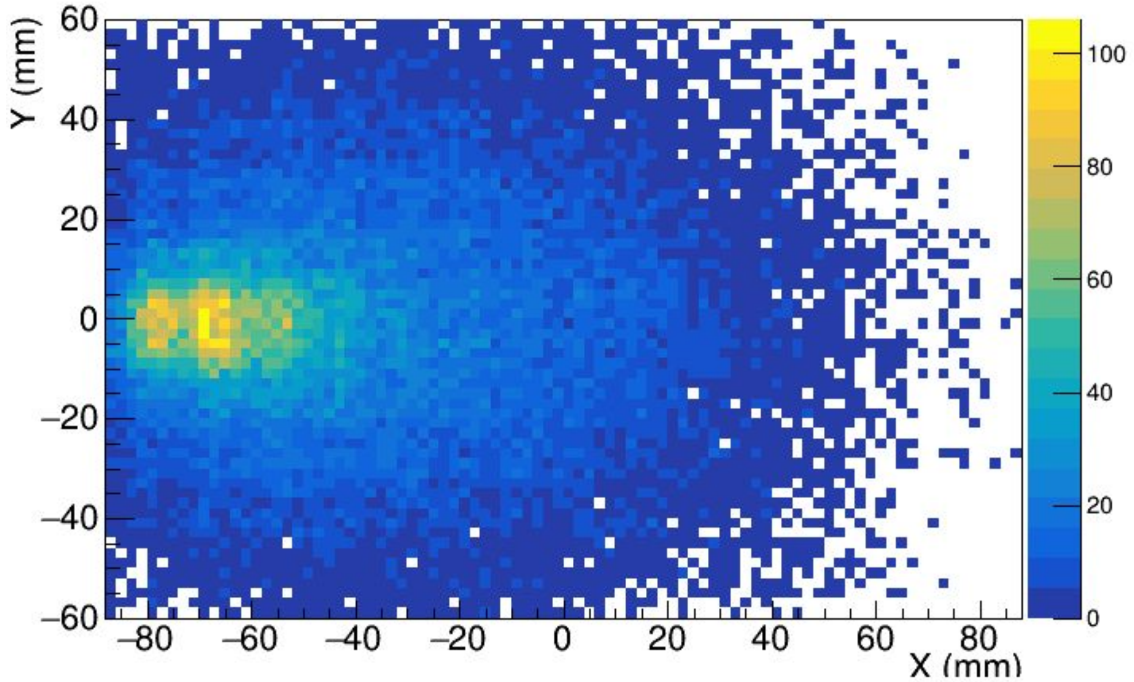
140 MeV



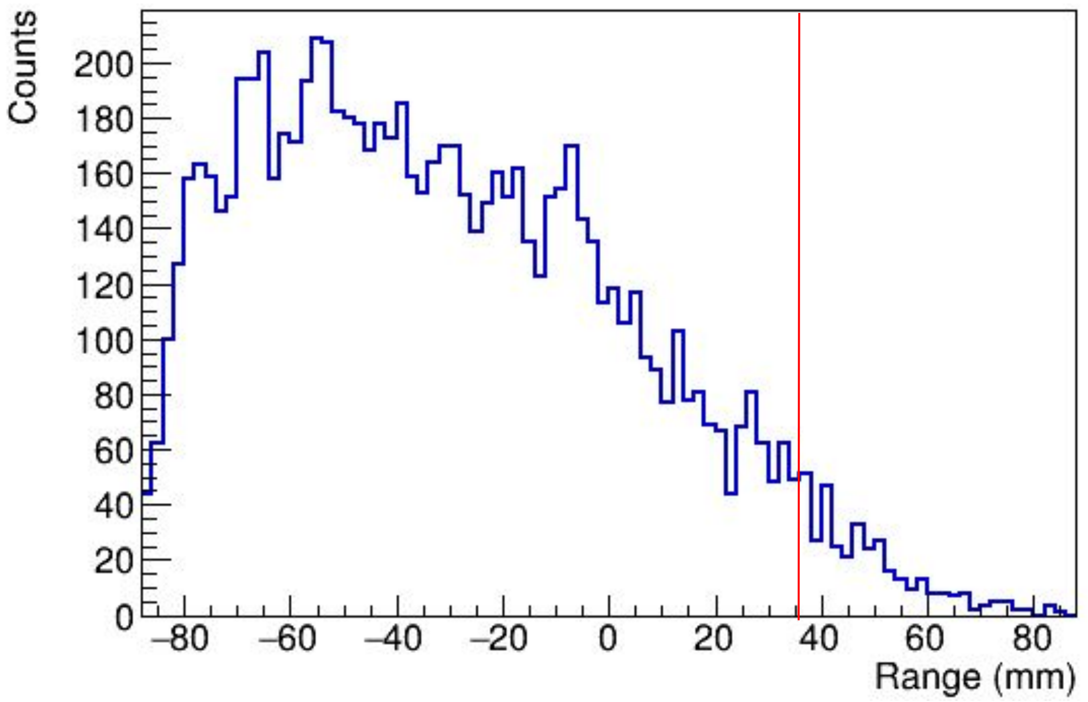
150 MeV

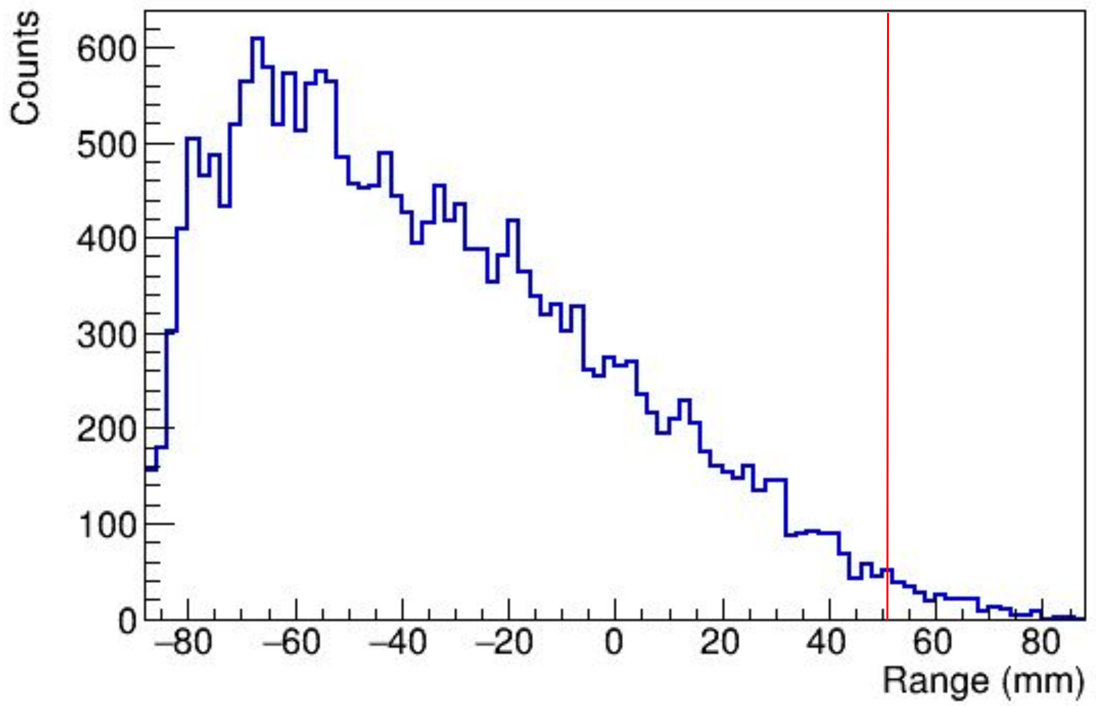


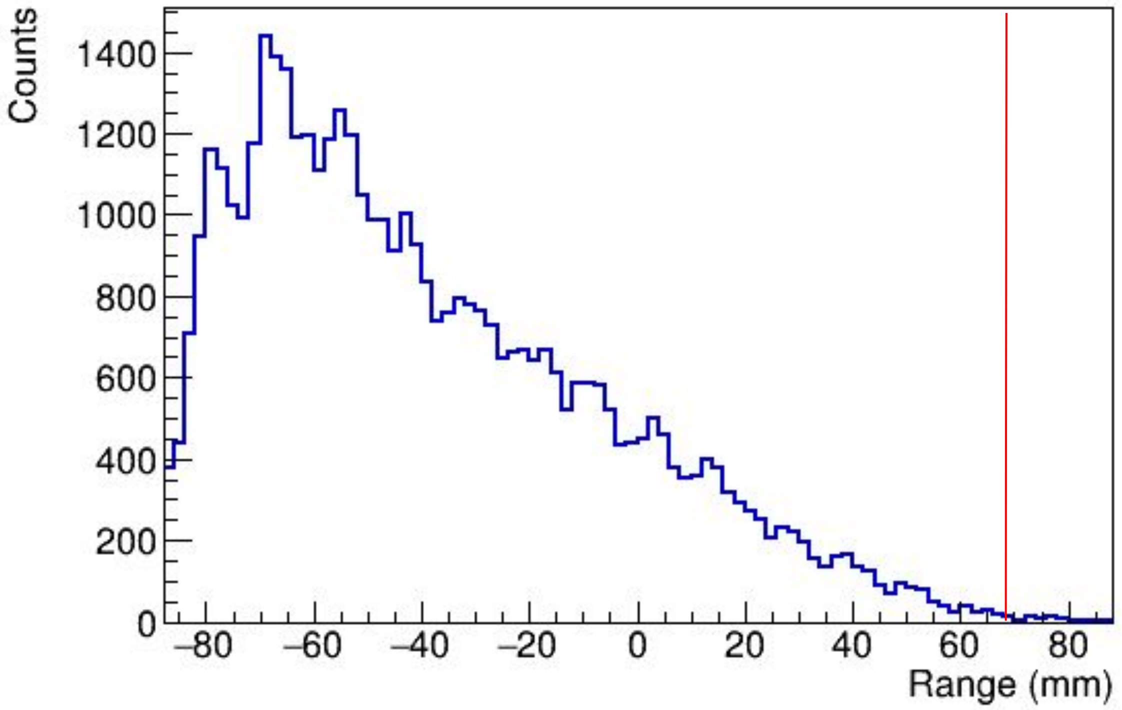
160 MeV

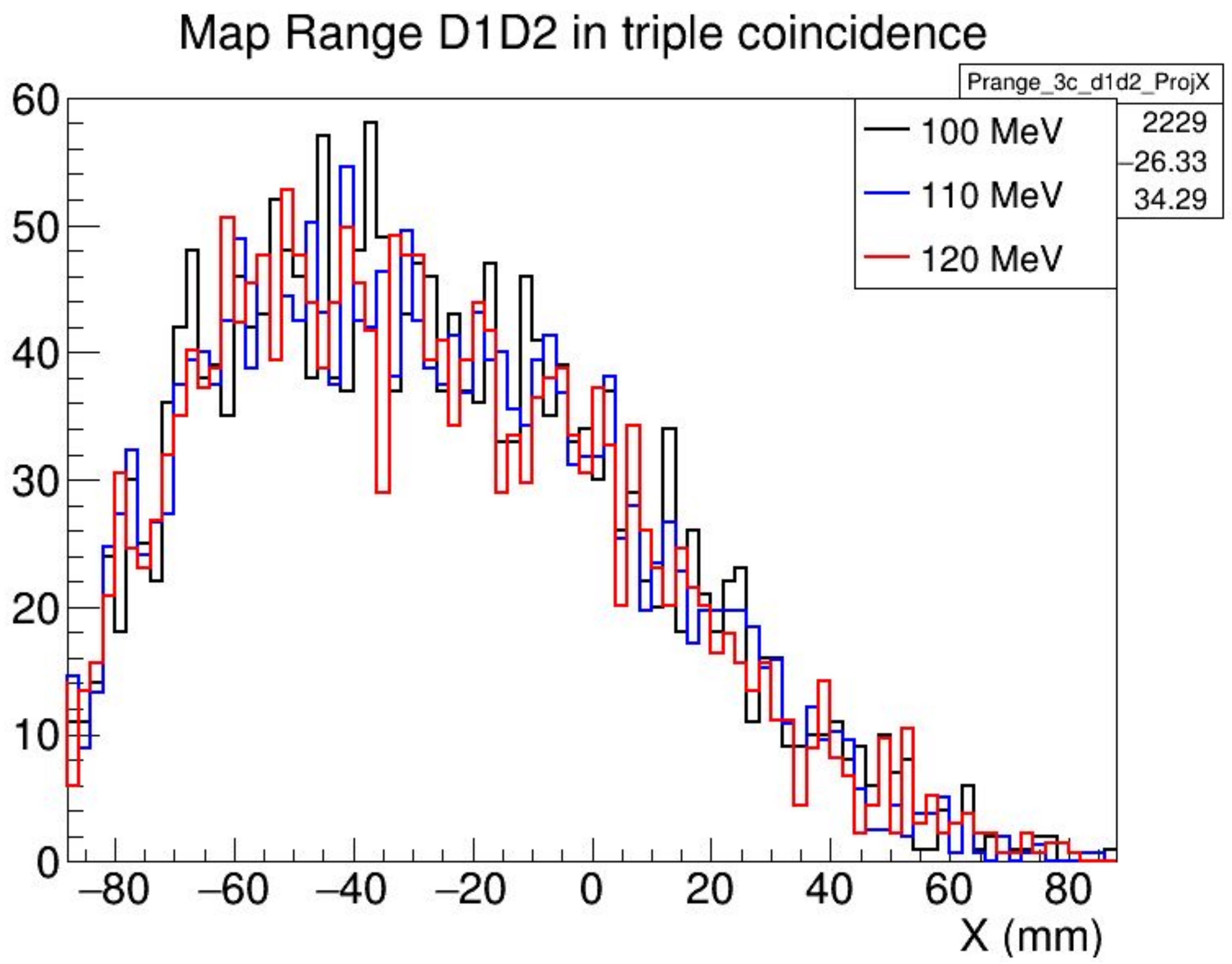


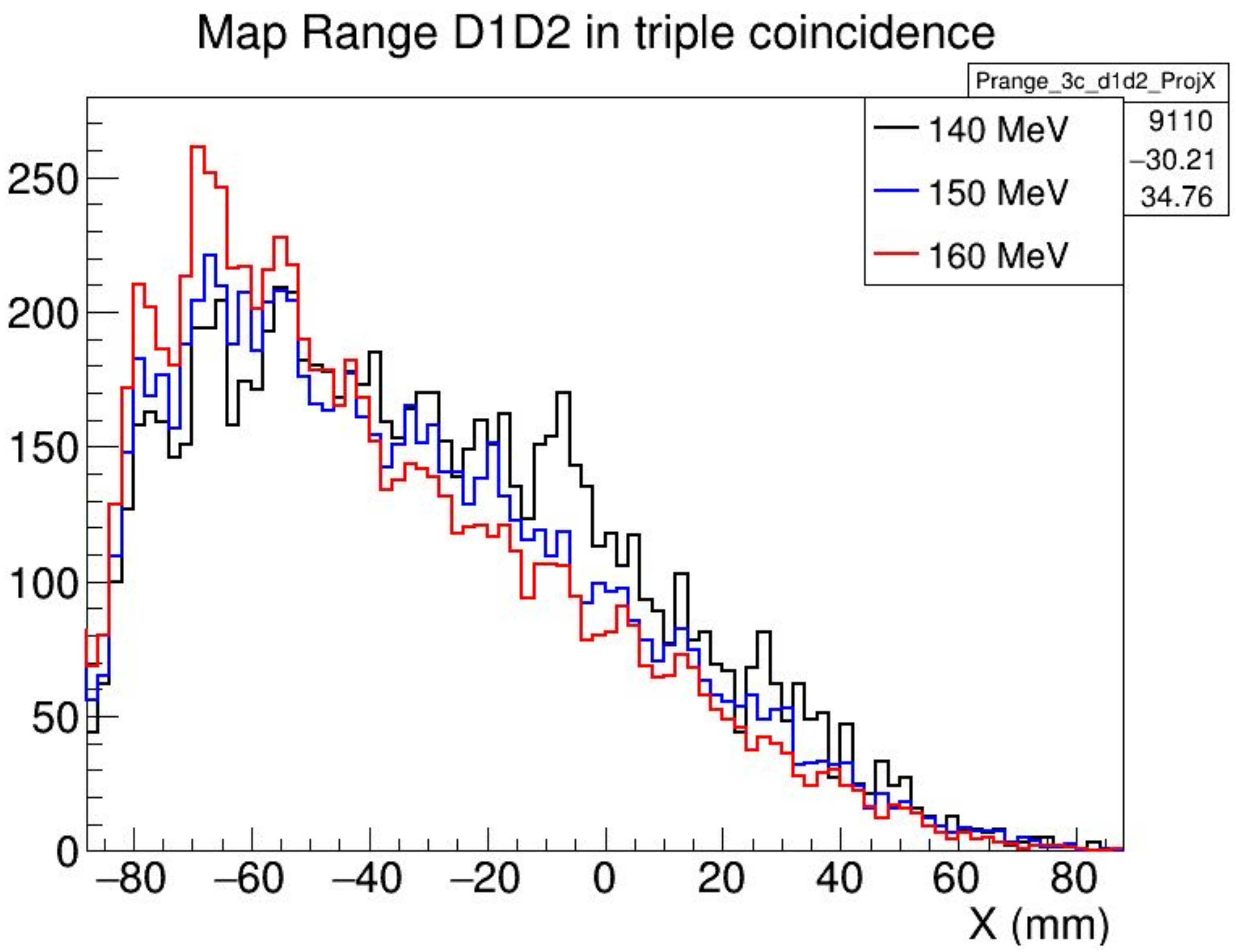
X Projection











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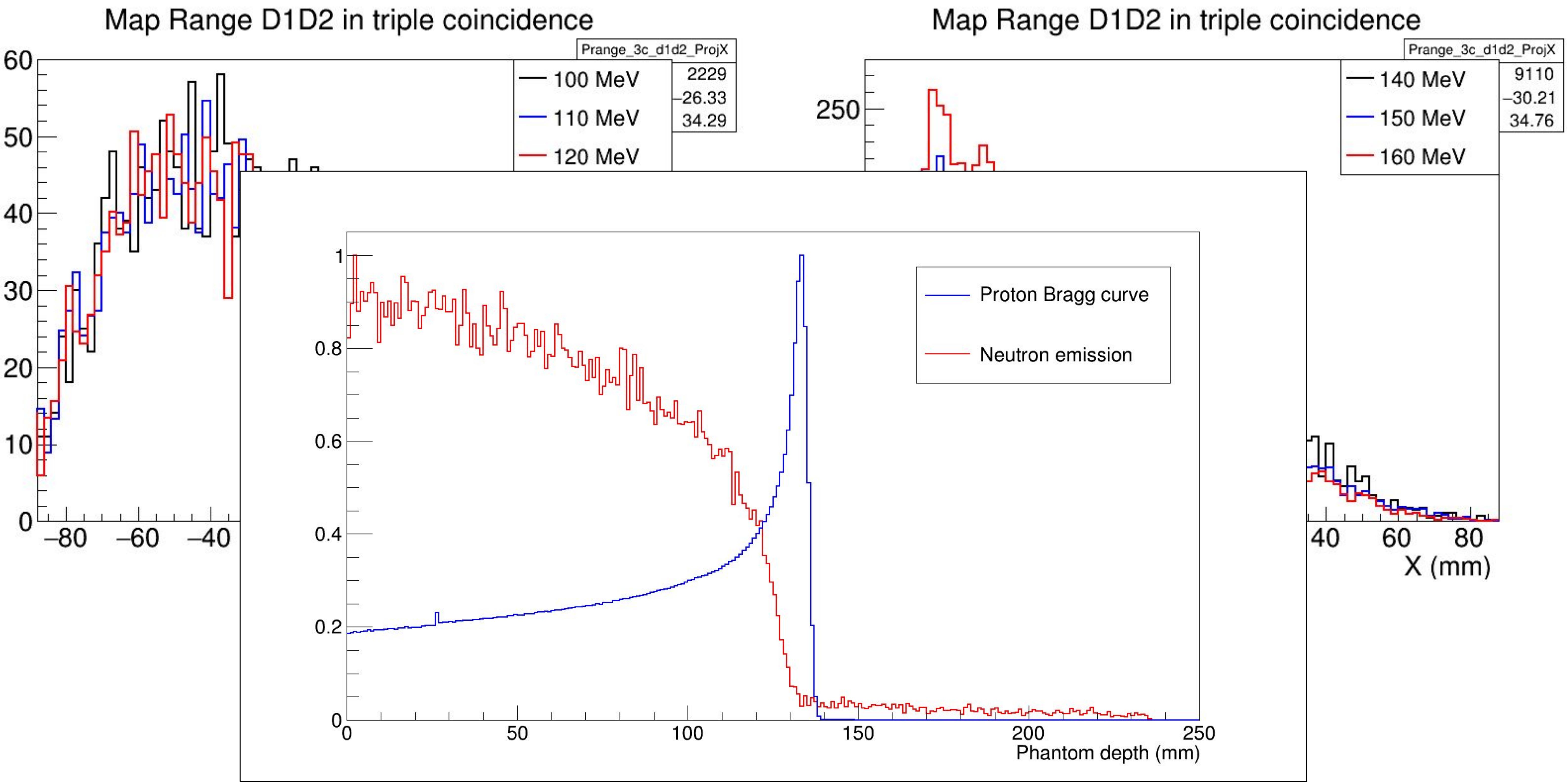
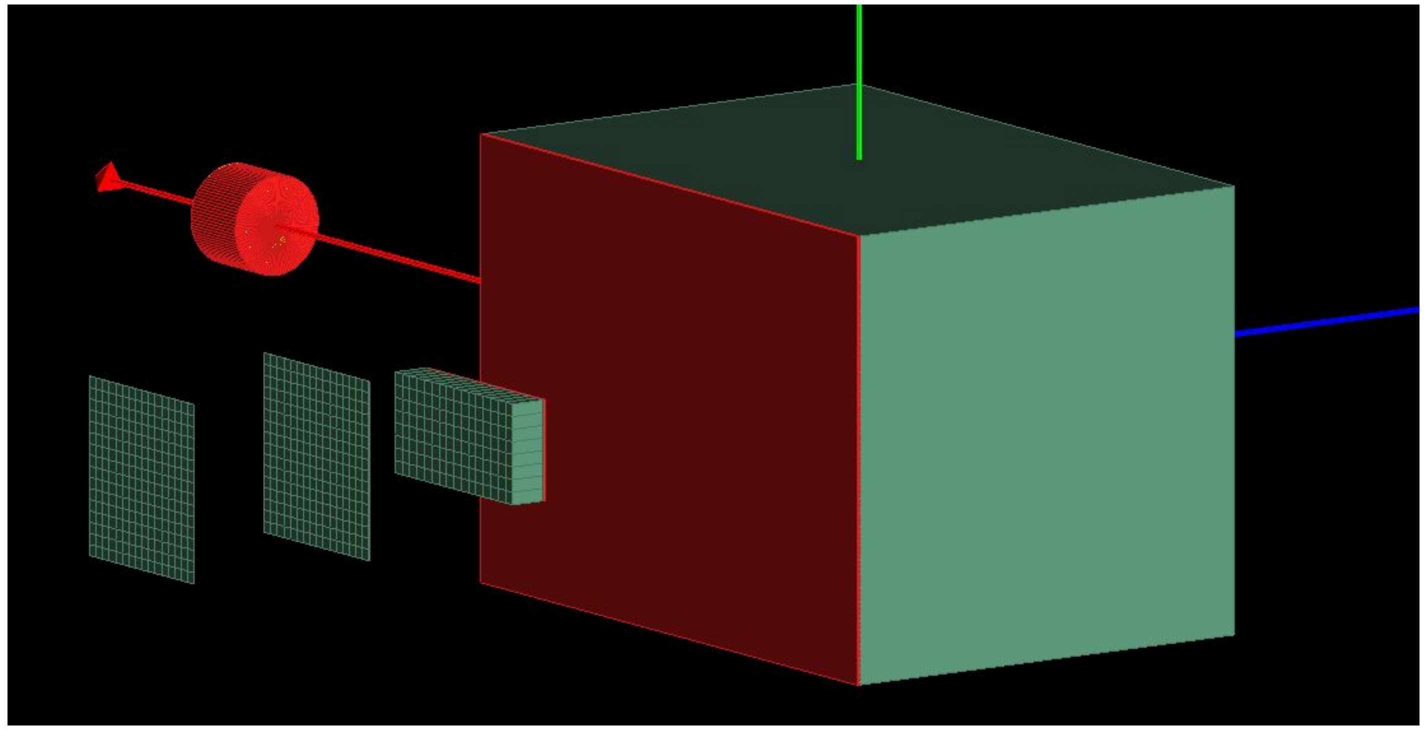
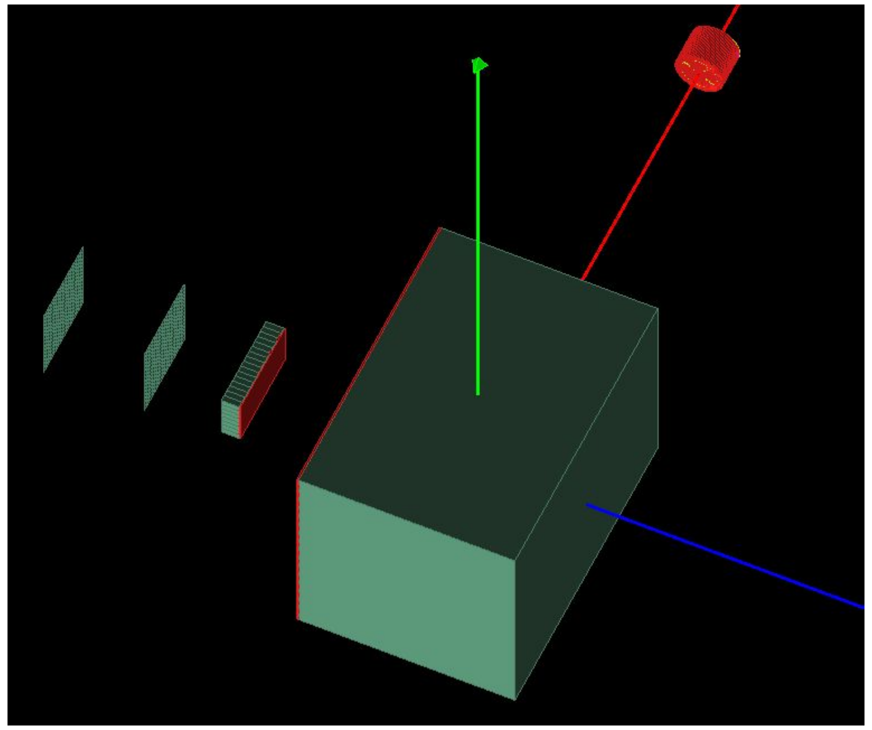
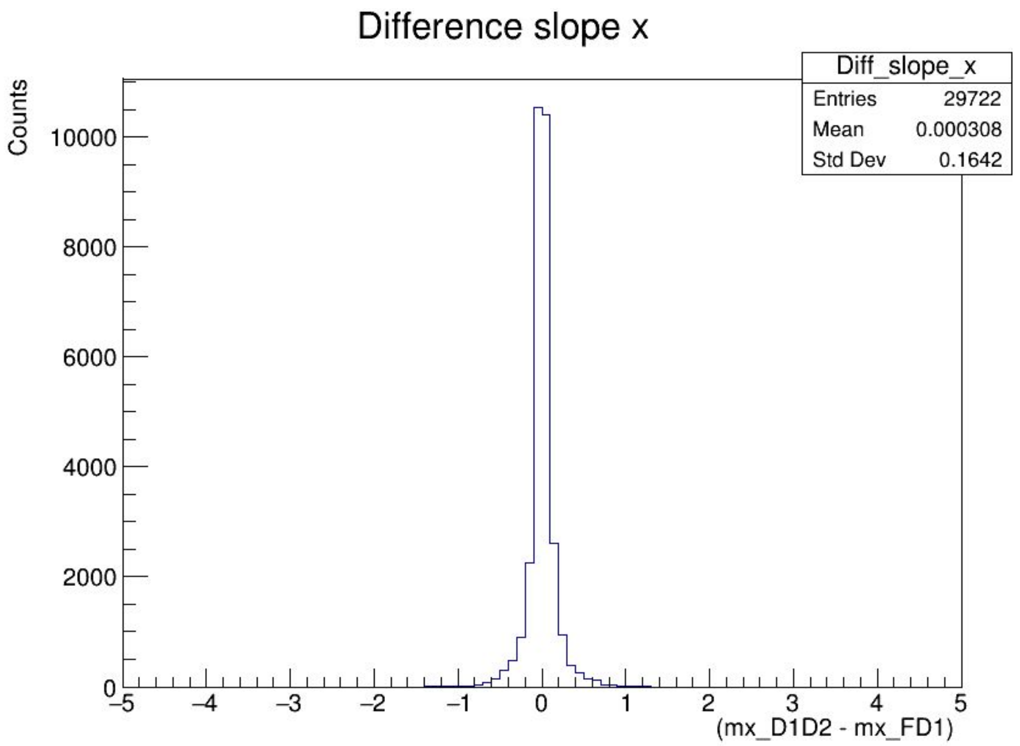

Map Range D1D2 in triple coincidence
Prange_3c_d1d2_ProjX
100 MeV
110 MeV
120 MeV
2229
-26.33
34.29
Map Range D1D2 in triple coincidence
Prange_3c_d1d2_ProjX
140 MeV
150 MeV
160 MeV
9110
-30.21
34.76
X (mm)
Proton Bragg curve
Neutron emission
Phantom depth (mm)

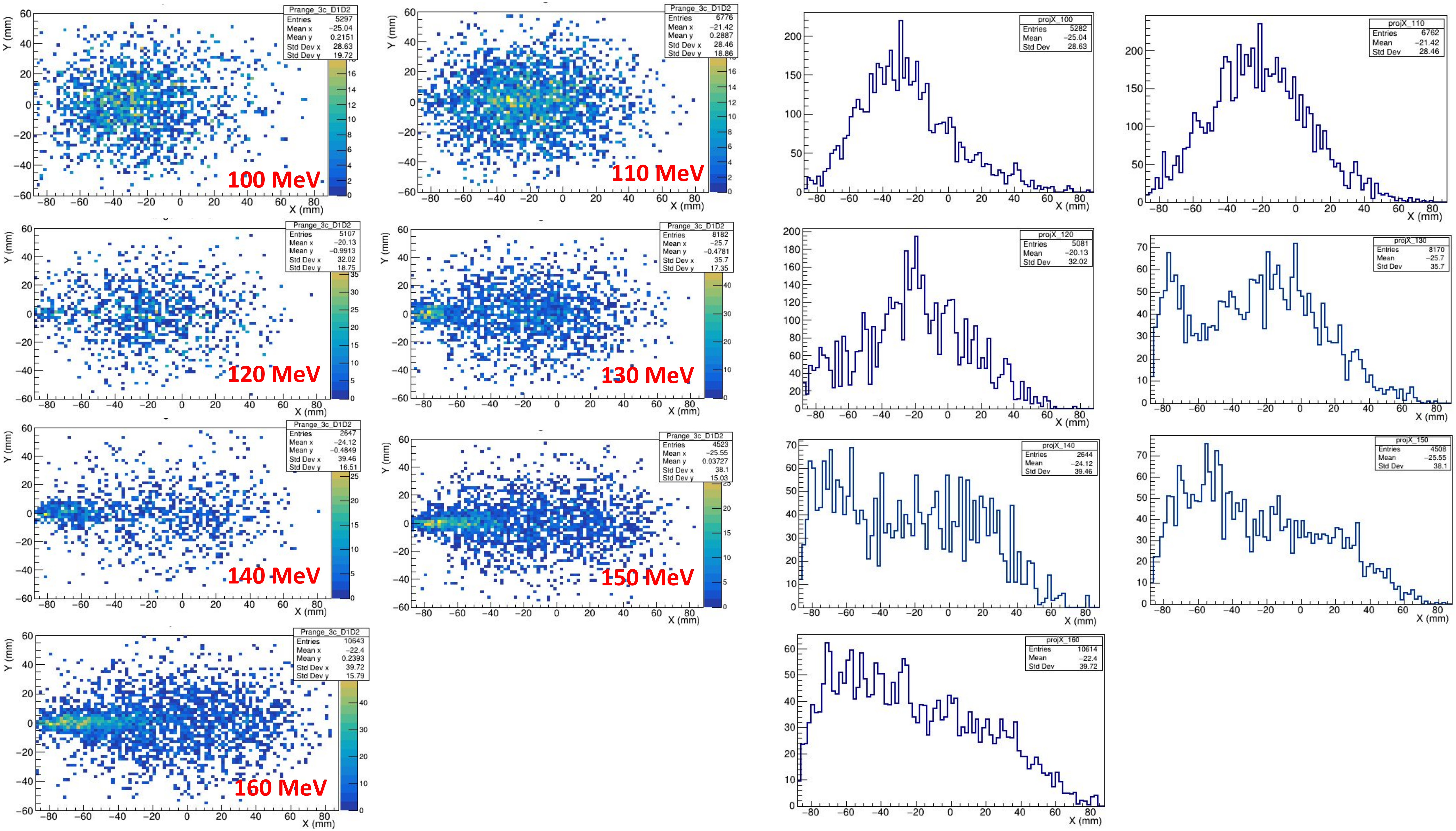
Simulation - Lateral configuration



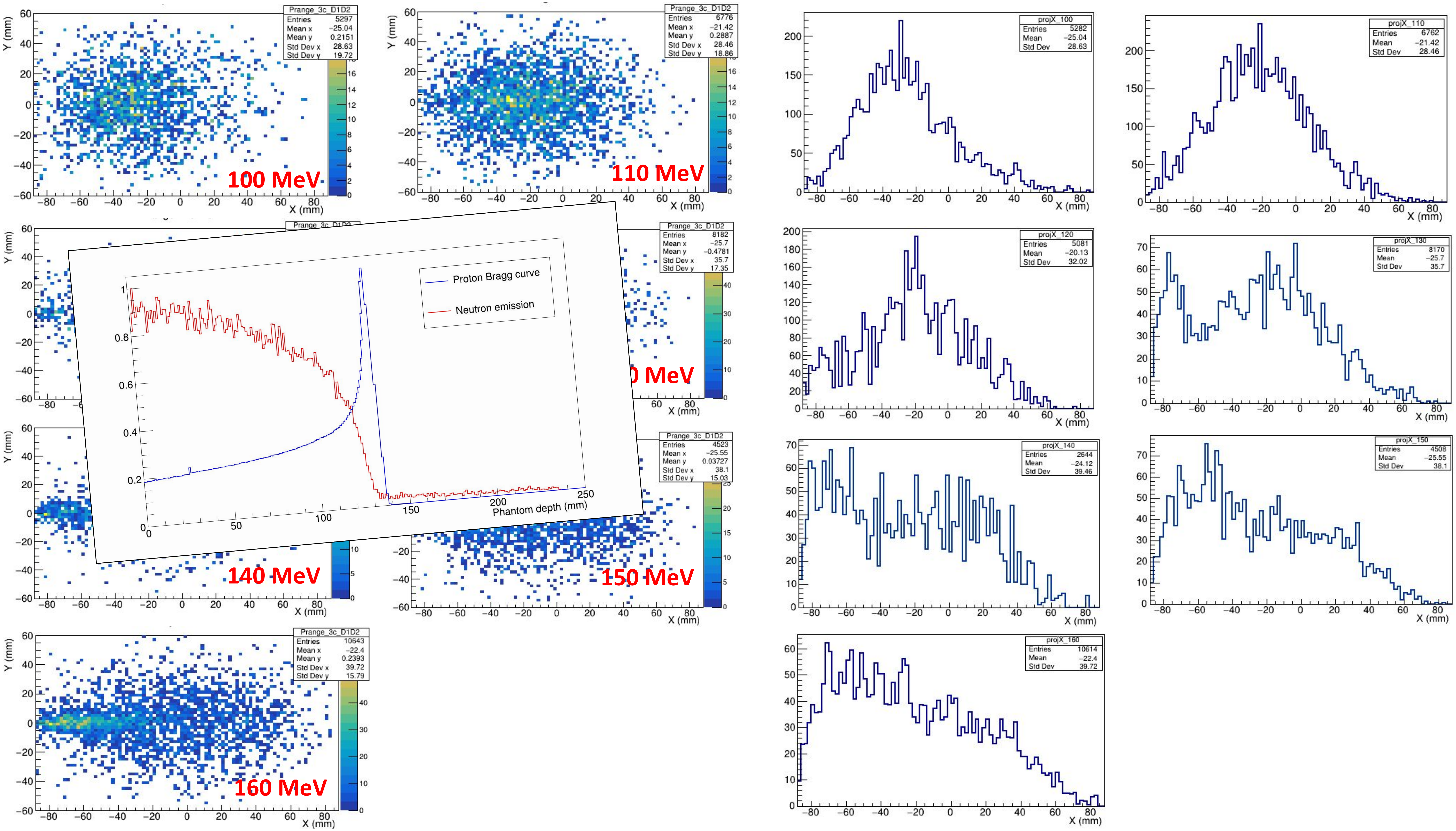




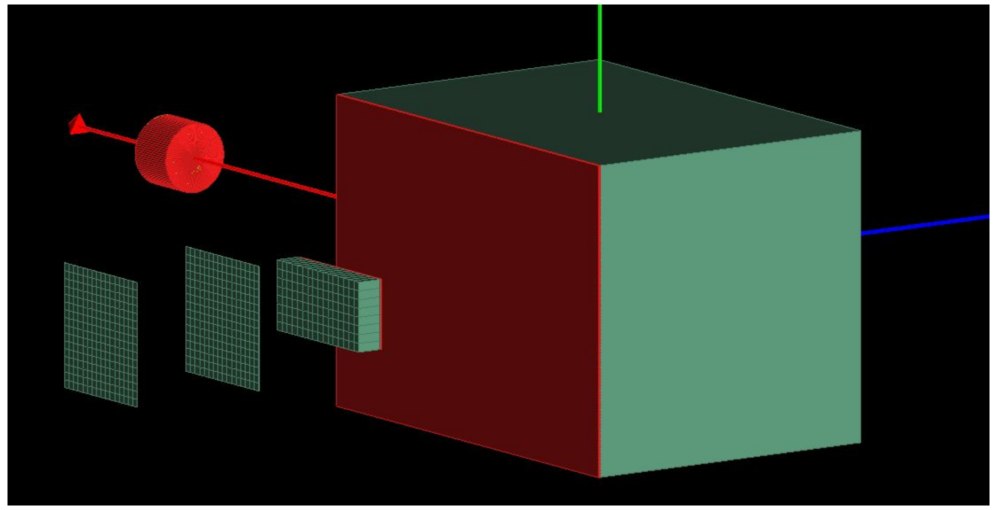
PRIDE Monte Carlo

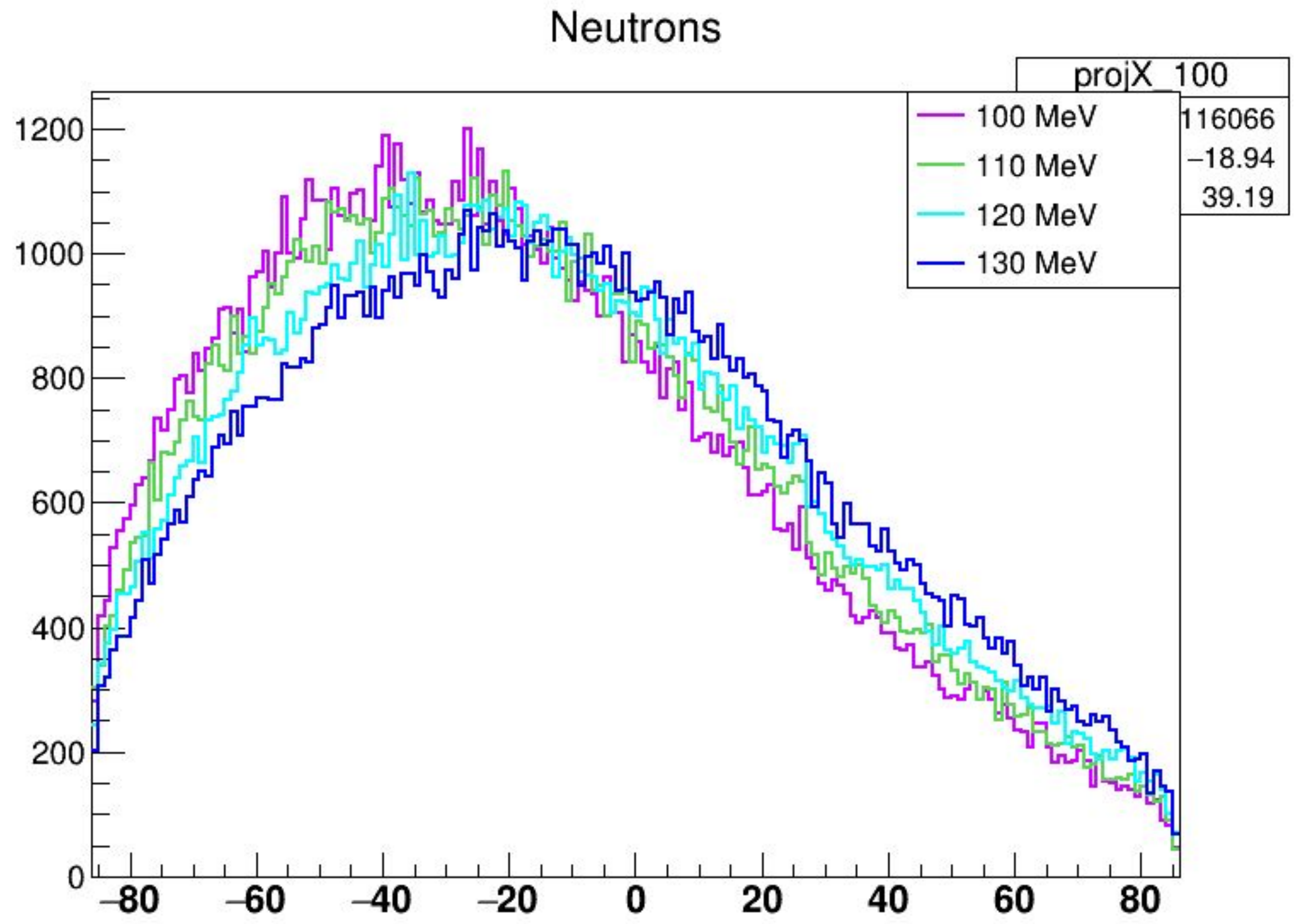


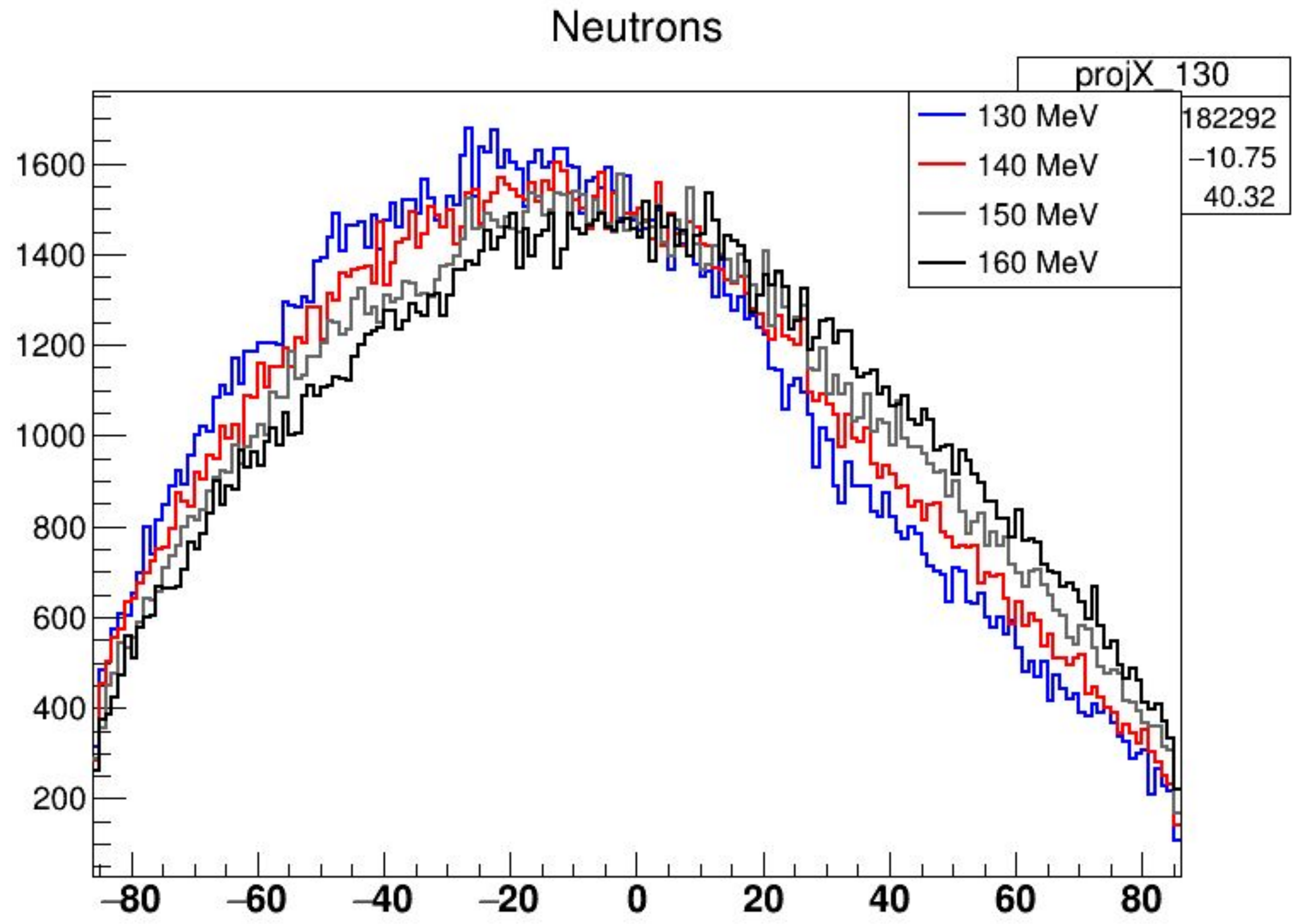
PRIDE Monte Carlo



Simulation - Lateral configuration







Summary

- Preliminary results confirm the feasibility of obtaining information on the position of the Bragg peak by detecting secondary particles.

- A clear dependence was observed between the count rate of the different components (γ, (n,p), (n,α)) and the energy of the proton beam.

  The exponential fits obtained allow us to define a calibration function with which the proton range can be estimated from the count.

  Experimental validation showed a maximum deviation of a few millimeters from the theoretical range, indicating good potential for the method, although further improvement in accuracy is still required through more comprehensive modeling.

- Lateral reconstruction shows structure, although it requires more statistics and detector optimization.

- Simulations confirm the observed trends and guide the next model adjustments.

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V Jornadas RSEF / IFIMED

THANK YOU FOR YOUR ATTENTION!

Contact us

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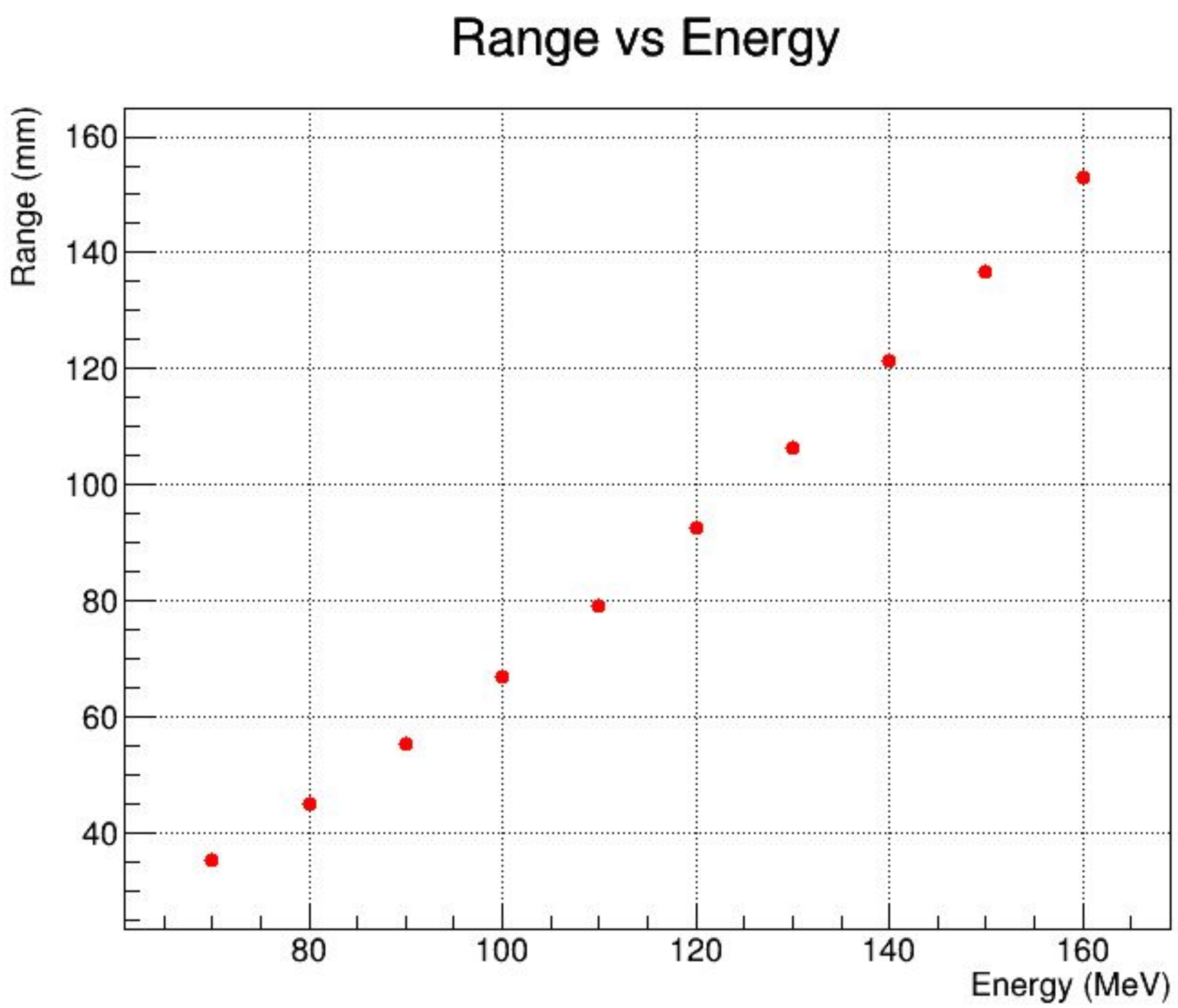
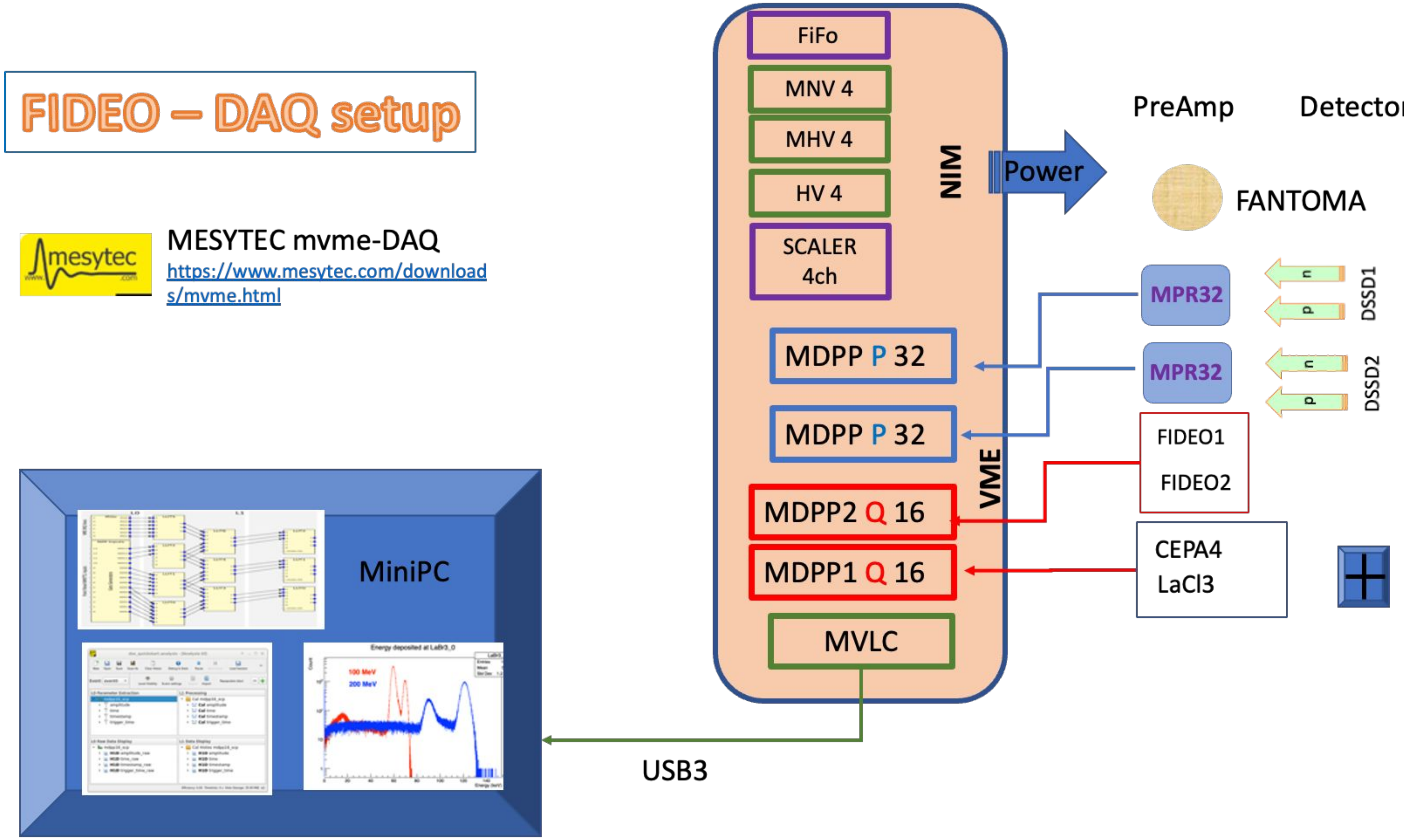
Extra Slides

Proton energy (MeV)	Range (mm,Nucl)	Range (mm,NIST)
70	35.3	35.2
80	44.9	44.7
90	55.4	55.2
100	66.8	66.5
110	79.2	78.8
120	92.4	91.9
130	106.4	105.8
140	121.2	120.6
150	136.8	136.1
160	153.1	152.1
170	170.2	169.1
180	187.9	186.7
190	206.3	205.0
200	225.3	223.9
210	245.0	



FIDEO – DAQ setup

MESYTEC mvme-DAQ
https://www.mesytec.com/downloads/mvme.html



Possible Candidates

35Cl(n,p)35S
35Cl(n,a)32P

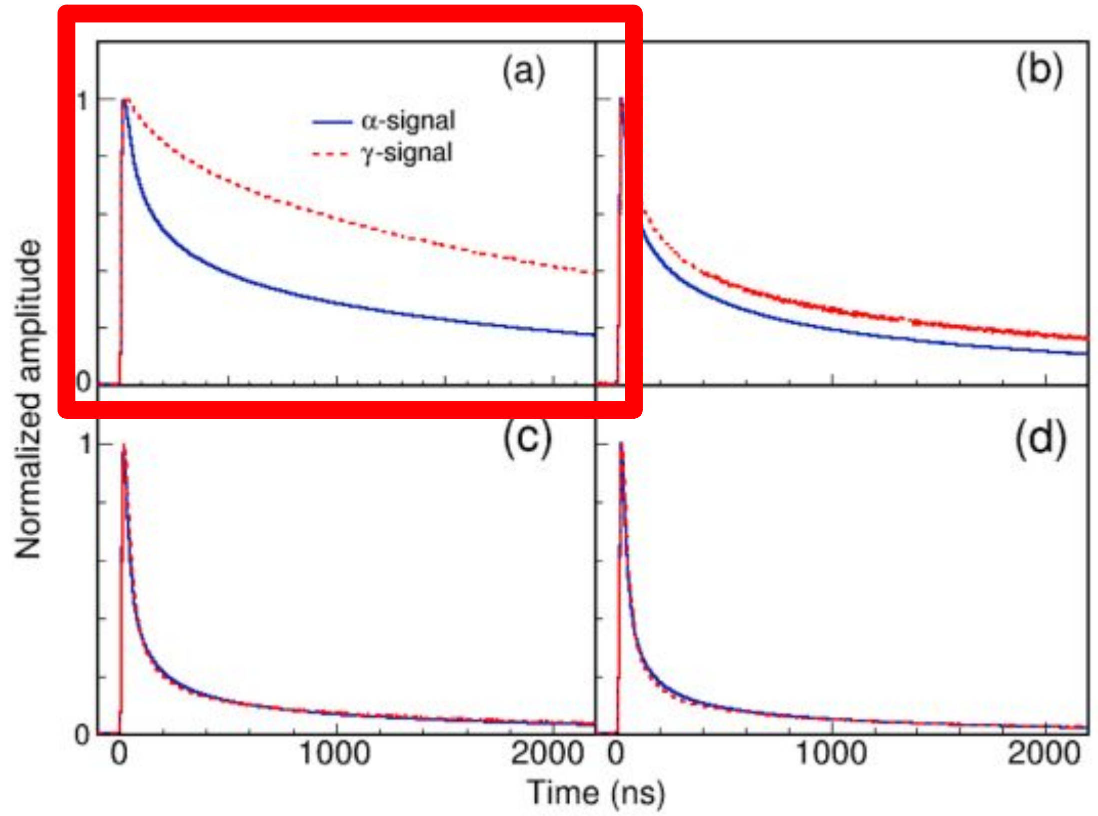
- **CLYC** ($Cs_2\,Li\,Y\,Cl_6\!:\!Ce$)

  Whit a good PSD capability neutron-γ but cannot discriminate the reaction products within the crystal. It's better for slow neutrons

- $\boldsymbol{LaCl_3\!:\!Ce}$

  The best **FOM** values were estimated to be 2.5, 1.8, 0.9, and 0.8 for pure, 0.01%, 0.05%, and 0.1% Ce-doped LaCl3 crystals, respectively.

  Decreasing Ce concentration produces a better PSD discrimination.



(a) Pure **(b)** 0.01% **(c)** 0.05% **(d)** 0.1% Ce Doped LaCl3 crystals

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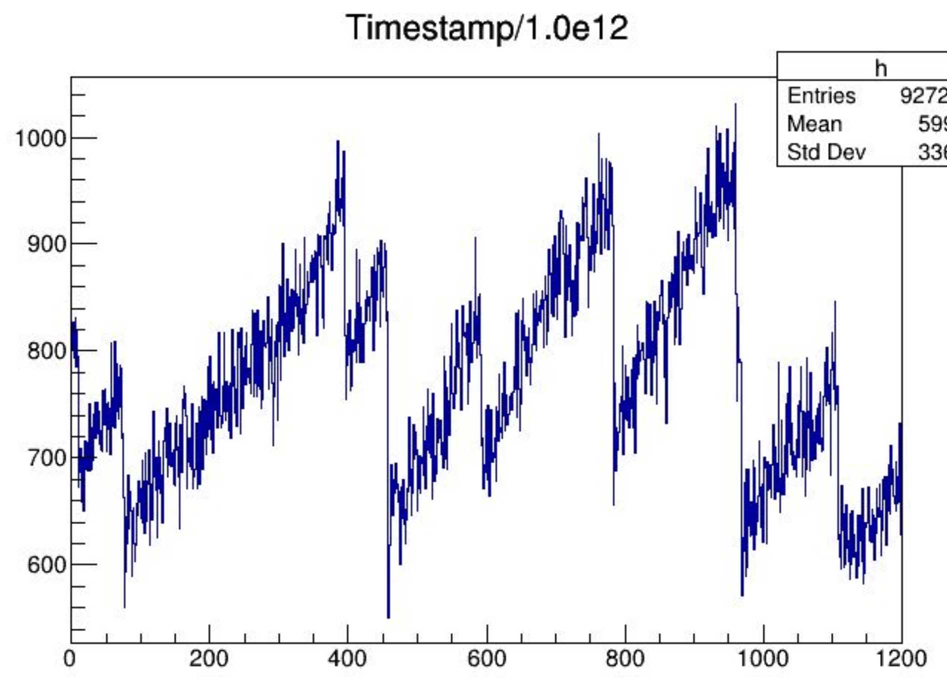
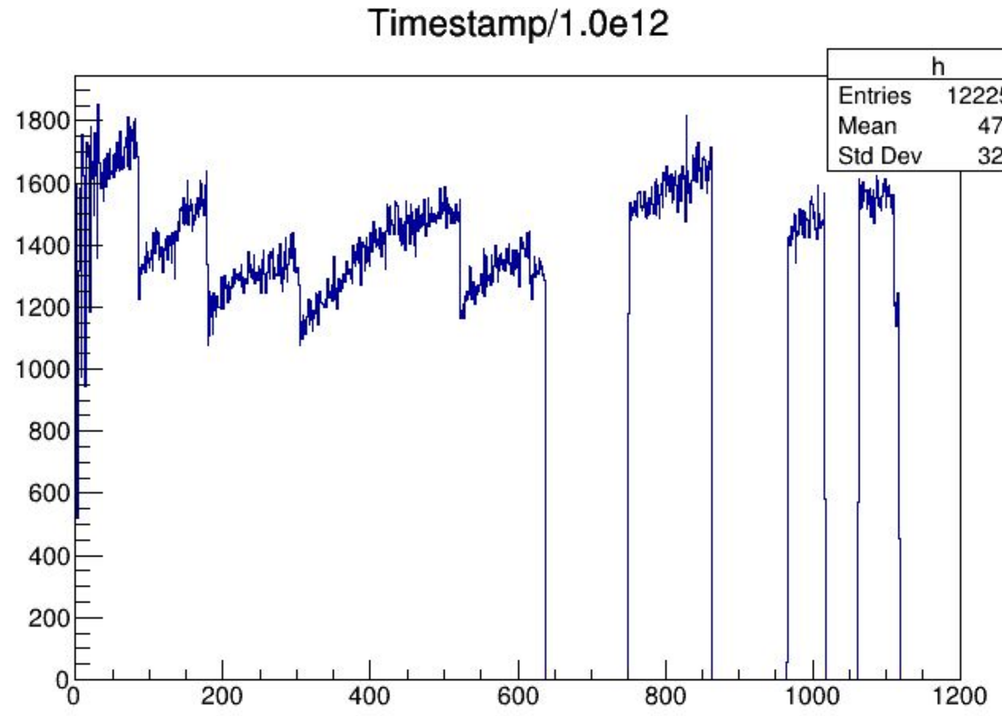
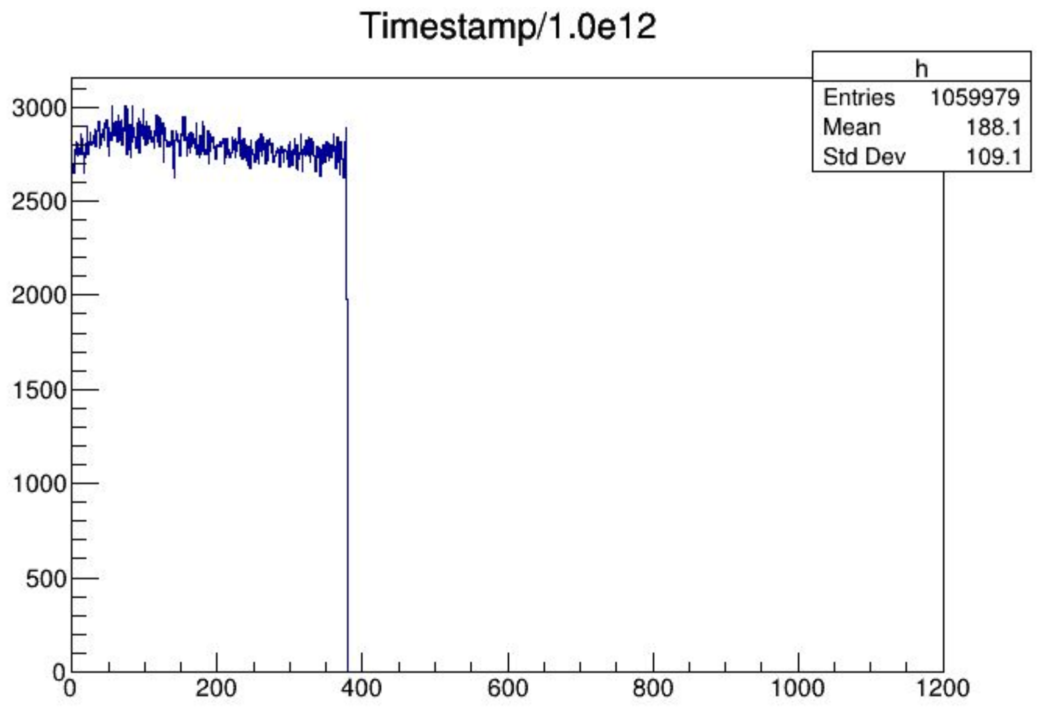
130 MeV run 025
m = 772.61917



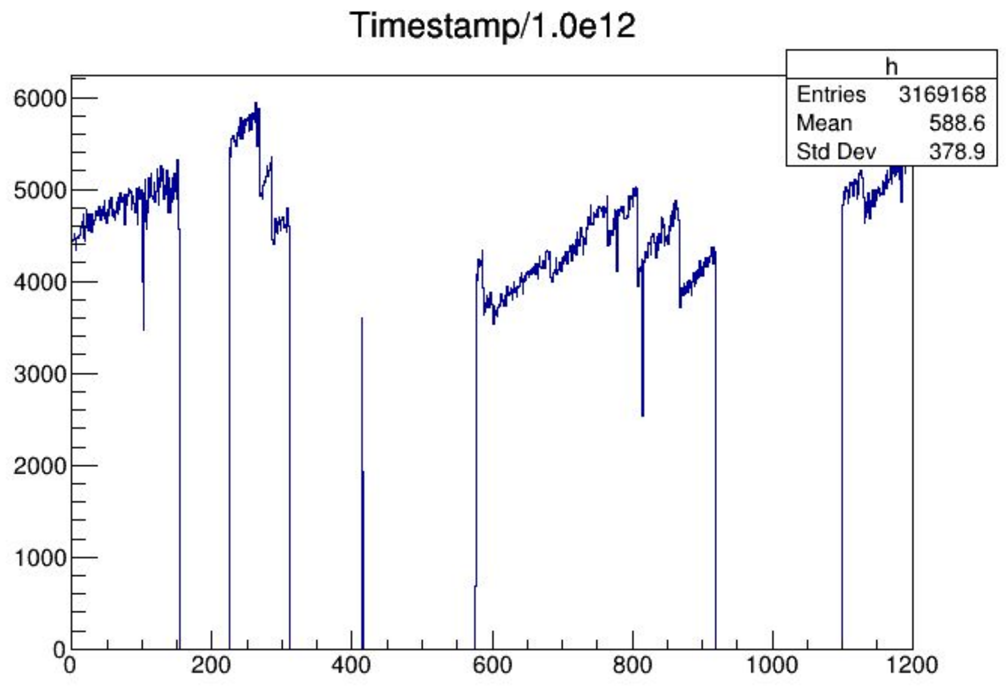
140 MeV run 027



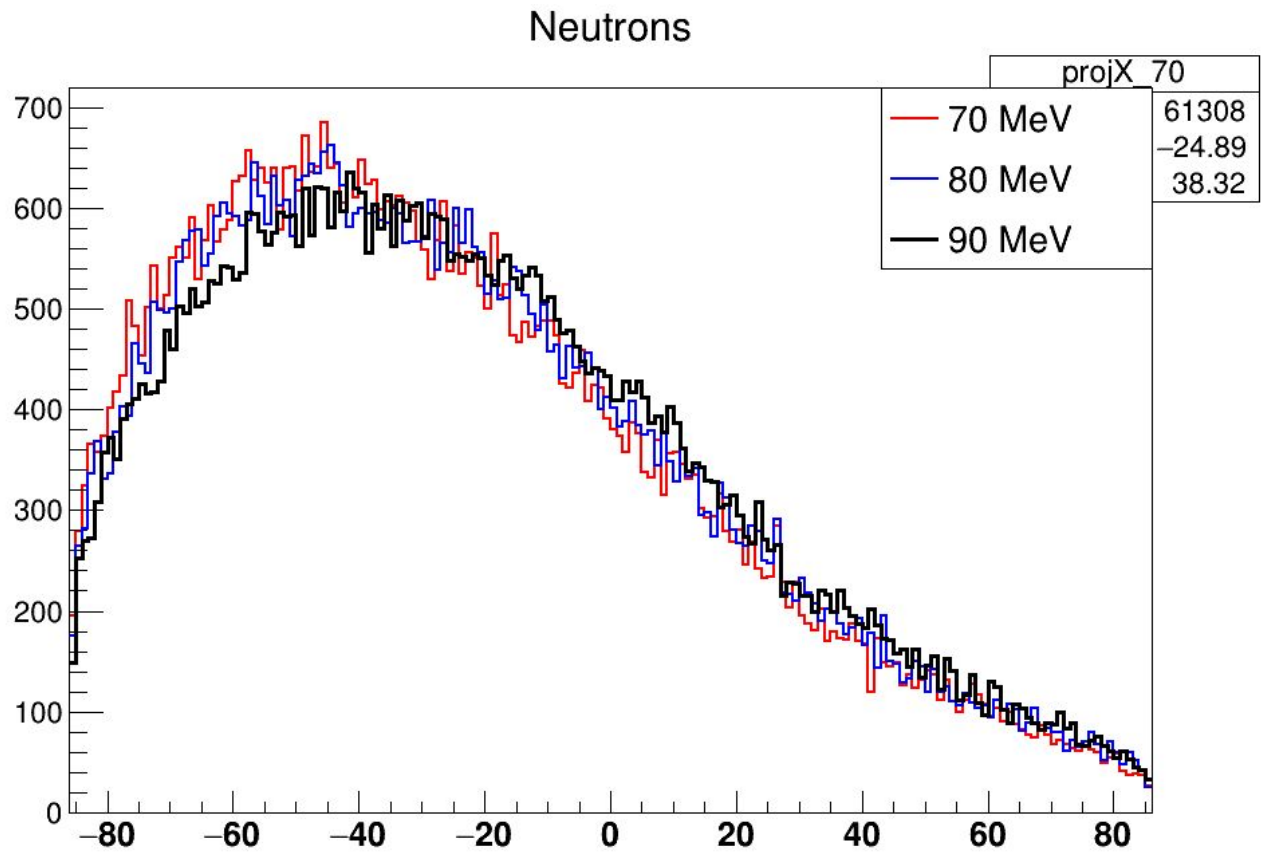
150 MeV run 014

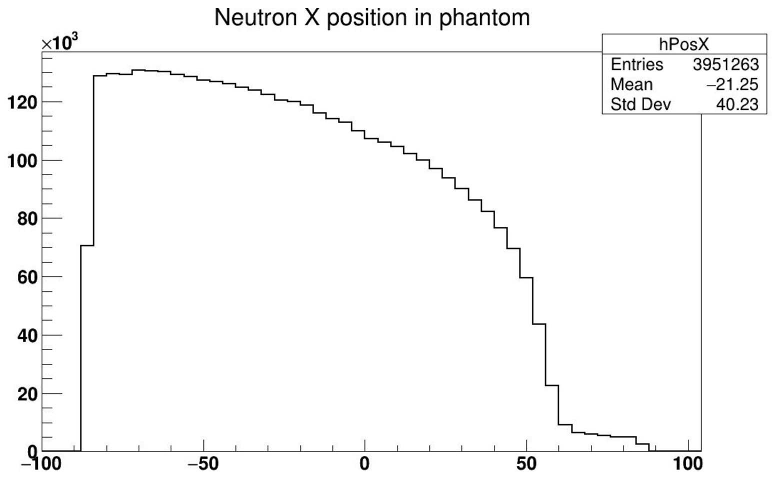


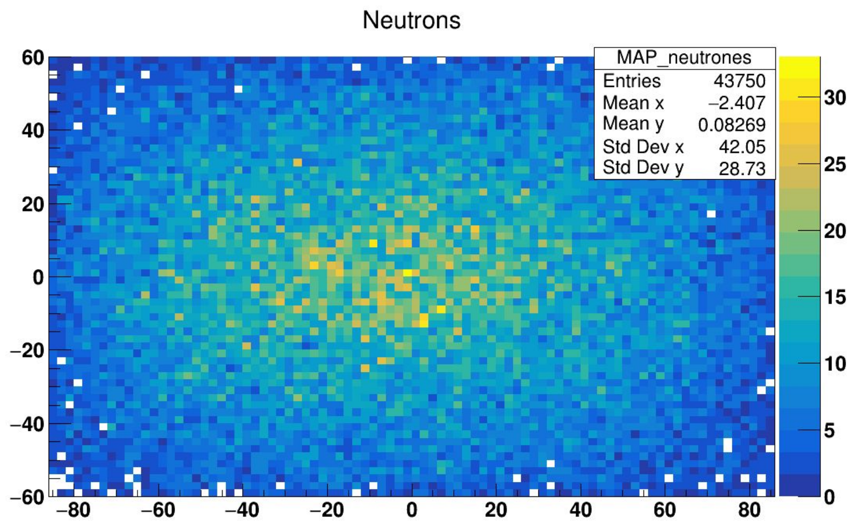
160 MeV run 009

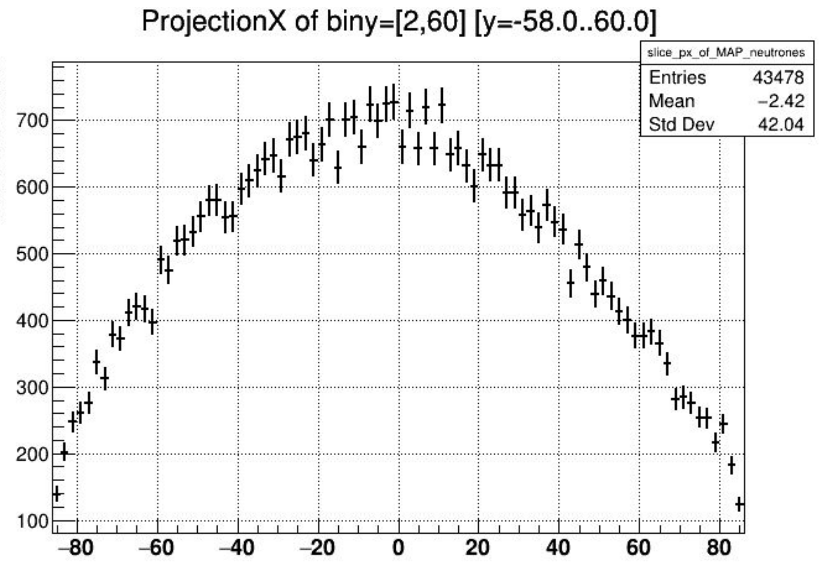


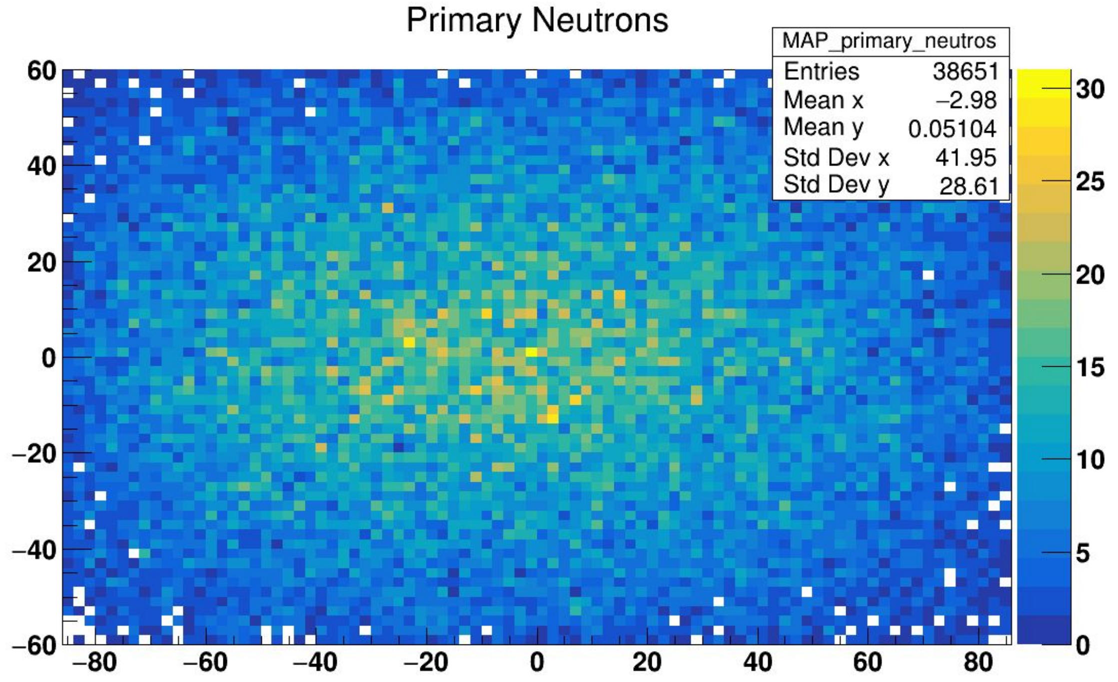
Simulation - Lateral configuration

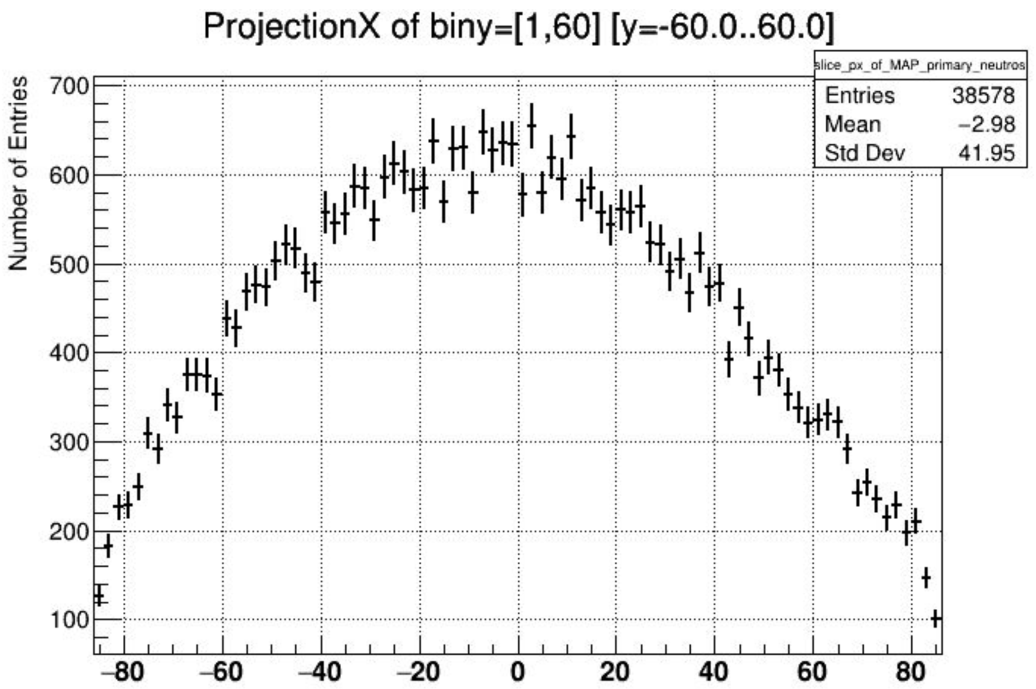












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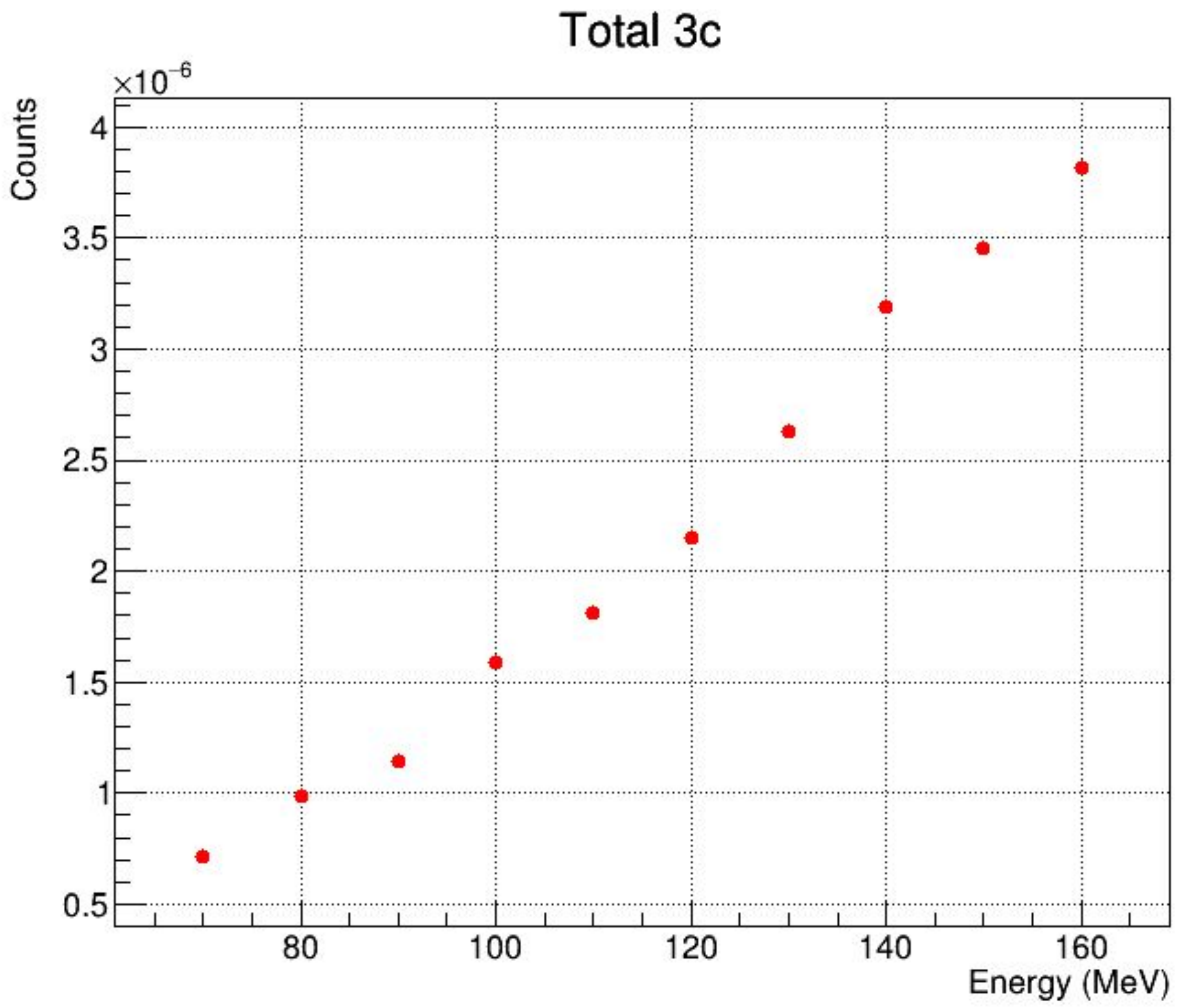
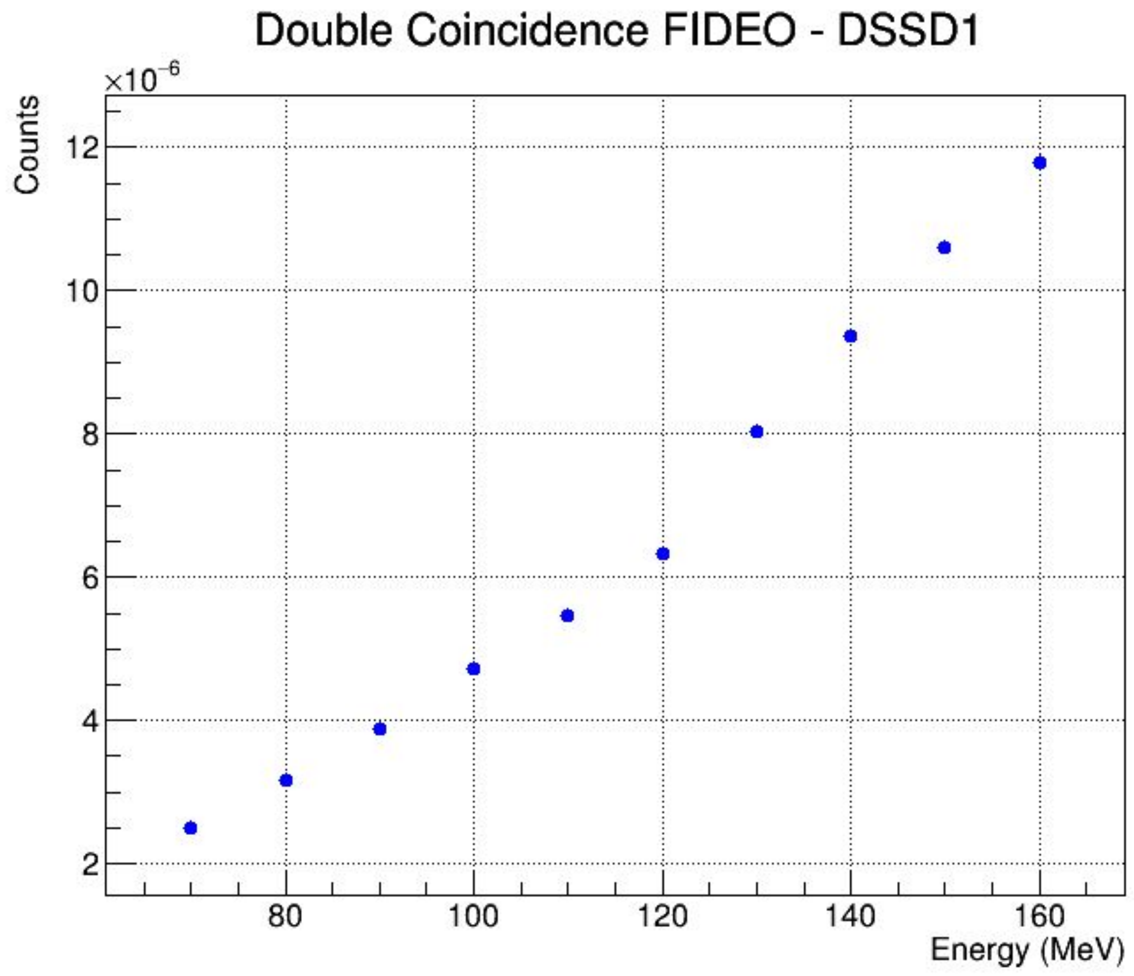
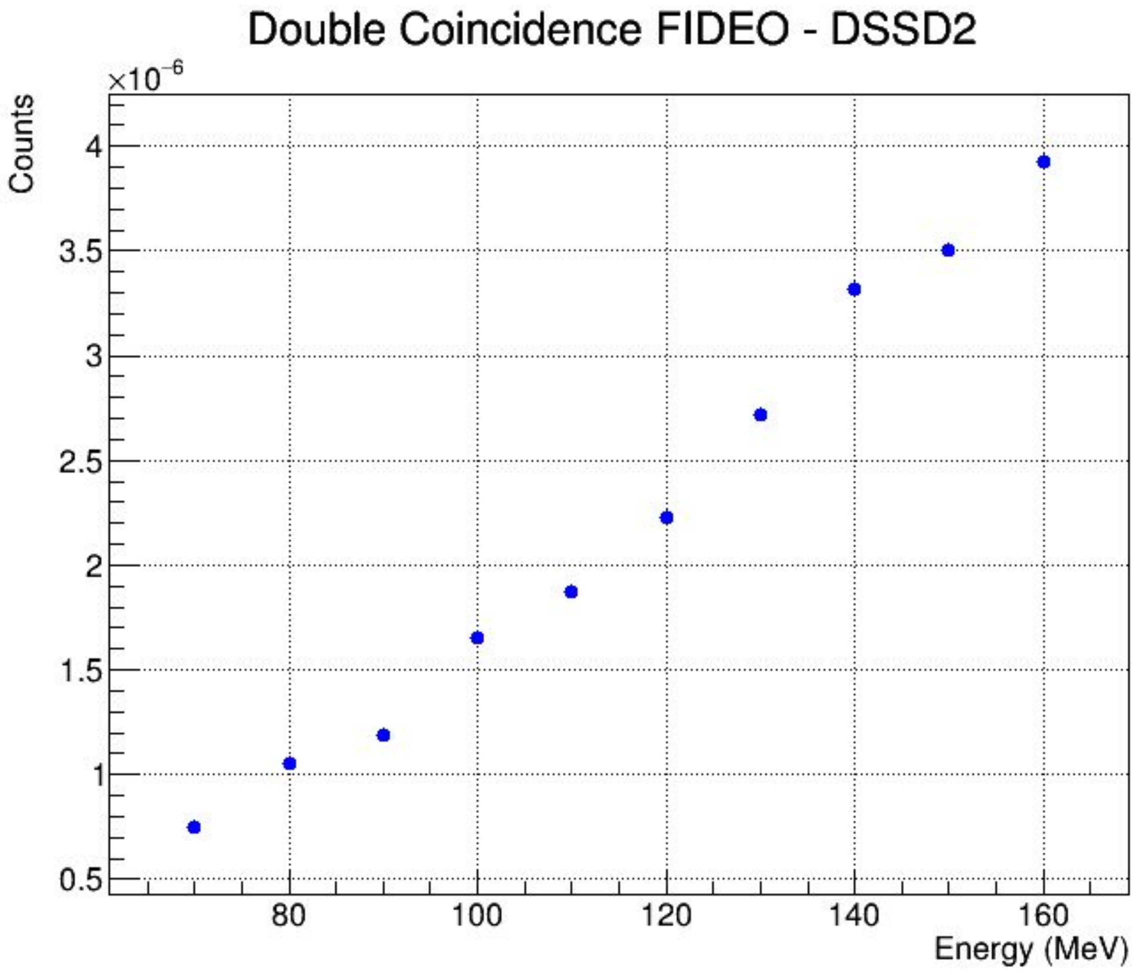
Rate lateral Simulations







-Sensitivity

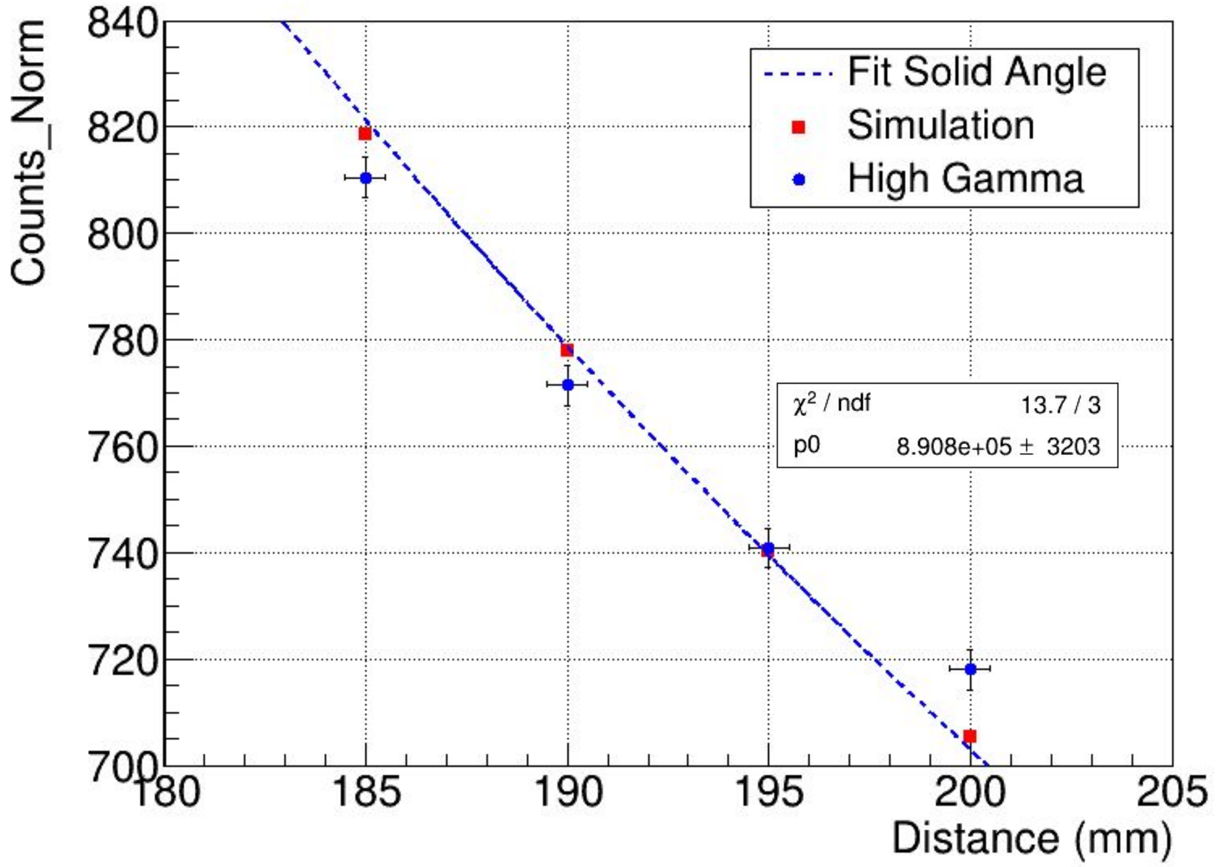
Distance (mm)	Counts Alpha	Counts total gammas	Counts protons	Counts High Gamma
185	256	11766	405	810
190	242	11356	386	771
195	232	10957	368	741
200	222	10652	356	718

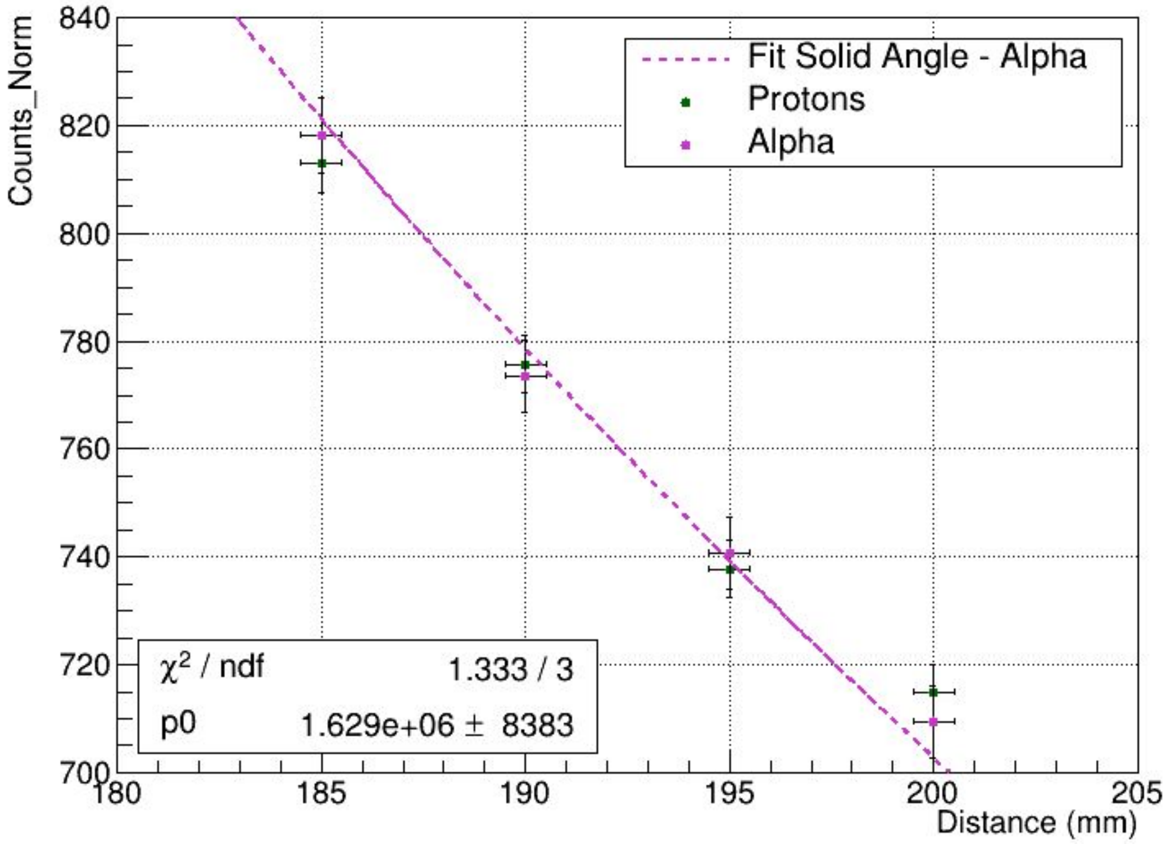
Target of 9Be

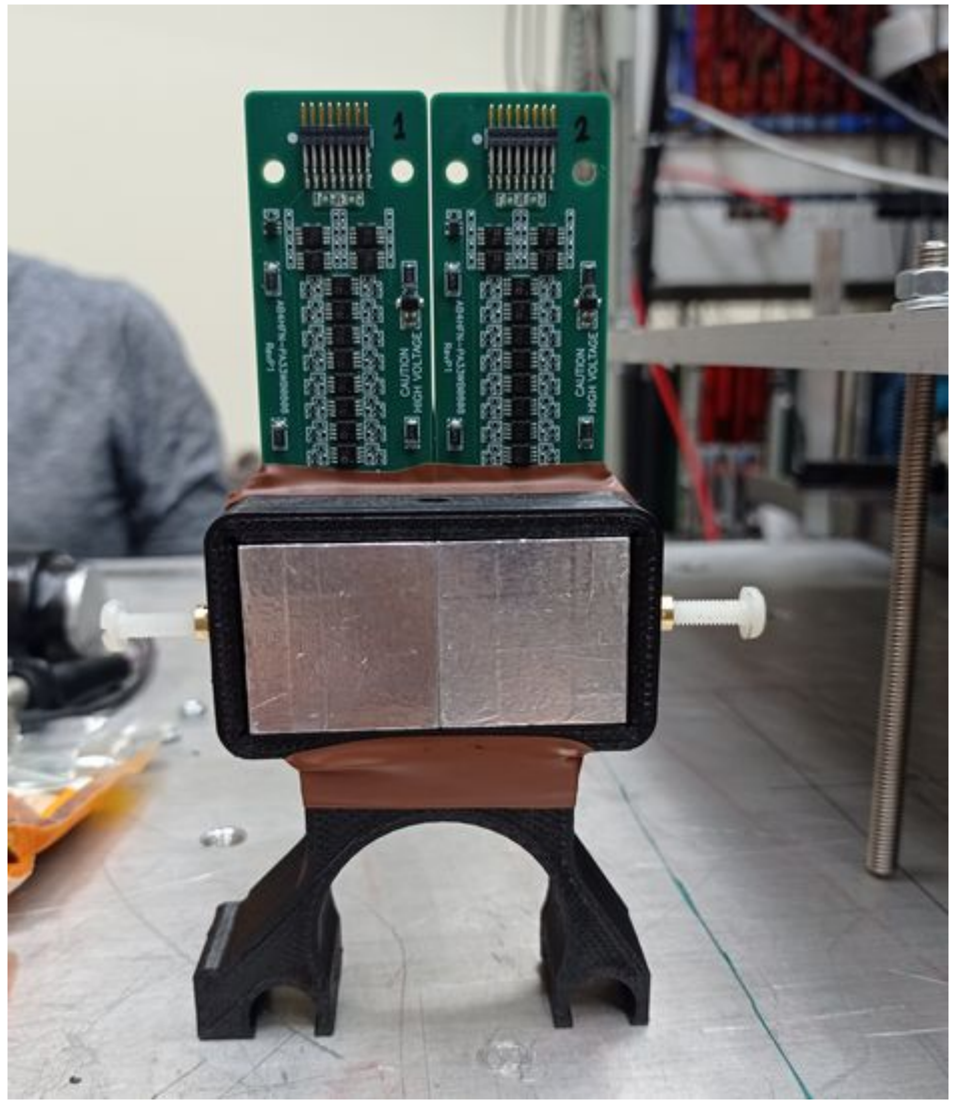
Alphas 4 MeV

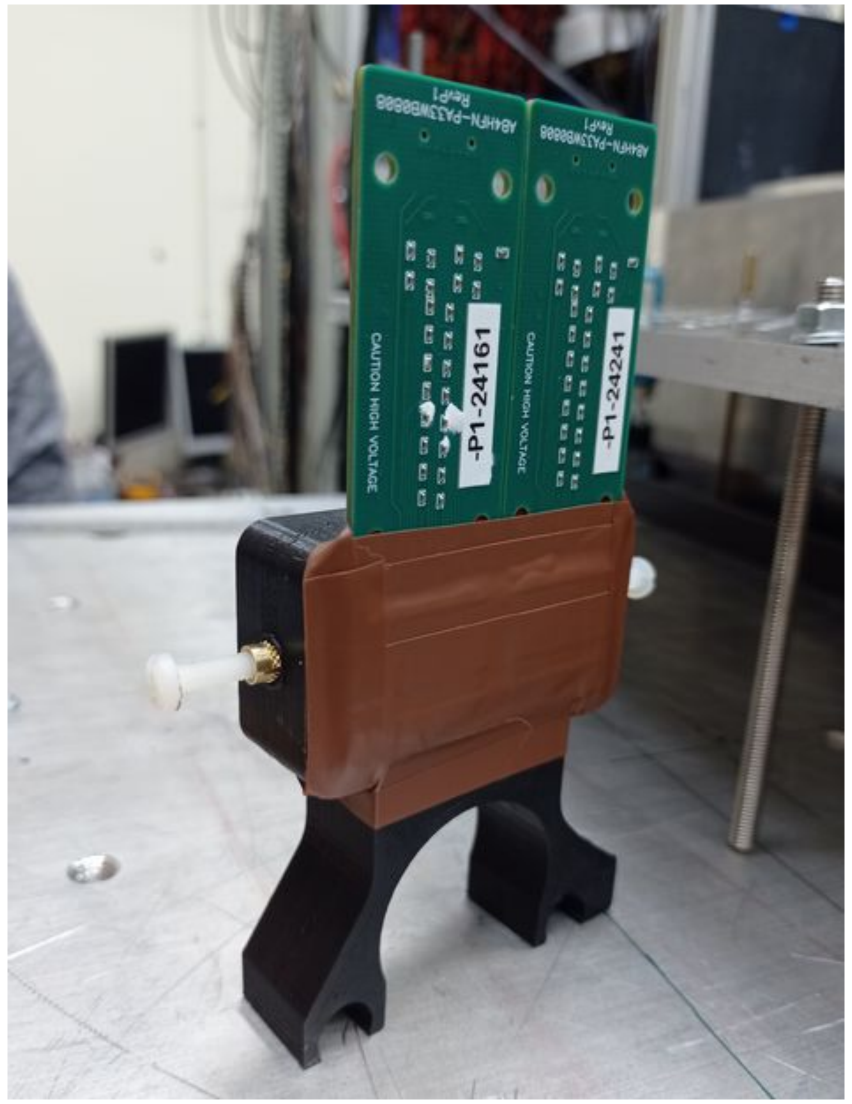
HV: -1100

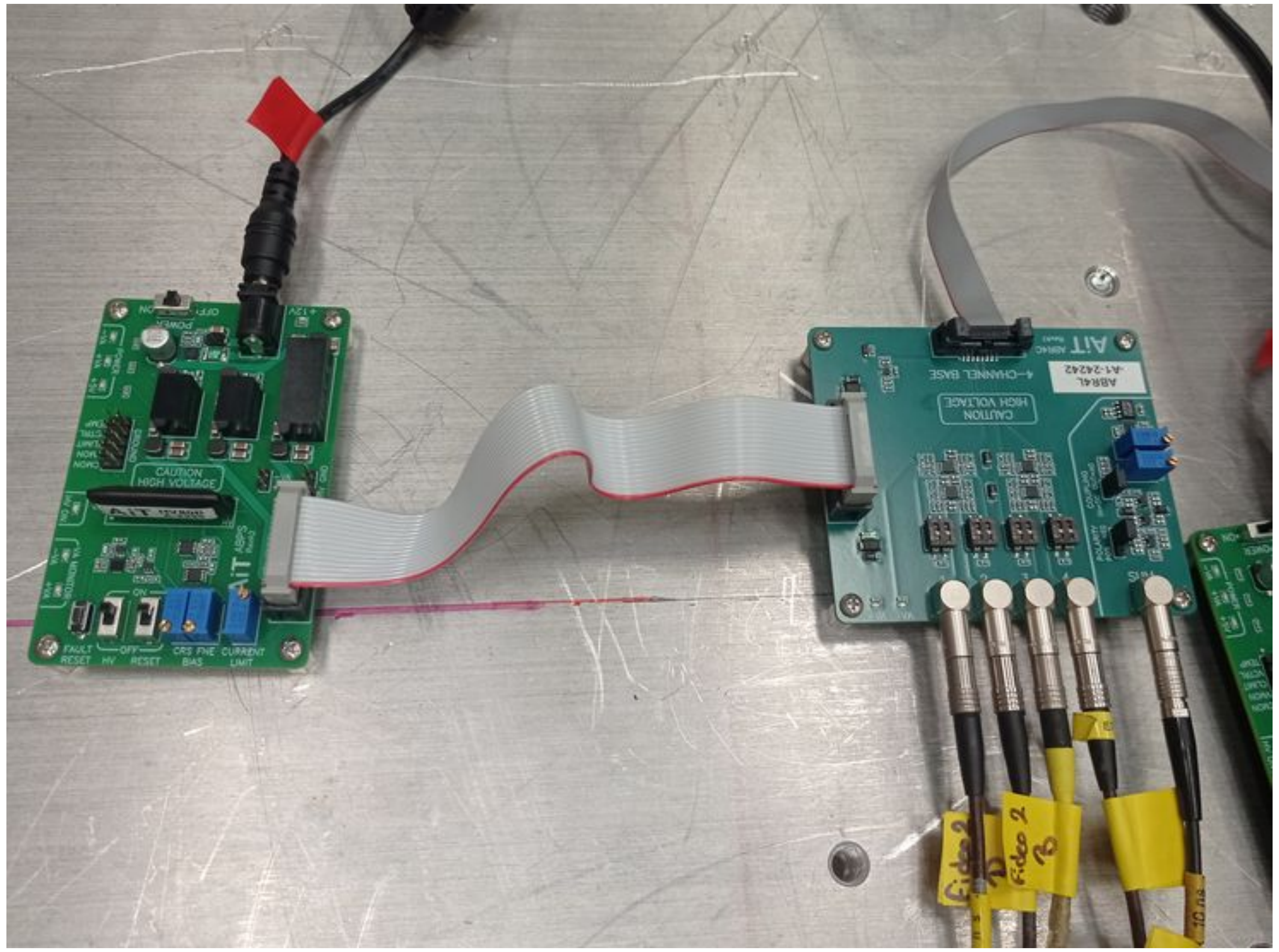
$$\frac{\Omega}{4\pi} = \frac{p0}{2} \cdot \left(1 - \frac{x}{\sqrt{x^2 + r^2}}\right)$$

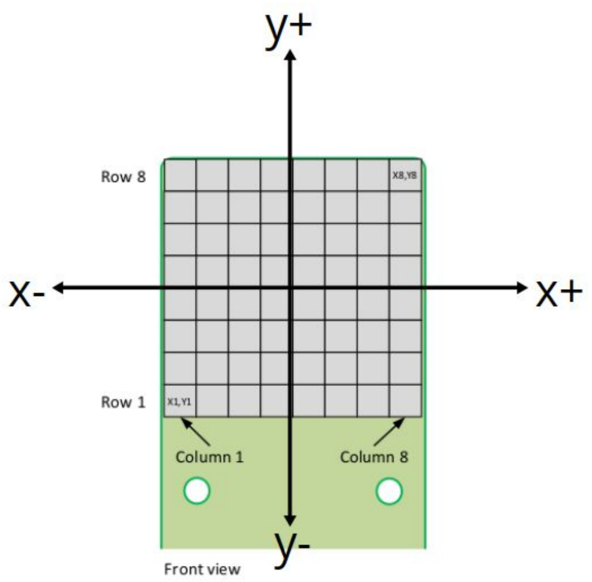








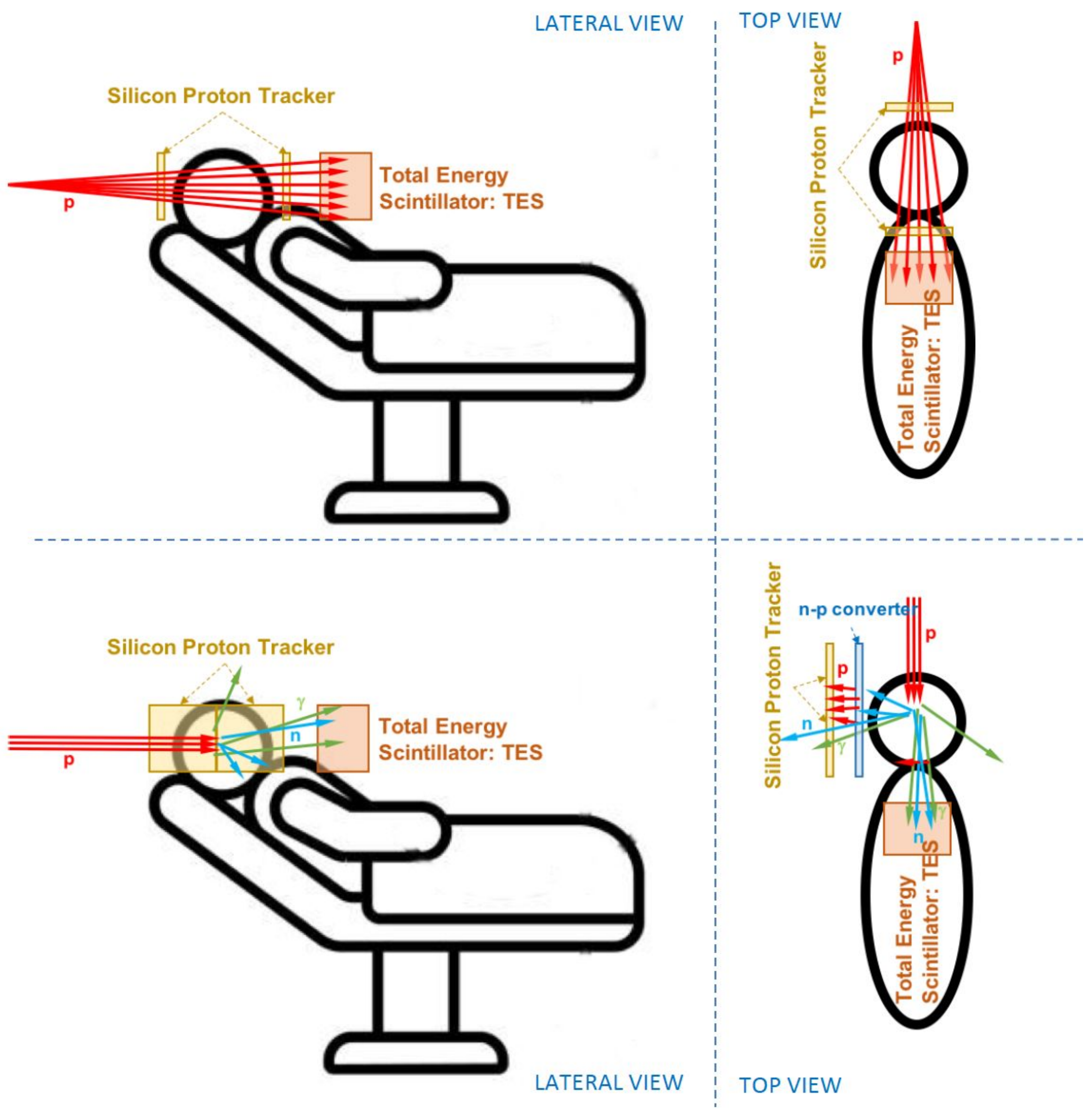




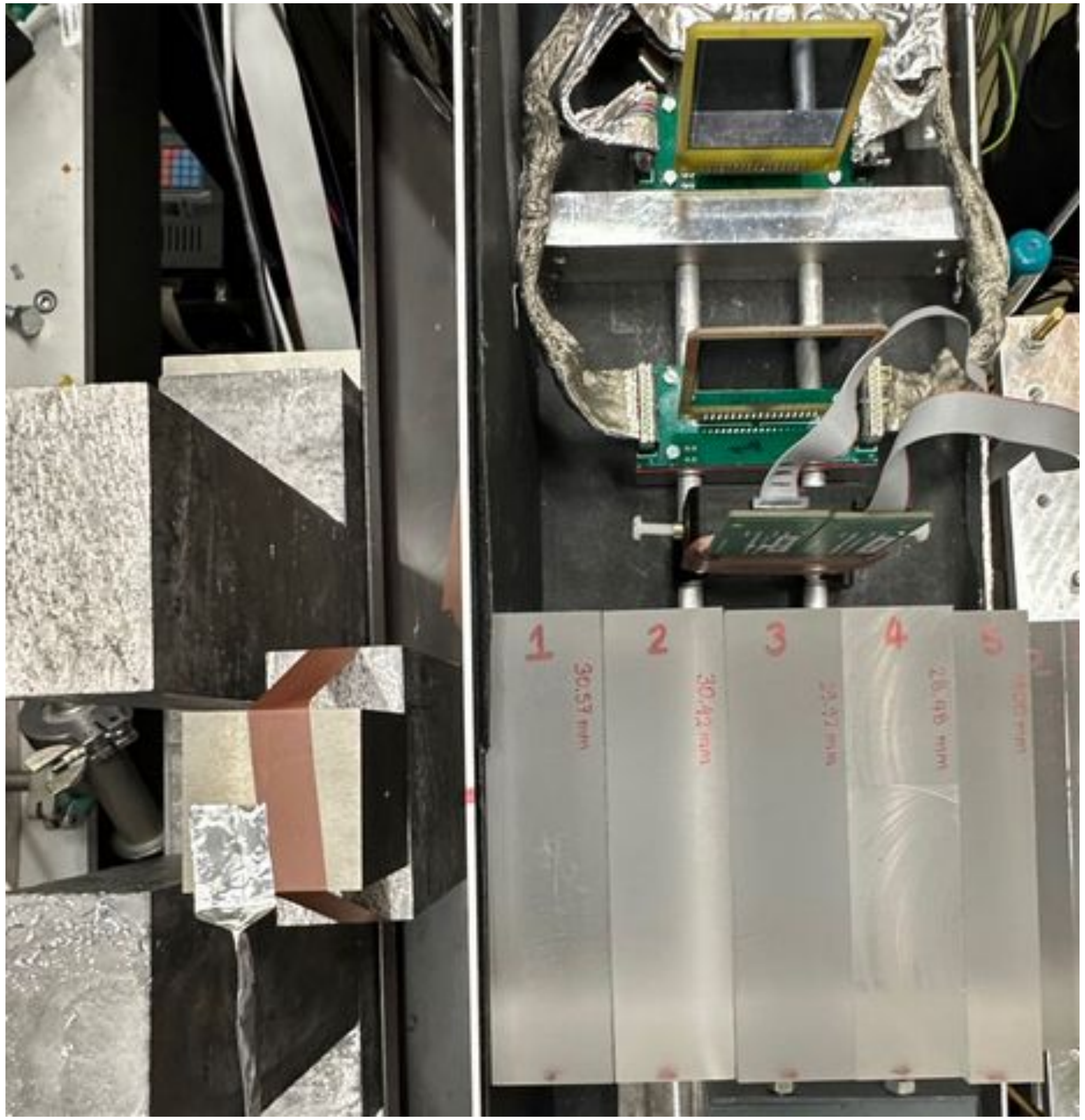
Typical event position calculation:

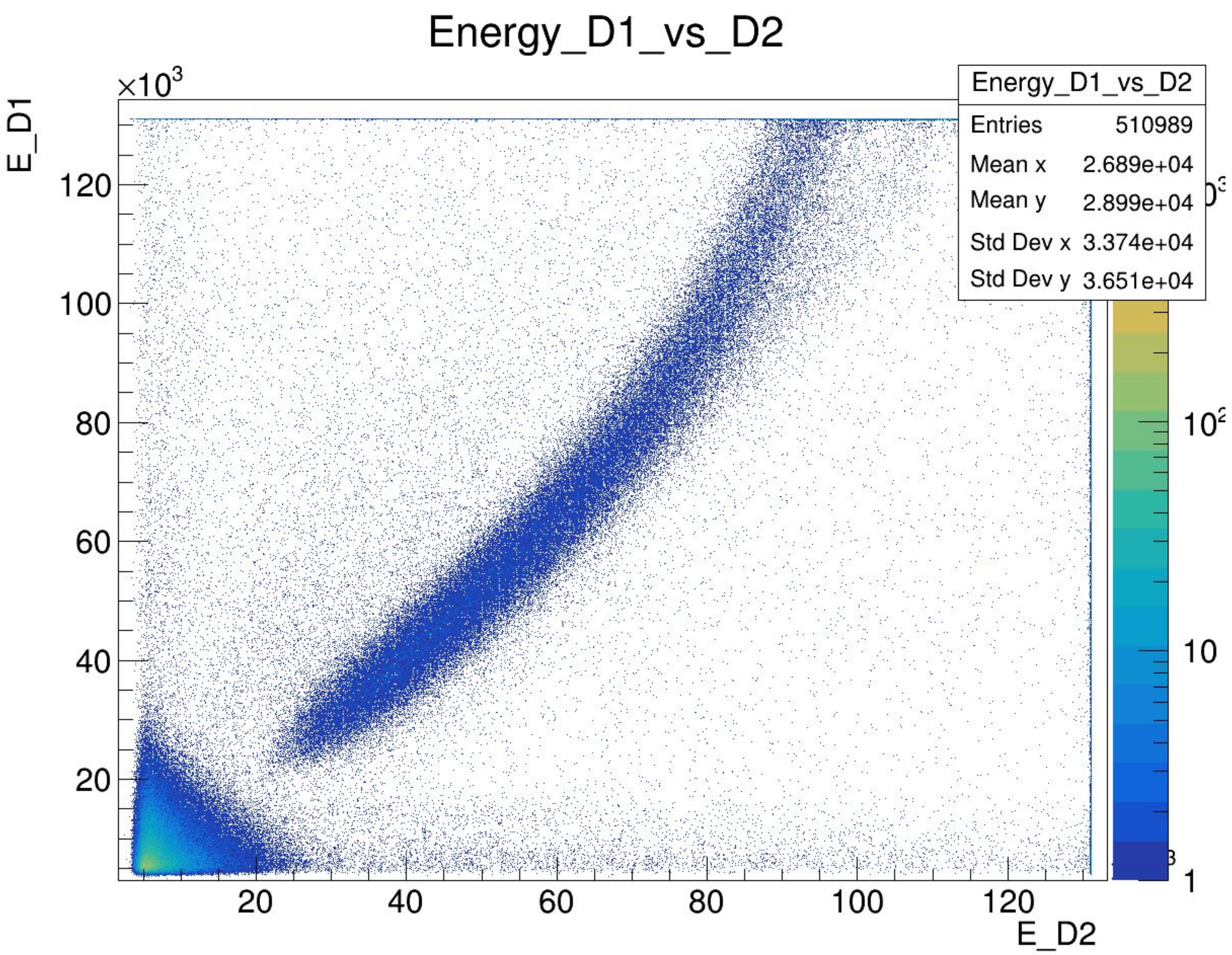
X column = (X+ - X-) / (X+ + X-)

Y row = (Y+ - Y-) / (Y+ + Y-)



LATERAL VIEW
TOP VIEW
Silicon Proton Tracker
p
Total Energy
Scintillator: TES
Silicon Proton Tracker
p
Total Energy
Scintillator: TES
Silicon Proton Tracker
γ
n
p
Total Energy
Scintillator: TES
Silicon Proton Tracker
n-p converter
p
p
n
γ
n
Total Energy
Scintillator: TES
LATERAL VIEW
TOP VIEW



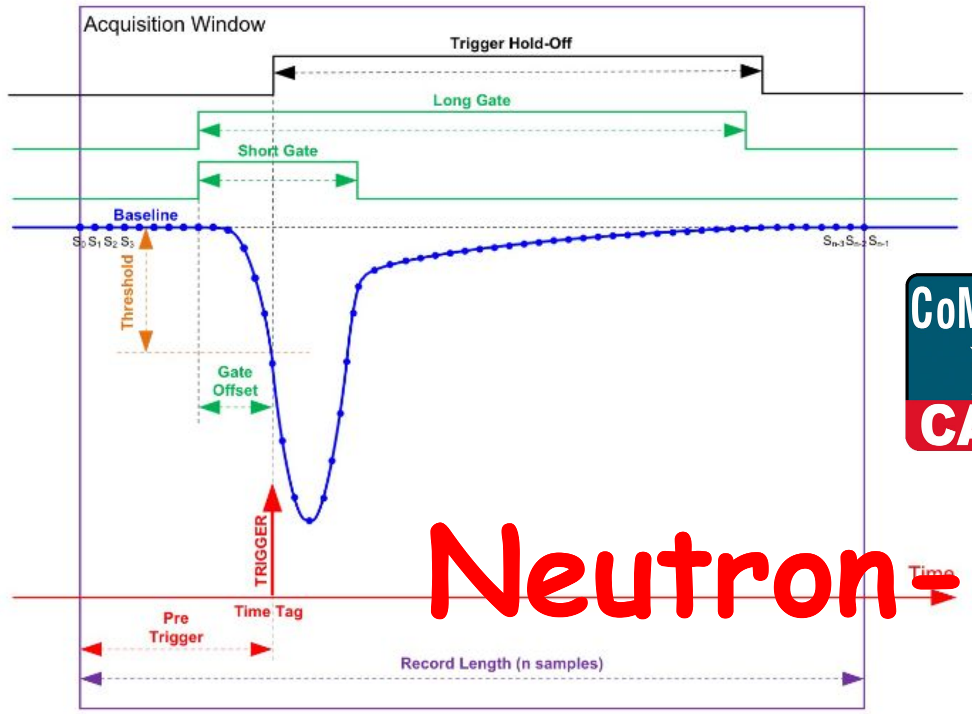

Energy_D1_vs_D2
Energy_D1_vs_D2
Entries 510989
Mean x 2.689e+04
Mean y 2.899e+04
Std Dev x 3.374e+04
Std Dev y 3.651e+04
×10^3
E_D1
120
100
80
60
40
20
20
40
60
80
100
120
E_D2
10^2
10
1

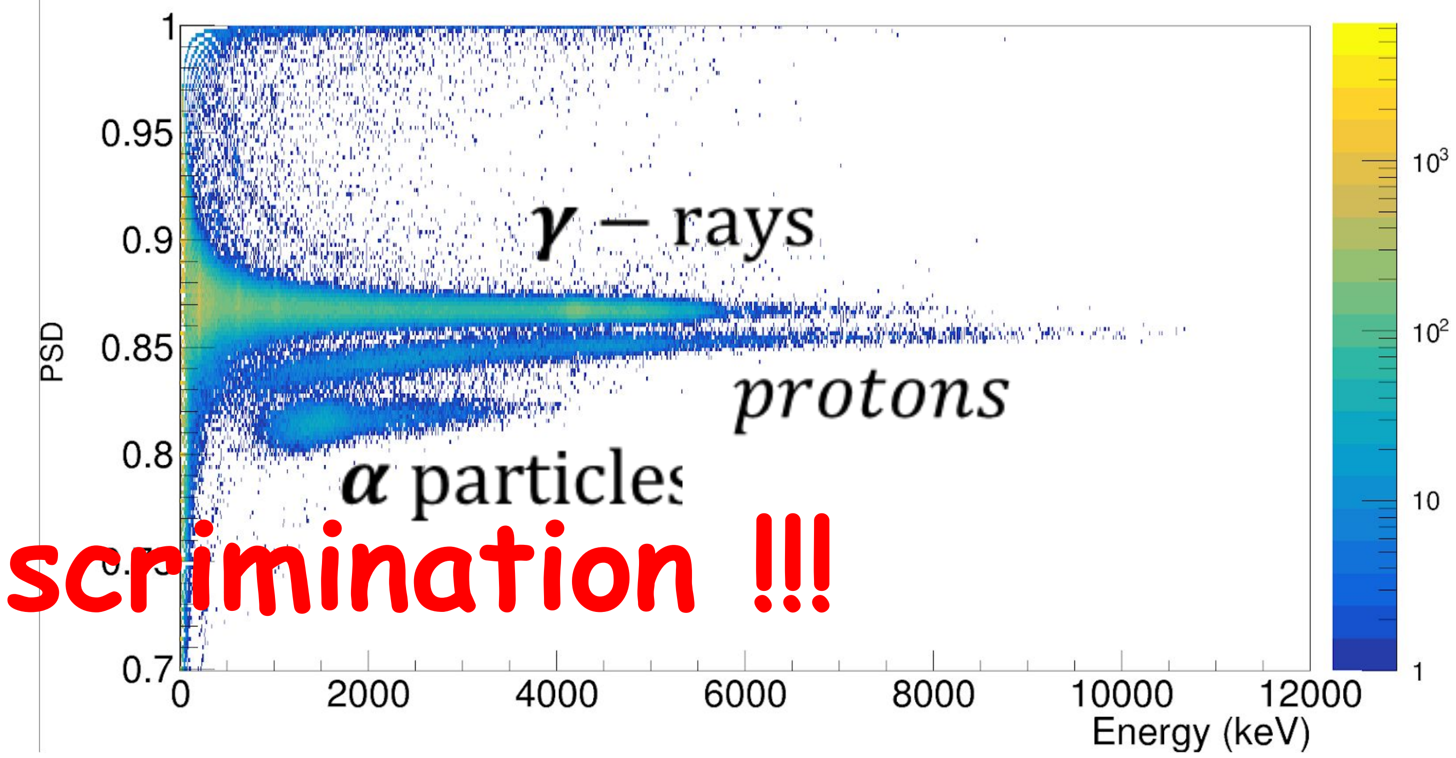
(PSD) Pulse Shape Discrimination

$$PSD = \frac{Q_{LG} - Q_{SG}}{Q_{Lg}}$$

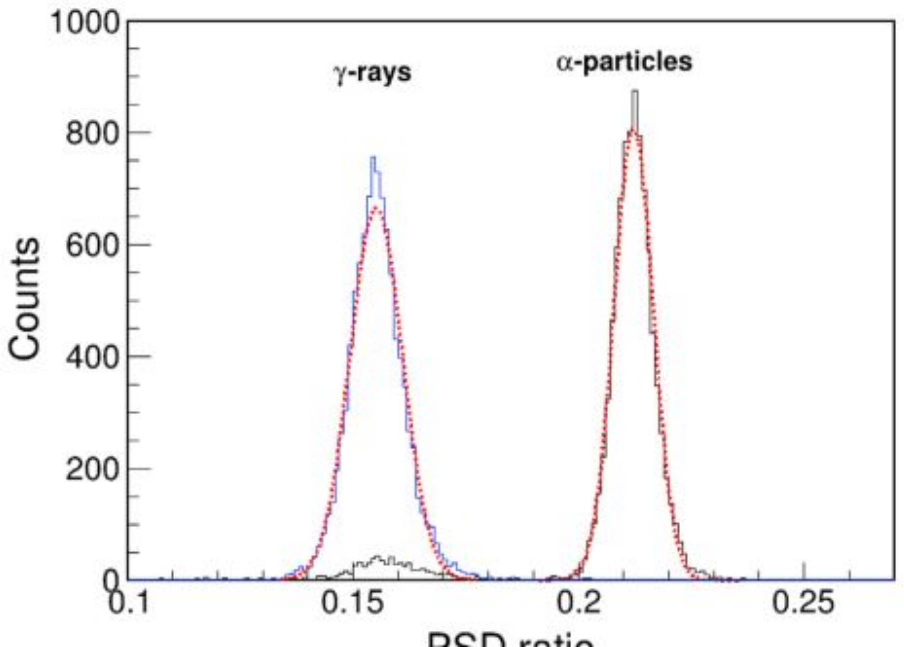
Q_{LG} *charge acumulate in Long Gate*

Q_{SG} *charge acumulate in Short Gate*





Neutron-γ discrimination !!!



$$\mathrm{FOM} = \frac{|P_\alpha - P_\gamma|}{FWHM_\alpha + FWHM_\gamma}.$$

$FOM > 1.5$

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