A new electromagnetic calorimeter for BabyIAXO to search for axions from solar fusion and supernova explosions

ALPS group
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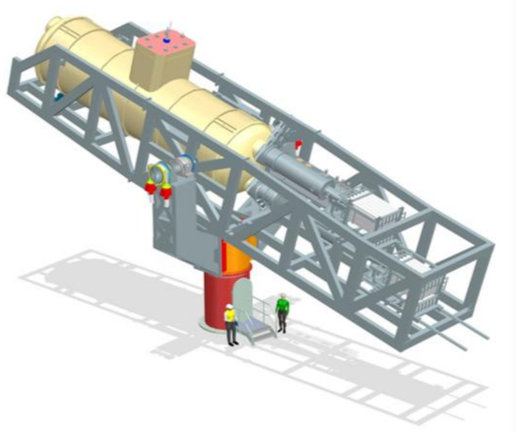


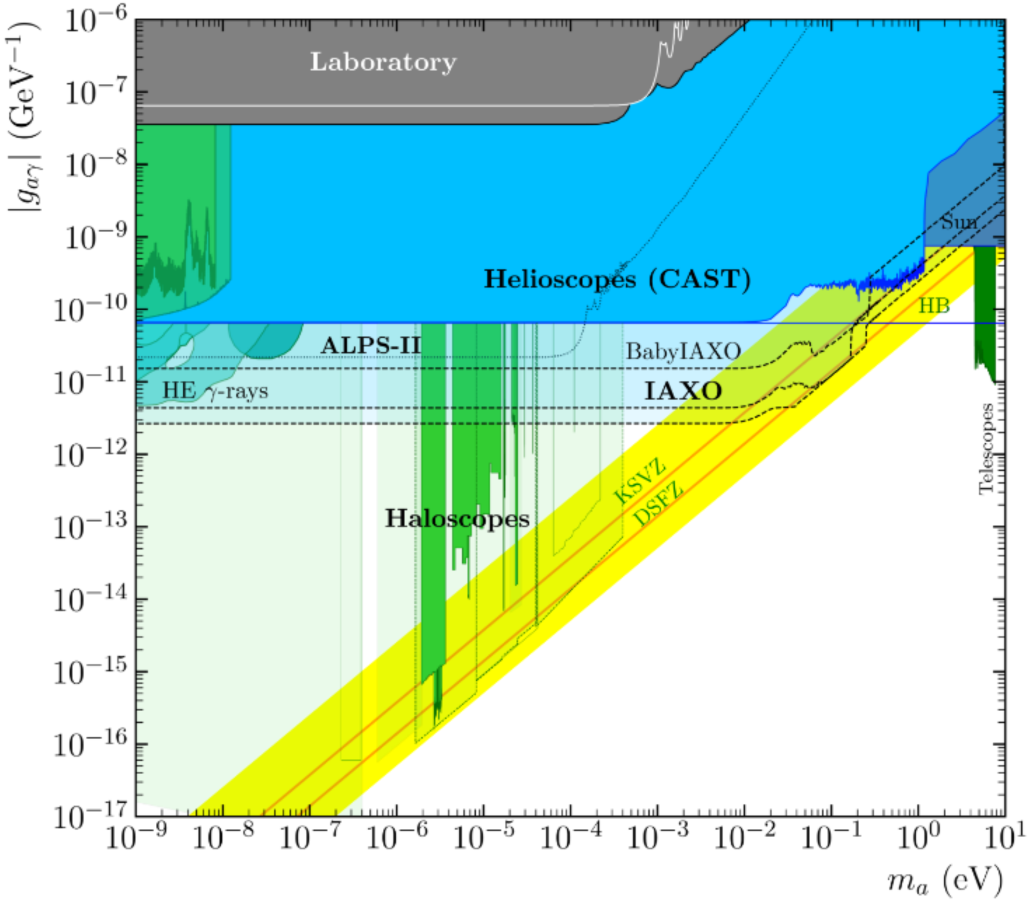
Courtesy of Axel Lindner

Outline

- Axion Motivation and Helioscope as a probe
- Motivation for the BabyIAXO Gamma-ray Calorimeter
- Initial Calorimeter Performance Study
    - Acceptance vs Geometry, Materials, Positions, and Energy
    - Shower Profile : 5.5 MeV Gamma vs Cosmic Muon (background)

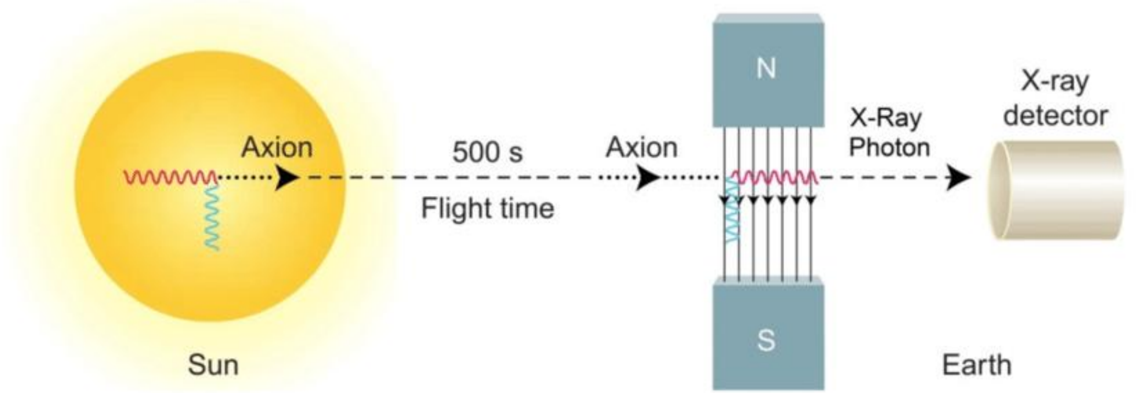
Axion Motivation

- Solving strong CP problem
  - Explaining missing neutron electric dipole moment
- Candidate for dark matter
- Light axions can be probed via axion-photon conversion



https://doi.org/10.1007/JHEP05(2021)137

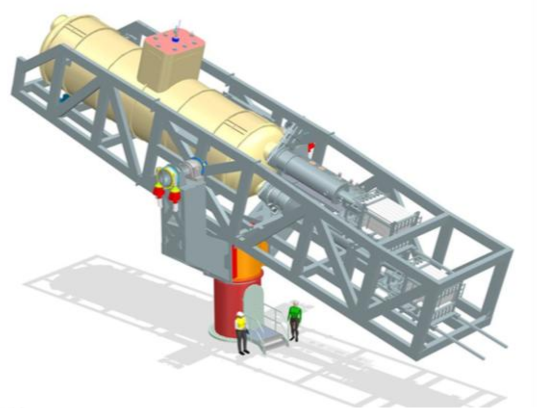
Helioscope & BabyIAXO



High magnetic fields for fundamental physics - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/The-axion-helioscope-concept-Axions-are-produced-in-the-sun-and-travel-towards-the_fig6_323904881 [accessed 4 Sept 2025]

$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

Enhanced axion helioscope:
Irastorza et al.,JCAP1106:013,2011



$g_{a\gamma} \gtrsim 0.58 \times 10^{-10}\ \mathrm{GeV}^{-1}$

$\mathrm{B} = 9.5\ \mathrm{T}$

$\mathrm{L} = 9\ \mathrm{m}$

$\mathrm{A} = 0.003\ \mathrm{m}^2$

Completed

$g_{a\gamma} \gtrsim 0.15 \times 10^{-10}\ \mathrm{GeV}^{-1}$

$\mathrm{B} = 2\ \mathrm{T}$

$\mathrm{L} = 10\ \mathrm{m}$

$\mathrm{A} = 0.385\ \mathrm{m}^2$

Entering construction

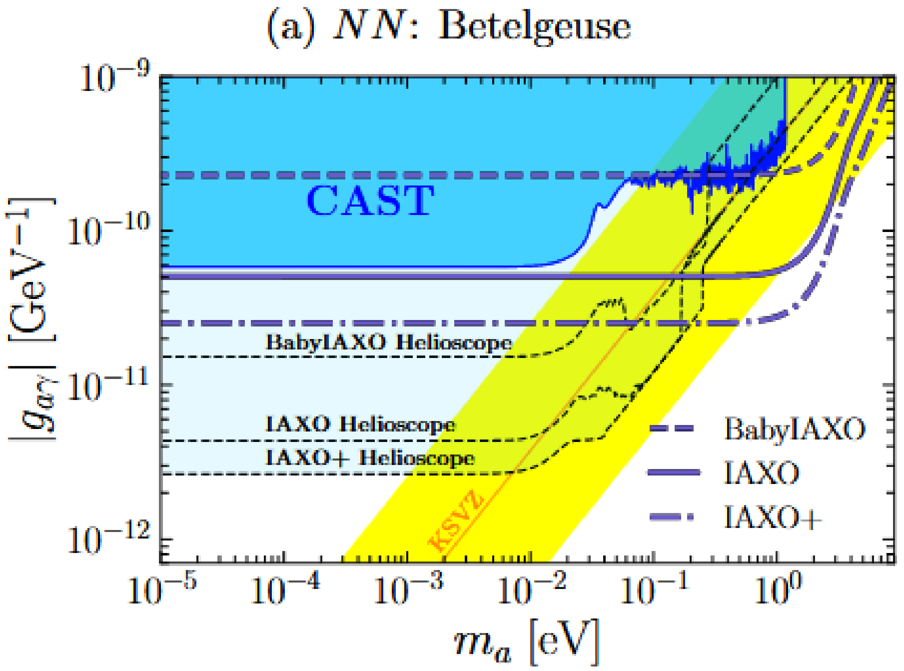
https://indico.fysik.su.se/event/8808/

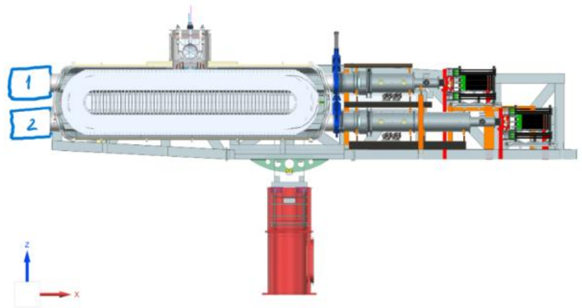
https://agenda.infn.it/event/34455/contributions/204049/attachments/108291/153183/PATRAS_Schneekloth_IAXO.pdf

BabyIAXO Gamma-ray Detector Motivation

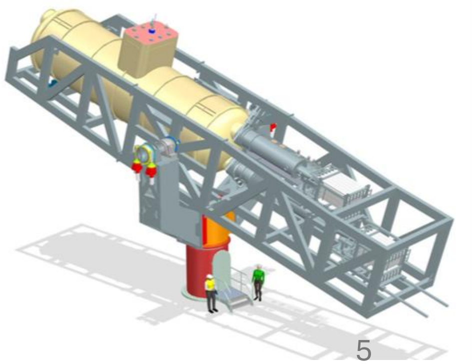
- Energy
  - 5.5 MeV
    - $p + d \rightarrow {}^{3}\mathrm{He} + \mathrm{A} \ \ (5.5\ \mathrm{MeV})$
  - ~ 100 MeV
    - Supernova
- Probe axion-nucleon coupling & axion-photon coupling at higher masses
- Instrument is originally designed for X-ray

  → need additional calorimeters





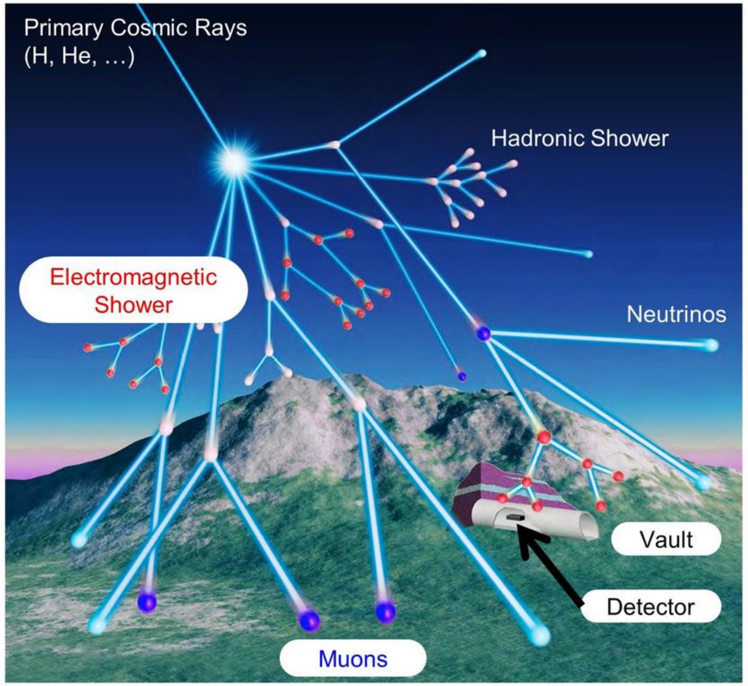
(reverse direction)

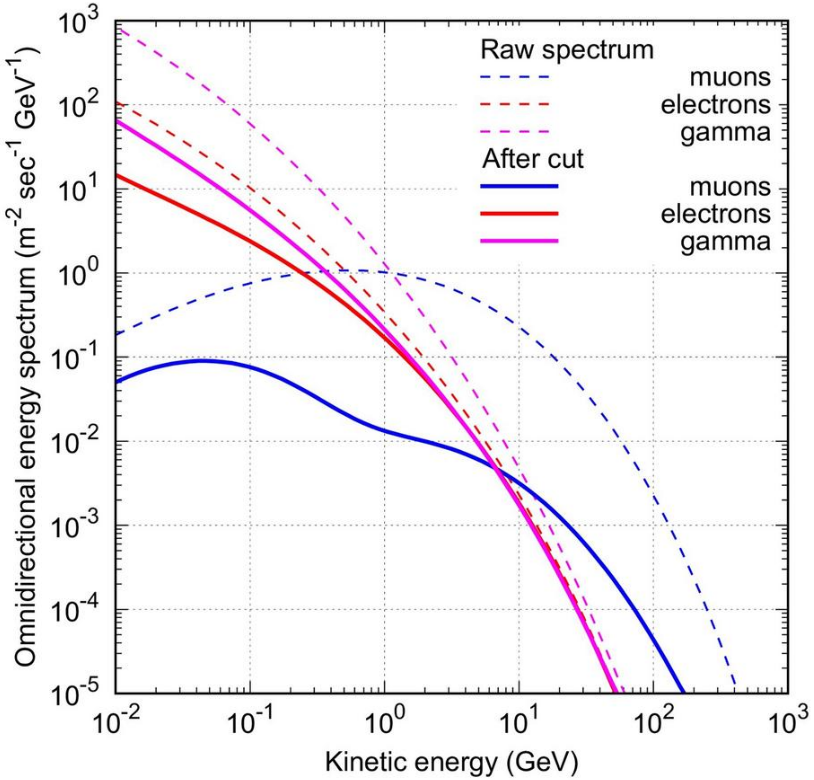


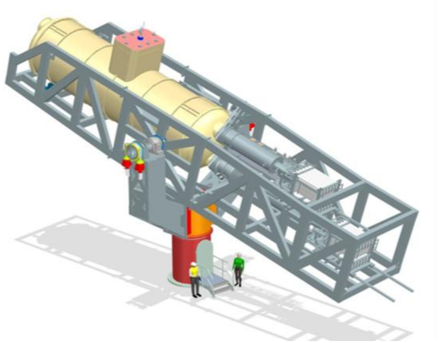
arXiv:2502.19476

arXiv:2504.19135

Background Dispersion (Cosmic Muon)







Cosmic Muon Interactions → Muon Showers

https://www.nature.com/articles/s41598-022-24765-7

Project Goal

1. To study effects on 5.5-MeV and 100-MeV detector acceptance due to detector positions, sizes, and materials

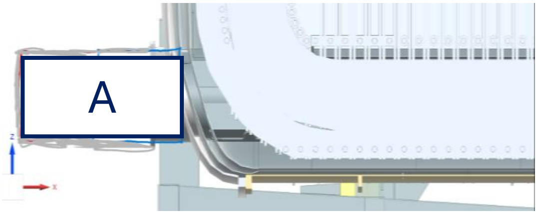
2. To analyze gamma-ray shower profile comparing to simulated background muon profile to further cut out backgrounds

Methodology for Acceptance Study

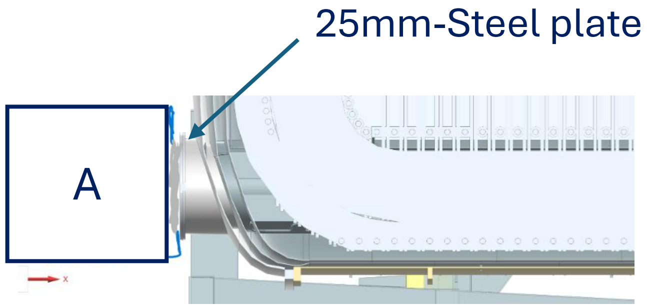
- Using **OpenGATE (Geant 4-based)** to simulate interactions between radiation and detector for many events ($10^5 - 10^6$)
- Choosing Materials:
  - High energy resolution but expensive : GAGG
  - Medium energy resolution with medium price : NaI, CsI
  - Low energy resolution but cheap : polystyrene (plastic)

Name	**Density(g/cm^3)**	**Resolution**	**Price/cm^3**
GAGG:Ce	6.63	~5 – 6 %	$160 – 200
NaI (Tl)	3.67	~6 – 7 %	$20 – 30
CsI (Tl)	4.51	~6 – 8 %	$10 – 20
Polystyrene	1.02	~20 – 25%	< $5

- Extract the acceptance for each given variations

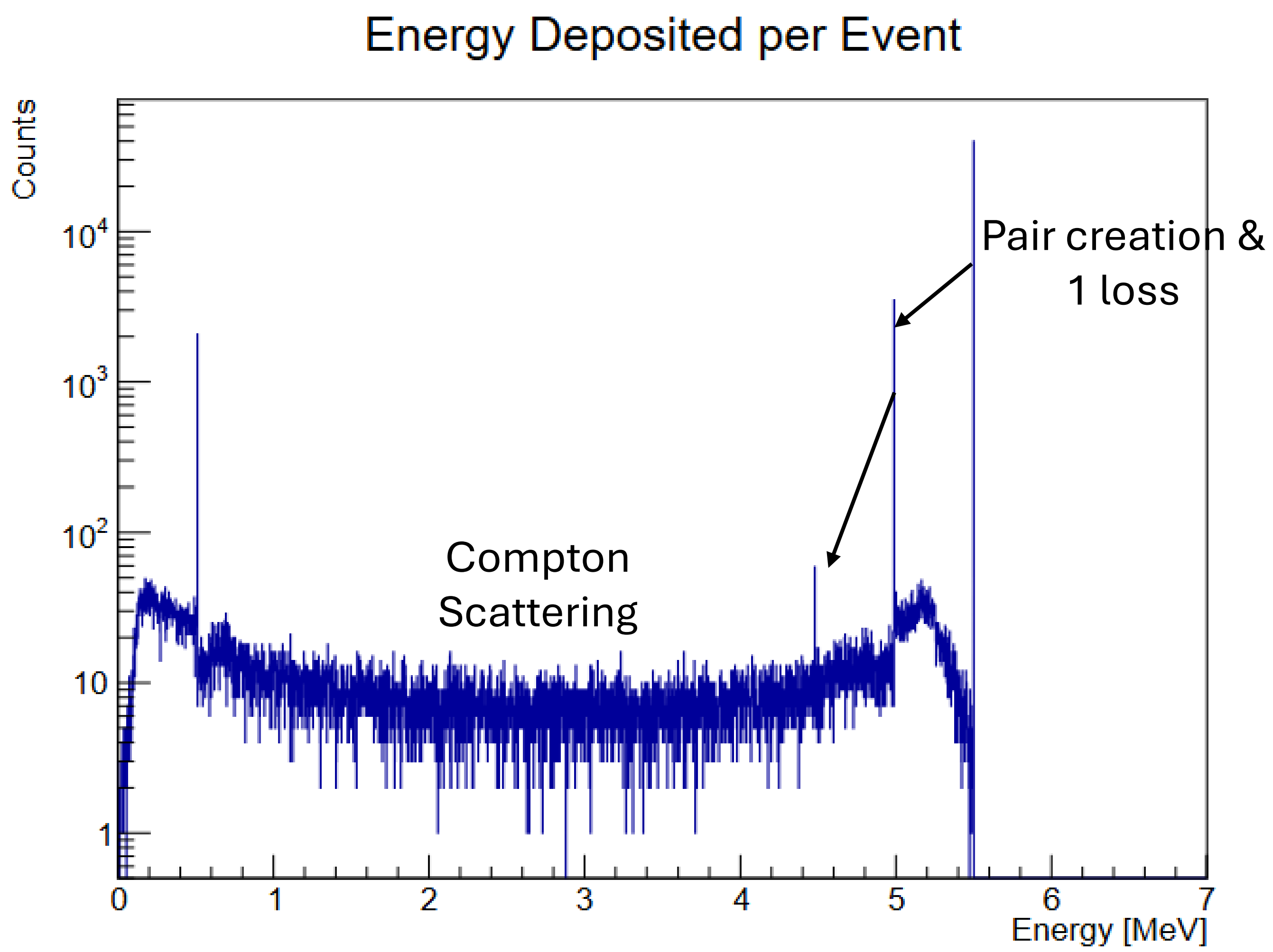


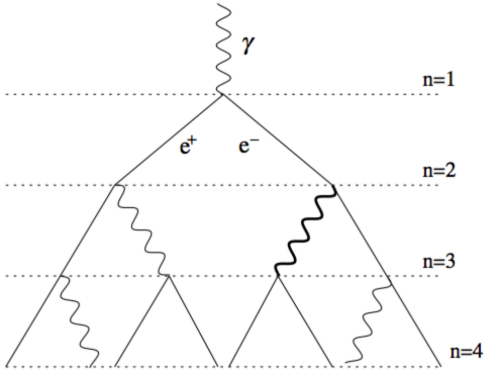
5.5 & 100 MeV detected
in vacuum



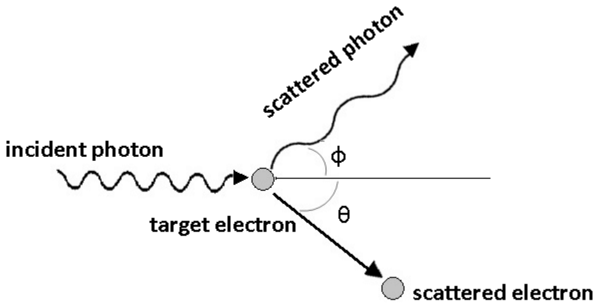
5.5 & 100 MeV detected
outside vacuum (air)

Deposited Energy Histogram





Pair Creation : 0.511 MeV & 0.511 MeV

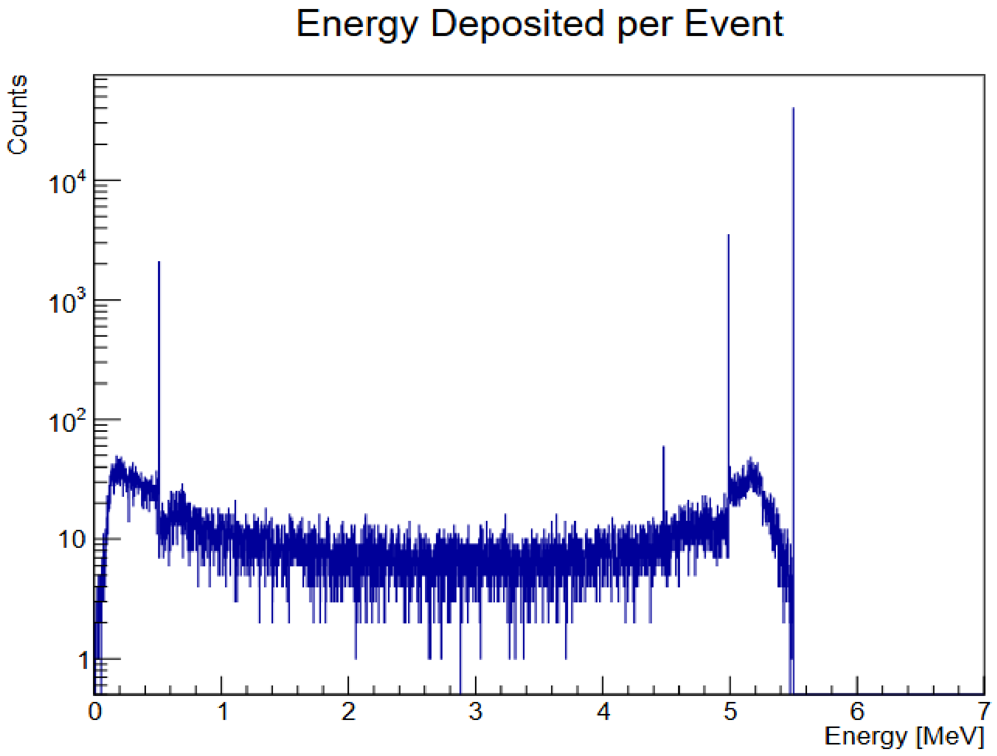


Compton Scattering

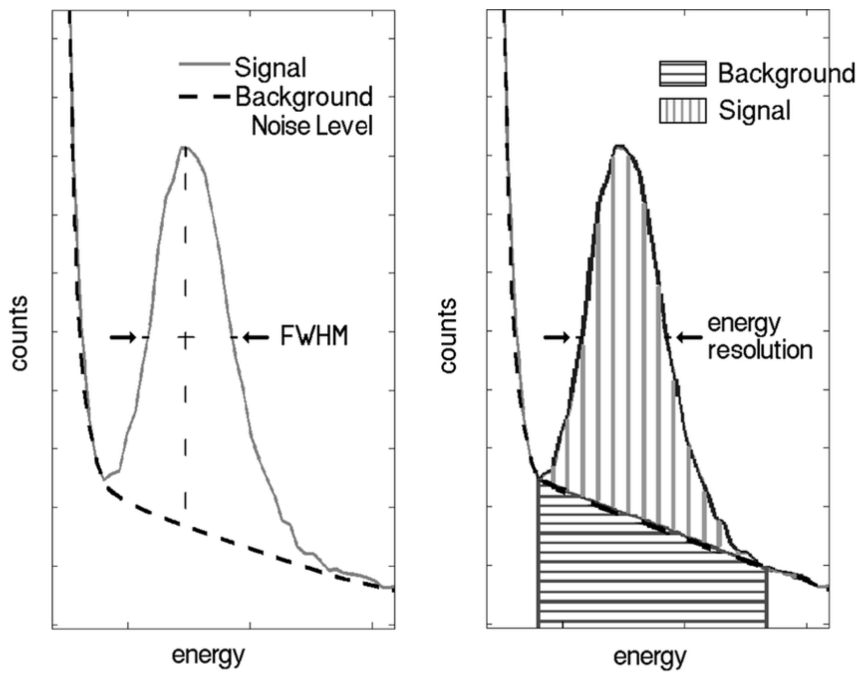
https://www.researchgate.net/figure/The-geometry-of-Compton-scattering-showing-the-directions-of-the-scattered-photon-and_fig1_236737231 [accessed 4 Sept 2025]

https://w3.iihe.ac.be/~aguilar/PHYS-467/PA3.html

Deposited Energy Histogram (included energy resolution)

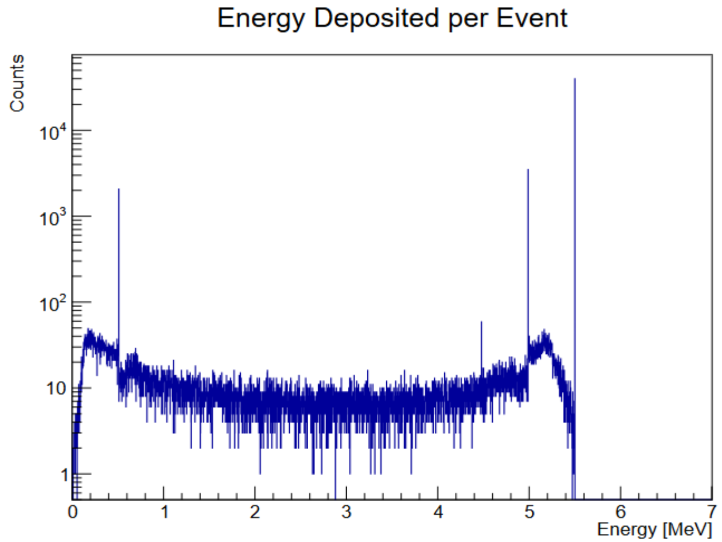


+



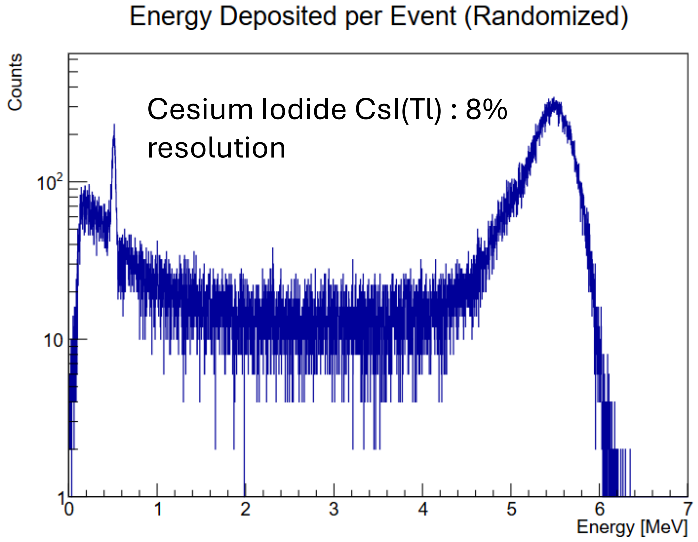
https://www.researchgate.net/figure/Definition-of-the-energy-resolution-and-photopeak-efficiency-PE-deduced-from-the-energy_fig2_224601073

Deposited Energy Histogram (included energy resolution)



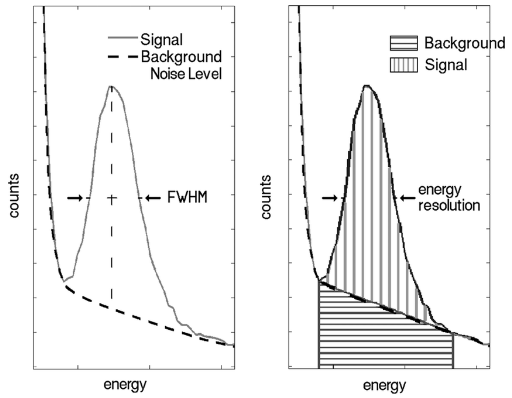
Gaussian

Sampling



Cesium Iodide CsI(Tl) : 8% resolution

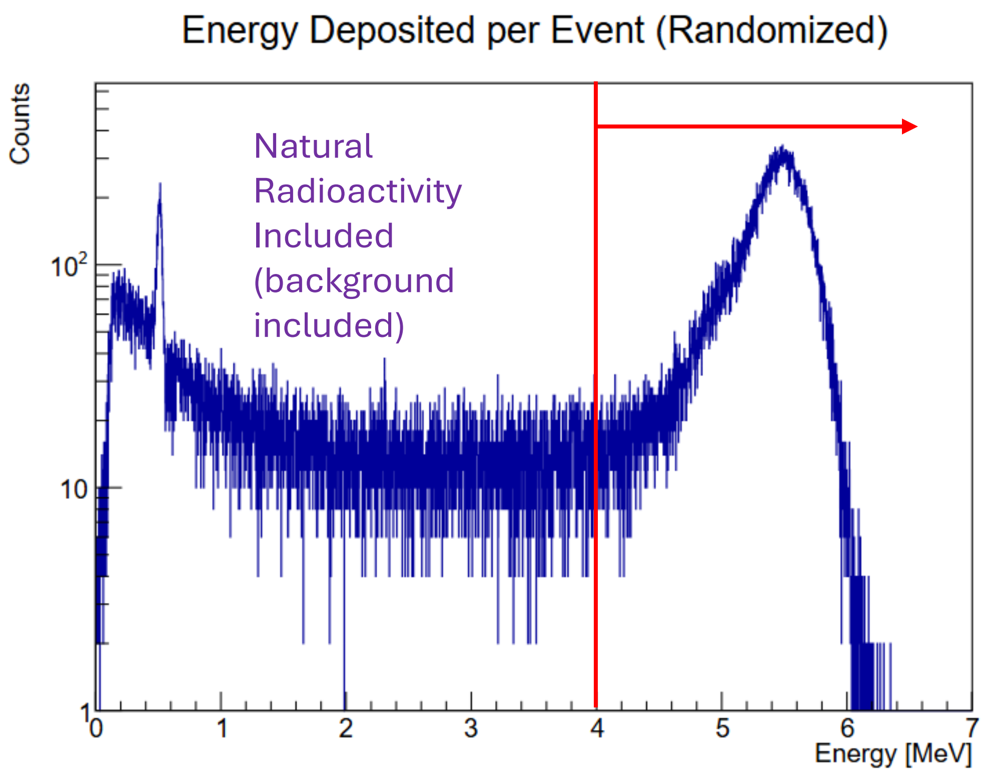
Limited by material density



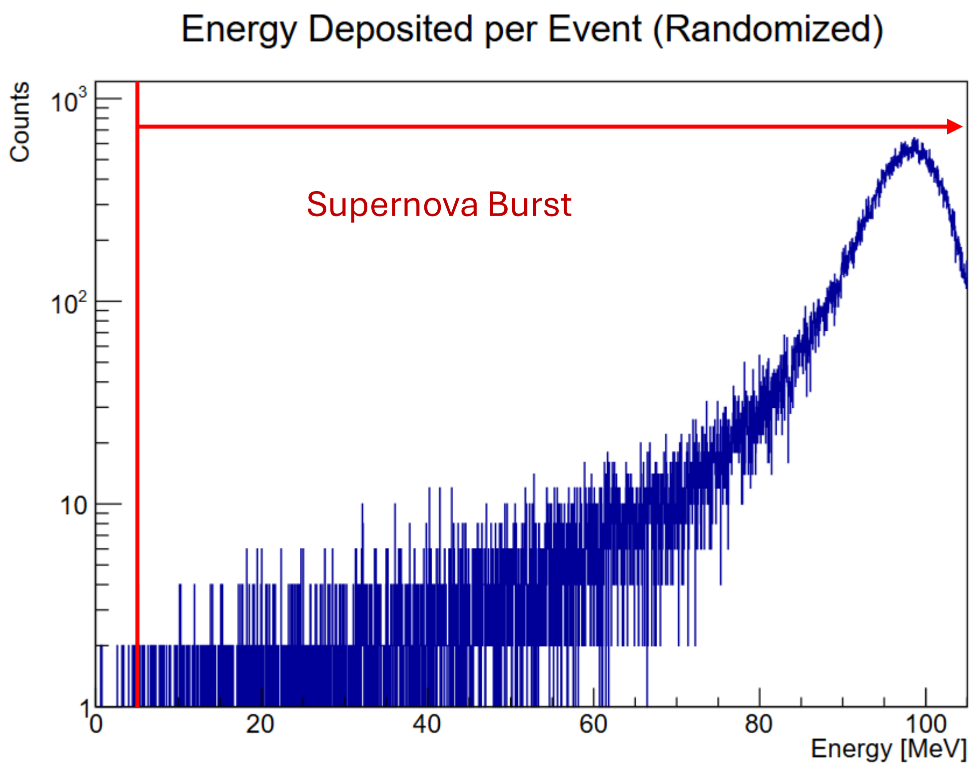
Limited by material density & energy resolution

https://www.researchgate.net/figure/Definition-of-the-energy-resolution-and-photopeak-efficiency-PE-deduced-from-the-energy_fig2_224601073

Calculating Acceptance with Energy Cut

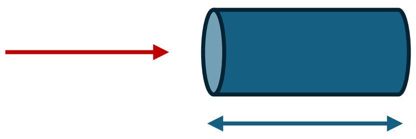


5.5 MeV : cut at 4 MeV



100 MeV : cut at 5 MeV

$$\text{acceptance} = \frac{\text{total event counts above the energy cuts}}{\text{number of all simulated events}} \cdot 100\%$$

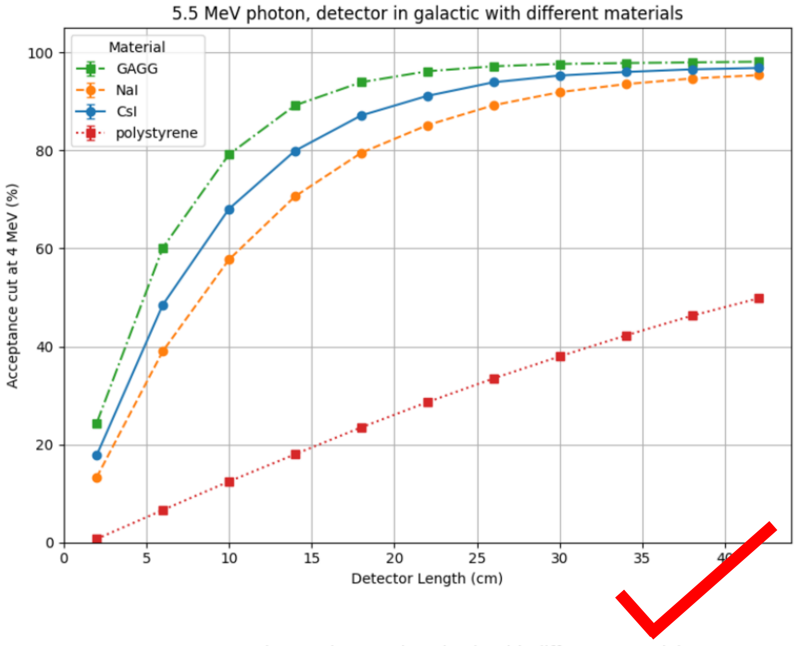


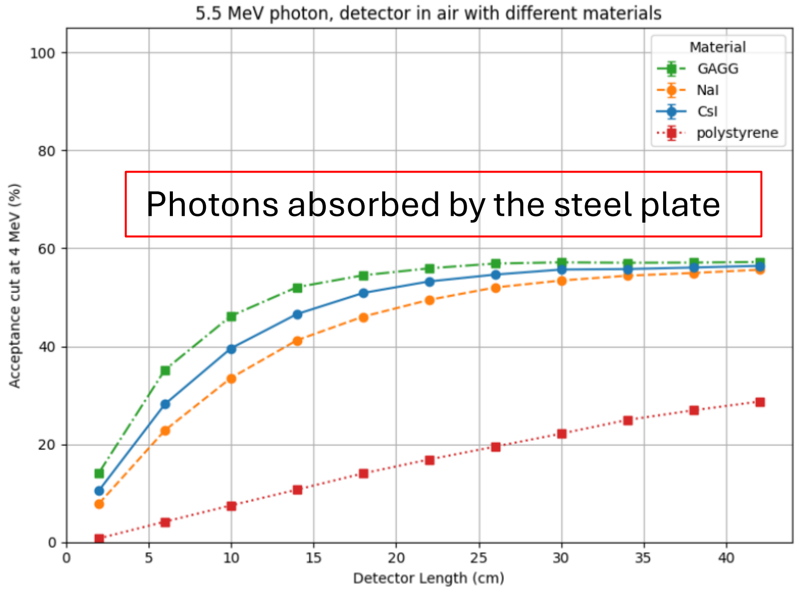
Acceptance vs. Detector length

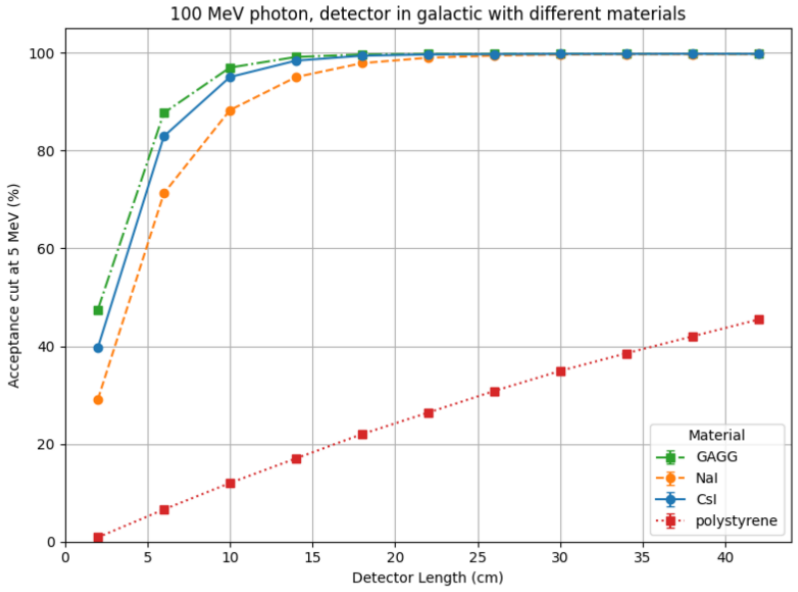
Top: 5.5 MeV

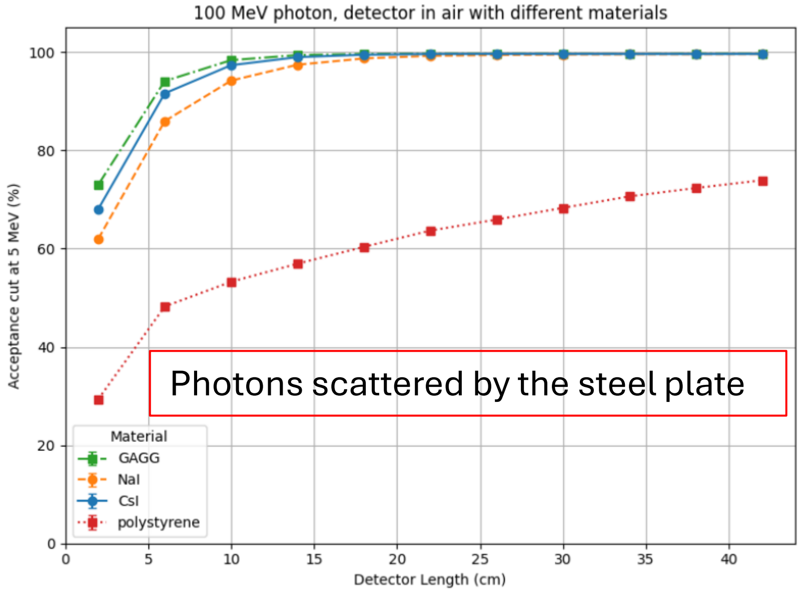
vacuum (left) & air (right)

Bottom: 100 MeV







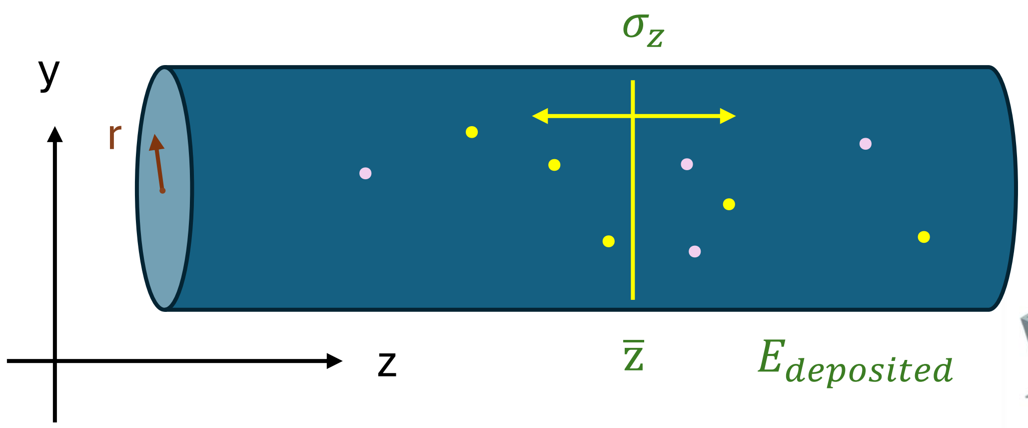


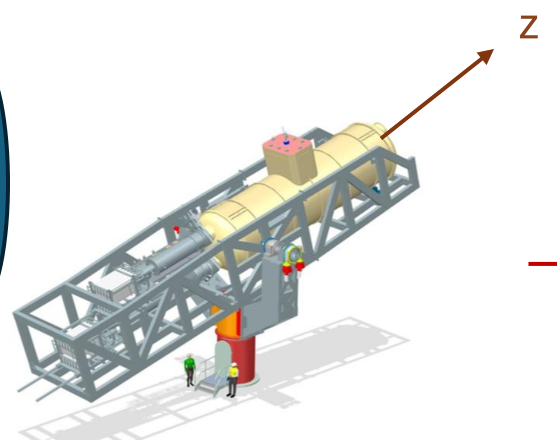
Methodology for Shower Profile Study

- Describe shower profile with $\bar{x}, \bar{y}, \bar{z}, \bar{r}$ and $\sigma_x, \sigma_y, \sigma_z, \sigma_r$ for each individual events
- Study 100-MeV gamma's shower coverage (not shown here)
- Compare 5.5-MeV gamma profile to cosmic muon's (1 GeV)
- Analyze differences between background cosmic muons and gamma-ray signals

$$\bar{x} = \frac{\sum_{i=1}^{N} w_i x_i}{\sum_{i=1}^{N} w_i}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} w_i (x_i - \bar{x}_w)^2}{\frac{(N'-1)\sum_{i=1}^{N} w_i}{N'}}}$$

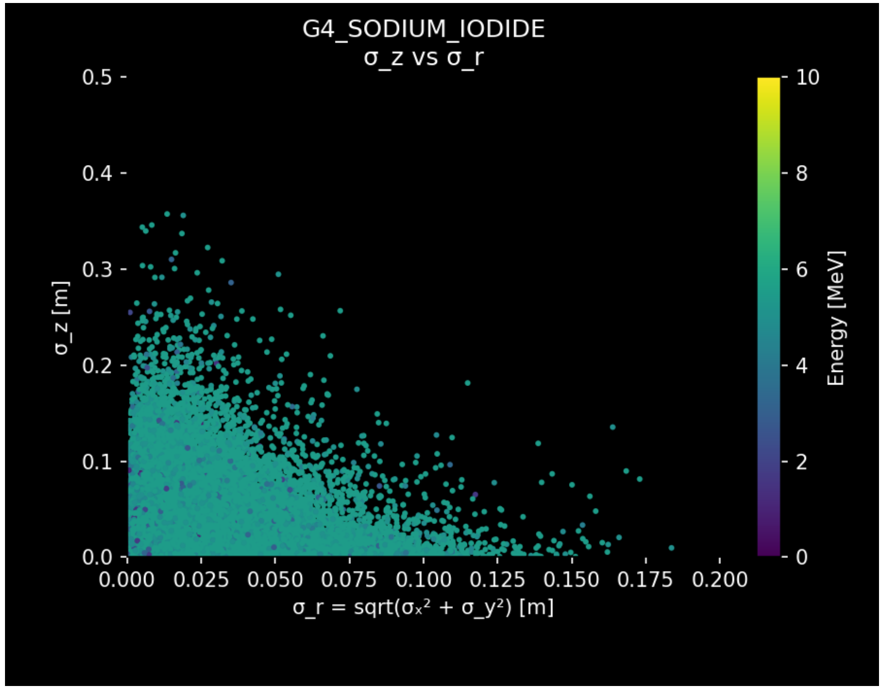




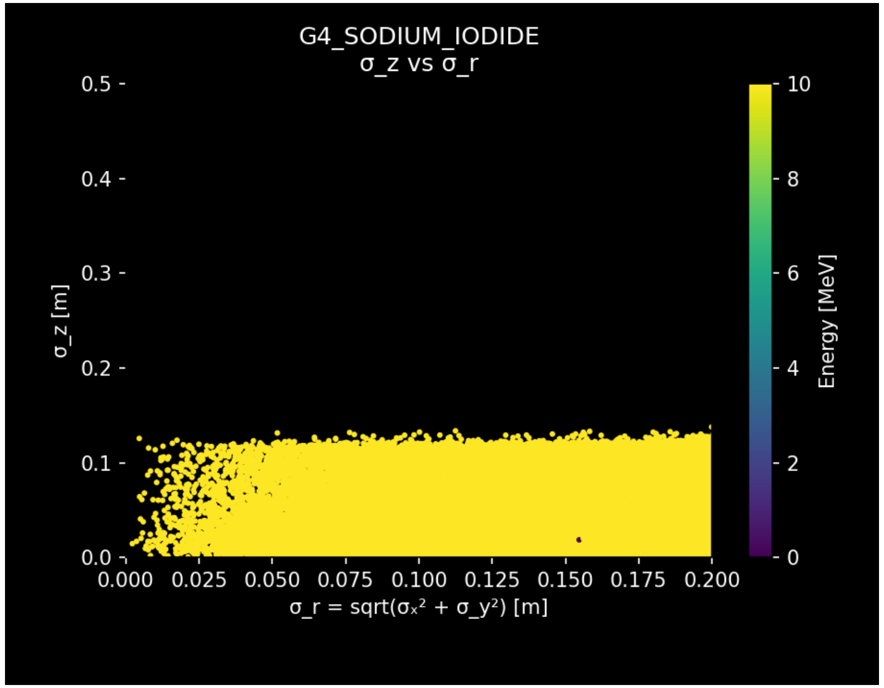
Selected Results : $\sigma_z \ vs. \ \sigma_r$

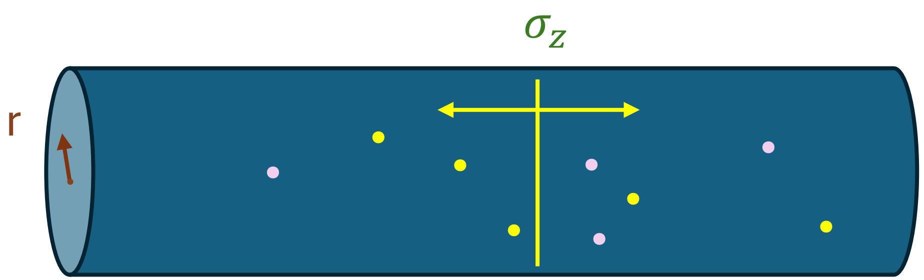
GAMMA 5.5 MeV

σ_z and σ_r are correlated



COSMIC MUON





https://www.hilger-crystals.co.uk/materials/sodium-iodide/

Conclusion

- BabyIAXO's potential for detecting MeV photons

  → higher axion masses detection

- Considering acceptance
  - Detector is better equipped in vacuum for 5.5 MeV (better acceptance)
  - Equally good for 100 MeV (no significant difference)
  - Materials: GAGG, CsI, NaI behave similarly; better to choose CsI (higher acceptance at lower price)

- The shower from gamma-ray and muon background differs significantly for muons entering perpendicular to the beam axis in energy range and shapes

BACKUP SLIDES

Solar Axion Interactions

2.1. Axion-nucleon coupling

Coupling to nucleons occurs through the spin operator σ [6] and because axions carry spin-parity $J^P = 0^-, 1^+, 2^-, \ldots$ nuclear deexcitation via axion emission occurs predominantly via M1 magnetic nuclear transitions. Several channels for solar axion emission via these transitions [28, 29, 15], such as

$$^7\mathrm{Li}^* \rightarrow {}^7\mathrm{Li} + a \quad (0.478\ \mathrm{MeV}), \tag{3}$$

$$\mathrm{p} + \mathrm{d} \rightarrow \mathrm{He}^3 + a \quad (5.5\ \mathrm{MeV}). \tag{4}$$

2.3. Expected axion flux from $D(p,\gamma)^3He$

Also of interest for hadronic axions is the radiative capture of protons on deuterium, also referred to as proton-deuteron fusion [28]. The reaction

$$p + d \rightarrow ^3 \mathrm{He} + \gamma \tag{11}$$

The branching ratio for axion emission $\frac{\Gamma_a}{\Gamma_\gamma} = 0.98 g_3^2.$

https://www.arxiv.org/pdf/0904.2103v3

Supernova Axions

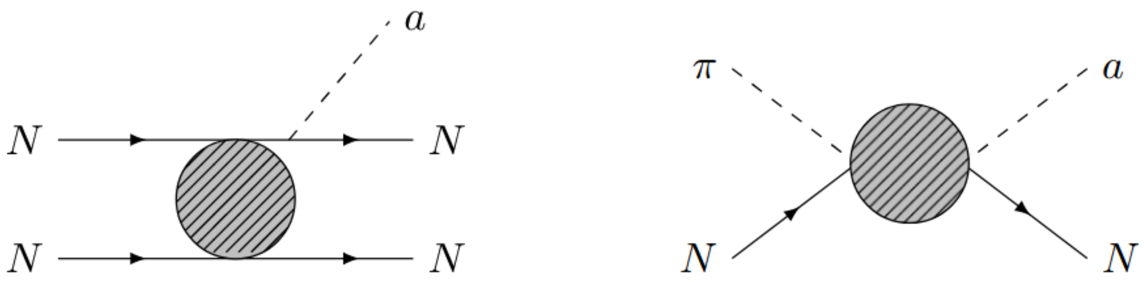


Figure 1: Schematic representation of the Feynman diagrams for the NN bremsstrahlung (*left panel*) and the pionic Compton-like process (*right panel*).

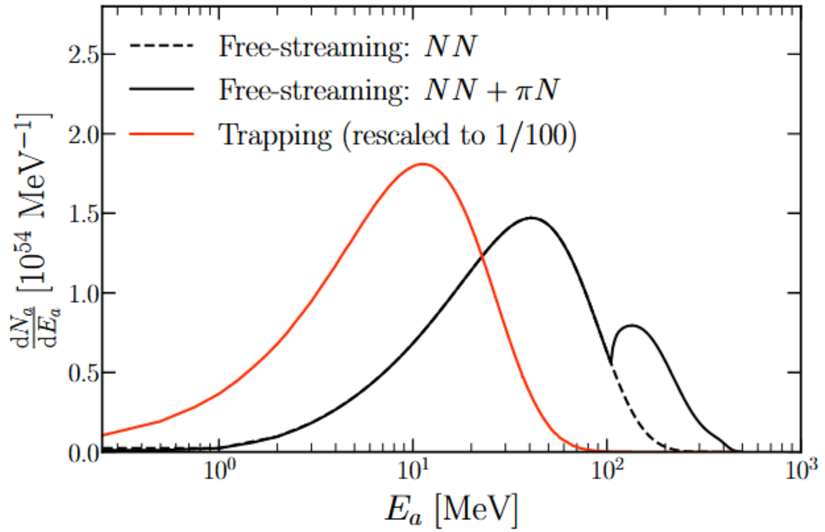
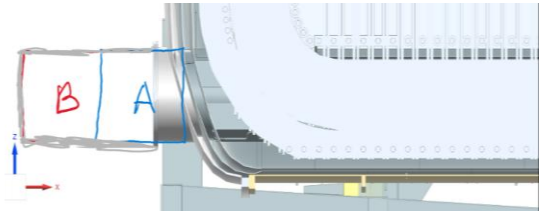


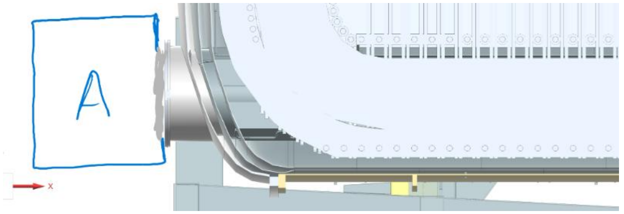
Figure 2: Time-integrated ALP emission spectrum from our benchmark SN model [38]. The continuous black line depicts the spectrum line-shape including both contributions from NN bremsstrahlung (NN) and pion conversions (πN), while the dashed black line refers to the bremsstrahlung-only contribution in the *free-streaming regime*. The corresponding spectrum for the *trapping regime* is depicted as a continuous red line. Note that we rescaled the trapping curve by a factor of 1/100 for the visualization. Here the ALP-neutron coupling is fixed at $g_{an} = 0$, while the ALP-proton coupling is set at $g_{ap} = 5 \times 10^{-10}$ free streaming scenario and at $g_{ap} = 3 \times 10^{-6}$ in the trapping case.

arXiv:2502.19476

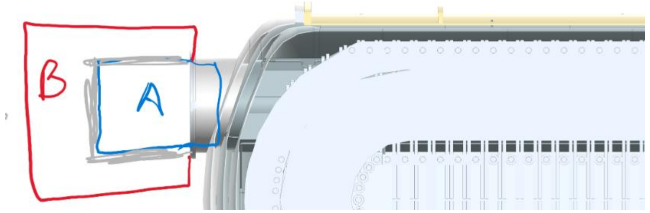
Variations in Configurations



5.5 & 100 MeV detected
in vacuum



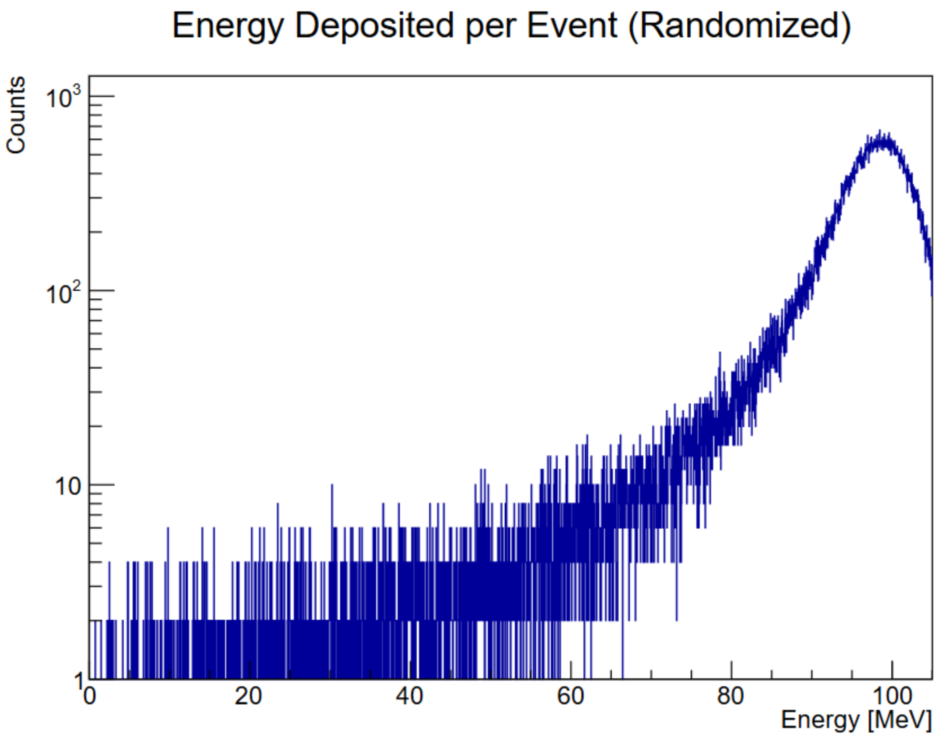
5.5 & 100 MeV detected
outside vacuum (air)



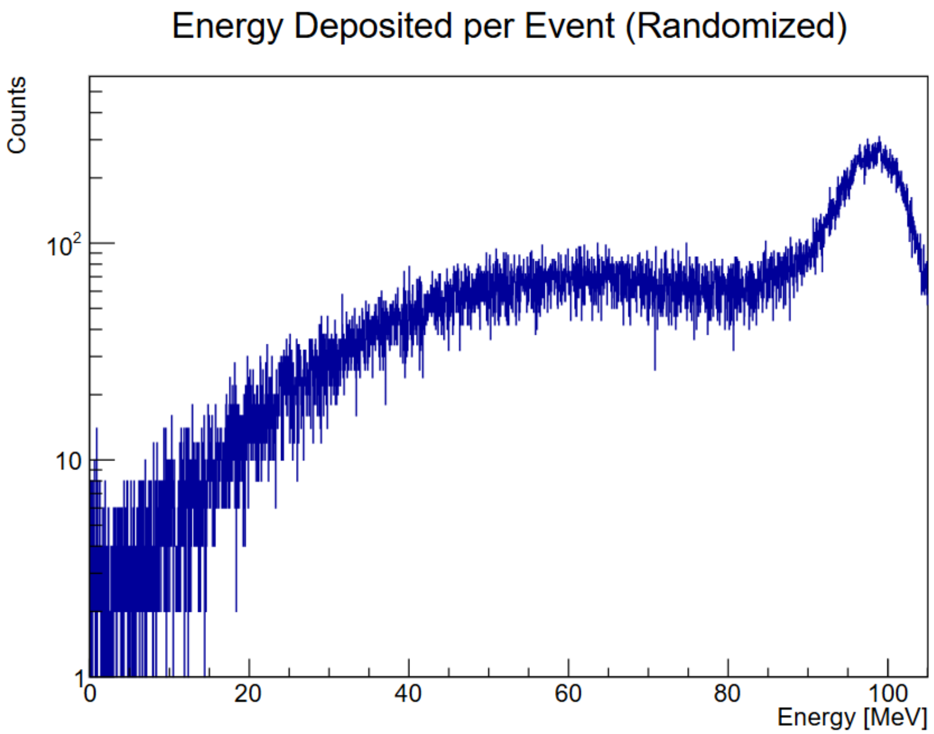
Capture full showers & bg

100 MeV : Vacuum vs. Air

- Spectra

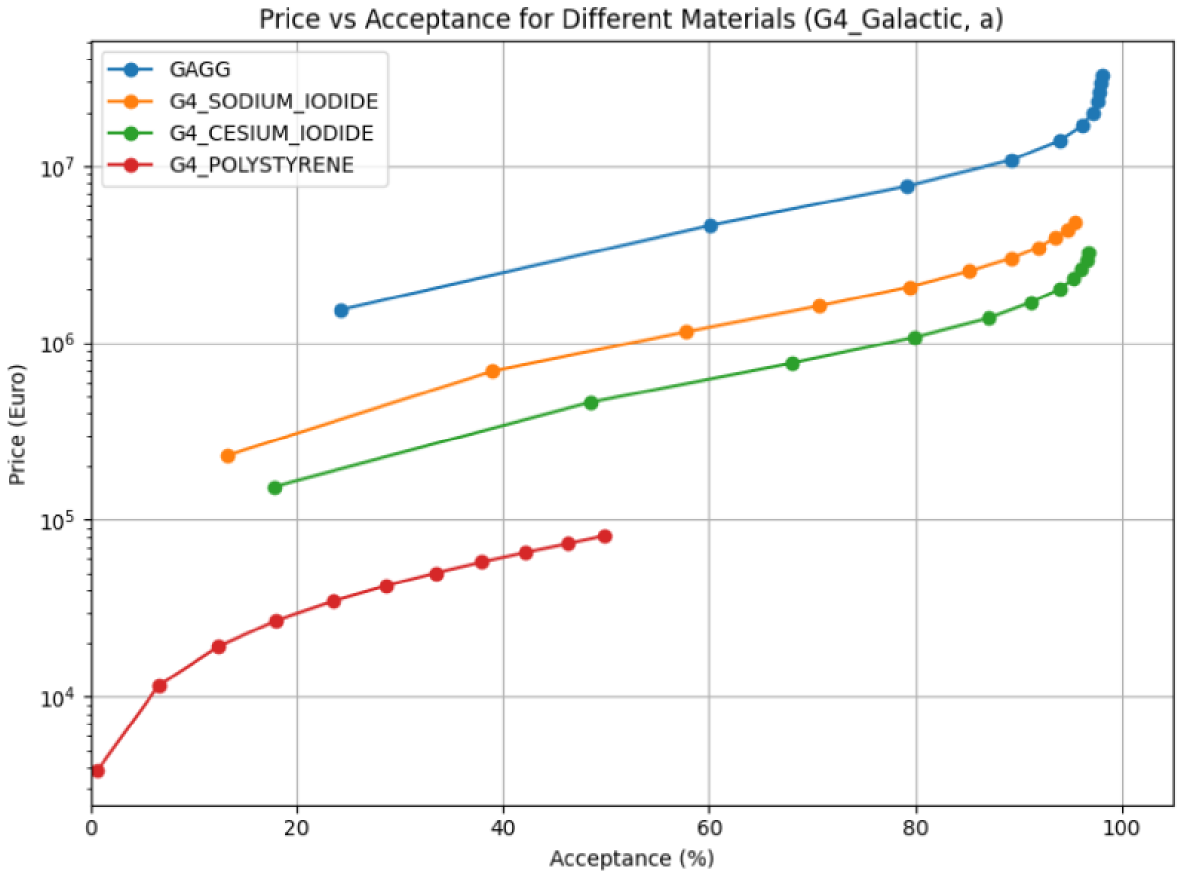


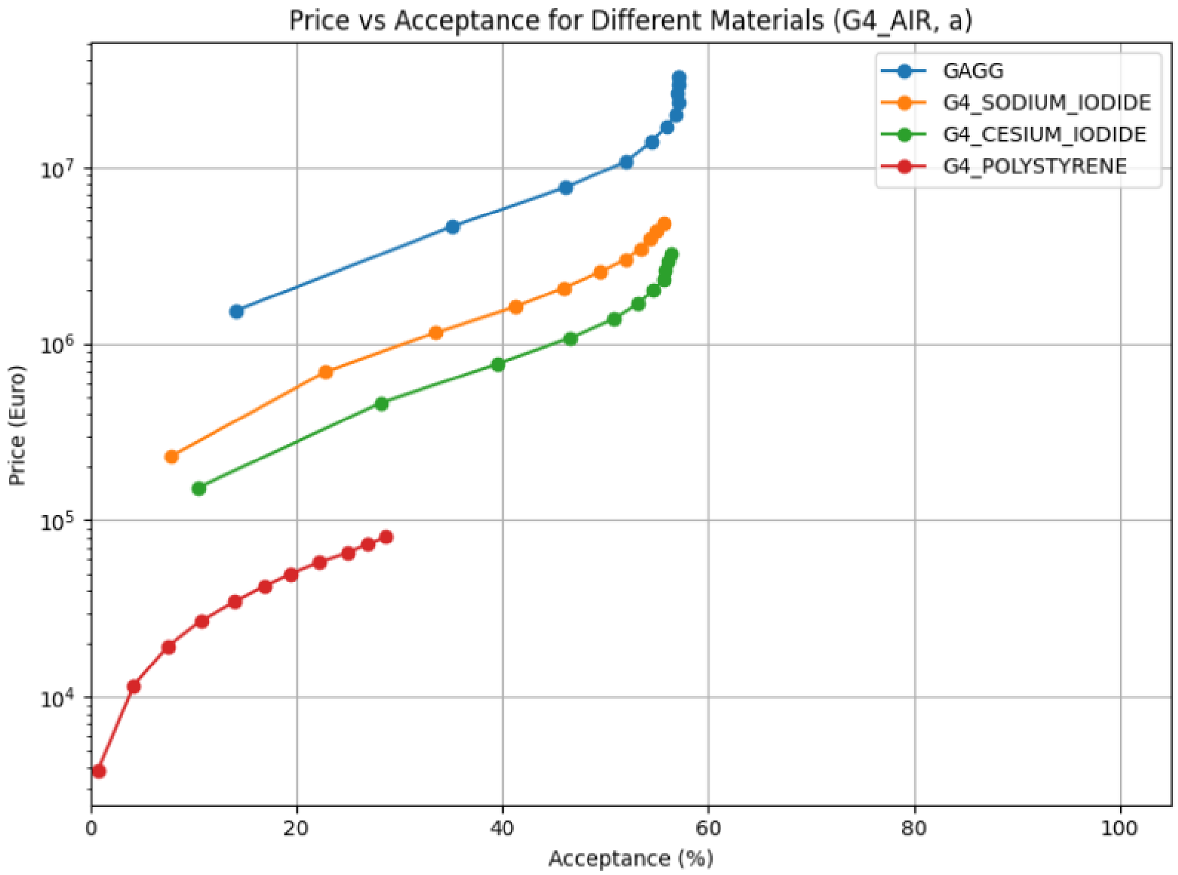
VACUUM



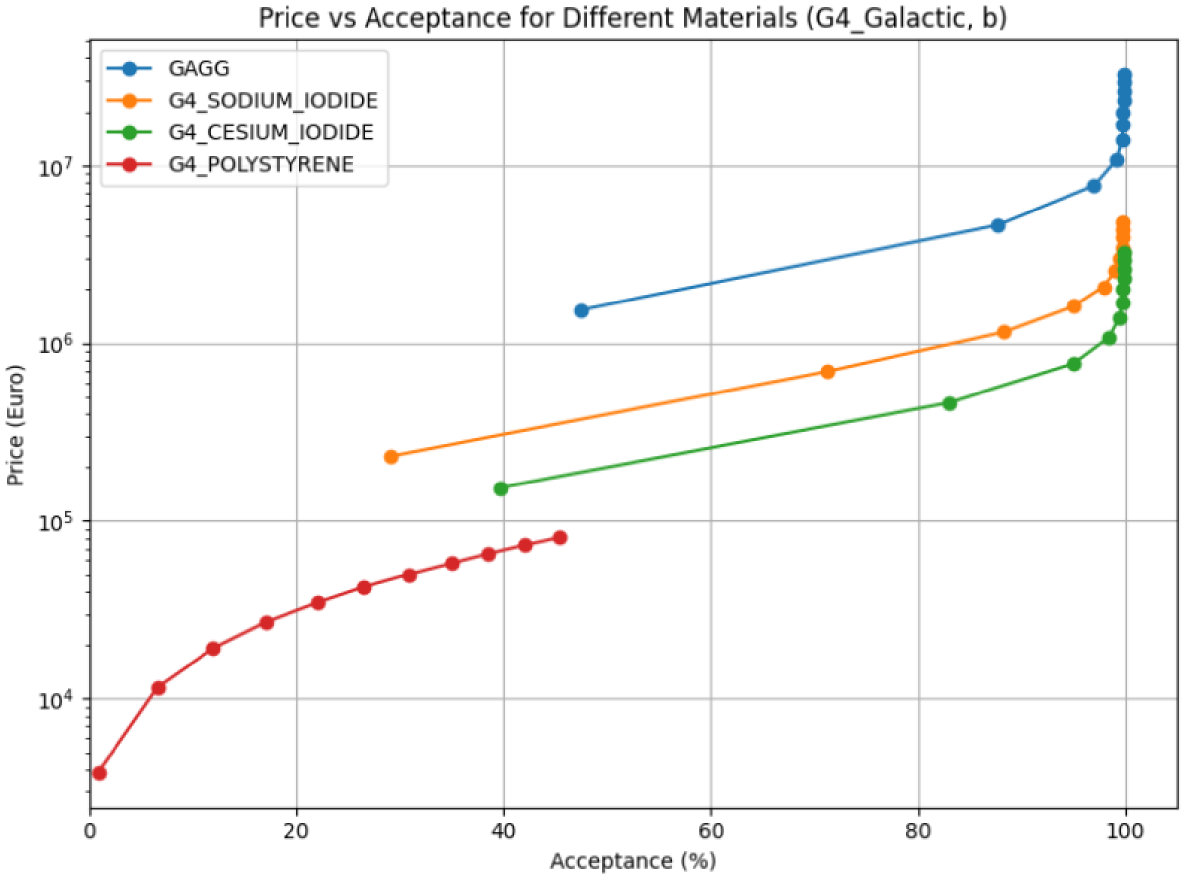
AIR

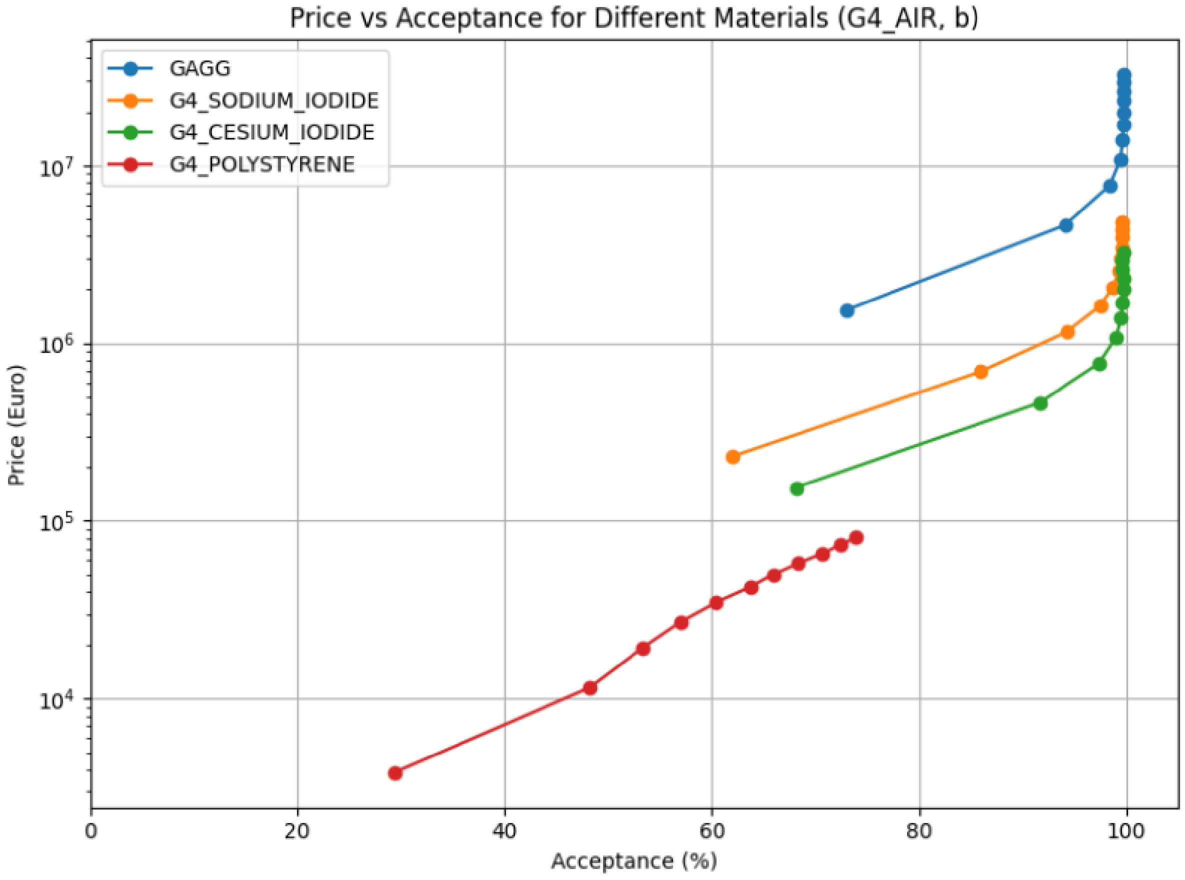
Price vs. Acceptance

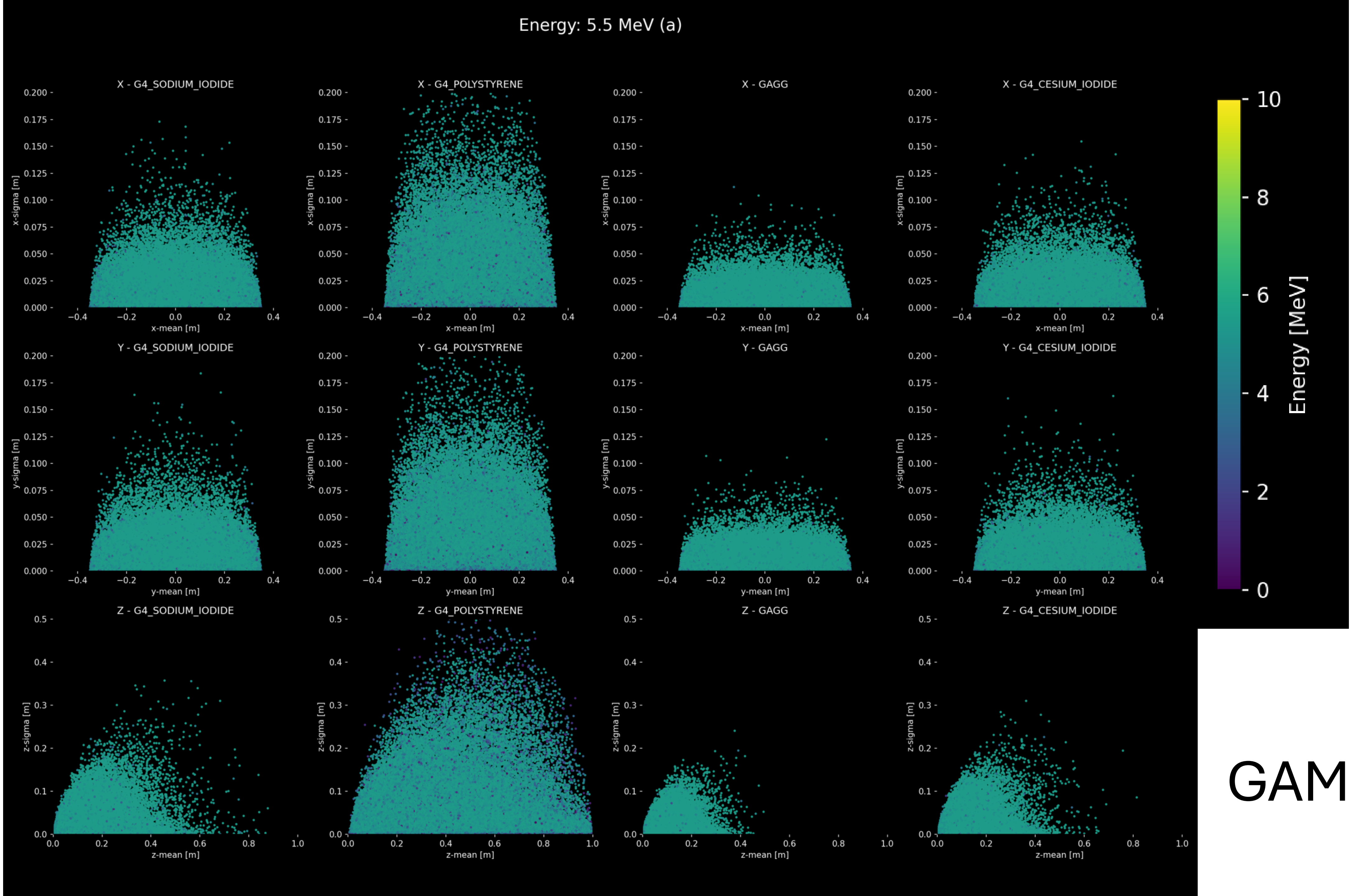




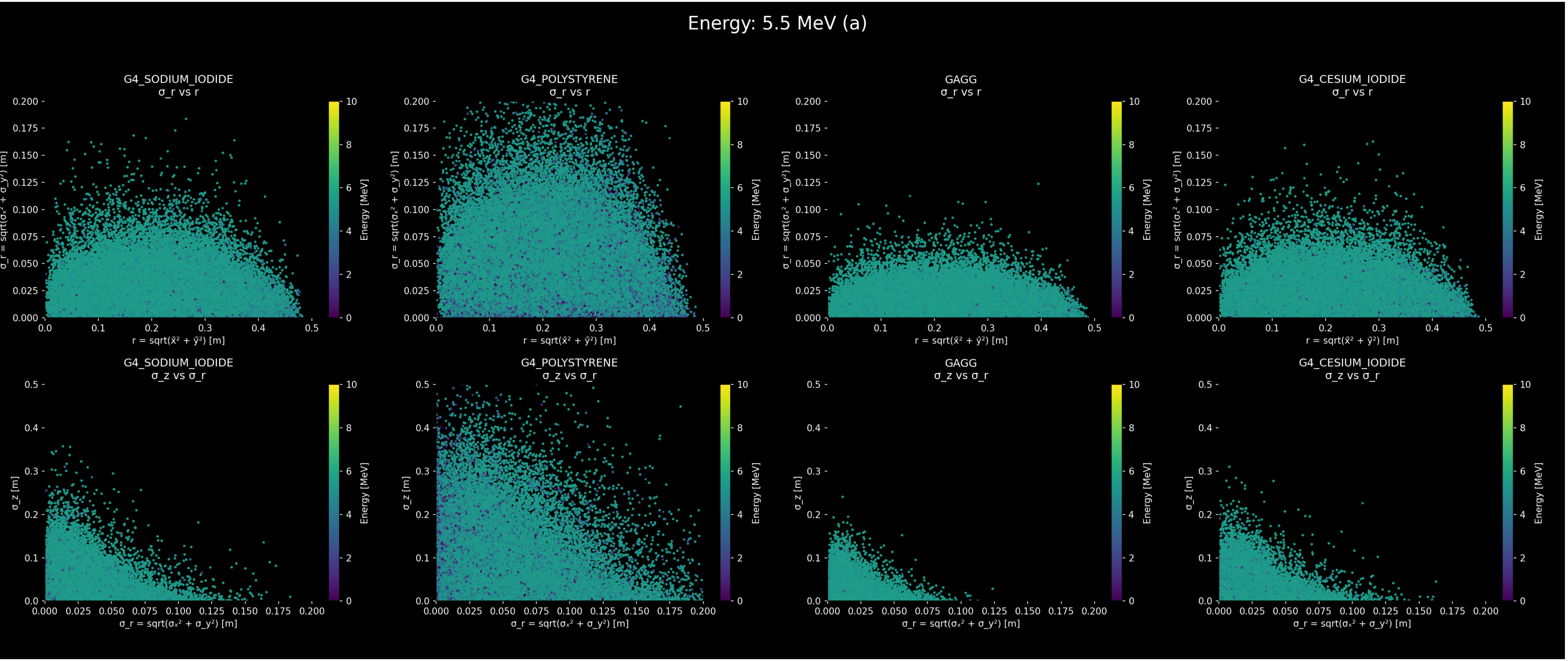
Price vs. Acceptance



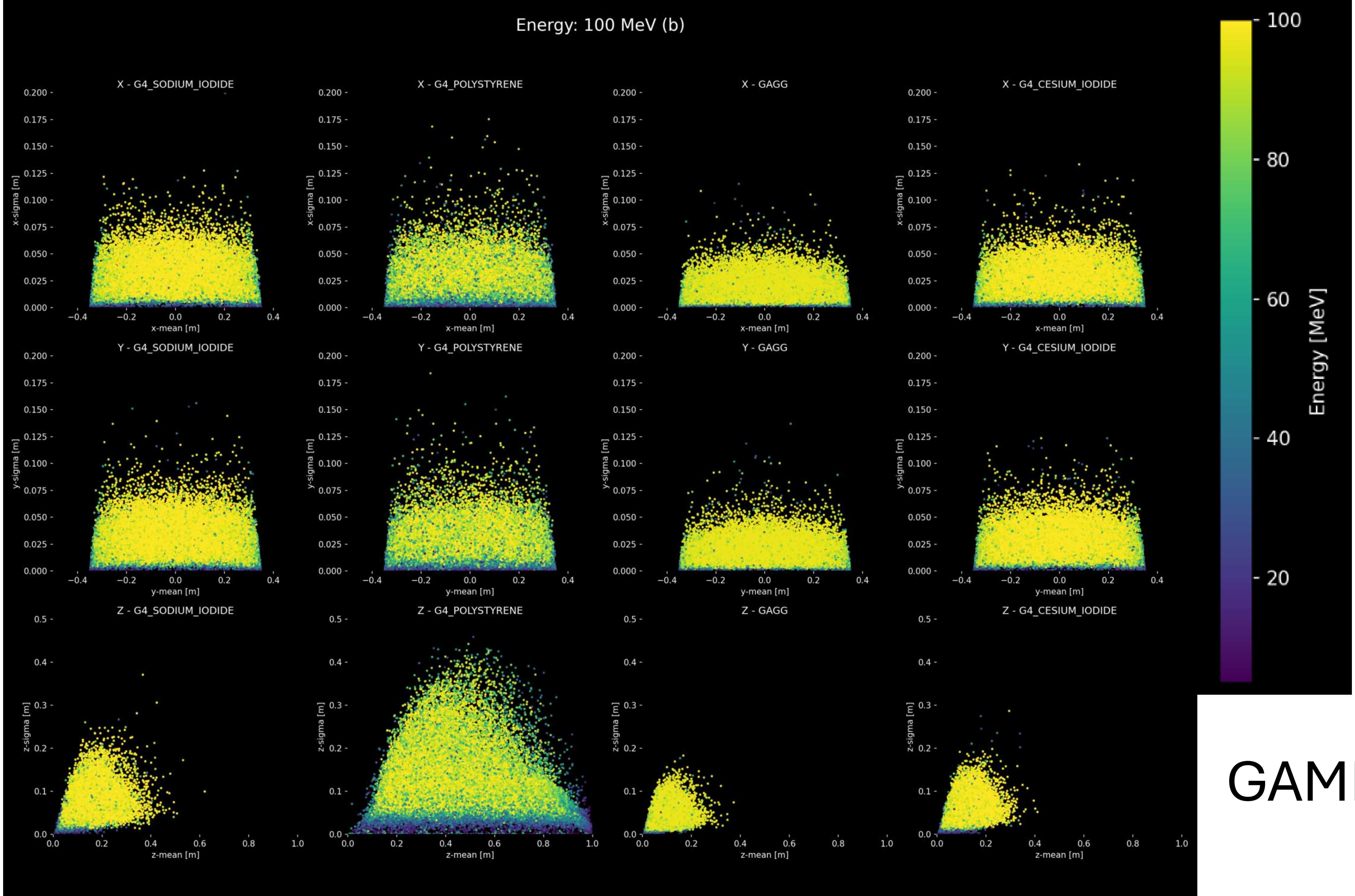



Energy: 5.5 MeV (a)
X - G4_SODIUM_IODIDE
X - G4_POLYSTYRENE
X - GAGG
X - G4_CESIUM_IODIDE
Y - G4_SODIUM_IODIDE
Y - G4_POLYSTYRENE
Y - GAGG
Y - G4_CESIUM_IODIDE
Z - G4_SODIUM_IODIDE
Z - G4_POLYSTYRENE
Z - GAGG
Z - G4_CESIUM_IODIDE
x-sigma [m]
x-mean [m]
y-sigma [m]
y-mean [m]
z-sigma [m]
z-mean [m]
Energy [MeV]

GAMMA/a

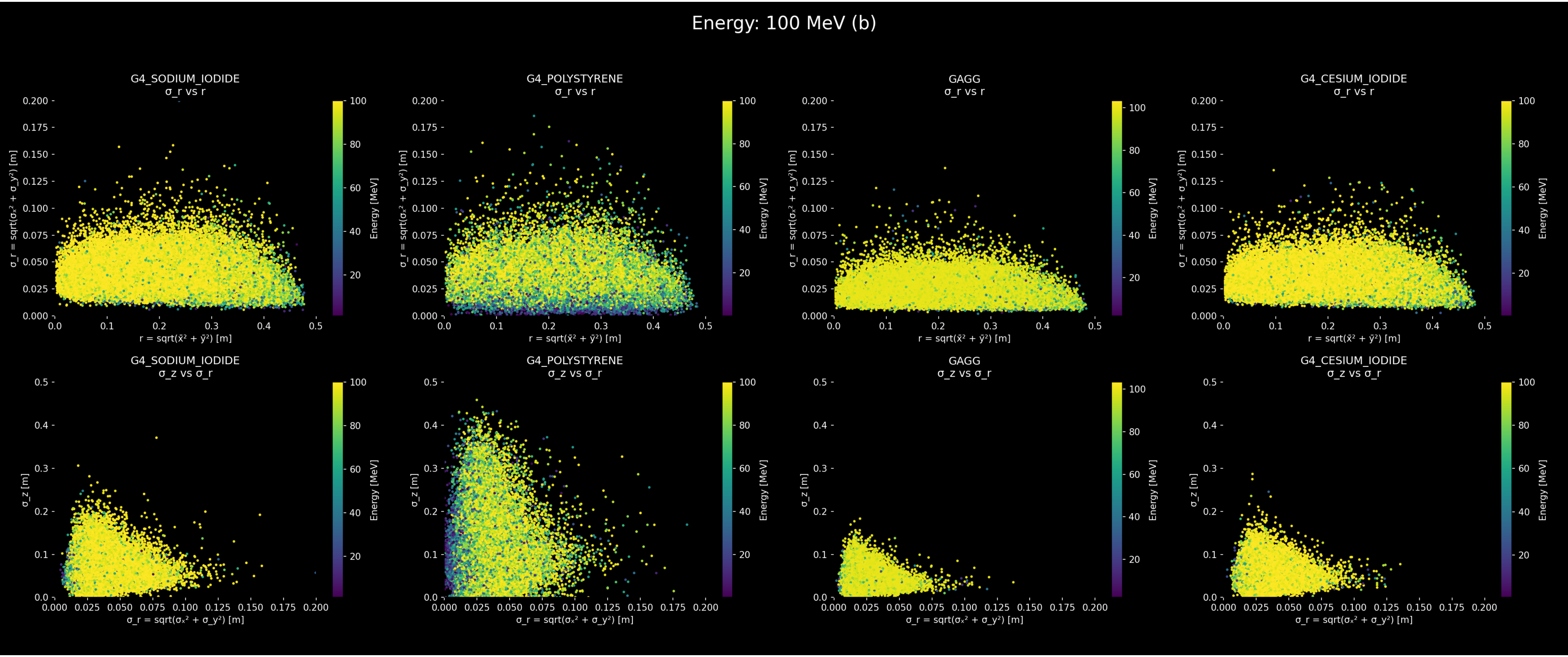

Energy: 5.5 MeV (a)
G4_SODIUM_IODIDE
σ_r vs r
G4_POLYSTYRENE
σ_r vs r
GAGG
σ_r vs r
G4_CESIUM_IODIDE
σ_r vs r
σ_r = sqrt(σₓ² + σ_y²) [m]
r = sqrt(x̄² + ȳ²) [m]
Energy [MeV]
G4_SODIUM_IODIDE
σ_z vs σ_r
G4_POLYSTYRENE
σ_z vs σ_r
GAGG
σ_z vs σ_r
G4_CESIUM_IODIDE
σ_z vs σ_r
σ_z [m]
σ_r = sqrt(σₓ² + σ_y²) [m]
Energy [MeV]

GAMMA/a



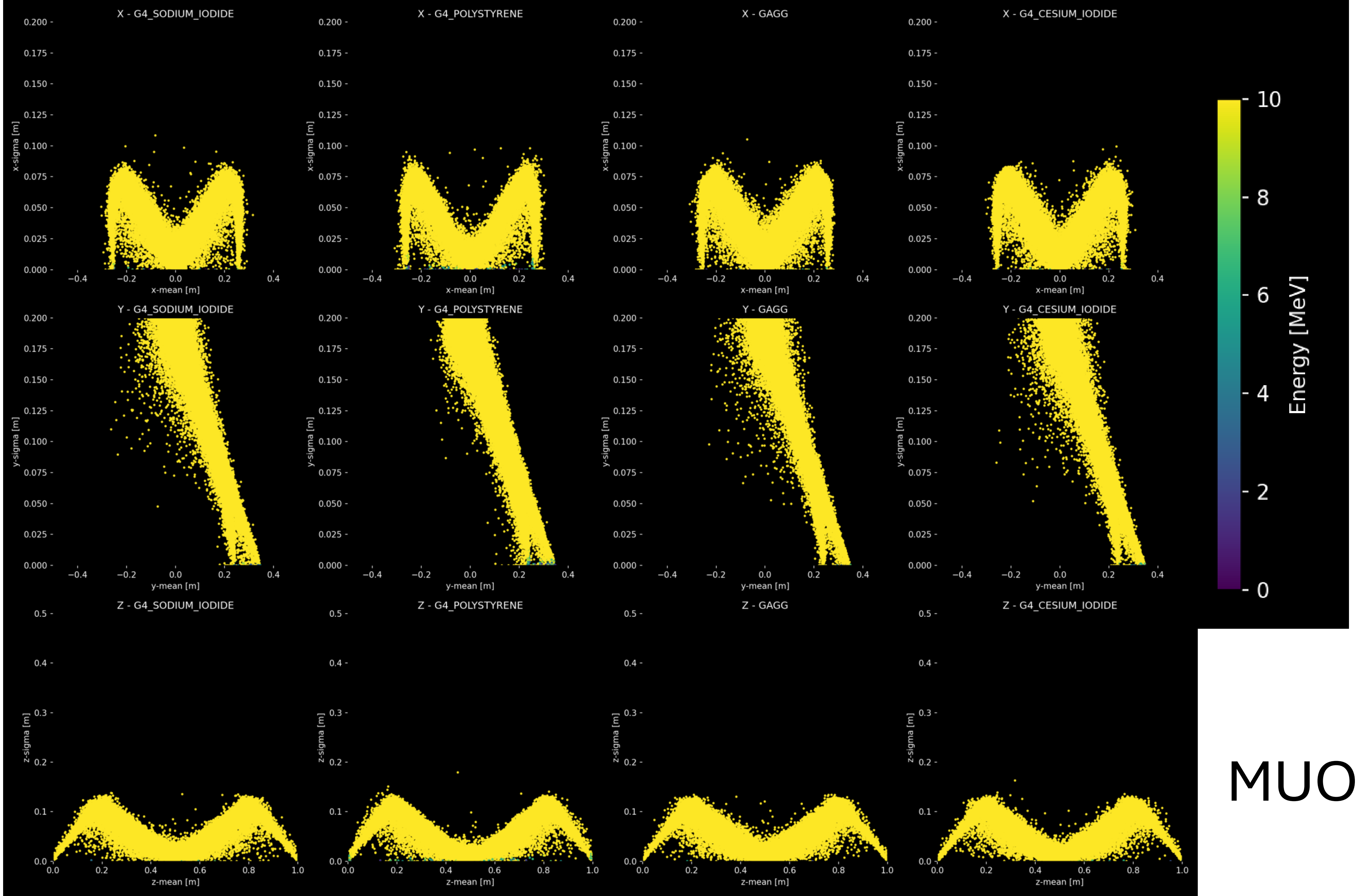
Energy: 100 MeV (b)
X - G4_SODIUM_IODIDE
X - G4_POLYSTYRENE
X - GAGG
X - G4_CESIUM_IODIDE
Y - G4_SODIUM_IODIDE
Y - G4_POLYSTYRENE
Y - GAGG
Y - G4_CESIUM_IODIDE
Z - G4_SODIUM_IODIDE
Z - G4_POLYSTYRENE
Z - GAGG
Z - G4_CESIUM_IODIDE
x-sigma [m]
x-mean [m]
y-sigma [m]
y-mean [m]
z-sigma [m]
z-mean [m]
Energy [MeV]

GAMMA/b

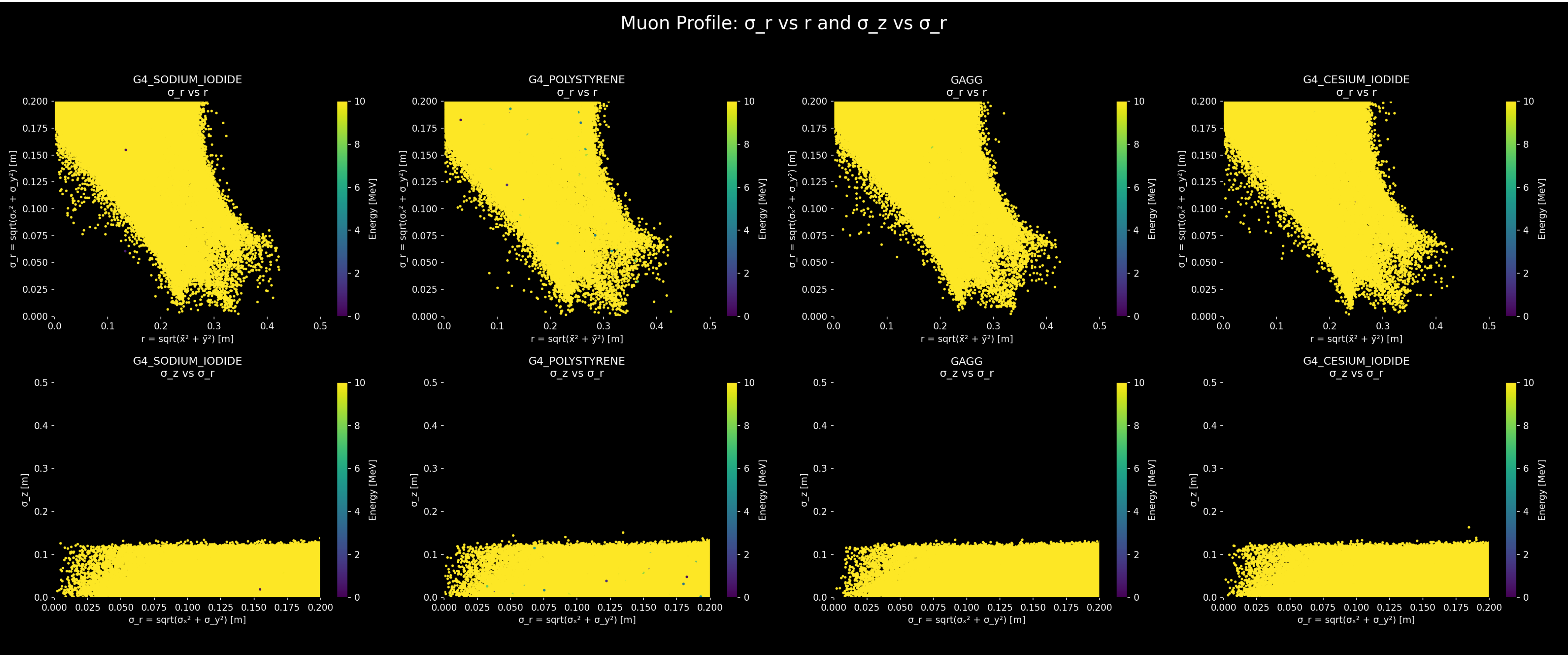


Energy: 100 MeV (b)
G4_SODIUM_IODIDE
σ_r vs r
G4_POLYSTYRENE
σ_r vs r
GAGG
σ_r vs r
G4_CESIUM_IODIDE
σ_r vs r
σ_r = sqrt(σₓ² + σ_y²) [m]
r = sqrt(x̄² + ȳ²) [m]
Energy [MeV]
G4_SODIUM_IODIDE
σ_z vs σ_r
G4_POLYSTYRENE
σ_z vs σ_r
GAGG
σ_z vs σ_r
G4_CESIUM_IODIDE
σ_z vs σ_r
σ_z [m]
σ_r = sqrt(σₓ² + σ_y²) [m]

GAMMA/b


X - G4_SODIUM_IODIDE
X - G4_POLYSTYRENE
X - GAGG
X - G4_CESIUM_IODIDE
Y - G4_SODIUM_IODIDE
Y - G4_POLYSTYRENE
Y - GAGG
Y - G4_CESIUM_IODIDE
Z - G4_SODIUM_IODIDE
Z - G4_POLYSTYRENE
Z - GAGG
Z - G4_CESIUM_IODIDE
x-sigma [m]
x-mean [m]
y-sigma [m]
y-mean [m]
z-sigma [m]
z-mean [m]
Energy [MeV]

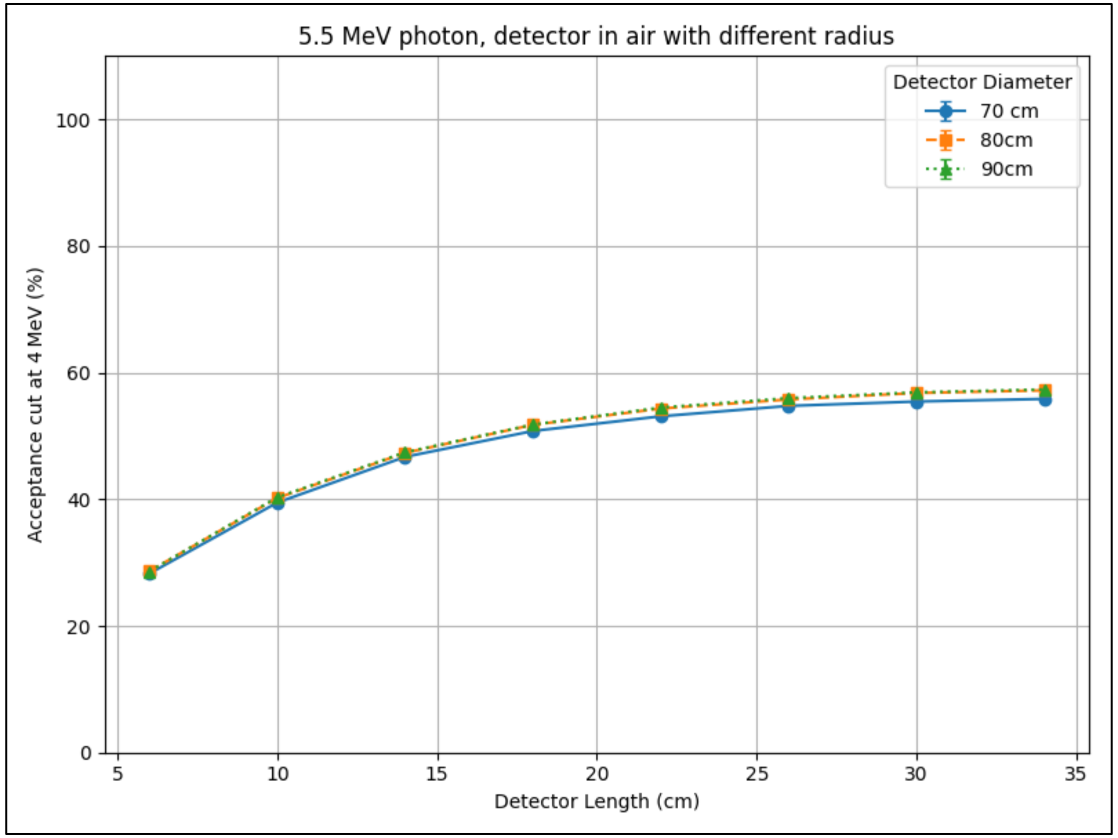
MUON

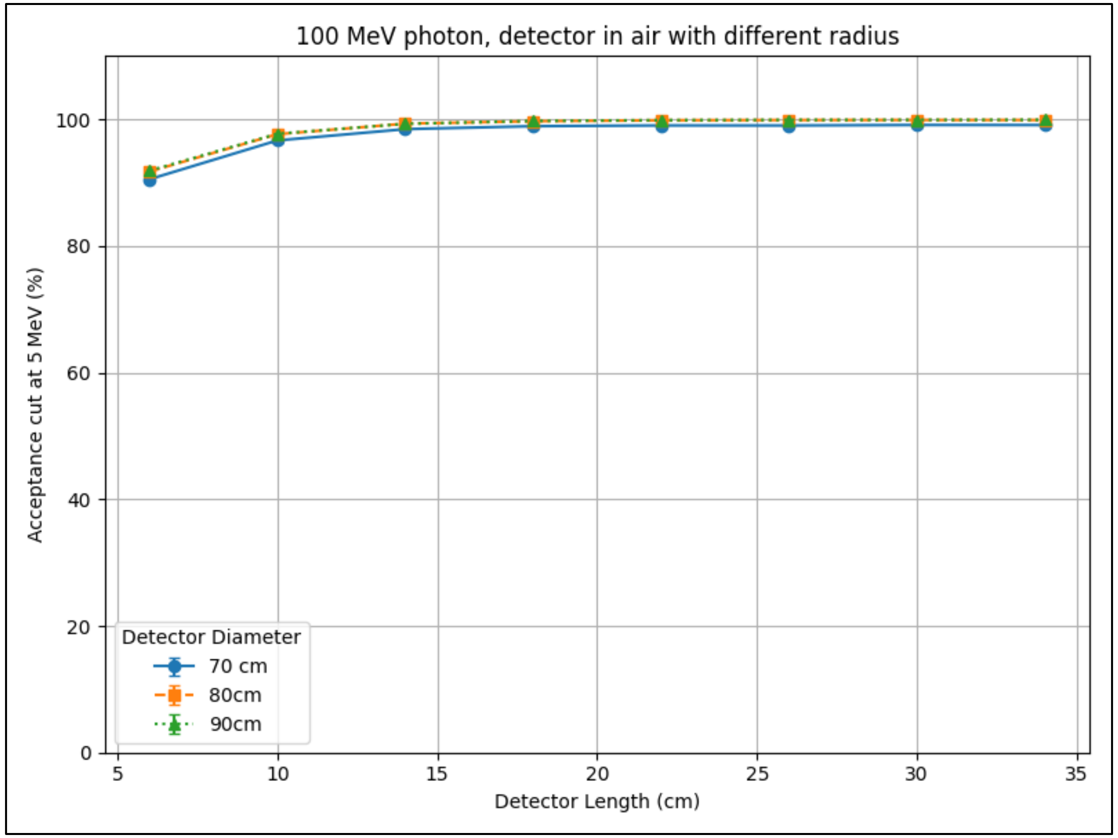


Muon Profile: σ_r vs r and σ_z vs σ_r
G4_SODIUM_IODIDE
σ_r vs r
G4_POLYSTYRENE
σ_r vs r
GAGG
σ_r vs r
G4_CESIUM_IODIDE
σ_r vs r
σ_r = sqrt(σₓ² + σ_y²) [m]
r = sqrt(x̄² + ȳ²) [m]
Energy [MeV]
G4_SODIUM_IODIDE
σ_z vs σ_r
G4_POLYSTYRENE
σ_z vs σ_r
GAGG
σ_z vs σ_r
G4_CESIUM_IODIDE
σ_z vs σ_r
σ_z [m]
σ_r = sqrt(σₓ² + σ_y²) [m]

MUON

Results: Radius (CsI)





'No significant effects'