Angle measurement with sampling calorimeter

KOTO Collaboration meeting

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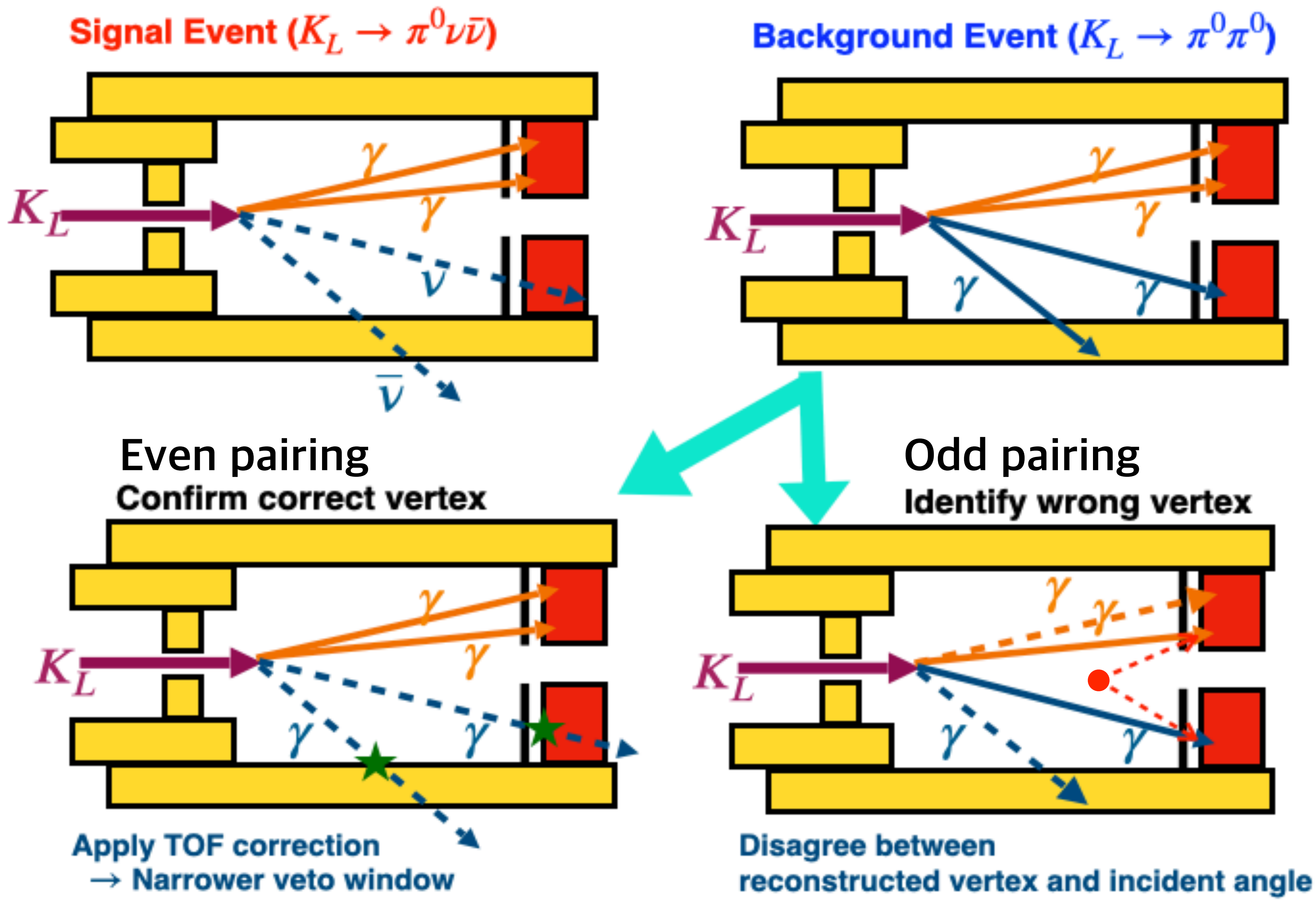
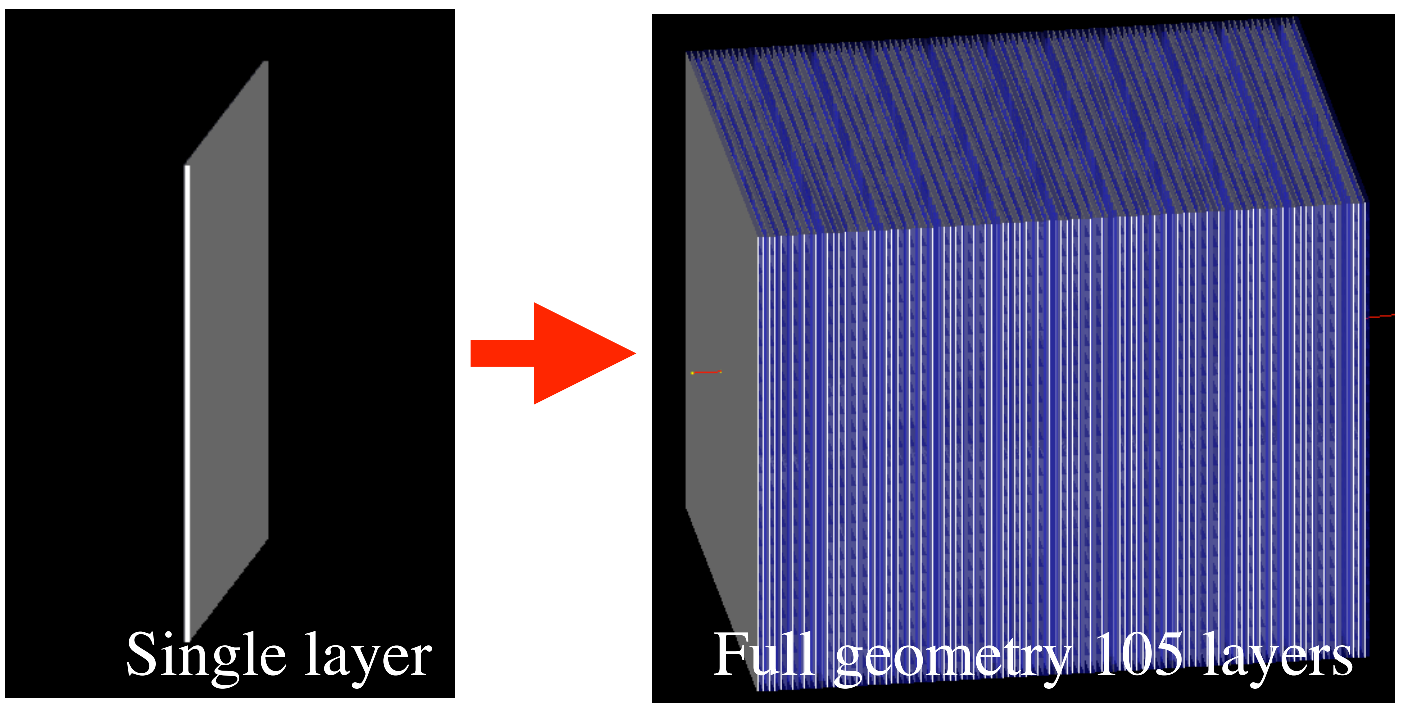
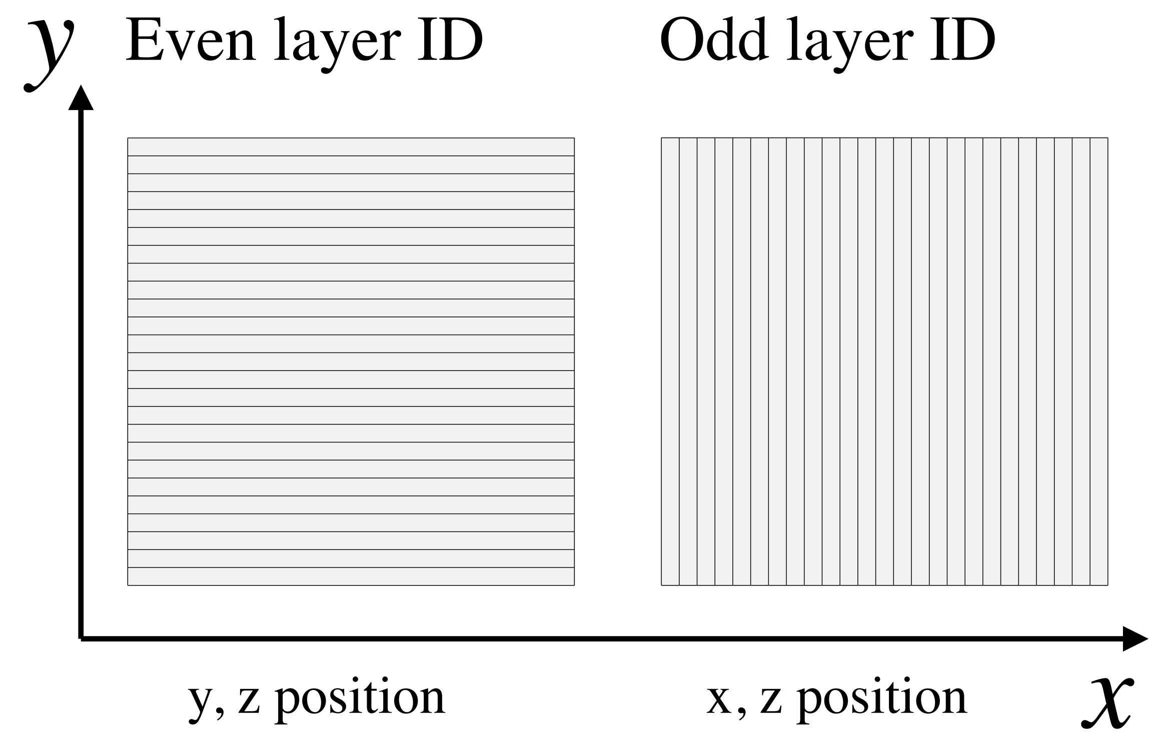
Why do we need γ tracking?



- **Two vertices from different observables**
  - Rejection power for backgrounds
  - To reduce accidental loss (at high beam rate)→ narrow veto window

Design of the Prototype Sampling Calorimeter





Single layer configuration:

Pb: 50 cm (l) × 50 cm (w) × 1 mm (t)

Scintillator: 50 cm (l) × (2 cm (w) × 25) × 5 mm (t)

Radiation length: $0.19X_0$

In total 105 layers:

$20X_0 = 0.19X_0 \times 105$

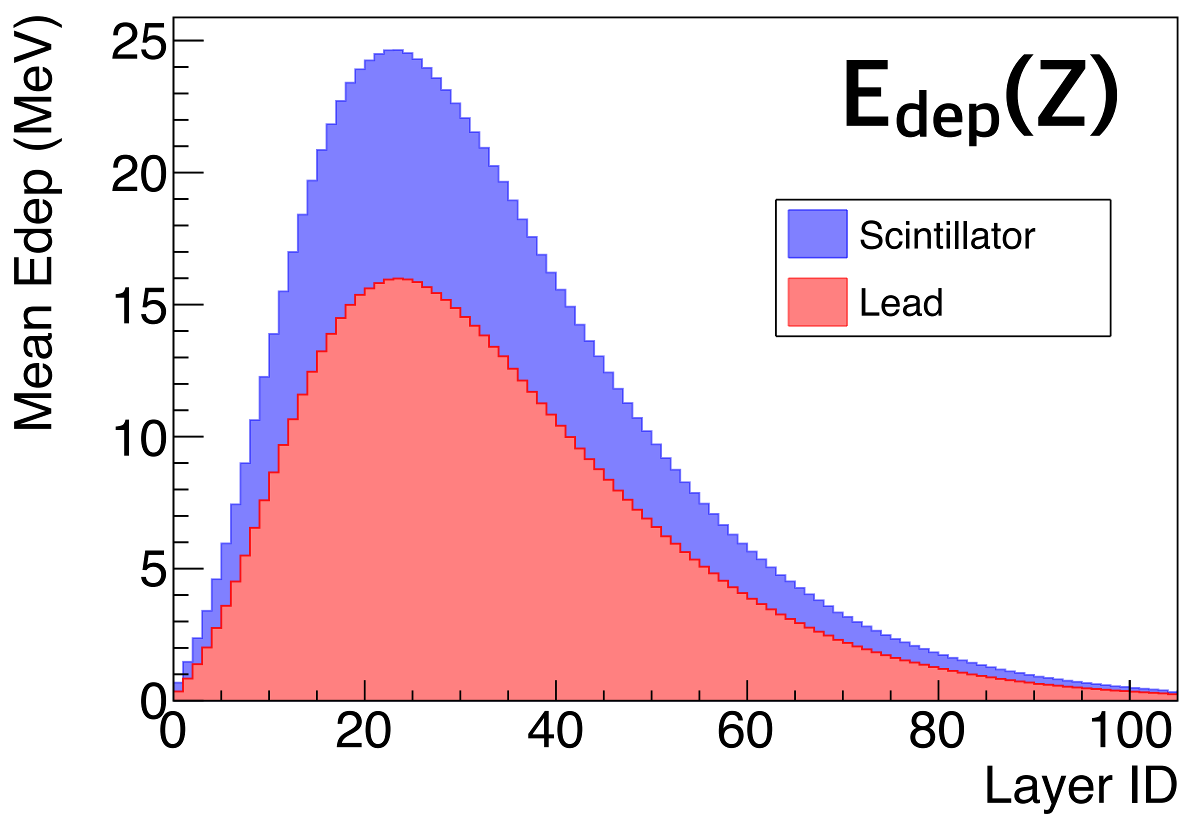
Alternatively aligned along x and y axis

→ Readout y, z position (even layer)

→ Readout x, z position (odd layer)

Shower Profile at 1 GeV photon

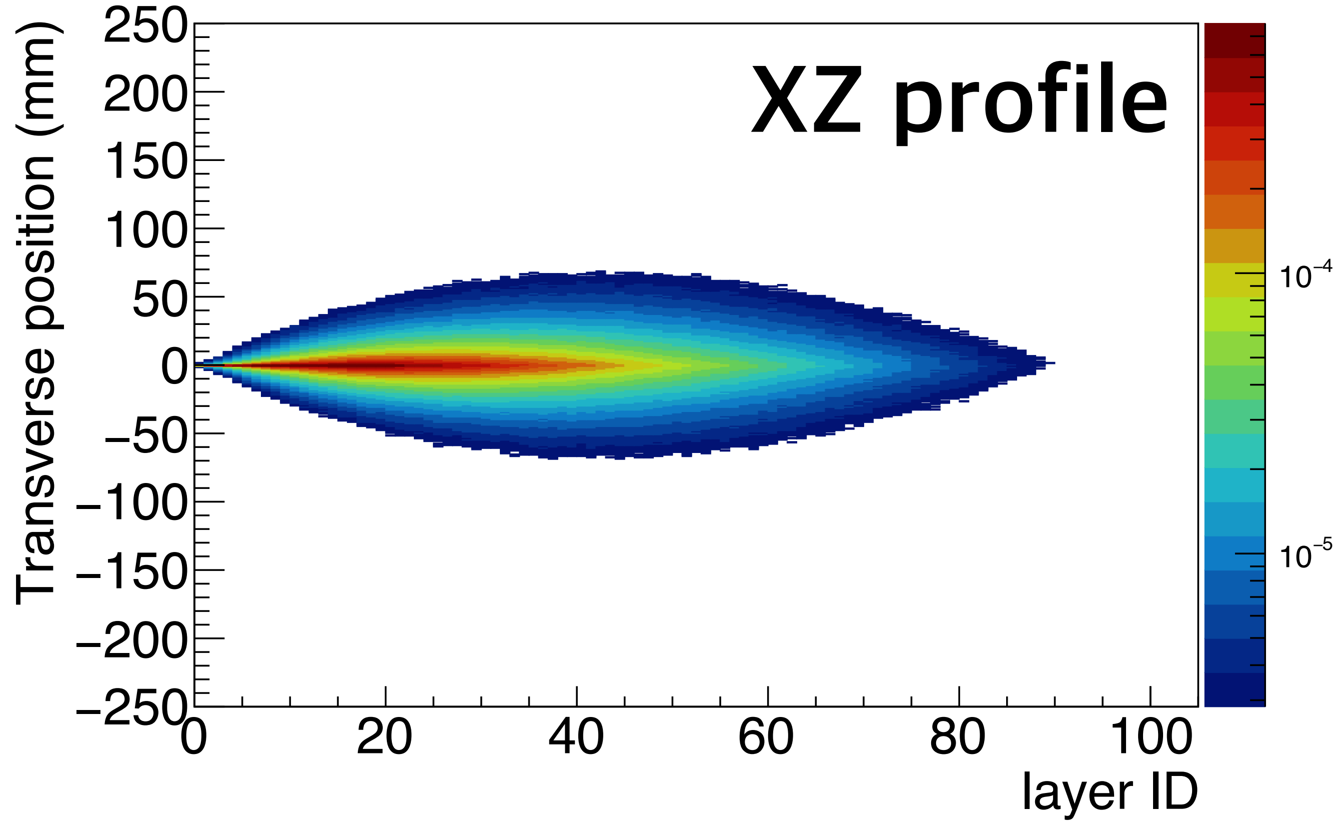
Longitudinal Profile



At 1 GeV photon

- Typical shower shape

2D Shower (Scintillator)



We will discuss relevant properties.

- Moliere radius
- Visible ratio

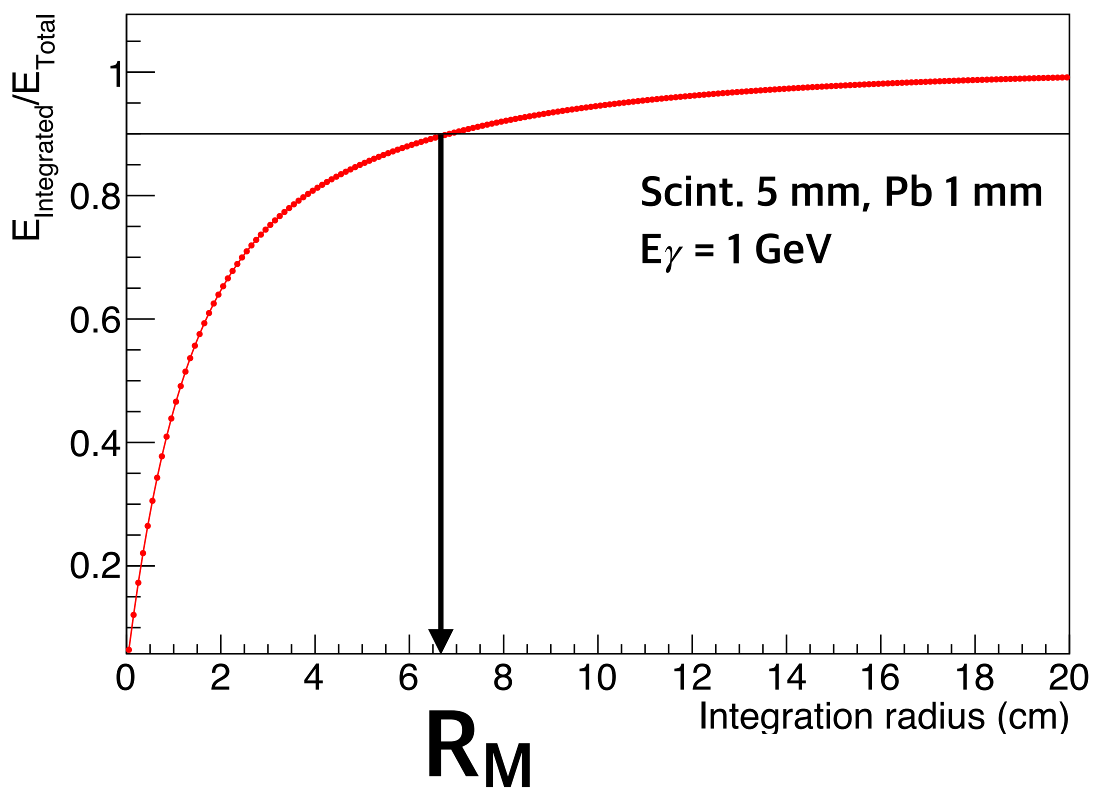
Moliere radius (R_M) and Visible ratio

- **Small Moliere radius** (separation of two photons)
- **Large visible ratio** (good energy resolution)

Moliere radius and visible ratio are studied with combinations of

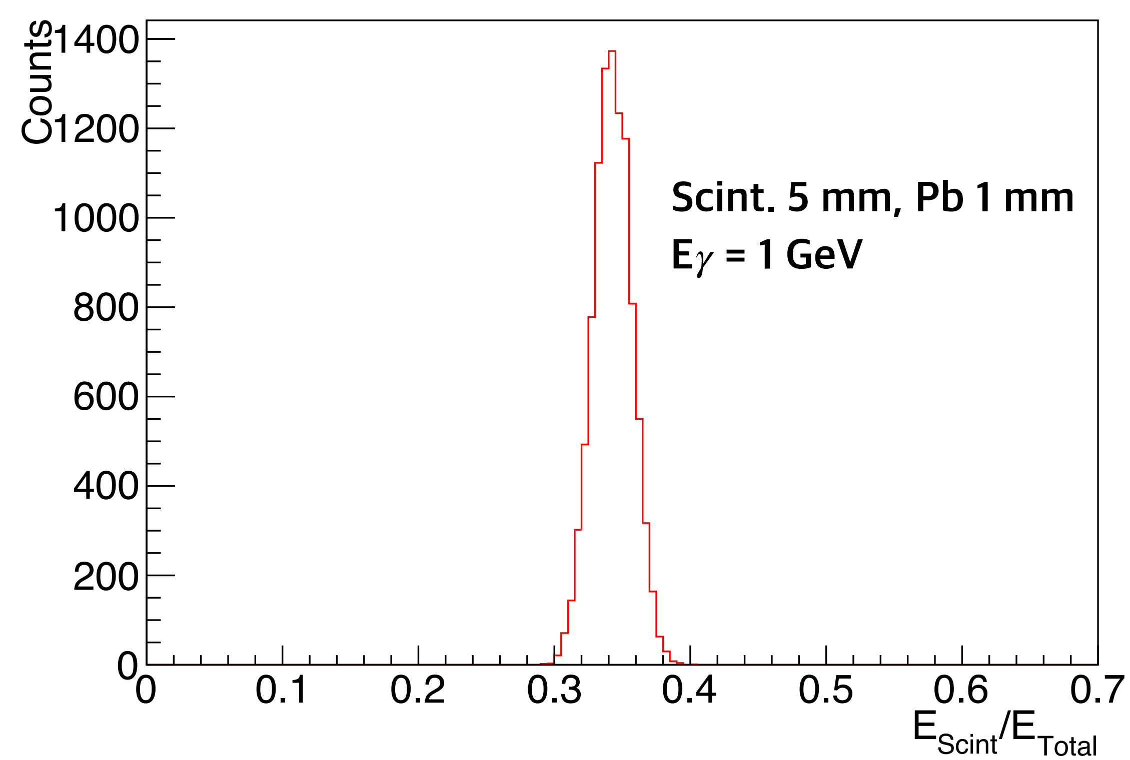
Scintillator		Converter (Pb)
2.5, 5, 10, 15, 20 (mm)	$\times$	0.5, 1, 2 (mm)

Moliere radius



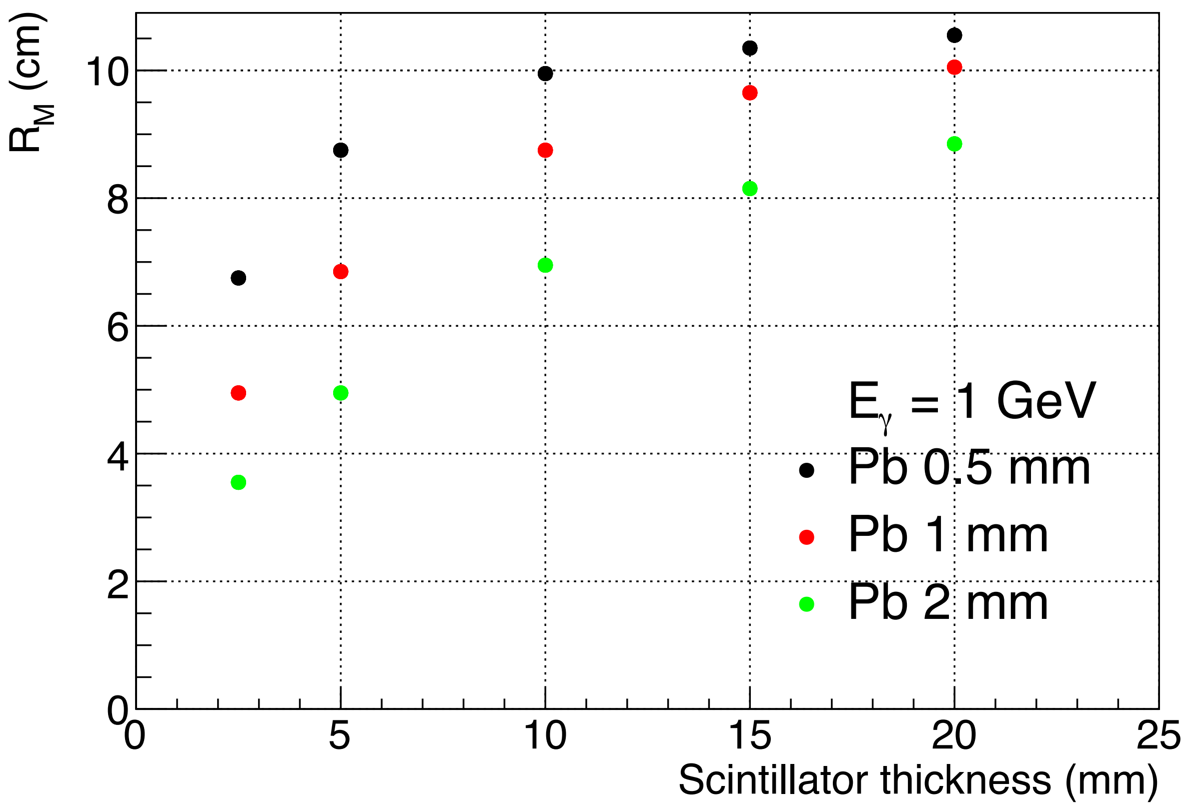
Radius of a cylinder containing on average **90%** energy deposit

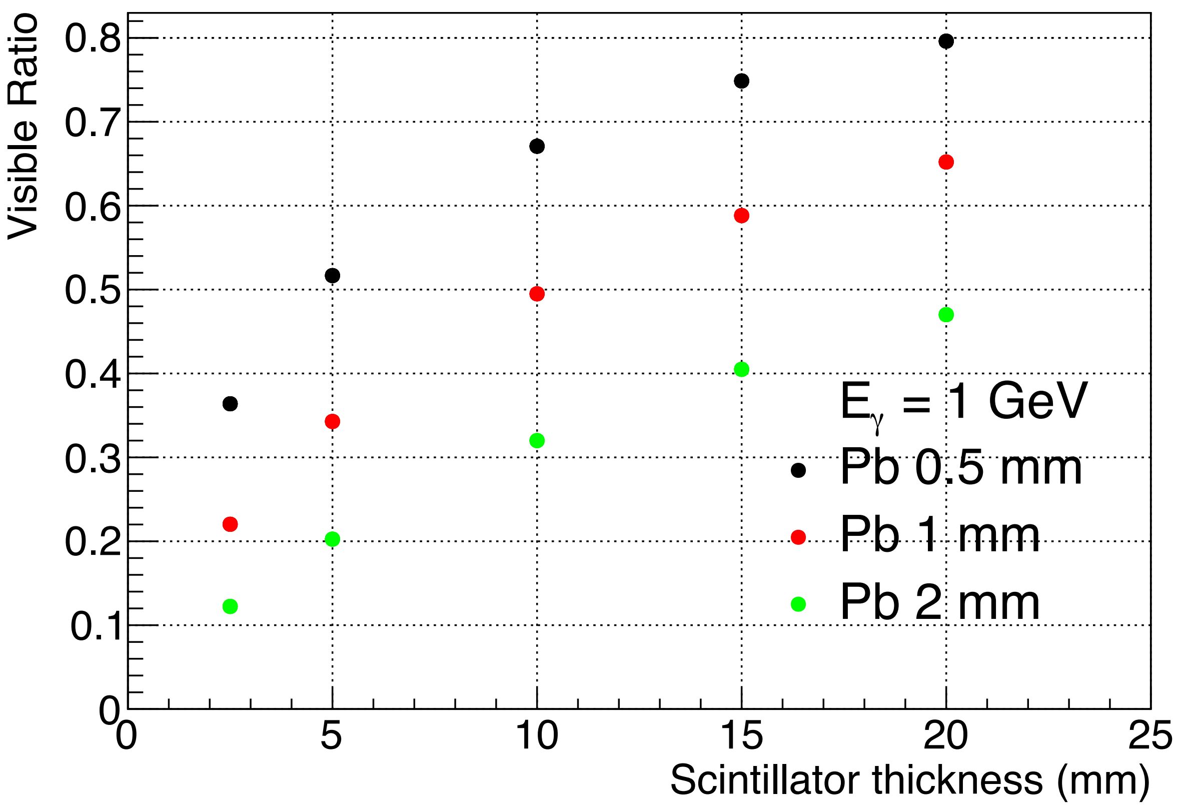
visible ratio

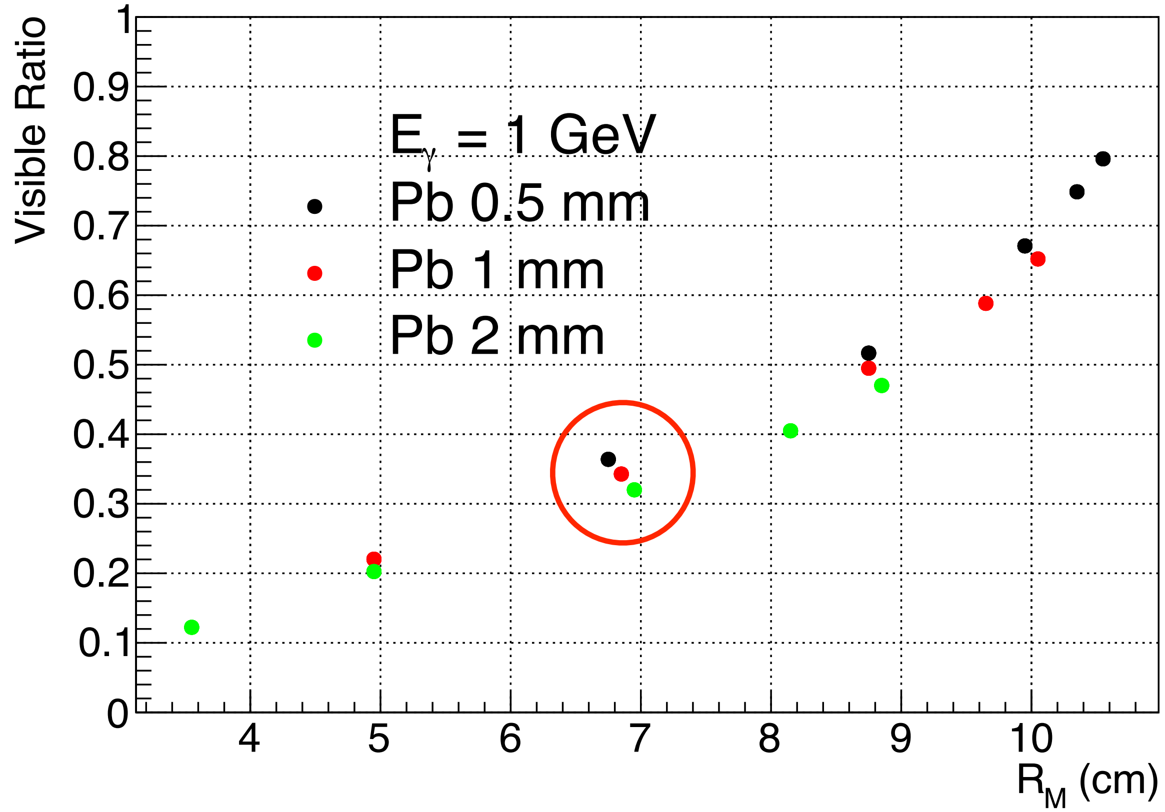


Mean value of the ratio $E_{\text{scint}}/E_{\text{total}}$

Moliere radius (R_M) and Visible ratio



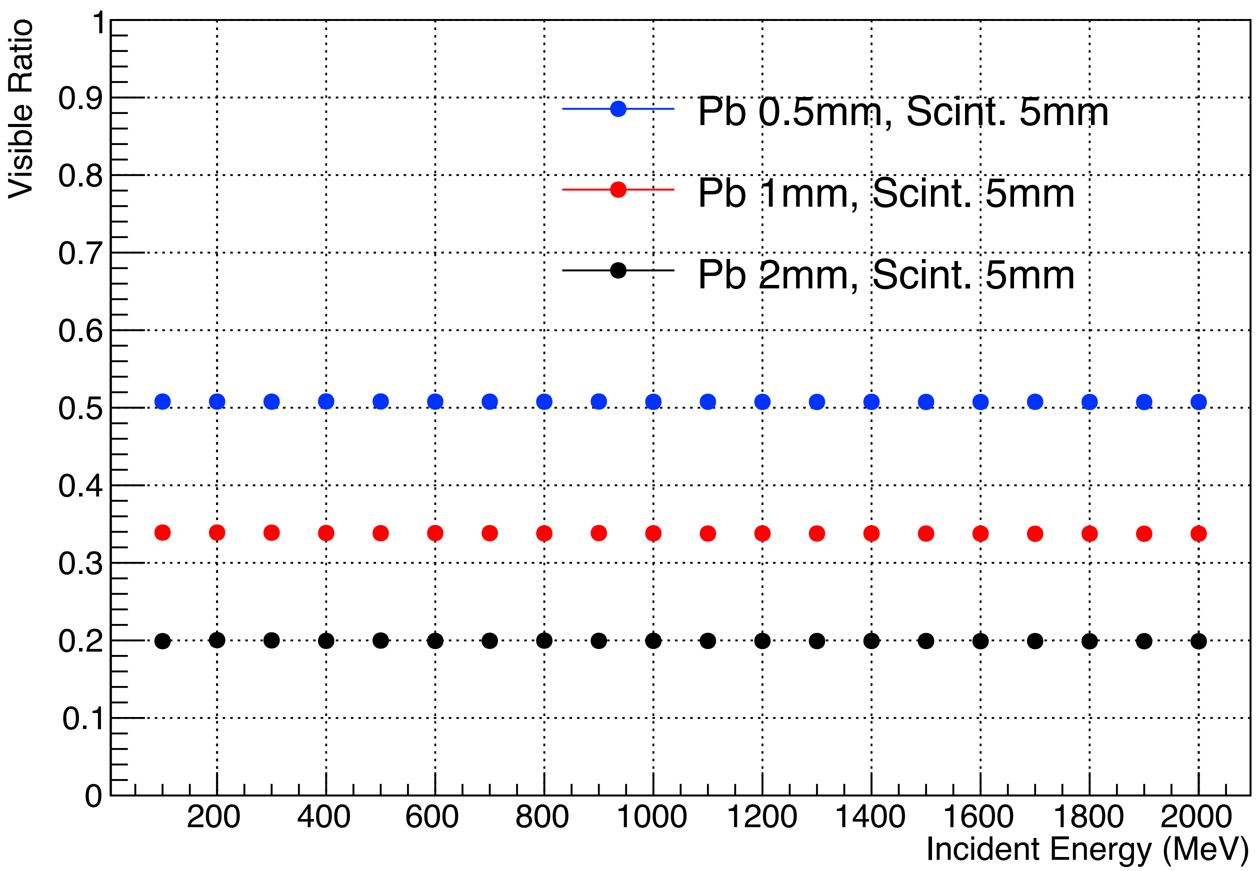




- **Moliere radius and visible ratio depend on ratio between amount of lead and scintillator.**
- Strong correlation between Moliere radius and visible ratio
- We chose the configuration (1 mm, 5 mm).
  (Pb, Scintillator)
- **R_M: 7 cm, visible ratio: 34%**

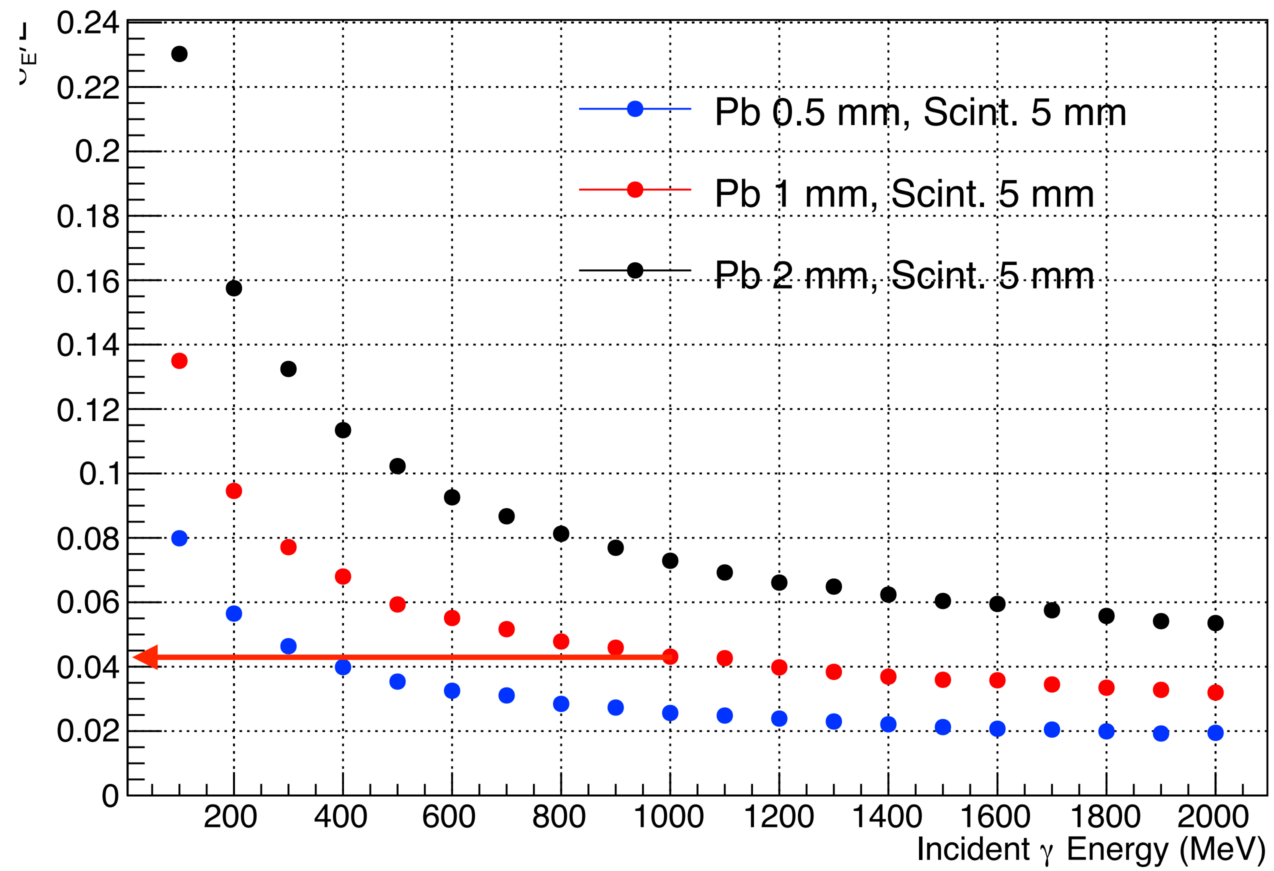
Energy Dependency

Visible ratio



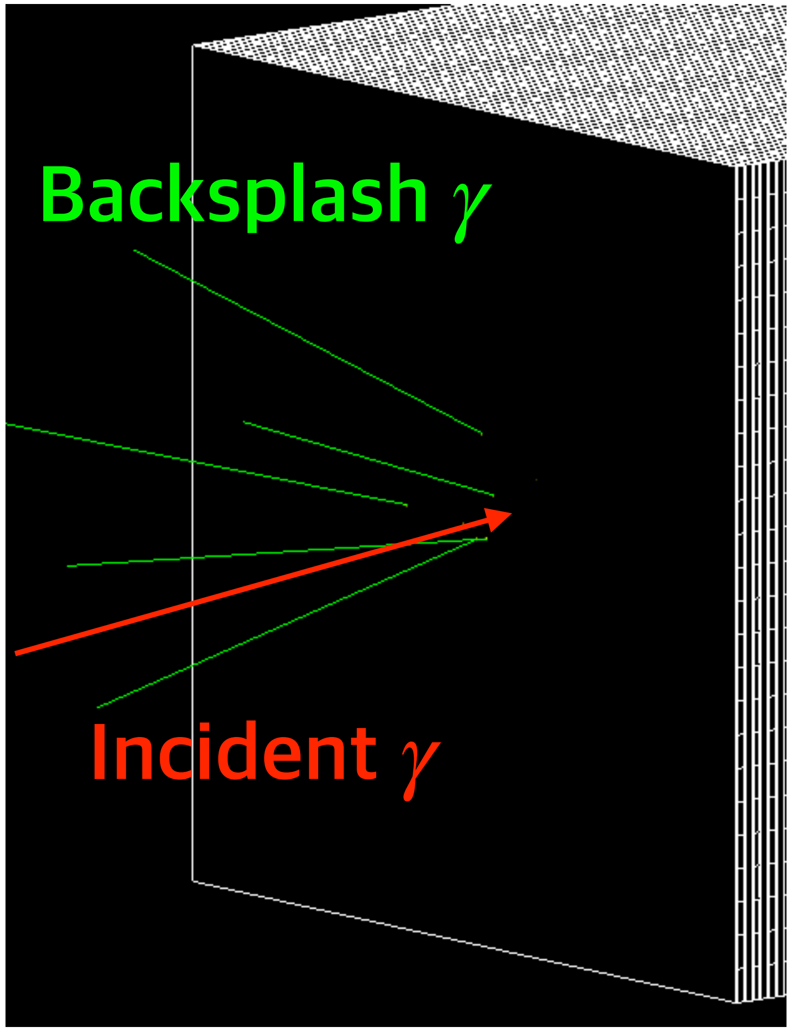
No energy dependency

Energy resolution



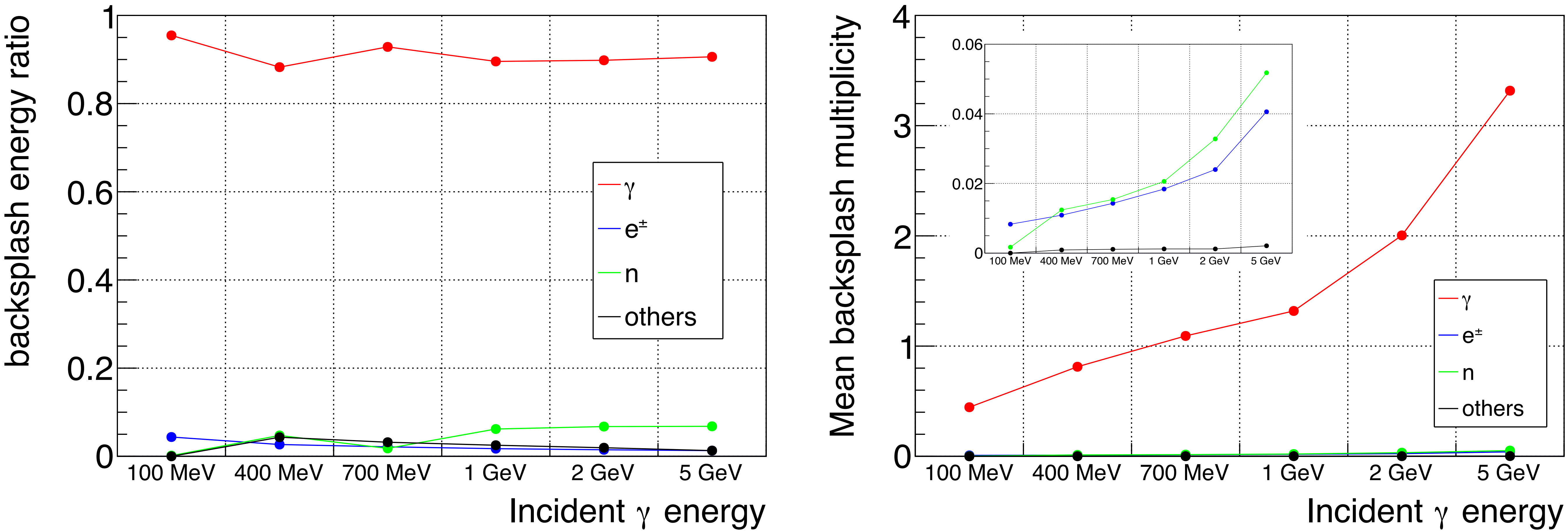
4% energy resolution at 1 GeV γ

Backsplash Events



- Backsplash particles: Outgoing particles through the incident surface
- Backsplash γ or $e^{\pm}$ is one of the most significant sources of the event loss.
- **The event veto rate of a single gamma event** is studied.
  - Event veto rate: The fraction of the number of events with backsplash particles

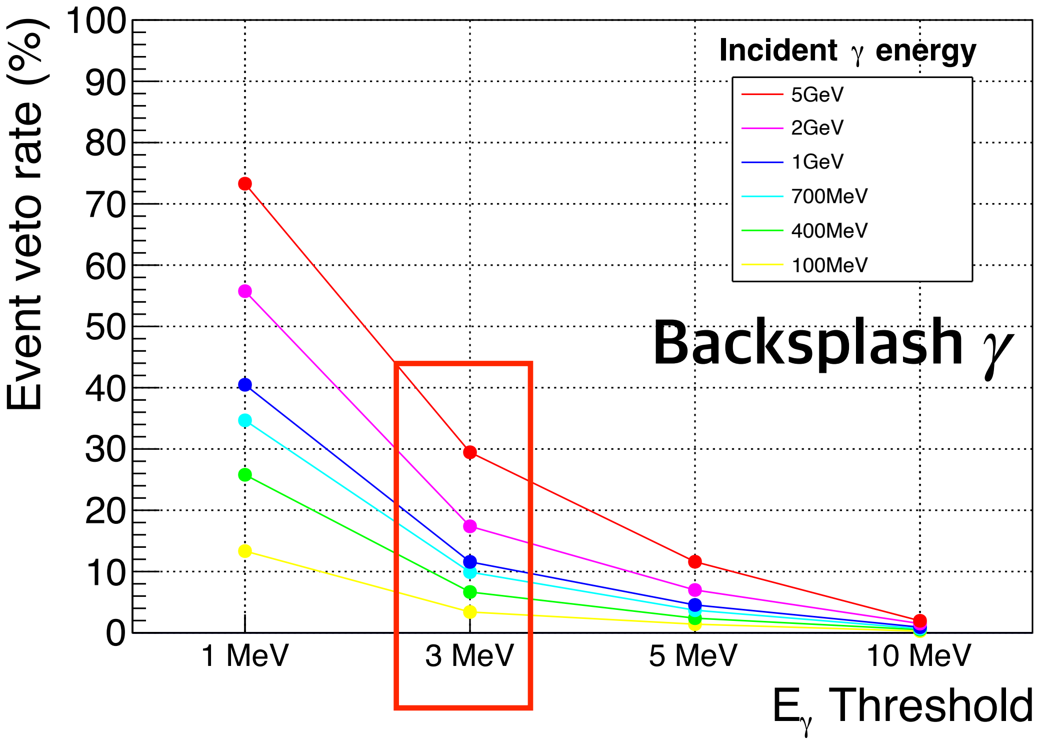
Backsplash Energy / Multiplicity

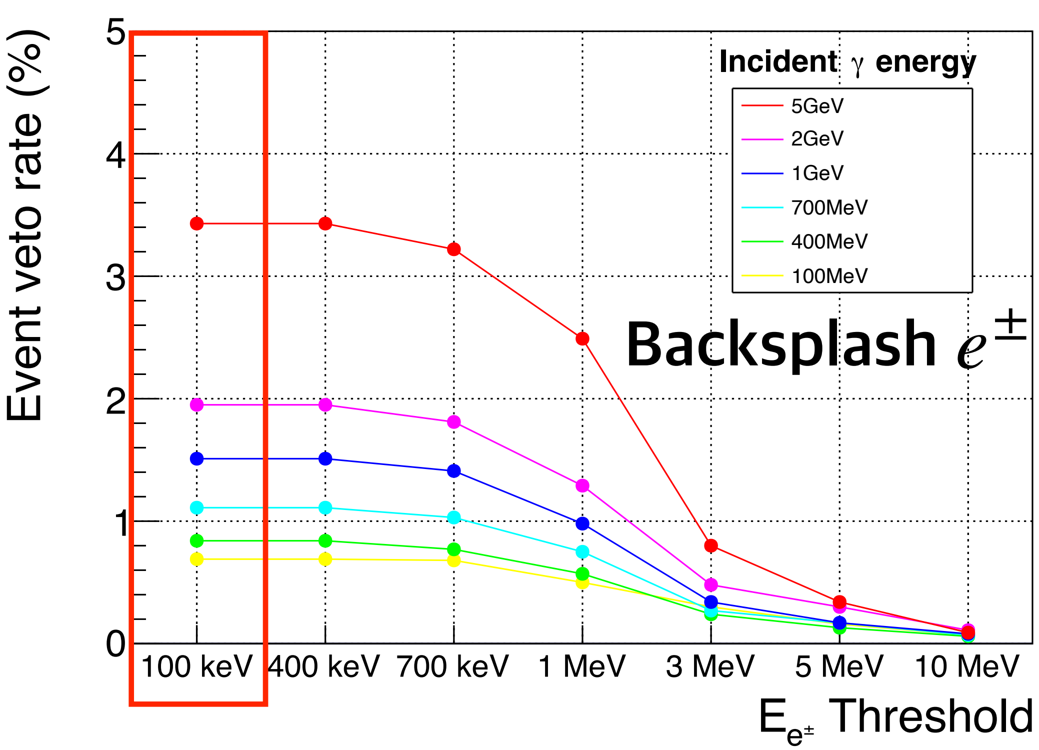


- Almost of backsplash particles are γ (> 90%).

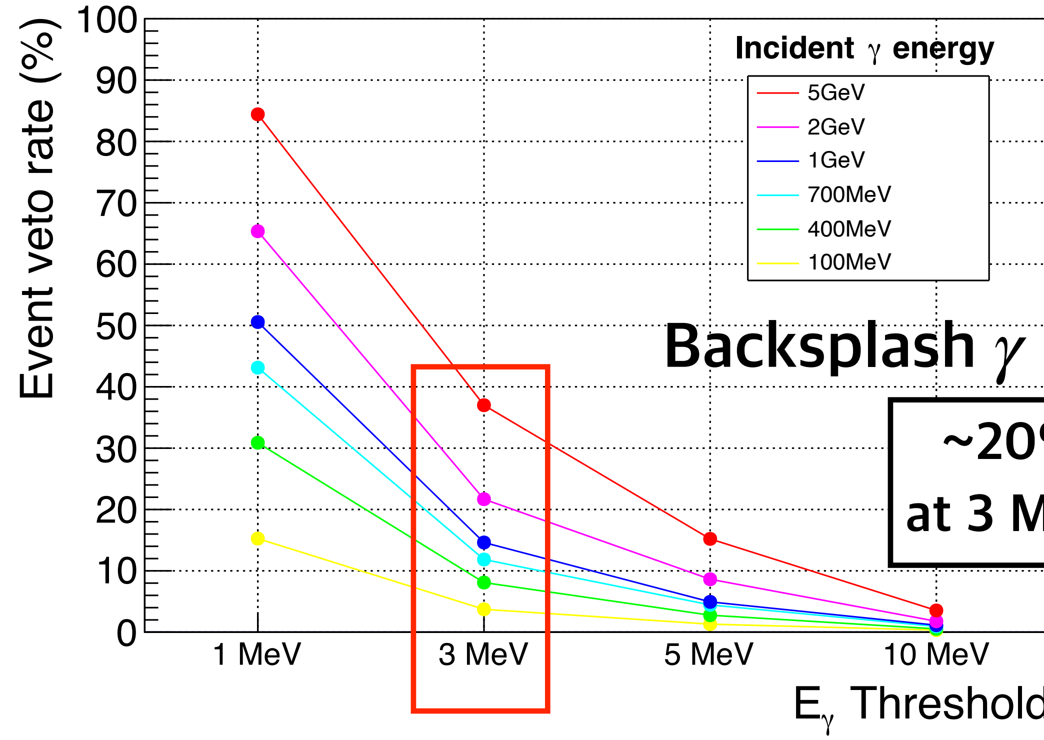
Event veto rate: $N_{\gamma/e^{\pm}} \geq 1$

Sampling Calorimeter

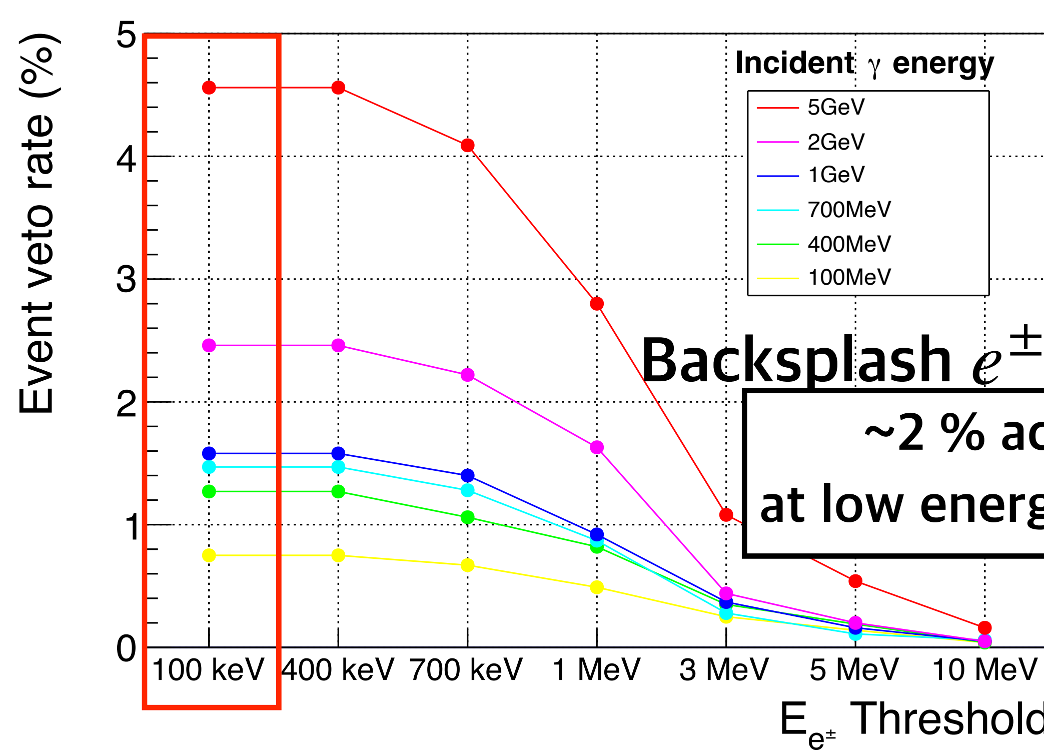




CsI Calorimeter



~20% accidental loss at 3 MeV threshold for γ



~2 % accidental loss at low energy threshold for e

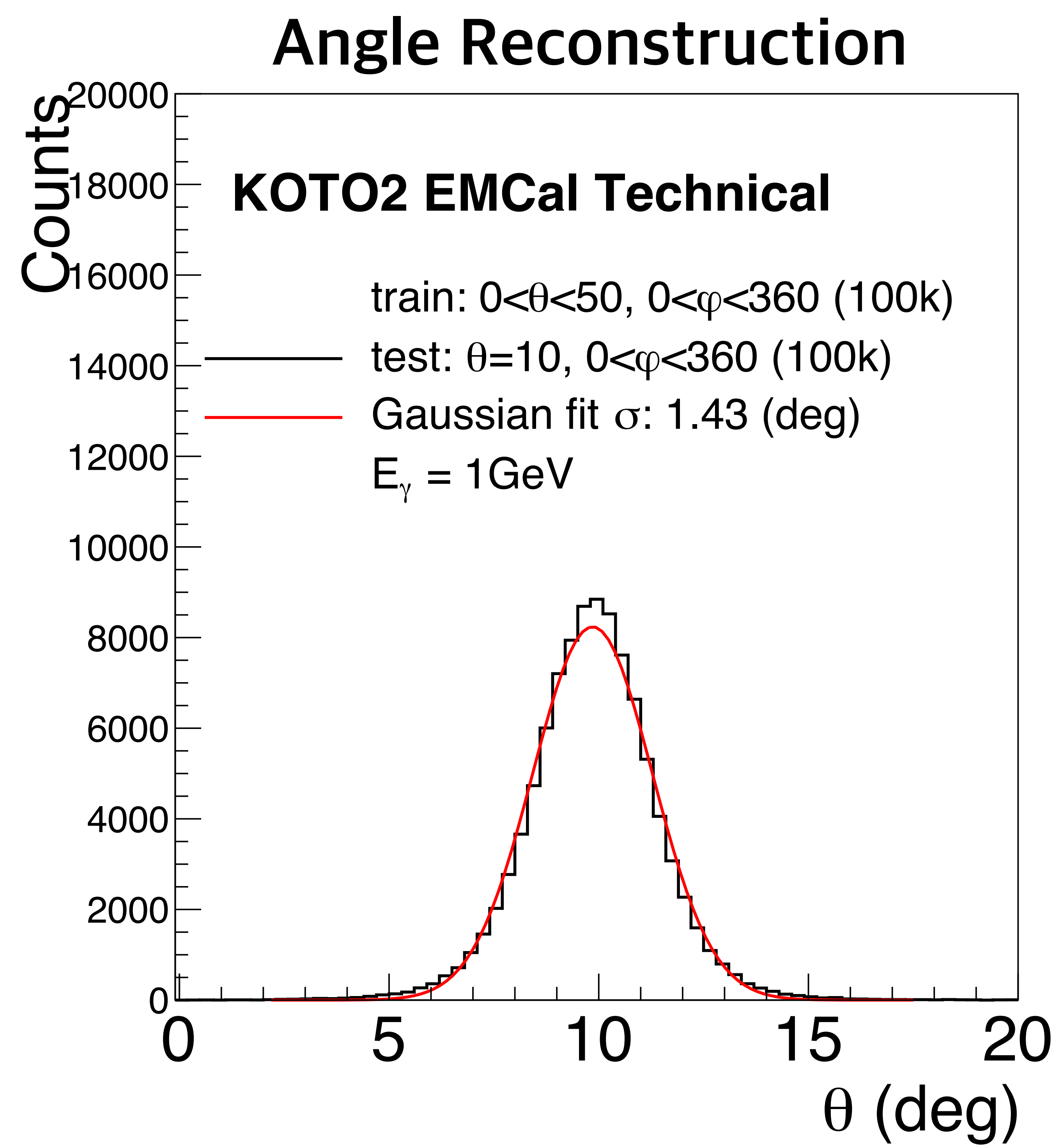
XGBoost: Machine Learning (ML) Toolkit

- We utilized a machine learning toolkit "XGBoost" to **reconstruct the incident angle of γ** via the **regressions process.**
  - XGBoost: Fast training, to prevent overtraining.
  - **arXiv:1603.02754**

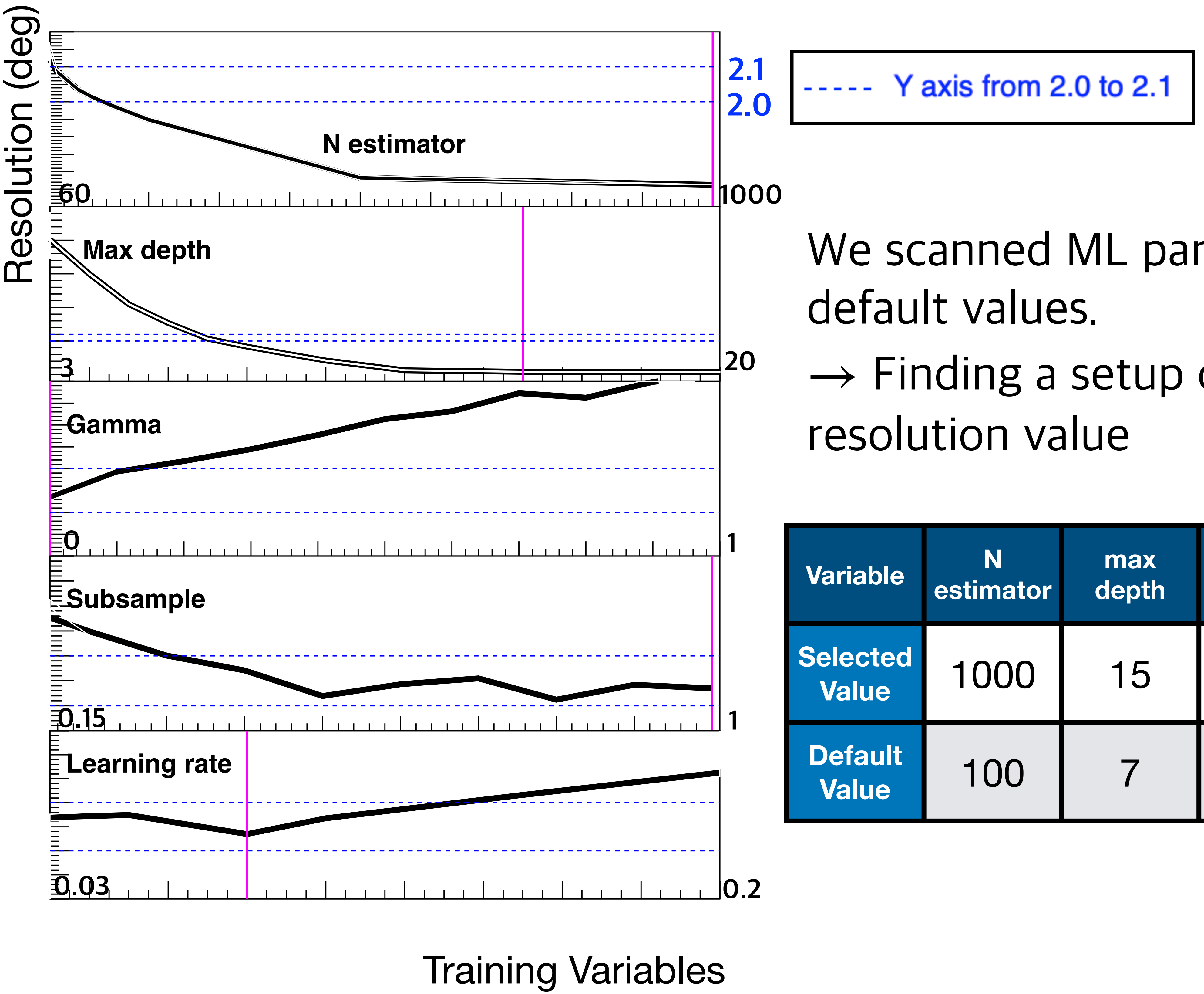
- Co-working with Junlee Kim (Jeonbuk National Univ.)

Angle Reconstruction via ML

- Input: detector responses (EM showers) from the Geant4
  - Deposit energy in each channel
- Output: the incident angle
  - $$\theta = \mathrm{atan}\left(\sqrt{(\Delta x/\Delta z)^2 + (\Delta y/\Delta z)^2}\right)$$
- Training
  - Training input:
    Detector responses + Target (true angle)
  - Training time:
    a few minutes to a few hours for 100k
- Reconstruction test
  - Test input:
    Detector responses
  - Test output:
    incident angle (prediction)
  - Test time: a few seconds for 100k



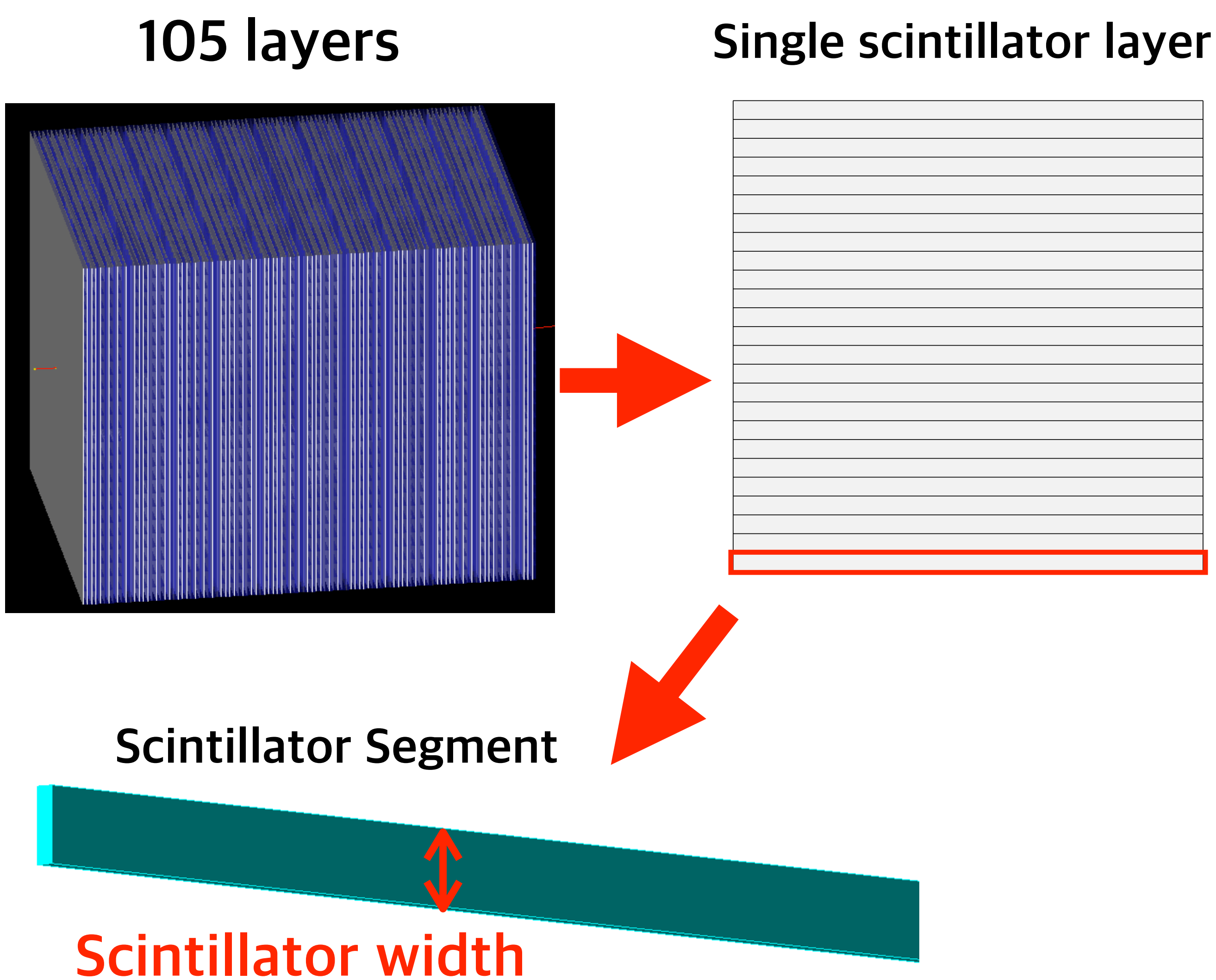
ML Parameters Setting

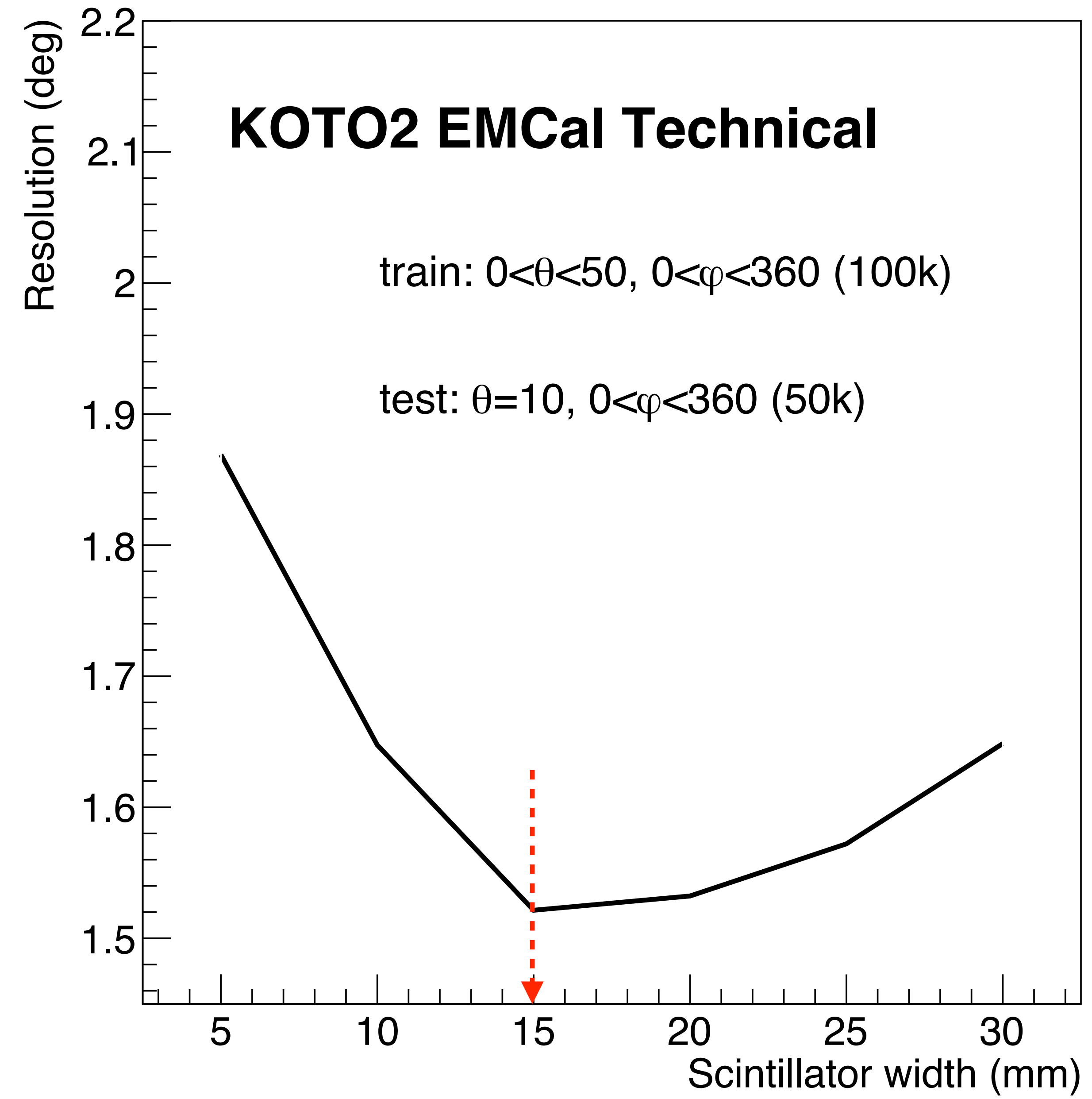


We scanned ML parameters from the default values.
→ Finding a setup of the best angular resolution value

Variable	N estimator	max depth	Gamma	Subsample	Learning rate
Selected Value	1000	15	0	1	0.08
Default Value	100	7	0	1	0.08

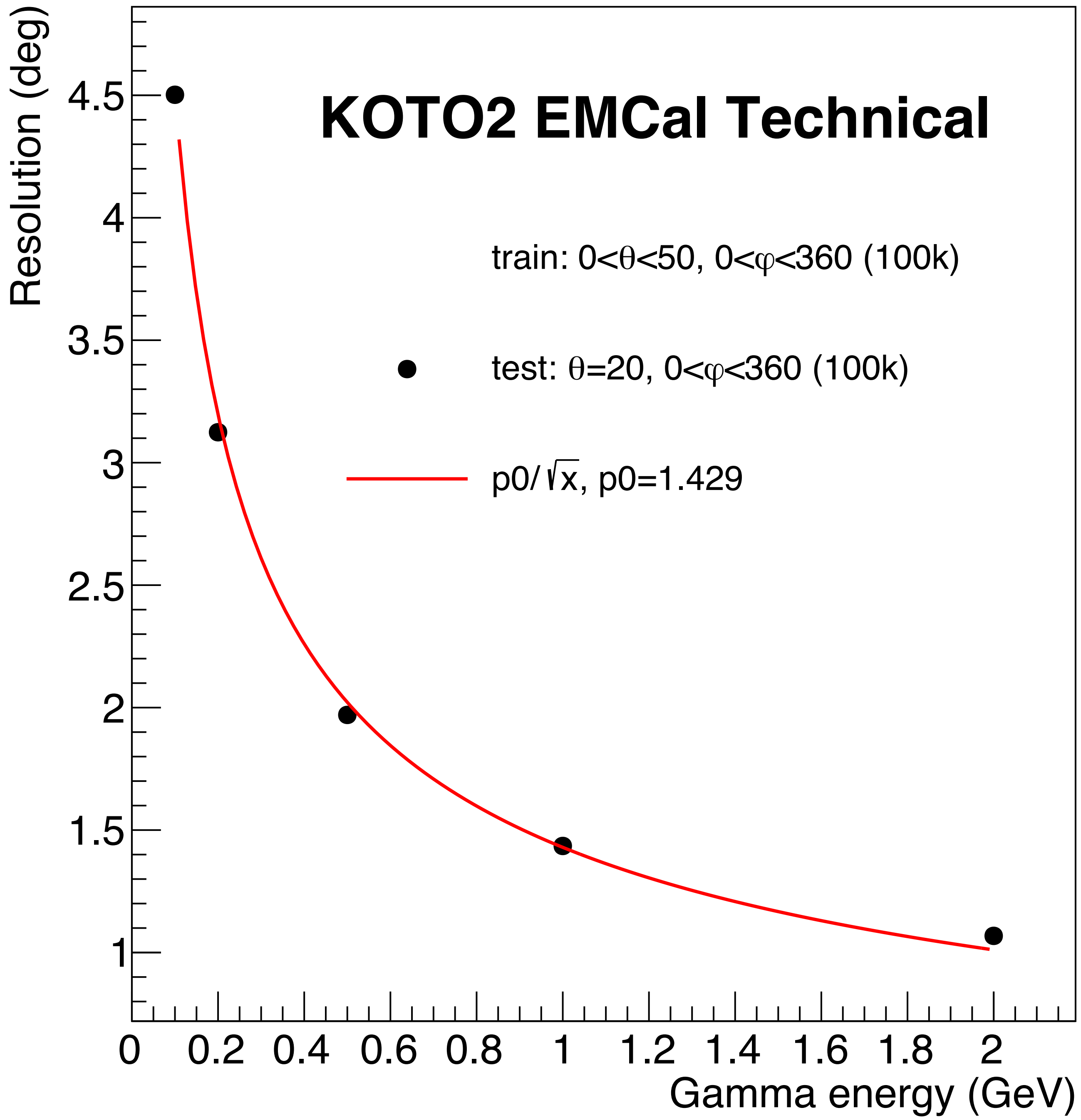
Detector Optimization: Scintillator Width





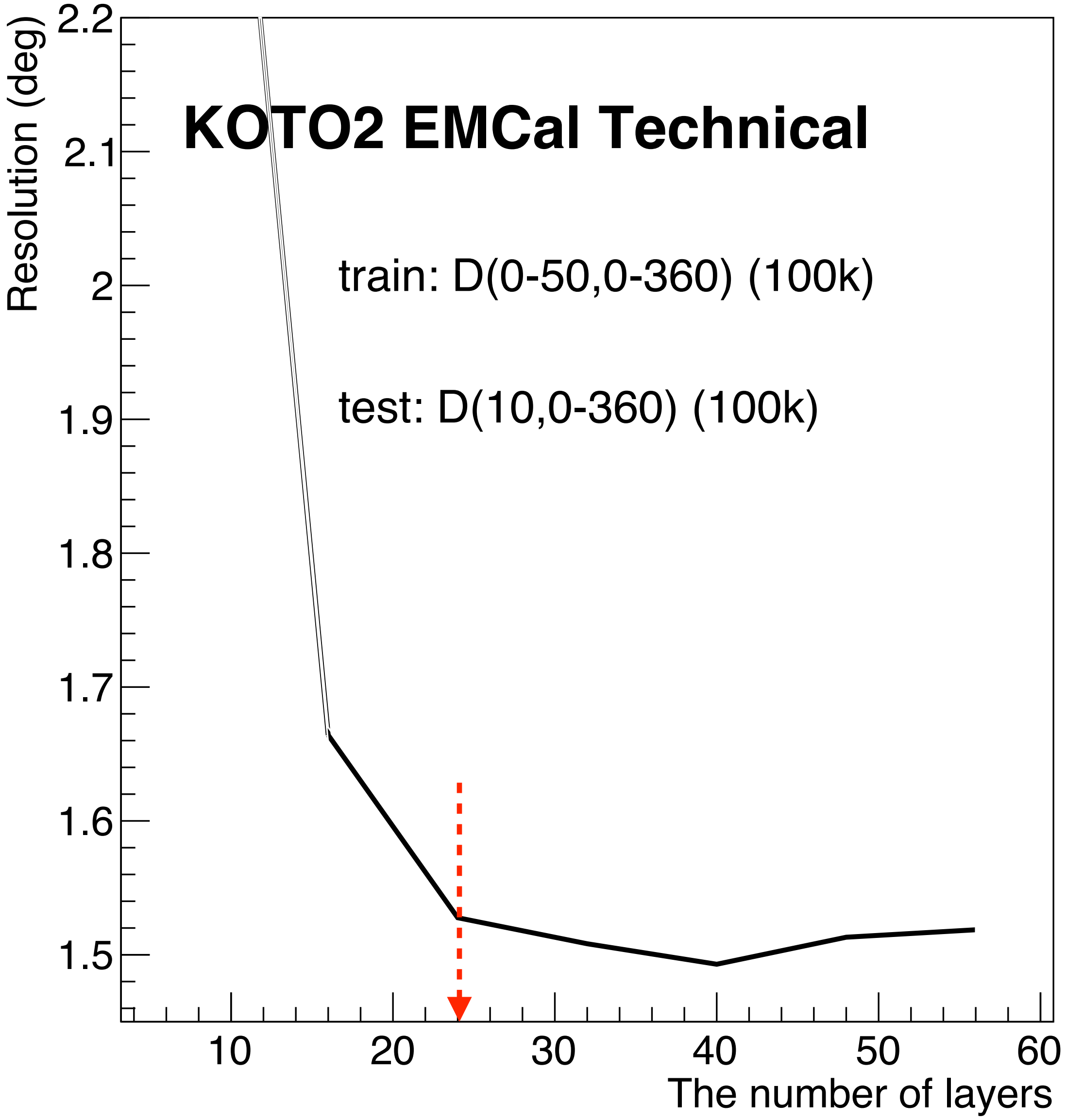
- Width of each segment: 15 mm (from 20 mm) with 1.5° angular resolution.

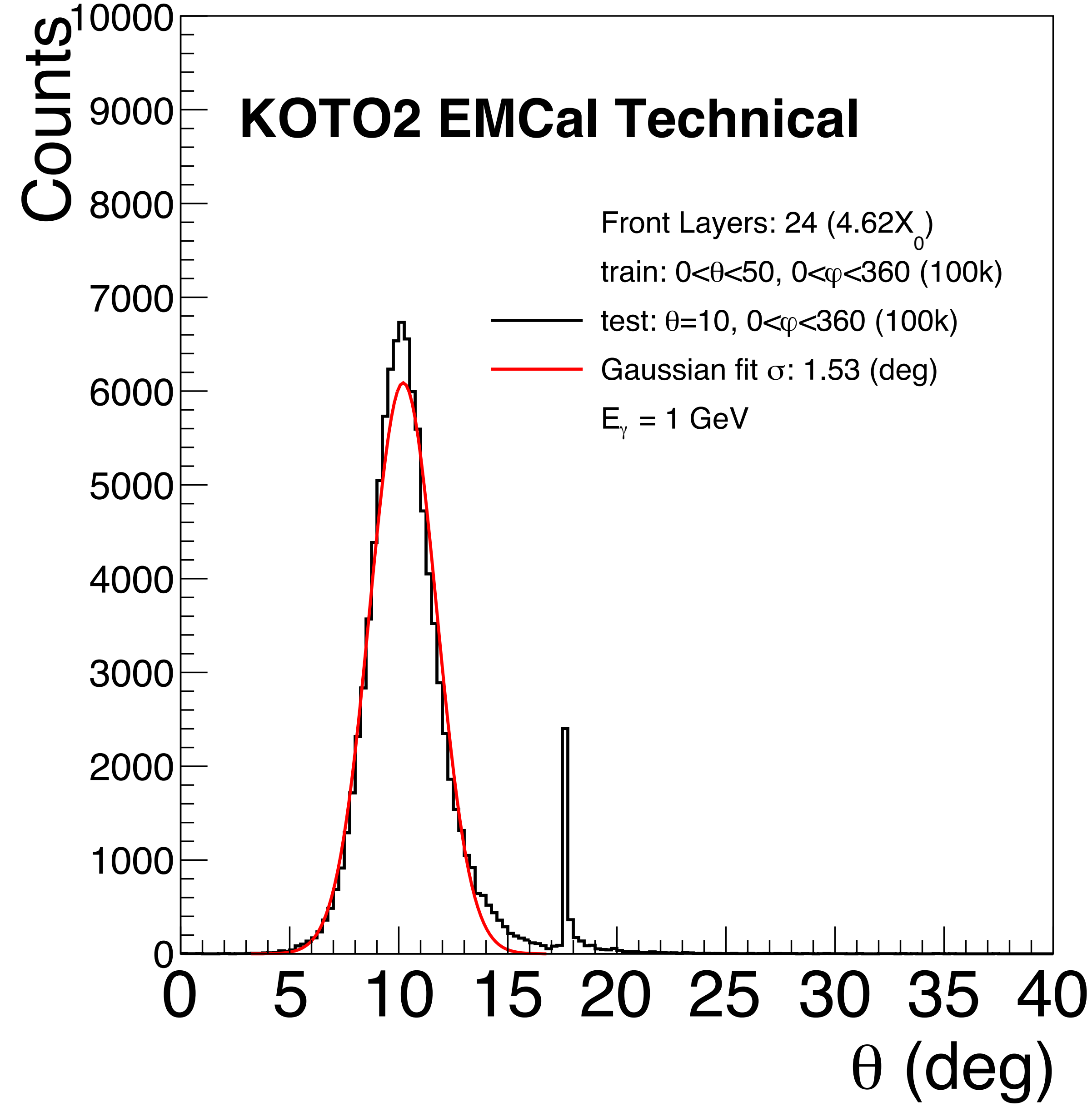
Energy Dependency of ML Results



- The angular resolution is proportional to $1/\sqrt{E}$
- The angular resolution is estimated to be 1.4° at 1 GeV

Detector Optimization: The Number of Front Layers





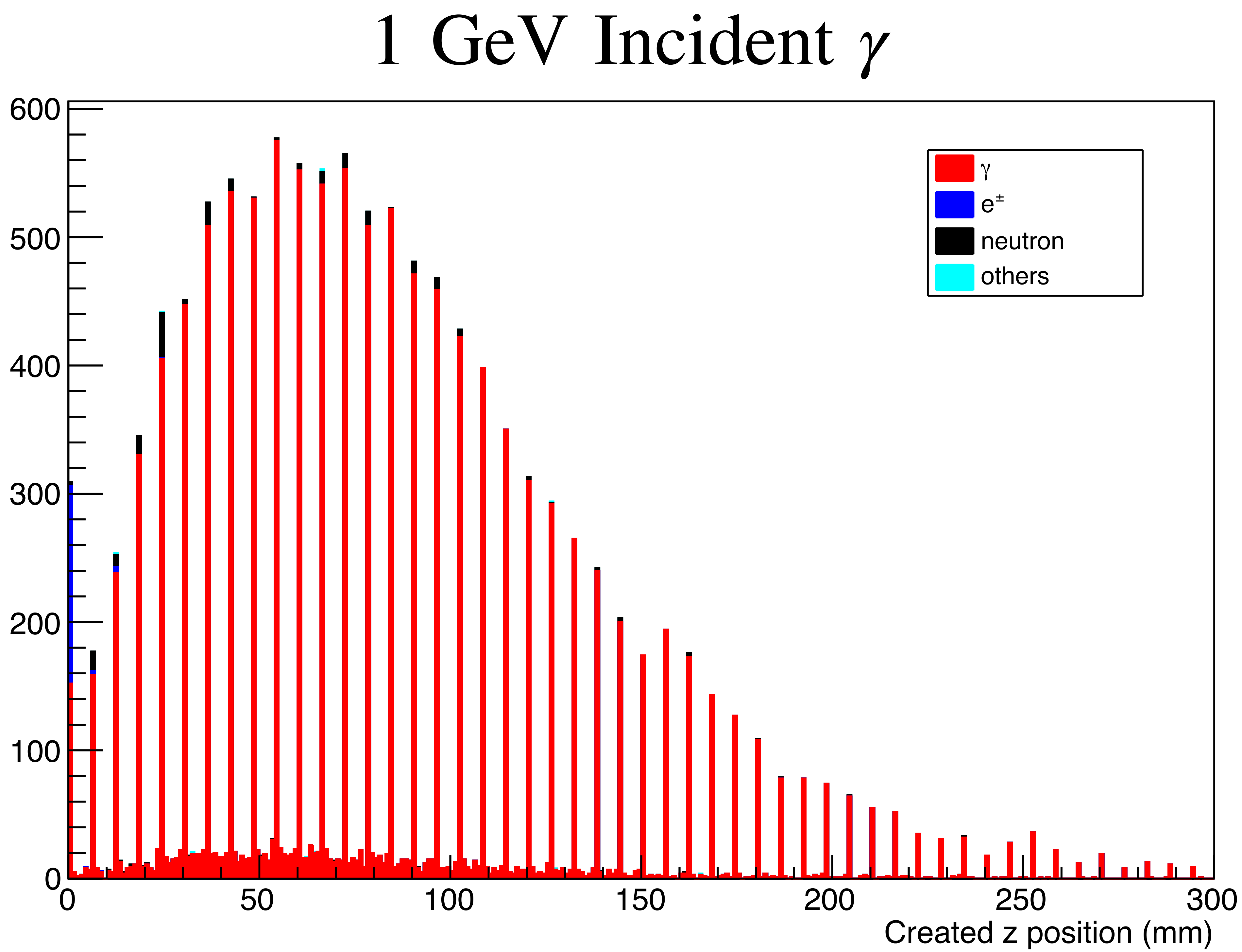
- The angle reconstruction with only front part of the detector
- Front 24 layers (total 105 layers) are enough to reconstruct the incident angle.
- Radiation length: 4.6 X_0 (total 20 X_0) with **1.5°** angular resolution and **3%** inefficiency

Conclusions

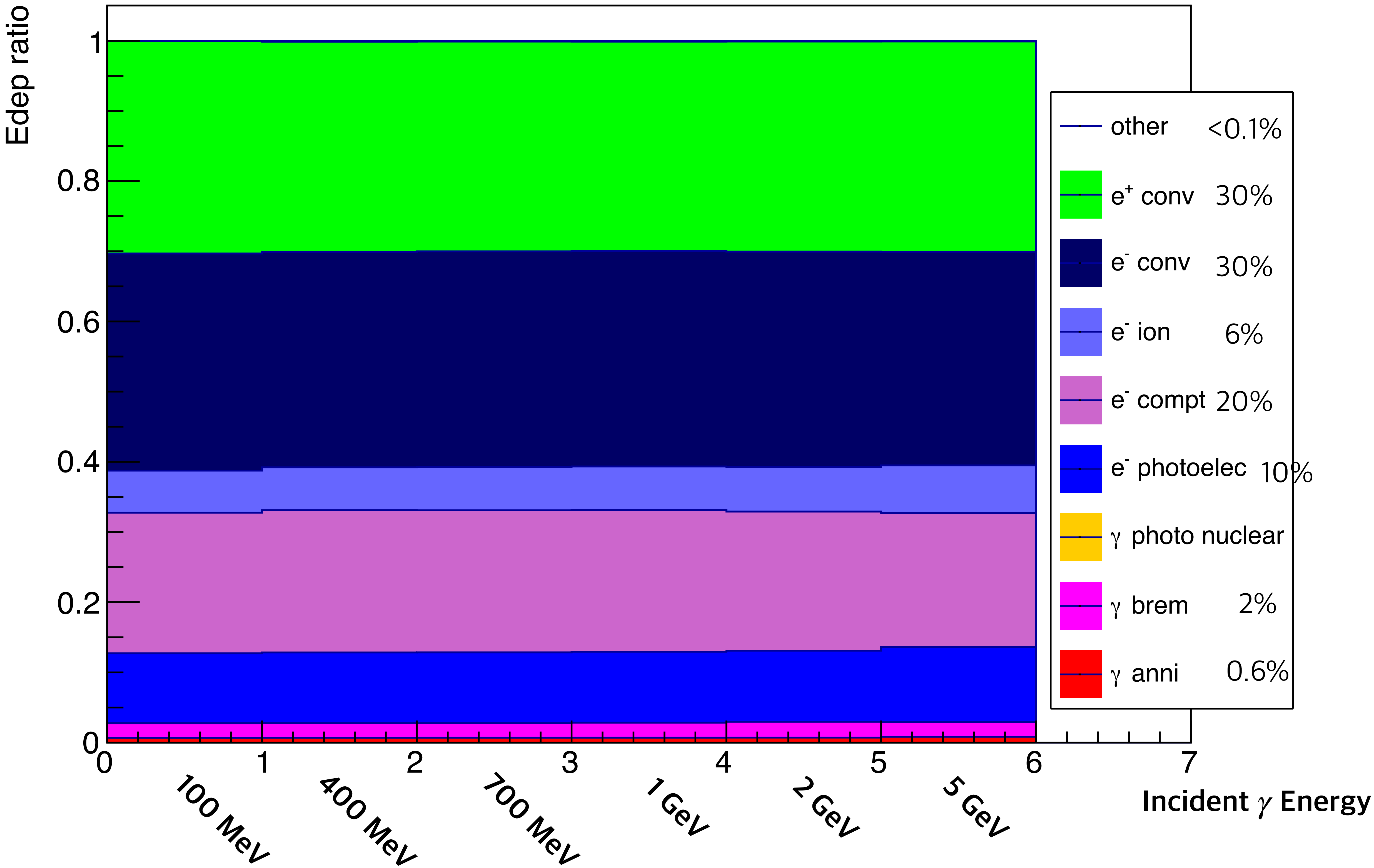
- We have been developing a sampling calorimeter for gamma tracking.
- We have checked several detector properties:
  - R_M = 7 cm, visible ratio = 34%, σ_E/E = 4% at 1 GeV
  - The sampling calorimeter is comparable with pure CsI for the accidental loss from backsplash particles.
- Angle reconstruction and Detector optimization:
  - A machine learning toolkit XGBoost is utilized for this study.
  - We have determined training parameters of XGBoost setup.
  - We have improved a geometry of the gamma tracking detector with the training setup
    - **15 mm for scintillator width**
    - **24 layers (4.6X_0) from 105 layers (20X_0)**
  - We have achieved 1.5° angular resolution with 3% inefficiency.
- Future plan:
  - Study with scintillating fiber + tungsten configuration
  - Hardware production and test

Backup

Creation position of backsplash particles

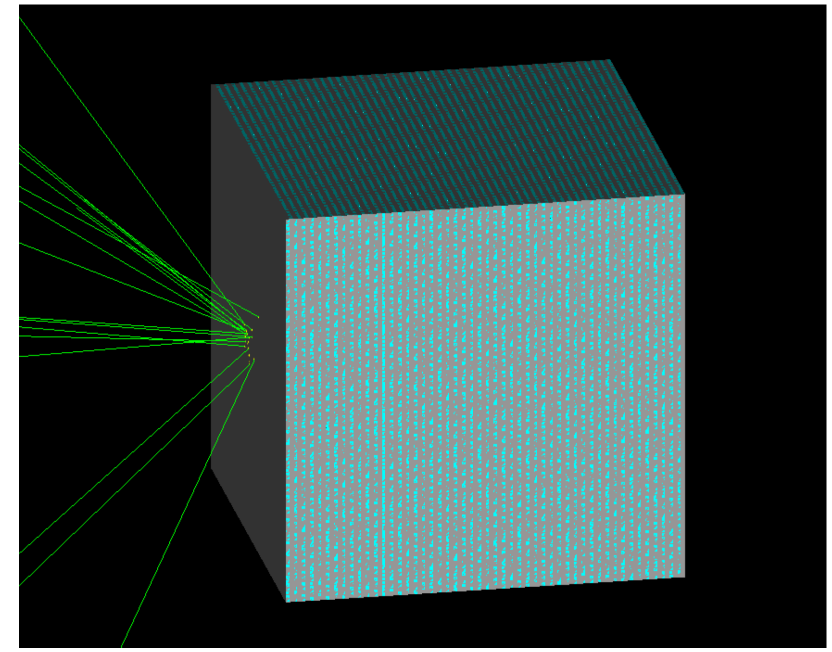


E_{dep} creation process



Pipe Type Design

Single segment



100 scintillators × 100 layers

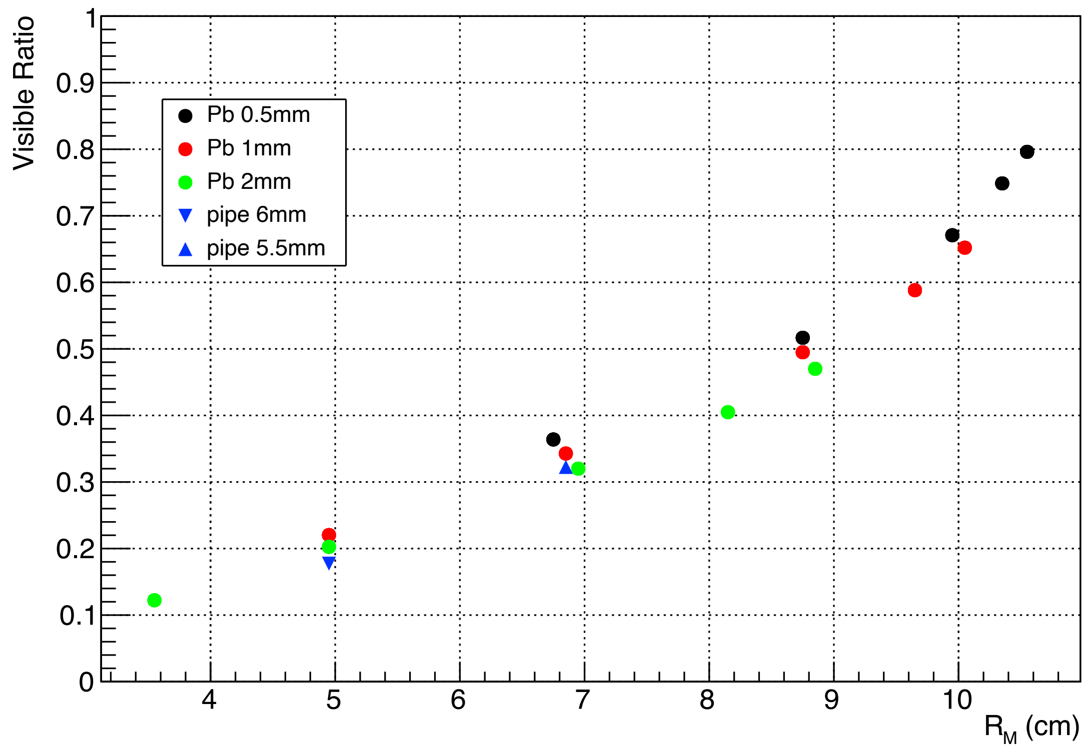
Design 1

Lead : 6 mm x 6 mm x 60 cm
Scintillator: 5 mm x 5 mm x 60 cm

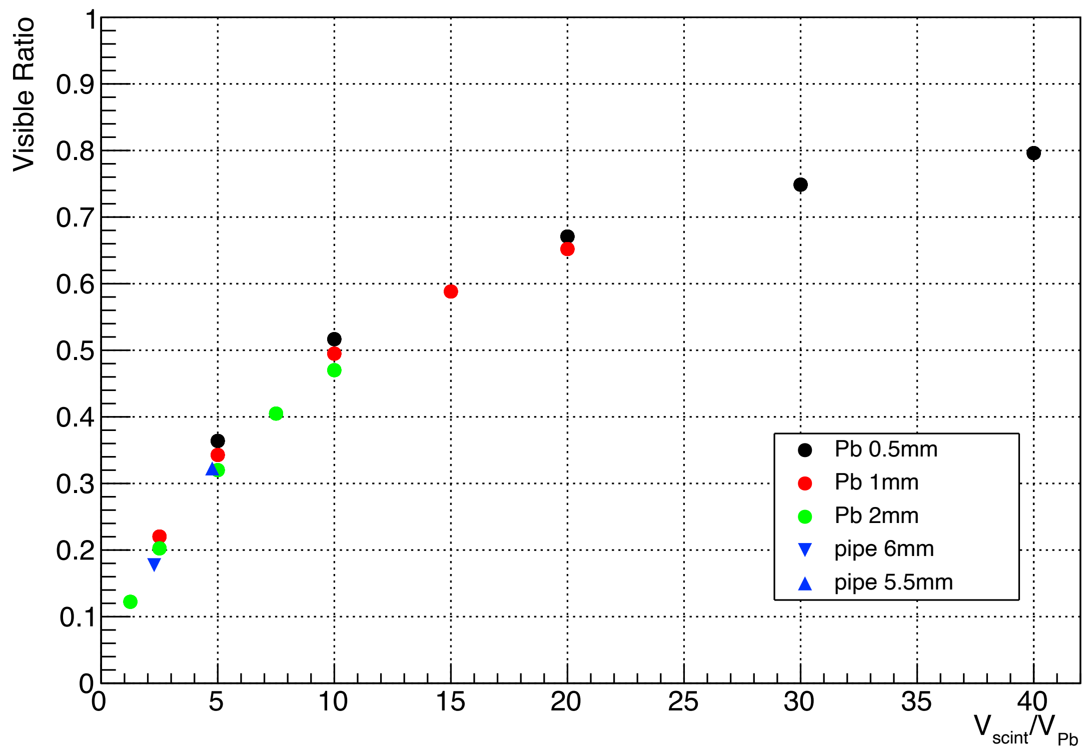
Design 2

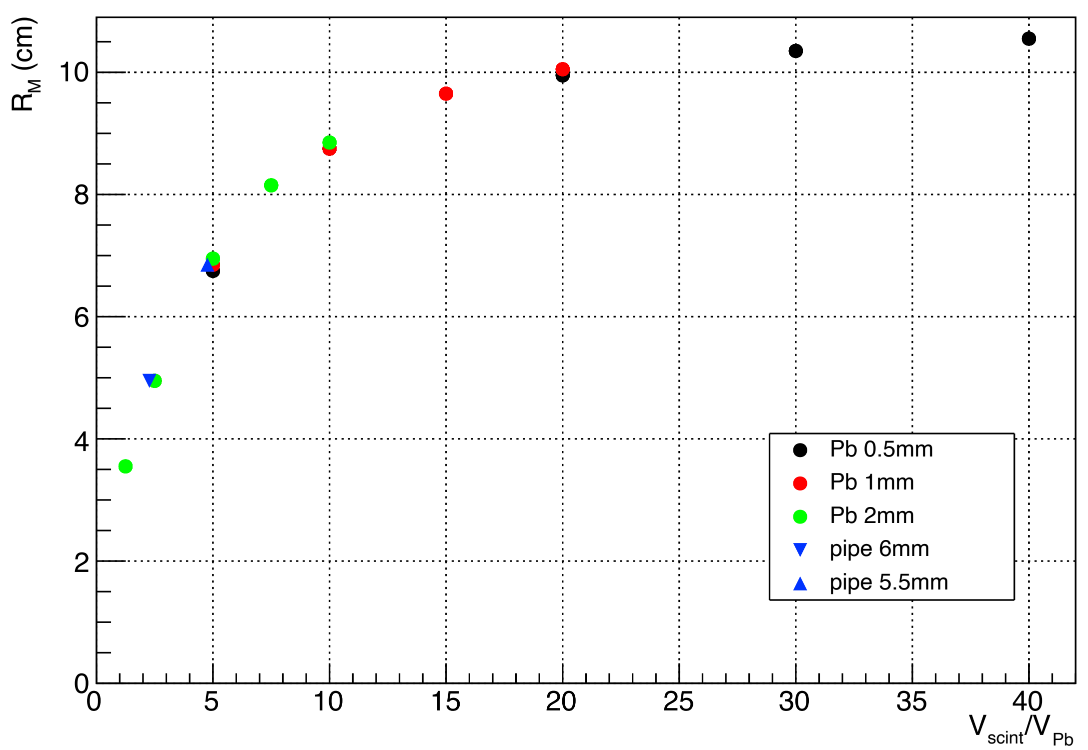
Lead : 5.5 mm x 5.5 mm x 55 cm
Scintillator: 5 mm x 5 mm x 55 cm

Pipe Type and Volume Ratio Dependency

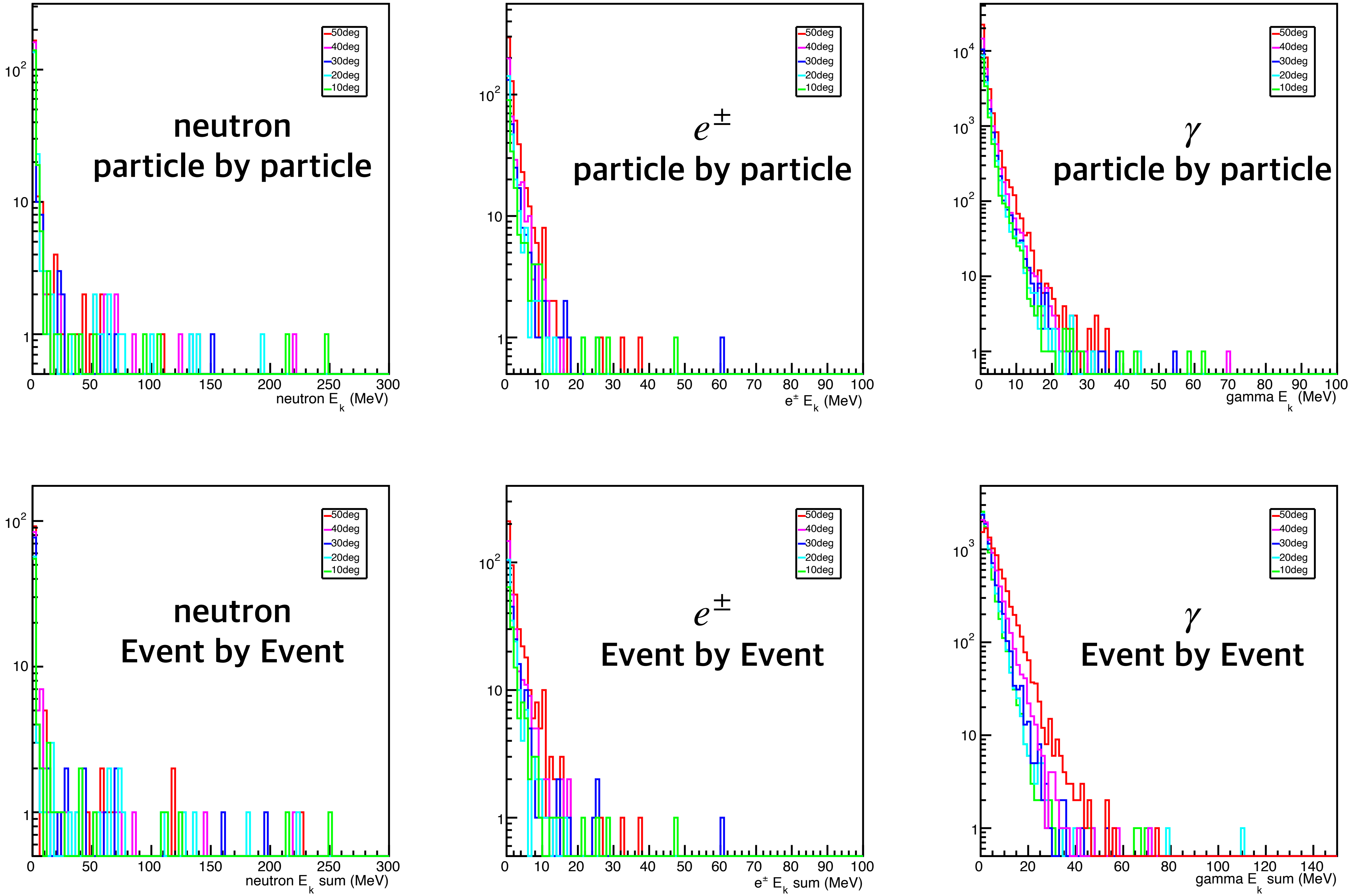


- **There is no meaningful improvement in different geometrical configuration**

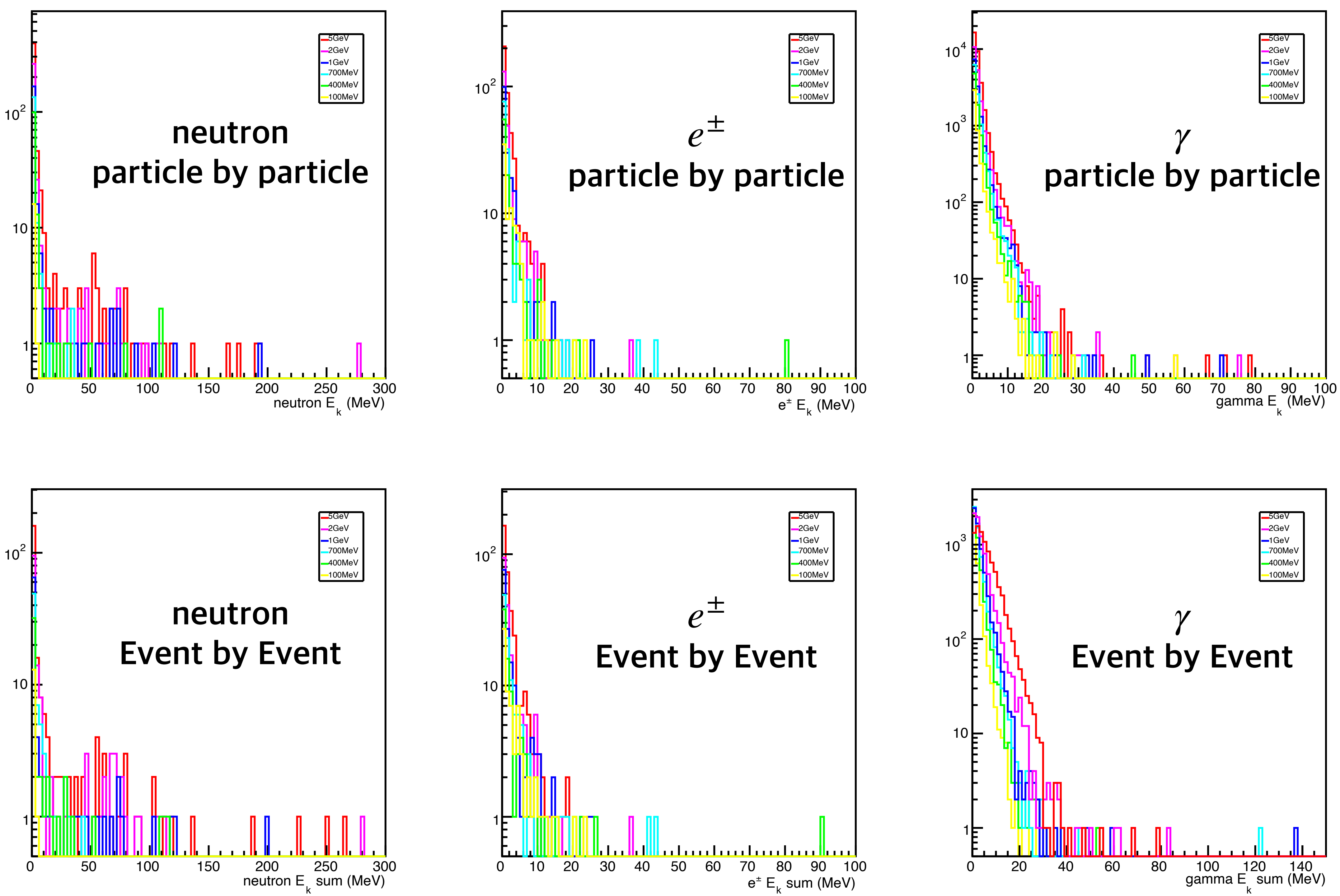




Backsplash particle energy distribution
1 GeV incident γ, incident angle dependence

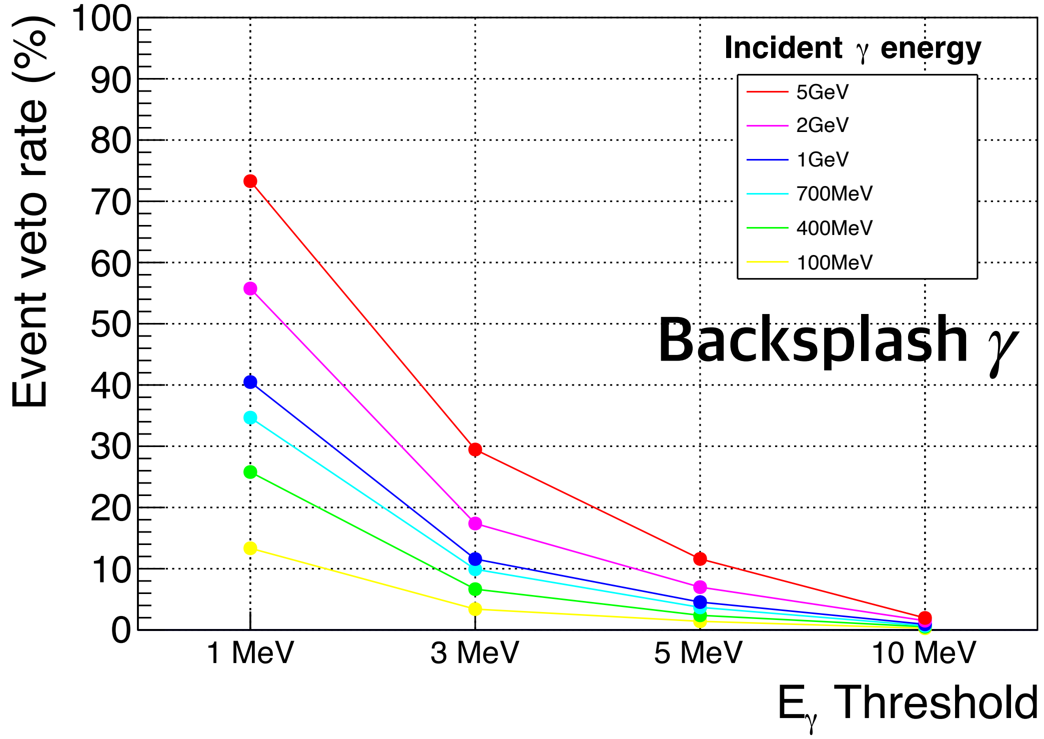


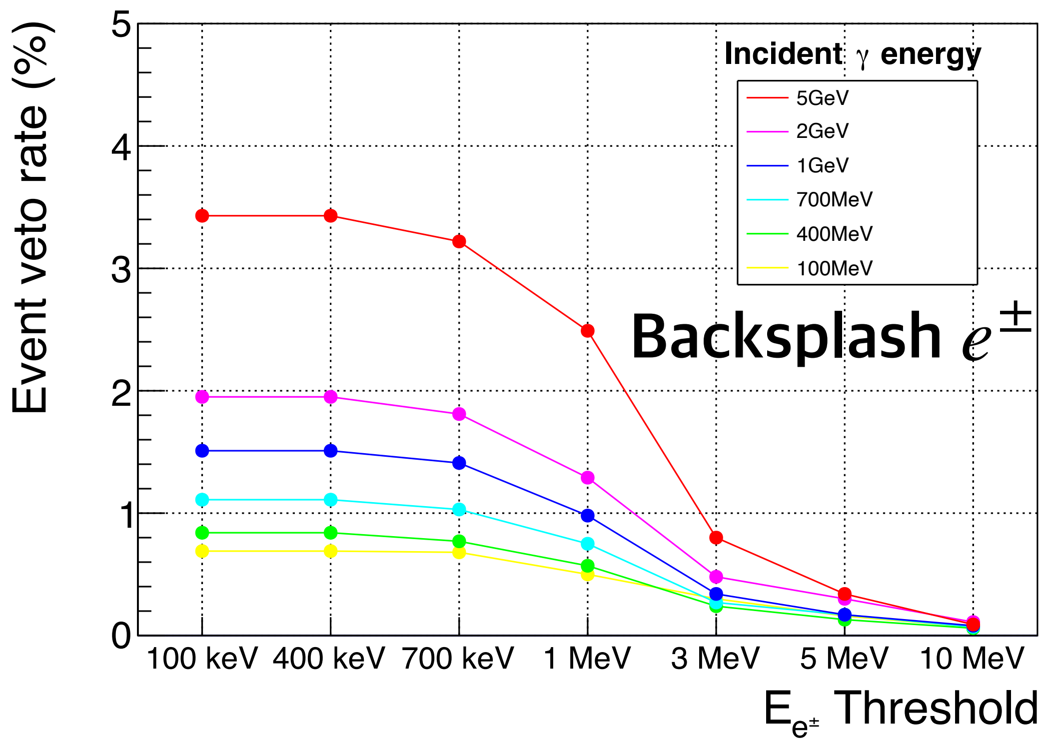
Backsplash particle energy distribution
Incident energy dependence



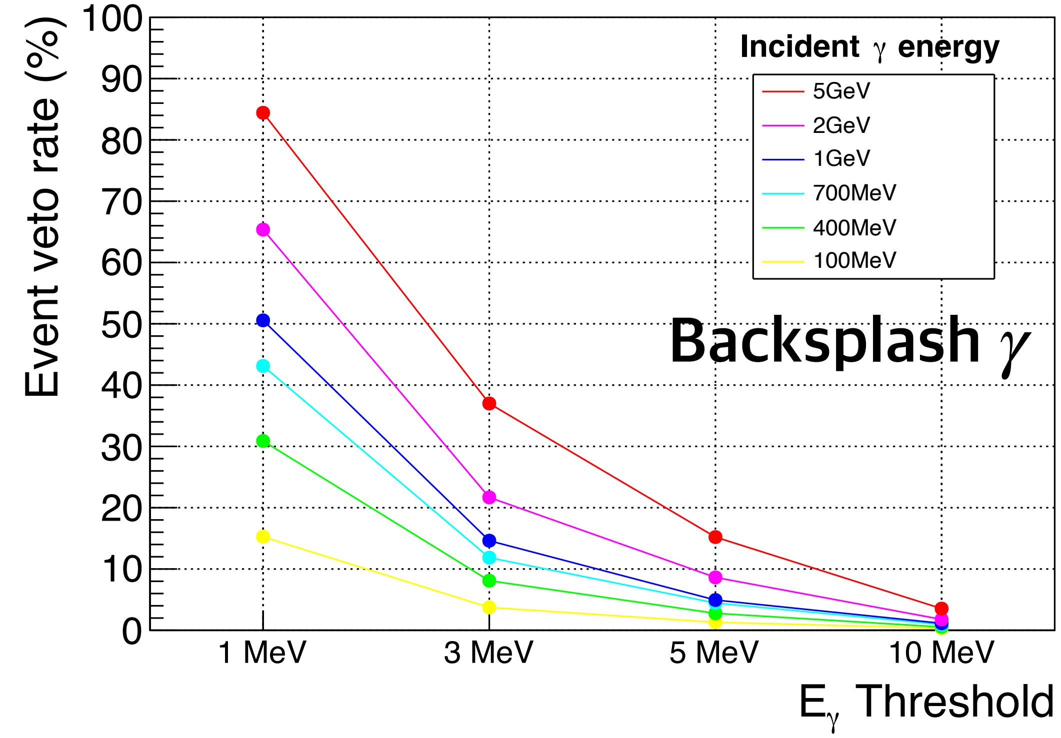
Event veto rate: $N_{\gamma/e^{\pm}} \geq 1$

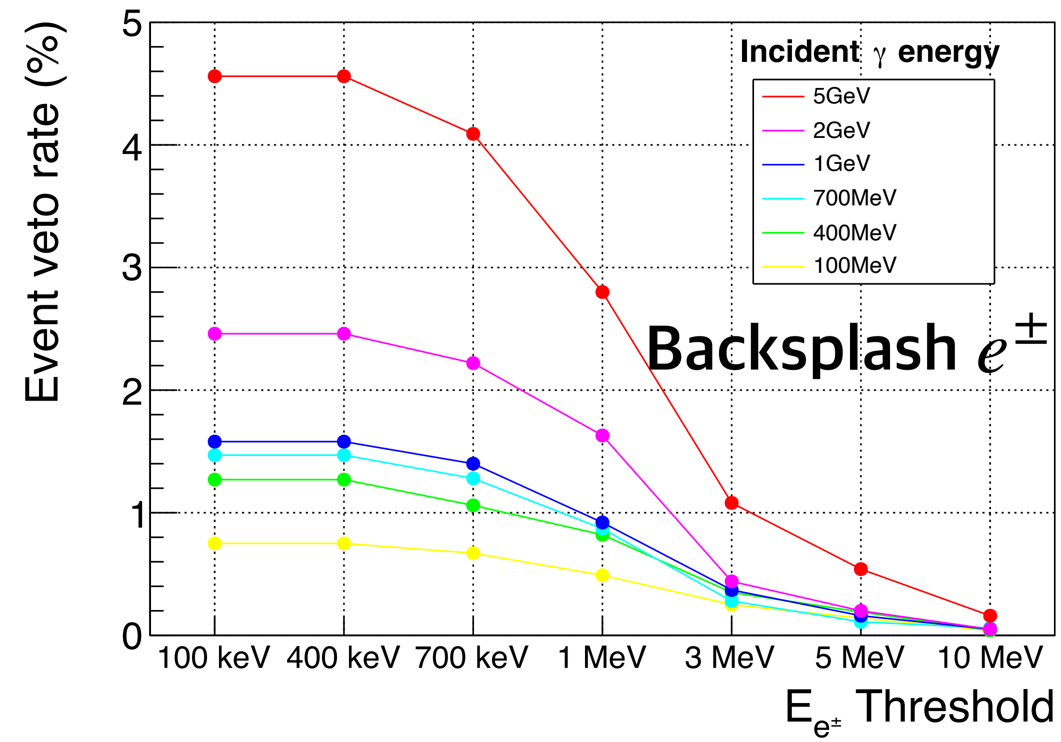
Sampling Calorimeter





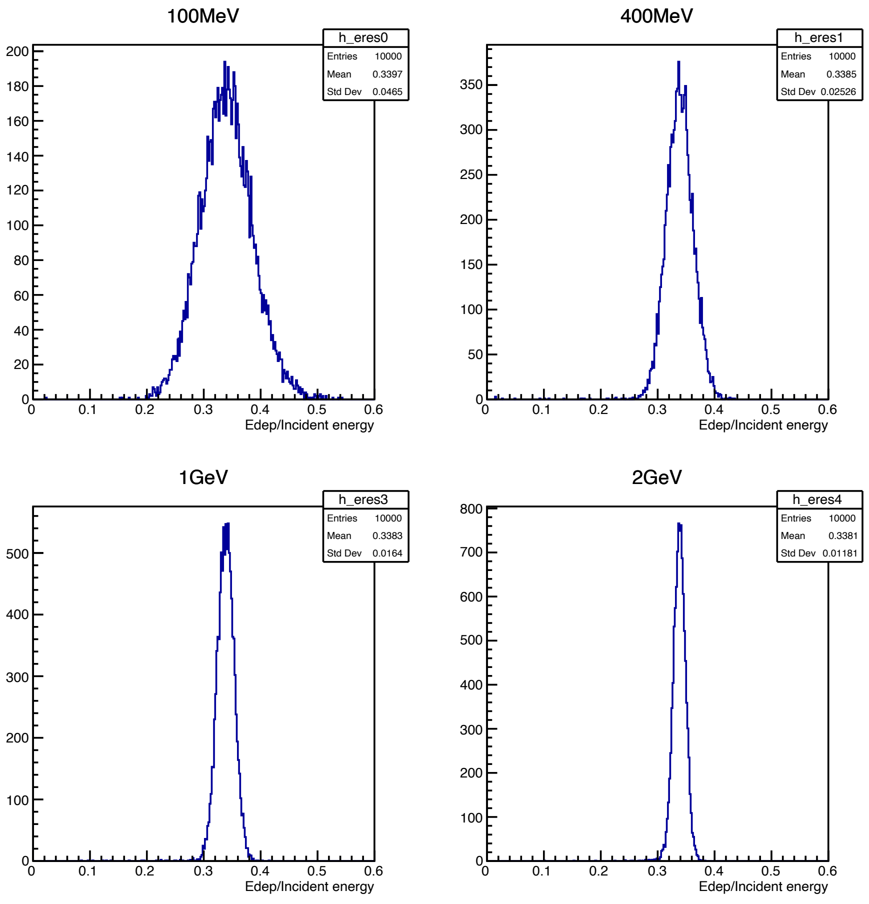
CsI Calorimeter



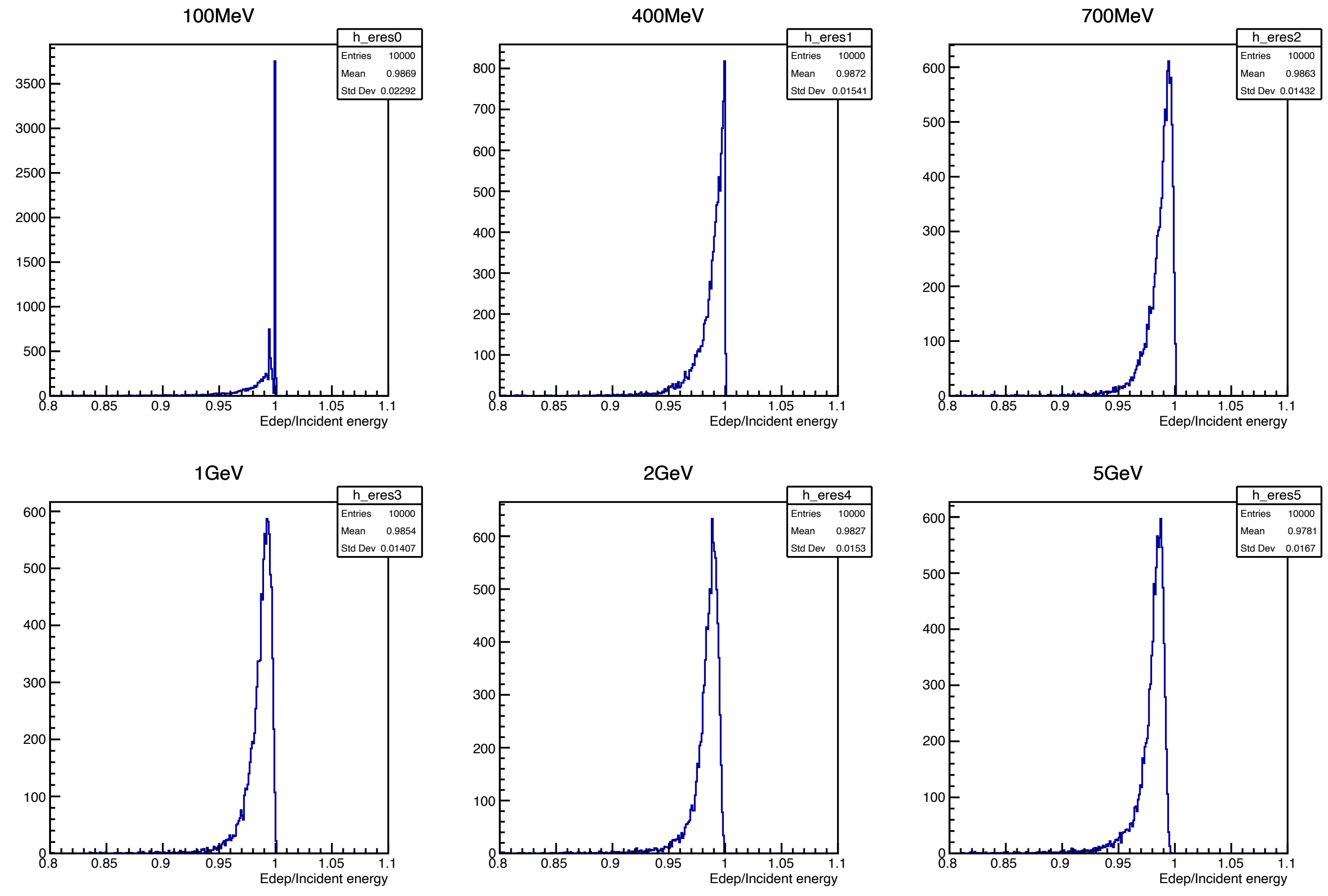


Energy deposit distribution

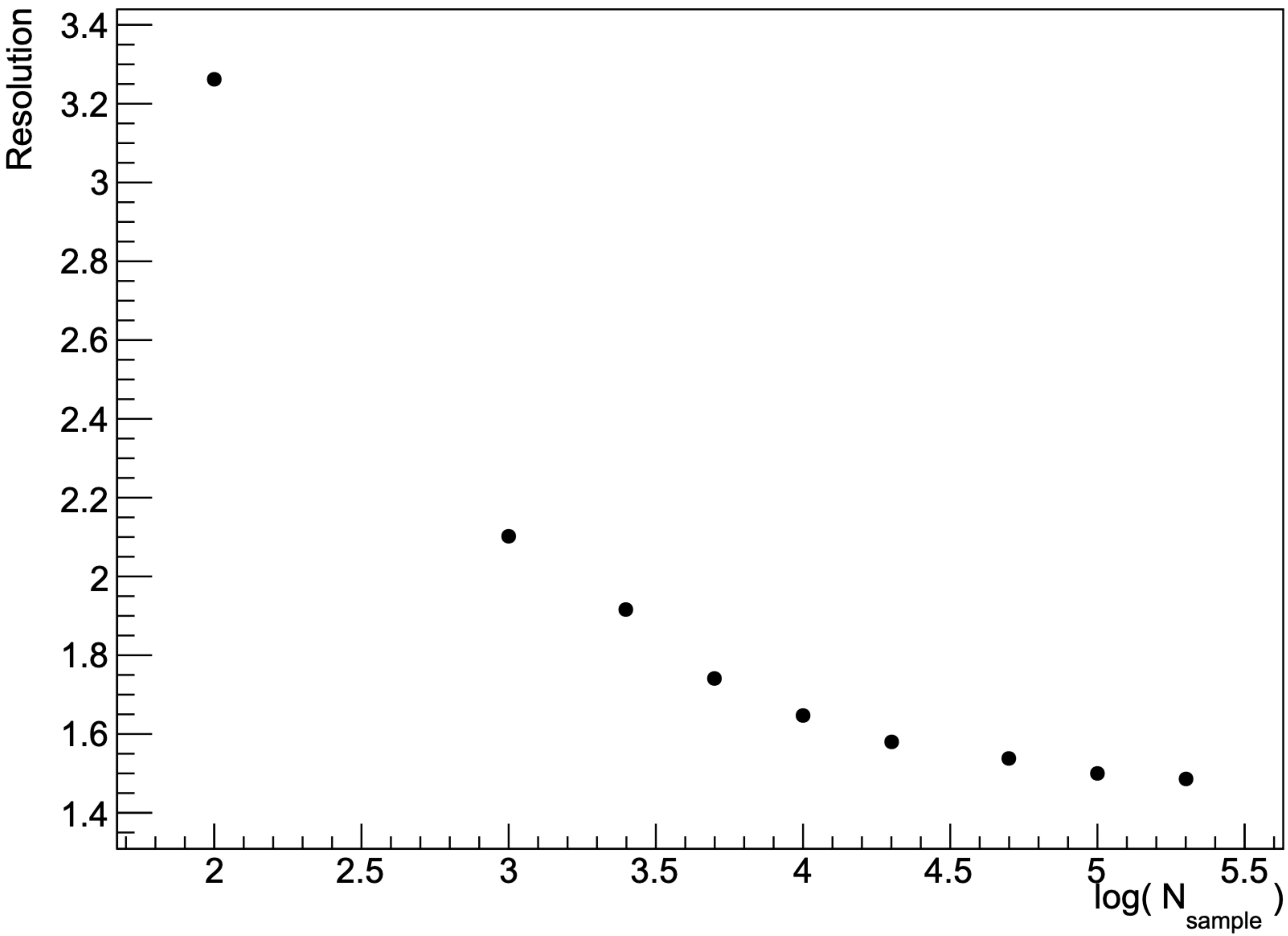
Sampling Detector



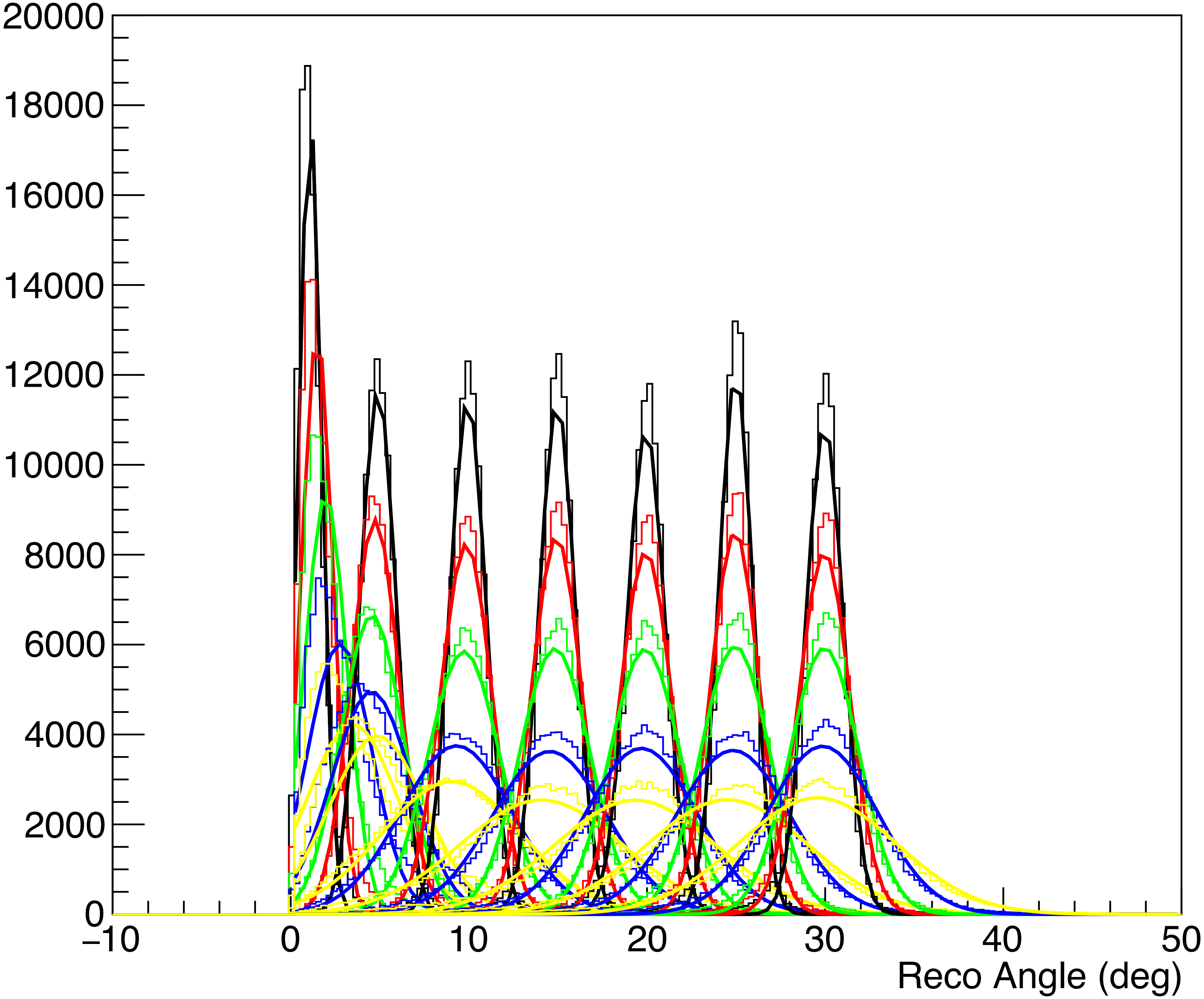
CsI Detector



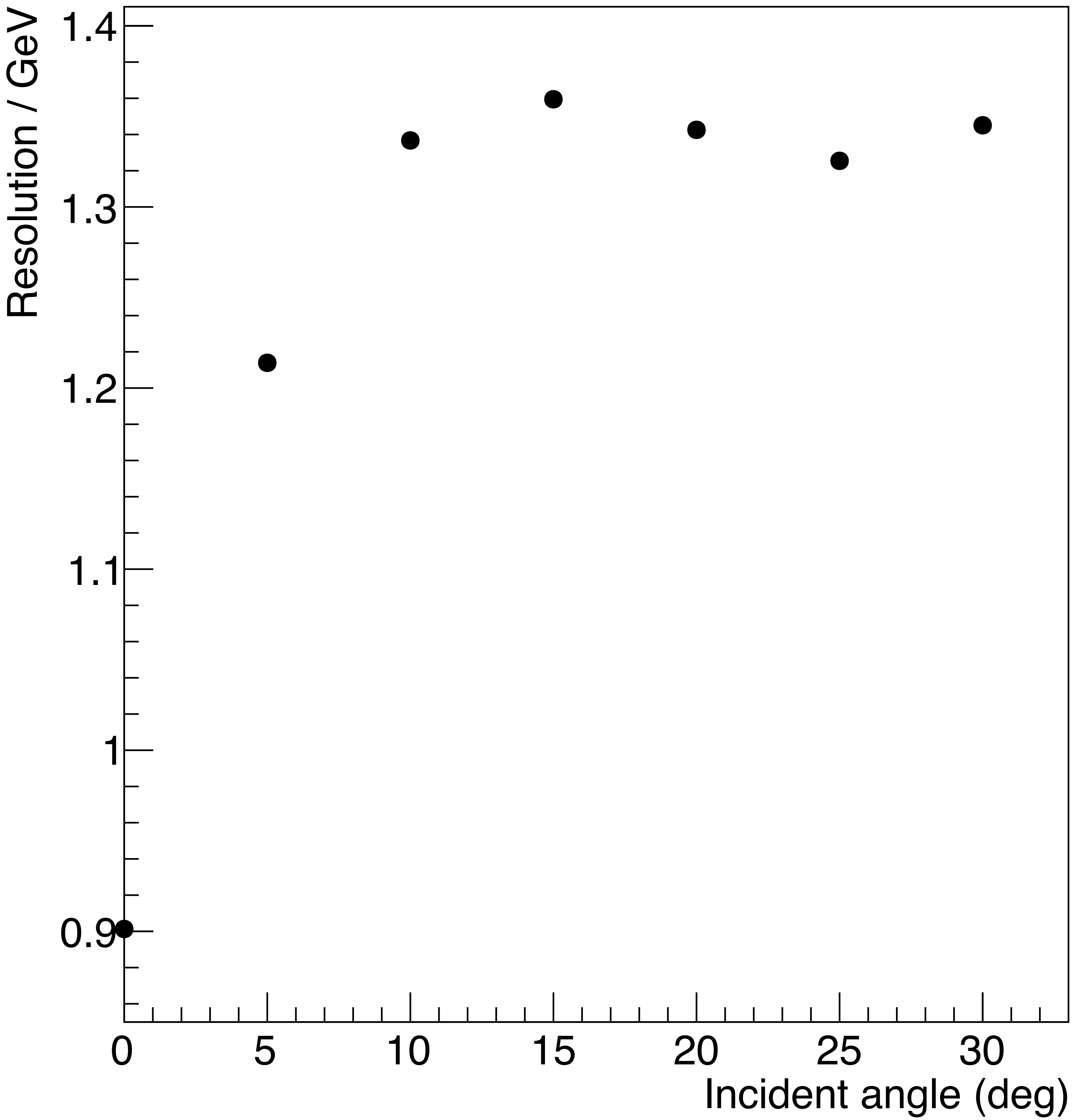
Number of training samples



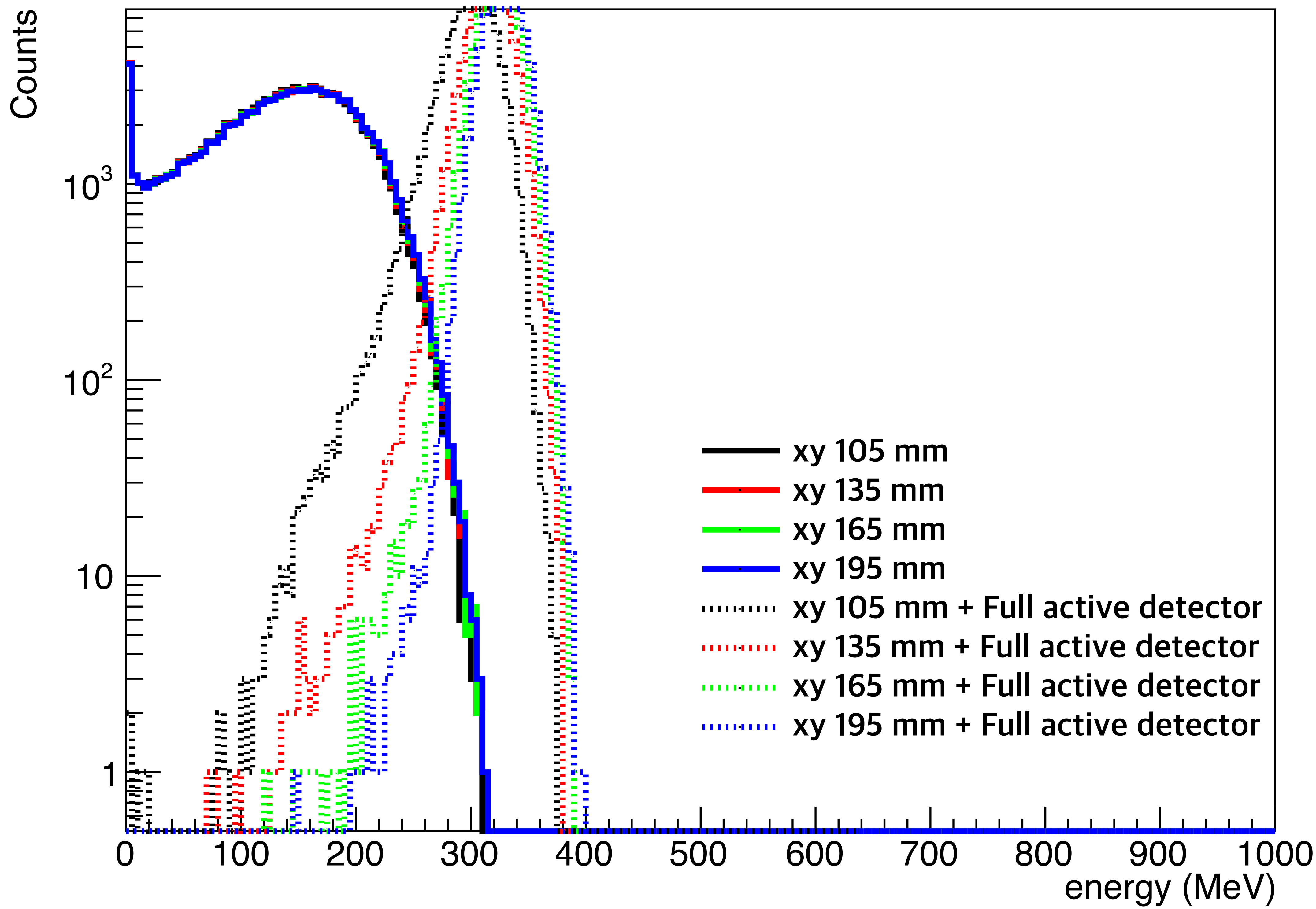
ML test at different E and angle



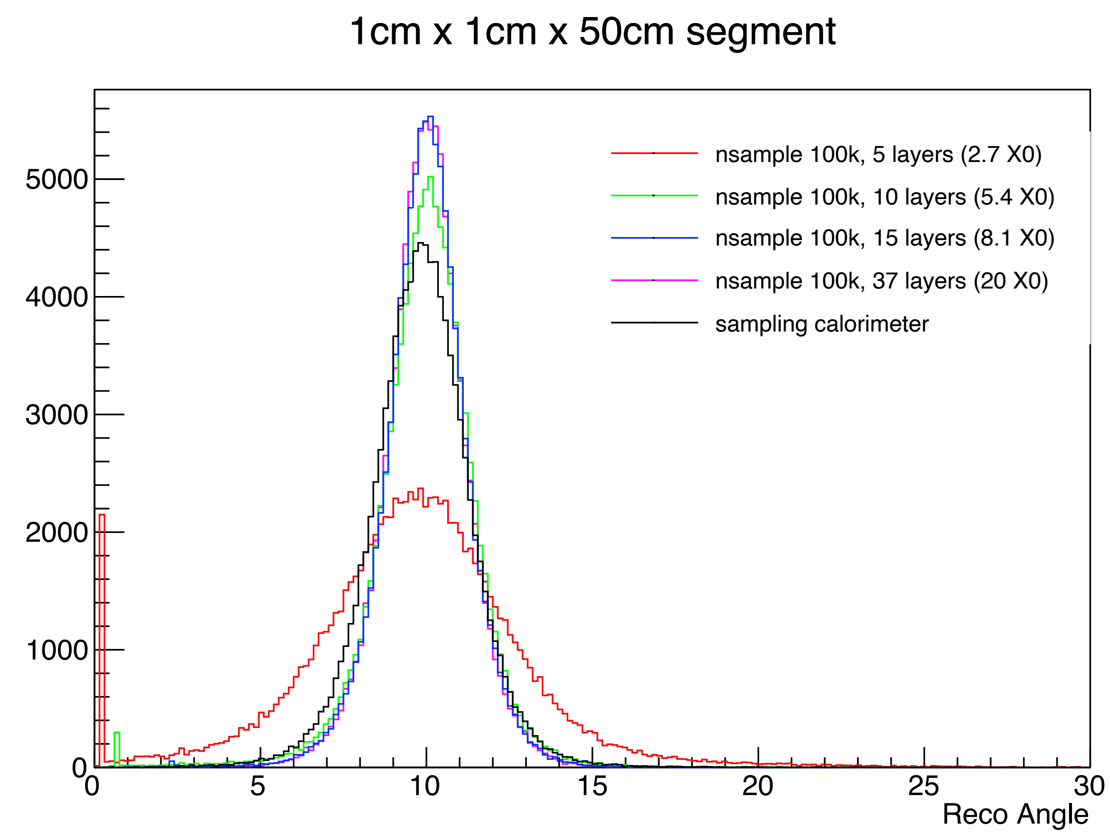
Angular resolution depending on incident angle and energy

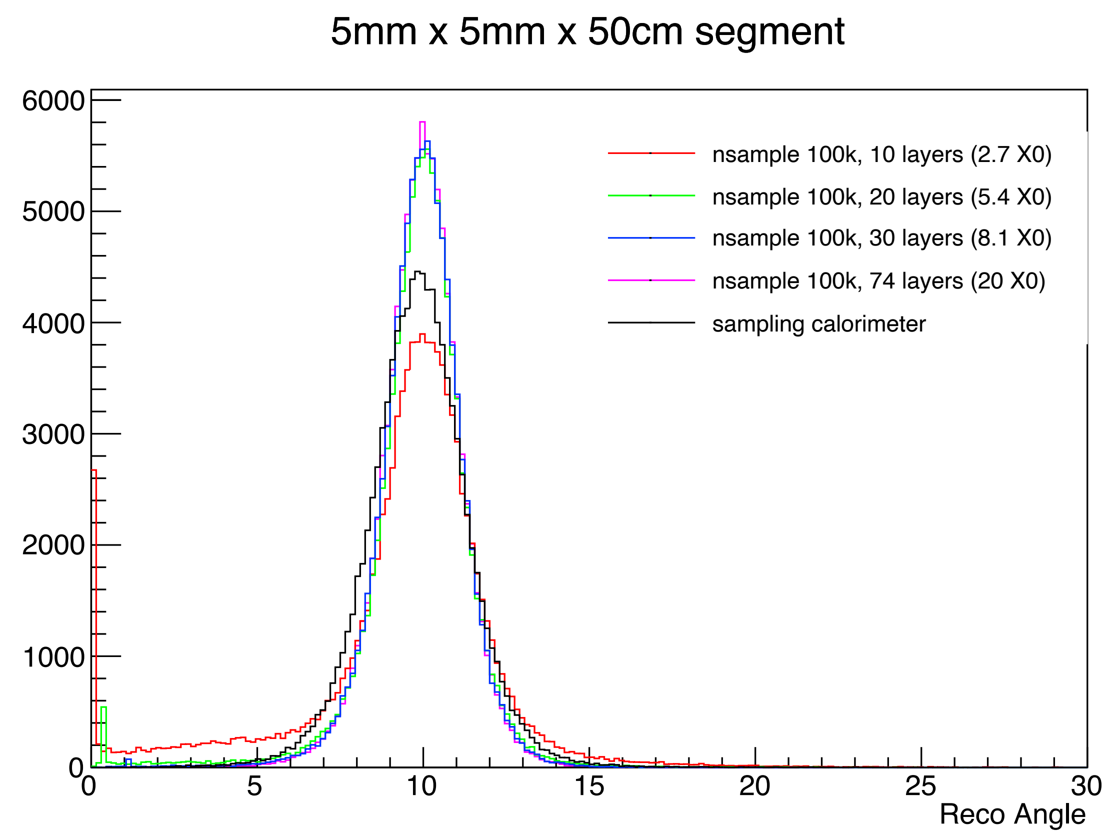


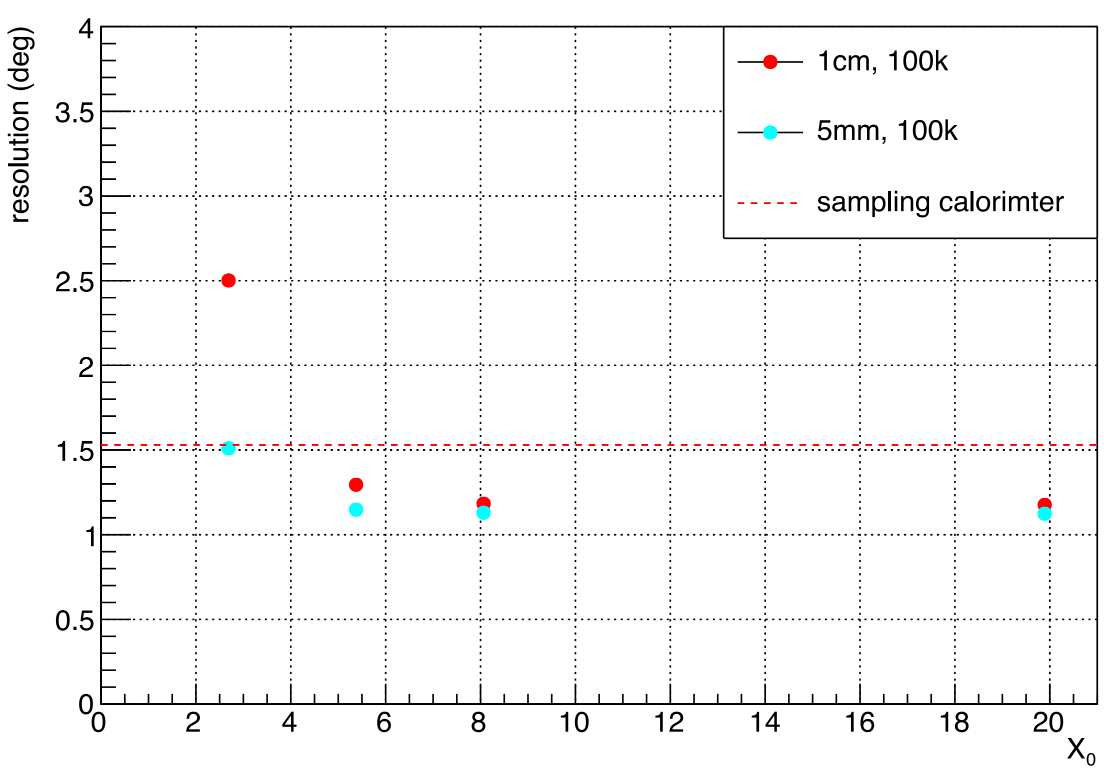
XY length reduction



Full active CsI detector

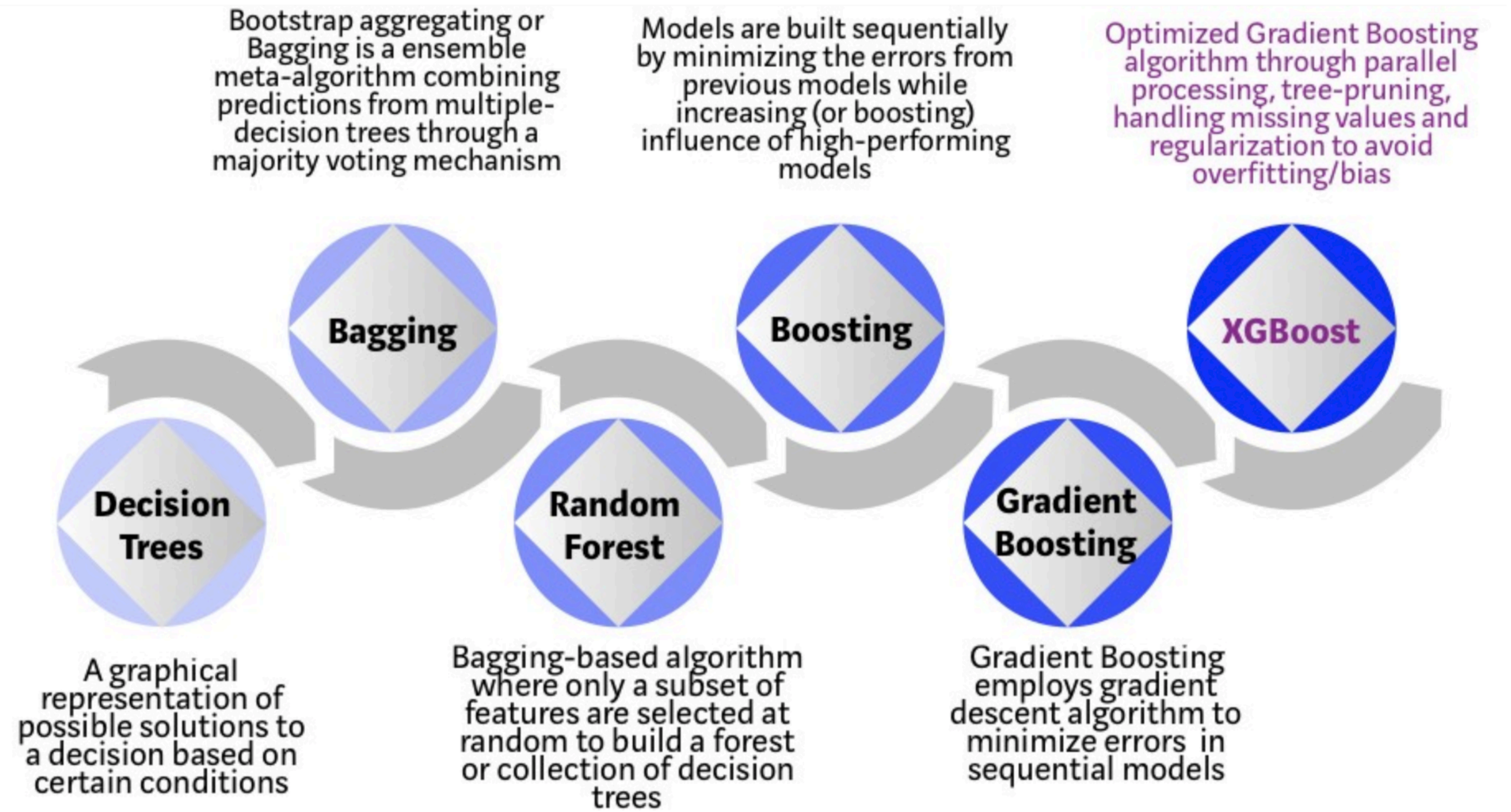






- Same studies are done with similar design of full active CsI detector.
- Fiber type segments are aligned along x and y axis.
- Angle reconstruction is studied with 5 mm and 1 cm segmentation.
- **1.1°** resolution with fine segmented full active detector
  1.5° resolution with sampling calorimeter at **1 GeV photon**

XGBoost: A scalable tree boosting system



arXiv:1603.02754

Table 1: Comparison of major tree boosting systems.

System	exact greedy	approximate global	approximate local	out-of-core	sparsity aware	parallel
XGBoost	yes	yes	yes	yes	yes	yes
pGBRT	no	no	yes	no	no	yes
Spark MLLib	no	yes	no	no	partially	yes
H2O	no	yes	no	no	partially	yes
scikit-learn	yes	no	no	no	no	no
R GBM	yes	no	no	no	partially	no