Crystal ECAL Optimization studies: transverse granularity and longitudinal depth

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Online mini-workshop on a detector concept with a crystal ECAL

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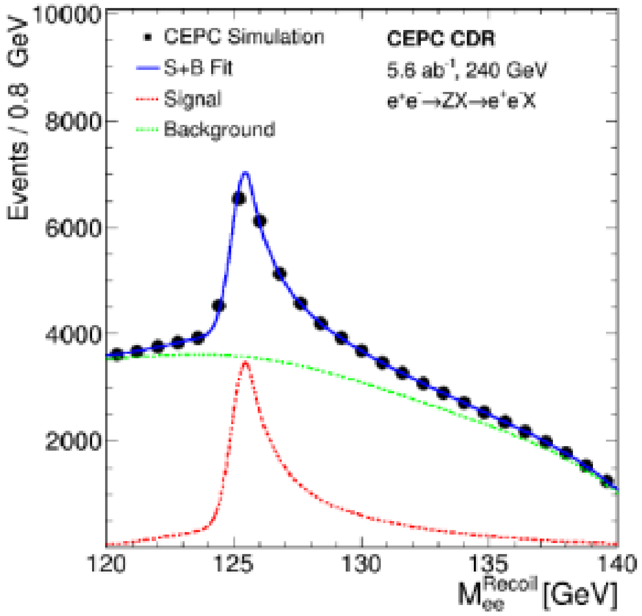
- Motivation
- Simulation in GEANT4 and Cluster reconstruction
- Crystal longitudinal depth optimization
  - Correction of the longitudinal shower energy leakage
  - Several factors affecting energy resolution
- Crystal transverse segmentation optimization
  - Separation performance of merged π^0 and γ
- Summary

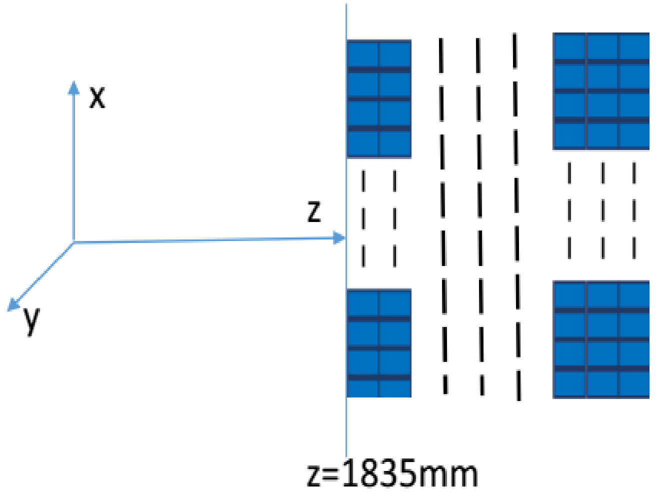
Overview: motivations



- Background: future lepton colliders (e.g. CEPC)
  - ➢Precision measurements with Higgs and Z/W
- Why crystal calorimeter?
  - ➢Homogeneous structure
    - Optimal intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - ➢Energy recovery of electrons: to improve Higgs recoil mass
    - Corrections to the Bremsstrahlung of electrons
  - ➢Capability to trigger single photons
    - Flavour physics at Z-pole, potentials in search of new physics, …
- Fine segmentation
  - ➢Potentials in PFA for precision measurements of jets

Simulation in Geant4 and Cluster reconstruction

- Construct a 3D BGO Matrix module with 60 ×60 ×60 cells/ cell size 1×1×1cm^3
  - Easily merge cells / layers
  - The front face of the array is 1835mm from zero (origin of coordinates), the inner radius of CEPC baseline ECAL Barrel.
- Without any photodetector materials and wrappers
- Without any materials in front of BGO Matrix module
- Geant4 simulates the energy deposited in crystal cell
- Cluster reconstruction of each layer is based on the method of the traditional crystal ECAL without longitudinal layer.



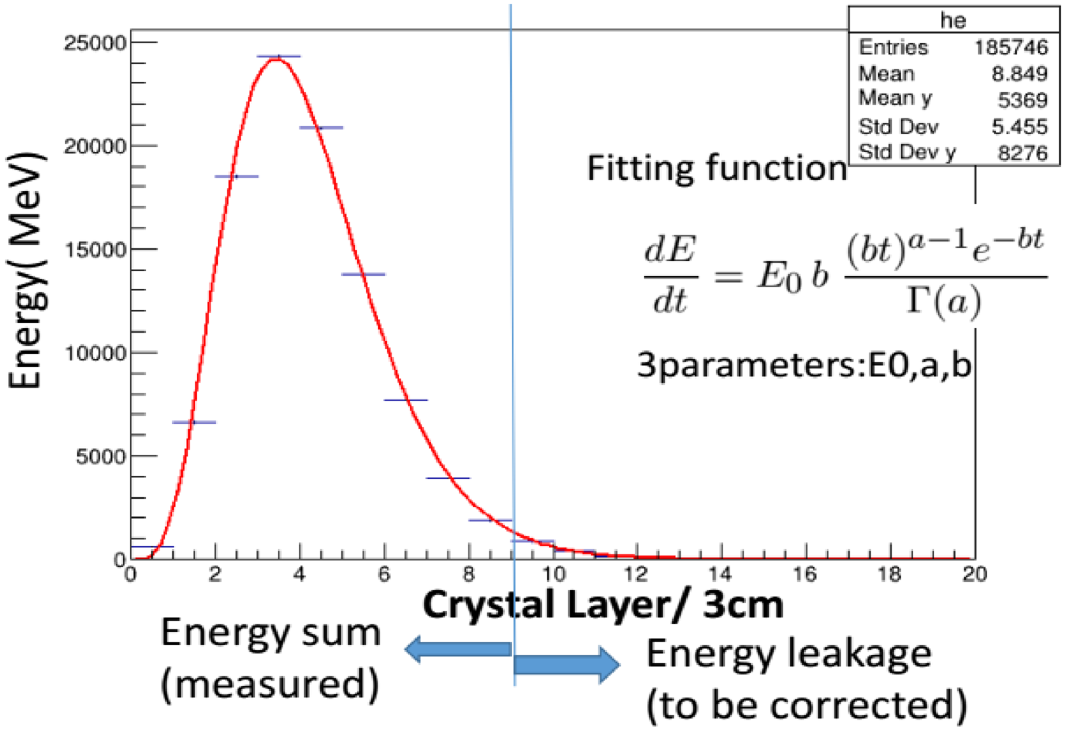
BGO crystal material properties:

Crystal radiation length: ~1.12cm;

Moliere radius R_M: 2.23cm;

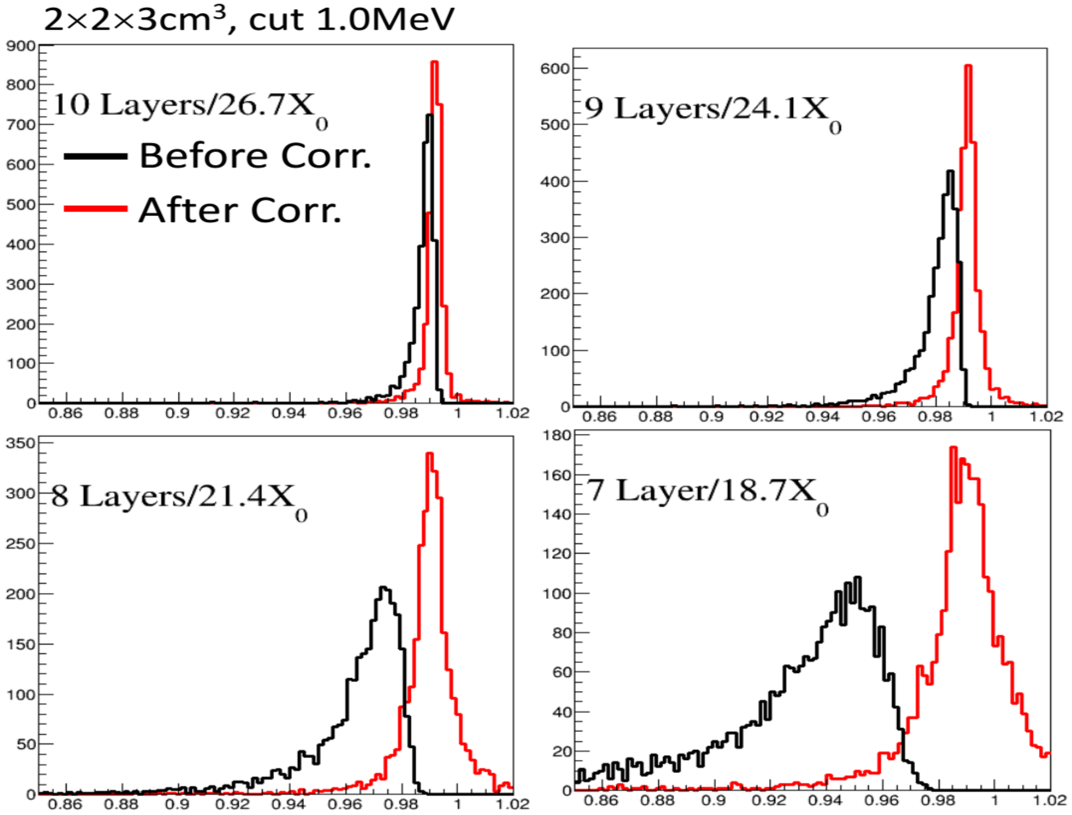
Energy leakage correction using longitudinal shower profile

- Based on the fine segmentation in crystal length
- Crystal layer depth with 3cm: The longitudinal shower profile can be described well.
- The longitudinal energy leakage can be corrected by fitting the shower profile.
- A good fitting needs at least 7-8 data points, so the depth of layer should not be larger than 3cm .
- So the 3cm/layer is set in the following studies



Energy leakage correction using longitudinal shower profile

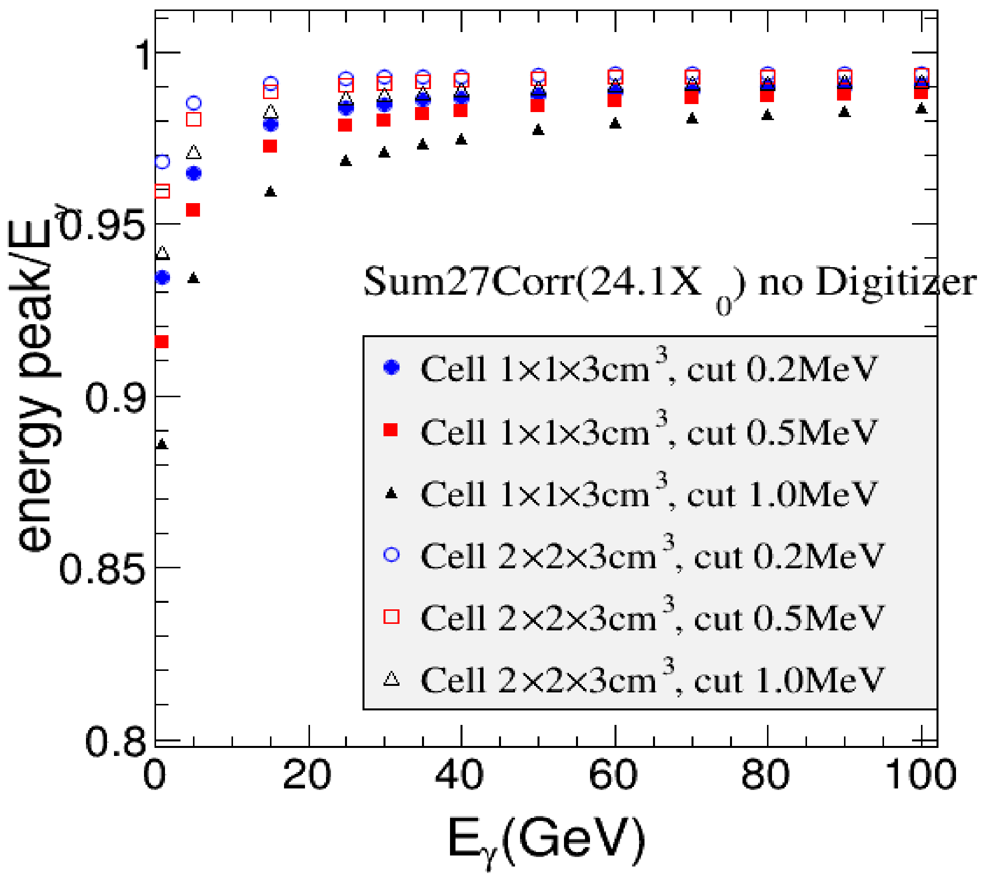
- γ energy reconstruction with all longitudinal layers
- The shower energy peak and resolution have a big improvement.



Rec. Energy/E_γ distribution of 100GeV γ

Impact of cell size and cell energy threshold on energy peak

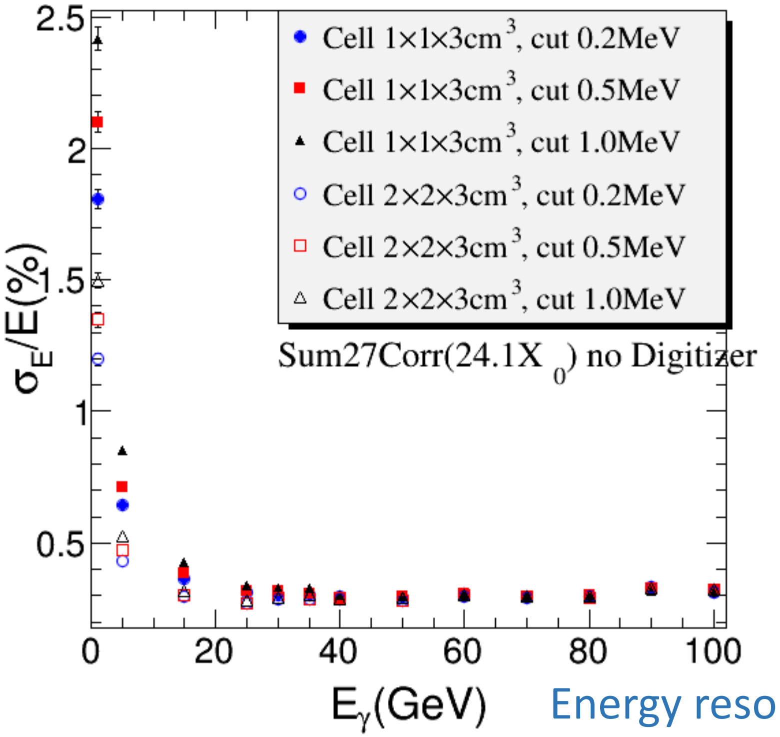
- Given the cell energy detection threshold
  - the larger cell size, the energy peak get closer to 1.
- Given the cell size
  - The larger cell energy threshold, the smaller the energy peak.
  - The energy linearity can be corrected.

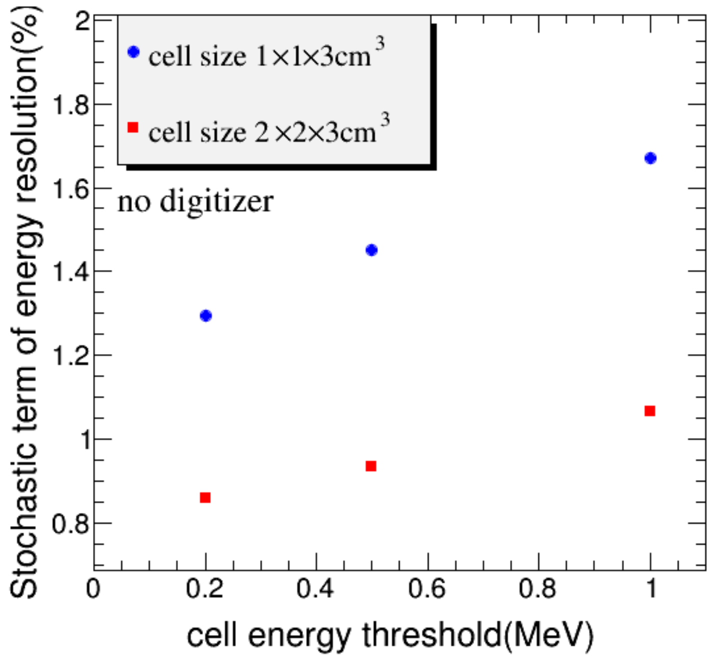


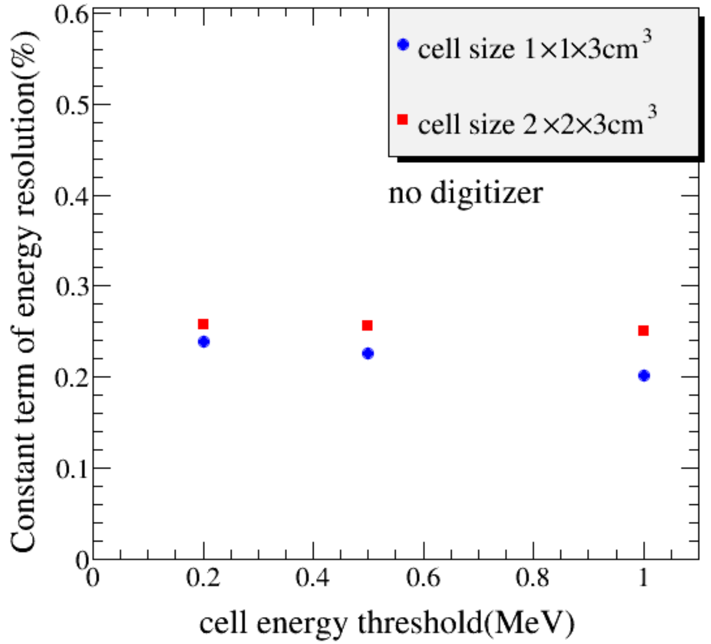
Energy peak after energy leakage correction

Impact of cell size and cell energy threshold on energy resolution

- The larger cell size, the energy resolution is better
- The smaller cell energy threshold, the energy resolution is better
- They mainly effect on the stochastic term of energy resolution.



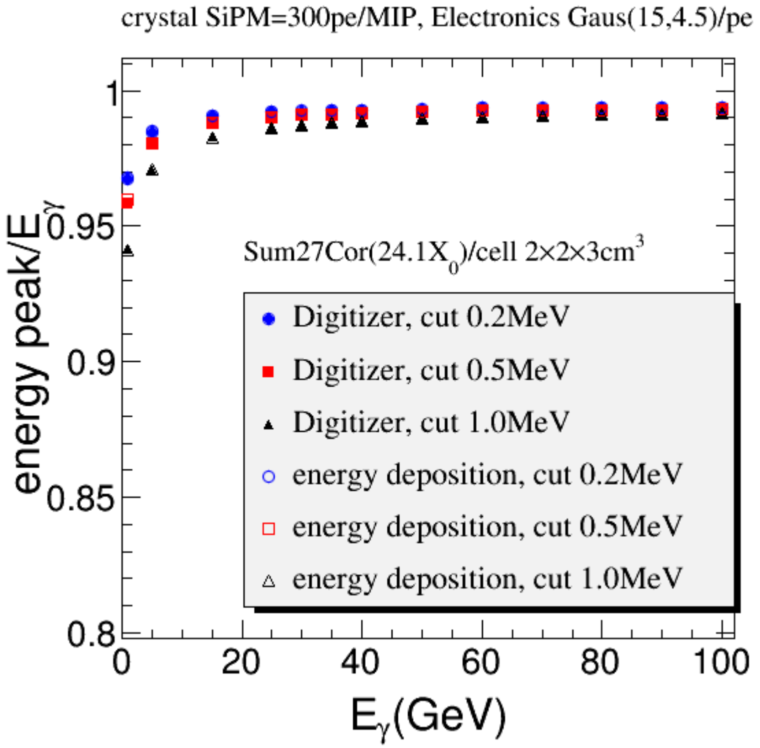


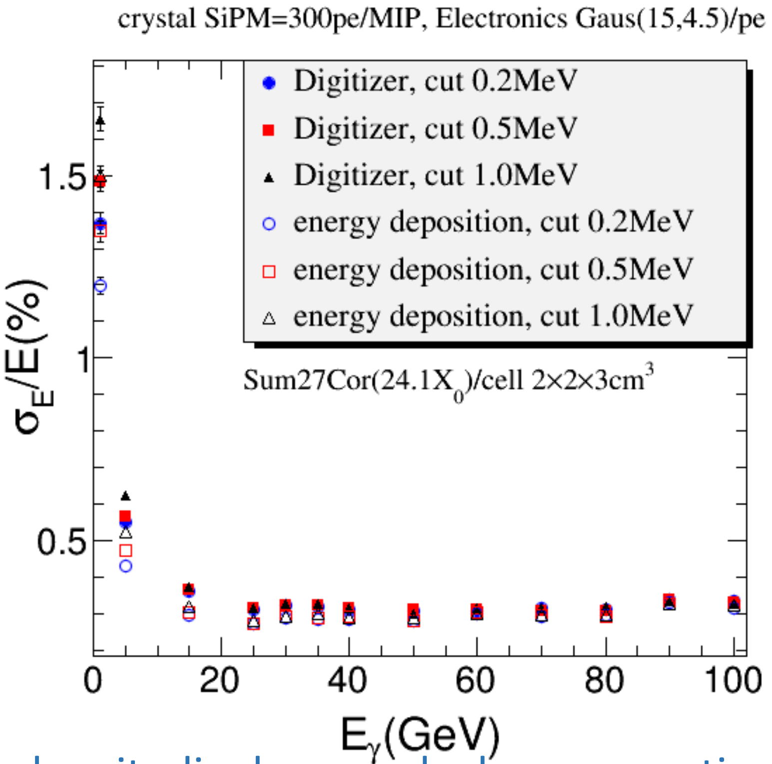


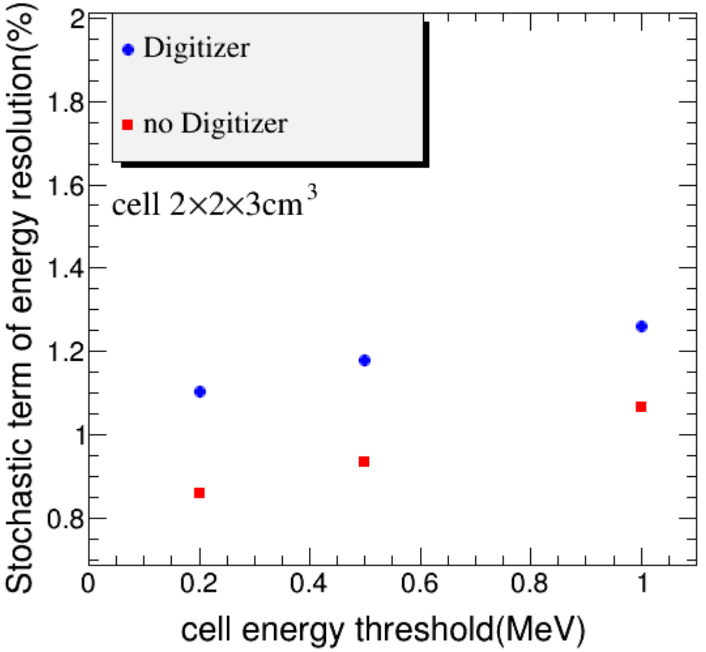
Energy resolution after the longitudinal energy leakage correction

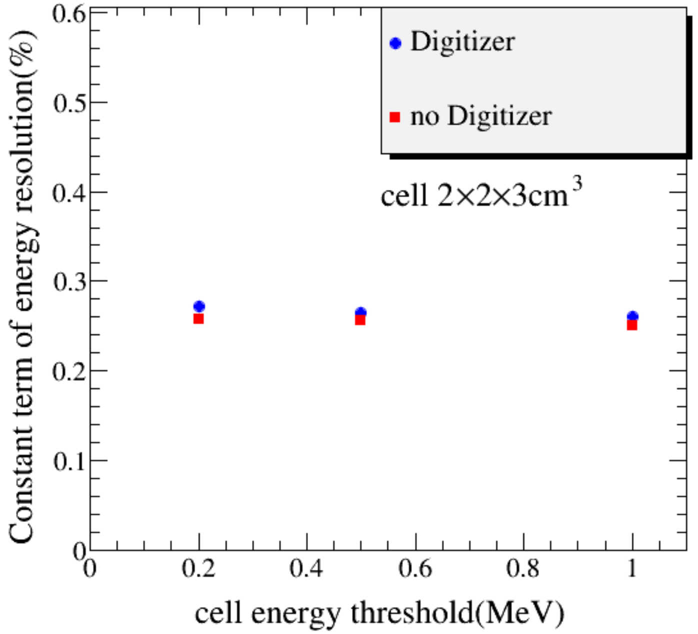
Impact of the digitization

- The fluctuations of photon electron and electronics gain
  - have effect on the stochastic term of energy resolution.
  - Almost no effect on the energy peak





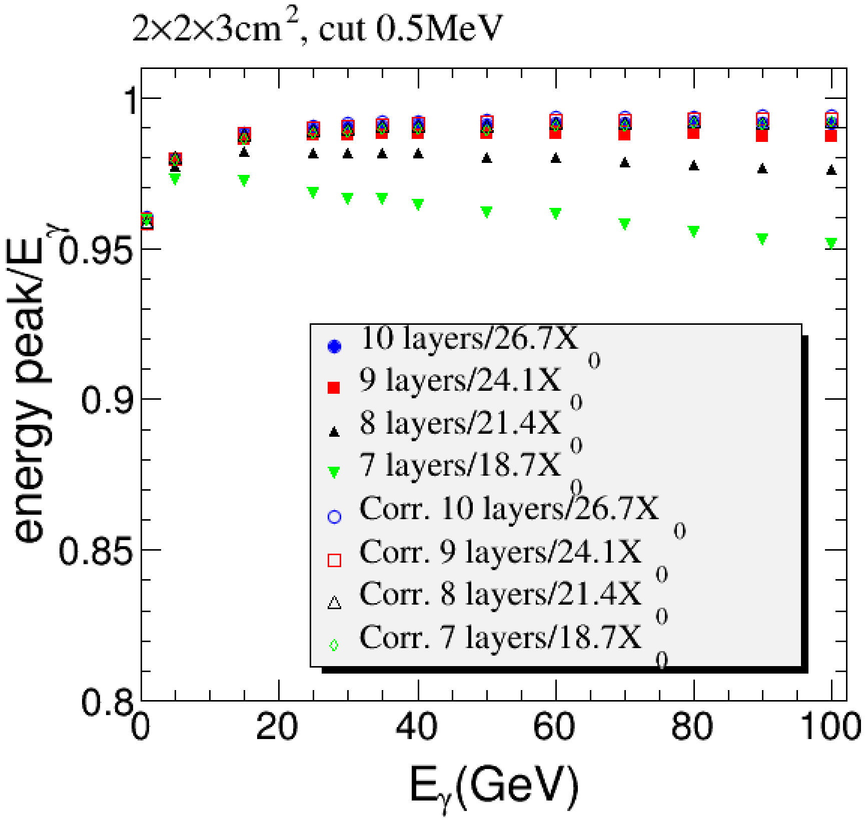


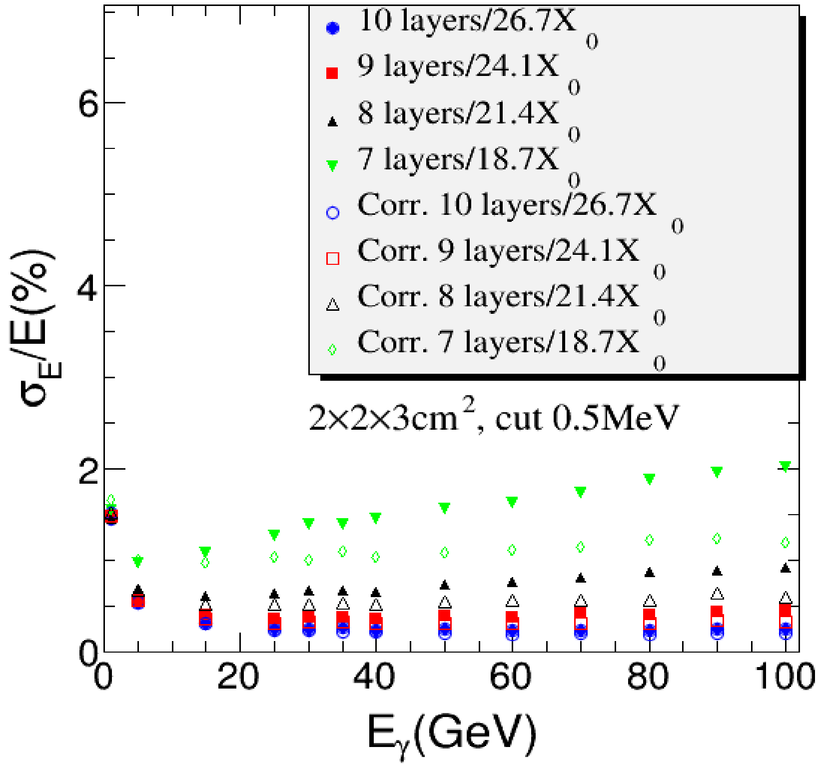


Energy peak and resolution after the longitudinal energy leakage correction

Impact of the crystal ECAL longitudinal depth

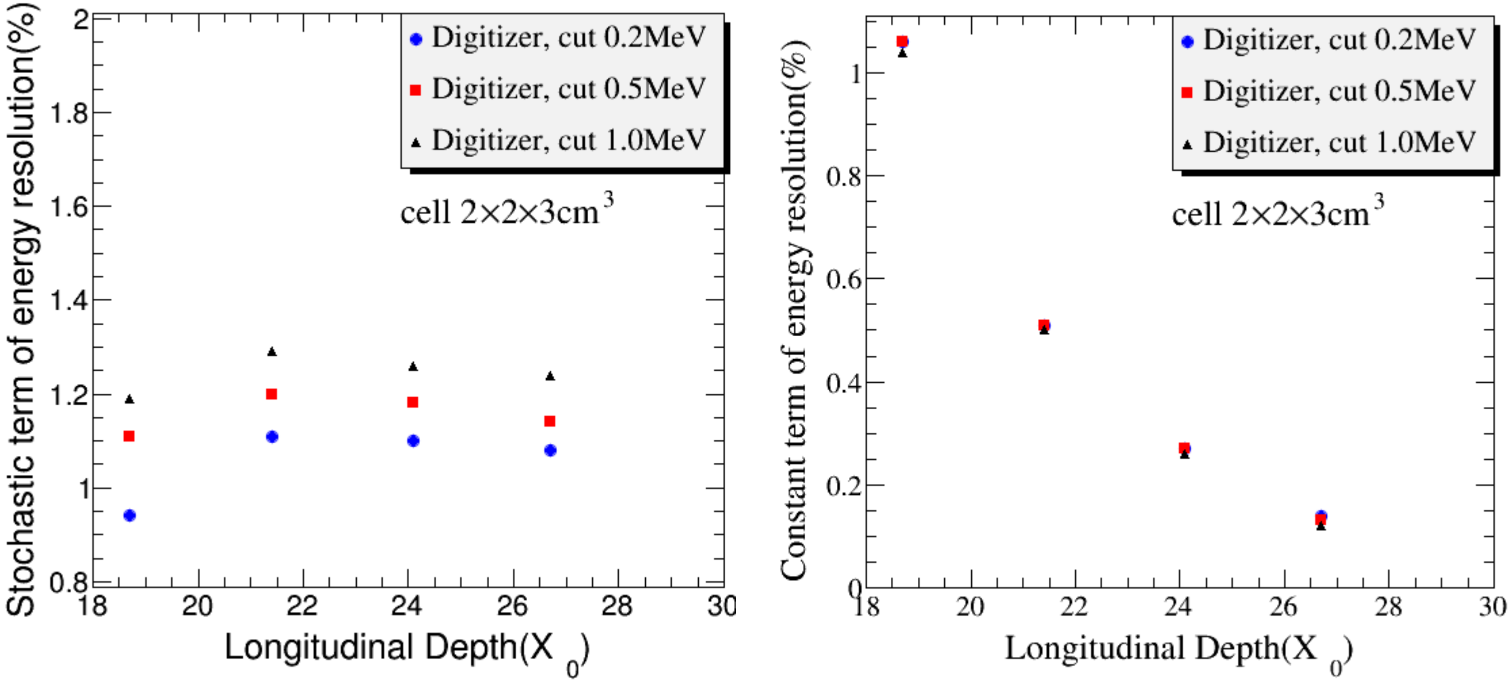
- Energy peak and resolution have been a big improvement after longitudinal energy leakage correction
- For 7 layers/18.7X_0
  - The effect of the energy leakage is very large.
  - The constant term of the energy resolution is larger than 1%





Performance of Longitudinal depth with different cell threshold

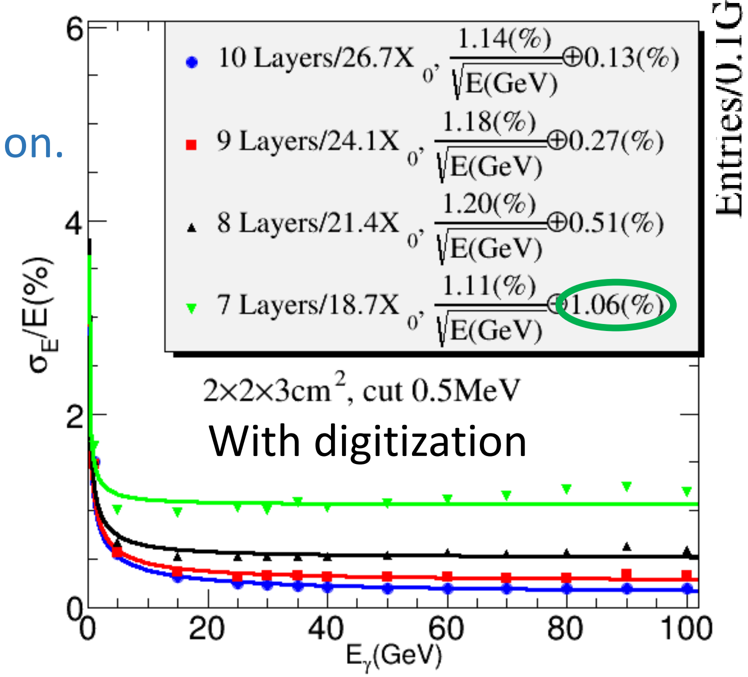
- Stochastic and constant terms of energy resolution
  - Cell energy threshold mainly effects on the Stochastic term
  - The longitudinal depth mainly effects on the constant term. For 7 layers/18.7X_0 the constant term is large than 1%



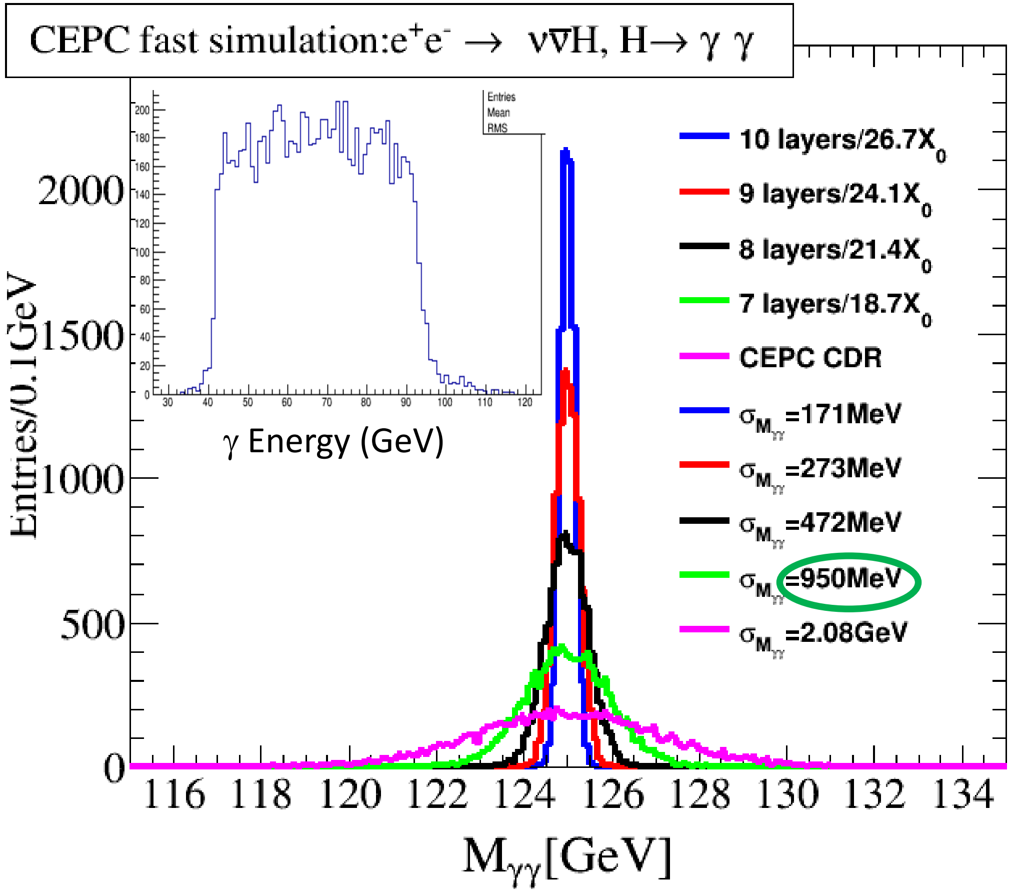
Energy resolution after the longitudinal energy leakage correction

Performance after the longitudinal energy leakage correction

- The γ energy of Higgs decay >35GeV
- For crystal ECAL, the invariant mass resolution of diphoton is mainly decided by the constant term of γ energy resolution.
- CEPC physics requirements:
  - The constant term: ~1%.
  - In fact, the γ energy resolution will be worse than the simulation.
  - The longitudinal depth: 9 or 8 layers is better.



The energy resolution of unconverted photons as a function of energy after the correction



the invariant mass distribution of diphoton

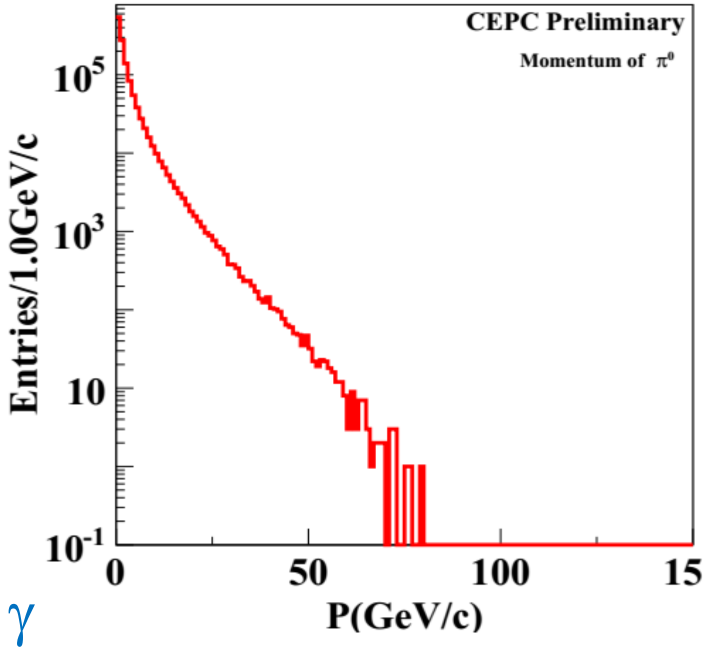
CEPC CRD: $\frac{\sigma_E}{E} = \frac{17\%}{\sqrt{E(GeV)}} \oplus 1\%$

Crystal transverse segmentation optimization

- In CEPC CDR requirement:

  over all solid angle. To identify the τ-leptons in the different decay modes, the photons should be distinguishable from π^0's with an efficiency and purity higher than 95% measured in the $Z \to \tau^+\tau^-$ event sample at the CEPC Z factory operation.

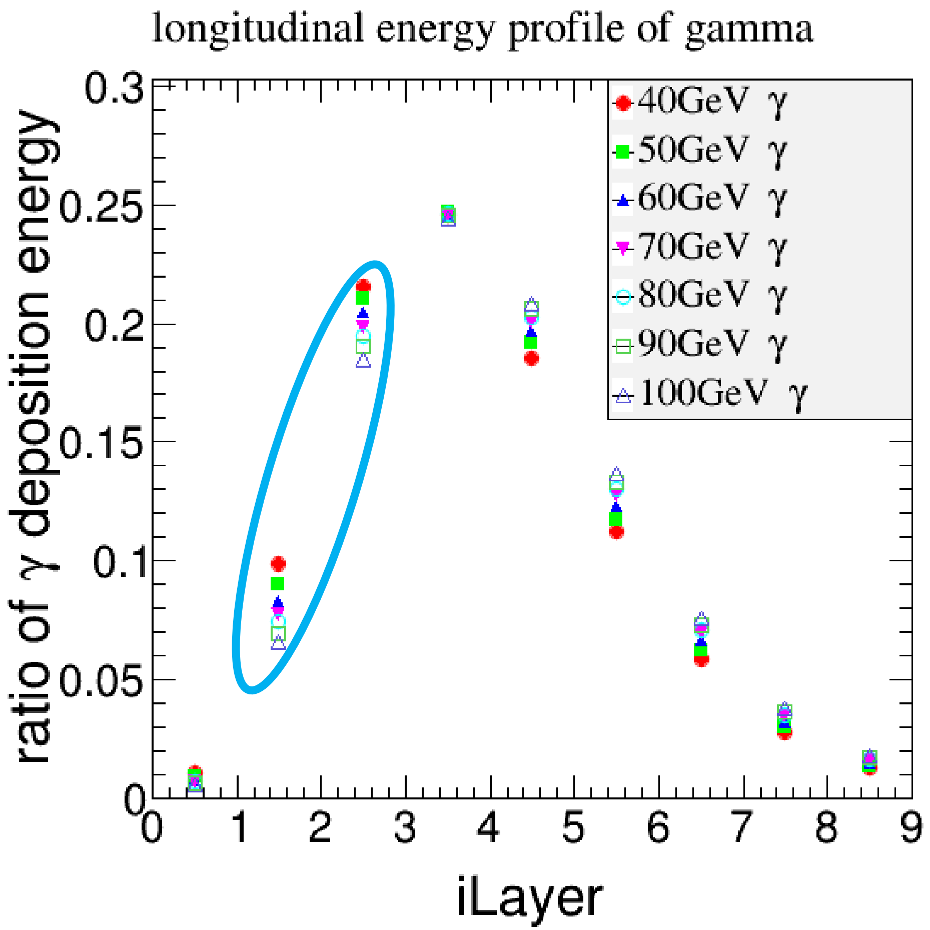
- Two types of π^0 event in ECAL reconstruction
  - One is the "resolved" π^0 from pair of photons.
  - Another is the "merged" π^0 from single cluster.
- The merged π^0 events
  - may become the background of the isolated photons
  - will also increase as the π^0 momentum and crystal transverse segmentation get bigger.
- In the following we study the separation performance of γ and merged π^0 .

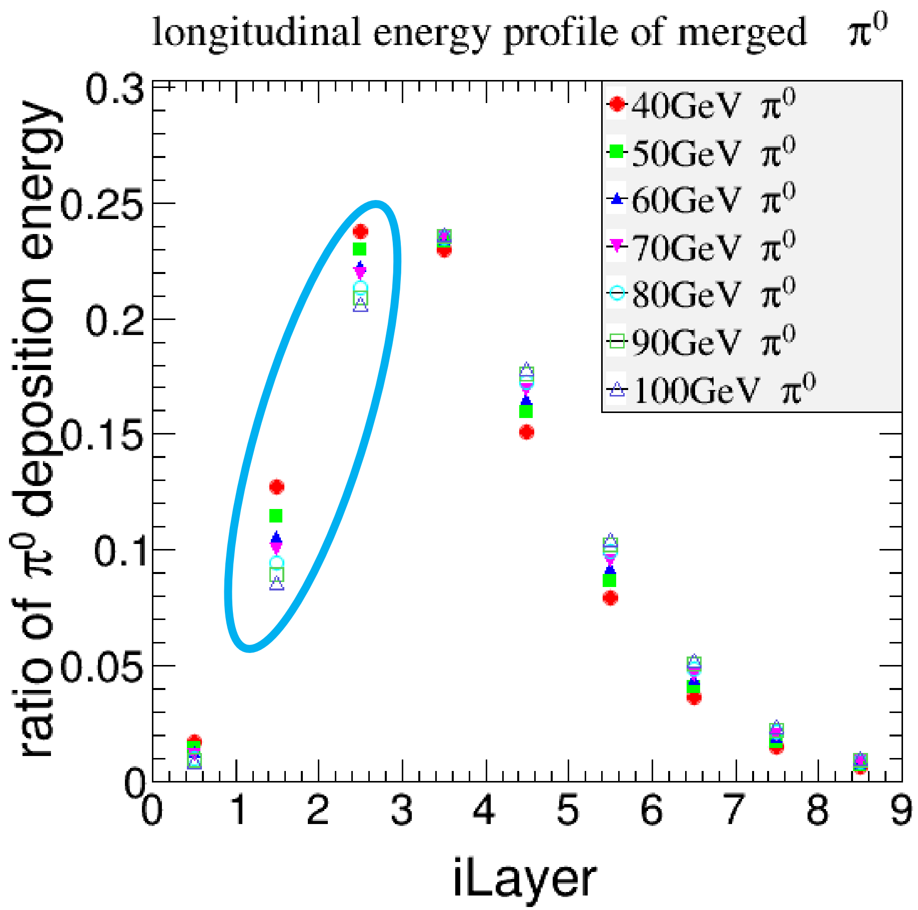


	π^0 Momentum	Cell 1×1×3cm³	Cell2×2×3cm³
Merged π^0	30GeV	0%	100%
	40GeV	~40%	100%

Longitudinal energy profile of γ and merged π^0

- There are some differences between γ and merged π^0, especially , 2nd and 3rd layers

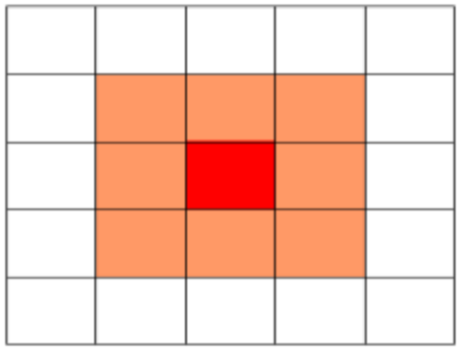




Study of the separation performance of γ and merged π^0

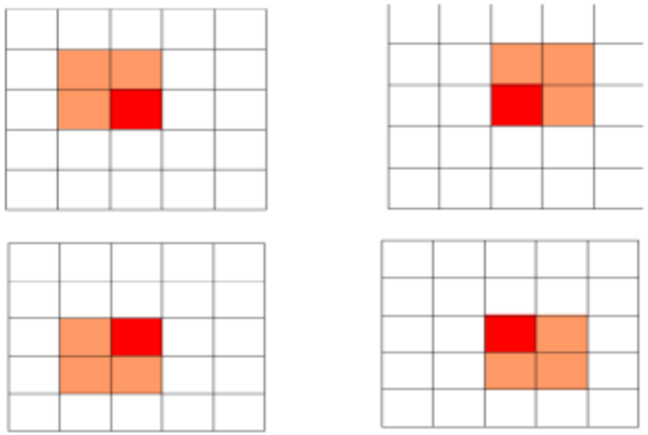
- Using the toolkit of multivariate data analysis (TMVA)
- Energy- related variables defined , and describe transverse shower profiles:

  S1/S4, S1/S9, S1/S25, S9/S25, S4/S9, F9, F16 and Second moment

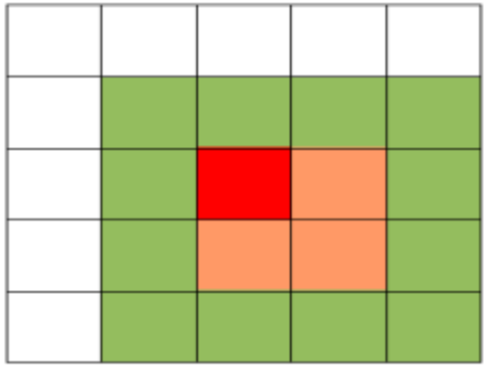


S1,S9,S25

$$F_9 = \frac{S9 - S1}{S9}$$



S4 the energy maximum
in the four 2x2 arrays



S16

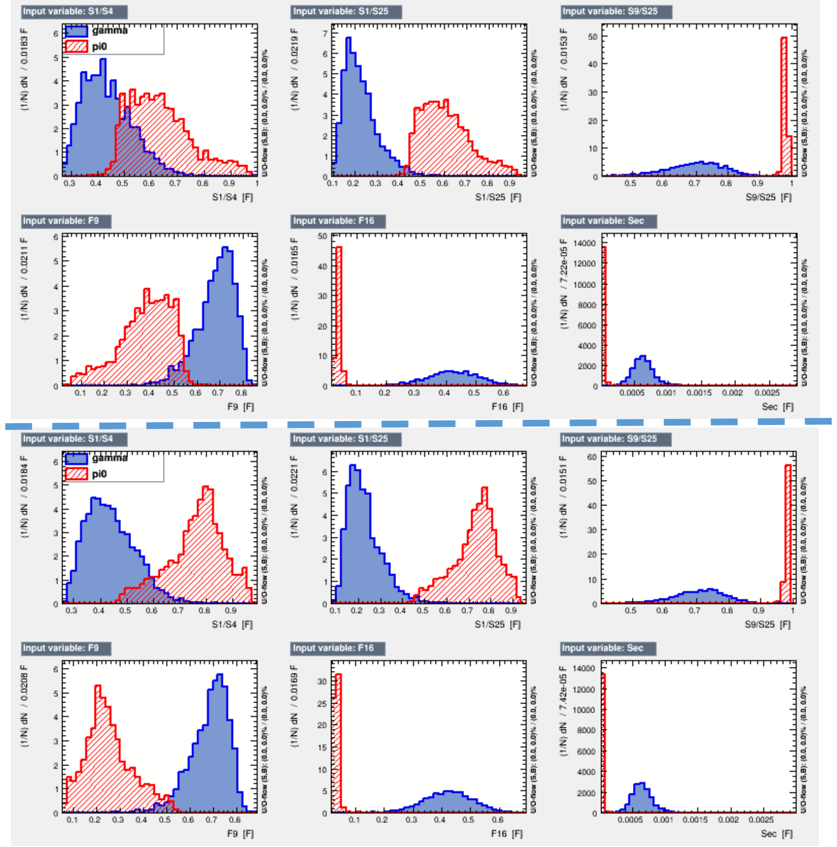
$$F_{16} = \frac{S16 - S4}{S16}$$

Separation performance of merged π^0 and γ

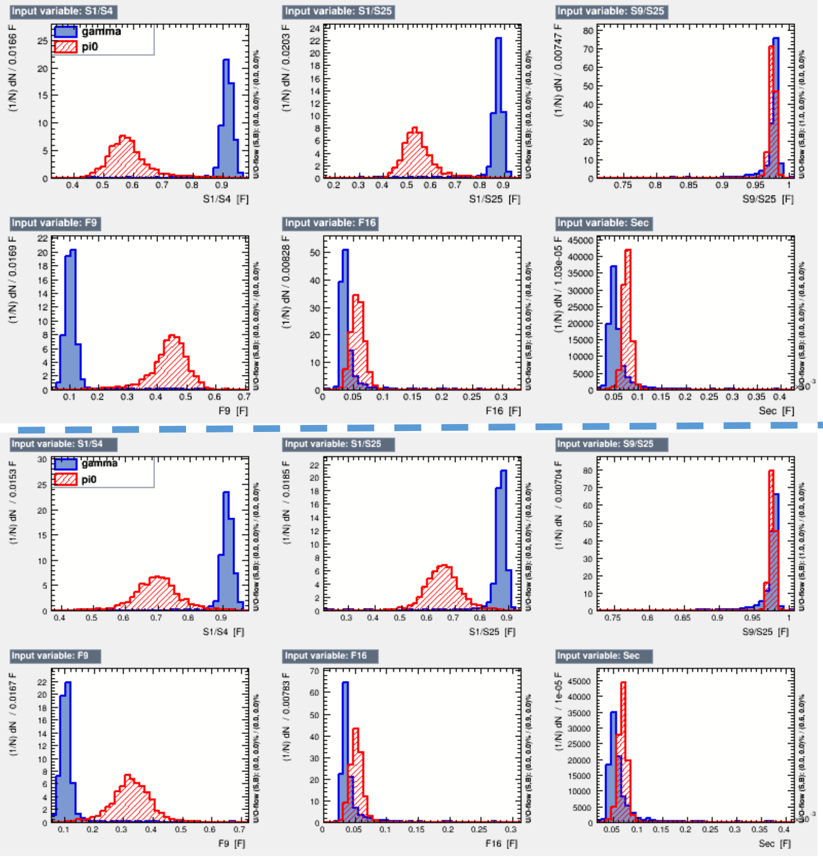
- As an example, for 40 and 50GeV the separation performance of γ and merged π^0.
  - The separation performance of 2nd and 3rd layers are very good, ~100%.

40 GeV

50 GeV



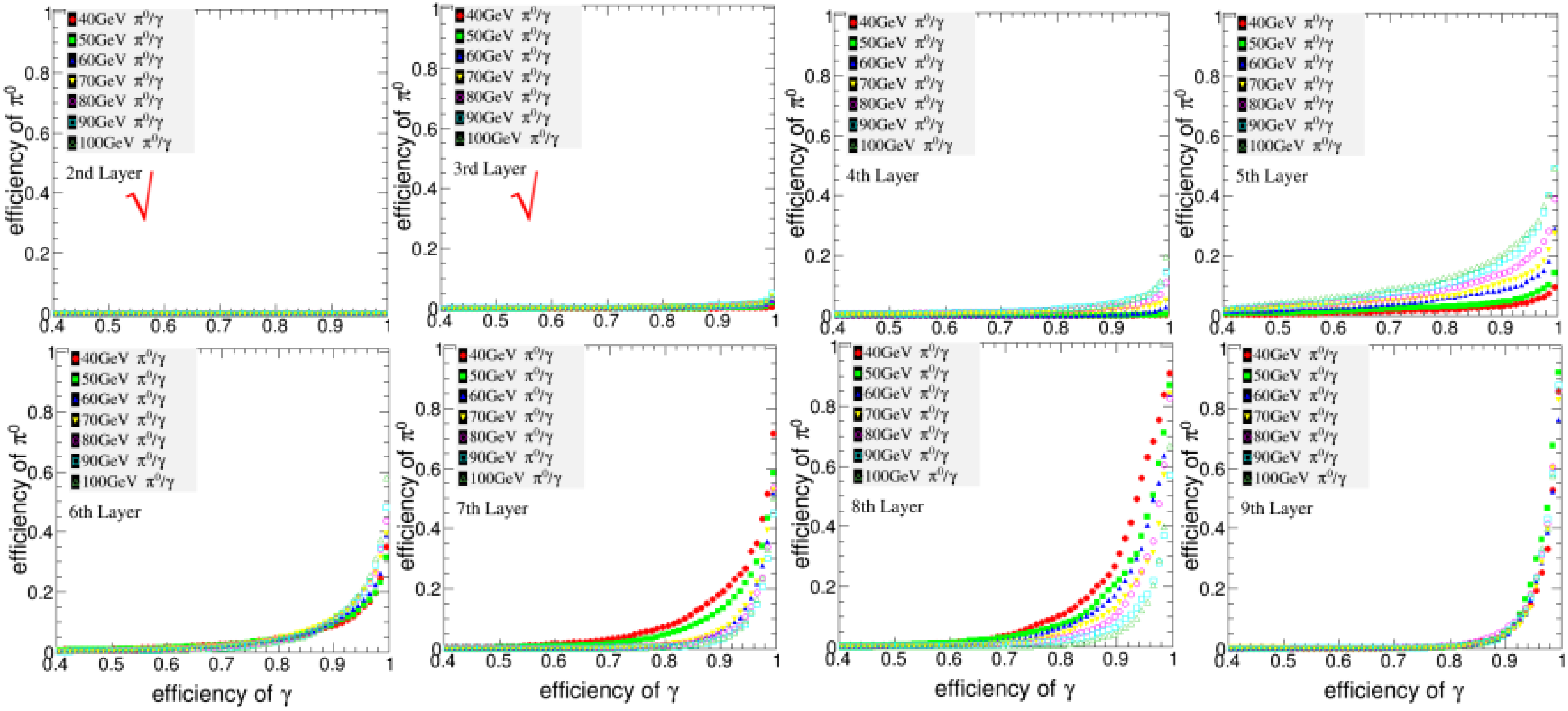
2nd Layer



3rd Layer

Separation efficiency of merged π^0 and γ

- Criteria of effective separation: efficiency of γ ➔ 1 and efficiency of π^0 ➔ 0
- 2nd and 3rd layers: ~100% separation for the different high energy



Summary

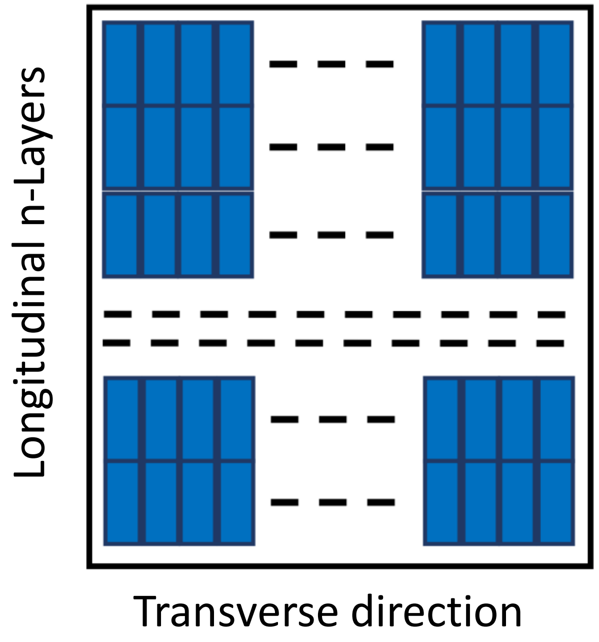
- Construct the BGO matrix module in G4, and reconstruct cluster of each layer
- Longitudinal depth optimization
  - several factors affecting energy resolution
    - cell size/cell energy threshold /digitization
    - crystal ECAL longitudinal depth
  - Correction of the longitudinal shower energy leakage
    - The energy resolution has a big improvement
    - Balance cost and performance of crystal ECAL:
      9 layers/24.1X_0 or 8 layers/21.4X_0 can be better
- Transverse granularity optimization
  - Separation performance of merged π^0 and γ /40-100GeV by using TMVA
  - For cell 2×2×3cm^3, the 2nd and 3rd layers: ~100% separation

Thank you!

Backup slides

New idea : High-granularity Crystal ECAL

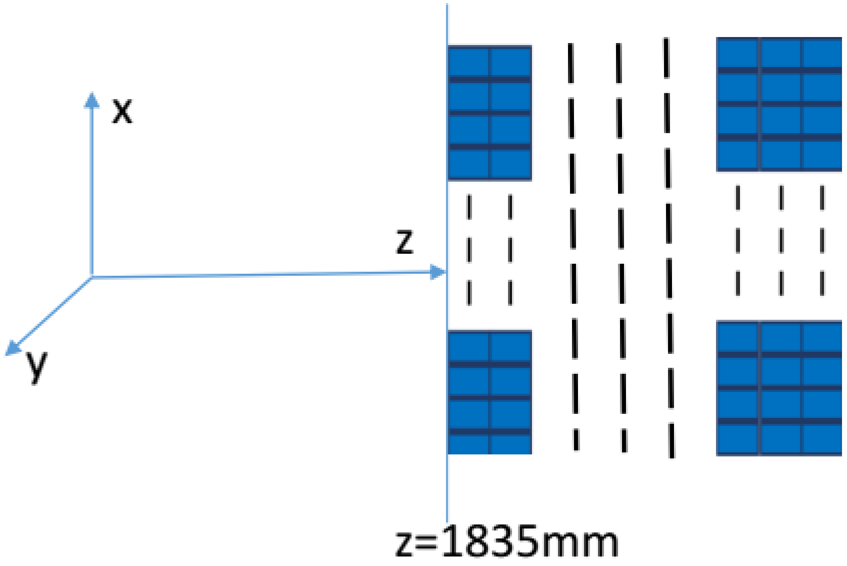
- Homogeneous crystal structure:
  - Cell size: ~moliere radius in transverse direction
  - N layers in longitudinal direction
- Key issues: optimization
  - Crystal options: BGO, PWO, etc.
  - Segmentation: in longitudinal and lateral directions
  - Performance: single particles and jets with PFA
  - Impacts from dead materials: upstream, services (cabling, cooling)
  - Costing
  - Fine timing information



Simulation in GEANT4 and Cluster reconstruction

MC simulation of a simplified crystal calorimeter module for CEPC

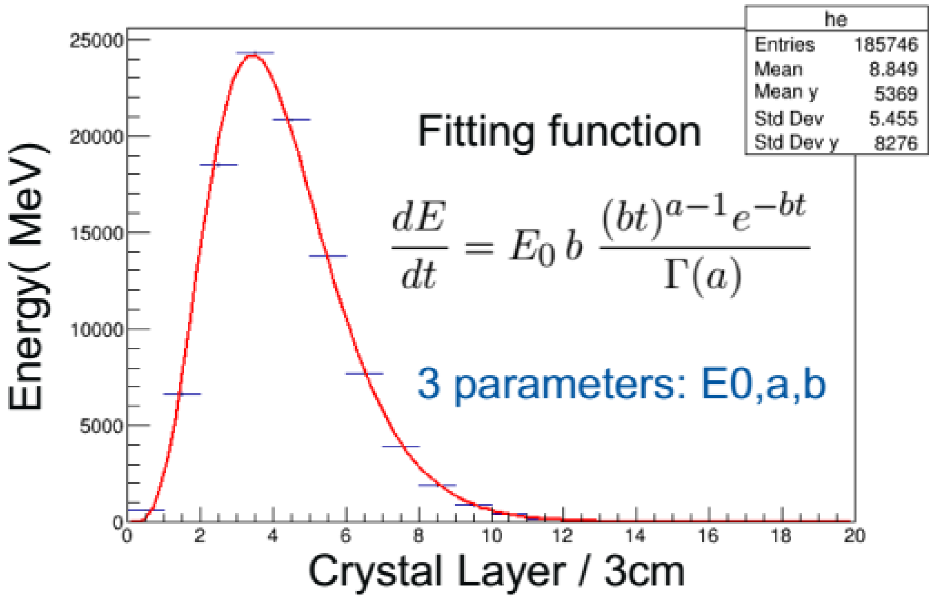
- Construct the Matrix module in GEANT4 v10.5.0
  - Cell size:$1\times1\times1cm^3$
    - Easily merge cells / layers
  - Construct a 3D BGO array with $60\times60\times60$ cells
  - The front face of the array is 1835mm from zero (origin of coordinates), the inner radius of baseline ECAL Barrel.
  - Cell Size 1cm is ~ 0.31224° solid angle at θ=90° in Barrel
- Without any photodetector materials and wrappers
- Geant4 simulates the energy deposited in crystal cell
- Cluster reconstruction of each layer based on the traditional Crystal ECAL



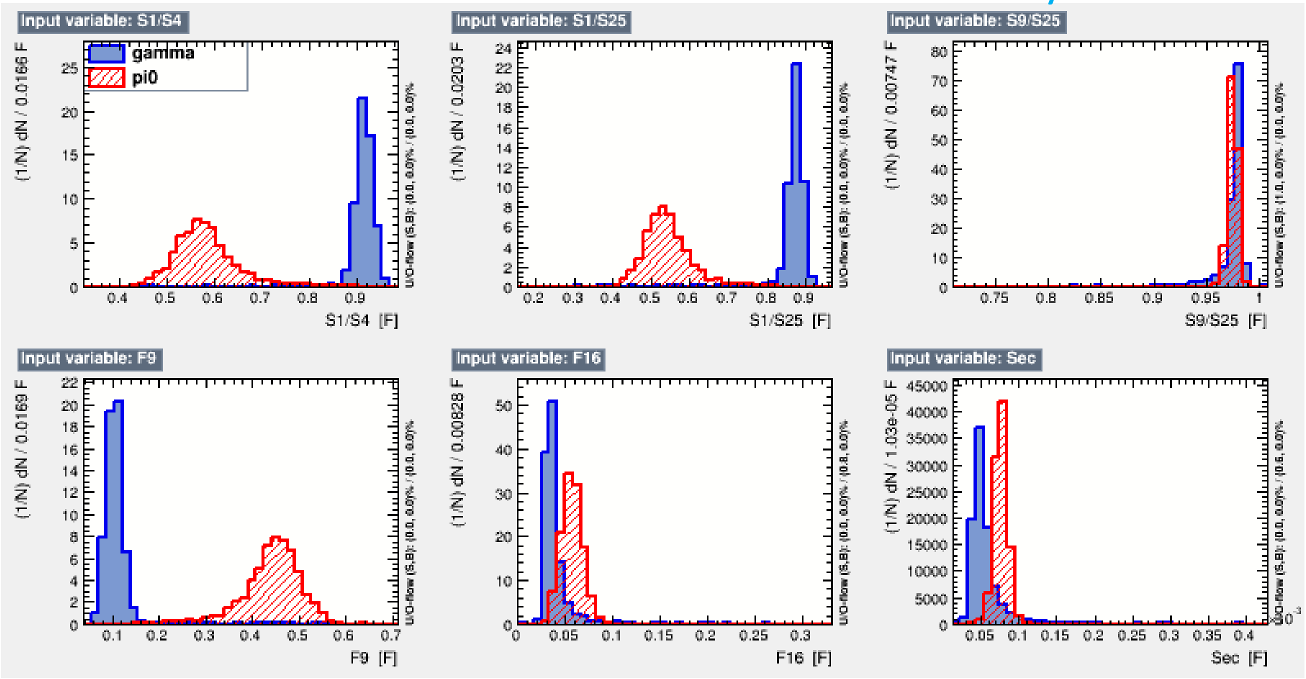
BGO crystal material properties:
Crystal radiation length:~1.12cm;
Moliere radius R_M: 2.23cm;

Crystal cell optimization

- Crystal longitudinal depth
  - Use shower profiles in segmented layers to correct for tails (energy leakage)
  - Aim for shorter crystal depth(cost), balance with performance (correction precision)
- Crystal transverse segmentation
  - Crystal transverse size: separation of merged π^0 and γ



40GeV 3rd Layer



Simplified digitization in the simulation

Cell deposition energy $\Rightarrow$ MIP number
$\Rightarrow N_{pe}$ the number of photon electron
$\Rightarrow$ADC

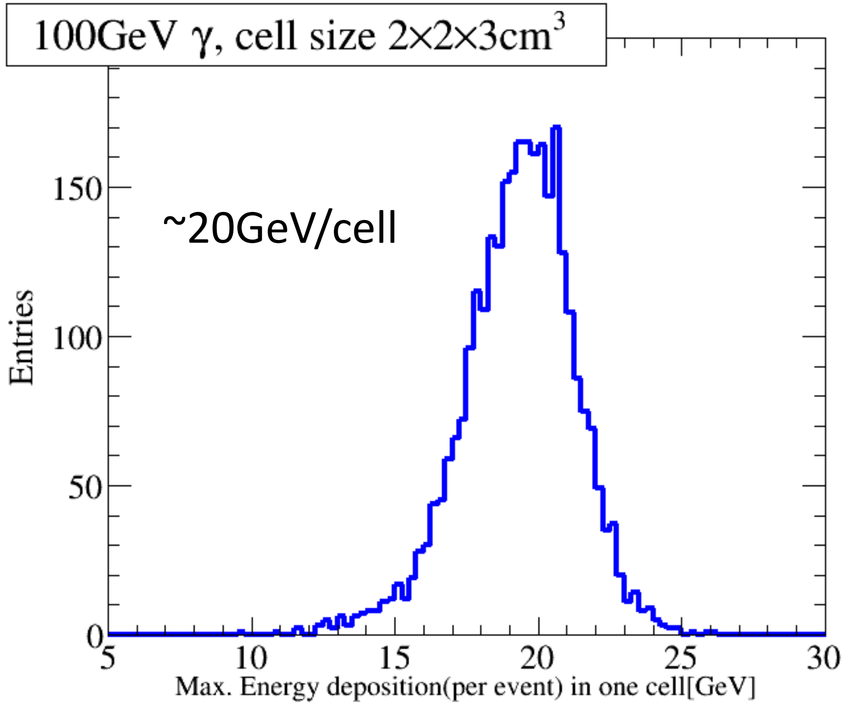
N_{pe} = Poisson(Edep(MeV)/10.16×300(p.e.)

ADC = $N_{pe} \times$ Gaus(15, $4.5/\sqrt{N_{pe}}$)

Here using 4 Parameters:

1. Scintillator Mean Light Yield:300 p.e. per MIP
2. SiPM Mean Gain:15ADC tics per p.e.,
3. Gain Sigma: 4.5ADC tics per p.e.
4. 1 MIP(120GeV muon) yields 10.16MeV energy deposition in the BGO crystal

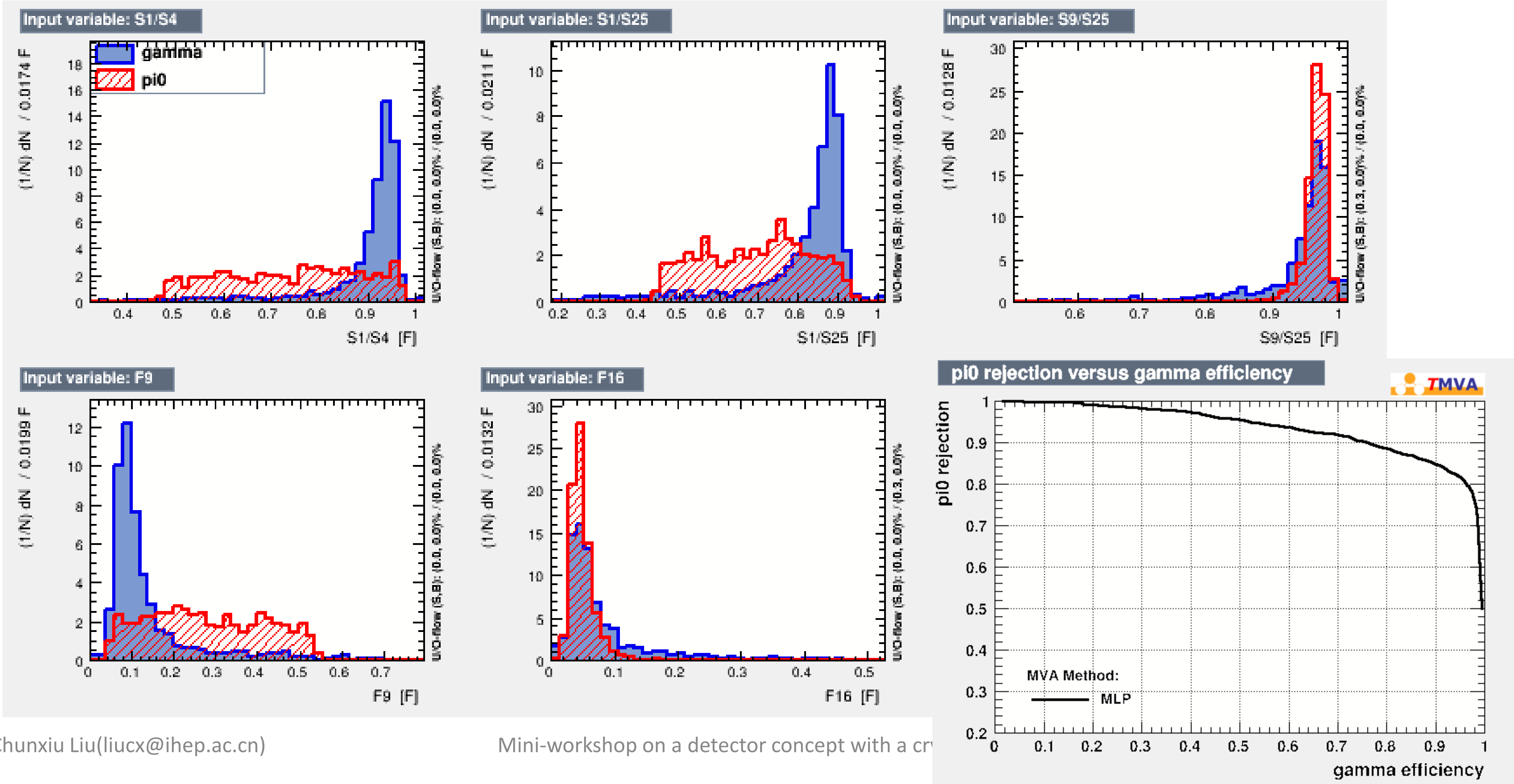
Crystal cell dynamic range: simulation with 100GeV γ



For 100GeV γ, MIP number per cell 2×2 ×3cm^2 can reach around 2500.

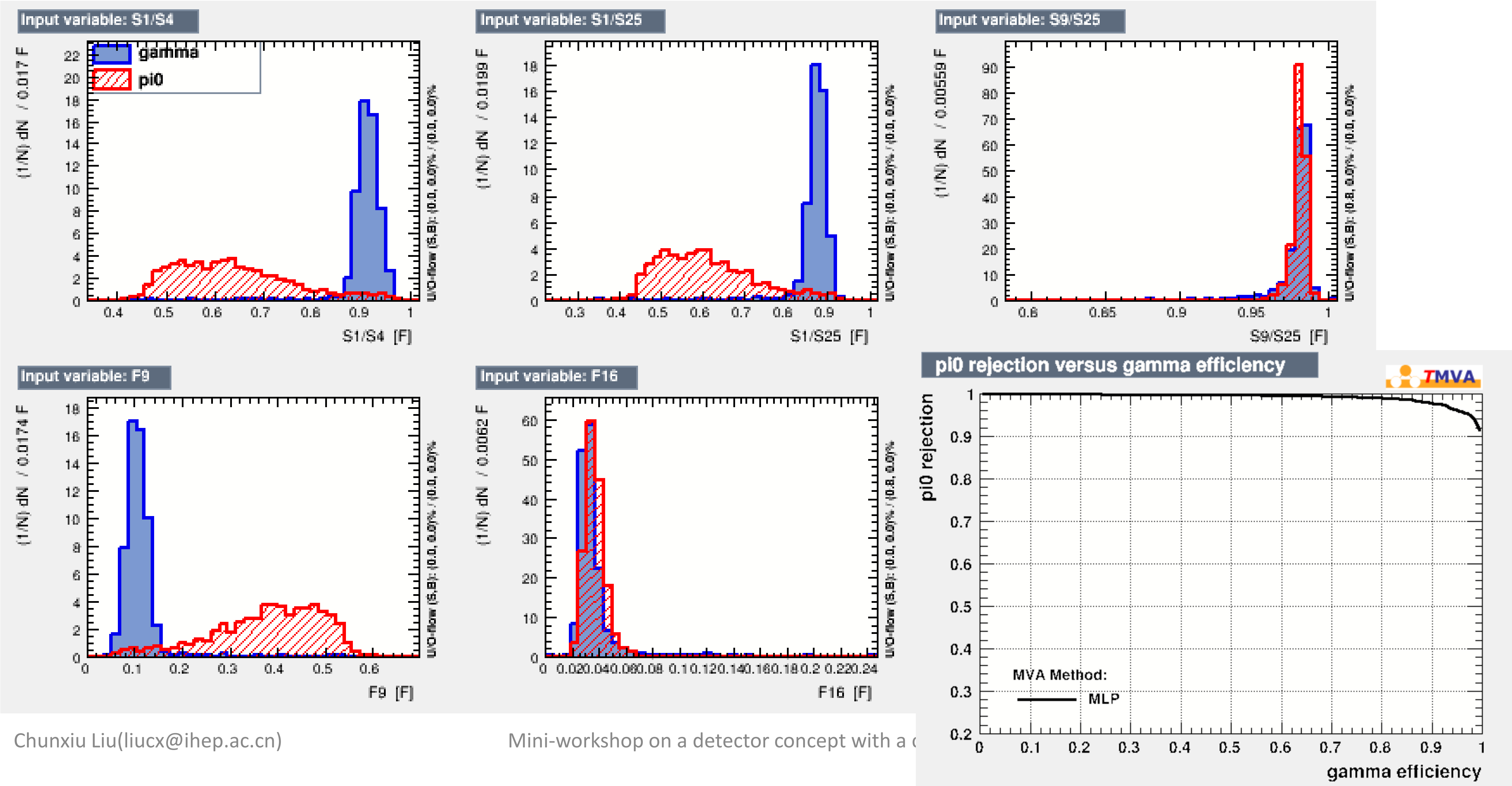
separation performance of the 40GeV γ and merged π^0

- alone the energy information of each layer with 3cm Depth with Cell 2x2cm^2 :1st layer



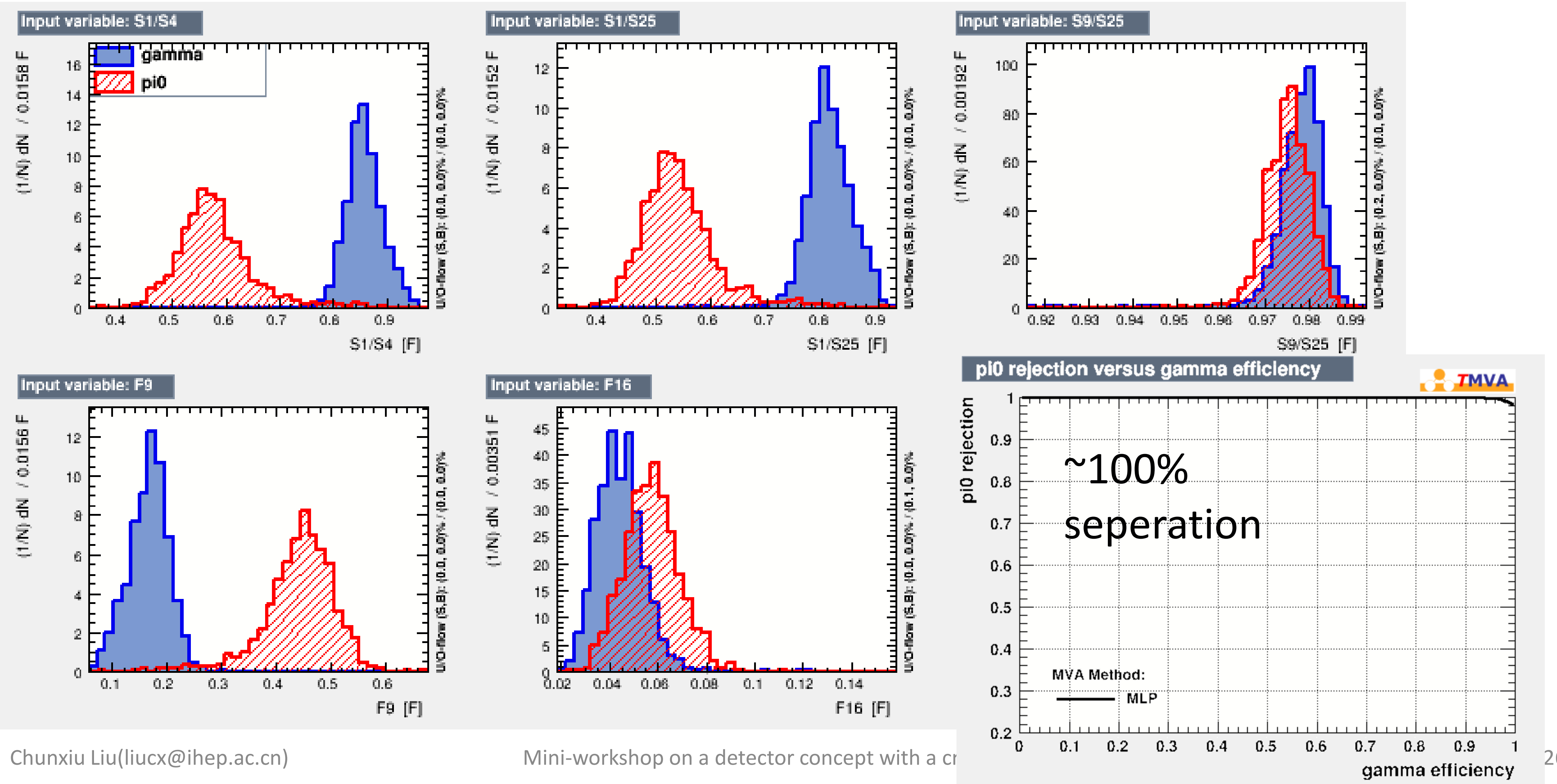
separation performance of the 40GeV γ and merged π^0

- alone the energy information of each layer with 3cm Depth with Cell 2x2cm^2 :2nd layer



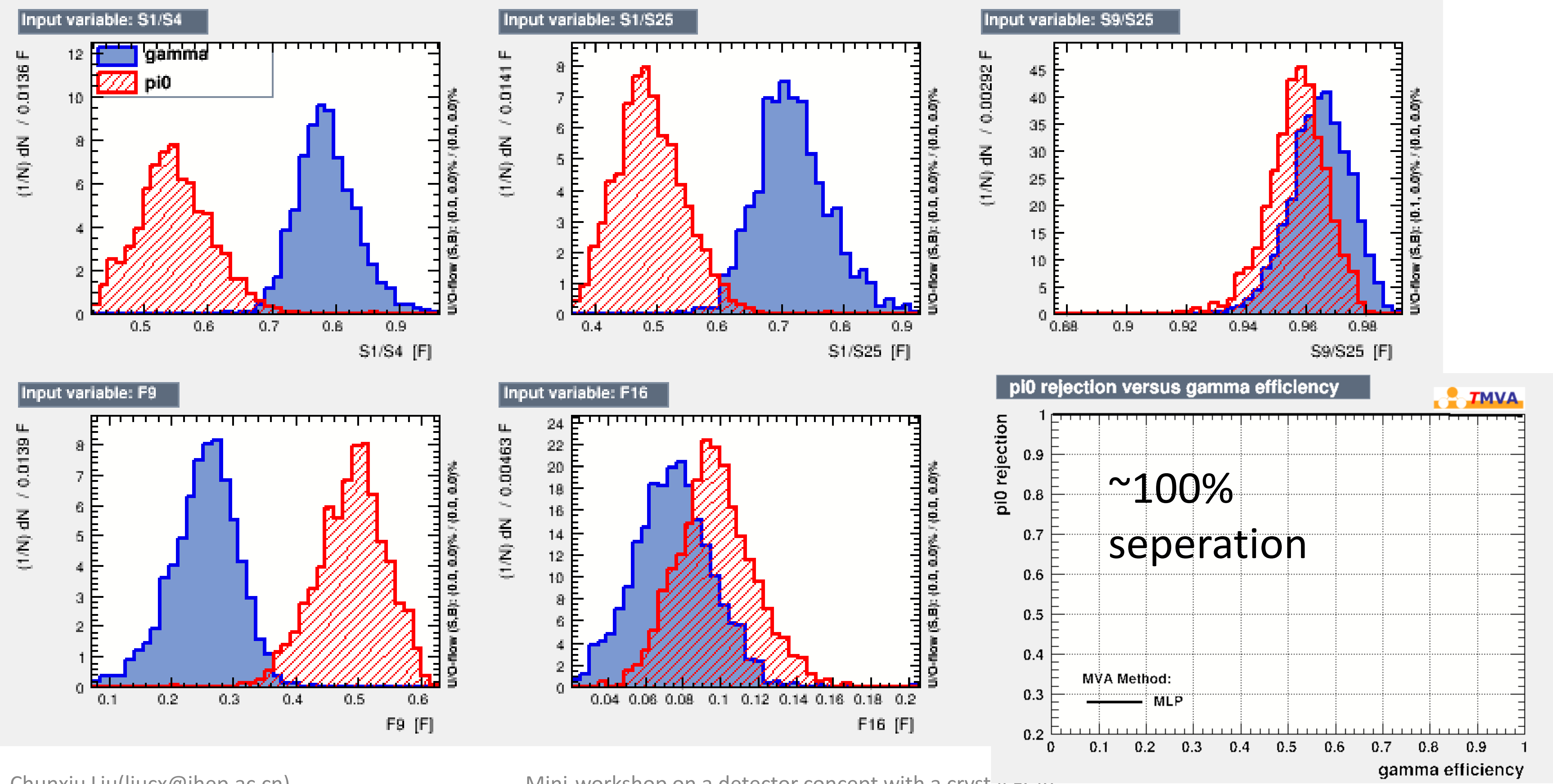
separation performance of the 40GeV γ and merged π^0

- alone the energy information of each layer with 3cm Depth with Cell 2x2cm^2 :3rd layer



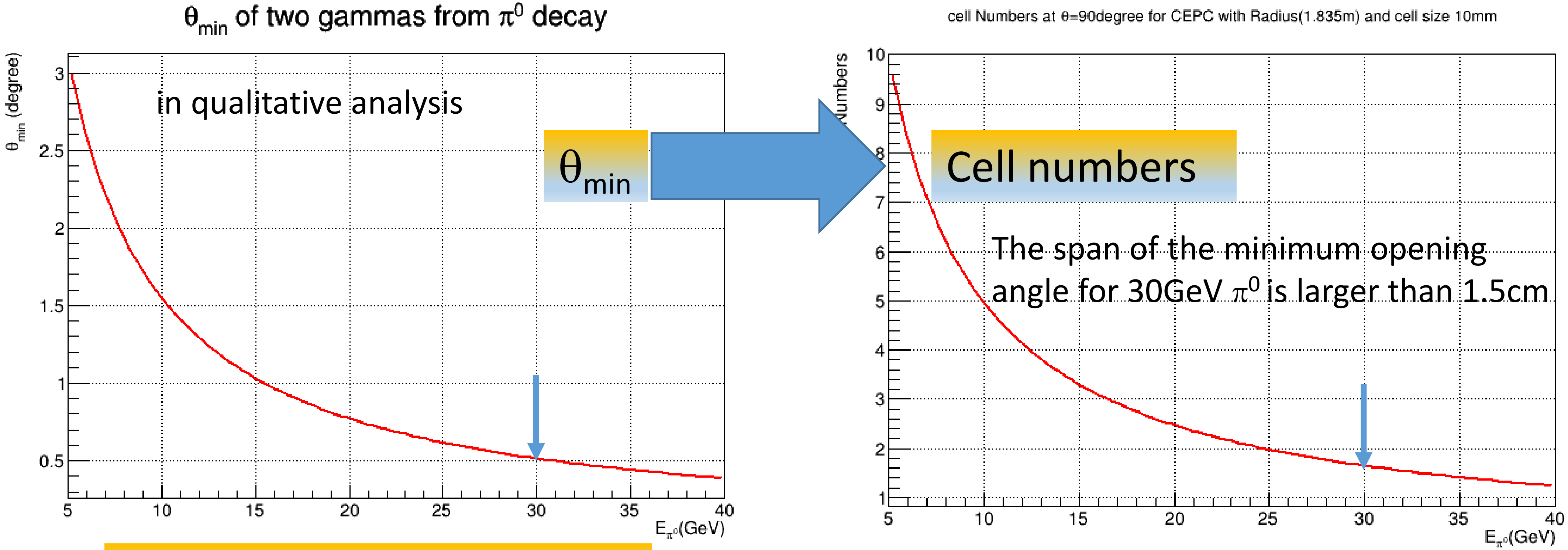
separation performance of the 40GeV γ and merged π^0

- alone the energy information of each layer with 3cm Depth with Cell 2x2cm^2 :4th layer



Separation performance of 2γ's from the high energy π^0 decay

- Convert the θ_{min} into the cell numbers at $\theta=90°$ for CEPC with Radius(1.835m) and the cell size 10mm.
- One crystal has the maximum angle~0.31224° at $\theta=90°$ in barrel.

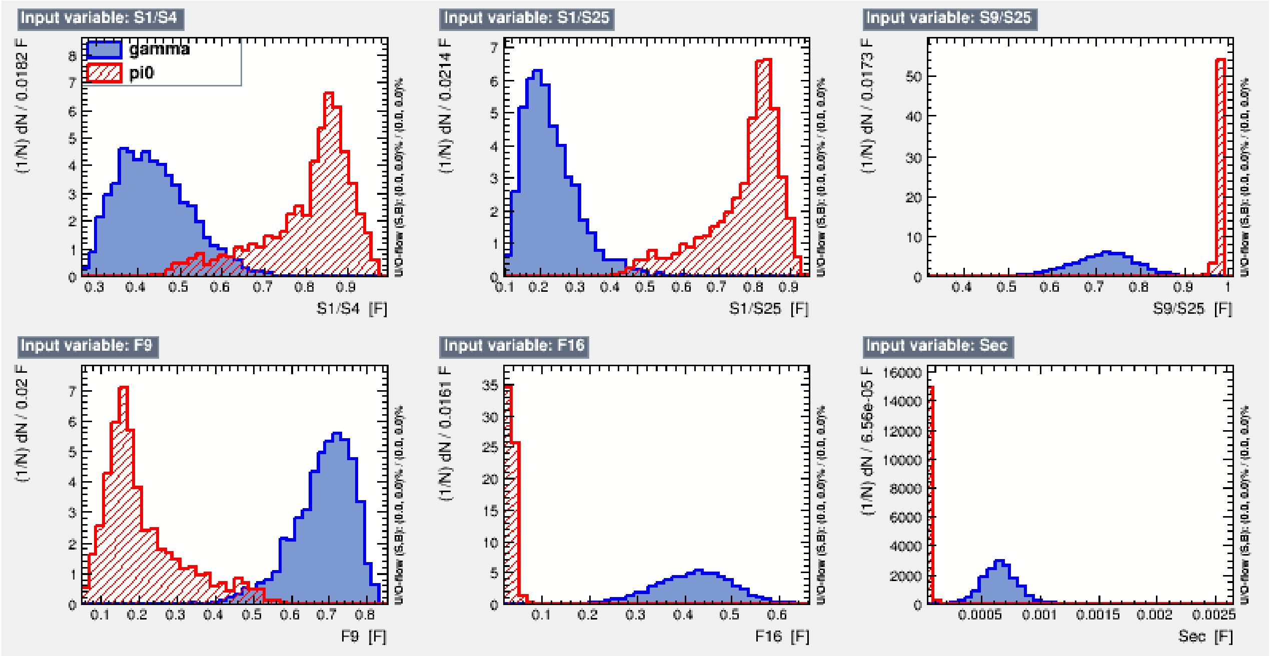


θ_{min} versus π^0 momentum

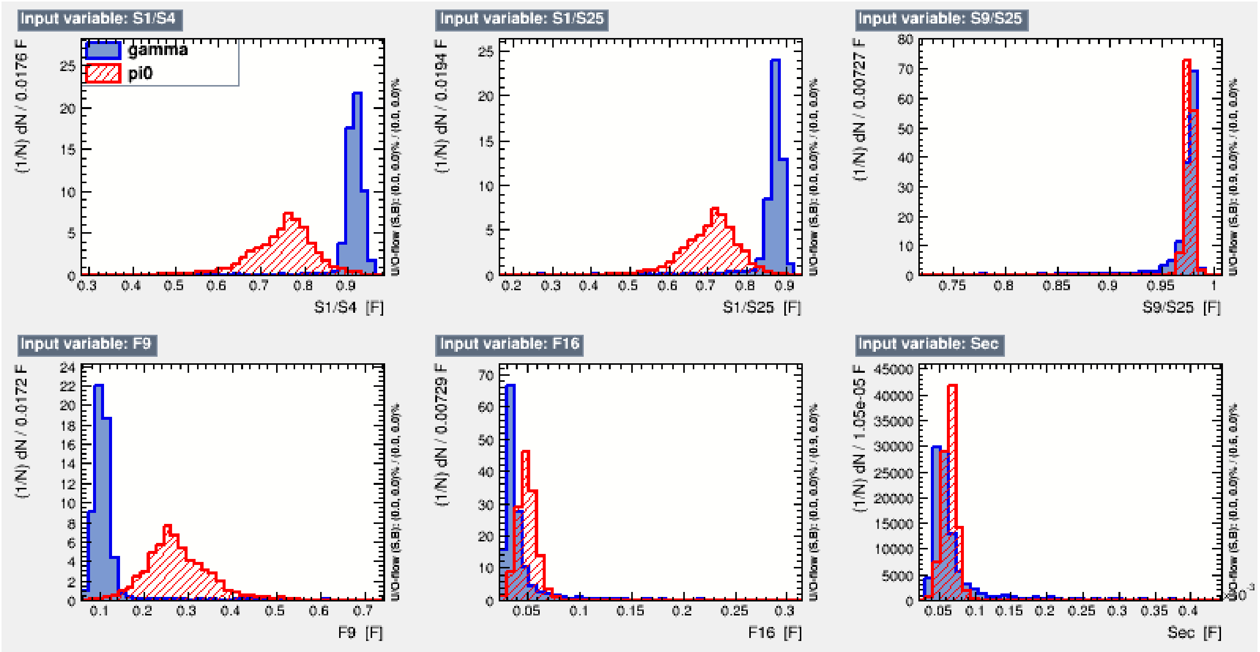
Cell numbers versus π^0 momentum

Separation performance of merged π^0 and γ

- For example, the separation performance of 60GeV γ and merged π^0.
  - The separation performance of 2nd and 3rd layers are very good.



60GeV : 2nd Layer



60GeV : 3rd Layer

Summary

- Construct the BGO matrix module: 60×60×60cm^3 in Geant4, and cluster reconstruction of each layer
- Longitudinal depth optimization
  - Study of factors affecting energy resolution
    - cell size/cell energy threshold /simplified digitization
    - crystal ECAL longitudinal depth
  - Correction of the longitudinal shower energy leakage
    - 10 layers/26.7X$_0$: $\frac{\sigma_E}{E} = \frac{1.14\%}{\sqrt{E(GeV)}} \oplus 0.13\%$, $\sigma_{M(H\to\gamma\gamma)}$=171MeV (fast sim.)
    - 9 layers/24.1X$_0$: $\frac{\sigma_E}{E} = \frac{1.18\%}{\sqrt{E(GeV)}} \oplus 0.27\%$, $\sigma_{M(H\to\gamma\gamma)}$=273MeV (fast sim.)
    - 8 layers/21.4X$_0$: $\frac{\sigma_E}{E} = \frac{1.20\%}{\sqrt{E(GeV)}} \oplus 0.51\%$, $\sigma_{M(H\to\gamma\gamma)}$=472MeV (fast sim.)
    - 7 layers/18.7X$_0$: $\frac{\sigma_E}{E} = \frac{1.11\%}{\sqrt{E(GeV)}} \oplus 1.06\%$, $\sigma_{M(H\to\gamma\gamma)}$=950MeV (fast sim.)
- Transverse granularity optimization
  - Separation performance of 2γ's from high energy π^0 decay
    - Cell 1×1×3cm^3 : ~100%/30GeV π^0, ~60%/40GeV π^0
    - Cell 2×2×3cm^3 : ~0%/30GeV and 40GeV π^0
  - Separation performance of merged π^0 and γ /40-100GeV by using TMVA
    - For cell 2×2×3cm^3, the 2nd and 3rd layers: ~100% separation

Thank you!