crystal ECAL granularity optimization and performance studies

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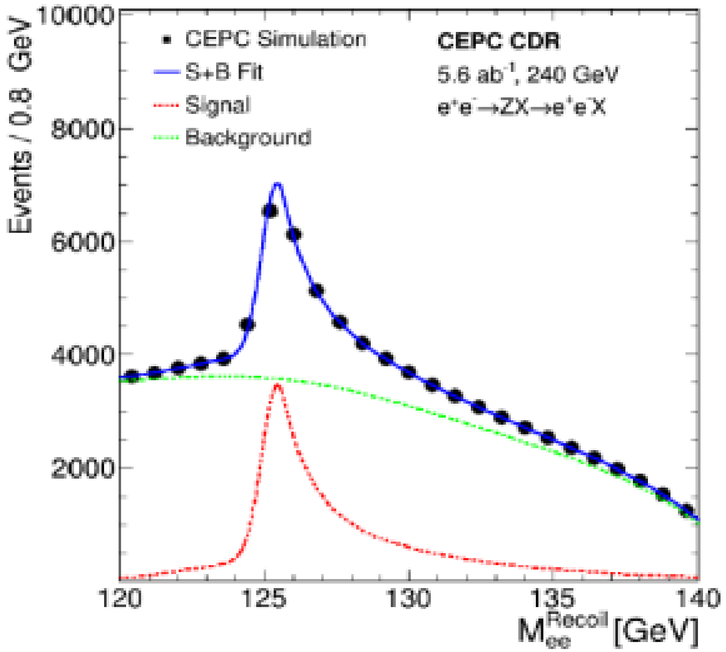
May 06, 2020

CEPC Physics&Detector meeting

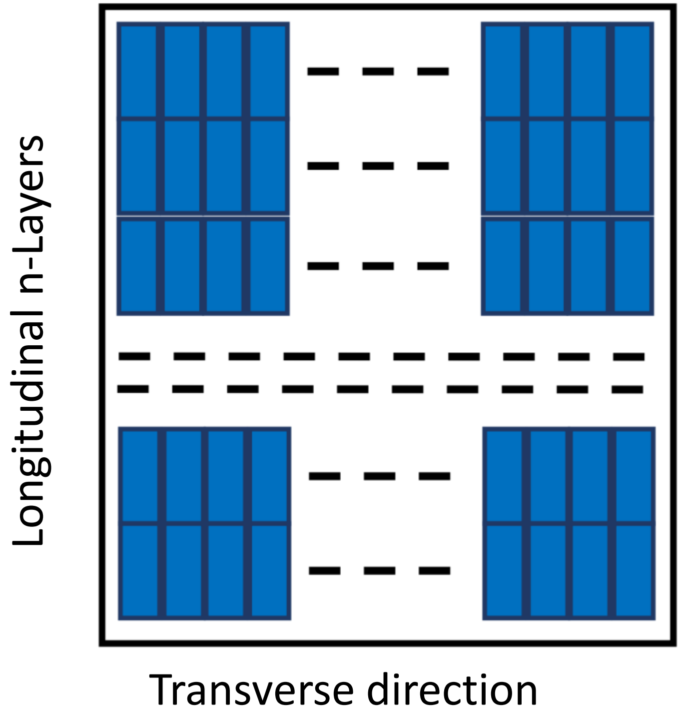
Overview: motivations



- Background: future lepton colliders (e.g. CEPC)
  - ➢Precision measurements with Higgs and Z/W
- Why crystal calorimeter?
  - ➢Homogeneous structure
    - Optimal intrinsic energy resolution: ~3%/ $\sqrt{E} \oplus$ ~1%
  - ➢High precision of electron energy : 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
  - ➢Potential in PFA for precision measurements of jets

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

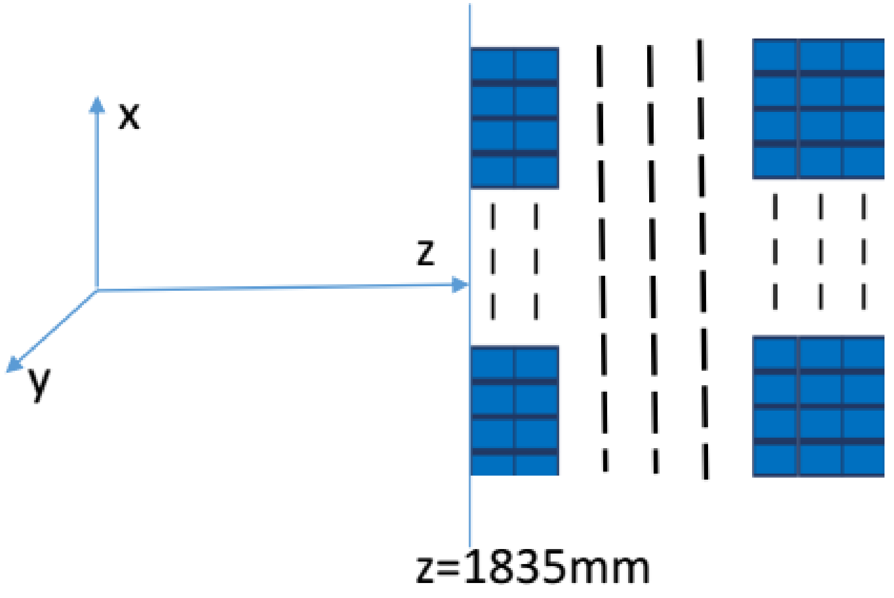
Study of the single particle performance

- Optimize the crystal granularity to realize the following performance
  - Whether the energy leakage can be corrected by the longitudinal profile of the cluster? (preliminary results presented)
  - Separation performance of 2 γ's from high energy π^0 decay (preliminary results presented)
  - Separation performance of γ and merged π^0 (preliminary results presented)
  - How to reconstruct the merged π^0 (in processing)
  - Separate γ and K_L by time and profile of the cluster
- How to arrange the crystals
  - Cell size?
  - How many layers?
  - depth of each layer?

Geometry construction in GEANT4 v10.5.0

MC simulation of a simplified crystal calorimeter module for CEPC

- Construct the Matrix module in GEANT4 v10.5.0
  - Cell size:$10\times10\times10mm^3$
    - ✓ Easy to 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 10mm is ~ 0.31224° solid angle at θ=90° in Barrel
- Without any photodetector materials and wrappers
- Geant4 simulates the energy deposited in crystal cell.



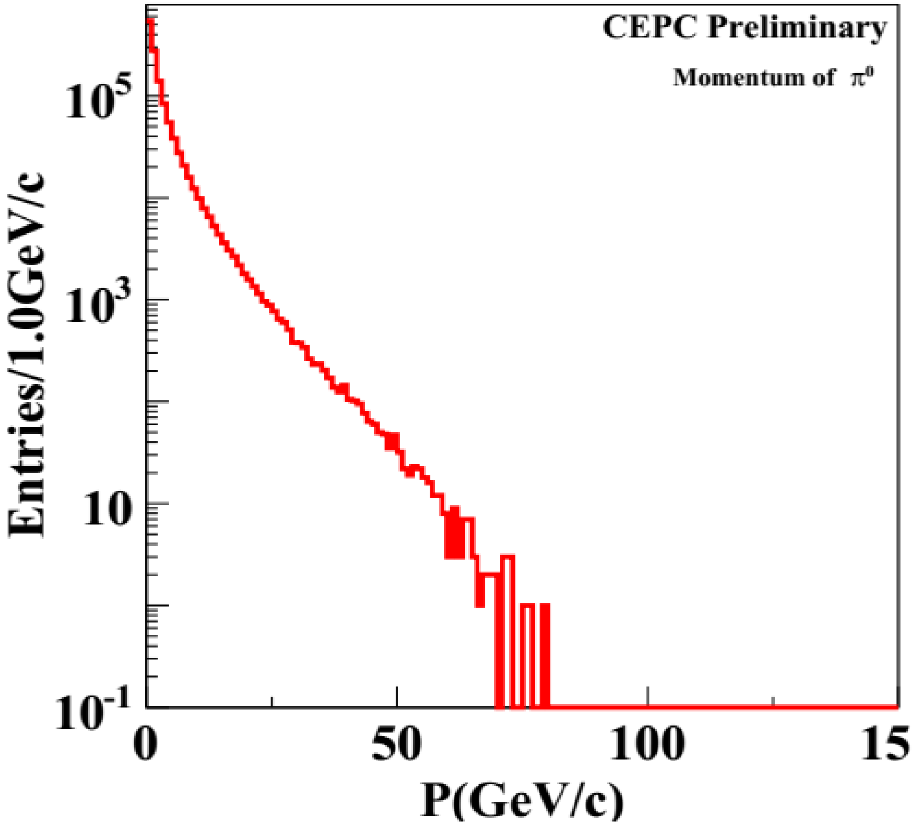
BGO crystal material properties:

Crystal radiation length:~1.12cm;

Moliere radius R_M: 2.23cm;

Generate the MC single γ and π^0 samples

- Generate the MC single particles samples in the following:
  - Gamma: 98GeV,100GeV,102GeV
  - π^0 : 30GeV, 40GeV
  - Momentum Direction：
    It goes from the origin to the center of the crystal.



The cluster reconstruction

- Cluster Reconstruction of each layer
  - According to the clusterisation procedure each local maximum originates the cluster. The local maximum cell with the energy deposition in excess of the energy deposition in each of its neighbouring cells.
  - To require the energy of local maximum to be in excess of 10MeV
  - The energy threshold of cell is 1MeV
- Cluster reconstruction after merging layers
- Reconstruction codes have been completed in root analysis(without any frame).

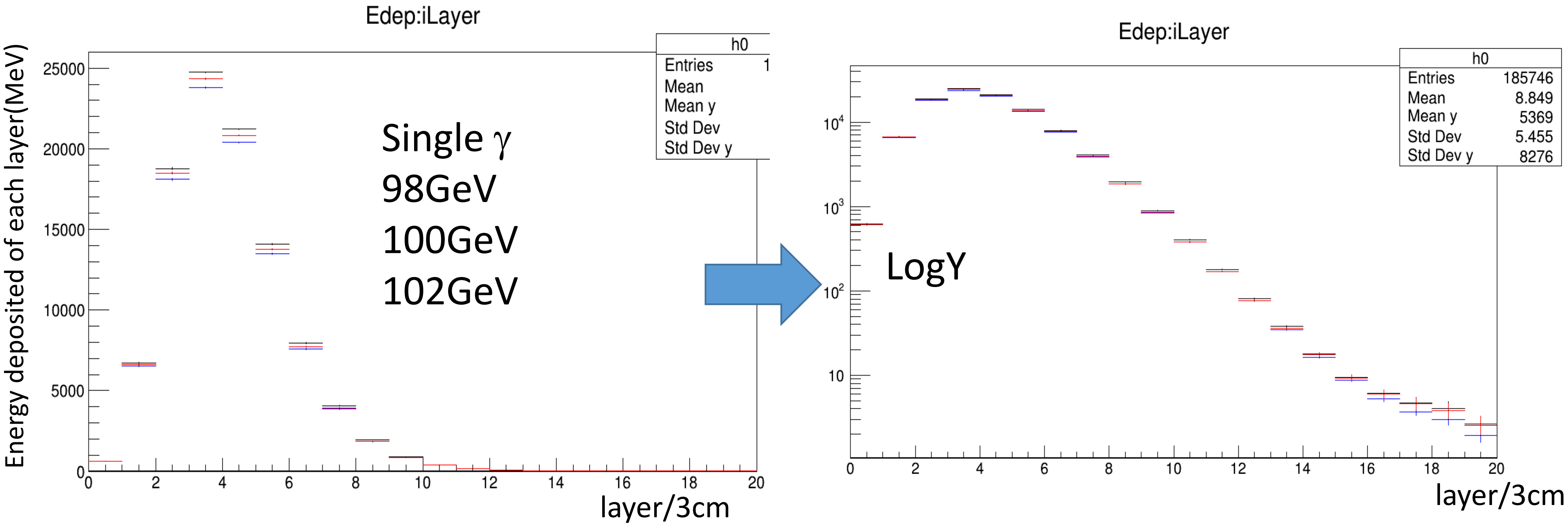
Study of the correction of the longitudinal shower energy leakage for high energy γ (e.g. 100GeV)

The correction of the Longitudinal shower energy leakage

- Generate 98GeV, 100GeV, 102GeV single γ
- The study based on the following ECAL detector.
  - ➢ Merge 3 layers into one layer, i.e., each layer/3cm depth
  - ➢ Consider the detector with the different length in the longitudinal direction
    - ✓ With 30cm (~26.8X_0) length BGO (a total of 10 layers)
    - ✓ With 27cm (~24.1X_0) length BGO (a total of 9 layers)
    - ✓ With 24cm (~21.4X_0) length BGO (a total of 8 layers)
- Study the correction of the Longitudinal shower energy leakage according to the longitudinal shower profile

the Longitudinal shower profile

Energy deposited (MeV) versus iLayer with each layer(3cm)



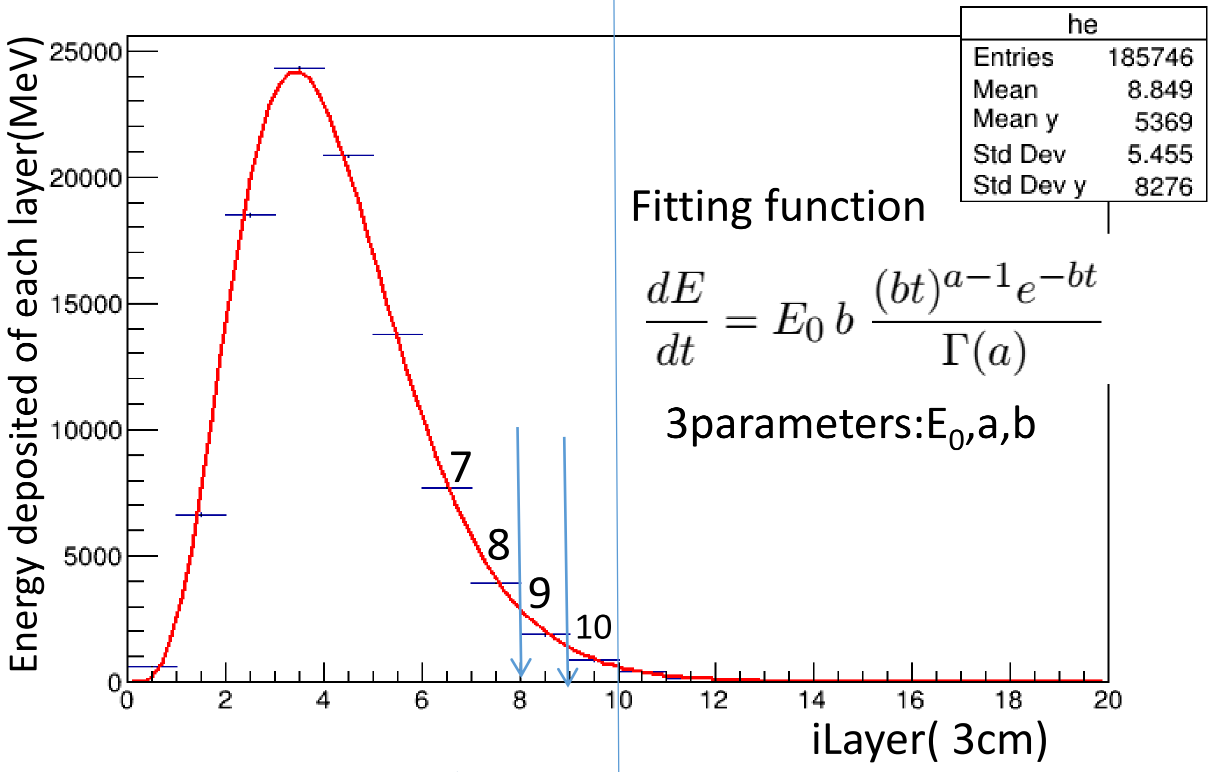
The shower maximum happens in around 10 to 12cm depth in longitudinal direction.

The method of the correction of longitudinal leakage

The fewer the data points, the greater the correction error.

The correction needs at least 7-8 data points ,

and the depth of layer should not be larger than 3cm .



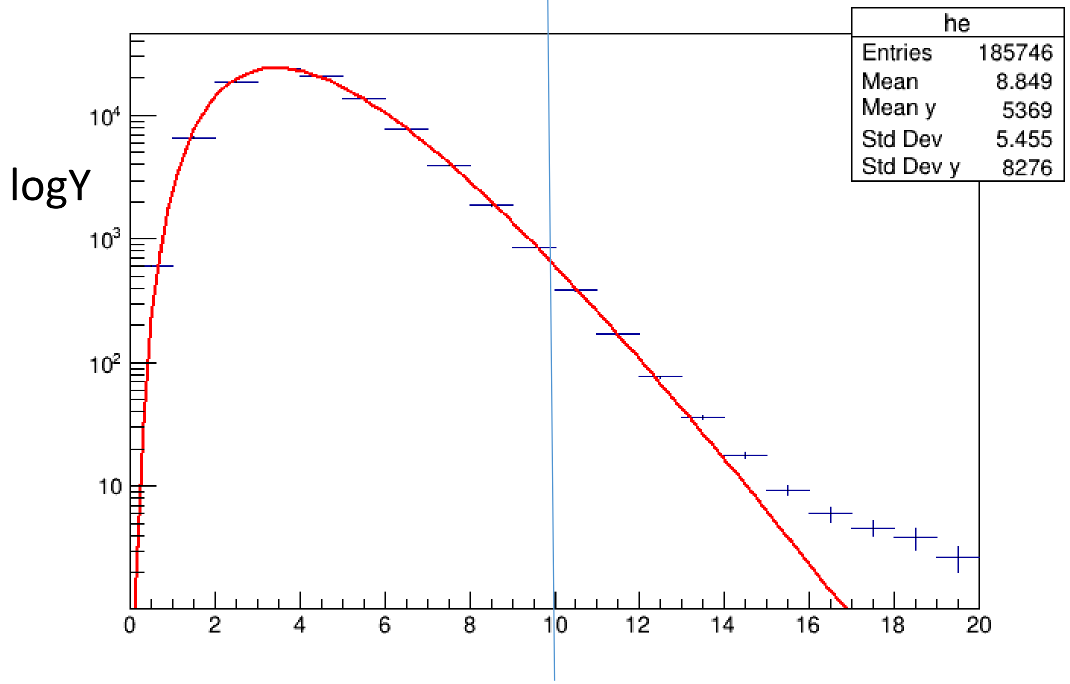
Fitting function

$$\frac{dE}{dt} = E_0 \, b \, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

3parameters:E_0,a,b

Esum30

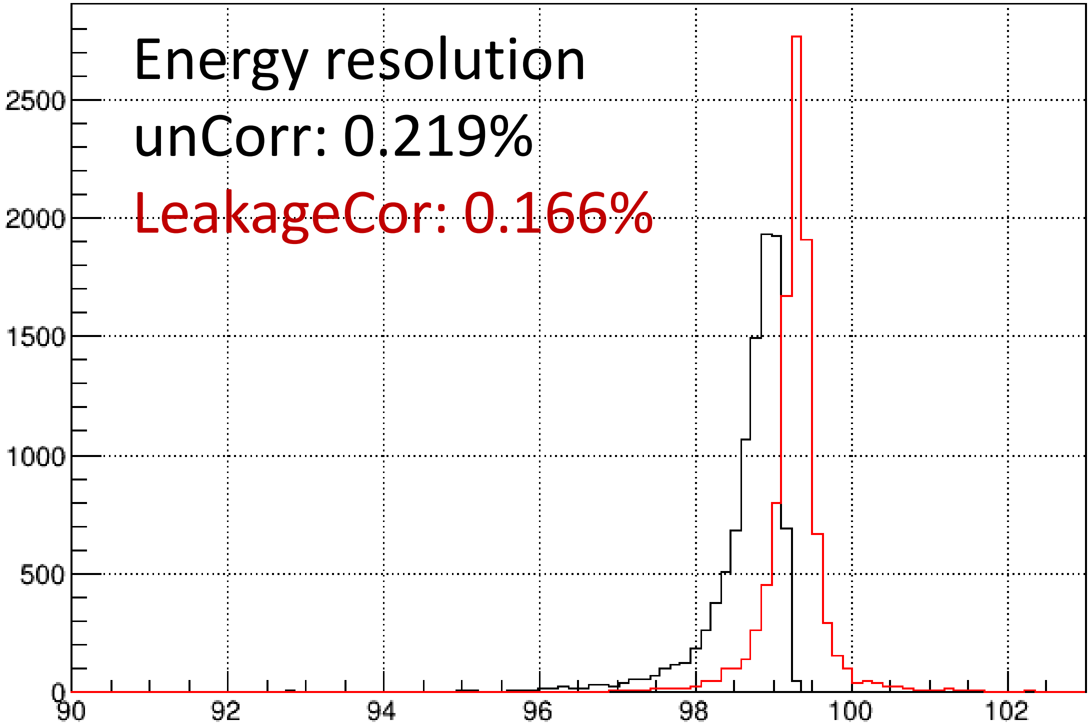
Ecorr=the integeration of fitting function in the region[10,17]



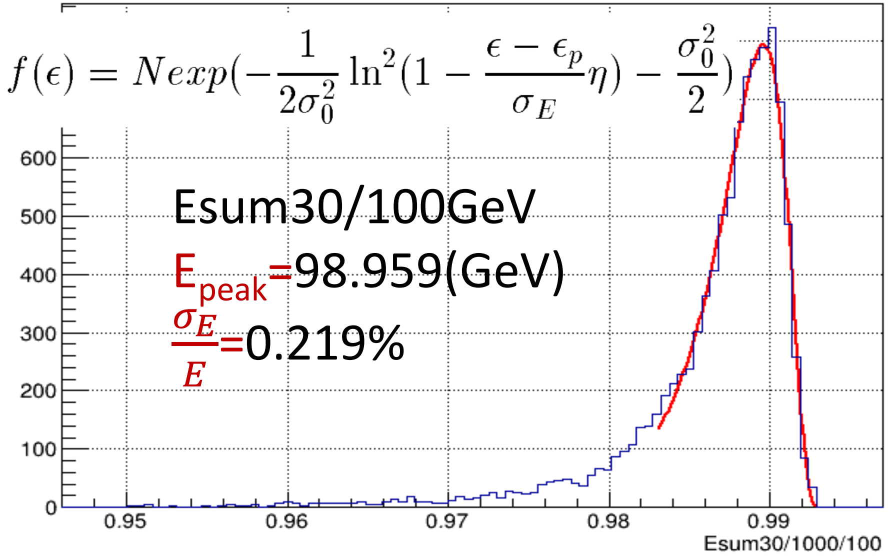
The fit function needs to be improved

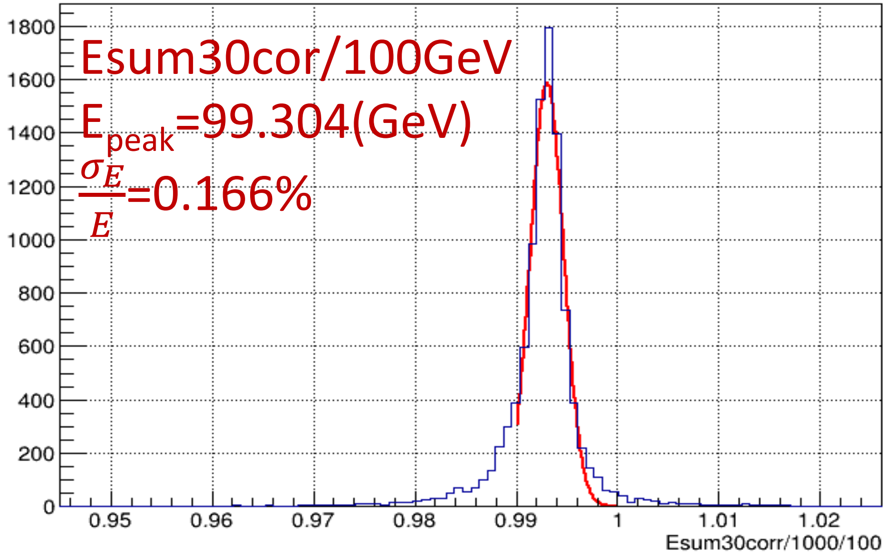
Energy measurement of 100GeVγ with 30cm depth crystal

30cm(~26.8X_0) length BGO
10 layers/3cm
Cell size 1x1cm^2



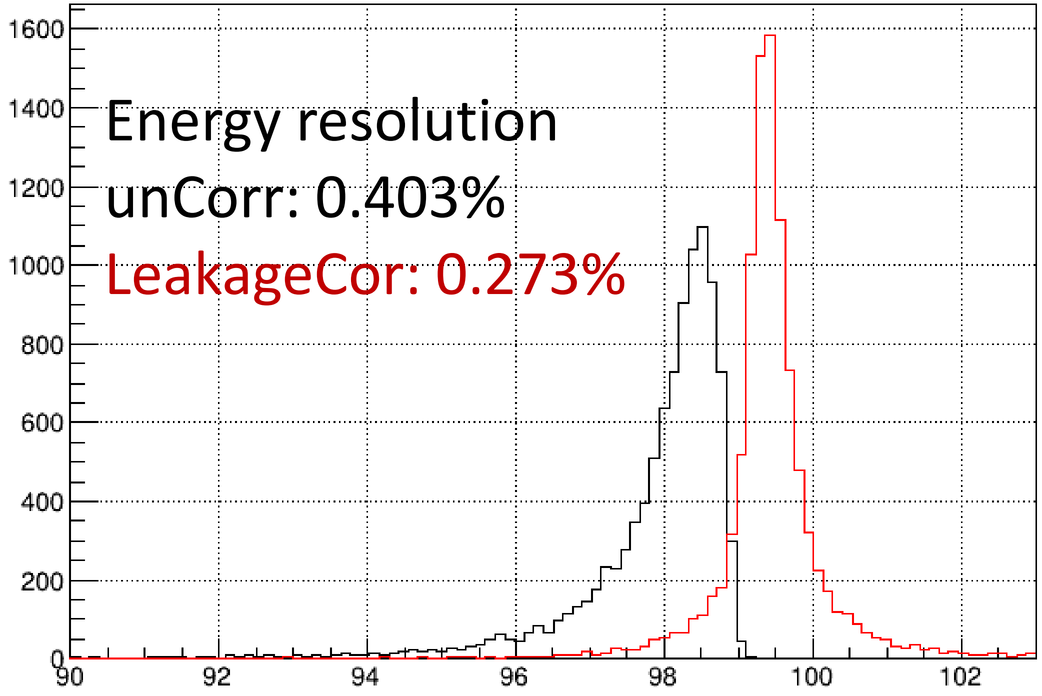
The energy resolution is optimized around 24%



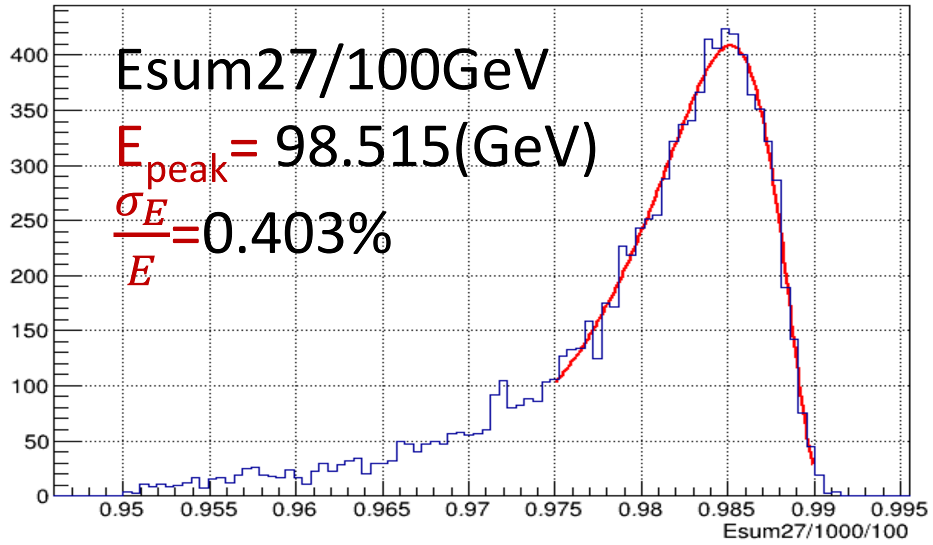


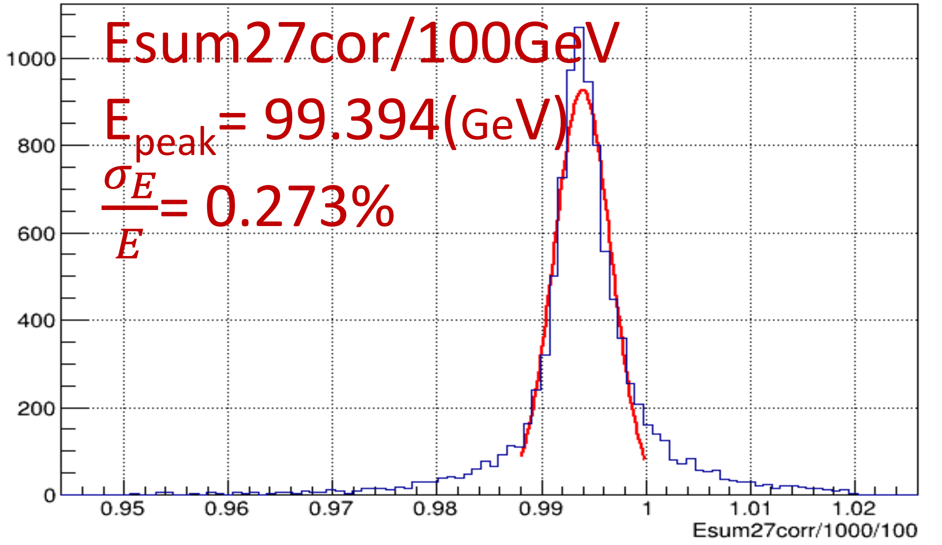
Energy measurement of 100GeVγ with 27cm depth crystal

27cm(~24.1X_0) length BGO
9 layers/3cm
Cell size 1x1cm^2



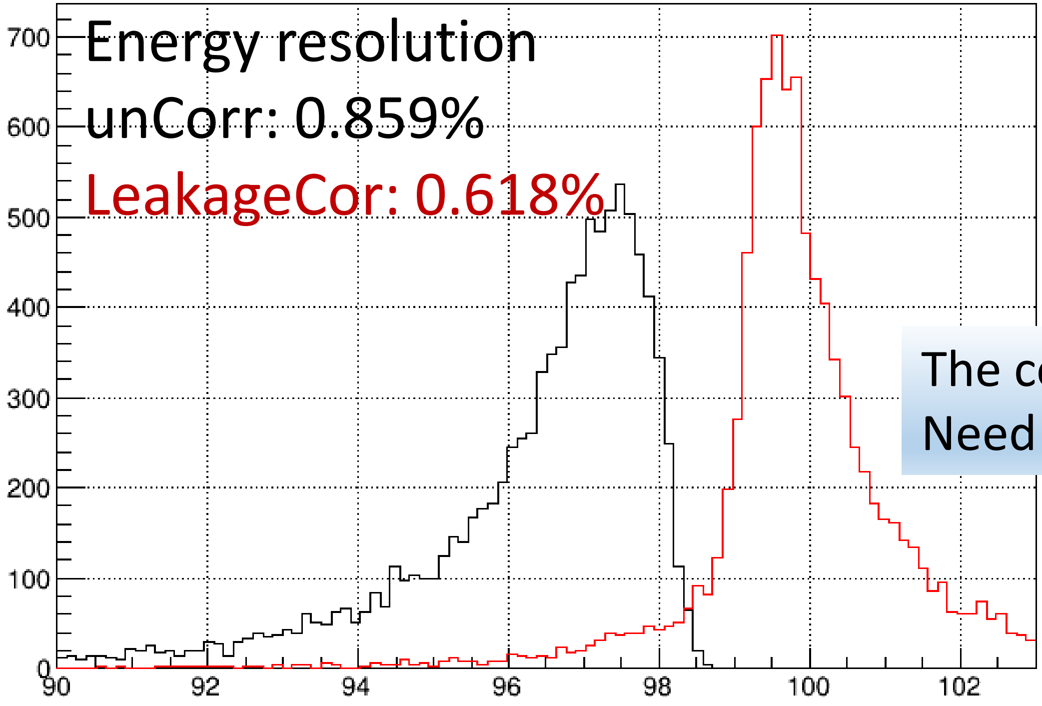
The energy resolution is optimized around 32%



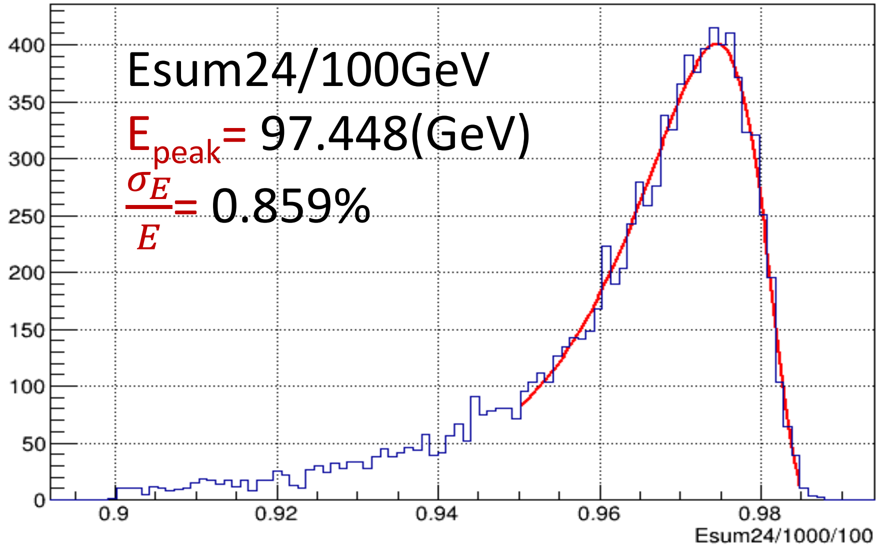


Energy measurement of 100GeV γ with 24cm depth crystal

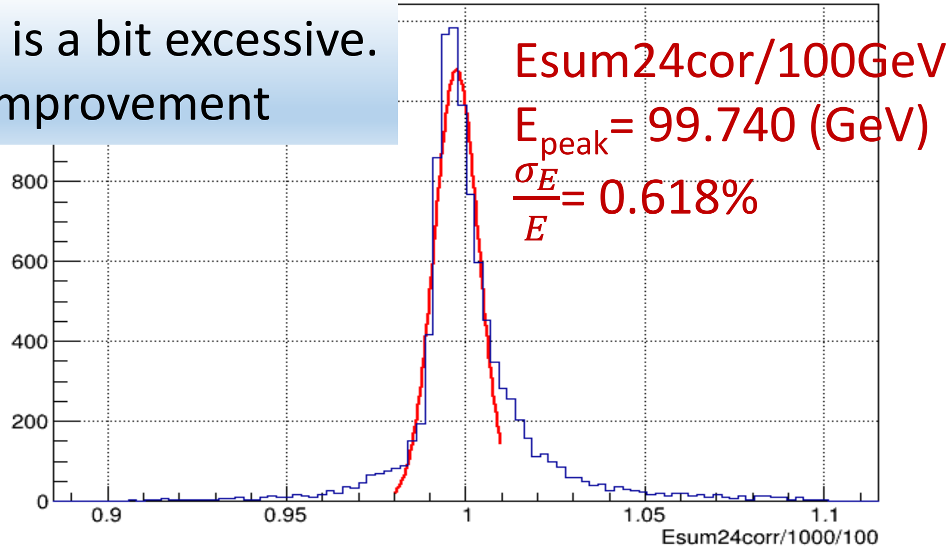
24cm(~21.4X_0) length BGO
8 layers/3cm
Cell size 1x1cm^2



The energy resolution is optimized around 30%

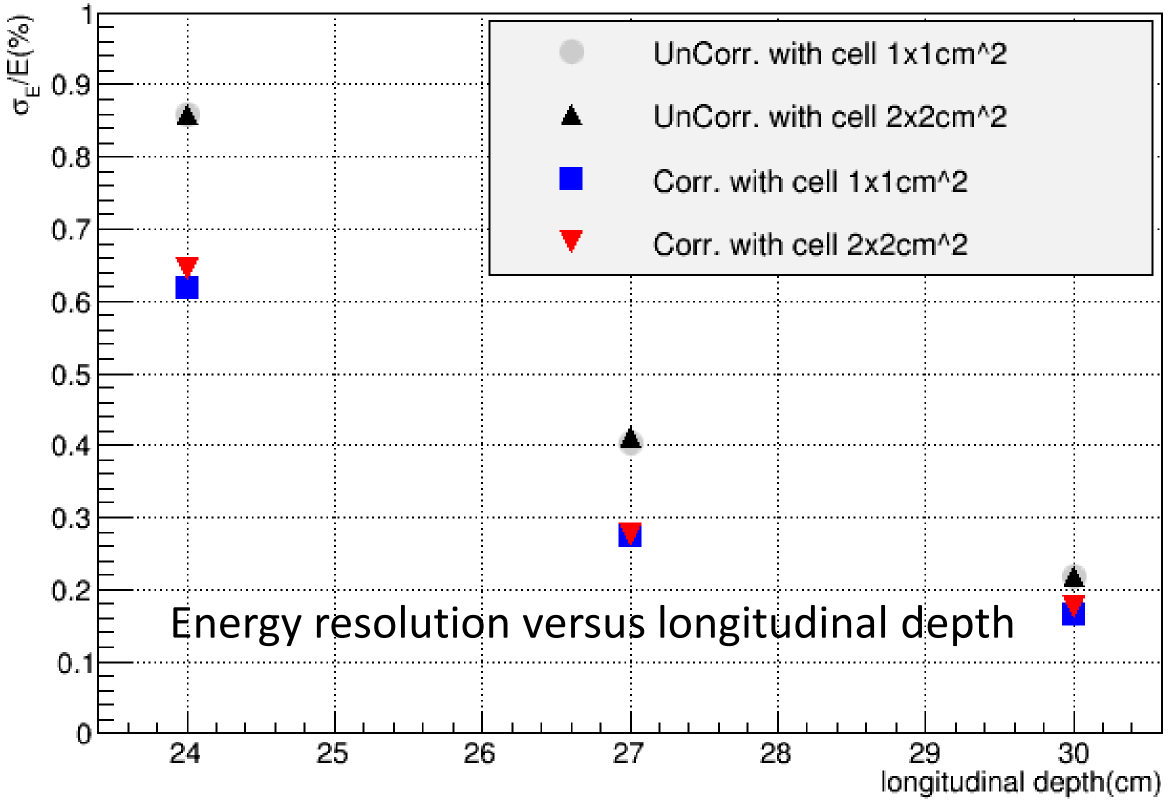


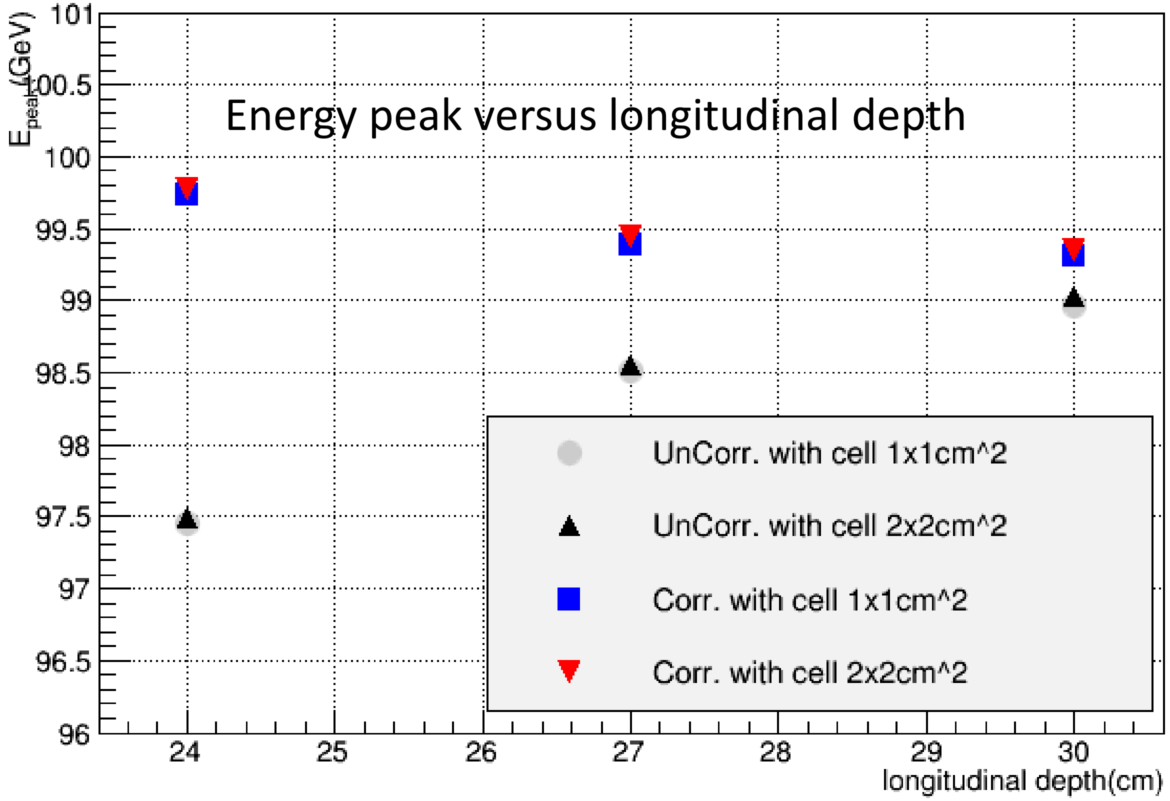
The correction is a bit excessive.
Need further improvement



The correction of the Longitudinal shower energy leakage

Preliminary results



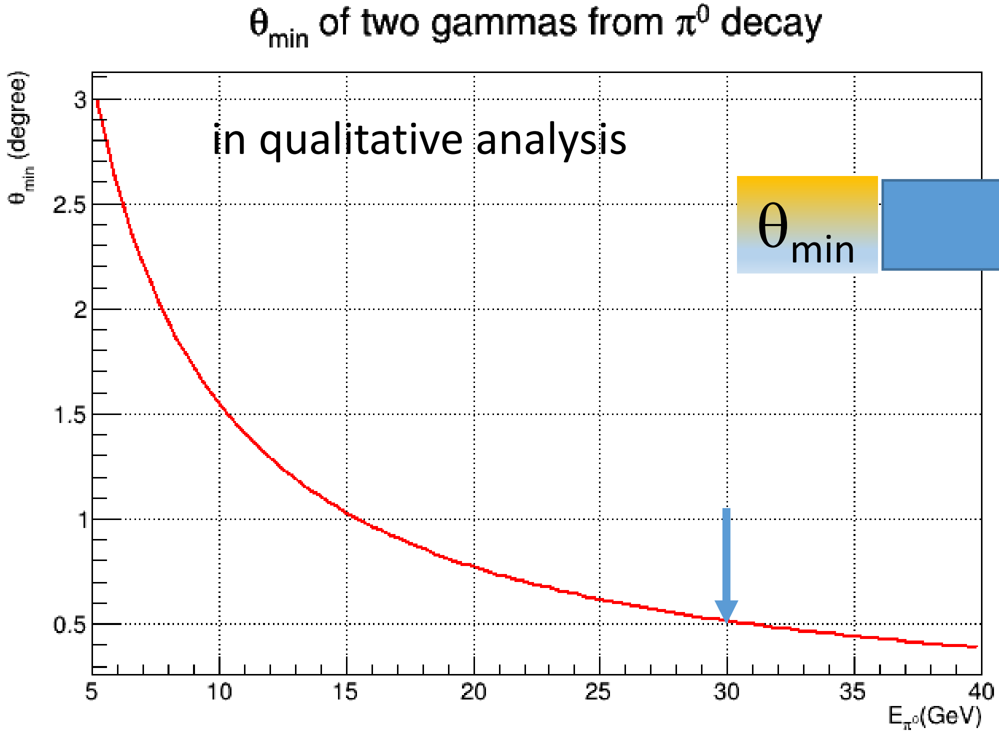


The energy peak has been corrected to 99.5%.
The energy resolution is also optimized around 20% to 30%

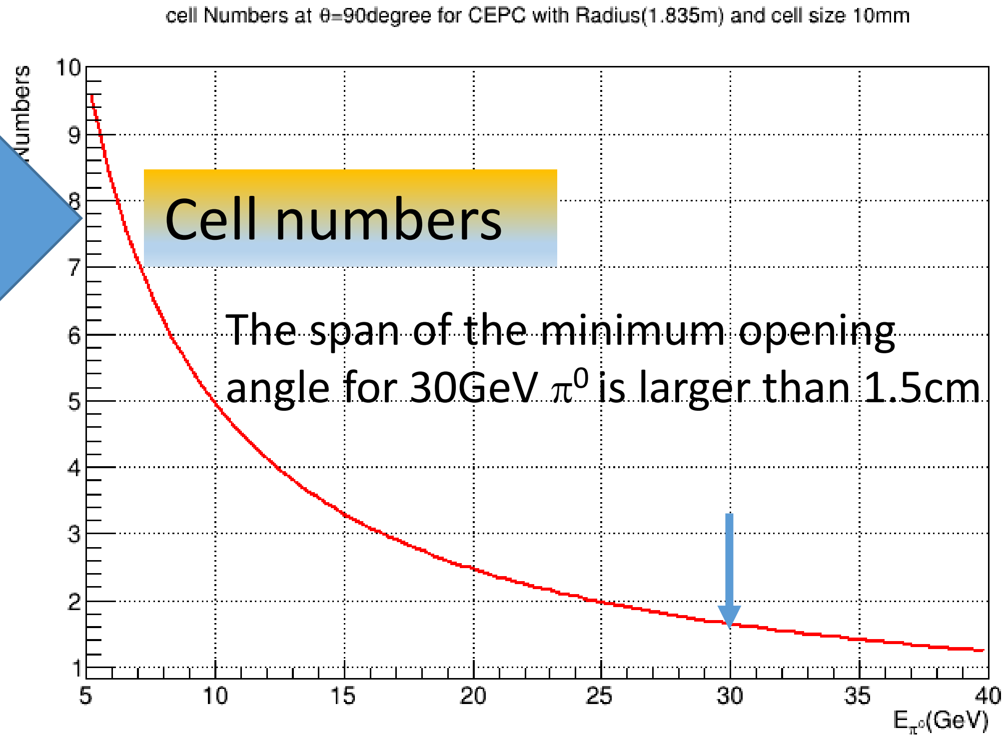
Study of the separation performance of γ and merged π^0

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

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



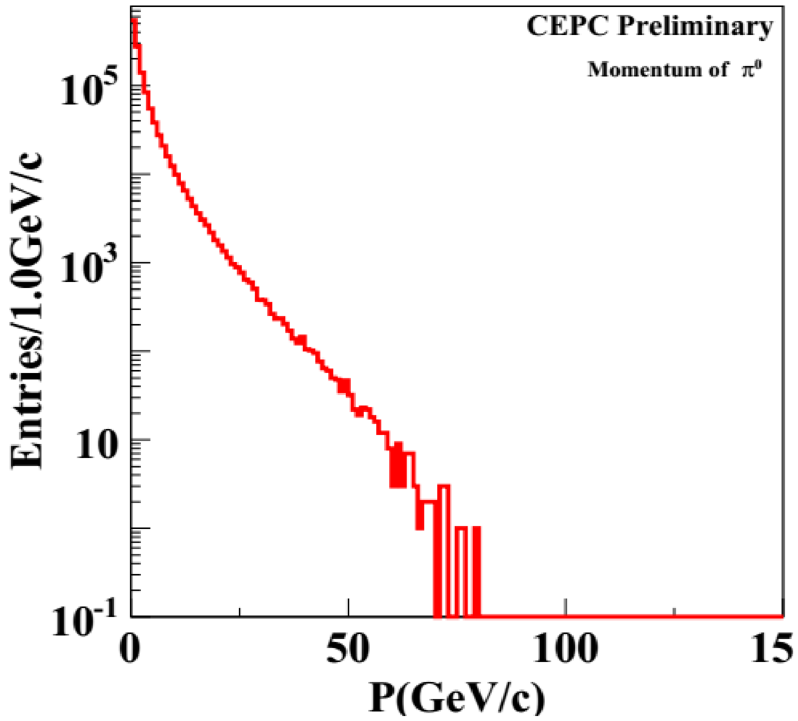
θ_{min} versus π^0 momentum



Cell numbers versus π^0 momentum

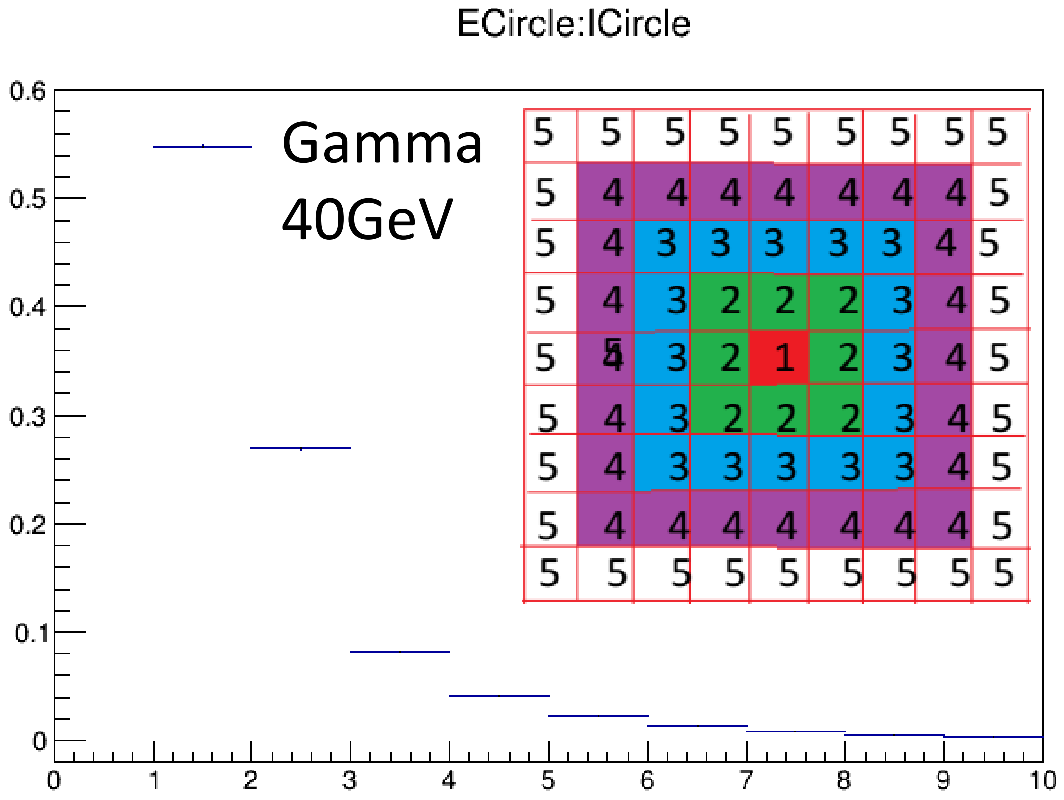
Separation Performance of 2γ's from high energy π^0 decay

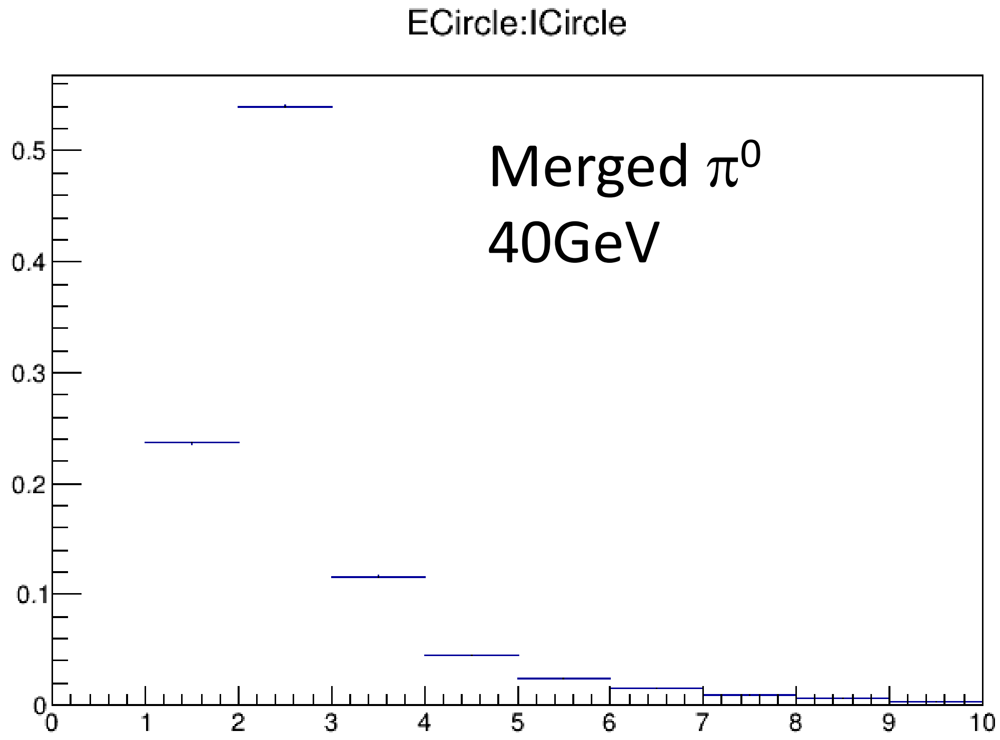
- For the purpose the decay events with the small opening angle are selected.
- There are two types of π^0 event in ECAL reconstruction
  - One type is the "resolved" π^0 from pair of photons.
  - Another type is the "merged" π^0 from single cluster.
  - Their proportions are shown in the right table.
- So in the following the study of the separation performance of γ and merged π^0 will use 40GeV π^0 samples.



	π^0 Momentum	Cell 1x1cm²	Cell2x2cm²
Resolved π^0	30GeV	~100%	0%
	40GeV	~60%	0%
Merged π^0	30GeV	0%	100%
	40GeV	~40%	100%

Lateral shower energy distribution for Cell 1x1x30cm^3





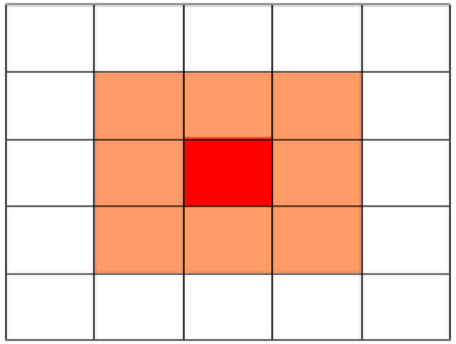
Energy of each circle versus circle number

For single γ, the lateral shower energy is symmetric at the shower center.
For merged π^0 , the lateral shower is asymmetric.

The shower shape variables

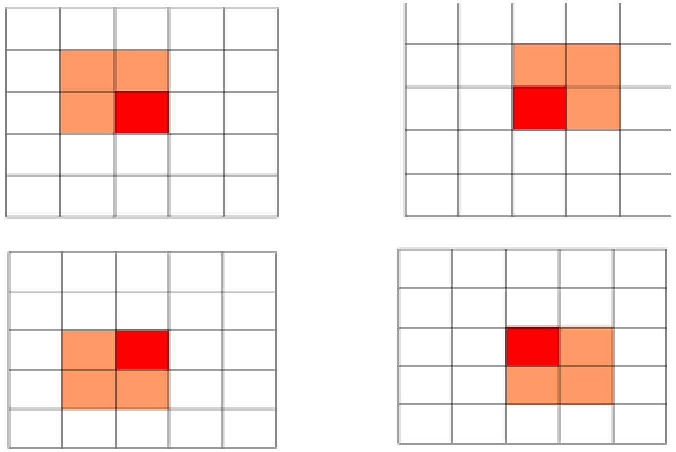
Study the separation performance of γ and merged π^0 by using the shower lateral shape variables

- S1/S4, S1/S9, S1/S25, S9/S25, S4/S9, F9, F16

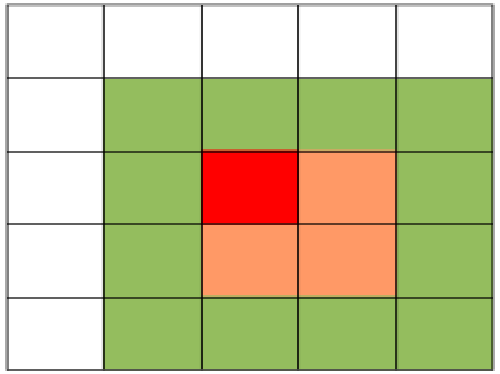


S1,S9,S25

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



S4 the energy maximum in the four 2x2 arrays



S16

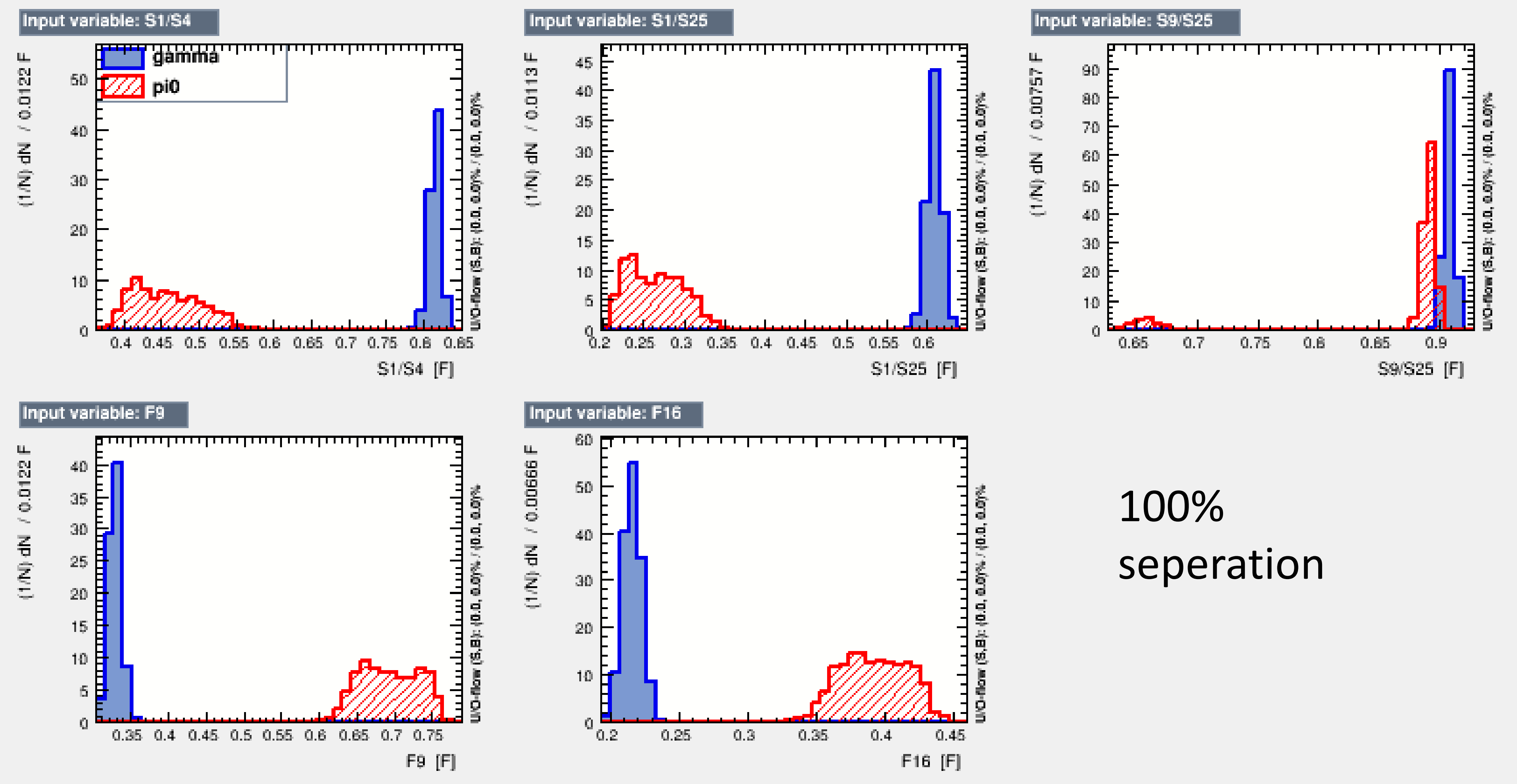
$$F_{16} = \frac{S16 - S4}{S16}$$

Study the 40GeV γ/merged π^0 separation in three ways in the following

- Using the whole reconstruction of 30cm Depth (merge 10Layers)
- Using the whole reconstruction of 24cm Depth (merge 8Layers)
- Using alone the energy information of each layer with 3cm Depth
- In the each way we consider two types of cell size.
    - Cell size 1x1 cm^2
    - Cell size 2x2 cm^2

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

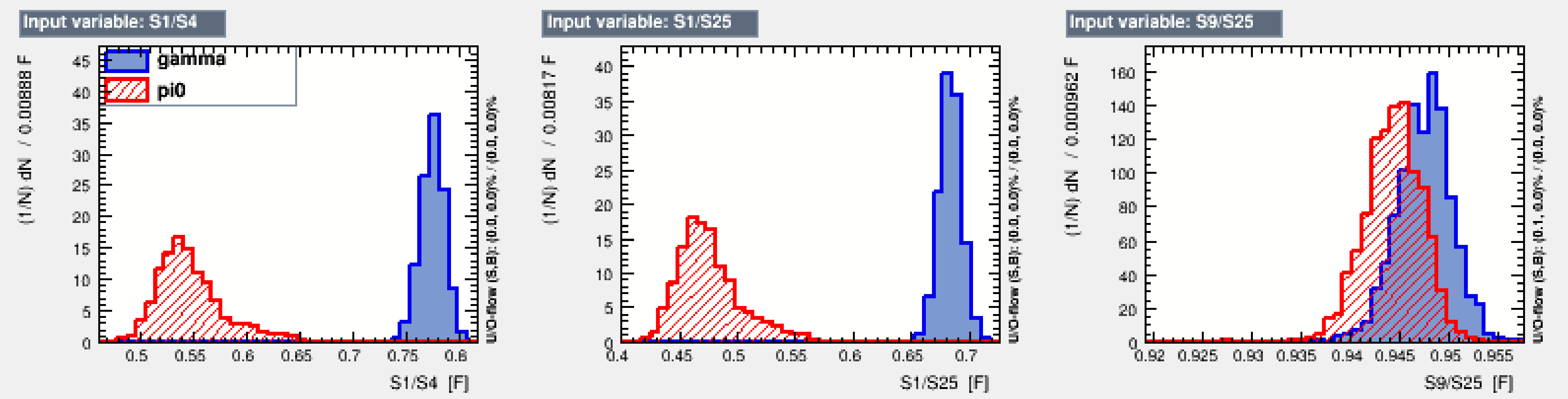
- the whole reconstruction of 30cm Depth with Cell 1x1cm^2

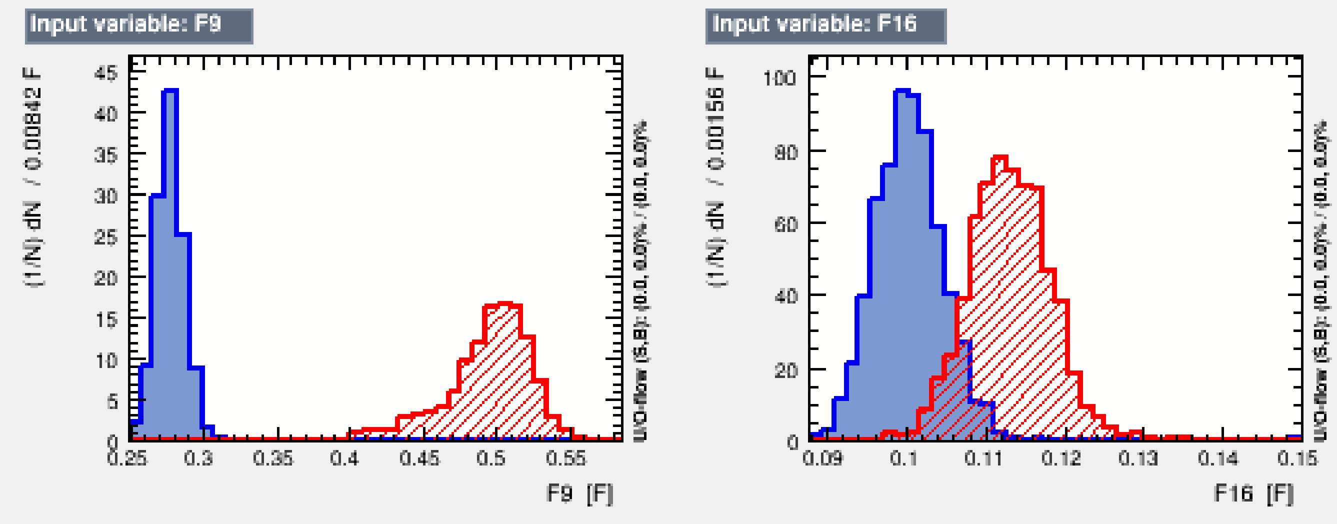


100%
seperation

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

- the whole reconstruction of 30cm Depth with Cell 2x2cm^2

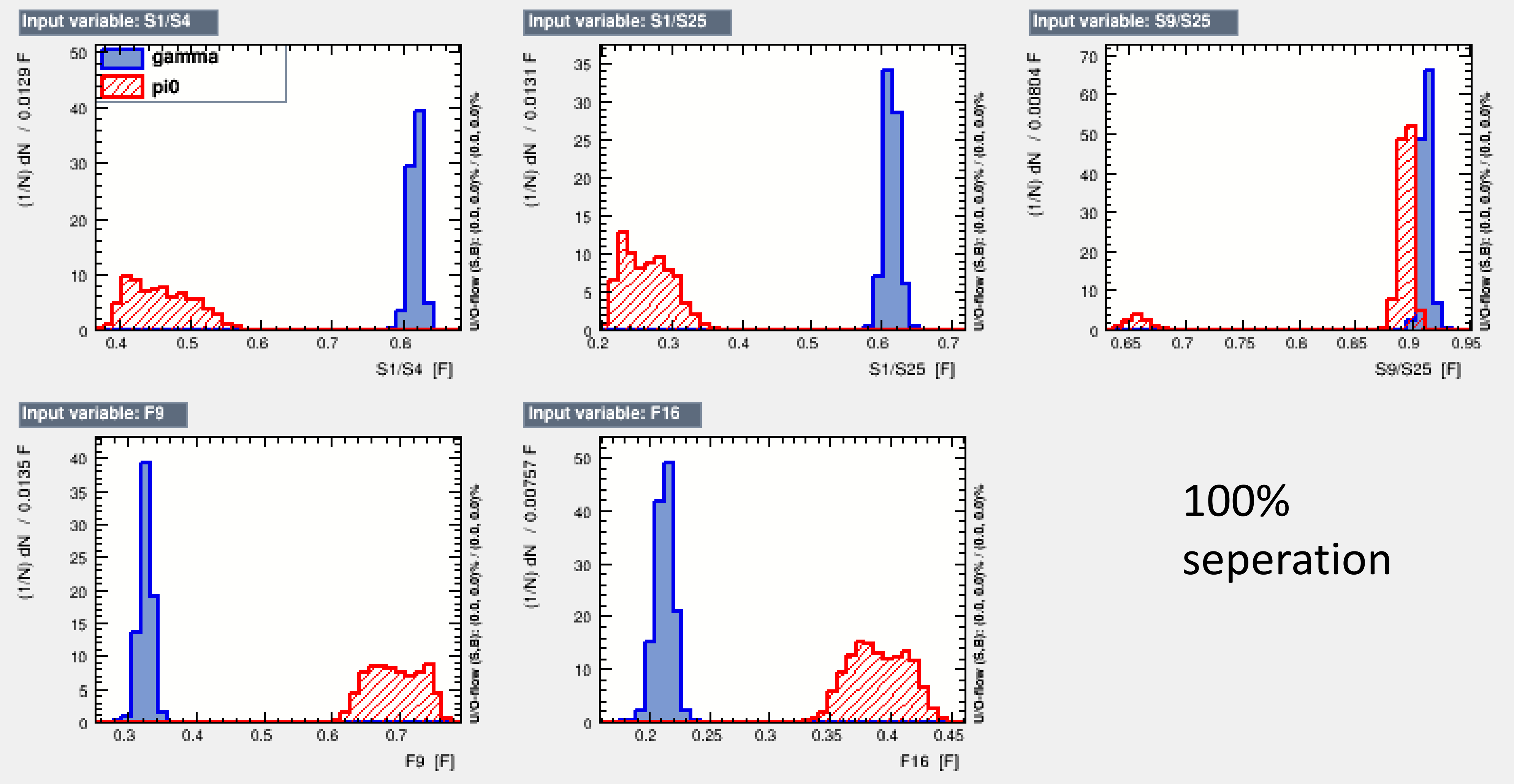




100%
seperation

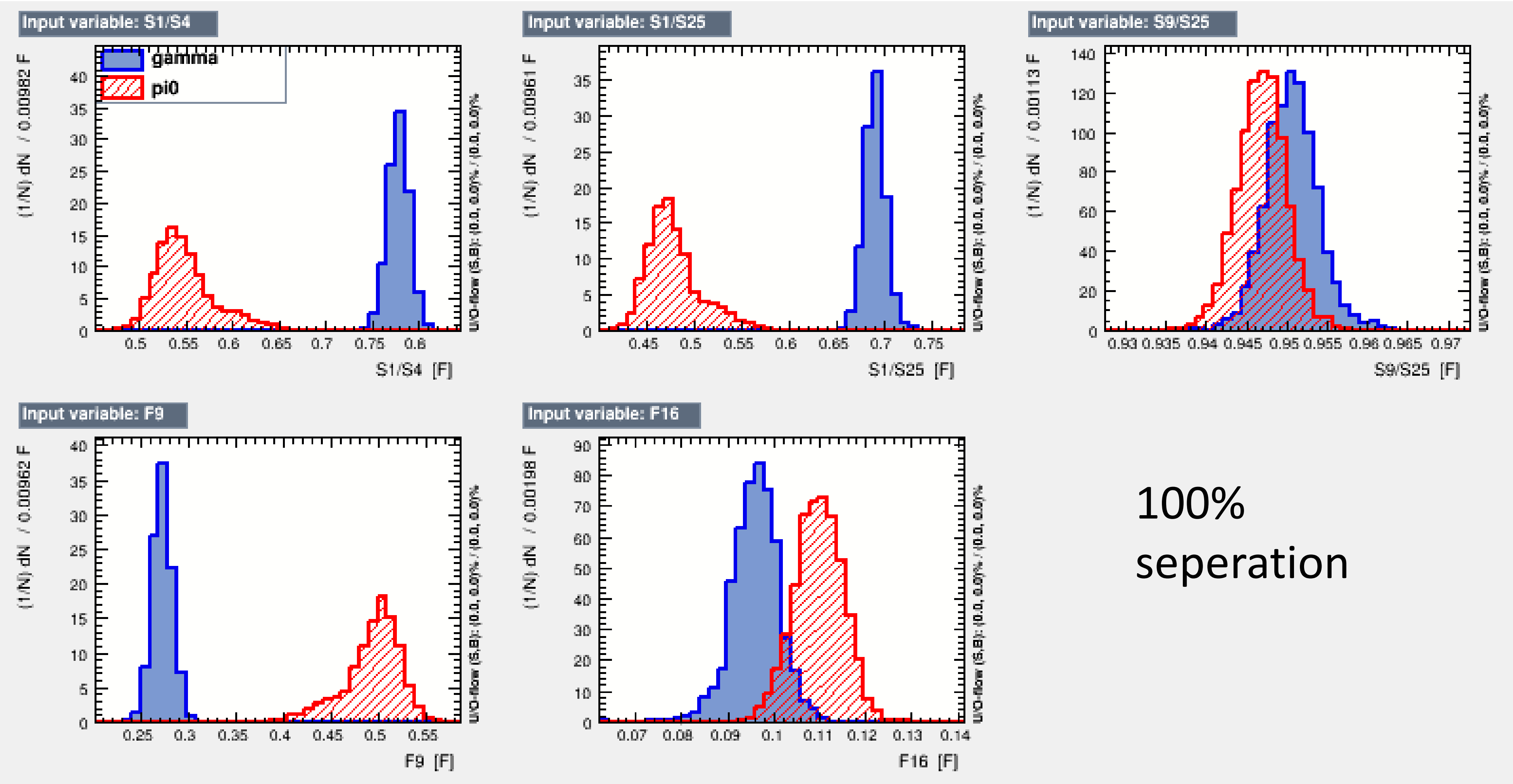
separation performance of the 40GeV γ and merged π^0

- the whole reconstruction of 24cm Depth with Cell 1x1cm^2



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

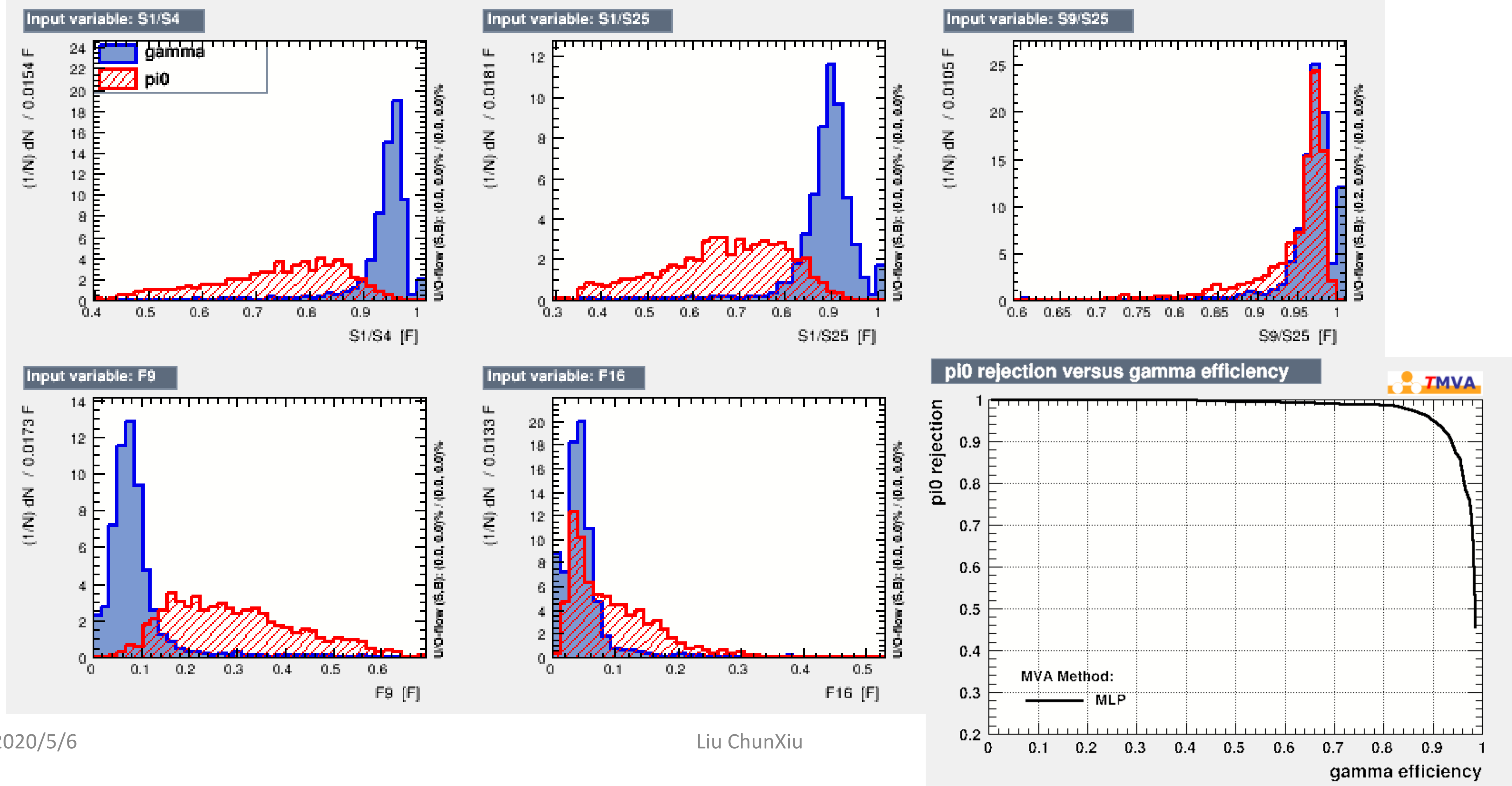
- the whole reconstruction of 24cm Depth with Cell 2x2cm^2



100%
seperation

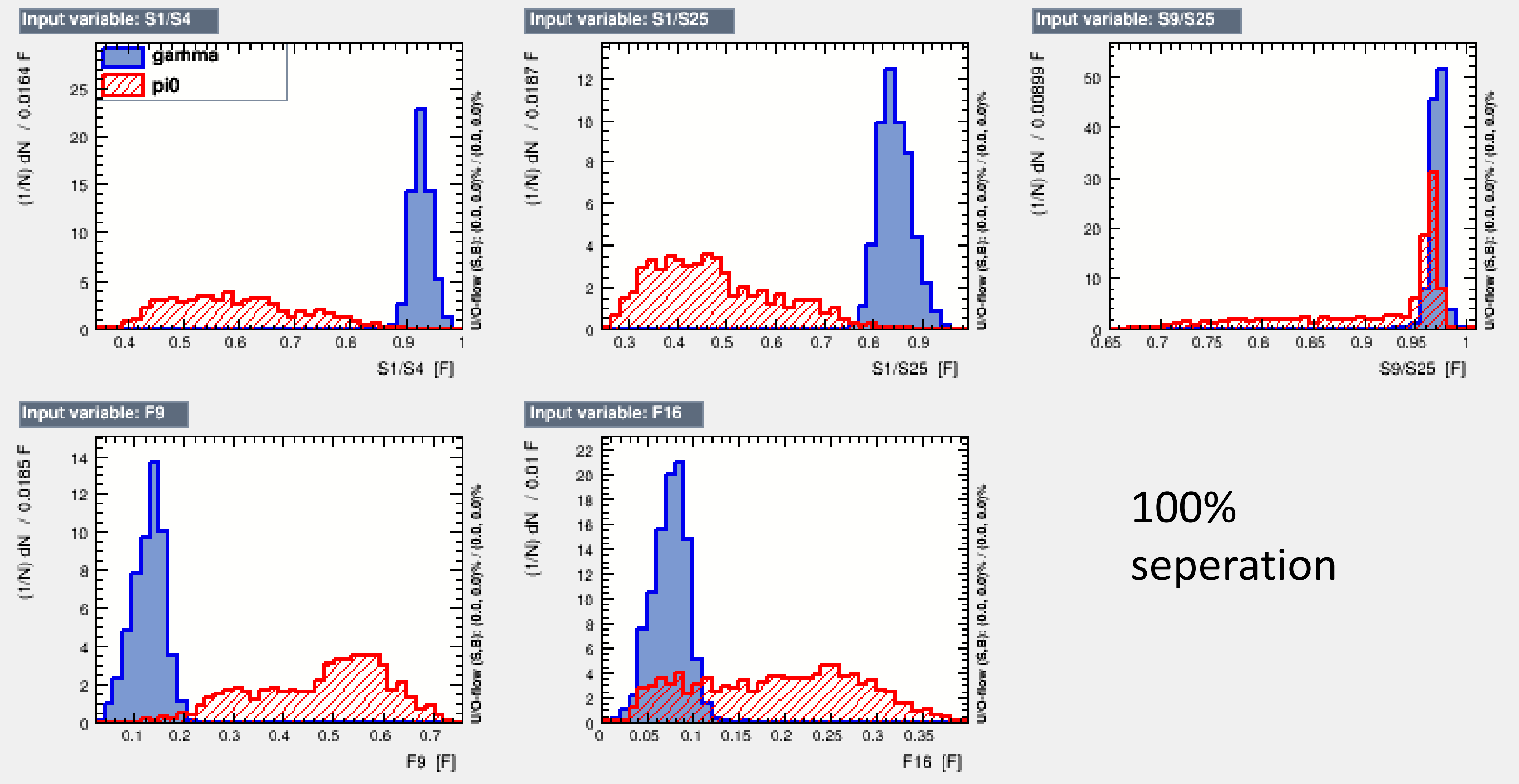
separation performance of the 40GeV γ and merged π^0

- alone the energy information of each layer with 3cm Depth with Cell 1x1cm^2 :1st layer



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

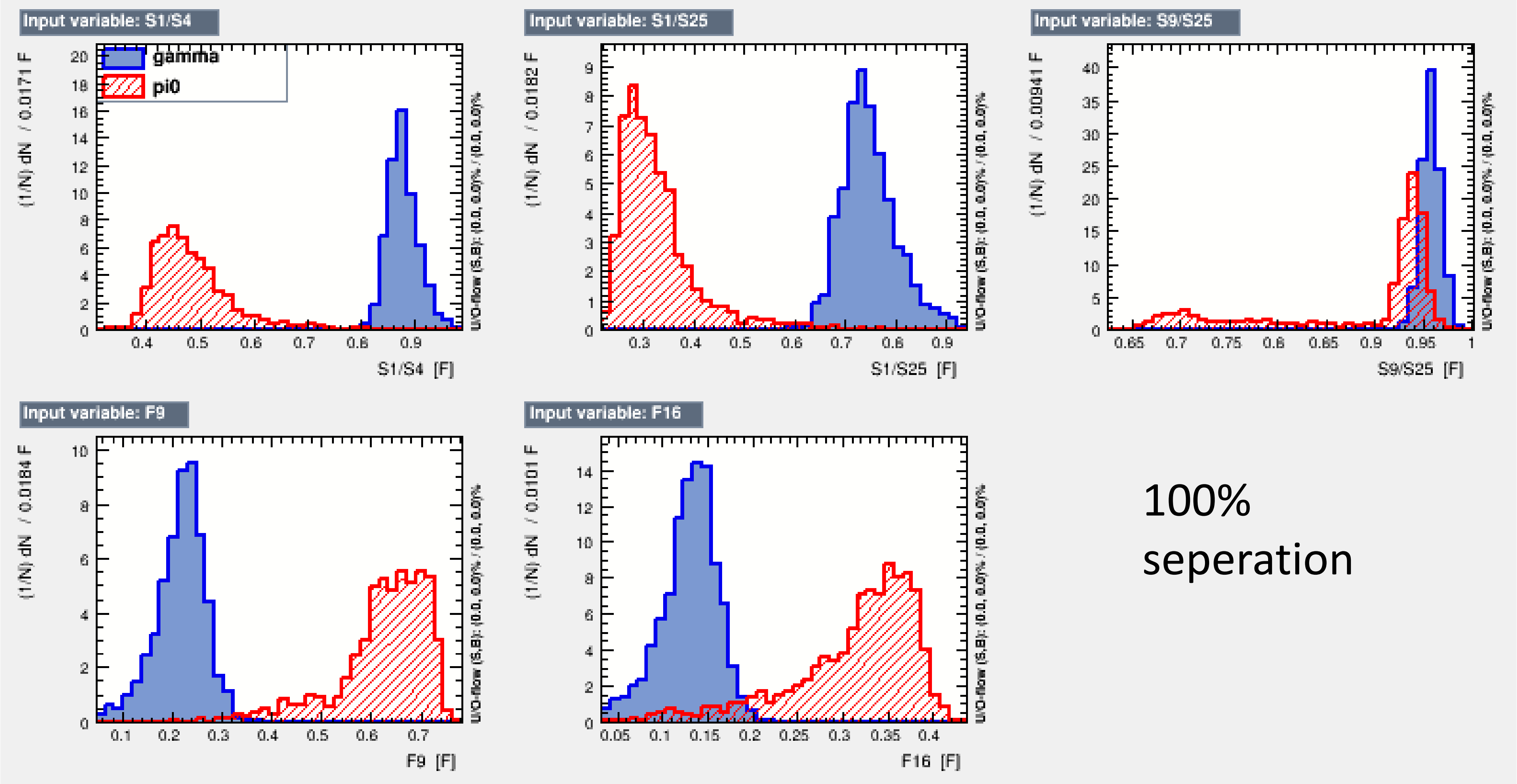
- alone the energy information of each layer with 3cm Depth with Cell 1x1cm^2 :2nd layer



100% seperation

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

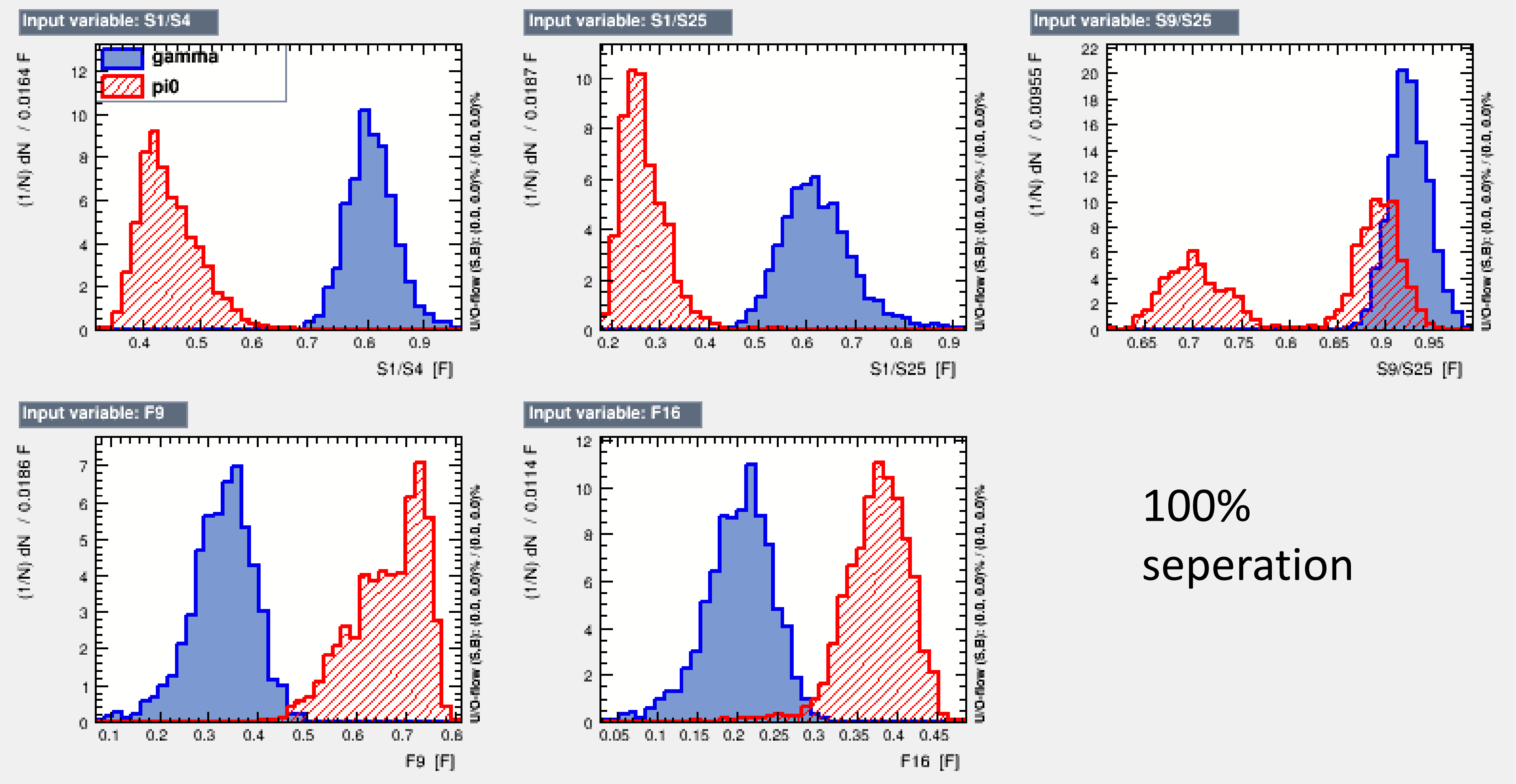
- alone the energy information of each layer with 3cm Depth with Cell 1x1cm^2 :3rd layer



100%
seperation

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

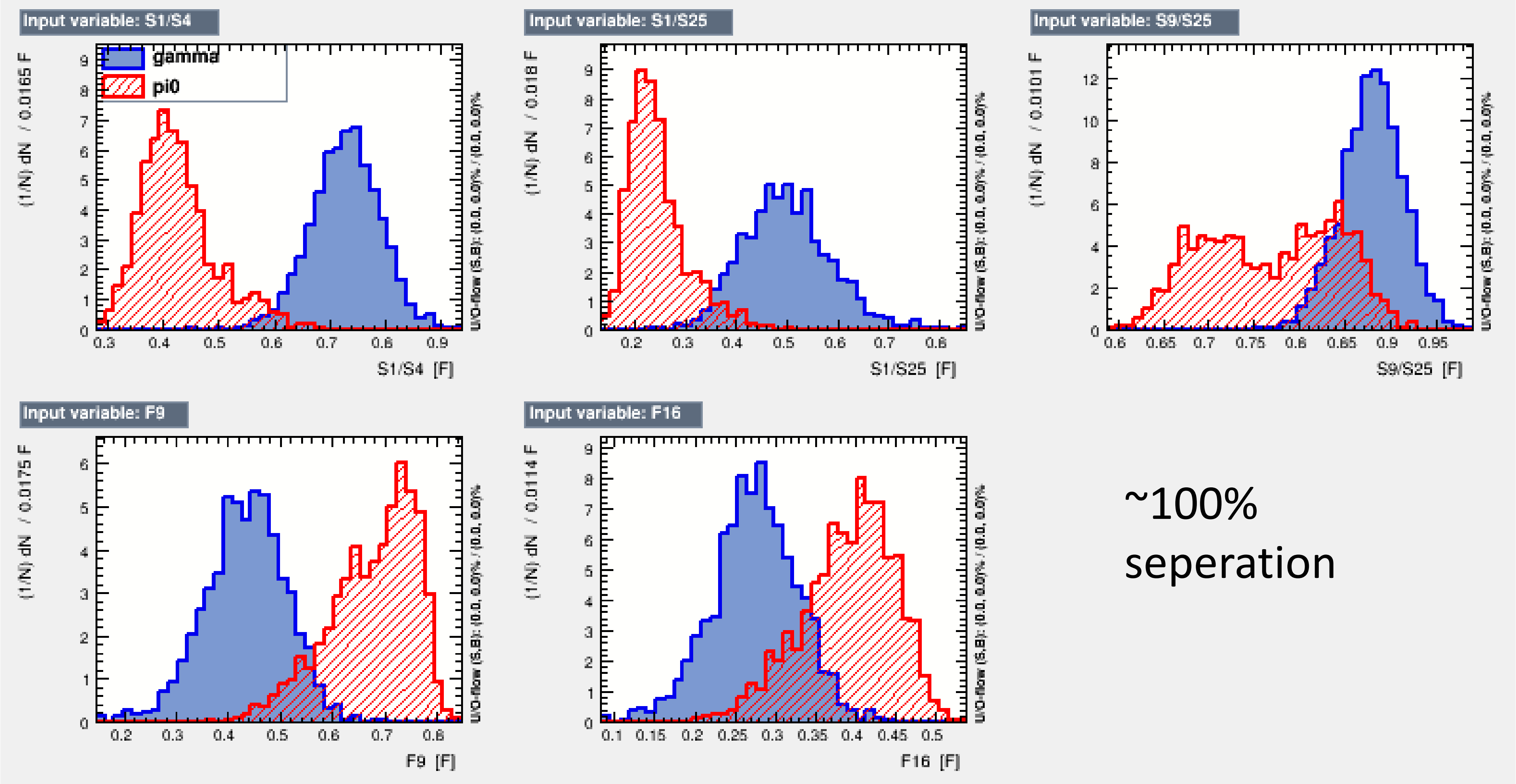
- alone the energy information of each layer with 3cm Depth with Cell 1x1cm^2 :4th layer



100%
seperation

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

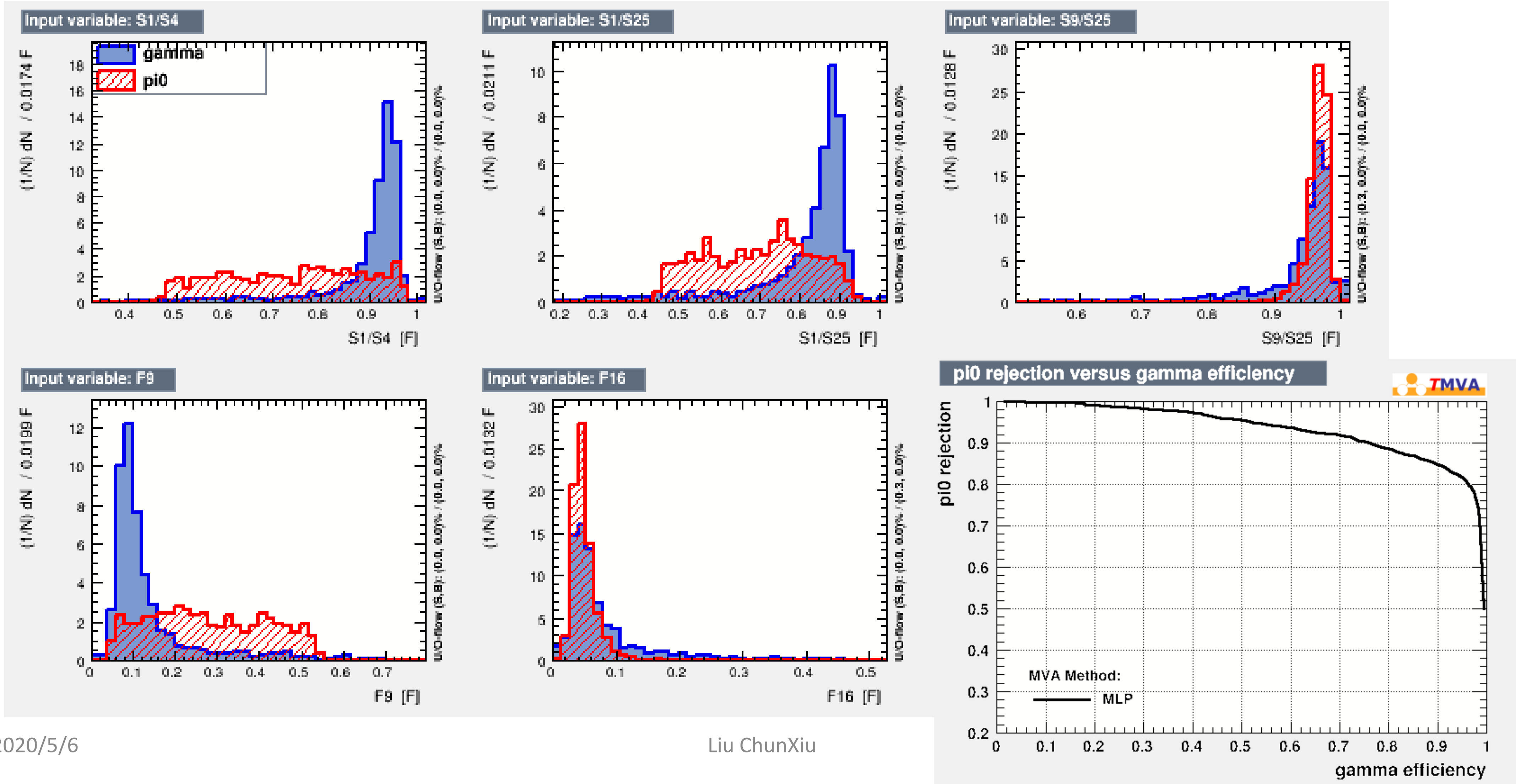
- alone the energy information of each layer with 3cm Depth with Cell 1x1cm^2 :5th layer



~100% seperation

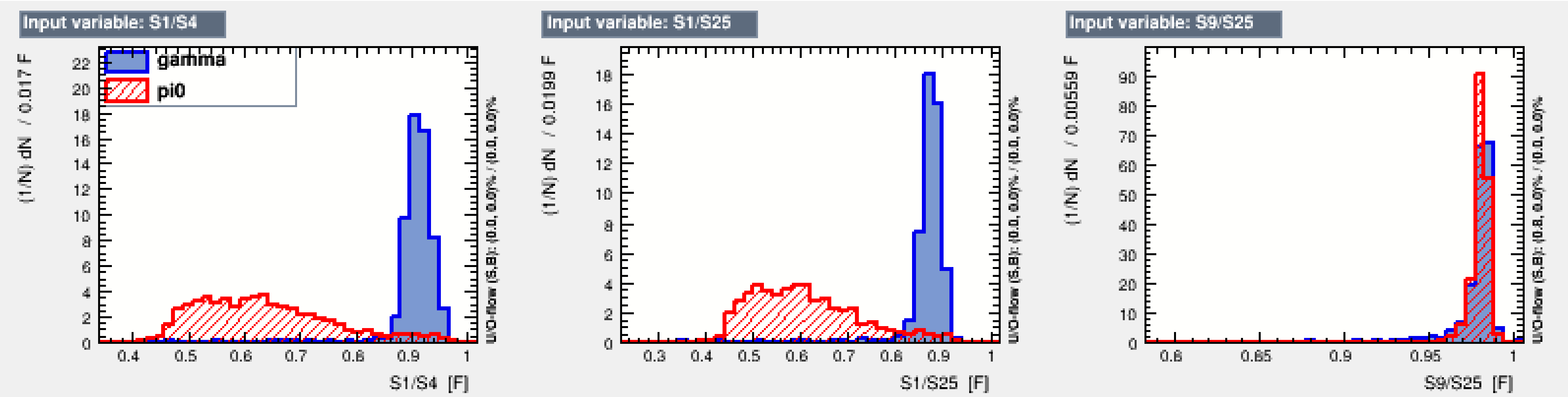
separation performance of the 40GeV γ and merged π^0

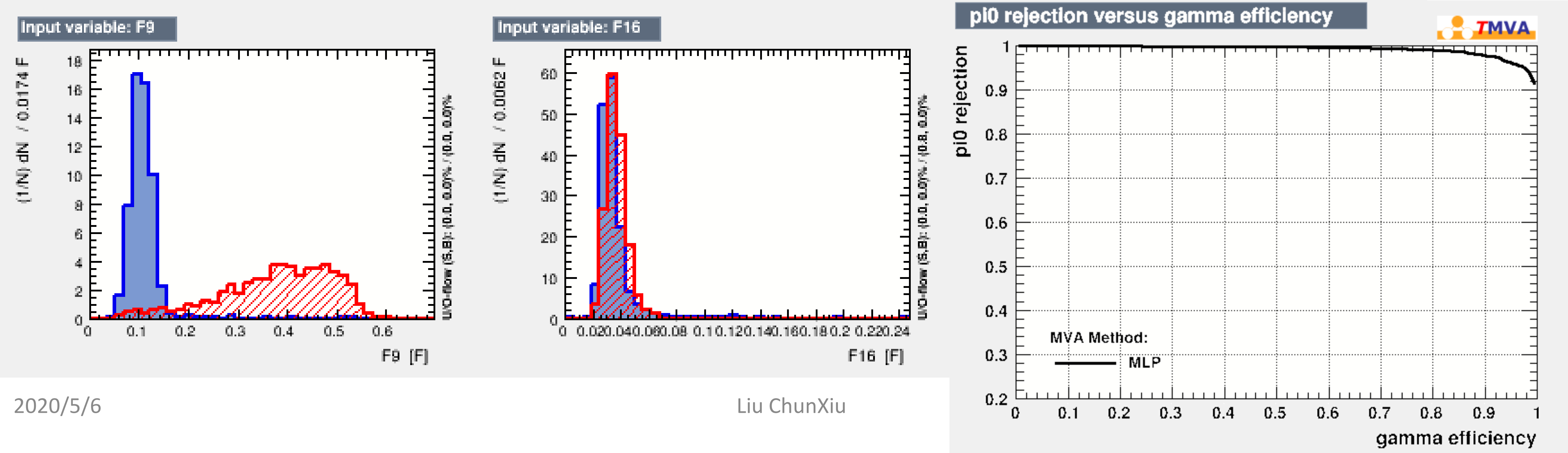
- alone the energy information of each layer with 3cm Depth with Cell 2x2cm^2 :1st layer



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

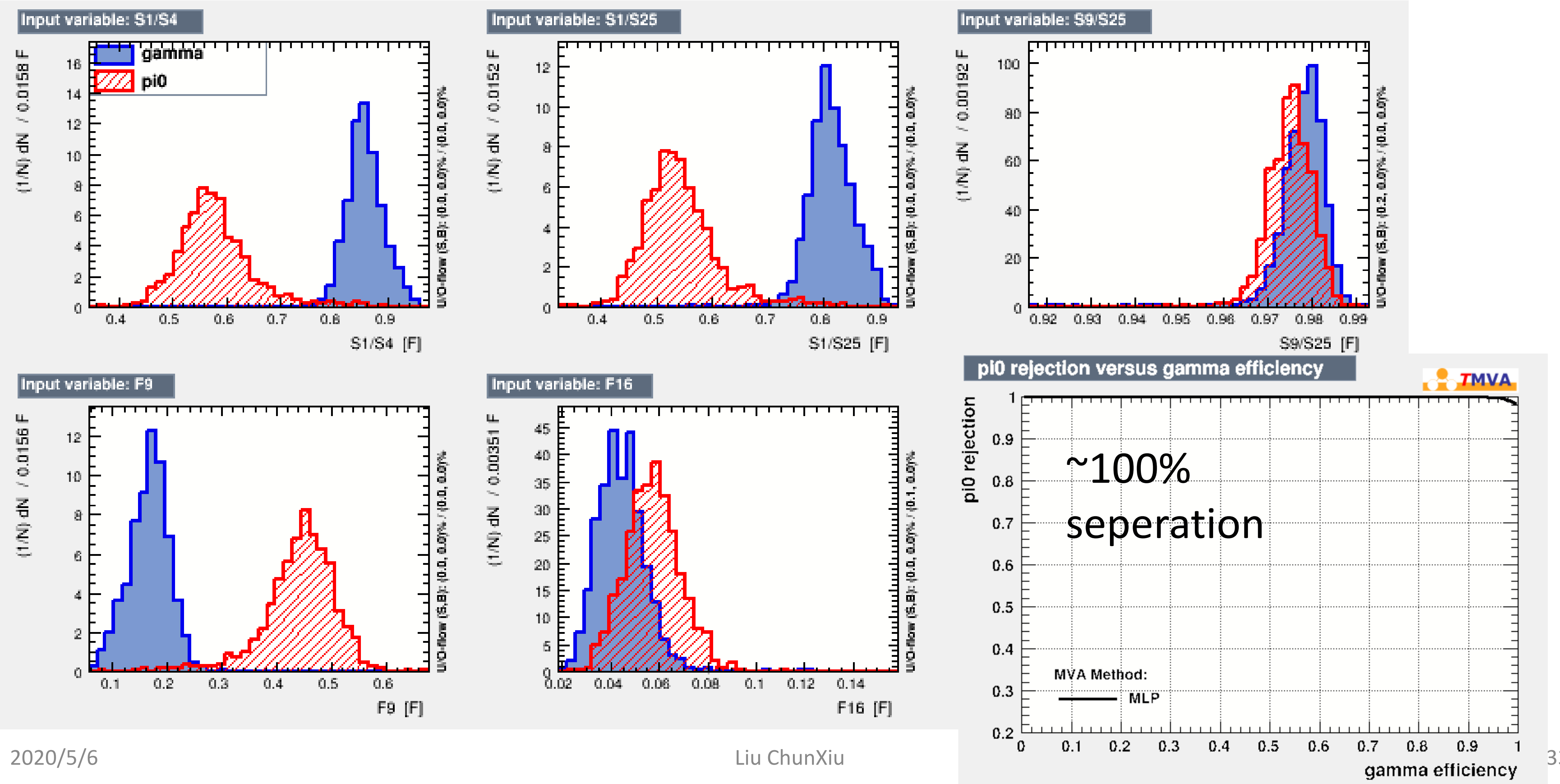
- alone the energy information of each layer with 3cm Depth with Cell 2x2cm^2 :2nd layer





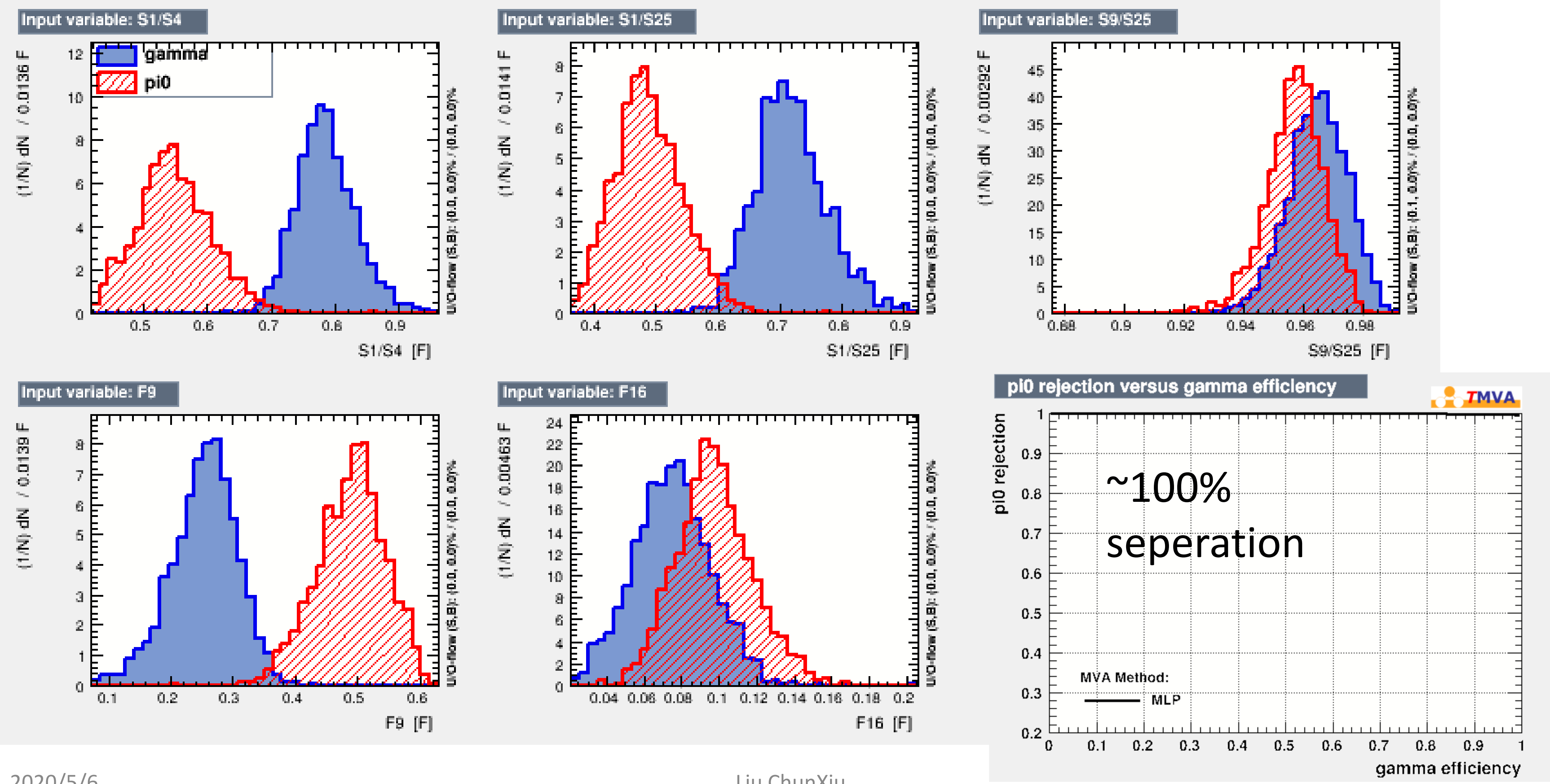
separation performance of the 40GeV γ and merged π^0

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



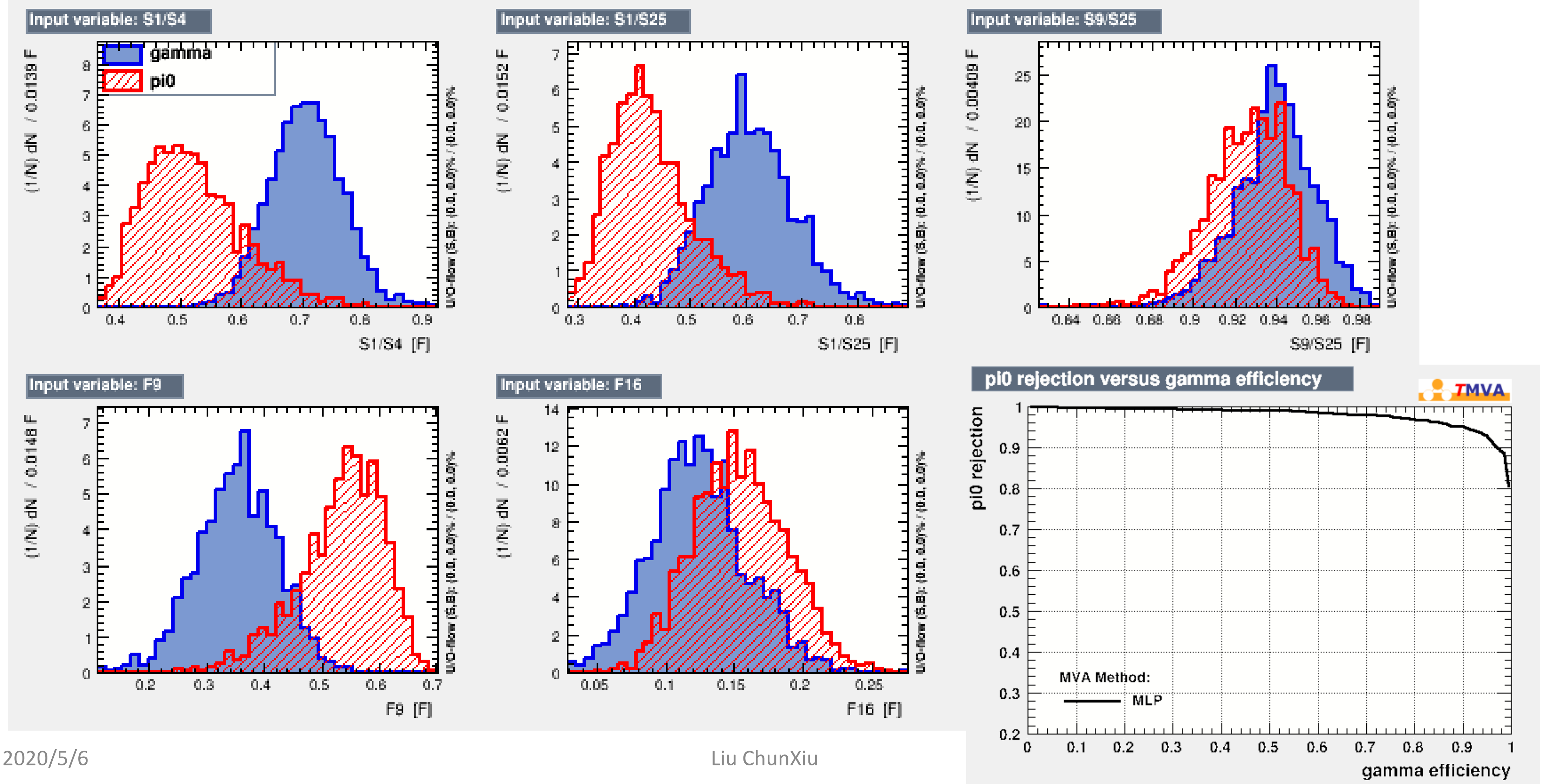
separation performance of the 40GeV γ and merged π^0

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



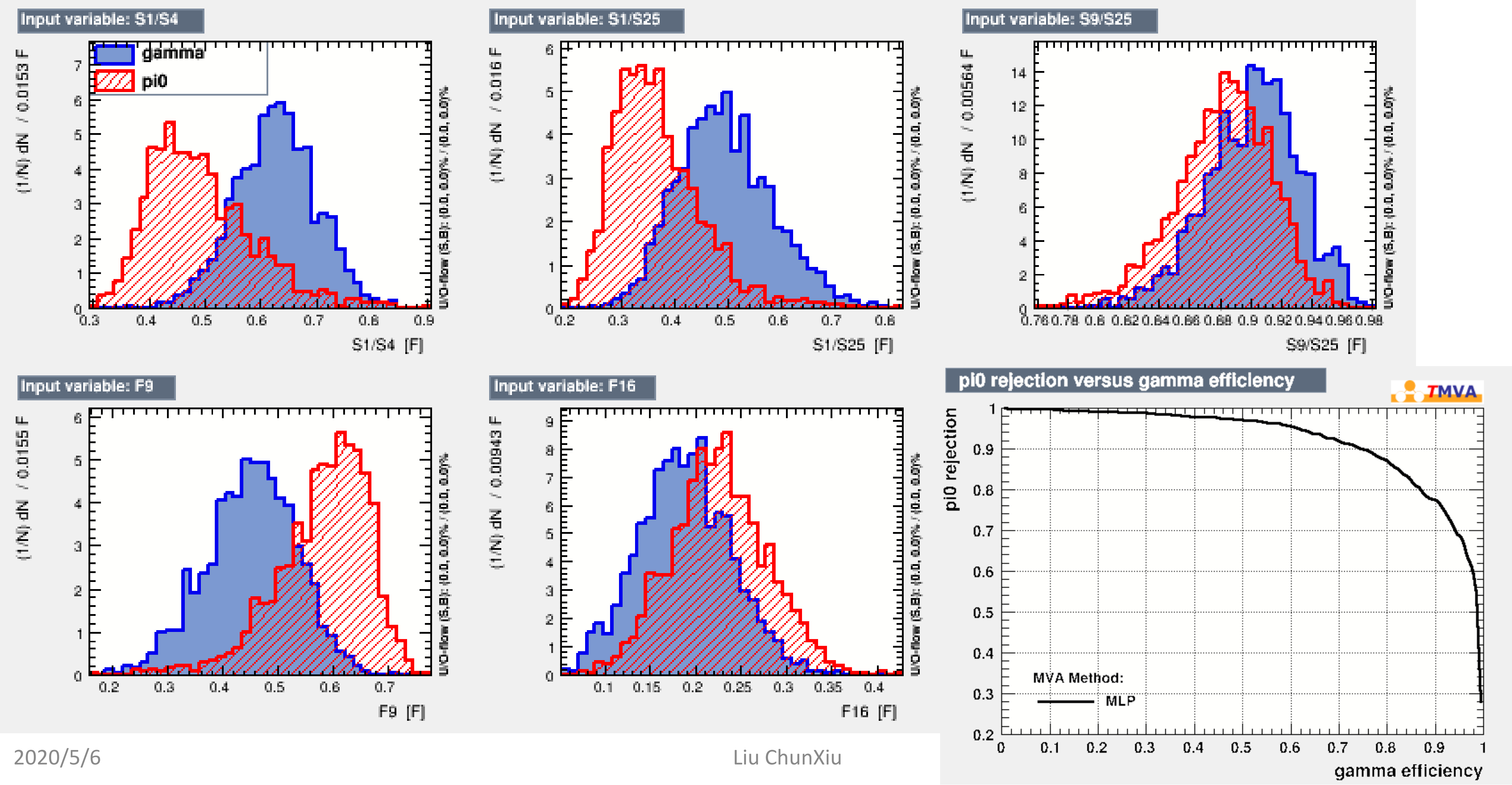
separation performance of the 40GeV γ and merged π^0

- alone the energy information of each layer with 3cm Depth with Cell 2x2cm^2 :5th layer



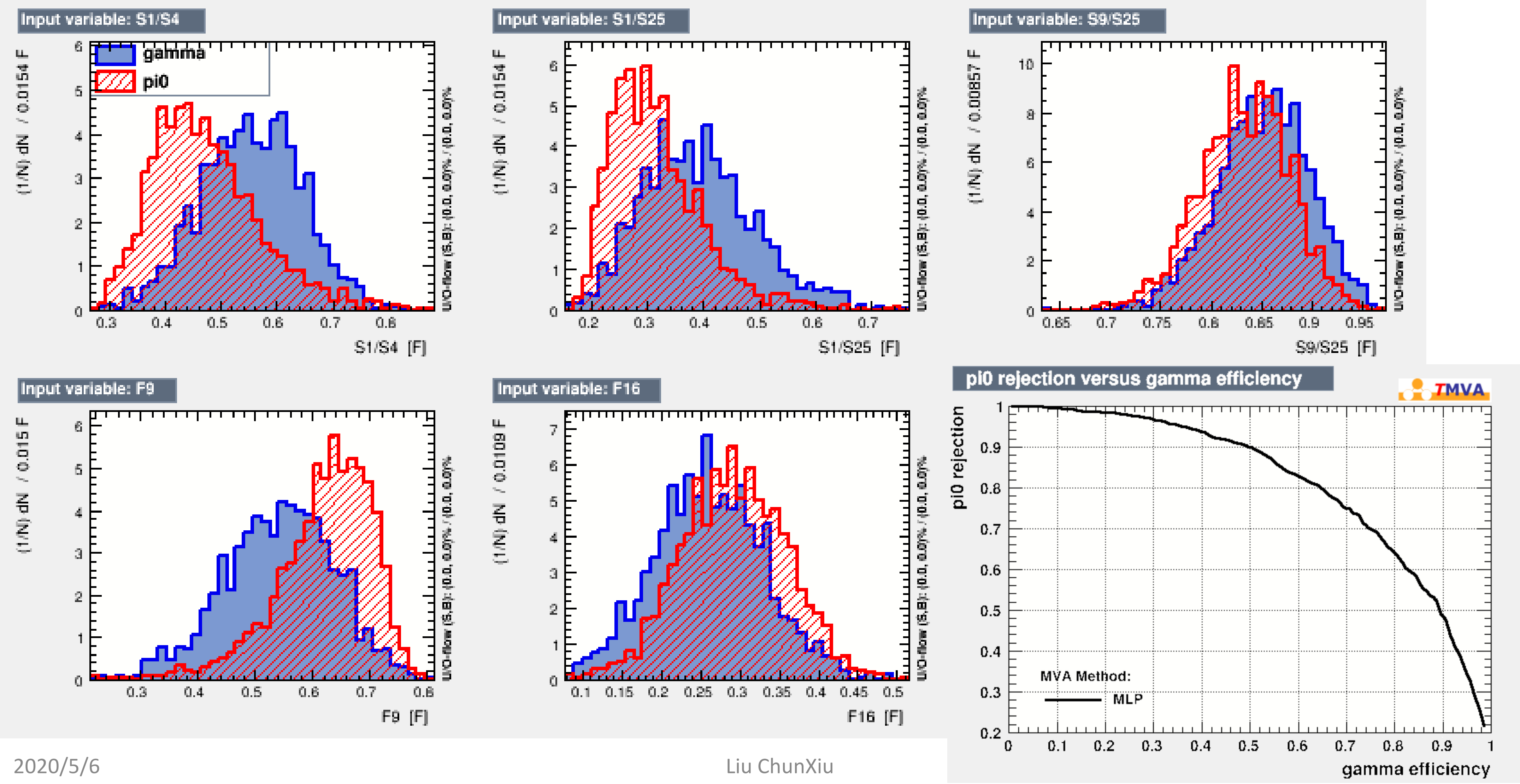
separation performance of the 40GeV γ and merged π^0

- alone the energy information of each layer with 3cm Depth with Cell $2x2cm^2$:6th layer



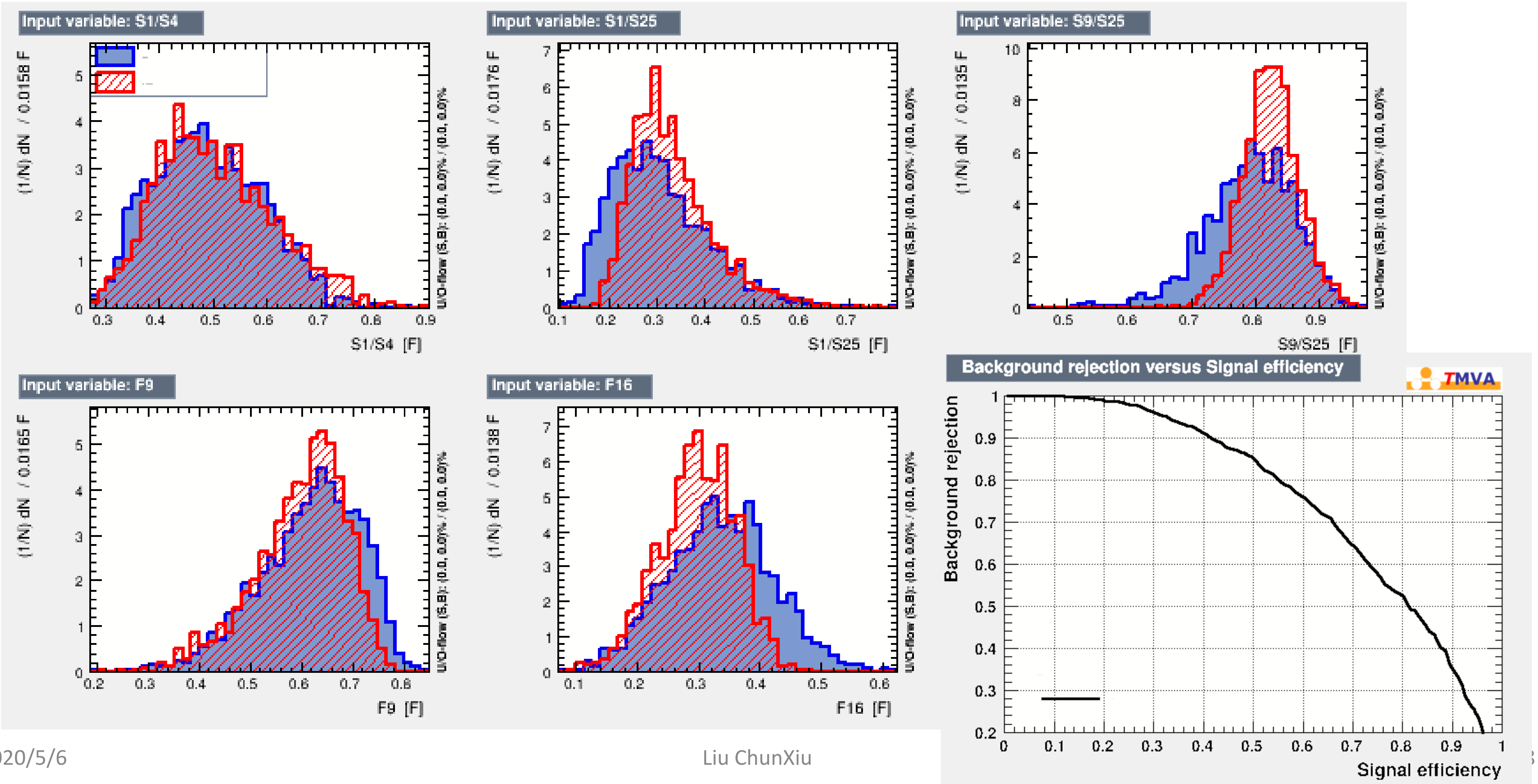
separation performance of the 40GeV γ and merged π^0

- alone the energy information of each layer with 3cm Depth with Cell 2x2cm^2 :7th 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 :8th layer



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

- 30cm Depth (merge 10Layers), and 24cm Depth (merge 8Layers)
  - separation performance is 100% for cell 1x1cm^2 and 2x2cm^2
- using alone the reconstruction of each layer with 3cm Depth
  - In the maximum shower layer, the separation performance is best, especially, for cell 2x2 cm^2.

Summary

- Construct the BGO matrix module with $60x60x60cm^3$ in Geant4
- Complete the cluster reconstruction of each layer
- Give some preliminary study results
  - Study the correction of the longitudinal energy leakage, the energy resolution can be improved by ~20%-30%. The preliminary results show that longitudinal direction needs at least 7~8 layers, and each layer depth should not be larger than 3cm.
  - Separation performance of 2γ's from high energy π^0 decay,
    - For cell $1x1cm^2$, "resolved" π^0 is ~100% for 30GeV and ~60% for 40GeV
    - For cell $2x2cm^2$, "resolved" π^0 is 0%.
  - Separation performance of 40GeV γ and merged π^0 is ~100%, for cell $1x1cm^2$ and $2x2cm^2$.
  - Need to further study

merged π^0 reconstruction in processing

Next to work:

- Investigate the methods of merged π^0 reconstruction
  - ➢Two second moment methods:
    - to estimate the invariant mass of the π^0 system based on the shape of the merged cluster
  - ➢The third method:
    - the single cluster of the merged π^0 is split into two interleaved 3x3 subclusters built around the two main cells in the original cluster.
- ....

Thank you!