Software Studies of GLD Calorimeter

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- Digital hadron calorimeter
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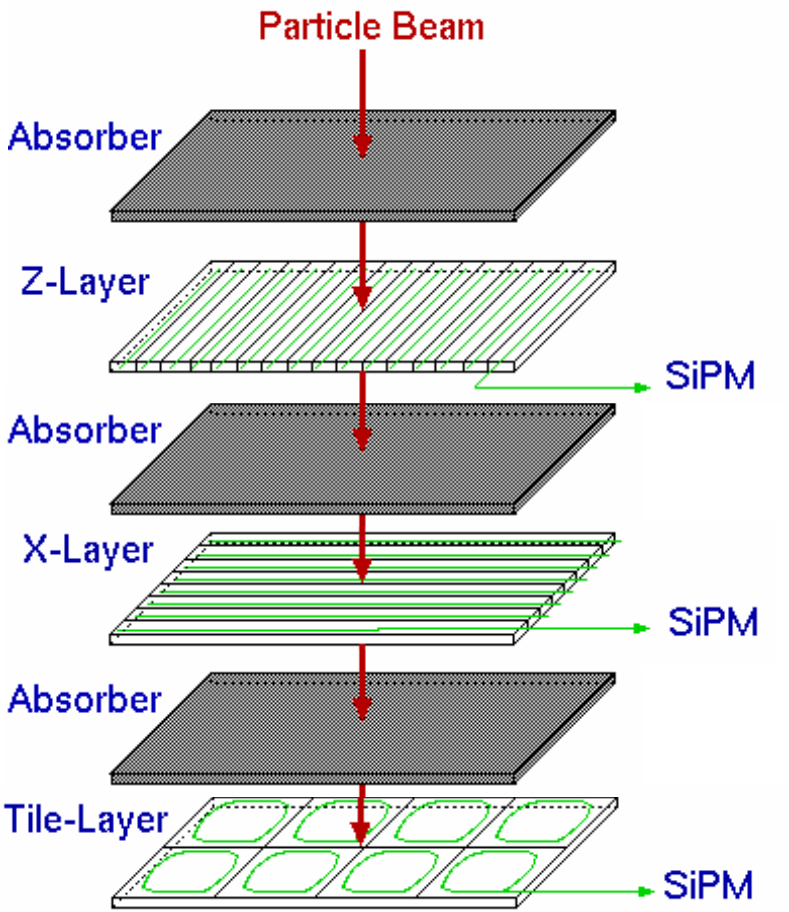
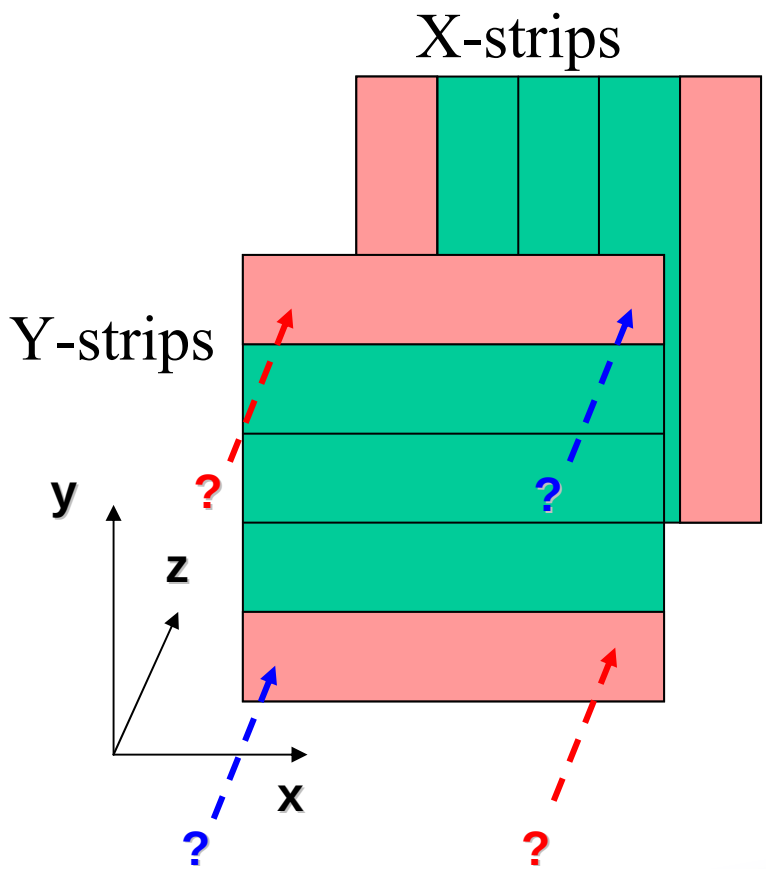
Calorimeter Design

- Baseline design
  - Scintillator/absorber sandwich
    - Two orthogonal strip layers
      - Effective granularity ~ 1cm x 1cm
    - Additional tile layer
  - WLS fiber
  - MPPC photon sensor



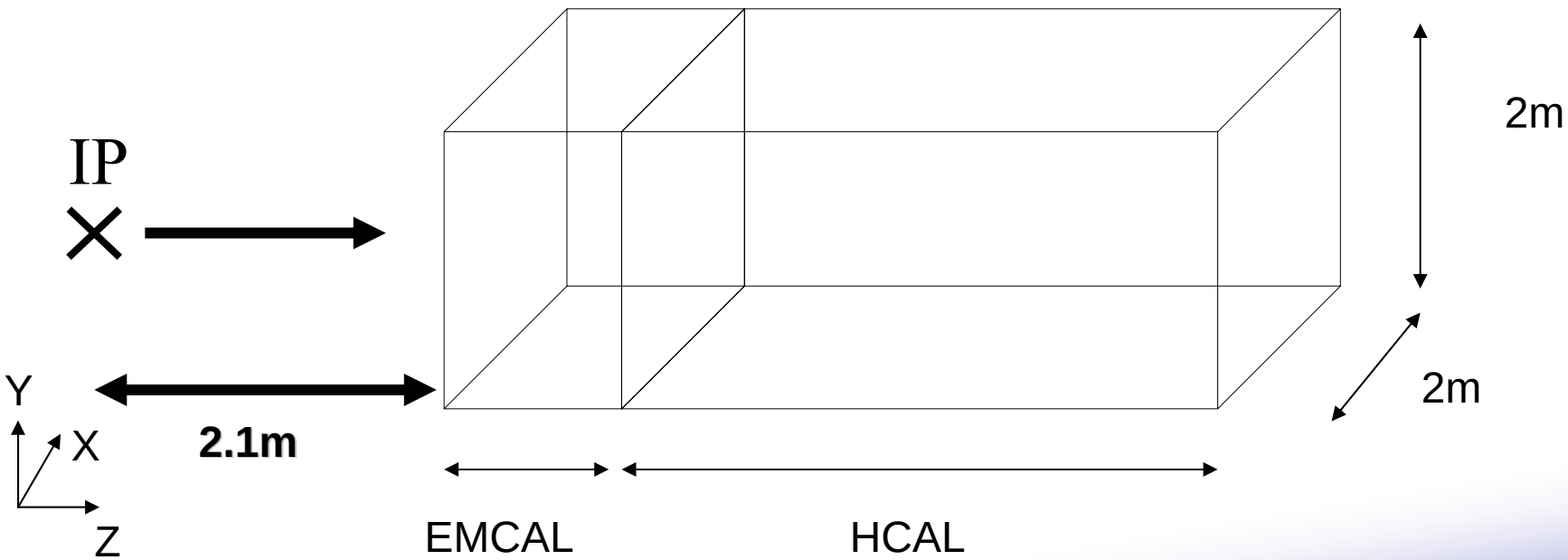
Clustering in the strip configuration

- Clustering is difficult in the strip configuration
- In case of multi particles going into calorimeter:
  - Ghost hits could be reconstructed
  - Three-dimensional reconstruction may enable us to choose correct incident positions



Setup

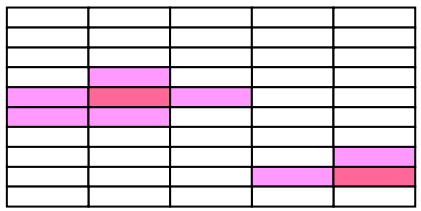
- GEANT4 based stand-alone simulator
- EMCAL: W(3mm)+Sci(2mm)+Air(1mm), 30 Layers
- HCAL: Pb(20mm)+Sci(5mm)+Air(1mm) , 50 Layers
- π^0's are generated at the interaction point



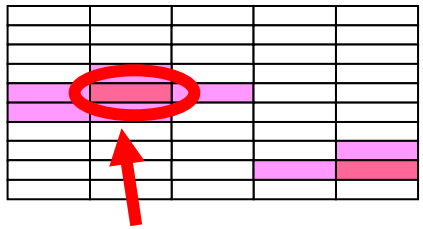
Clustering procedure

Threshold for a hit: 0.1MIP

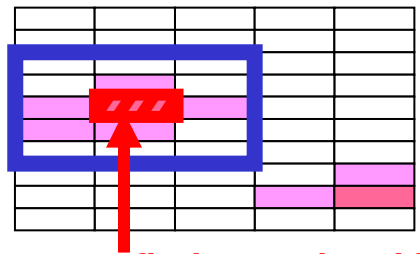
Do this clustering for both X- and Y-strips



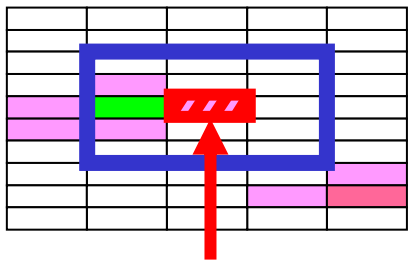
Two particles coming in



Find a strip with the largest energy deposit



Try to find associated hits Three-dimensionally



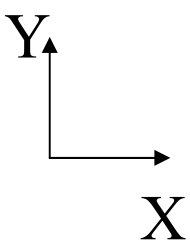
Redo recursively

Cluster is built

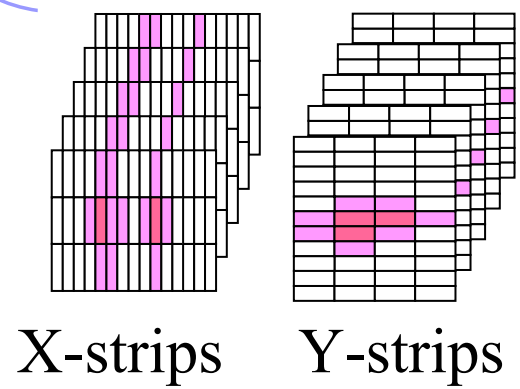
Try again for remaining hits

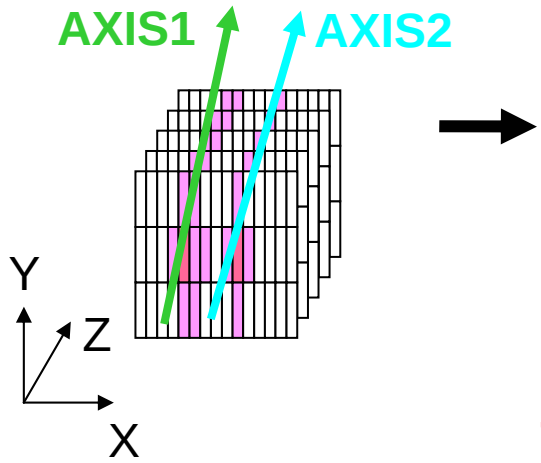
Cluster1

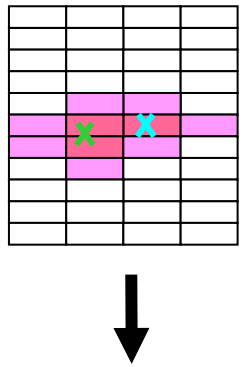
Cluster2

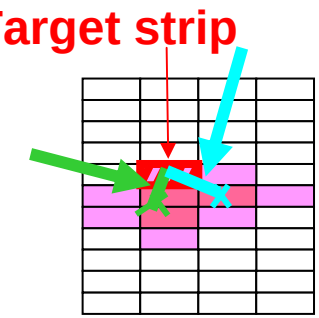


Two cluster separation (1)

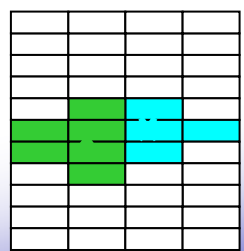






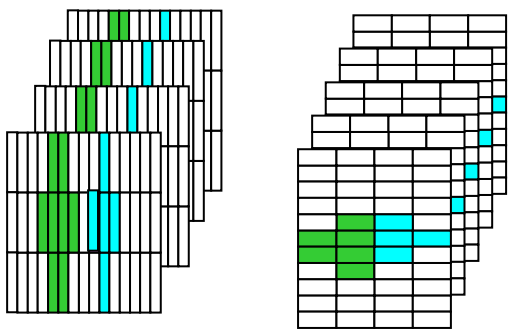


Compare distances

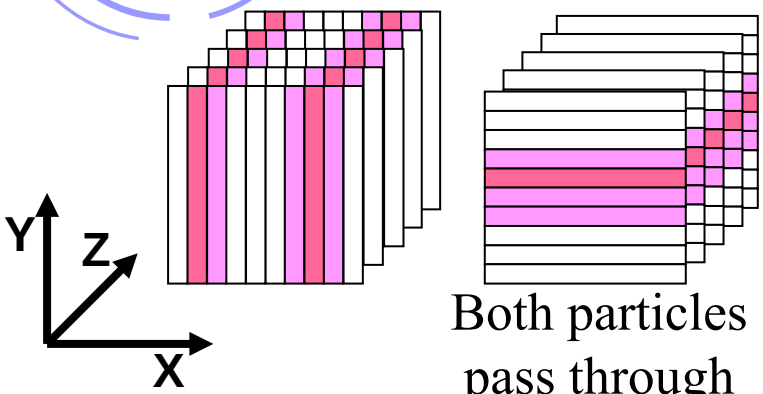


Do the same thing for all layers

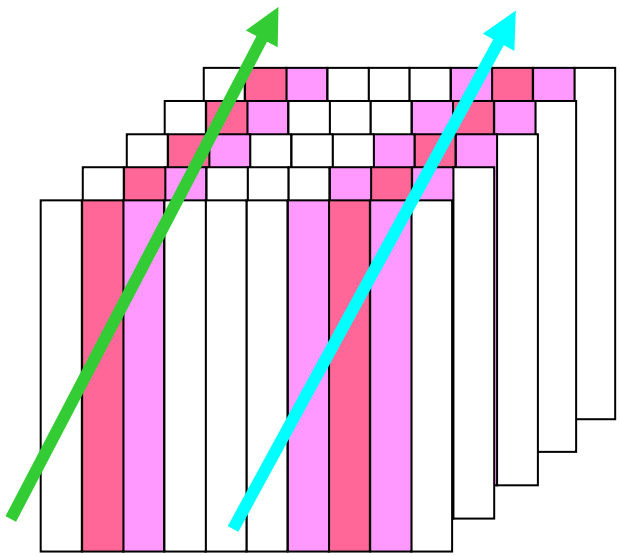
Two clusters can be separated



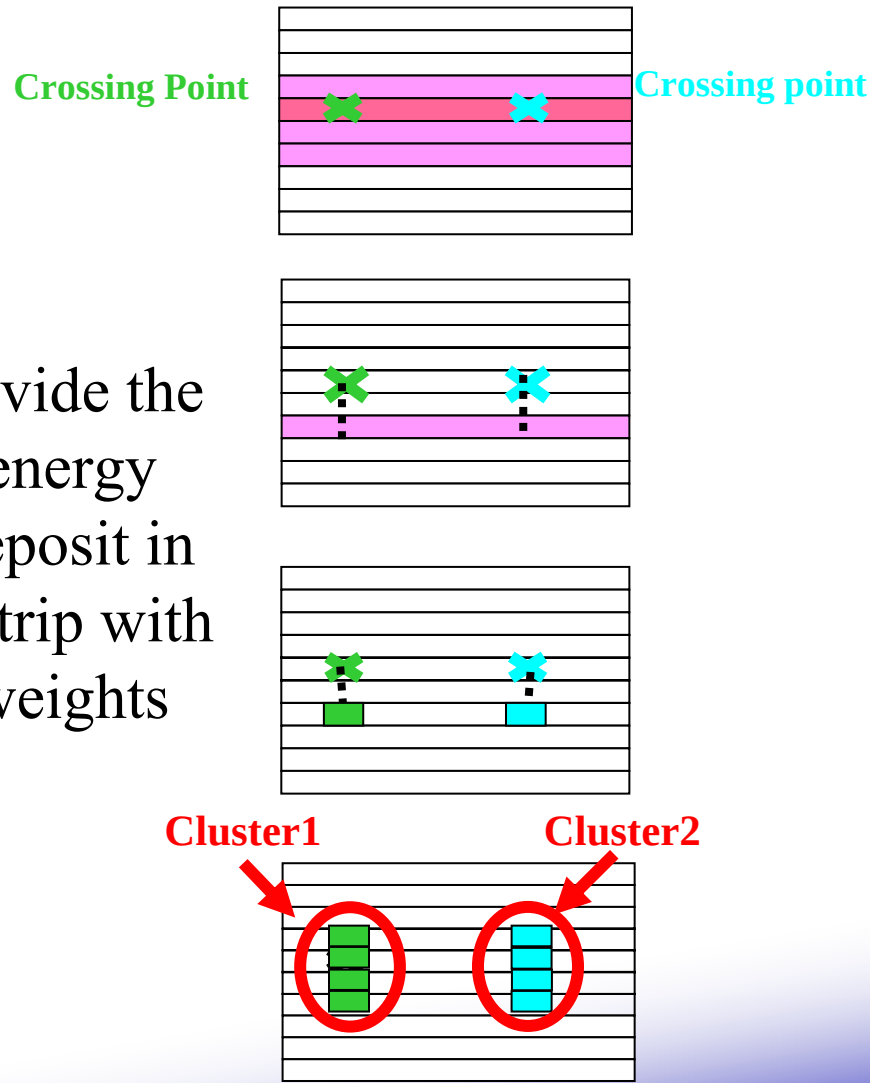
Two cluster separation (2)



Both particles pass through the same strip

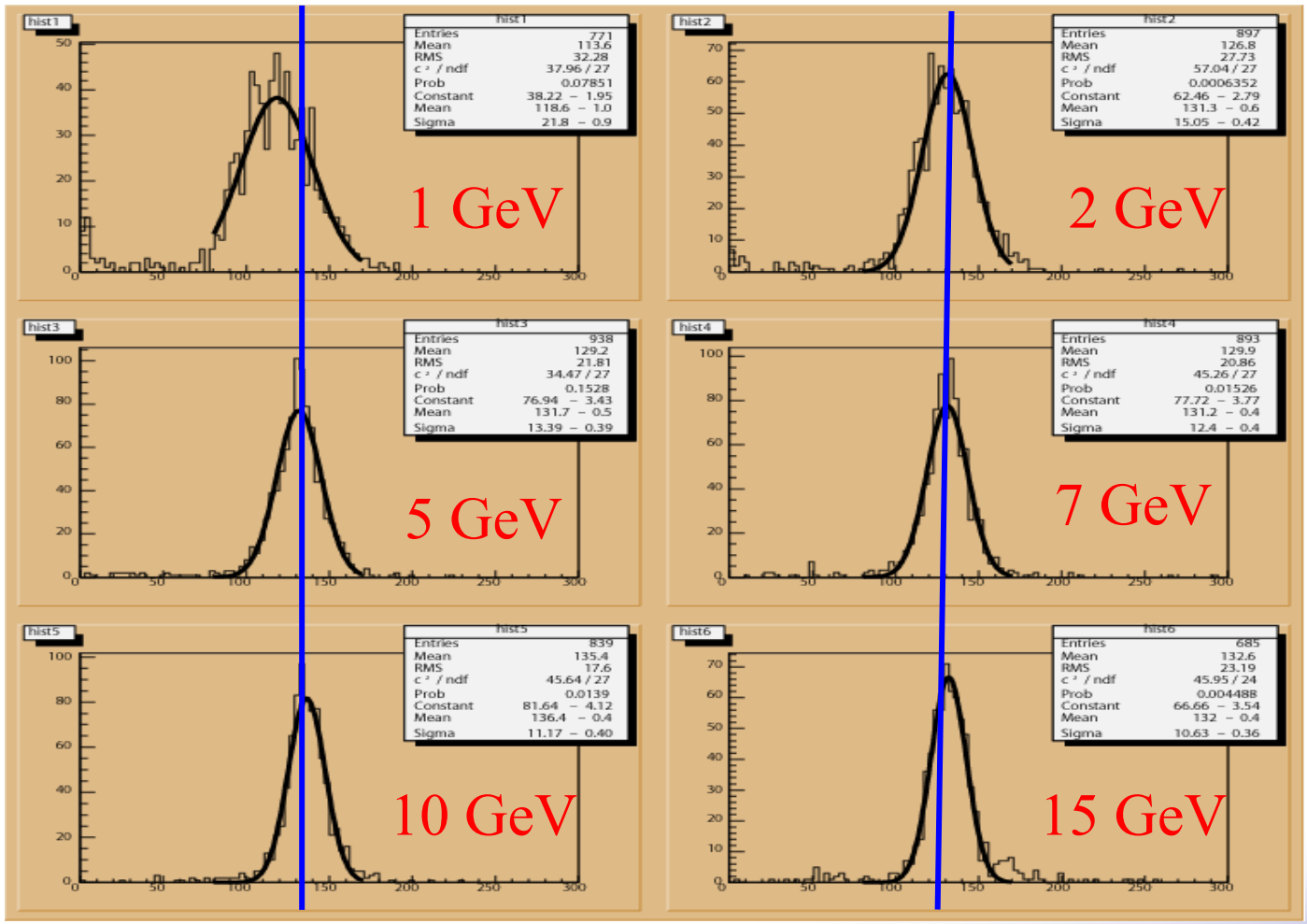


Divide the energy deposit in a strip with weights



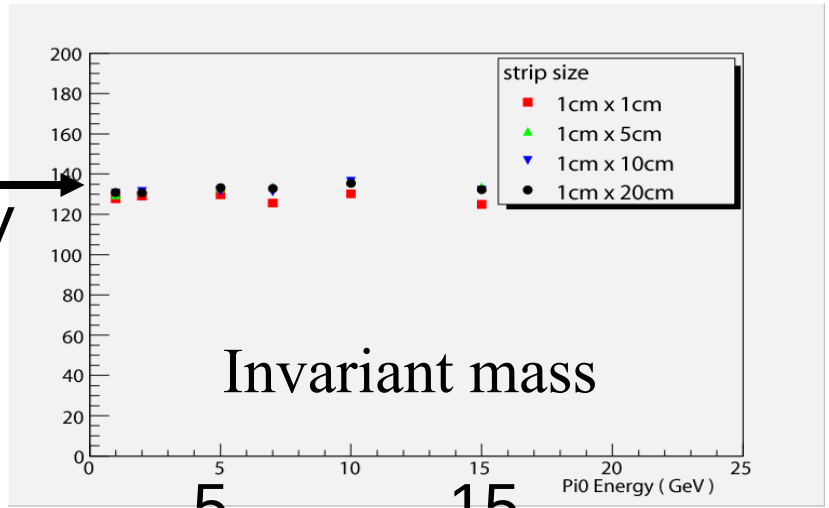
π^0 reconstruction (1cm×10cm strip)

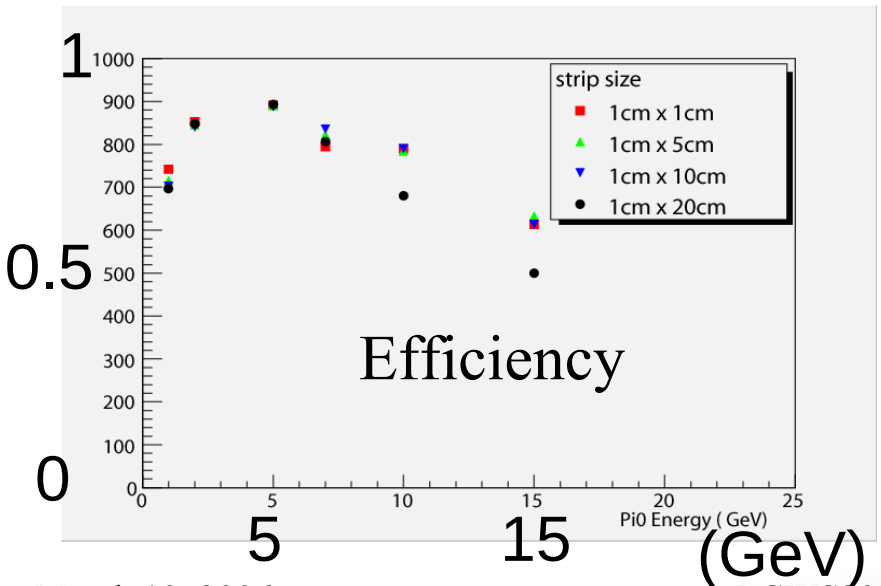
135MeV 135MeV

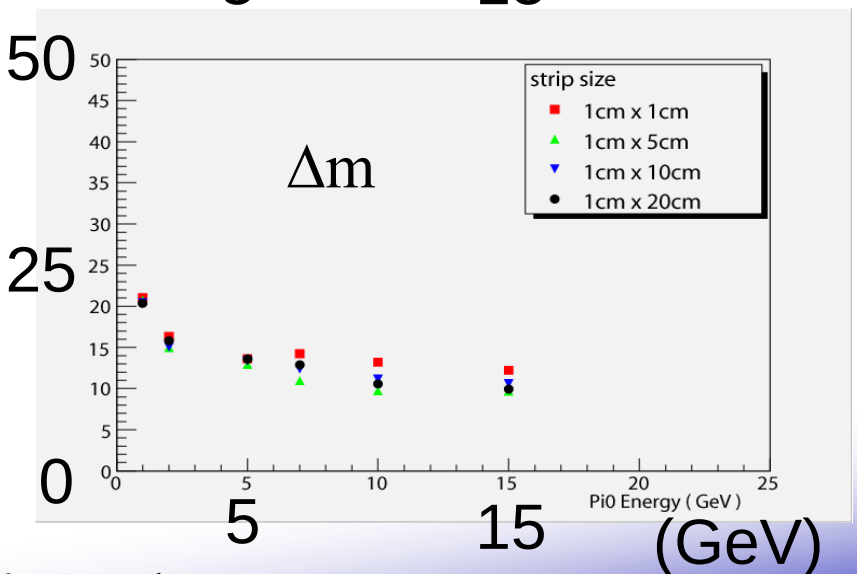


Performance

- Performance is stable if scintillator length is less than 10cm







Digital Calorimeter

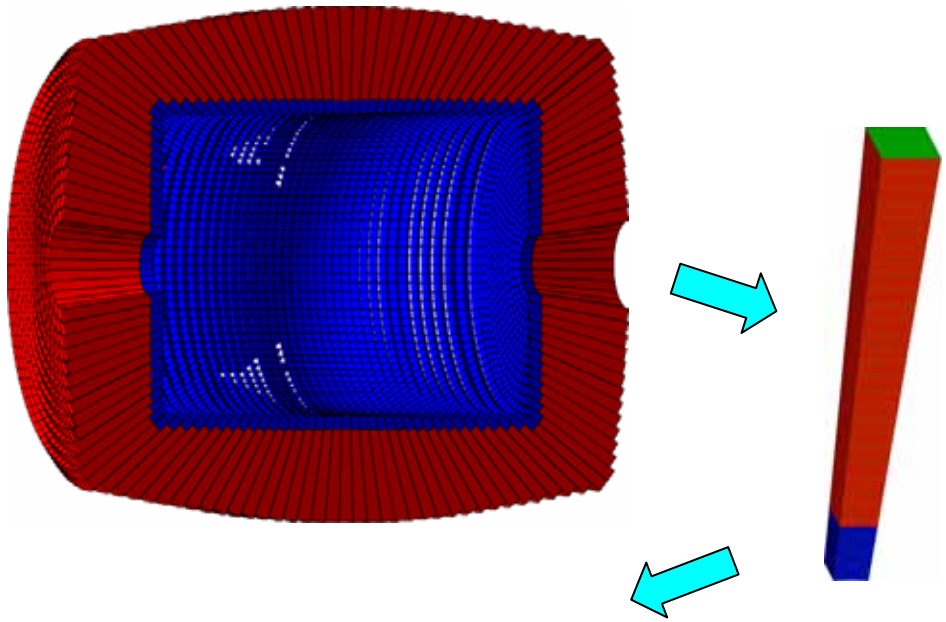
- Very fine granularity is preferred for PFA
  - Number of readout channels become huge
  - Electronics cost will be expensive

→ Digital Calorimeter

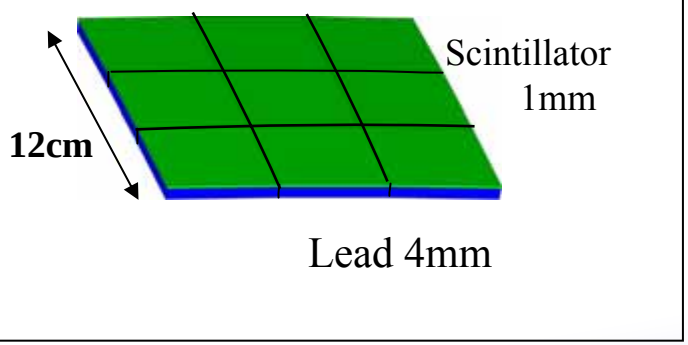
- One option for GLD HCAL
  - Performed simulation study with full simulator
    - Scintillator tile size down to 1cm x 1cm

GLD Simulator (Jupiter)

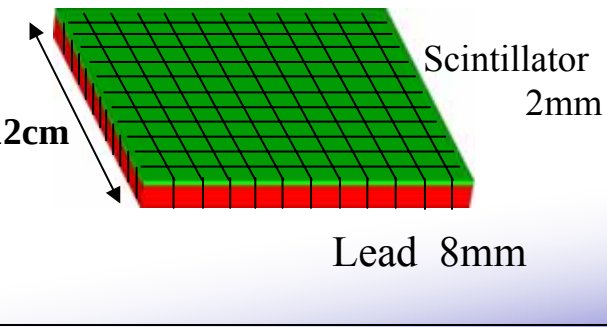
- GEANT4-based
- Tower structure
- ECAL tile size：
  4cm×4cm
- HCAL tile size：
  1cm×1cm ~ 3cm×3cm



ECAL 38 layers: 27 X_0

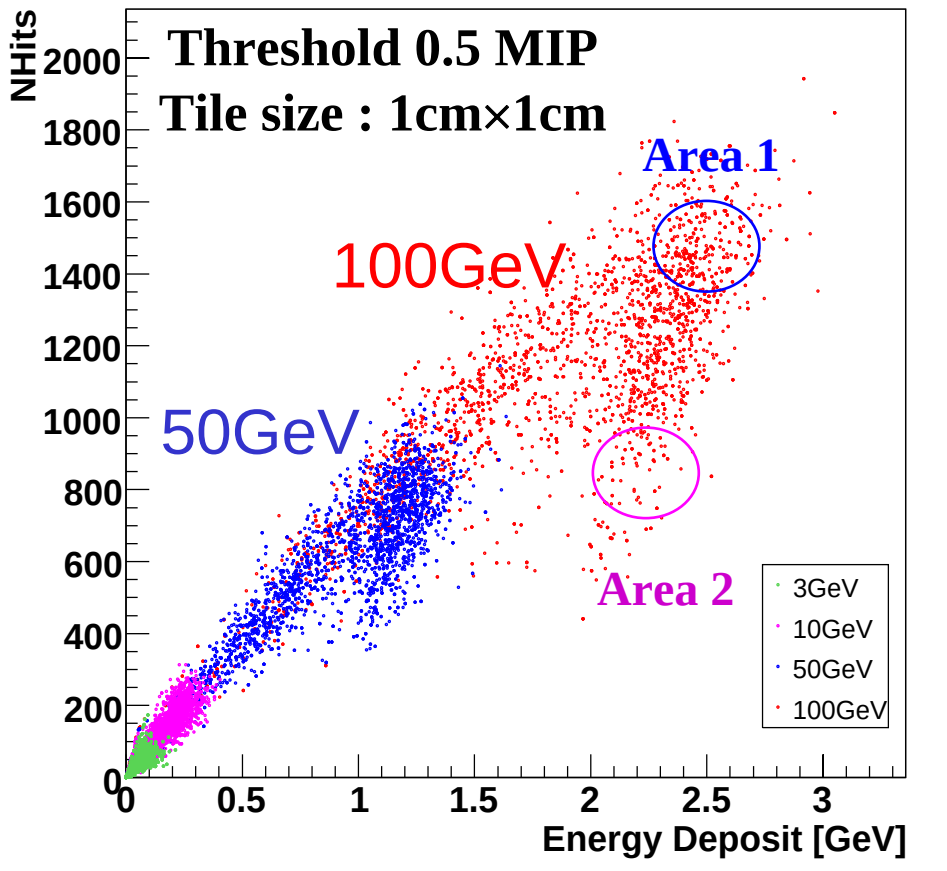


HCAL 130 layers: 6.1 λ_0



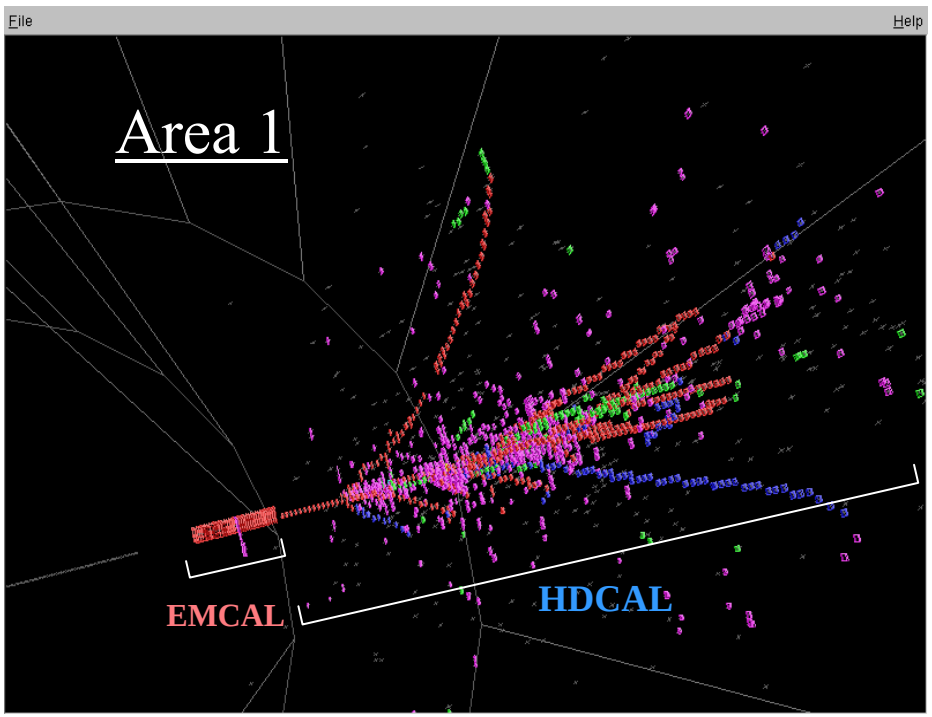
Responses to Single Particles

- Charged pions
  - 3, 10, 50 and 100 GeV
  - 3000 events each
- HCAL tile size:
  1cm×1cm ~ 3cm×3cm
- Kink structure exists in responses for high energy particles

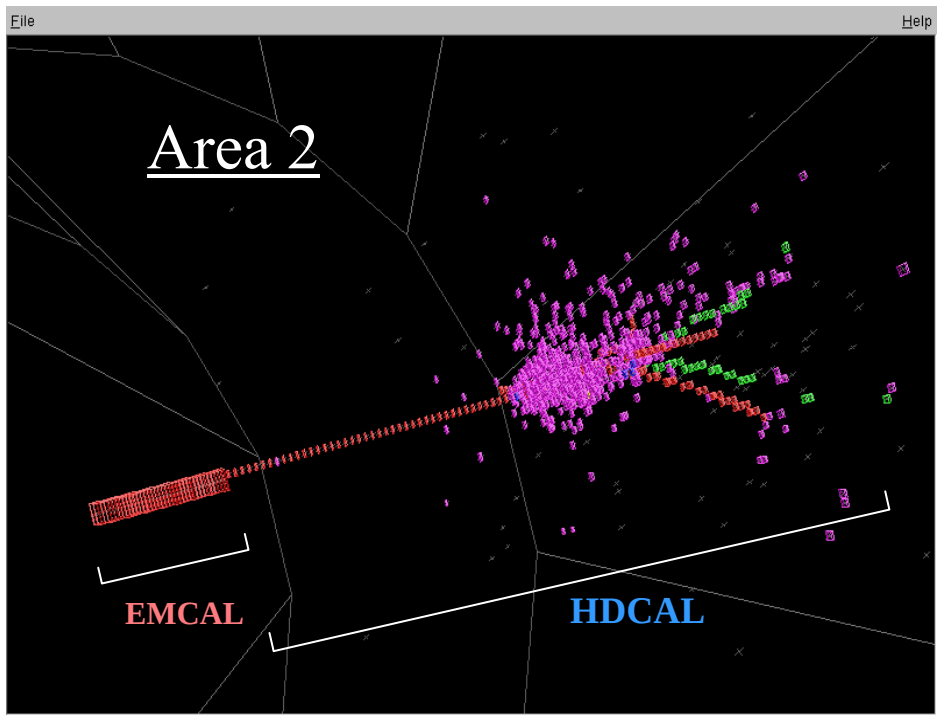


Two types of events (100GeV pions)

Pure hadron shower



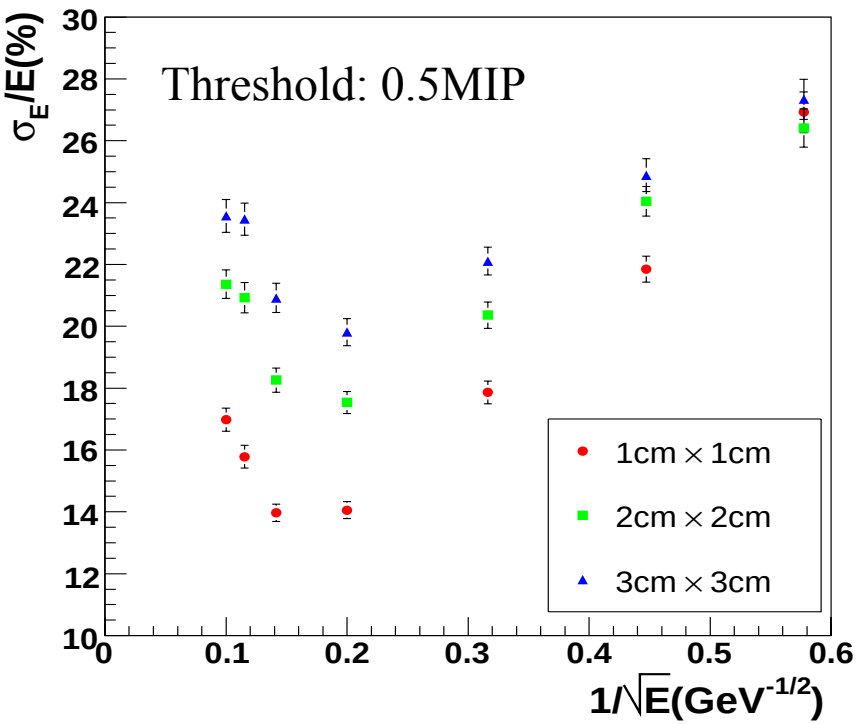
Large EM shower component



Pink: electron Blue: muon Red: pion Green: proton

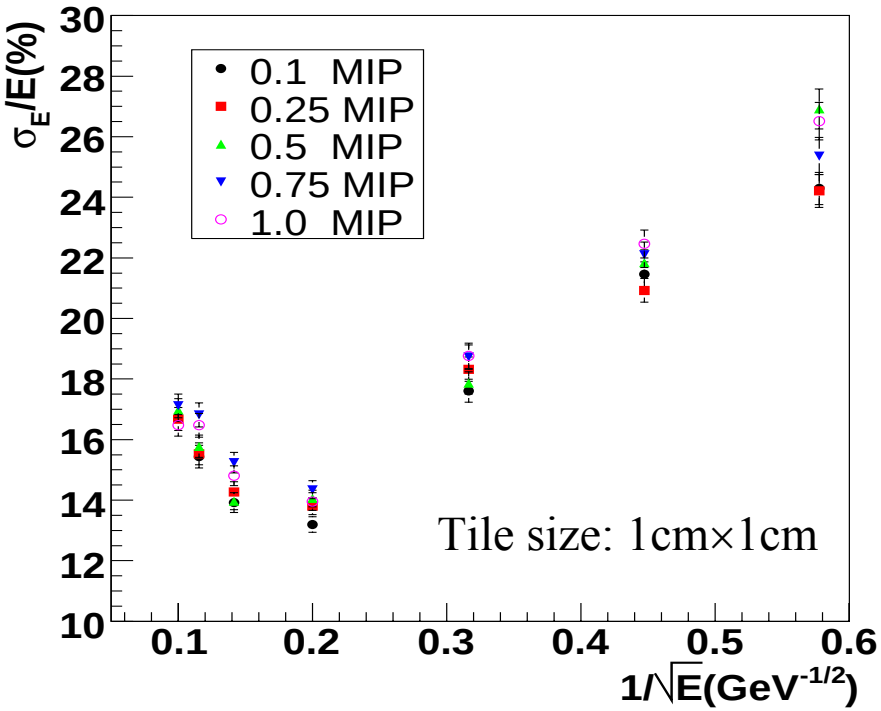
Energy Resolution

Segmentation dependence



→ Smaller size is better in high energy region

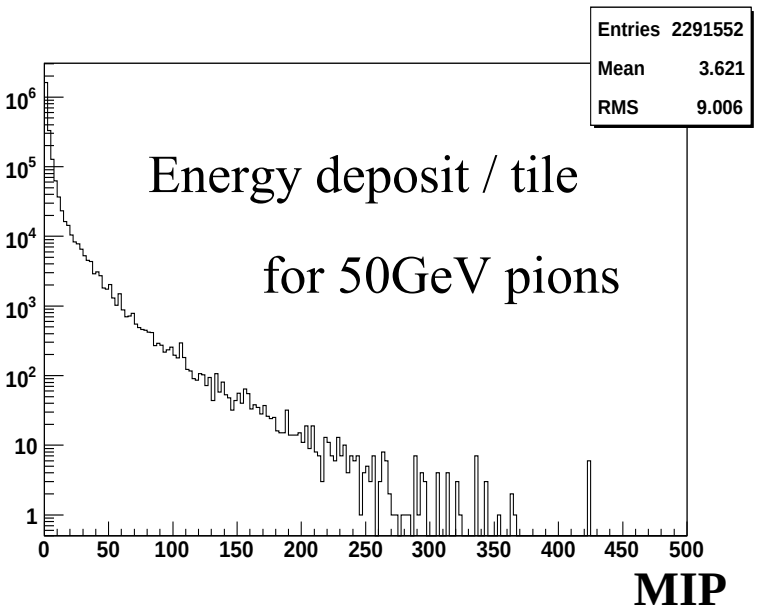
Threshold dependence



→ No significant difference

Semi-digital (2-bit) Calorimeter

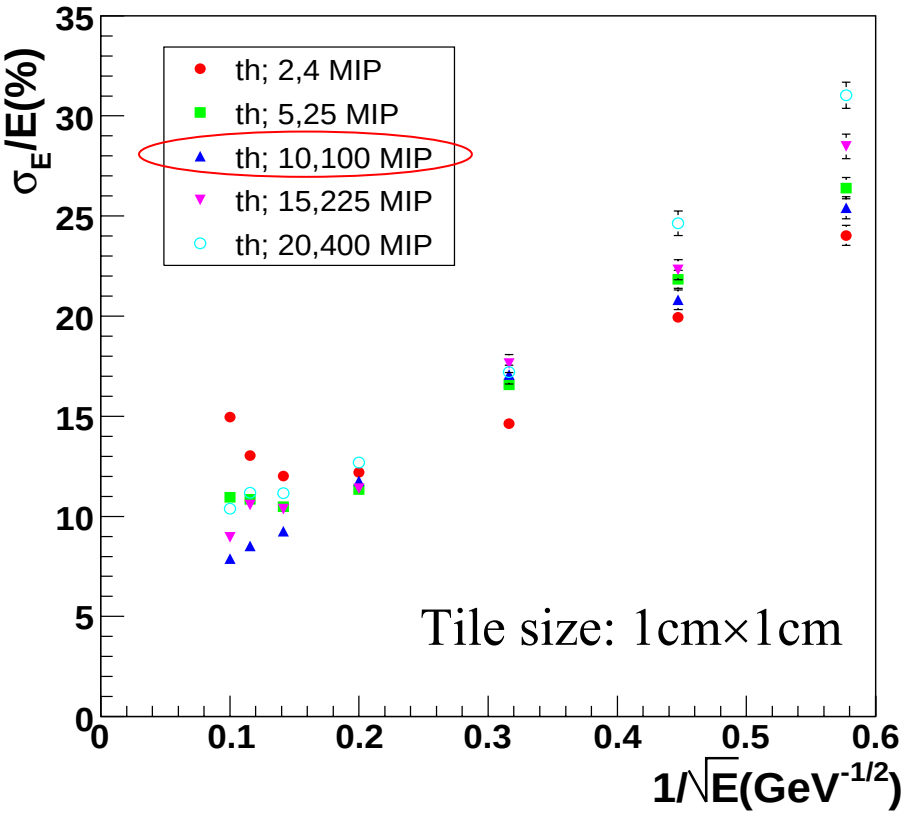
Digital Calorimeter is not suitable for high energy particles
Much larger energy deposit per tile than 1 MIP
→ Try semi-digital (2 bit)



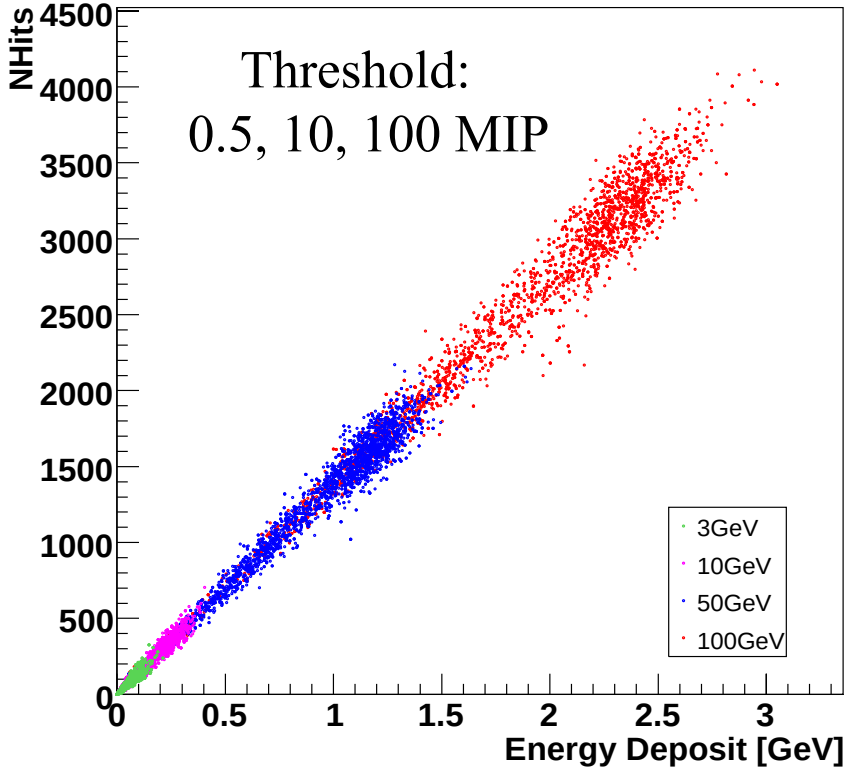
- Three thresholds
  - Lowest is fixed at 0.5 MIP
- Other two should be optimized

Energy deposit (MIP)	# of hits
0 ~ 0.5	0
0.5 ~ n	1
n ~ n^2	n
n^2 ~	n^2

Threshold optimization



→ The best resolution is obtained when two higher thresholds are set to 10, 100 MIP



→ Linearity become much better than that of 1-bit digital readout

Comparison of Energy Resolutions

$$\frac{\sigma}{E} = \sqrt{\frac{\sigma_{stochastic}^{2}}{E} + \sigma_{constant}^{2}}$$

- Analog : $\sigma_{sto} = 48.9 \pm 0.6$ %
  $\sigma_{con} = 5.0 \pm 0.2$%
- Digital : $\sigma_{sto} = 37.0 \pm 0.9$%
  $\sigma_{con} = 13.8 \pm 0.2$%
- Semi : $\sigma_{sto} = 45.1 \pm 0.6$%
  $\sigma_{con} = 6.8 \pm 0.1$%
- Real data (analog) :
  $\sigma_{sto} = 46.7 \pm 0.6$%
  $\sigma_{con} = 0.9 \pm 0.9$%

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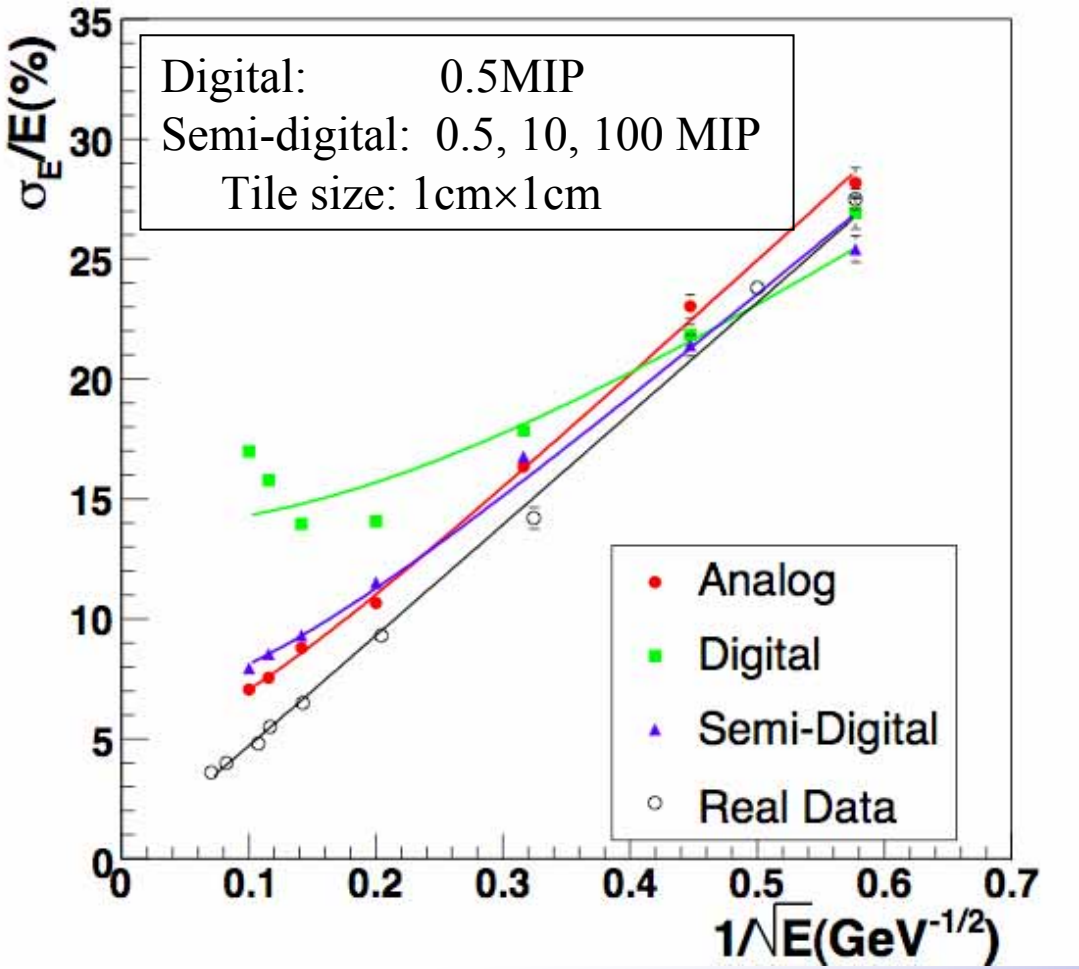
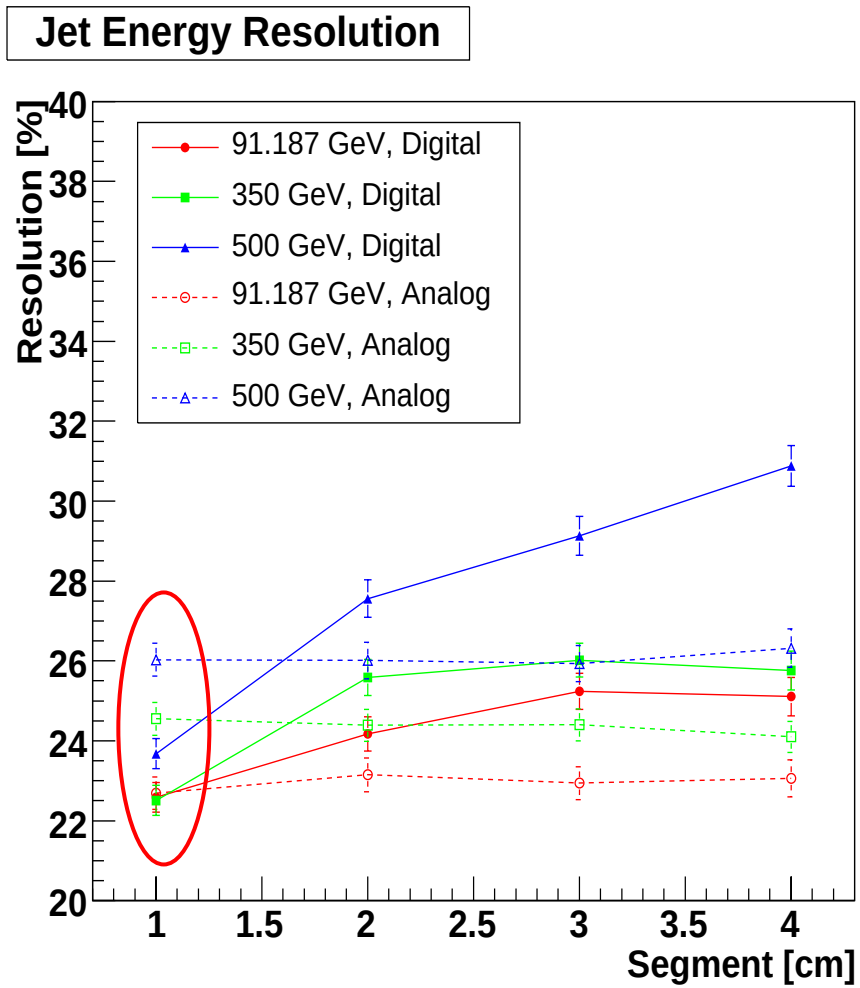


Jet Energy Resolution

- $e^+e^- \rightarrow qq$ (u/d/s)
  - $\sqrt{s} = 91, 350, 500$ GeV
- Energy measurement with (perfect) PFA
- In case of 1×1 cm^2 tile size, digital calorimeter achieved similar or slightly better jet energy resolution



Summary

- We tried to reconstruct π^0 in the strip configuration
  - 80% reconstruction efficiency for 10GeV π^0
- Have studied digital calorimeter with single pion and jet
  - Better resolution was obtained with smaller tile size
  - No significant dependence on (lowest) threshold
  - Bad energy resolution/linearity for particle with >50GeV
    - Need at least 2-bit readout
  - For jets, performance is similar to analog readout
    - Tile size is 1cm×1cm, $\sqrt{s} < 500$ GeV

Backup

X, Y-cluster association

- Minimize χ^2
  - $\chi^2=\{(Ex-Ey) / (\sigma_{Ex-Ey})\}^2 + \{(Xx-Xy) / (\sigma_{Xx-Xy})\}^2 + \{(Yx-Yy) / (\sigma_{Yx-Yy})\}^2+\{(Zx-Zy) / (\sigma_{Zx-Zy})\}^2$
- σ is determined by single photon

σ	Value
σ_{Ex-Ey}	$0.031 \times \sqrt{(Ex+Ey)}$ (MeV)
σ_{Xx-Xy}	15.16 (mm) / $\sqrt{Ex}$ (MeV)
σ_{Yx-Yy}	16.42 (mm) / $\sqrt{Ex}$ (MeV)
σ_{Zx-Zy}	46.42 (mm) / $\sqrt{Ex}$ (MeV)