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Simulated Performance of the SiD Digital ECal Based on Monolithic Active Pixel Sensors

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on behalf of
the SiD MAPS Collaboration
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UNIVERSITY OF OREGON

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"The SiD Digital ECal Based on Monolithic Active Pixel Sensors",
10.3390/instruments6040051, Instruments, 6, 51 (2022)

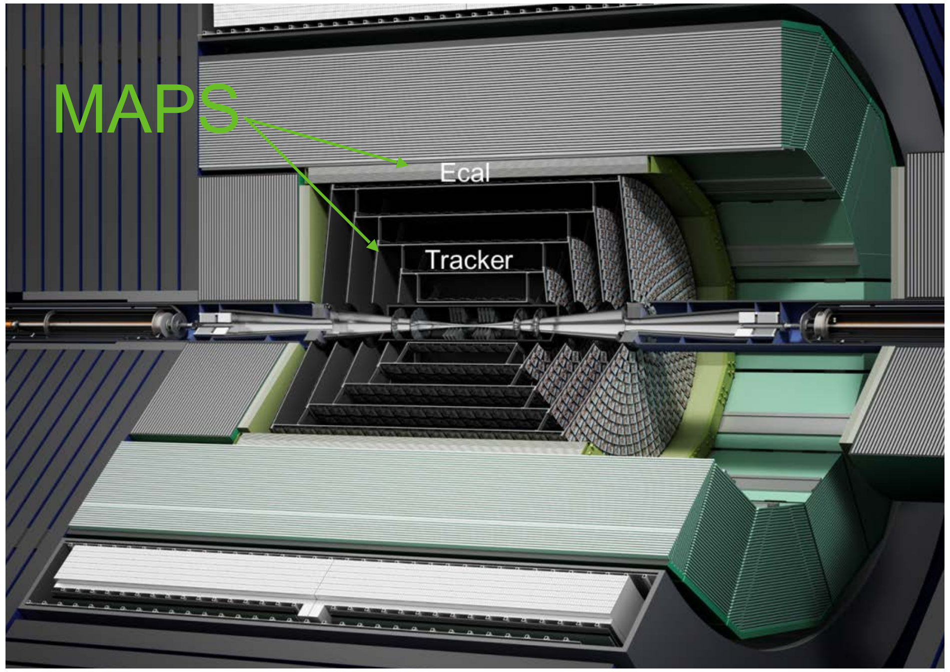
SiD Digital ECal Based on MAPS

- Upgrade ILC TDR design to replace sensors with 13 mm^2 analog pixels with 25 x 100 μm^2 (or 25 x 50 μm^2) digital pixels.
    - 13/(.1 x .025) = 5200x granularity
- How well can we measure energy and structure with digital system:
    - Compared to SiD baseline of analog measurements?
    - Can the detailed structural measurements be used to improve measurement?
    - Would a neural net optimization offer an improvement?
- What are the limits of transverse separation?

Large area MAPS for SiD tracker & ECal

Benefits of large-area MAPS:

- Standard CMOS foundry, low resistivity: **cost ⇩**
- Sensing element and readout electronics on same die
  - In-pixel amplification: **noise ⇩, power ⇩**
  - No need for bump-bonding: **cost ⇩**
- Area > 10x10 cm^2 → enable O(1) m^2 modules



An example of the SiD Tracker and the ECal overall design

Several design challenges:

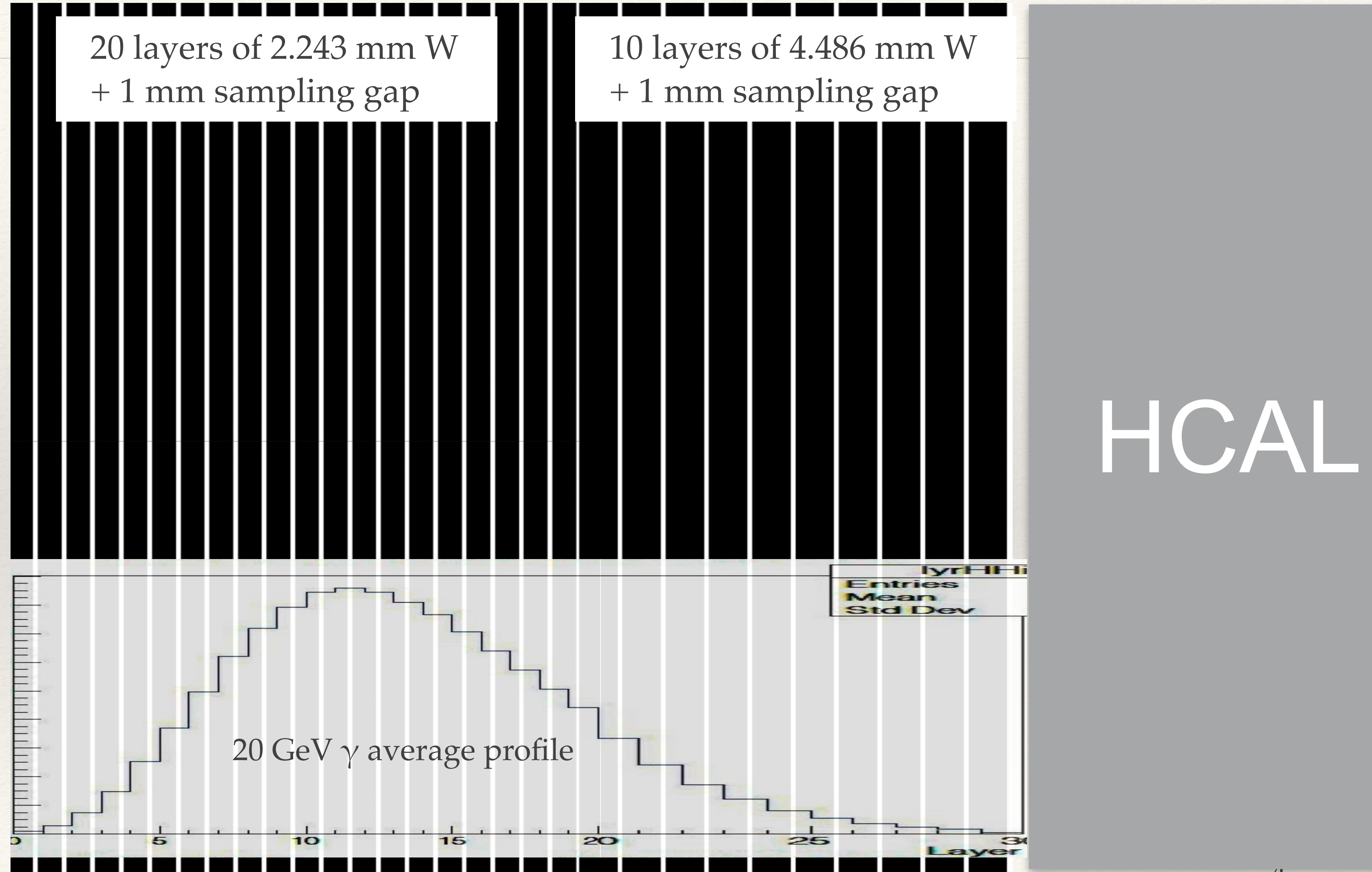
- Large on-die variations, mismatch
- Yield
- Stitching layout rules
- Distribution of power supply
- Distribution of global control signals/references

Goals of R&D: find solutions and explore novel design techniques

Model of longitudinal structure of SiD ECal

Total = 27 X_0

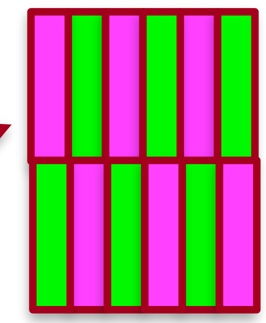
Minimize sampling gap to achieve optimal Moliere radius and shower separation



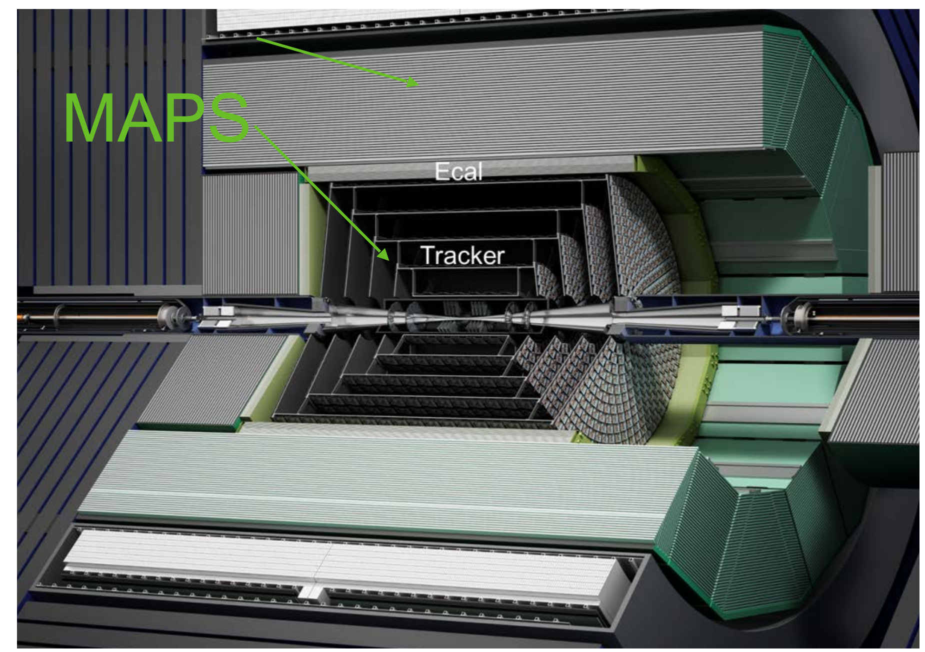
Main specifications for Large Area MAPS development

TID-AIR

Parameter	Value	Notes
Min Threshold	140 e^-	0.25*MIP with 10 μm thick epi layer
Spatial resolution	7 μm	In bend plane, based on SiD tracker specs
Pixel size	25 x 100 μm^2	Optimized for tracking (note: 25 x 50 μm^2)
Chip size	10 x 10 cm^2	Requires stitching on 4 sides
Chip thickness	300 μm	<200 μm for tracker. Could be 300 μm for EMCal to improve yield.
Timing resolution (pixel)	~ ns	Bunch spacing: C^3 strictest with 5.3->3.5 ns; ILC is 554 ns
Total Ionizing Dose	100 kRads	Total lifetime dose, not a concern
Hit density / train	1000 hits / cm^2	
Hits spatial distribution	Clusters	Due to jets
Balcony size	1 mm	Only on one side, where wire-bonding pads will be located.
Power density	20 mW / cm^2	Based on SiD tracker power consumption: 400W over 67m^2



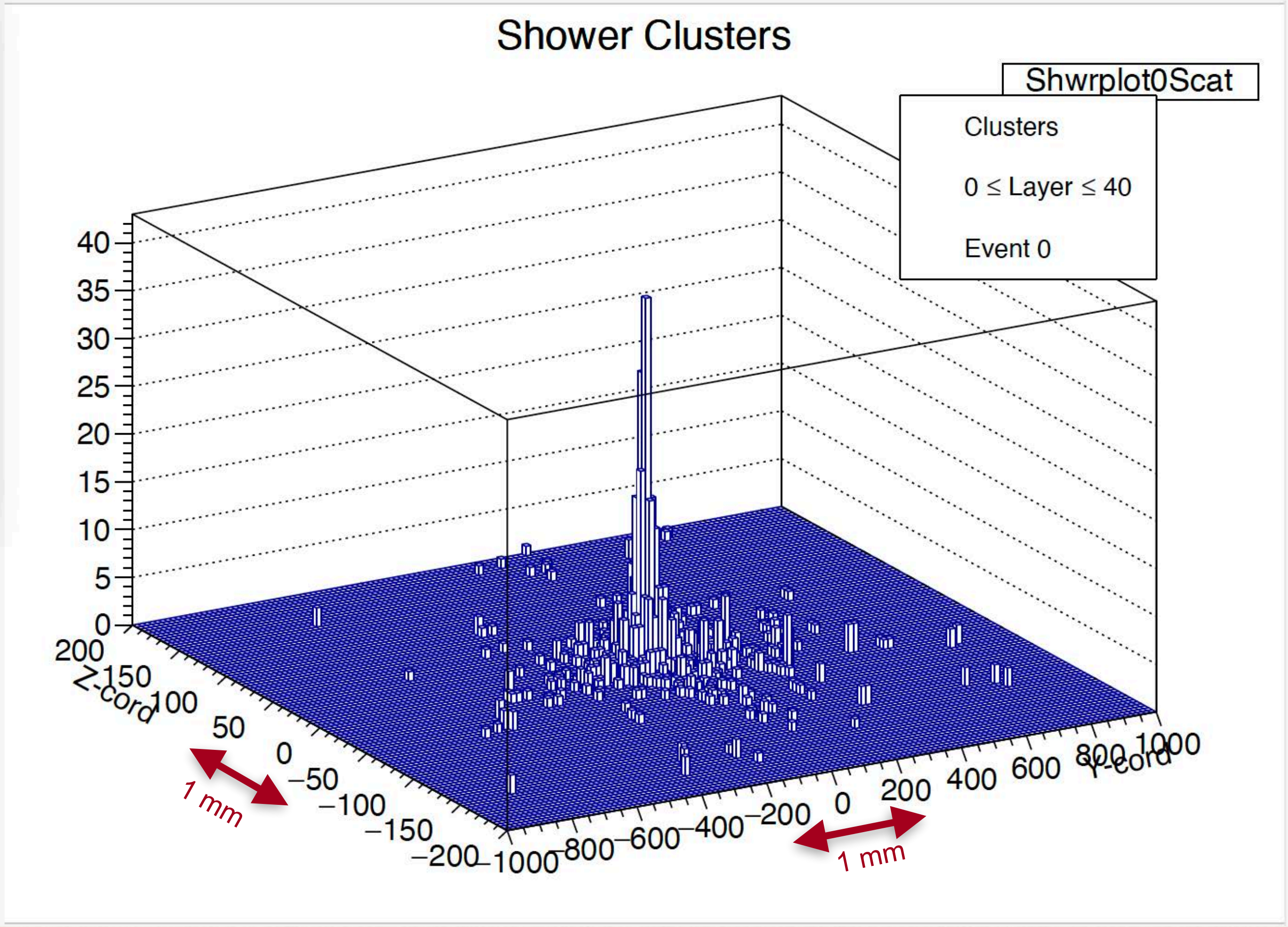
25 x 100 μm^2
ECal performance
same as
50 x 50 μm^2
(Note: may use 25 x 50 μm^2)

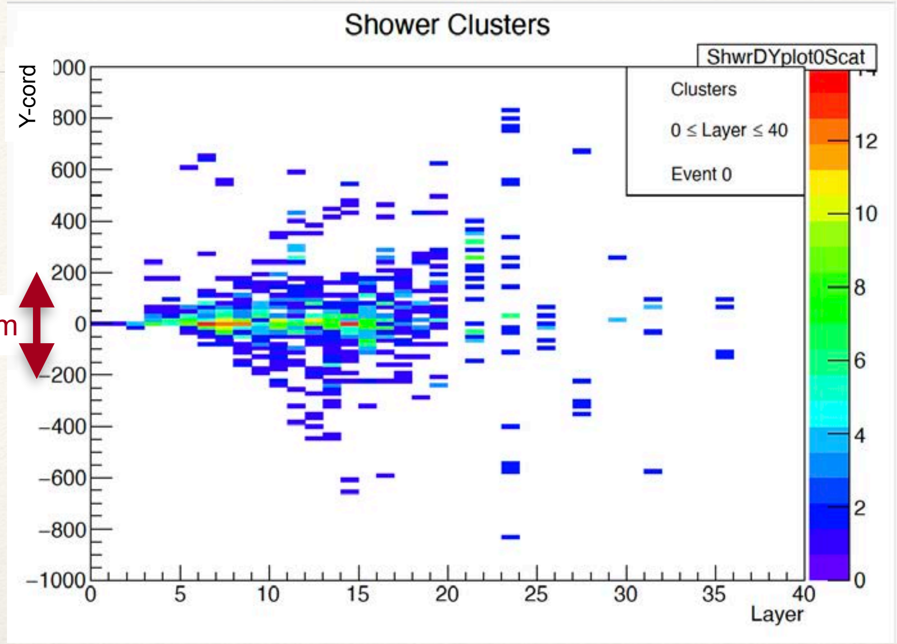


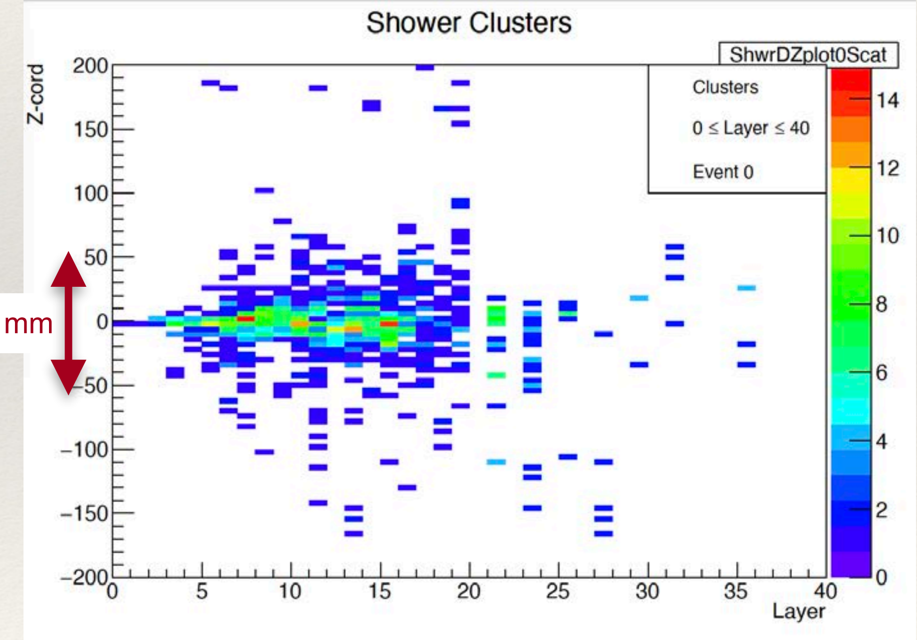
SiD Tracker and the ECal

L. Rota

10 GeV Shower in 25 x 100 μm²

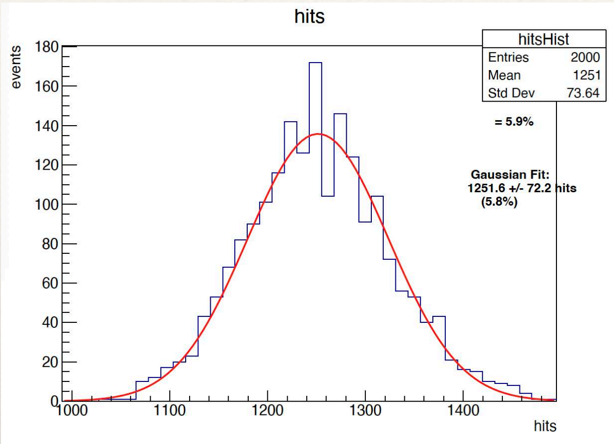


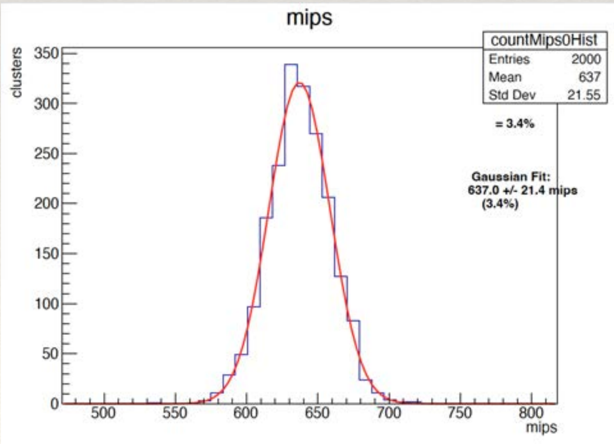


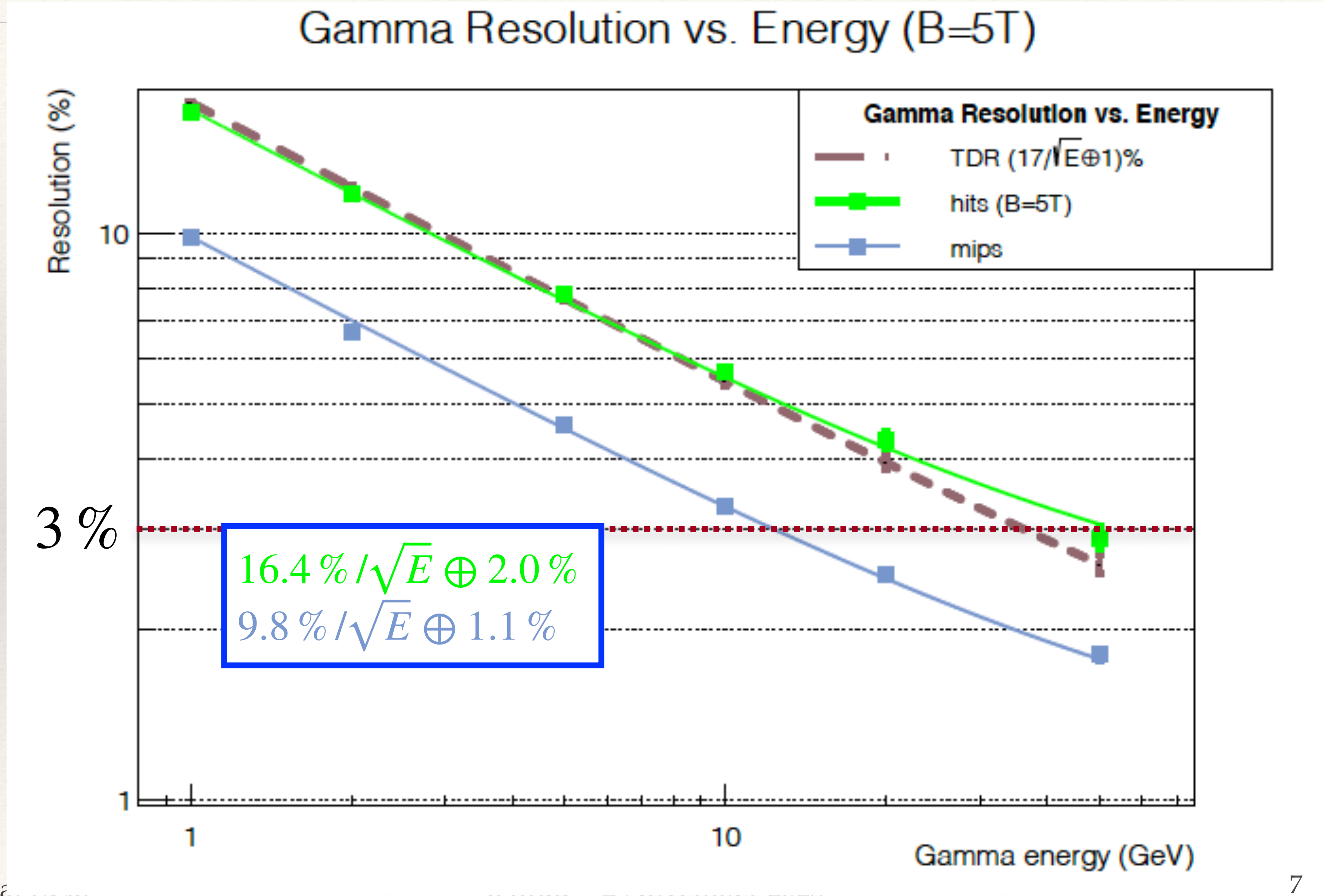


Resolution vs. Energy (hits & mips)

Resolution vs. Energy (hits & mips)

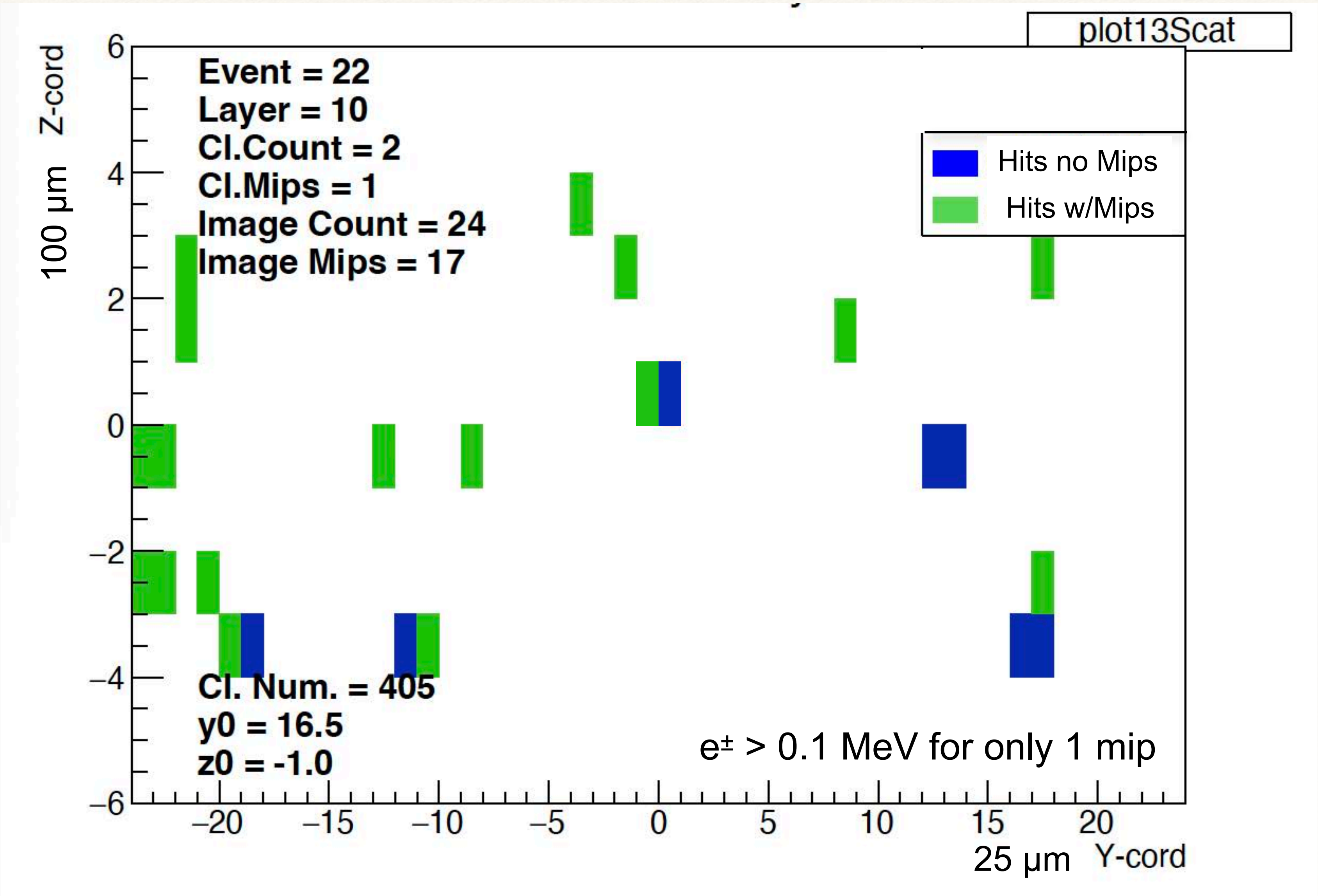




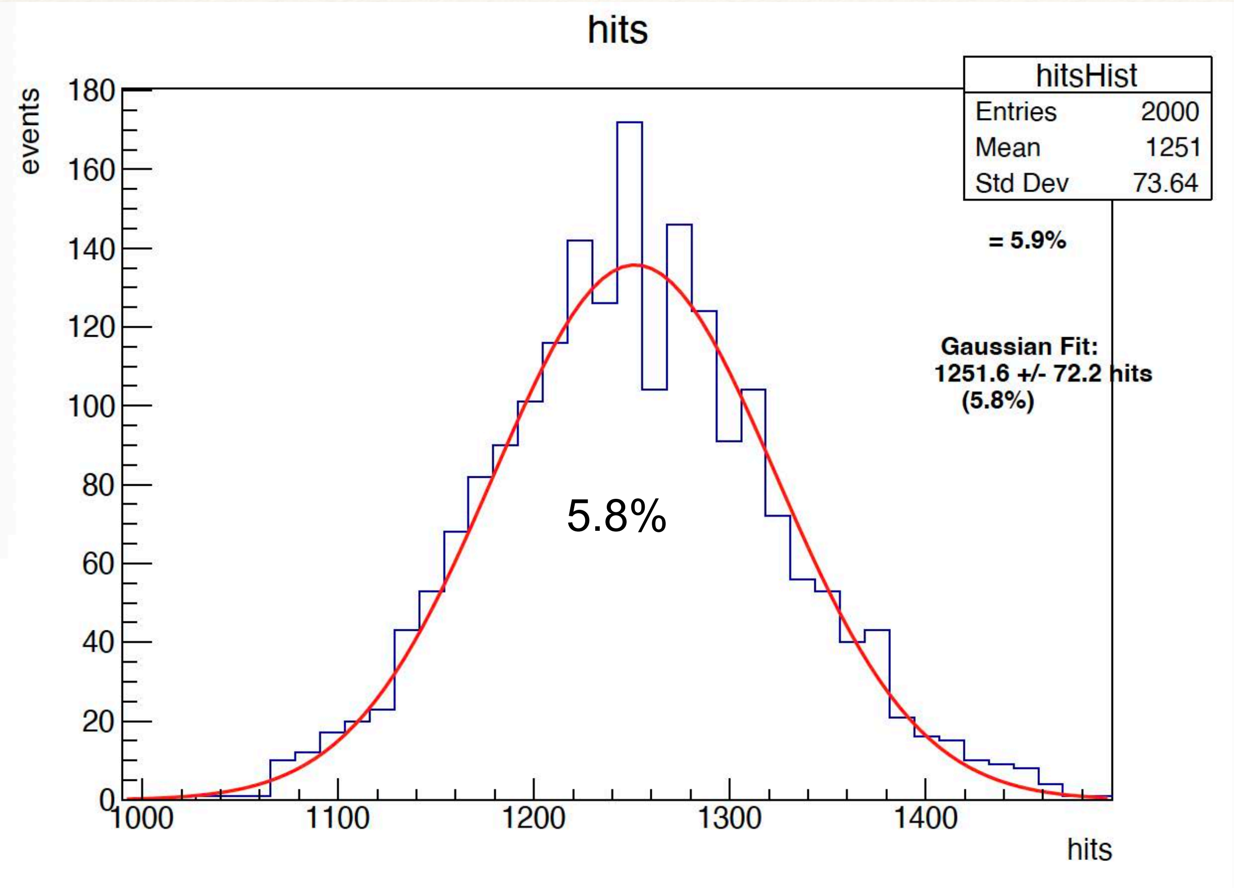


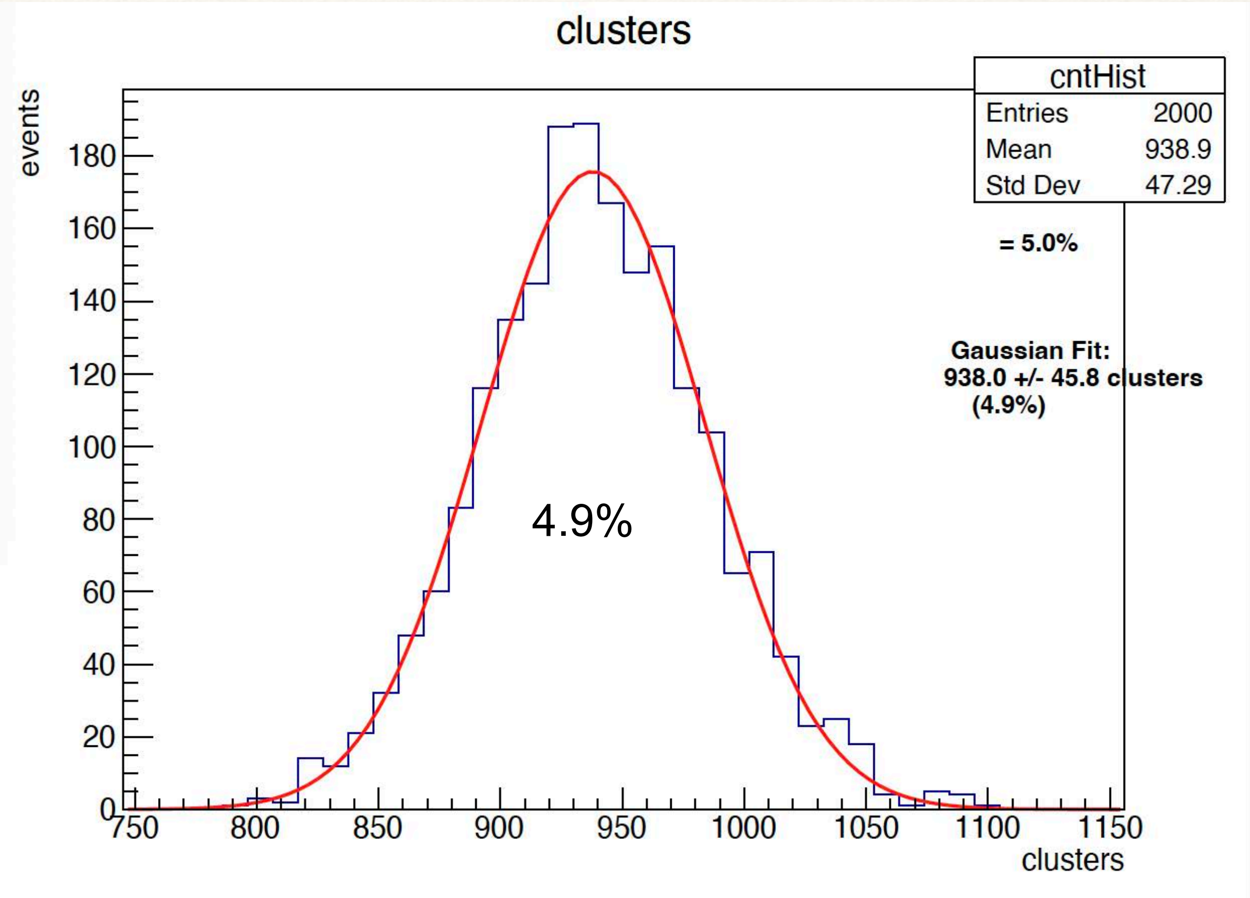
Example of hit distribution in a MAPS

- Most hits isolated
  - Single hit cluster
- Multiple hit clusters
  - Single mip, or
  - No mip
- Counting clusters should reduce fluctuations

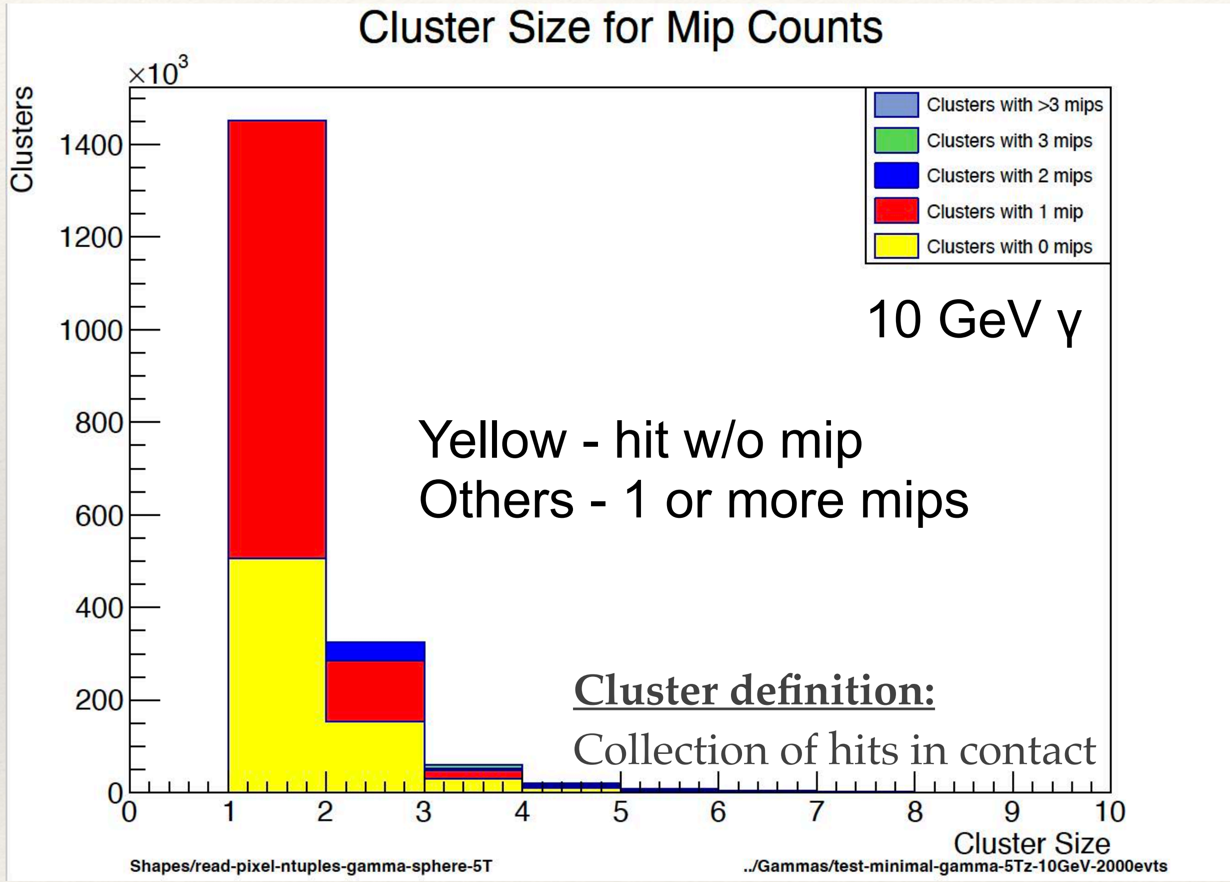


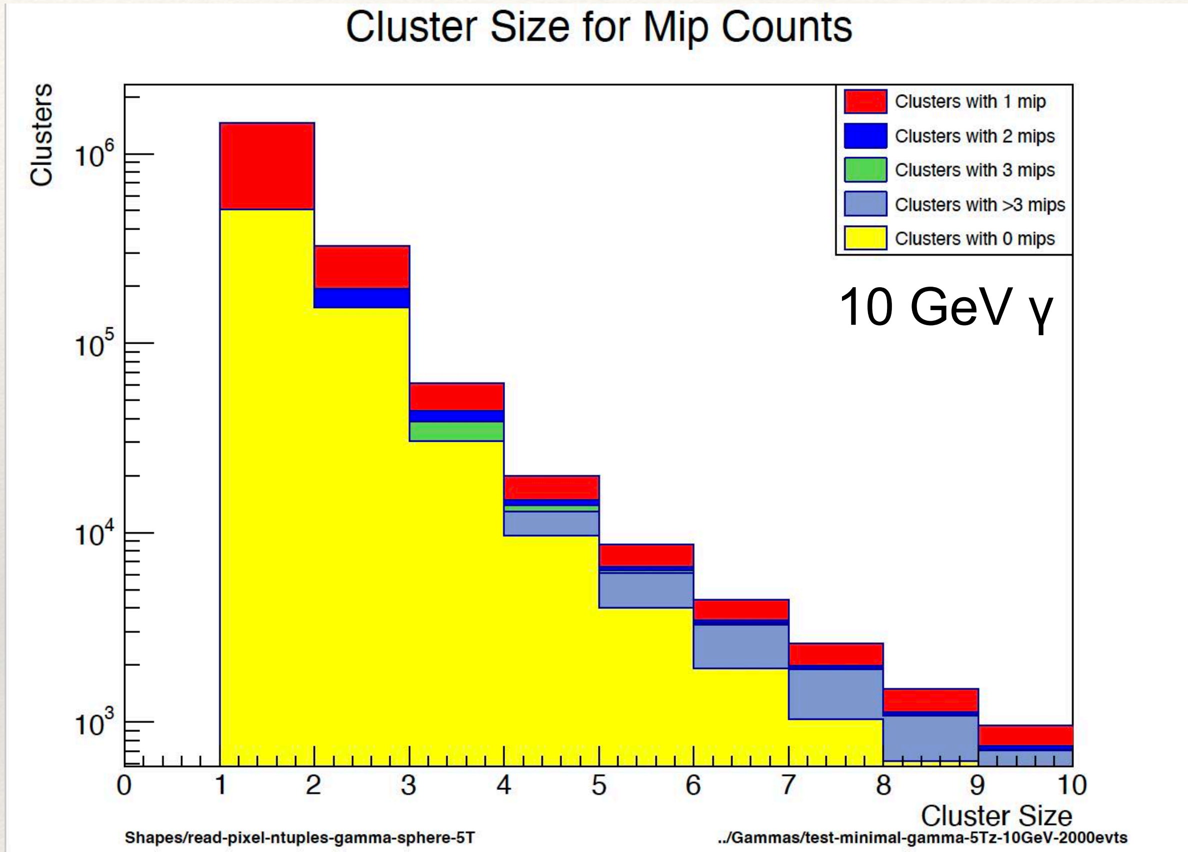
Hits & Clusters (10 GeV γ)





Cluster summary (10 GeV γ)



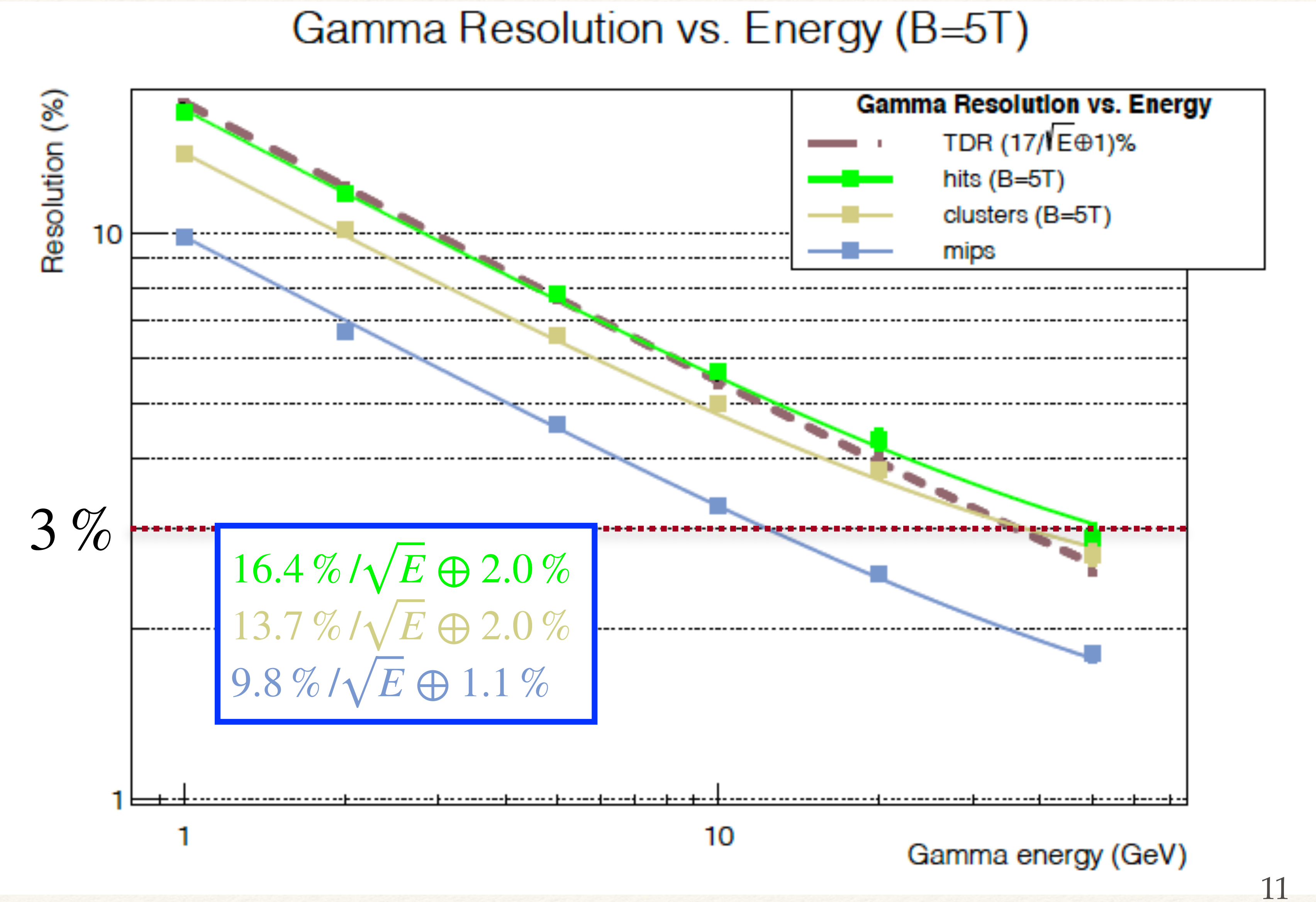


Cluster count is closer to mip count, reducing fluctuations from multiple hits.

Resolution vs. Energy (hits/clusters/mips)

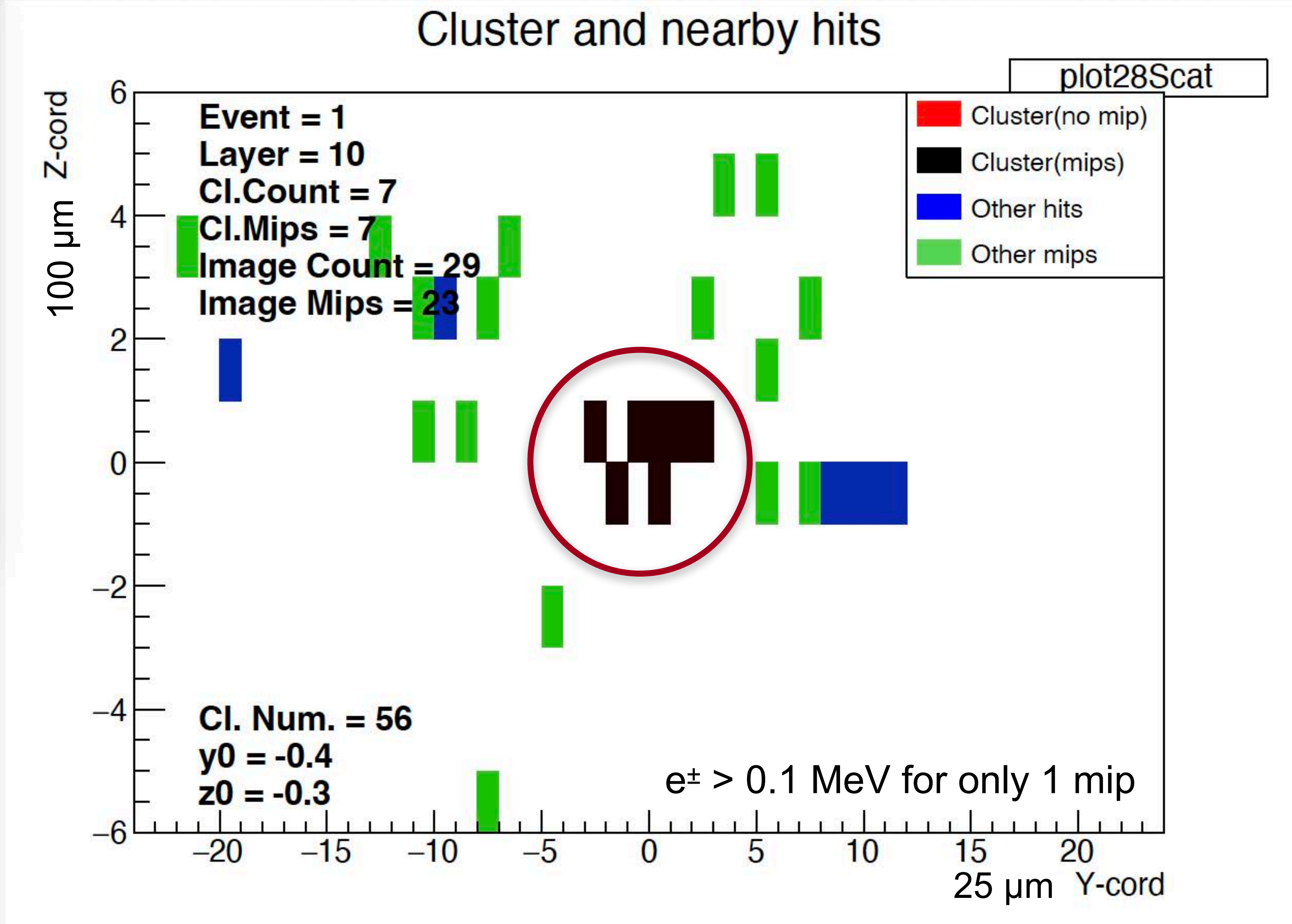
Resolution vs. Energy (hits/clusters/mips)

Simple cluster performance is better than hit counting.

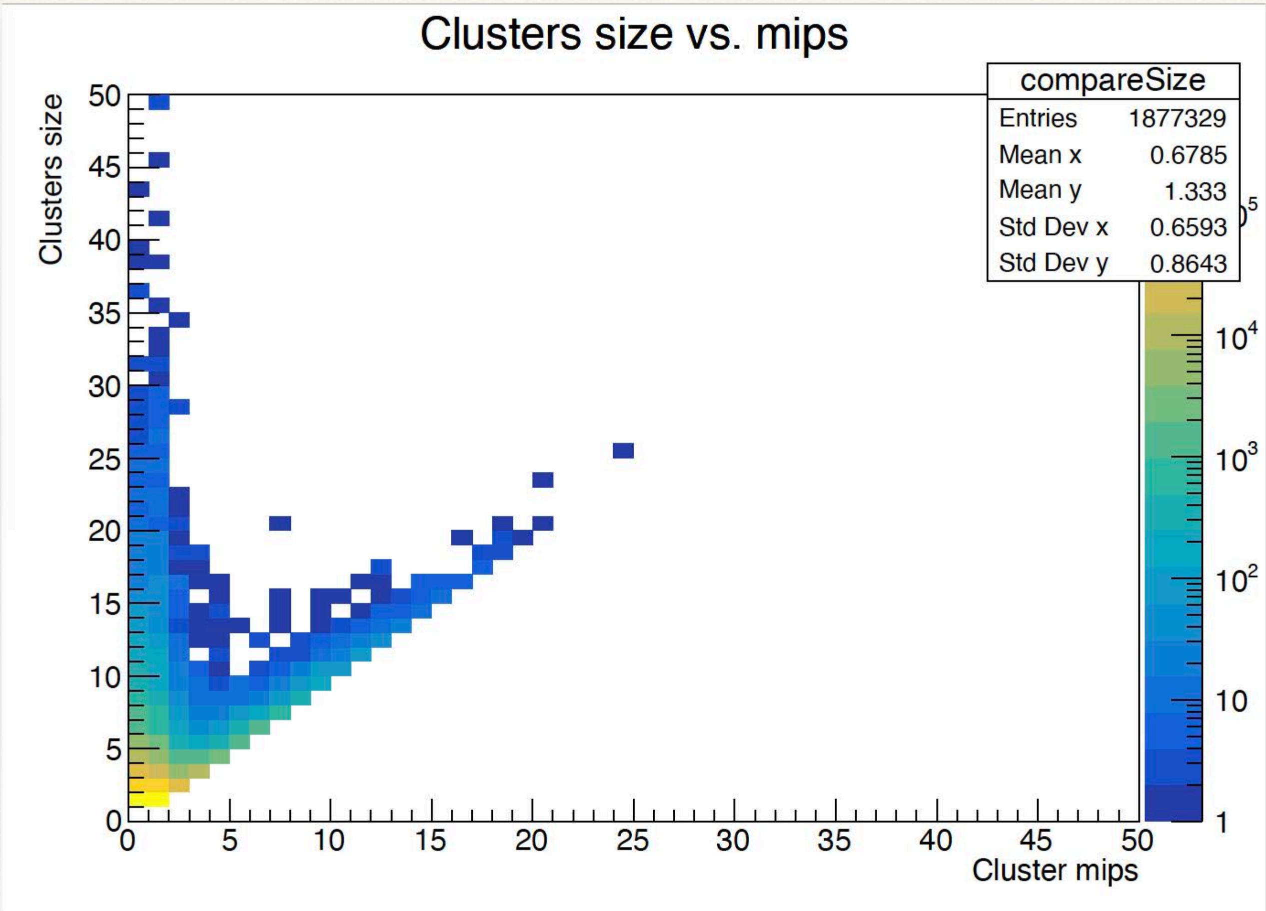


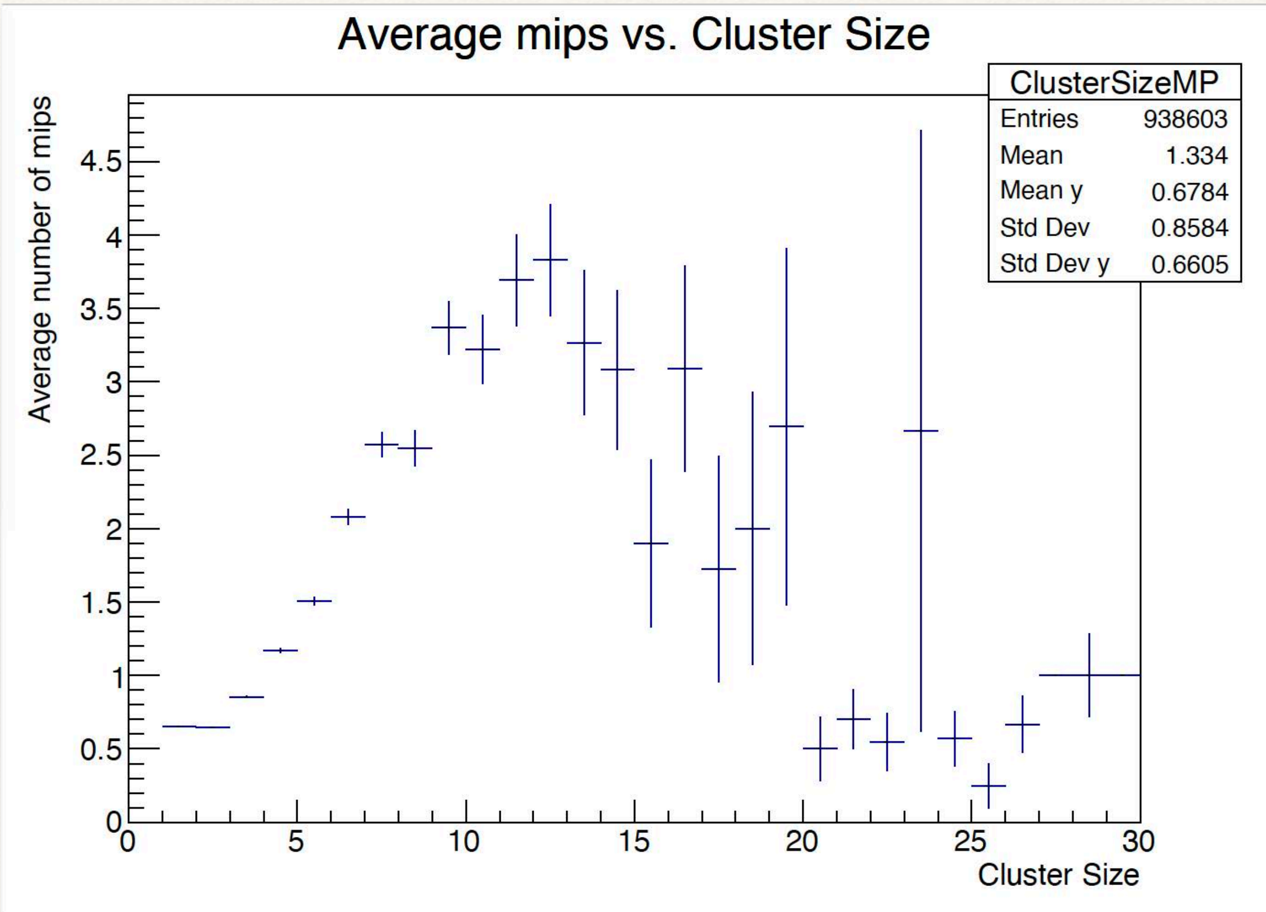
All Clusters are not the same

Some clusters are numerous mips.

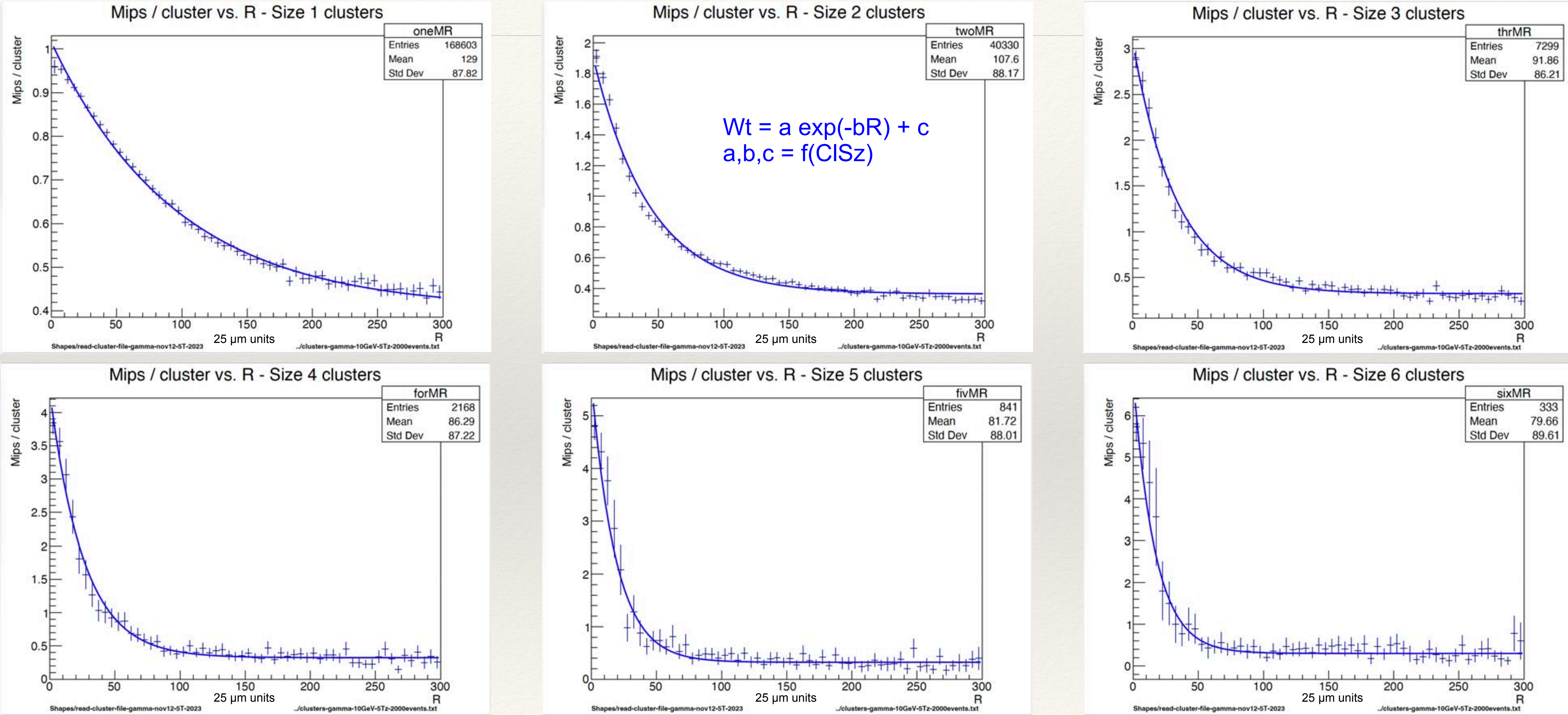


10 GeV γs - 2000 showers

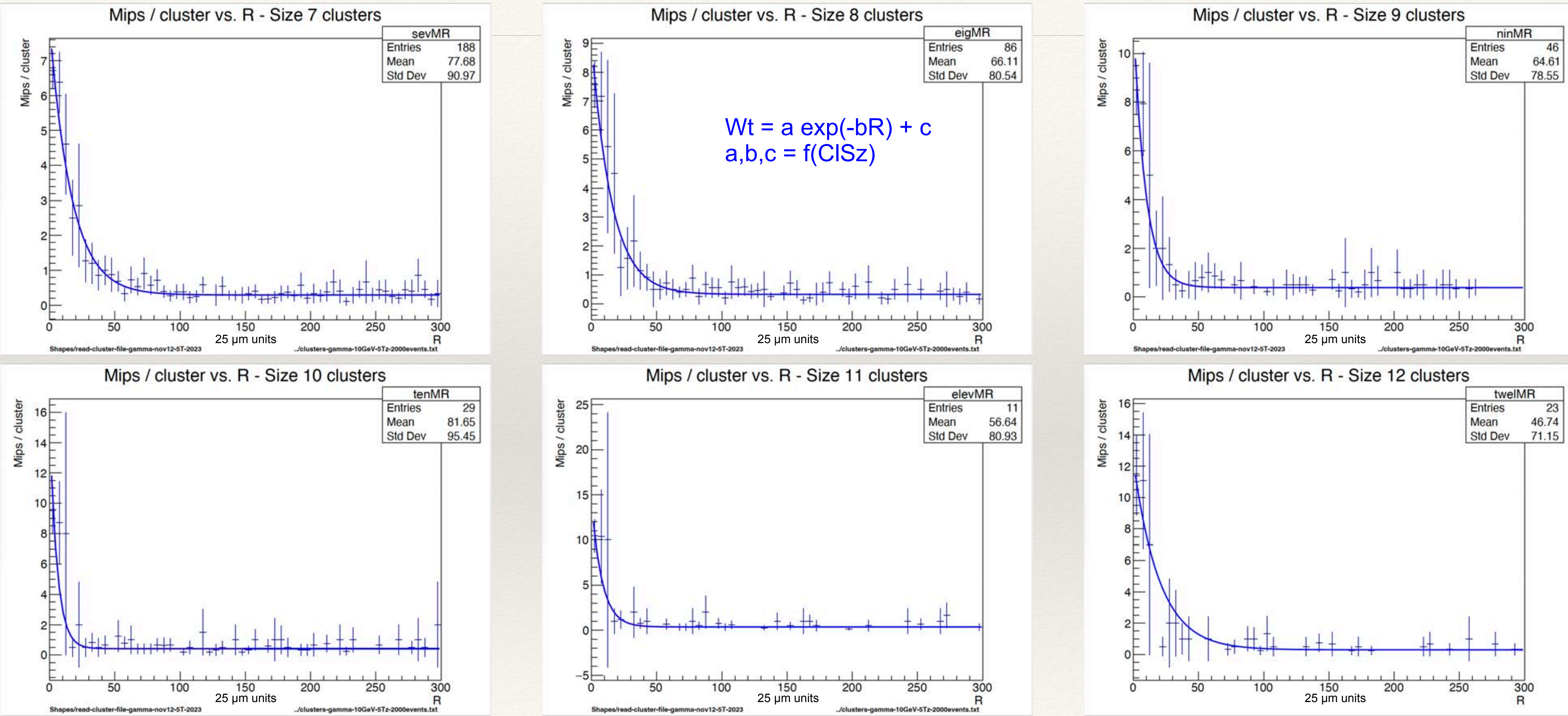




10 GeV γs - 2000 showers



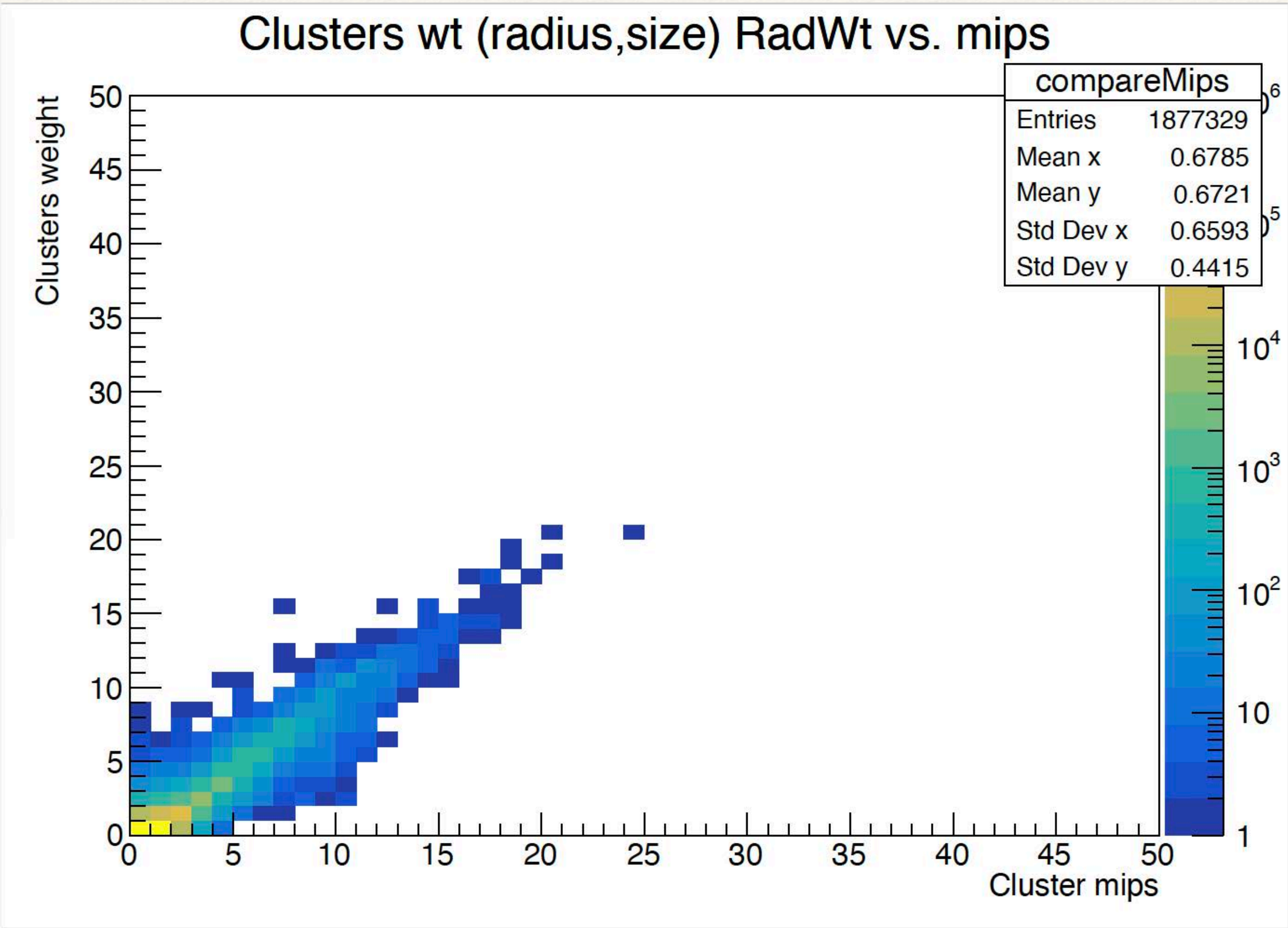
10 GeV γs - 2000 showers



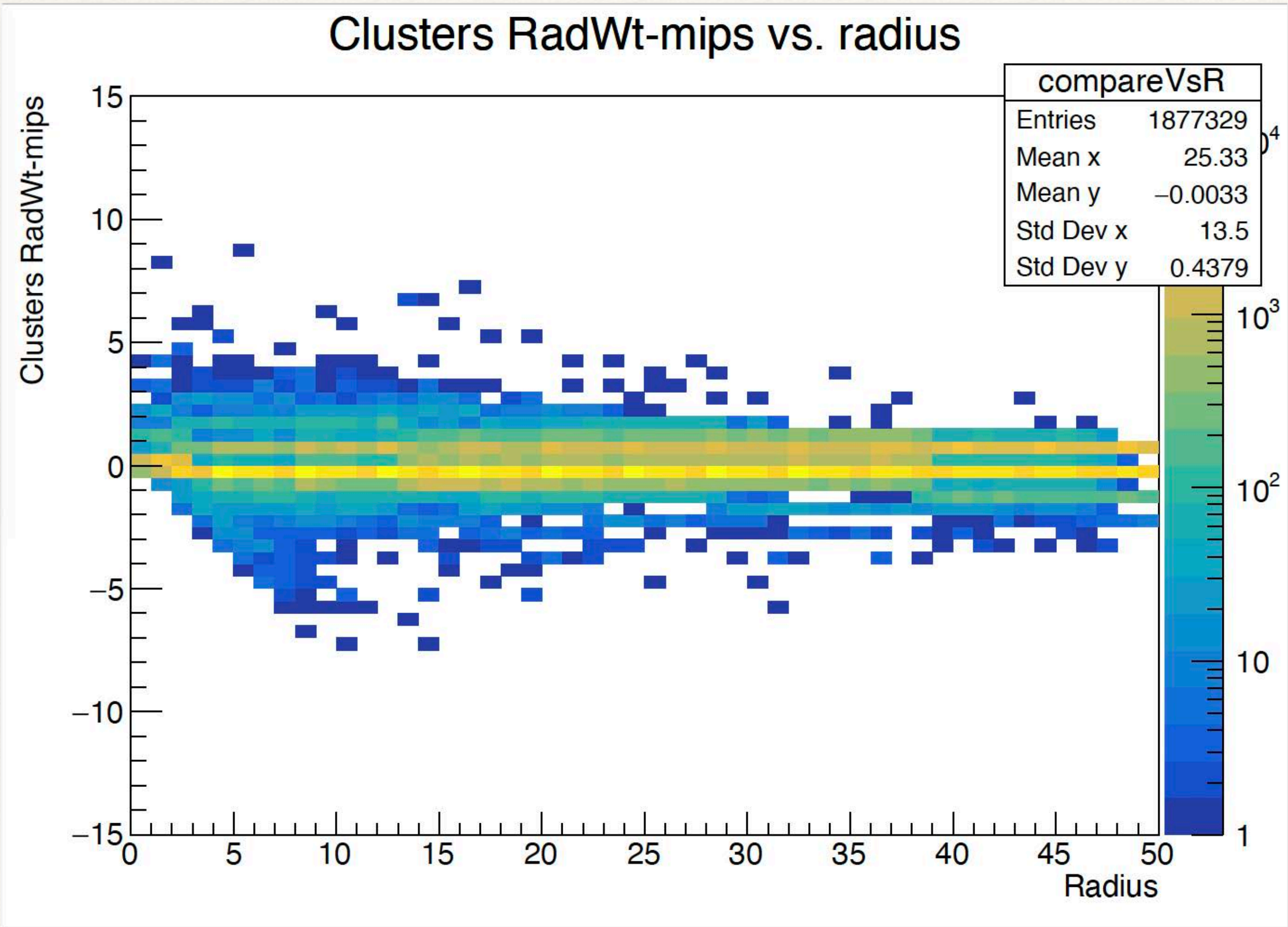
10 GeV γs - 2000 showers

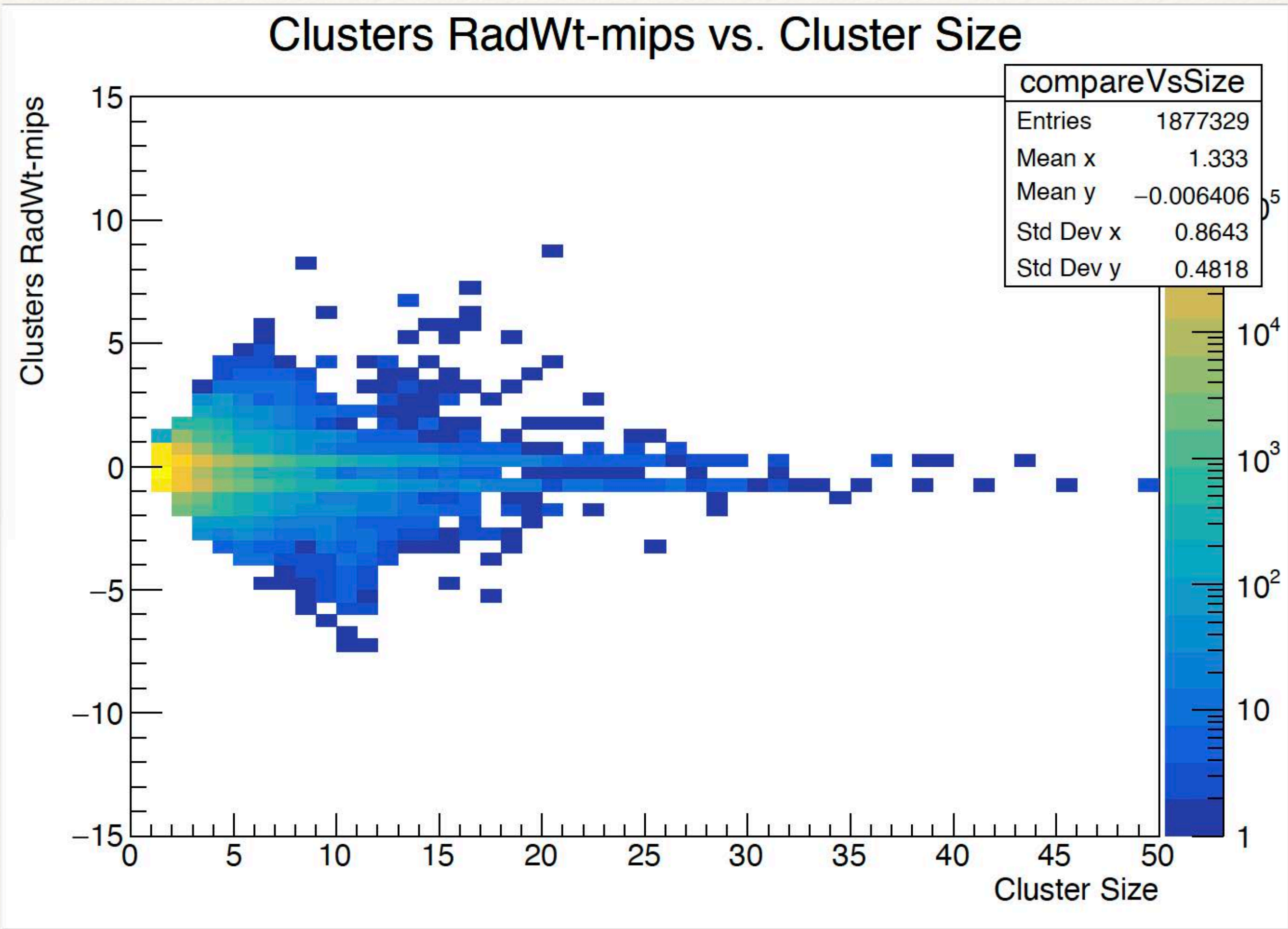
RadWt = a exp(-bR) + c

a,b,c = f(ClSz)

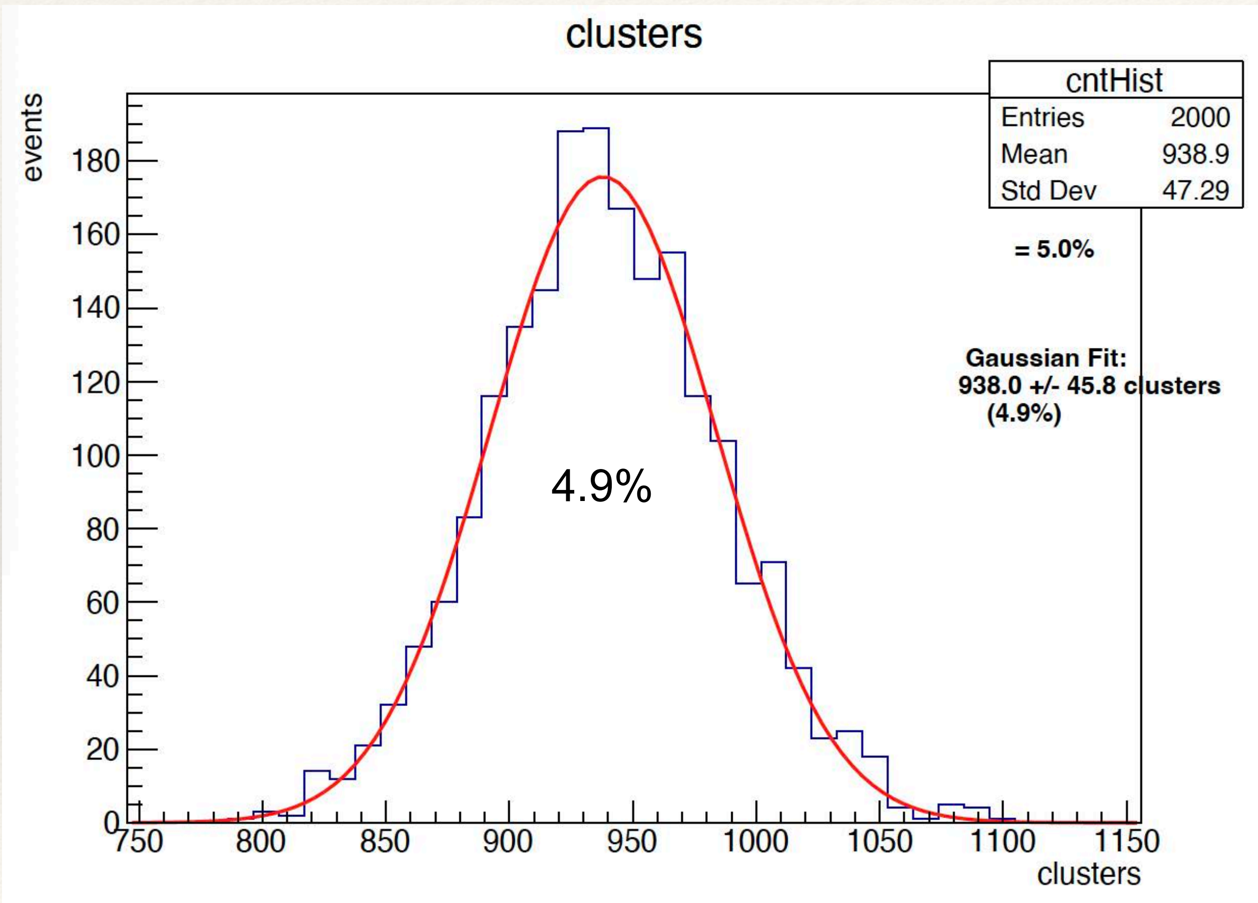


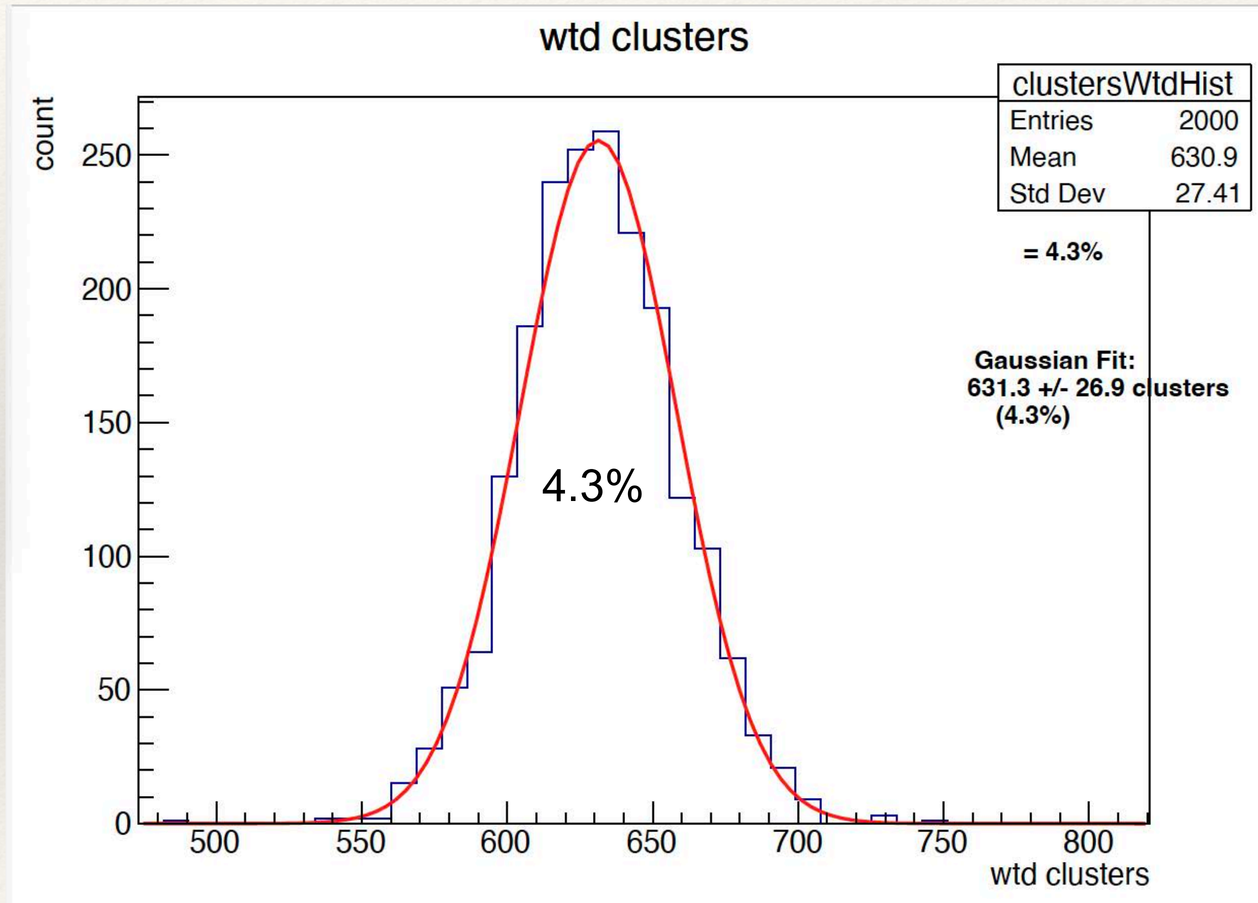
10 GeV γs - 2000 showers





Weights (mips/hit in cluster) improve resolution
10 GeV γs



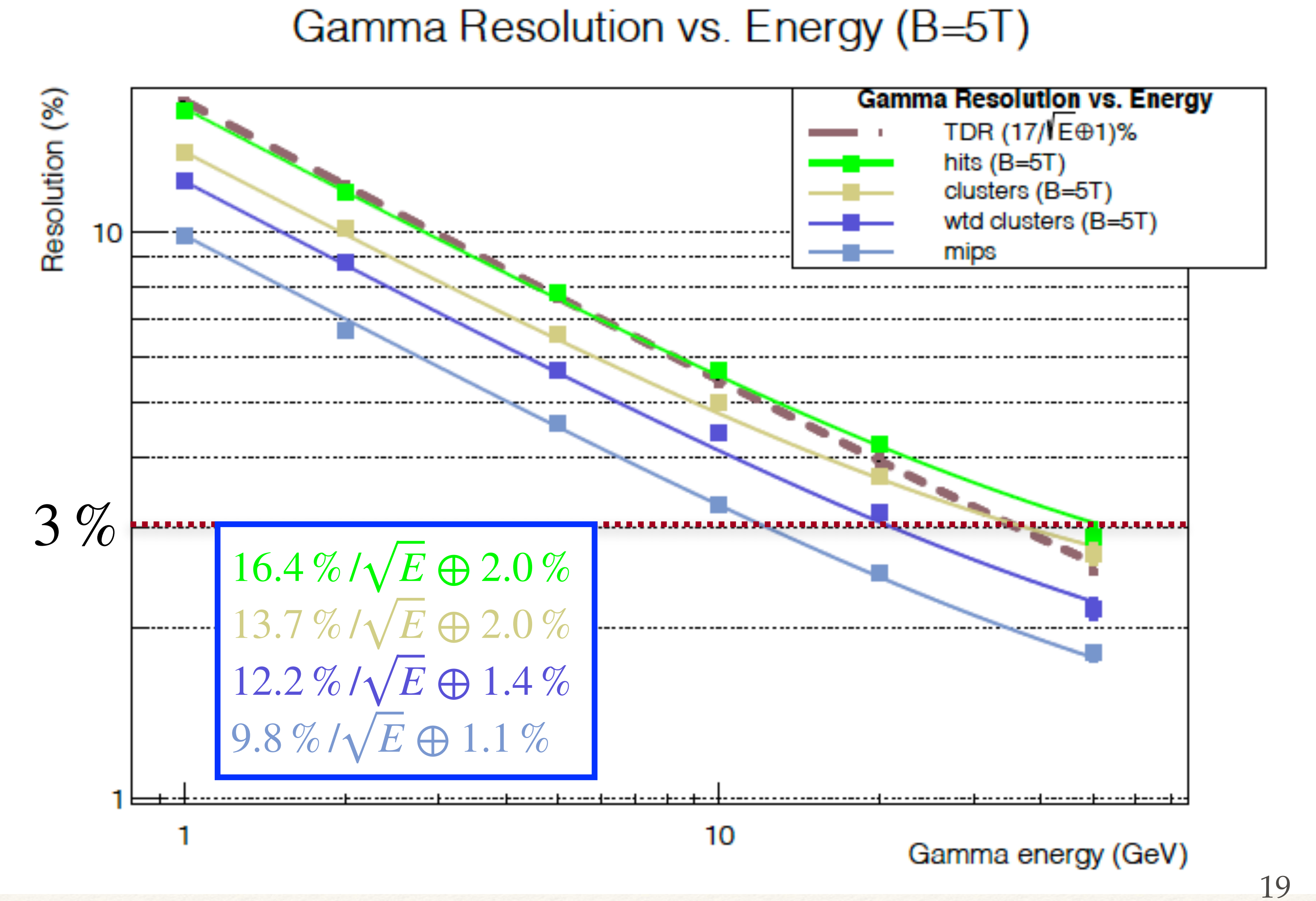


Resolution vs. Energy (hits/clusters/mips)

Resolution vs. Energy (hits/clusters/mips) & **weighted clusters.**

Simple cluster performance is better than hit counting.

When cluster properties are taken into account with weighting, performance improves.

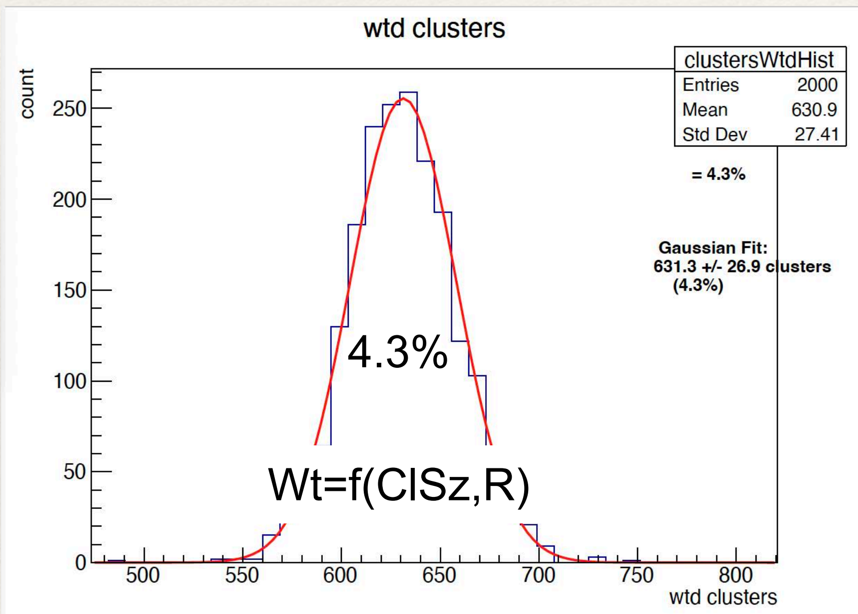


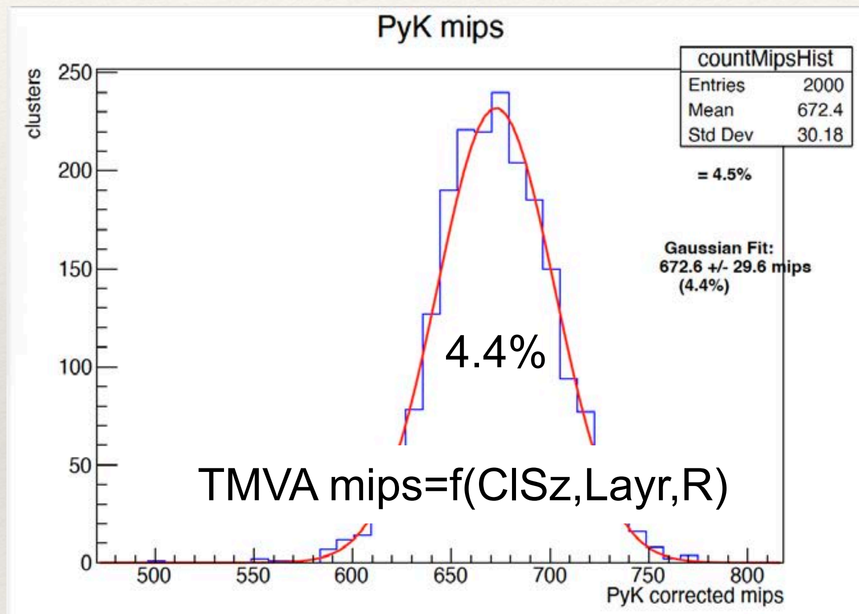
TMVA Neural Net

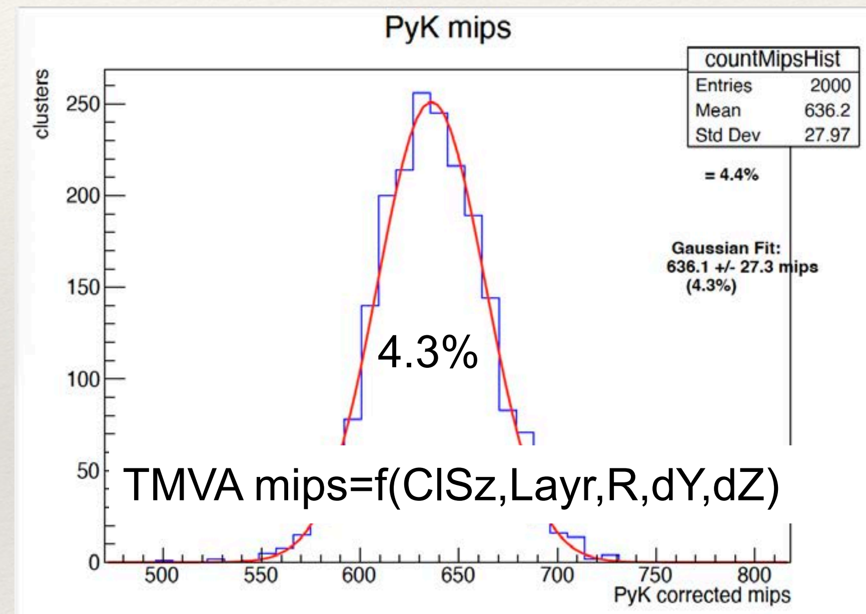
TRAINING - 10 GeV
2000 events
2,502,000 hits
1,878,999 clusters

```
# Store model to file
model.save('modelRegression%s.h5'%Efact)
model.summary()

# Book methods
factory.BookMethod(dataloader, TMVA.Types.kPyKeras, 'PyKeras',
    'H:!
V:VarTransform=D,G:FilenameModel=modelRegression%s.h5:FilenameTrainedModel=
trainedModelRegression%s.h5:NumEpochs=20:BatchSize=32'%(Efact,Efact))
```

Weighted function vs. TMVA neural net (10 GeV γs)







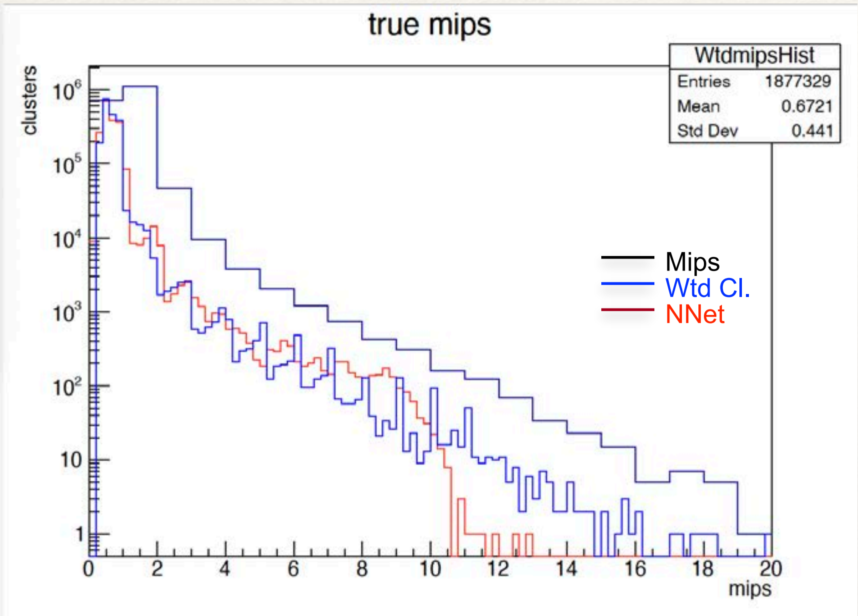
Results: Energy Resolution

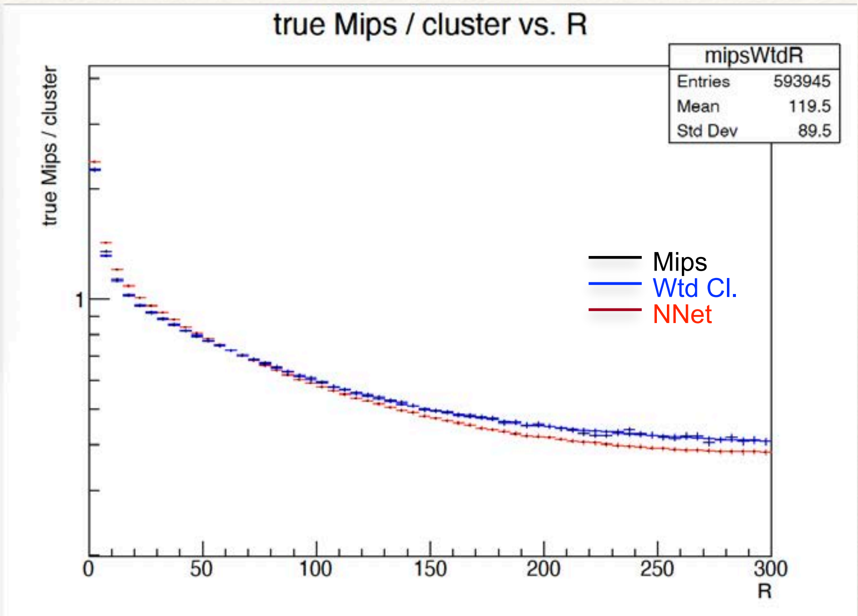
Energy	1	2	5	10	20	50
clusters	13.8%	10.1%	6.6%	5.0%	3.7%	2.7%
wtd clusters	12.3%	8.8%	5.7%	4.4%	3.2%	2.2%
3 par TMVA	12.6%	9.5%	6.2%	4.4%	3.4%	2.2%
5 par TMVA	12.8%	9.4%	5.9%	4.3%	3.1%	2.2%

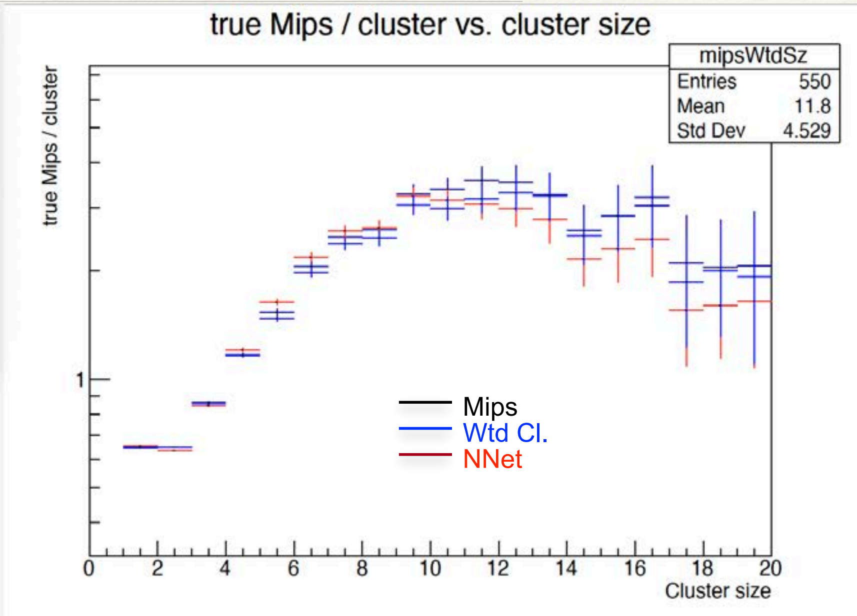
- Weight fits for 2, 10, 50 GeV; extrapolated for 1, 5, 20 GeV.
- NN optimized for each energy
- 3 par = cluster size, layer, radius
- 5 par = cluster size, layer, radius, dY, dZ

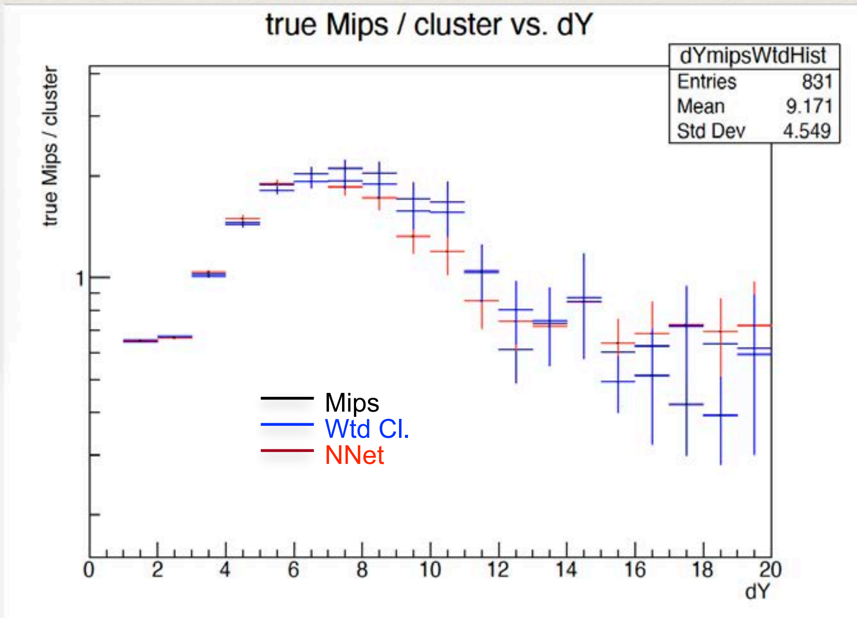
Weighted clusters already achieve performance of this neural net.

10 GeV γs


true mips
WtdmipsHist
Entries 1877329
Mean 0.6721
Std Dev 0.441
Mips
Wtd Cl.
NNet
clusters
mips


true Mips / cluster vs. R
mipsWtdR
Entries 593945
Mean 119.5
Std Dev 89.5
Mips
Wtd Cl.
NNet
true Mips / cluster
R


true Mips / cluster vs. cluster size
mipsWtdSz
Entries 550
Mean 11.8
Std Dev 4.529
Mips
Wtd Cl.
NNet
true Mips / cluster
Cluster size

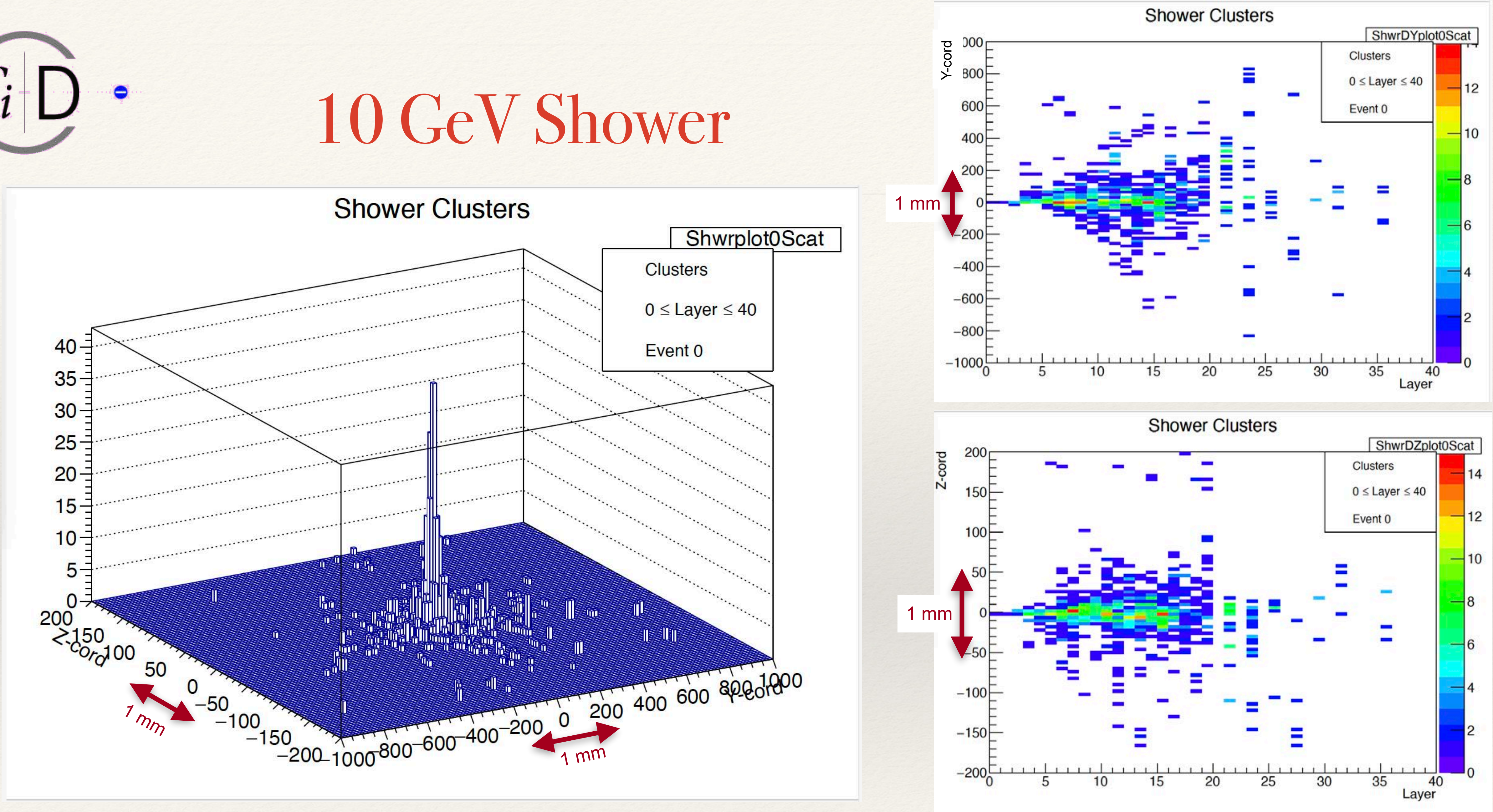

true Mips / cluster vs. dY
dYmipsWtdHist
Entries 831
Mean 9.171
Std Dev 4.549
Mips
Wtd Cl.
NNet
true Mips / cluster
dY

TMVA Code

```
# Define model
model = Sequential()
model.add(Dense(64, activation='tanh', input_dim=5))
model.add(Dense(1, activation=‘linear'))

# Set loss and optimizer
model.compile(loss='mean_squared_error', optimizer=SGD(learning_rate=0.01), weighted_metrics=[])

# Store model to file
model.save('modelRegression%s.h5'%Efact)
model.summary()

# Book methods
factory.BookMethod(dataloader, TMVA.Types.kPyKeras, 'PyKeras',
        ‘H:!
V:VarTransform=D,G:FilenameModel=modelRegression%s.h5:FilenameTrainedModel=trainedModelRegression%s
.h5:NumEpochs=20:BatchSize=32'%(Efact,Efact))

# Run TMVA
factory.TrainAllMethods()
factory.TestAllMethods()
factory.EvaluateAllMethods()
```

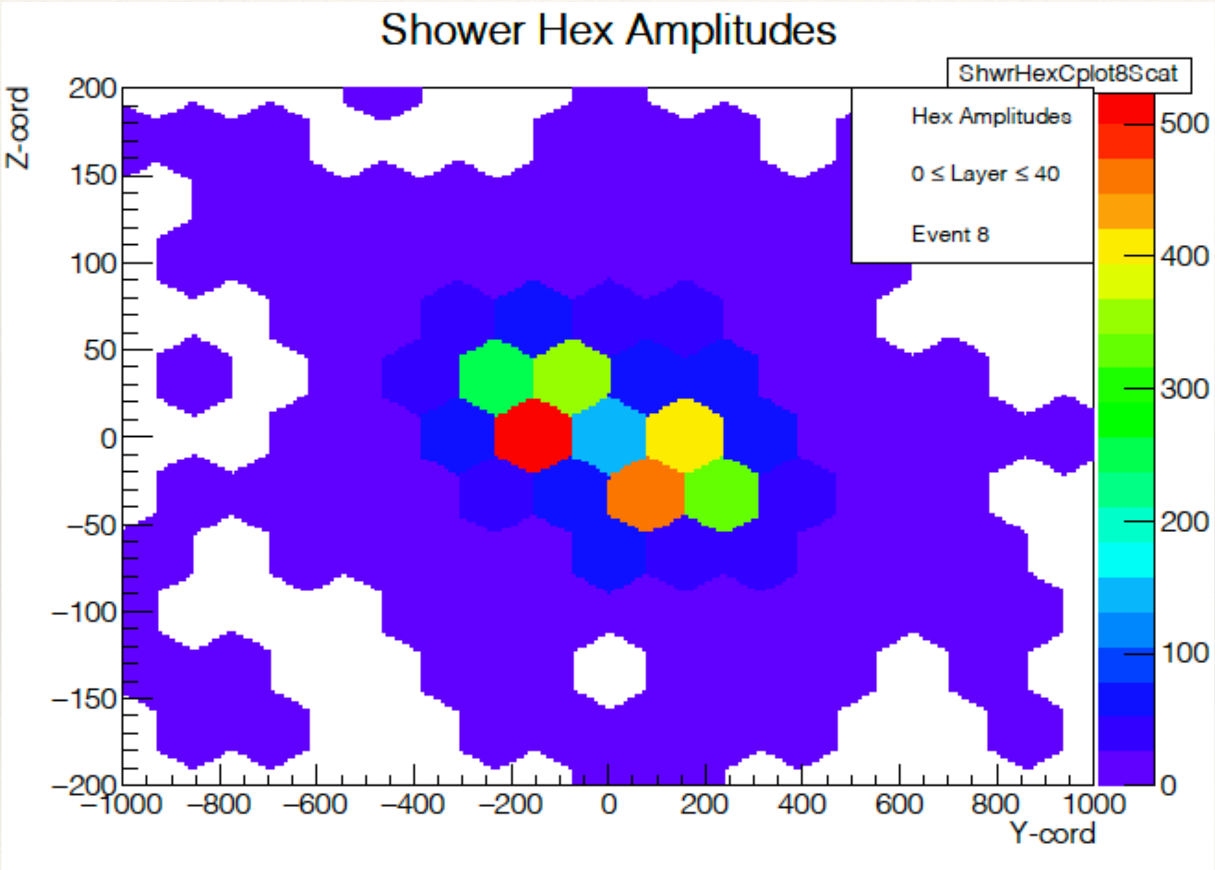
Transverse Shower Structure

10 GeV Shower

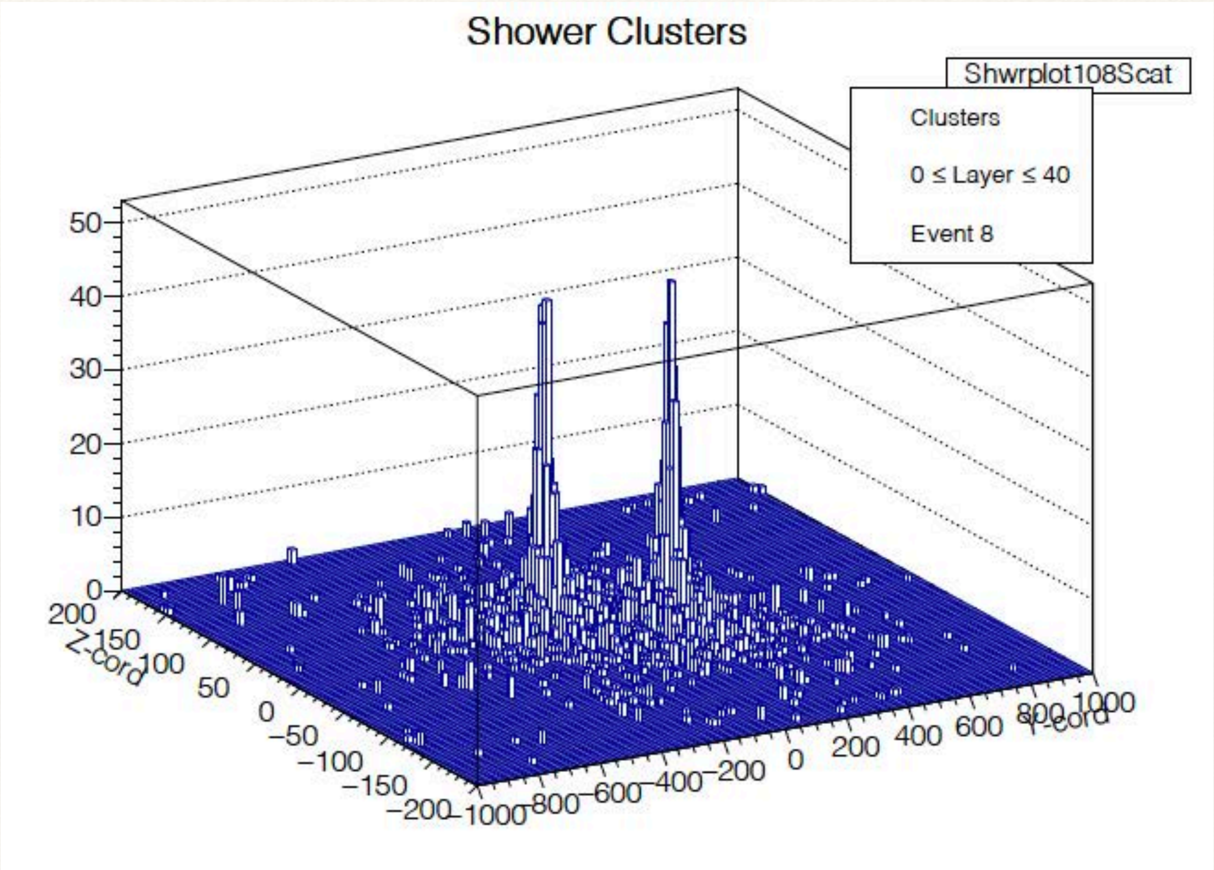


Multi-shower of SiD MAPS compared to SiD TDR

40 GeV $\pi^0 \rightarrow$ two 20 GeV γ's



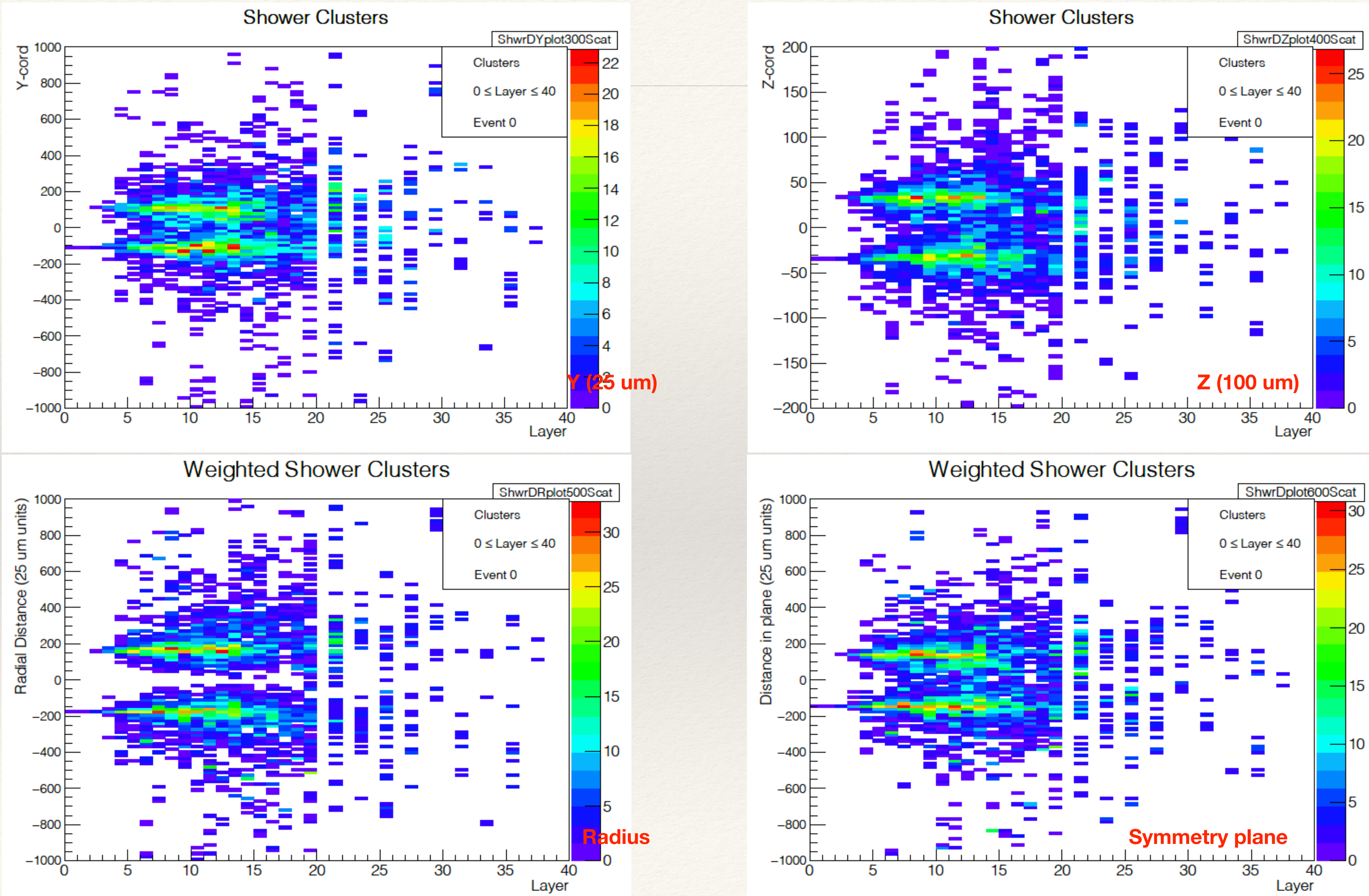
SiD TDR hexagonal sensors
13 mm² pixels

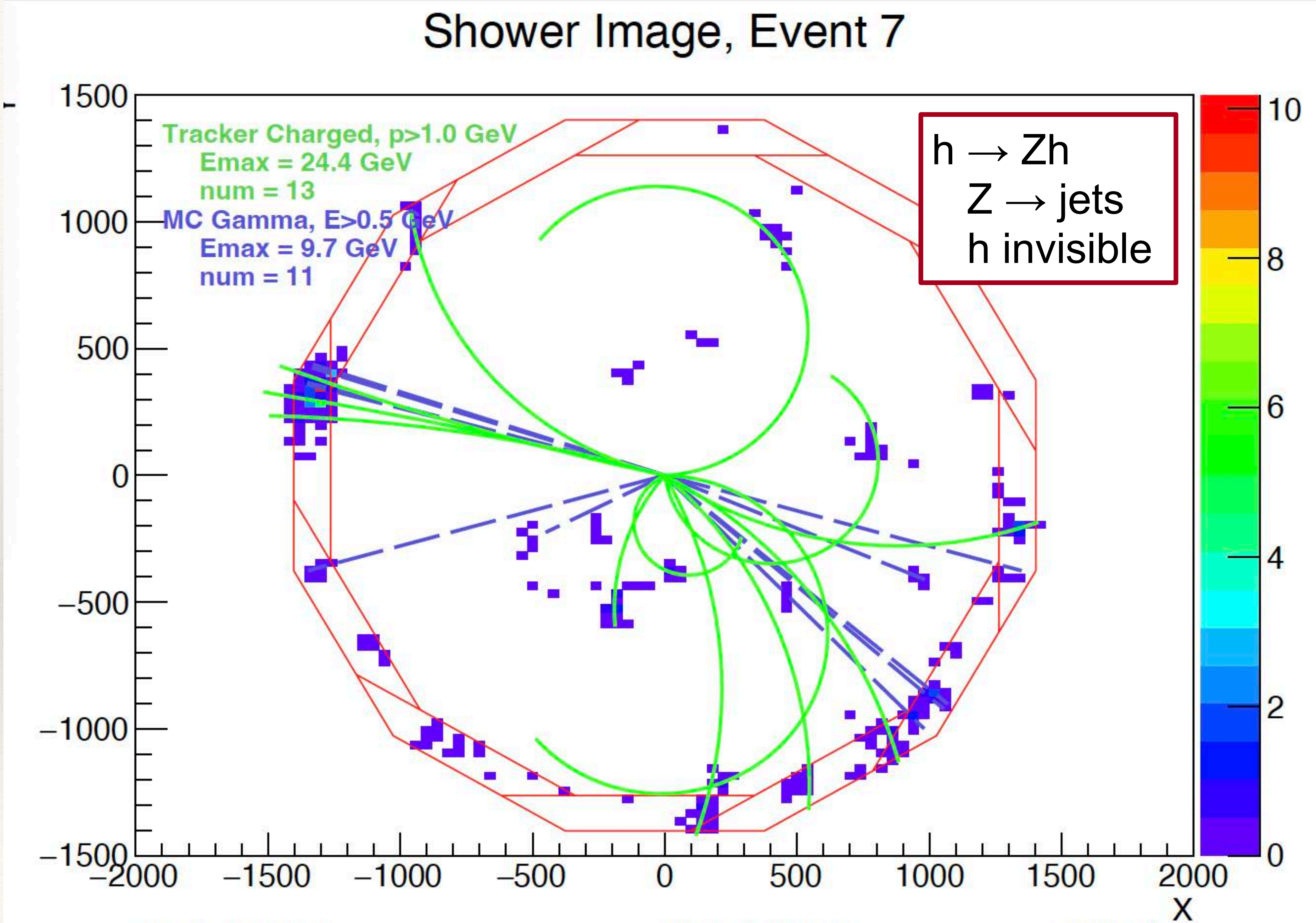


New SiD fine pixel sensors
25 μm x 100 μm pixels

40 GeV $\pi^0 \rightarrow$ two 20 GeV γ's

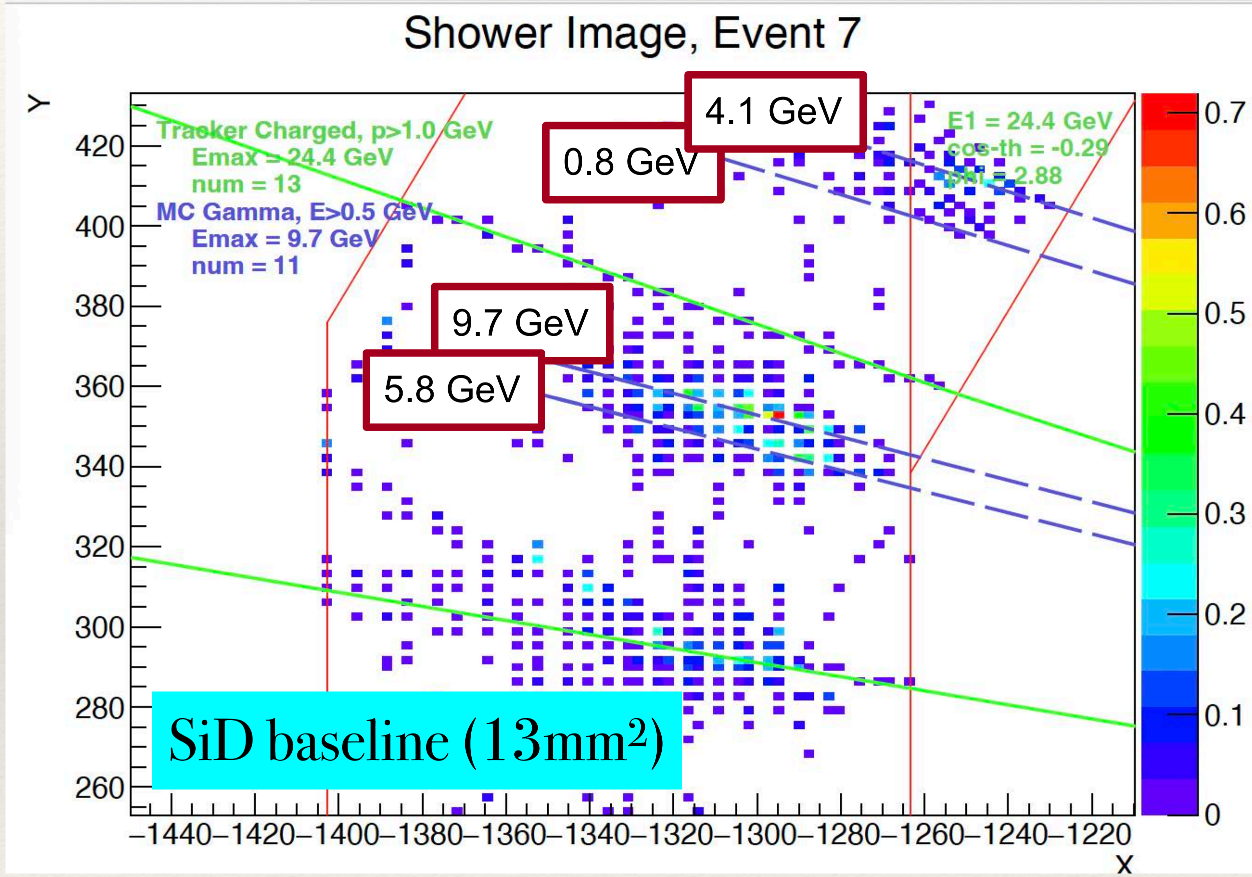
Vertical bin
400 um

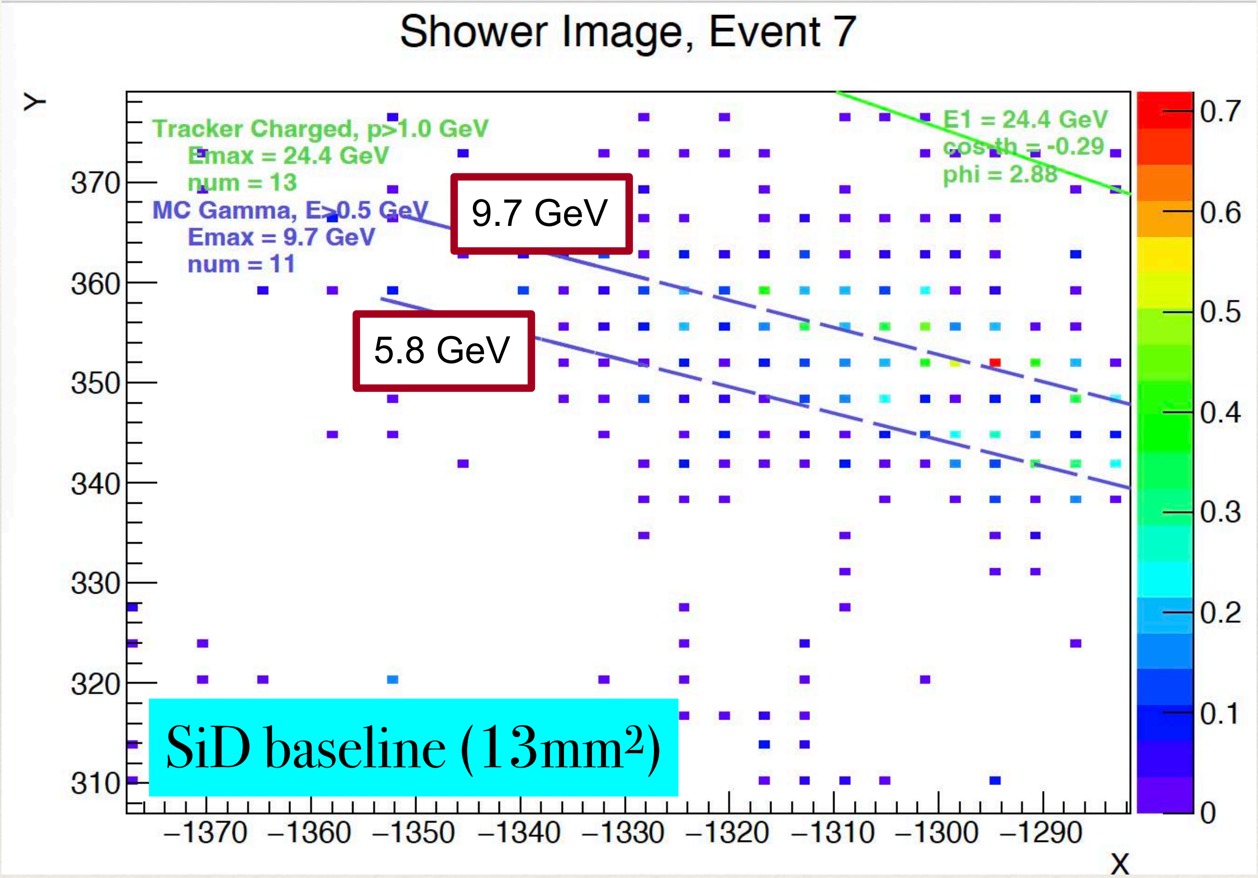




Shower Image, Event 7
Tracker Charged, p>1.0 GeV
Emax = 24.4 GeV
num = 13
MC Gamma, E>0.5 GeV
Emax = 9.7 GeV
num = 11
h → Zh
Z → jets
h invisible
1500
1000
500
0
−500
−1000
−1500
−2000
−1500
−1000
−500
0
500
1000
1500
2000
X
10
8
6
4
2
0

γ's in jet / SiD baseline ECal (13mm² pixels)





- 13 mm² pixels of analog SiD ECal
- 5000x granularity with digital MAPS ECal - What is scale of improvement?

Conclusion

- Application of monolithic active pixel sensors to SiD digital ECal offers excellent performance:
  - Energy measurement
  - Transverse energy containment & multiple shower separation
- The well defined structure of EM showers allows simple algorithmic improvement in energy measurement.
- Neural nets have been studied to improve energy measurement:
  - They have not yet provided improved performance over the simple algorithm.
- Future - simulation of full SiD detector with high granularity of MAPS ECal