Single Photon/Di-photon Reconstruction Performance in Full Simulation

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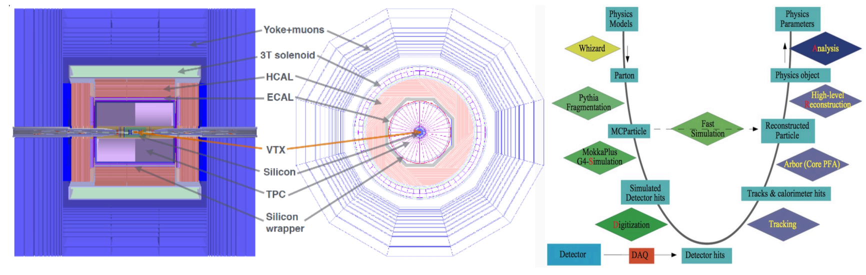
Motivation

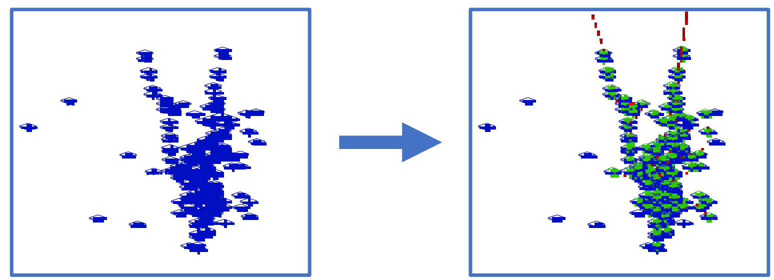
- Photon reconstruction in CEPC
- Potential mistakes
  - Cluster merging
  - Cluster split

Photon reconstruction in CEPC

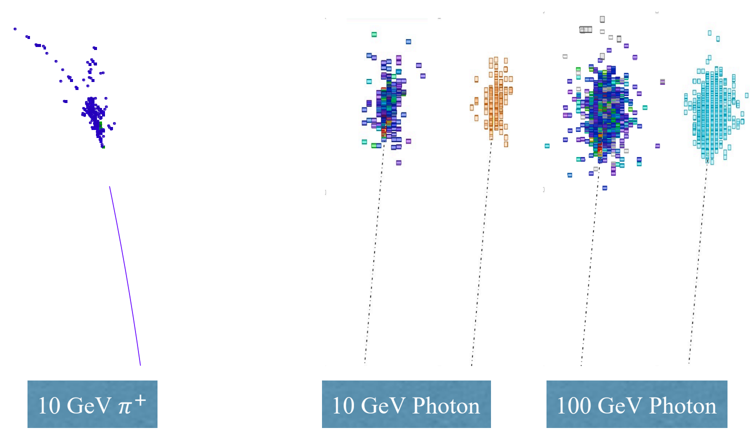
- The CEPC baseline detector is a particle flow oriented detector and equips a dedicated particle flow reconstruction algorithm, Arbor.



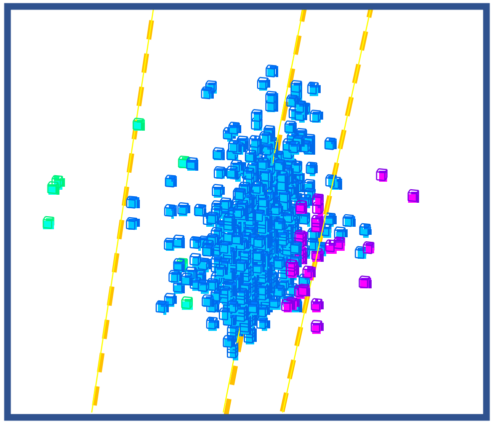
- Benefit from the high granular calorimeter design, the topological of particle shower could be observed.



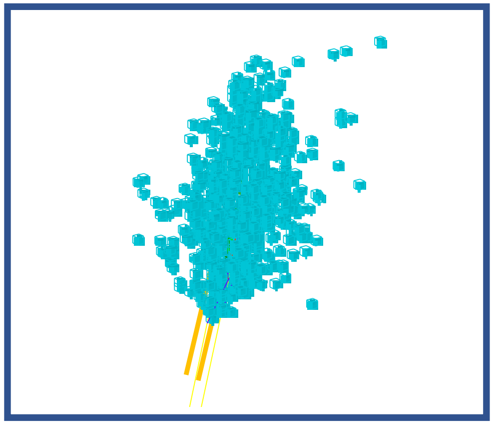
- After reconstruction, the charged particle is reconstructed as a cluster and a matched trajectory.
- And neutral particle is reconstructed as only a cluster.



Potential mistakes



(a) Cluster **splitting**



(b) Cluster **merging**

A photon shower reconstructed as more than one clusters.

The split phenomenon could be well characterized by **single photon reconstruction.**

The two shower are closed with each other.

They could be merged together and reconstructed as only one cluster.

The separation performance of nearby photon clusters, can be characterized by π^0 **reconstruction.**

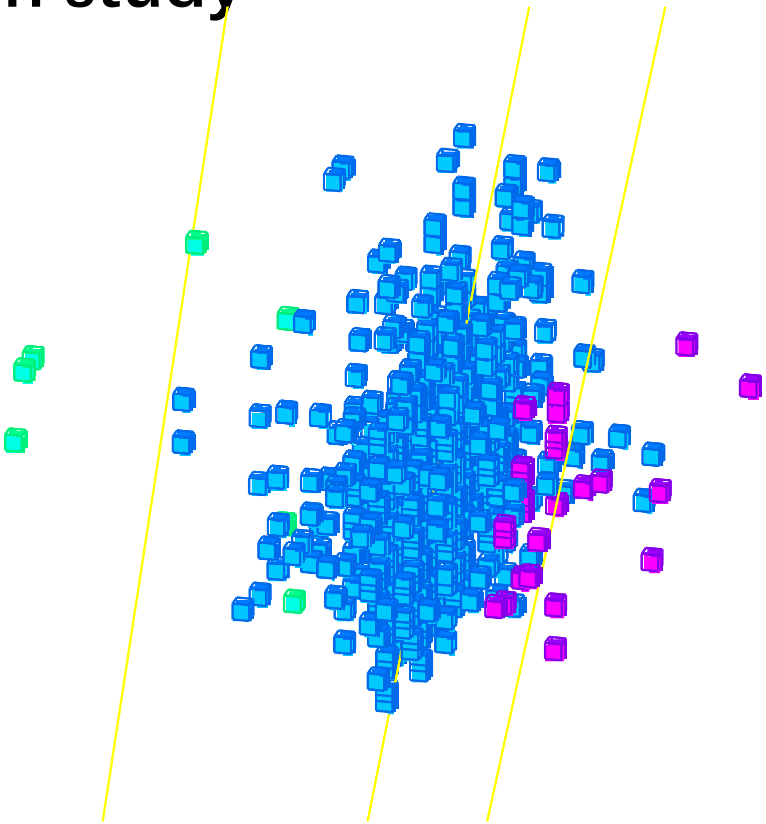
Both single photon study and single π^0 study are fundamental researches to understand the behaviors of the detectors.

Single photon/π^0 reconstruction performance

- Hit collection efficiency
- Split probability
- Energy resolution and linearity

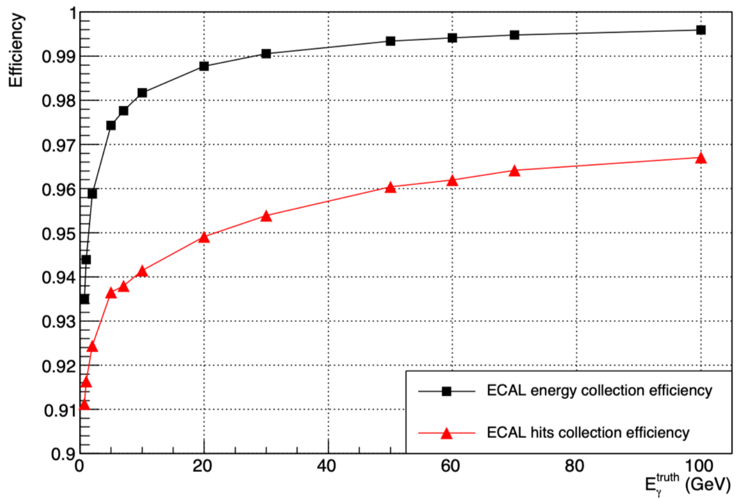
Single photon/π^0 reconstruction performance

Single photon study

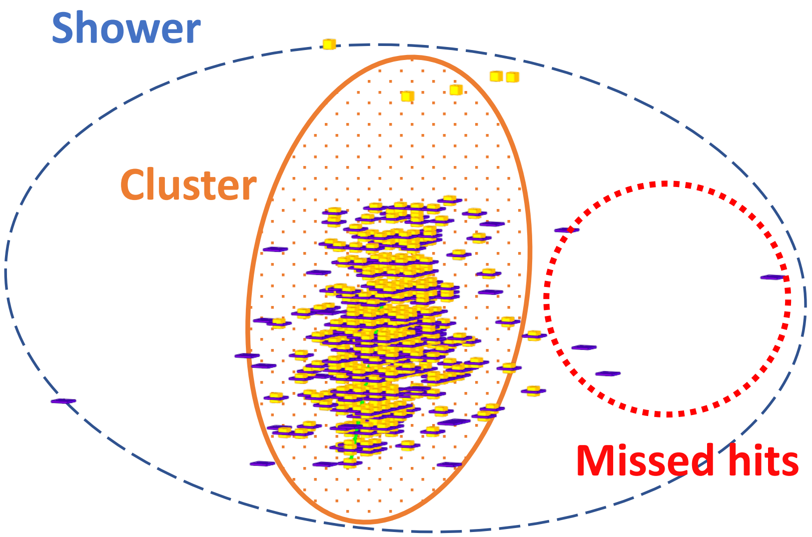


A split photon shower

Hit collection efficiency



(a) $\varepsilon = \frac{hits\ in\ cluster}{all\ hits}$



(b) Event display: the **purple flake markers** represent the calorimeter hit and the **yellow cube markers** represent the clusters

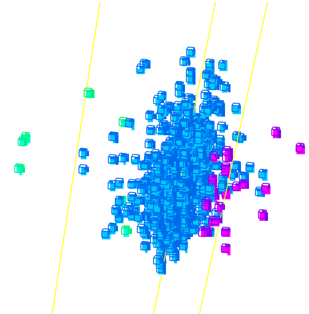
Hit collection efficiency as a function of incident energy .

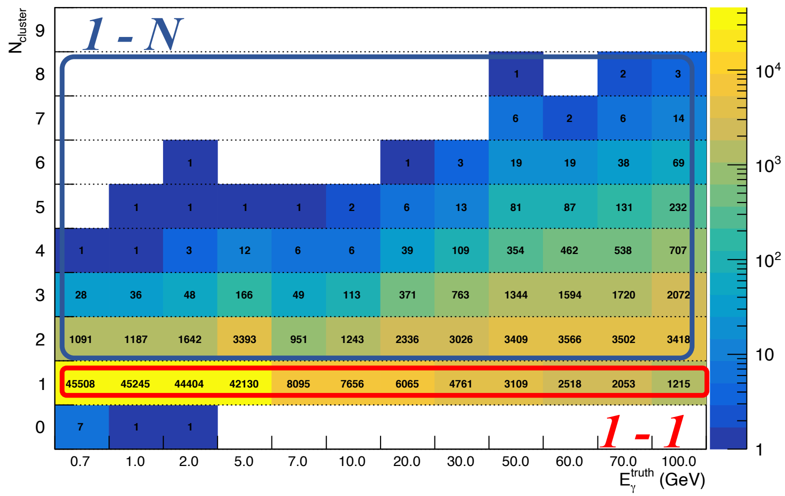
The **black** line represents the collection efficiency weighted by **hit energy**.

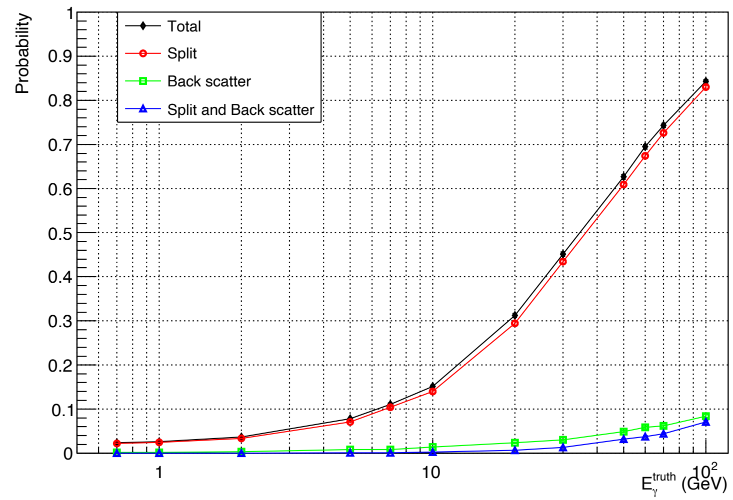
The **red** line represents the unweighted collection efficiency just counted by **hits number**.

The right plot displays the uncollected hits of a photon shower.

Number of clusters and splitting probability







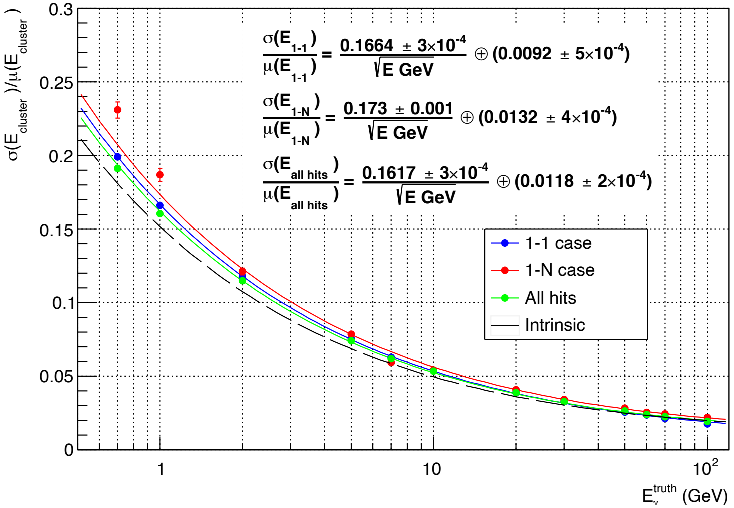
The left plot shows the number of reconstructed clusters in each event.

1-1 corresponding events called ***1-1 case***, while multi-cluster events called ***1-N case***.

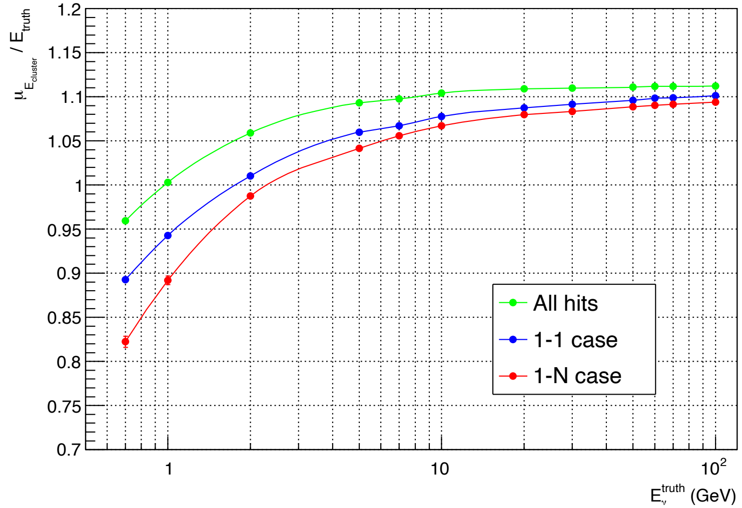
The right plot shows the ratio of 1-N events and total events number, in which split and backscatter events number are estimated and shown as red line and green line.

Energy response of 1-1 case & 1-N case

Both the hit missing and split effect reduce the energy reconstruction performance.



Energy resolution: $\frac{\sigma(E_{cluster})}{\mu(E_{cluster})}$



Energy linearity: $\frac{\mu(E_{cluster})}{E_{truth}}$

In ***1-1 case***: $E_{cluster} = \sum\left\{E_{hit}^{The\ only\ cluster}\right\}$

In ***1-N case***: $E_{cluster} = \sum\left\{E_{hit}^{Leading\ cluster}\right\}$, where the ***leading cluster*** is the most energetic cluster.

In ***All hits***: $E_{cluster} = \sum\{E_{hit}^{in\ ECAL}\}$

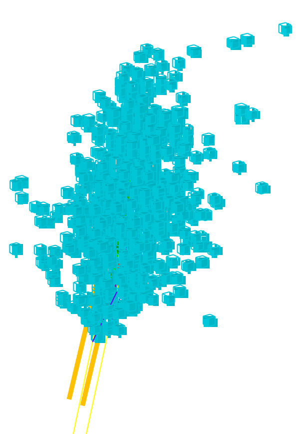
The difference between ***all hits*** and ***1-1 case*** shows the performance reduce from energy loose (low hit collection efficiency).

The difference between ***1-1 case*** and 1-N case shows the influence of split effect.

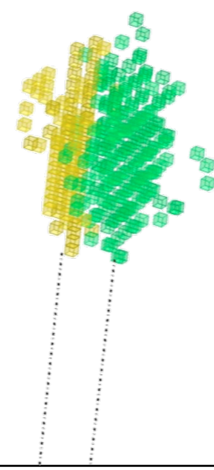
Actually, the energy of a reconstructed neutral particle is the hits energy sum times a correction factor, so the final energy linearity value could be lower than what's shown here. About more detail of photon energy correction, see back up.

di-photon & π^0 reconstruction

The photon reconstruction, especially the **separation performance** of nearby photon clusters, can be characterized by di-photon & π^0 reconstruction.

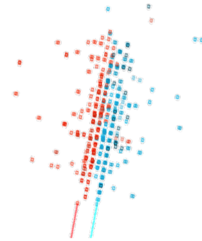


(a) Cluster merging: two photon clusters from a 25 GeV π^0 are too closed with each other to be distinguished by the reconstruction algorithm.

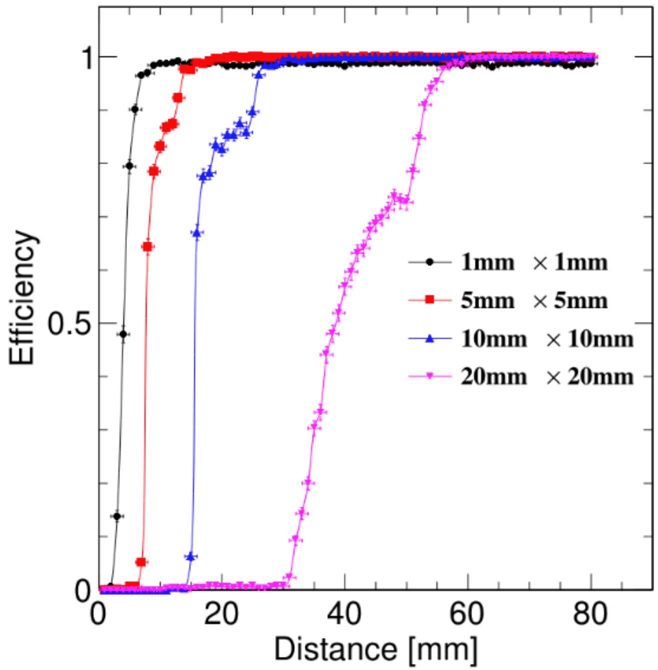


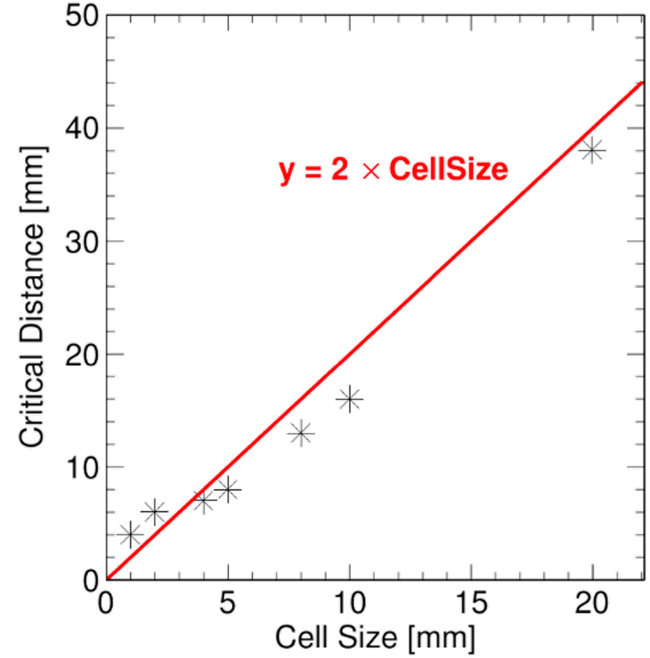
(b) A successfully reconstructed 19 GeV π0: The calorimeter showers are close to each other but can be separated.

Di-photon reconstruction: Critical distance



Events display: Reconstructed di-photon events. The left plot is with 1 mm cell size ECAL, each photon has an energy of 5 GeV, and the distance between them is 4 mm. The right plot is with 5 mm cell size ECAL and the distance between them is 11 mm.





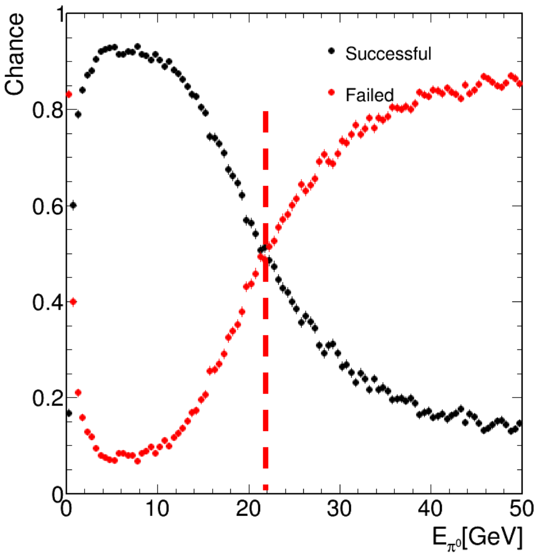
We define **the reconstruction efficiency** as the probability to successfully reconstruct two photons with anticipated energy. An event would be marked a **successfully reconstructed** if both the reconstructed photons have more than 1/3 and less than 2/3 of all the deposit energy of the both photons.

The left plot shows the **reconstruction efficiency** of di-photon samples at different cell size. The distance of the photons is scanned from 1 to 80 mm.

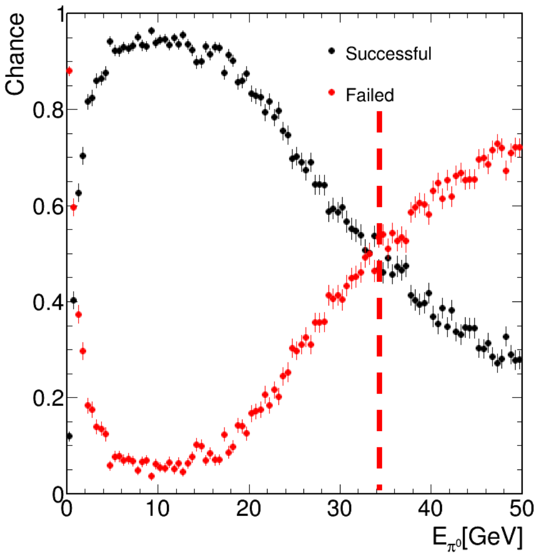
The right plot shows the **critical separation distance** versus different cell size.

H. Zhao, C. Fu, D. Yu, Z. Wang, T. Hu, and M. Ruan, *Particle Flow Oriented Electromagnetic Calorimeter Optimization for the Circular Electron Positron Collider*, J. Inst. **13**, P03010 (2018).

π^0 reconstruction: Critical energy



Barrel: |cosθ | < 0.8

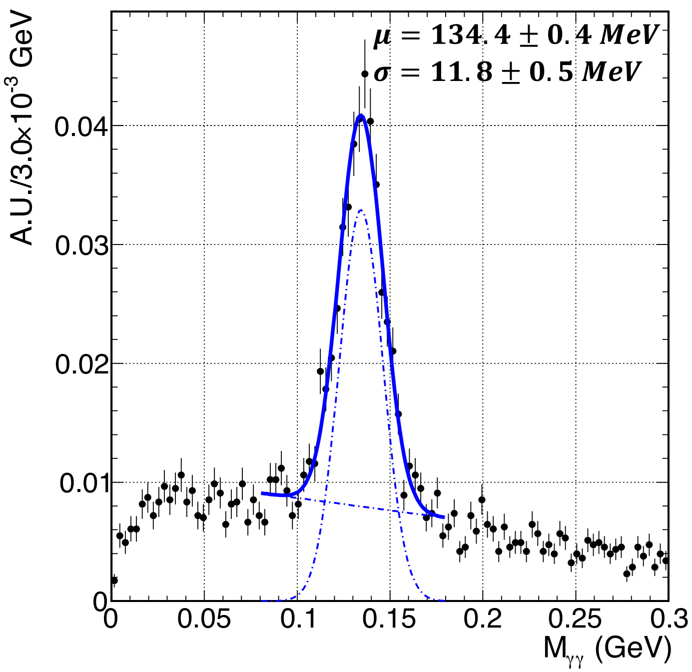


Endcap: |cosθ | > 0.8

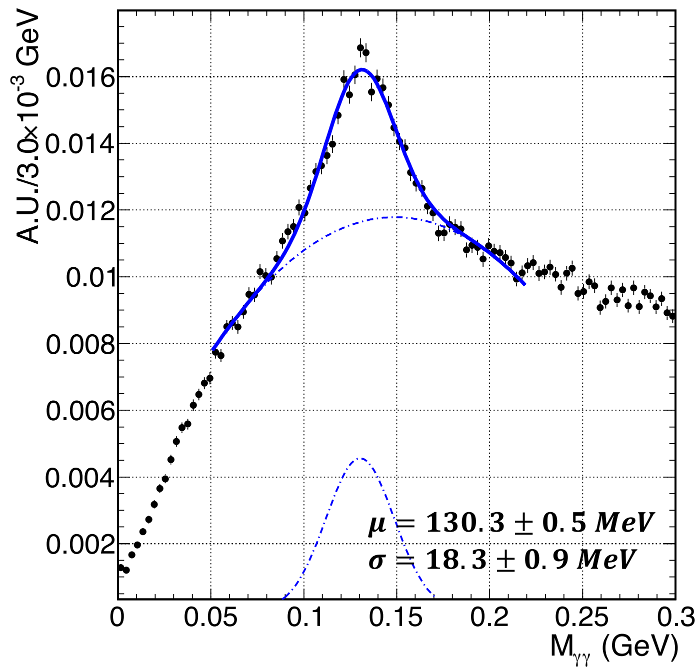
The chance of the successfully reconstructed π^0 is defined as the probability of successfully reconstructed two photons at least and with the leading invariant mass between (0.135-5σ, 0.135+5σ) MeV.

If the π^0 energy is lower than the critical energy (22/34 GeV at the barrel/endcap), the algorithm is expected to reconstruct the pion under a success probability higher than 50%.

π^0 invariant mass distribution in $Z \to \tau\tau$ and $H \to bb$ events



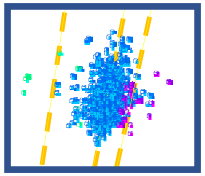
(a) $Z \to \tau\tau$ sample

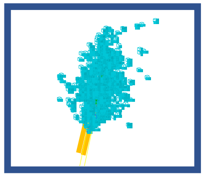


(b) $H \to bb$ sample

The π^0 invariant mass spectrum in $Z \to \tau\tau$ events (left) and $H \to bb$ events (right).

Summary


(a) Cluster **splitting**


(b) Cluster **merging**

Two confusions reduce the reconstruction performance:

Cluster splitting & **Cluster merging**

Cluster splitting is researched in the single photon sample:

- Single photon reconstruction performance is characterized by several factors:
  - Hit collection efficiency & split probability
  - Energy resolution & linearity

  which are depending on incident photon energy.

Cluster merging is researched in the di-photon and π^0 sample:

- Quantified the separation power by **critical distance (about 2 cell size)** between the two closed photon clusters, in di-photon events.
- We analyze the π^0 reconstruction efficiency as a function of the π^0 energy, the **critical energy** of **22/34 GeV** at the barrel/endcap region (corresponding to 50% of the successful reconstruction rate) is observed.
- The $\boldsymbol{\pi^0}$ **invariant mass resolution** in $Z \to \tau\tau$ and $H \to bb$ events are evaluated as 11.8 and 18.3 MeV

Future

Future

How to quantify and understand the behaviors of the detector and Arbor?

Single photon

- Split

Di-photon

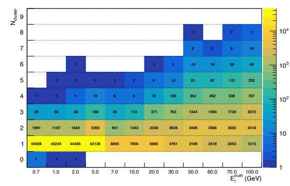
- Split
- Merging

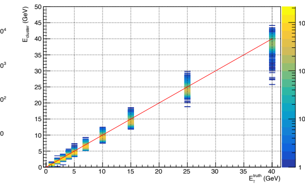
Real physical sample

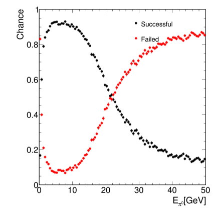
- Neutral split
- Charged split
- Merging

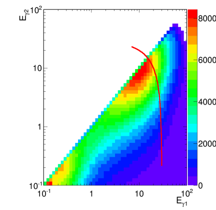
Full Simulation

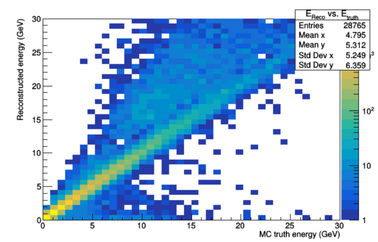
Fast Simulation

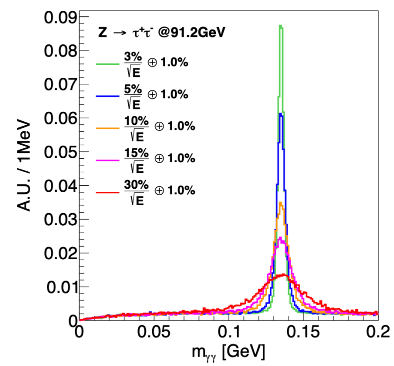












The last plot is from Yuexin(IHEP).

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Thanks for your attention!

April 14, 2021, Yangzhou

Back Up

Pre-treatment of single photon sample

- Remove the converted photon events.

Energy (GeV)	0.7	1.0	2.0	5.0	7.0	10.0
Statistic	50000	50000	50000	50000	10000	10000
Selected	46635	46471	46100	45702	9102	9020
Energy (GeV)	20.0	30.0	50.0	60.0	70.0	100.0
Statistic	10000	10000	10000	10000	10000	10000
Selected	8818	8675	8323	8249	7991	7730

Table 1: Statistic and number of selected events of the first sample group, in which photons are created with direction of $\cos\theta = 0.17$ and $\phi = 1.4870rad$

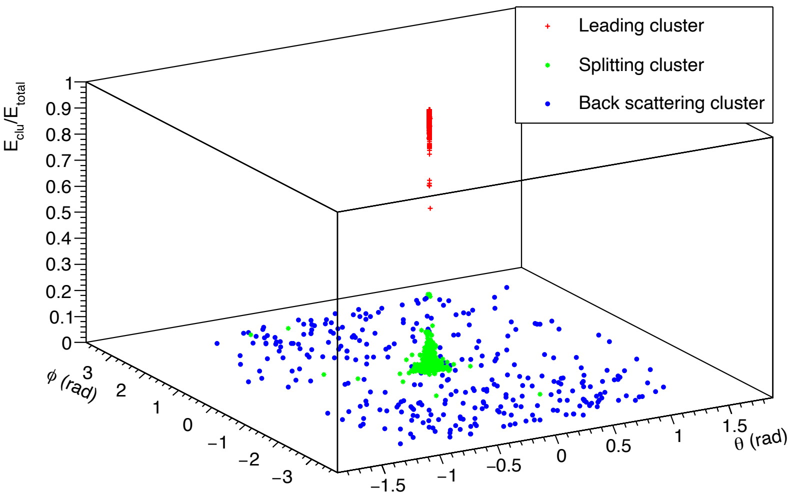
$\cos\theta$	0.1	0.17	0.3	0.4	0.5	0.65	0.7	0.8	0.9
Statistic	10000	10000	10000	10000	10000	10000	10000	10000	10000
Selected	9002	9042	8987	8894	8947	8726	8711	7192	7197

Table 2: Statistic and number of selected events of the second sample group, in which photons are created with energy of 10.0 GeV and $\phi = 1.4870rad$

Backscatter and split

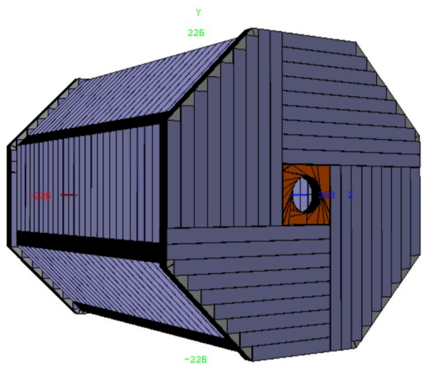
For 1-N cases of single photon sample:

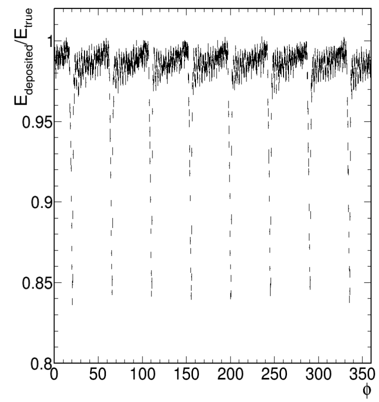
- **Leading Cluster**: The clusters with highest energy
- **Split**: The clusters that split from leading cluster because of Arbor algorithm
- **Back Scatter**: The clusters that created by back scattering particles, such as photon or neutron.

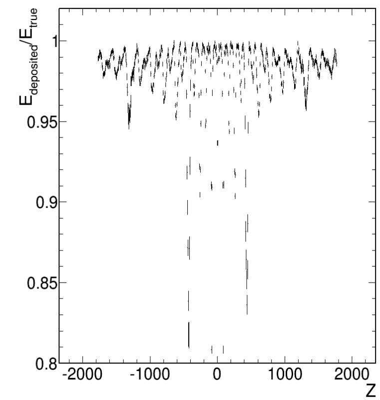


Position and energy distribution of the leading clusters, split clusters and backscatter clusters in several events of energy point 5, 7, 10 GeV. The blue markers represent the backscatter clusters and are apart from the leading cluster for longer distances than the split clusters.

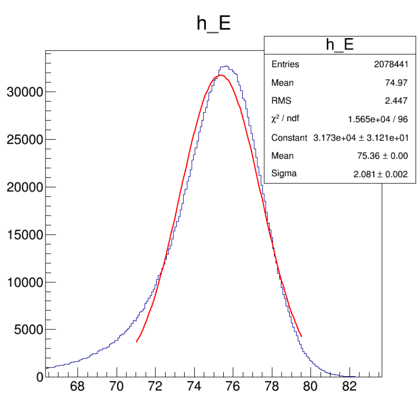
Cluster energy evaluator: Energy correction

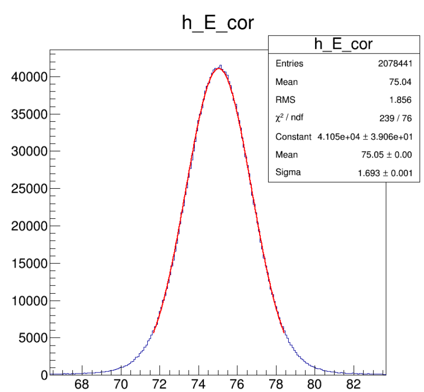






The geometry-based correction algorithm has been developed to scale the EM clusters located at the geometry cracks.

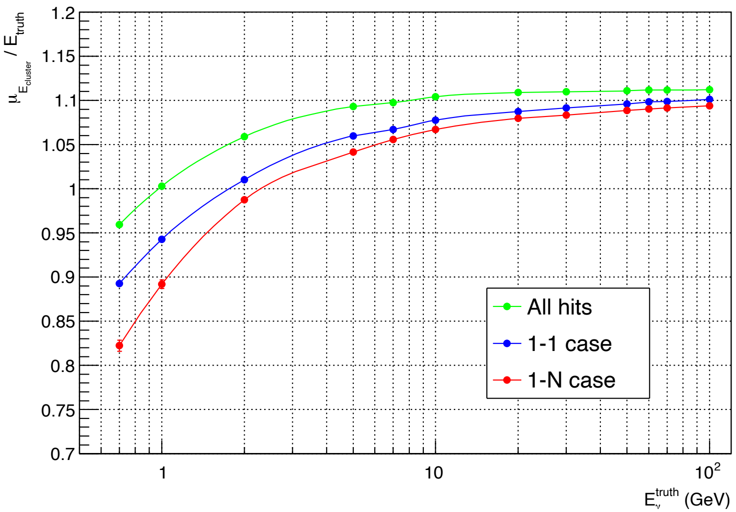


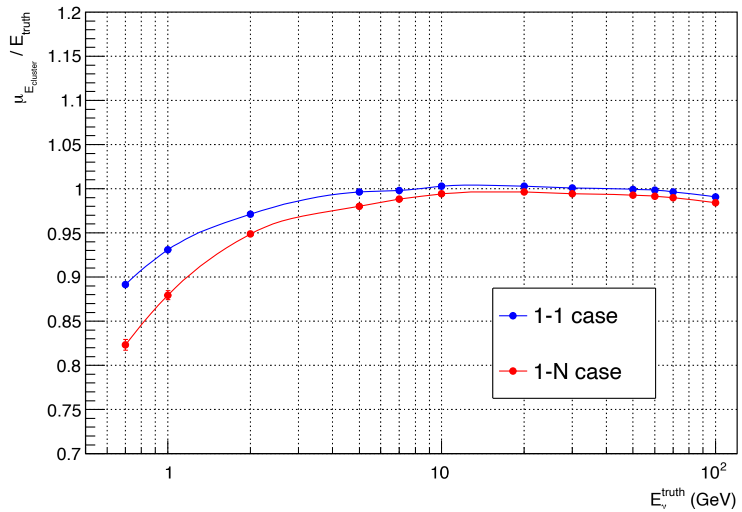


$$E_{deposited}^{corrected} = \frac{E'_{true}}{E'_{deposited}} \times E_{deposited}$$

where the correction factor is built from Mont Calo data of the 50 GeV photon sample.

Cluster energy evaluator



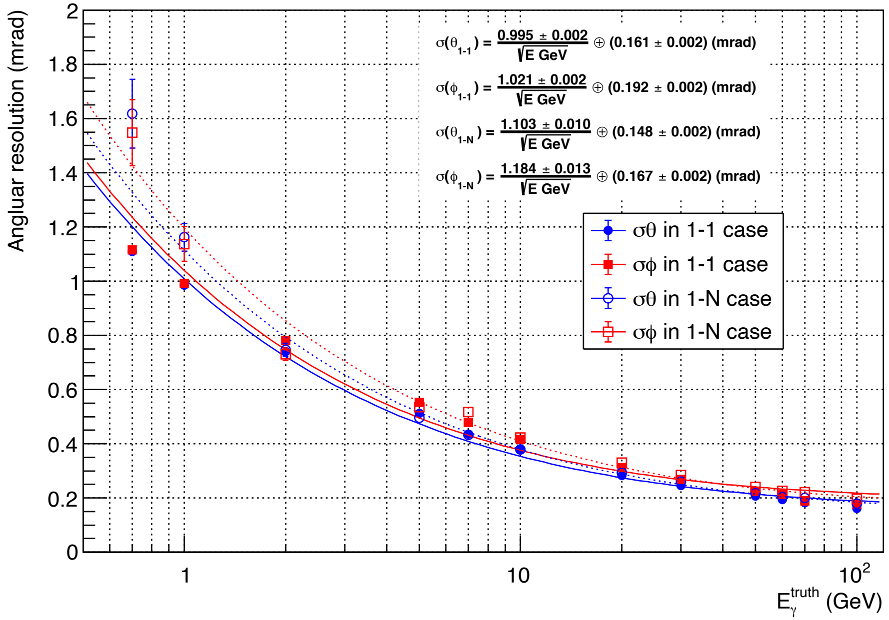


The linearity of single photon reconstructed energy.

In the left plot, reconstructed energy is counted by **the sum of all hits** in the cluster, skipped the energy correction.

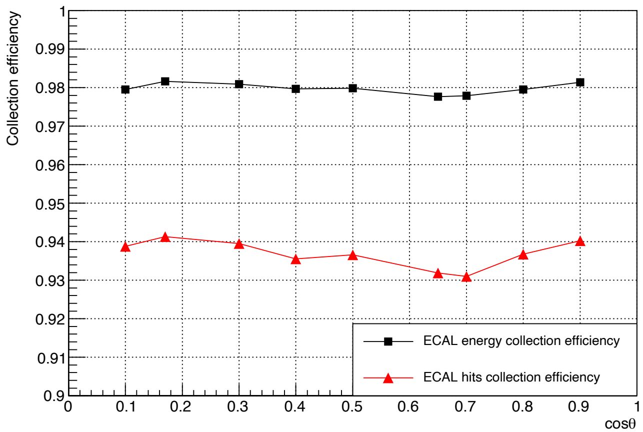
In the right plot, reconstructed energy is counted by the evaluated energy of the cluster **after energy correction.**

Angular response

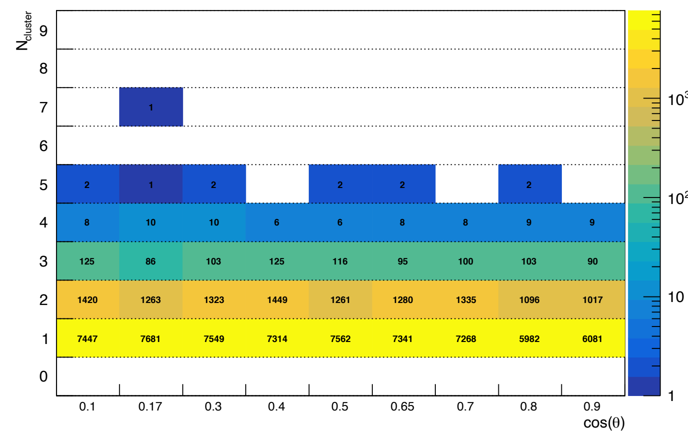


The θ *and* ϕ resolutions of single photon for both the 1-1 and 1-N case are less than 2 mrad.

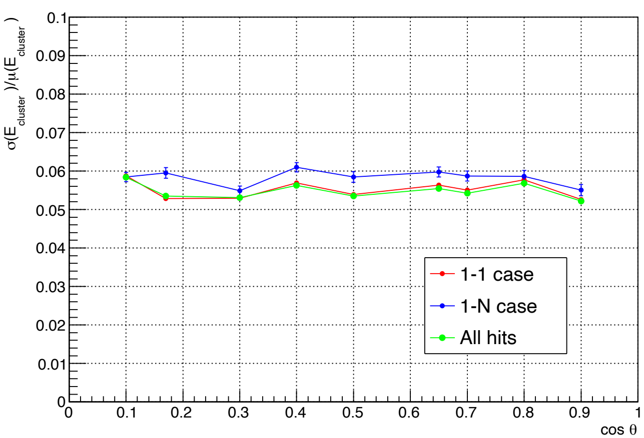
The dependency on the incident polar angle



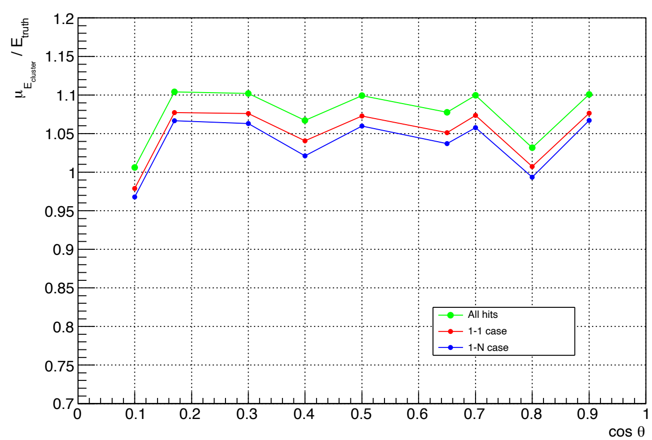
(a) Hit collection efficiency



(b) Num. of clusters

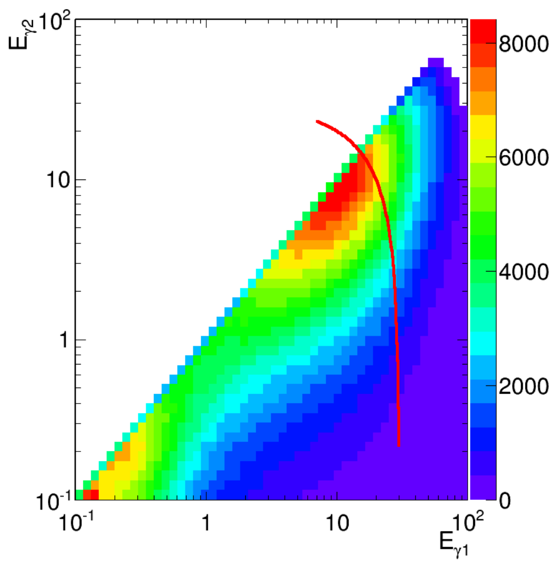


(c) Energy resolution

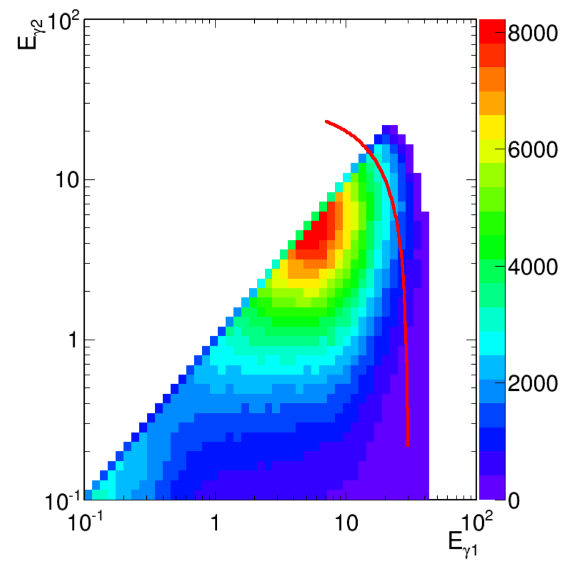


(d) Energy linearity

π^0 reconstruction efficiency



Inclusive Higgs sample

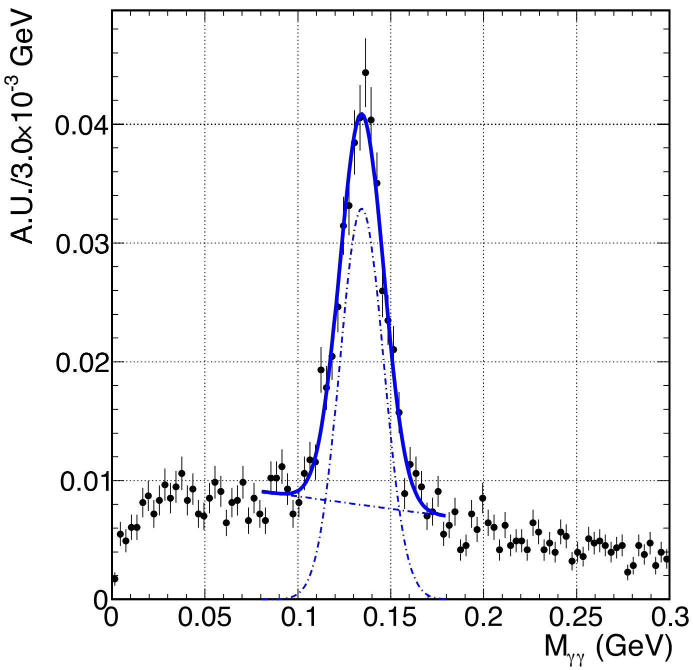


$Z \rightarrow \tau\tau$ sample

The two plots are the generated π^0 distributions in different samples. Roughly 15% of the π^0 generated in the inclusive Higgs sample has its energy above the average critical energy (30 GeV). Only 3% of the π^0 generated in $Z \rightarrow \tau\tau$ events exceeds the critical energy threshold.

π^0 invariant mass distribution in real physics samples

Fit result:



(a) $Z \to \tau\tau$ sample

Formula:

[0]*TMath::Gaus(x,[1],[2]) + [3]*x^2 + [4]*x + [5]

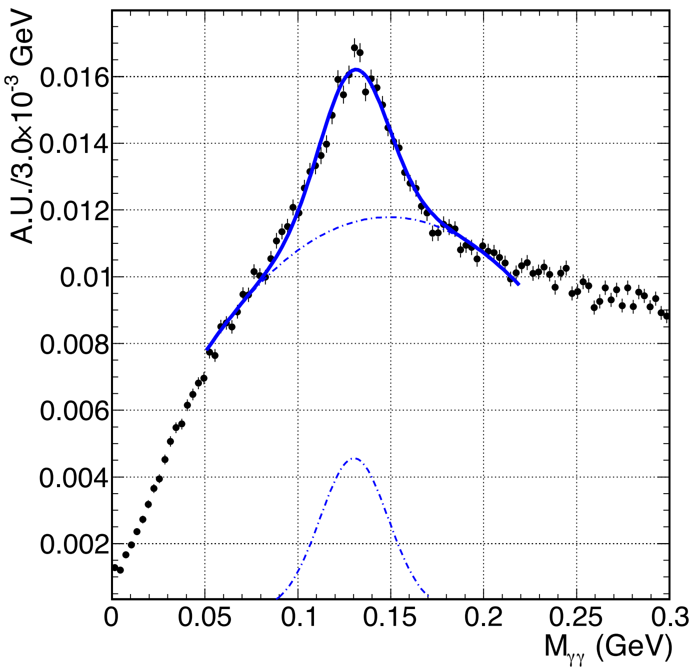
FCN=42.6399 FROM MIGRAD STATUS=CONVERGED 592 CALLS 593 TOTAL

EDM=3.34576e-08 STRATEGY= 1 ERROR MATRIX UNCERTAINTY 2.3 per cent

EXT PARAMETER NO.	NAME	VALUE	ERROR	STEP SIZE	FIRST DERIVATIVE
1	p0	3.29010e-02	1.21468e-03	1.34290e-06	-2.25937e-01
2	p1	1.34388e-01	4.25525e-04	1.12432e-06	3.29554e-01
3	p2	1.18082e-02	4.63546e-04	-1.19191e-07	-4.38864e-01
4	p3	-2.09269e-02	8.45866e-03	-7.35863e-06	-8.85263e-02
5	p4	1.07665e-02	1.13867e-03	8.91593e-07	-8.64292e-01

π^0 invariant mass distribution in real physics samples

Fit result:



(b) $H \to bb$ sample

Formula:

[0]*TMath::Gaus(x,[1],[2]) + [3]*x^2 + [4]*x + [5]

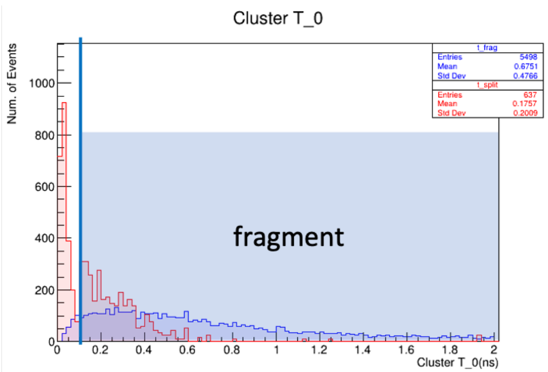
FCN=85.7509 FROM MIGRAD STATUS=CONVERGED 1396 CALLS 1397 TOTAL

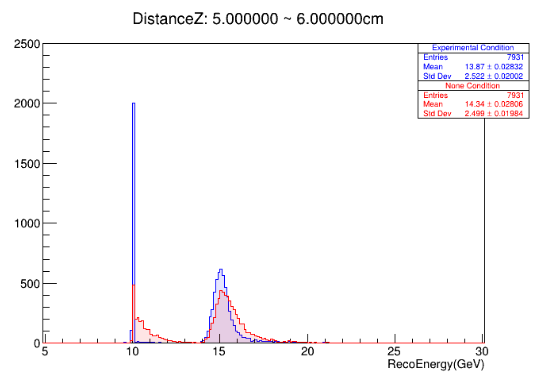
EDM=1.95653e-06 STRATEGY= 1 ERROR MATRIX ACCURATE

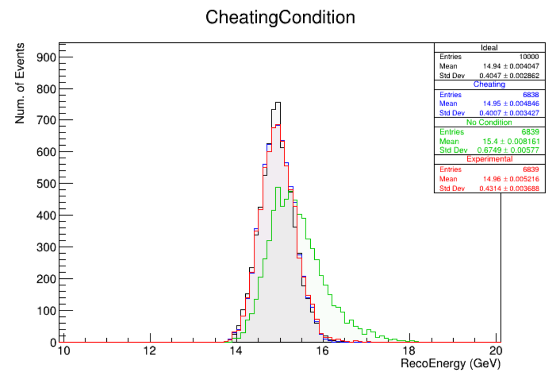
EXT PARAMETER NO.	NAME	VALUE	ERROR	STEP SIZE	FIRST DERIVATIVE
1	p0	4.56197e-03	1.67363e-04	3.74814e-07	-1.47854e+01
2	p1	1.30304e-01	4.78353e-04	2.02004e-06	2.28012e+00
3	p2	1.82950e-02	8.55496e-04	1.62205e-06	7.62941e-01
4	p3	-4.13869e-01	3.45147e-02	5.82189e-06	1.73929e-01
5	p4	1.23362e-01	9.14628e-03	1.00859e-06	2.58986e-01
6	p5	2.59201e-03	4.51258e-04	1.43302e-07	-4.02186e+00

How to operate the reconstruction software?

ToF information is a potentially useful feature to veto split from photon clusters.







Fragments have longer time of fly, which is expected to be used to distinguish fragment and photon clusters.