Optimization Studies on the CEPC PFA-oriented Calorimetry

YuKun Shi

State Key Laboratory of Particle Detection and Electronics
University of Science and Technology of China
On behalf of CEPC calorimeter working group

OutLine

- Introduction
- Calorimeter Optimization
  - Simulation Setup
  - Calibration method
  - CellSize Optimization
- Conclusion

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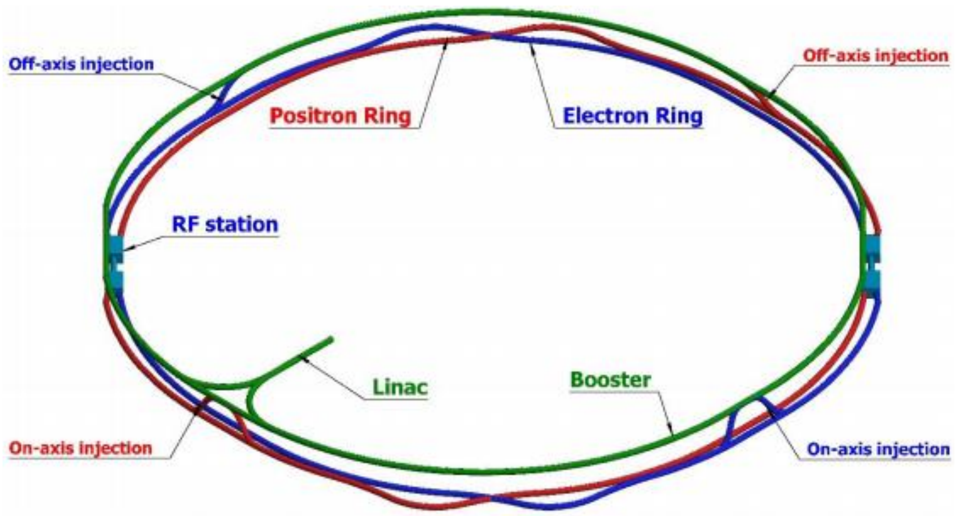
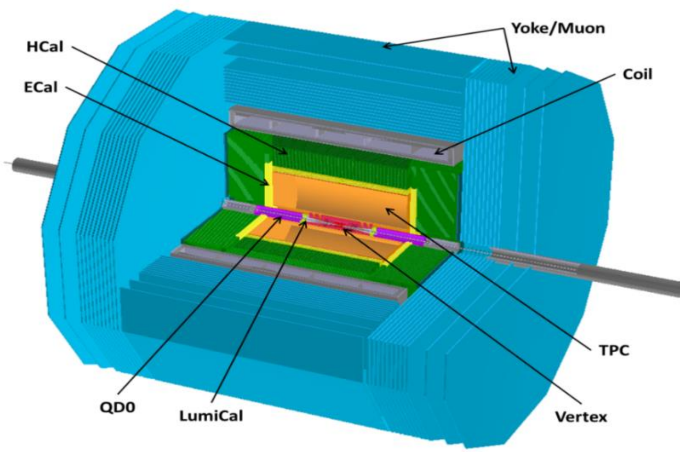
CEPC

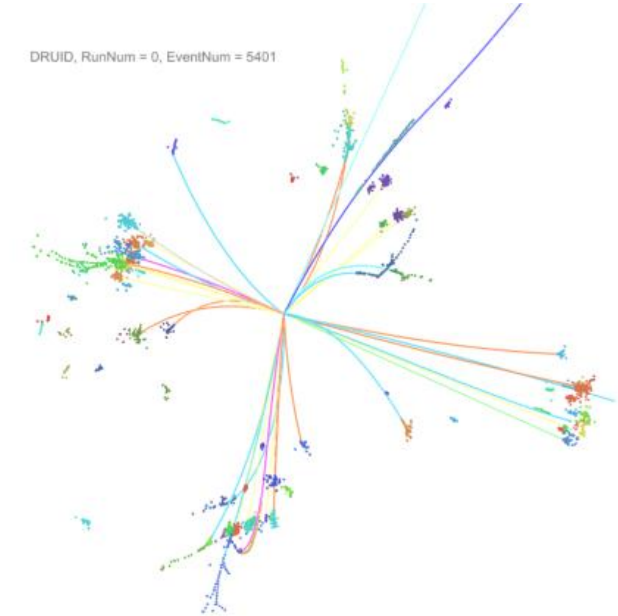
Circular Electron Positron Collider(CEPC) is designed as a Higgs factory, the Particle Flow Algorithm(PFA) oriented HCAL is one of the option for Hadron Calorimeter



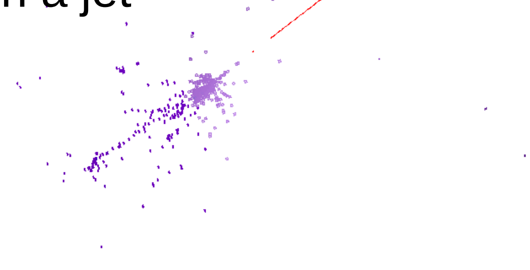


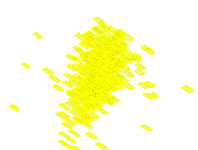
Particle Flow Algorithm

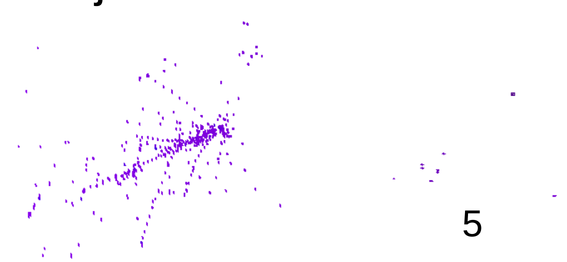
- PFA
  - The resolution of tracker,ECAL and HCAL is quite different
  - The optimal detector to detect different components of a jet
  - Granularity is the key parameter for PFA calorimeter



Charged particles	photons	Neutral Hadrons
Charged particles carry 65% energy in a jet	photons carry 25% energy in a jet	Neutral Hadrons carry 10% energy in a jet

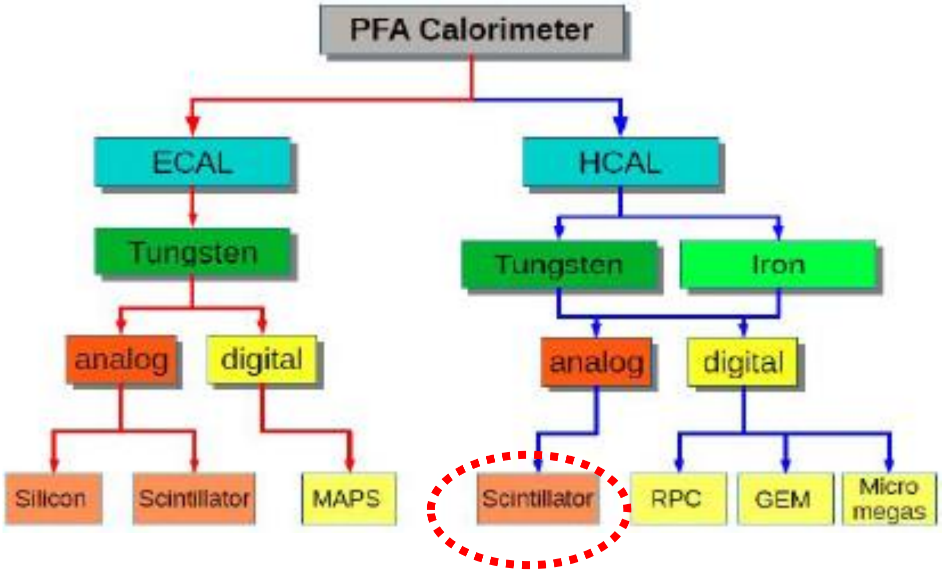


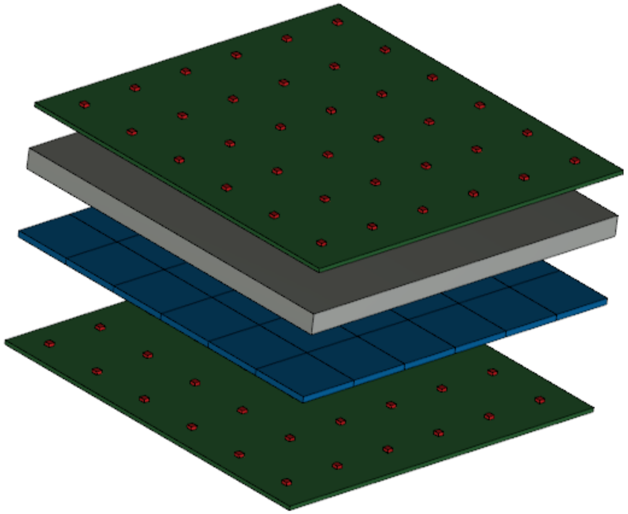




PFA Calorimetry

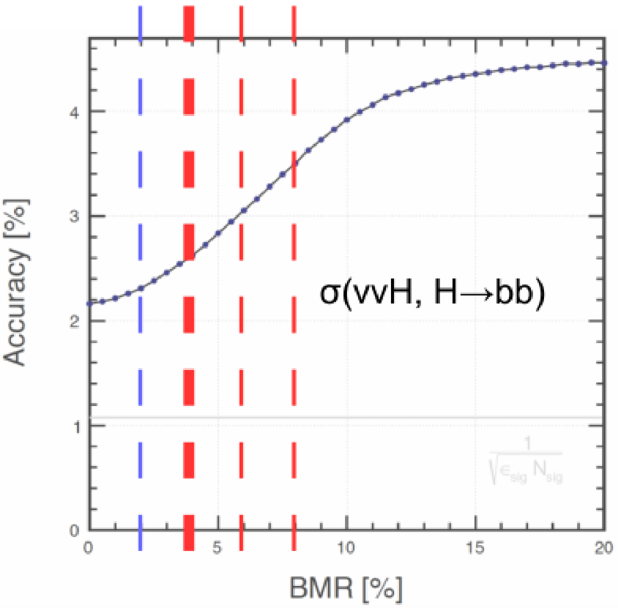
- ECAL
  - 30 layers
  - Absorber:2.8 mm tungsten
  - Si:10×10×0.5 mm^3
  - PCB:2 mm
- HCAL
  - 40 layers
  - Absorber:20 mm Fe
  - Scintillator:30×30×3 mm^3
  - PCB:2 mm

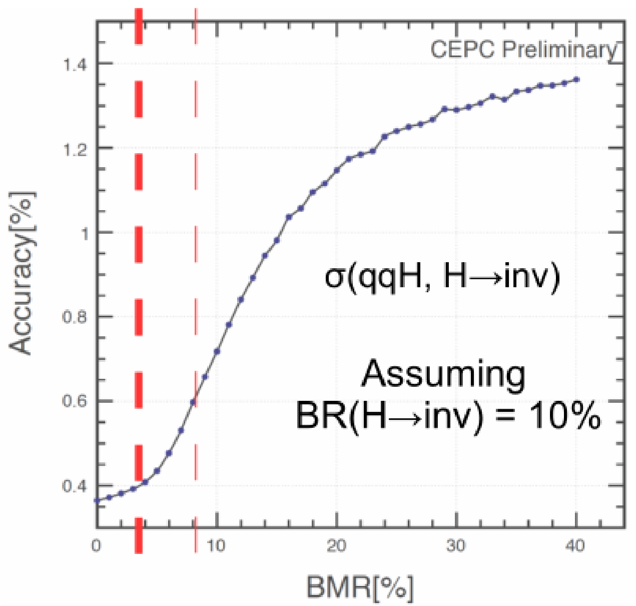


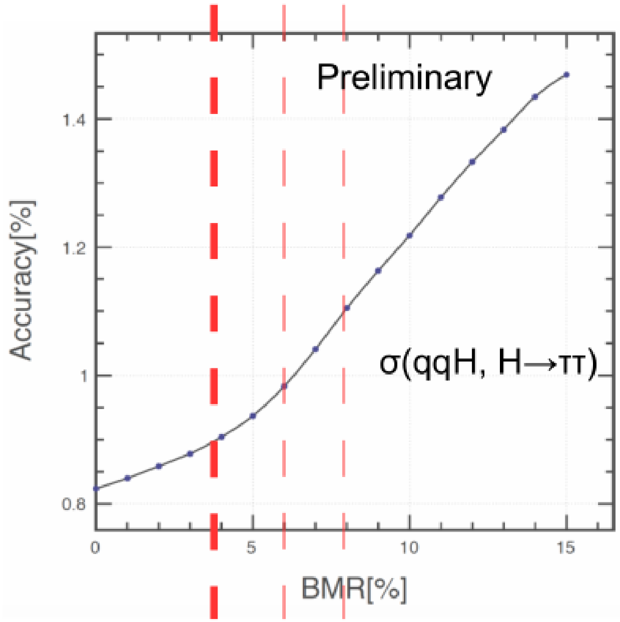


Physics Requirement

- 1/3 Higgs events have 2 jets : determined by hadronic decay boson
- The requirement from benchmark physics processes on boson mass resolution(BMR) : 4%
- Calorimeter cell size should be optimized in terms of BMR







$$\text{Accuracy}=\frac{\sqrt{S+B}}{S}$$

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Simulation Setup

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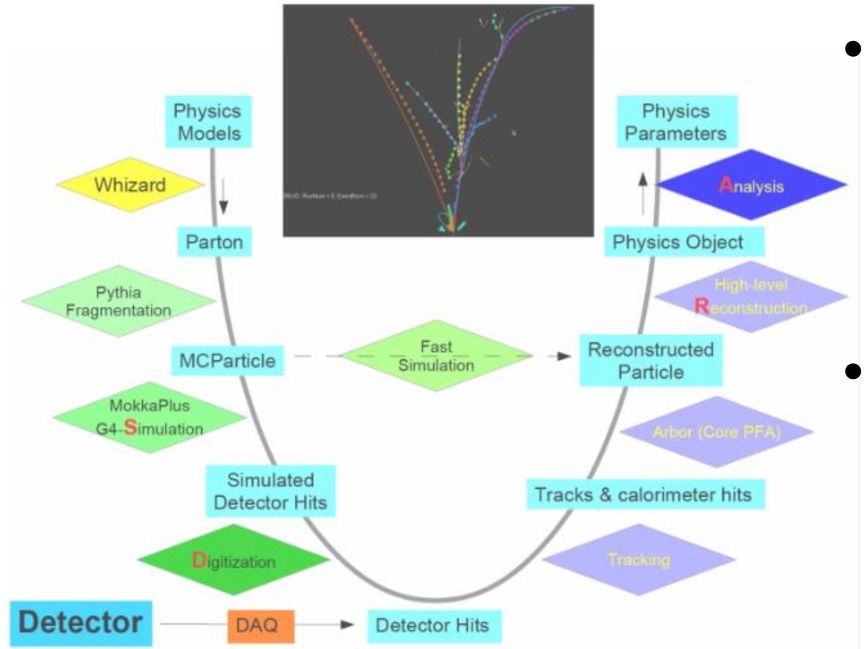
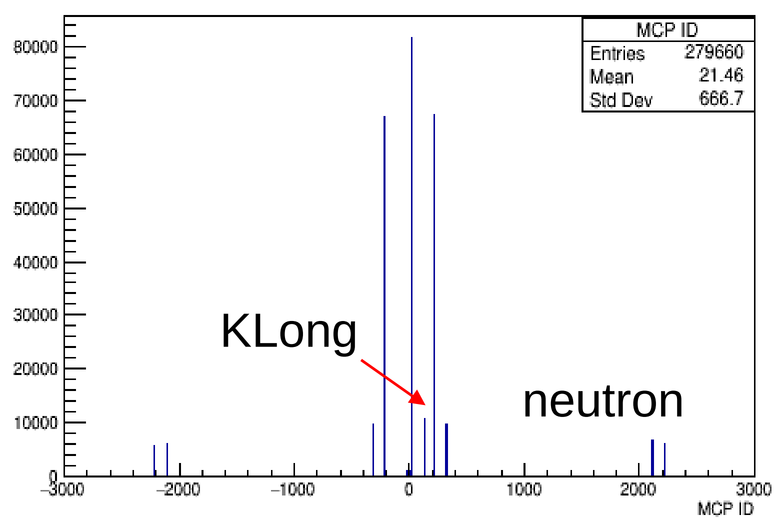
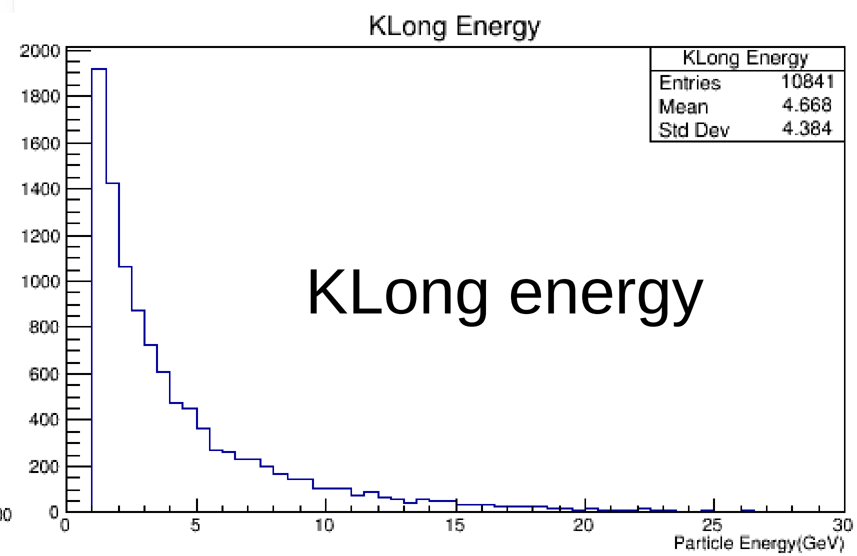


- CEPC V4 Geometry
  - Tracker
  - Si-W ECAL
  - Sci-Fe HCAL(replacing DHCAL)
- vvH-gg event
  - A clean channel with hadronic final state
  - A good benchmark to study HCAL performance





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Intrinsic HCAL response

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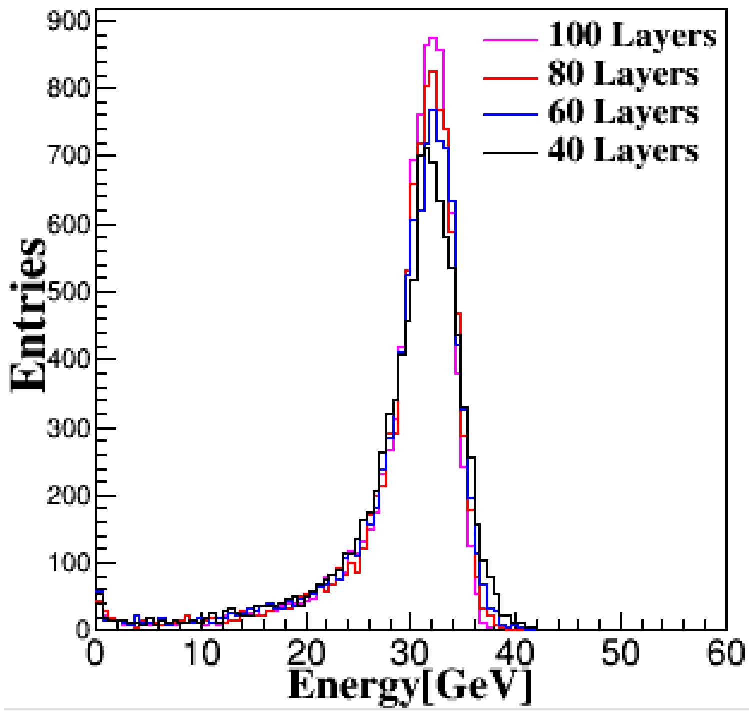
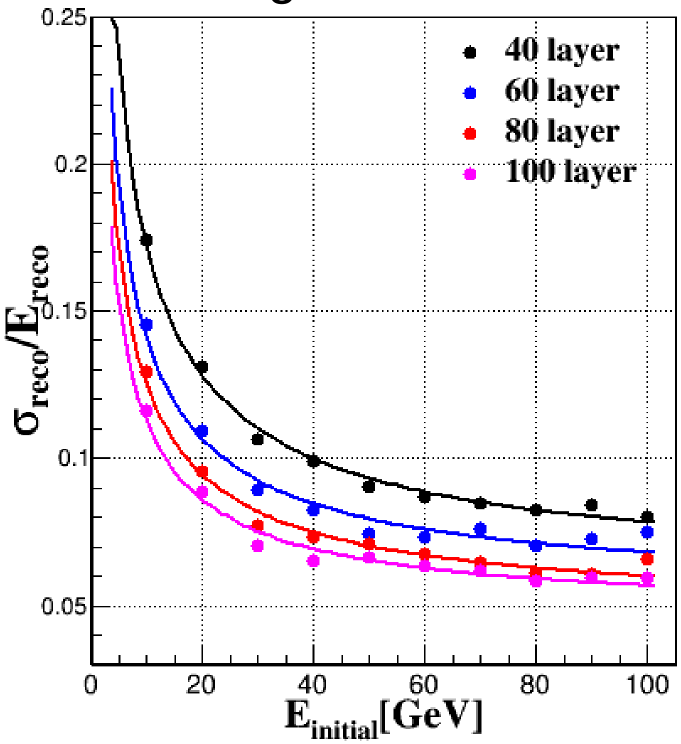
- Only HCAL is included to study intrinsic HCAL response for Klong
- Total absorber thickness fixed, change number of layer

KLong energy deposition



KLong resolution



Intrinsic HCAL response

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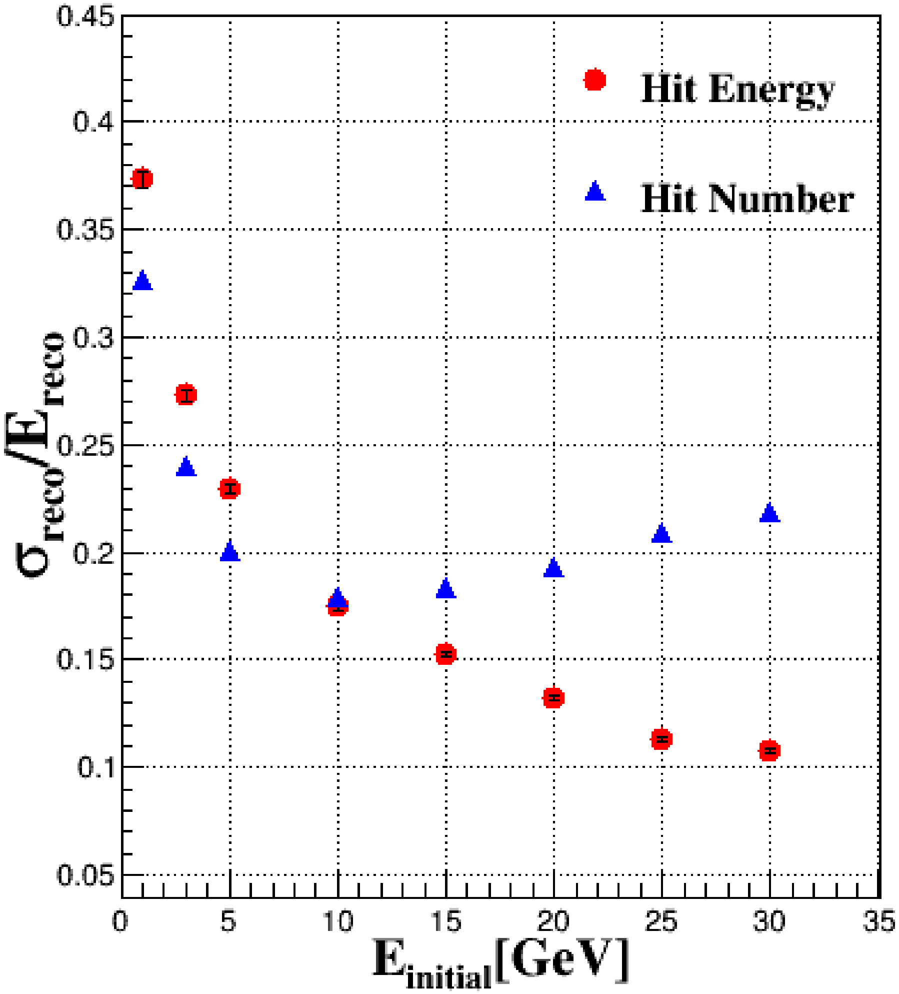
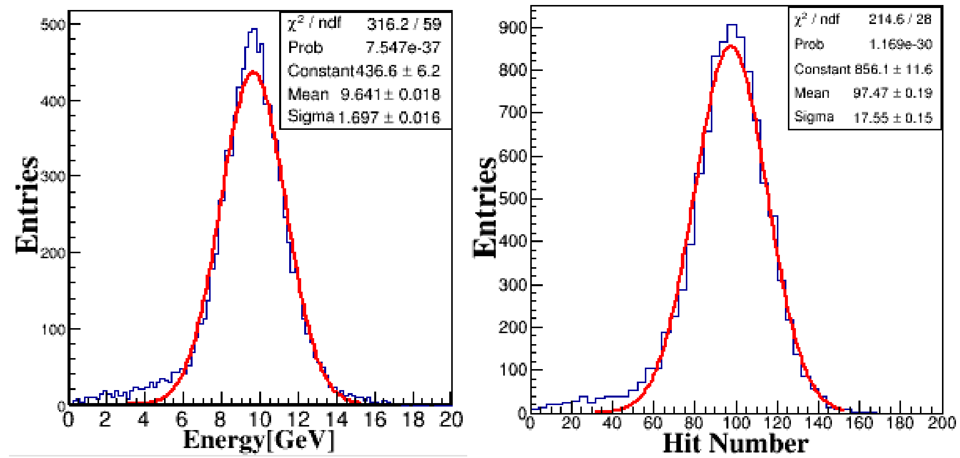


KLong 10GeV

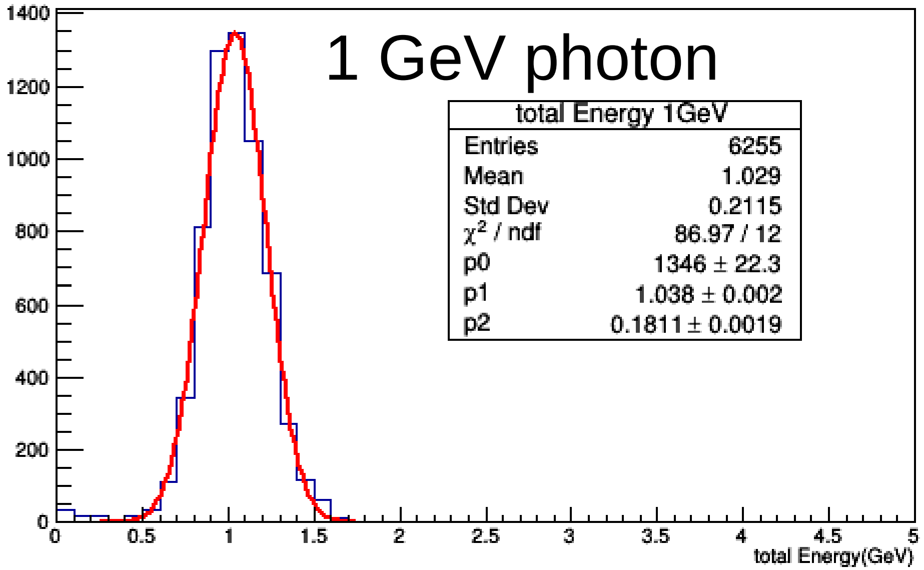


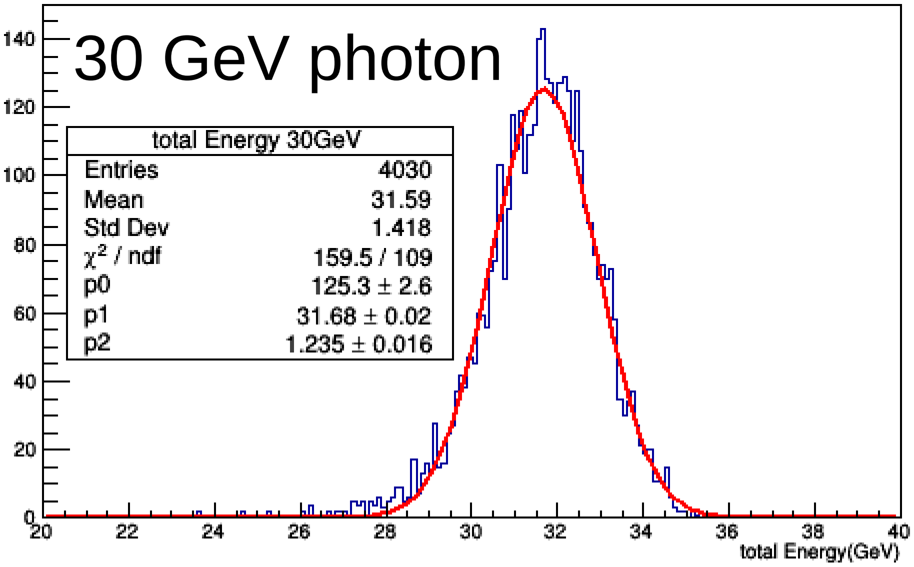
- Hit number has better resolution at low energy
- Hit number saturate at high energy causing a poor resolution

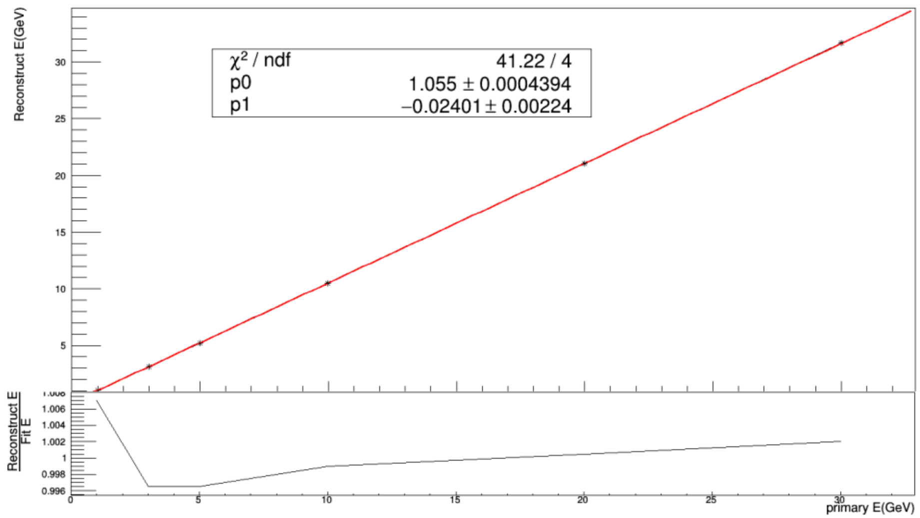
Calibration

- Calibration is done under V4 Geometry at hit level
- Event Selection
  - incident particle direction : $\cos\theta < 0.85$
  - Cell energy threshold : 0.5MIP
  - KLong must end in Hadronic calorimeter
- Analog and Digital mode
  - Analog mode: $\mathrm{E} = E_{ECAL} \times a + E_{HCAL} \times b$
  - Digital mode : $\mathrm{E} = E_{ECAL} \times a + N_{HCAL} \times b$
- Minimum χ^2 method
  - $\chi^2 = \sum(ECAL \times a + HCAL \times b - E_{in})^2$
  - a is determined by gamma
  - b is determined by Klong

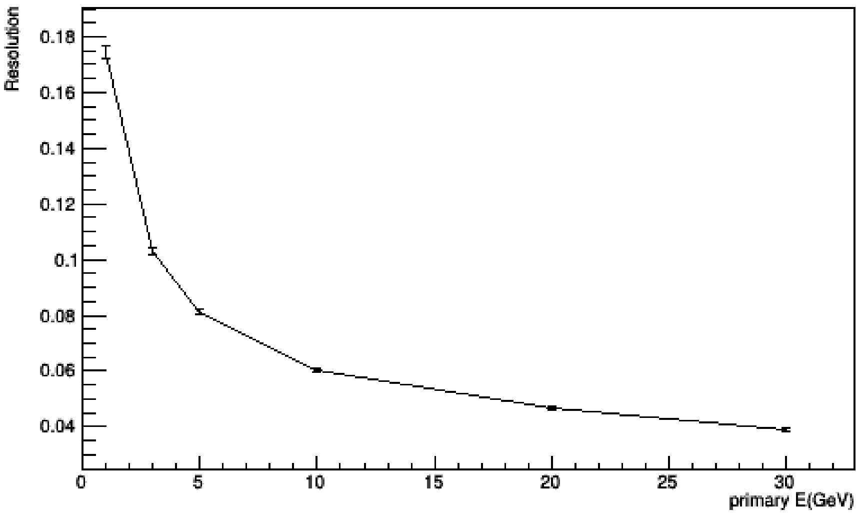
Photon response







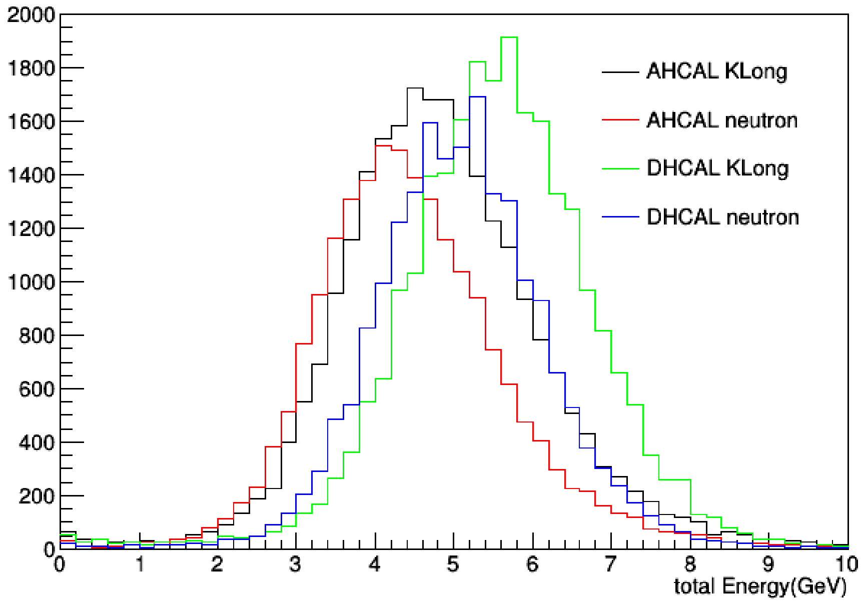
photon linearity



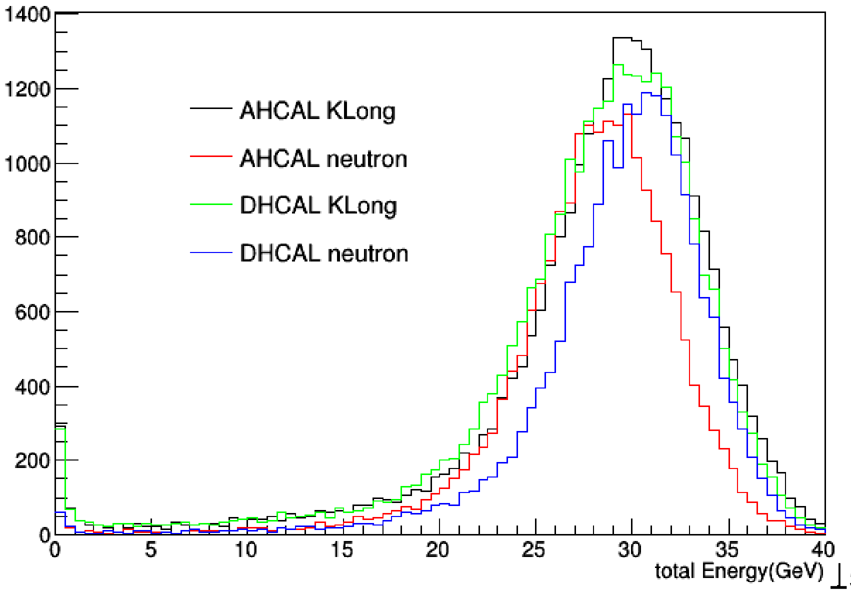
photon resolution

Hadron response

- KLongs of 5-30 GeV are used to determine calibration constant b
- Neutron use the same calibration constant as KLong
- DHCAL and AHCAL stand for analog and digital calibration mode, not geometry



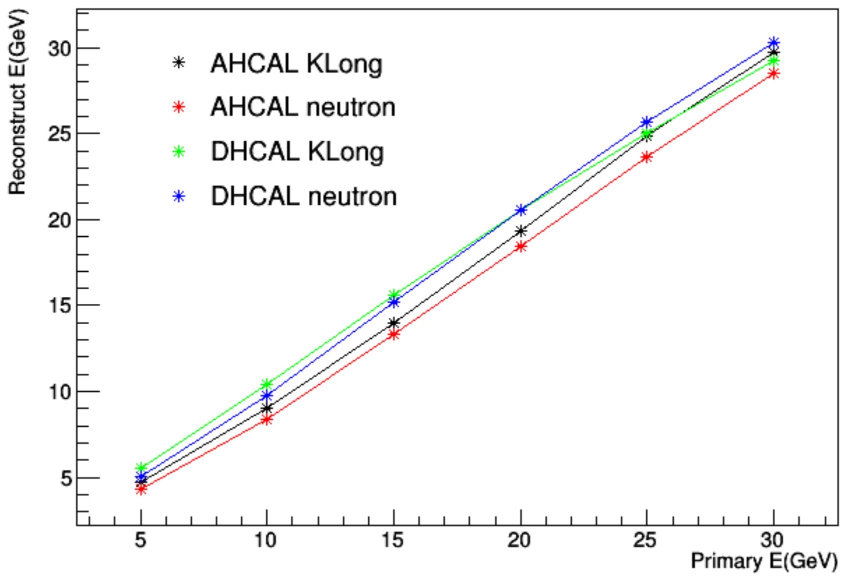
5 GeV neutral Hadron



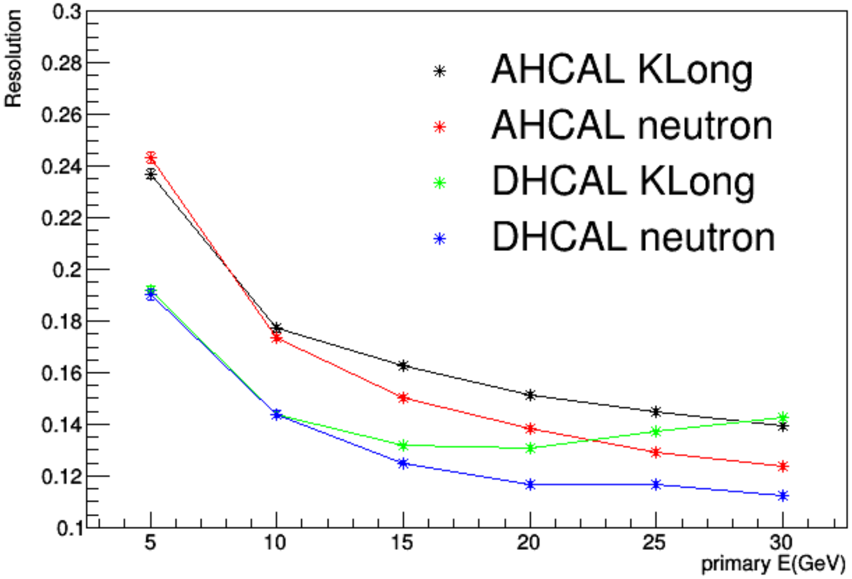
30 GeV neutral Hadron

Hadron response

- This calibration result is consistent with HCAL intrinsic Hadron response
- So digital calibration mode is used in this simulation while better algorithm is still on progress , but a reliable algorithm is essential to fully dig out Sci-Fe HCAL's potential



neutral Hadron linearity



neutral Hadron resolution

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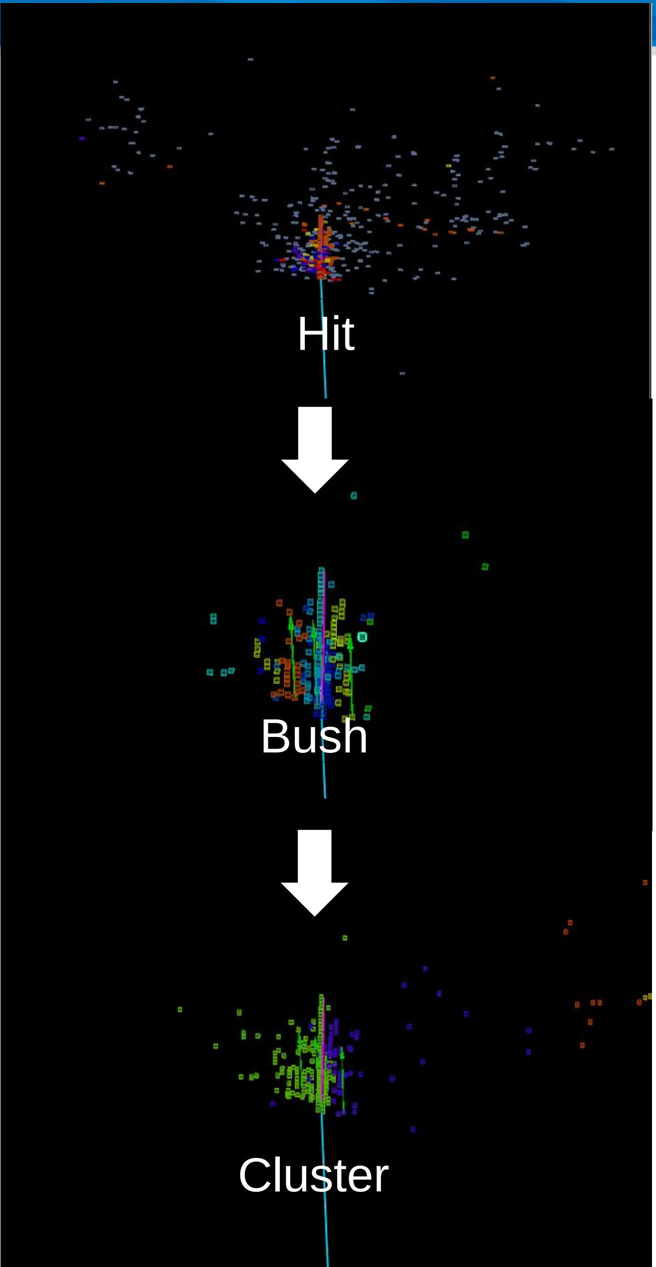
PFA Reconstruction

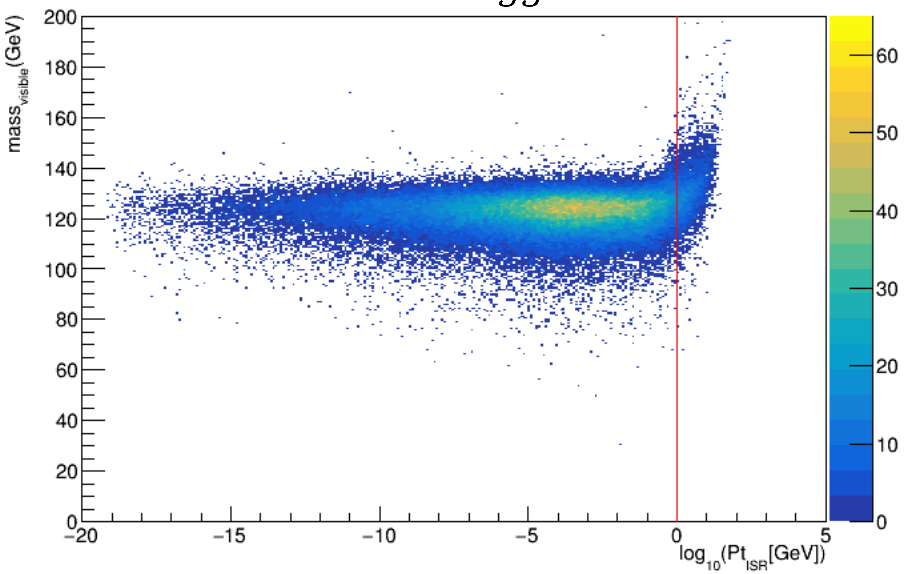


- Arbor processor : connect hits into a bush
- Bushconnect processor : connect bushes into a cluster,build a particle, gives its four-momentum
- LICH processor : judge a particle’s type precisely
- In vvH-gg event Higgs four-momentum is sum of four-momentum of all reconstructed particles

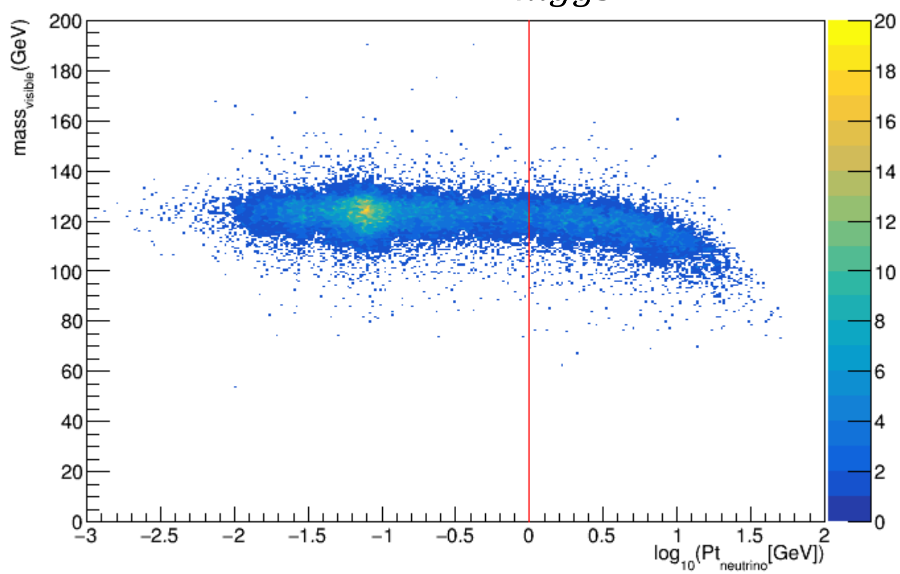
Event selection

- ISR(initial state radiation):Sum of ISR photons Pt < 1GeV
- Neutrinos generated by Higgs decay products:Sum of neutrinos Pt < 1GeV
- Acceptance of the detector: $|\cos\theta_{jet}| < 0.85$

$Pt_{ISR} - mass_{higgs}^{reconstructed}$



$Pt_{neutrino} - mass_{higgs}^{reconstructed}$

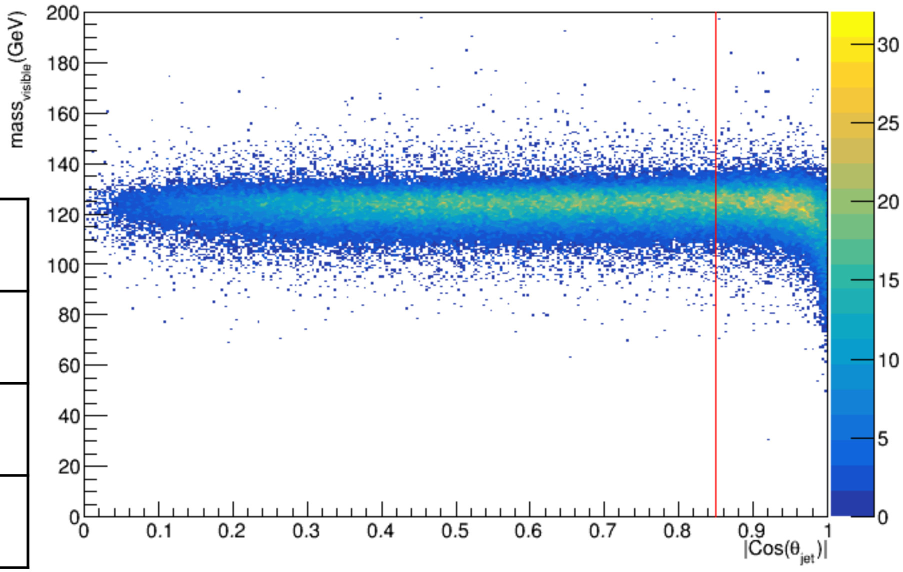


Event selection

- Efficiency for selection in good agreement with baseline DHCAL

Efficiency(%)	AHCAL	DHCAL
$Pt_{ISR} < 1\mathrm{GeV}$	95.20	95.15
$Pt_{neutrino} < 1GeV$	89.38	89.33
$\lvert\cos\theta_{jet}\rvert < 0.85$	67.32	67.30

$|\cos\theta_{jet}| - mass_{higgs}^{reconstructed}$



- After selection,the Higgs mass spectrum is almost dominant by detector response

CellSize optimization

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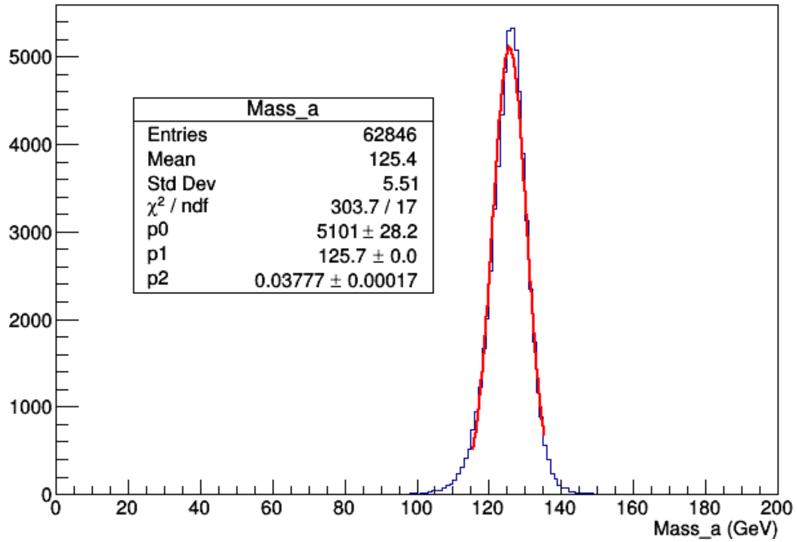
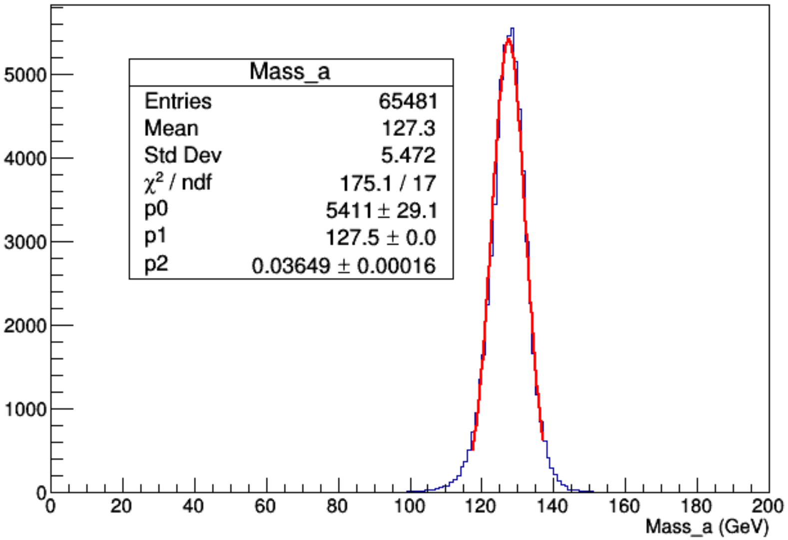
- Boson mass resolution(BMR)
  – Higgs Boson is reconstructed at different HCAL Cell Size from 10mm to 70mm
  – Energy is calibrated using digital mode



BMR HCAL cell 10mm



BMR HCAL cell 20mm

CellSize Optimization

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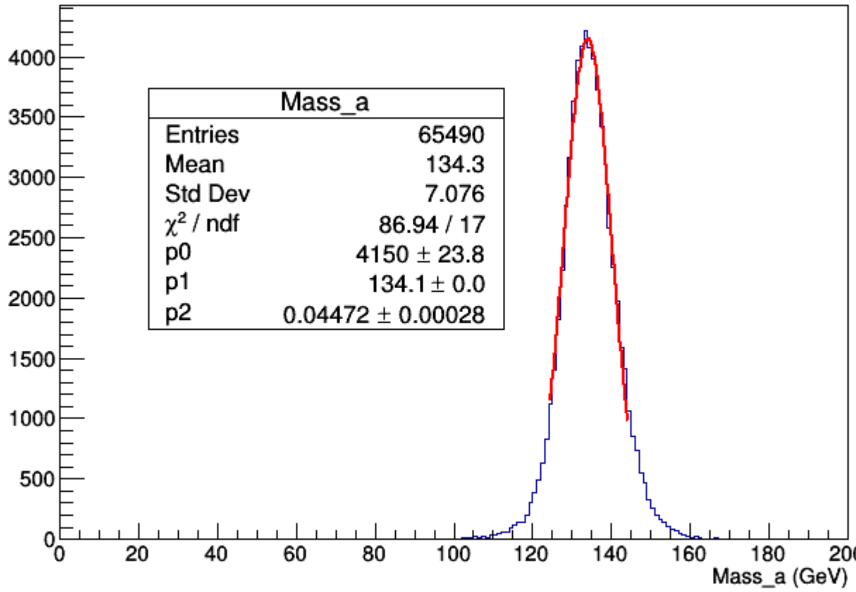
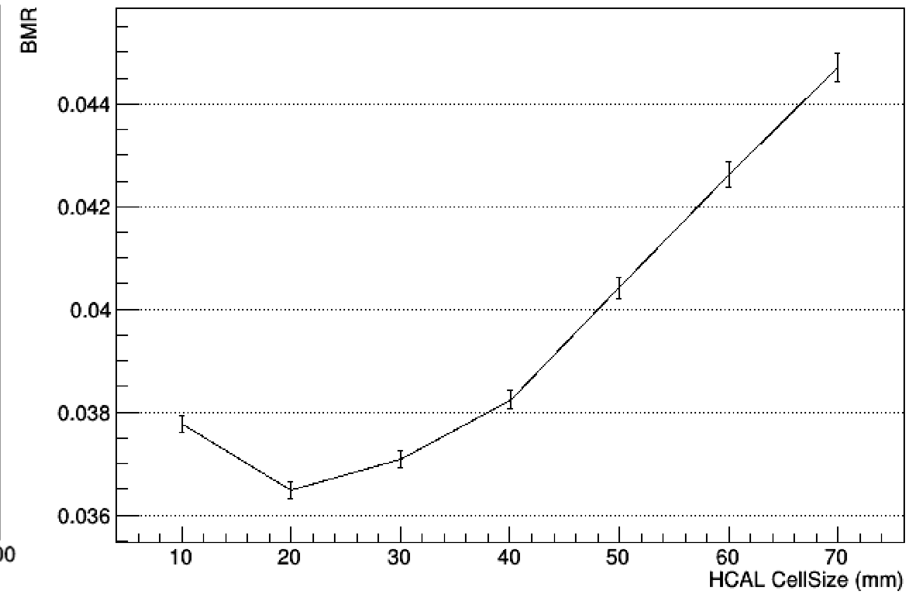
- Cell Size optimization
  - 40 mm still has BMR under 4%



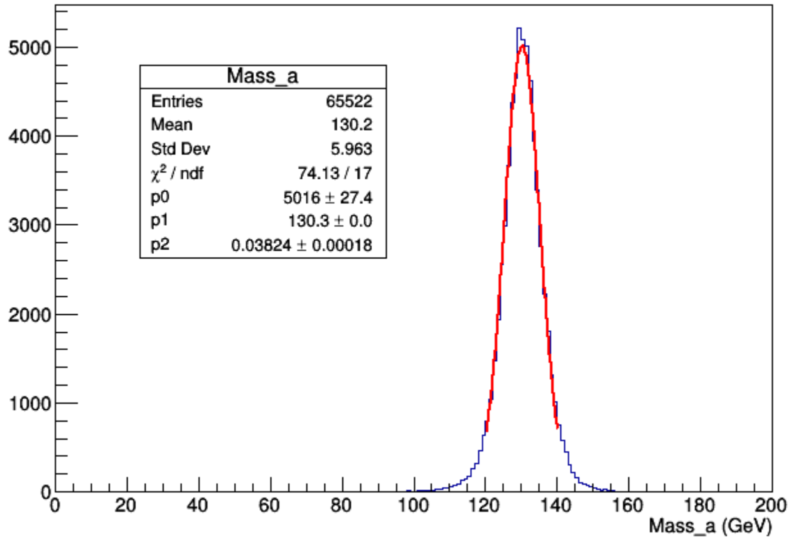
BMR HCAL cell 70mm



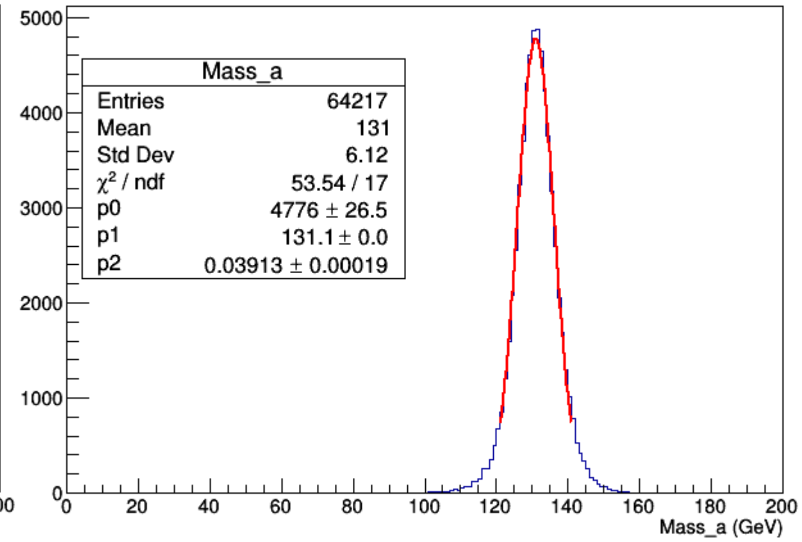
BMR - HCAL Cell Size

CellSize optimization

- Boson mass resolution(BMR)
  - HCAL Cell Size is 40mm
  - Higgs Boson is reconstructed at different ECAL Cell Size from 10mm to 60mm



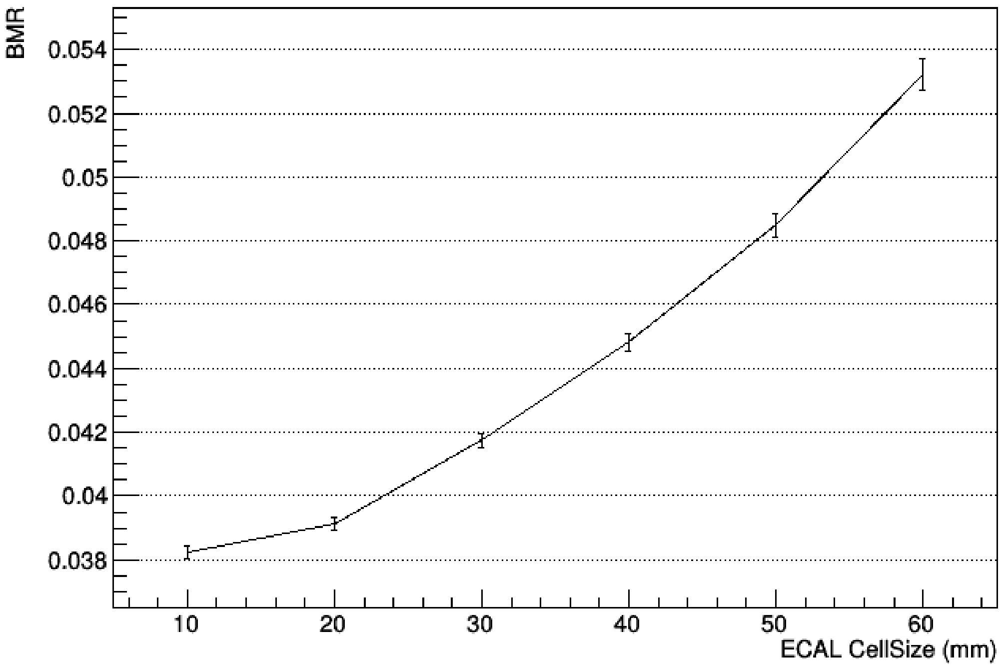
BMR ECAL cell 10mm



BMR ECAL cell 20mm

CellSize Optimization

- Cell Size optimization
  - ECAL Cell Size can be increased to 20mm in terms of BMR in ννH-gg event
  - Other physics goals may have more strict requirement for ECAL Cell Size



BMR - ECAL Cell Size

Conclusion

- PFA oriented Sci-Fe HCAL is one option for CEPC HCAL
- Cell Size is optimized under CEPC software environment with PFA , 40 mm is the appropriate choice in terms of BMR
- From now on, more algorithm will be developed to find out the potential of this kind of calorimeter and a prototype will be built in 2 years to prove this

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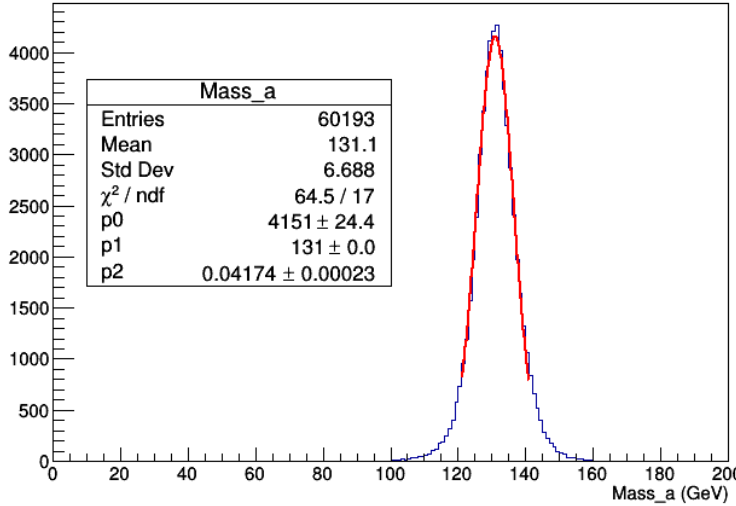
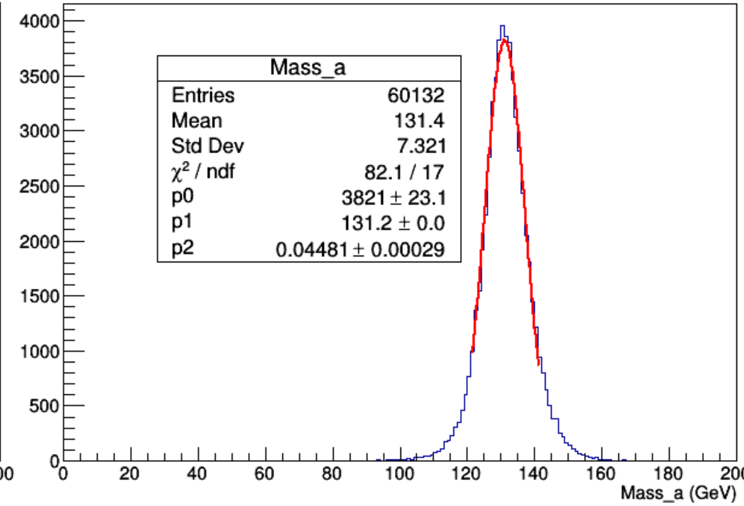
Thanks!

backup

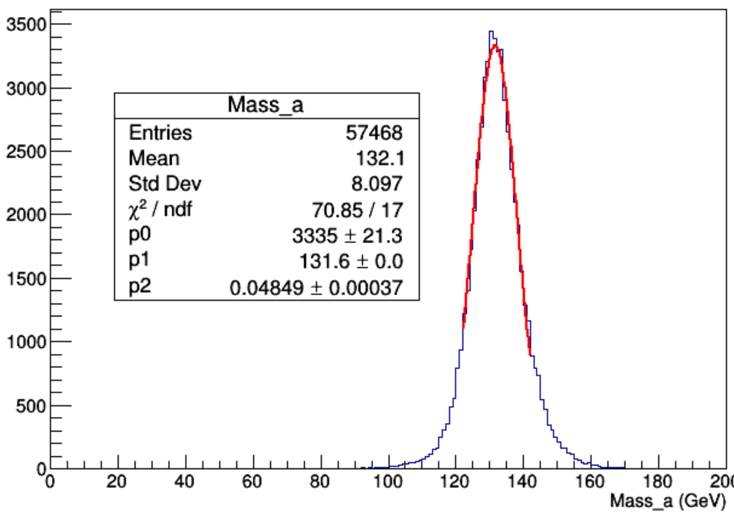
CellSize optimization



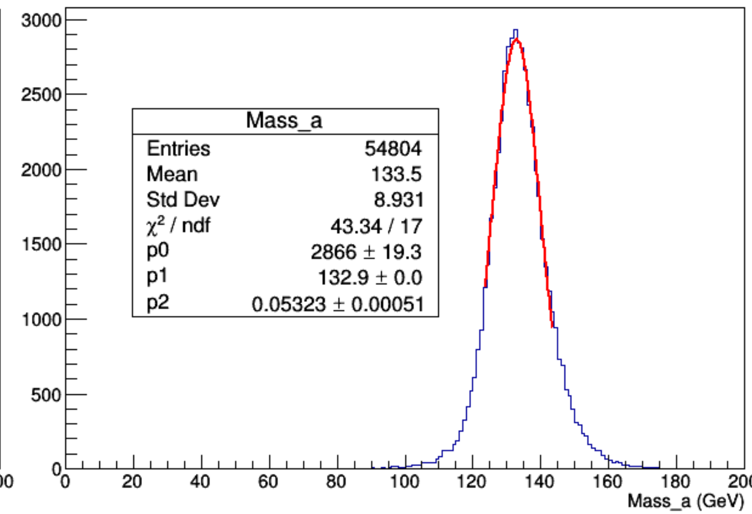
BMR HCAL cell 30mm



BMR HCAL cell 40mm



BMR HCAL cell 50mm



BMR HCAL cell 60mm

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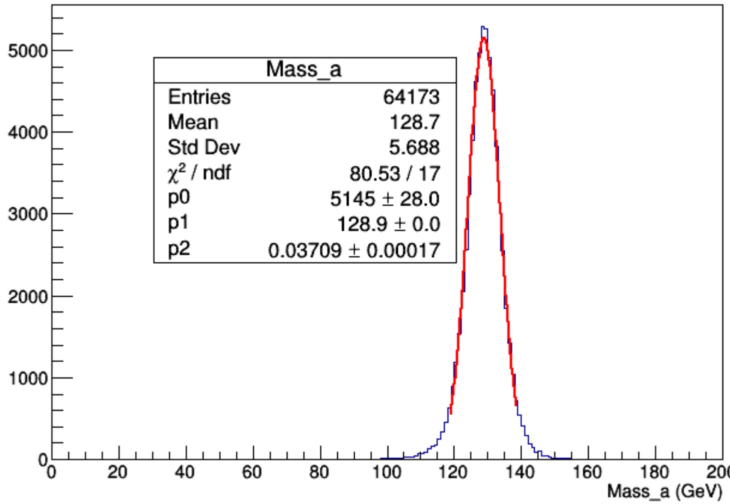
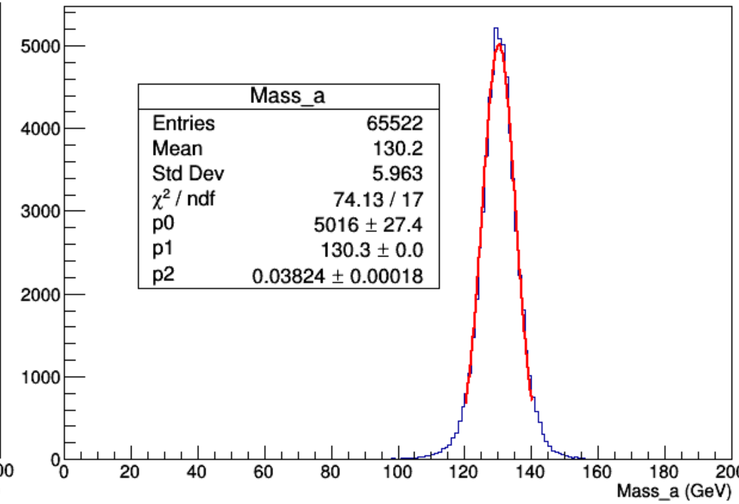
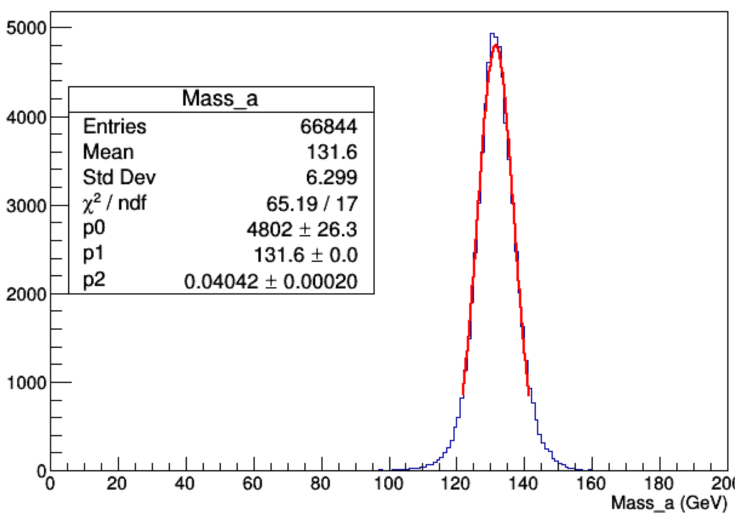


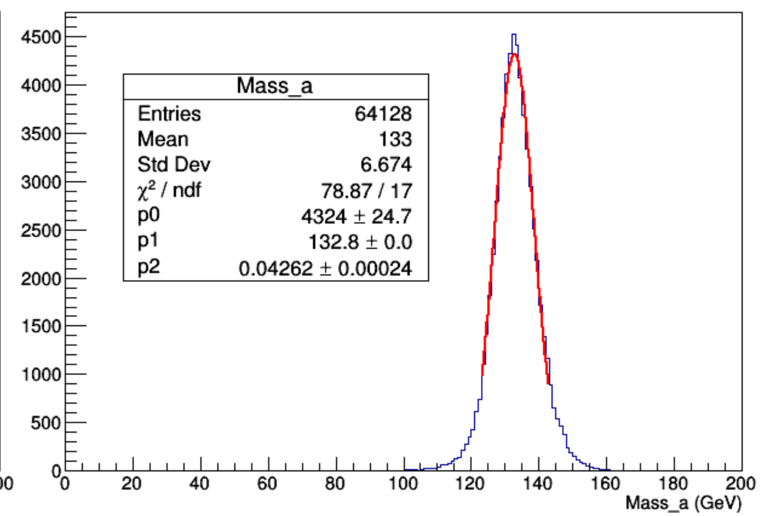
BMR HCAL cell 30mm



BMR HCAL cell 40mm



BMR HCAL cell 50mm



BMR HCAL cell 60mm

vvH

- WW fusion,ZZ fusion,ZH Z to vv

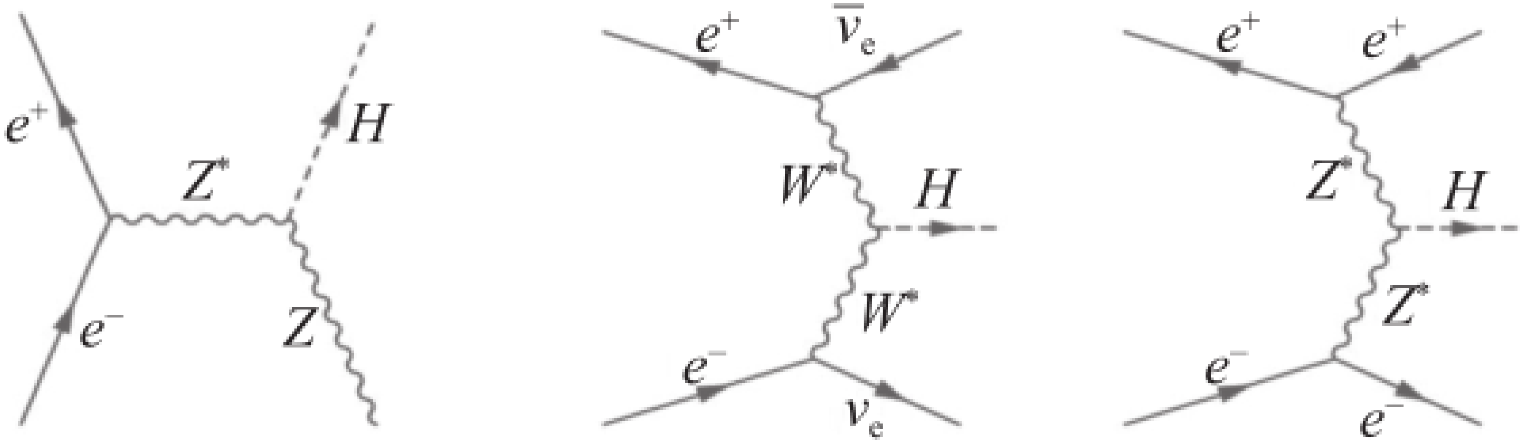
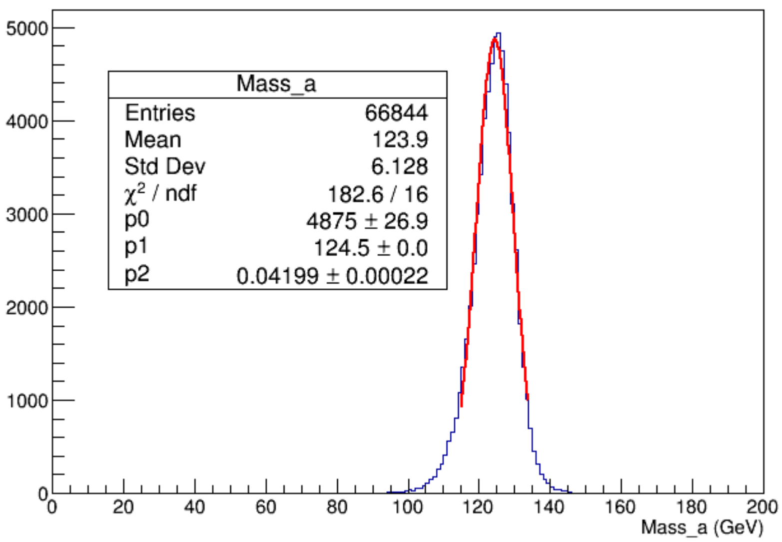


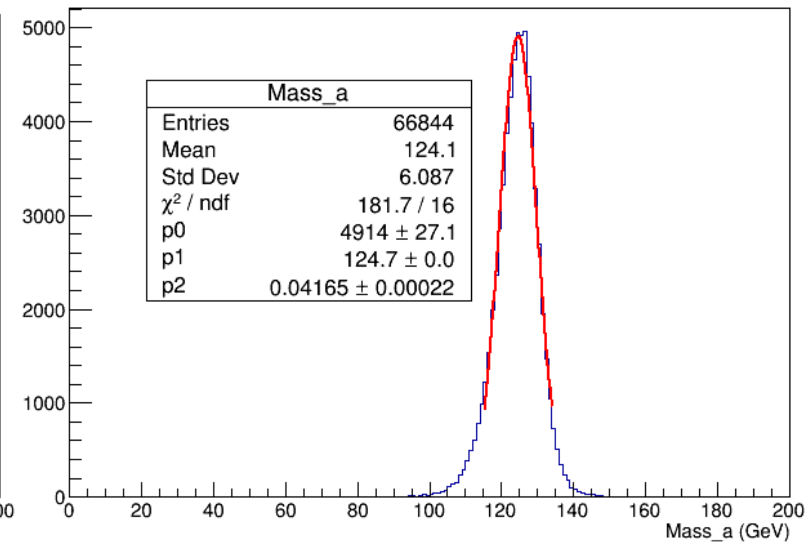
Fig. 1. Feynman diagrams of the Higgs production mechanisms at the CEPC: the Higgsstrahlung, *WW* fusion, and *ZZ* fusion processes.

CellSize optimization

- Boson mass resolution(BMR)
  - Higgs Boson is reconstructed at different AHCAL Cell Size from 10mm to 70mm
  - Higgs BMR is fitted by gaus function

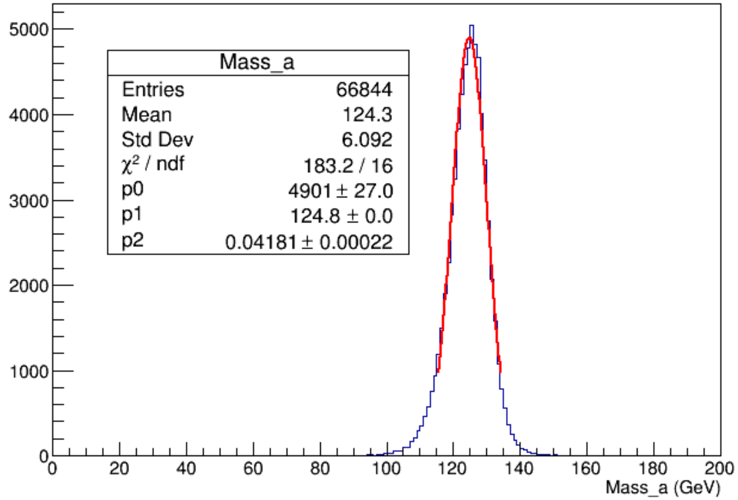


BMR HCAL cell 10mm

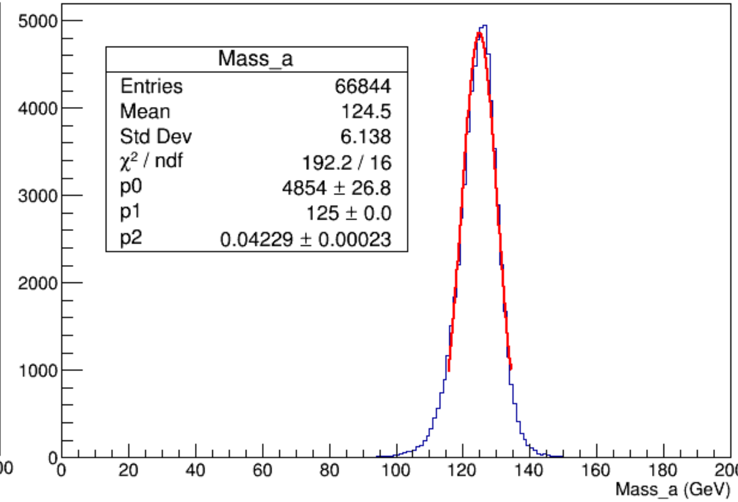


BMR HCAL cell 20mm

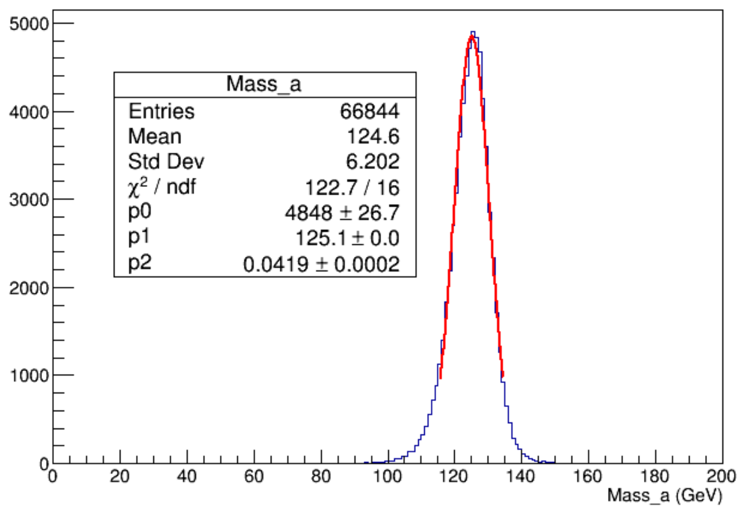
CellSize optimization



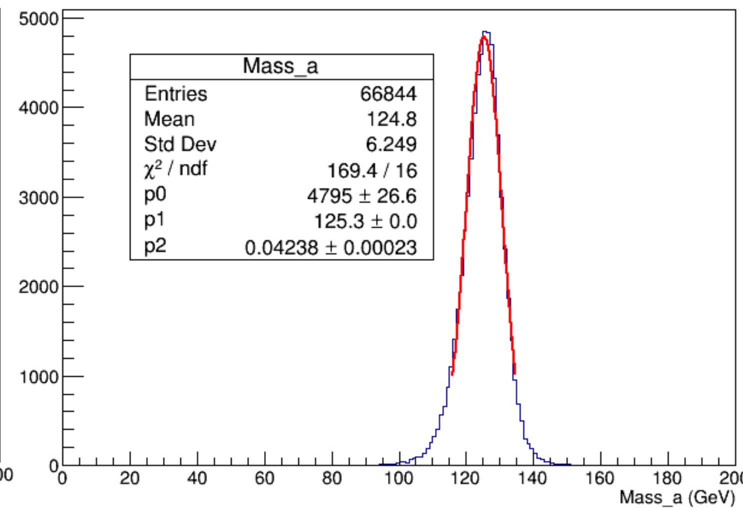
BMR HCAL cell 30mm



BMR HCAL cell 40mm



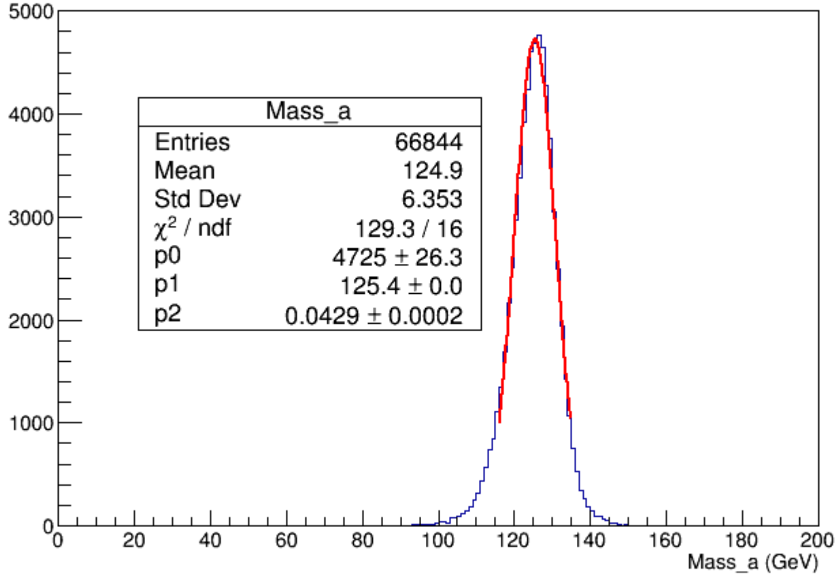
BMR HCAL cell 50mm



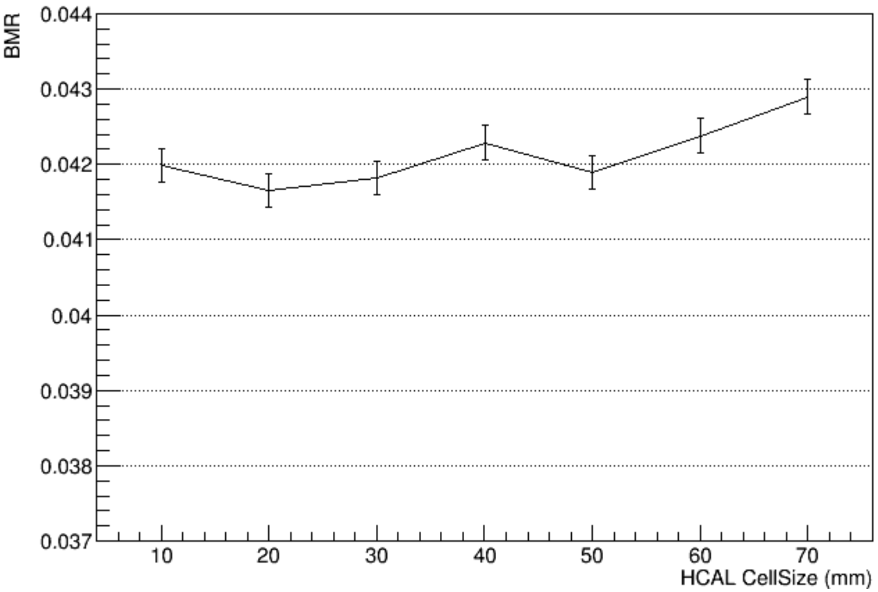
BMR HCAL cell 60mm

CellSize Optimization

- Cell Size optimization
  - 30 mm is a appropriate choice

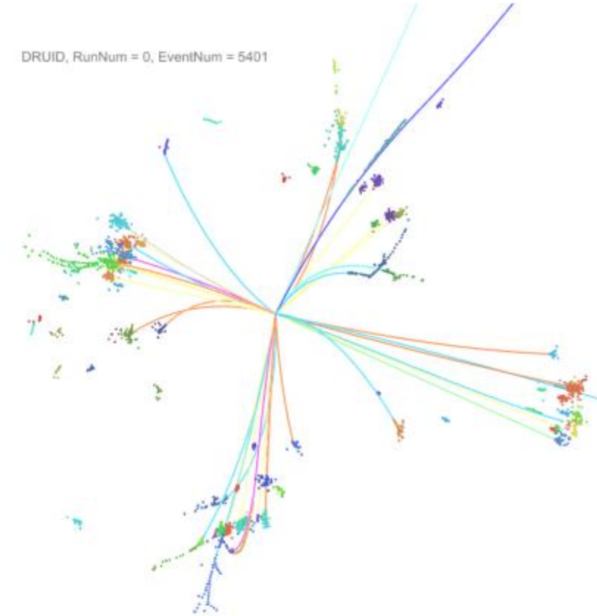


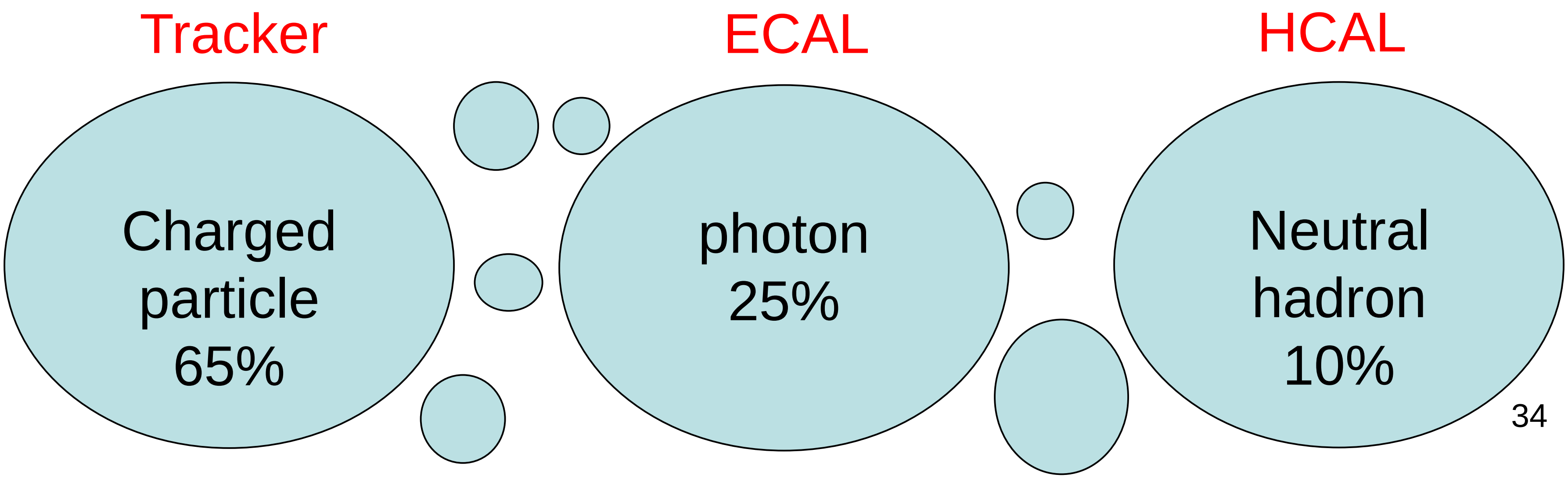
BMR HCAL cell 70mm



BMR - HCAL Cell Size

- PFA
  - The resolution of tracker,ECAL and HCAL is quite different
  - The optimal detector to detect different components of a jet
  - granularity is the key parameter for PFA calorimeter

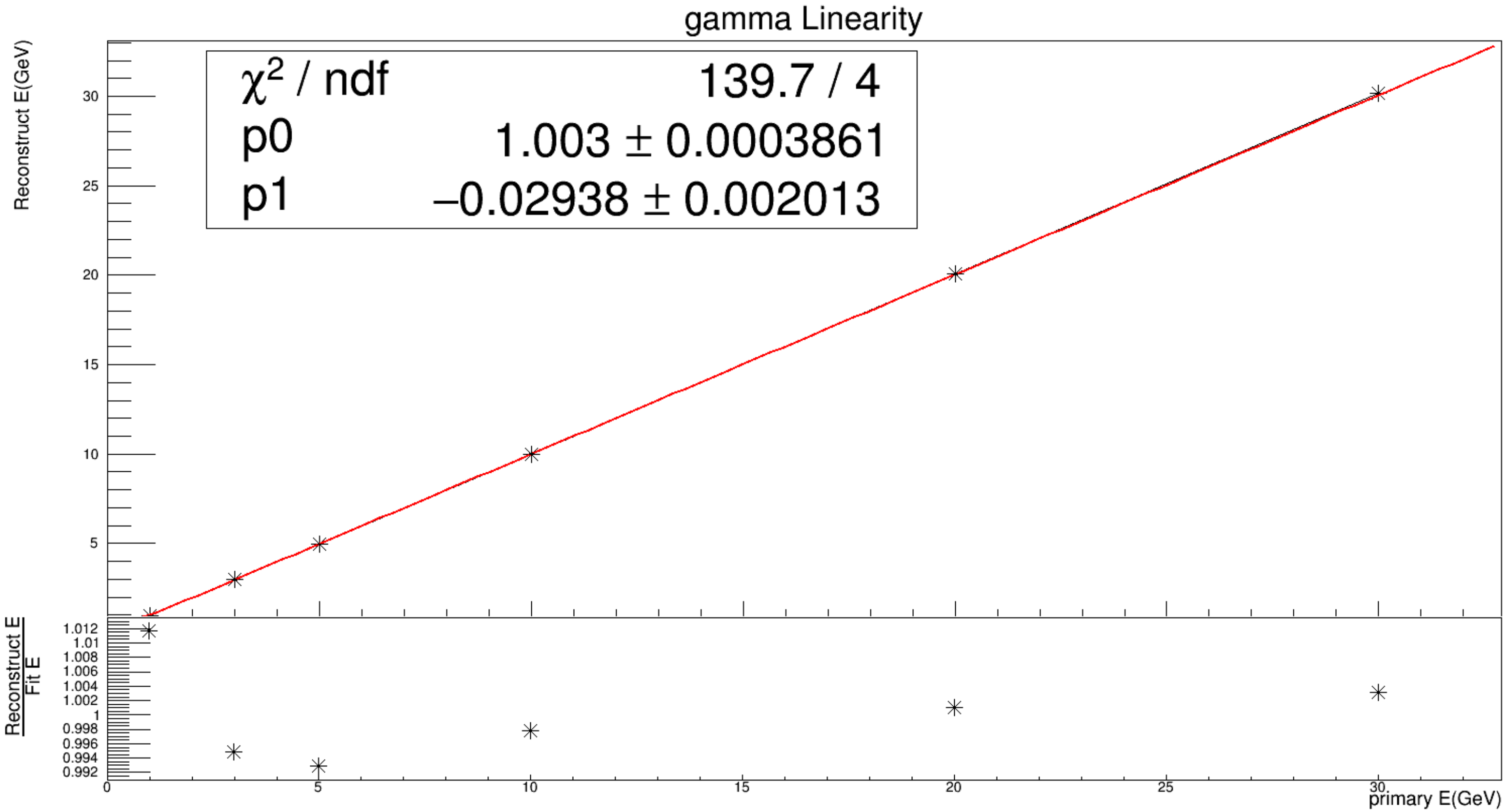




Calibration Method

- Event Selection
  - MC particle direction $\frac{P_z}{P} < 0.85$
  - Hit Energy > 0.5MIP(0.5MeV)
  - Incident particle must end in calorimeter
- Analog and Digital mode
  - Analog:$\mathrm{E} = E_{ECAL} \times a + E_{HCAL} \times b$
  - Digital:$\mathrm{E} = E_{ECAL} \times a + N_{HCAL} \times b$
- Minimum χ^2
  - $\chi^2 = \sum(ECAL \times a + HCAL \times b - E_{in})^2$
  - a is determined by gamma
  - b is determined by KLong

- Gamma Linearity



Hadron

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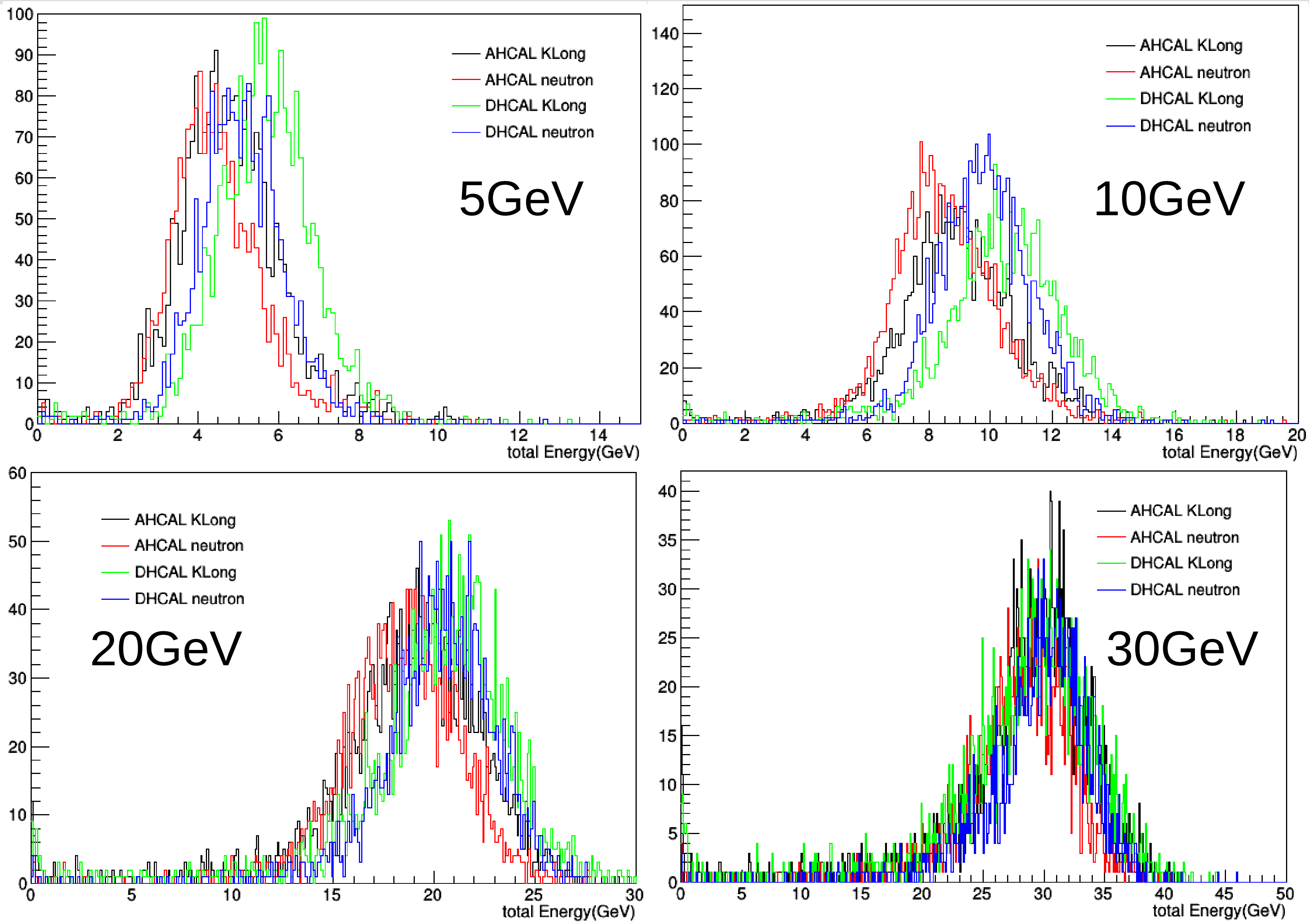
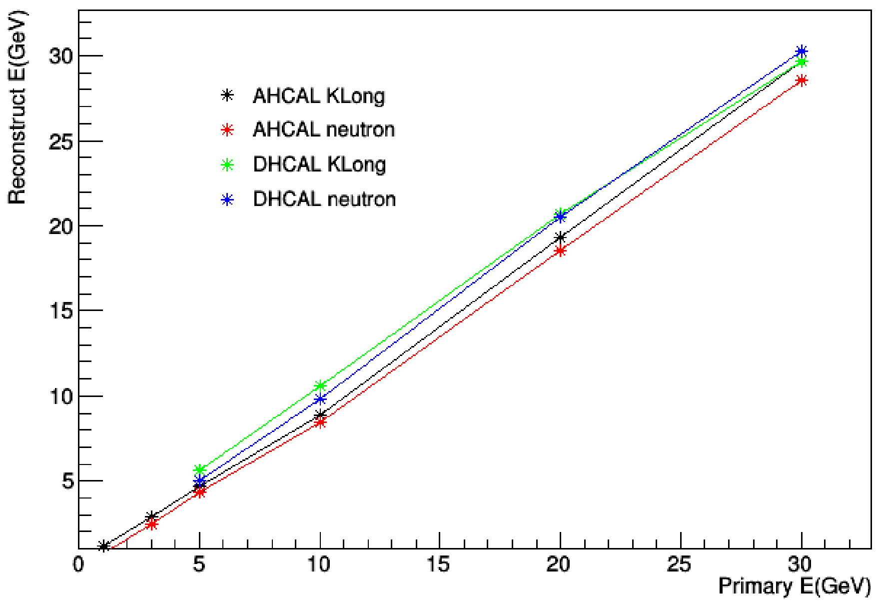
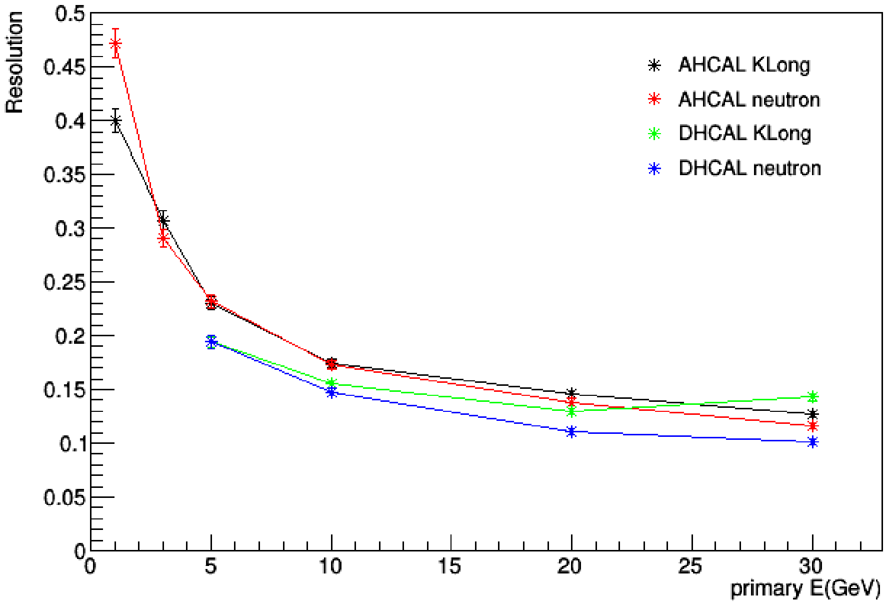


Hadron

- Linearity and Resolution
  - Analog mode has good linearity and worse resolution
  - Digital mode has saturation effect for KLong but neutron seems not to be influenced





AHCAL budget

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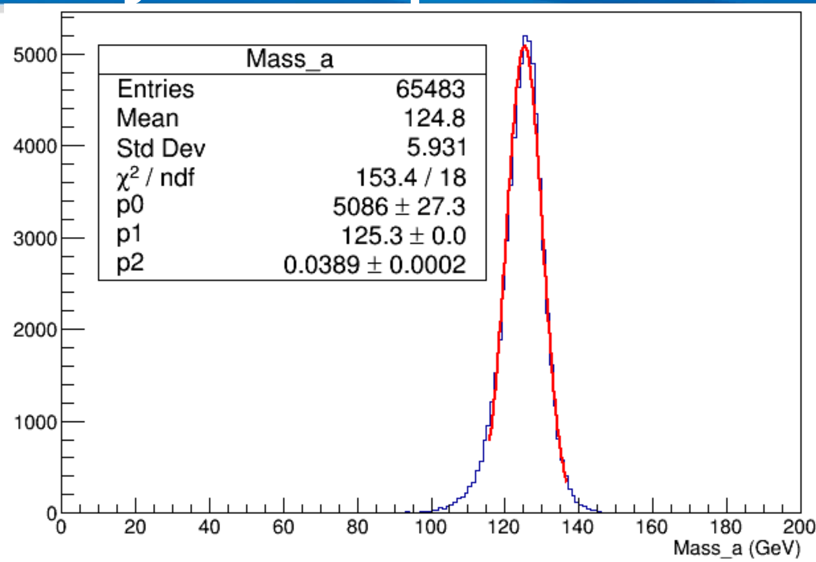
- Price per channel
  - Combination of readout layers can reduce cost of SPIROC, Electronic calibration and DIF：41¥ per channel

	scintillator	SiPM	SiPM power	SPIROC	Electronic calibration	HBU Soldering	LED and temperature	DIF	total
price per channel	10	55	7	25	3	10	12	13	135

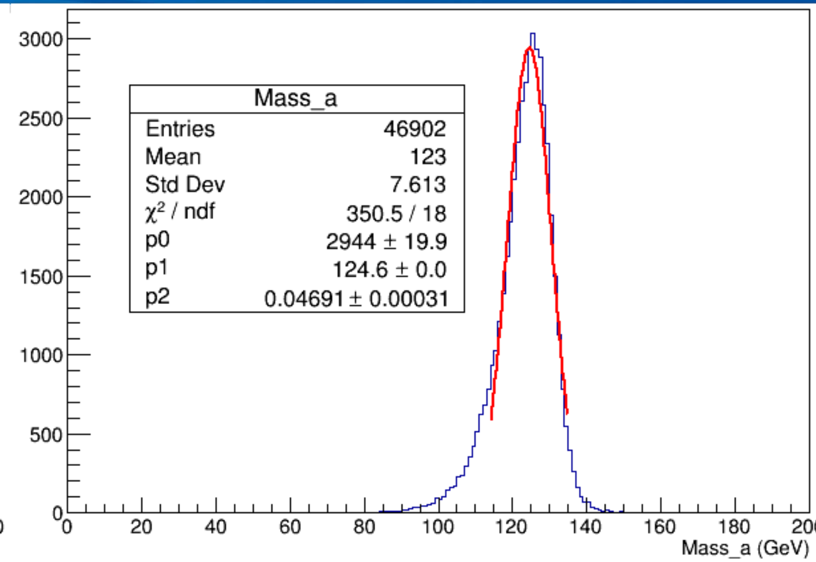
- Budget also includes absorber,PCB,DAQ,mechanical structure,wrapping machine and test machine
- Back up ratio 0.1

Size(channel No)	30mm cell	40mm cell	40mm cell 30 layer	30mm cell 30 layer
$0.5 \times 0.5m^2$	267(11560)	212(6760)		
$0.7 \times 0.7m^2$	488(21160)	397(12960)	312(9720)	384(15870)

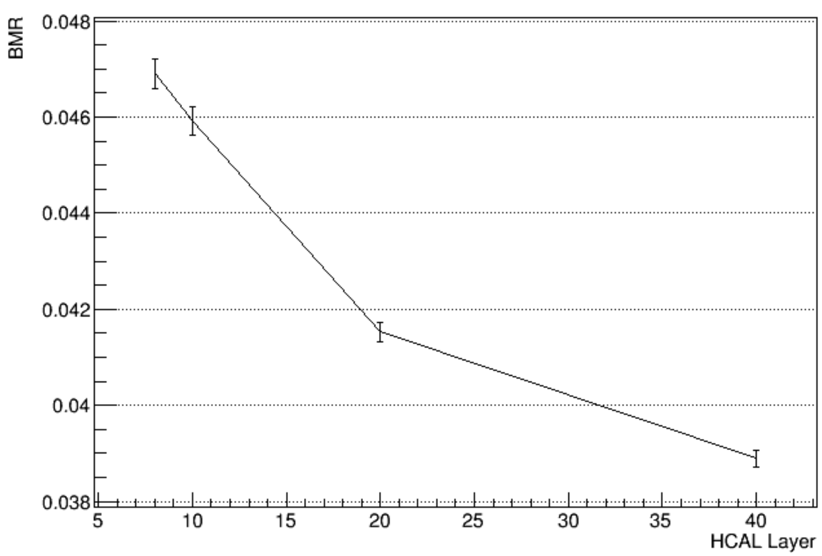
Number of Readout Layers Optimization



BMR HCAL Layer 40



BMR HCAL Layer 8



- Readout layer combination
  - This idea is to combine adjacent sampling layers inreadout
  - There are always 40 sampling layers
  - AHCAL Cell Size is fixed to 30mm
  - Readout layer range from 40 to 8

ECAL with AHCAL digital mode

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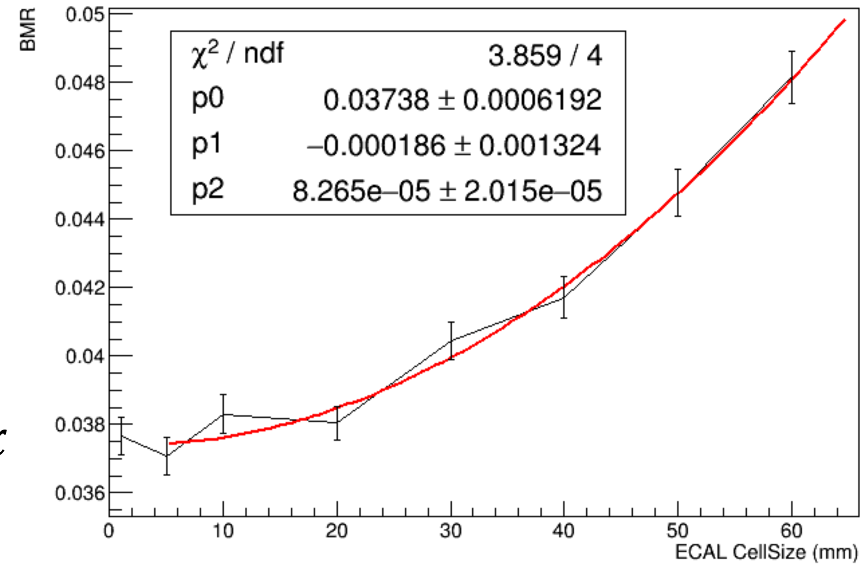
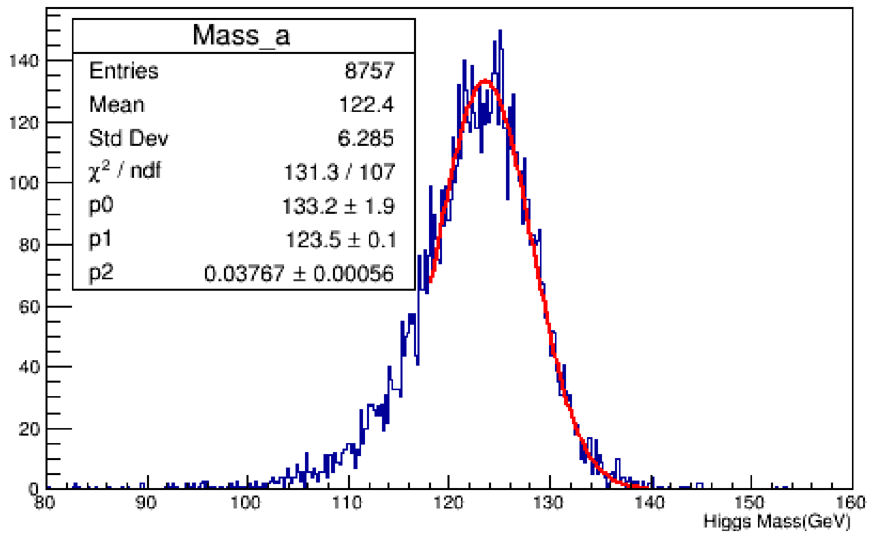
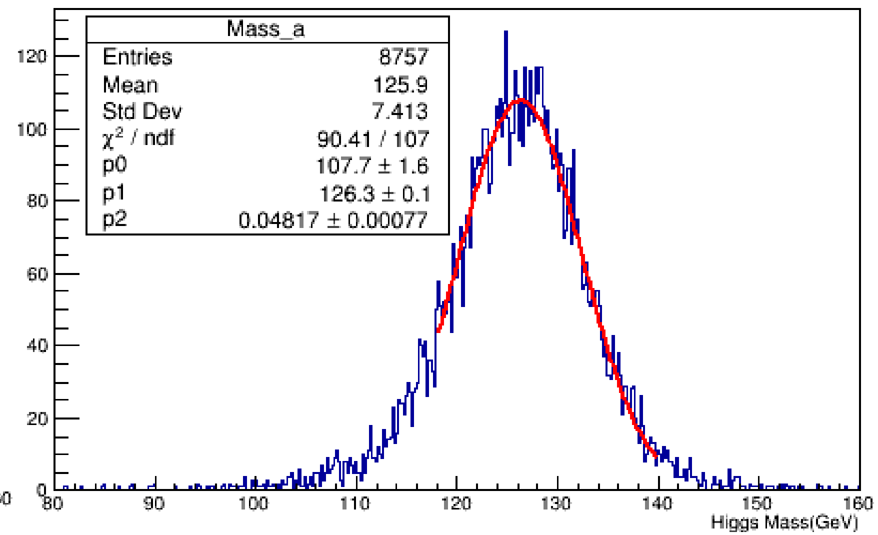
- ECAL Cell Size Scan
  - AHCAL cell size 10 mm
  - AHCAL work in digital mode
  - Similar results from Hγγ channel suggests ECAL cell size should be less than 10mm
- $BMR = 3.74\% \times (1 - 1.86 \times 10^{-4}x + 8.265 \times 10^{-5}x^2)$





ECAL cell 1mm



ECAL cell 60mm

ECAL with AHCAL digital mode

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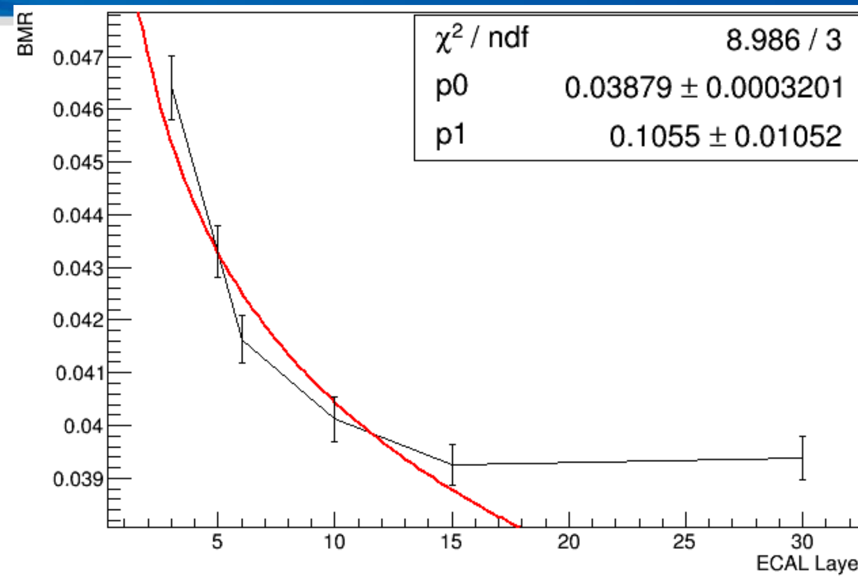
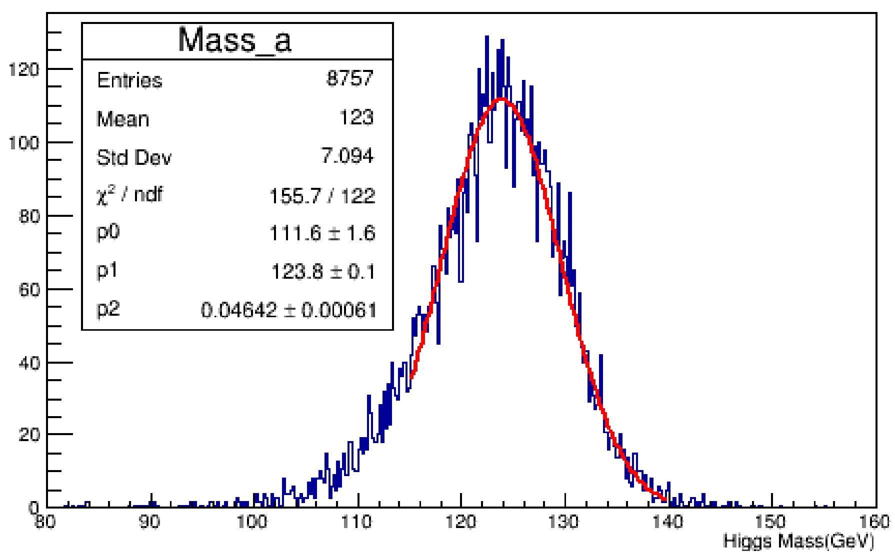
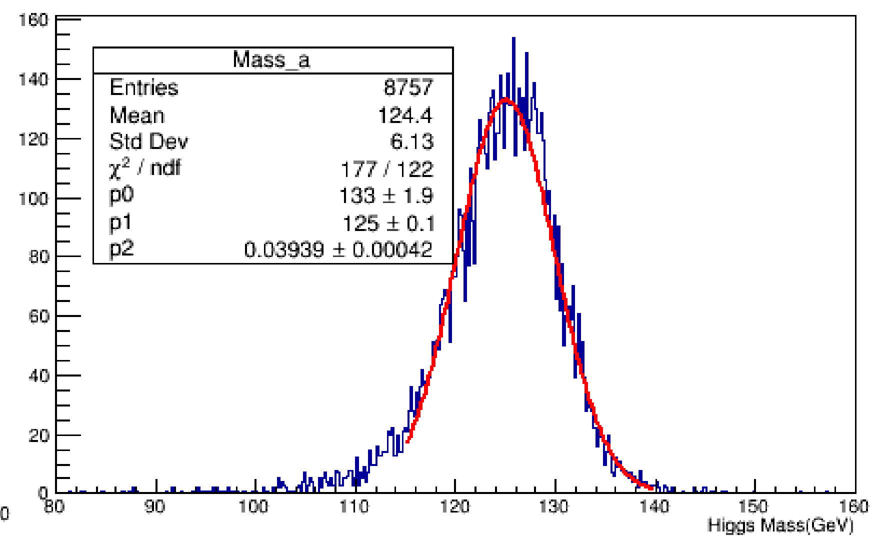
- ECAL Readout Layer Scan
  - ECAL Cell Size 10mm
  - Similar results from Hγγ channel suggests ECAL Layer should be larger than 15
- $BMR = 3.88\% \times (1 + 0.106 \times ln\frac{15}{x})$





ECAL Layer 40



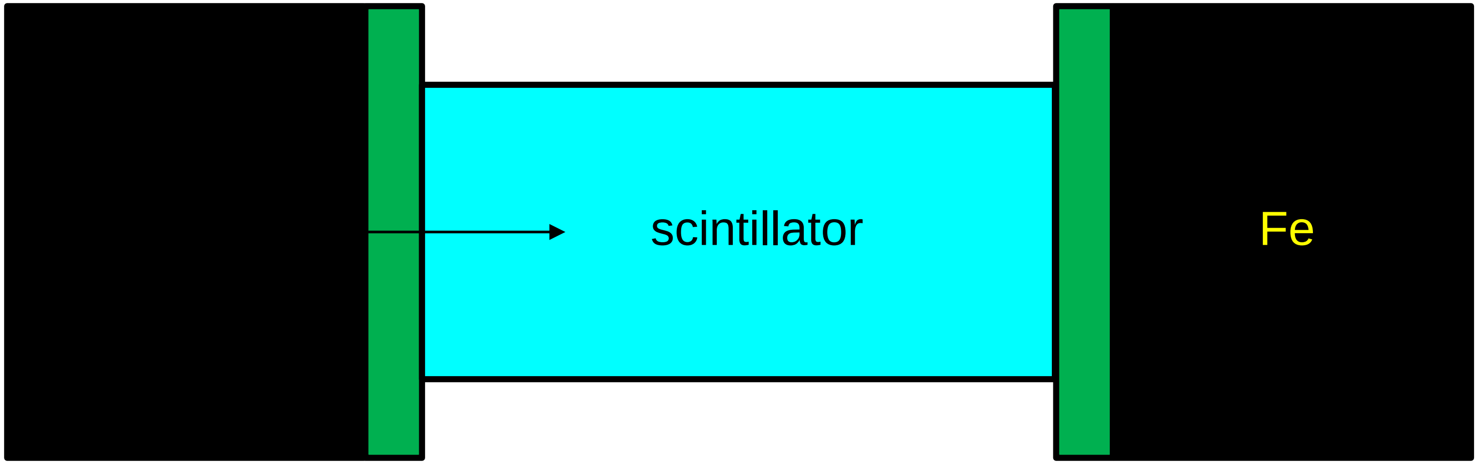
ECAL cell 60mm

Calorimeter BMR model

- BMR
  - $BMR = 3.74\% \times (1 + 16.48 \times 10^{-4}HC + 2.54 \times 10^{-5}HC^2) \times (1 + 0.061 \times ln\frac{40}{HL}) \times (1 - 1.86 \times 10^{-4}EC + 8.265 \times 10^{-5}EC^2) \times (1 + 0.106 \times ln\frac{15}{EL})$
  - HC : HCAL CellSize , EC : ECAL CellSize
  - HL : HCAL readout layer , EL : ECAL readout layer
- Channel Number
  - SiW ECAL Total Channel : 24.3M
  - HCAL(10mm) Total Channel : 64M
  - Minum Channel for 4% BMR : 15.2M
    - ECAL : 10 readout layer , 10 mm cellsize
    - HCAL : 40 readout layer , 30 mm cellsize
  - Minum Channel for 4.3% BMR : 6.025M
    - ECAL : 10 readout layer , 20 mm cellsize
    - HCAL : 40 readout layer , 40 mm cellsize

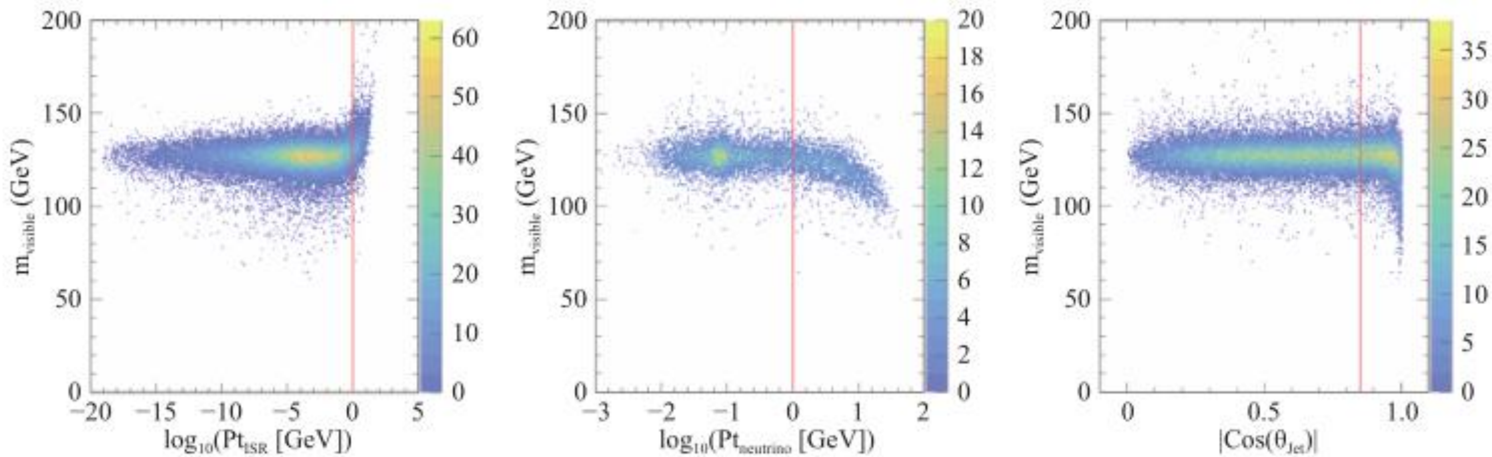
New design AHCAL

- Geometry
  - 20 layer scintillator : $30 \times 30 \times 30mm^3$(even can longer)
  - 20 layer Fe : 26mm
  - 40 layer PCB : double side readout at Z axis
  - 4.5λ : worse resolution at high energy but better for low energy neutral Hadron(<30GeV)



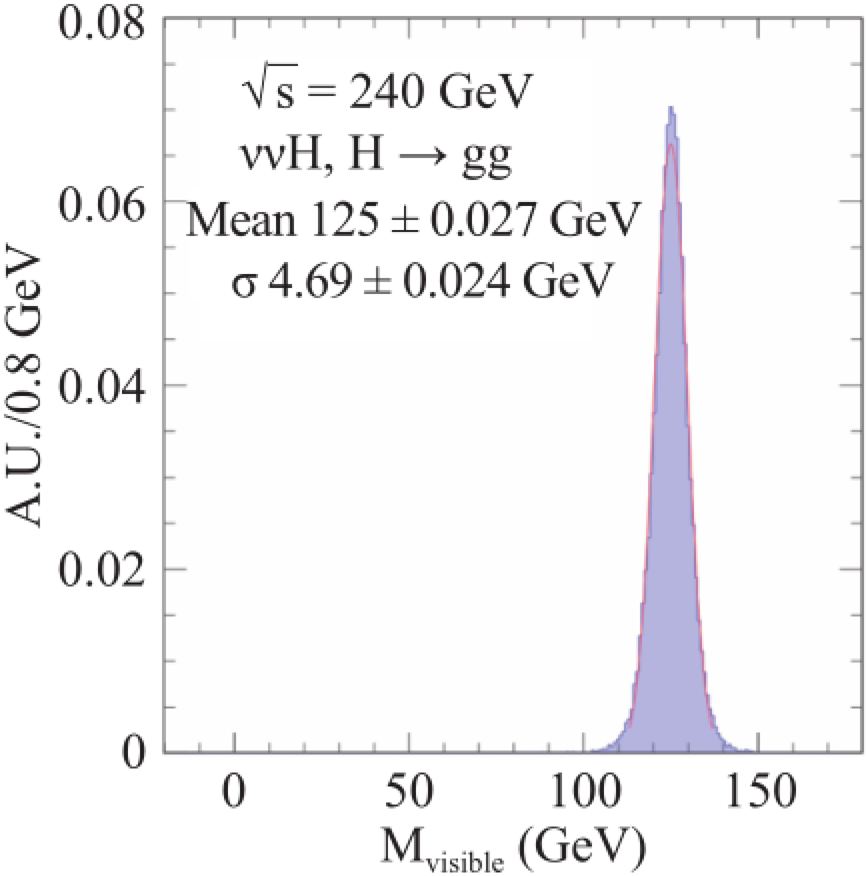
Event selection

- vvh-gg
  - ISR(initial state radiation): no parent , first 4 created photon



	gg(%)	bb(%)	cc(%)	WW^*(%)	ZZ^* (%)
Pt_ISR < 1 GeV	95.15	95.37	95.30	95.16	95.24
Pt_neutrino < 1 GeV	89.33	39.04	66.36	37.46	41.39
|Cos(Theta_Jet)| < 0.85	67.30	28.65	49.31	–	–

- Zhaohang's works



	Total # channels [M(10^6)]	Occupancy [%]	Nbit /channel	# Channels readout/evt [k(10^3)]	Volume /evt [MBytes]	Data rate @100 kHz [GBytes/s]
Vertex	690	0.3	32	2070	8.3	830
Silicon Tracker						
Barrel	3238	0.01 ~ 1.6	32	1508	3.15	315
Endcap	1238	0.01 ~ 0.8	32	232	0.4	40
TPC	2	0.1-8	30	1375	5	500
Drift Chamber	0.056	5-10	480		3	300
ECAL						
Barrel	17/7.7	0.17	32	28.8/13.1	0.117/0.053	11.7/5.3
Endcap	7.3/3.3	0.31	32	22.4/10.2	0.090/0.041	9.0/4.1
AHCAL						
Barrel	3.6	0.02	32	0.72	0.0029	0.3
Endcap	3.1	0.12	32	3.72	0.015	1.5
DHCAL						
Barrel	32	0.004	8	1.28	0.00128	0.13
Endcap	32	0.01	8	3.2	0.0032	0.32
Dual Readout Calorimeter	22	0.4-1.6	64	88-352	0.704-2.8	70-280
Muon						
Barrel	4.9	0.0002	24	0.01	< 0.0001	< 0.01
Endcap	4.6	0.0002	24	0.01	< 0.0001	< 0.01
LumiCal	0.5	0.2	12	0.5	0.0007	0.07

Table 8.1: CEPC DAQ data rate estimation. TPC and drift chamber are options for the outer tracker. AHCAL and DHCAL are two options for the PFA hadronic calorimeter, while the Dual Readout Calorimeter is a calorimeter option to cover both the ECAL and HCAL functionality. With the level-1 trigger operating at 100 kHz, the total raw data rate is 2 TBytes/s.

AHCAL Optimization

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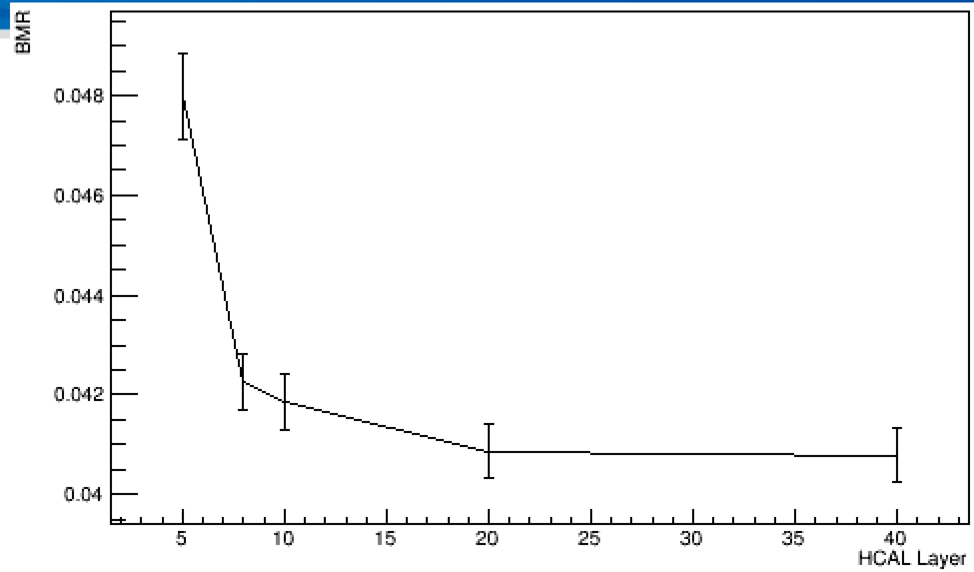
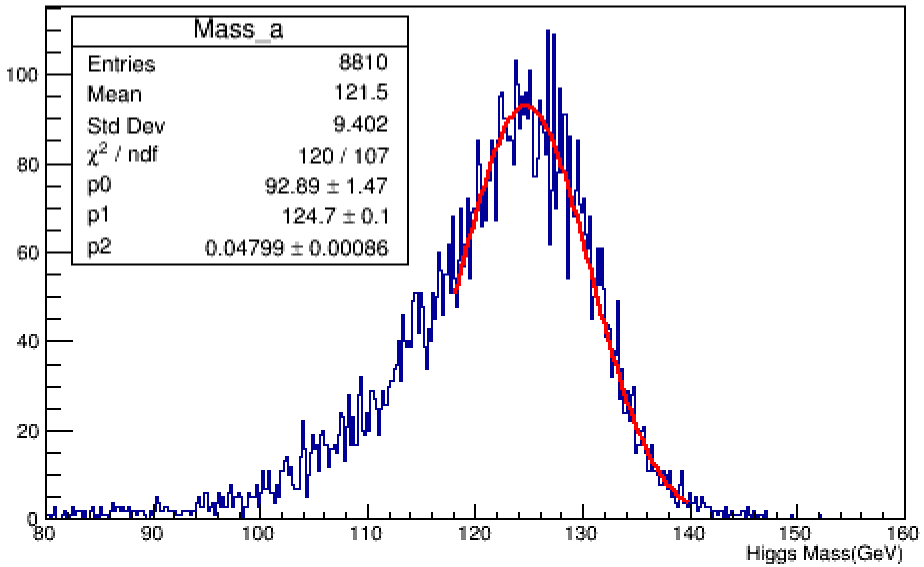
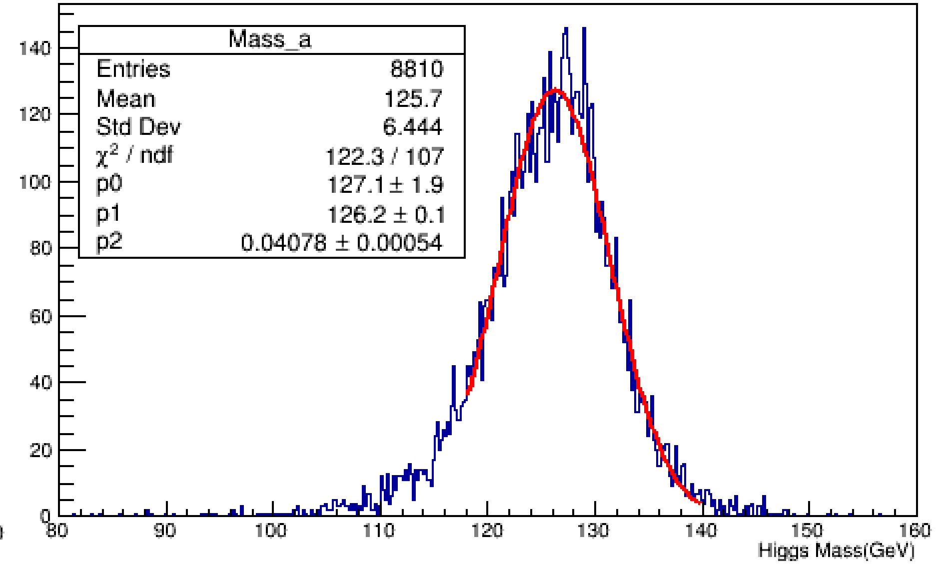
- Readout Layer optimization
  - AHCAL Cell Size is 30 mm
  - Only readout is combined , there are always 40 layers for sampling
  - The hit position after combining is set at the position of the 1st layer





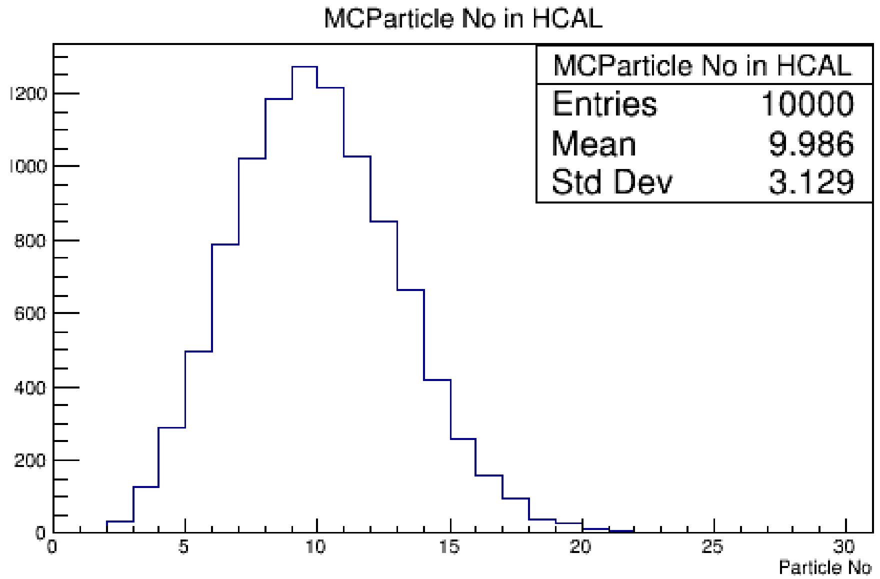
HCAL Readout Layer 5

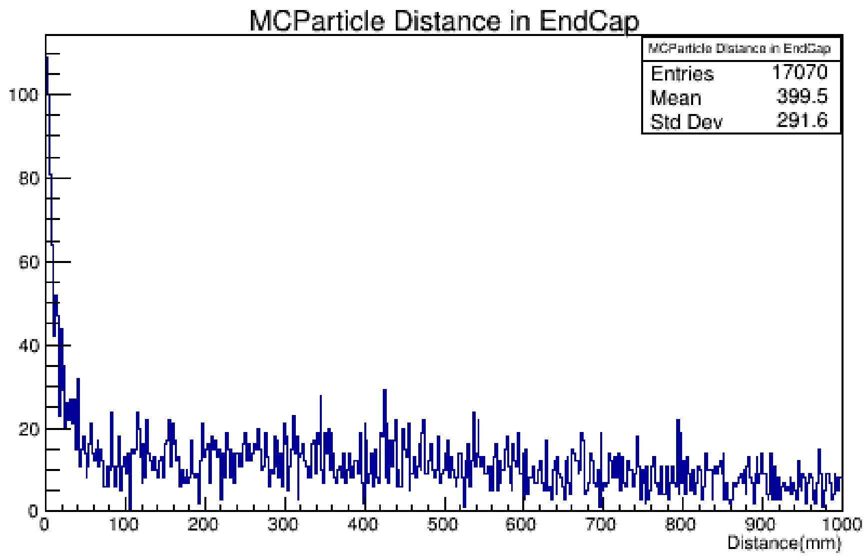


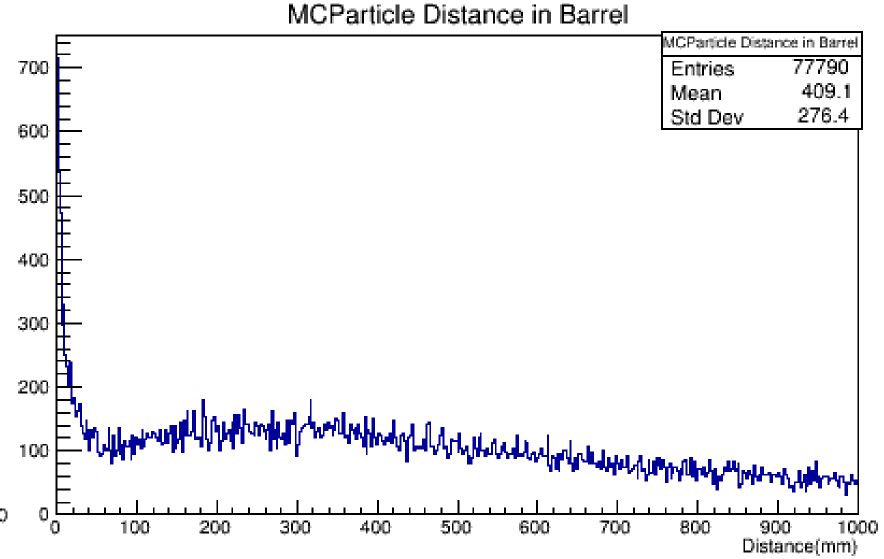
HCAL Readout Layer 40

MCtruth

- MC particle in HCAL
  - Energy < 30GeV
  - Number is not large
  - Distance can be close

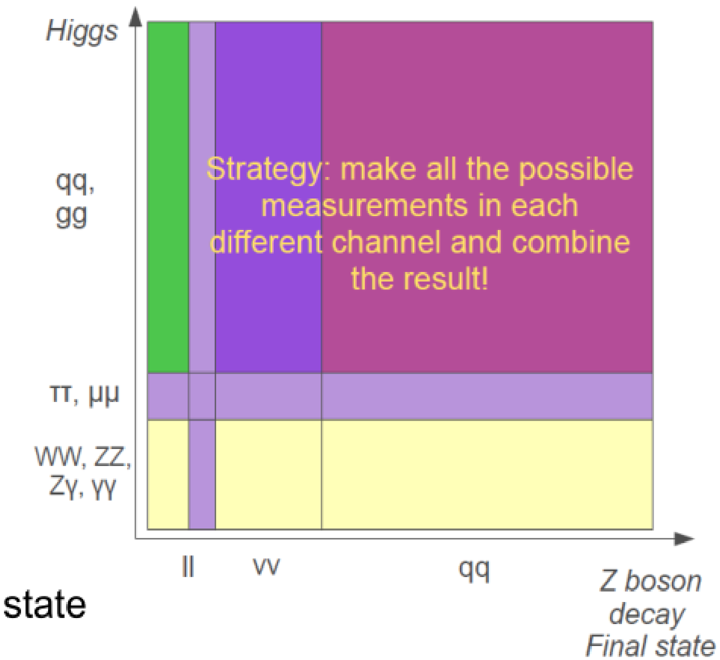






Recent Highlight: Jet study

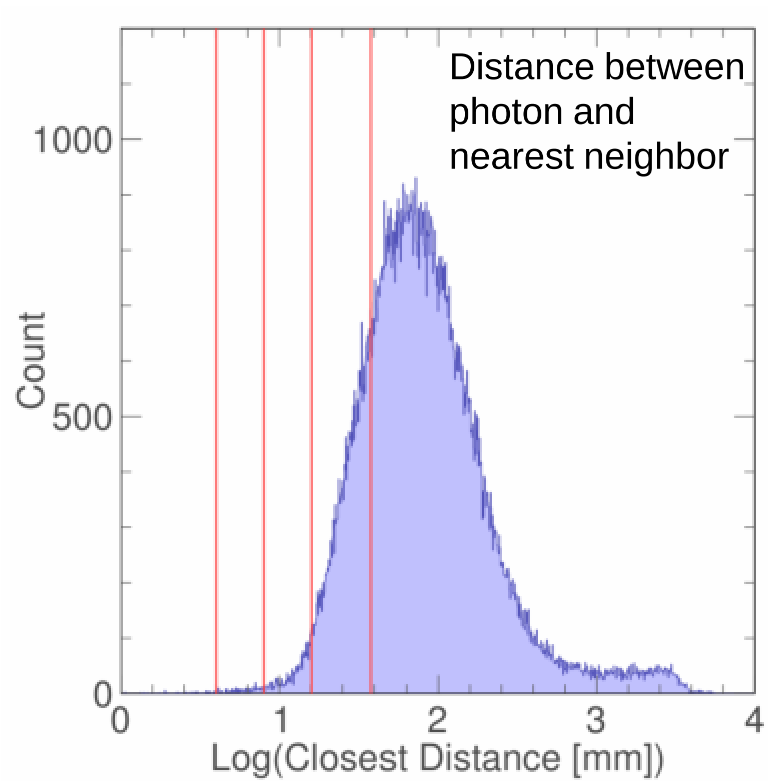
- SM Higgs
  - ***0 jets: 3%:*** *Z→ll, νν (30%); H→0 jets (~10%, ττ, μμ, γγ, γZ/WW/ZZ→leptonic)*
  - ***2 jets: 32%***
    - *Z→qq, H→0 jets. 70%*10% = 7%*
    - *Z→ll, νν; H→2 jets. 30%*70% = 21%*
    - *Z→ll, νν; H→WW/ZZ→semi-leptonic. 3.6%*
  - ***4 jets: 55%***
    - *Z→qq, H→2 jets. 70%*70% = 49%*
    - *Z→ll, νν; H→WW/ZZ→4 jets. 30%*15% = 4.5%*
  - ***6 jets: 11%***
    - *Z→qq, H→WW/ZZ→4 jets. 70%*15% = 11%*

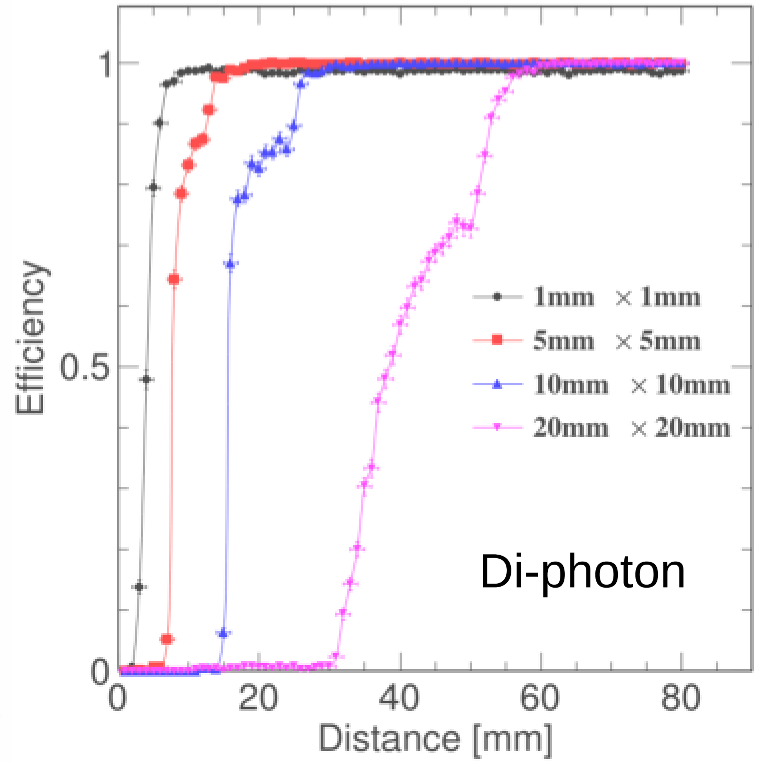


- **97%** of the SM Higgsstrahlung Signal has Jets in the final state
- **1/3** has only 2 jets: be described by the mass resolution of the hadronic decay boson (**BMR**)
- **2/3** need color-singlet identification: grouping the hadronic final sate particles into color-singlets
- Jet is important for EW measurements & jet clustering is essential for **differential** measurements

ECAL optimization

- SiECAL





Cell Size	Critical Separation Distance with Arbor	Percentage of $Z \to \tau^+\tau^-$
1 mm	4 mm	0.07%
5 mm	8 mm	0.30%
10 mm	16 mm	1.70%
20 mm	38 mm	19.6%

Conclusion and plan

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- Simulation
  - Cell combine and calibration
  - Reconstruction
- AHCAL budget
  - Combine readout:save 1058000
  - BNU SiPM:15 per pitch;save 846400

name	scintillator	scintillator wrapping machine	electronics	calibration	SiPM	stainless steel	total
unit price	10	350000	00	23	55	2744	
quantity	21160	1	21160	21160	21160	40	
total	211600	350000	2116000	486680	1163800	109760	4437840

OutLine

- Background and Simulation Setup
- Reconstruction Process
- CellSize Optimization
  - Pion and KLong separation
  - Simple PFA method
- Read out layer Optimization
- Conclusion

Background and Simulation Setup

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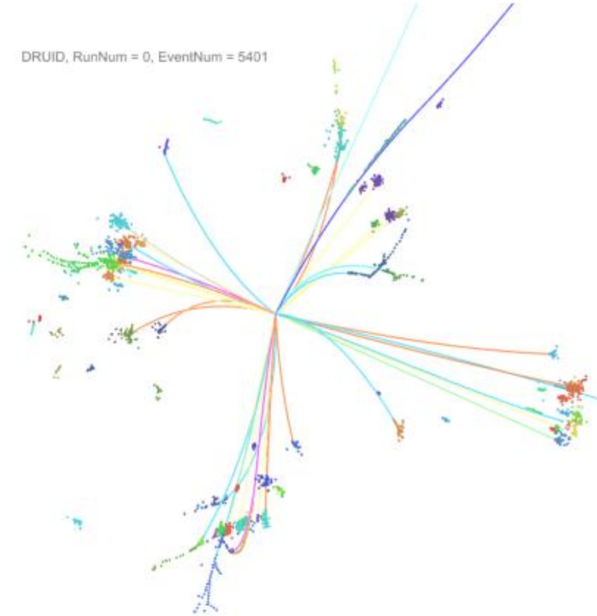
- PFA
  - The resolution of tracker,ECAL and HCAL is quite different
  - The optimal detector to detect different components of a jet
  - Cellsize is the key parameter for PFA calorimeter



Tracker

ECAL

HCAL

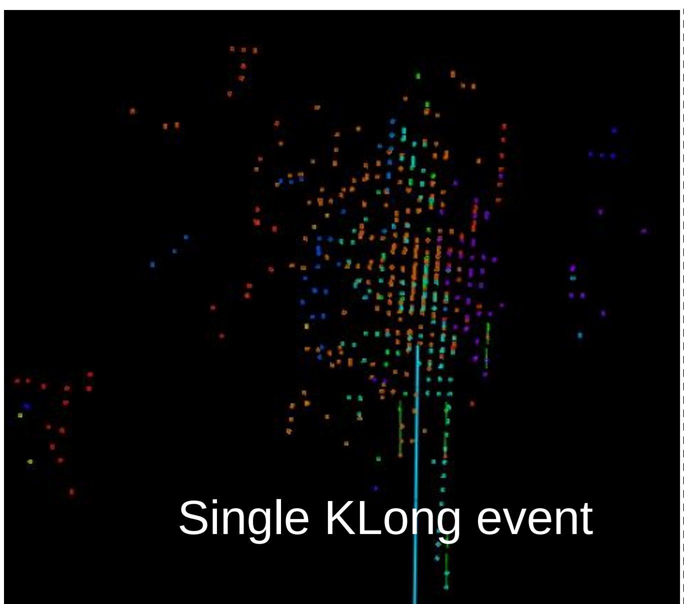
Charged particle 65%

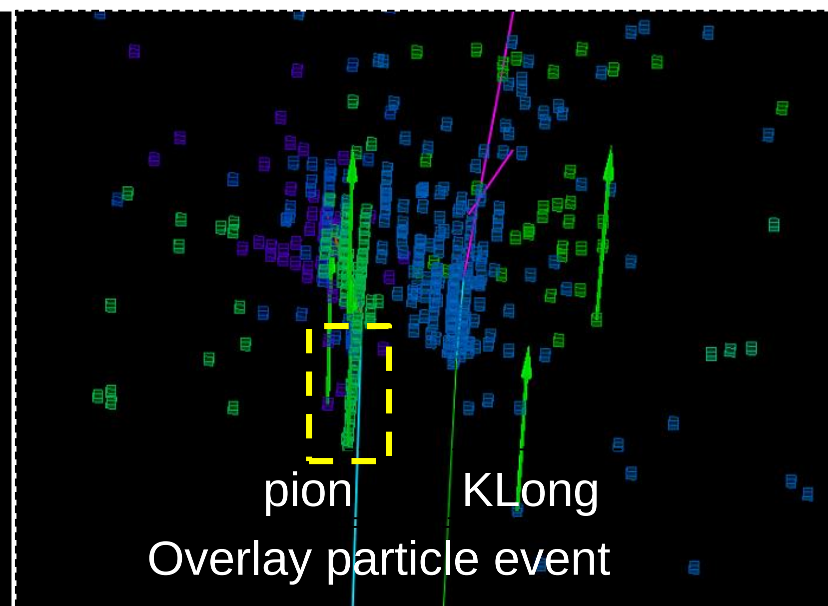
photon 25%

Neutral hadron 10%

Background and Simulation Setup

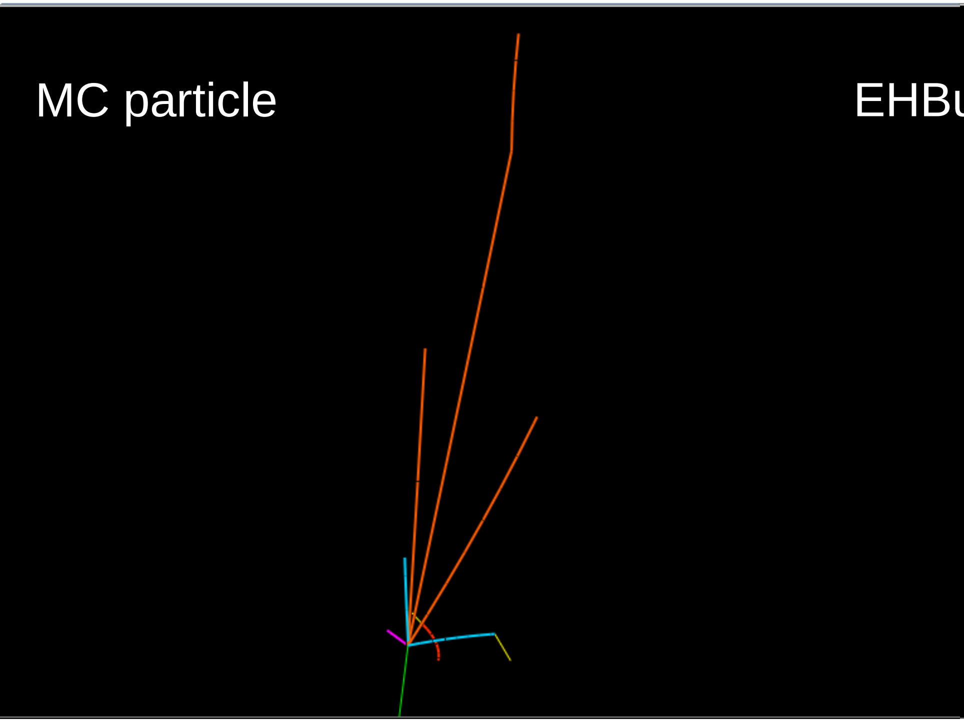
- Incident particle
  - 10 GeV pion-
  - 10 GeV KLong: abundant in H-gg event
- Feature of KLong
  - KLong usually doesn't deposit significant energy in ECAL so that it doesn't have a 'stick' in the front
  - KLong is wider than pion

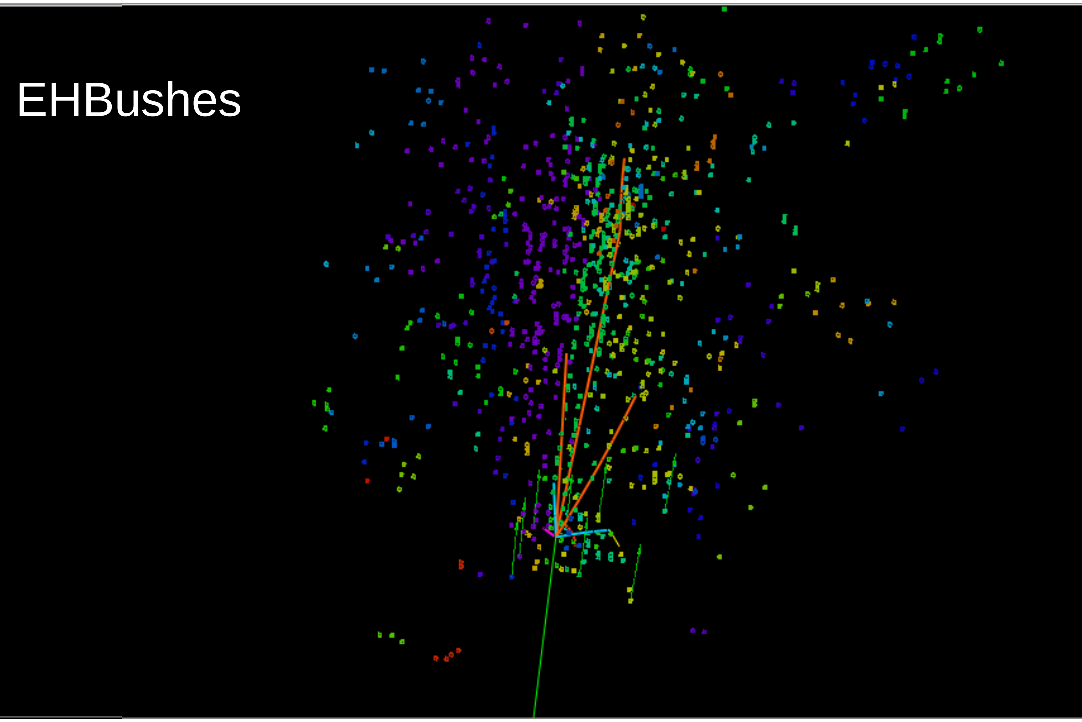




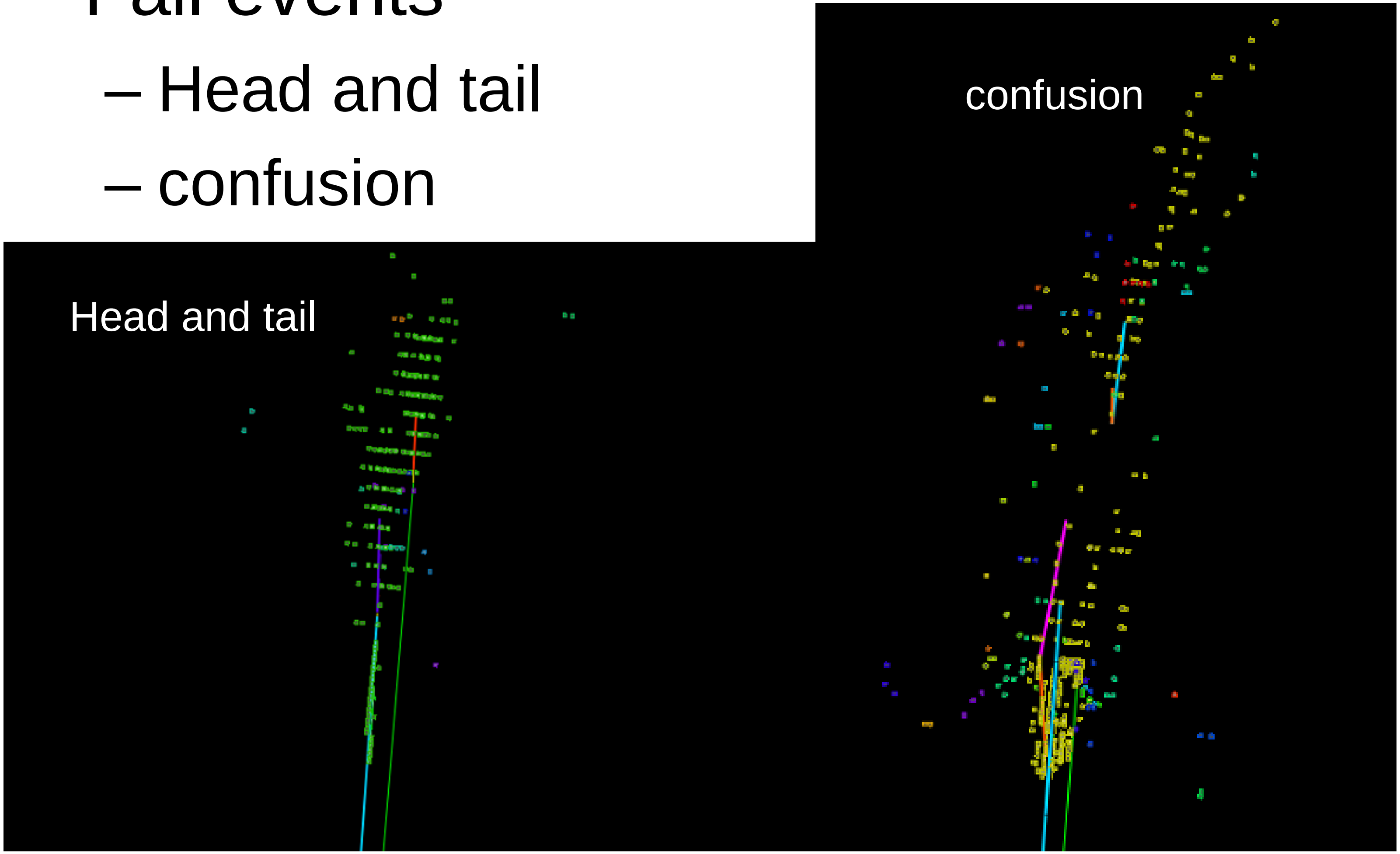
Reconstruction Process

- The physical structure of a shower is exactly like a tree
- So we reconstruct bushes first



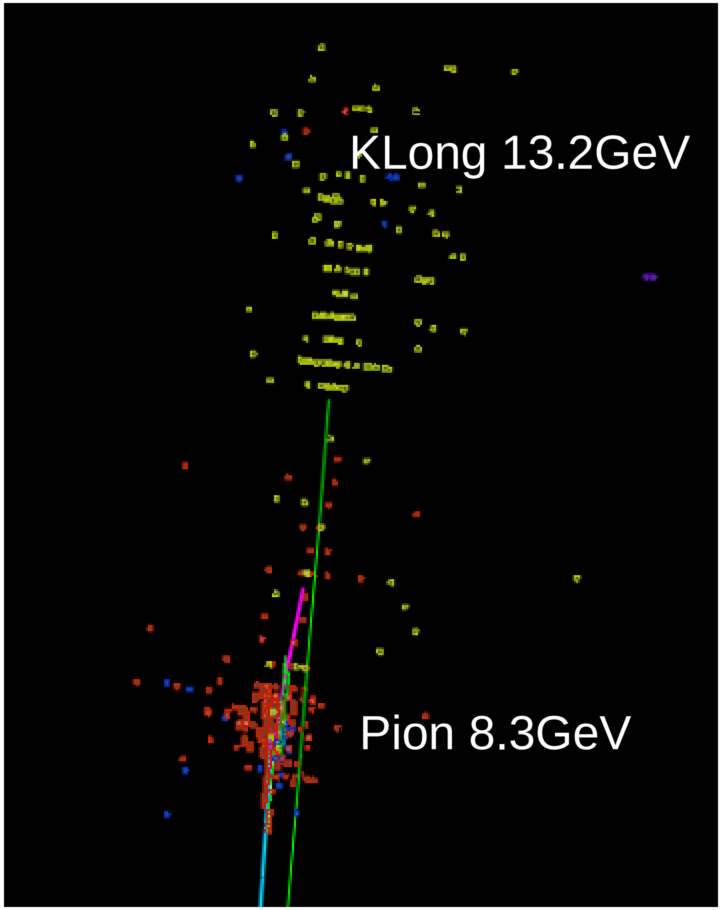


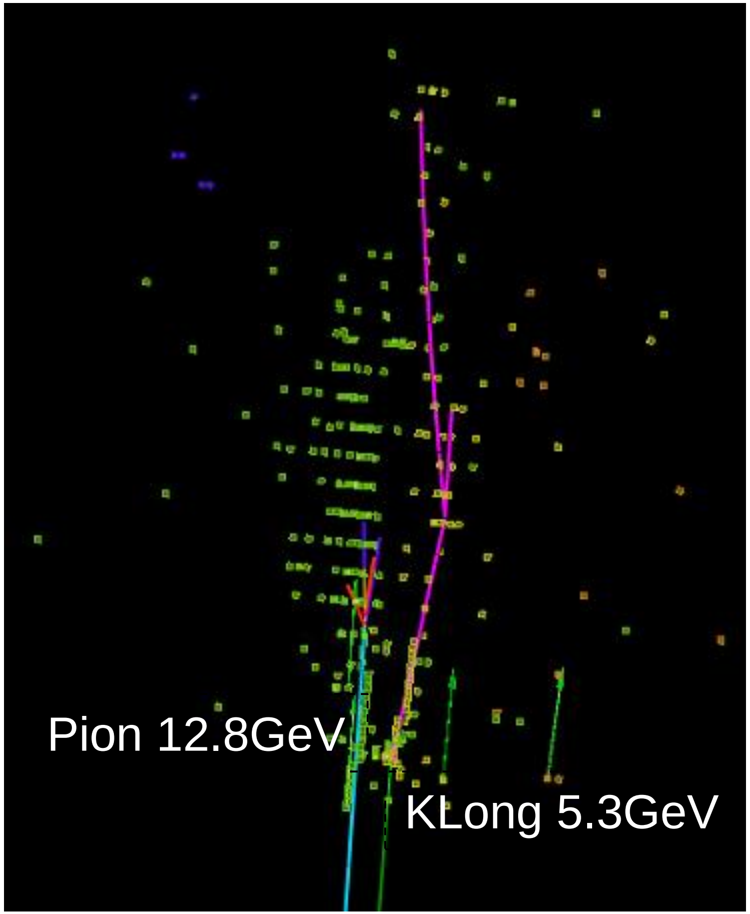
- Fail events
  - Head and tail
  - confusion



Reconstruction Process

- Successful event
  - Pion KLong distance 30mm





Reconstruction Process

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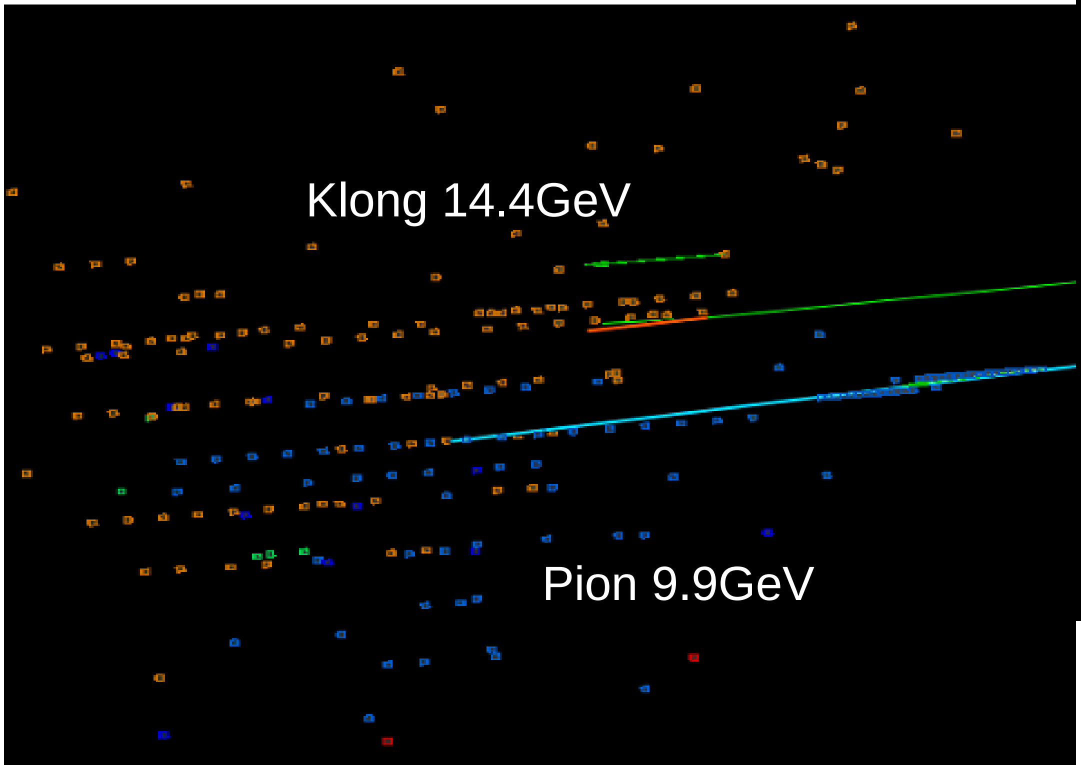
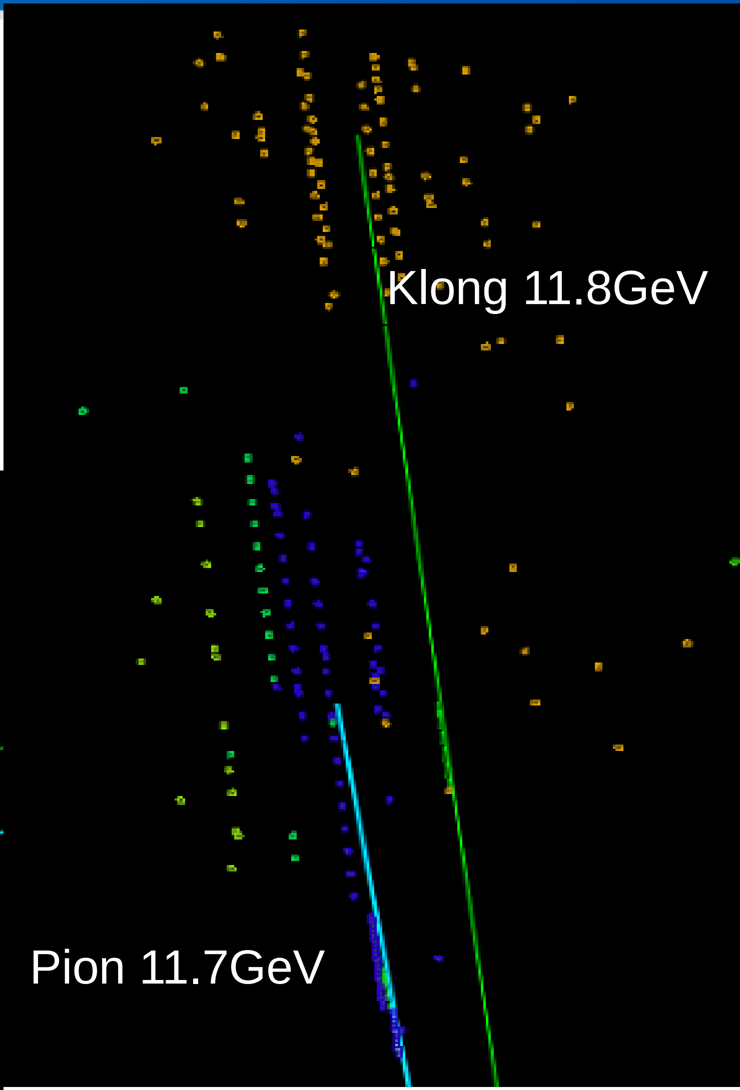
- 70mm cellsize
  - Incident position
    - pion:75mm
    - Klong:0mm



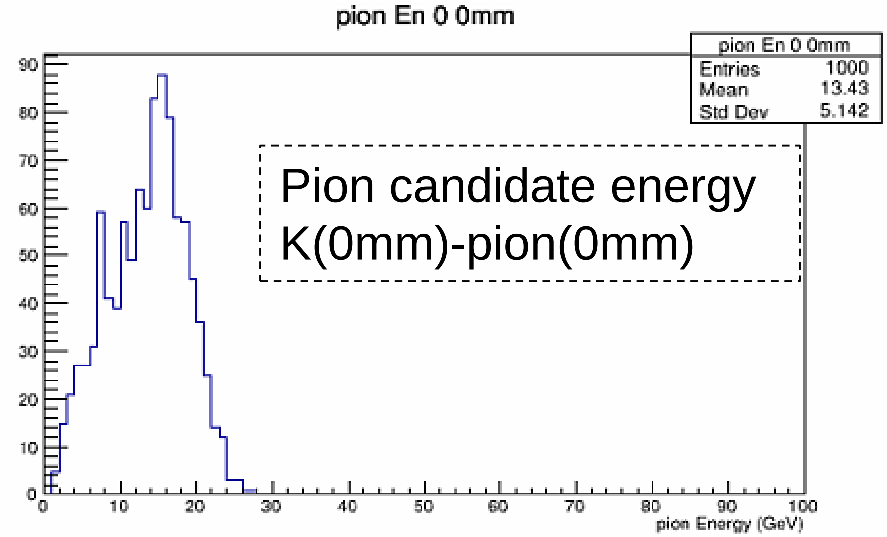


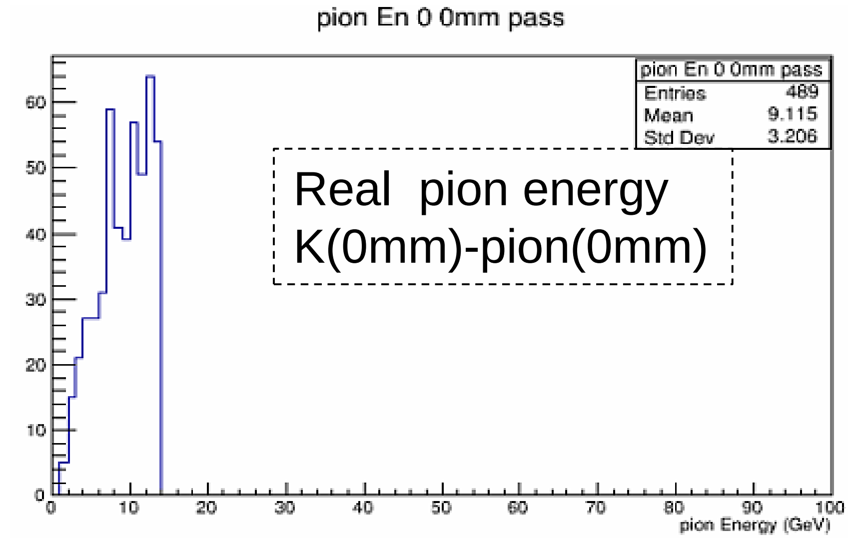
Pion and KLong separation

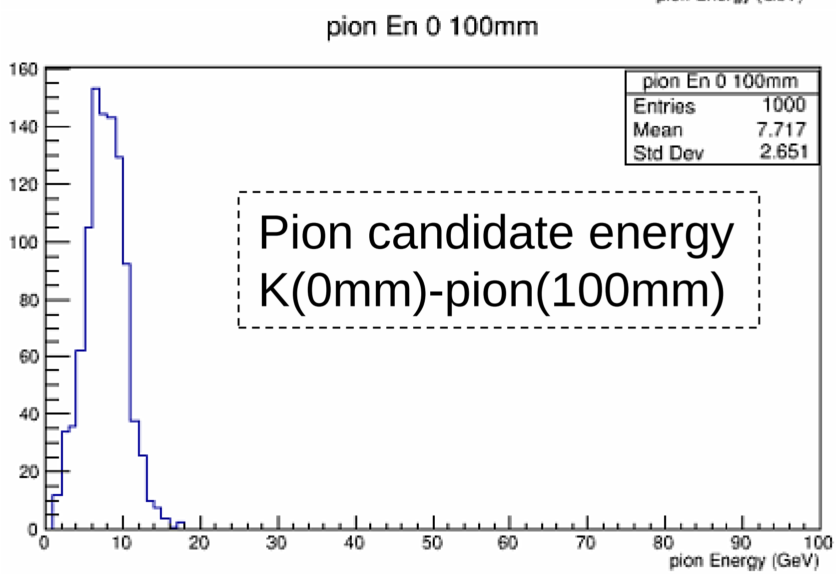
- Real situation
  - Charged particle: track can provide energy and direction
  - Uncharged particle: even don't know the number of them
- Strategy for pion, K in MC
  - Assume that the incident direction is the track in Simplified geometry
  - Pion, K candidate selection
    - $Pion_{candidate}$: cluster closest to pion track and energy >mean - 3σ
    - $K_{candidate}$: cluster doesn't match pion track with largest cluster energy
    - KLong fragment : cluster away from pion track
  - Efficiency for pion, K
    - Real pion:| energy $pion_{candidate}$ – $mean_{pion}$| <3σ && close to track(COG dis < 80mm && Angle < 30degree)
    - Real KLong:|energy $K_{candidate}$ – $mean_{K}$| <3σ && close to track
    - All : a Event with a real pion and a real KLong

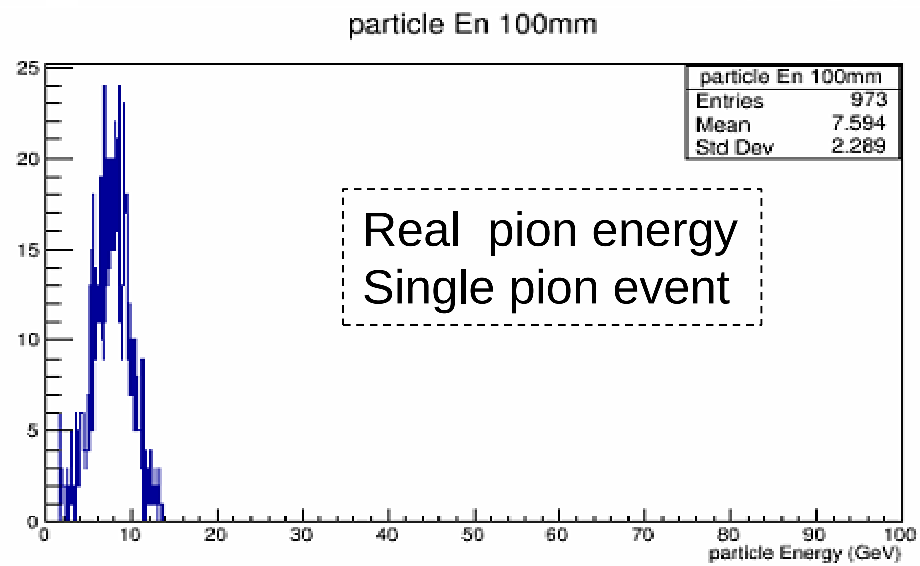
Pion and KLong separation

- Pion$_{candidate}$ energy distribution



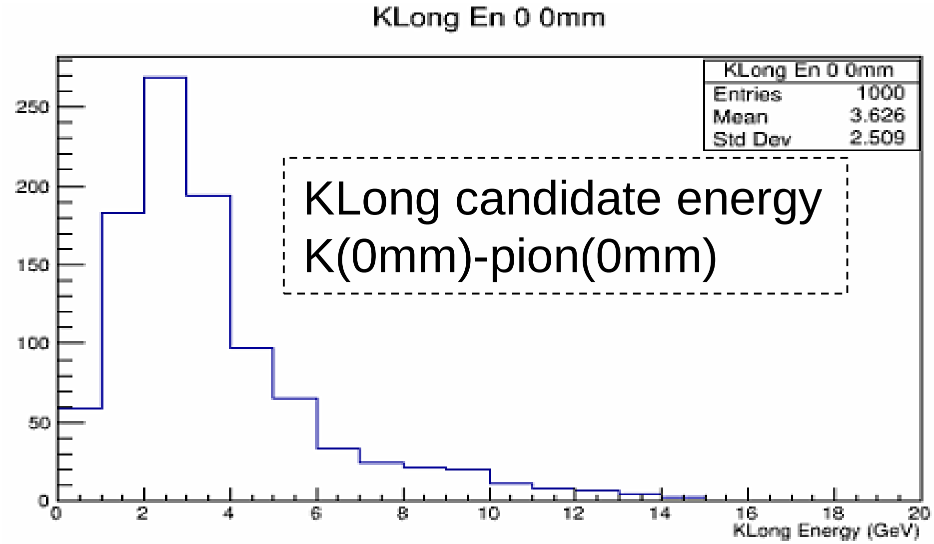


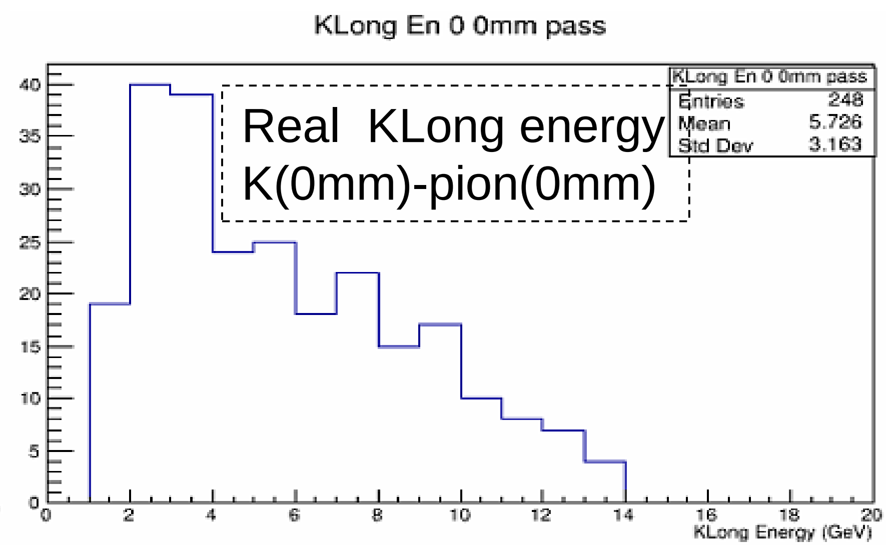


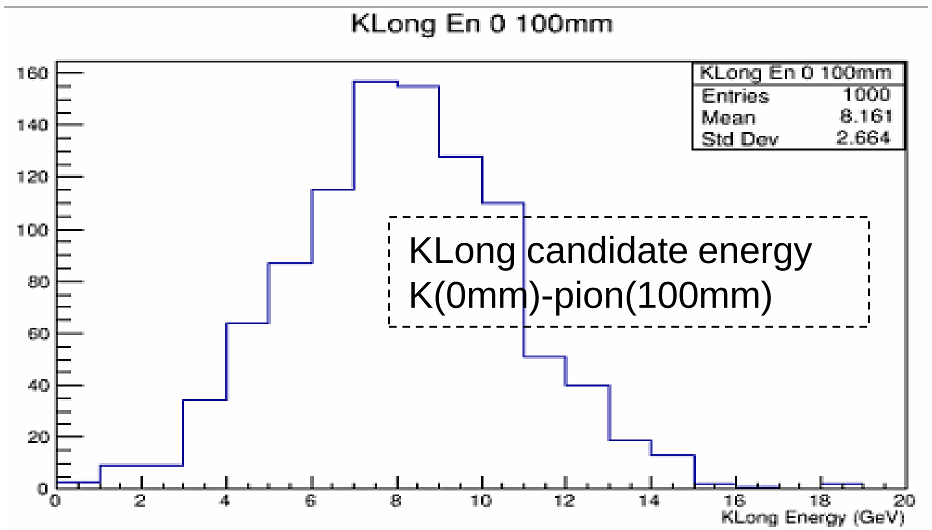


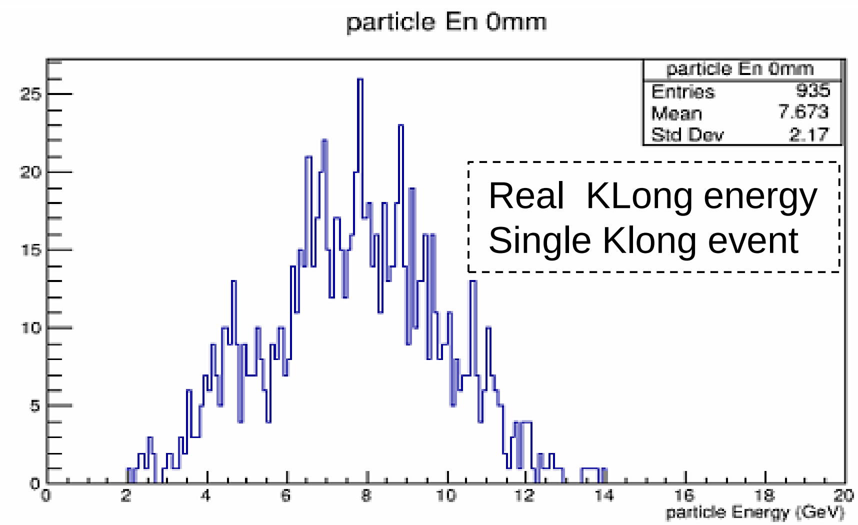
Pion and KLong separation

- $\text{KLong}_{\text{candidate}}$ energy distribution









Pion and KLong separation

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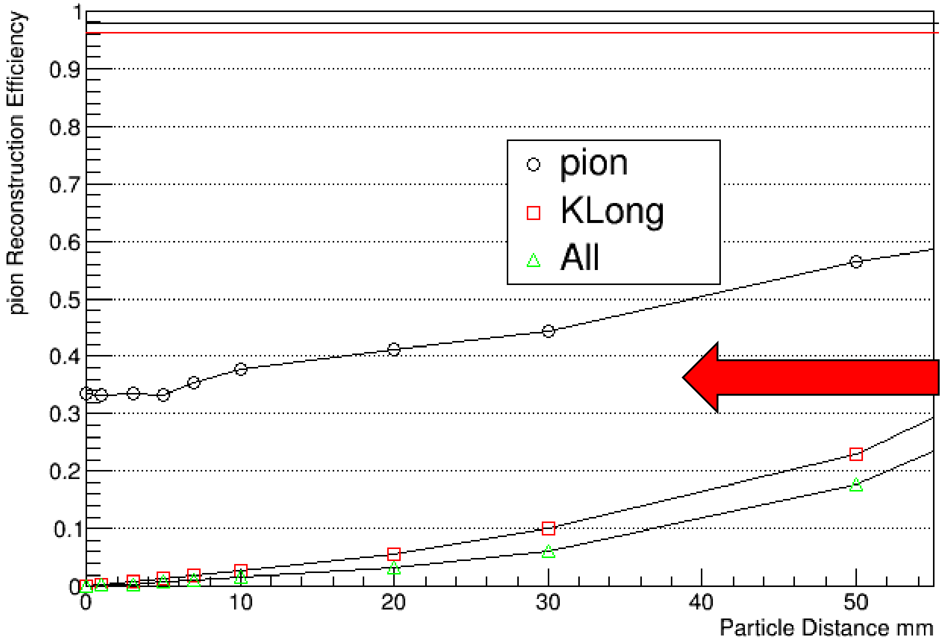
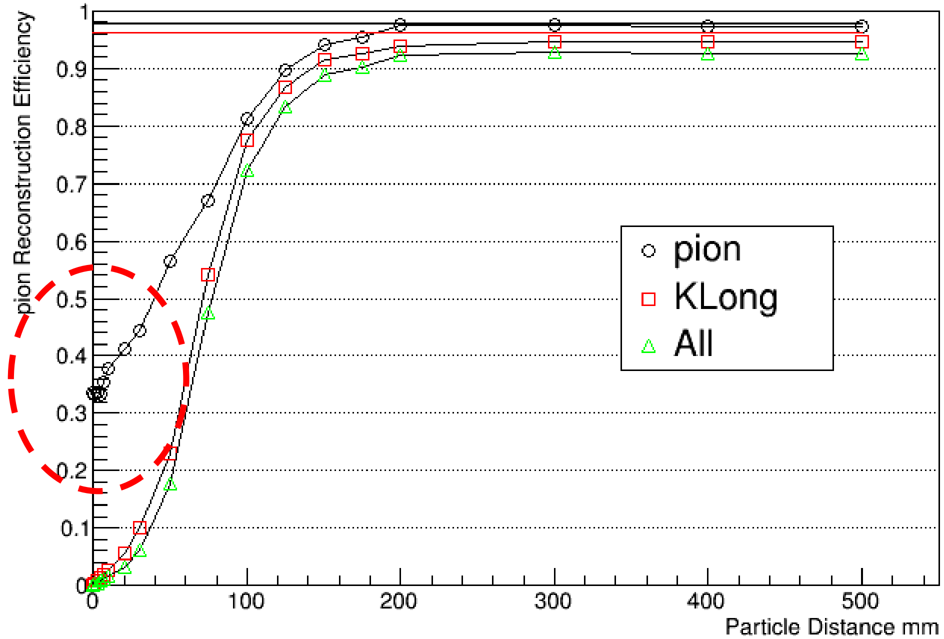
- Straight Line is efficiency of single particle event
- Marker is efficiency of di particle event
- particle distance is the distance of 2 particle on ECAL surface

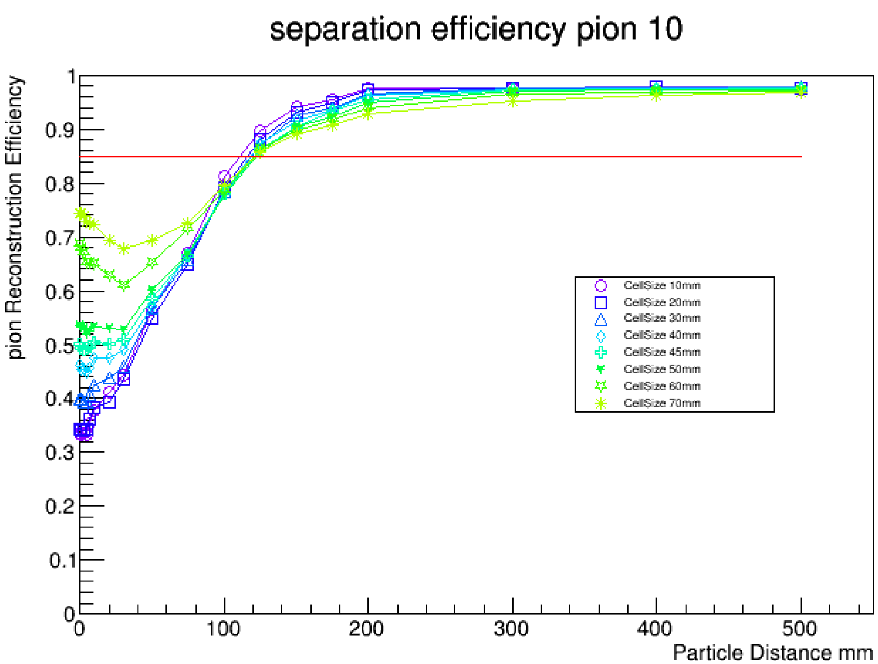




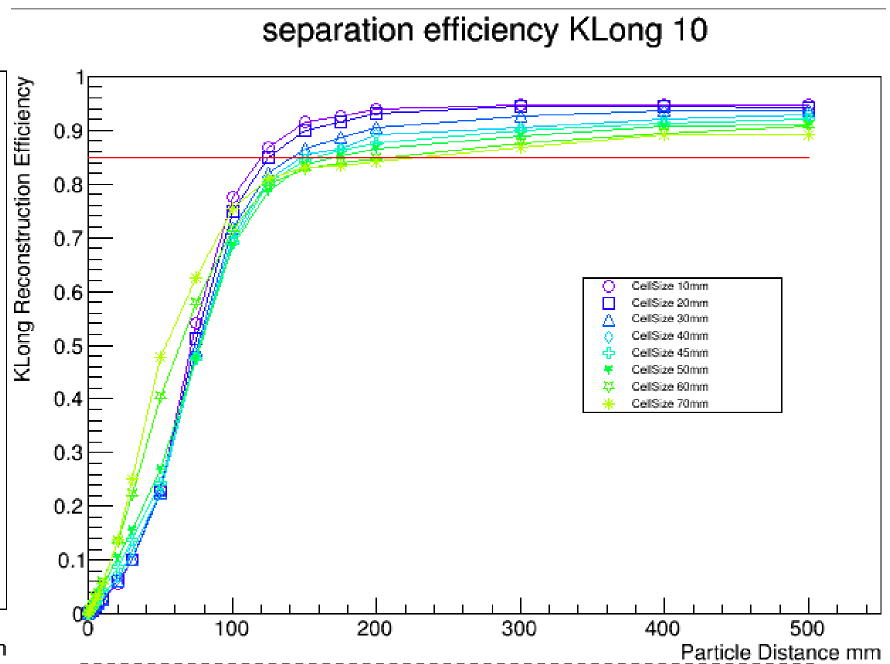
10mm cellsize

Pion and KLong separation

- Different cellsize
  - Keep the energy mean of single particle similar
  - Energy sigma stays unchanged as 10mm cellsize situation



Pion reconstruction efficiency



KLong reconstruction efficiency

Pion and KLong separation

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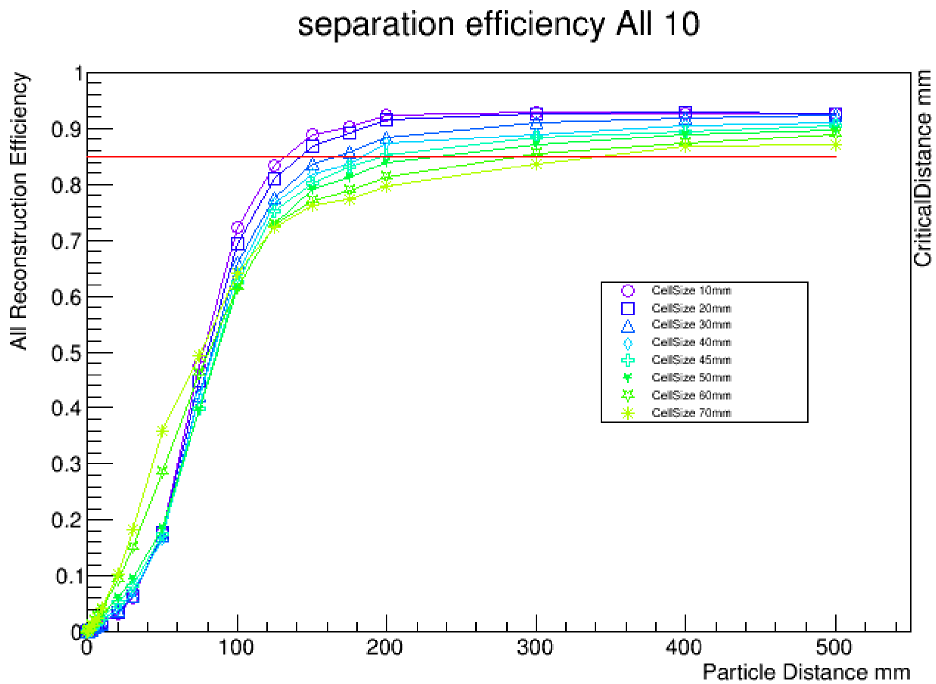
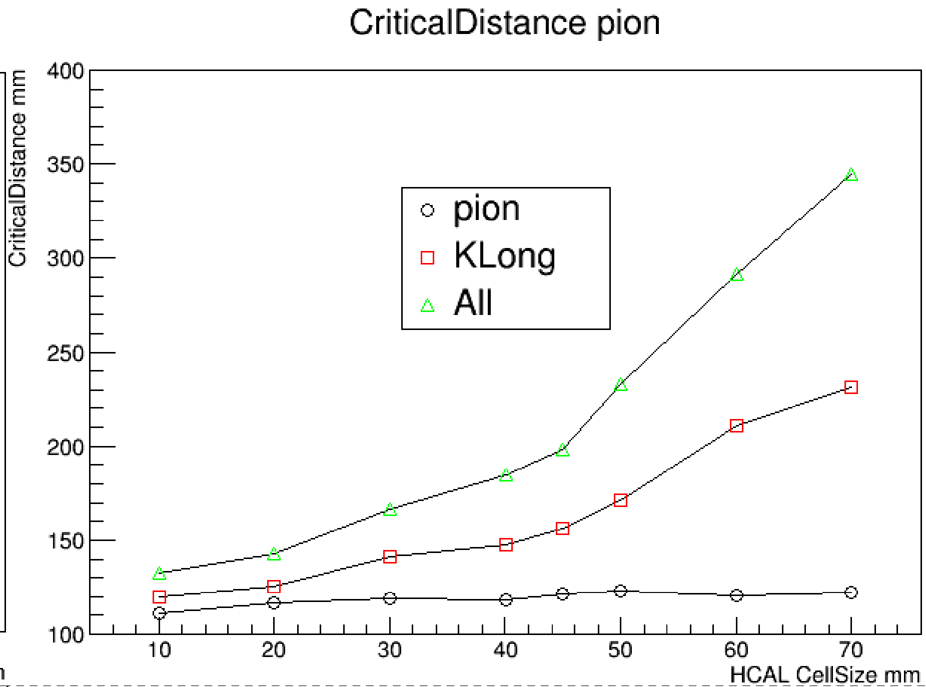
- Critical Distance
  - The distance which has 85% efficiency is define as critical distance





Pion and K reconstruction efficiency	Critical distance – HCAL cellsize

Simple PFA method

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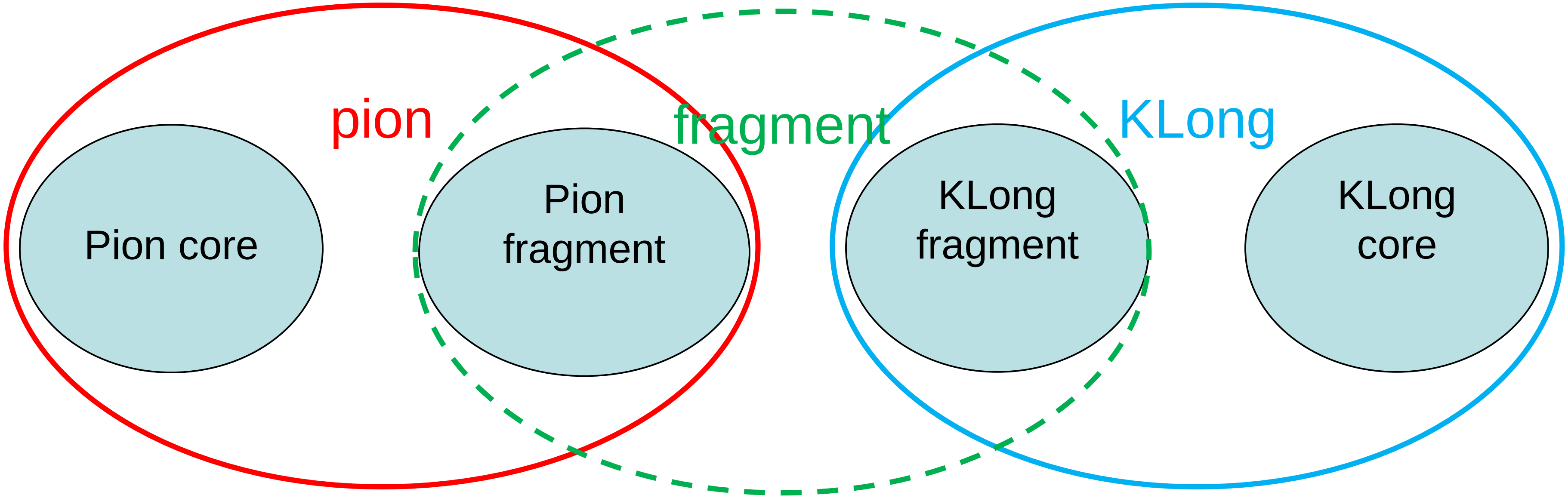
- Simple PFA method
  - PFA:E = pion track + KLong calorimeter
  - Real situation:E = pion track + part of pion fragment + KLong



Simple PFA method

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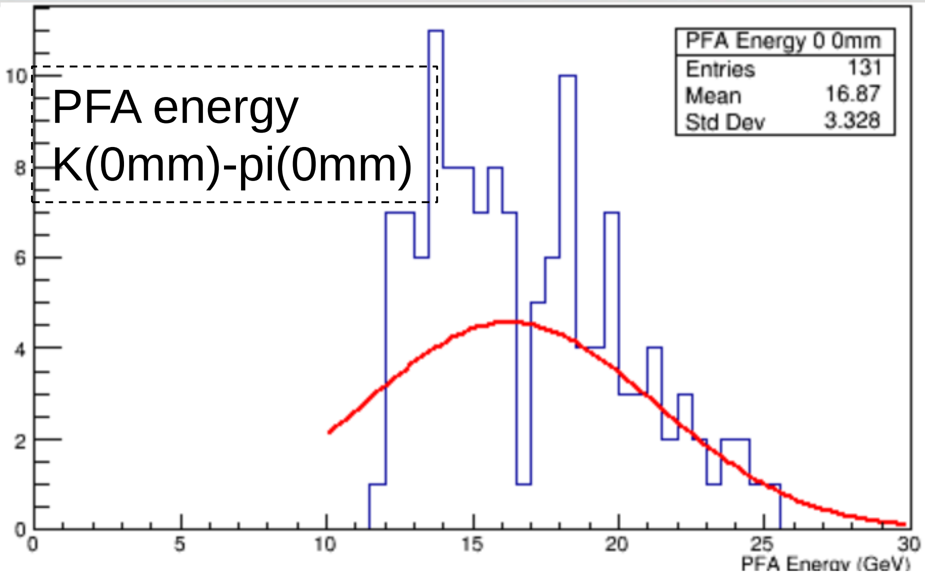
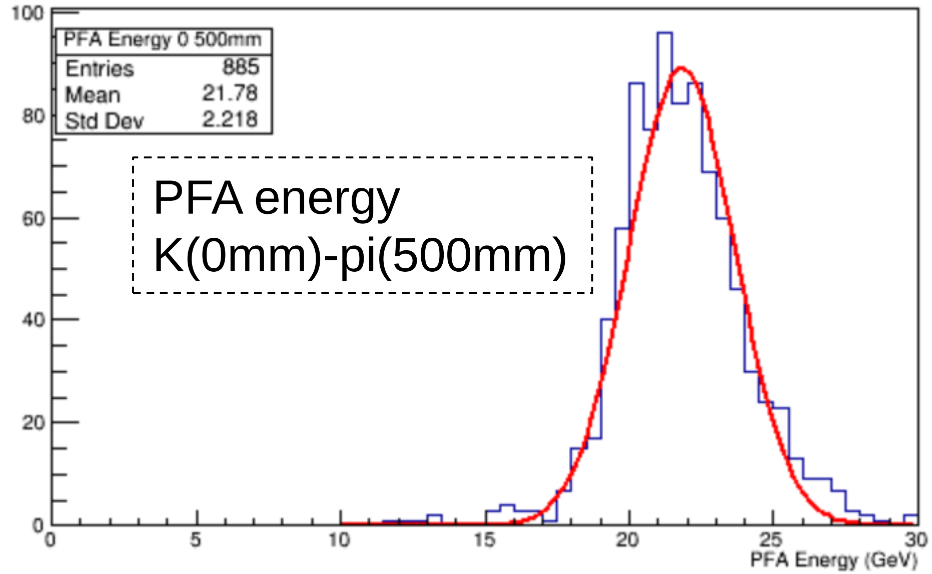
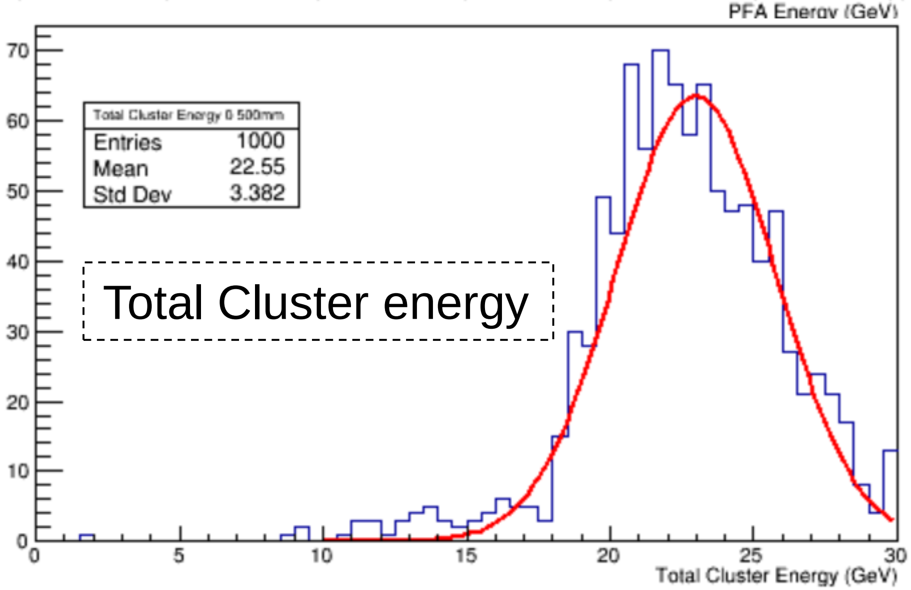
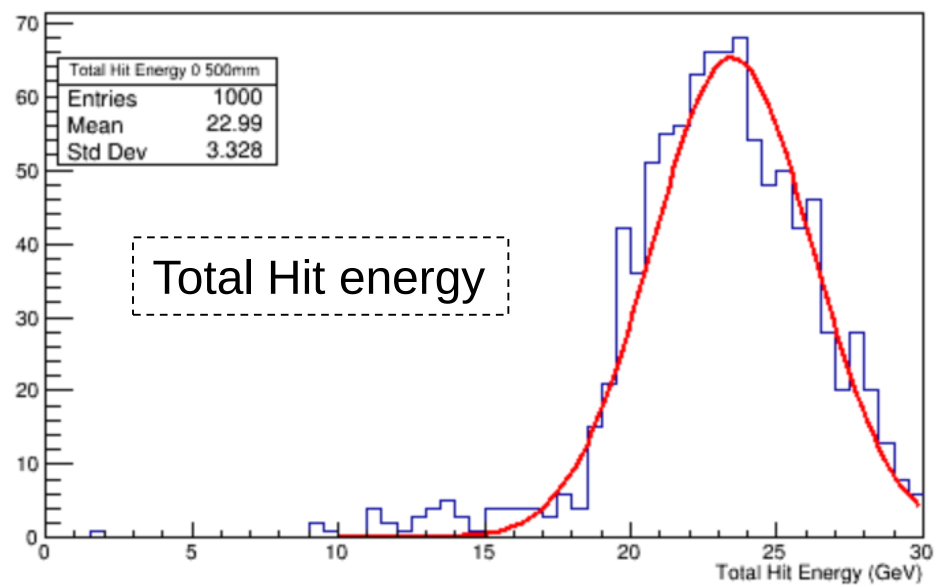


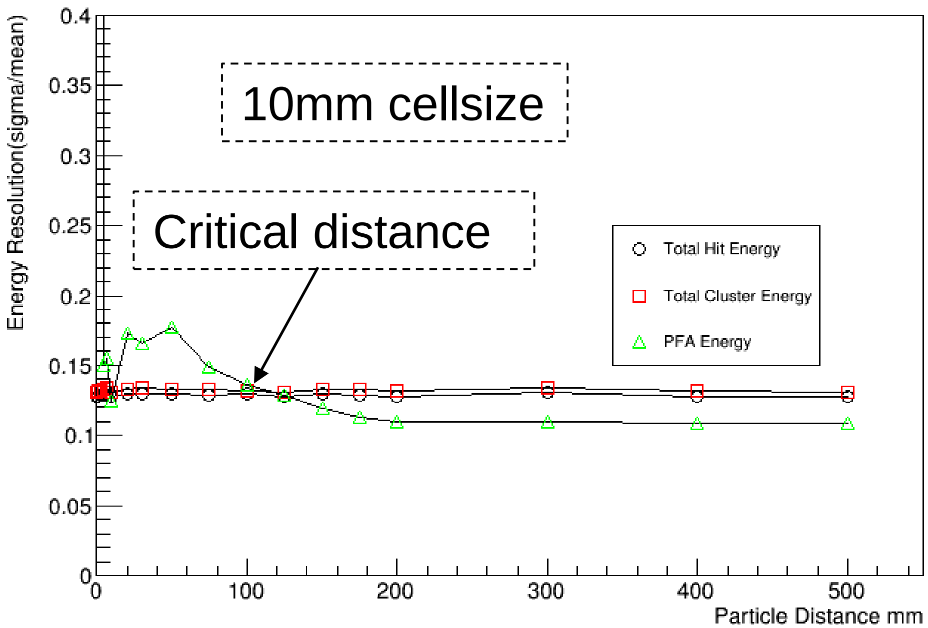


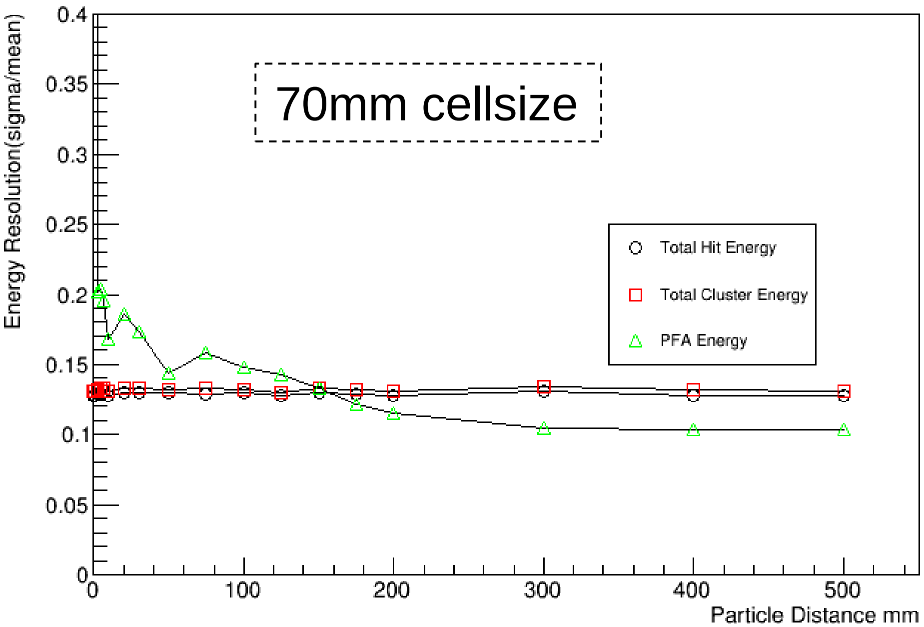




Simple PFA method

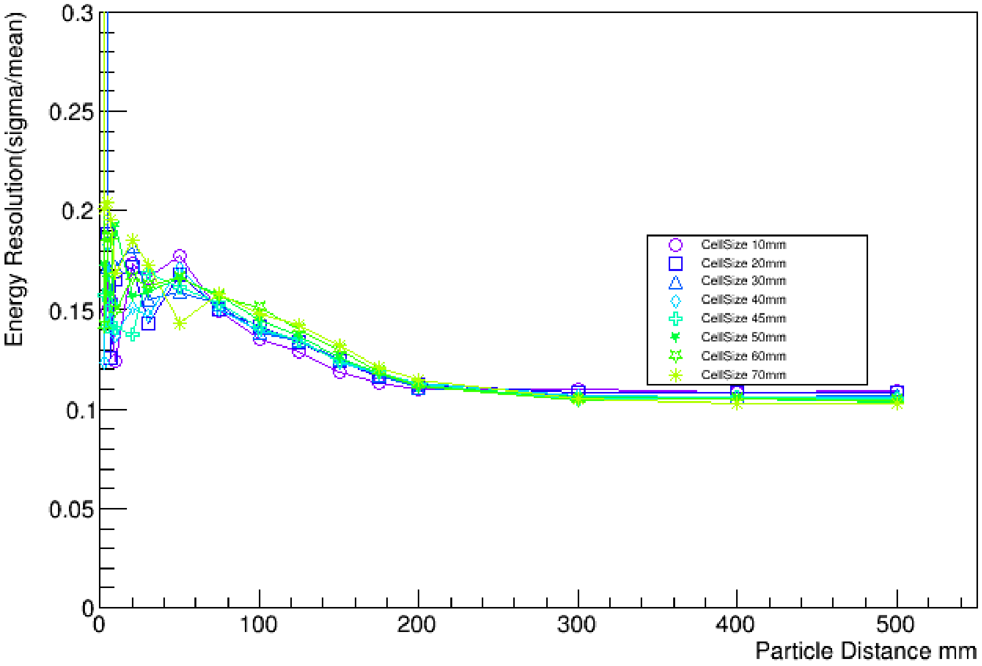
- Energy resolution
  - Total Hit energy resolution
  - Total cluster energy resolution
  - Simple PFA resolution

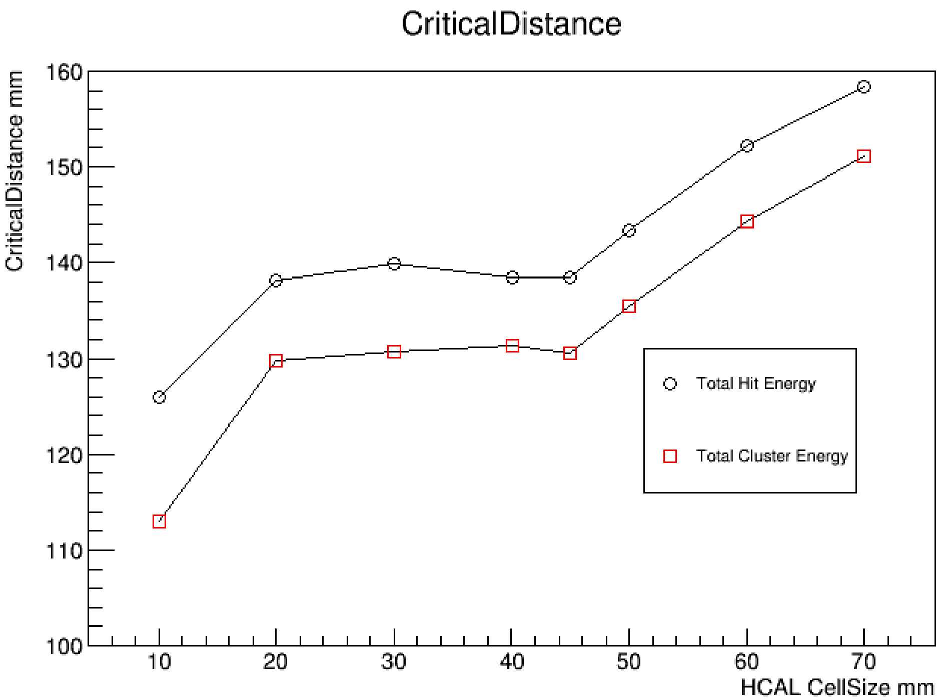




Simple PFA method

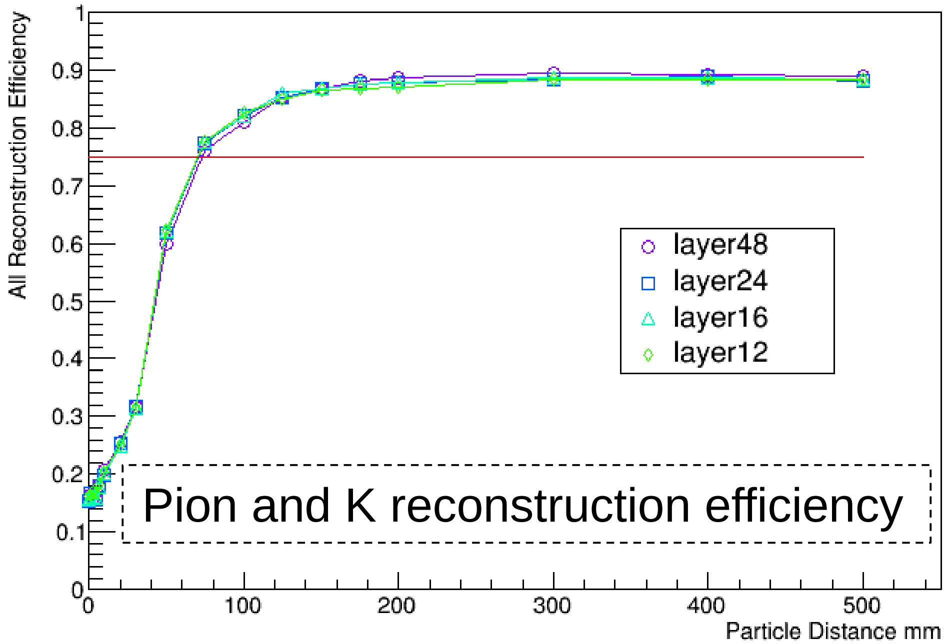
- 50mm is obviously worse than others
- 30mm is a safe choice

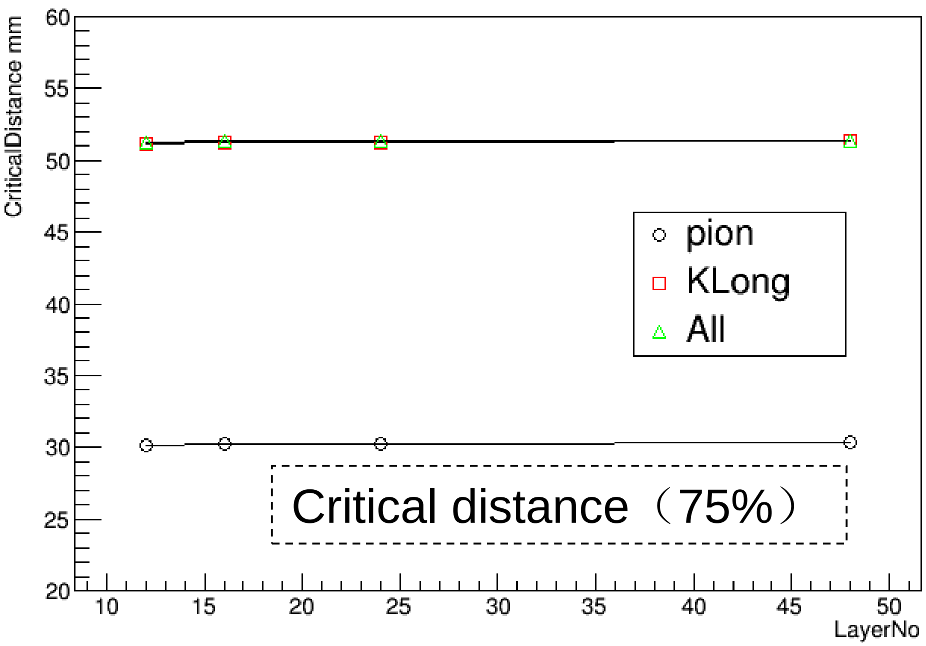




Read out layer optimization

- Setup
  - Optimization of read out layer is done with 30mm cellsize
  - The optimization is done by combining the read out of adjoint layers
  - Layer ranges from 48 to 24,16,12
  - Hit position after combining is set to the 1st layer of combined layers





Read out layer optimization

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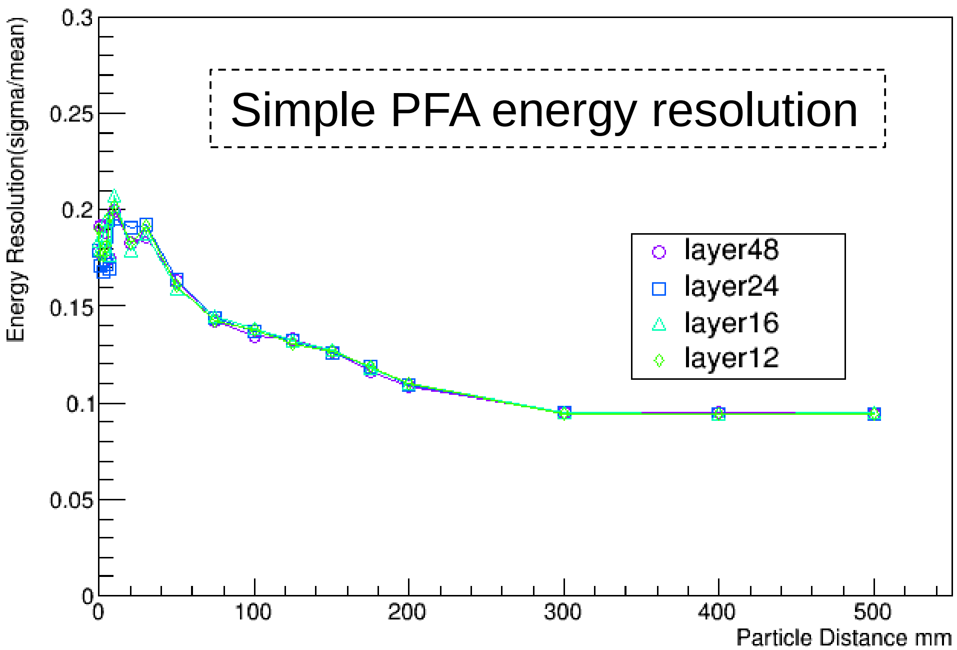
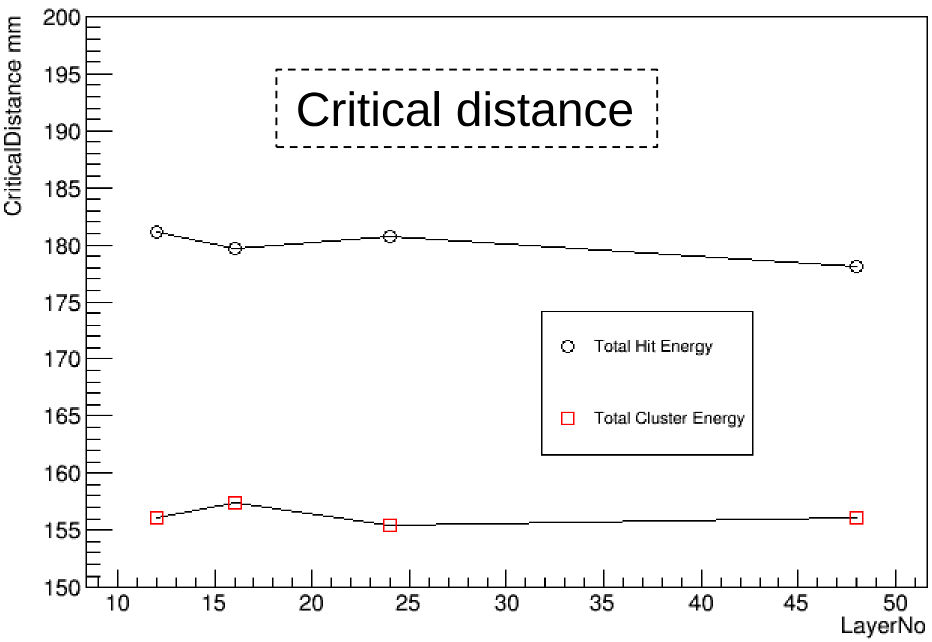
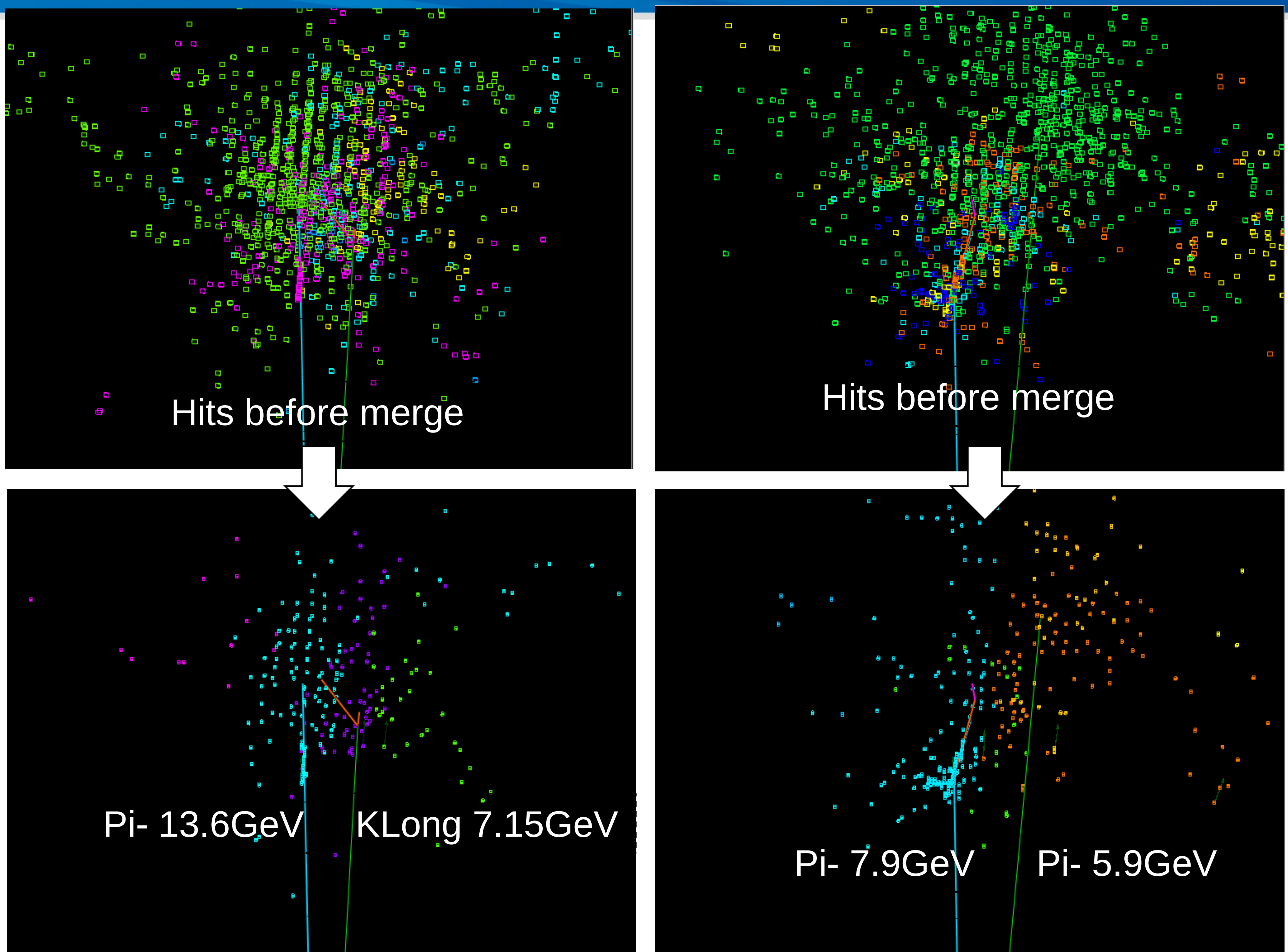
- Results
  - No significant influence is observed till 12 layer





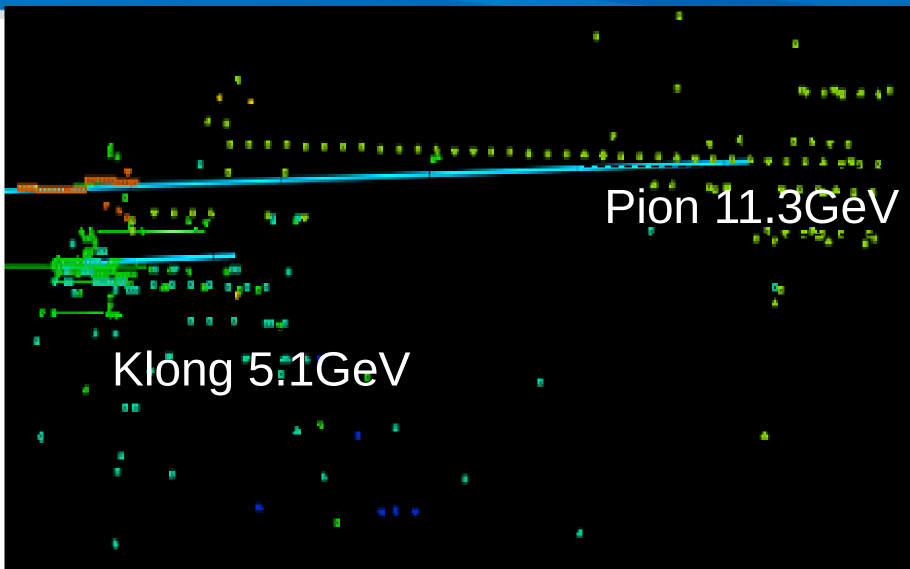
Read out layer optimization

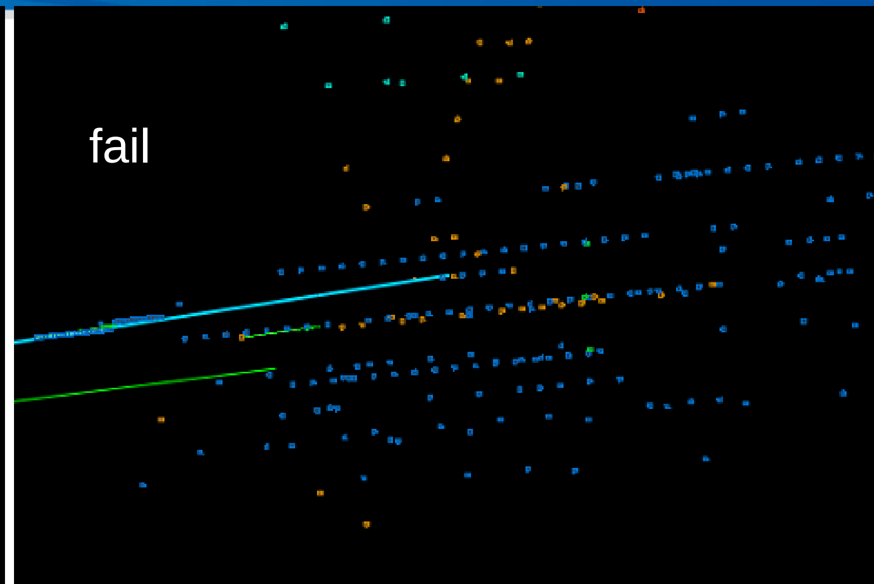


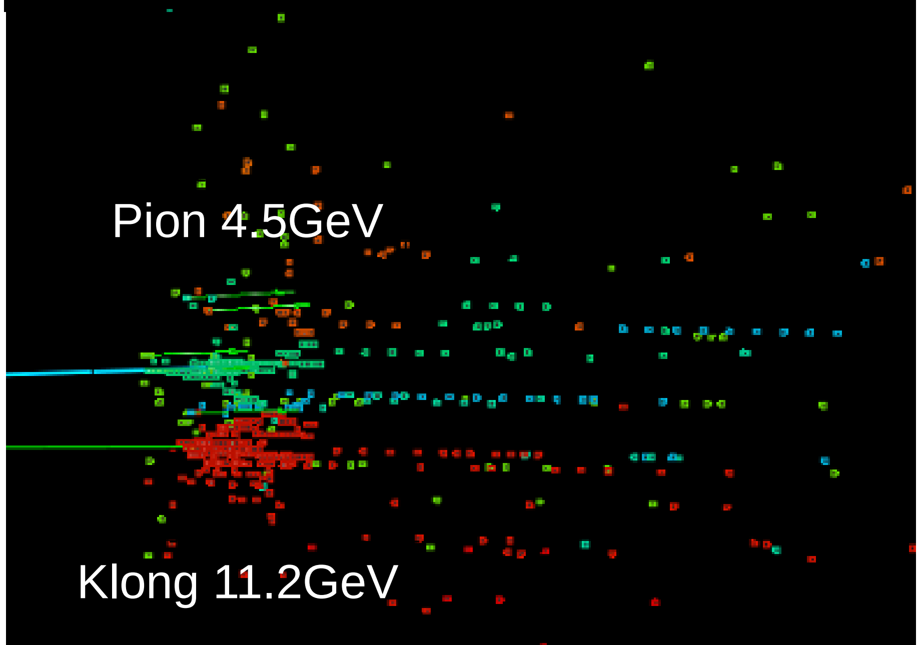
Conclusion

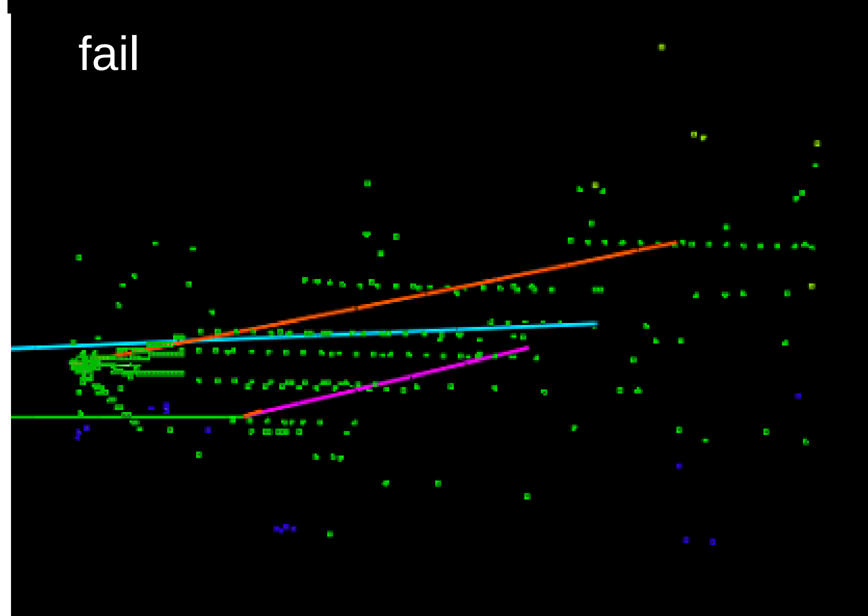
- CellSize
  - Performance for different AHCAL cellsize has been studied
  - 30mm is a safe choice
- Readout layer number
  - Performance stays unchanged till 12 layer
  - Double layer combined readout won’t affect PFA

Pion and KLong separation



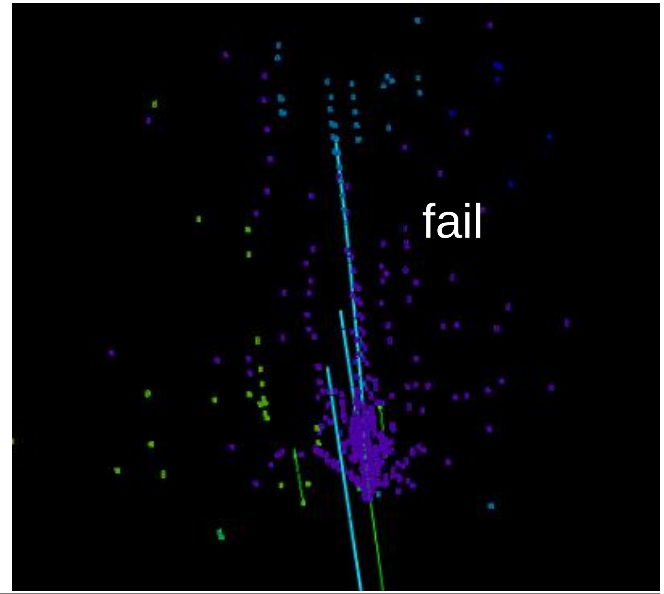


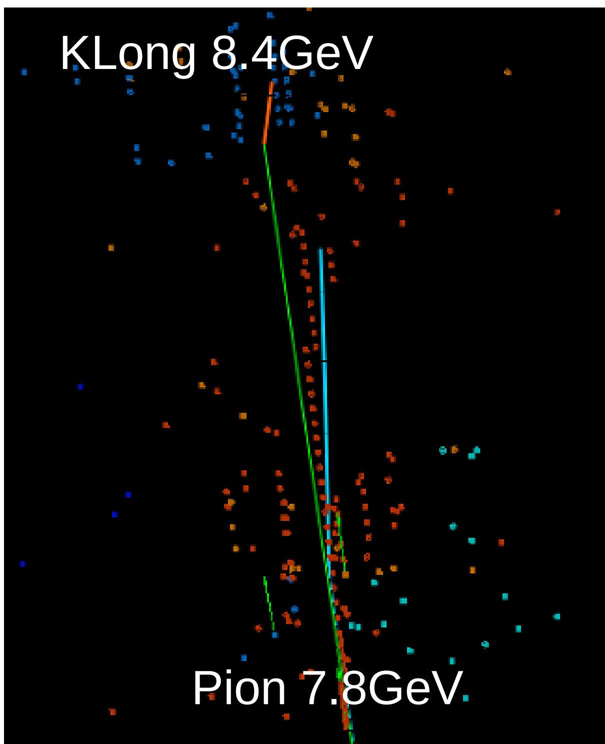


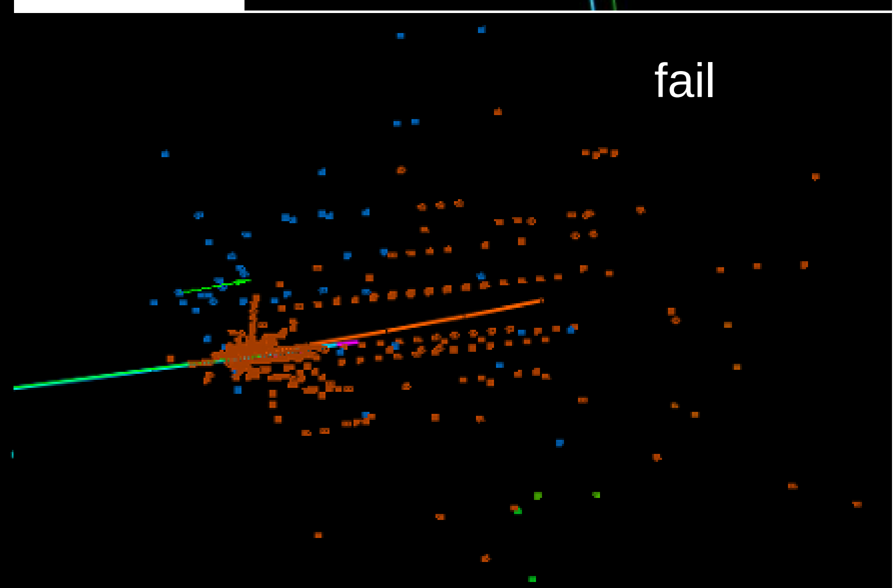


Pion and KLong separation

- 70mm cellsize
  - Incident position
    - pion:0mm
    - Klong:0mm







Marlin arbor and Cluster building

- Digitization
  - Combine small cell into the size we want
- arbor
  - 6 parameter in total
  - EE connection(xy direction and z direction)
  - EH connection
  - HH connection(xy direction and z direction)
  - EE Seed connection

Marlin arbor and Cluster building

- Bush merge
  - Merge small cluster into core and fragment
  - Cluster Seed:hit closest to origin point in cluster
  - Cluster COG:center of energy gravity
  - Cluster direction:vector connecting COG and Seed
  - Joint:close hits from different cluster
  - Cluster depth:distance from cluster Seed to ECAL surface
  - Connection of EE,EH,HH clusters has different cut on cluster Seed difference,COG difference,number of joints,transSeed difference
  - Only deeper cluster can be merge into shallower cluster

Reconstruction Process

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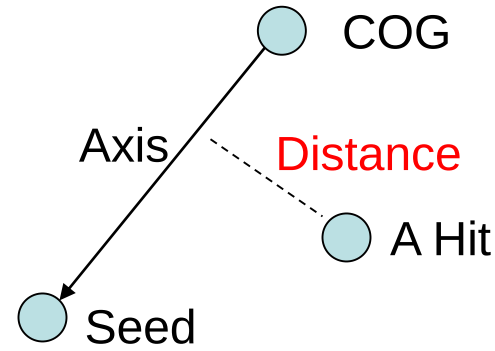
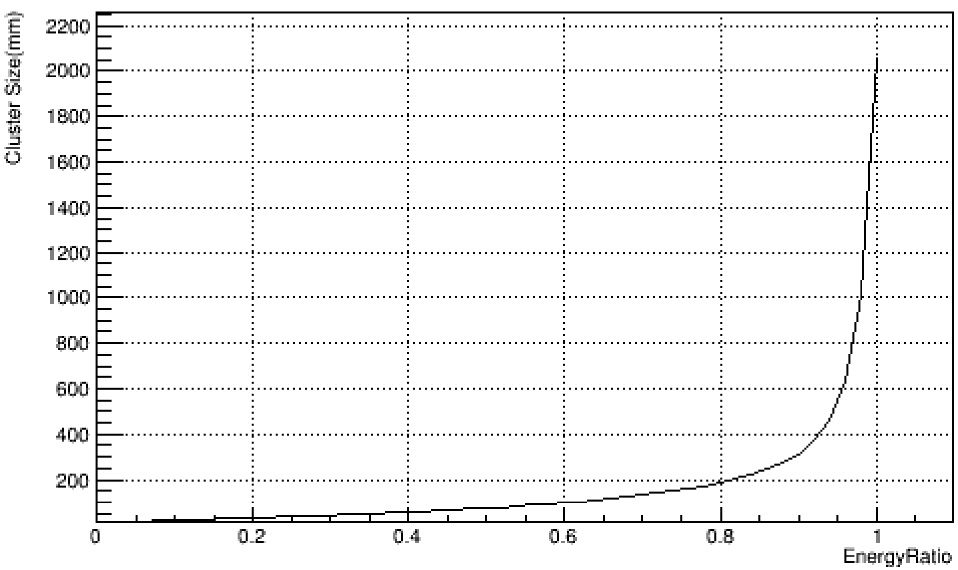
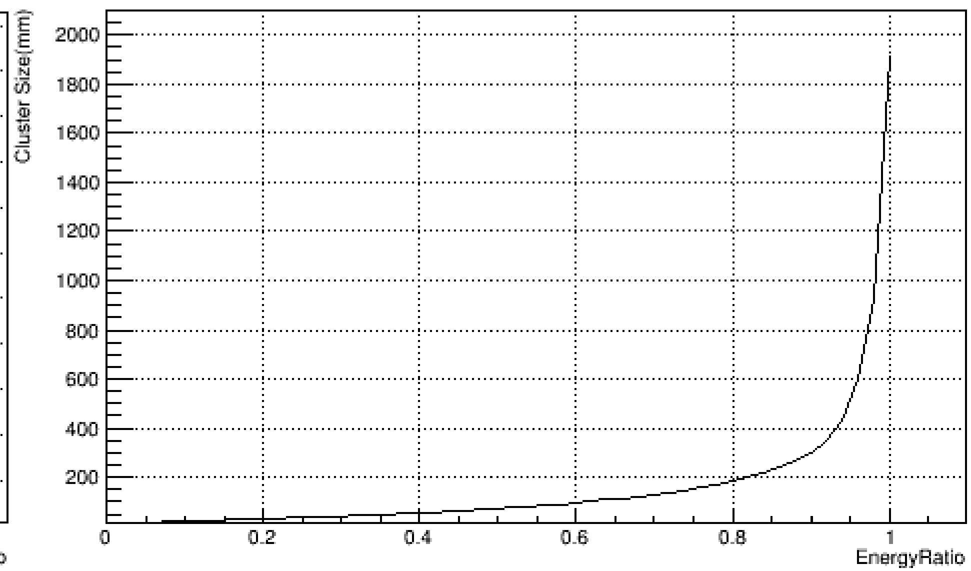
- Cluster Size
  - Use all hits in a single events
  - $Cluster\ Size:\ \frac{\sum_{distance<cluster\ size} E_{hit}}{total\ energy} = \text{energy ratio}$





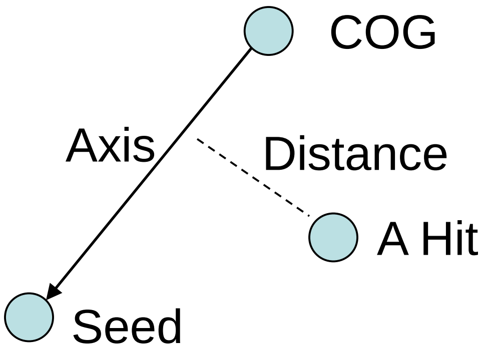
Pion Cluster Size(mm)

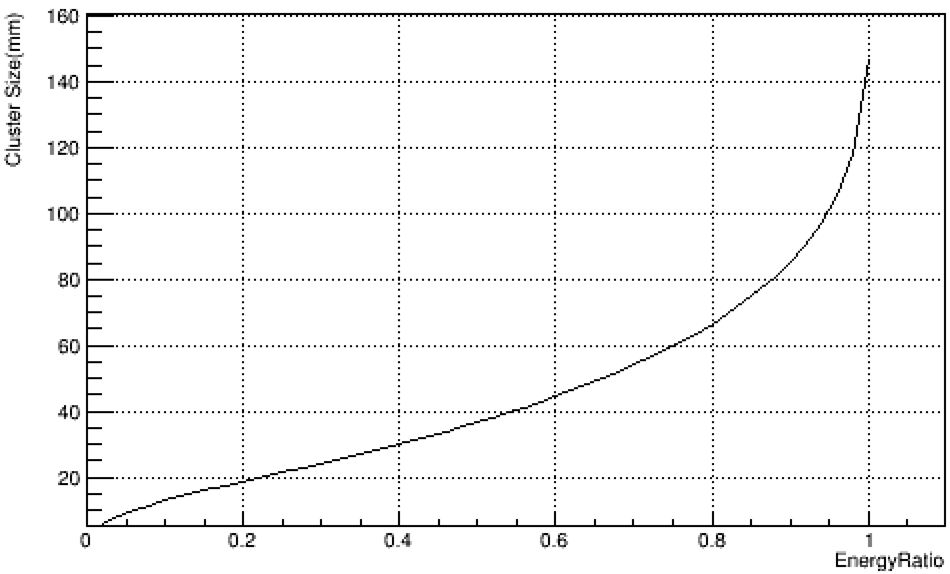


KLong Cluster Size(mm)

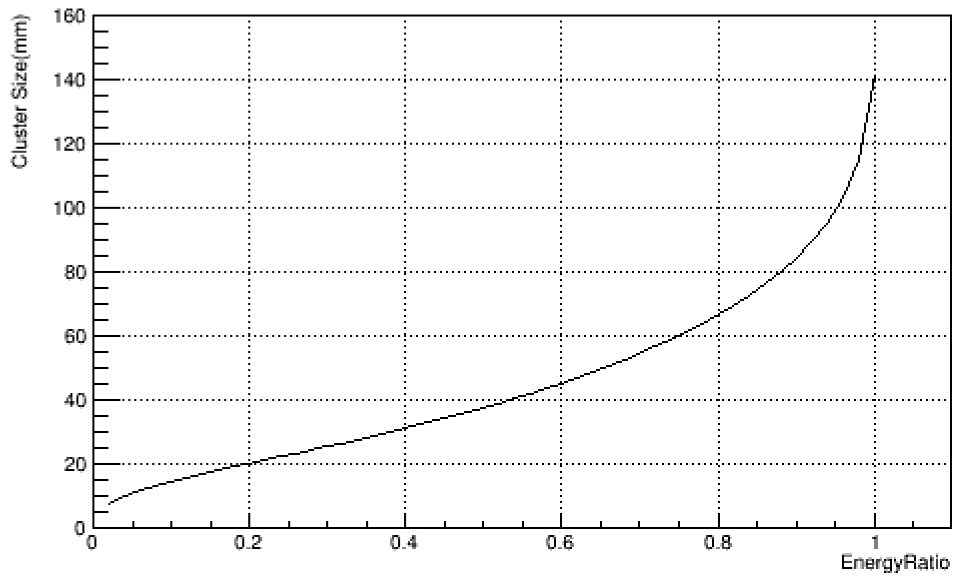
Reconstruction Process

- Cluster Size with energy weight
  - Use all hits in a single events
  - $Cluster\ Size = \frac{\sum_{hit} Distance_{hit-axis} \times E_{hit}}{\sum_{hit} E_{hit}}$





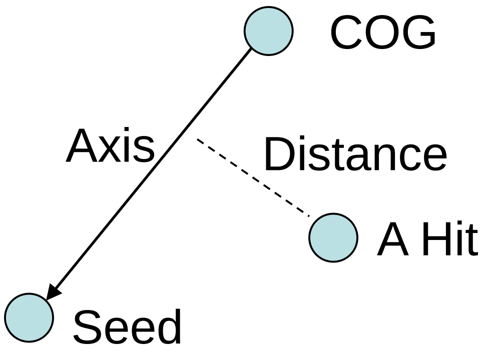
Pion Cluster Size(mm)

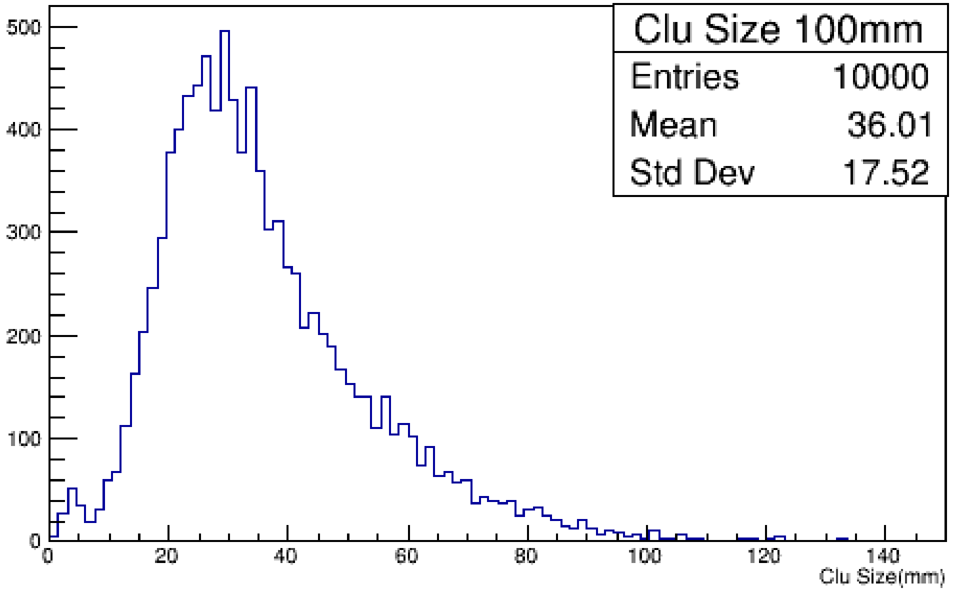


KLong Cluster Size(mm)

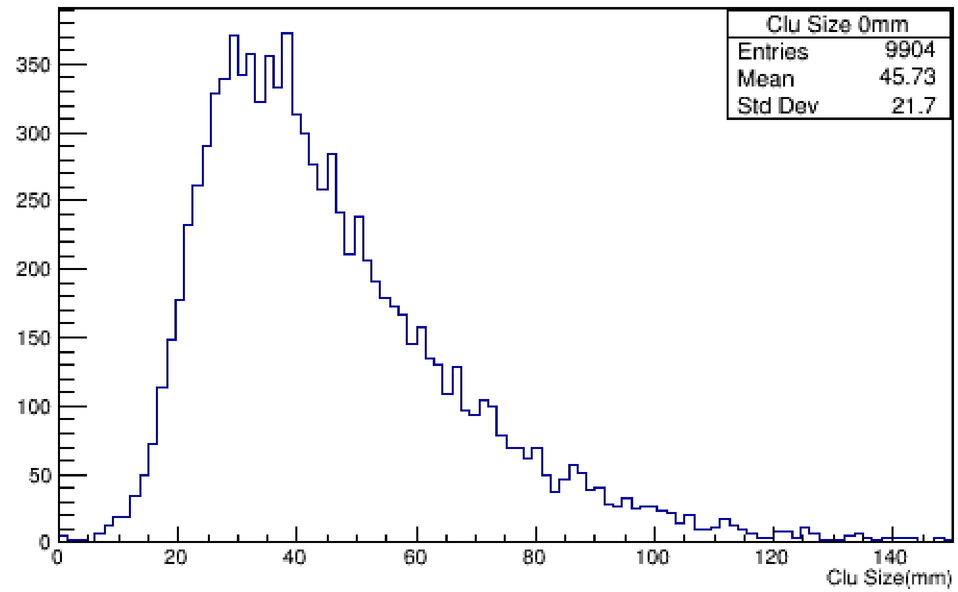
Reconstruction Process

- Cluster Core Size with energy weight
  – Use hits in Core (contains 60% of the particle energy)
  – $Cluster\ Size = \frac{\sum_{hit} Distance_{hit-axis} \times E_{hit}}{\sum_{hit} E_{hit}}$





Pion Core Size(mm)



KLong Core Size(mm)

Marlin arbor and Cluster building

- For single pion event in 10mm cellsize