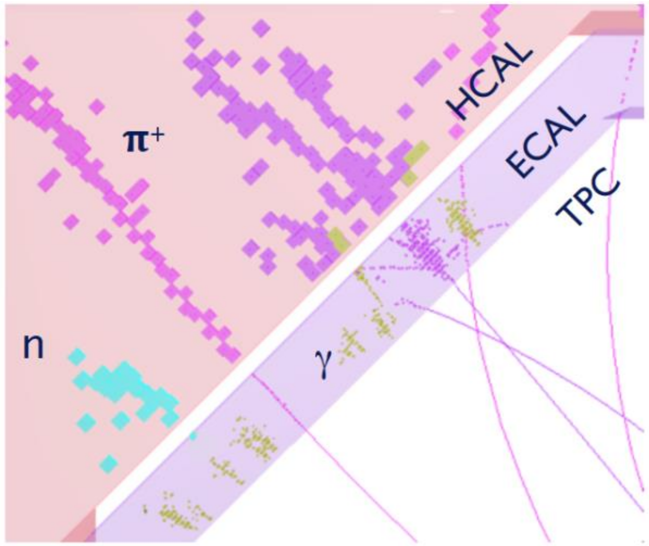
High-granularity Crystal Calorimeter: PFA performance studies

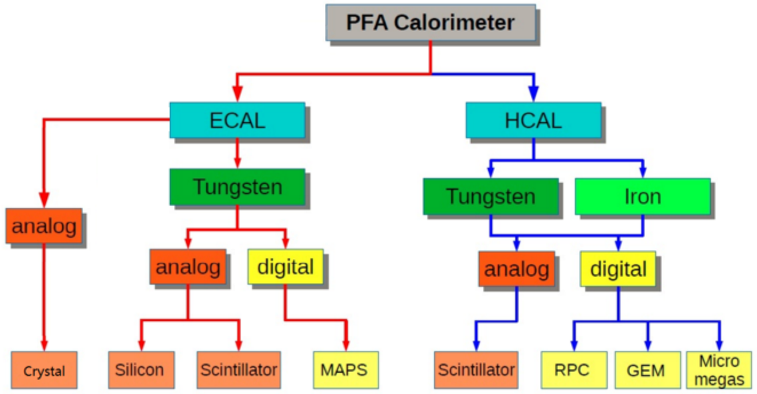
Yong Liu (Institute of High Energy Physics, CAS),
on behalf of the CEPC Calorimetry Working Group

CEPC Day
October 29, 2021

Motivations

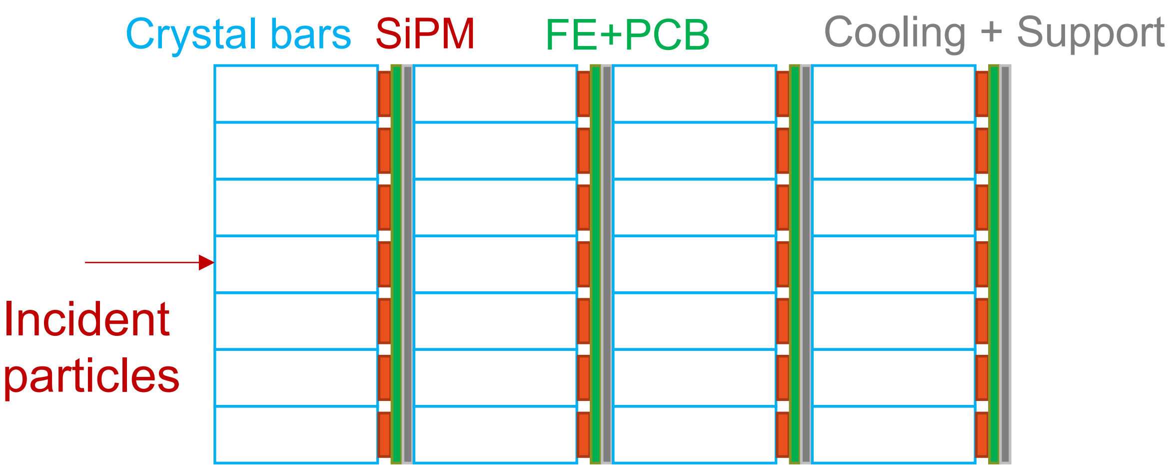
- Calorimetry for future lepton colliders (e.g. CEPC, etc.)
  - Precision measurements with Higgs and Z/W
  - Jet energy resolution requires better than $30\%/\sqrt{E_{\mathrm{jet}}(\mathrm{GeV})}$
  - Particle flow paradigm: high-granularity calorimetry
- Why crystal calorimeter?
  - Homogeneous structure
    - Optimal EM energy resolution: $\sim3\%/\sqrt{E}\oplus\sim1\%$
  - High sensitivity to low energy particles
  - Capability to trigger single photons
  - Precision γ/π^0 reconstruction: flavour and BSM physics
  - Finely segmented crystals: PFA capability for jets (3~4% resolution)





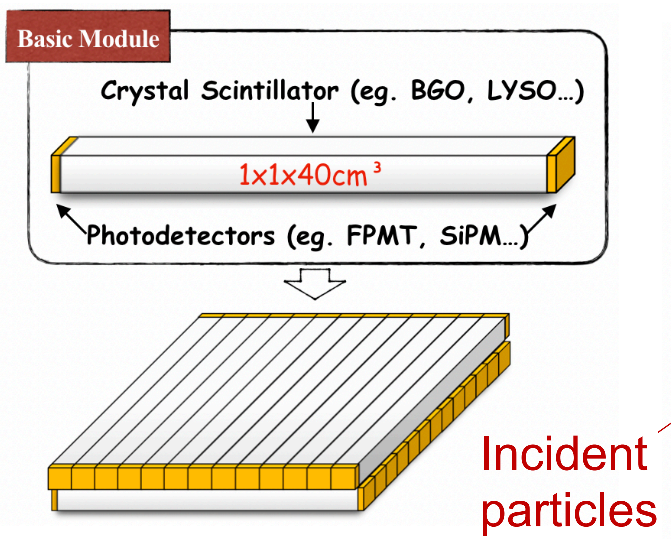
High-granularity crystal ECAL: 2 major designs

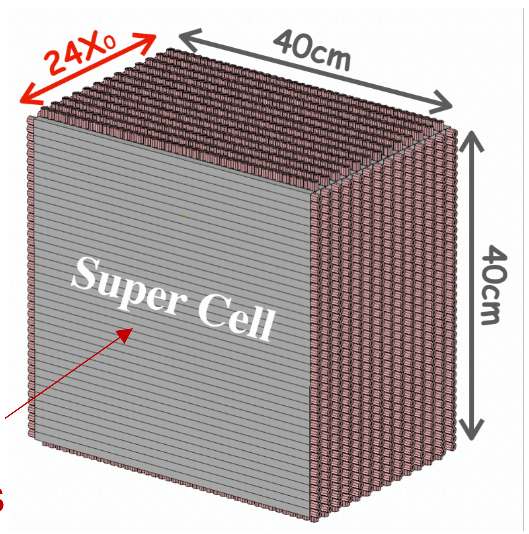
Design 1: short bars



- A natural design compatible with PFA
  - Fine segmentation in Both longitudinal and transverse
  - Single-ended readout with SiPM

Design 2: long bars

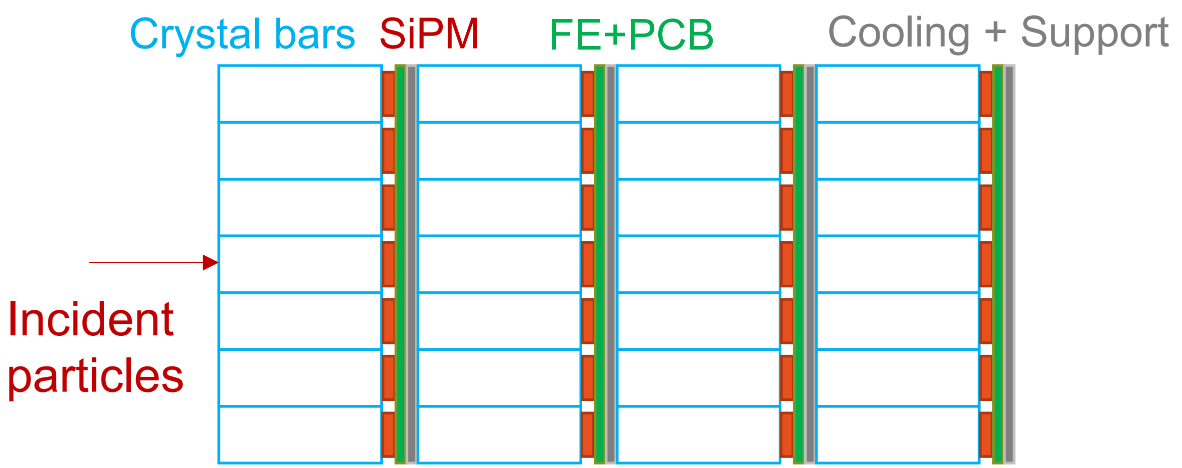




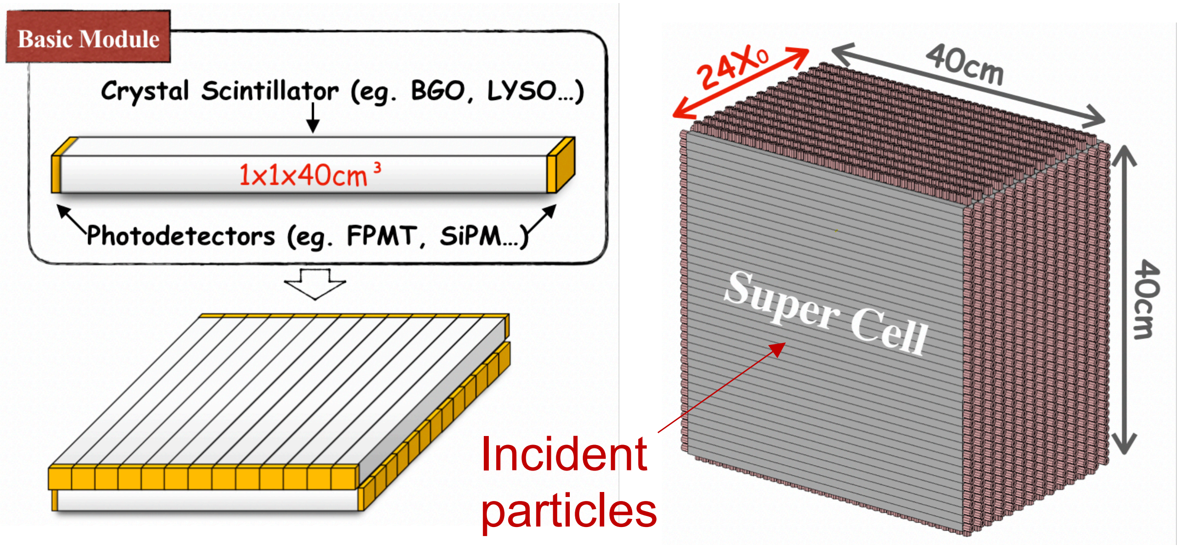
- Long bars: 1×40cm, double-sided readout
  - Super cell module: 40×40cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar

High-granularity crystal ECAL: 2 major designs

Design 1: short bars



Design 2: long bars



- **Focus on PFA performance studies**
- Crystal cubes (ideal granularity) for physics benchmarks
- Inputs for optimization of the existing PFA for crystals

- **Focus on new reconstruction algorithm development**
- **Key issues**
  - Separation capability of multiple incident particles (resolving "ghost hits")
  - Impact to PFA performance

Outline: recent progress on crystal calorimeter

- Updates since the CEPC Day in July 2021

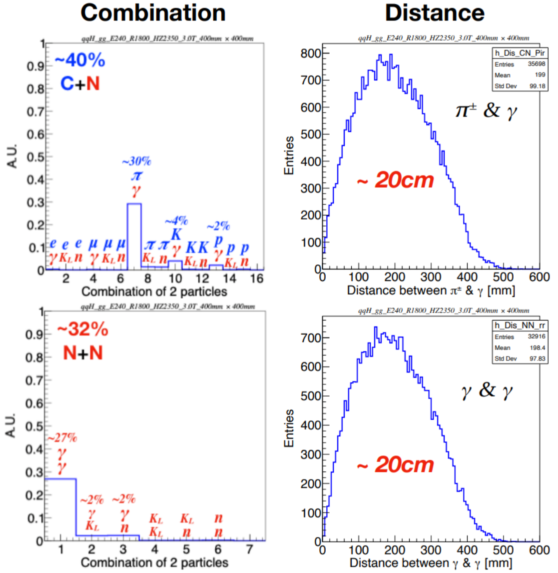
- PFA performance studies
  - Investigation of shower patterns with crystals: improvements in Arbor-PFA
  - Separation power with 2 incident particles: γ/γ and π^{+}/γ
  - Higgs benchmark with 2 jets: $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$

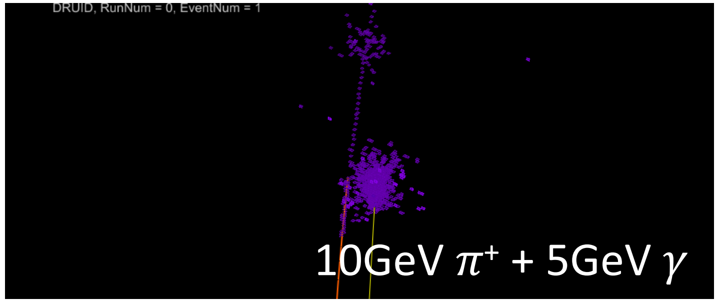
- New reconstruction algorithm dedicated to the design with long crystal bars
  - Details in the next talk (by Dr. Shengsen Sun)

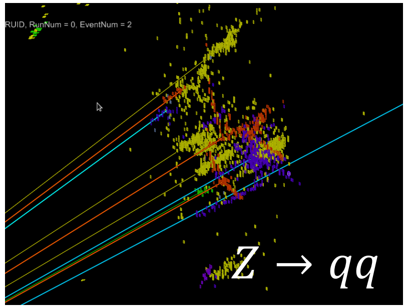
Introduction: crystal calorimeter for PFA

- Key performance: jet energy resolution $< 30\%/\sqrt{E_{\text{jet}}(\text{GeV})}$
- PFA paradigm for jet reconstruction
  - Typical components in a jet
    - ~62% charged particles (mostly hadrons): tracker
      - Matching tracks and clusters in calorimeters (essential)
    - 27% photons: ECAL
    - 10% neutral hadrons: ECAL+HCAL
    - ~1% neutrinos
- Categorize component combinations
  - Most common: 1 charged + 1 neutral, or 2 neutral particles
  - Need to evaluate how well these particles can be "correctly" separated
- Full simulation studies with "CEPCv4" geometry and ArborPFA

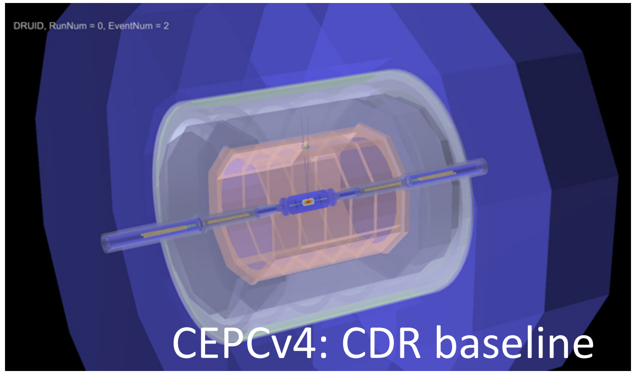
Components of jets at Z-pole







Same granularity: SiW and crystals ($1\times1\text{cm}^2$ transverse size, 28 longitudinal layers)



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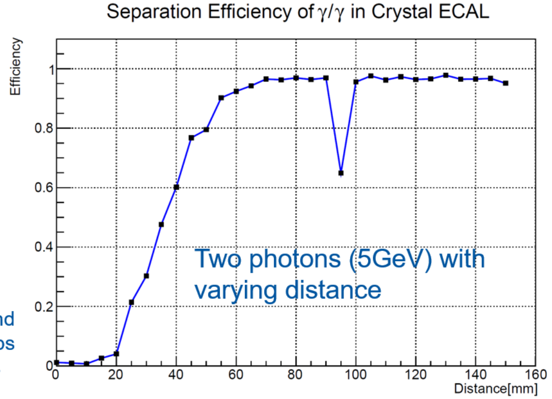
Separation power with Arbor-PFA (reminder)

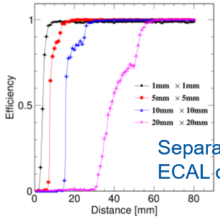
Status presented in
CEPC Day (July 29, 2021)

Separation of two gammas

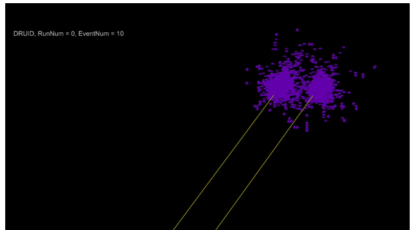
- Separation efficiency of two neutral particles
  - Expected less separation power than SiW option
  - Wider transverse EM shower profile in crystals
  - Moliere radius a factor of ~2 difference in the ideal case



Efficiency drop around 94mm due to the gaps between barrel slabs



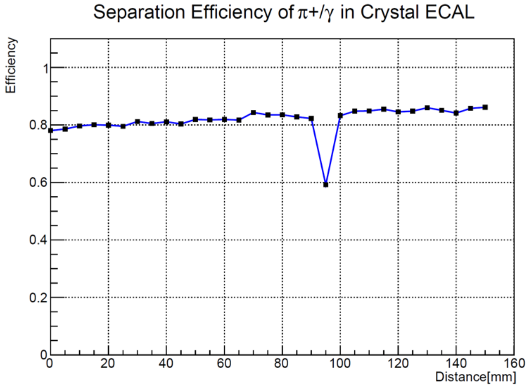
Separation efficiency of SiW ECAL option in CEPC-CDR

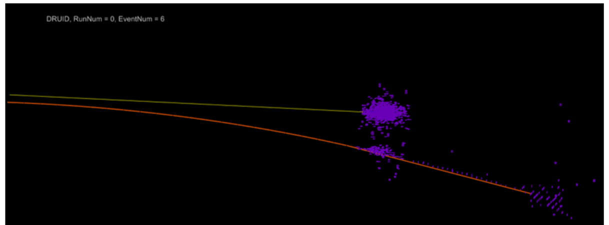


Two 5GeV photons: perpendicular incidence to ECAL (varying distance)

Separation of a gamma and a charged pion

- Separation efficiency of a charged particle and a neutral particle
  - Matching clusters of charged particle to the tracking detector





One 5GeV photon and one 10GeV charged pion (in 3T B-field)

Work in progress
- Distance of hit positions in the first ECAL layer: larger than originally set due to the bending curve of pion+ in 3T B-field
- Will continue to investigate details of ~20% inefficiency

- Success: correctly identify clusters of the neutral particle
- Failure: clusters of the neutral particle absorbed by the charged particle

Performance studies: crystal ECAL + ArborPFA

- Impacts of energy threshold (in digitization)
  - Shower profile (visual impressions)
  - Hit-level analysis (quantitative)
  - Separation efficiency
  - Energy linearity
  - Single photon energy resolution
- Comparison of separation power: SiW vs Crystal
  - γ/γ & $\pi+/\gamma$ separation efficiency
- Higgs benchmark ZH $(Z \rightarrow \nu\nu,\ H \rightarrow gg)$

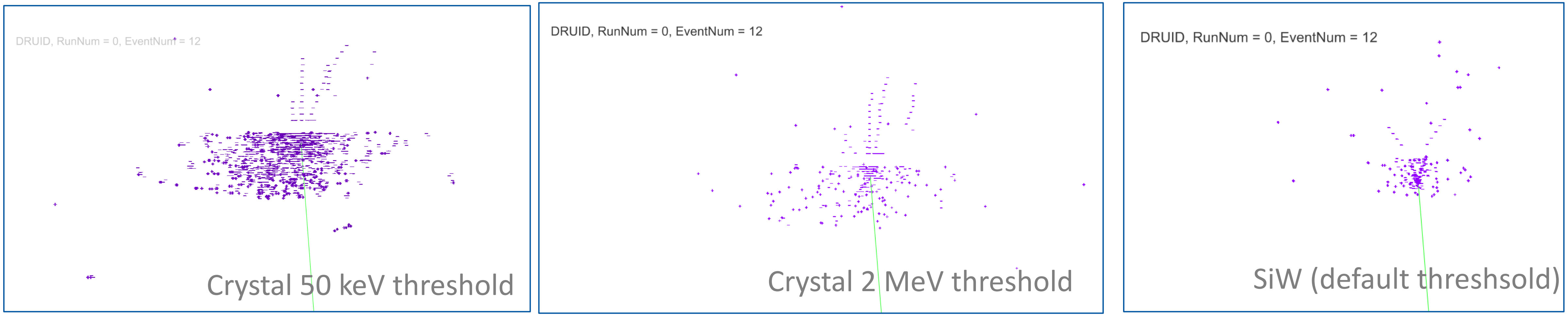
Impacts of energy threshold: shower profile

Baohua Qi (IHEP)

- Event display with neutral hadrons (10 GeV Kaon0L)
  - Hits (digitised) in calorimeters: displayed in purple
- Crystals sensitive to low energy particles

Molière radius:
- W: 0.9327 cm; BGO: 2.259 cm

Radiation length:
- W: 0.3504 cm; BGO: 1.118 cm



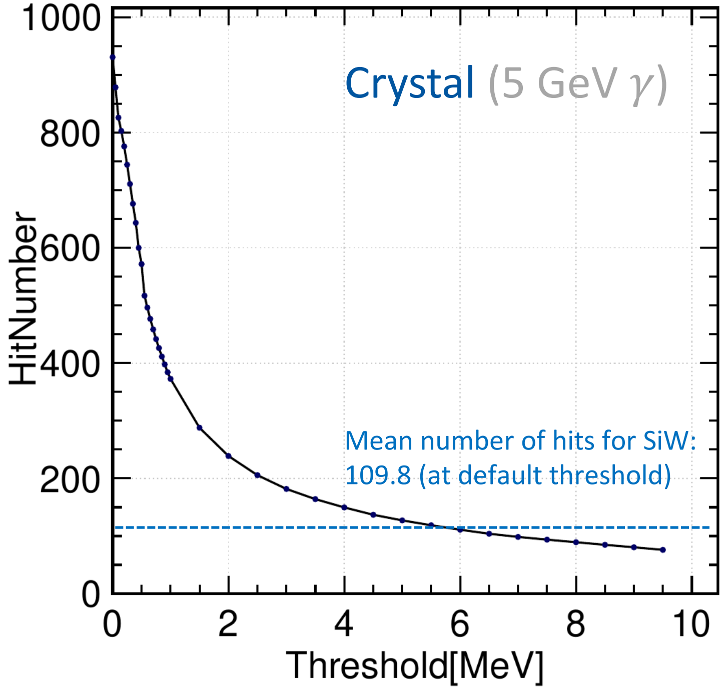
- Shower profiles: significantly wider in crystals than SiW, and more "isolated" hits
- Lower energy threshold: too many hits → wider shower profile → more vague shower boundaries → more challenging to distinguish
- Hints: higher energy threshold can reduce the shower size and #hit

Impacts of energy threshold: hit-level analysis

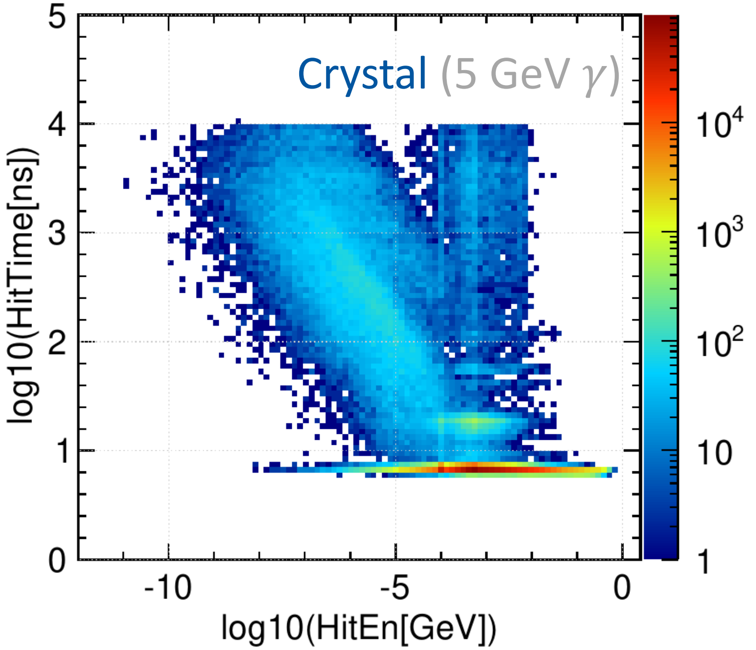
Dan Yu (IHEP)

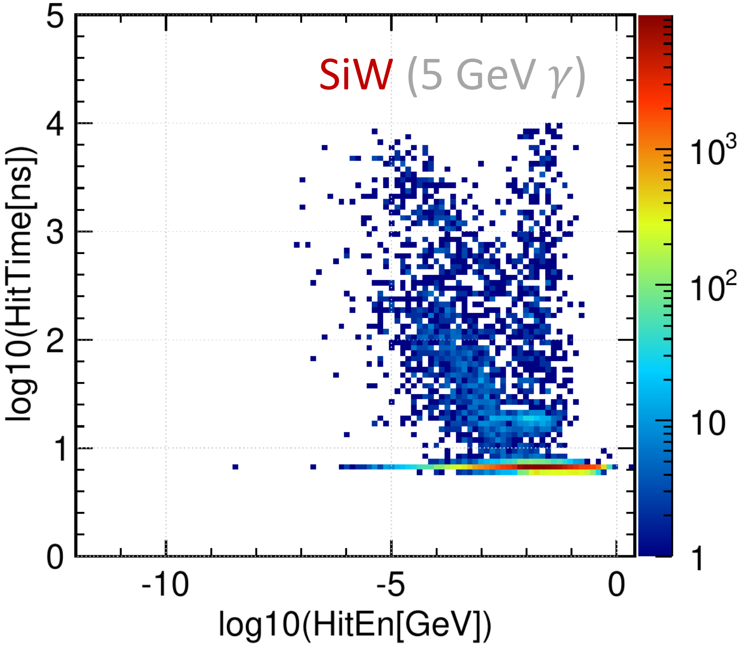
- As energy threshold increases, #hit decreases exponentially
- More late hits (mostly with low energy) in crystals compared to SiW

#Hit vs energy threshold



Hit energy vs hit time





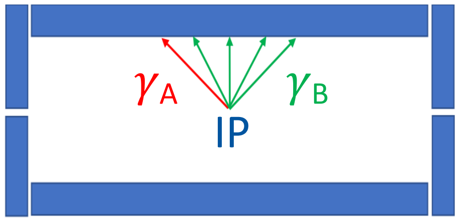
- Time information can help further remove late hits (e.g. back-scattering neutrons)

Impacts of energy threshold: separation efficiency

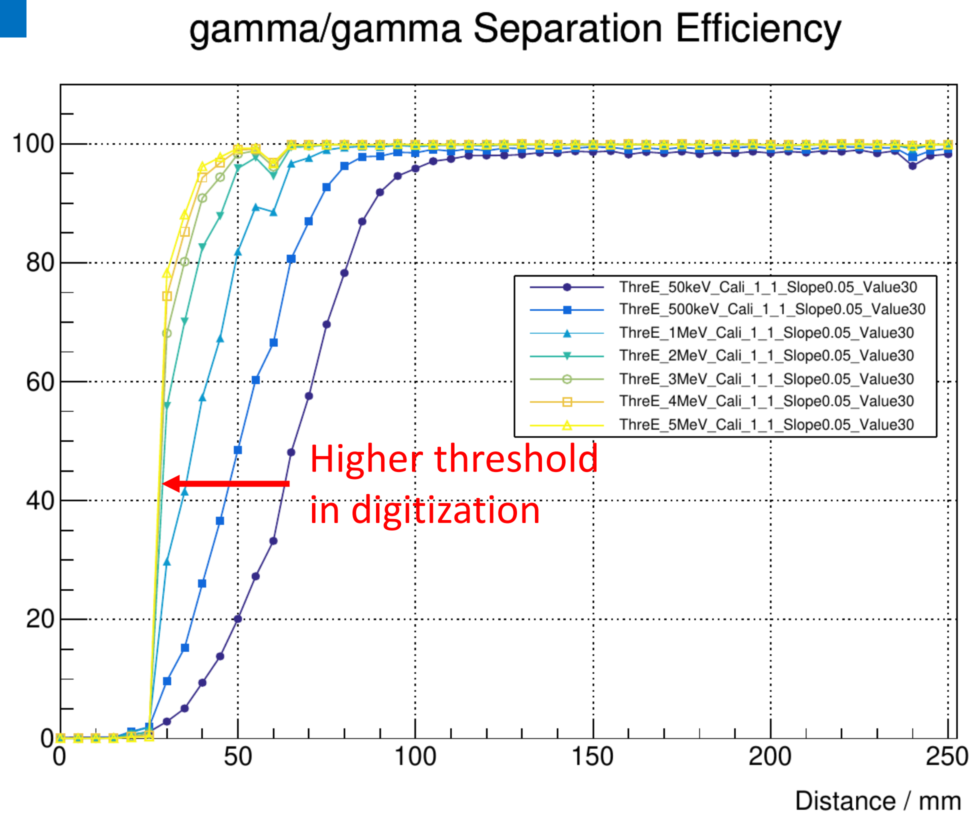
Baohua Qi (IHEP)

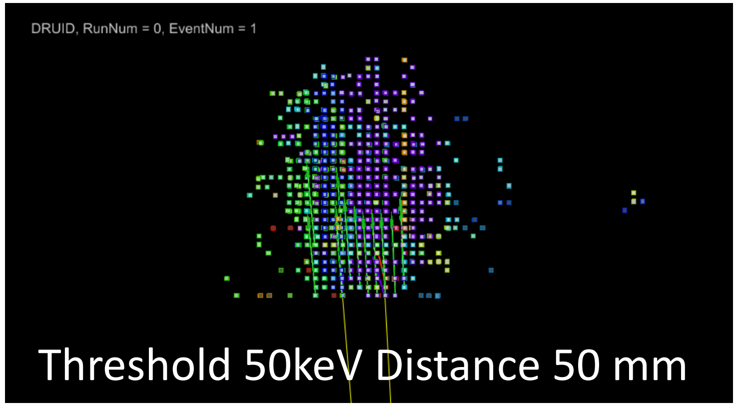
Separation of two gammas

Sketch of ECAL in r-z plane



- Two gammas (5GeV): varying distance
- Efficiency definition: successful reconstruction of **at least 2 neutral particles, both in 3.3GeV<E<6.6GeV**
- Removed events with γ-conversion before entering ECAL
- Applied energy calibration





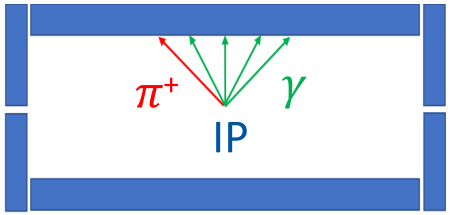
- Crystal ECAL: optimise energy threshold in digitization
- Higher energy threshold leads to better separation power
  - More compact showers, less vague boundaries

Impacts of energy threshold: separation efficiency

Baohua Qi (IHEP)

Separation of a gamma and a charged pion

Sketch of ECAL in r-z plane



- 10GeV π^+ and 5GeV γ: varying distance
- 3 T magnetic field
- π^+ momentum measured by tracker
- Efficiency definition: successful reconstruction of **3.3GeV<E_N<6.6GeV, 9.9GeV<E_C<10.1GeV**
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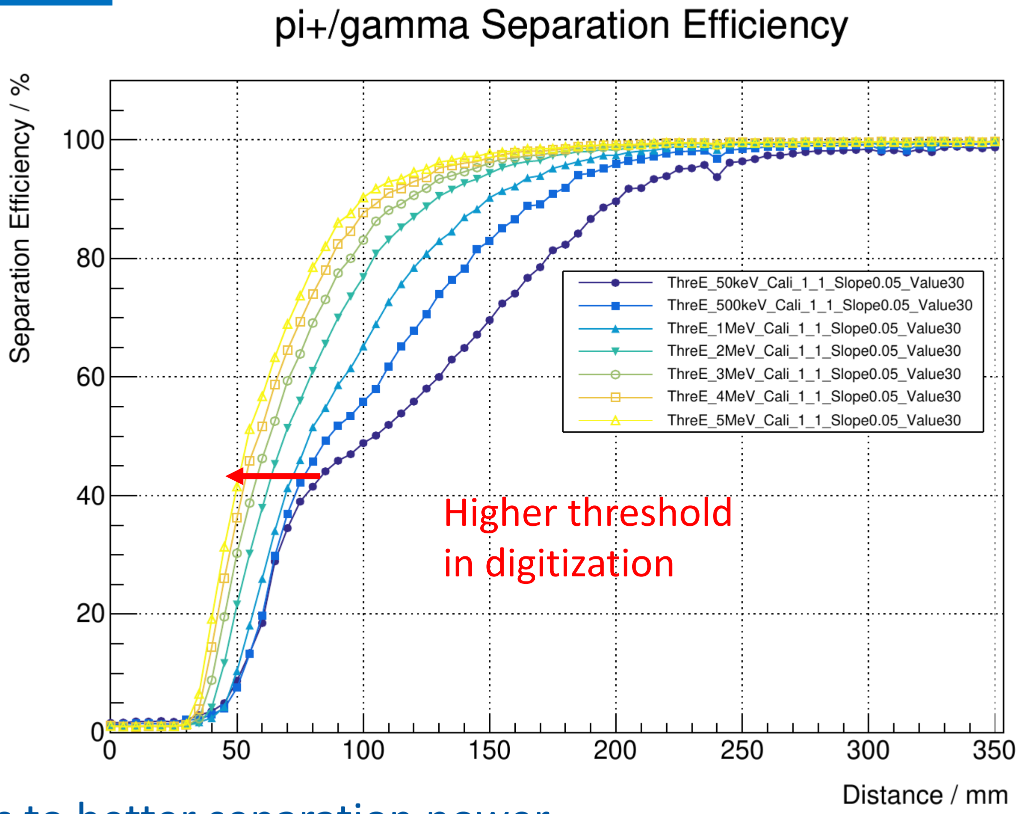
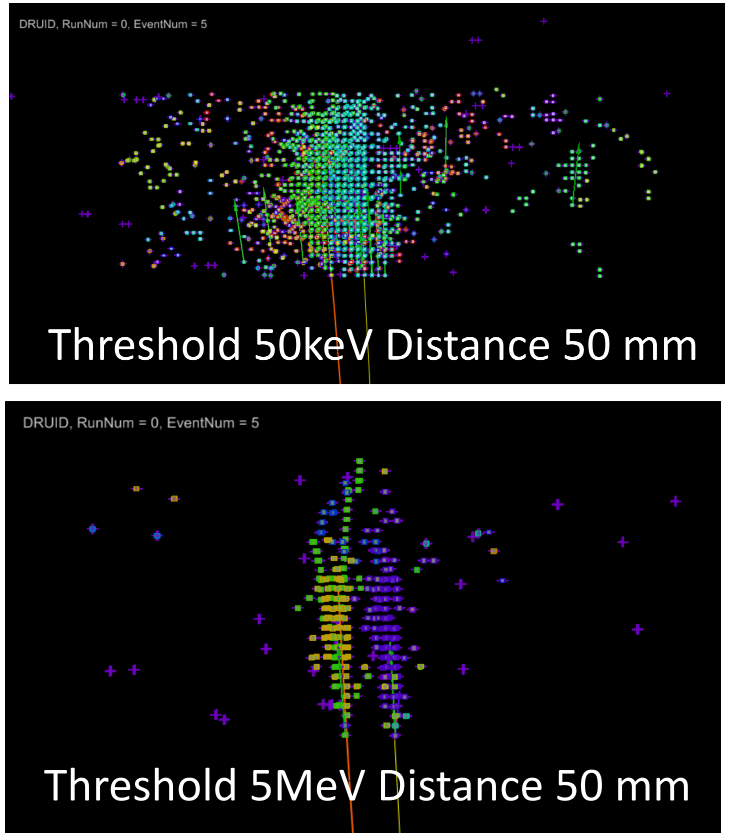




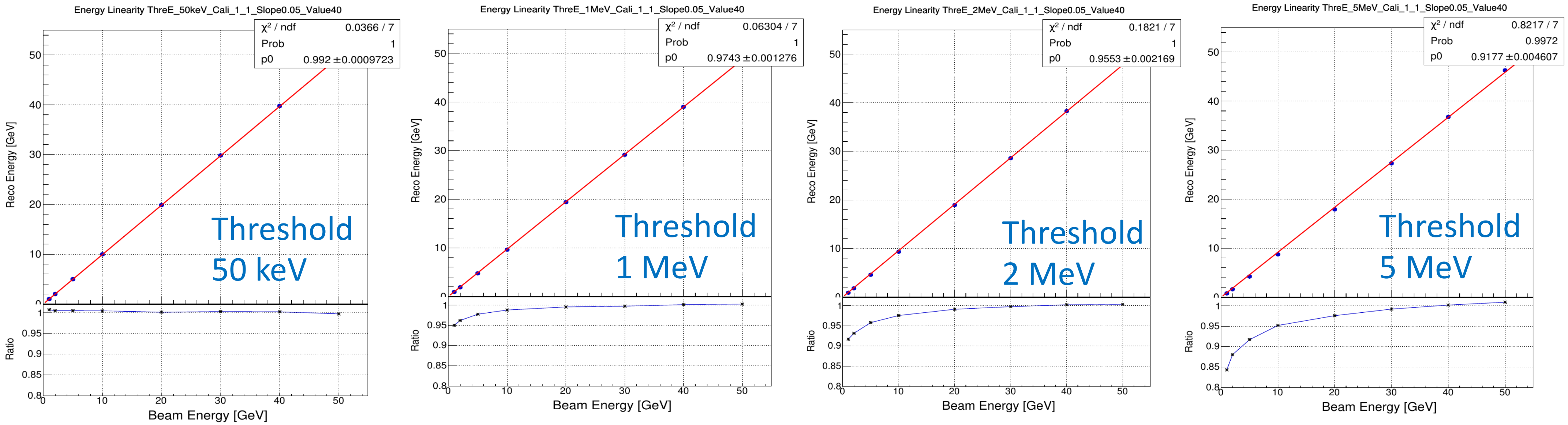
- Higher energy threshold leads to better separation power
- Hadronic showers show more complicated patterns
- Separation efficiency is also affected by
  - Clustering algorithm, matching of tracker and clusters in calorimeters

Impacts of energy threshold: energy linearity

Baohua Qi (IHEP)

- Increasing energy threshold (in digitisation)
  - Degrade the energy linearity, especially in low energy region (e.g. <10 GeV)

Energy sum of hits (after digitization)

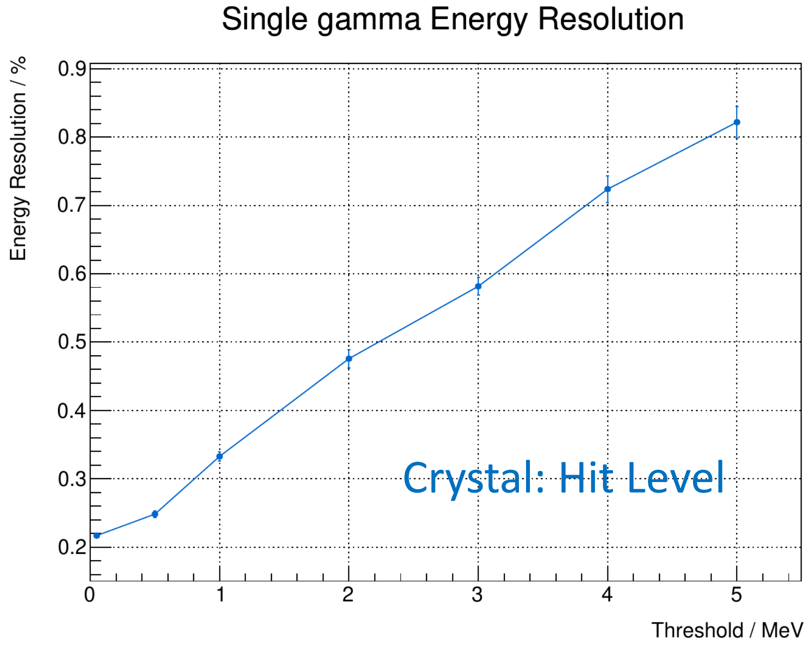


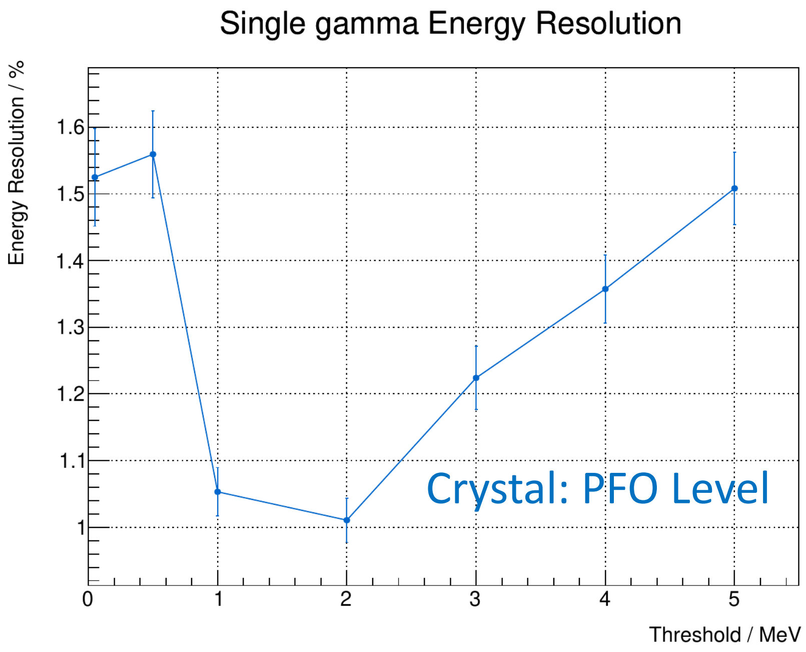
Note: energy threshold in digitization is like signal threshold in detector hardware
Schemes of two different thresholds: one for hardware (adequately low), and the other for PFA (relatively high)

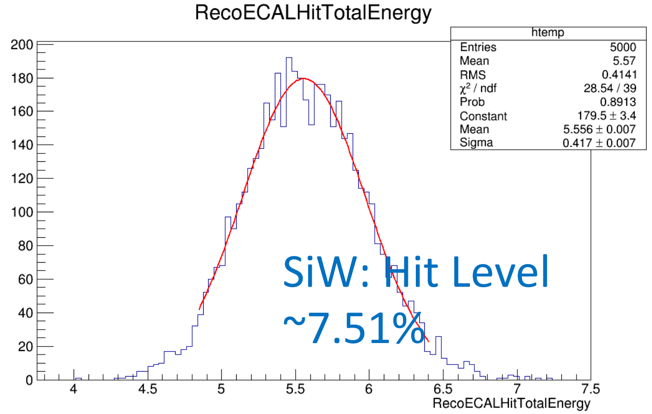
Impacts of energy threshold: single photon energy resolution

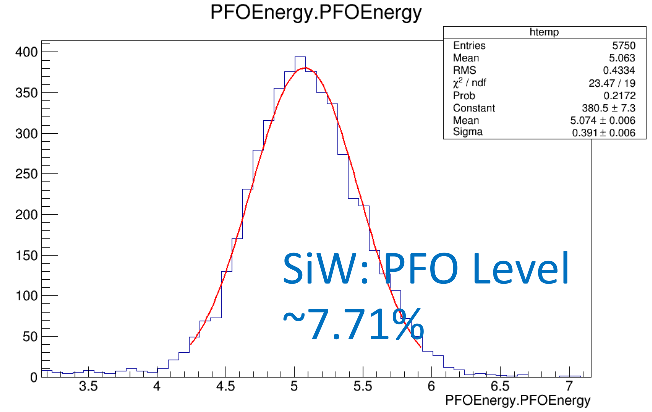
Baohua Qi (IHEP)

Energy Resolution with single photons









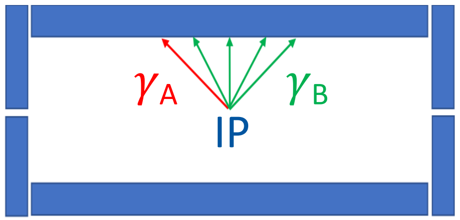
- PFO energy resolution: including contributions from clustering algorithm
- Crystal ECAL shows significantly better energy resolution
  - Single photon resolution ~1% with 2 MeV threshold on PFO level

Comparison of separation power: crystal vs SiW

Baohua Qi (IHEP)

Separation of two gammas

Sketch of ECAL in r-z plane



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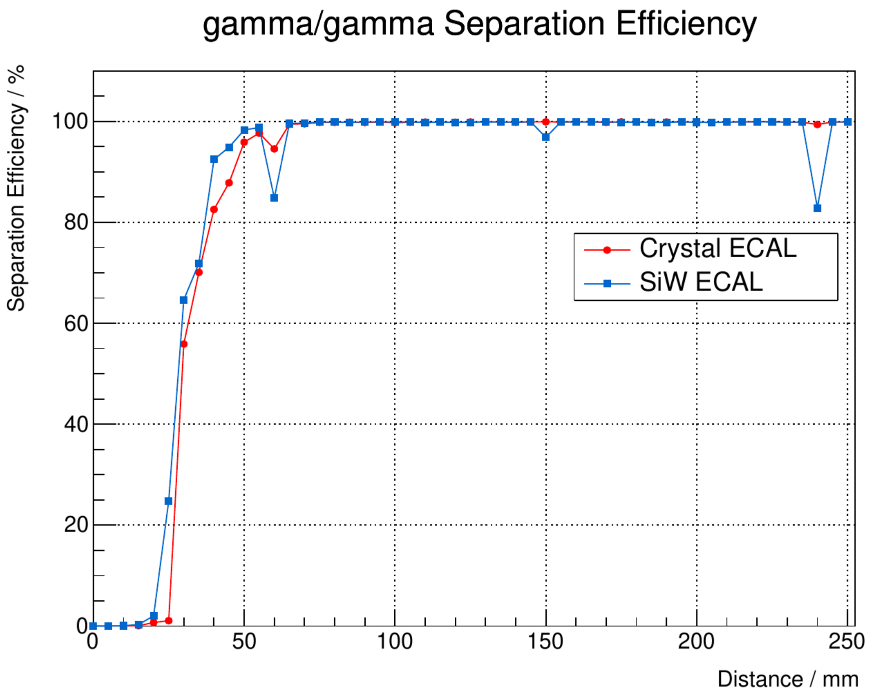
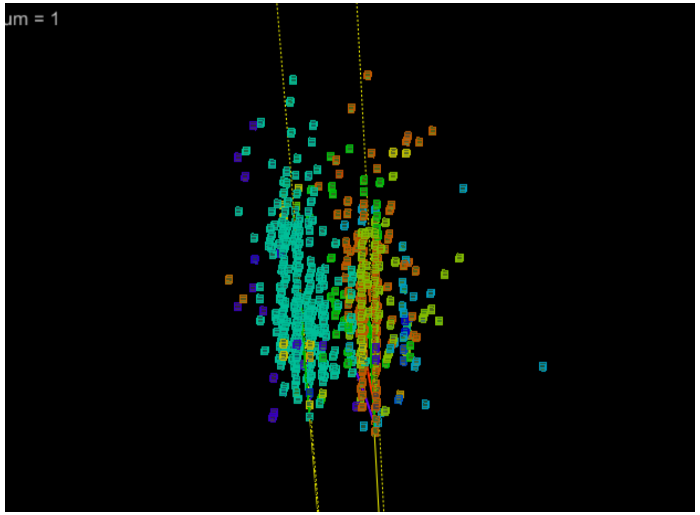


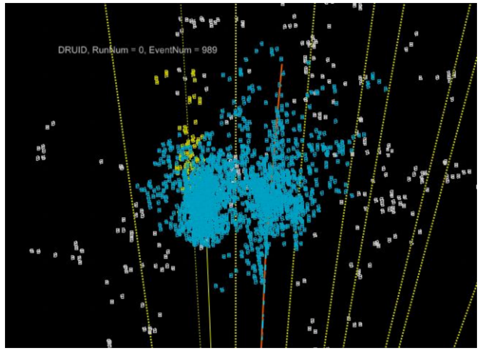
Threshold: SiW 50keV (~0.36MIP), crystal 2MeV (~0.26MIP)



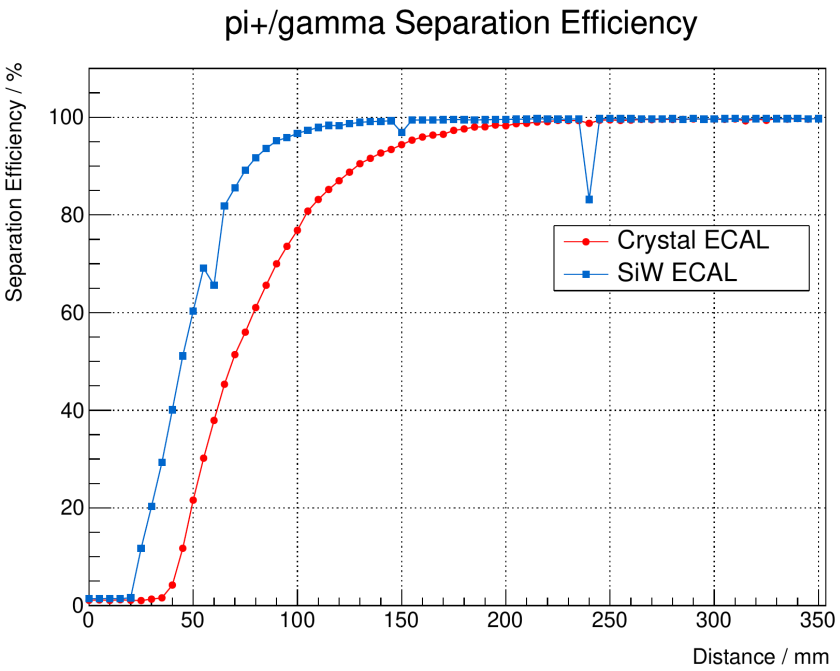
Crystal: distance 50 mm successfully reconstructed

- Using optimized ArborPFA and parameters (details in backup)
- Similar separation performance achieved in two ECAL options: crystal and SiW

Comparison of separation power: $\pi+/\gamma$



Separation of a gamma and a charged pion



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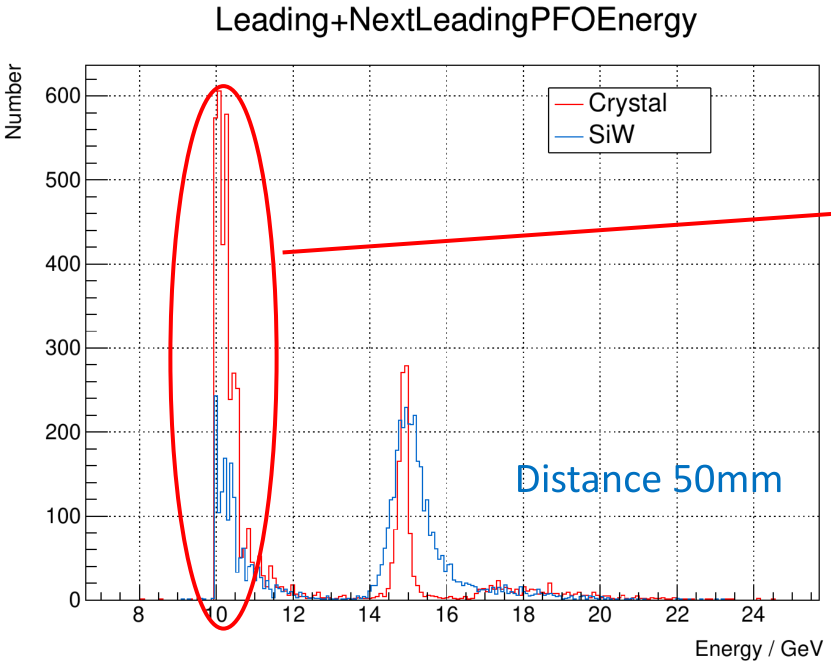
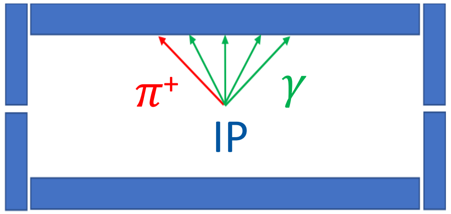


Failure in track-calo matching: cluster of photon (left) was wrongly absorbed into the cluster of π^+ (right), the energy of photon would be lost



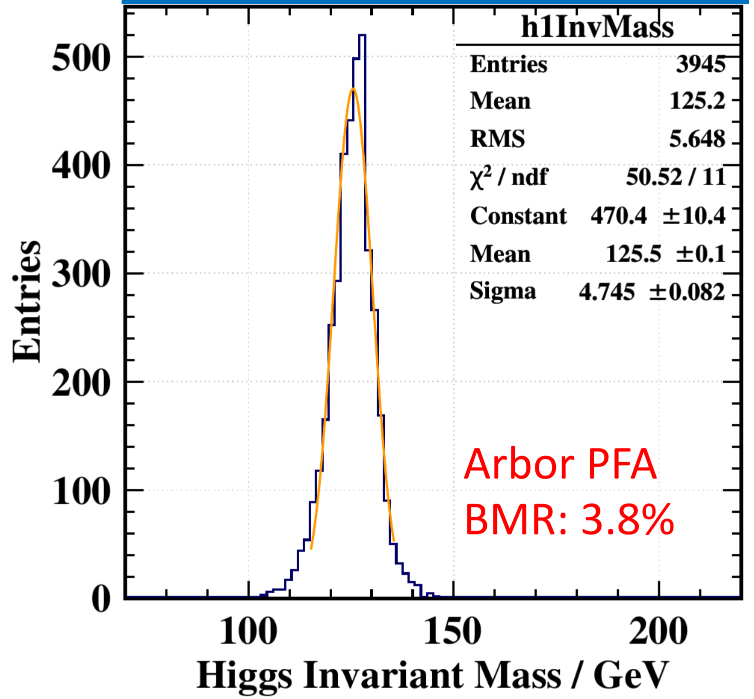
- 10GeV π^+ and 5GeV γ: varying distance
- 3 T magnetic field
- π^+ momentum measured by tracker
- Efficiency definition: successful reconstruction of **3.3GeV<E_N<6.6GeV, 9.9GeV<E_C<10.1GeV**
- Removed events with γ/π^+ interactions before entering ECAL
- Applied energy calibration

- Using optimized ArborPFA and parameters (details in backup)
- Separation performance: crystals not as good as SiW, esp. within 10cm
  - Still limited by the track-calo matching: pattern recognition

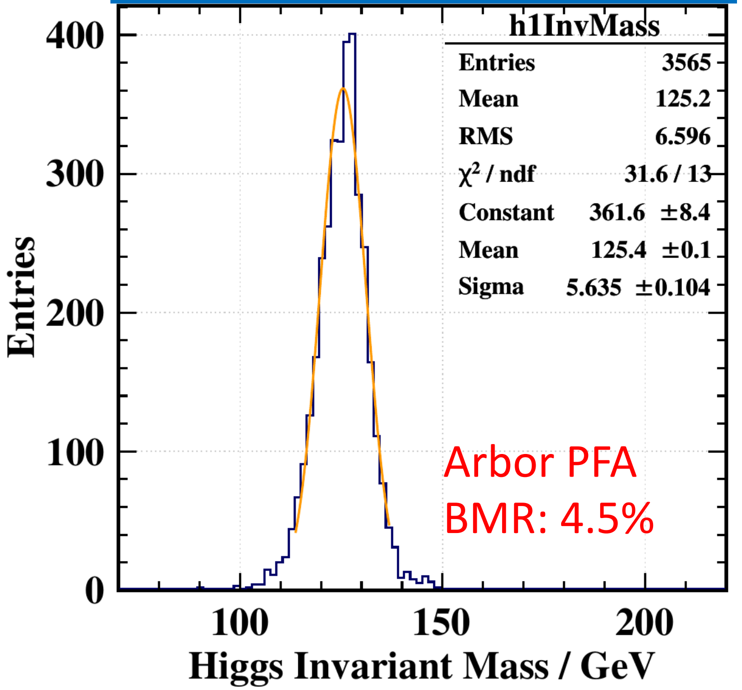
Higgs benchmark studies: reminder

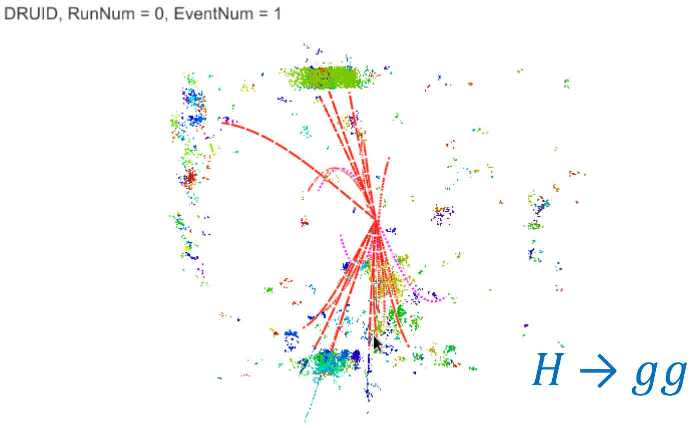
- 2-jet benchmark events in ZH ($Z \to \nu\nu, H \to gg$) at 240 GeV
- Reminder: results presented at Yangzhou Workshop (Apr 2021)
  - "Turn-key" configuration in ArborPFA, not optimised for crystals

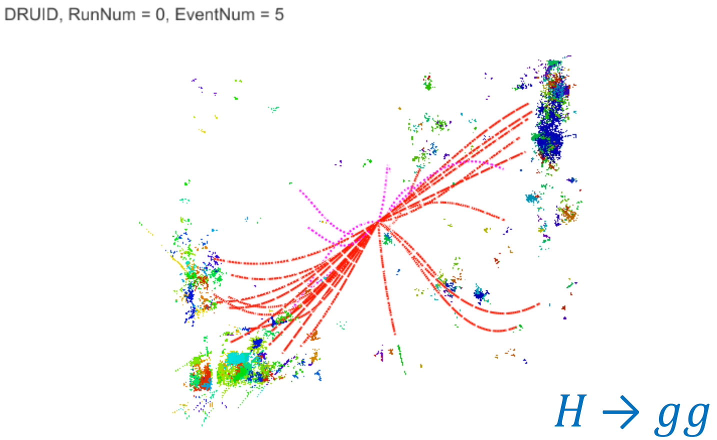
Detector with SiW ECAL option



Detector with Crystal ECAL option



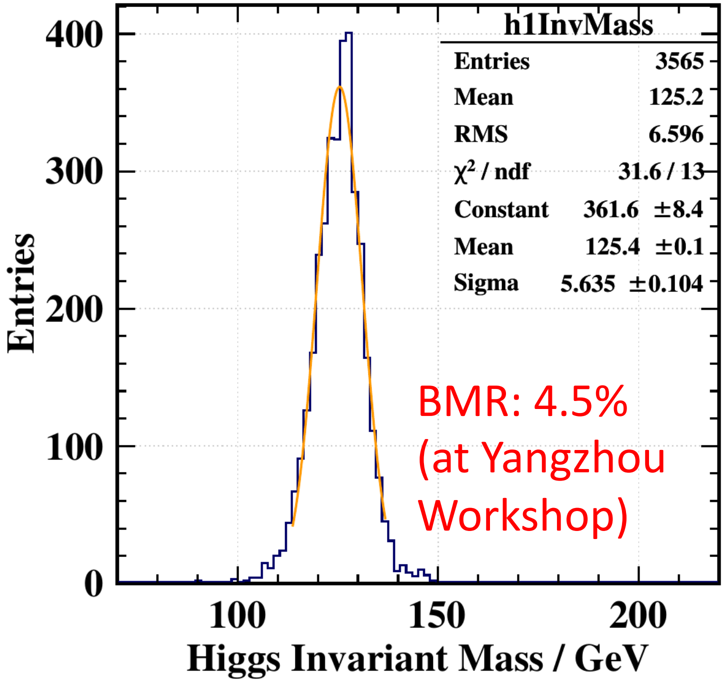




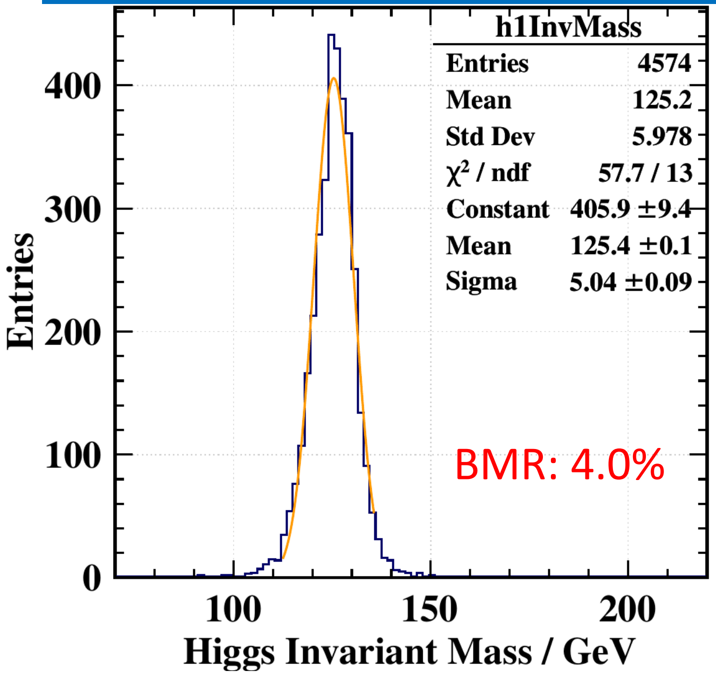
Higgs benchmark $ZH\ (Z \rightarrow \nu\nu, H \rightarrow gg)$

- 2-jet benchmark events in $ZH\ (Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV
- With updated parameters in ArborPFA
  - Parameters being optimised in reconstruction: energy threshold (in digitization), "Bush-Connect" parameters, …
- Significant improvement in BMR: from 4.5% to 4.0%
- Still potentials to be explored with precision information from crystals: e.g. energy and timing

Crystal ECAL: before ArborPFA update



Crystal ECAL: after ArborPFA update



Ongoing studies and plans

- Updates implemented in ArborPFA
  - New: application of energy information
    - “Hardware” threshold: low enough for better energy linearity
    - “Software” threshold: high enough for better separation power in ArborPFA
  - Results will be updated accordingly
- Impacts from crystal granularity to PFA performance
  - Vary the granularity, especially the transverse
    - Guided by physics performance (separation efficiency, BMR, etc.)
  - Trying to converge, with inputs extracted from reconstruction performance of long crystal bars
- Hardware: crystal and SiPM
  - Updating the test stand: to improve coupling stability, repeatable precision; test more SiPMs
  - Synergies with high-density scintillating glass R&D

Summary

- Steady progress to address key issues

- PFA performance studies with crystals
  - To use energy and time information in ArborPFA
  - Separation power of close-by particles
    - γ/γ separation: crystal shows similar performance to SiW
    - $\pi+/\gamma$ separation: significantly improved performance of with crystals, but also limited by track-calo matching
  - Higgs benchmark studies
    - Improvements with the updated ArborPFA
    - Detector with crystals: BMR achieved 4% for $H \rightarrow gg$ (previously 4.5%)

Thank you!

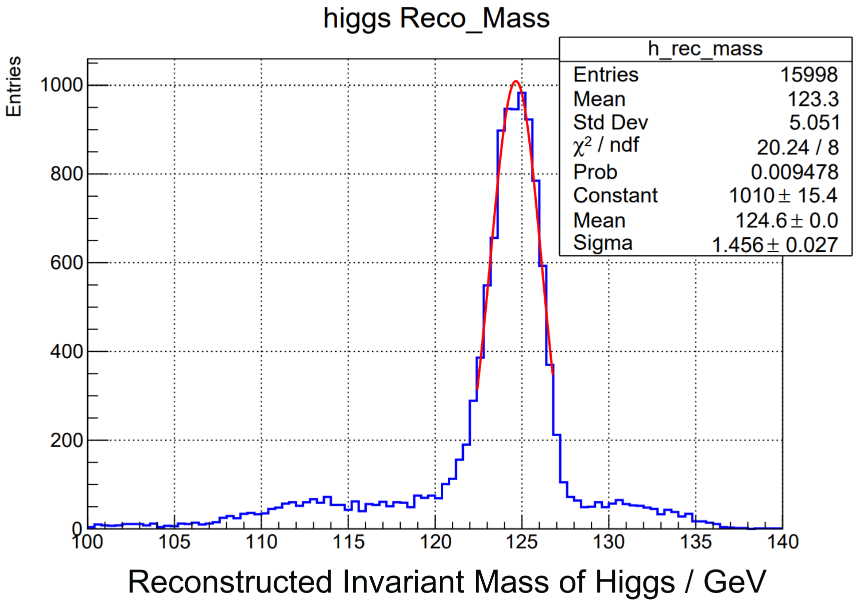
Backup slides

Physics benchmark with two photons in final states

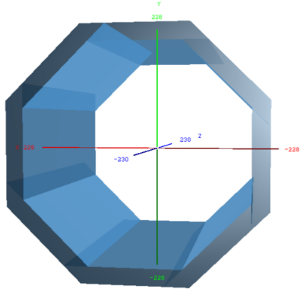
Zhiyu Zhao (IHEP/SJTU)

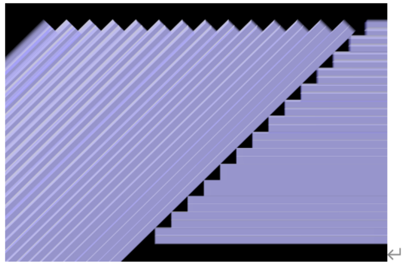
- Full simulation studies with $ZH(Z \rightarrow \nu\nu, H \rightarrow \gamma\gamma)$ at 240 GeV
- Updates: identified impacts of the geometry boundaries

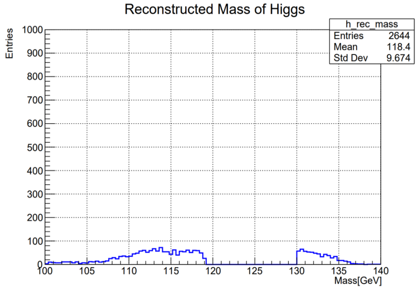
Structures around the Higgs invariant mass peak

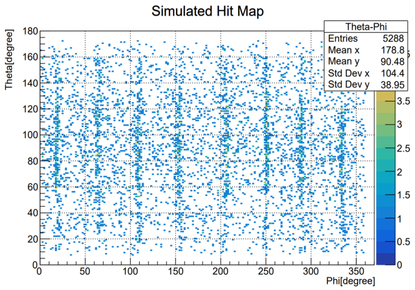


Gaps in the barrel ECAL (octaves)

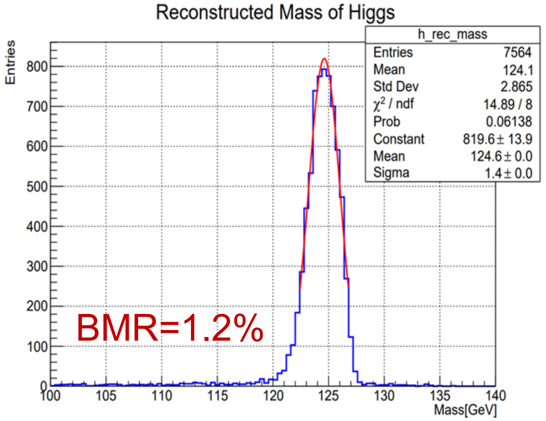


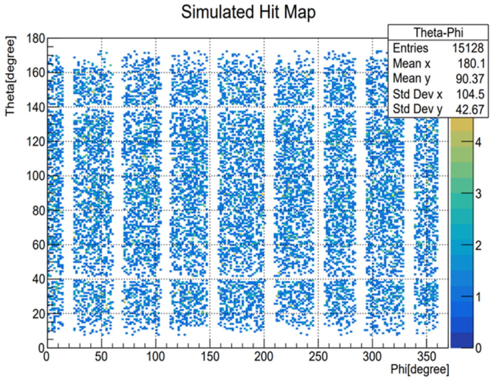






Excluding hits near gaps



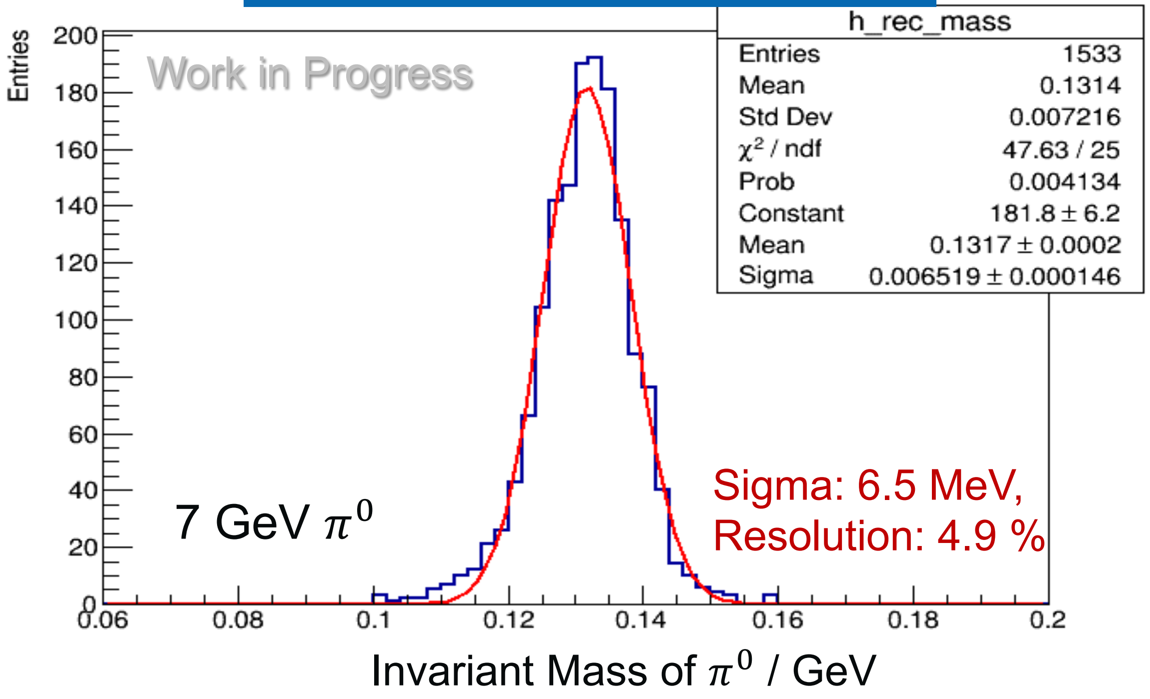


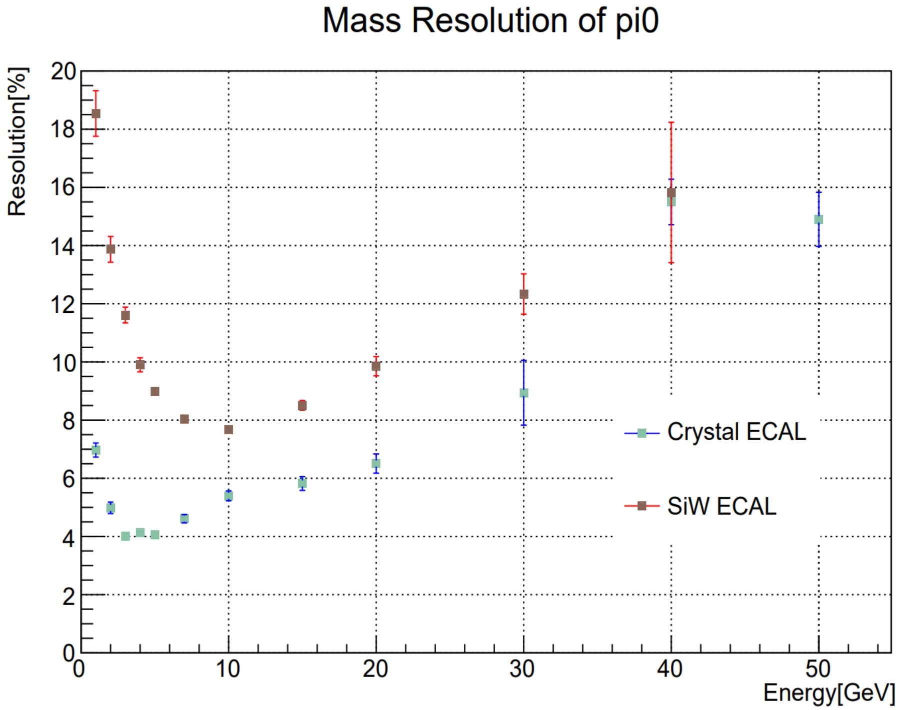
Performance studies: neutral pions with Arbor-PFA

Zhiyu Zhao (IHEP/SJTU)

- Reconstruction of π^0 in crystal ECAL: invariant mass and its resolution
  - Single π^0's generated by the particle gun

Detector with Crystal ECAL option

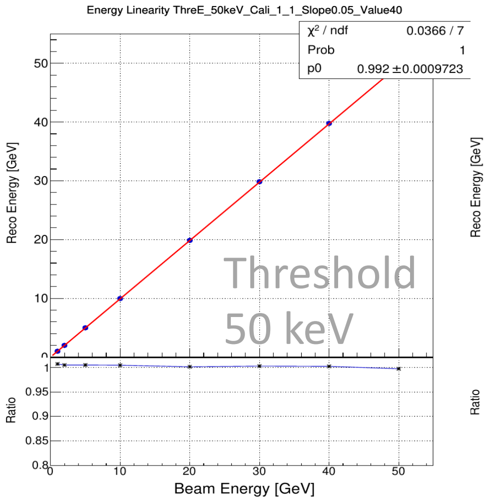


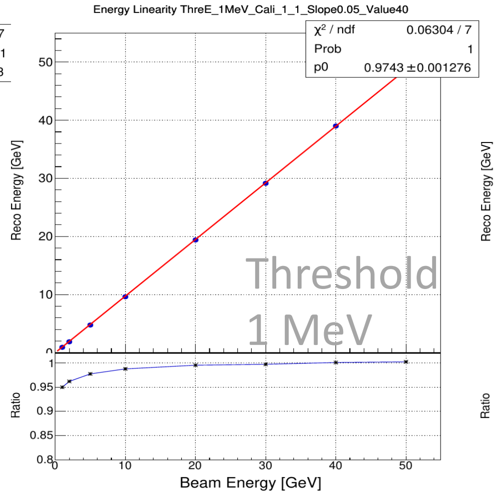


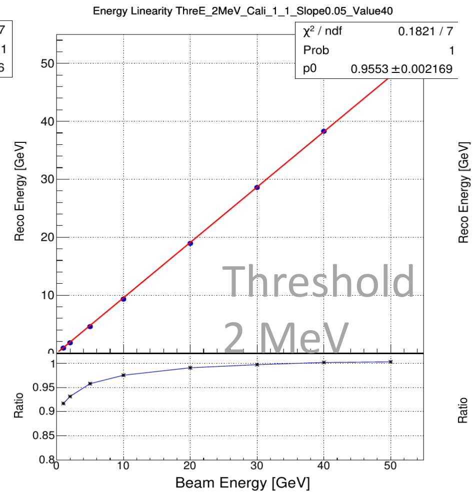
π^0 invariant mass resolution: dominated by EM resolution in lower energy region and in higher energy by angular resolution

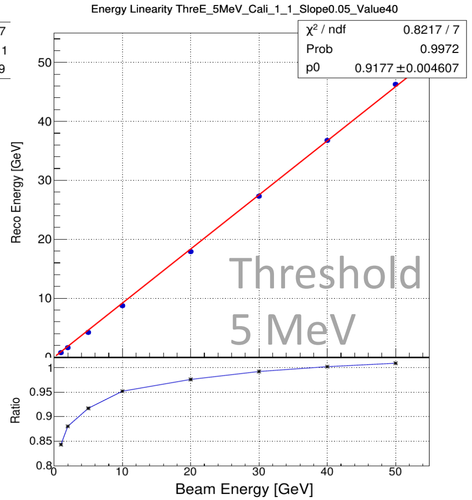
Impacts of energy threshold: energy linearity

Energy sum of hits (after digitization)

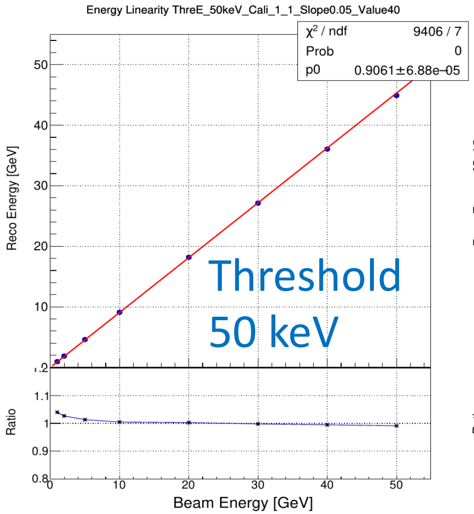


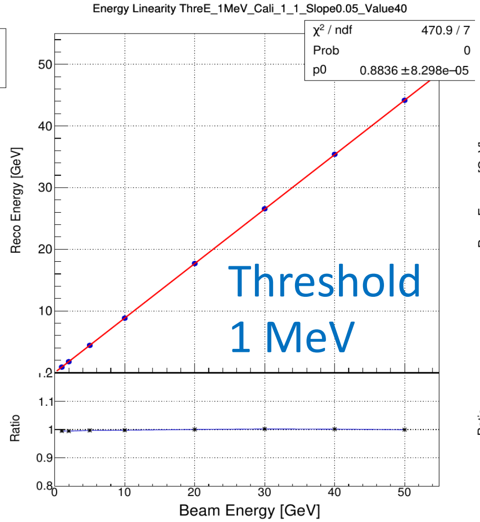


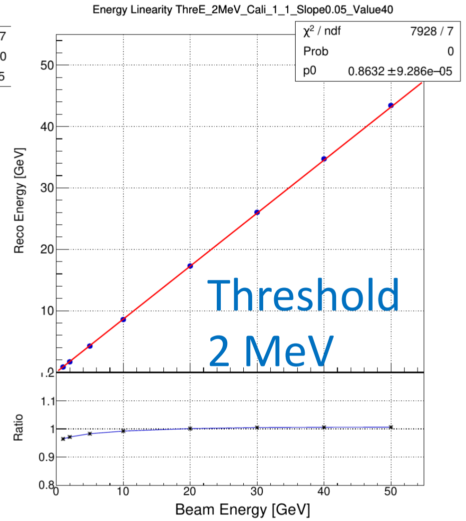


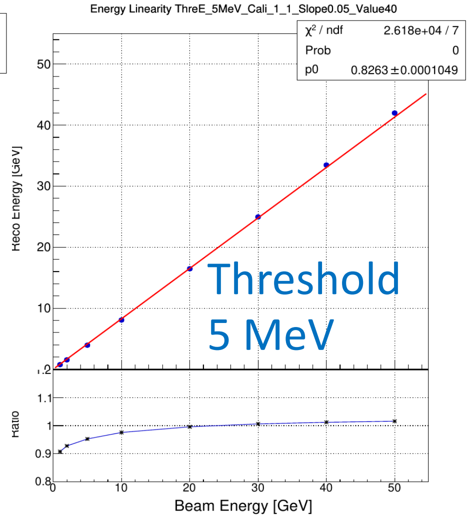


Reconstructed Gamma (PFO)



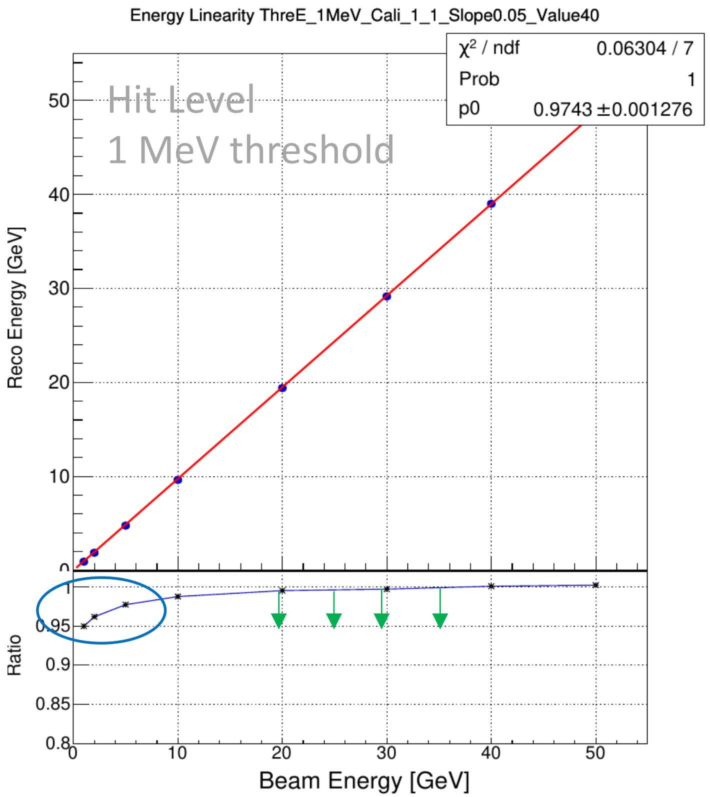


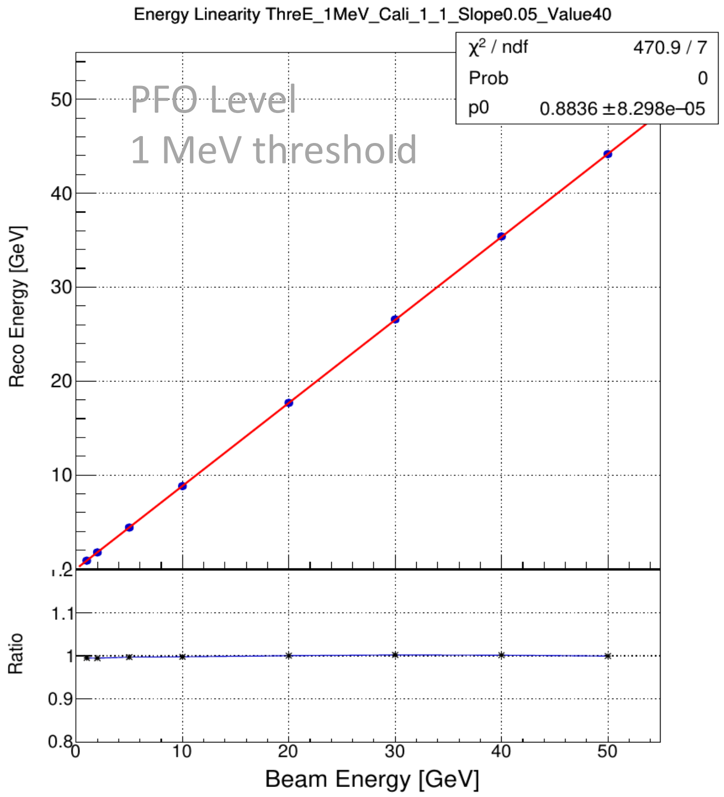




- PFO Level: non-linear response, clustering effect included

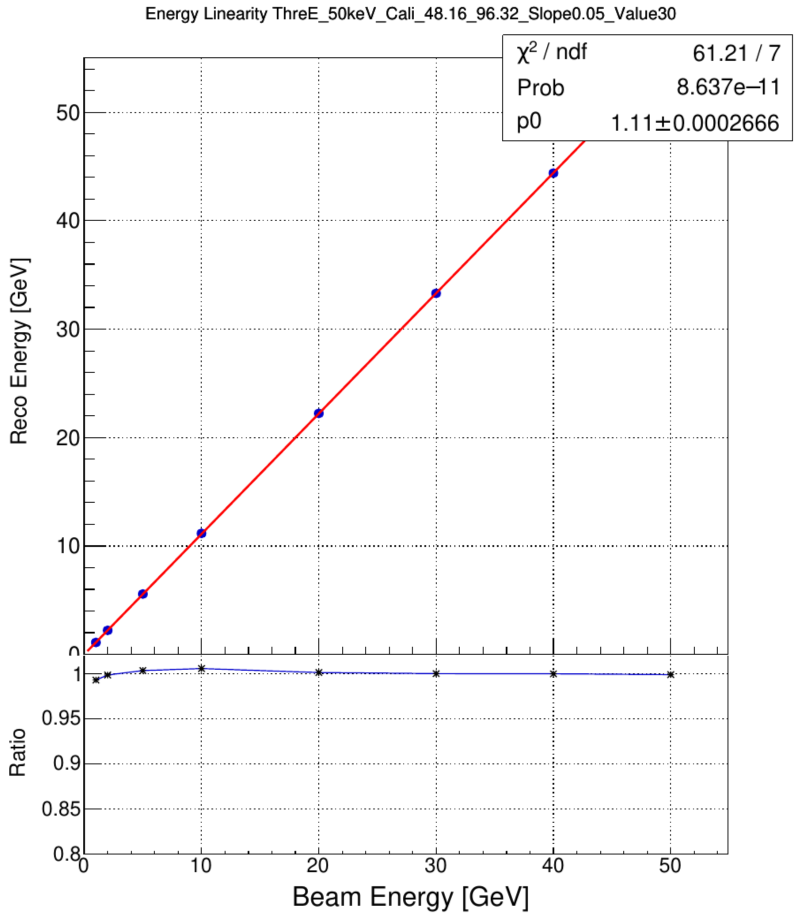
Impacts of energy threshold: energy linearity



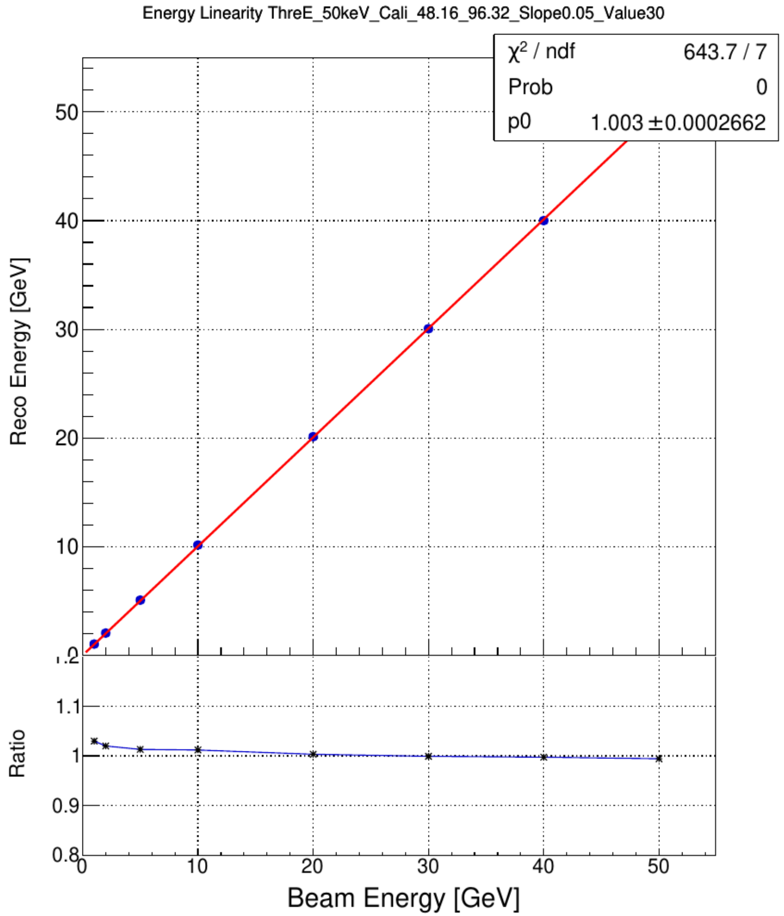


- Hit level: missing low energy hits will affect the response at low energy part
- PFO level: insufficiency of clustering will lower the response at high energy part

Impacts of energy threshold: energy linearity



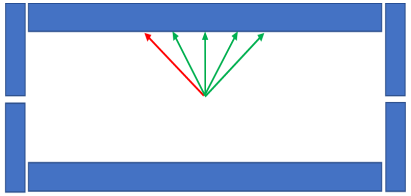
SiW Hit Level



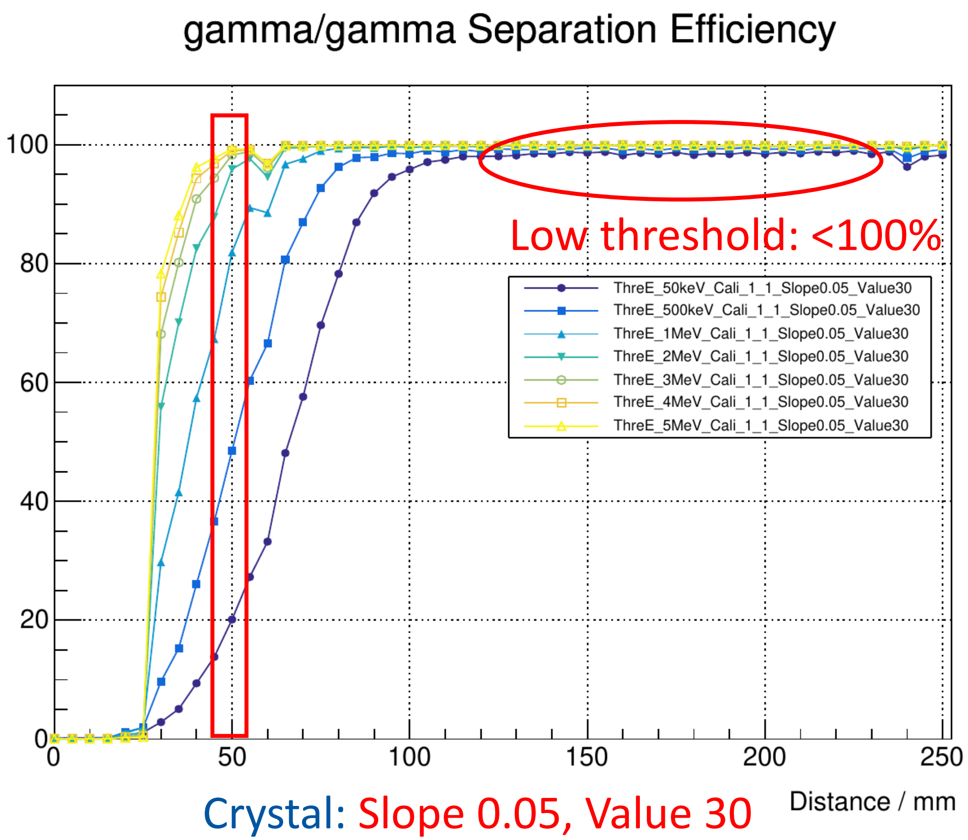
SiW PFO Level

γ/γ Separation: optimization

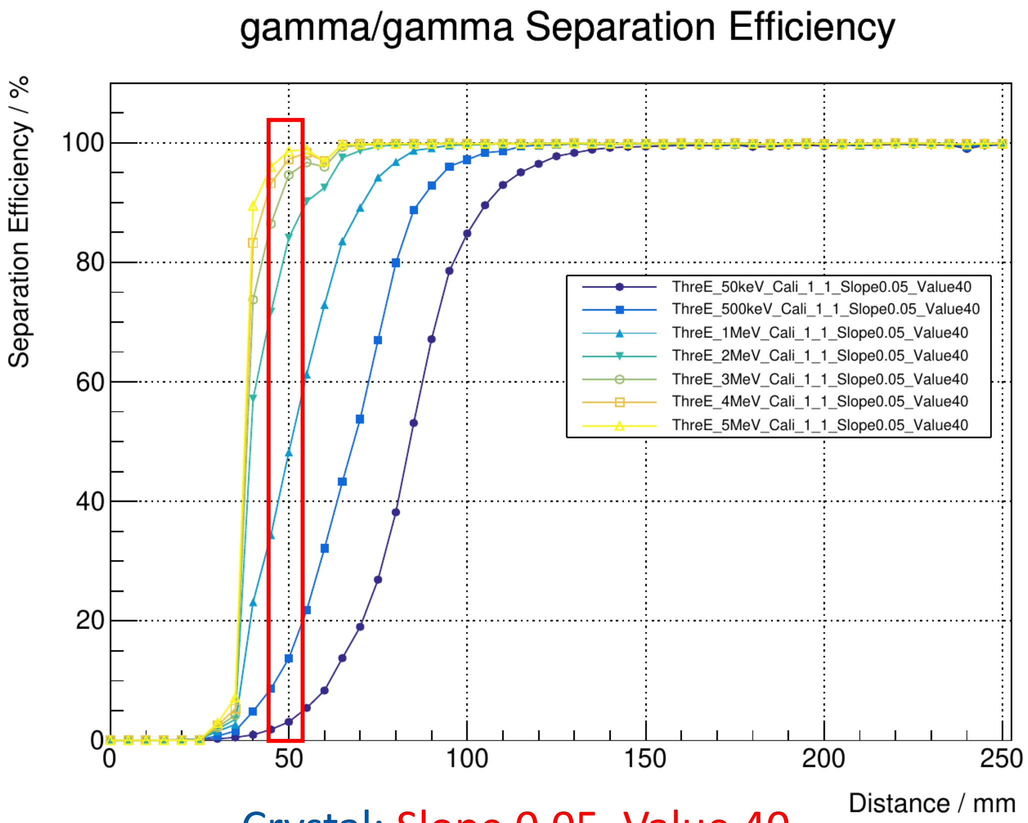
- Change threshold in digitization
- Comparison of different parameters



Two 5GeV γ, vary distance
Absolute energy calibration applied manually
Success reconstruction: 3.3GeV<E_γ<6.6GeV
Events that γ decays in tracker removed



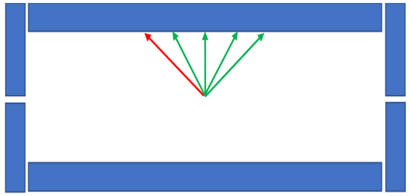
Crystal: Slope 0.05, Value 30



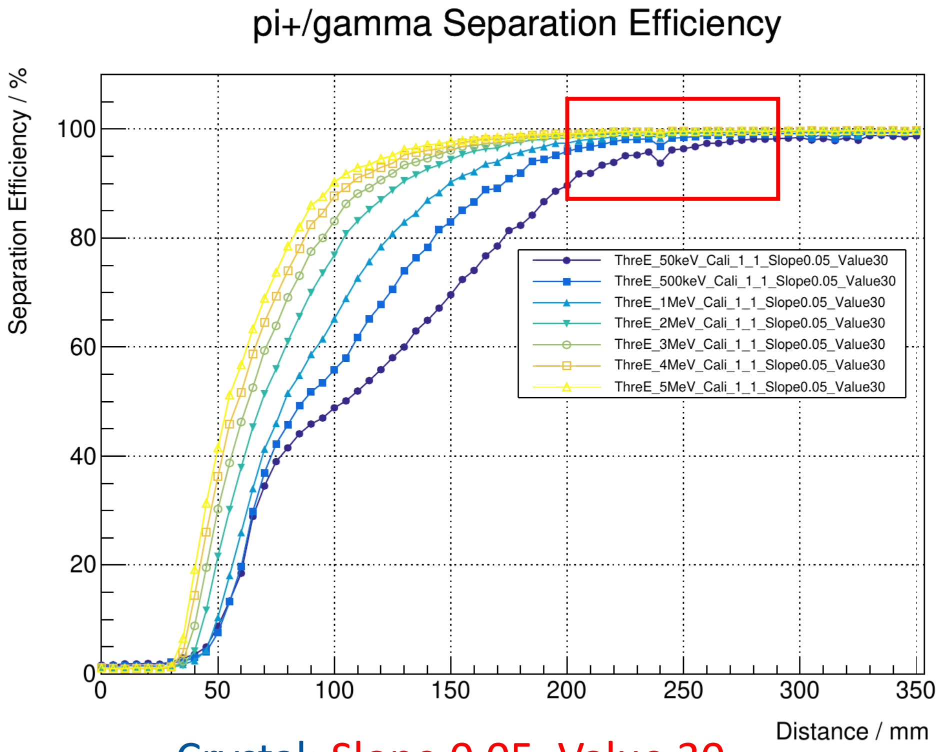
Crystal: Slope 0.05, Value 40

$\pi+/\gamma$ Separation: optimization

- Change threshold in digitization
- Comparison of different parameters

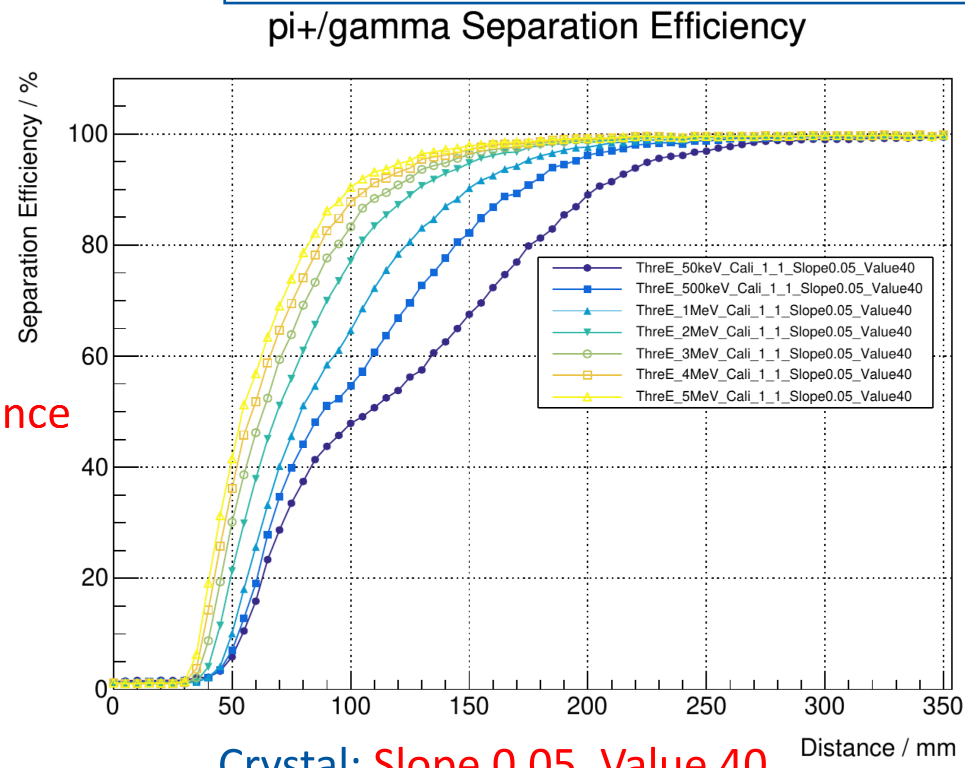


10GeV π^+ and 5GeV γ, 3T magnetic field, vary distance
Absolute energy calibration applied manually
Success reconstruction:
3.3GeV<E_γ<6.6GeV, 9.9GeV<$E_{\pi+}$<10.1GeV
Events that π^+/γ decays in tracker removed



Crystal: Slope 0.05, Value 30

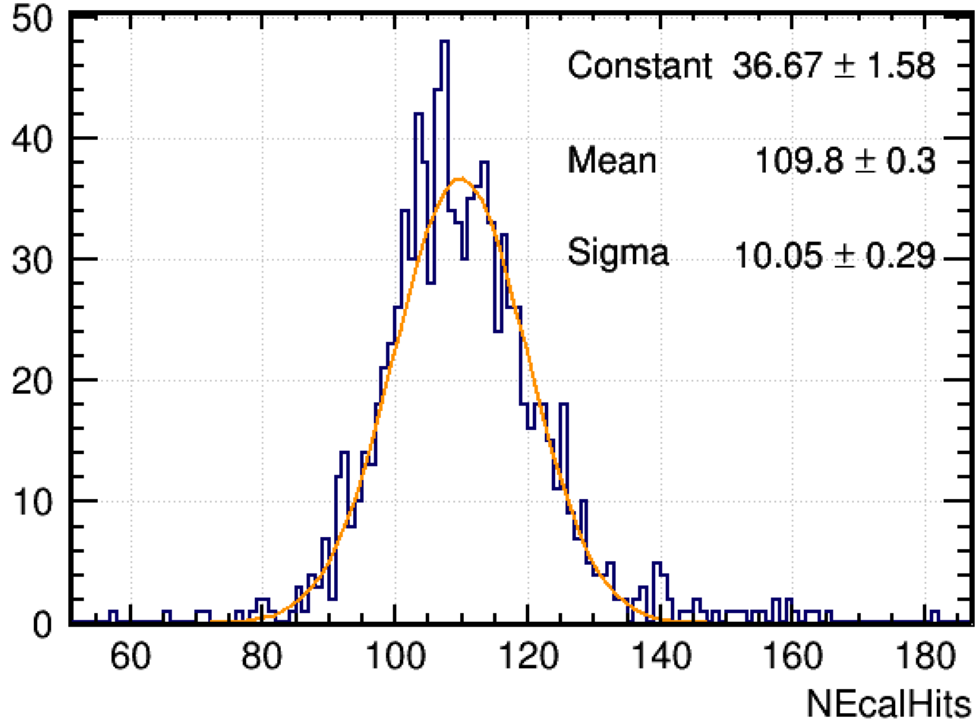
Minor difference



Crystal: Slope 0.05, Value 40

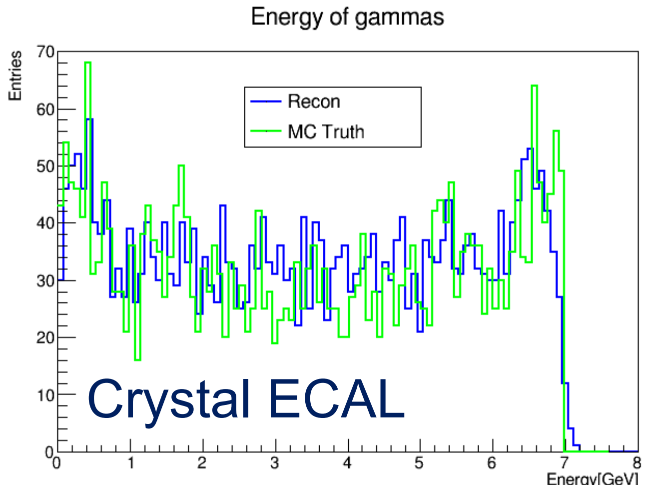
Study on hit level optimization

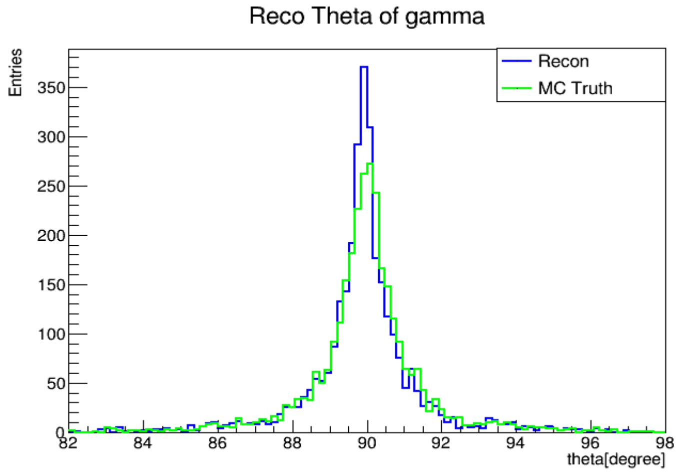
- SiW: hit number study with 5 GeV γ

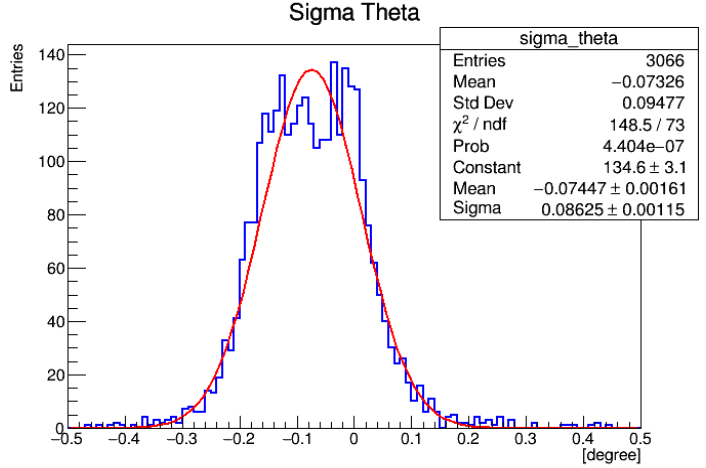


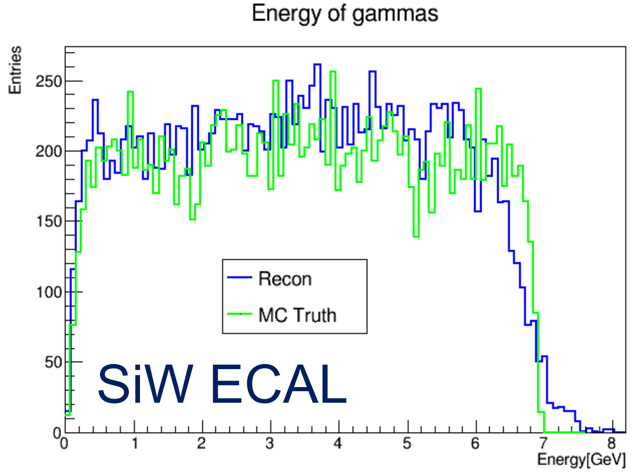
Neutral pion reconstruction: crosscheck with MC truth

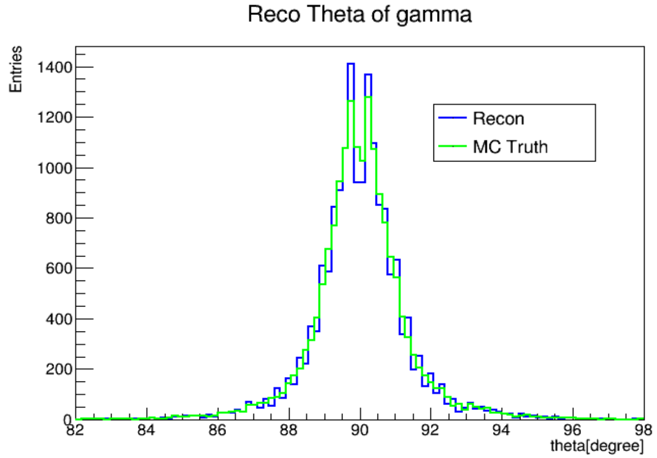
Photon Energy	Photon Anle in Theta	Photon Theta: Reco– MC

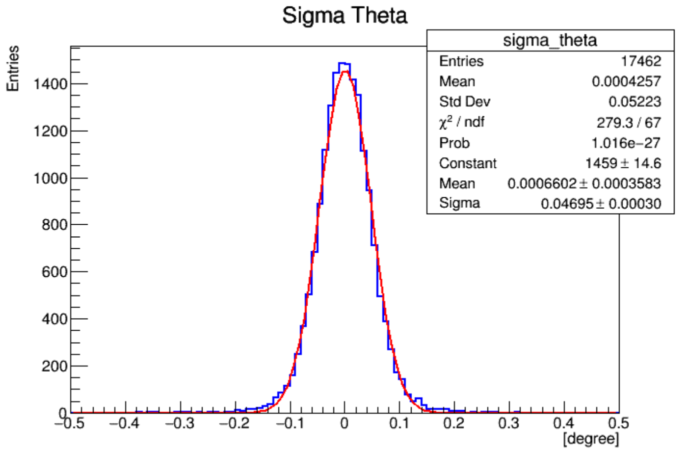






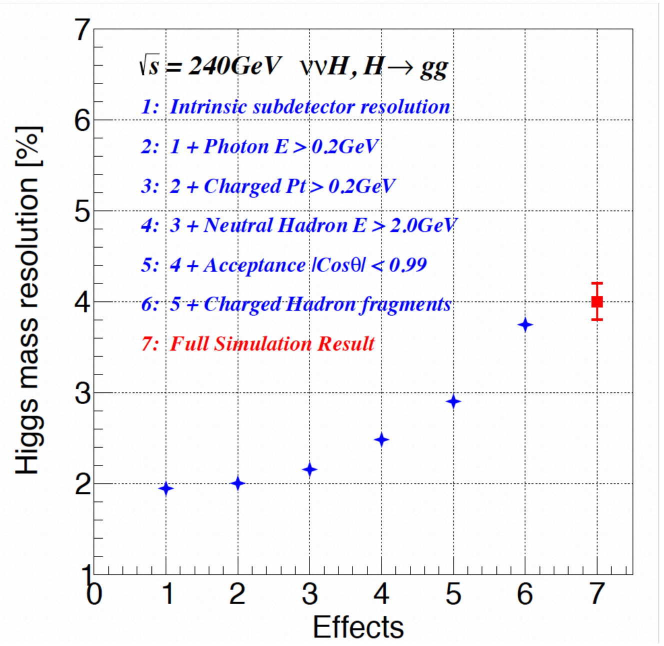


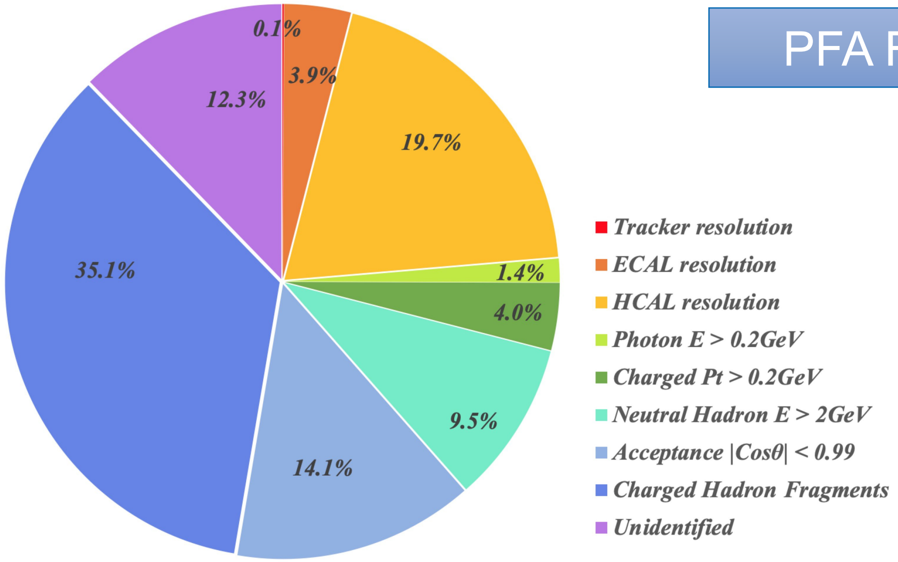




Impacts to Higgs mass resolution: reminder

Yuexin Wang (IHEP)



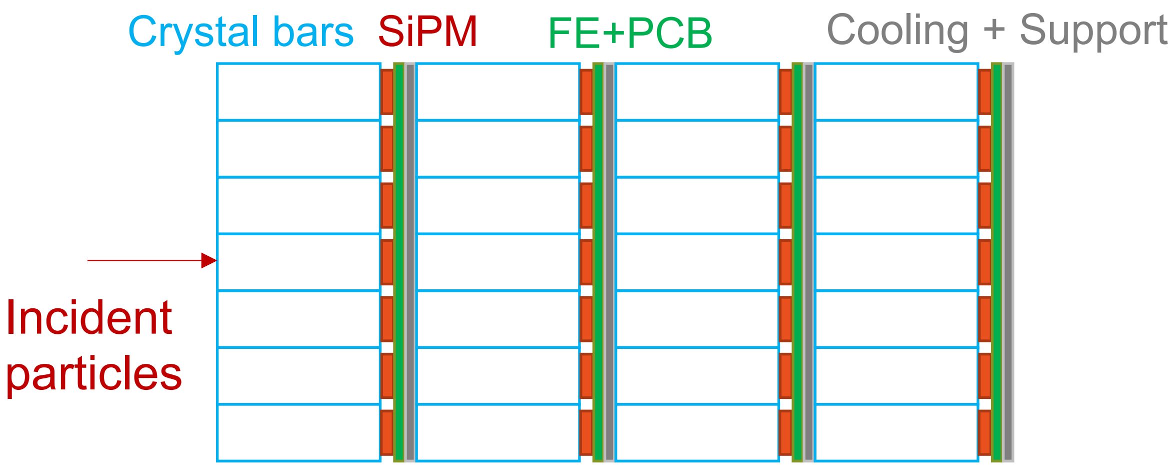


PFA Fast Simulation

- Full simulation with SiW-ECAL via the benchmark Higgs to 2 gluons
  - 10 longitudinal layers or more in ECAL can help achieve better than 4% of BMR
  - Expect small impact from ECAL intrinsic energy resolution (PFA fast simulation)
- Guidance for the longitudinal segmentation
  - Will perform more benchmark studies for crystal ECAL in the CEPC detector simulation

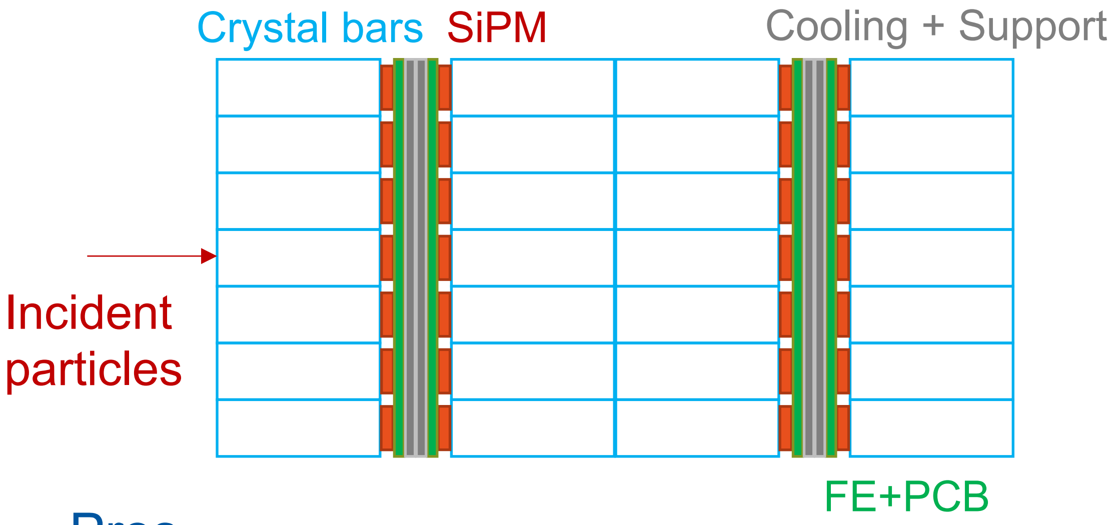
Considerations on detector layouts

Layout 1: same module for each layer



- Pros
  - Modular design
  - Uniform structure (easy calibration)
- Cons
  - Material budgets (cooling, mechanics)

Layout 2: every two layers share the same cooling service and mechanics



- Pros
  - Save material budget (e.g. a factor of two)
- Cons
  - Non-uniform sampling structure: will need specific considerations for calibration

Studies on physics requirements

Yuexin Wang (IHEP)

- Estimate the multiplicity level of jets: fast simulation
  - Detailed studies with 2 incident particles (from a jet) hitting the hottest tower