High-granularity Crystal ECAL for CEPC

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IHEP CAS

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Outline

- Introduction.

- PFA performance with crystal cube ECAL:
  - Separation power power with 2 incident particles.
  - Higgs benchmark @ CEPC $H \to \gamma\gamma$(2 photons), $H \to gg$ (2 jets).

- A new proto-PFA software for crystal bar ECAL.

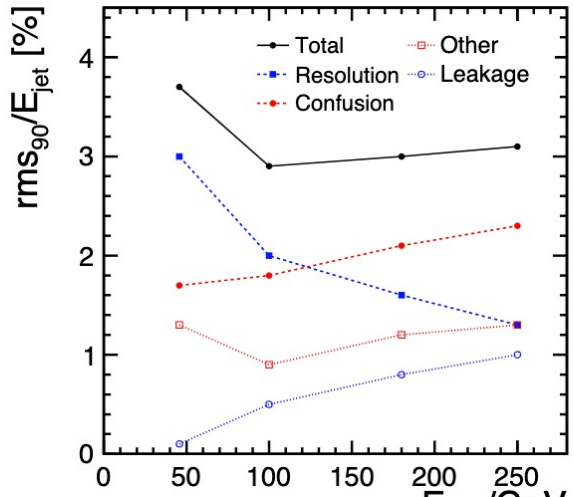
- Technical developments: crystals and SiPMs:
  - Uniformity: Geant4 simulation vs. Lab measurement.
  - Crystal measurement: energy resolution.

Introduction

- Future high energy lepton collider (e.g. CEPC):
  - Excellent high-energy jet energy measurement (3~4% resolution @100GeV) for Higgs and EW study.
  - Precise γ/π^0 separation for flavor physics and BSM.
- Particle-flow Approach (PFA):
  - Measure jet by its components: 60% charged particles, 30% photons, 10% neutral hadrons.
  - Final resolution: $\sigma_{Jet} = \sqrt{\sigma_{track}^2 + \sigma_{EM}^2 + \sigma_{Had}^2 + \sigma_{confusion}^2}$.

Component	Detector	Energy Fraction	Energy Resolution	Jet Energy Resolution
Charged Particles ($X^\pm$)	Tracker	$\sim 0.6\ E_J$	—	—
Photons (γ)	ECAL	$\sim 0.3\ E_J$	$\mathbf{0.15\sqrt{E_\gamma}}$	$\mathbf{0.08\sqrt{E_J}}$
			$\mathbf{0.03\sqrt{E_\gamma}}$	$\mathbf{0.016\sqrt{E_J}}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1\ E_J$	$0.55\sqrt{E_{h^0}}$	$0.17\sqrt{E_J}$

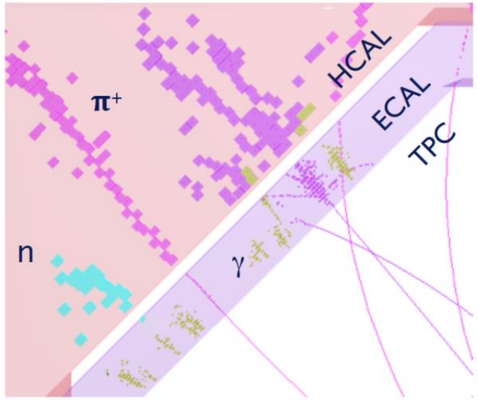
Jet E res.	W/Z sep
perfect	**3.1 σ**
2%	**2.9 σ**
3%	**2.6 σ**
4%	**2.3 σ**
5%	**2.0 σ**
10%	**1.1 σ**



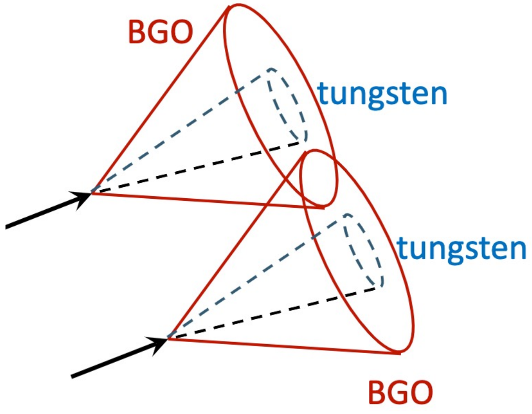
PandoraPFA result:
confusion is important in JER

Introduction

- PFA requirement: Hardware + Software
  - Distinguish showers in calorimeter ⇨ high granularity ECAL/HCAL.
  - Minimize transverse spread of EM shower ⇨ small Moliere radius R_M
    ⇨ SiW sampling ECAL in ILD.
  - Separate EM and Hadronic showers longitudinally ⇨ large λ_I/X_0 ratio.



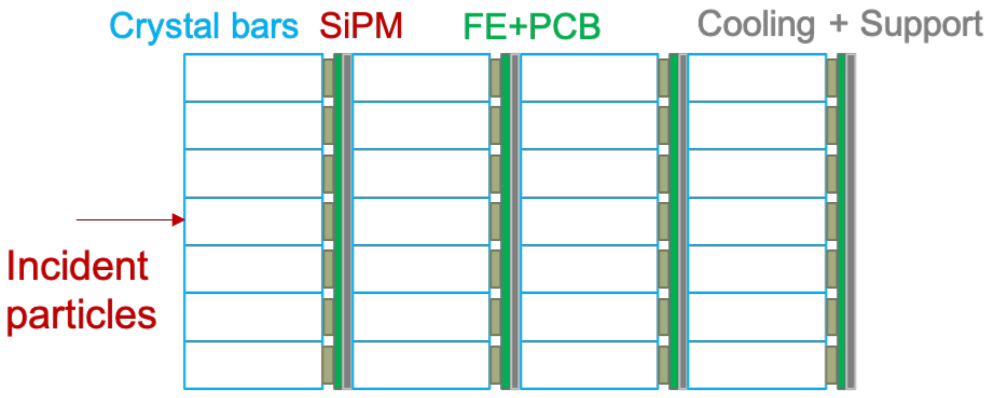
- Crystal ECAL:
  - Homogeneous structure ⇨ energy resolution $\sim 3\%/\sqrt{E} \oplus 1\%$.
  - Capability to trigger single photons ⇨ precise γ/π^0 reconstruction.
  - High sensitivity to low energy particles ⇨ essential for flavor physics.
  - Larger Moliere radius ⇨ larger probability of shower overlap.
  - Smaller λ_I/X_0 ⇨ larger probability of hadronic shower in ECAL.



Material	X_0 /cm	R_M /cm	λ_I /cm	λ_I/X_0
W	**0.35**	**0.93**	**9.6**	**27.4**
BGO	**1.12**	**2.23**	**22.8**	**20.3**
Ratio	3.2	2.4	2.4	0.74

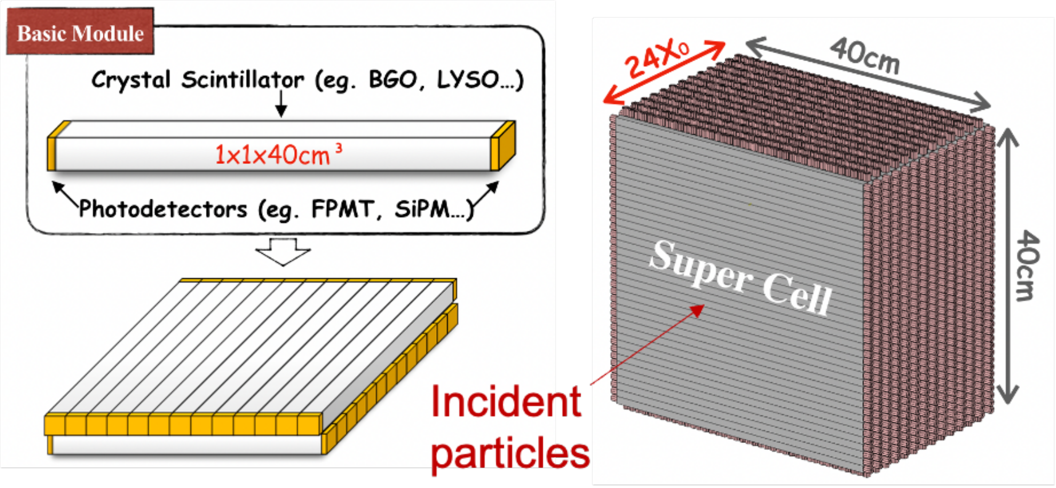
2 major designs for crystal ECAL

Design 1: high-granularity crystal cubes



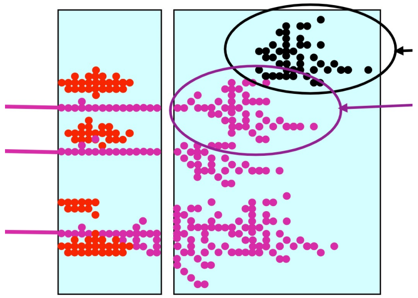
- Fine segmentation of crystal cube($1\times1\times 1\ cm^3$), single-ended readout with SiPM.
- Compatible with PFA.
- Focus on PFA performance studies with ArborPFA.

Design 2: cross arranged crystal bars

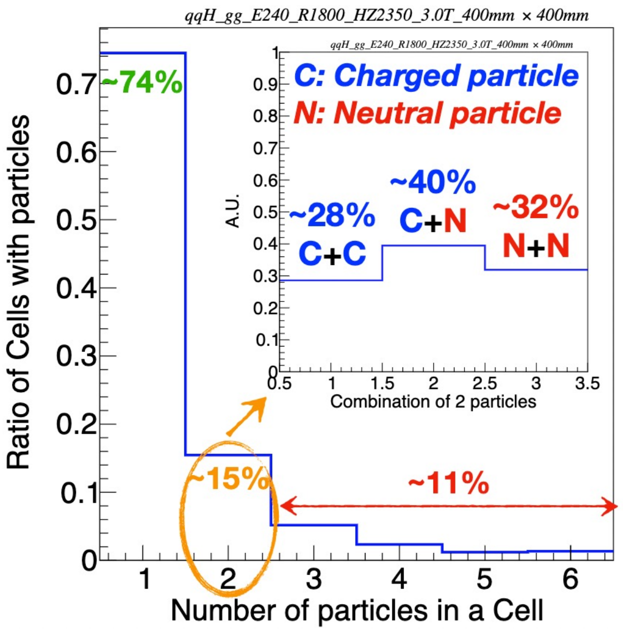


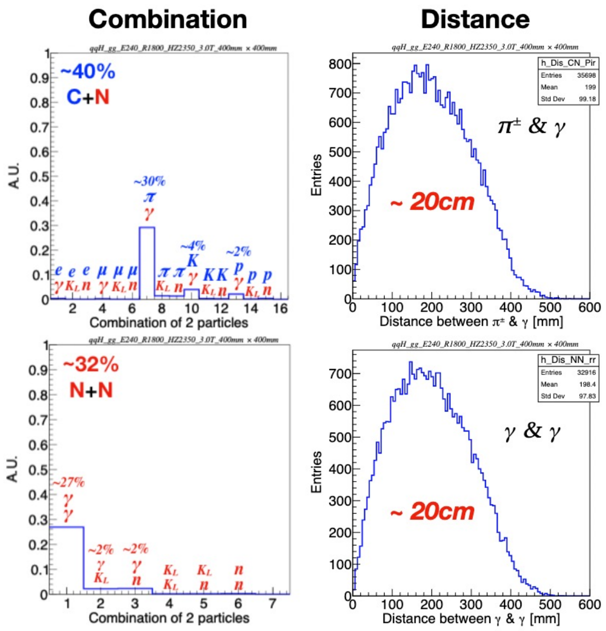
- Long crystal bars: $1\times1\times40\ cm^3$, double-side readout with SiPM.
- Crossed arrangement in adjacent layers + timing at 2 sides for positioning.
- Super cell module: $40\times40\ \mathrm{cm}^2$
- Save #channels and minimize dead materials.
- Focus on reconstruction algorithm development

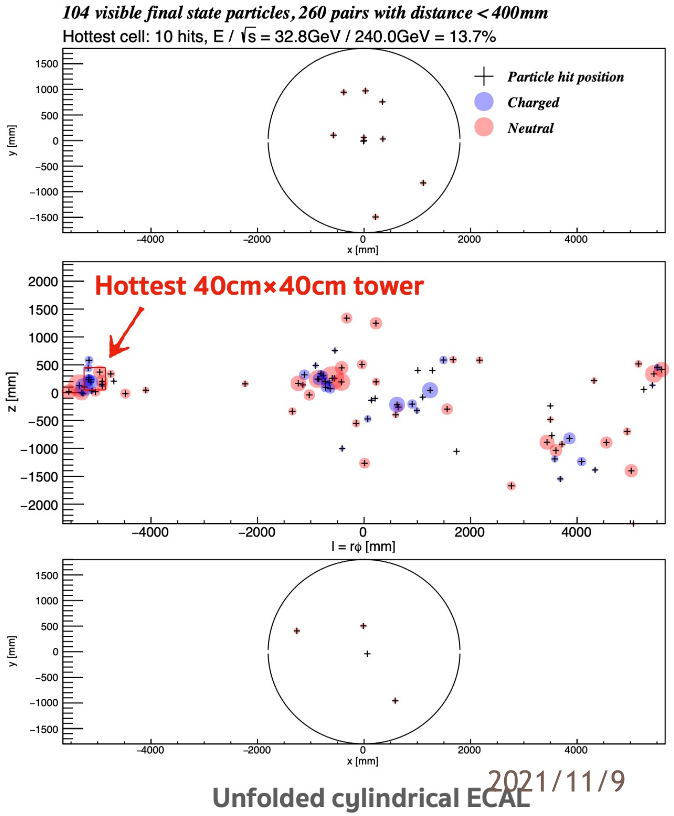
PFA performance with crystal ECAL



- Confusion term in jet energy resolution $\sigma_{confusion}$:
  - Pattern recognition: distinguish nearby clusters from different particles.
  - But how often will this confusion happen in detector?
- Physics topology for 4-jet event in CEPC: $ee \rightarrow ZH \rightarrow qqgg$.
  - Multiplicity in a $40 \times 40\ cm^2$ tower: ≤ 2 particles for 90% cases.
  - Separation between $\gamma + \gamma$ and $\gamma + \pi^{\pm}$ can be a mark of σ_{conf}.







Yuexin Wang's report @ Crystal ECAL workshop, 2020

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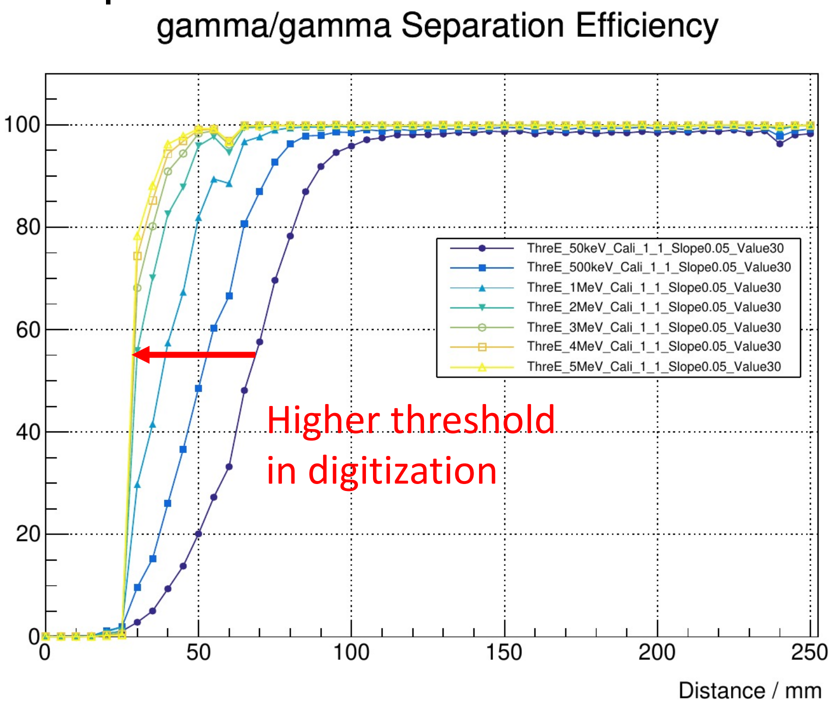
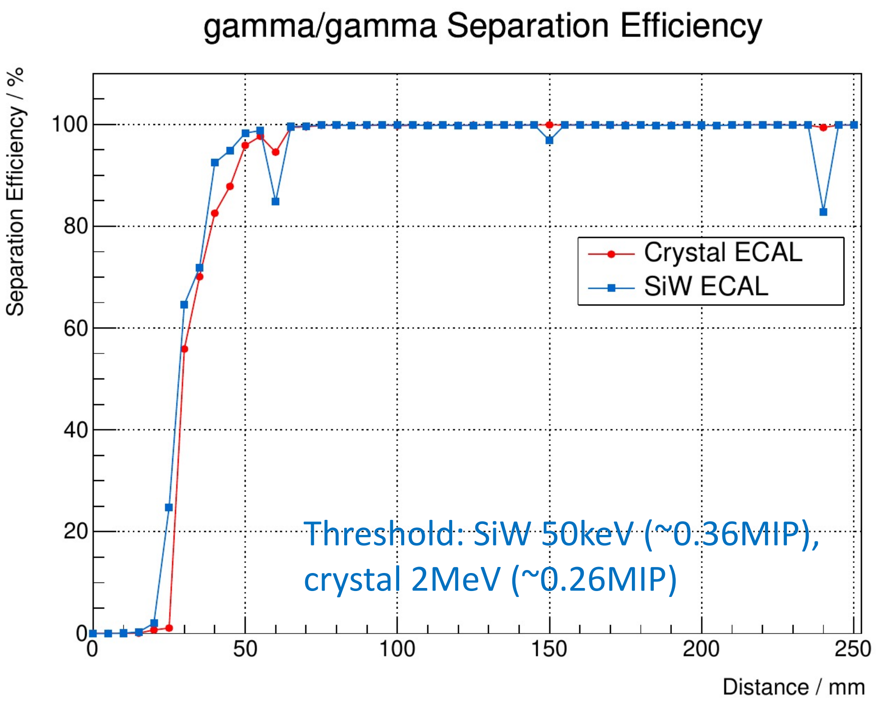
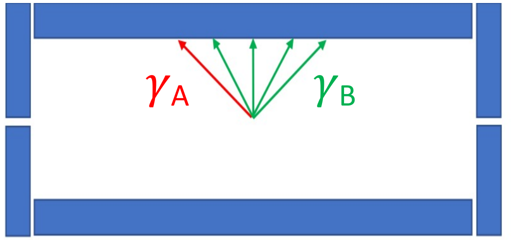
PFA performance with crystal ECAL

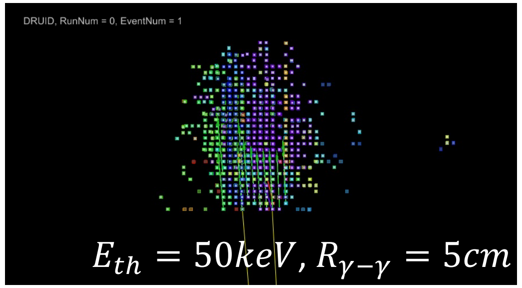
- Diphoton separation in ArborPFA: overlap between two EM shower.
  - Dominant by Moliere radius of BGO: 2.23cm.
  - Solution: first use a higher energy threshold to extract EM shower core for separation, then use low threshold to recover the energy (WIP).
  - With a proper energy threshold crystal ECAL can reach similar separation power with SiW ECAL.

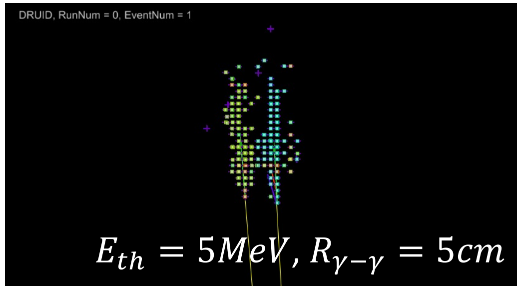






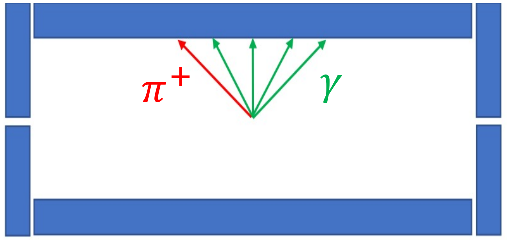
Particle gun event of 2 5GeV photons. Scan the angle(distance) between two photons, check the successful reconstruction efficiency.



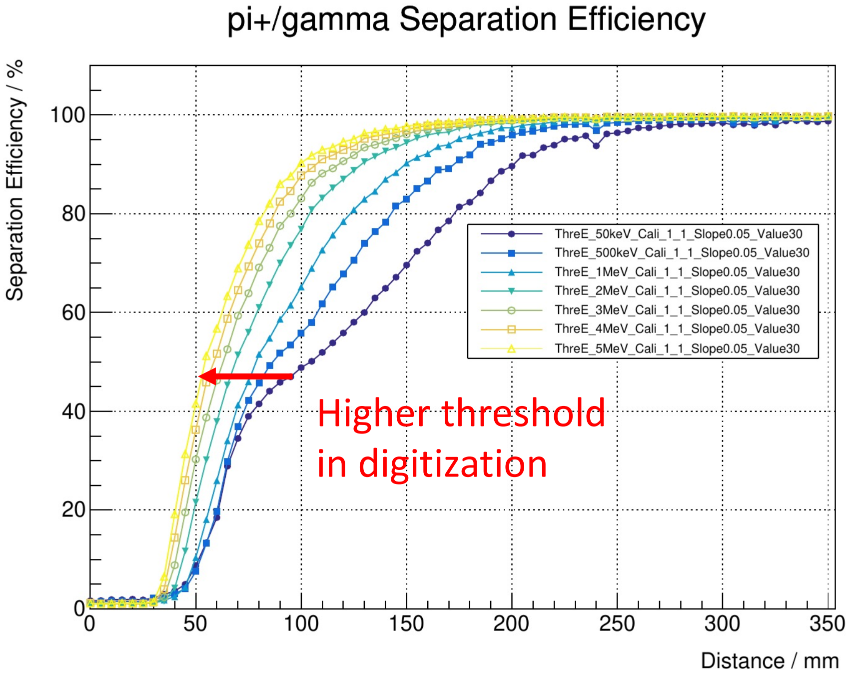


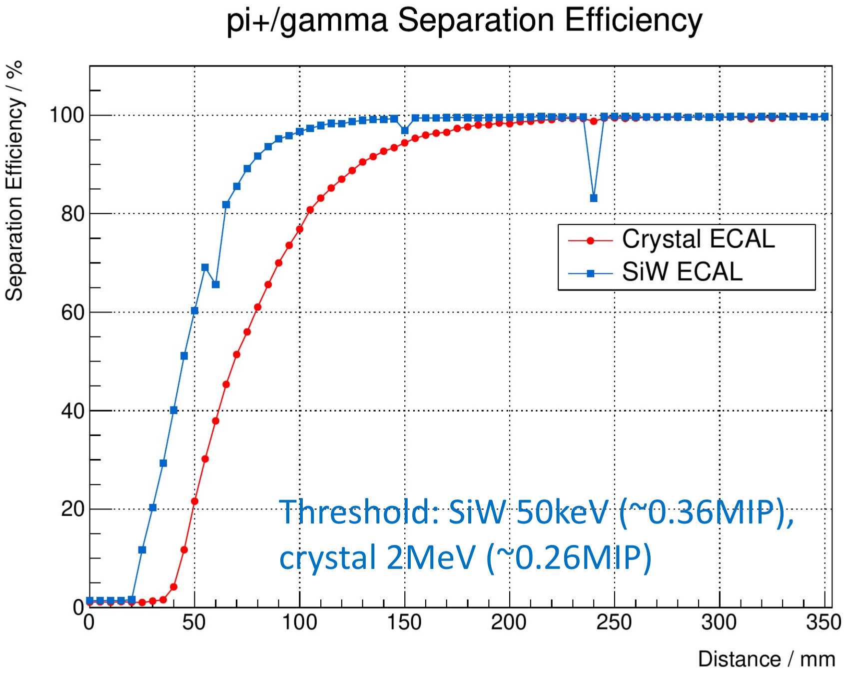
PFA performance with crystal ECAL

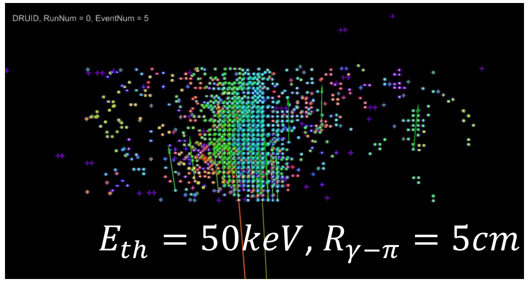
- $\gamma + \pi^+$ separation in ArborPFA: much more complex.
  - BGO vs. SiW: larger transverse spread (R_M) and longitudinal overlap probability (λ_I / X_0).
  - High threshold may lose hadronic shower fractions.
  - Parameter tuning in ArborPFA: cluster merging.

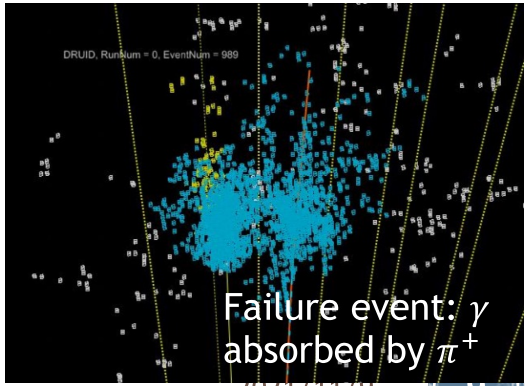


Particle gun event of 5GeV γ + 10GeV π^+.
Scan the angle(distance) between γ and π^+, check the successful reconstruction efficiency.



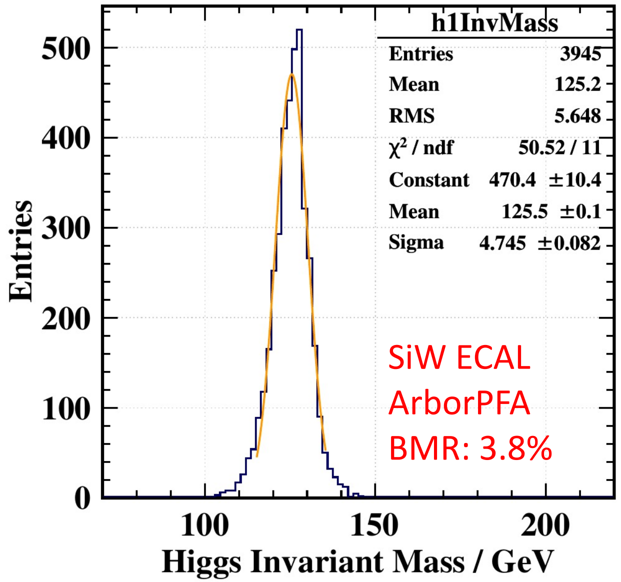


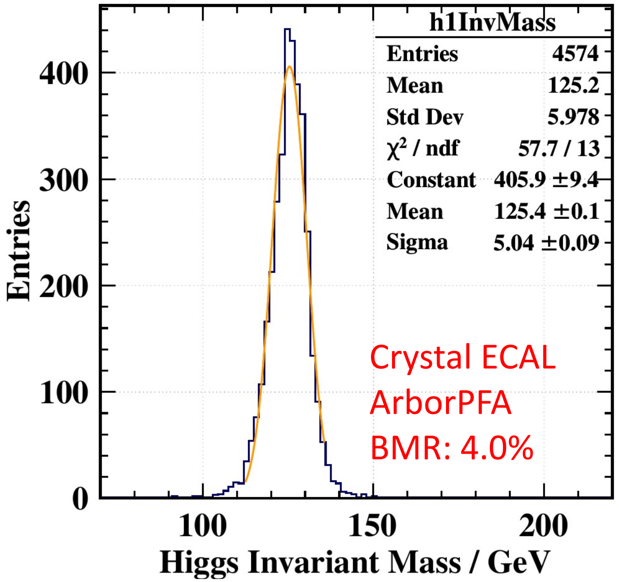


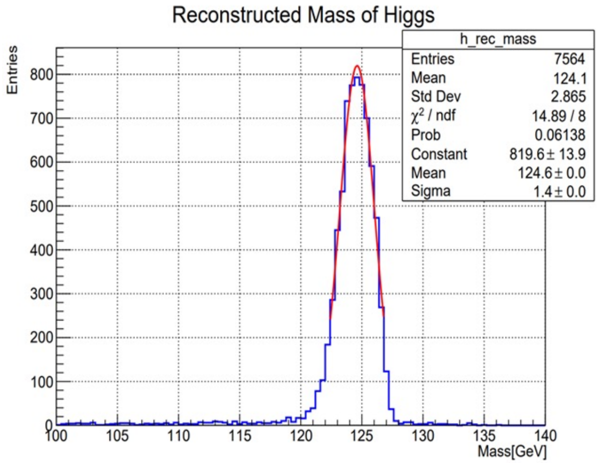


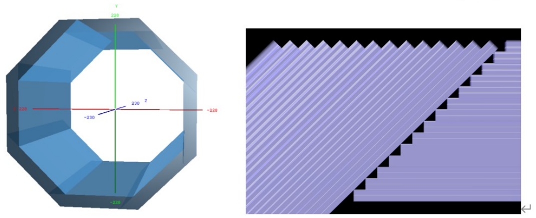
PFA performance with crystal ECAL

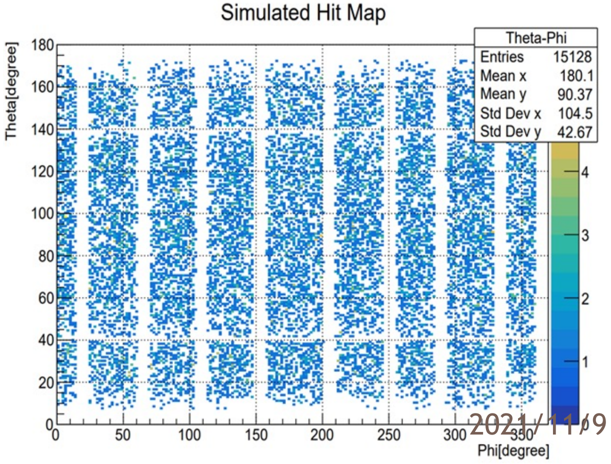
- Physics benchmark: full simulation of ZH process:
  - $e^+e^- \rightarrow ZH \rightarrow \nu\nu\gamma\gamma$ process @ 240GeV: BMR=1.1%
    - Compensation and correction in ECAL barrel gaps has not been finished in crystal ECAL, hits near gaps are excluded.
  - $e^+e^- \rightarrow ZH \rightarrow \nu\nu gg$ di-jet process @ 240GeV:
    - Tuned the parameters in ArborPFA: digitization threshold, bush-connect parameters, etc.
    - Get significant improvement from 4.5% @Yangzhou to present 4.0%, get closer to SiW result 3.8%.











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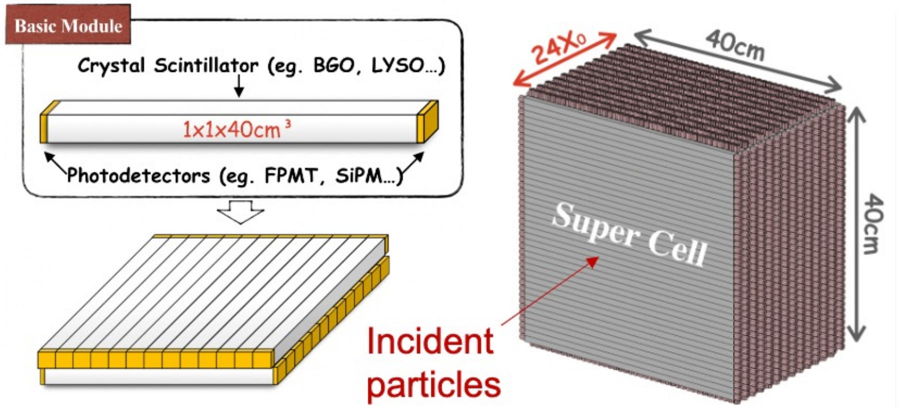
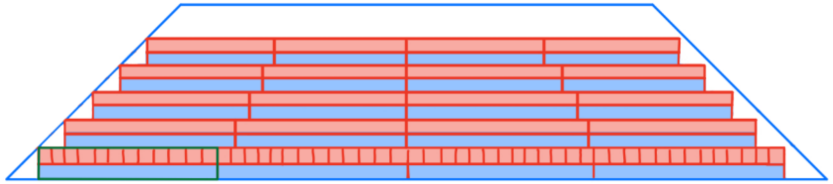
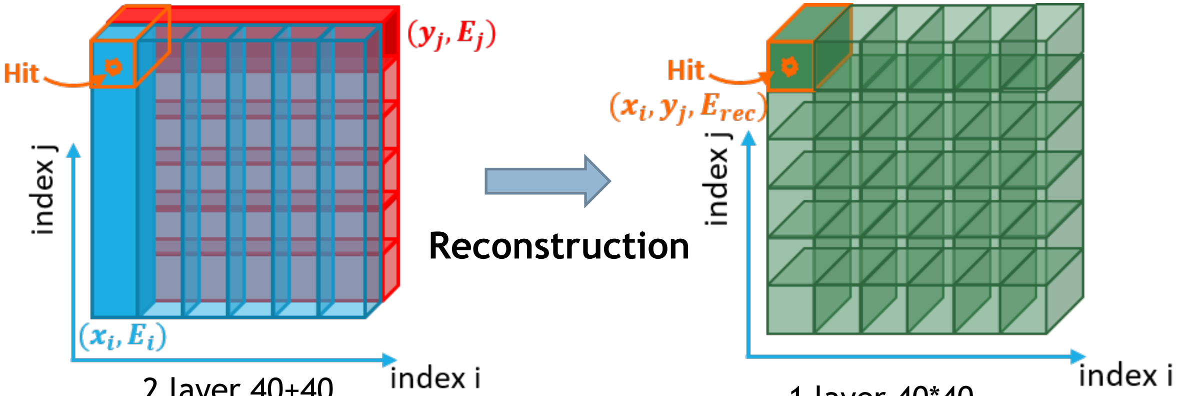
Proto-PFA for crystal bar ECAL

- Crystal Bar ECAL design: more tracker-like structure.
  - Less #channels and materials in ECAL.
  - Ambiguity problem from 2D measurement (ghost hit)
  - Identification of energy deposits from particles (confusion)
- A special software for this ECAL design:
  - basic unit: double layer with crossed bars.
  - Combine 2 layers to mimic a high-granularity ECAL.
  - Use time + similar energy in adjacent layer for cross-location.

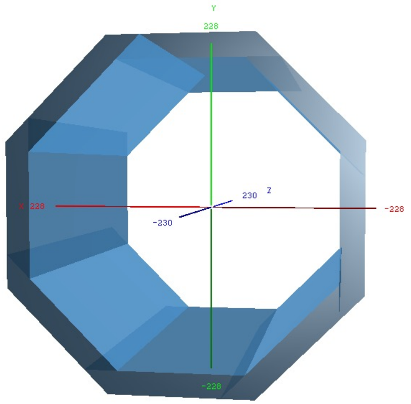






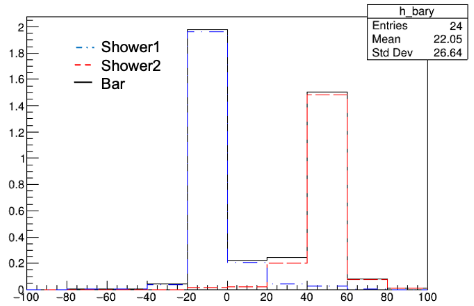
2 layer 40+40
$1\times1\times40\ cm^3$
crystal bars

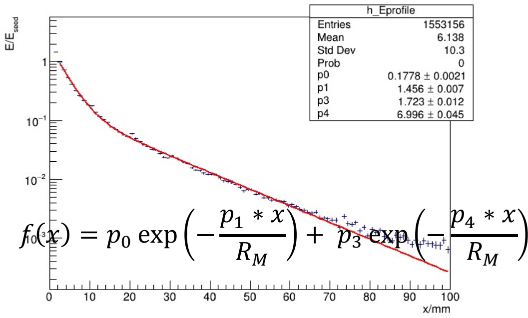
1 layer 40*40
1*1*2 cm^3 cells

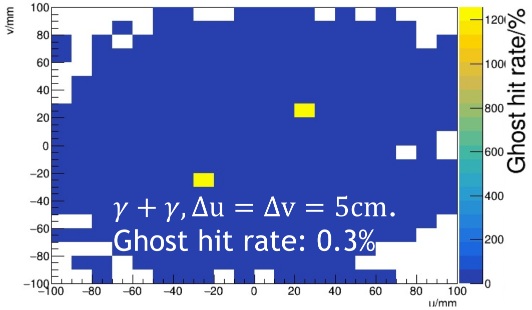


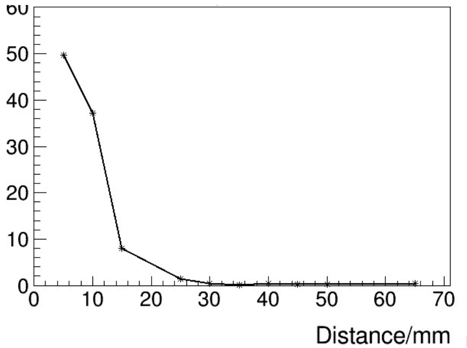
Proto-PFA for crystal bar ECAL

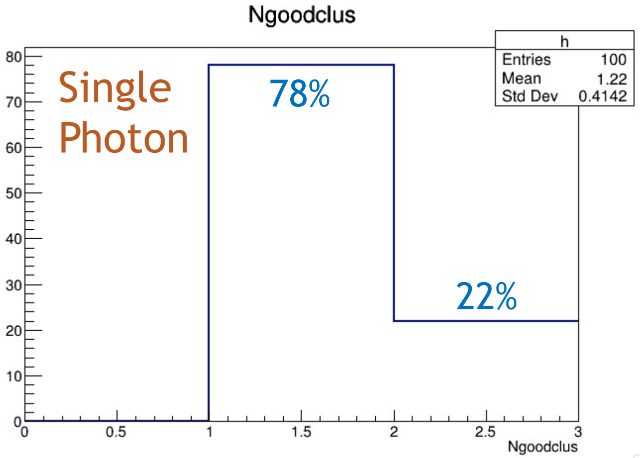
- Reconstruction flow:
  - 1D: clustering and energy splitting.
    - Cluster the neighbor fired bars.
    - Use EM shower profile to split two nearby showers.
  - 2D: Energy + time matching in 2 adjacent layers for ghost hit removal
    - Define a χ^2 with both energy and timing info.
    - Reject the wrong combination with χ^2.
  - 3D: Cluster ID + cone clustering.
    - Use lateral moment $LAT = \frac{\sum_{i=3}^{N} E_i r_i^2}{\sum_{i=3}^{N} E_i r_i^2 + E_1 r_0^2 + E_2 r_0^2}$ for cluster ID
    - longitudinally cone clustering for MIP/EM/Hadronic showers.
  - WIP: cluster merging, track-cluster matching, etc.





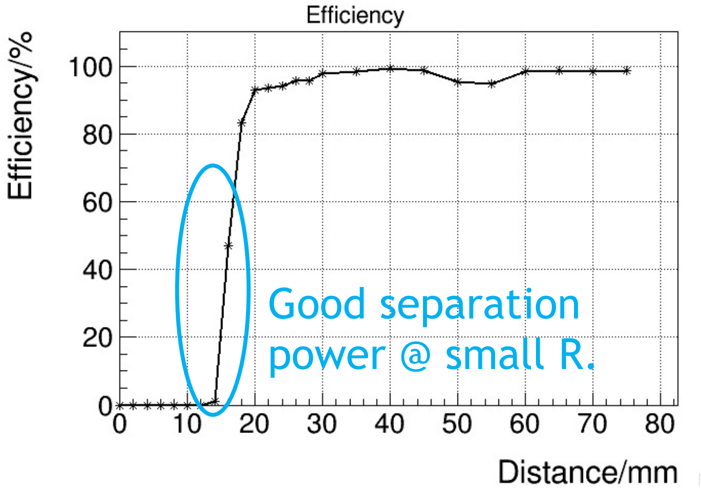


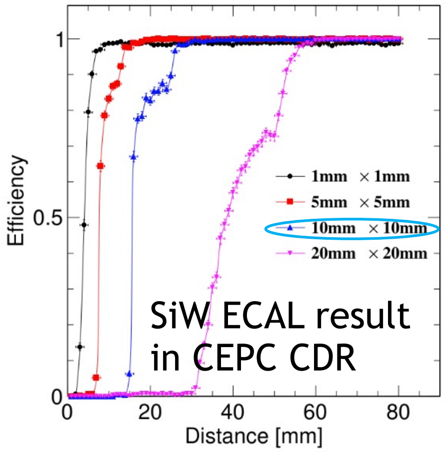


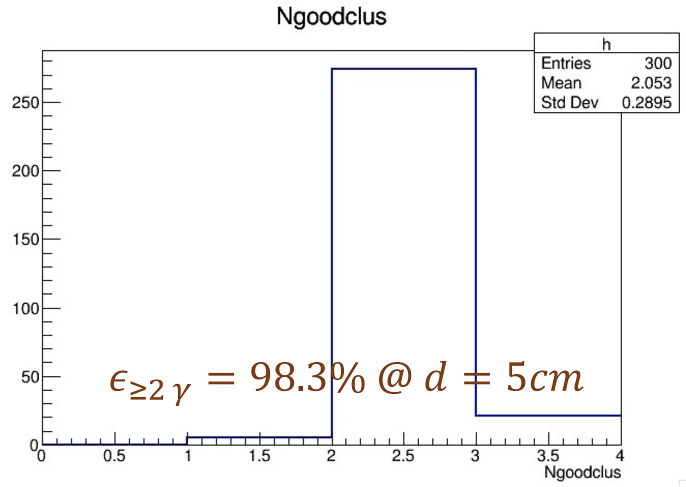


Proto-PFA for crystal bar ECAL

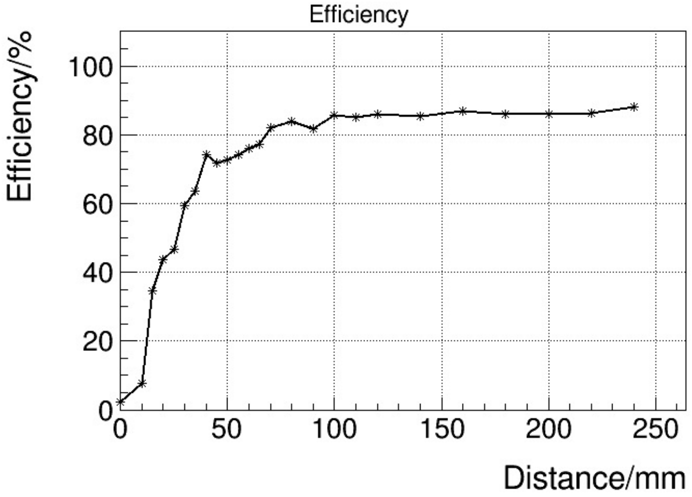
- Separation: very preliminary result.
  - Diphoton separation: two 5GeV photons

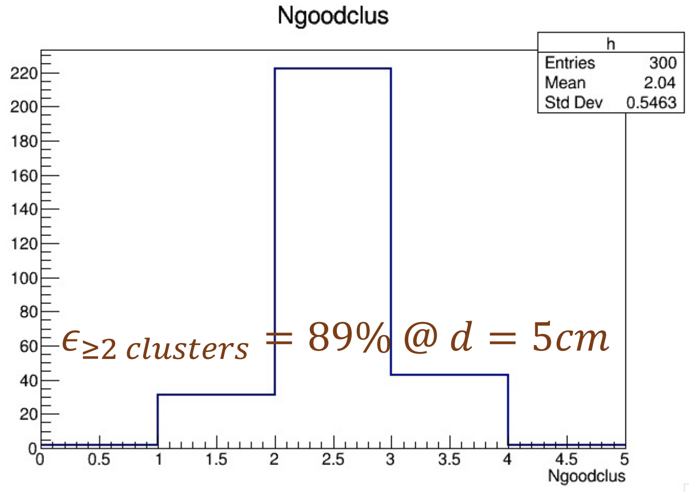






  - $\gamma + \pi^-$ separation: 5GeV γ + 10 GeV π^-. WIP.





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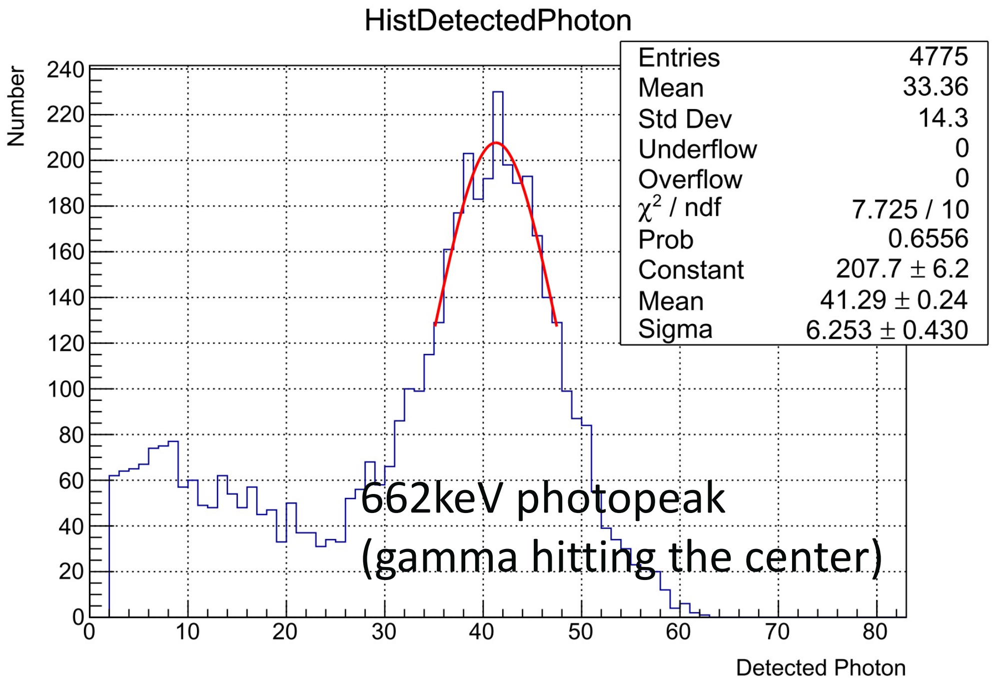
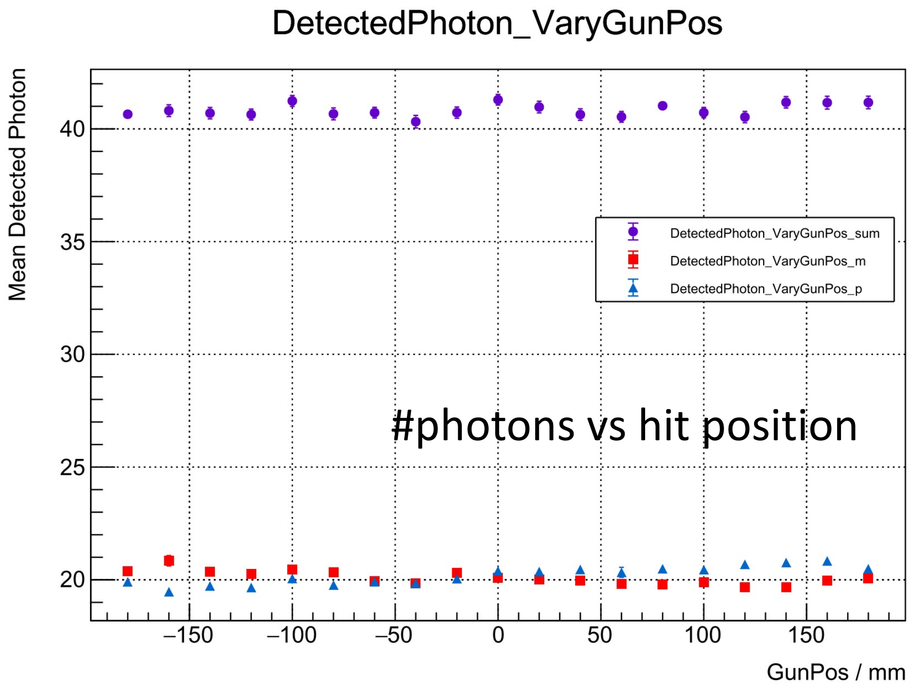
Crystal uniformity measurement

- BGO response simulation with Geant4 10.7:
  - 400mm BGO crystal bar, transverse 1cm^2
  - 662keV gamma from Cs-137
  - Varying Cs-137 position.
  - fit 662keV photon peak to get #photons

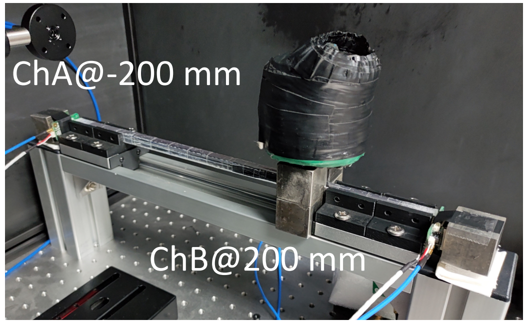


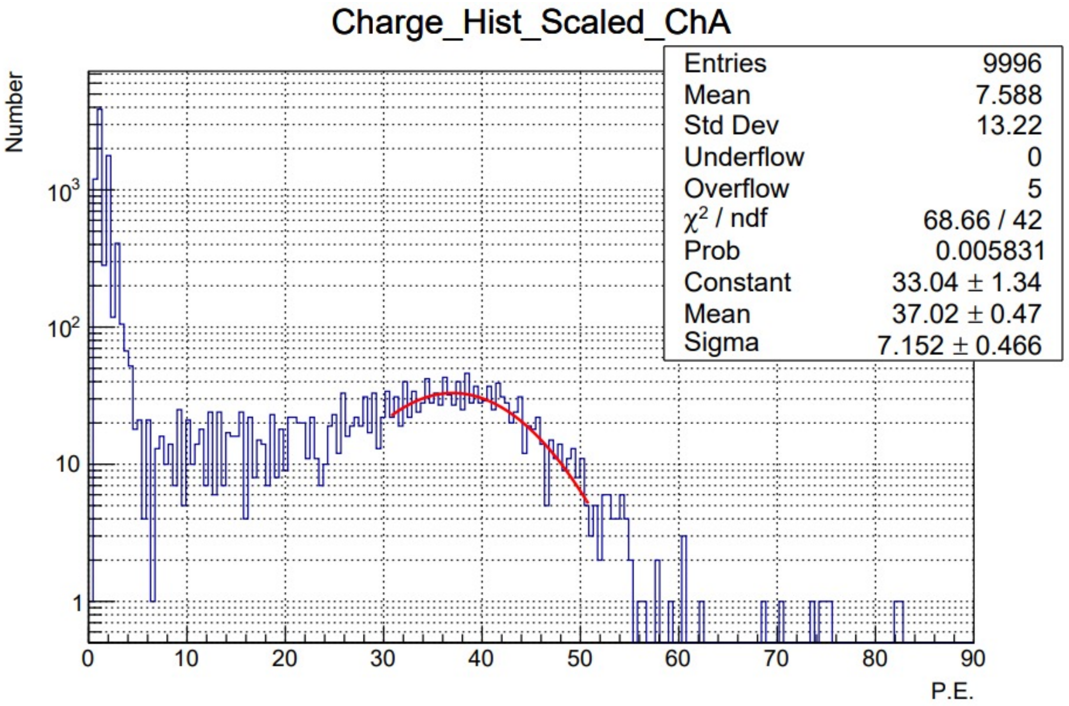


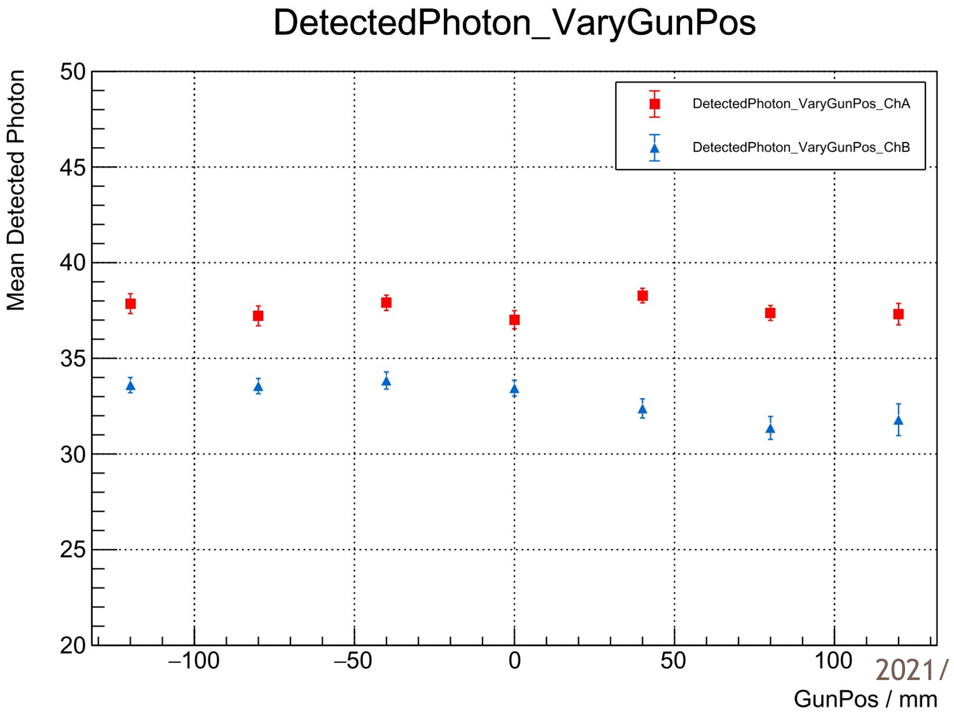
- Generally good response uniformity expected in G4 simulation.

Crystal uniformity measurement

- BGO response in lab:
  - Setup: 400mm long BGO crystal (with ESR foil) and Cs-137 source.
  - The same configuration as the simulation.
  - Trends are not significant enough due to the systematic difference between 2 SiPMs.
  - Work plan: to use optical grease to improve the crystal-SiPM coupling and reproducibility

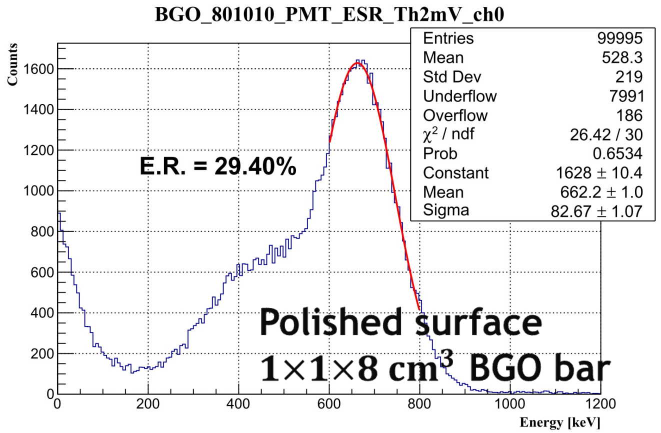


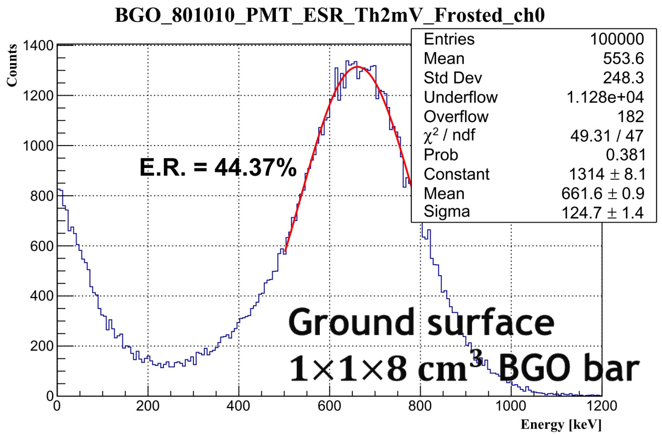


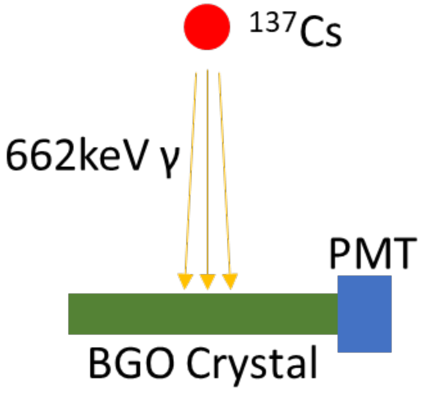


Crystal response in Lab

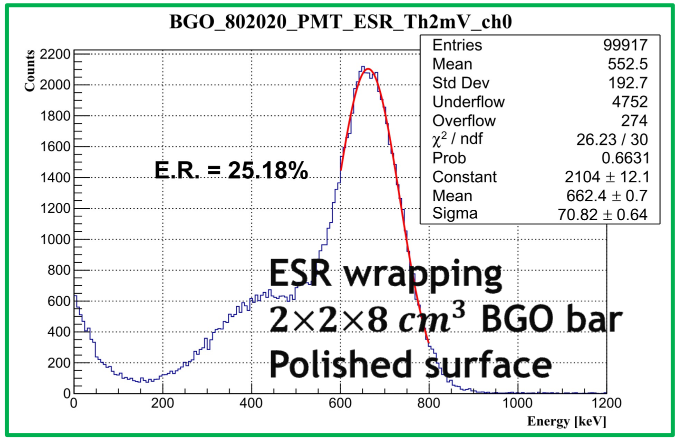
- Photon energy resolution with impacts of:
  - Surfaces: polished/ground.

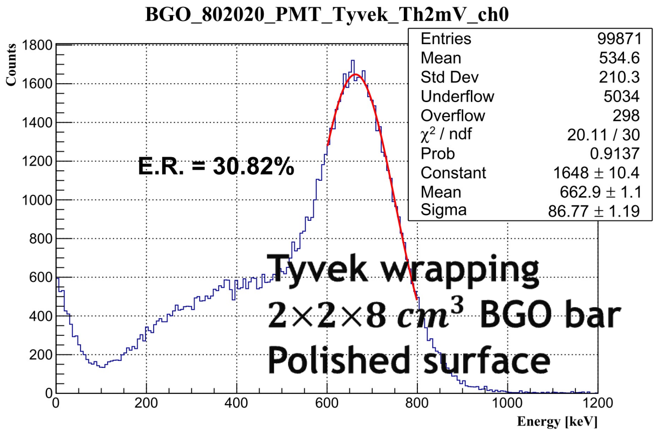


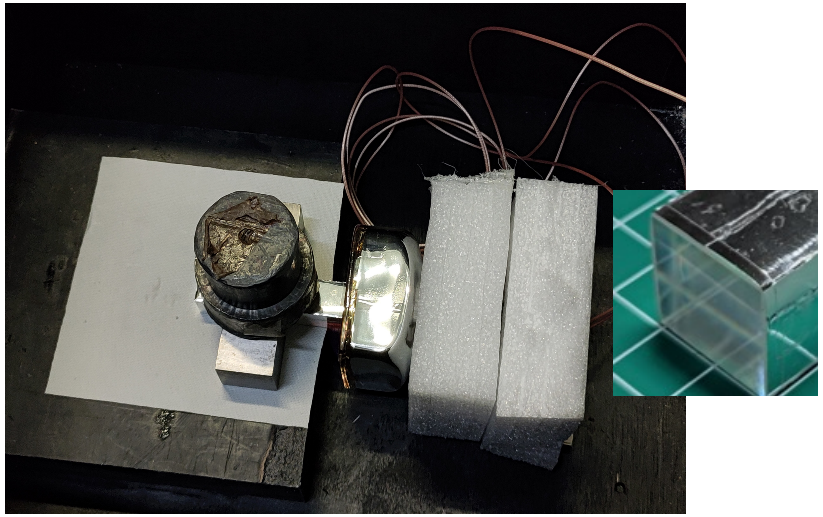




  - Wrapping: ESR/Tyvek.



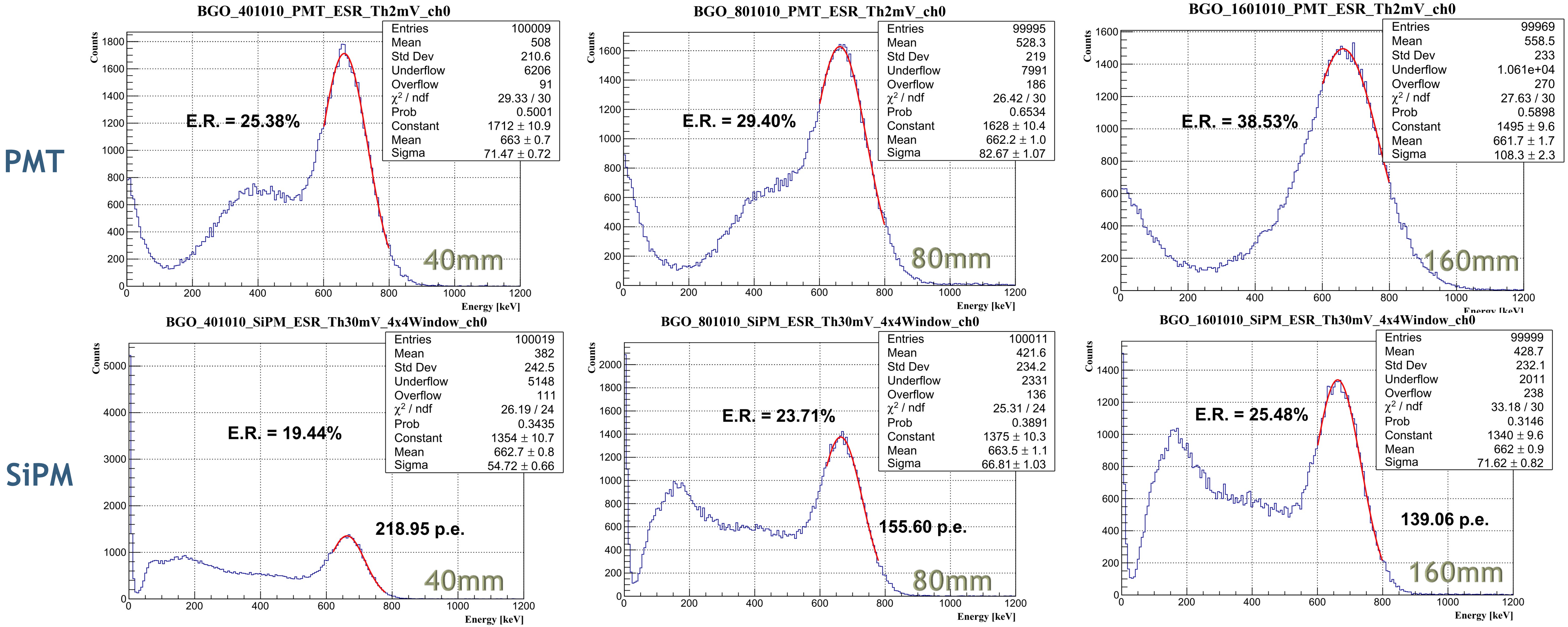




Energy Resolution (E.R.) = $2.355 \times \frac{\sigma}{mean}$, defined as FWHM

Crystal response in Lab

- Photon energy resolution with impacts of crystal length and photosensitive device



- PMT has better acceptance (full coverage of crystal transverse area) than SiPM, to be updated with larger SiPMs
- Further comparisons will be done with simulation

Summary

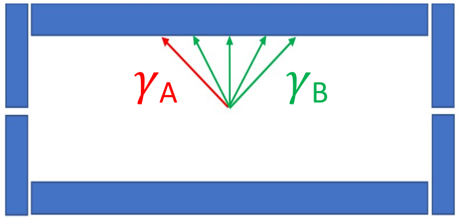
- Steady progress to address key issues.
- Performance studies with crystals using Arbor-PFA:
  - Separation power of close-by particles.
  - Performance studies with Higgs events: closer to SiW.
- Developing a new proto-PFA software for crystal ECAL:
  - Traditional PFA: fine granularity + small R_M + less hits (sampling) for separation.
  - Crystal PFA: precise energy (homogeneous) + shower profile for separation.
  - Key issue: ghost hit and confusion problem can be solved. Preliminary result is promising.
  - Many details still need optimization.
- Technical developments:
  - Good uniformity with long crystal bar, and experiment can match Geant4 simulation.
  - BGO crystal shows better than 20% energy resolution to 662keV photons.

Backup

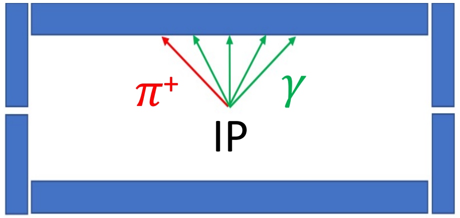
PFA performance with crystal ECAL

- $\gamma + \gamma$ separation criteria:
  - 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

Sketch of ECAL in r-z plane



- $\gamma + \pi^+$ separation criteria:
  - 10GeV π+ and 5GeV γ: varying distance
  - 3 T magnetic field
  - π+ momentum measured by tracker
  - Efficiency definition: successful reconstruction of 3.3GeV<EN<6.6GeV, 9.9GeV<EC<10.1GeV
  - Removed events with γ/π+ interactions before entering ECAL
  - Applied energy calibration

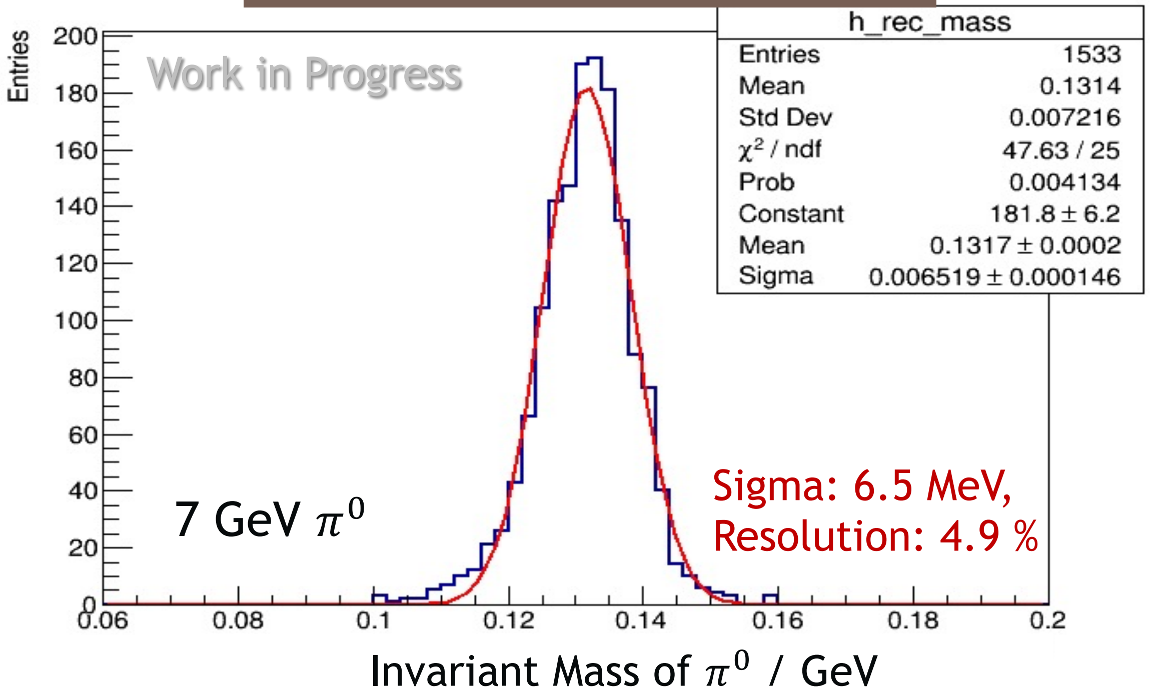


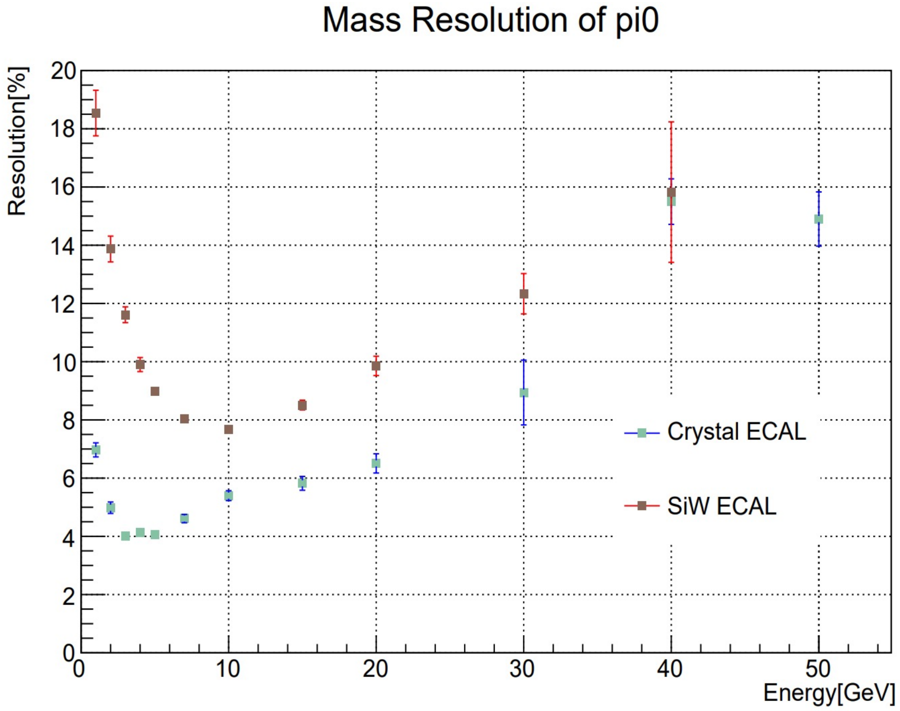
Performance studies: neutral pions with Arbor-PFA

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

Zhiyu Zhao (IHEP/SJTU)

Detector with Crystal ECAL option



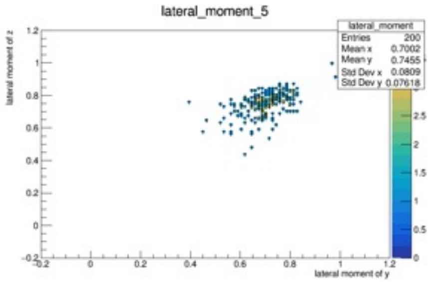


Reconstruction: 3D

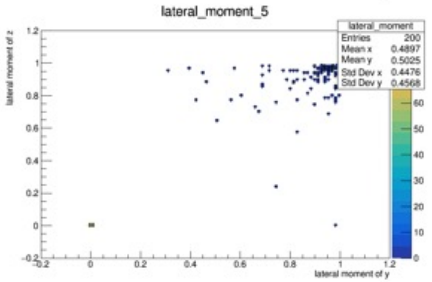
- Longitudinal linking for 3D cluster:
  - Cone-based clustering algorithm.
  - Get the very preliminary 3D structure, identify the cluster (MIP/EM/Hadron) with lateral moment: $LAT = \frac{\sum_{i=3}^{N} E_i r_i^2}{\sum_{i=3}^{N} E_i r_i^2 + E_1 r_0^2 + E_2 r_0^2}$
    - MIP: $\sqrt{LAT_X^2 + LAT_Y^2} < 0.05$
    - EM: $0.05 < \sqrt{LAT_X^2 + LAT_Y^2} < 0.12$
    - Had: $\sqrt{LAT_X^2 + LAT_Y^2} > 0.12$

Truth 10GeV \ PID	MIP	EM	Had
MIP	0.975	0.01	0
EM	0	0.99	0.01
Had	0.44	0.1	0.275

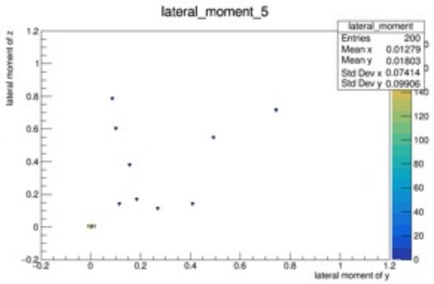
EM



Had



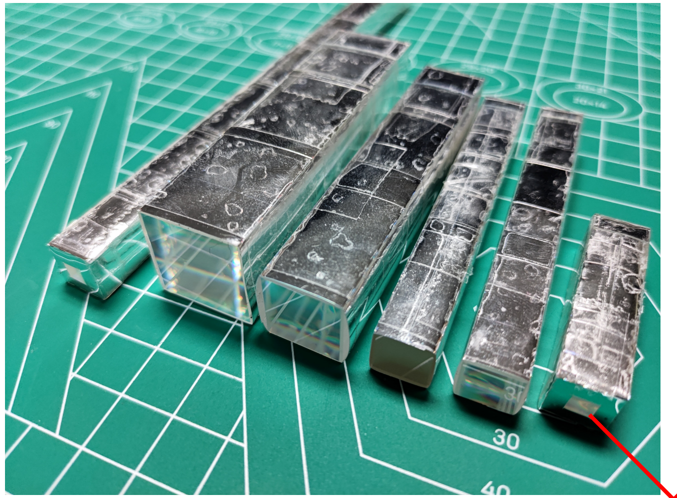
MIP

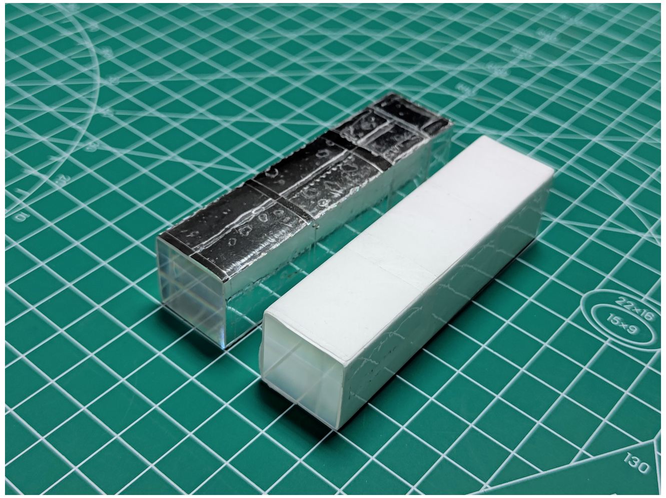


Measurements of the BGO energy resolution: setup

BGO Crystal:

- Lengths: 40/80/160mm
- Widths: 20/15/10mm
- Surfaces: polished/ground
- Tyvek / ESR wrapping





$4 \times 4mm^2$ window for SiPM readoout

Photosensitive Device:

- SiPM & PMT
- SiPM: S13360-3050CS
  - 50μm pitch, $3 \times 3mm^2$, 3600 pixels
- PMT: R11065
  - 76mm (3”), gain: 5×10^6