CEPC Crystal ECAL
Transverse Granularity Studies

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CEPC Day

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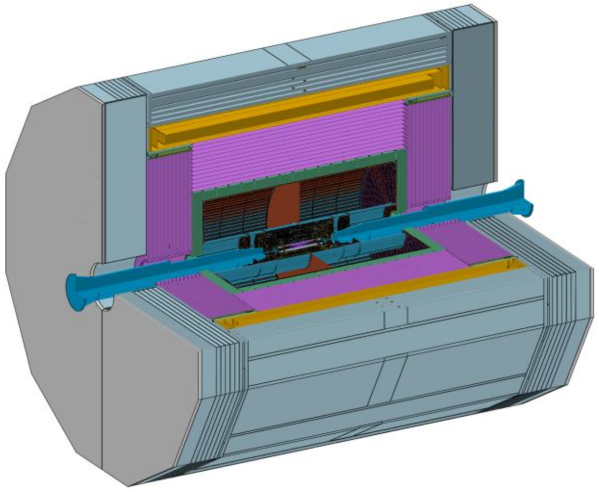
Overview: EM calorimeter in CEPC Ref-TDR

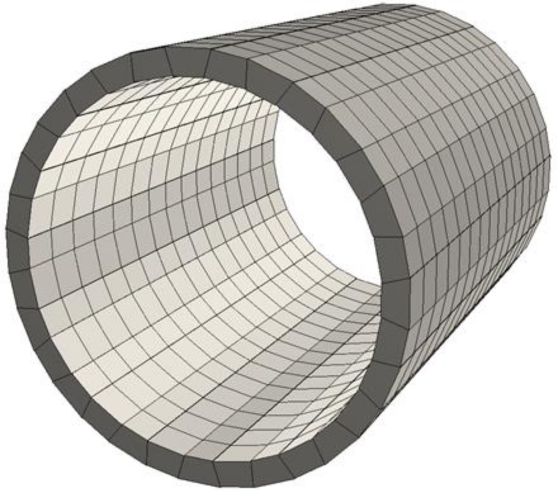
- Crystal calorimeter as the baseline ECAL design
  - To achieve an EM energy resolution better than 3% and be compatible with PFA
  - Long crystal bars: orthogonal arrangement in every two layers → fine segmentations and minimum insensitive materials in the longitudinal direction

CEPC Reference Detector



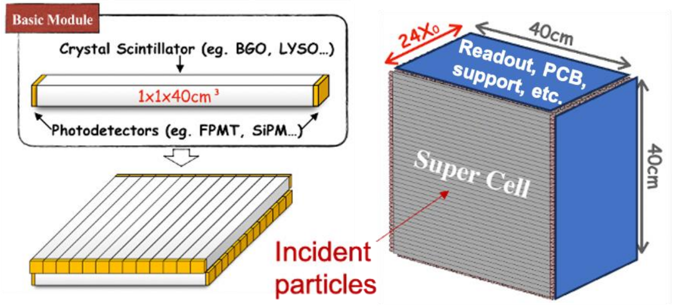
Depth: 24X0 with scintillating crystals (BGO/BSO)
Barrel ECAL: 5800 mm in length
Endcap ECAL: 4260 mm in outer diameter

Barrel ECAL schematics

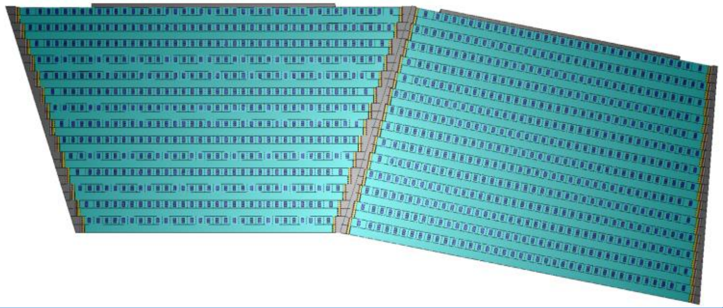


- **BGO bars in $1 \times 1 \times \sim 40\ \mathrm{cm}^3$**
- **Effective granularity $1 \times 1 \times 2\ \mathrm{cm}^3$**
- **Modules: avoid projectile cracks from IP**

Module schematics



Barrel modules: in trapezoid shapes



ECAL granularity optimisation: major motivations (1)

- The first IDRC review report in October 2024 (reminder)
  - ECAL part: suggestions focused on granularity optimisation and performance

Excerpted from the 2024 IDRC Review Report

- *"Design choices should be thoroughly justified by physics goals achieved with simulation of a full detector model. Alternative parameter choices should be considered and evaluated for physics outcomes. For example, ECal crystals of 1 cm (transverse) x 2 cm (depth) would reduce channel count and cost. Does it impact physics performance? "*
- *"Some specific performance issues that would be interesting to more fully understand. These include higher energy π^0 reconstruction, which may benefit, for example, from a staggered bar arrangement or finer granularity in the first few layers."*

ECAL granularity optimisation: major motivations (2)

- Crystal transverse granularity: $10 \times 10\ \mathrm{mm}^2$(*current design*) $\rightarrow$ $15 \times 15\ \mathrm{mm}^2$(*new*)
  - Significantly reduce the total readout channels
    - **Cost savings** in electronics (chips) and SiPMs; **reduction of power dissipation**
  - **Facilitate production and processing** of long crystal bars (~40cm)
  - Possible issue: more challenging in **pattern recognition** → separation power
    - Figures of Merit: Boson Mass Resolution (BMR), π^0 reconstruction performance

Crystal transverse granularity	$10 \times 10\ \mathrm{mm}^2$	$15 \times 15\ \mathrm{mm}^2$
Total Readout Channels	1.35 M	0.6 M
Unit Cost: SiPM and FEE per channel	78 CNY (63 CNY/SiPM, 15 CNY per FEE ch)	
Total cost of SiPMs and FEE	105 M CNY	47M CNY
Power consumption per channel	15 mW/ch (design target)	
Total power dissipation	20.3 kW	9.0 kW

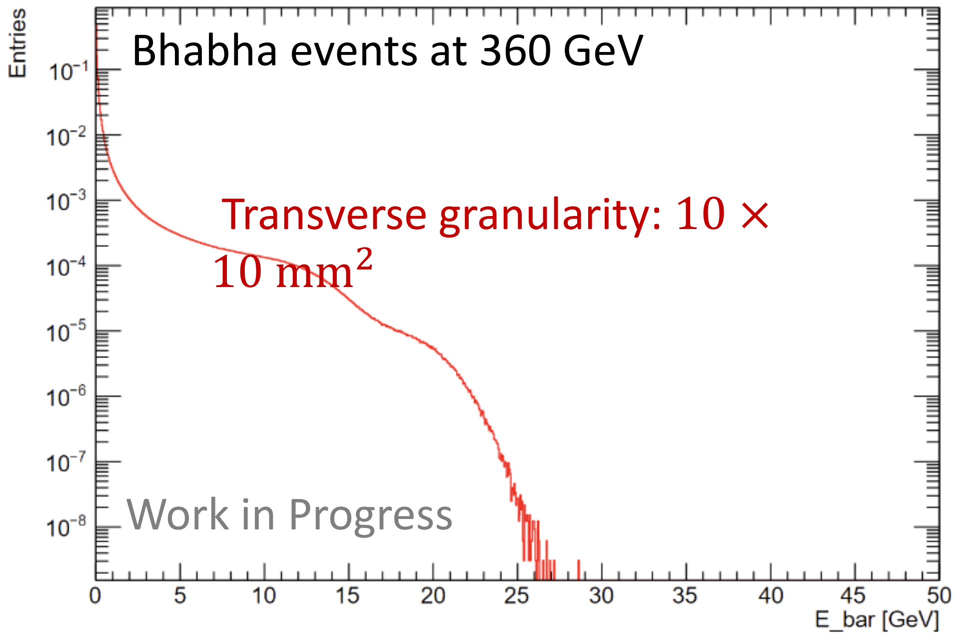
ECAL transverse granularity studies

- Preliminary results presented in this talk
  - Signal dynamic range
  - Single photon reconstruction
  - Two-particle separation power
  - Higgs hadronic decay: jet performance
  - π^0 reconstruction performance
- Planning
  - Beam-induced backgrounds at Higgs and Z-pole: updates for 15mm ECAL
    - Estimates of occupancy and hit rate; radiation damages (TID, NIEL)
  - Joint efforts of software/physics teams: further flavour physics studies

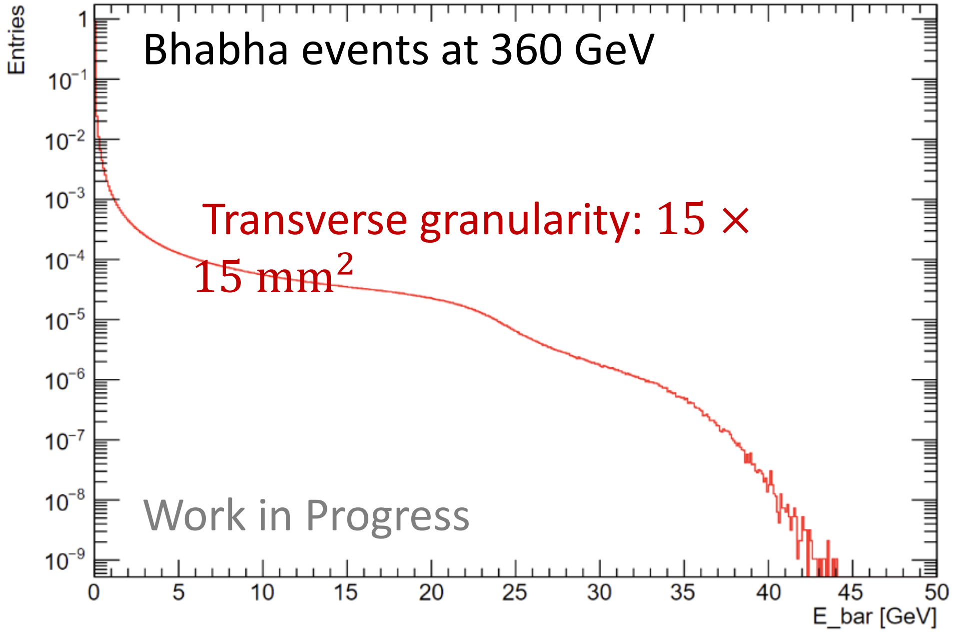
ECAL dynamic range: Bhabha at 360 GeV

- Bhabha events will be used for ECAL energy calibration
  - Maximum energy deposition per crystal: ~30 GeV (10mm) vs. ~45 GeV (15mm)
  - Reminder: the fraction with max. energy deposition is extremely low ($\sim 10^{-8}$)

Energy Deposition per Crystal



Energy Deposition per Crystal

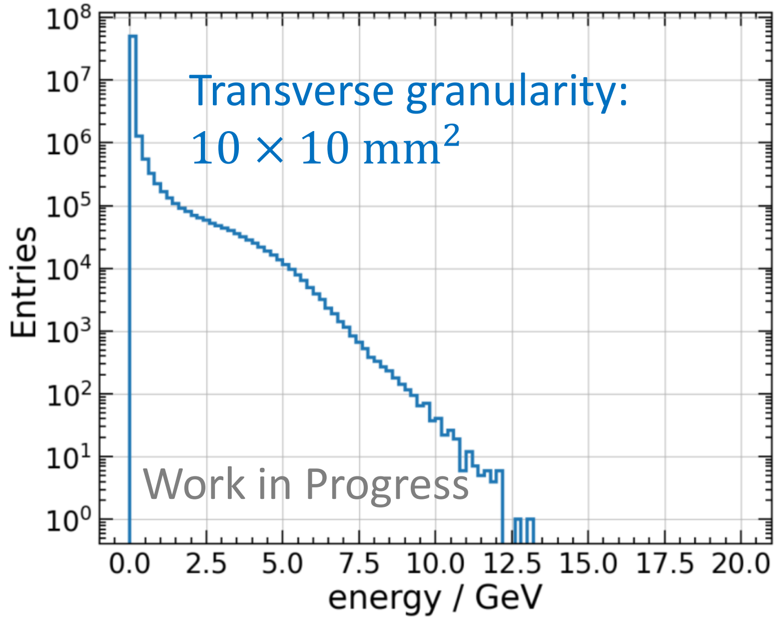


1 Million Events:
180 GeV electrons
($\theta = 30 \sim 60°$,
$\varphi = 0 \sim 360°$)

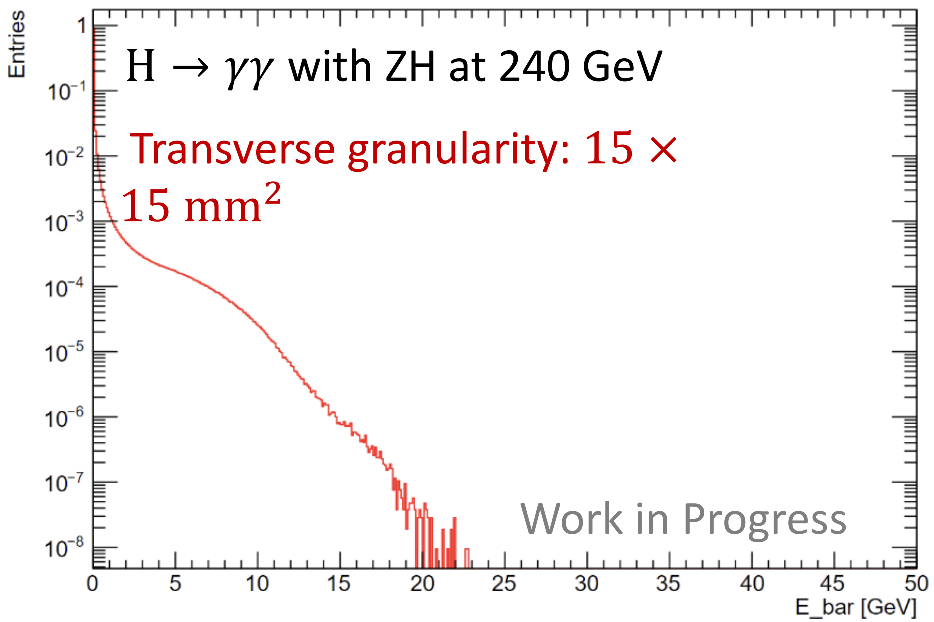
Signal dynamic range: Higgs at 240 GeV

- Higgs decaying to two photons: physics benchmark crucial for ECAL
  - $\mathrm{H} \rightarrow \gamma\gamma$ provides the highest possible photon energy
  - Maximum energy deposition per crystal: ~15 GeV (10mm) vs. ~25 GeV (15mm)
  - Reminder: the fraction with max. energy deposition is extremely low ($\sim 10^{-8}$)

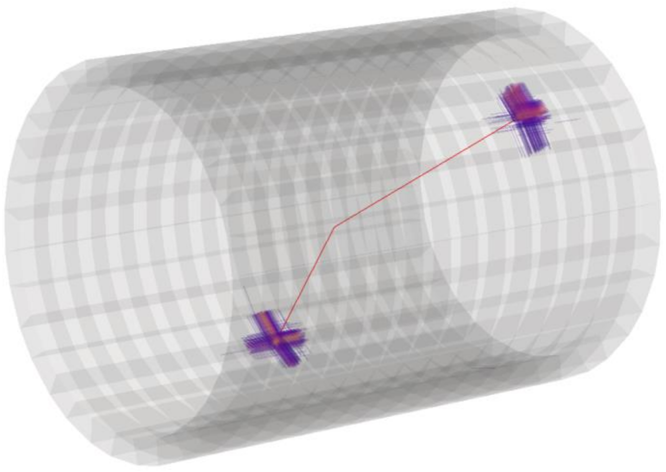
Energy Deposition per Crystal



Energy Deposition per Crystal



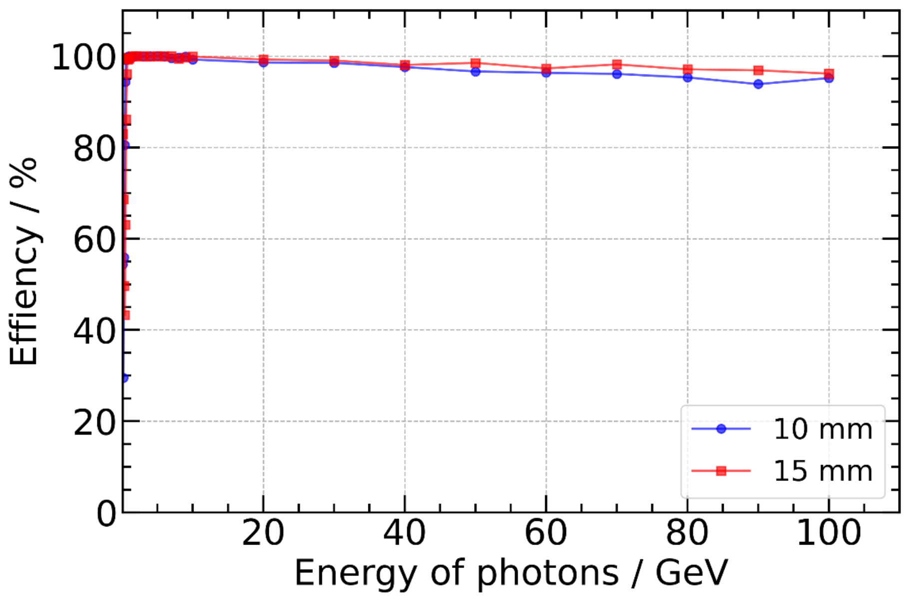
$\mathrm{H} \rightarrow \gamma\gamma$ Event Display



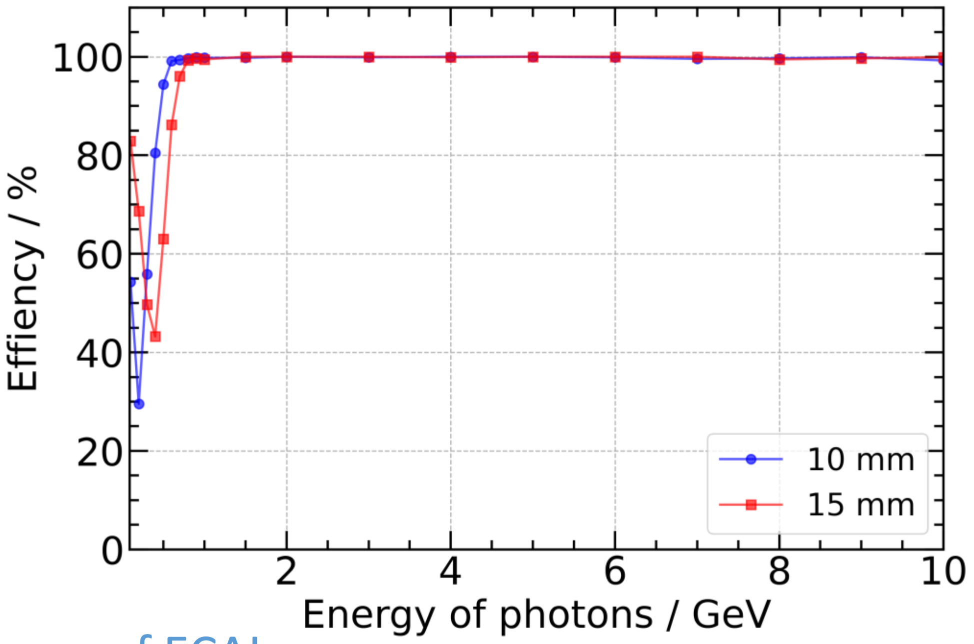
Photon reconstruction performance

- Performance comparison: $10 \times 10\ \mathrm{mm}^2$ vs. $15 \times 15\ \mathrm{mm}^2$
  - Single photons in a wide energy range: 0.1 – 100 GeV
  - Similar reconstruction efficiency with the ECAL granularity of 10mm and 15mm
    - 15mm: degraded efficiency in low energy region <1GeV

Reconstruction efficiency in 0.1 – 100 GeV



Reconstruction efficiency in 0.1 – 10 GeV



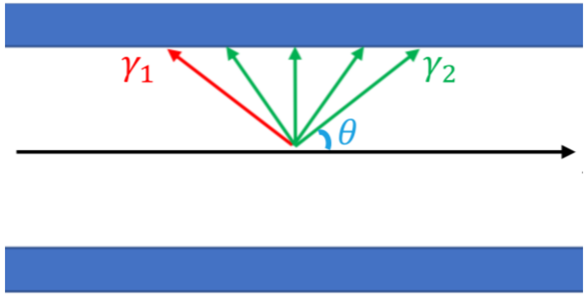
- $E_\gamma: 0.1 - 100GeV$
- $\theta = 91°, \phi = 0°$
- $N_{cluster} \geq 1$
- $|E_{cluster} - E_{truth}| < 5\sigma$

Excluded particles with interactions in upstream of ECAL

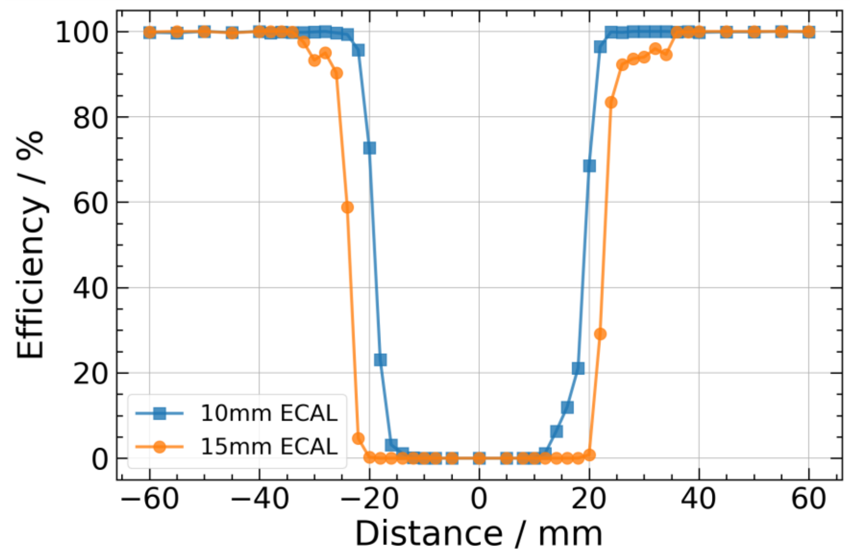
CyberPFA separation power: two photons

- Performance comparison: $10 \times 10\ \mathrm{mm}^2$ vs. $15 \times 15\ \mathrm{mm}^2$
  - Varying distance between two incident photons
  - 15 mm granularity shows slight degraded performance in separation efficiency and PFO resolution

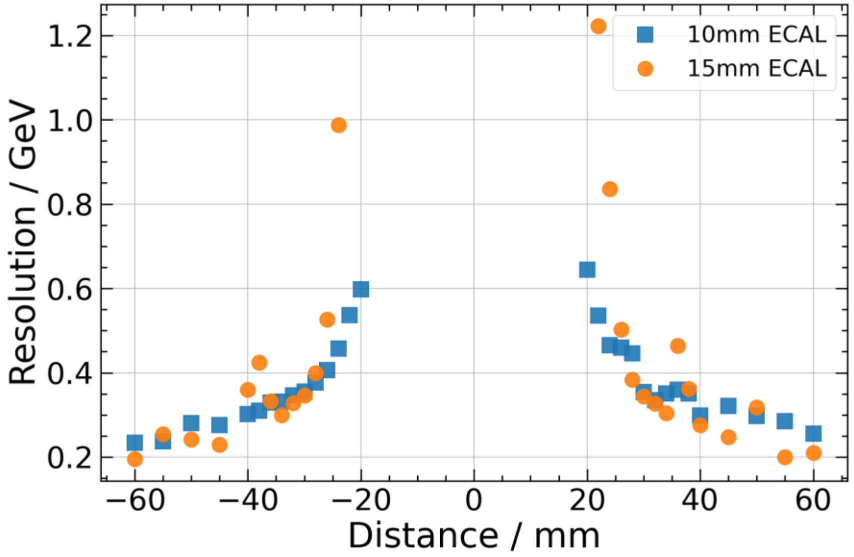
  → further performance evaluation with neutral pions



Separation Efficiency vs. Distance



PFO resolution vs. Distance

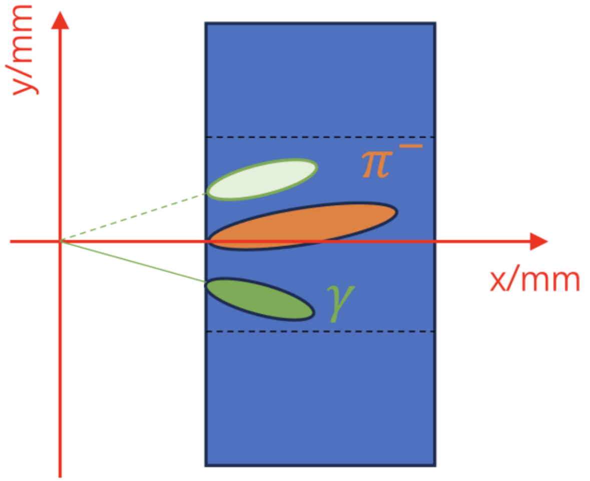


- Incident photons
  - $E_{\gamma 1} = E_{\gamma 2} = 5GeV$
- Success separation:
  - ≥2 PFOs
  - $|E_\gamma - E_{PFO}| < \frac{1}{3} E_\gamma$
  - $|\theta_\gamma - \theta_{PFO}| < 0.$ for 10mm; $|\theta_\gamma - \theta_{PFO}|$<0.45 for 15mm

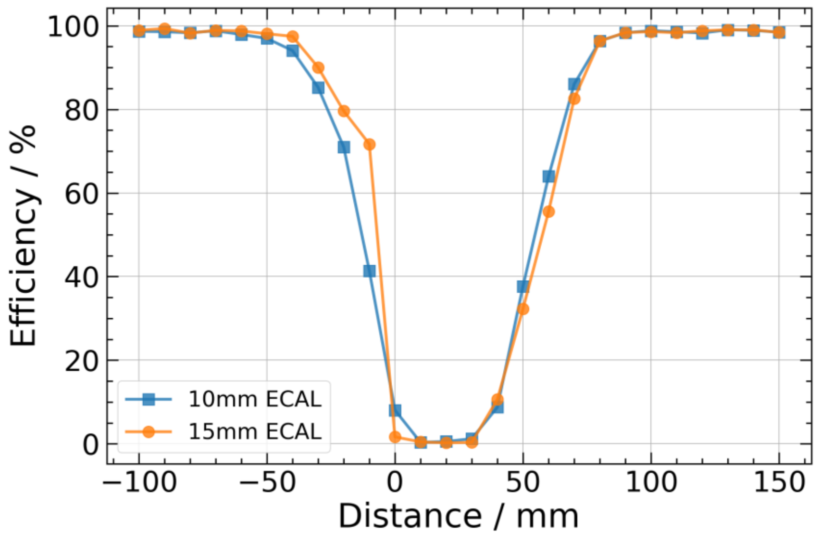
CyberPFA separation power: photon-pion

- Performance comparison: $10 \times 10\ \mathrm{mm}^2$ vs. $15 \times 15\ \mathrm{mm}^2$
  - Varying distance between the photon and charged pion
  - 15 mm granularity shows similar performance to 10mm granularity in separation efficiency and PFO resolution

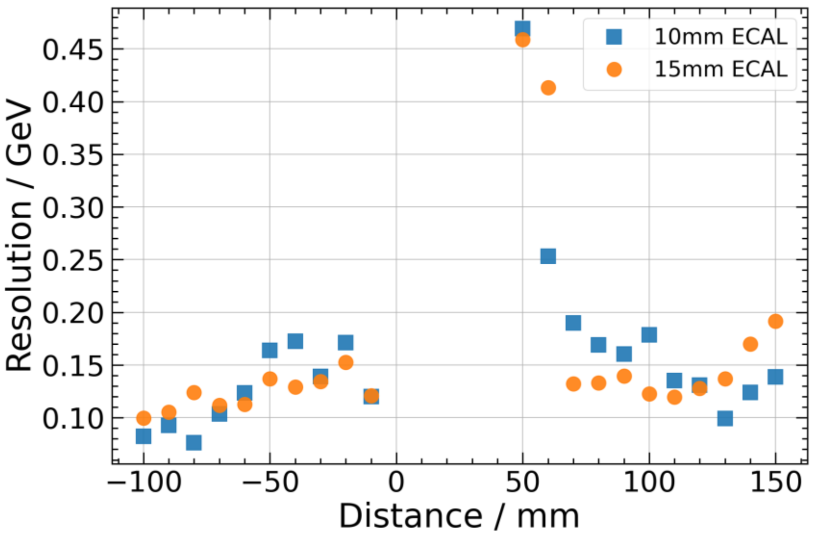
  → further performance evaluation with jets



Separation Efficiency vs. Distance



PFO resolution vs. Distance

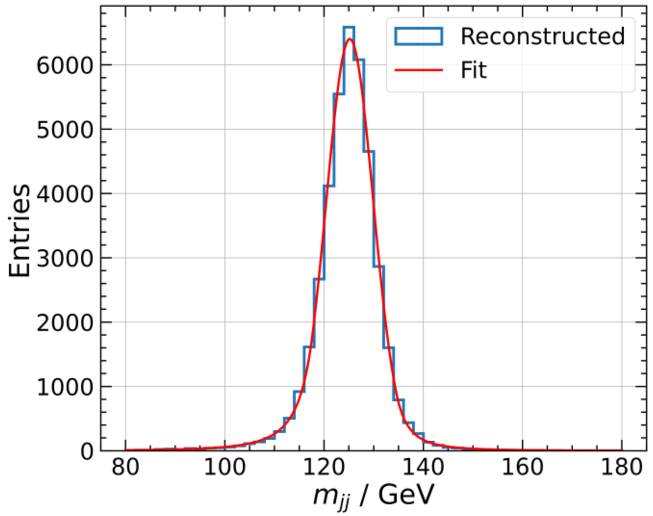


- $E_\gamma = E_{\pi^-} = 5GeV$
- Success separation:
  - 1 charged PFO, ≥1 neutral PFO
  - $|E_\gamma - E_{neutral\ PFO}| < \frac{1}{3} E_\gamma$
  - $|y_{gamma} - y_{PFO}| < 30mm$

Excluded particles with interactions in upstream of ECAL

Jet performance with CyberPFA

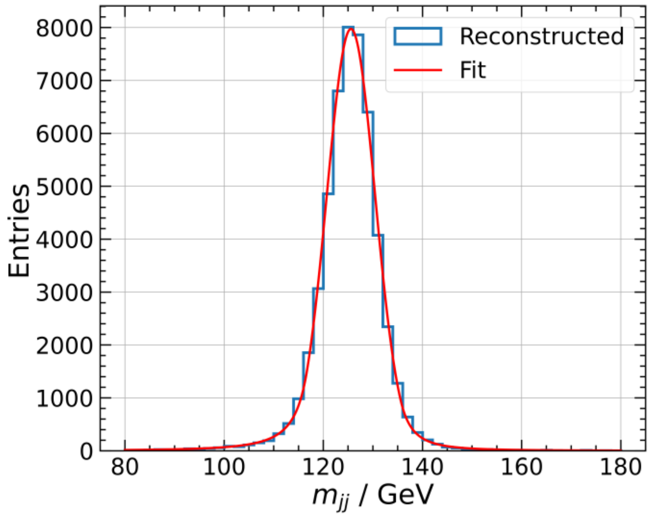
- Full detector reconstruction: Higgs decaying to two gluon jets
  - Vertexing and tracking, Crystal ECAL, Glass Scintillator HCAL
  - CyberPFA : dedicated tuning parameters related to ECAL granularity (10mm/15mm)
  - Similar BMR for Higgs hadronic decays: 3.82% (10mm) vs. 3.89% (15mm)



ECAL granularity of 10 mm

$\boldsymbol{m_{jj} = 124.6 \pm 4.8}$ **GeV**

BMR = $\mathbf{3.82 \pm 0.03\%}$



ECAL granularity of 15 mm

$\boldsymbol{m_{jj} = 125.0 \pm 4.9}$**GeV**

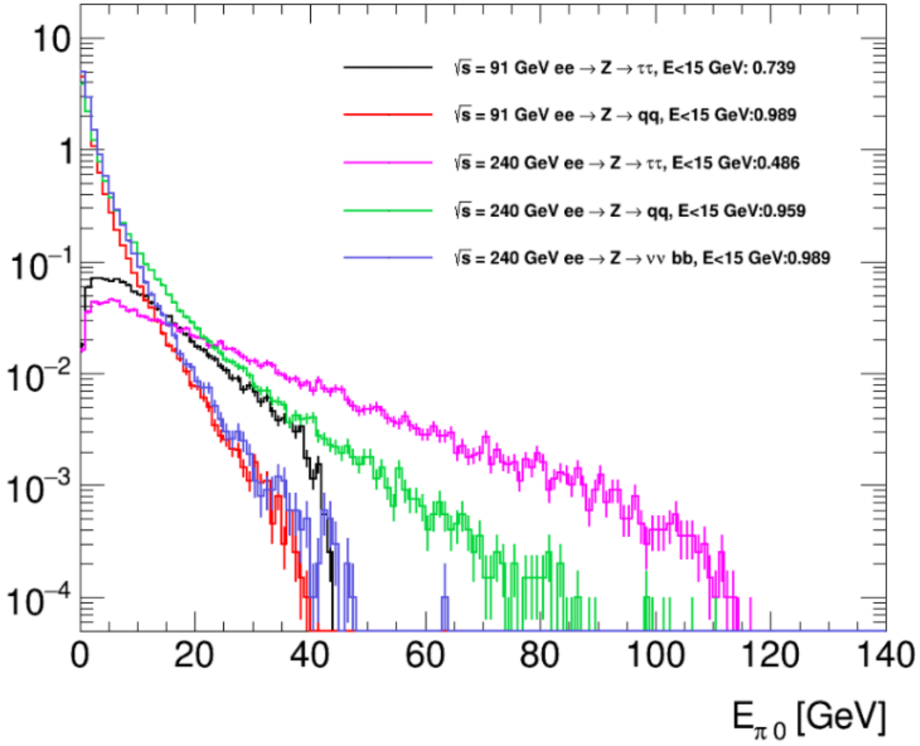
BMR = $\mathbf{3.89 \pm 0.02\%}$

- Track selection: a BDTG-based selection
- ECAL and HCAL: including digitisation for scintillator, SiPM and readout electronics
- ~200k events generated, ~50k selected for barrel only

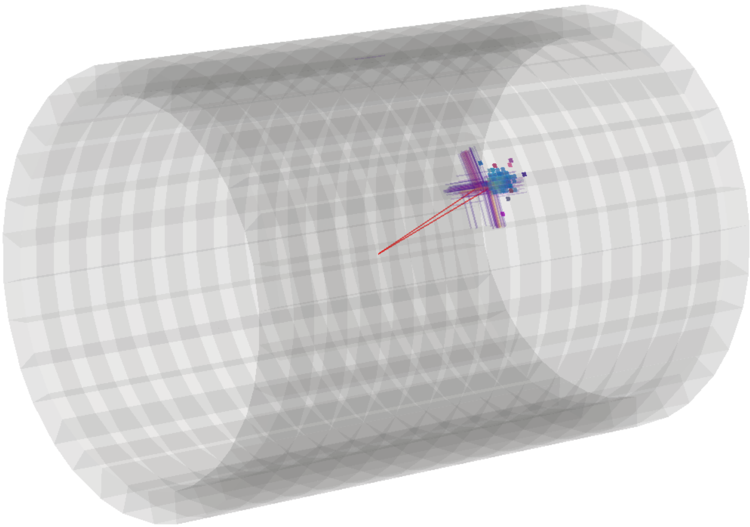
π^0 reconstruction and performance evaluation

- π^0 reconstruction in lower/higher energy regions
  - 1-20 GeV: evaluate π^0 reconstruction efficiency and mass resolution with CyberPFA
  - 20 – 80 GeV: discriminate γ/π^0 using EM shower profiles

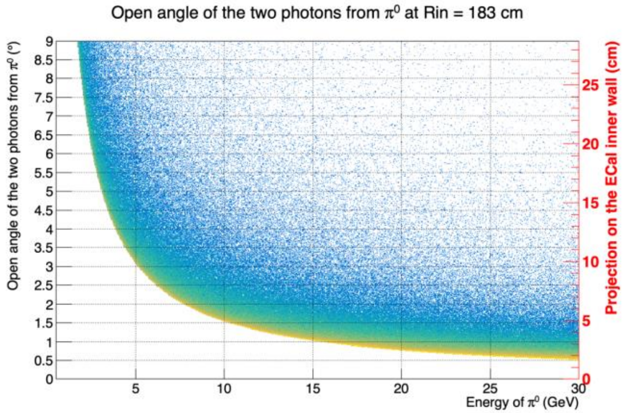
π^0 energy distributions in tau's and jets



(9 GeV) $\pi^0 \to \gamma\gamma$ Event Display



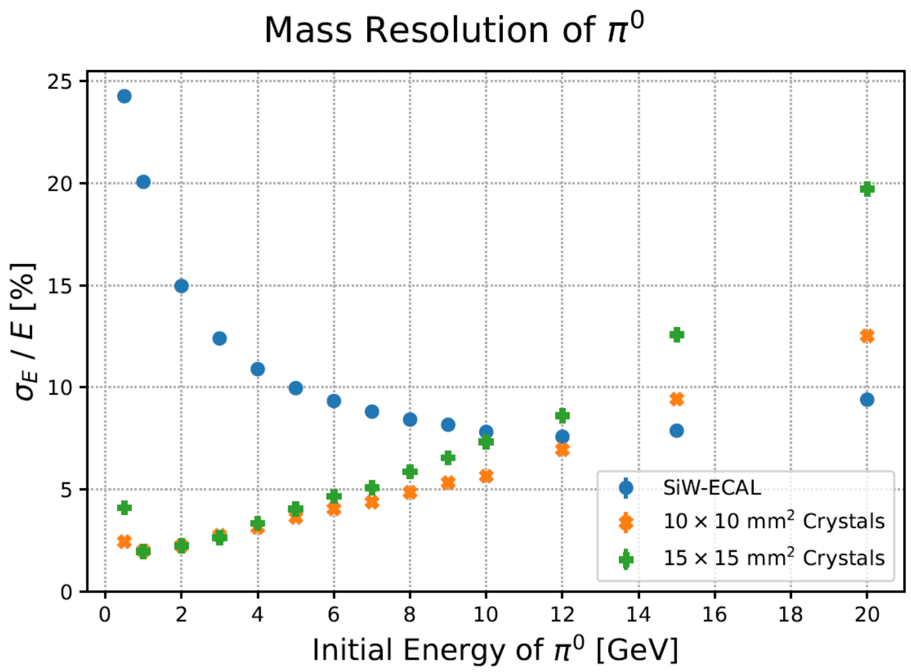
Open angles of photons in π^0

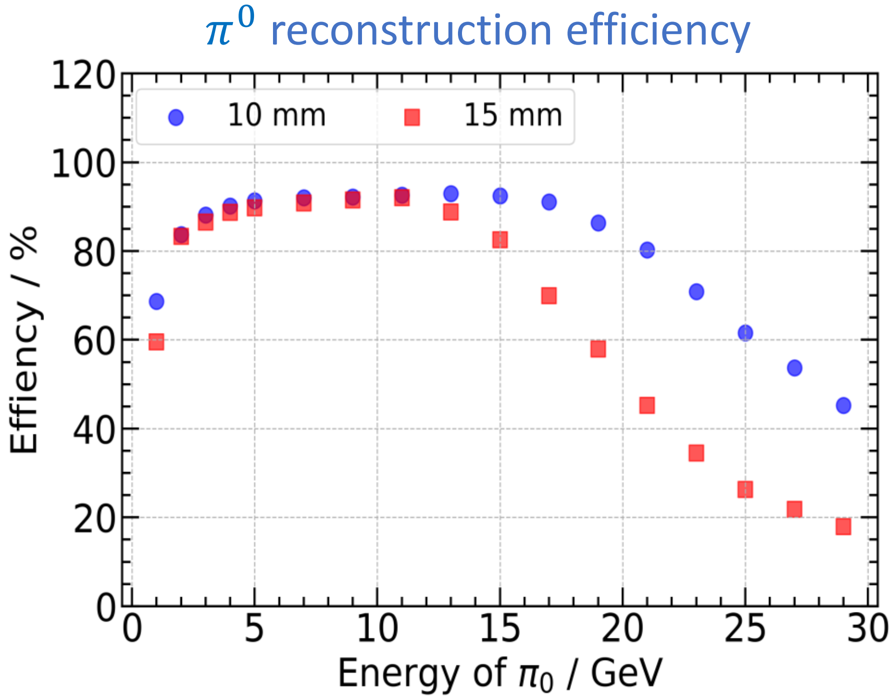


Z-pole: abundant π^0 in energy region < 45 GeV (from tau leptons and jets)

π^0 performance with CyberPFA

- Crystal ECAL: generally better π^0 mass resolution in <10 GeV than SiW-ECAL
- In 1–6 GeV, π^0 mass resolution degrades < 20% with $15 \times 15\ \mathrm{mm}^2$ crystals
- $15 \times 15\ \mathrm{mm}^2$: significant performance degrade in energy region >15 GeV
  - But still can use EM shower profiles to distinguish γ/π^0 (next page)





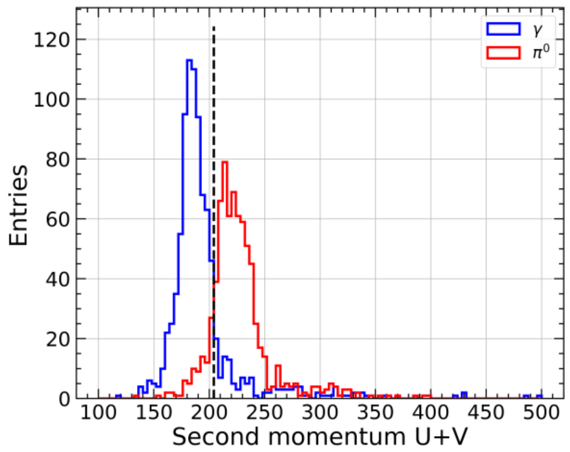
Photons from high-energy π^0 can not be well separated and thus will be reconstructed as only one cluster

γ/π^0 discrimination technique

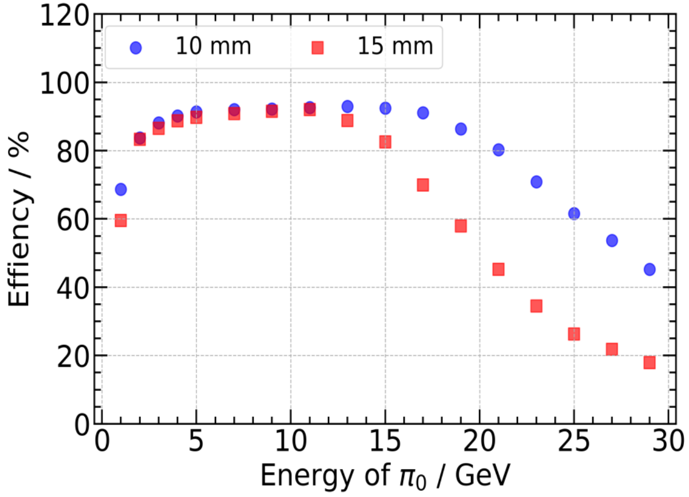
- Use EM transverse shower profiles to distinguish γ/π^0
  - Based on high-granularity features: promising performance in high energy region
  - Machine learning can further improve π^0 efficiency and reduce misidentification rate of γ as π^0 (successfully applied in CMS Crystal ECAL)

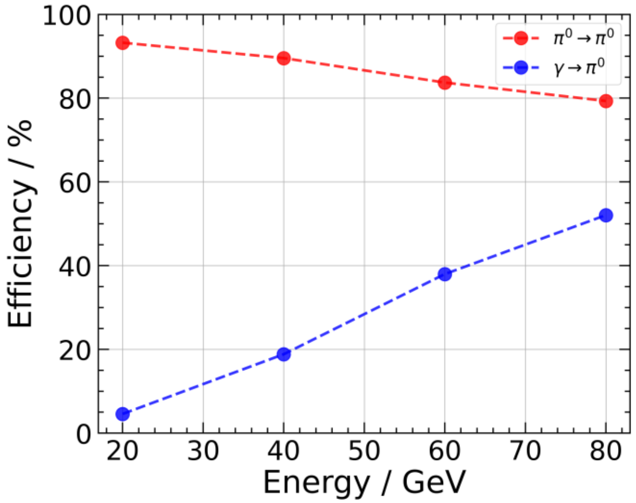
γ-π^0 separation with transverse profiles:

Second momentum $S = \frac{\sum(E_{hit} r_{hit}^2)}{\sum E_{hit}}$



Distribution of S of 40GeV γ and π^0





Second moment improves high-energy π^0 efficiency (work in progress)

Summary

- Crystal ECAL transverse granularity studies
  - Transverse granularity: $10 \times 10\ \mathrm{mm}^2$(*current design*) $\rightarrow$ $15 \times 15\ \mathrm{mm}^2$(*new*)
  - Advantages in significant savings in ECAL cost and power dissipation, also facilitation of crystal production/processing
  - Enormous efforts on the CyberPFA optimisations by the software team
  - Similar jet performance: BMR=3.8-3.9% for Higgs hadronic decays
  - π^0 performance is degraded in high energy with $15 \times 15\ \mathrm{mm}^2$, but can be improved by the γ/π^0 discrimination technique
  - Dynamic range requirement: ~50% increase of max. signals with $15 \times 15\ \mathrm{mm}^2$
- Planning
  - Beam-induced backgrounds at Higgs/Z-pole: updates for $15 \times 15\ \mathrm{mm}^2$ ECAL
  - Joint efforts of software/physics teams: further flavour physics studies

Summary and discussions

- Crystal ECAL transverse granularity studies
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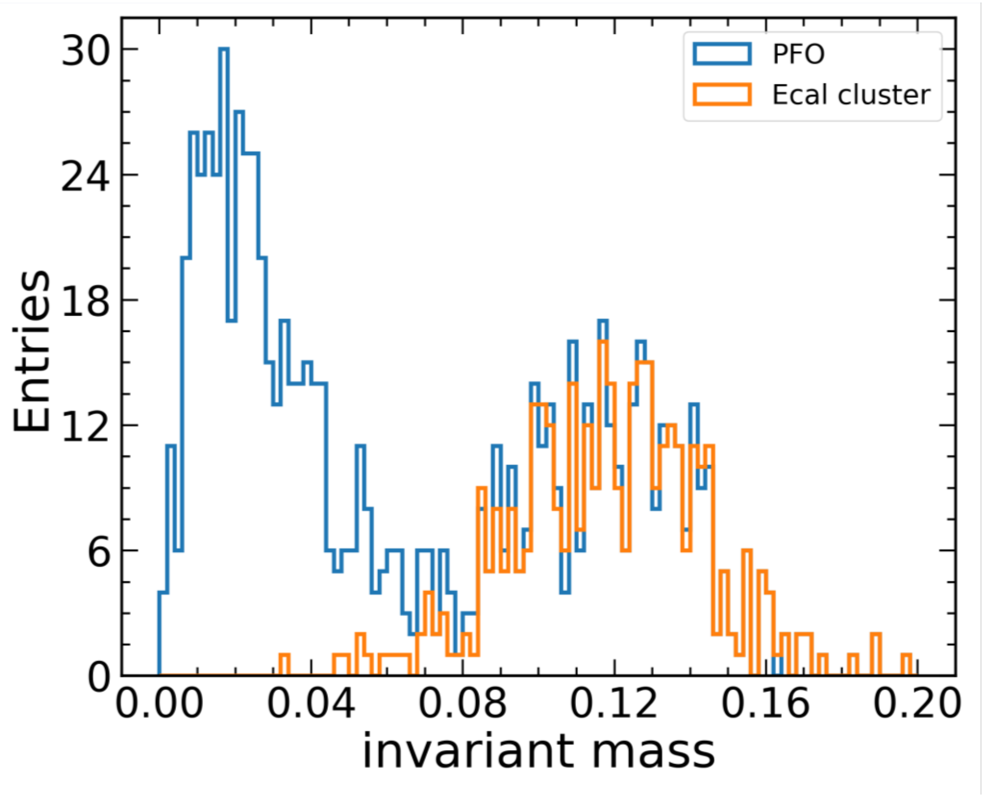
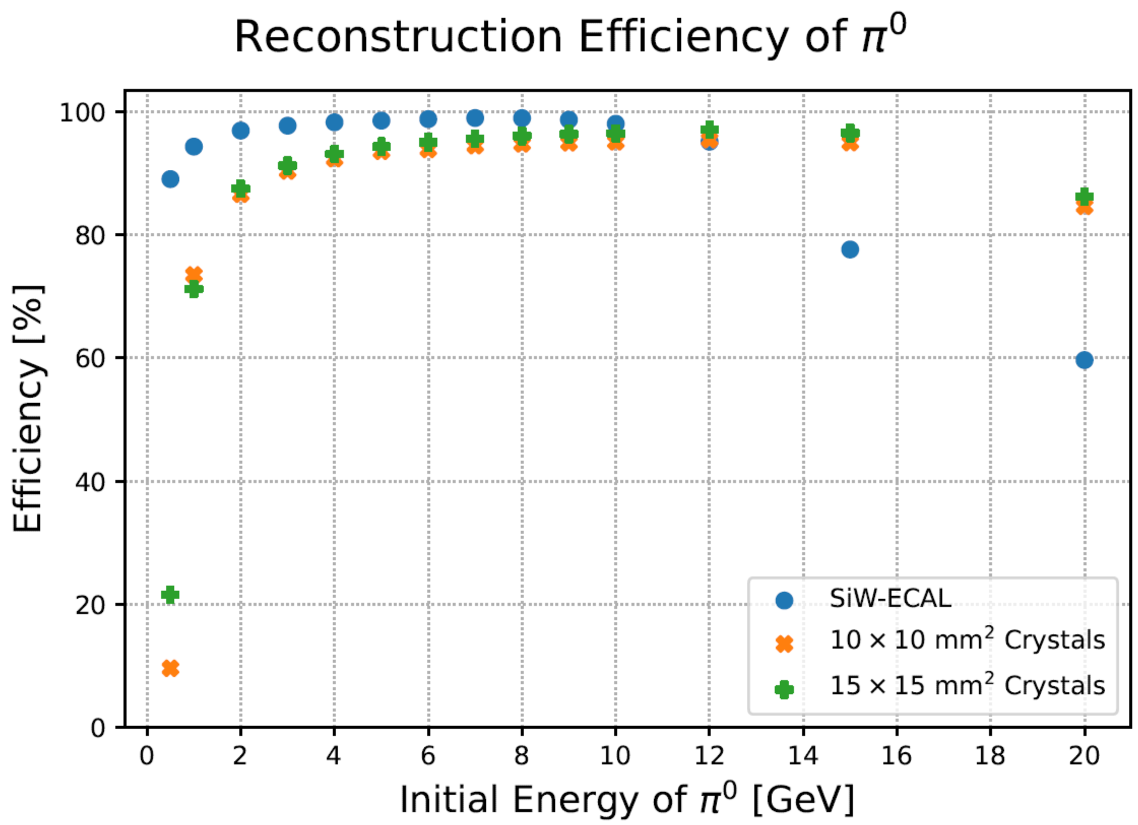
  - Similar jet performance: BMR=3.8-3.9% for Higgs hadronic decays
  - π^0 performance is degraded in high energy with $15 \times 15\ \mathrm{mm}^2$, but can be improved by the γ/π^0 discrimination technique
  - Dynamic range requirement: ~50% increase of max. signals with $15 \times 15\ \mathrm{mm}^2$
- Critical decision: discussions
  - $15 \times 15\ \mathrm{mm}^2$: significant advantages, potentials to further improve the degraded performance in π^0 in high energy
  - Proposal to change the ECAL transverse granularity to $15 \times 15\ \mathrm{mm}^2$ in Ref-TDR, while still continuing studies on π^0 performance and related physics benchmarks

Backup Slides

CyberPFA: latest result

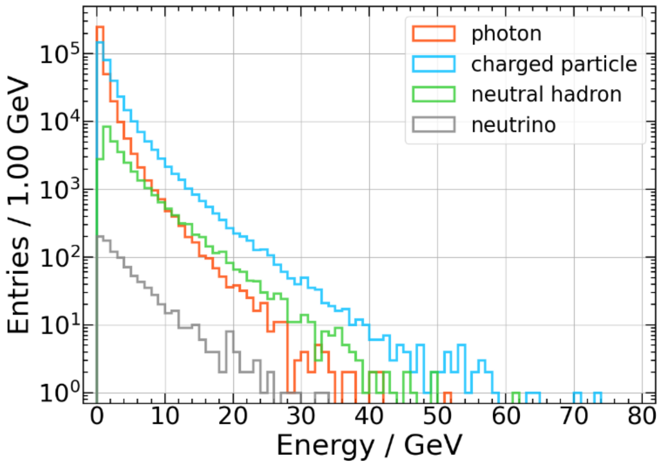
- Cluster ID in latest version of CyberPFA
  - Based on the ECAL and HCAL information

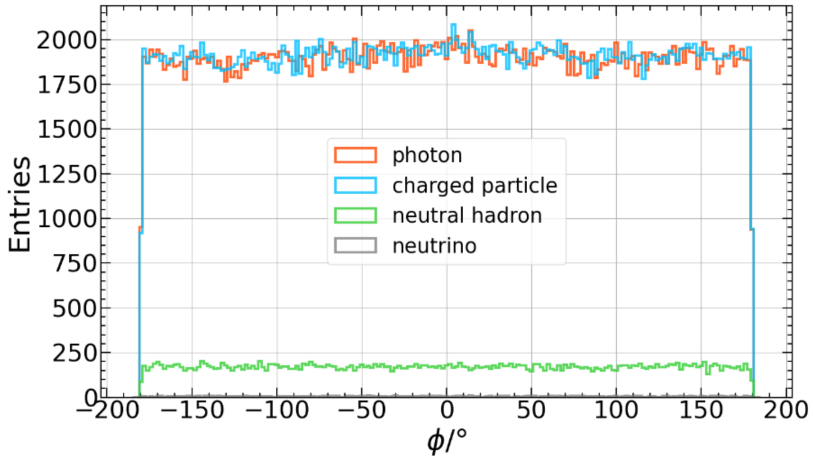


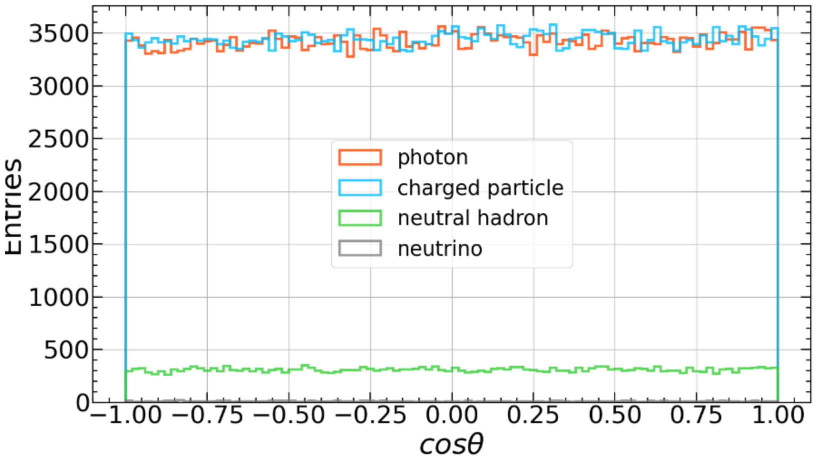


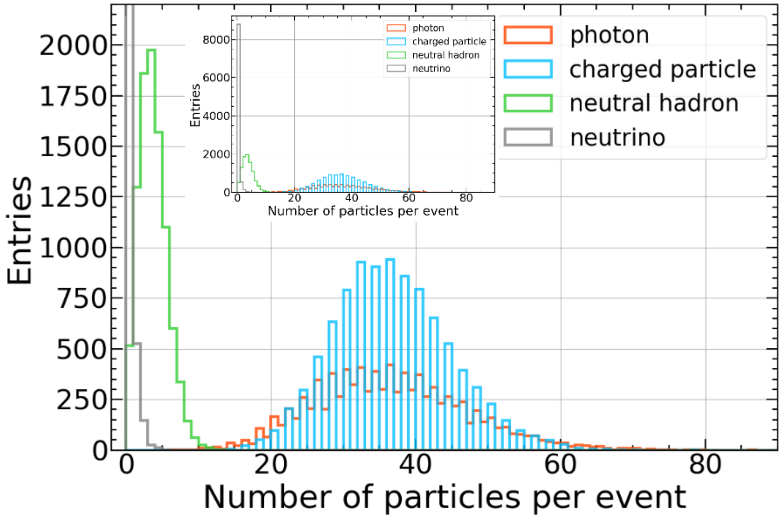
MC information: $H \rightarrow gg$

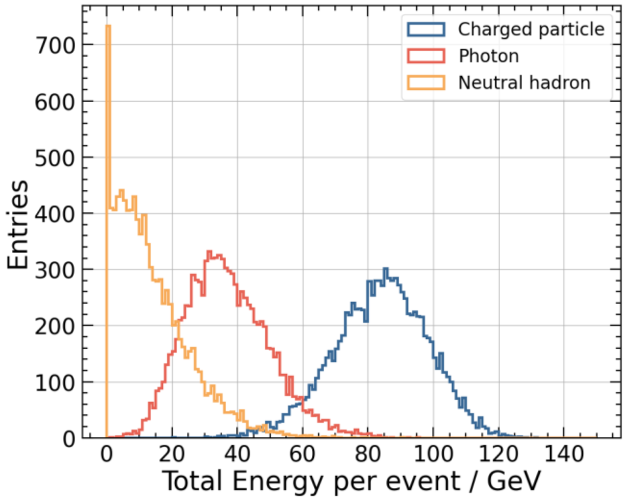
- Higgs decays to two gluon jets

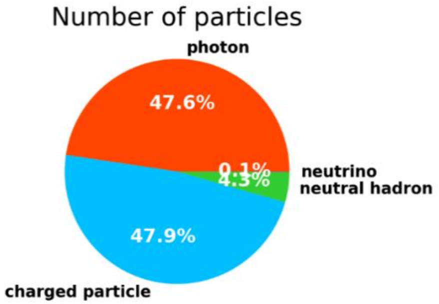


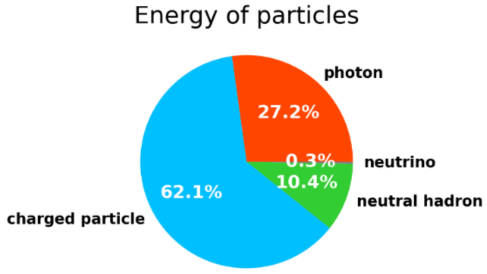












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