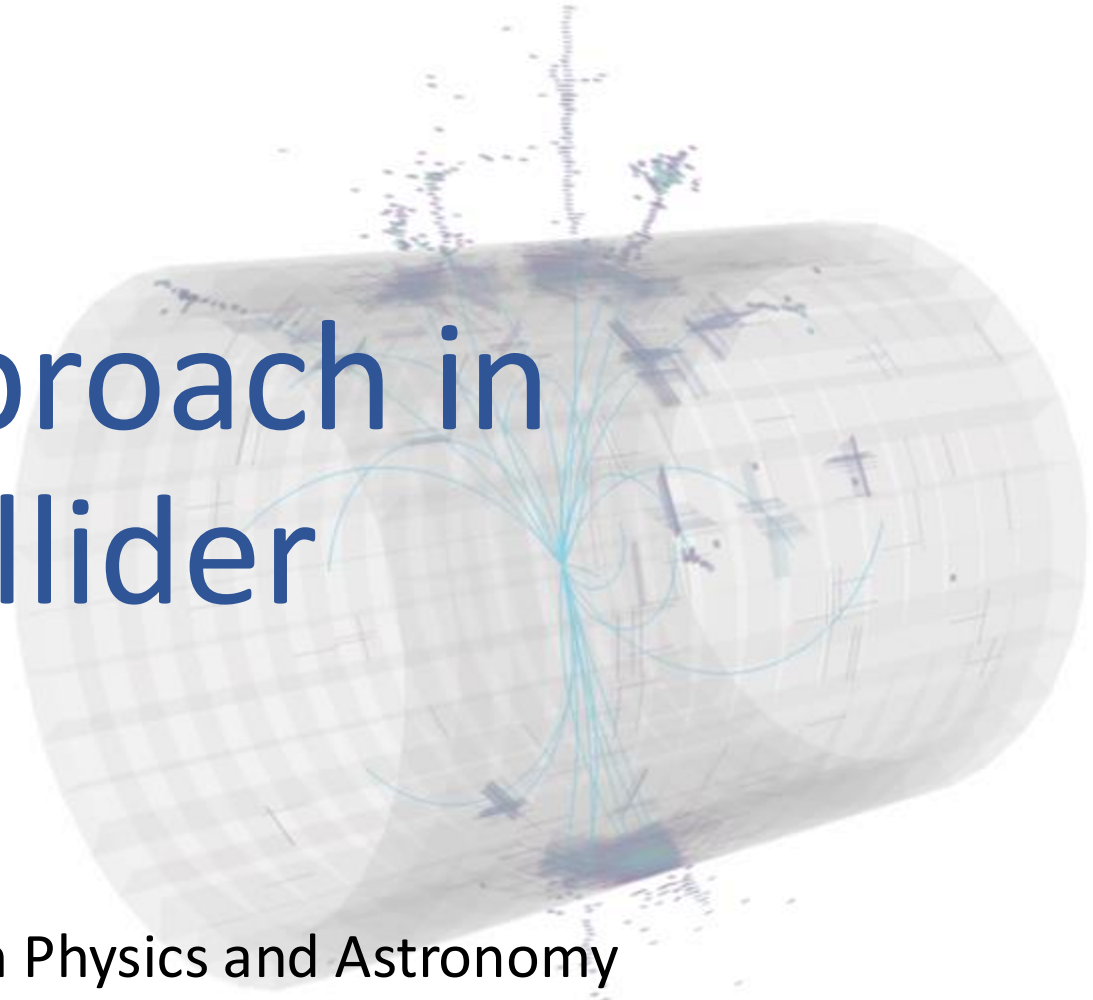


Particle flow approach in future lepton collider

Fangyi Guo, IHEP

2025 Postdoctoral Frontier Symposium in Physics and Astronomy

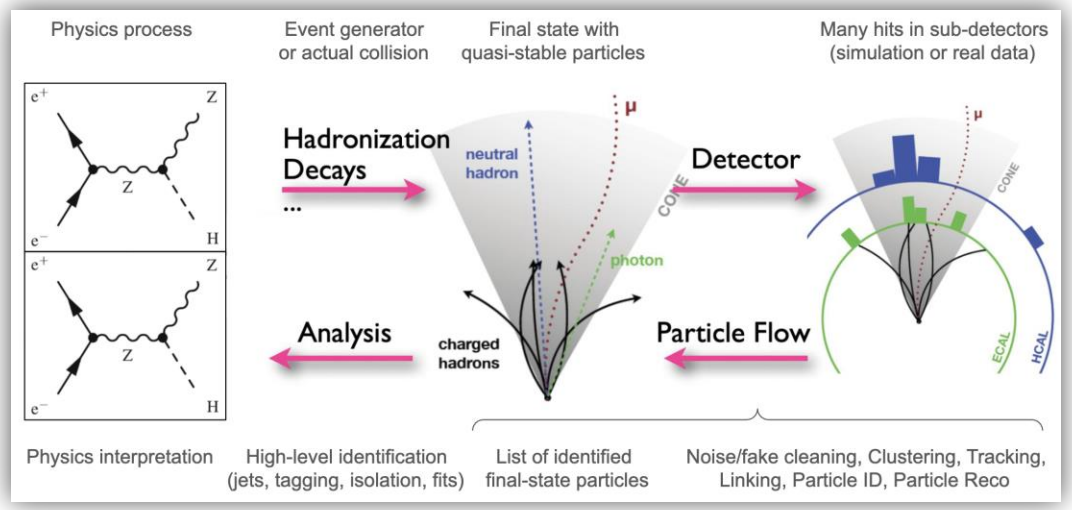
Sep. 24 2025, T.D.Lee Inst. Shanghai

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

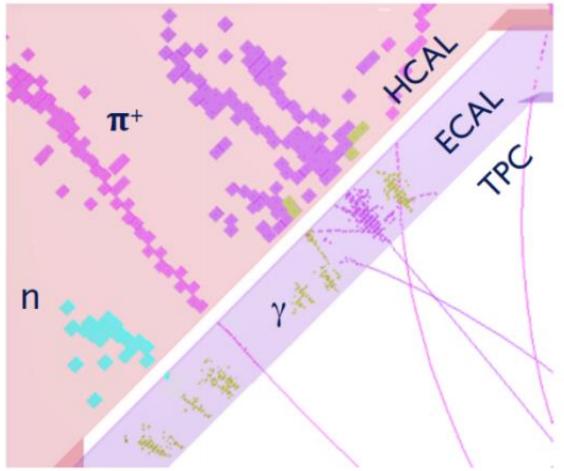
Introduction: what is particle flow?

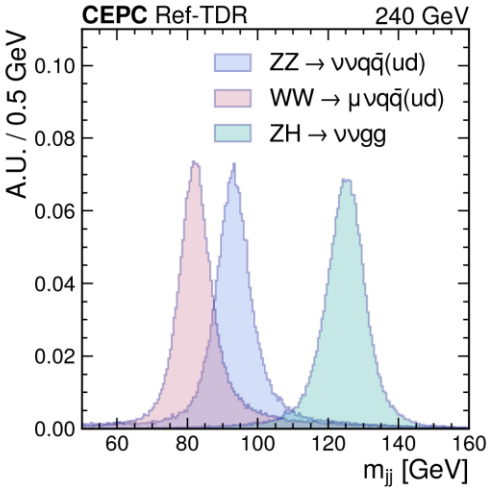
- **Ideally: reconstruct & identify all stable particles in detector**
  - With best possible resolution / efficiency / purity and minimum overlap.
  - **"As perfect as generator-level analysis"**
- **Approach: correlate measurements from all sub-detectors.**
  - Optimal for jet measurement: determined by its component $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
  - Expect jet energy resolution $\sigma_E/E \sim 0.19/\sqrt{E}$, never achieved in HEP experiment.

Component	Detector	Energy fract.	Energy res.	Jet energy res.
Charged particles ($X^{\pm}$)	Tracker	$\sim 0.6Ej$	$10^{-4}E^2_{X^{\pm}}$	$< 3.6 \times 10^{-5}E_j^2$
Photons (γ)	ECAL	$\sim 0.3E_j$	$0.15\sqrt{E_\gamma}$	$0.08\sqrt{E_j}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1E_j$	$0.55\sqrt{E_{h^0}}$	$0.17\sqrt{E_j}$



Patrick Janot in FCC PF workshop



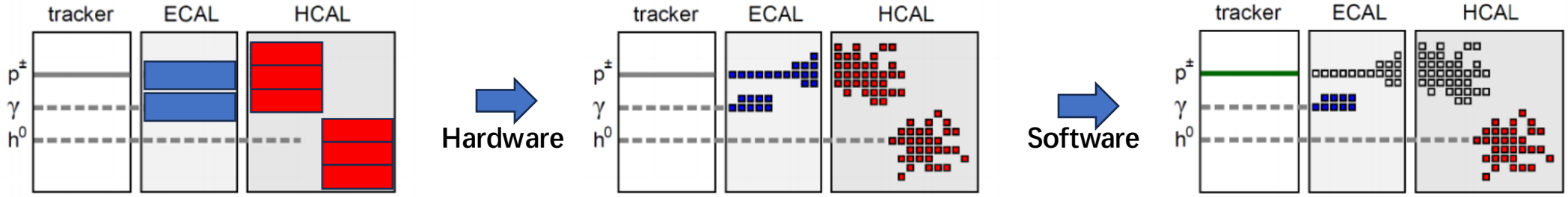


Introduction: how we can reach

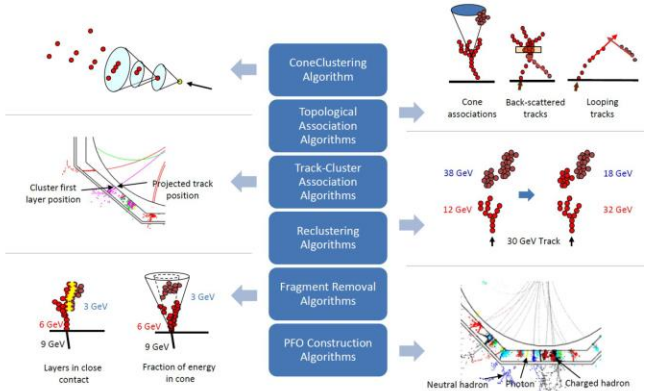
- **Particle flow is a combined requirement:**

Hardware: separate clusters from different particles.
- High granularity.
- Compact sampling structure.

Software: correctly assign calorimeter energy deposits to the particles.
- Clustering
- Pattern recognition.



- **Proof-of-principle: ILD + PandoraPFA**
  - Limited silicon vertex & tracker + TPC (minimum material)
  - High granularity Si-W ECAL + Steel-Scintillator HCAL (segmentation)
  - Large magnetic field 3.5 T ($h^{\pm}$, $l^{\pm}$ separation)
  - PandoraPFA for reconstruction
  - **Jet energy resolution: 2.9% @ 100 GeV**
    - **Contribution: intrinsic resolution + leakage + confusion + …**



M.A. Thomson, NIM 611 (2009) 24-40

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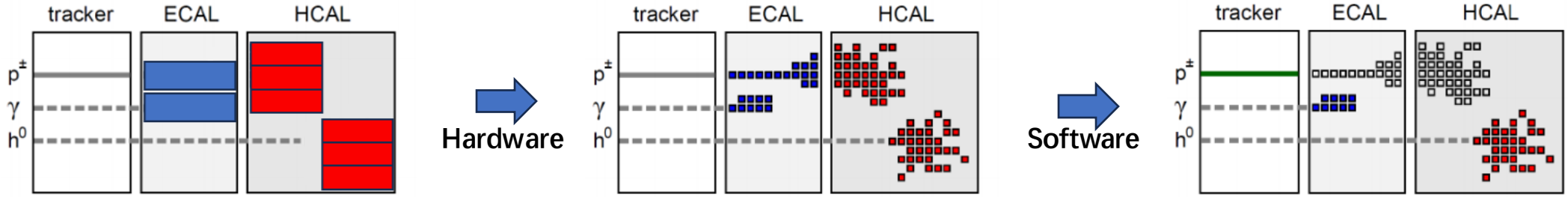

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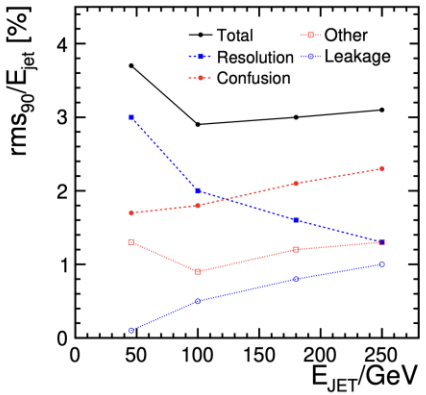
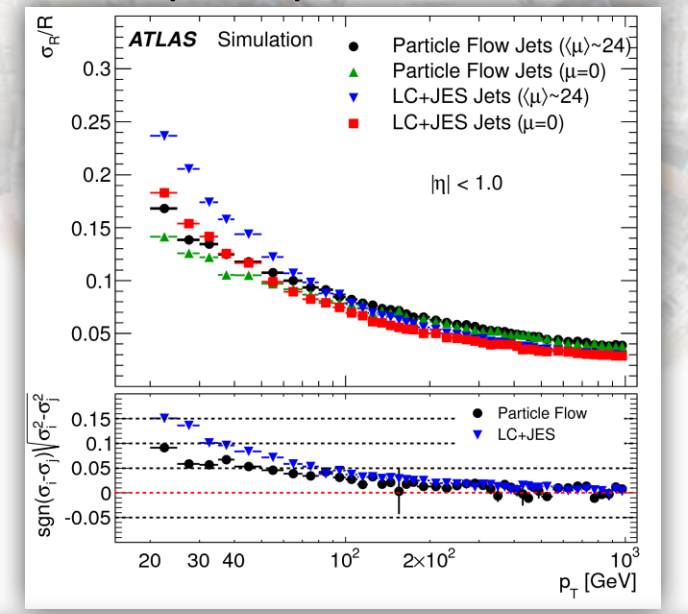
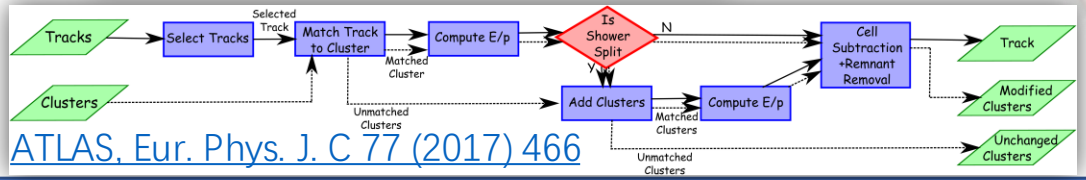


M.A. Thomson, NIM 611 (2009) 24-40

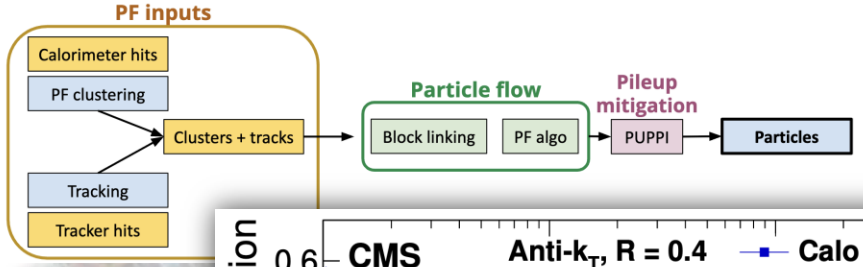
Particle flow in ATLAS and CMS

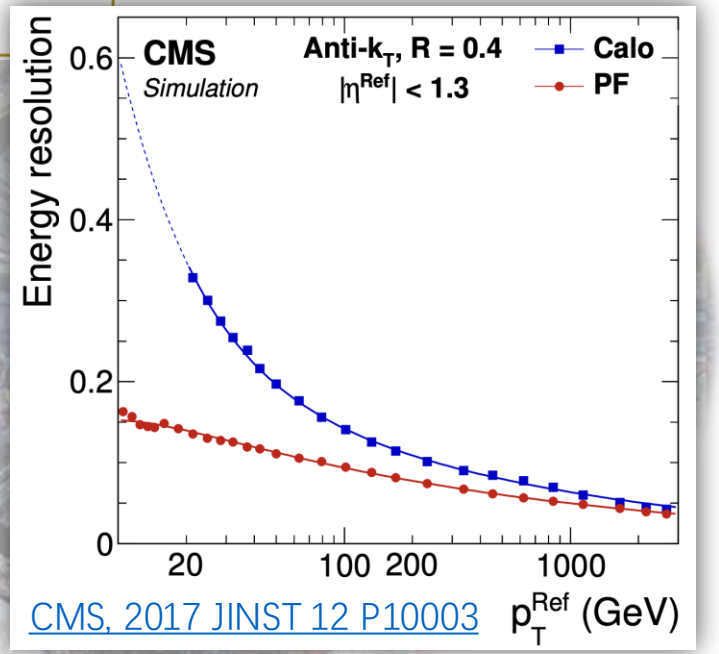
- **“With any detector / collider you can perform PF reconstruction”**
  - Neither ATLAS or CMS detector is designed with PF idea
  - But PF improves the performance w.r.t. calorimetric-only / tracking-only reconstruction.
  - While pile-up indeed introduced some trouble…





ATLAS, Eur. Phys. J. C 77 (2017) 466

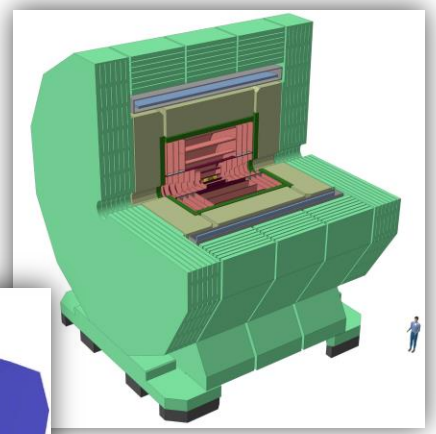




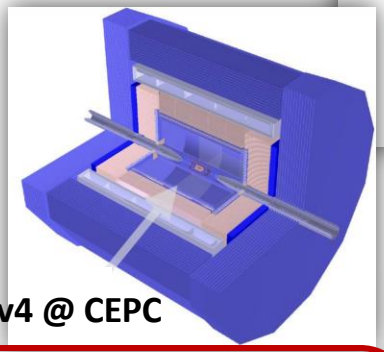
CMS, 2017 JINST 12 P10003

Particle flow in future lepton collider

- **"But some detectors are more equal than others"**
  - As precision frontier machine, lepton collider need PF.
  - Detector can be designed & optimized for PF from beginning.
    - Low material @ tracker, granularity @ Calo, …
  - Life is much easier in e^+e^- colliders: no PU, less multiplicity, …
- **CEPC Reference Detector: traditional and new**
  - Low material before calo: Silicon vertex & ITK + gas TPC.
  - 3T magnet outside HCAL.
  - **Optimal EM resolution & similar cost as Si-W**:
    - Homogeneous crystal ECAL compatible with PFA.
    - $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 1\%$
  - **Better hadronic resolution:**
    - Scintillating glass high granularity HCAL.
    - $\sigma_E/E \sim 30\%/\sqrt{E} \oplus 5\%$

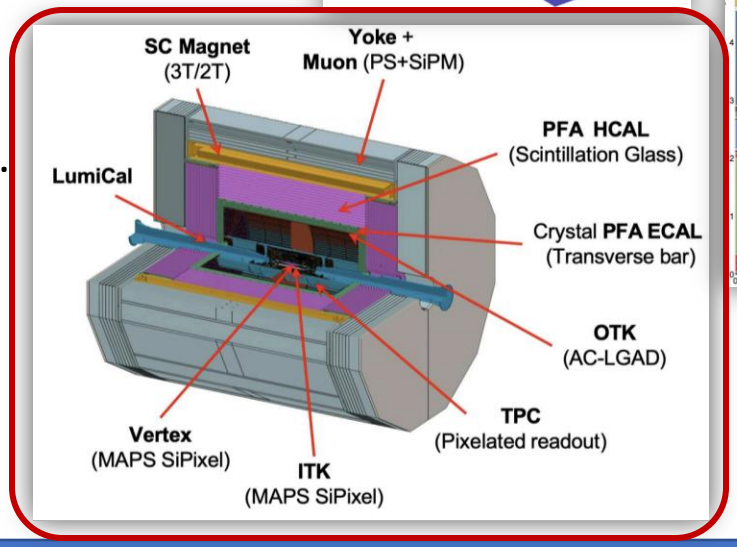


CLD @ FCC



CEPC_v4 @ CEPC

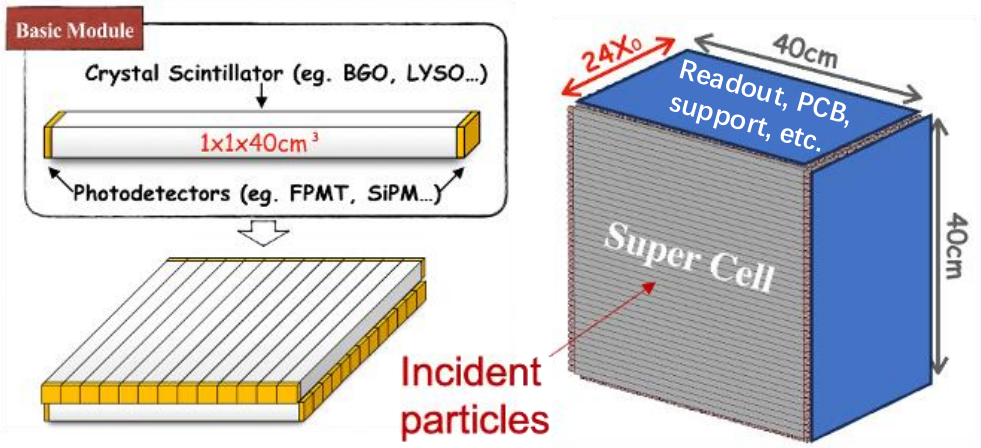
ALLEGRO @ FCC



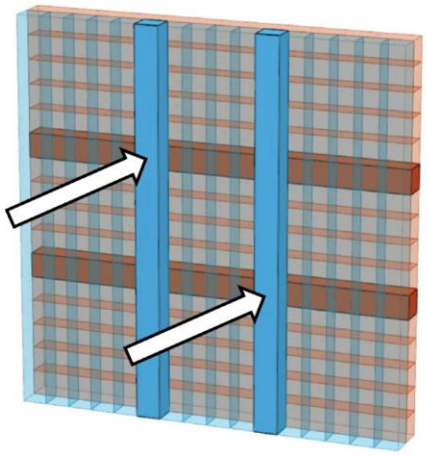
Reference Detector @ CEPC

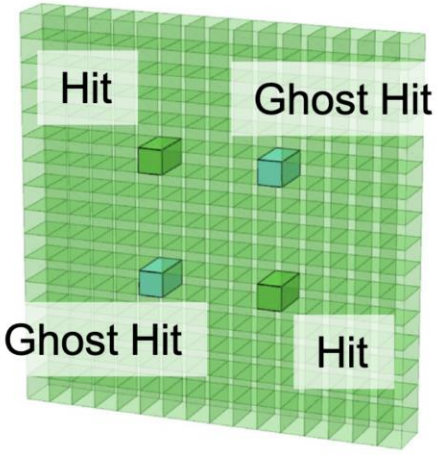
CEPC Reference detector and PF

- **Homogeneous ECAL: alternative way for PF**
  - Orthogonal arranged crystal bars $1.5 \times 1.5 \times \sim 40\ \mathrm{cm}^3$, double-side readout with SiPM.
  - High granularity from bar cross-location + timing.
  - Minimum longitudinal dead material in layers for optimal EM resolution.
  - Less readout channels, lower cost.



- **But at what cost…**
  - Unprecedented challenge in reconstruction:
    - Shower overlap: $R_M \sim 2.23\ \mathrm{cm}$ w.r.t $\sim 1\ \mathrm{cm}$ in Si-W.
    - Ghost hit: ~5 particles in one module in O(100) GeV jet
  - **Need a new PF algorithm to solve them: CyberPFA**





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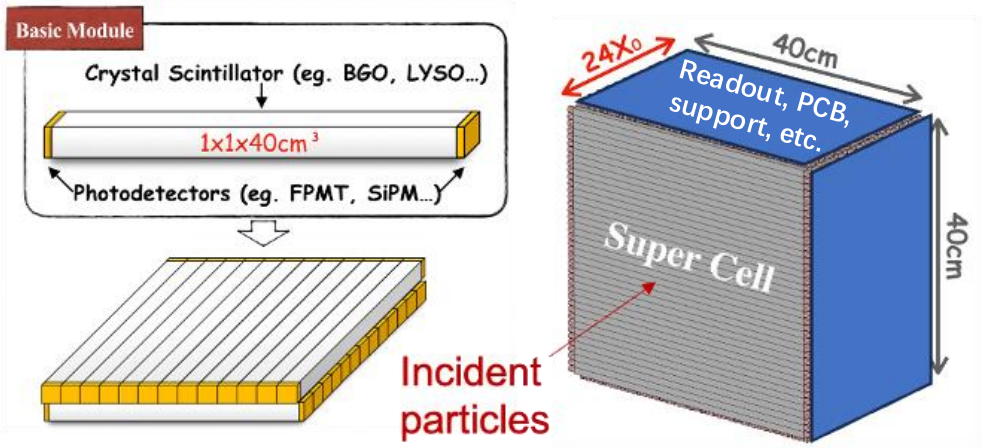

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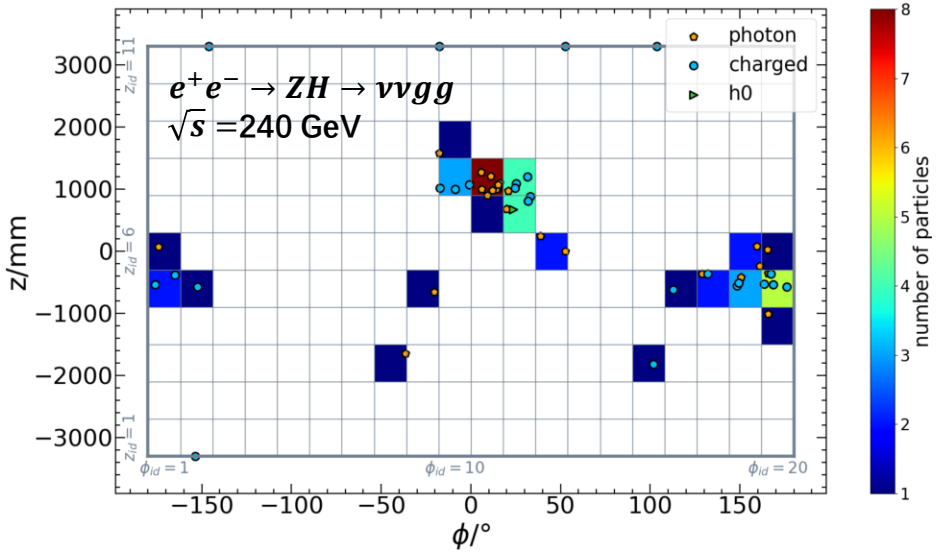
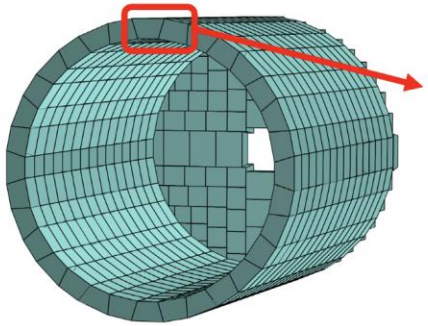
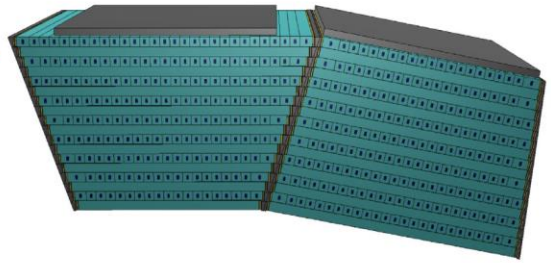


CEPC Reference detector and PF

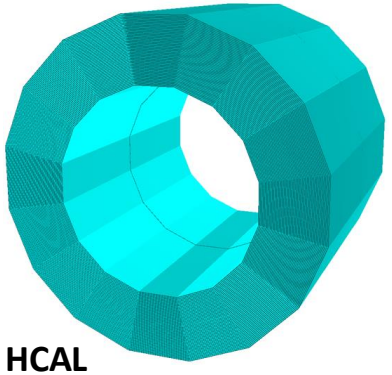
- **A realistic detector description: BGO crystal ECAL + glass-scintillator HCAL**



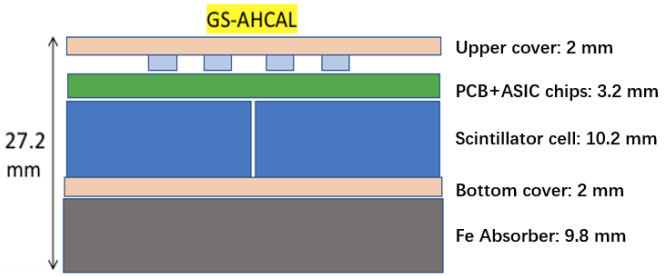
ECAL



Invert trapezoid module

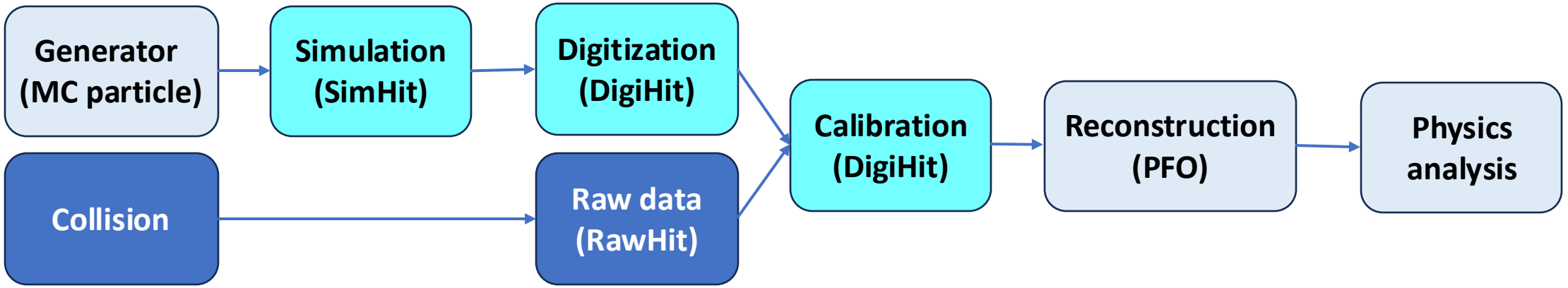


HCAL



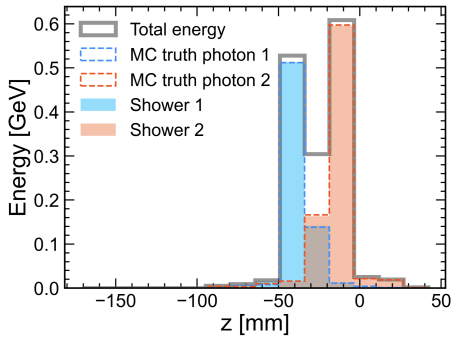
Sandwich cell structure

- **Digitization & calibration:**
  - Energy → scintillating photons → p.e. in SiPM → ADC in ASIC → digitalized energy → calibration

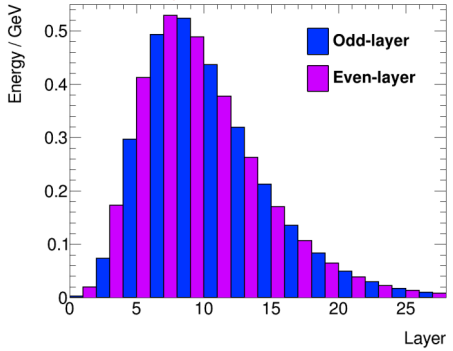


CyberPFA: PFA for crystal bar ECAL

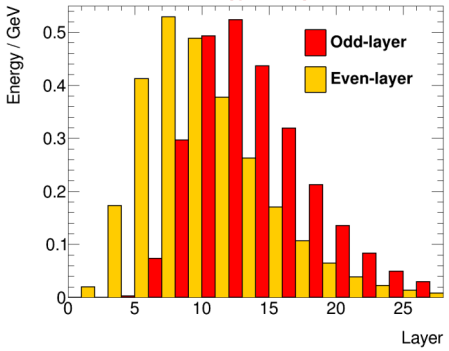
Step 1: preparation
Step 2: shower recognition
Step 3: energy splitting & ambiguty removal
Step 4: clustering & re-clustering



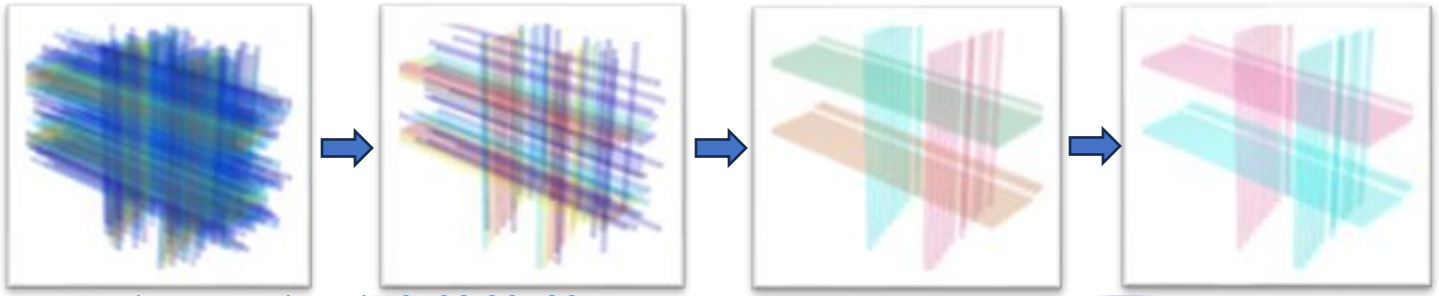
Correctly matched shower



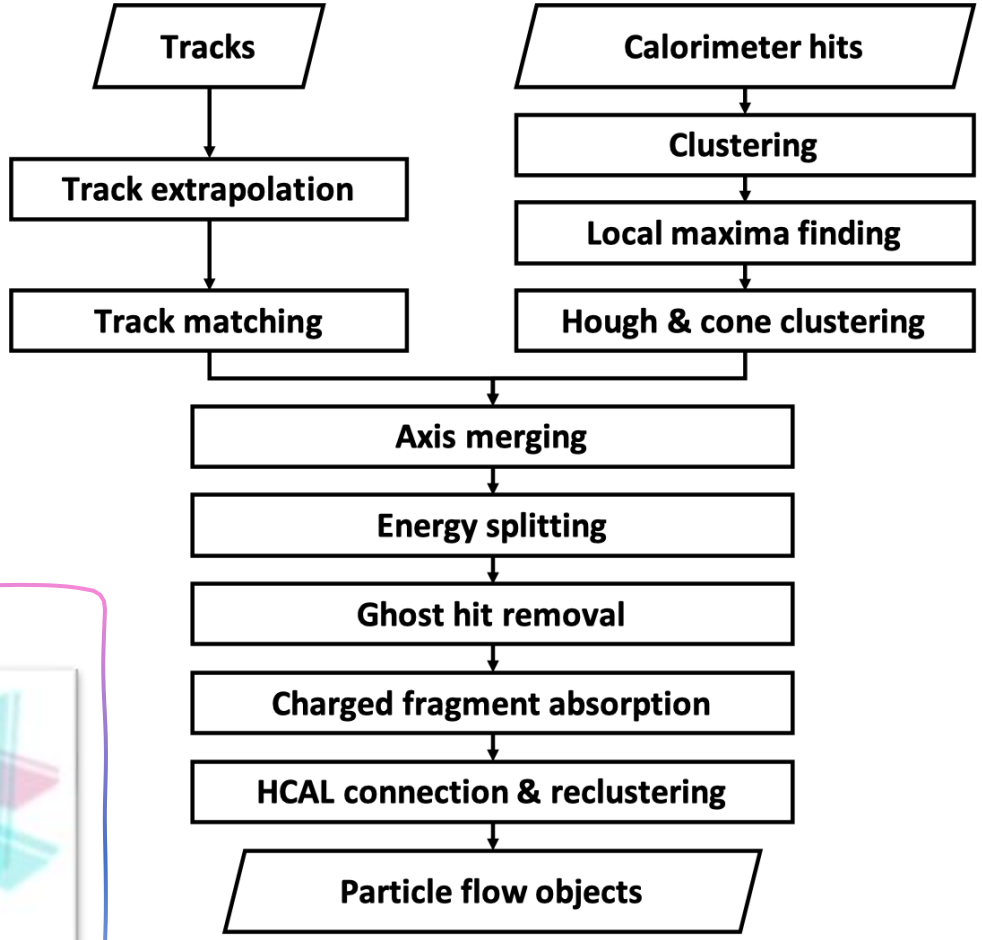
Mis-matched (ghost) shower



Event display: 2 photons, $E_\gamma = 5$ GeV, distance = 15×15 cm.

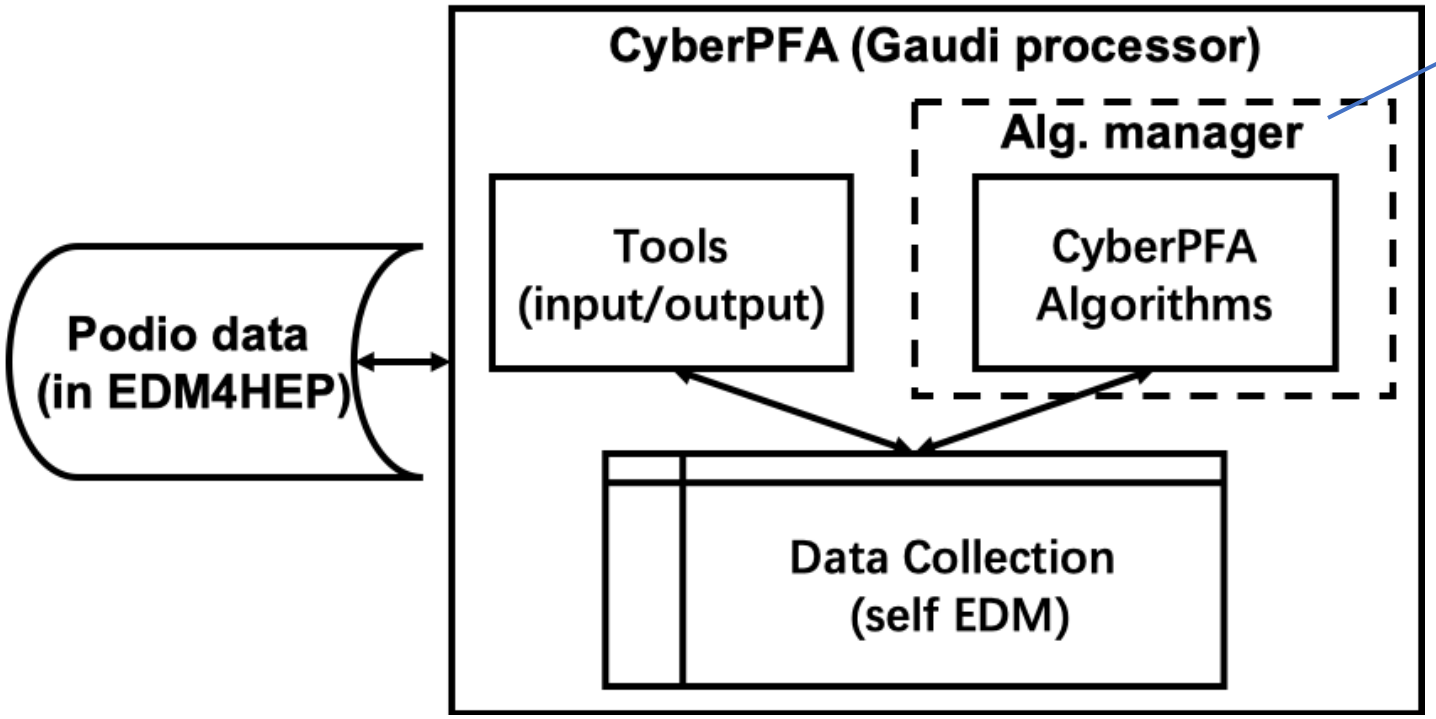


Yang Zhang et.al, arxiv 2508.20728



CyberPFA: PFA for crystal bar ECAL

- **Software structure: modulized algorithm in Key4HEP**
  - Building-block algorithm arrangement, friendly for future extension.
  - Parameters / settings in steering file, easy to tune.
  - Data management independent with algorithms.

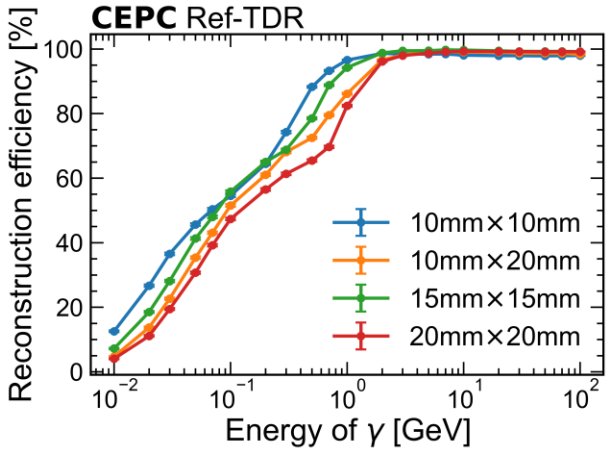


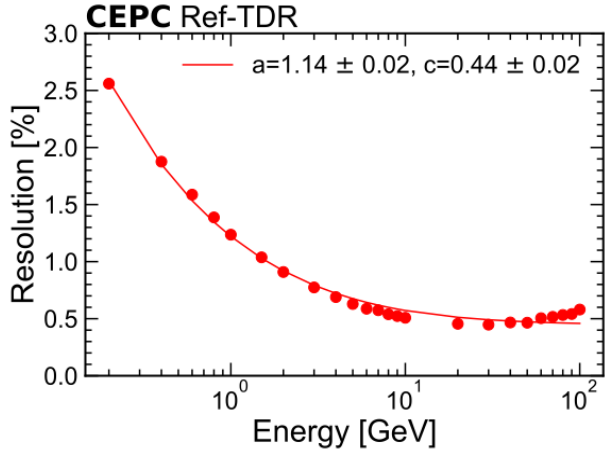

```
//Readin collections
m_pMCParticleCreator->CreateMCParticle( m_DataCol, *r_MCParticleCol );
if(m_useMCPTrk) m_pTrackCreator->CreateTracksFromMCParticle(m_DataCol, *r_MCParticleCol);
else m_pTrackCreator->CreateTracks( m_DataCol, r_TrackCols, r_MCPTrkAssoCol );
m_pCaloHitsCreator->CreateCaloHits( m_DataCol, r_CaloHitCols, map_readout_decoder, map_Cal

//Perform PFA algorithm
m_algorithmManager.RunAlgorithm( m_DataCol );

m_pOutputCreator->CreateOutputCollections( m_DataCol,
                                           w_RecEcalCol,
                                           w_RecCoreCol,
                                           w_RecHcalCol,
                                           w_RecTrkCol,
                                           w_ClusterCollection,
                                           w_ReconstructedParticleCollection);
```

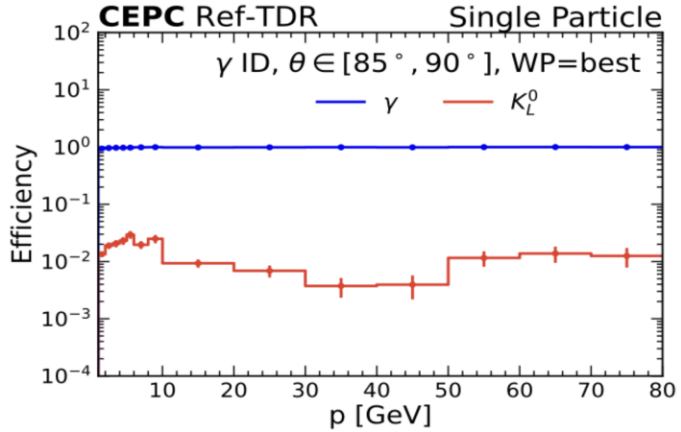
```
StatusCode RunAlgorithm( CyberDataCol& m_datacol ){
  for(auto iter : m_algorithmNames){
cout<<"Processing Algorithm: "<<iter<<endl;
    m_algorithmMap[iter]->Initialize(m_datacol);
    m_algorithmMap[iter]->RunAlgorithm(m_datacol);
    m_algorithmMap[iter]->ClearAlgorithm();
  }
  return StatusCode::SUCCESS;
}
```

Physics performance with CyberPFA

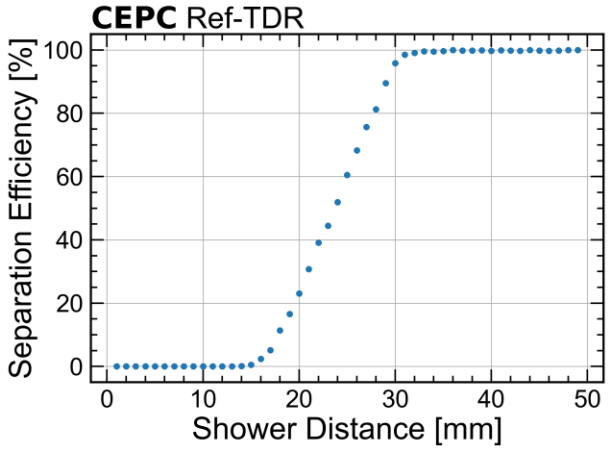
- **Single photon efficiency and resolution: superior with crystals**

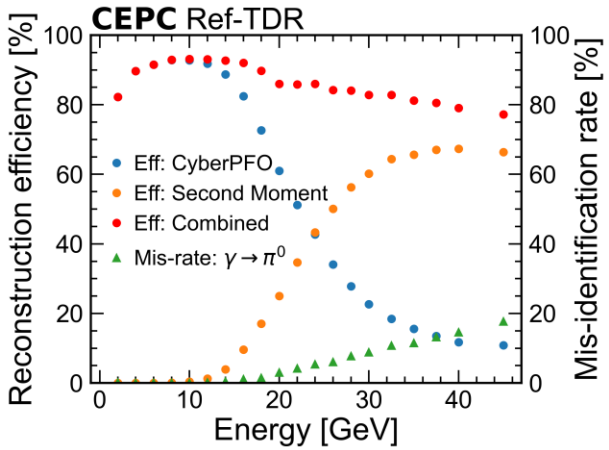




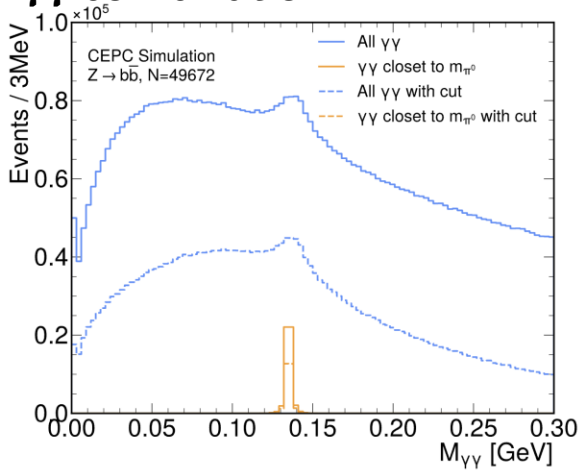


- **Close-by photon separation & π^0 reconstruction:**



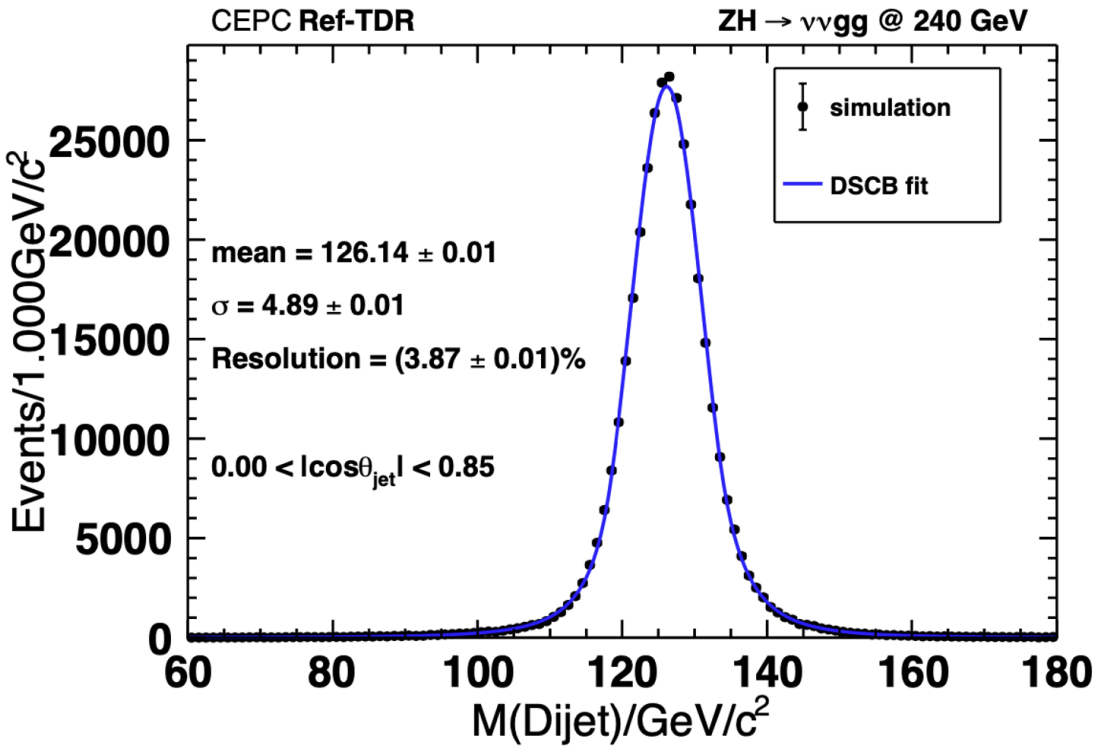


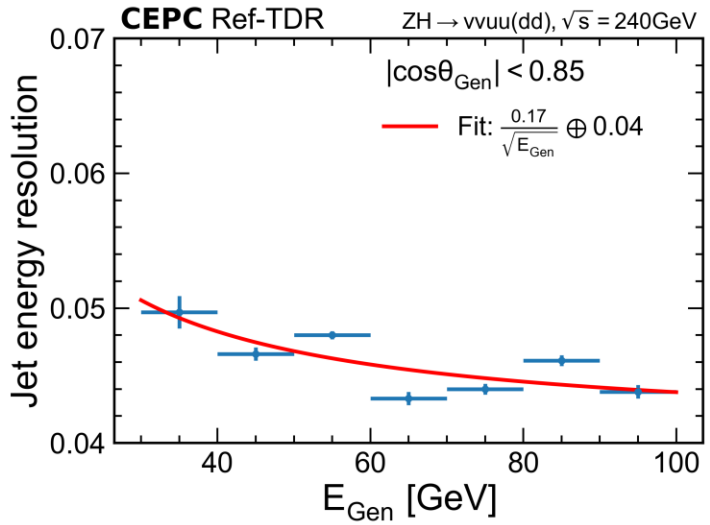
All γγ combination in $ee \to Z \to b\bar{b}$

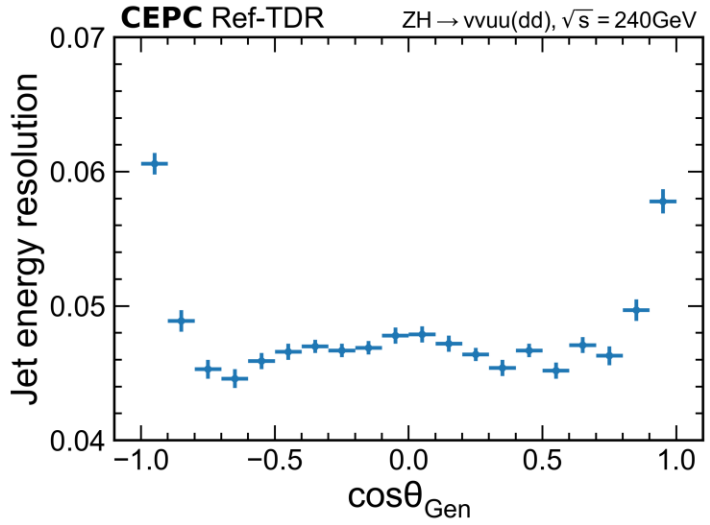


Physics performance with CyberPFA

- **Performance in jet environment:**
  - BMR in $ee \to ZH \to \nu\nu gg$ process: 3.87%.
  - Jet energy resolution in $ee \to ZH \to \nu\nu uu/dd$: ~ 5%.
  - **Satisfy physics requirement in CEPC.**

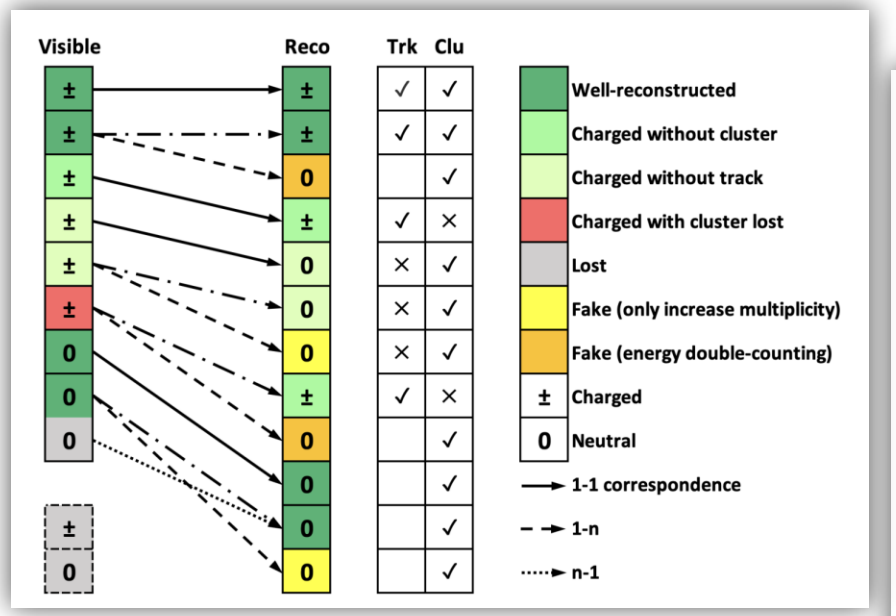


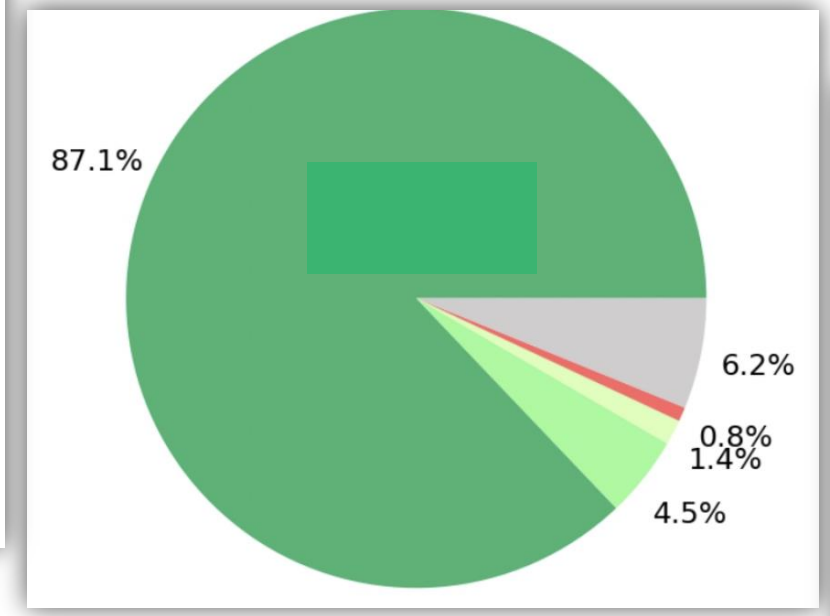


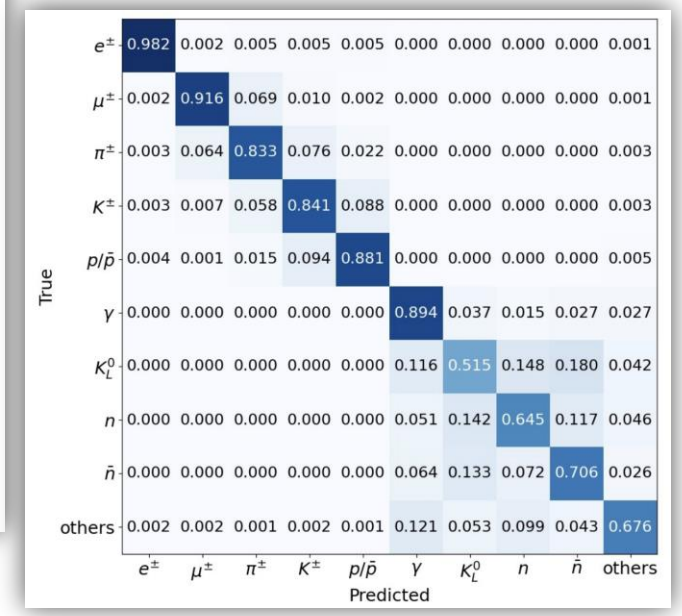


Physics performance with CyberPFA

- **“1-1 correspondence” approach: global reco-PFO identification**
  - Towards the original idea of PF: 1 (particle) - 1 (reco object)
  - Identify PFO with Par-T: 87.1% can be identified.
  - BMR is expected to be improved ~ 6%.



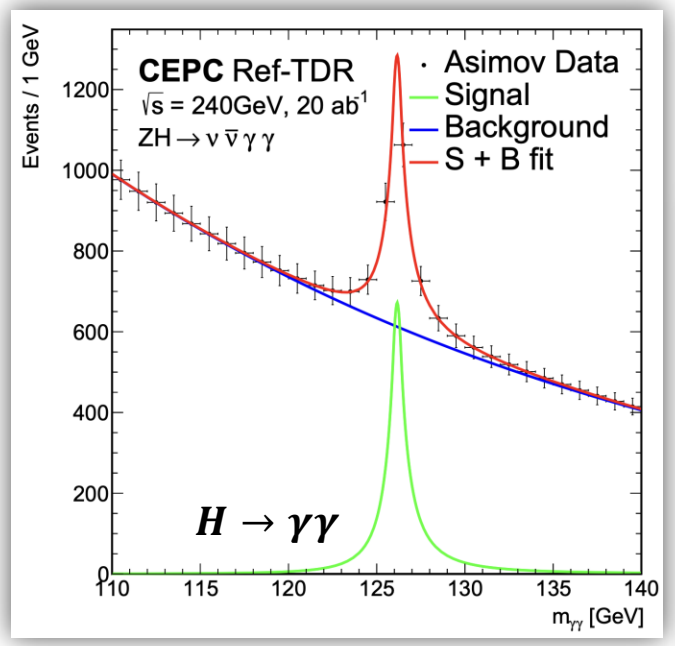


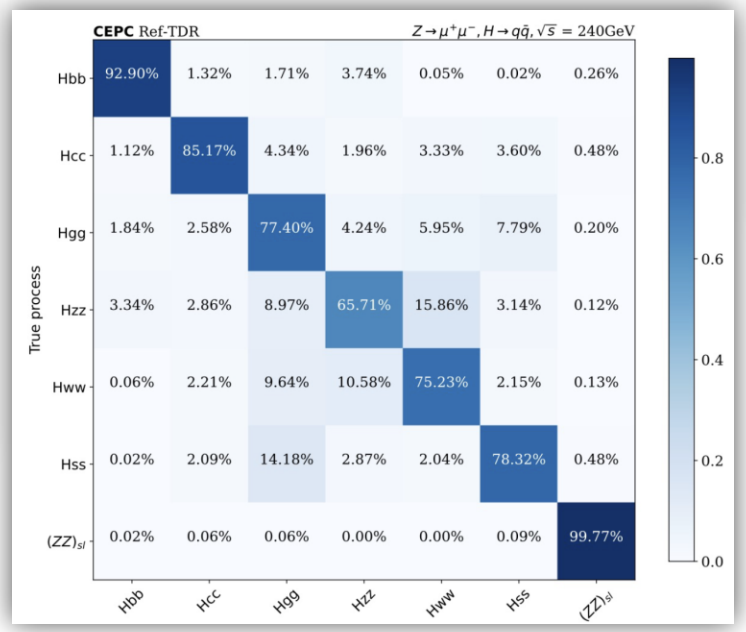


Yuexin Wang et.al, Comput. Phys. Commuon. 314 (2025) 109661

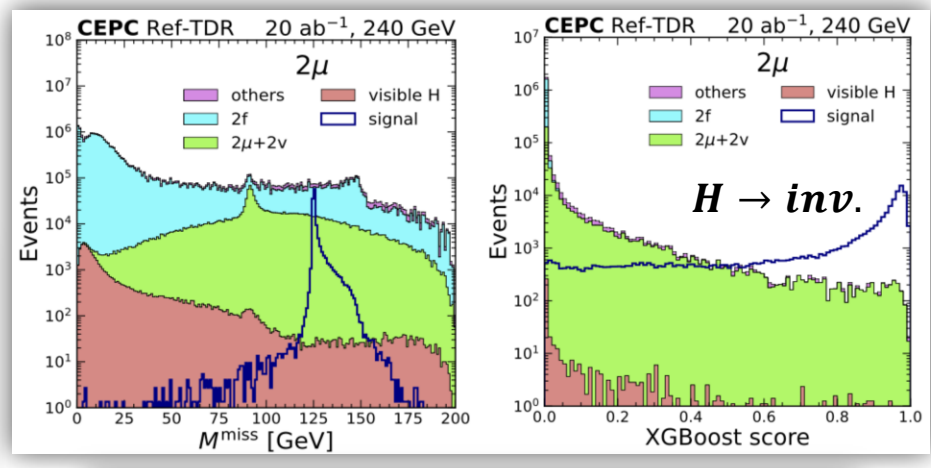
Physics performance with CyberPFA

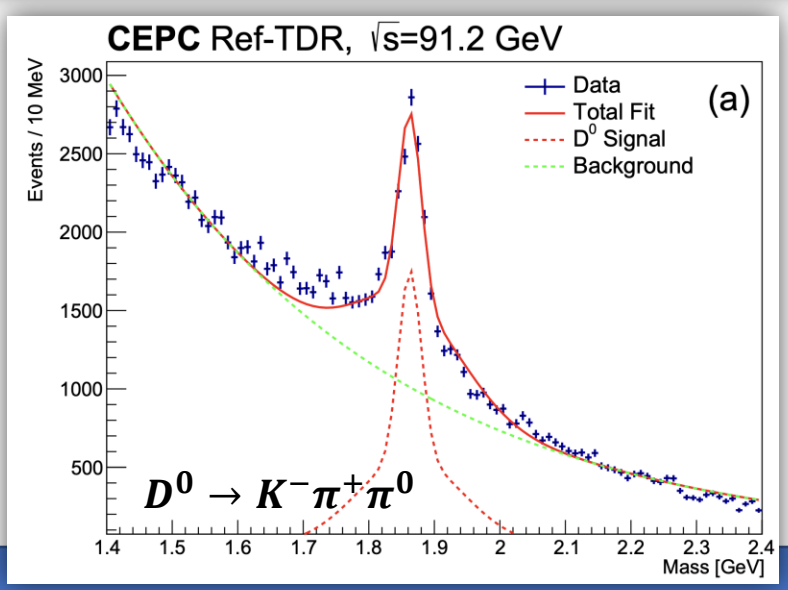
- **Fruitful physics analyses in CEPC is ongoing with CyberPFA**





Global Higgs hadronic decay





Conclusion and prospects

- **Particle flow reconstruction is a core system in lepton collider:**
  - Essential for precise measurement of jet final state.
  - Connects the chain in collider experiment: detector hardware – **PF reconstruction** – physics.

- **CyberPFA for CEPC Reference detector is an innovation to PF**
  - **First time** homogeneous pseudo-HG ECAL is compatible with PFA.
  - Comparable performance with traditional PFA in PF-oriented detector.
  - It already supports plenty of performance & physics analysis studies in CEPC.

- **Future in CEPC:**
  - Continue R&D activities for Reference Detector: hardware + software
  - Optimization & performance for CyberPFA: still a long way to go
  - ML-based reconstruction / identification: next generation for PF.

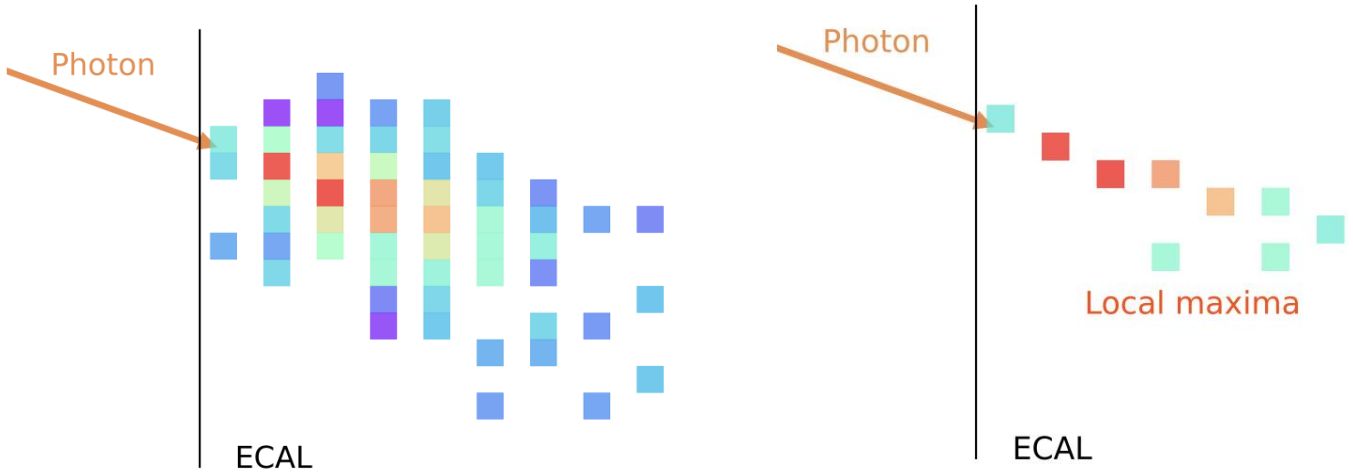
Backup

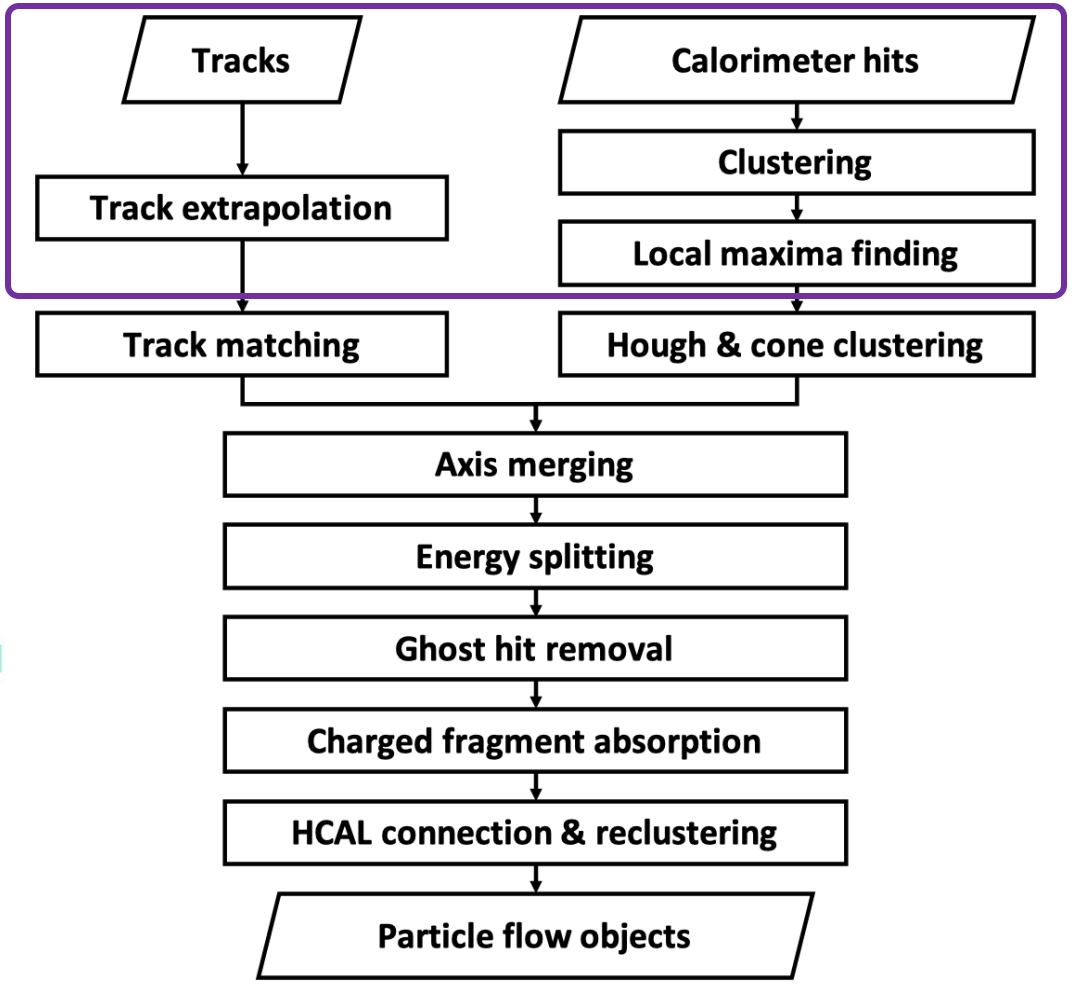
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

CyberPFA: PFA for crystal bar ECAL

Step 1: preparation

- Track cleaning and extrapolation
- Global neighbor clustering in full detector.
- Find the local maximum: 1st pattern recognition



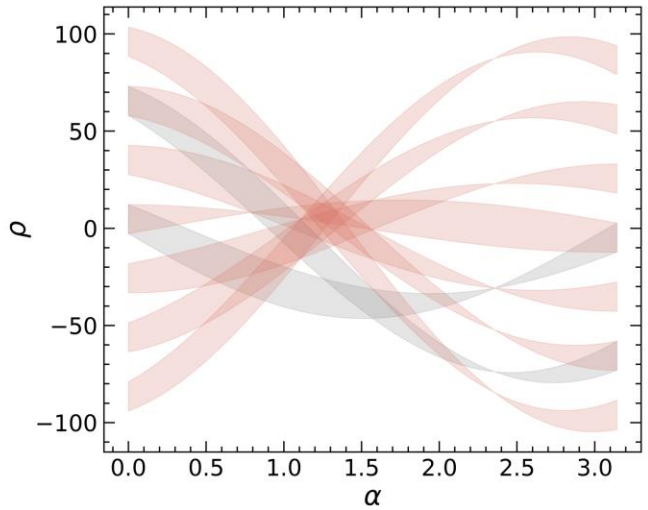


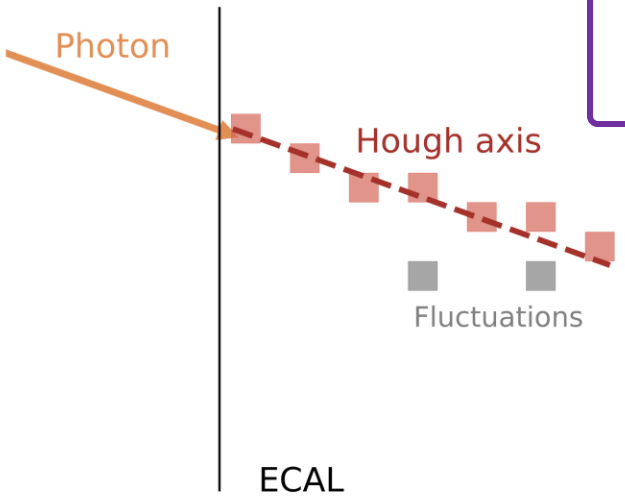
Yang Zhang et.al, arxiv 2508.20728

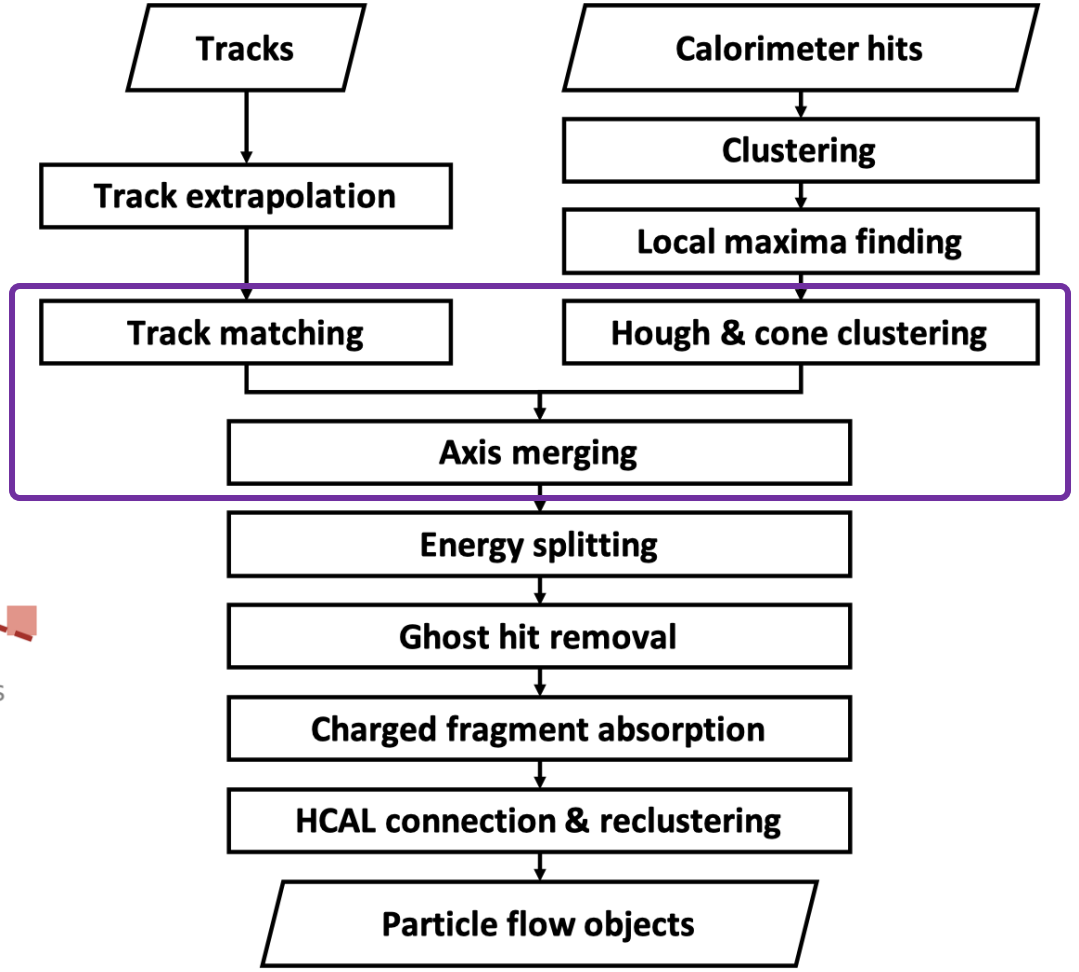
CyberPFA: PFA for crystal bar ECAL

Step 2: shower recognition

- Tracking in ECAL: find patterns with 3 individual algorithms.
- A set of topological cluster merging





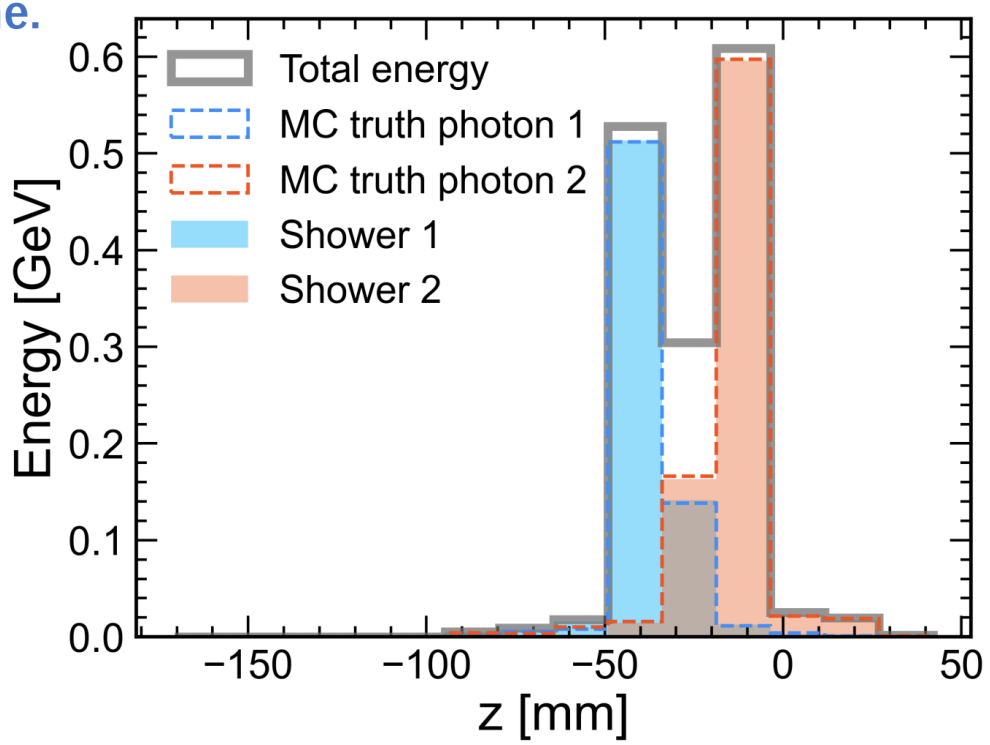


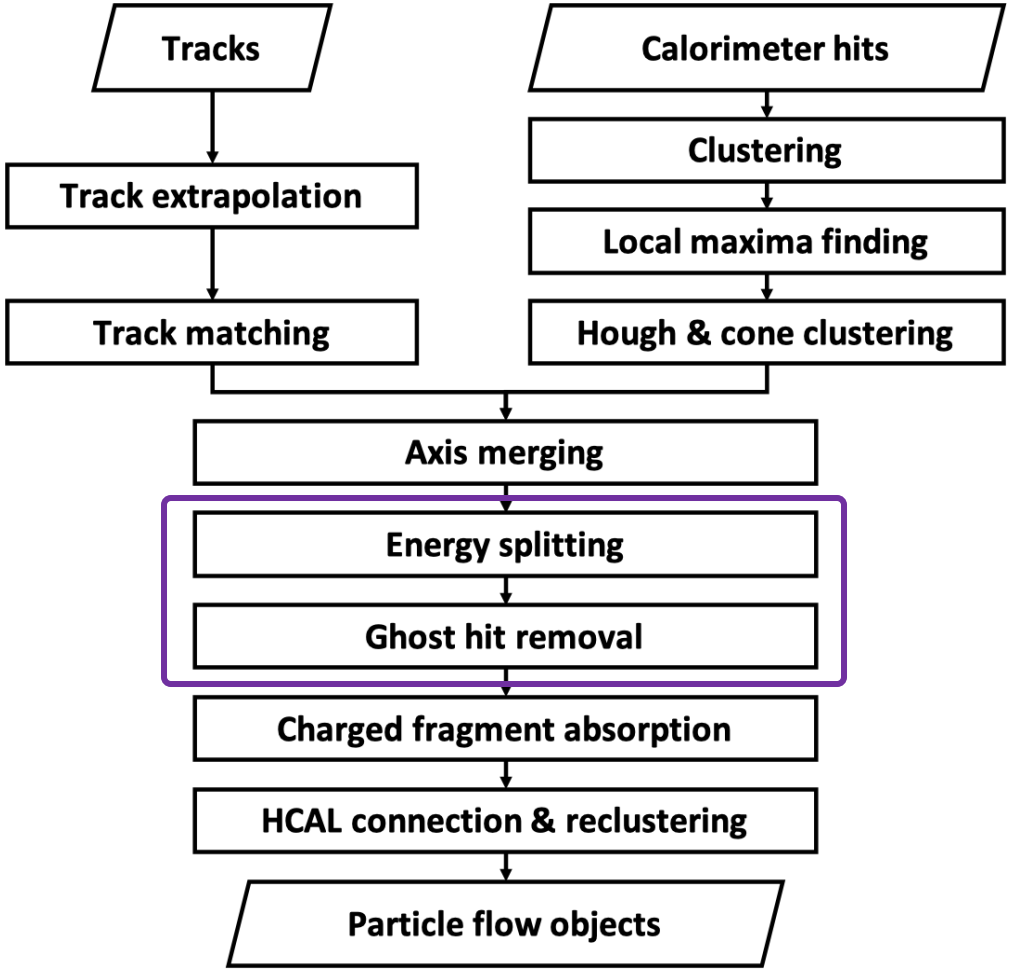
Yang Zhang et.al, arxiv 2508.20728

CyberPFA: PFA for crystal bar ECAL

Step 3: energy splitting & ambiguty removal

- Split the energy with EM profile.
- Remove ambiguity from track + neighbor module + time.





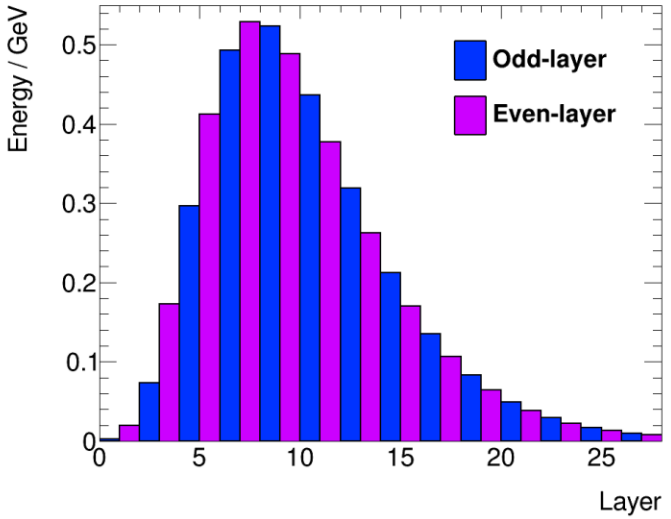
Yang Zhang et.al, arxiv 2508.20728

CyberPFA: PFA for crystal bar ECAL

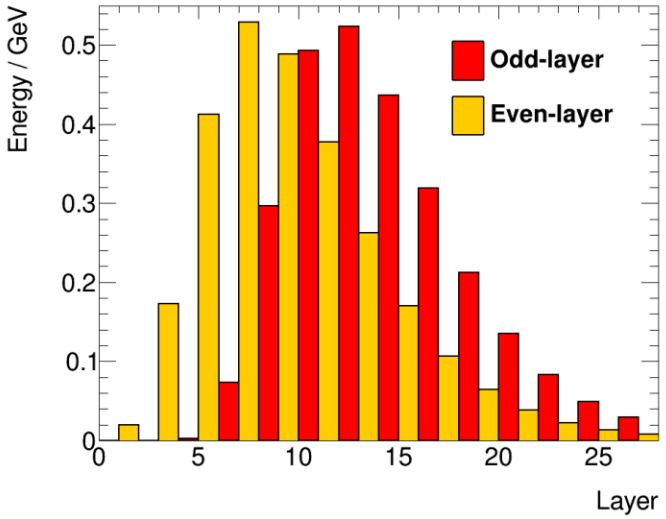
Step 3: energy splitting & ambiguty removal

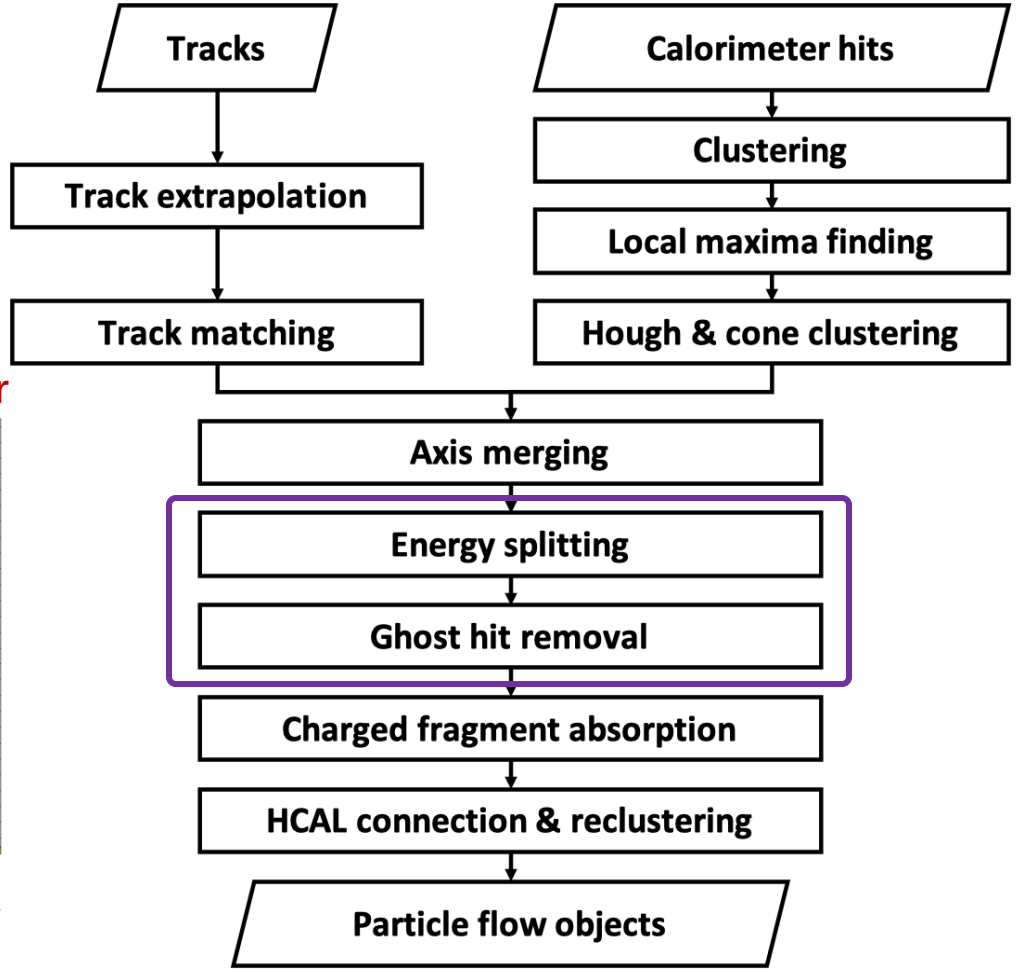
- Split the energy with EM profile.
- Remove ambiguity from track + neighbor module + time.

Correctly matched shower



Mis-matched (ghost) shower

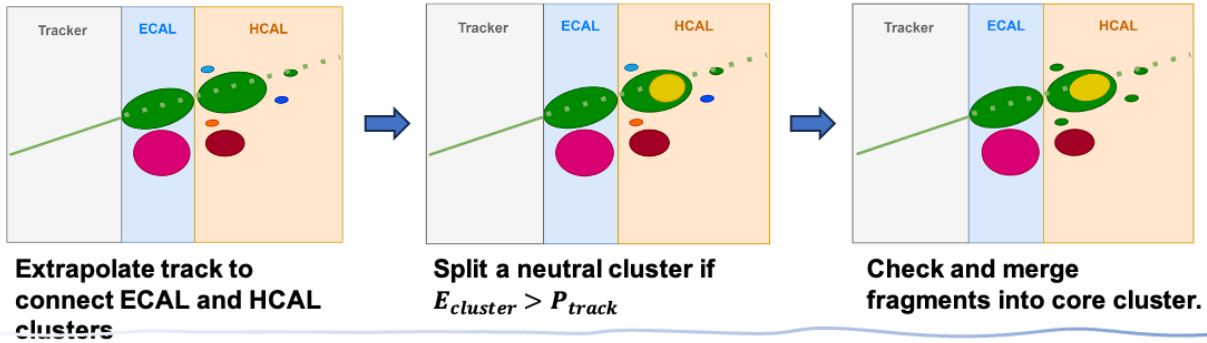




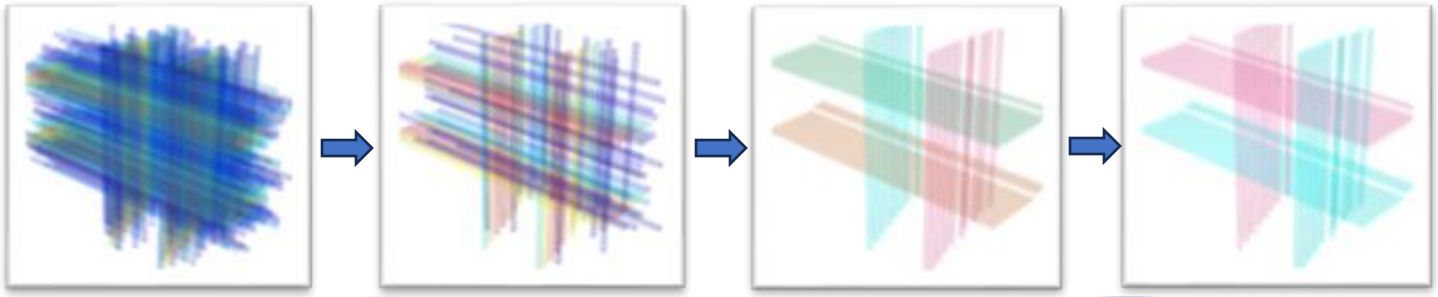
CyberPFA: PFA for crystal bar ECAL

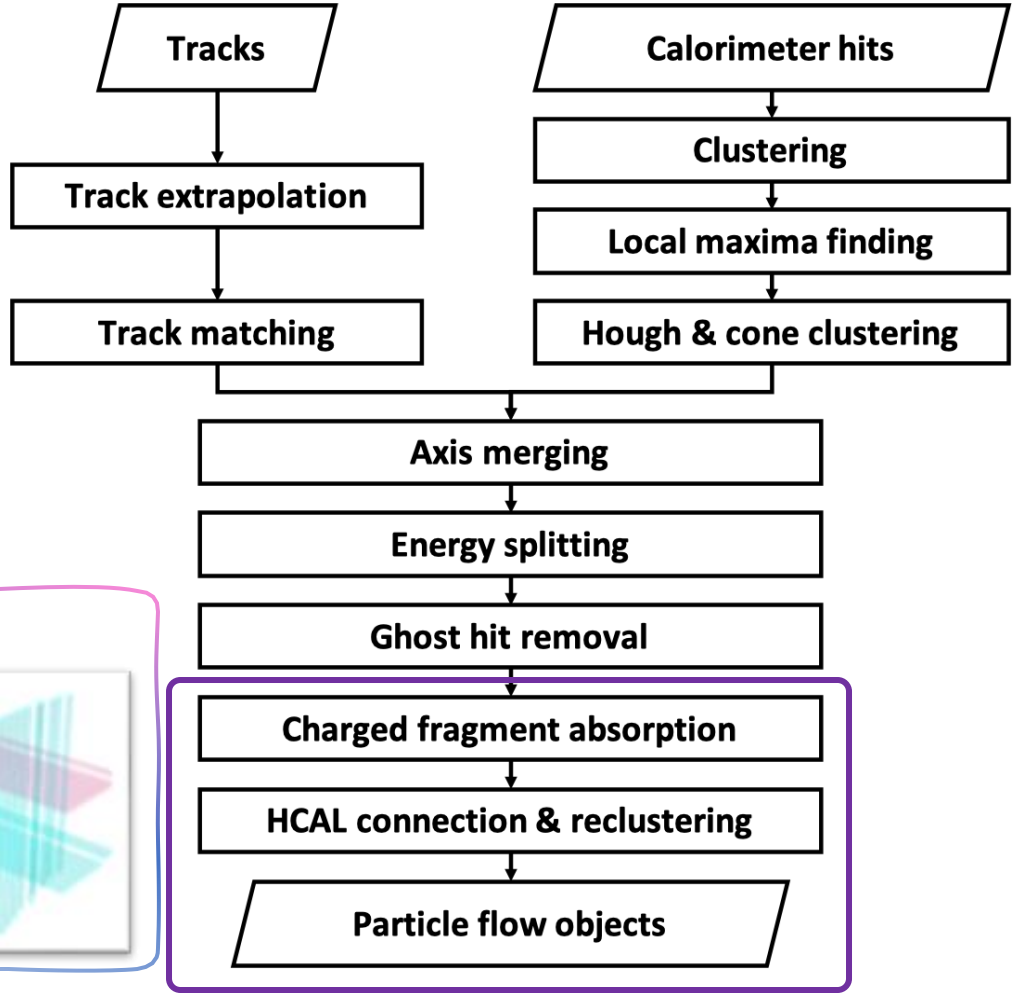
Step 4: clustering & re-clustering

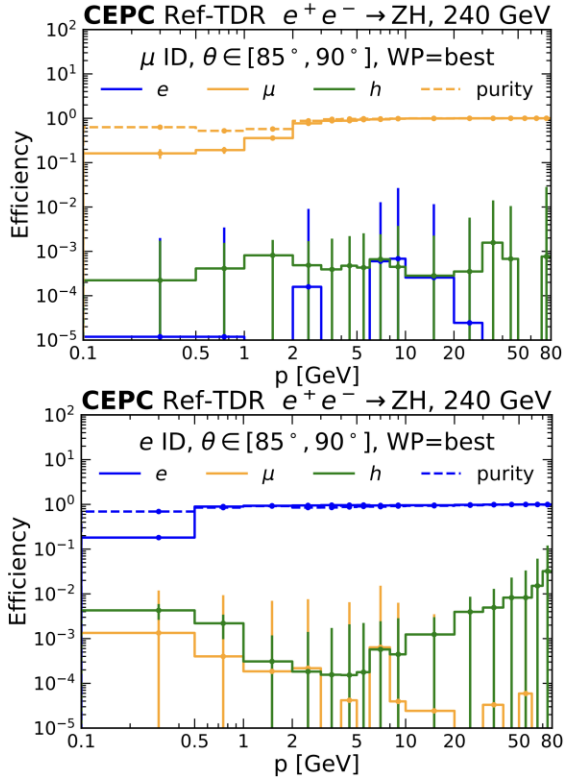
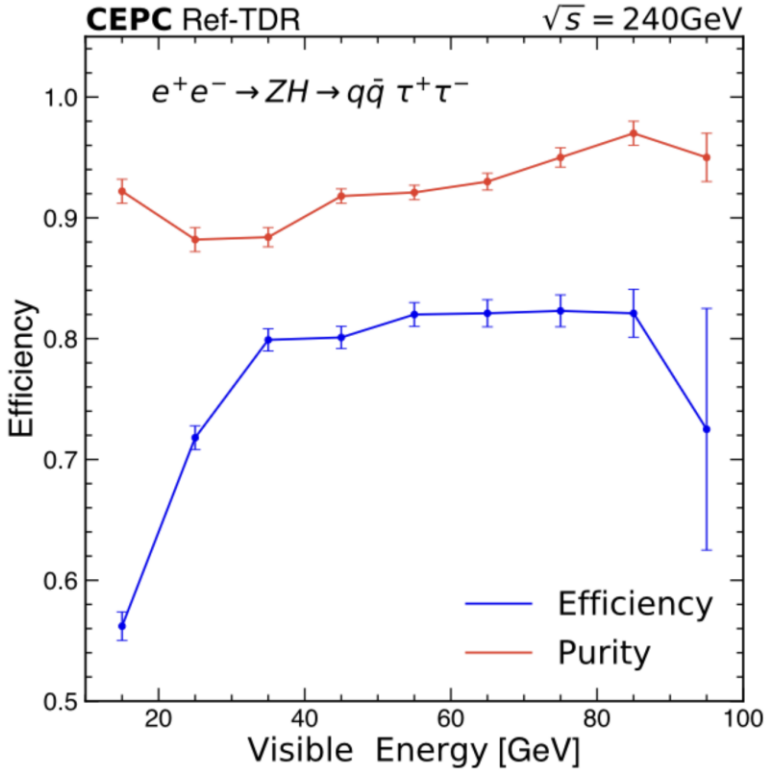
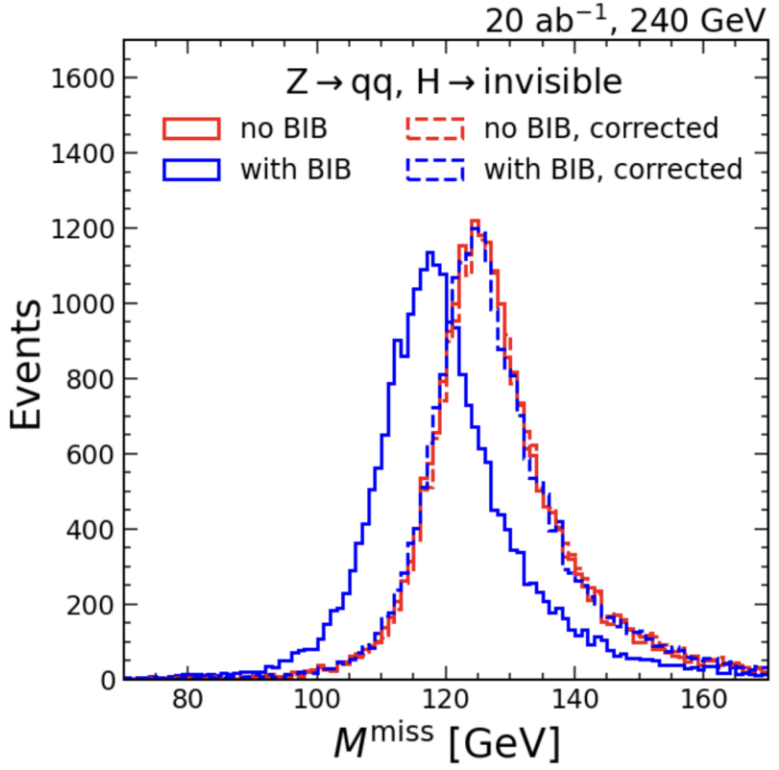
- Traditional PFA idea: $E_{cluster} \sim P_{track}$ match.



Event display: 2 photons, $E_\gamma = 5$ GeV, distance = 15×15 cm.





Physics performance with CyberPFA

- **Object identification and reconstruction:**
  - XGBoost-based lepton ID: sufficient to distinguish e/μ from charged hadrons.
  - LCFIPlus (BDT-based) hadronic τ-lepton ID.
  - Missing mass reconstruction: robust with BIB