FCC-ee Workshop on Particle Flow Reconstruction: Insights

entsprechend den Gestaltungsrichtlinien von Februar 2025

Ánuar Sifuentes Name | 18. September 2025

ETP – Institut für experimentelle Teilchenphysik

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3. PF Performance and Machine Learning Particle Flow (MLPF)

Particle Flow (PF) Reconstruction for Future Colliders

Workshop Overview

- **Event:** FCC-ee Particle Flow Workshop, CERN, 1–5 Sept 2025
- **Goal:** discuss in details the particle flow approaches for the experiments on the Future Circular Collider (FCC-ee).
- **Format:** 3 days of talks + 2 days of hands-on hackathon
- **Participants:** Around 100 persons
- **Key Question:** *How can we reconstruct particles with high precision in the complex FCC-ee environment?*

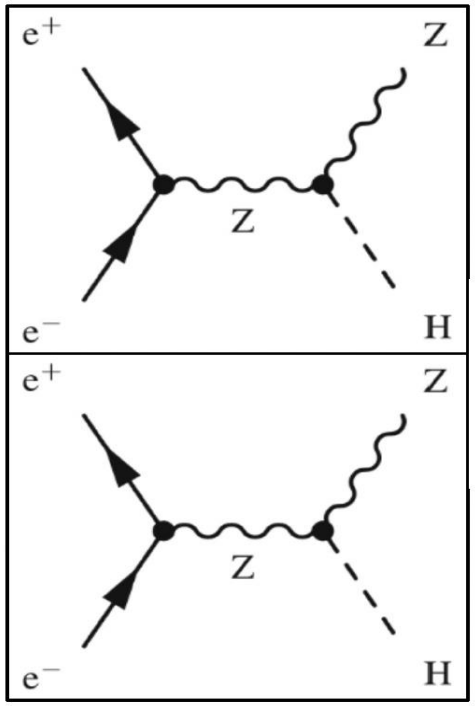
What is Particle Flow Reconstruction?

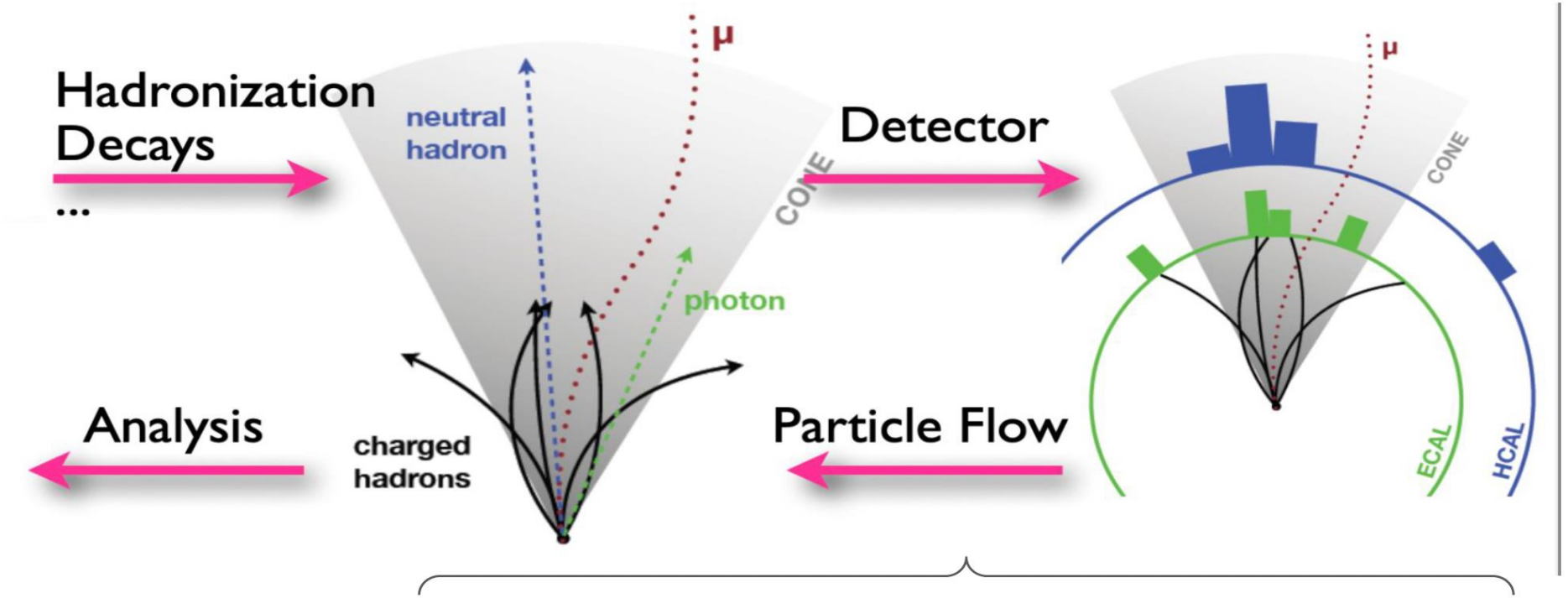
Physics process

Event generator or actual collision

Final state with quasi-stable particles

Many hits in sub-detectors (simulation or real data)





Physics interpretation

High-level identification (jets, tagging, isolation, fits)

List of identified final-state particles

Noise/fake cleaning, Clustering, Tracking, Linking, Particle ID, Particle Reco

Source: Patrick Janot. *The Particle Flow Approach* ***https://indico.cern.ch/event/1567387/timetable/***

Why Particle Flow Reconstruction?

Goal: Reconstruct collisions as precise as possible

How it works:

It combines data from all **sub-detectors** (tracker, calorimeter, muon system) to **identify every particle** in the event

- **What:** Origin, direction, energy and type (e.g. photon, electron, hadron)
- **Why:** Achieve **generator-level precision** – matching the “true” particles produced in the collision

Key advantages:

- **Maximizes resolution:** Best possible energy/momentum measurements
- **Avoids double-counting:** Each particle is reconstructed **once**, eliminating overlaps
- **Enables physics analysis:** From jet tagging to missing energy searches (e.g. dark matter, Higgs decays)

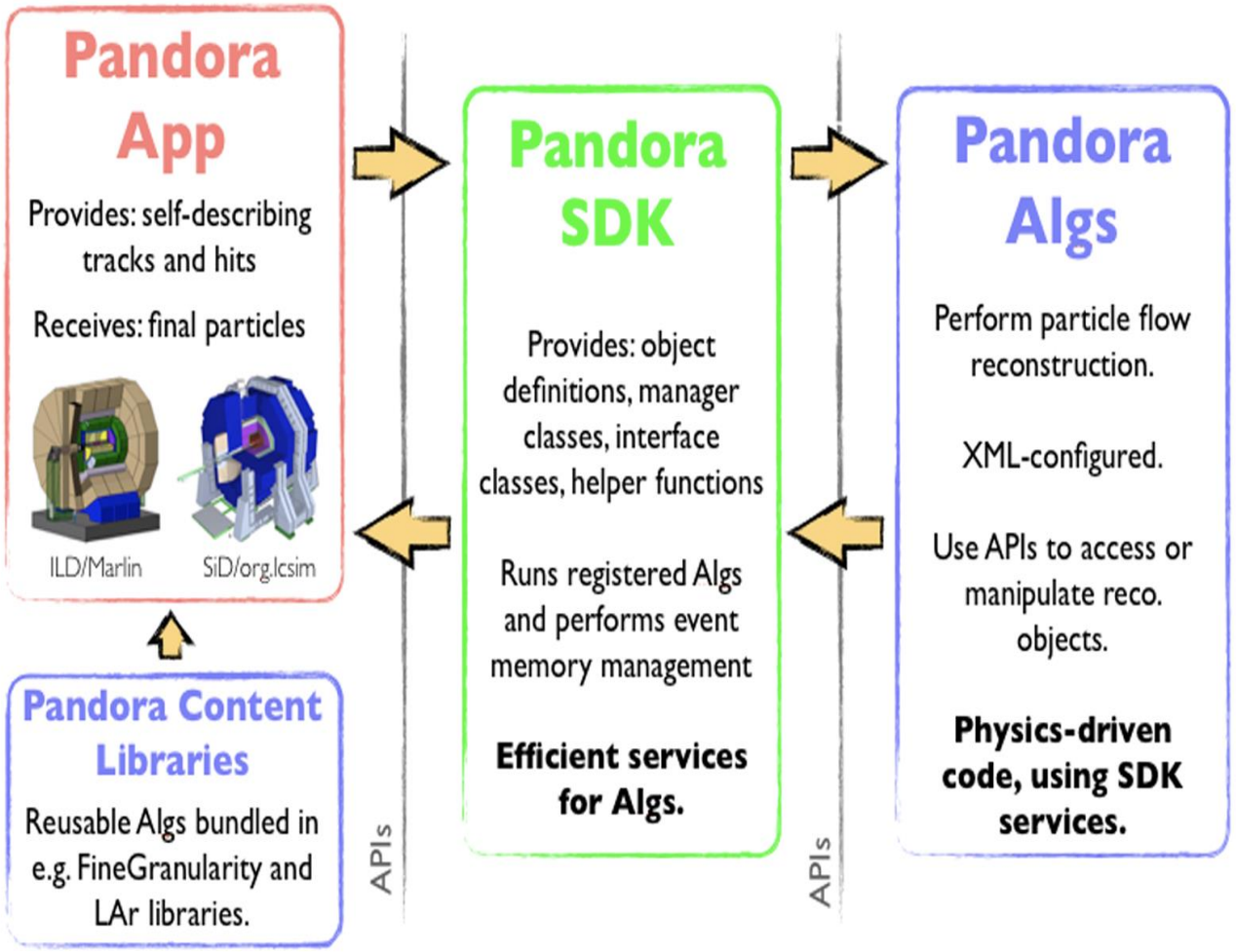
Ideal outcome:

deliver a ***complete and accurate*** **list of all particles produced in a collision**— matching the 'true' physics event as closely as possible.

How to do PF Reconstruction? Introducing Pandora

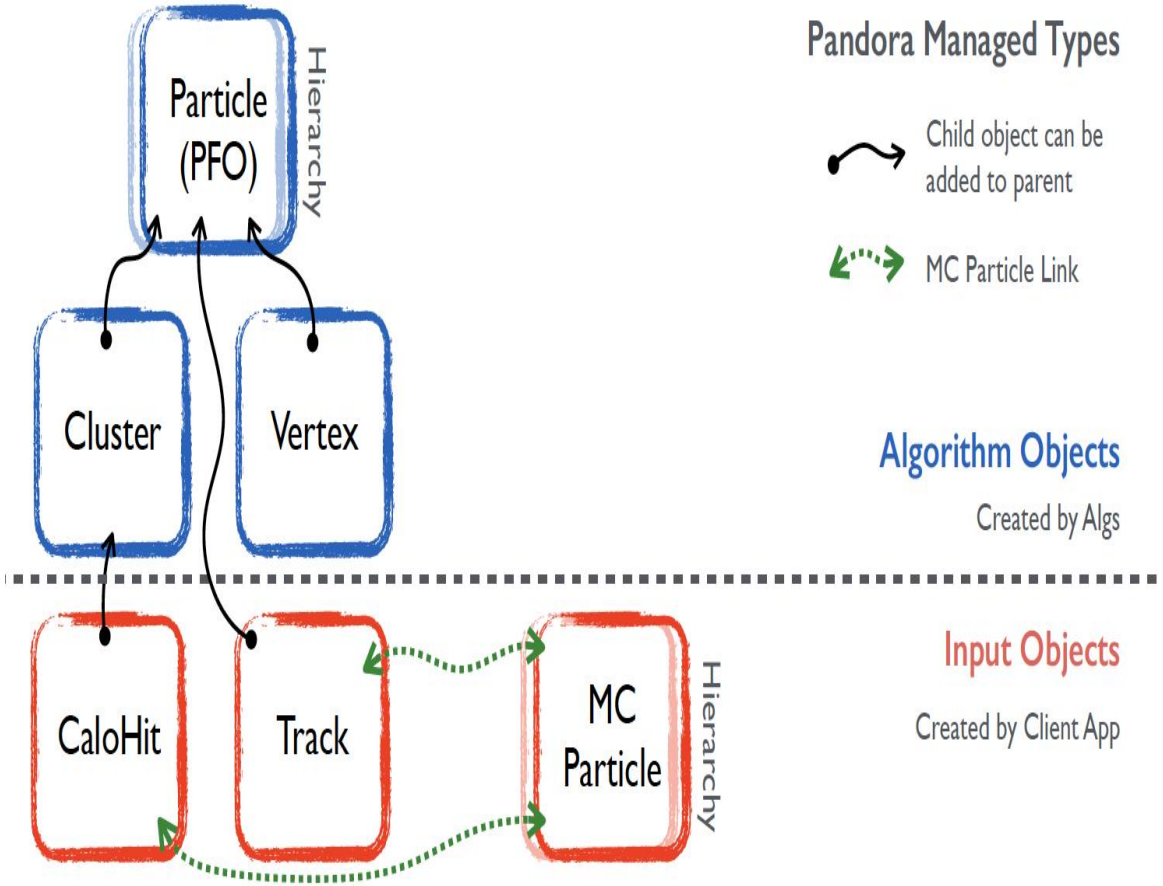
Introduction to Pandora – The PF Framework

- **What:** Open-source software that combines data from all sub-detectors to reconstruct individual particles
- **Purpose:** It uses a modular and multi-algorithm approach to PF reconstruction:
  - **Clustering:** Organizes raw detector hits into **clusters**
  - **Cluster refinement:** Merges/split clusters to optimize purity/efficiency
  - **Hierarchichal Grouping:** Assambles Clusters into **Particles**
  - **Iterative Processing:** Gradually builds complex event structures via **sequential algorithms**



Source: J. S. Marshall and M. A. Thomson. *Pandora Particle Flow Algorithm* arXiv:1308.4537 **[physics.ins-det]**

Event Data Model: Bridge between Detector Data and Particle Reconstruction



Source: J. S. Marshall. *Pandora SDK*
https://indico.cern.ch/event/1567387/timetable/

What is EDM: Standardized data format for pattern recognition problems to represent:

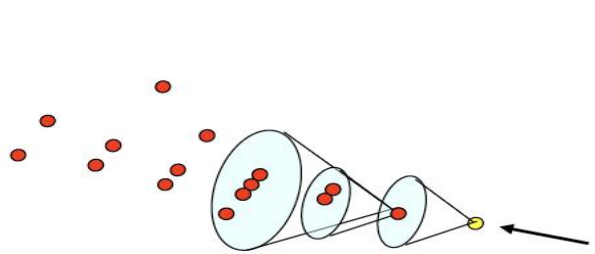
- **Raw inputs:** Detector hits (CaloHits and Tracks)
- **Reconstructed objects:** Particles, Vertices, Clusters

Why: EDM decouples algorithms from detector specifics
Its aim is to be **self-describing,** each object provides all information required to allow investigation

Pandora's Use of EDM:

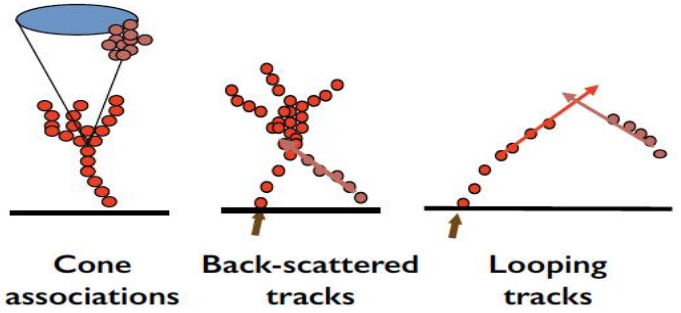
1. **Input:** Reads EDM Objects (Calohits, tracks, MC Particle for validation)
2. **Process:** Runs clustering / PID algorithms on EDM objects
3. **Output:** Writes Particle Flow Objects (PFO. Particles with metadata describing them)

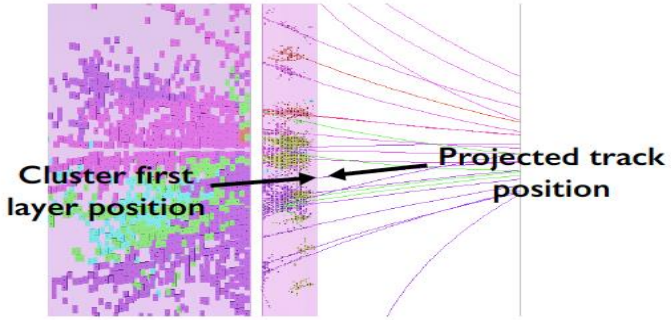
Pandora – Particle Flow Algorithms



ConeClustering

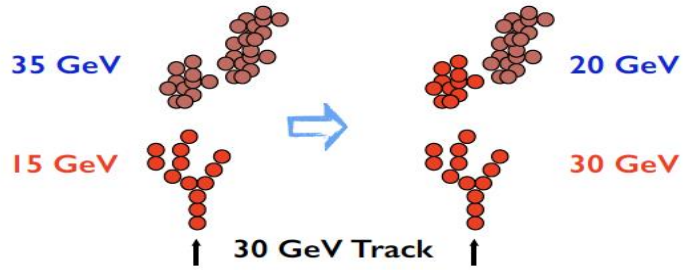
Topological Association

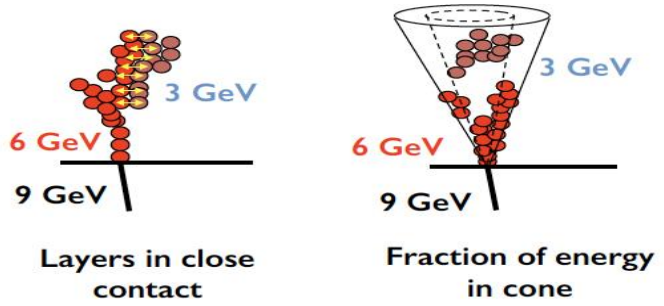




Track-Cluster Association

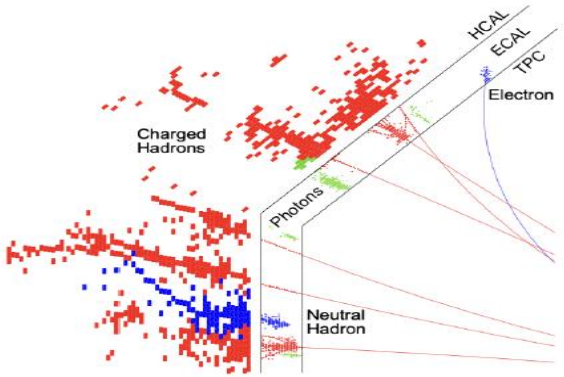
Reclustering





Fragment Removal

PFO Construction



Source: J. S. Marshall. *Pandora SDK*
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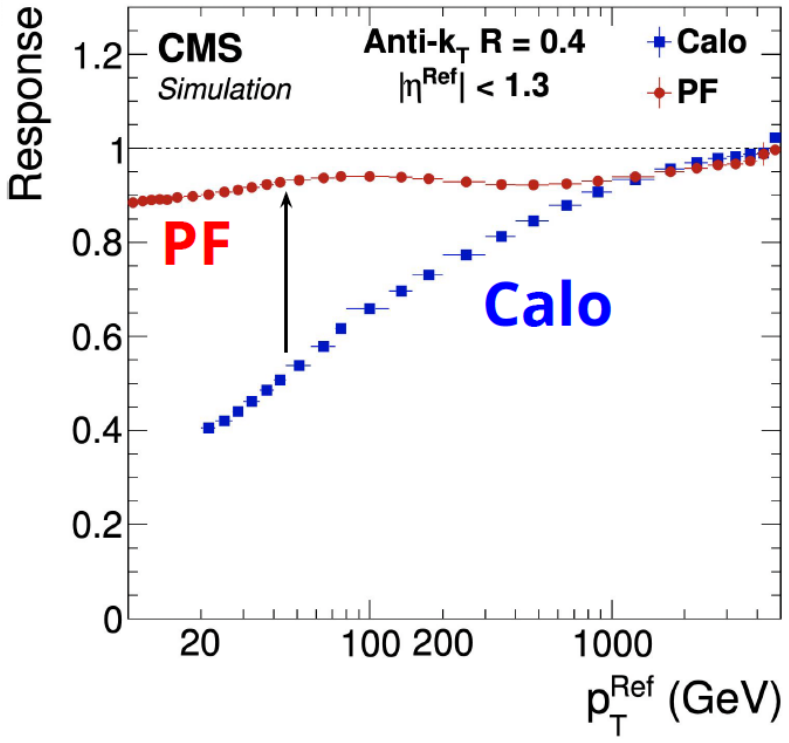
Particle Flow Performance and Machine Learning Particle Flow (MLPF)

PF in the past: Lessons from CMS

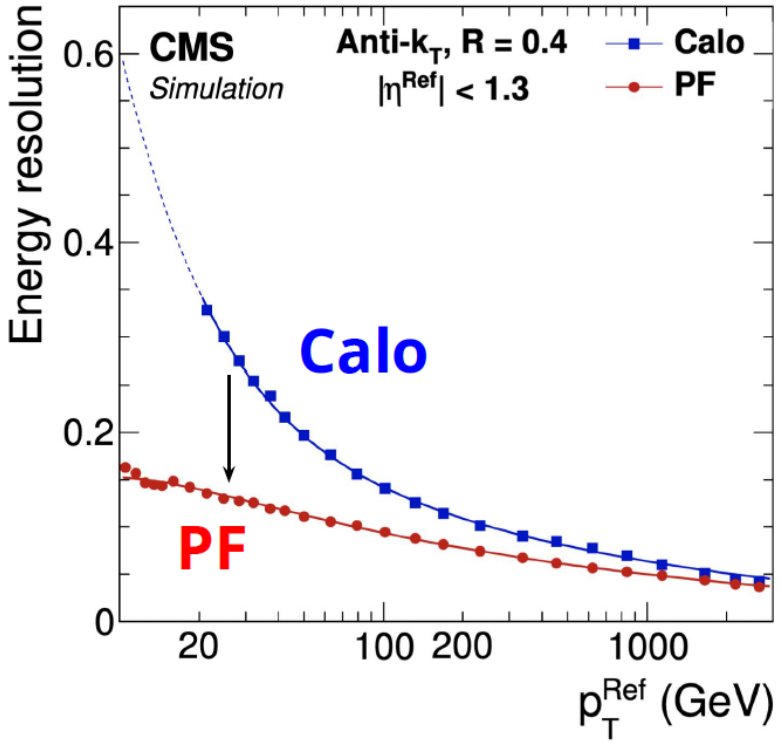
PF algorithm has been **crucial** for **physics measurements,** improving the performance of:

- Jets and missing transverse momentum (magnitude and direction)

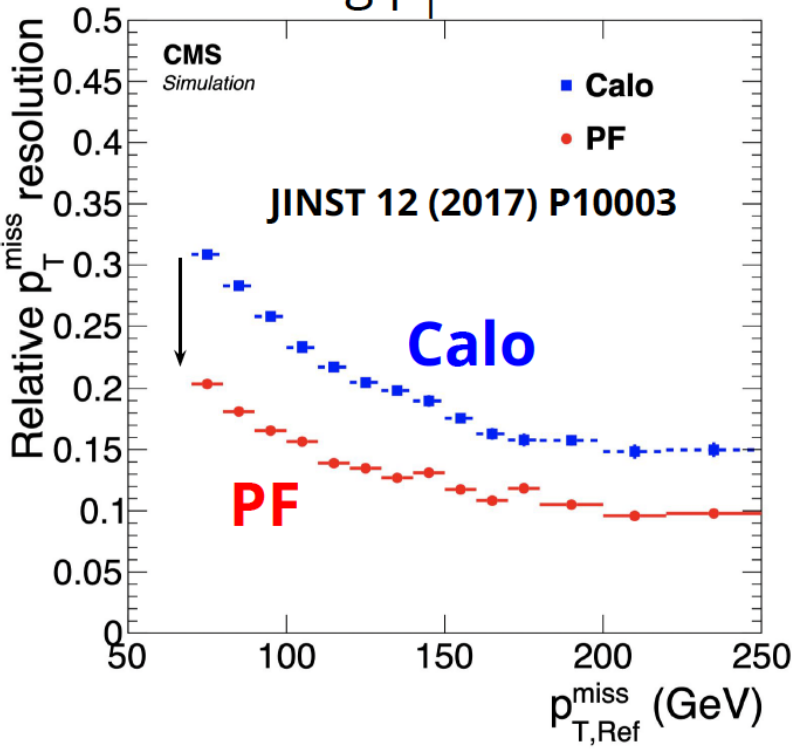
Jet energy response



Jet energy resolution



Missing p_T resolution



Source: *Andre Ståhl. Overview of Particle-Flow in CMS*
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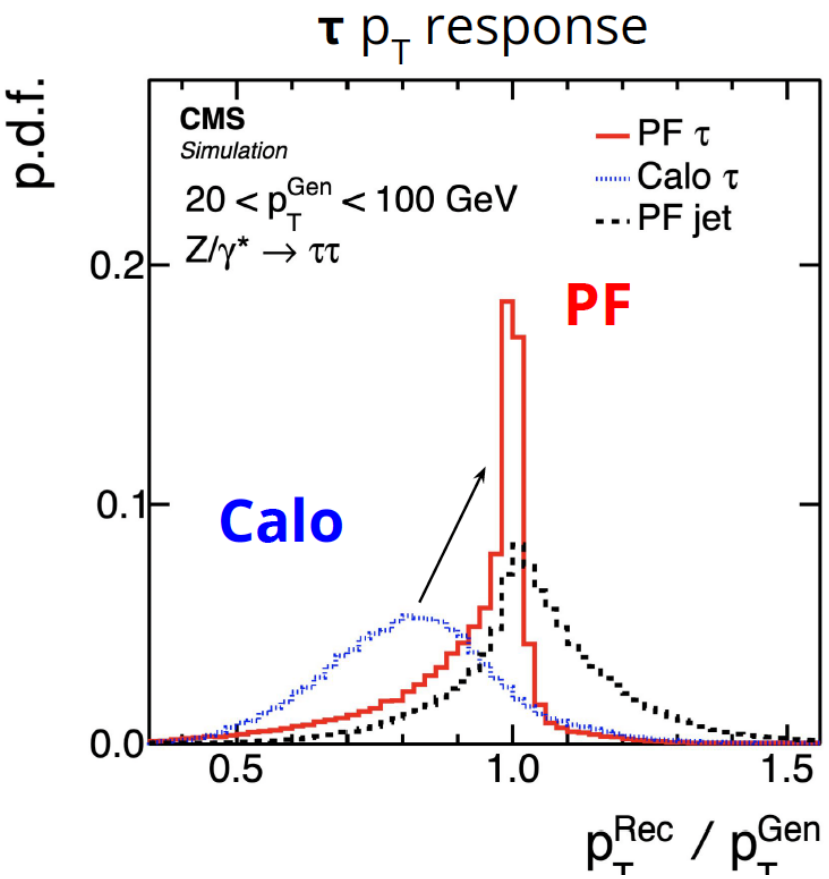
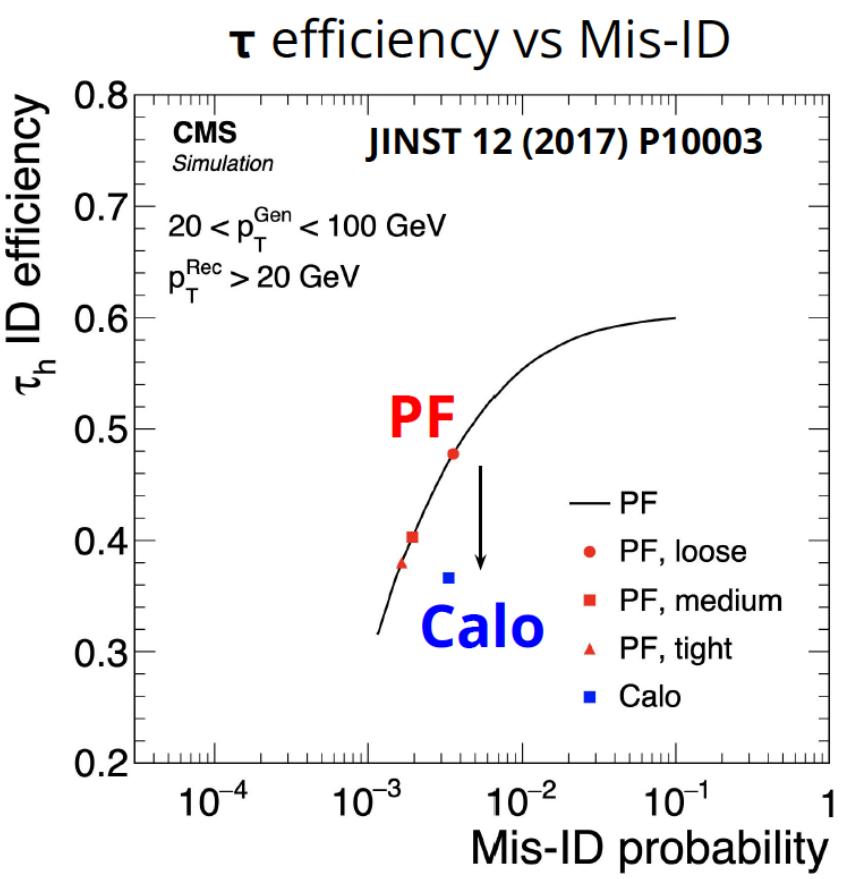
- Jets and missing transverse momentum
- Hadronic taus and particle identification in general





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Machine Learning Particle Flow (MLPF)

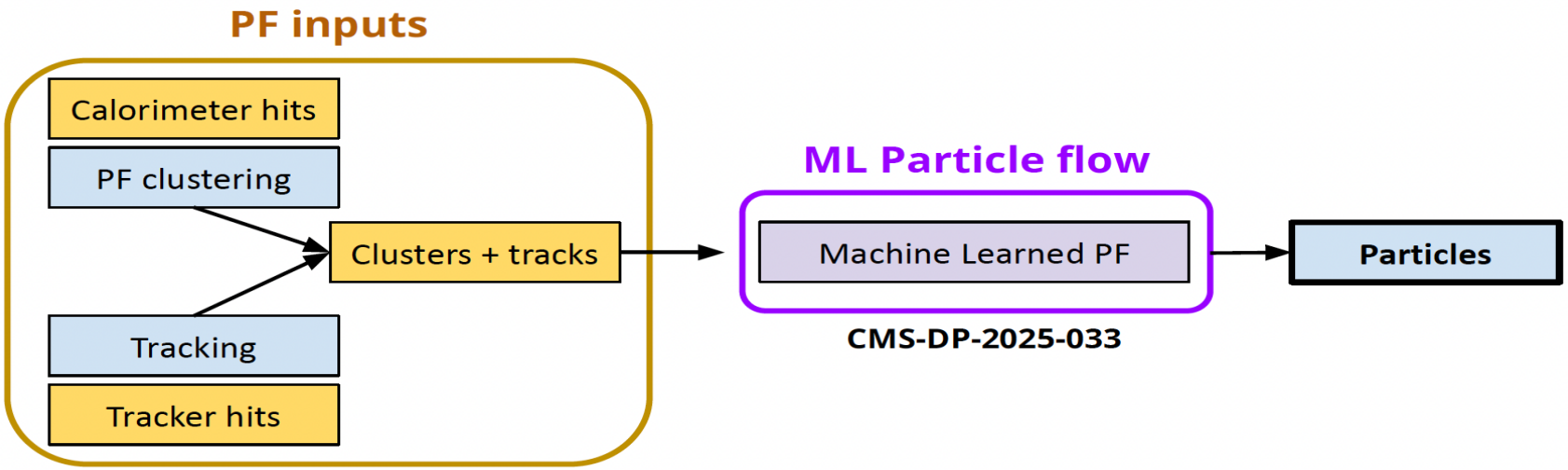
The use of **Machine Learning (ML)** can improve the general performance of PF!

Key strengths of ML:

- Pattern Recognition (e.g. identifying particle signatures)
- Classification (e.g. distinguishing photons from neutral pions)
- Regression (e.g. predicting particle energy/momentum)

CMS provides a **unique opportunity** to study ML_based MLPF, it improves:

- Particle ID (neutral vs charged hadrons)
- Pileup mitigation (separating signal from noise in high-luminosity collissions)



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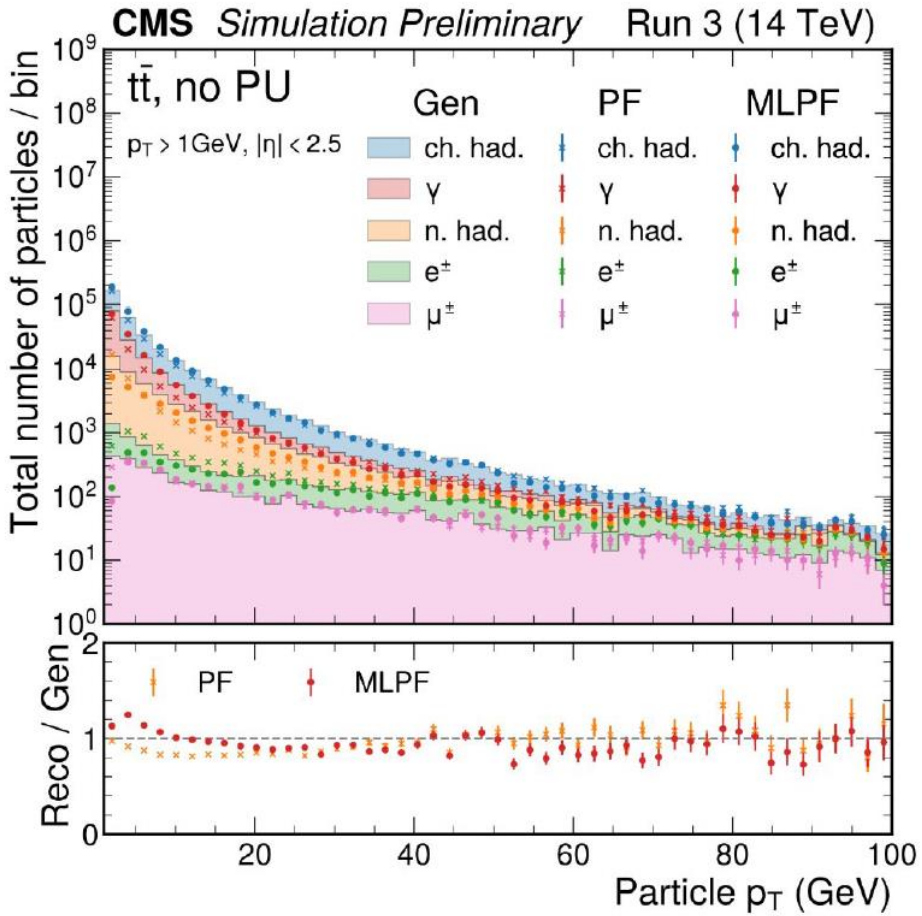
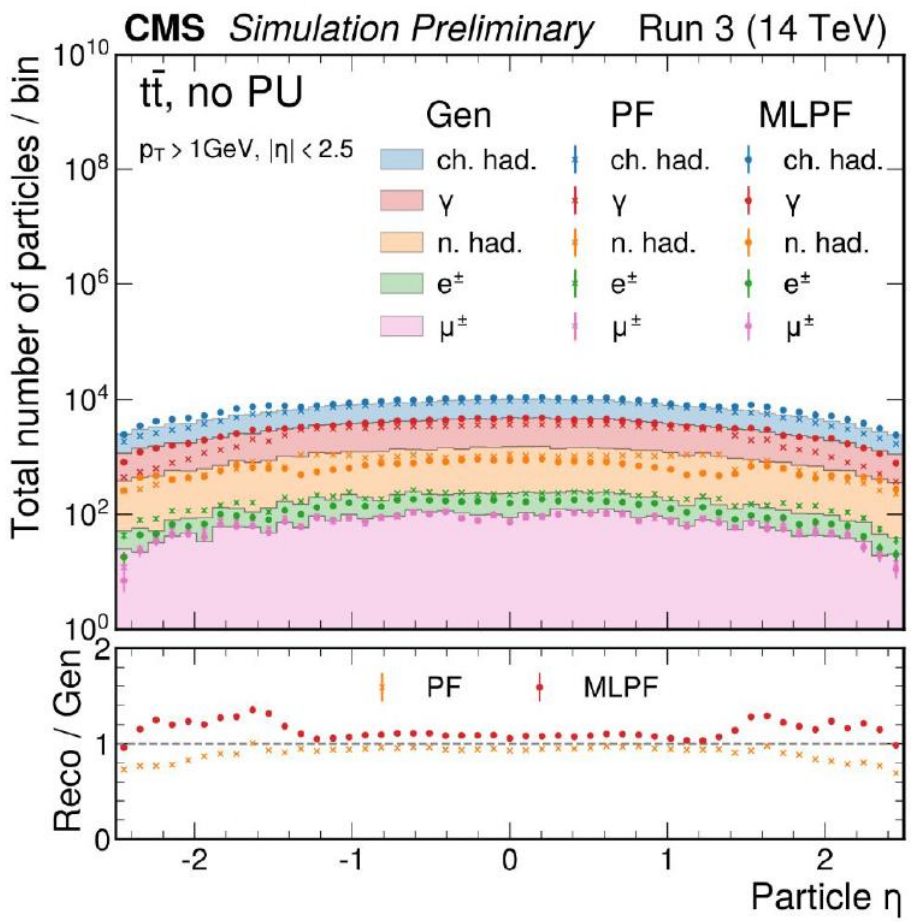
Particle Reconstruction Performance with MLPF

MLPF shows realistic particle-level performance





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Conclusions & Opportunities for KIT

- **Particle Flow Reconstruction** is a powerful tool to improve reconstruction (in comparison to calorimetric-only or track-only reconstruction)
- It provides the **best (and easiest to obtain)** analysis performance
- **Pandora for FCC:** It is an existing, robust, modular framework for PF.
- **Pandora** offers a **"near-of-the-shell" solution** for PF in FCC-ee detector concepts, enabling quick deployment
- **Pandora is open to innovation:** Plenty of opportunities to develop new algorithms and optimize performance with its robust structure
- **Machine Learning PF** is a great tool to enhance PF

KIT's Unique Opportunities

Area	Action
PF Implementation in FCC-ee	**Implement and validate PF reconstruction** for **all FCC-ee detector concepts** (CLD, IDEA, etc.) using **Key4hep/EDM4hep**.
ML Innovation	Develop KIT-specific ML Models (e.g. GNN for shower reconstruction)
Pandora Algorithm Expansion	**Add and optimize new algorithms** in Pandora. Contribute upstream to the **PandoraPFA** framework
Training	Host a **PF/MLPF hackathon** at KIT to train students/postdocs and prototype new ideas. Invite CMS/CEPC experts for cross-collaboration.

Thank you for your attention!