Particle flow approach in future lepton colliders

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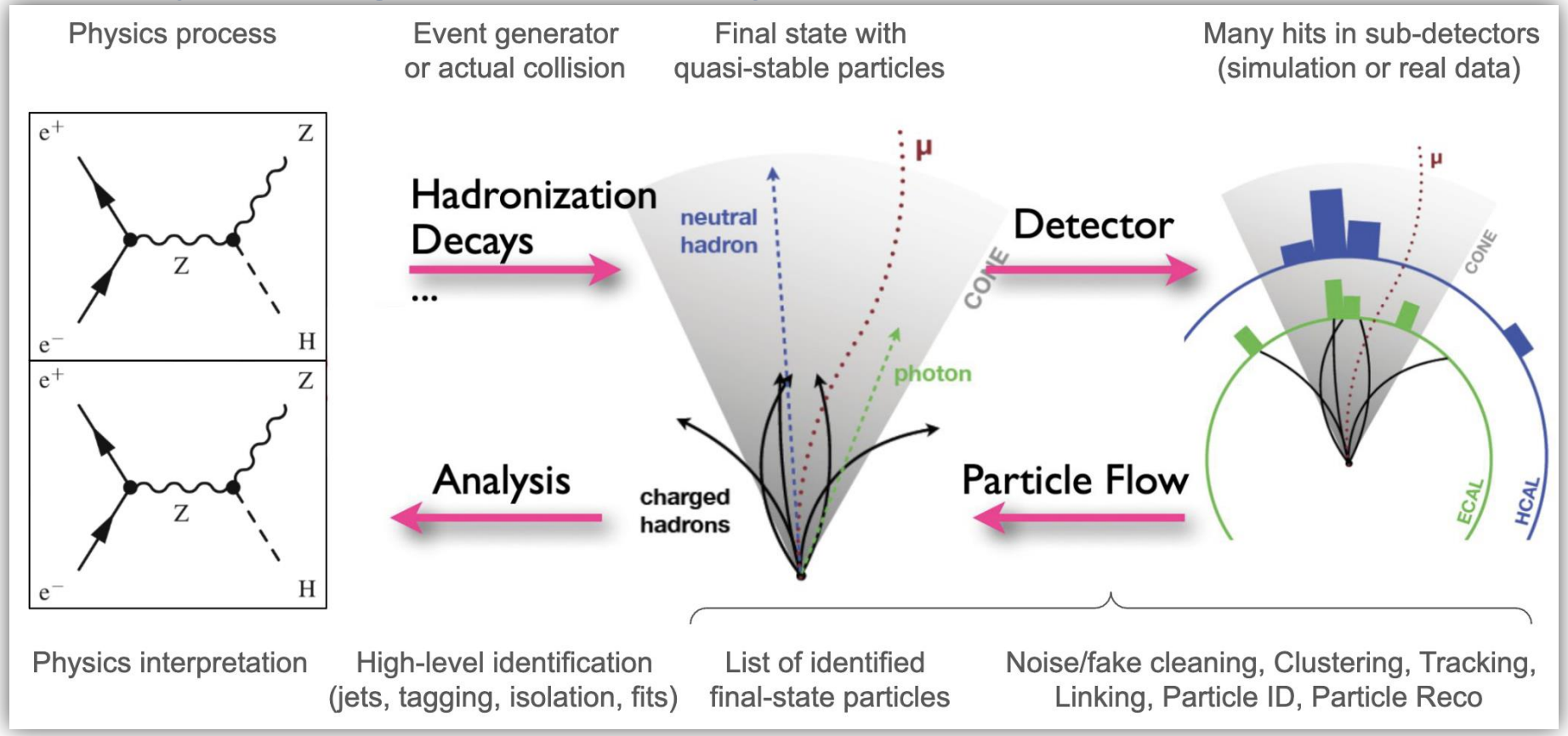
Introduction: what is particle flow?

- **Ideally: reconstruct & identify all stable particles in detector**
  - With best possible resolution / efficiency / purity and minimum overlap.
  - **"As perfect as generator-level analysis"**

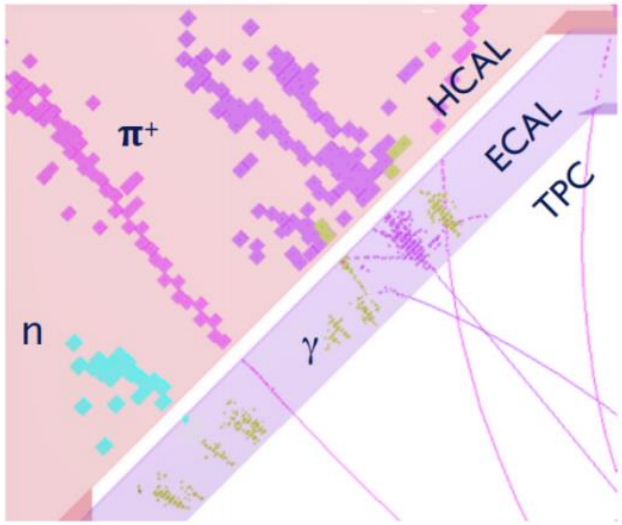


P. Janot, FCC-ee workshop

Introduction: how we can reach

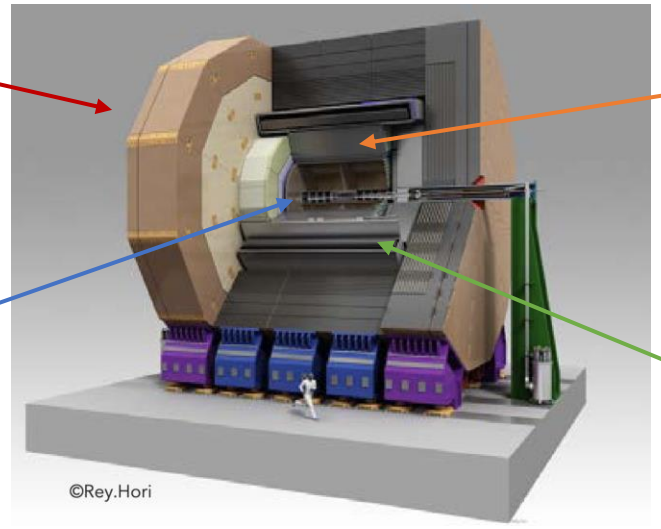
- **Correlate measurements from all sub-detectors:**
  - Jet measured by its component $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$.

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	$\sim 0.1E_j$	$0.55\sqrt{E_{h^0}}$	$0.17\sqrt{E_j}$



- **Specific detector design: ILD as 1st proof-of-principle**

4π hermeticity.



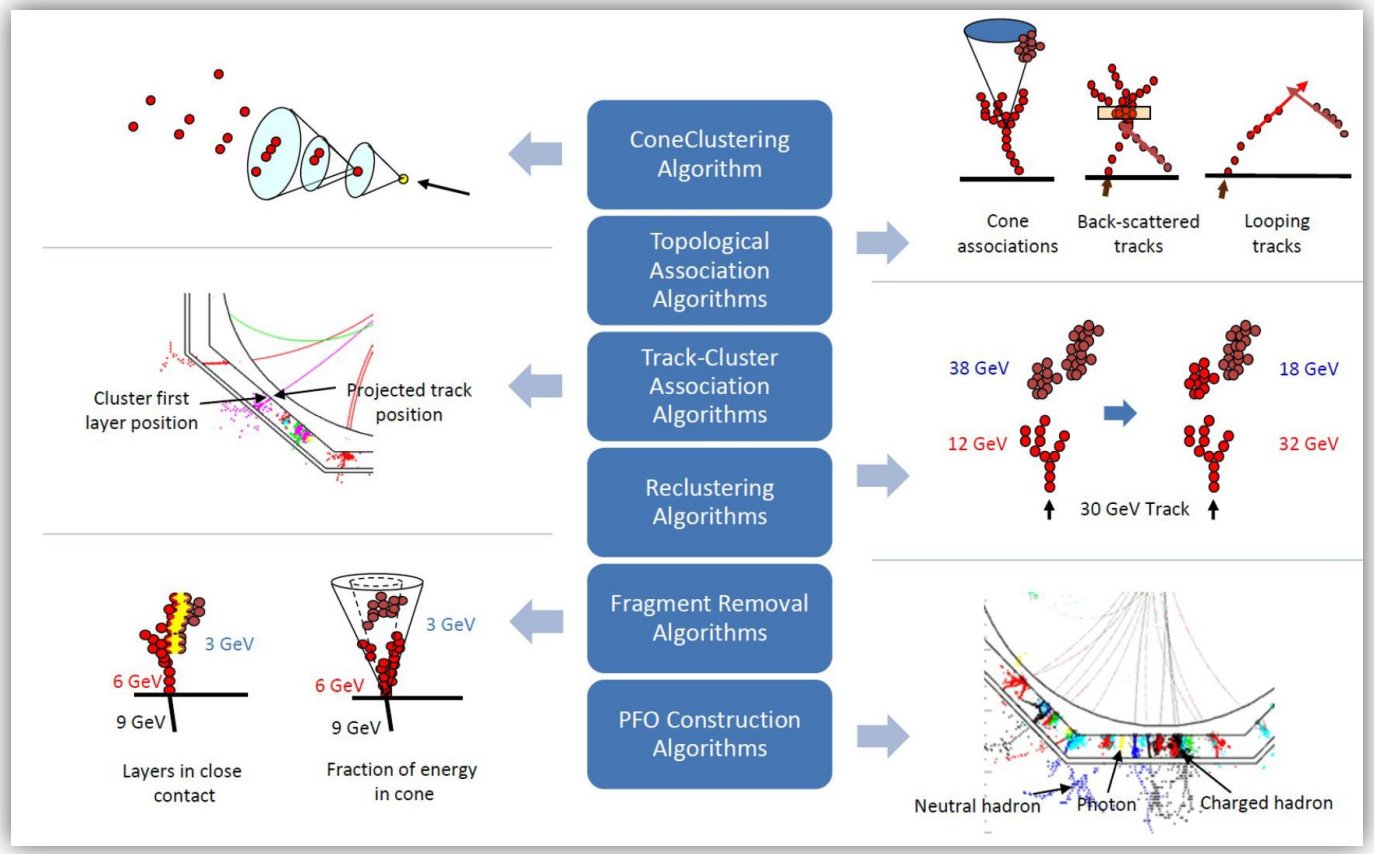
Fine 3D segmentation + shower compactness in calos:
Si-W ECAL + Steel-Scintillator HCAL

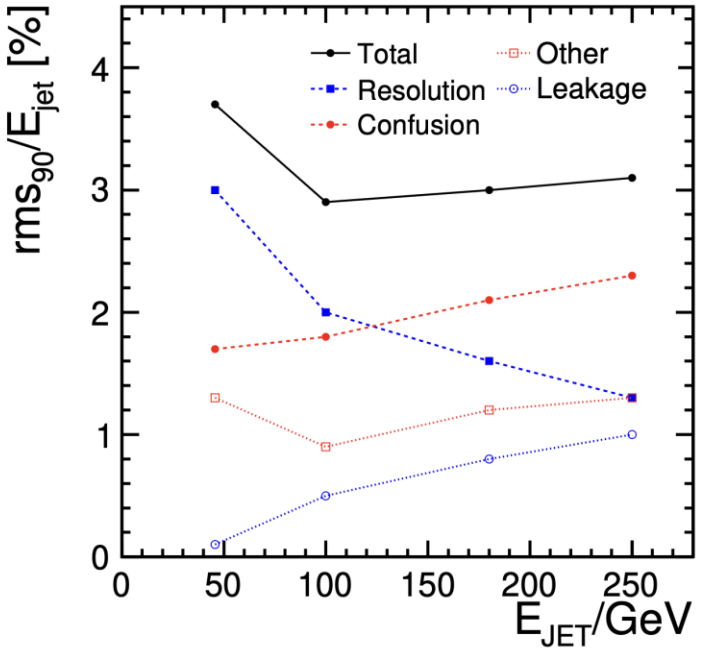
Little material in front of the calorimeters:
SiT + TPC as main tracker

Large magnetic field for $h^{\pm}$/ $l^{\pm}$ separation:
3.5 T solenoid.

Introduction: how we can reach

- **Off-line Reconstruction: PandoraPFA**
  - Jet energy resolution: **2.9% @ 100 GeV.**
    - Contribution: intrinsic resolution + leakage + confusion + …



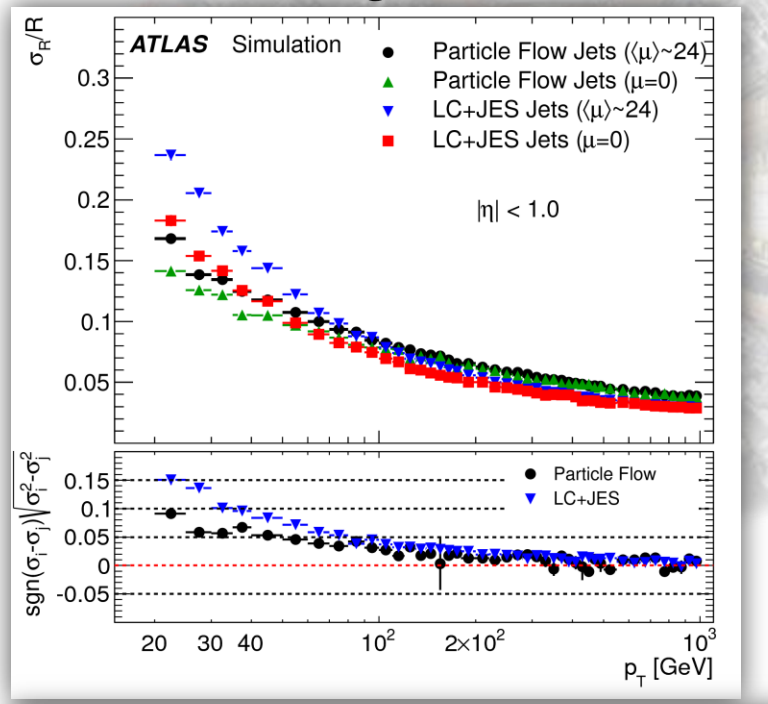


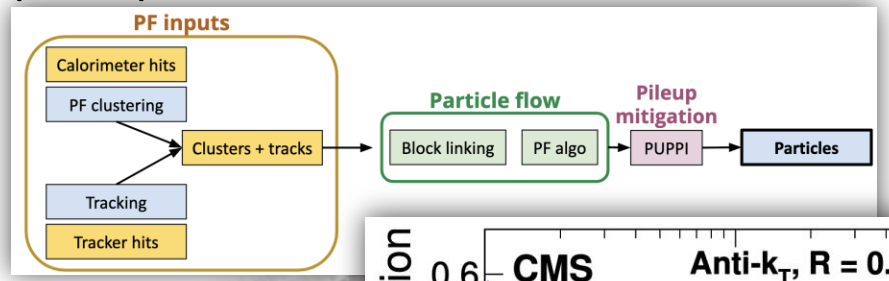
M.A. Thomson, NIM 611 (2009) 24-40

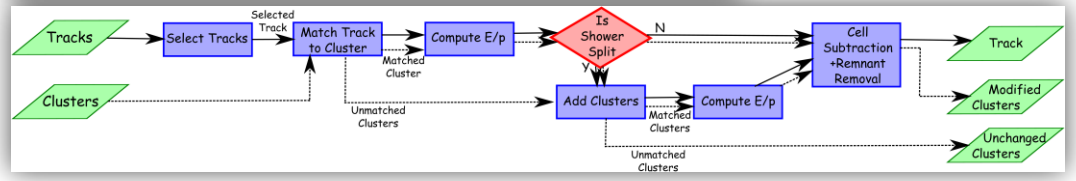
Particle flow in ATLAS and CMS

- **The PF idea has been validated in ALPHE, ATLAS and CMS**
  - Even though none of them is designed with PF principle.

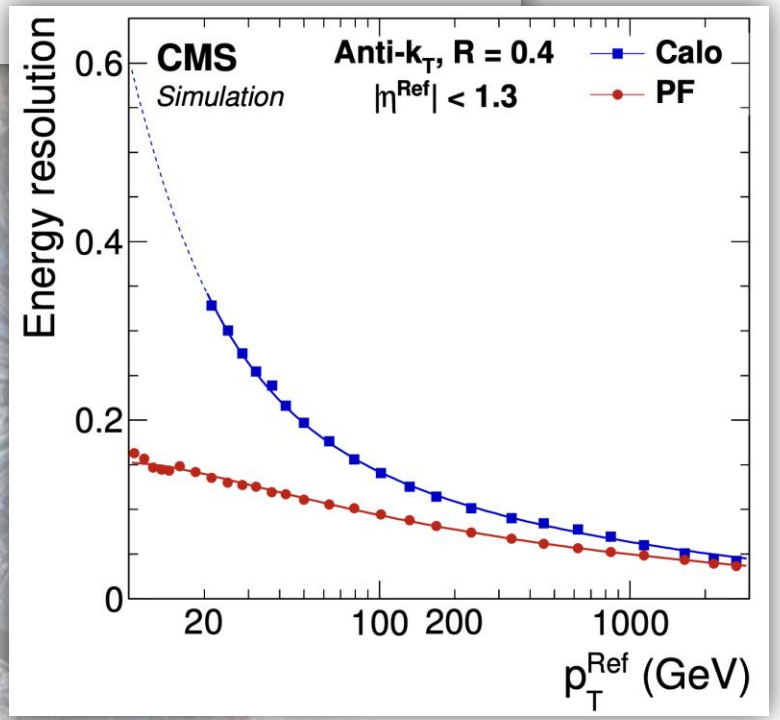
CMS, 2017 JINST 12 P10003





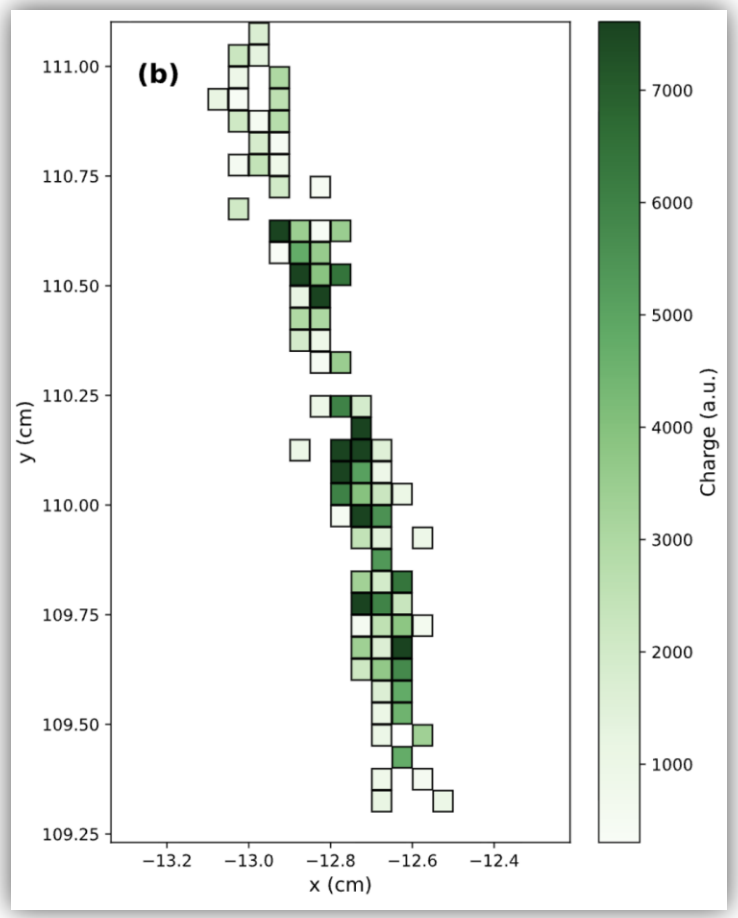


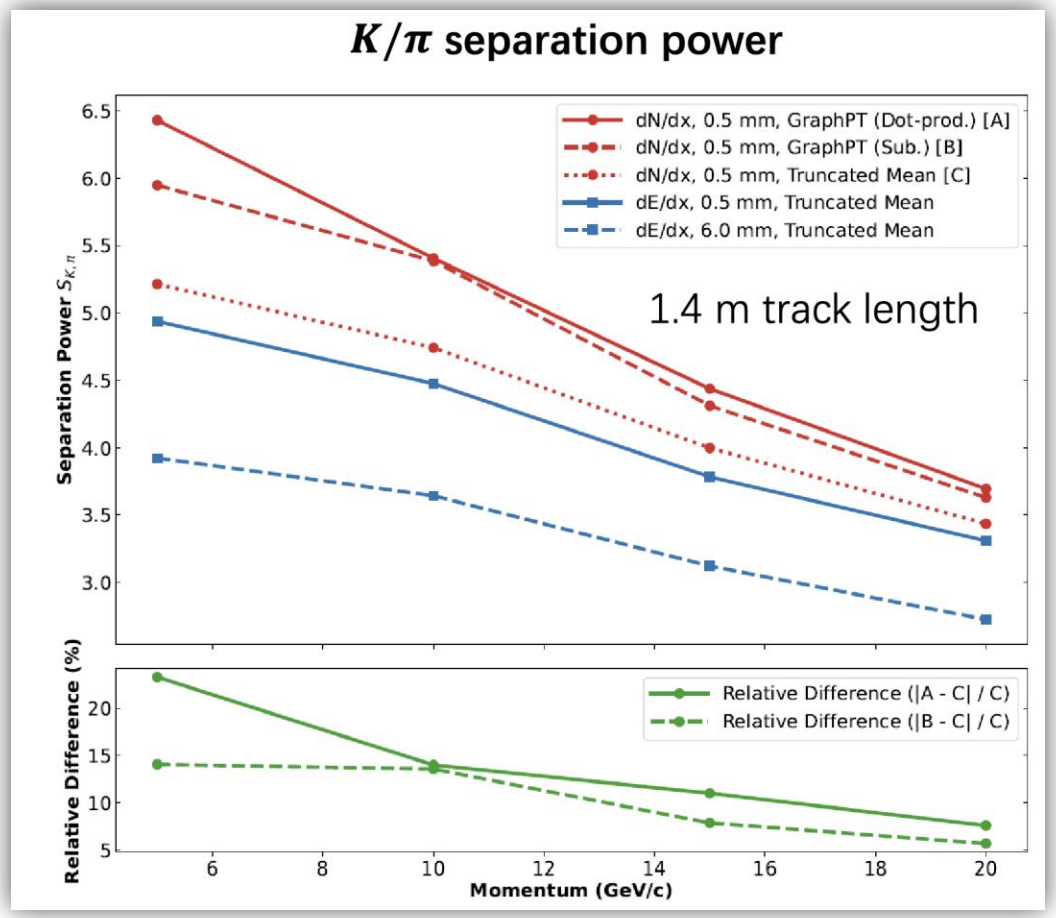
ATLAS, Eur. Phys. J. C 77 (2017) 466



Particle flow in future: next stage?

- **Tracking with PID and timing ability**
  - Cluster counting (dN/dx) technology in gaseous detector + graphPT



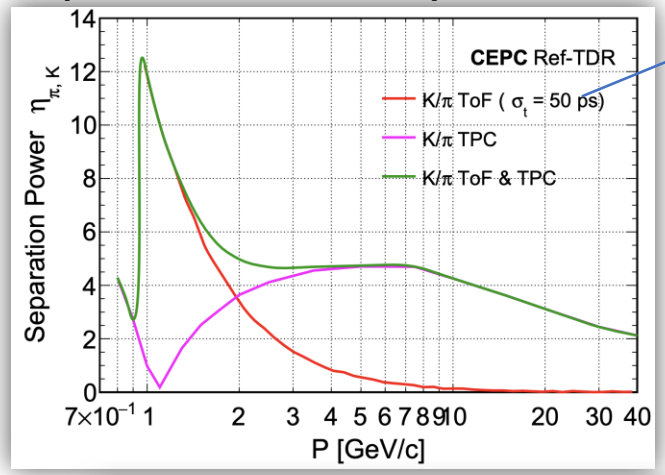


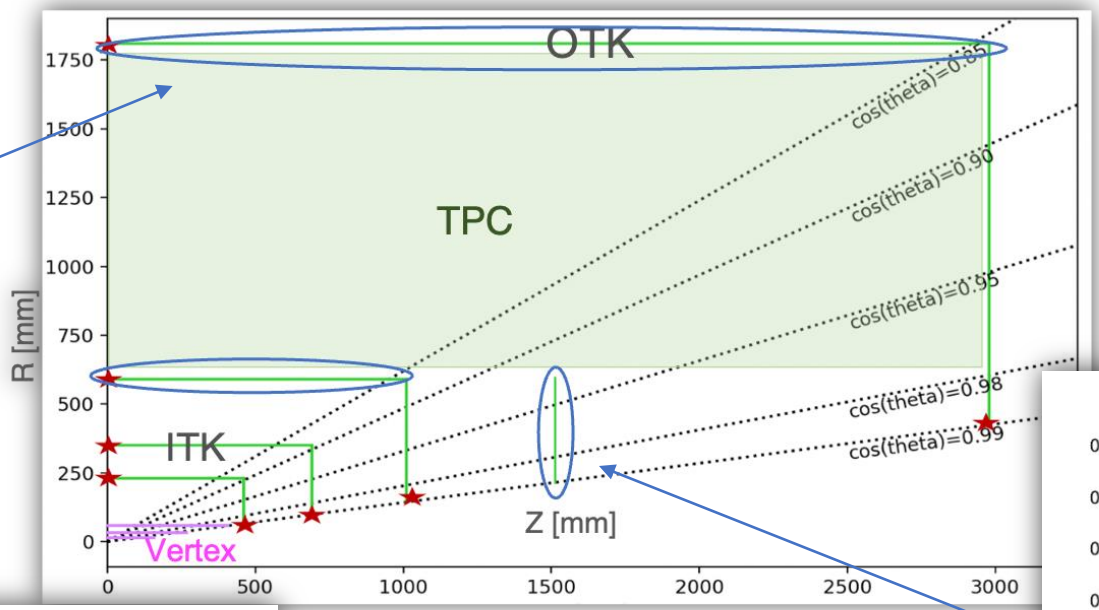
Guang Zhao et.al, arxiv 2510.10628

Particle flow in future: next stage?

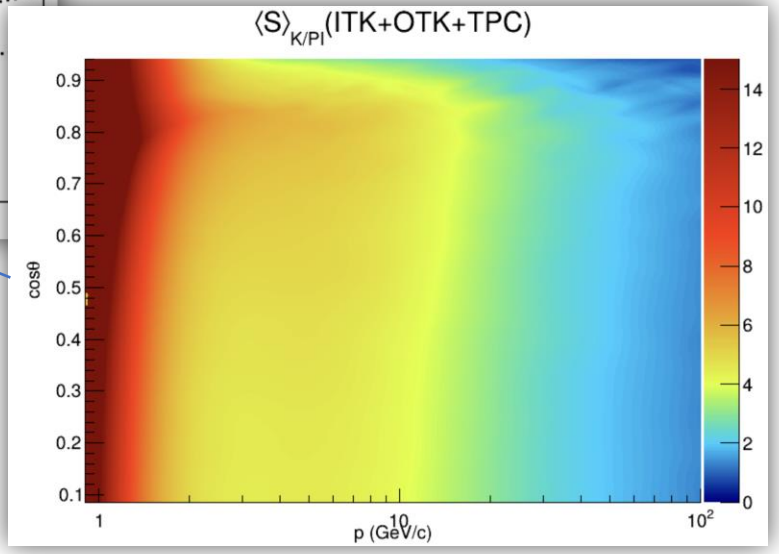
- **Tracking with PID and timing ability**
  - Timing layers in Silicon tracker (LGADs): 4D tracking

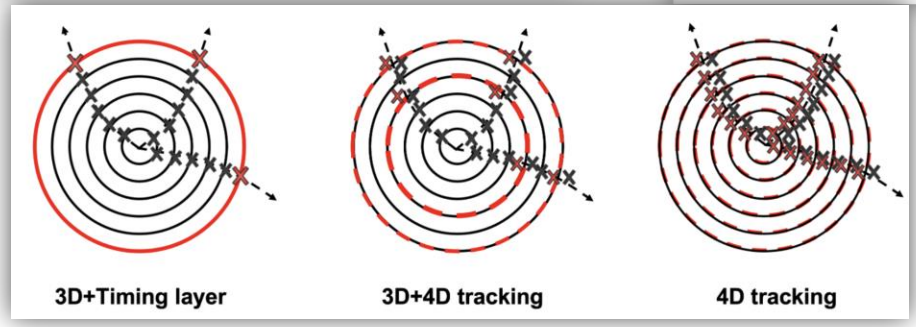
With timing in outmost layer (CEPC Ref-Det TDR)





With timing in last layer ITK (Dian Yu et.al, arxiv 2507.18164)

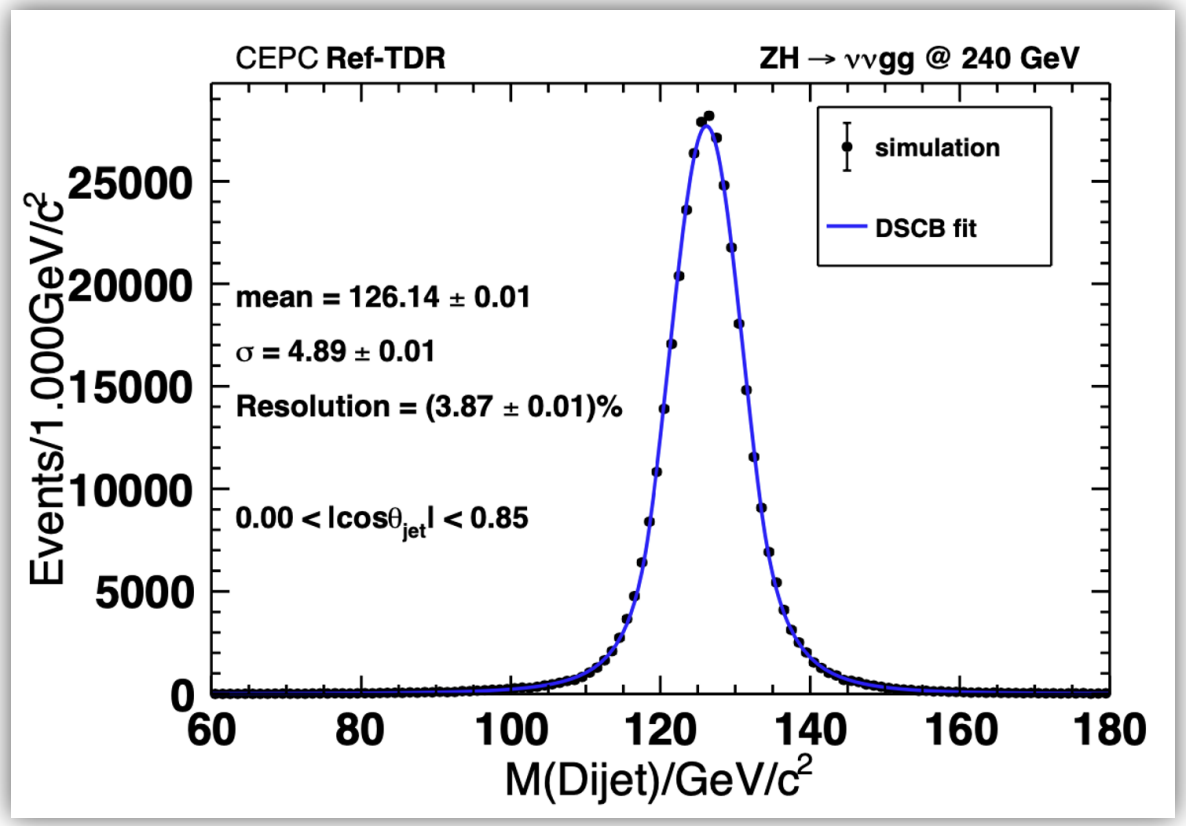


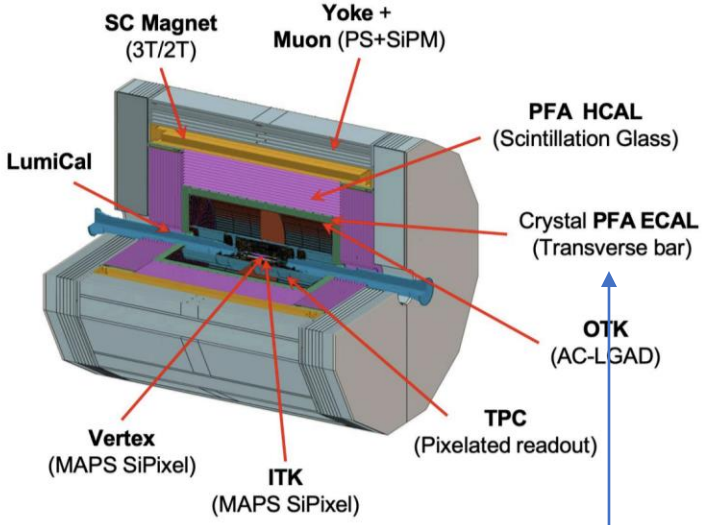


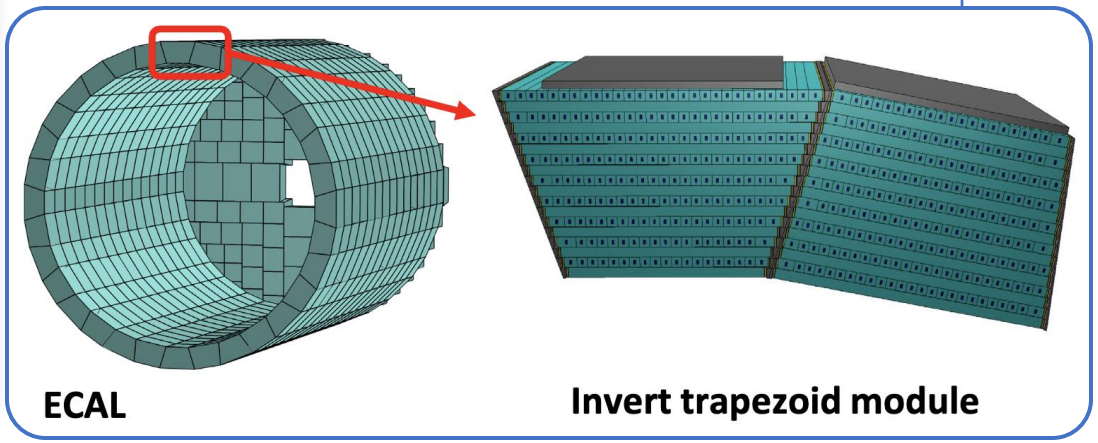
With timing layer in all Si-tracker ?

Particle flow in future: next stage?

- **Homogeneous calorimeter + pseudo High granularity @ CEPC Ref-Det**
  - Crystal-bar structure: better EM resolution, less readout channels.
  - CyberPFA: maintain the similar jet performance.

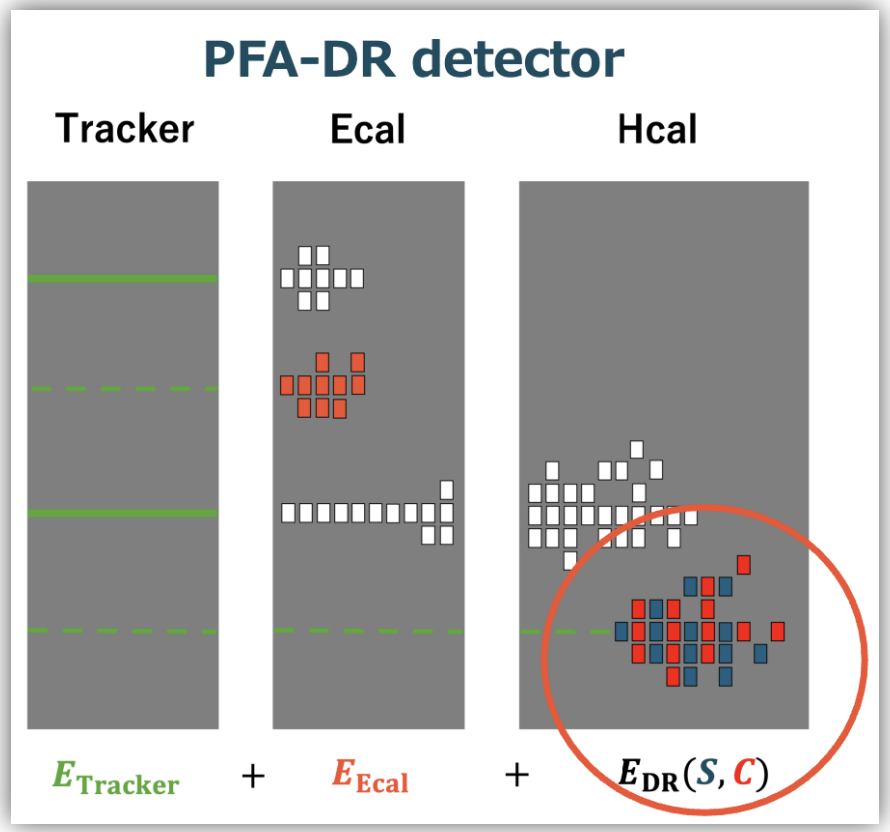


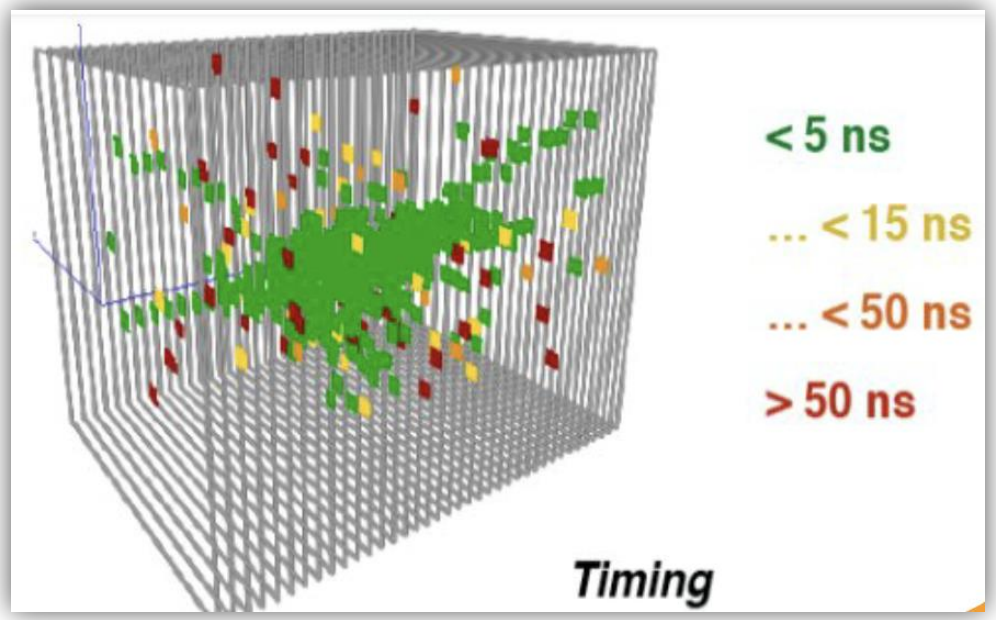




Particle flow in future: next stage?

- **Dual-readout + timing + PFlow: additional dimension of information**
  - Shower clustering + PID with timing
  - Excellent hadronic resolution from S + C measurement for EM and non-EM component.



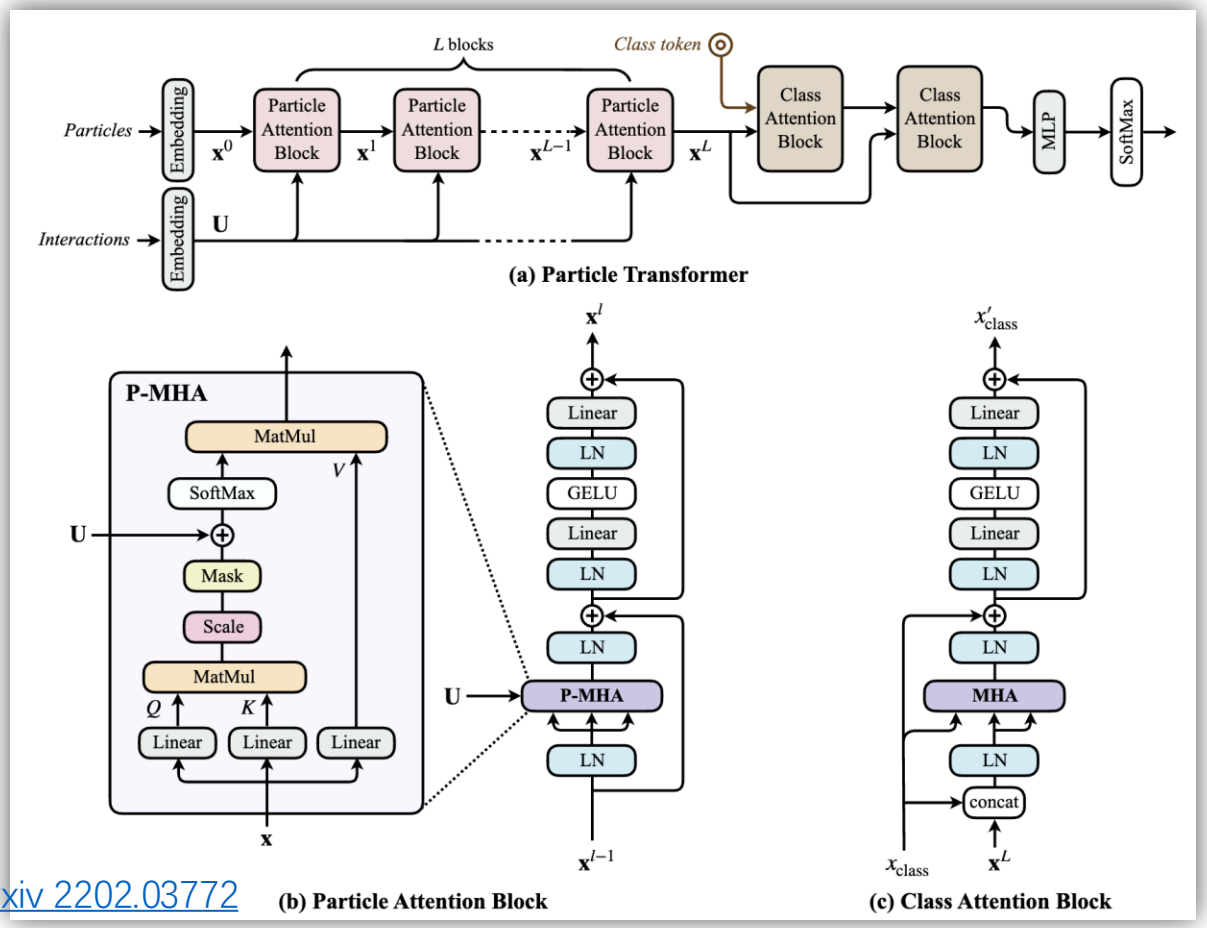


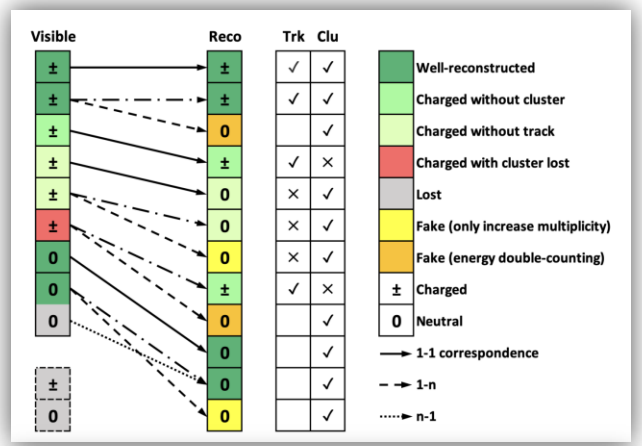
Vincent's report

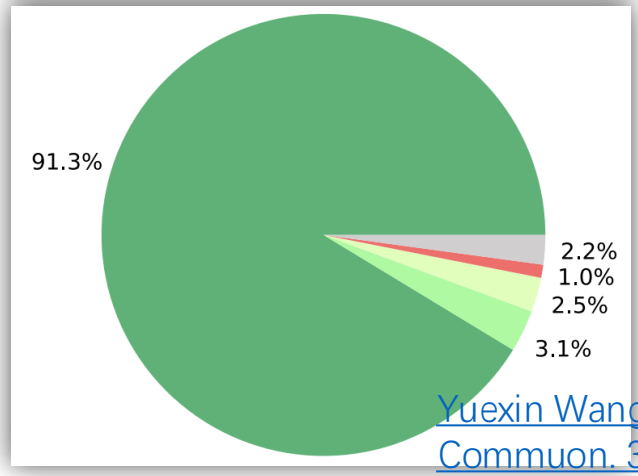
Taiki Kamiyama's report

Particle flow in future: next stage?

- **PFlow with advanced AI tools: 1-1 correspondence**
  - Ultimate target of PFlow: match PFOs with Particles **("as perfect as generator-level analysis")**







Qu Huilin et.al, arxiv 2202.03772

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

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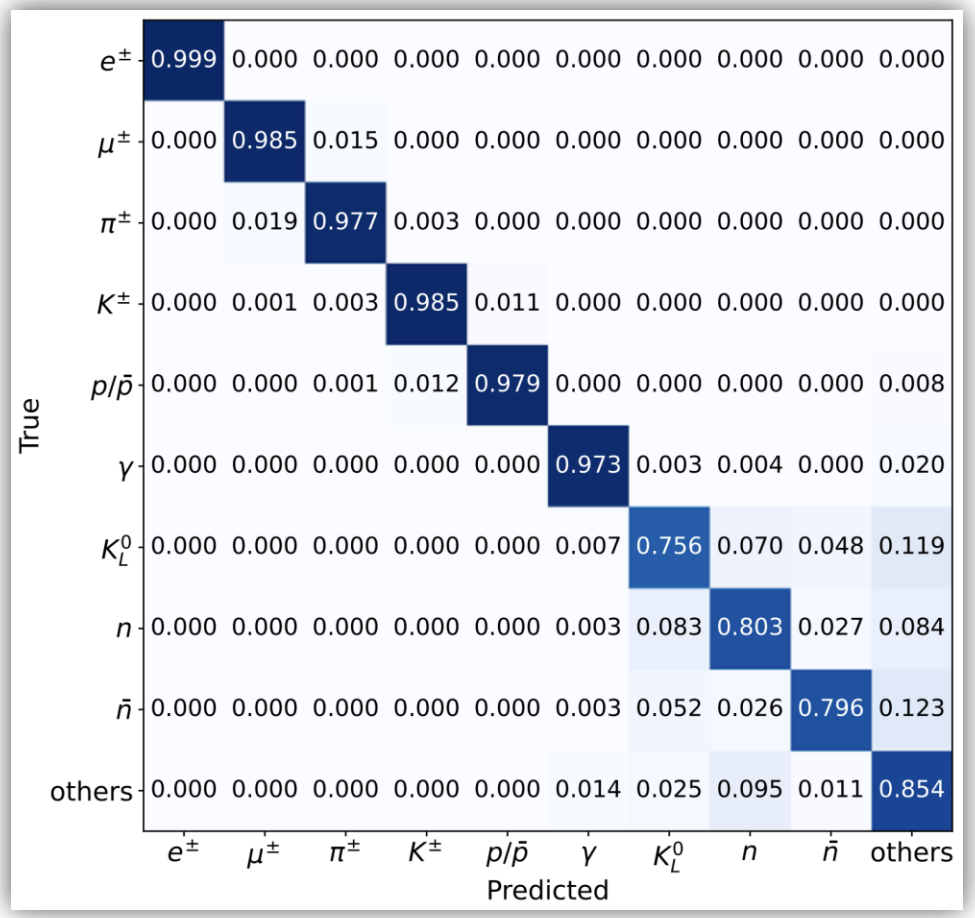
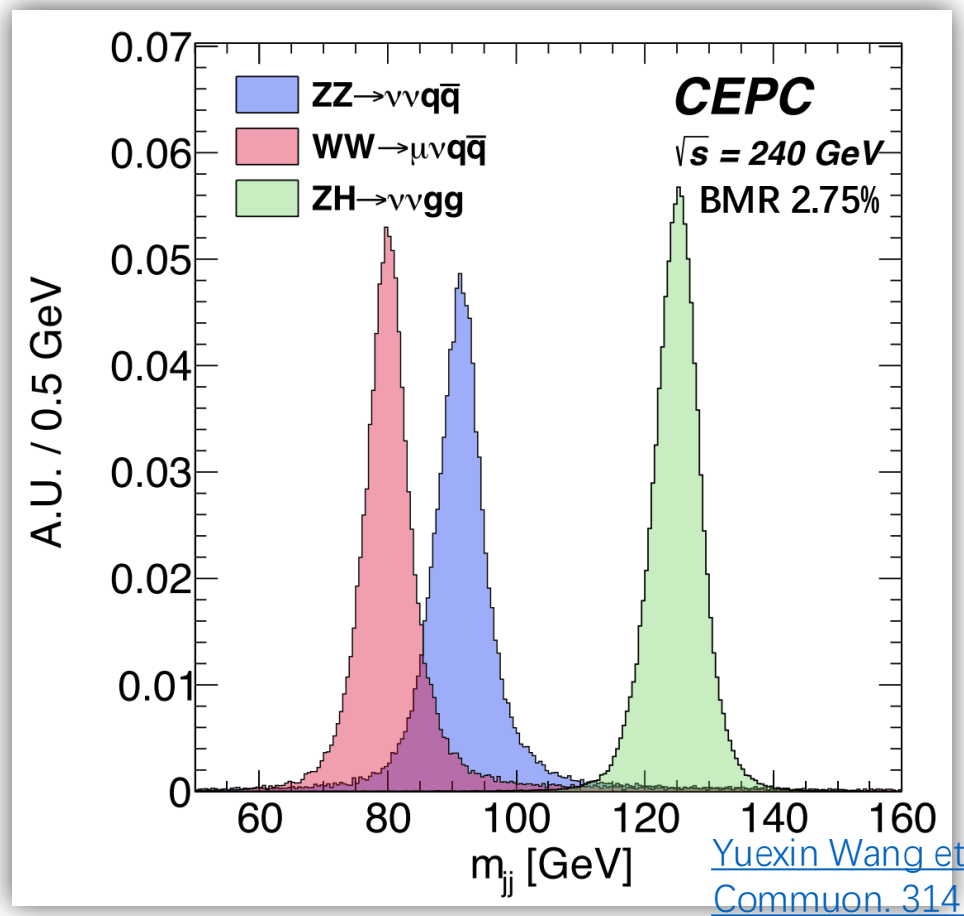
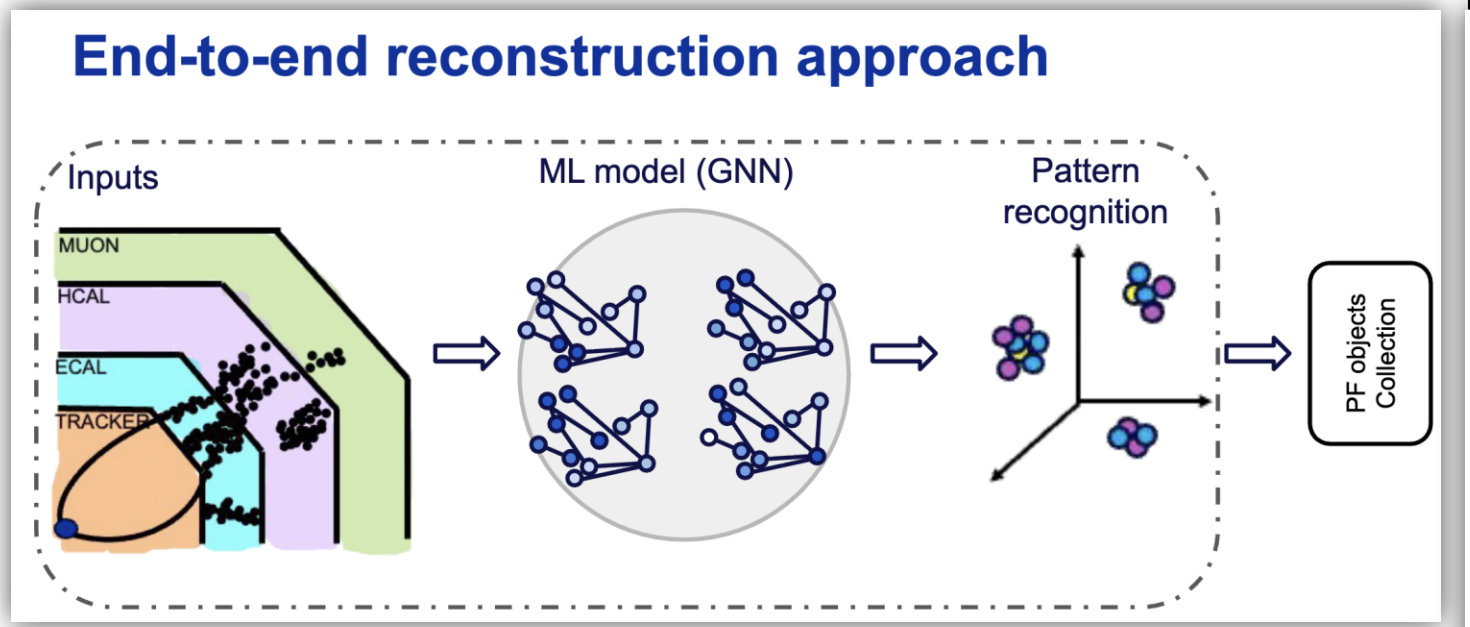


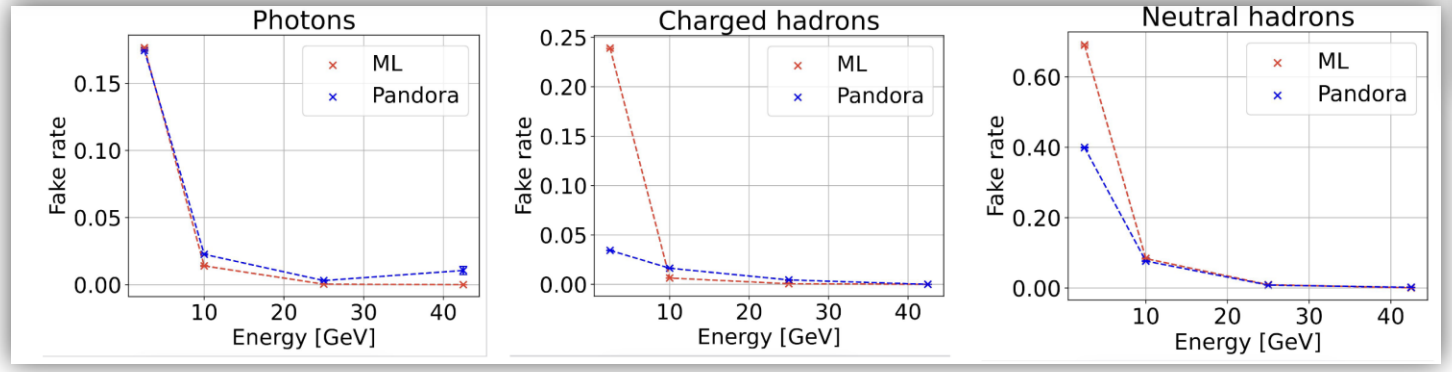


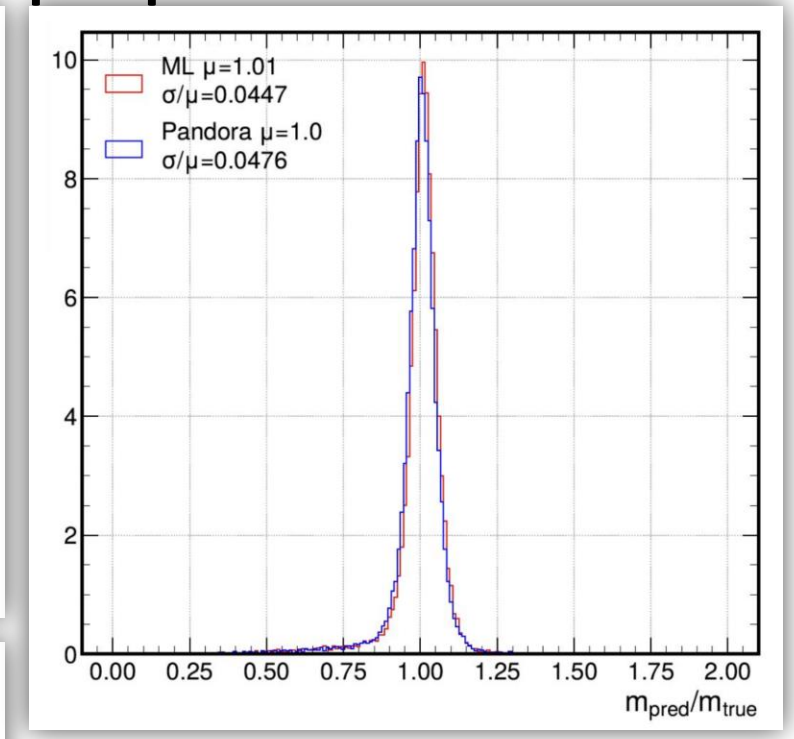
Yuexin Wang et.al, Comput. Phys. Commuon. 314 (2025) 109661

Particle flow in future: next stage?

- **ML-based Particle flow reconstruction: state-of-art but prospective**







$H \to s\bar{s}$ mass: comparable performance as PandoraPFA

Dolores Garcia, FCC-ee PFlow workshop

Summary

- **Particle flow is a innovative idea for collider experiments**
  - Has demonstrate excellent performance in ALPHE, ATLAS and CMS.
  - Core idea for future collider design & optimization.

- **After ~25 years' development, PFlow needs to go to next stage.**
  - New technologies can contribute to the detector design & construction:
    - 4D tracking, 5D / 6D calorimeter, AI, …
  - Lots of R&D efforts in hardware and software are desired.

- **Looking forward to the birth of 1st real PF-oriented detector!**

Thank you for attention!