Particle flow (in ALLEGRO)

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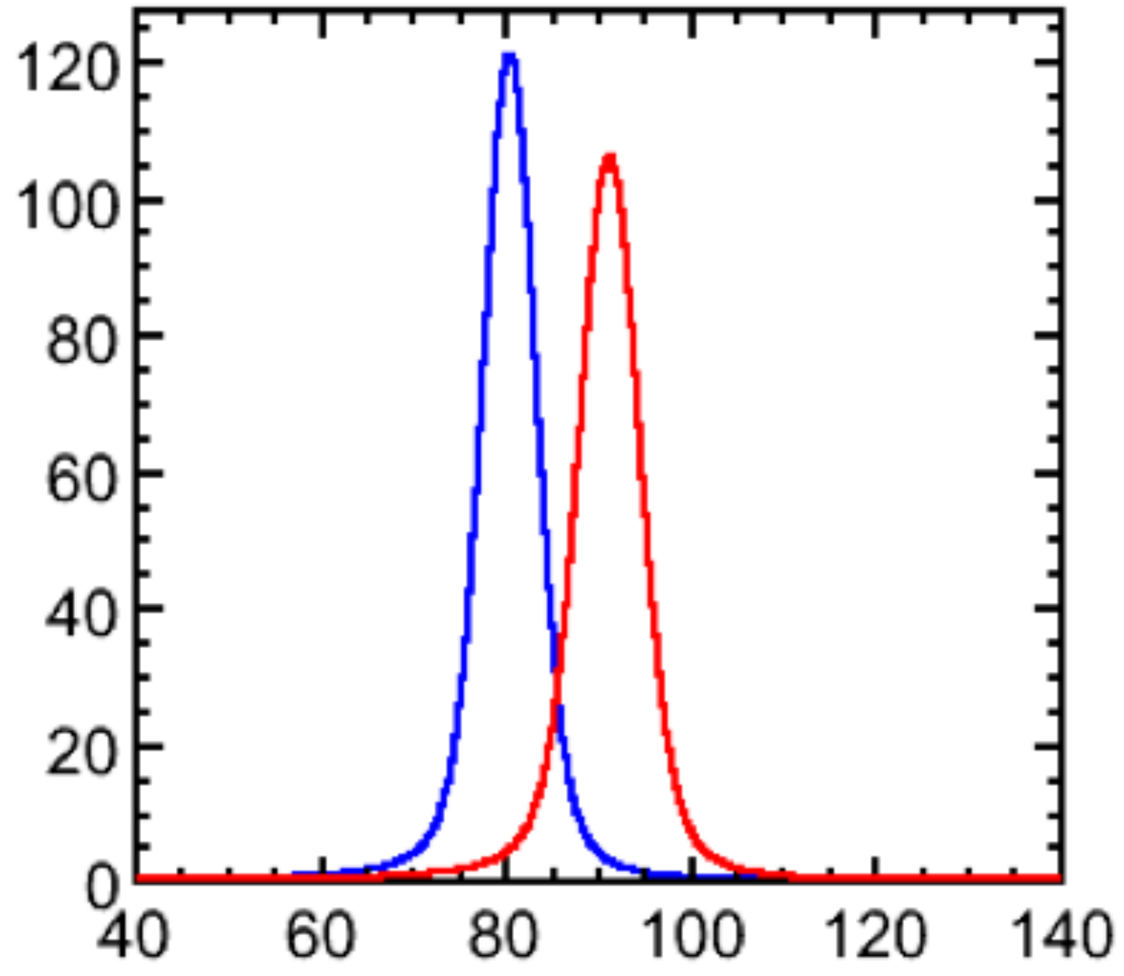
27 November 2025

FCC and particle-flow calorimetry

- Strict requirements on jet energy resolution at FCC-ee to achieve desired precision: 3-4% over wide jet energy range (>~40 GeV), to e.g. separate W/Z hadronic decays
- Typical jet energy composition: 30% photons / 70% hadrons (60% charged / 10% neutral)
- Three possible ways to get to desired resolution
  - have both ECAL and HCAL with excellent EM and hadronic energy resolution
    - E.g. 40 GeV jet, ECAL with 5%/√E and HCAL with 30%/√E => 4% => expensive / hard (R&D)
  - correct HCAL event-by-event through measurement of EM fraction with dual readout calorimeter, even with relatively modest EM resolution (15%/√E)
  - use particle-flow algorithm to leverage excellent momentum resolution from tracker for charged hadron contribution
    - Same 40 GeV jet, and 2x worse resolutions - HCAL with 60%/√E, ECAL with 10%/√E => 3%

3%



Particle flow - principle and limitations

- **In a typical jet:**
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10 % in neutral hadrons (mainly *n* and K_L)
- **Conventional calorimetric approach:**
  - Measure all components of jet energy in ECAL/HCAL
  - 50-70% of energy measured in HCAL: $\sigma_E/E \approx 60\% /\sqrt{E}$
- **Particle Flow Calorimetry: reconstruct individual particles**
  - Charged particle momentum measured in tracker (essentially perfectly)
  - Photon energies measured in ECAL
  - **Neutral hadron energies measured in HCAL**

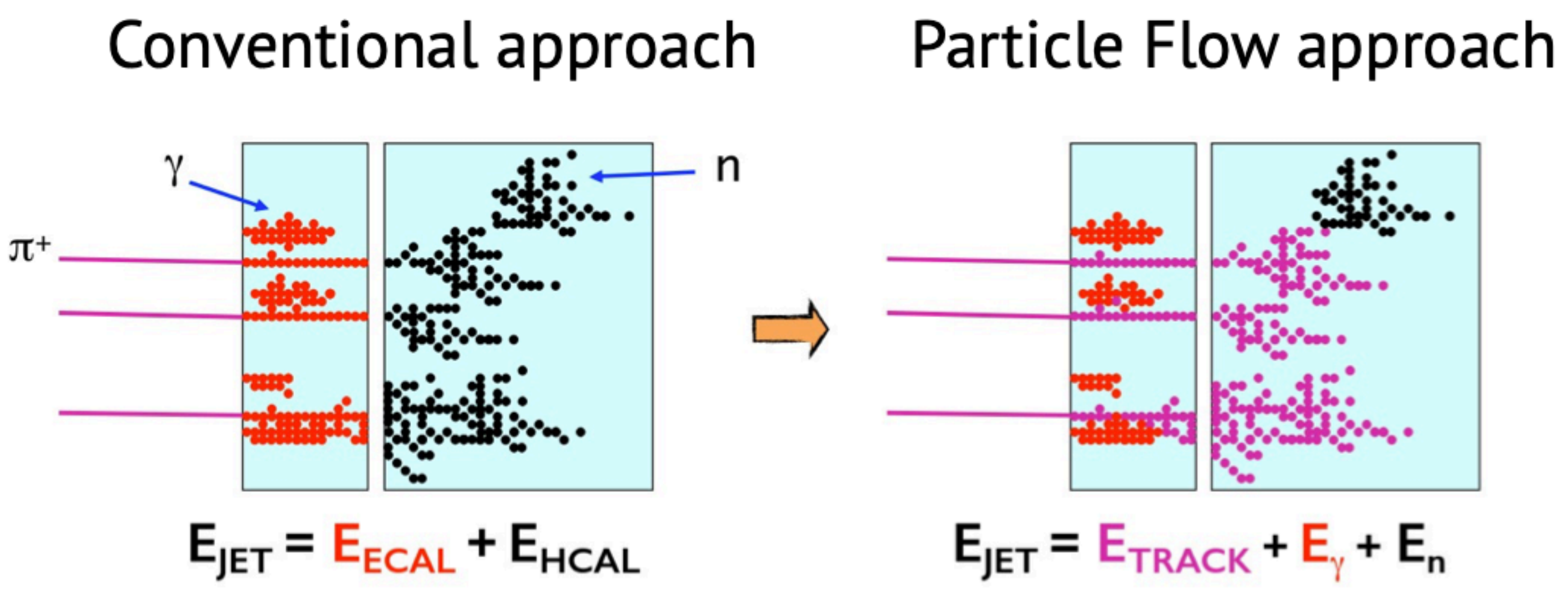
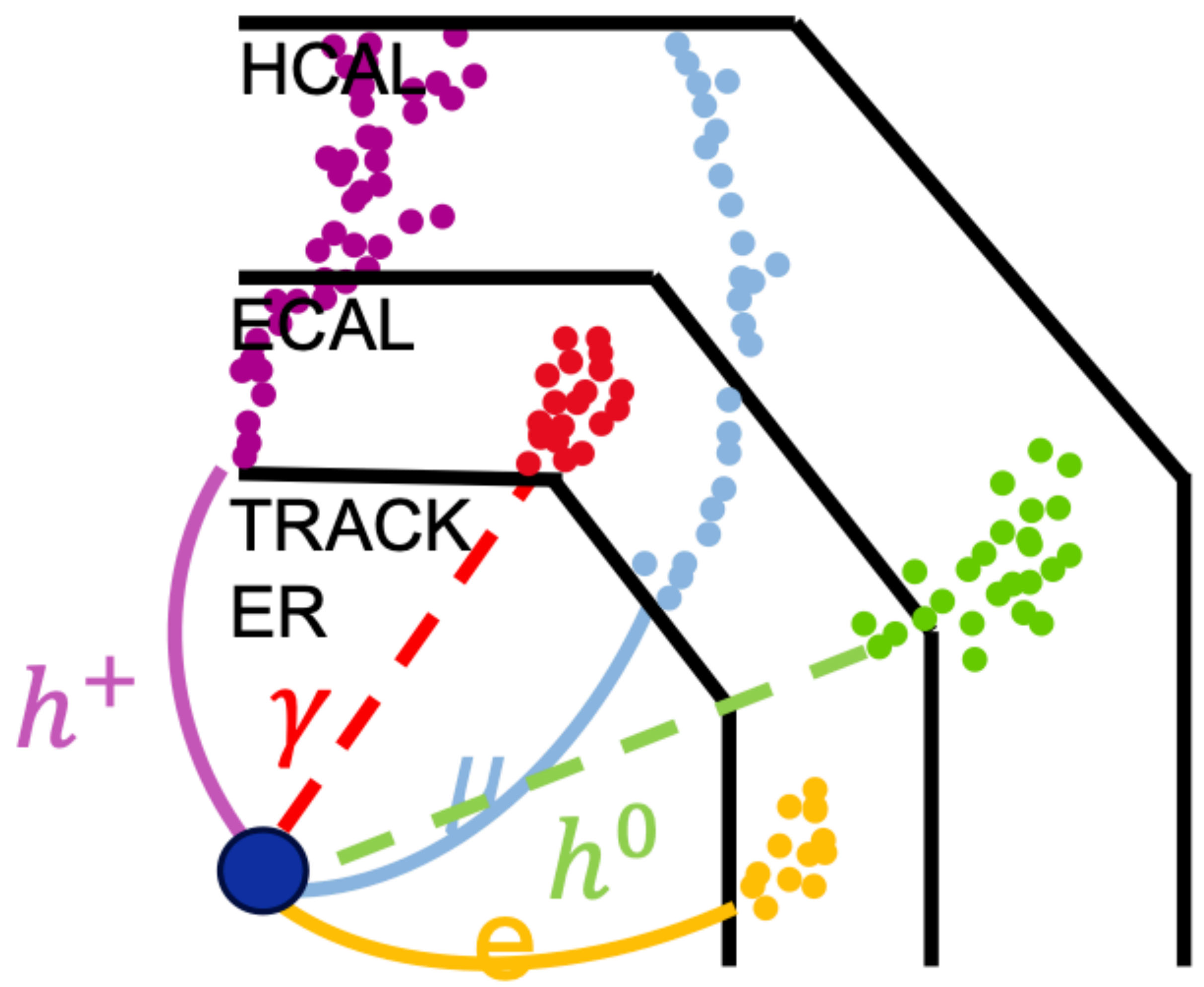


Figure taken from the link

- **Limiting factors**
  - **HCAL resolution** for neutral hadrons
  - **Confusion term** (assignment of calorimeter energy deposits to wrong particles) => granularity, material between detectors ..

Particle flow approaches

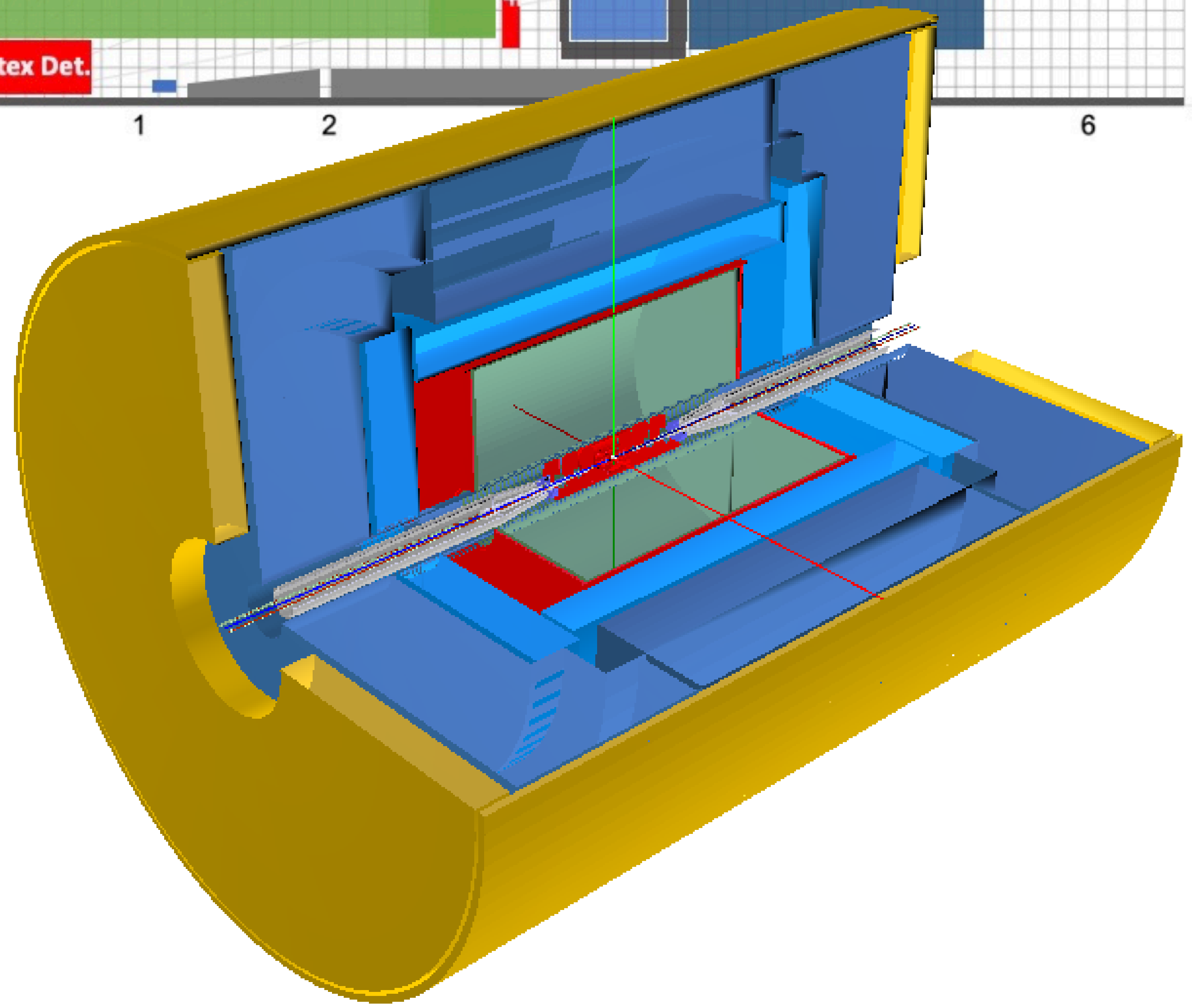


- Traditional approach: **“geometric”**
  - Extrapolate tracks to calorimeters
  - Use matching algorithms (e.g. cone-finding) to associate hits within clusters and match clusters to tracks to reconstruct particle candidates
  - Perform selections on quantities such as track/cluster match, cluster width, hits in HCAL and MUON / … to decide type of particle and apply proper energy calibrations (MIP/hadronic/em particles) to estimate the particle kinematics
  - Implemented in “**Pandora**” framework developed for LC
  - Easy to understand in principle, hard to develop/maintain in practice (many algorithms to handle various configurations, many parameters to tune, largely dependent on the detector design)
- Novel approach: **machine-learning based**
  - Simulate a sufficient large number of events with particles of different types, producing various signatures in the detectors (tracks and hits in the calorimeters + muon taggers)
  - Let the machines learn about the different correlations between the signals for the various particle types, and exploit them to infer particle type and properties (energy, direction)
  - Under development in “**MLPF**" framework for CLD detector concept
  - More difficult to understand (black box), easier to deploy (detector agnostic, adaptable to changing conditions)

Detector simulation

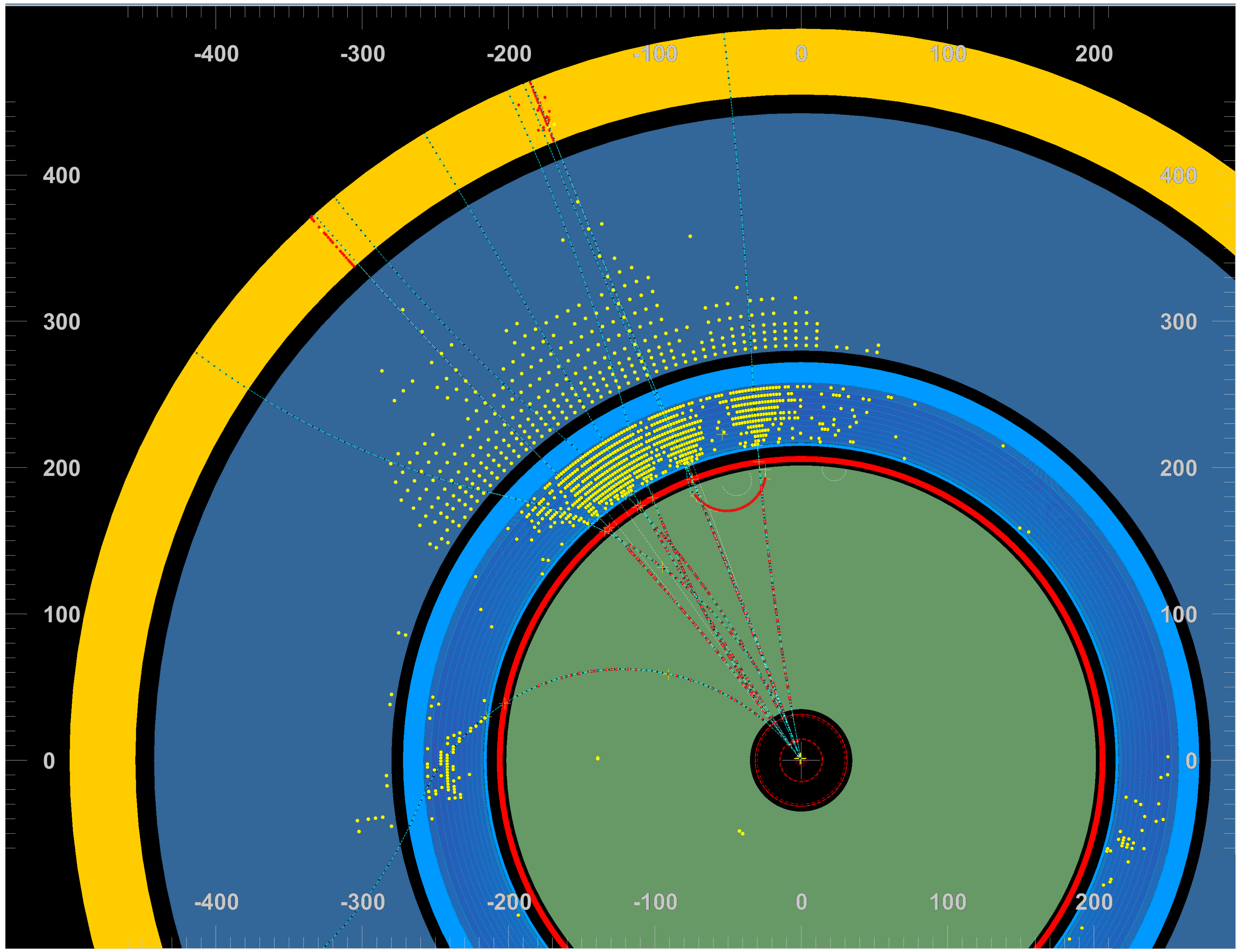
- ALLEGRO: full detector concept integrating
  - MAPS-based **vertex** detector
  - **Tracking**: drift chamber (baseline), straw tracker (alt.)
  - **Si wrapper**
  - Highly granular noble-liquid **ECAL** inside solenoid
  - **Solenoid** (B=2T) sharing cryostat with ECAL
  - High granularity **HCAL** (scintillating tiles)
  - **Muon** tagger

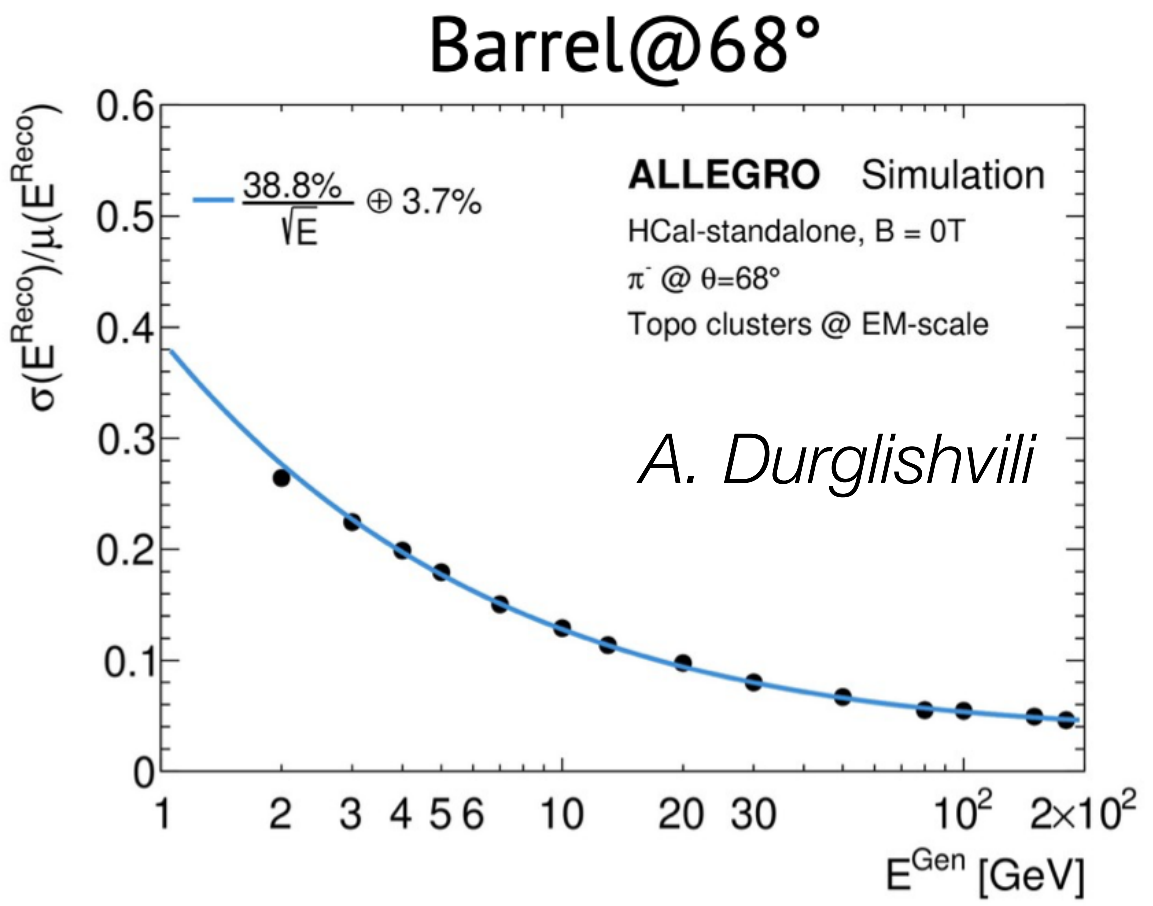
- Detector choices and design optimisation not complete yet
- Baseline detector geometry implemented in Geant4/DDSIM

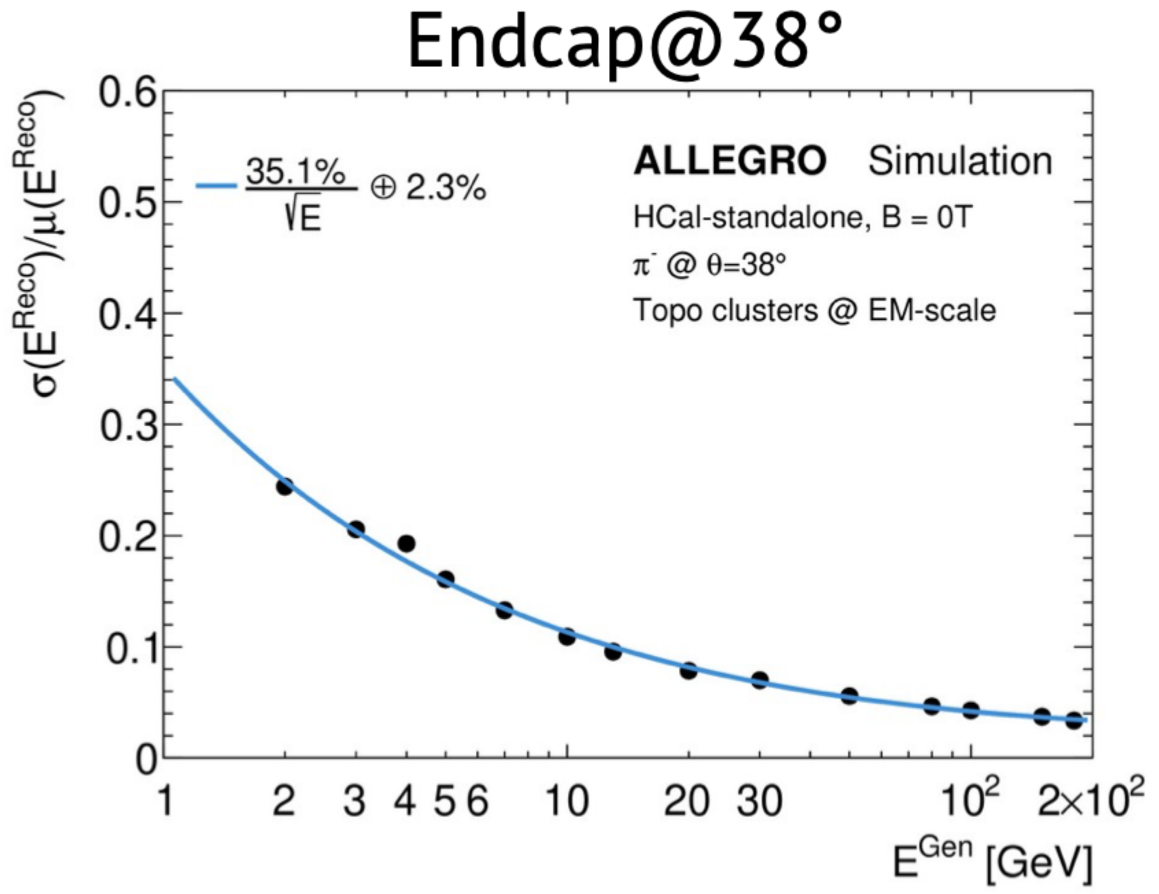


Low-level reconstruction

- Digitisation implemented for all the detectors
- Tracking not yet implemented (some challenges in drift chamber track reconstruction, but good progress recently)
  - Replace reconstructed tracks with truth charged particle parameters as a temporary workaround
- Sufficient to start performing p-flow studies (as well as performance studies with simple clustering algorithms/setup)







Pandora implementation for ALLEGRO

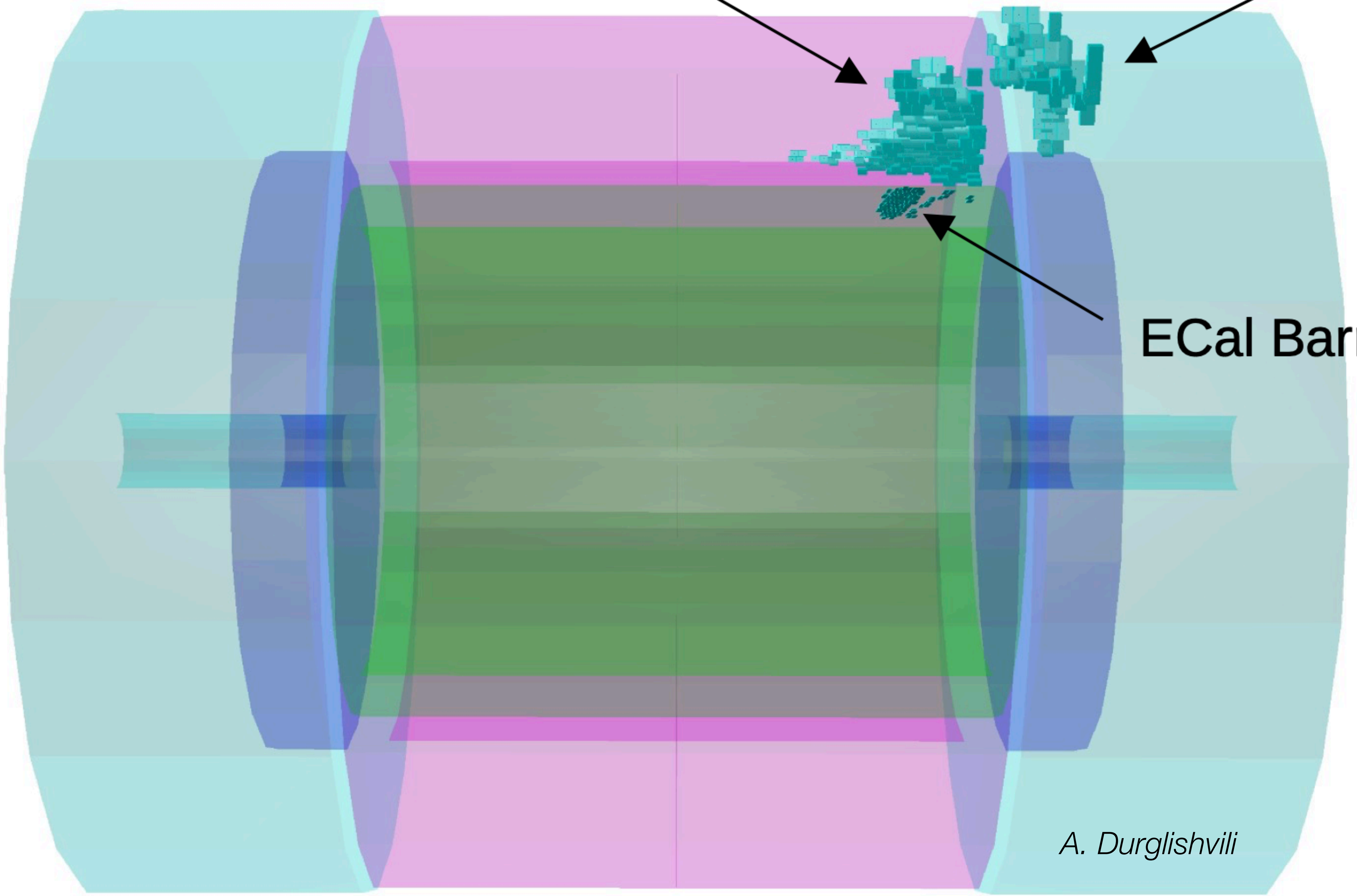
- Performed a certain number of technical developments in order to make Pandora run OOTB with ALLEGRO (find the proper input tracks and hits collections, retrieve the correct geometry parameters e.g. tracking volume, cell granularities, …)
  - Updated PandoraSDK (custom fork) to provide cell geometry matching our granularity (projective theta-phi grid)
  - Updated Marlin<->Pandora interface (DDMarlinPandora) and Pandora algs (LCContent) to create Pandora objects properly encoding information about tracks (number of hits, positions of various track states..) and hits (e.g. cell size in the two directions) as well as detector information
  - Simplified Pandora algorithms sequence (starting from CLD one) upon discussion with Pandora experts and other users to try having a better understanding of what is going on behind the scenes, and updated some calibration constants
  - Provided README to setup and run Pandora with ALLEGRO

- Started to adjust some of the main parameters of the algorithms (energy calibrations, tracking requirements, shower widths..) and to investigate performance of algorithm for simple cases (e.g. single particles / two particles)

- ***Disclaimer: all this is very preliminary and work in progress…***

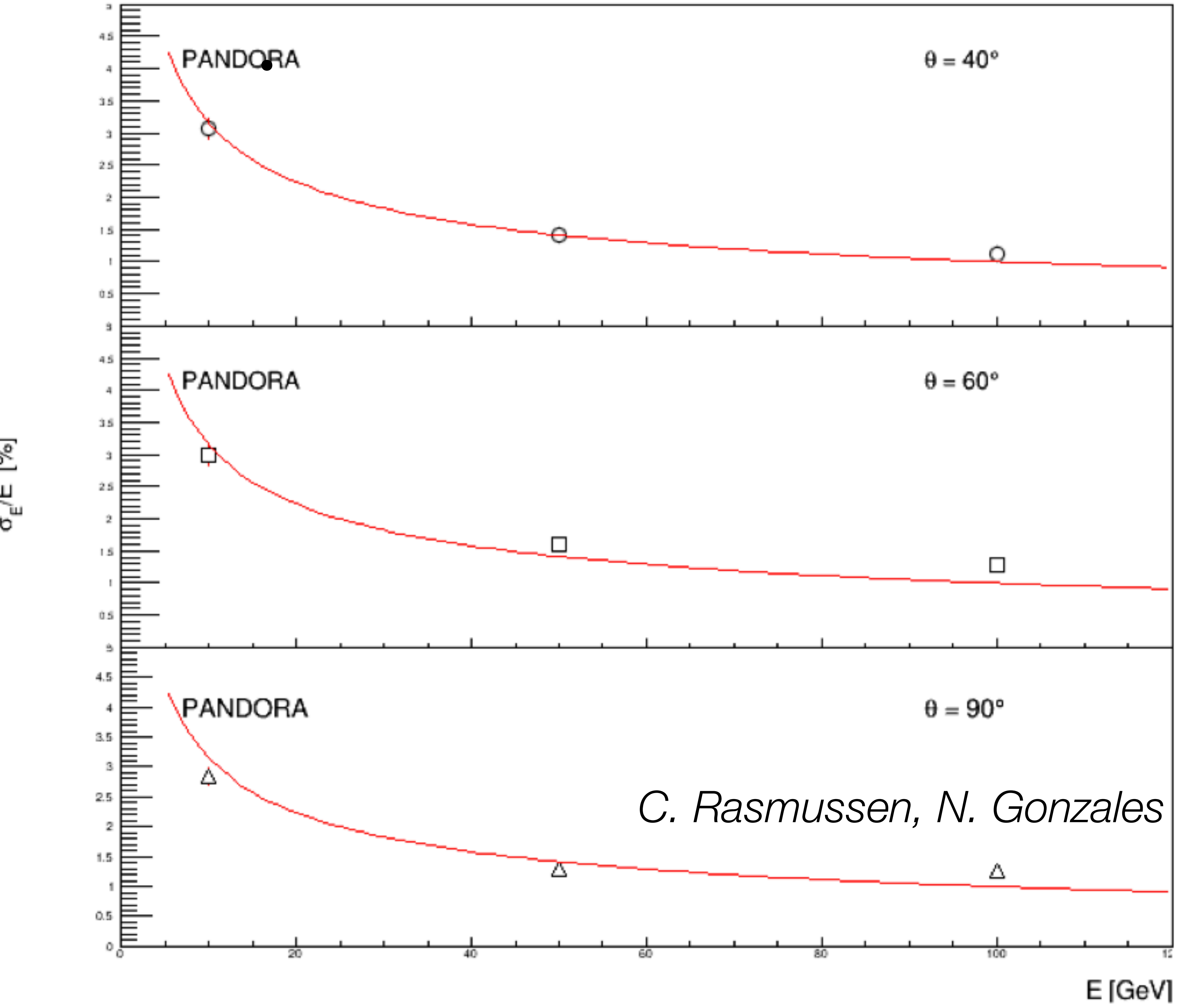
Pandora implementation for ALLEGRO

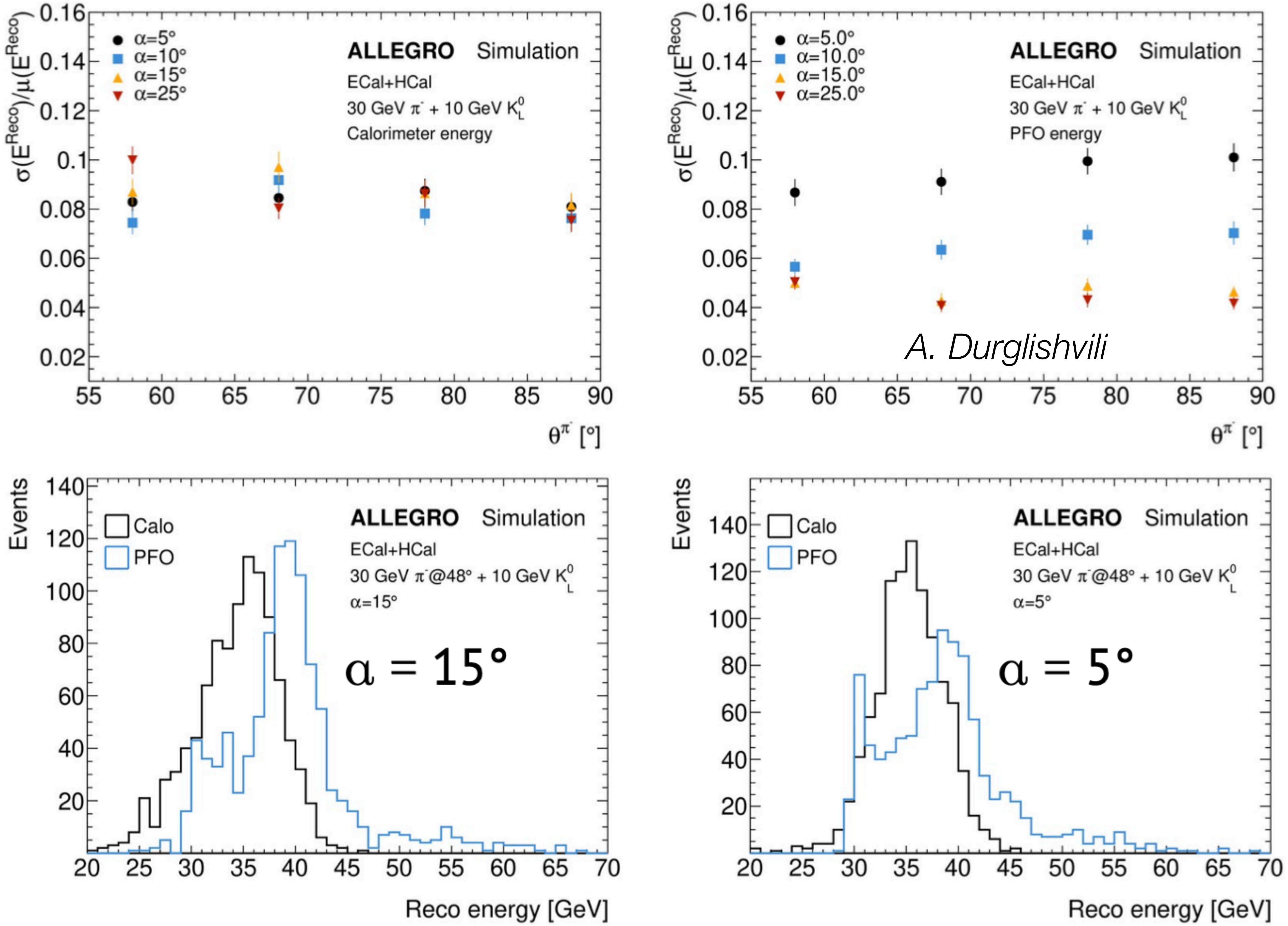
50 GeV K^0_L in ALLEGRO



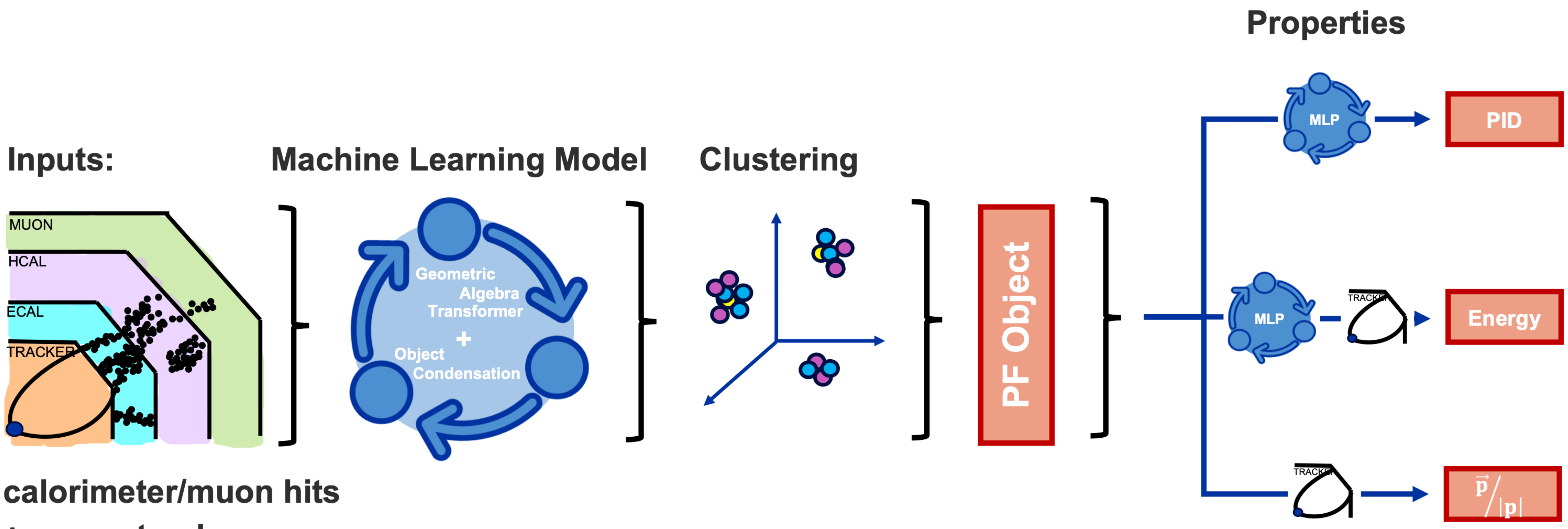
Status of Pandora for ALLEGRO

- High reconstruction efficiency with good identification for "simple" single particles (e/γ, π, μ)
- EM resolution consistent with 8%/sqrt(E) in barrel observed with other clustering algorithms (SW, topoclustering)
- Recent study of two close-by hadron reconstruction (30 GeV π^- + 10 GeV K_L) shot at various angles, separated by 5-25°
  - barrel: PF resolution is better than Calo for α = 15° and worse for α = 5° → PF algorithm needs to be tuned
  - endcap: large fraction of confusion → PF algorithm needs to be tuned





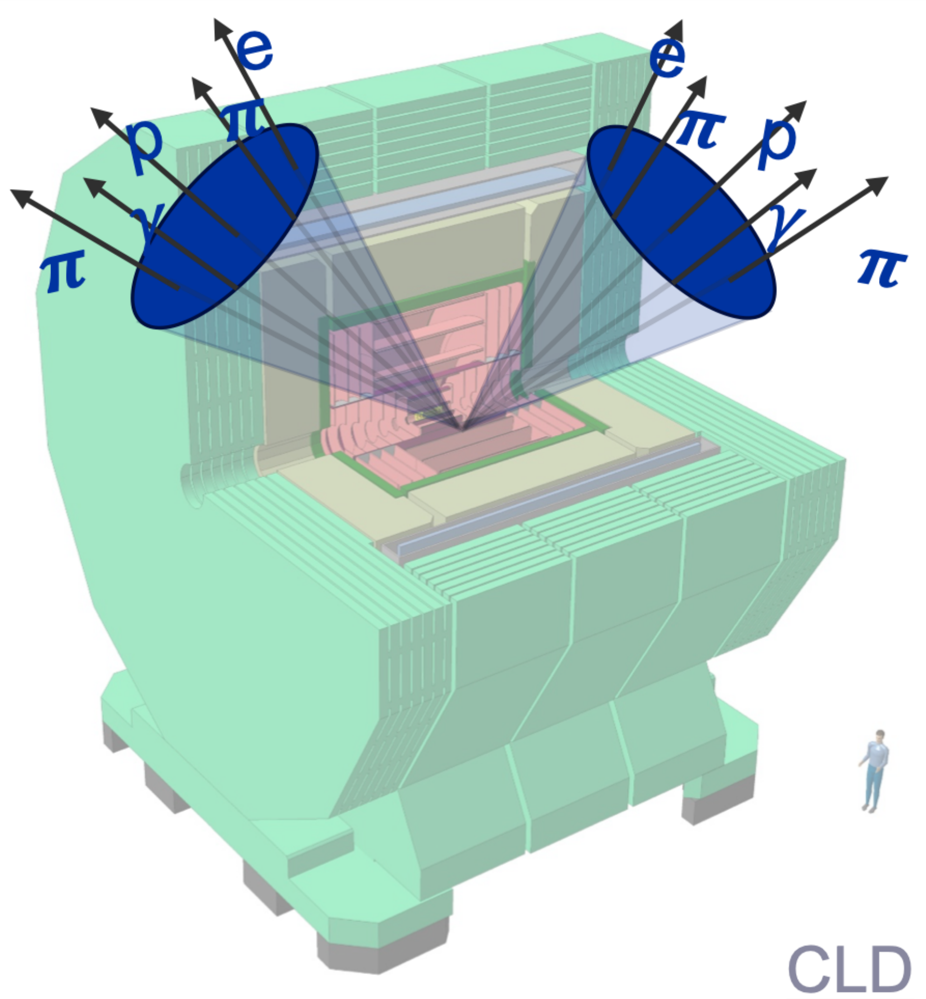
Machine-learning particle flow



calorimeter/muon hits
+ recon. tracks

- ➔ Energy
- ➔ Coordinates (x,y,z)
- ➔ Type (ECAL, HCAL, muon, track)

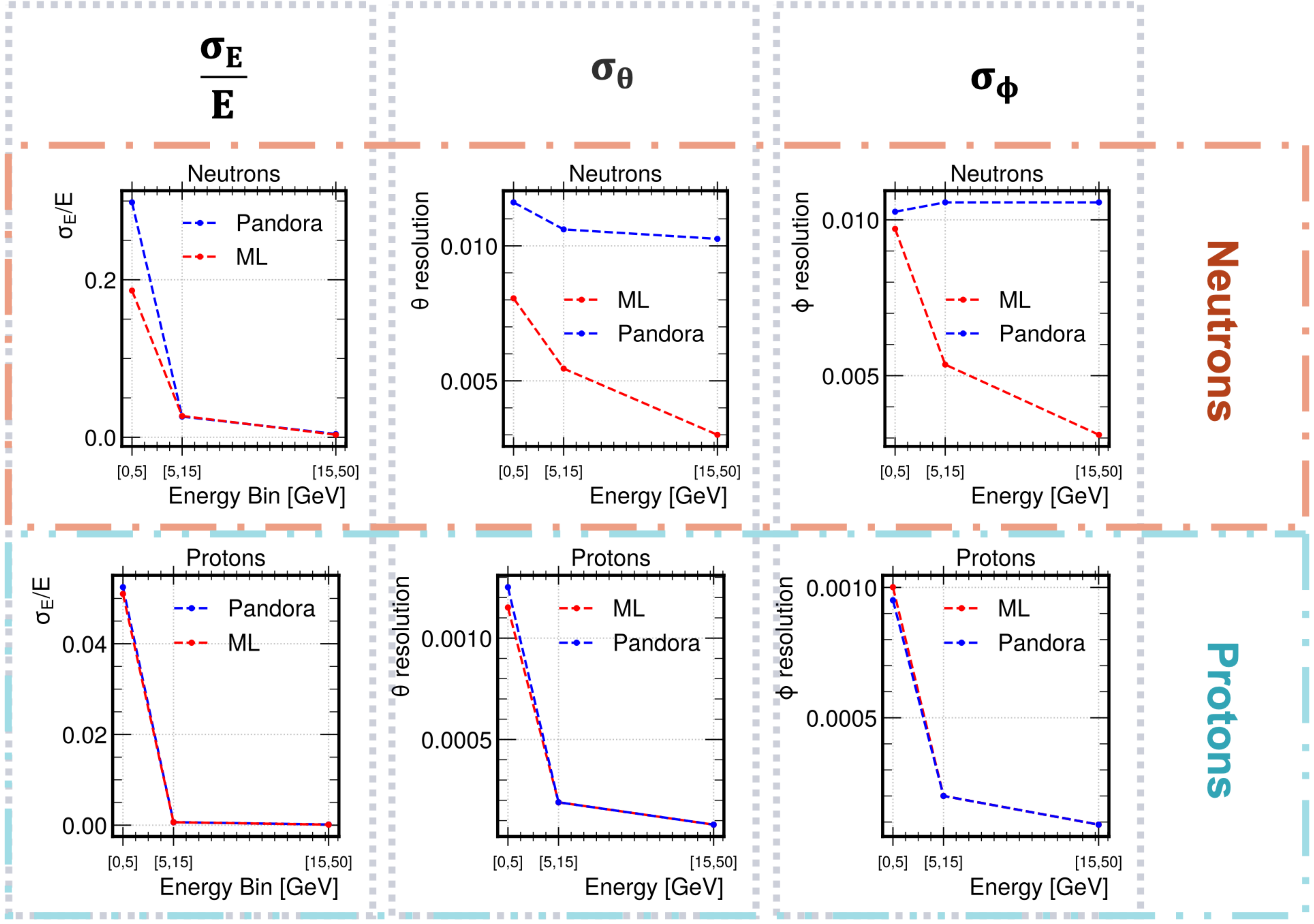
L. Hermann, M. Selvaggi, D. Garcia, G. Krzmanc

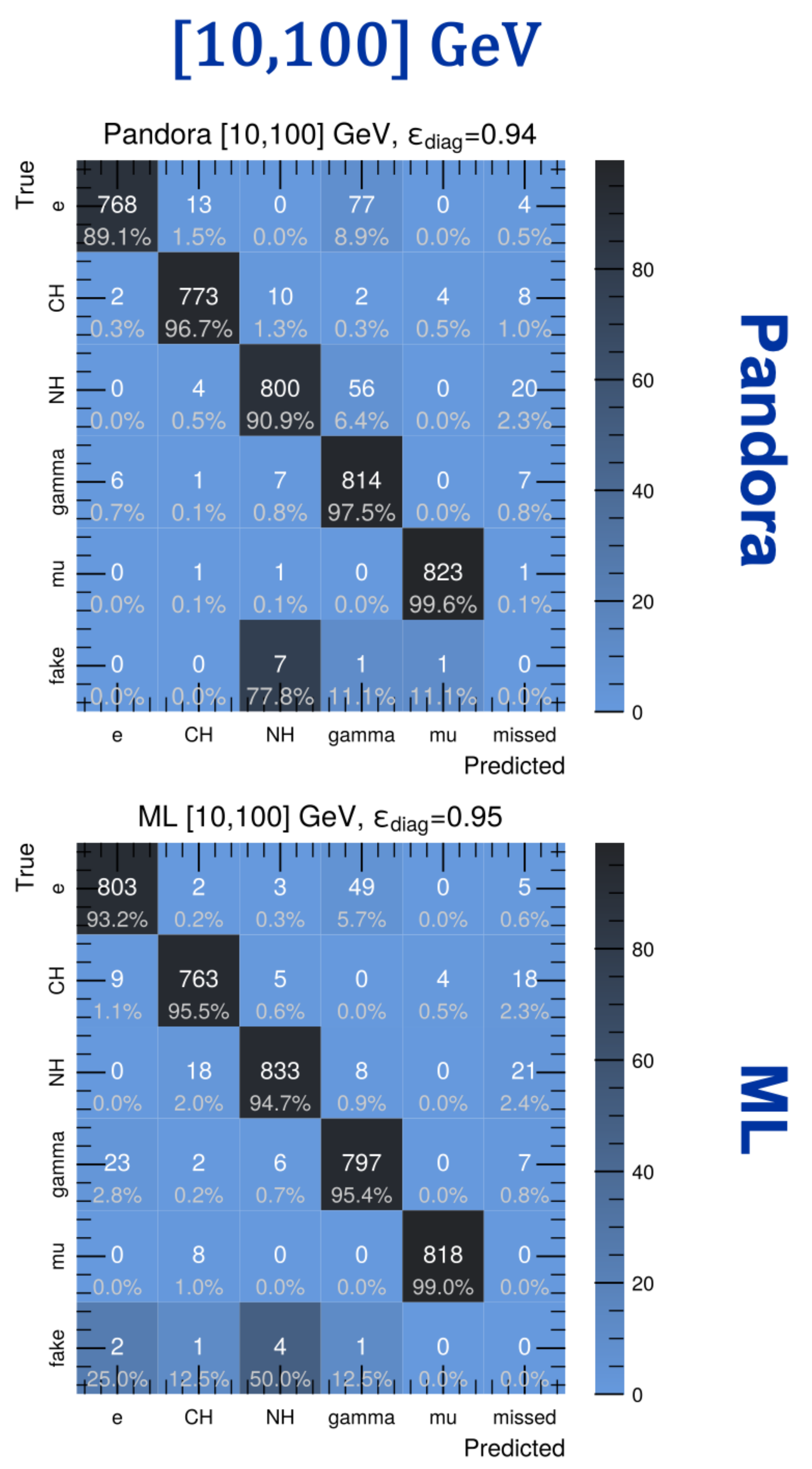


CLD

- Train on O(1M) events generated with jet-like particle gun (~15 particles per event, balanced in p/n/K_L/π/e/γ/μ, 0.5-50 GeV) or Z->qq

MLPF on CLD (WIP)





L. Hermann, FCC week

- Very good clustering performance - improved energy and angular resolution for neutral hadrons compared to Pandora; similar for charged particles (determined by tracking system)
- Similar overall PID efficiency, but significant reduction in fake neutral hadrons

MLPF on ALLEGRO (even more WIP)

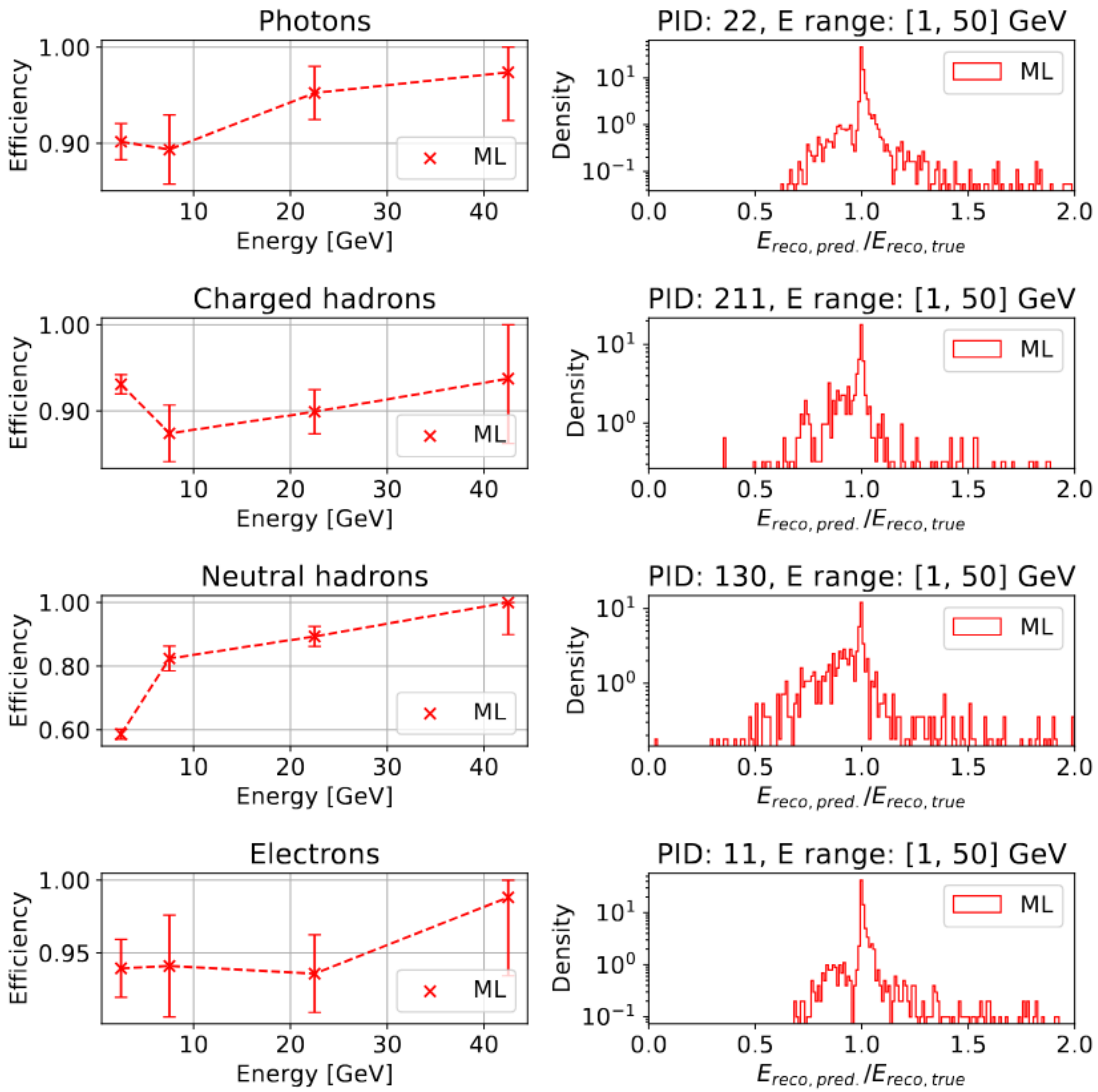
- Implemented generation of ALLEGRO training dataset within MLPF framework (link)

- Generated 1M gun-like events

- Training ongoing - very very preliminary results

- Note: this is the very first attempt at running MLPF on ALLEGRO
  - more a demonstration of the technical feasibility than an assessment of the expected performance
  - next steps: understand performance, investigate origin of low efficiency / large misid / poor resolution, improve algorithms, retrain -> repeat till good performance obtained
  - also: need to include PID information from drift chamber (dN/dx) and wrapper (timing)

R. Chaafa, L. Hermann, D. Garcia



Conclusion

- Particle flow reconstruction needed for ALLEGRO (as well as other FCC detector concepts such as CLD, ILD) to reach few% jet energy resolution needed for FCC-ee physics
  - 5% without p-flow with baseline ECAL and HCAL designs

- Two approaches currently being pursued
  - Classic/geometrical (Pandora)
  - Machine-learning based (MLPF)

- Full detector simulation + digitisation and technical development on both Pandora and MLPF from ALLEGRO's side allow both algorithms to be run OOTB for ALLEGRO
  - Understanding of results & tuning of the algorithms ongoing, needing much more effort in the future
  - Good performance already achieved for CLD

- Once a reasonable baseline is reached, use these tools to inform detector design optimisation

Object Condensation

arxiv2002.03605

- Each particle object has one condensation point x_a

- Attractive potential to 'condensation point' if hits belong to same particle object; repulsive potential otherwise

$$q_{\alpha k} = max_i q_i M_{ik}$$

$$\widetilde{V_k}(x) = ||x - x_a||^2 \; q_{\alpha k}$$

$$\widehat{V_k}(x) = \max(0, 1 - ||x - x_a)||) \; q_{\alpha k})$$

$$L_V = \frac{1}{N}\sum_{j=1}^{N} q_i \sum_{k=1}^{K} \left(M_{jk}\widetilde{V_k}(x_j) + (1 - M_{jk})\,\widehat{V_k}(x_j)\right)$$

Effective potential