Simulation studies of particle flow reconstruction for the CLIC and FCC-ee calorimetery

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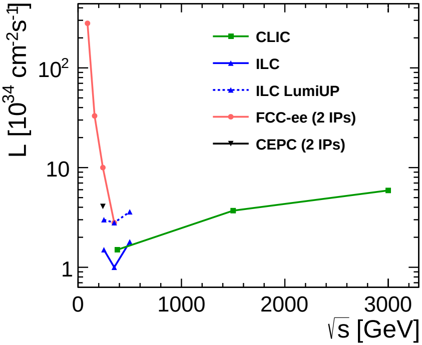
Introduction

CLIC

- Compact Linear Collider ($e^- e^+$)
- 3 energy stages:
  380 GeV, 1.5 TeV, 3 TeV
- 156 ns long bunch trains with
  0.5 ns bunch separation;
  20 ms distance between trains

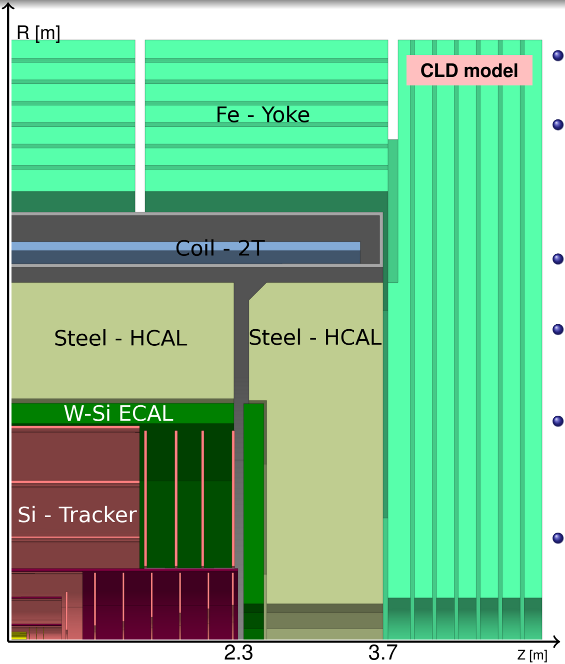
FCC-ee

- Future Circular Collider ($e^- e^+$)
- 4 energy stages: Z, WW, HZ, $t\bar{t}$
- Bunch spacing: 20 - 8533 ns

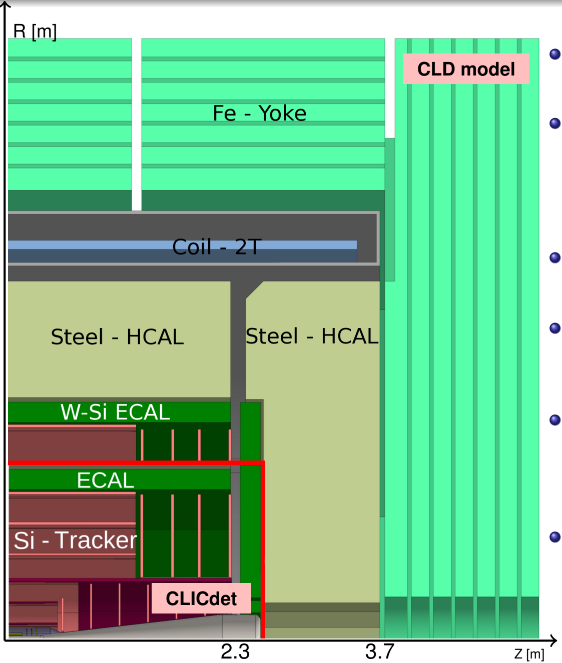


- Both experiments demand state-of-the-art detectors with:
  - low-material tracking system
  - precise calorimetery
- CLICdet - proposed detector model for CLIC with 4 Tesla magnetic field
- CLD - detector model for FCC-ee derived from CLICdet and optimized for FCC-ee experimental conditions

CLD and CLICdet detector models



- 4 T magnetic field
  2 T magnetic field - CLD
- Full silicon VTX and Tracker:
  - $\geqslant$12 hits per track
  - $r_{inner} = 31$mm, $r_{outer} = 1.5$m
    $r_{inner} = 17$mm, $r_{outer} = 2.1$m - CLD
    increased material budget for 50% in VTX - CLD
- W-Si ECAL
  - 40 layers, 22 X_0
- Fe-Scint HCAL
  - 60 layers, 7.0 λ_I
    44 layers, 5.5 λ_I - CLD
- Steel return yoke with 6 RPC muon chambers:
  - 2 m thickness
    1.5 m thickness - CLD
- CLICdet provides larger coverage of the forward region
  CLD - MDI (forward region):
  $<$ 150 mrad, accommodates LumiCal



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Particle Flow Analysis: PandoraPFA

- Particle identification at CLICdet and CLD is based on the particle ID algorithms used in PandoraPFA
- Pandora aims at reconstructing and identifying each particle reaching the detector. The reconstructed particle types are $\mu\pm$, $e\pm$, γ, charged hadrons ($\pi\pm$) and neutral hadrons (n)
- The main objective of Pandora algorithm: excellent jet energy resolution needed to achieve the desired precision involving hadronic final states
- Pandora is also used for identification of isolated single particles

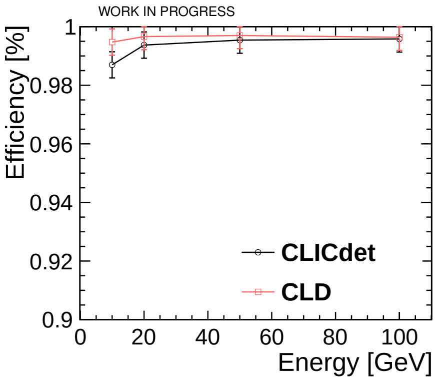
In order to achieve the best resolution, Pandora uses most precise information associated with the particle: the energy of charged particles is measured by the tracking system, energy of neutral particles by the calorimeters

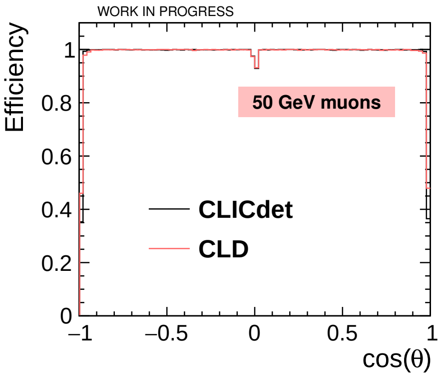
Single particle efficiency

- Single particle performance is studied for μ-, π-, *e*- and γ
- Simulate single particles with isotrop $cos(\theta)$ distribution and fixed energy: 5, 10, 20 ,50 and 100 GeV
- PID efficiency definition:
  - reconstructed PFO and true (MC) particle have to be of the same type
  - angular matching: $\Delta\theta < 0.01$rad and $\Delta\phi < 0.02$rad
  - energy matching:
    - charged particles: $|p_T^{truth} - p_T^{PFO}| < 5\%\ p_T^{truth}$
    - photons: $\Delta E < 5 \times \sigma(\text{ECal}) \approx 0.75 \times \sqrt{E}$

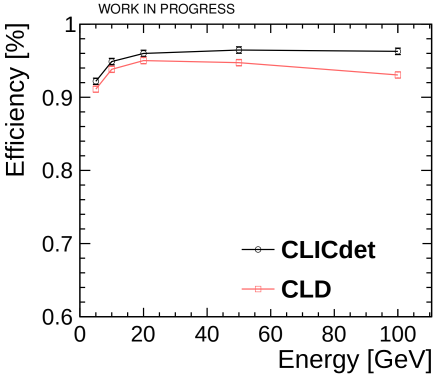
- reconstructed PFO types: $\mu\pm$, $e\pm$, γ, charged hadrons ($\pi\pm$) and neutral hadrons (n)

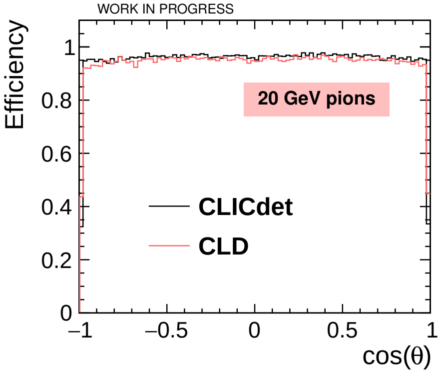
Single muon efficiency



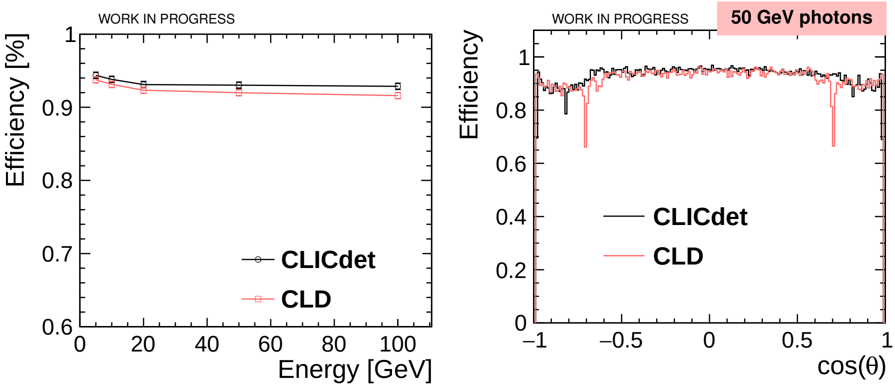


- Type, angular and energy matching with the true muon
- Muon efficiency is 99% or larger for all energies both for CLICdet and CLD
- Small inefficiency at $\cos(\theta) = 0$ due to reconstruction algorithm $\rightarrow$ work ongoing

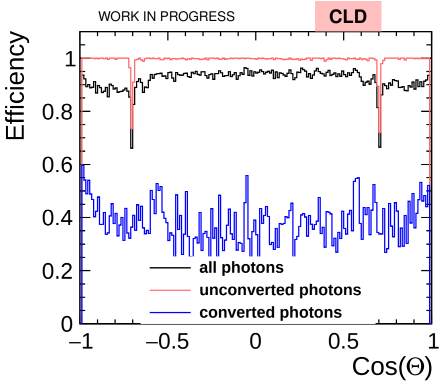


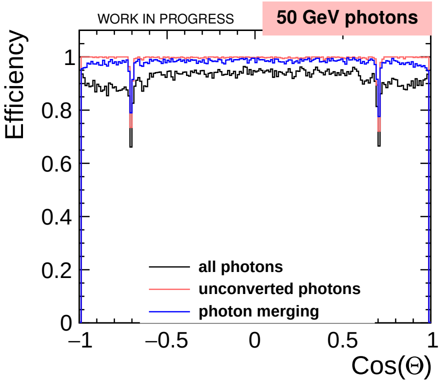


- Type, angular and energy matching with true pion
- Pion efficiency is 95-96% for CLICdet and 93-94 % for CLD
- Difference between CLICdet and CLD models are under investigation

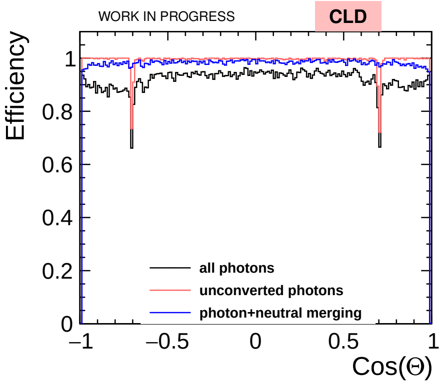


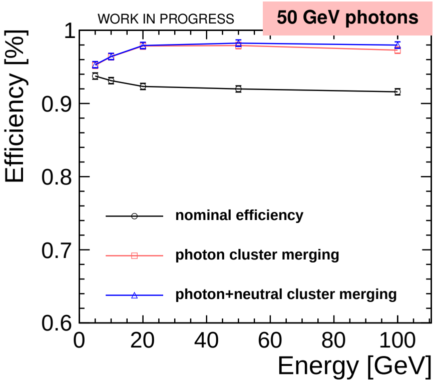
- Type, angular and energy matching with true photon
- Photon inefficiency is due to photon conversion which happens late in the tracking system → two reconstructed photons (likely fails angular and/or energy matching)



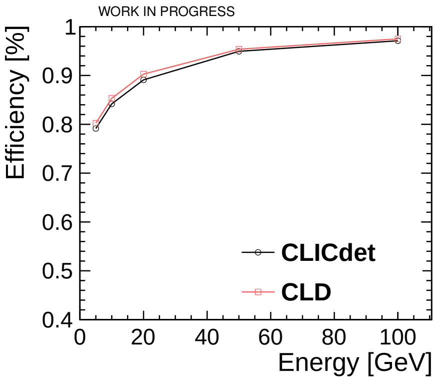


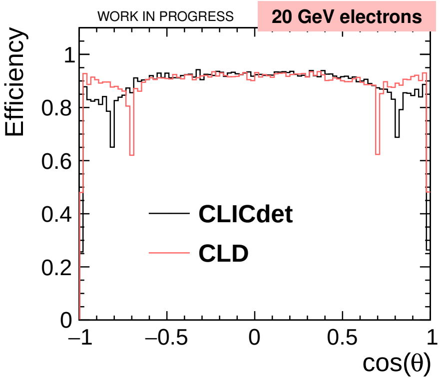
- Efficiency for unconverted photons reaches 99 % when efficiency for converted photons is only $\approx$ 30-40 %
- merging close photons allows to almost completely recover the efficiency



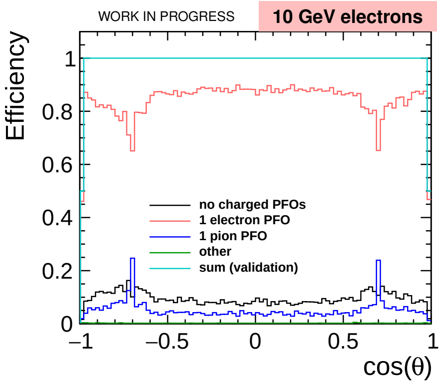


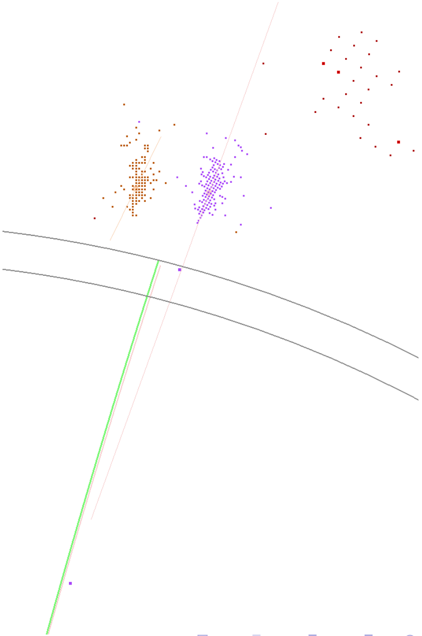
- Photon calo hits can be split into EM and neutral clusters in calorimeter transition region due to due to an imperfect overlap between barrel and endcap calorimeters (space between end of barrel and endcap parts reserved for cables)
- Merging of close neutral cluster allows recovering efficiency there.
- Efficiency reaches 98% for CLD (similar for CLICdet models)





- study of electron PID efficiency is more complicated due to Bremsstrahlung
- impose only particle type matching (no angular and energy matching)
- unexpectedly low efficiency for lower energy electrons

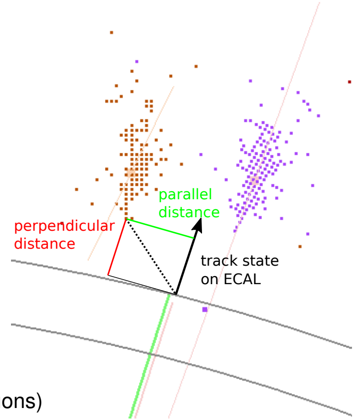




- in 10-13% of events no charged PFO is reconstructed in the event
- track-cluster association algorithm fails to attach track to cluster (as shown on the right)
- in 3-6% of events fake “pion” is reconstructed
- in calorimeter transition region a small fraction of electrons is reconstructed as “pions”

Track-cluster association algorithm in Pandora

- Get track state on ECAL inner surface
- Loop through all hits within a cluster
- Calculate perpendicular and parallel distance between calo hit and track state position with respect to track state direction
- Find hit with minimal perpendicular distance → this value is the track-cluster distance
- Default Pandora settings in electron reconstruction algorithm: the track is matched if track-cluster distance < **10 mm**



Photon reconstruction algorithm

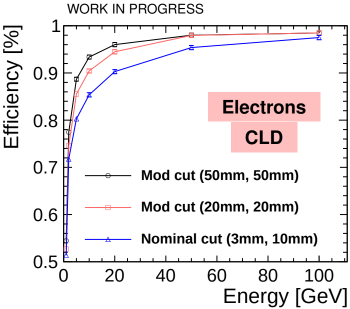
- Second PID algorithm run by Pandora (after muons)
- if there is a track within **3 mm** - check if cluster should be discarded since it's probably an electron → the cluster is likely reconstructed as an electron
- otherwise (if track-cluster distance > **3 mm**) consider EM cluster trackless and run photon ID test → the cluster is likely reconstructed as a photon

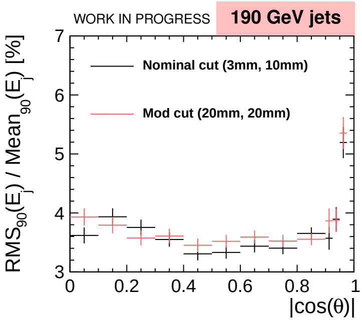
Vary these 2 parameters to investigate an effect on the electron ID efficiency

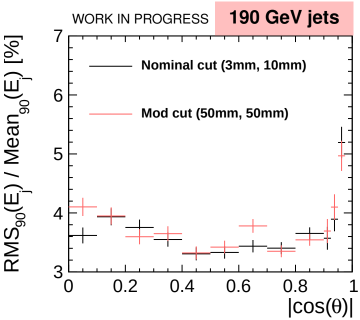
Single electron efficiency: track-cluster association

- compare 3 sets of track-cluster distance cut: (3mm, 10mm), (20mm, 20mm), (50mm, 50mm)
- Increasing of track-cluster distance requirement allows to recover efficiency
- Improvement of PID efficiency at low energies (85% $\rightarrow$ 95% for 10 GeV electrons)

- Loosening track-cluster distance requirement doesn't have a significant impact on jet energy resolution





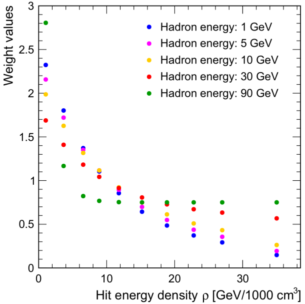


Software Compensation

- Software compensation is an energy "regularisation" techniques
- Idea to correct with software for (on average) larger response of hadron showers with large electromagnetic component → improves energy measurement of cluster energies
- Software compensation technique (developed by CALICE) is implemented in PandoraPFA now

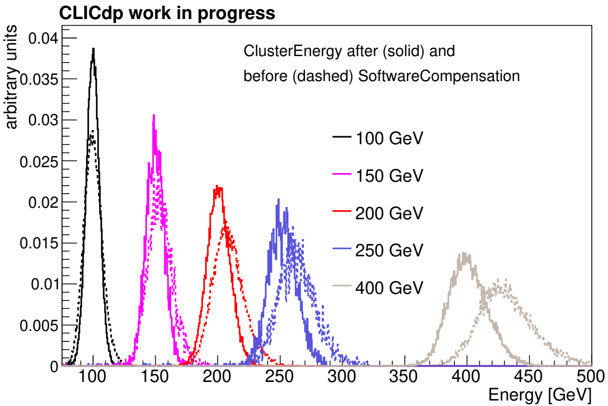
Software compensation:

- Electromagnetic component of shower typically denser
- Software compensation reweights hits in HCAL depending on the hit energy density
- In total 9 different parameters are used
- Weight includes an energy dependence



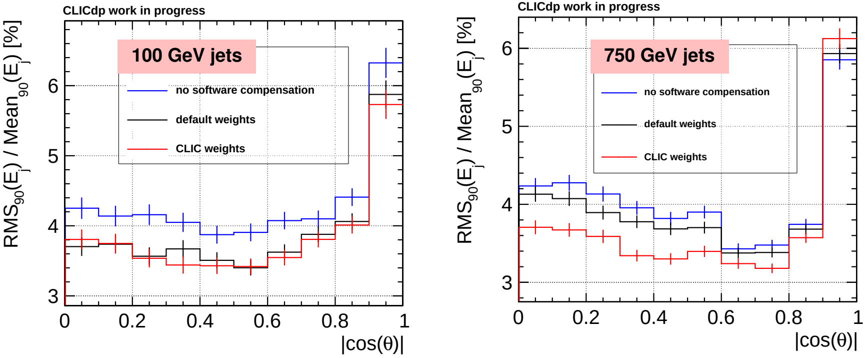
Default weight tuned for ILD experiment at ILC up to 100 GeV, at CLIC expect to reach higher hadron energies, at 3 TeV sometimes beyond 500 GeV → retune parameters for CLIC (Follow description of paper EPJC 77 (2017) 698)

Software Compensation at CLIC

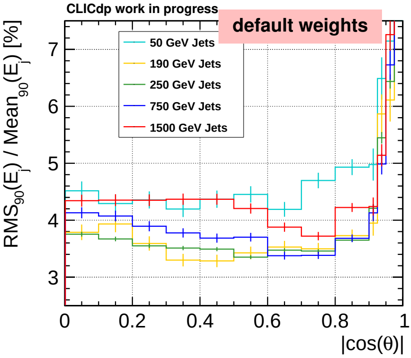


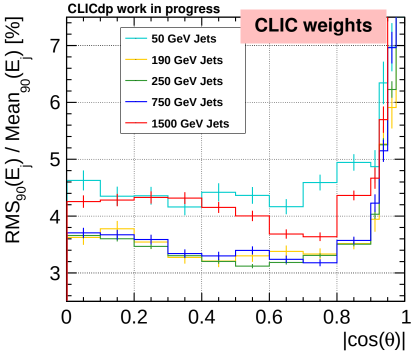
- Software compensation weights derived using several fully simulated neutron and K0L single particle datasets
- Mean and resolution after software compensation largely improved
- Software compensation corrects for nonlinear response of hadrons on the fly

Jet energy resolution at CLIC with dijet events



- applying software compensation always improves jet energy resolution
- comparable performance of CLIC tuned weight at low jet energies (left plot)
- significant improvement at high jet energies (right plot)





- Comparable performance for jets up to 190 GeV
- Improvement of jet energy resolutions by around 10% for larger jet energies
- Achieve jet energy resolution between 3.1 % and 4.5 % with CLIC tuned weights

Summary

Performance of Pandora PFA has been studied with isolated single particles and dijet event for CLICdet and CLD detectors

- Pandora provides good single particle ID efficiency for both detectors
- Photon conversion and electron Bremsstrahlung can be addressed by cluster merging and tuning of the track-cluster distance requirement

CLIC specific software compensation parameters have been determined

- Comparable jet energy resolution for low energetic jets ($<$250 GeV)
- Jet resolutions improved by around 10 % for high energetic jets ($>$250 GeV) when using previous default parameters
- Confusion term reduced by more accurate cluster energy estimation

Thank you for your attention!

BACKUP