Fine-grained calorimeters for experiments at CLIC and FCC-ee

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on behalf of the CLICdp and FCC-ee collaborations

CERN

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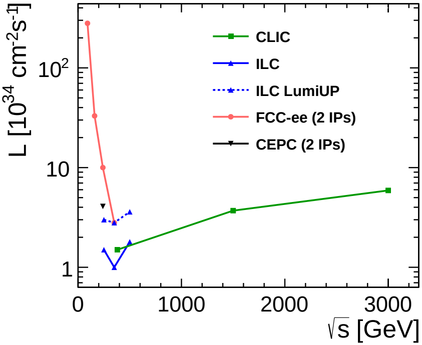
Introduction

CLIC

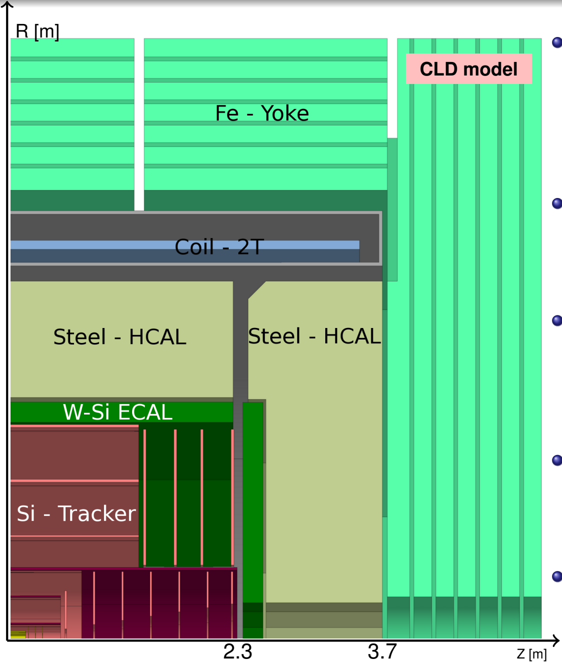
- Compact Linear Collider ($e^- e^+$)
- 3 energy stages:
  380 GeV, 1.5 TeV, 3 TeV
- bunch trains are 156 ns long and distance between trains is 20 ms
  $\rightarrow$ Power Pulsing of electronics

FCC-ee

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



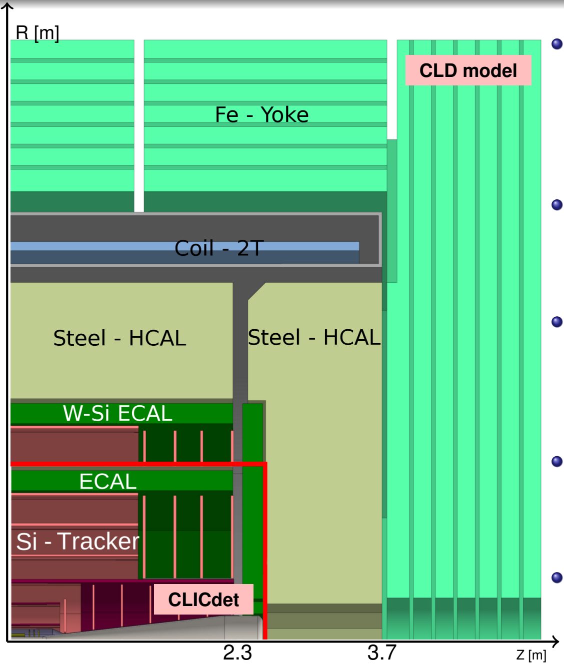
- Both experiments demand state-of-the-art detectors with:
  - low-material tracking system
  - precise calorimetery
- CLICdet - proposed detector model for CLIC with 4 Tesla magnetic field
- CLD - detector model for FCC-ee derived from CLICdet and optimized for FCC-ee experimental conditions
- Maximum possible detector magnetic field at FCCee is 2 Tesla (to preserve beam emittance)



- Full silicon tracking system - provides $\geqslant$12 hits per track
  - $R_{outer} = 1.5$m - CLICdet
  - $R_{outer} = 2.1$m - CLD

  increased material budget for 50% in VTX - CLD
- Fine-grained ECAL and HCAL optimised for particle flow reconstruction
- Superconducting solenoid is outside of the calorimeters
  - 4T field - CLICdet
  - 2T field - CLD
- Steel return yoke with muon chambers
  - 2 m thickness - CLICdet
  - 1.5 m thickness - CLD
- Support structures, cables and services are implemented in the simulation models

CLD and CLICdet detector models



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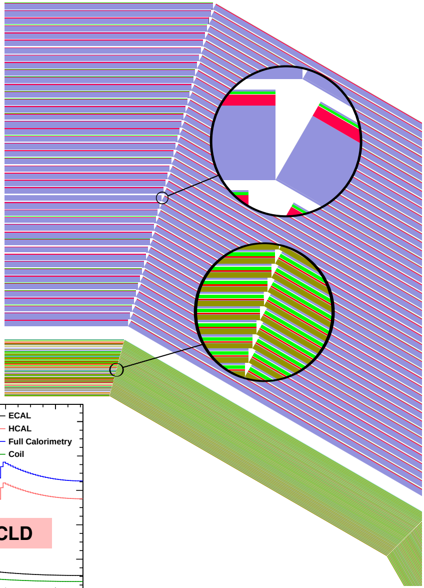
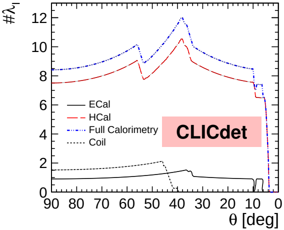
Electromagnetic Calorimeter

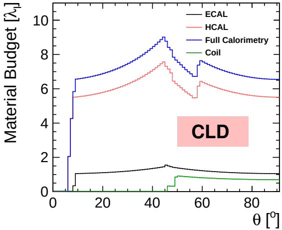
- Si-W sampling calorimeter
- cell size 5x5 mm^2
- 40 layers (1.9 mm thick W plates)
- Depth: 22 X_0, 1 λ_I, 20 cm

Hadronic Calorimeter

- Scintillator-steel sampling calorimeter
- cell size 30x30 mm^2
- 60 layers (CLICdet) / 44 layers (CLD) (19 mm thick steel plates)
- Depth: 7.5 λ_I (CLICdet) / 5.5 λ_I (CLD)







Simulation and reconstruction software tools

- Performance studies of CLICdet and CLD detector models were done with iLCSoft software used by the CLIC and ILC community.

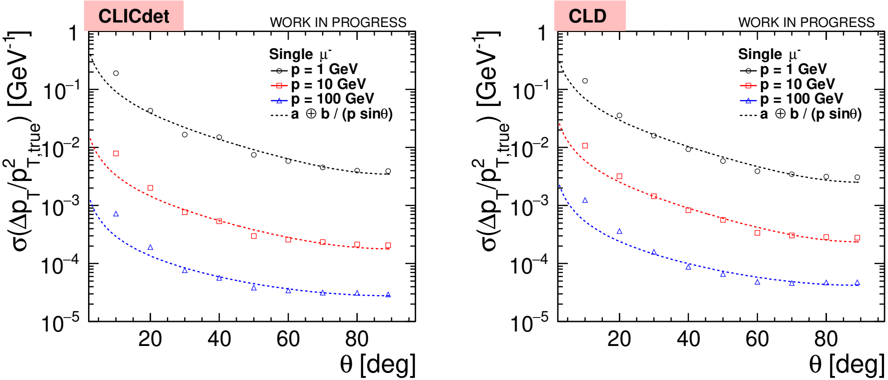
- Detector geometry description and event simulation: DD4hep
- Event Reconstruction: Marlin

- Track Pattern recognition: ConformalTracking
- Particle Flow Reconstruction: PandoraPFA
  - PandoraPFA is used both for jet and isolated particle ID studies

- Geometry of detector models are implemented in lcgeo package:
  - CLIC_o3_v14
  - FCCee_o1_v03

Detector performances have been studied with full detector simulation

- Transverse momentum resolution for single muons with CLICdet and CLD detector models as a function of θ for 1, 10 and 100 GeV energies



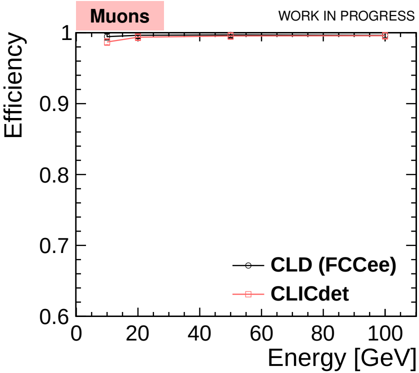
- Overall comparable tracking performance of both detectors
- Achieved momentum resolutions for 100 GeV muons at $\theta = 90^\circ$:
  - $3\text{x}10^{-5}$ GeV^{-1} - CLICdet
  - $4\text{x}10^{-5}$ GeV^{-1} - CLD

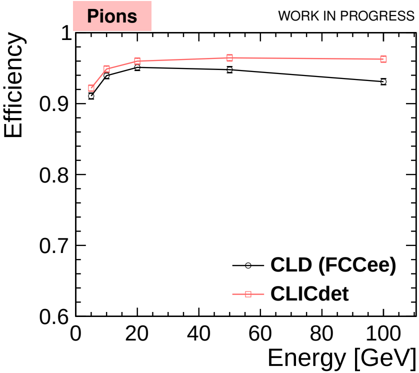
Particle ID efficiency

- ✳Single isolated particles
- ✳Leptons in $t\bar{t}$ events

- Efficiency = fraction of matched reconstructed particles out of the simulated MC particles:
  - reconstructed particle of the same type as simulated MC particle
  - angular matching: $\Delta\theta < 1$ mrad and $\Delta\phi < 2$ mrad
  - energy matching:
    - charged particles: $|p_T^{truth} - p_T^{PFO}| < 5\%\ p_T^{truth}$
    - photons: $\Delta E < 5 \times \sigma(\text{ECal}) \approx 0.75 \times \sqrt{E}$

Sample: single particles with flat $\cos(\theta)$ distribution and fixed energy

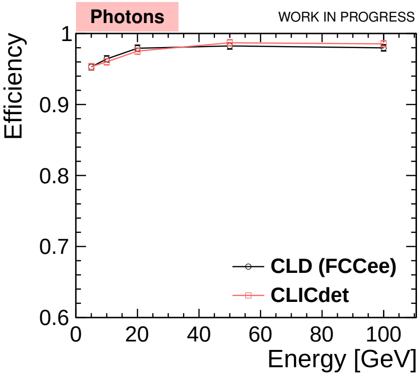


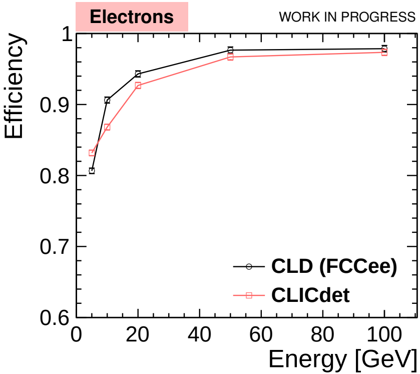


- $>$99% muon efficiency and 93-96% pion efficiency for E$>$10 GeV
- Inefficiency at high energies with CLD is caused by a larger rate of pions being mis-reconstructed as muons

Single particle identification efficiency

- Photon merging procedure is used to recover inefficiency due to photon conversion and electron Bremsstrahlung
- Pandora electron ID parameters were retuned in order to recover hard electron Bremsstrahlung (loosen maximum track-cluster distance requirement to recover events when a track is not associated to either of EM clusters)

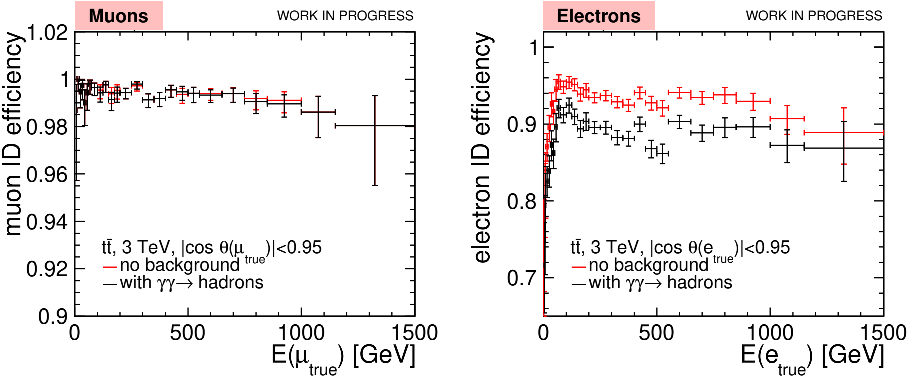




- $>$ 95% efficiency for $>$10 GeV photons and $>$20 GeV electrons
- Further optimization of electron Bremsstrahlung recovery procedure may improve electron efficiency (e.g. at lower energies)

Lepton identification efficiency in $t\bar{t}$ events at CLIC

- Lepton ID efficiency in $t\bar{t}$ events at 3 TeV at CLIC
- Only direct leptons from W decays are considered
- Requirement of angular matching within 1°is imposed.



- Muons are identified with more than 98% efficiency for all energies
- Electrons are identified with 90-95% efficiency at energies of 20 GeV and higher
- Presence of beam background doesn't affect muon ID while electron ID decreases by about 5%

Jet performance

- ✴Software compensation
- ✴Jet Energy Resolution

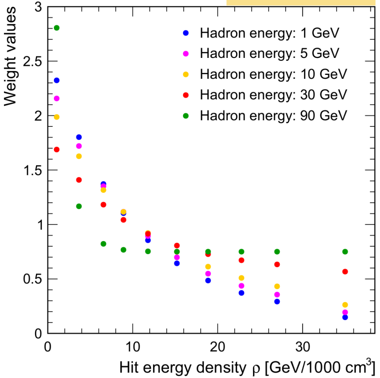
- Software compensation is an energy “regularisation” techniques (JINST 7 (2012) P09017)
- Idea is to correct with software for (on average) larger response of hadron showers with large electromagnetic component → improves energy measurement of cluster energies
- Software compensation technique (developed by CALICE) is implemented in PandoraPFA now

Software compensation:

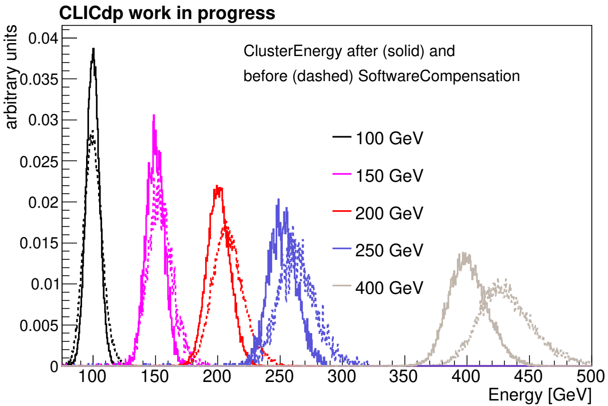
- Electromagnetic component of shower typically denser
- Software compensation reweights hits in HCAL depending on the hit energy density
- Weights are calculated by formula: $\omega(\rho) = p_1 \exp(p_2 \rho) + p_3$ where each parameter is an energy dependent → 9 different parameters are used in total

Detector specific software compensation weights were obtained for CLICdet and CLD

EPJC 77 (2017) 698

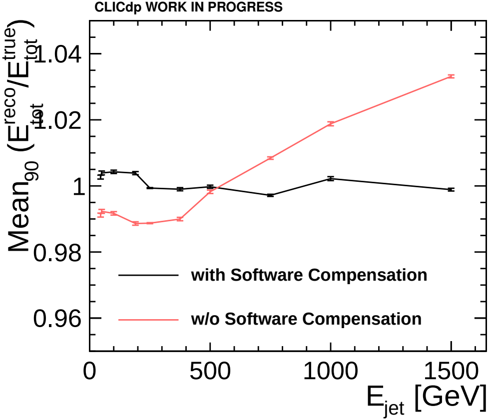


Hadron response with Software Compensation



- 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

- Dijet events of a Z-like particle decaying into pair of light quarks (u, d, s) at several centre-of-mass energies



- Ratio of total reconstructed energy to total simulated energy (excluding neutrinos)
- Software compensation provides reconstruction of total energy within 0.5% accuracy in light-quark dijet sample.

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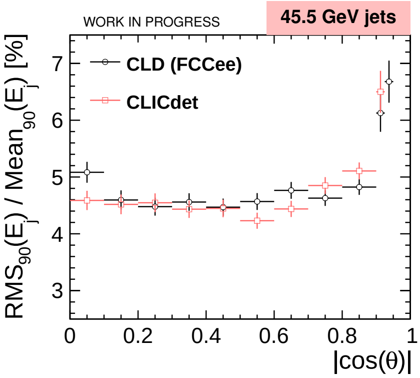
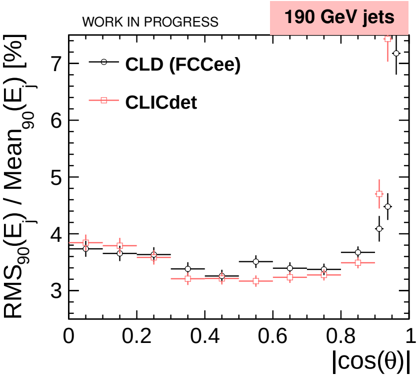
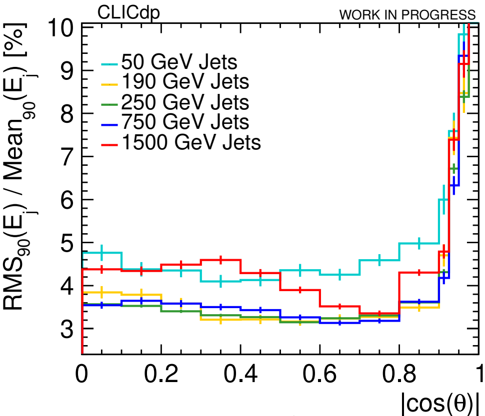




- Comparable resolution for both detectors
- Jet energy resolution in barrel region:
  - 45.5 GeV jets: 4-5 %
  - 190 GeV jets: 3-4 %

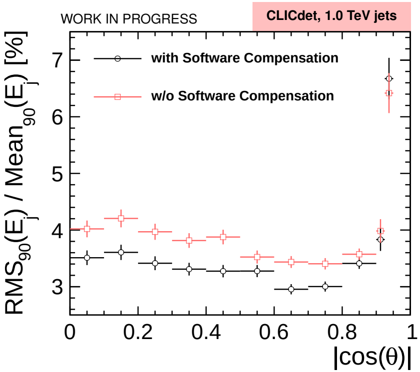
Jet energy (E_j) is measured as a half of total energy (E_{jj}) of Z→ $q\bar{q}$ (q=u,d,s) di-jet event

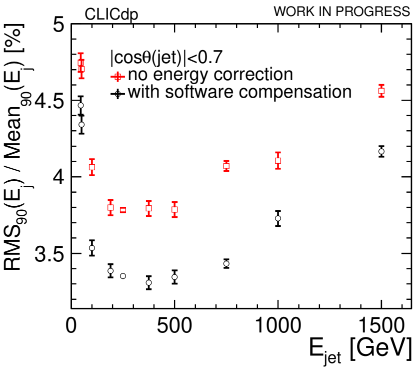
$$\frac{\mathrm{RMS}_{90}(E_j)}{\mathrm{mean}_{90}(E_j)} = \frac{\mathrm{RMS}_{90}(E_{jj})}{\mathrm{mean}_{90}(E_{jj})}\sqrt{2}$$



- Default Software compensation are tuned for hadrons up to 100 GeV (optimized for ILD detector at ILC), at CLIC expect to reach higher hadron energies, at 3 TeV sometimes beyond 500 GeV → extend applicability range and retune for CLIC
- Excellent jet energy resolution (3.5-4.5 %) for most jet energies up to the endcaps ($|\cos(\theta)| > 0.925$)
- Conformal tracking is not yet fully efficient at 1500 GeV and work is ongoing → jet energy resolution is expected to become better

Jet energy resolution with and w/o Software compensation





- Software compensation improves jet energy resolution within the whole θ range in all energies
- Improvement reaches 10-25 % in barrel region
- Software compensation performs well even with high jet energies

Summary

Performance of CLICdet and CLD detectors have been studied with PandoraPFA with isolated single particles and dijet events:

- Good single particle ID efficiency for both detectors ($>$95% from 20 GeV for charged particles)
- Excellent jet energy resolution (3.5-4.5 %) for most jet energies up to the endcaps

Overall calorimetry performance of CLD detector (FCCee) is similar to CLICdet

Software compensation:

- improves jet energy resolution by 10-25%
- provides reconstruction of total energy in dijet events with accuracy of 0.5%
- performs well even at high jet energies (tested up to 3 TeV centre-of-mass-energy)

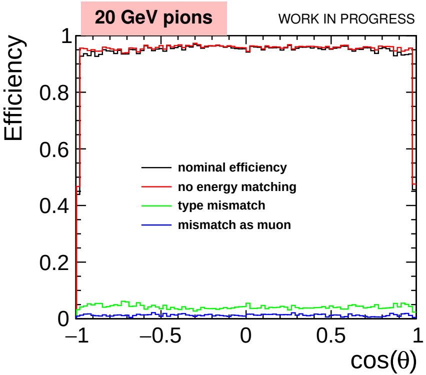
Thank you for your attention!

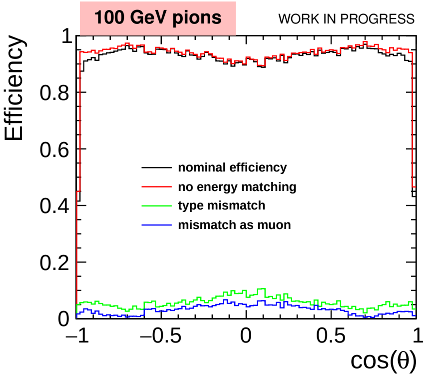
BACKUP

Overall dimensions of CLIC and FCC-ee detectors

	CLICdet		CLD
VTX Barrel	31-60 mm	$\Longrightarrow$	17-59 mm
VTX Endcap	Spirals	$\Longrightarrow$	Disks
Tracker radius	1486 mm	$\Longrightarrow$	2100 mm
ECAL thickness	40 layers, 22 X_0	$\Longrightarrow$	40 layers, 22 X_0
HCAL thickness	60 layers, 7.5 λ_I	$\Longrightarrow$	44 layers, 5.5 λ_I
Yoke thickness	1989 mm	$\Longrightarrow$	1521 mm
MDI (forward region)		$\Longrightarrow$	$<$ 150 mrad
Solenoid field	4 Tesla	$\Longrightarrow$	2 Tesla

- Pion ID efficiency and inefficiency as function of cos(θ)

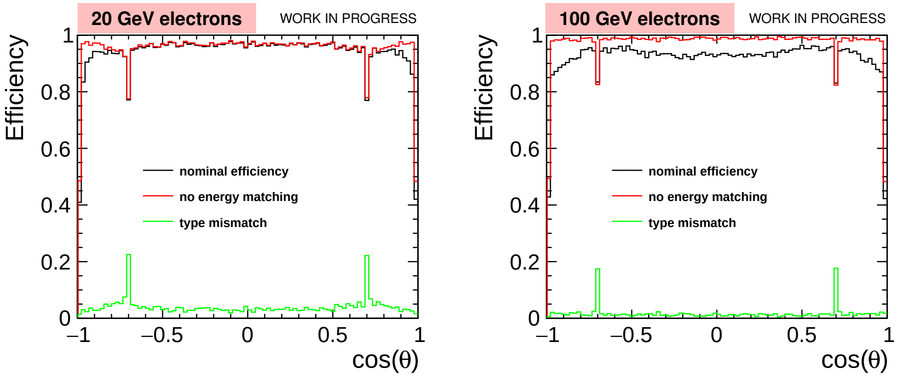




- High momentum pions more often are misreconstructed as muons in barrel

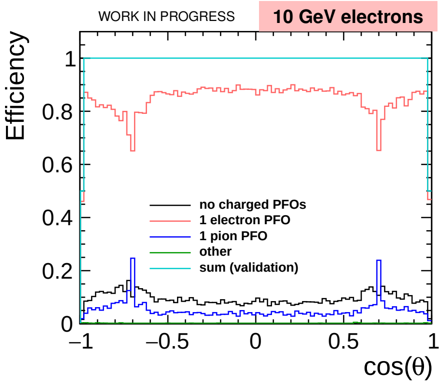
Electron identification efficiency

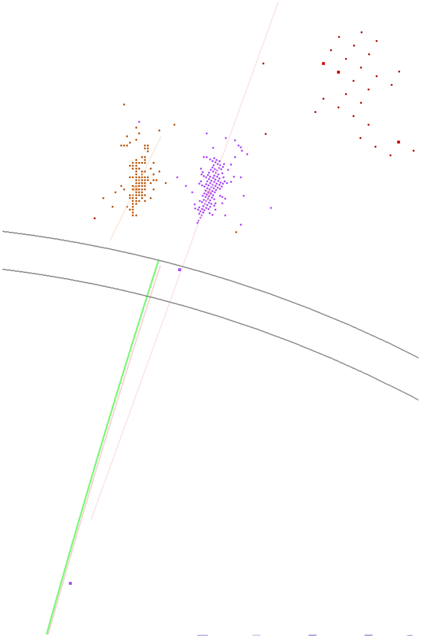
- Electron ID efficiency and inefficiency as function of cos(θ)



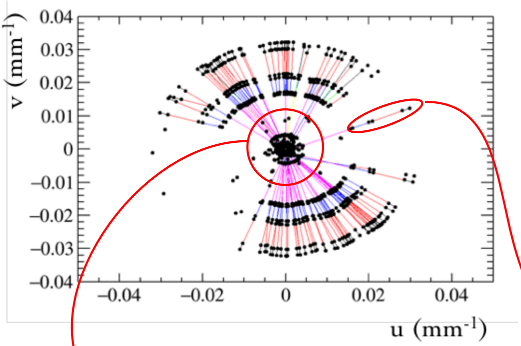
- Inefficiency for high-momentum electrons can be recovered by better Bremsstrahlung recovery algorithm

Electron identification efficiency (Pandora track-cluster association algorithm)





- 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 fitting is done in the conformal space:

$$u = \frac{x}{x^2 + y^2} \qquad v = \frac{y}{x^2 + y^2}$$

Cellular automaton is used to perform straight line search

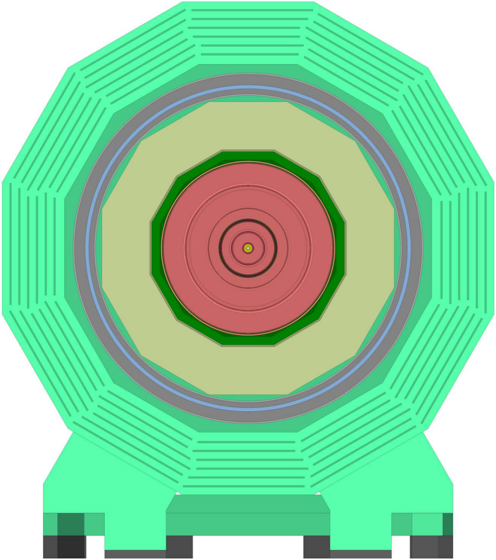
Hits from the Vertex

Hits from the Tracker

- Conformal tracking is used as the main track pattern recognition algorithm at CLIC

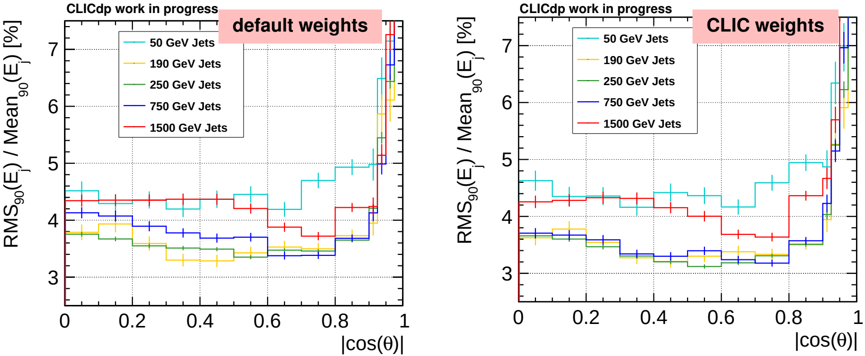
LCWS presentation about CLIC Conformal Tracking performance

CLD detector layout: x-y view



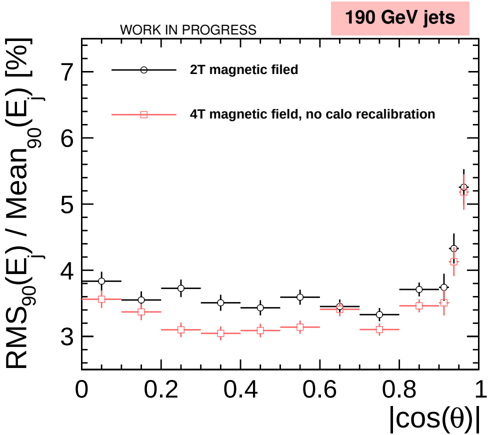
Concept	CLICdet	CLD
Vertex inner radius [mm]	31	17
Tracker technology	Silicon	Silicon
Tracker half length [m]	2.2	2.2
Tracker outer radius [m]	1.5	2.1
Inner tracker support cylinder radius [m]	0.575	0.675
ECAL absorber	W	W
ECAL X_0	22	22
ECAL barrel r_{min} [m]	1.5	2.15
ECAL barrel Δr [mm]	202	202
ECAL endcap z_{min} [m]	2.31	2.31
ECAL endcap Δz [mm]	202	202
HCAL absorber	Fe	Fe
HCAL λ_{I}	7.5	5.5
HCAL barrel r_{min} [m]	1.74	2.40
HCAL barrel Δr [mm]	1590	1166
HCAL endcap z_{min} [m]	2.4	2.4
HCAL endcap Δz [mm]	1590	1166
Solenoid field [T]	4	2
Solenoid bore radius [m]	3.5	3.7
Solenoid length [m]	8.3	7.4
Overall height [m]	12.9	12.0
Overall length [m]	11.4	10.6

Jet energy resolution: CLIC specific SWC weights



- 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

Jet energy resolution at CLD: 2T vs 4T



- Increasing magnetic field of detector significantly improves jet energy resolution

There are three main sources of beam related backgrounds at CLIC:

- $e^+ e^-$ pairs which are predominantly produced with low transverse momenta p_T
- $\gamma\gamma \rightarrow$ hadrons (from the interaction of real and virtual photons from the colliding beams) which result in pile-up of low energy particles with $p_T < 5$ GeV
- beam halo muons