CLIC-inspired detector for FCC-ee

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on behalf of the FCC and CLICdp collaborations

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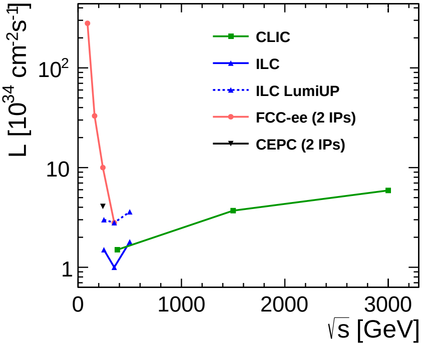
CLIC

- Compact Linear Collider ($e^- e^+$)
- 3 energy stages:
  380 GeV, 1.5 TeV, 3 TeV
- 0.5 ns between bunches
- 20 ms between bunch trains
  $\rightarrow$ Power Pulsing of electronics

FCC-ee

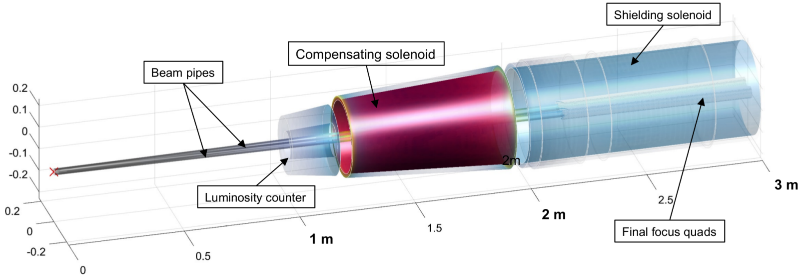
- Future Circular Collider ($e^- e^+$)
- Continuous operation
- 4 energy stages:
  Z, WW, HZ, $t\bar{t}$
- Bunch spacing:
  20, 163, 994, 3396 ns



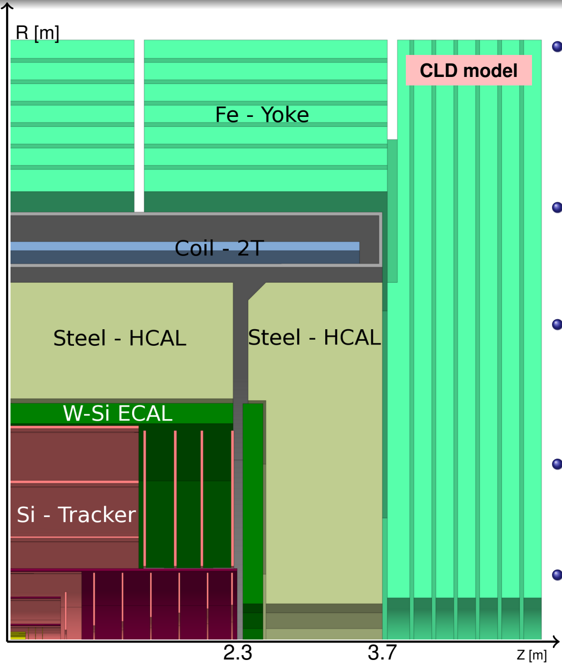
- Both experiments demand state-of-the-art detectors with:
  - low-material tracking system
  - precise calorimetery
- **CLD** - “**C**LIC **L**ike **D**etector”, model derived from CLICdet and optimized for FCC-ee experimental conditions
- There is a second proposal for FCC-ee which is called IDEA (see backup).

- In order to maximize luminosity final focusing quadrupole chosen to be at 2.2m from IP - **inside the detector**.
- Compensating solenoid to protect the beam from detector magnetic field.
- Luminosity monitor (LumiCal) is inside MDI region.
- Central detector has to be fitted within $\pm$**150mrad** $\rightarrow$ constrains forward region.

- To prevent emittance blow-up from detector magnetic field due to non-zero crossing angle the maximum possible **detector magnetic field is constrained to 2T.**



CLD and CLICdet detector models



- 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

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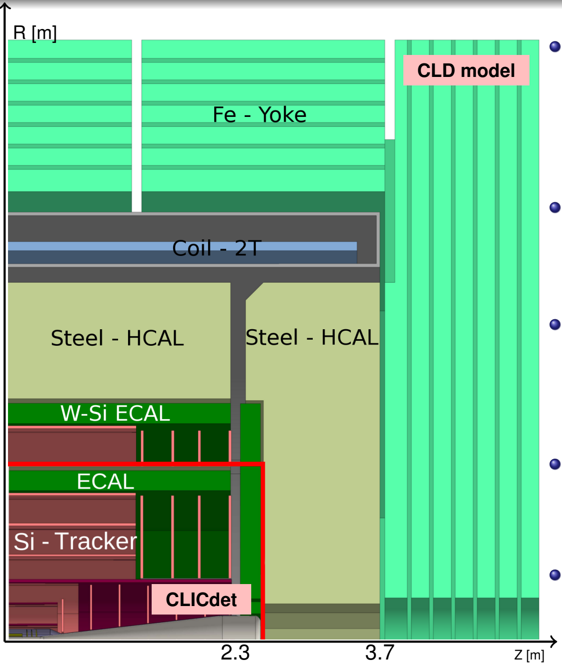

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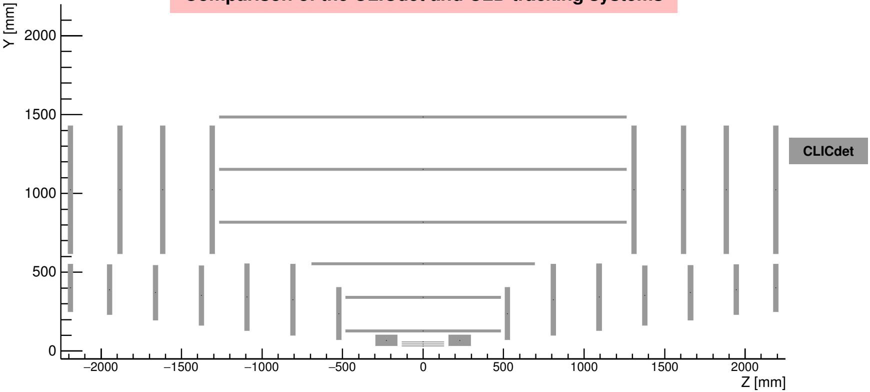
- Vertex detector
  - **Barrel**: 3 equidistant double layers at **17-60 mm** (31-60 mm at CLICdet)
  - **Endcap**: 3 double layer disks instead of spiral structure (no air cooling)
  - **Material budget**: 0.6% X0 per double layer
    (+50% compared to CLICdet for additional cooling, inspired by ALICE ITS upgrade technology)
- Tracker
  - Outer radius of 2.1 m (1.5 m at CLICdet)
- Forward region
  - 150 mrad reserved for MDI

Comparison of the CLICdet and CLD tracking systems



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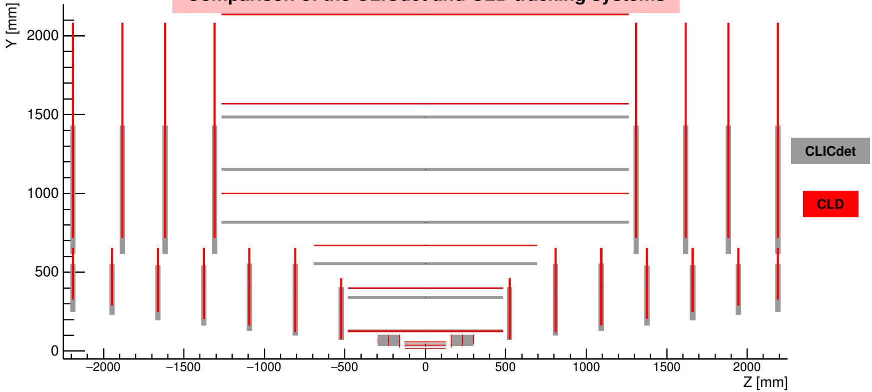


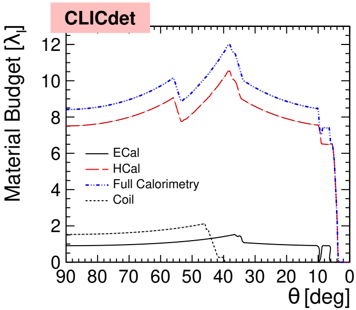
Electromagnetic Calorimeter

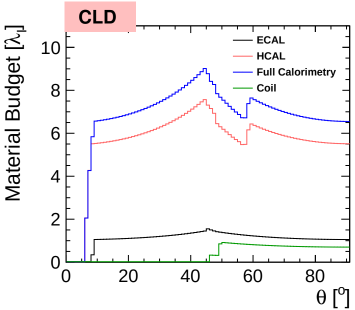
- Si-W sampling calorimeter
- cell size 5x5 mm^2
- 40 layers (1.9 mm thick W plates)
  - options with 30, 20+10 and 20 layers are considered as well
- Depth: 22 X_0, 1 λ_I, 20 cm

Hadronic Calorimeter

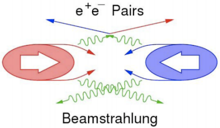
- Scintillator-steel sampling calorimeter
- cell size 30x30 mm^2
- 44 layers
  - 60 layers (CLICdet)
- Depth: 5.5 λ_I (inspired by ILD)
  - 7.5 λ_I (CLICdet)

No studies concerning CLD calorimeter cooling were done. It is assumed to be the same as for CLICdet.



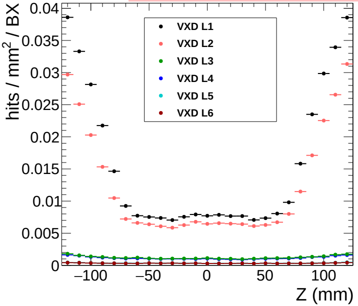


- Synchrotron radiation
  - Appropriate masking stops SR photons from hitting the central beam pipe
  - Small effect
- Beamstrahlung induced backgrounds
  - Incoherent e^+e^- pair production (is simulated during performance studies)
  - $\gamma\gamma \rightarrow$ hadrons (small effect)

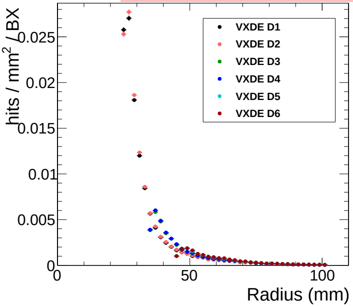


- Beam-gas interactions and radiative Bhabhas
  - expected to have small effect

91.2 GeV, Vertex Barrel

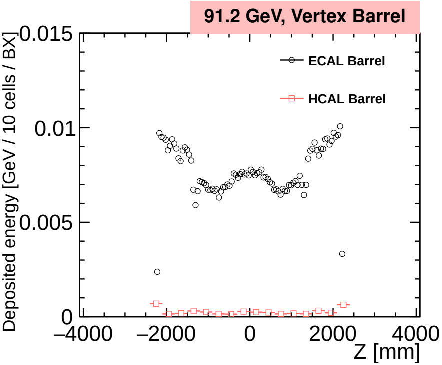


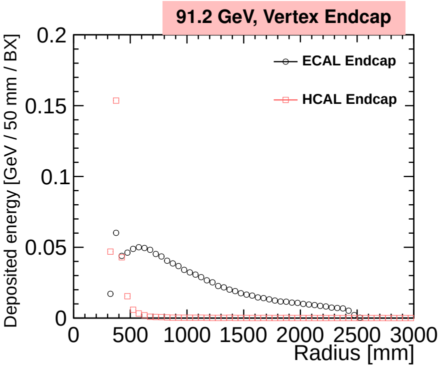
91.2 GeV, Vertex Endcap



Beam-induced backgrounds at FCC-ee

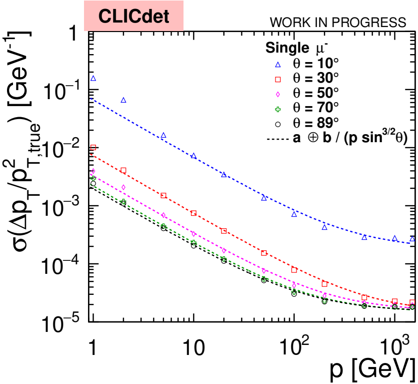
- The energy from incoherent pairs deposited in the ECAL and HCAL
- Has been studied as a function of z in the barrel and as function of radius in the endcap

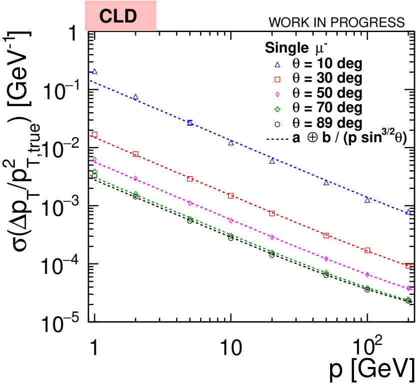




- For background studies with CLD following number of bunch crossings (BX) are overlaid to the physics event:
  - 20 at $\sqrt{s} = 91.2$ GeV
  - 3 at $\sqrt{s} = 365$ GeV
- Energy deposits reach up to 0.2 GeV / 10 cells in ECAL Barrel and 3 GeV / 50 mm in HCAL Endcap per 20 BX

- Transverse momentum resolution for single muons with CLICdet and CLD detector models as a function of momentum for different θ angles.

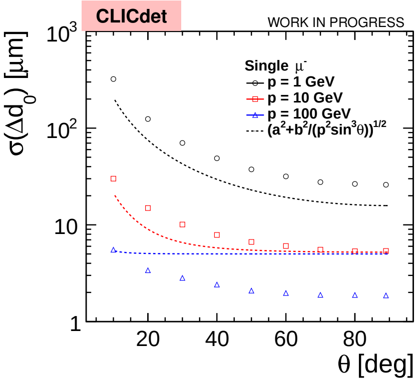


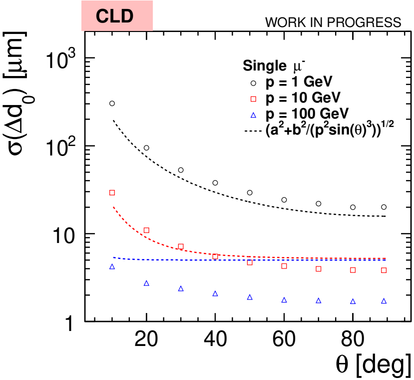


- Overall comparable tracking performance of both detectors
- Both detectors reach designed momentum resolution of $2\times10^{-5}\mathrm{GeV}^{-1}$
  - the lower magnetic field of the CLD model is compensated by a larger radius of tracker

d_0 resolutions: CLICdet vs. CLD

- d_0 resolution for single muons with CLICdet and CLD detector models as a function of θ for 1, 10 and 100 GeV energies



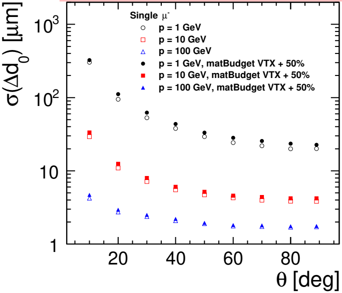


- CLD detector model has superior d_0 resolution due to smaller radius of innermost vertex layer (17 mm for CLD versus 31 mm for CLICdet)

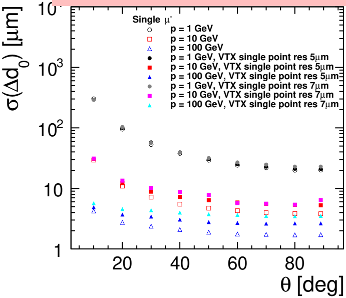
d_0 resolution with CLD

- Continuous operation of FCC-ee doesn't allow power-pulsing → an airflow cooling is not sufficient for VTX detector.
- Nominal CLD material budget is 0.6% X_0 per double layer in Vertex (inspired by ALICE ITS upgrade technology).
- See effect from additional +50% increase in material budget (0.9% X_0) and from a variation of single point resolution.

+50% of VTX material budget



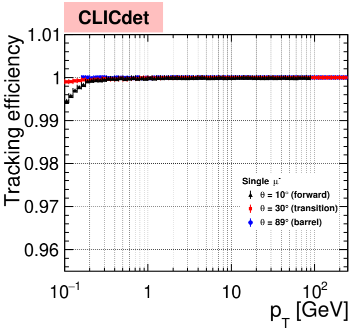
variation of single point resolution

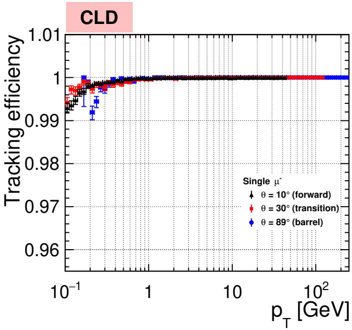


- Mild impact with +50% increase of vertex detector material budget
- A strong correlation of d_0 resolution with single point resolution particularly at high momenta

Tracking performance with prompt muons

- Tracking efficiency with isolated prompt muons:
  - efficiency = fraction of reconstructed particles out of the reconstructable
  - reconstructable particle:
    - $p_T > 0.1$ GeV
    - $|\cos\theta| < 0.99$
    - $\#$ unique hits: 4 for prompt muons

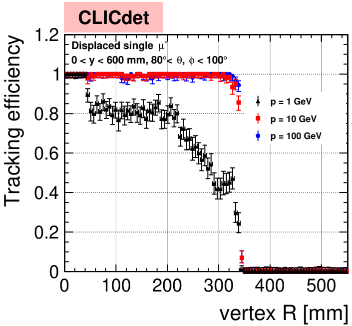


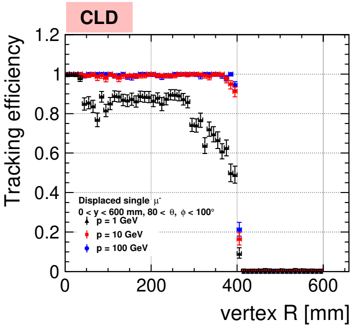


- Conformal tracking has been additionally tuned for CLD detector
- Tracking is fully efficient starting from 100 MeV

Tracking performance with displaced muons

- Tracking efficiency with displaced prompt muons:
  - efficiency = fraction of reconstructed particles out of the reconstructable
  - reconstructable particle:
    - $p_T > 0.1$ GeV
    - $|\cos\theta| < 0.99$
    - $\#$ unique hits: 5 for displaced muons

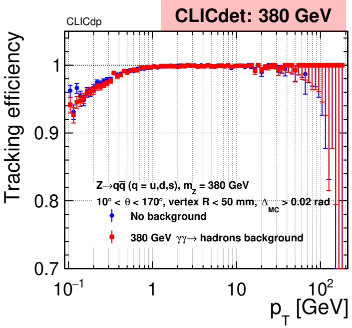


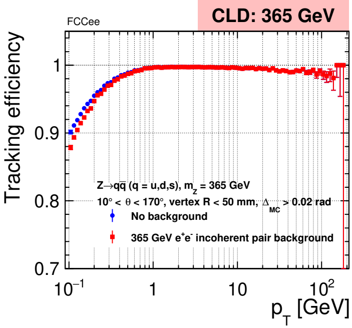


- Tracking algorithm successfully reconstructs displaced tracks:
  - sharp drops at ~340 mm for CLICdet and ~400 mm for CLD correspond to the position of 8-th silicon layer
    $\rightarrow$ not enough hits for track reconstruction (5 hits per track is required)

Tracking performance in complex events

- Tracking efficiency with light flavour di-jets $Z \to q\bar{q}$ ($q = u, d, s$) with and without beam induced background:
  - additional requirement on track purity $> 75\%$
  - purity = #hits left by MC particle / #hits in track





- Tracking is fully efficient from $p_T \approx 500$ MeV
- > 90 % efficiency for low momentum tracks (p_T = 100 - 500 MeV)
- Robustness against beam background

CLD tracking performance with $Z \to b\bar{b}$

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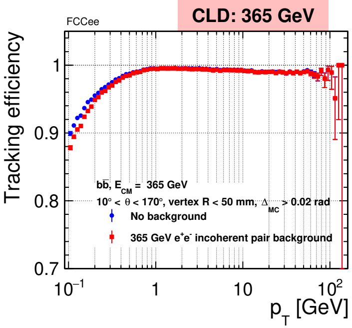

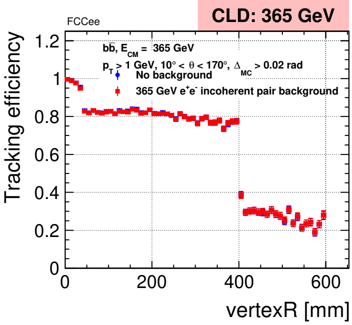

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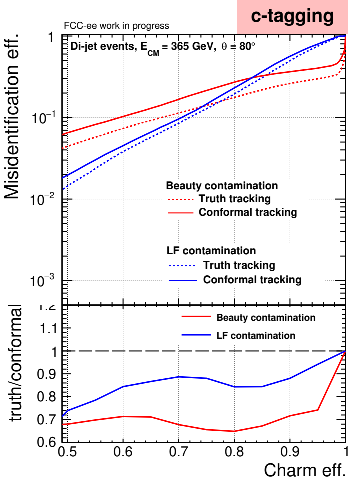
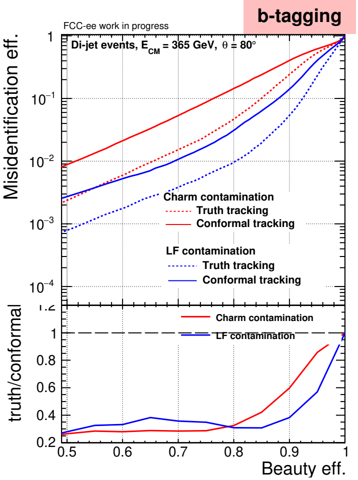
Heavy flavour tagging efficiencies at CLD

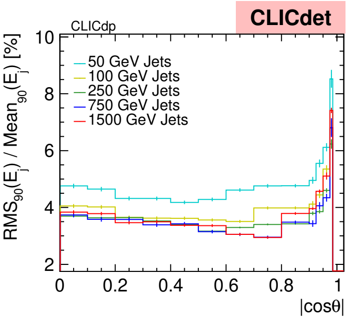
- c- and b-tagging efficiencies for central region ($\theta = 80^{\circ}$) of CLD model:
  - comparison of tagging efficiencies with using conformal and truth tracking
  - truth tracking = assuming perfect pattern recognition

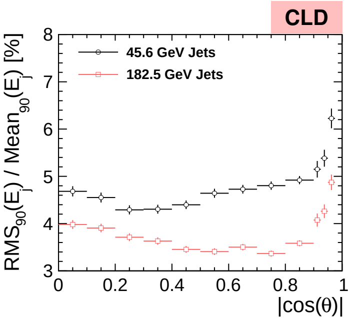




- b-tagging (c-tagging) at 80% eff.: ≈ 4% (15%) miss-id. for c (b) and ≈ 1% (20%) for light flavour
- Some deviation between truth and conformal tracking → work is ongoing
- Flavour tagging performance with CLICdet can be found at a talk by Erica

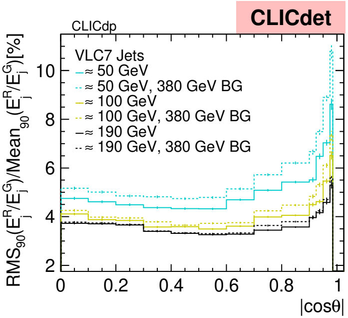
- Event reconstruction is done with PandoraPFA particle flow package
- JER is studied with di-jet events using $Z \to q\bar{q}, (q = u, d, s)$
  - no simulation of beam-induced background effects
  - jet energy is calculated as half of the energy sum of all reconstructed particles

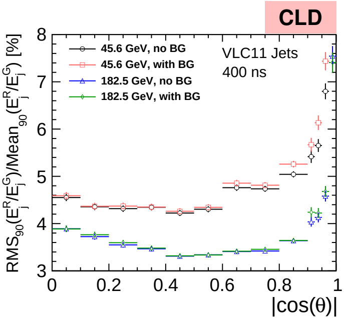




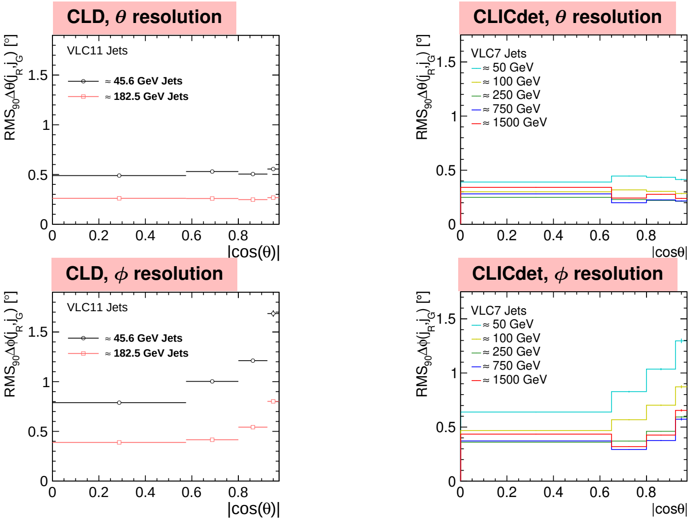
- Comparable jet energy resolutions for CLICdet and CLD models:
  - 4-5 % with ≈50 GeV jets
  - 3-4 % with ≥100 GeV jets

- Jets are reconstructed with Valencia clustering algorithm in two-jet exclusive mode
  - CLICdet: ΔR = 0.7, loose PFO selection applied to suppress beam-induced background
  - CLD: ΔR = 1.1, no timing or p_T cuts are applied, 400 ns integration time window





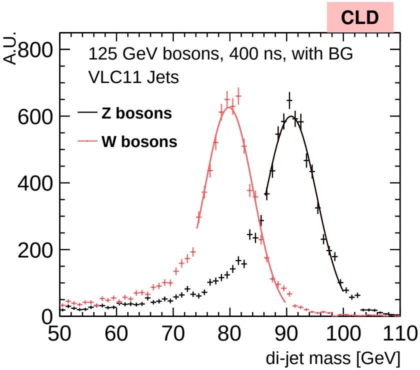
- mild increase of the jet energy resolution due to background for CLICdet
- overall the impact of beam-induced background at FCC-ee is negligible at both centre-of-mass energies except a very forward region

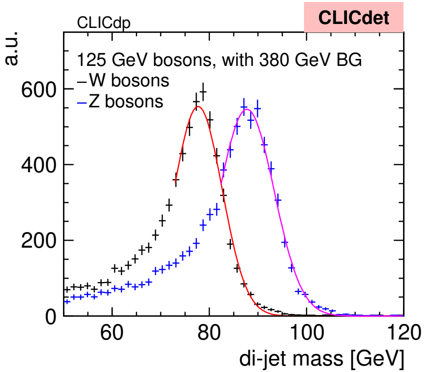


- Comparable resolutions for both detector models
- The ϕ resolution for jets is worse than the θ resolution due to the effect of the magnetic field
- Degradation of the ϕ resolution with $\cos(\theta)$ can be explained with detector granularity

W-Z Mass Peak Separation

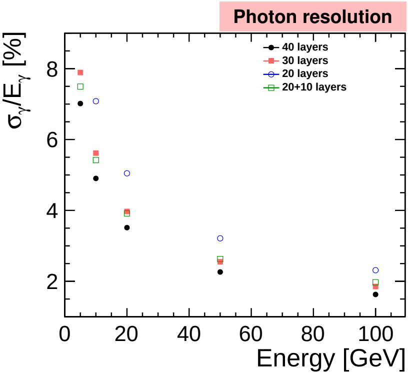
- Study of the ability to distinguish hadronic decays of W- and Z-bosons
- Two processes of interest: $WW \to \mu\nu_\mu qq$ and $ZZ \to \nu\nu qq$ (250 GeV)
  - decay products from leptonic decays of bosons are excluded from the jet reconstruction





- Due to different background different ΔR values have been used for VLC clustering algorithm for CLD (ΔR = 1.1) and CLICdet (ΔR = 0.7)
- Both detectors provide a possibility to distinguish W- and Z-boson peaks with separation power of 2.2-2.5 σ

- CLD ECAL performance for different sampling options
  - all options have the same total thickness of $\approx 22\ X_0$



Layer structure	Thickness tungsten alloy [mm]	Total thickness per layer [mm]
40 uniform	1.9	5.05
30 uniform	2.62	5.77
20 uniform	3.15	7.19
20 thin + 10 thick	1.9 + 3.8	5.05 + 6.95

- 40 layers configuration provides the best photon performance
- 20+10 layers configuration provides better performance at low energies compared for 30 layers which probably better fits needs of FCC-ee
- 20 layers option leads to significant degradation of photon resolution

The CLD detector model is the most mature detector concept for FCC-ee which:

- is based on the CLICdet concept
- has well-understood detector performance with FCC-ee experimental conditions based on full simulation studies (thanks to iLCSoft)
- provides a possibility to make physics analyses including the effect from beam-induced backgrounds

Ongoing studies and plans

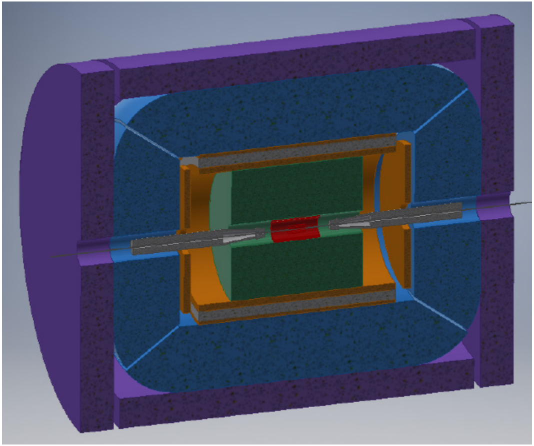
- Detector performance with reduced beam pipe diameter
- Calorimeter layout optimization
- Possibilities of more compact tracker
- Increase ECAL forward coverage
- Detector-MDI integration studies

Thank you for your attention!

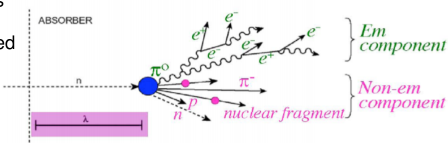
BACKUP

IDEA detector concept

- Vertex Si detector
  - 7 pixel layers
- Ultra light wire drift chamber
  - 4m long, 2m of radius, 0.4%X_0
  - 112 hits per track with particle ID
- One Si layer outside drift chamber
- Ultra-thin 20-30cm solenoid (2T)
  - Acts as preshower ($1X_0$)
- Dual readout fibre calorimeter
  - 2m long, longitudinal segmentation
- Instrumented return yoke



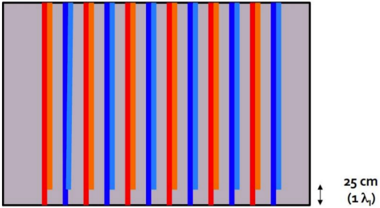
- **Main idea** to use 2 different sampling processes:
  - Cherenkov light (produced by relativistic particles and dominated by the el.-m. shower component)
  - Scintillation light production (for the total deposited energy)



- Calorimeter consists from 2 types of fibers, Cherenkov and Scintillation fibres, which provides two different measurements:

$$C = E[f_{em} + \frac{1}{(e/h)_C}(1 - f_{em})]$$
$$S = E[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})]$$

- Allows to measure f_{em} fluctuations correction event-by-event



- Longitudinal segmentation provided by using short and long fibers
- Dedicated test beams are ongoing