FUTURE CIRCULAR COLLIDER

The CLD Detector Concept

André Sailer, Philipp Roloff

CERN

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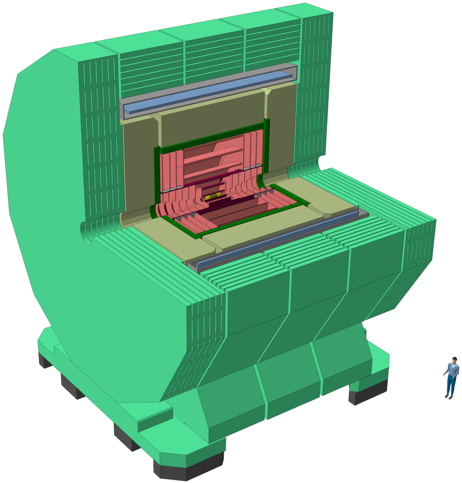
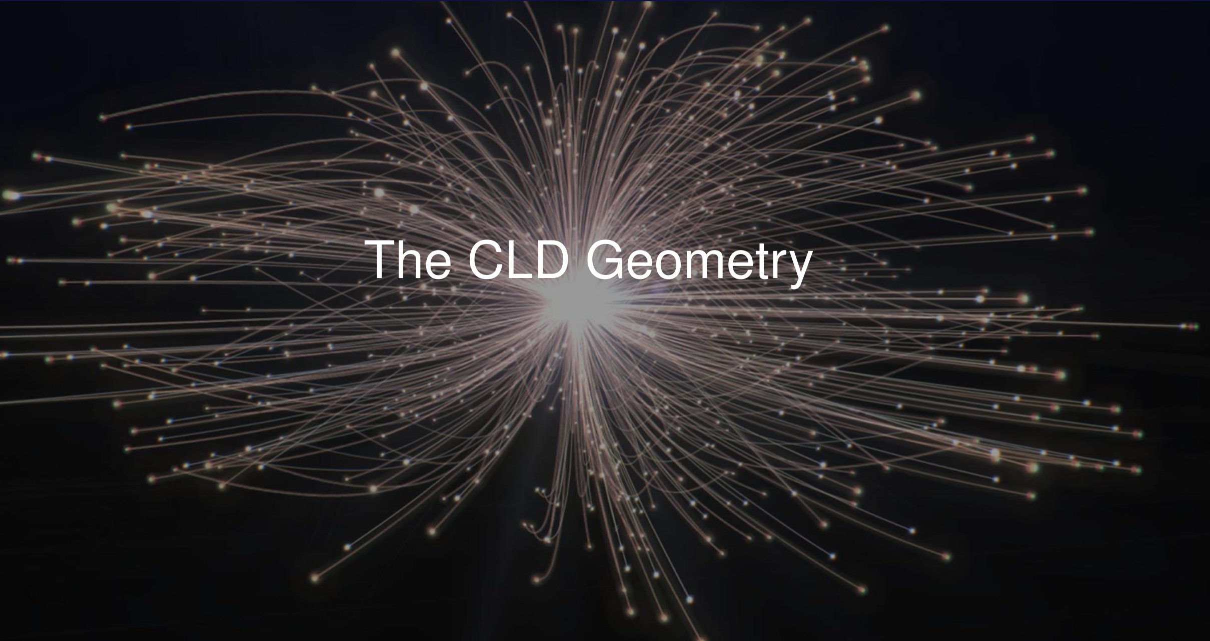


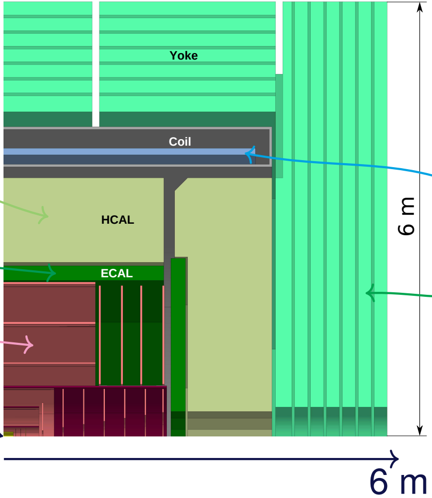


The CLD Geometry

Detector for FCCee

General purpose detector for Particle Flow reconstruction [1]

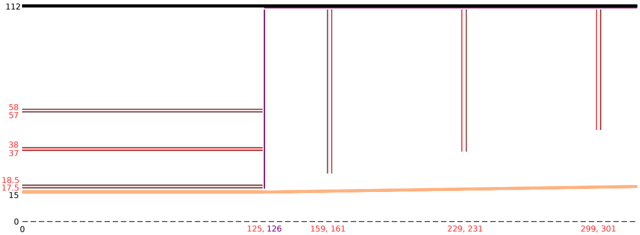
- Steel–Scintillator HCal with 3 cm cell-size
- Silicon–Tungsten ECal with 5 mm cell-size
- Silicon Tracker, mostly 50 µm pitch strips
- Vertex Detector with 25 µm pixels

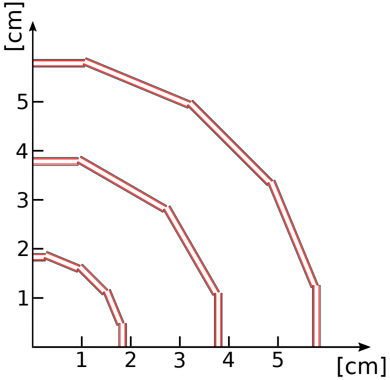


- Superconducting Solenoid of 2 T
- Iron Yoke with RPCs for Muon ID

Vertex Detector

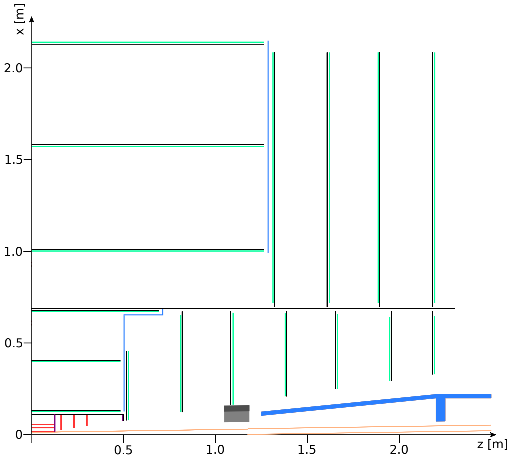
- Silicon vertex detector: precise vertex reconstruction
- $25 \times 25\ \mu m^2$ pixels, 3 µm single point resolution
- 50 µm silicon thickness
- Double layers ($0.3\% X_0$ per detection layer)
- $R_{in} = 17.5$ mm





Silicon Tracking

- Inner and Outer Tracker
  - Support tube for extraction with beam-pipe assembly
- 3 short and 3 long barrel layers, 7 inner and 4 outer endcaps
- 200 μm Silicon thickness, 50 μm $\times$ 0.3 mm cell size, 7 μm $\times$ 90 μm single point resolution (except first inner tracker disk, $5 \times 5\ \mu m^2$)
- At least 8 hits for $\theta > 8.5^\circ$
- Material budget: 1.1 % – 2.2 % X_0 per layer (including overlaps)
- Some studies for re-scaling were done [1]



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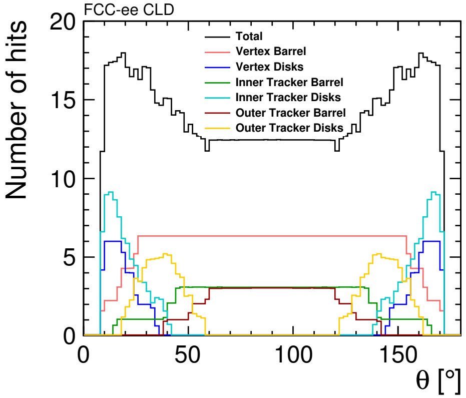

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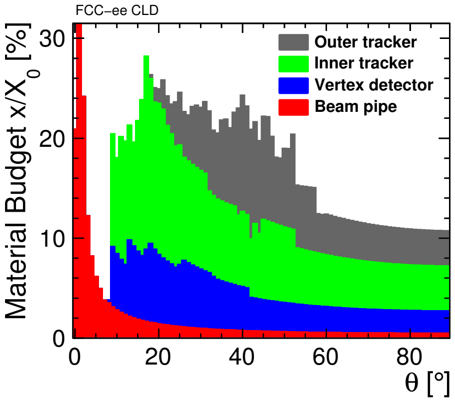


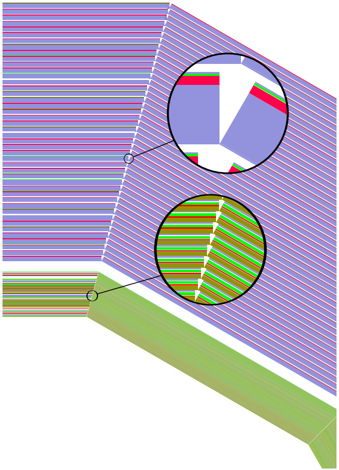
Calorimeters

ECal

- 40 layers, 1.9 mm tungsten absorber, 22 X_0
- 0.5 mm thick silicon sensors with 5×5 mm^2 granularity
- ECal optimisation studies [1, 2]

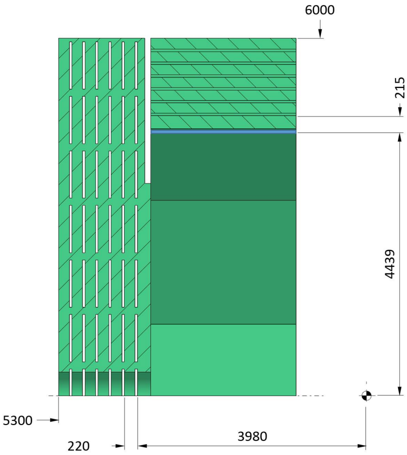
HCal

- 44 layers, 19 mm steel absorber, 5.5 (+1) λ_I
- 3 mm thick scintillator tiles with 3×3 cm^2 granularity



Magnet and Muon System

- 2 Tesla Solenoid Field
- Return yoke contains Muon system with 6 equidistant layers
  - One additional layer after the solenoid to serve as a *tail-catcher*



Performance

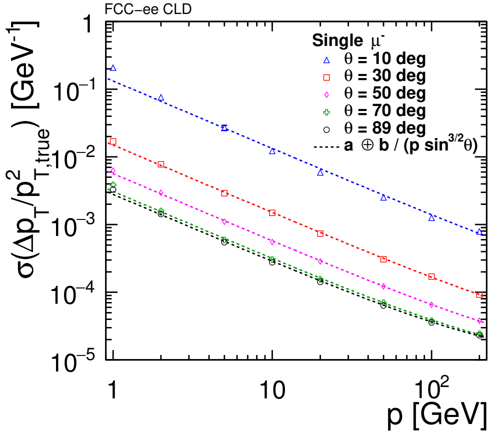
Performance Requirements and Studies

- Performance of CLD detector detailed in the note [1]
- Requirements for FCC detector [3]

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_\mathrm{T}) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_\mathrm{T} \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^\mathrm{jet}/E \sim 3 - 4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%\ (\mathrm{GeV})$

Tracking

- Momentum resolution
- Impact parameter resolution
  - Also estimated for larger material budget in the vertex detector
- Single particle efficiency w.r.t. transverse momentum
- Single particle efficiency w.r.t. radius
- Efficiency in jets
- Re-scaling Studies: $R_{max} \in (2.1, 2.0, 1.9, 1.8)$ m



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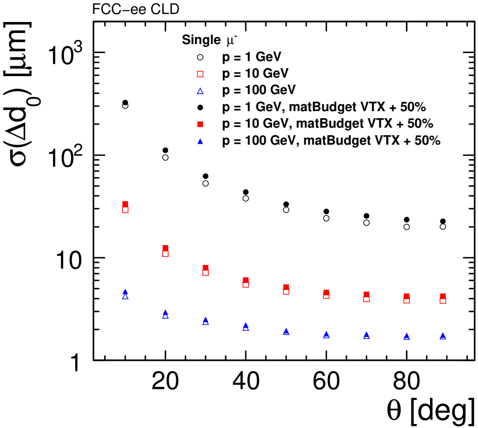

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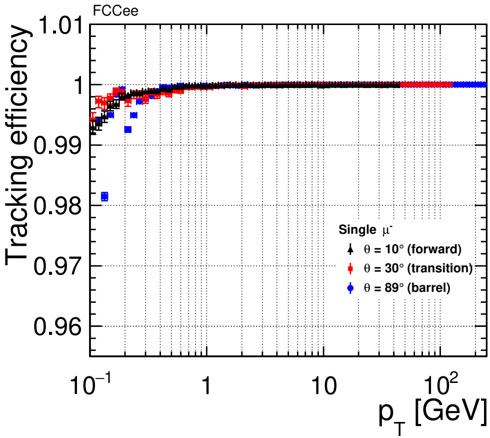

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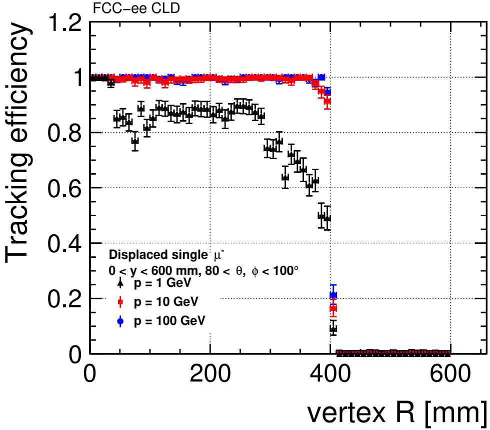

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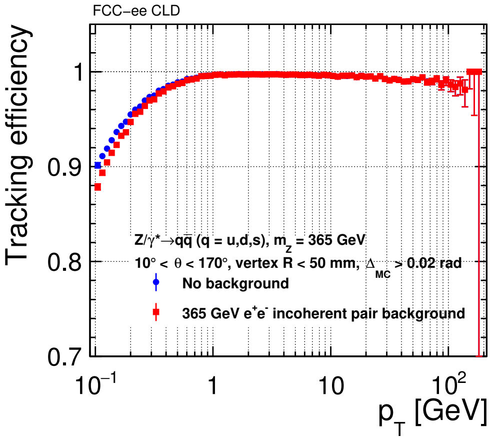

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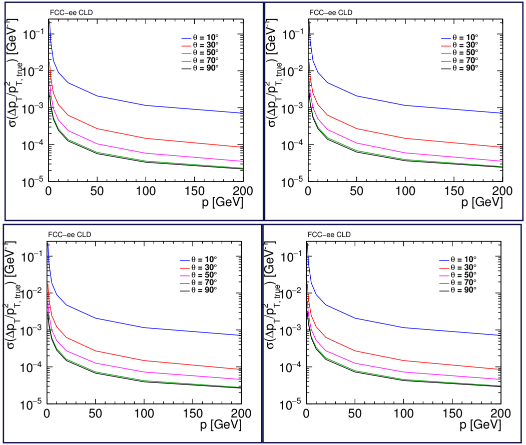
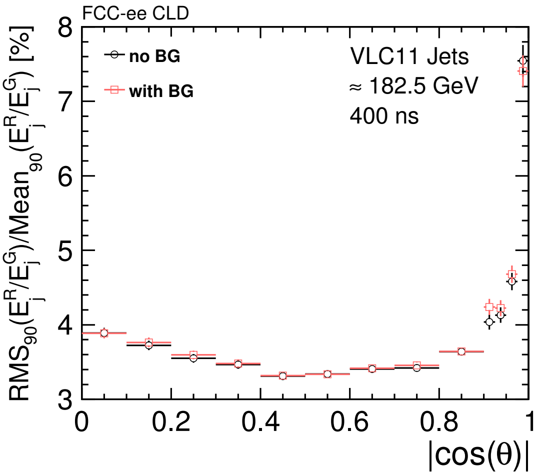


Jets

Examples

- Jet energy resolution including incoherent pair backgrounds
- Boson separation power
- Flavour Tagging



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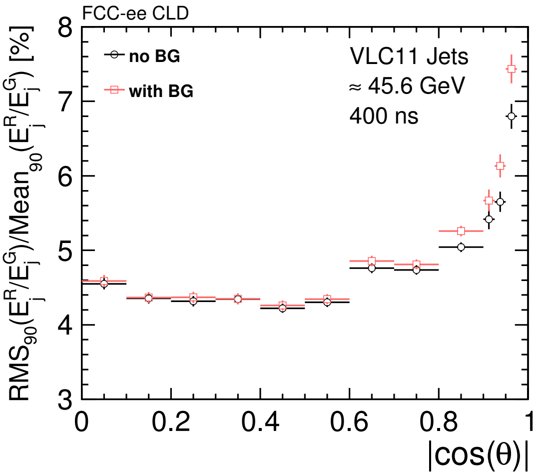

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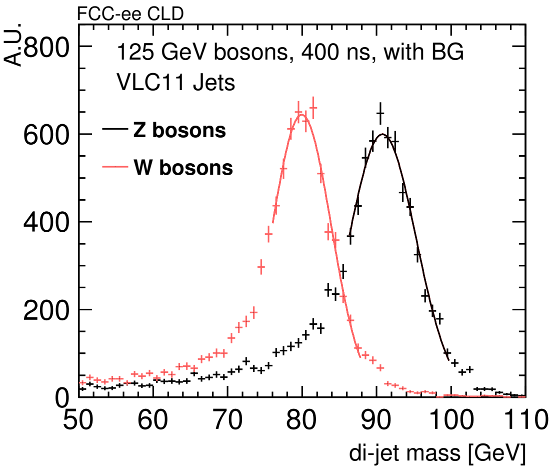
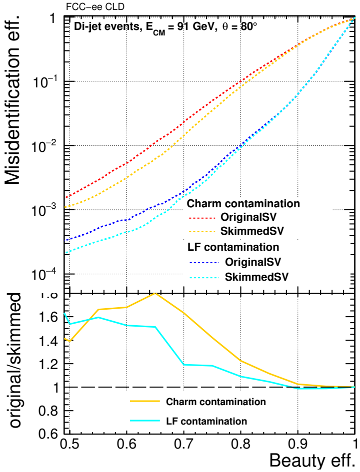


Jets

Examples

- Jet energy resolution including incoherent pair backgrounds
- Boson separation power
- Flavour Tagging
  - Improving BTag performance by ignoring secondary vertices from material



Software

Key4hep Software

- Software for CLD part of the Key4hep software stack
- Available on CVMFS: `/cvmfs/sw.hsf.org/key4hep/setup.sh`
- Documentation: **https://key4hep.web.cern.ch**
- See also **presentation by V. Volkl**

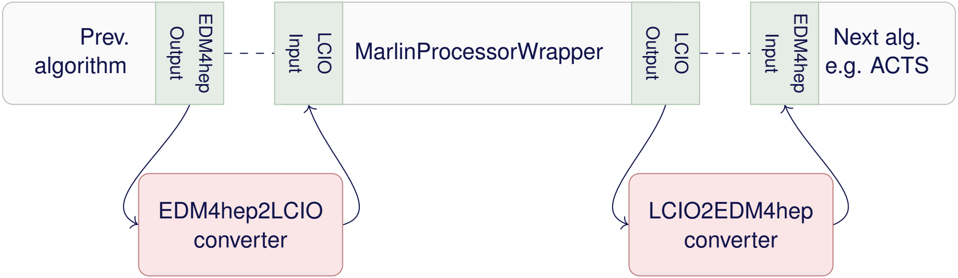
Full Simulation with DDSim

- Using `ddsim` and the CLD specific steering file
  - 30 mrad crossing angle
  - configuration of sensitive detectors, particularly Scintillator HCal (Birks' Law), and silicon tracking sensors
  - Physics list, simulation parameters (e.g., stepper, range cut)

```
source /cvmfs/sw.hsf.org/key4hep/setup.sh
git clone https://github.com/iLCSoft/CLICPerformance
cd CLICPerformance/fcceeConfig/
ddsim --compactFile $LCGEO/FCCee/compact/FCCee_o2_v01/FCCee_o2_v01.xml \
      --inputFiles ../Tests/yyxyev_000.stdhep \
      --numberOfEvents 3 \
      --steeringFile fcc_steer.py \
      --outputFile tops_edm4hep.root
```

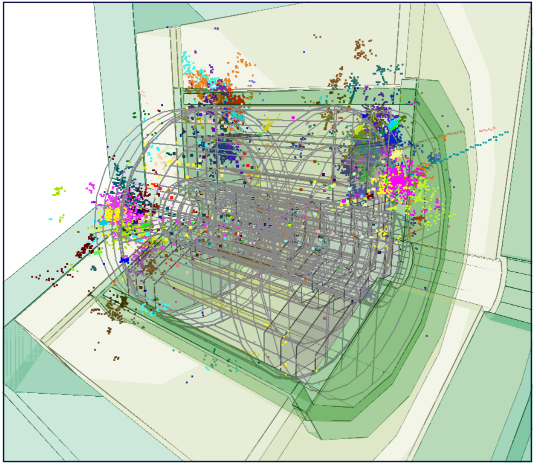
Reconstruction

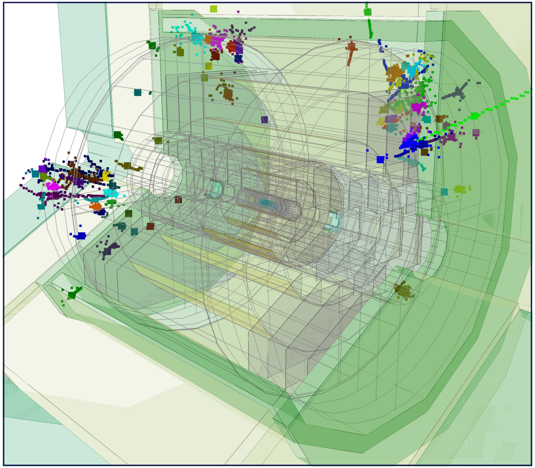
- Reconstruction, consisting of,
  - Background Overlay, Digitisation
  - Track Pattern Recognition (ConformalTracking [4]), track fit
  - Particle Flow Reconstruction (PandoraPFA [5])
  - Vertexing and Flavour Tagging (LCFIplus [6])
- Run with Gaudi via the k4MarlinWrapper: `k4run fccRec_e4h_input.py`*
  - Input and output in EDM4hep



*`wget https://raw.githubusercontent.com/key4hep/k4MarlinWrapper/master/test/gaudi_opts/fccRec_e4h_input.py`

Event Displays





Ideas for Further Studies

Ideas for Further Studies I

Vertex detector and flavour tagging:

- Study implications of cooling needs at FCC-ee due to absence of power pulsing $\rightarrow$ so far only rough estimate of additional material
- Optimisation of the vertex detector for the Z pole (backgrounds, lower jet energies)
- Improved treatment of material in the vertex detector region (in particular cooled beam pipe)
- Investigate potential of PID in the flavour tagging (together with physics performance)

Tracking:

- Study implications of cooling needs at FCC-ee due to absence of power pulsing $\rightarrow$ so far only rough estimate of additional material
- Further optimisation of the tracker configuration $\rightarrow$ e.g., overall size and trade-off between more material from additional layers and better acceptance for long-lived particles
- Explore compatibility of alternative options (e.g., gaseous tracking) with the presence of beam-induced background

Ideas for Further Studies II

Calorimetry:

- Study implications of cooling needs at FCC-ee due to absence of power pulsing $\rightarrow$ additional space needed / impact on sampling fractions
- Impact of full beam-induced background in the forward direction at the Z pole
- Explore if alternative technology options are compatible with PFA calorimetry and can provide better resolution for single EM particles $\rightarrow$ currently limited by Si-W ECAL
  - Scintillating sampling ECAL technology [7]
  - Or for the more speculative approach: Chromatic calorimetry with *Quantum Dots* [8]?

Luminosity detectors:

- Further background studies
- Inclusion of the MDI region and in particular the luminosity detectors in the CLD simulation

Ideas for Further Studies III

Precise timing capabilities:

- Potential of timing information with O(few ns) precision to reject particles from beam-induced background (including backscattered fragments)
- Impact of very precise timing information with O(few 10 ps) precision for PID $\rightarrow$ comparison of different approaches (ECAL or dedicated timing layer, maybe complemented by time information from tracking layers)

Further PID issues:

- Investigate if dE/dx from (thin) tracking layers can be useful
- Add RICH detector

Readout considerations:

- Further studies of detector integration times
- More detailed look at data rates and the possible need for a trigger

Calibration:

- Impact of calibration issues and the resulting systematic uncertainties with an emphasis on issues at the Z pole for which full simulation is needed (together with physics perf.) $\rightarrow$ e.g. uncertainties of various potential luminosity measurements, calibration of the b-tagging and c-tagging efficiencies and fake rates

Summary

Summary

- CLD detector model implemented for full simulation and reconstruction
  - Initial focus was on 250 GeV and above
- Many interesting opportunities for improvements and detailed studies
  - Software developments in Key4hep
  - Geometry and detector technology optimisation
  - Physics studies

References

[1] N. Bacchetta et al. *CLD – A Detector Concept for the FCC-ee*. 2019. arXiv: 1911.12230 [physics.ins-det].

[2] O. Viazlo and A. Sailer. “Efficient Iterative Calibration on the Grid using iLCDirac”. In: *EPJ Web Conf.* 245 (2020), p. 03003. DOI: 10.1051/epjconf/202024503003.

[3] C. Grojean. “FCC physics case: the once, the now and the future”. In: *FCC Week 2022*. 2022. URL: https://indico.cern.ch/event/1064327/contributions/4893259/.

[4] E. Brondolin et al. “Conformal tracking for all-silicon trackers at future electron–positron colliders”. In: *Nucl. Instrum. Meth.* A956 (2020), p. 163304. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2019.163304.

[5] J.S. Marshall and M.A. Thomson. “The Pandora Software Development Kit for Pattern Recognition”. In: *Eur.Phys.J.* C75.9 (2015), p. 439. DOI: 10.1140/epjc/s10052-015-3659-3.

[6] T. Suehara and T. Tanabe. “LCFIPlus: A Framework for Jet Analysis in Linear Collider Studies”. In: *Nucl. Instrum. Meth.* A808 (2016), pp. 109–116. DOI: 10.1016/j.nima.2015.11.054.

[7] E. Auffray. “Scintillating sampling ECAL technology for the Upgrade II of LHCb”. In: *CALOR 2020*. 2022. URL: https://indico.cern.ch/event/847884/contributions/4833006/.

[8] M. Doser. *Quantum detectors for (low and high energy) particle physics*. 2022. URL: https://indico.cern.ch/event/1152324/.

Thank you for your attention

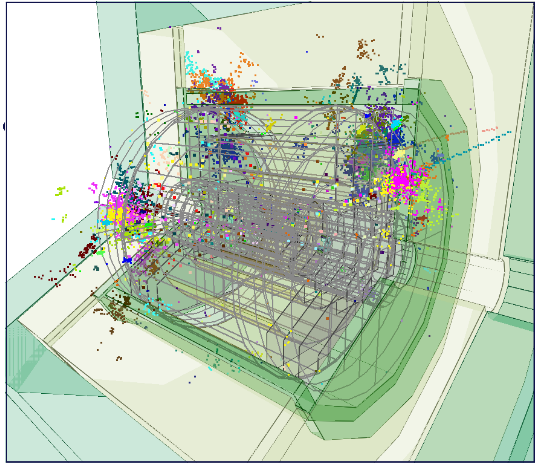
Backup Slides

DetectorModels

- CLD Software based on Key4hep: All software available on Key4hep CVMFS
  `source /cvmfs/sw.hsf.org/key4hep/setup.sh`
  - DD4hep detector models
    - **FCCee_o1_v04 (lcgeo)**: detector model used for most of the performance note [1]
    - **FCCee_o2_v01 (lcgeo)**: detector model with updated beam pipe/VXD radii (10 mm)
    - **FCCee_o2_v02 (FCCDetectors)**:

Event Display

- `ced2go -d $LCGEO/FCCee/compact/FCCee_o2_v01/FCCe`
  `-v CEDViewer sim.slcio`



Event Display

- `ced2go -d $LCGEO/FCCee/compact/FCCee_o2_v01/FCCe`
  `-v CEDViewer sim.slcio`
- Needs simulation output in slcio format (`ddsim ... -O sim.slcio ...`)
- `ced2go` is a wrapper around Marlin running a `CEDViewer` processor, so in principle we should be able to use this event display via `k4MarlinWrapper` and `EDM4hep` as well. . .