FUTURE CIRCULAR COLLIDER

The CLD Detector Concept

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CERN

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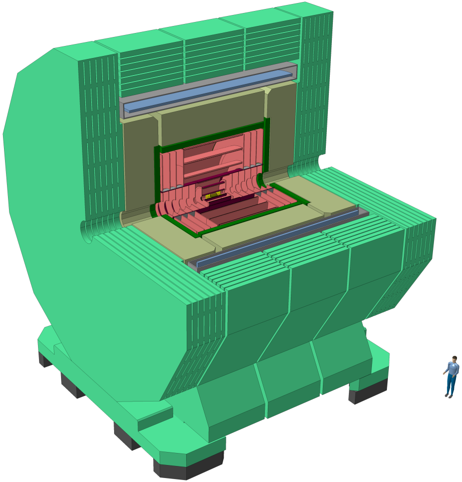
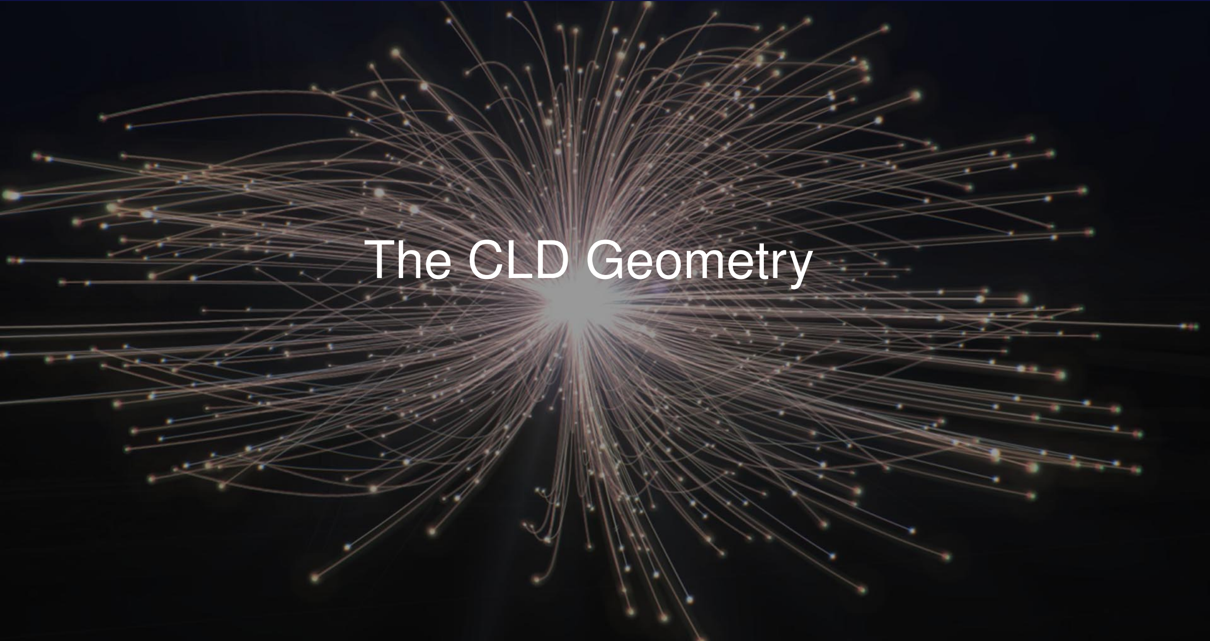


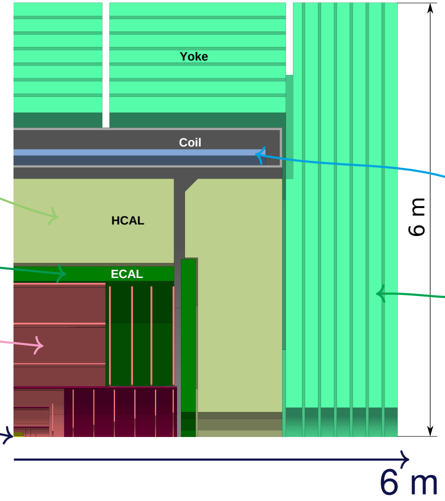


The CLD Geometry

Detector for FCCee

General purpose detector for Particle Flow reconstruction [1]

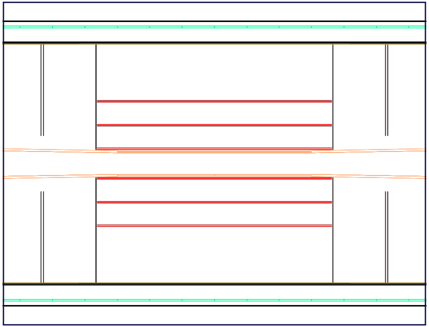
- Steel–Scintillator HCal with 3 cm cell-size
- Silicon–Tungsten ECal with 5 mm cell-size
- Silicon Tracker, mostly 50 µm pitch strips
- Vertex Detector with 25 µm pixels



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

Vertex Detector

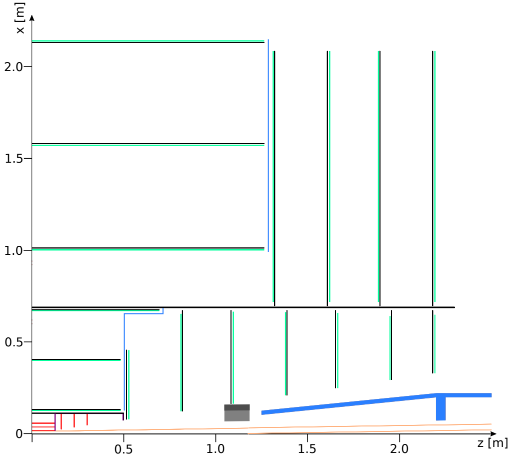
- Silicon vertex detector: precise vertex reconstruction
- $25 \times 25\ \mu m^2$ pixels, 3 μm single point resolution
- 50 μm silicon thickness
- Double layers ($0.3\% X_0$ per detection layer)
- $R_{in} = 13.0$ mm



Cut through the vertex detector around the interaction point

Silicon Tracking

- Inner and Outer Tracker
  - Support tube ($R \approx 0.7$ m for extraction with beam-pipe assembly
  - Material to represent support, service routing
- 3 short and 3 long barrel layers, 7 inner and 4 outer endcaps
- 200 µm Silicon thickness, 50 µm × 0.3 mm cell size, 7 µm × 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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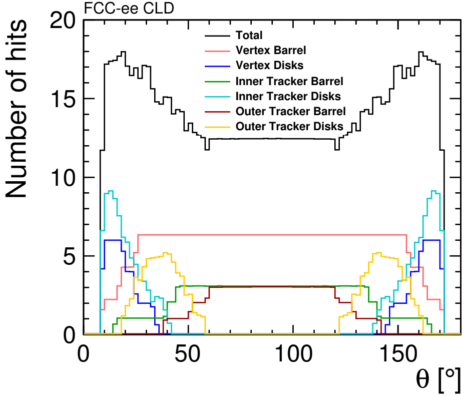

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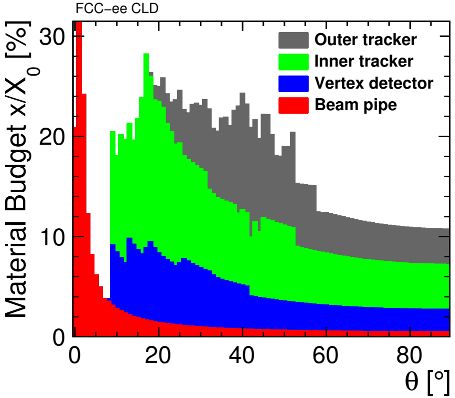


Calorimeters

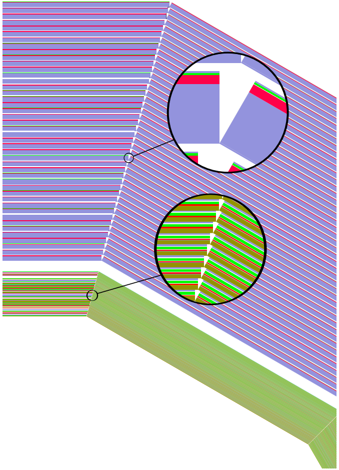
ECal

- 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

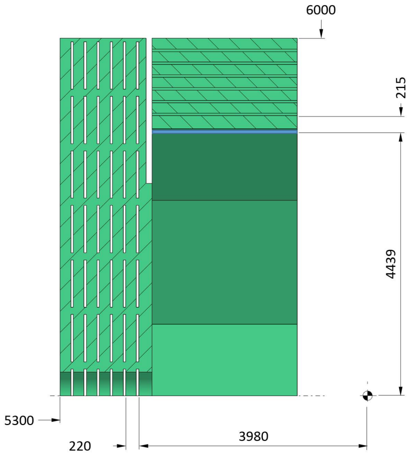
- 44 layers, 19 mm steel absorber, 5.5 (+1) λ_I
- 3 mm thick scintillator tiles with 3×3 cm^2 granularity

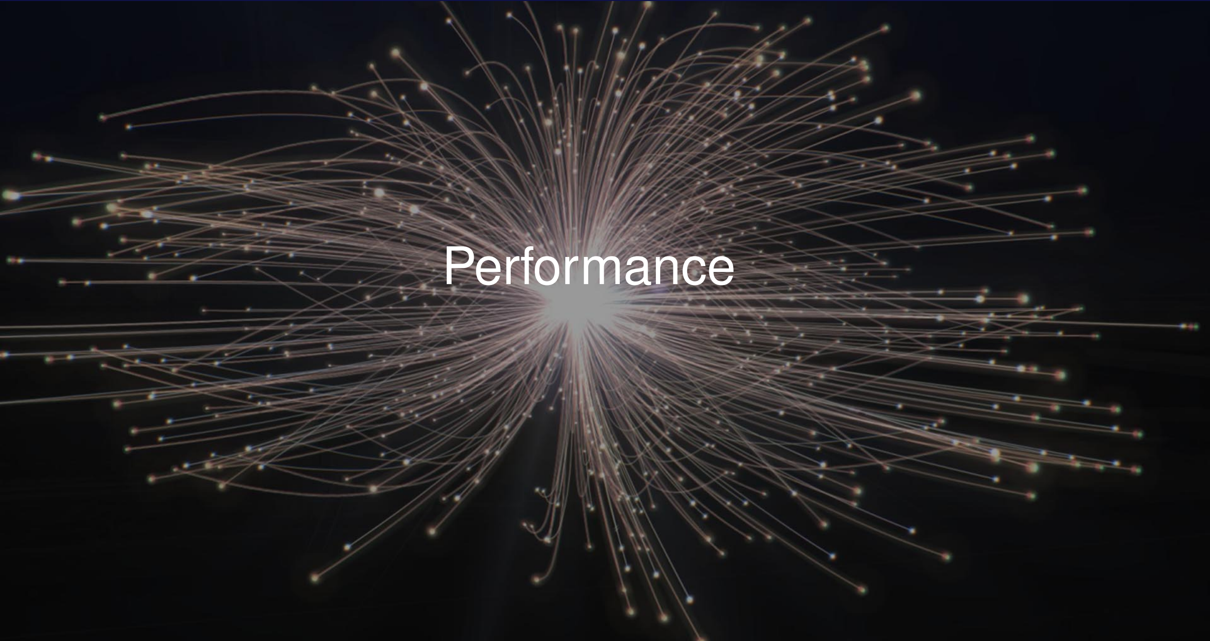
No detailed mechanincal design so far



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

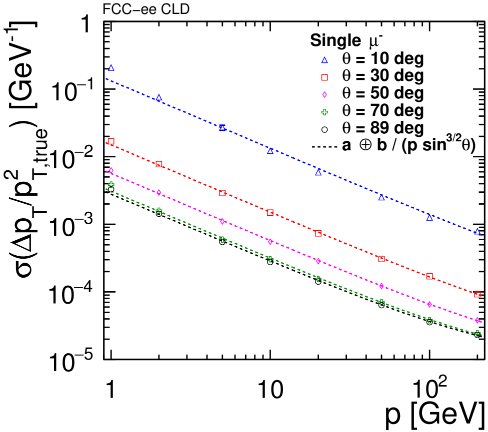
Performance Requirements and Studies

- 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	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (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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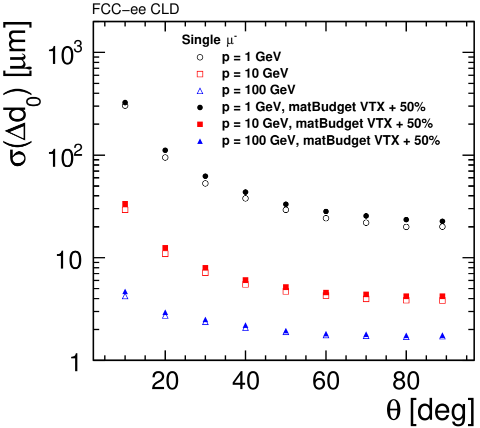

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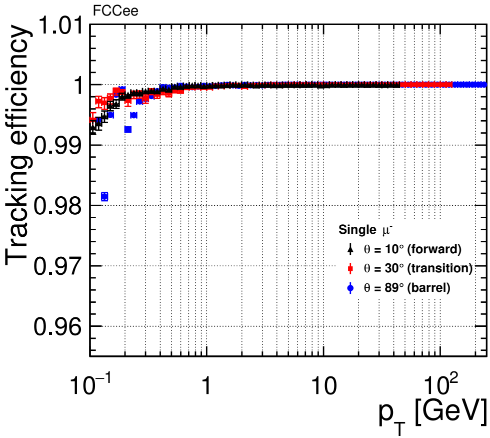

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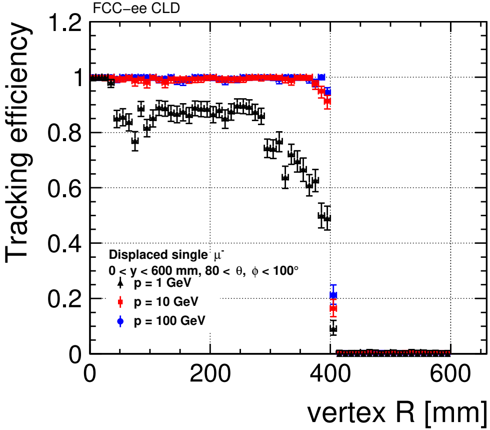

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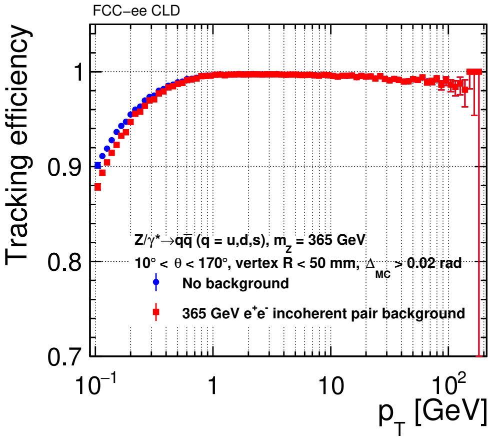

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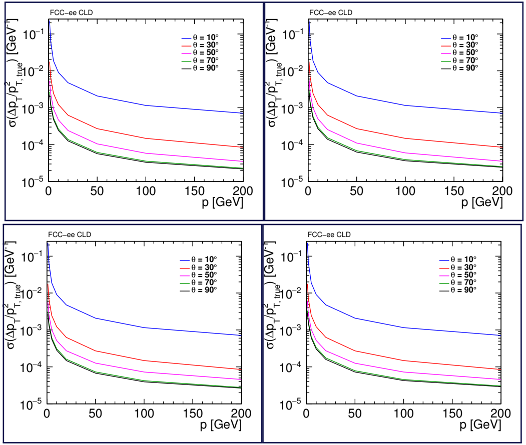
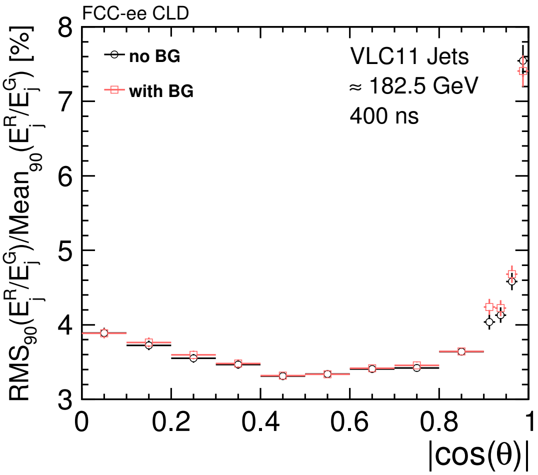


Jets

Examples

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



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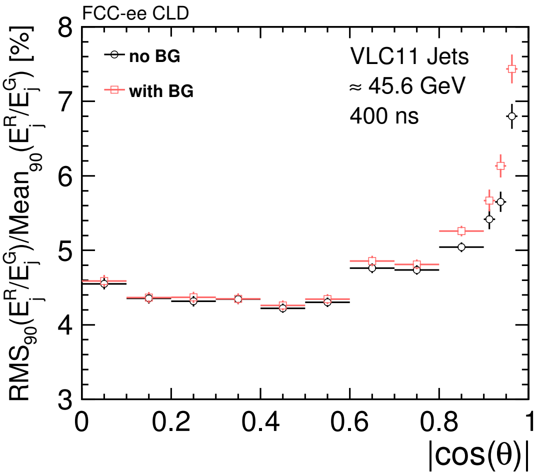

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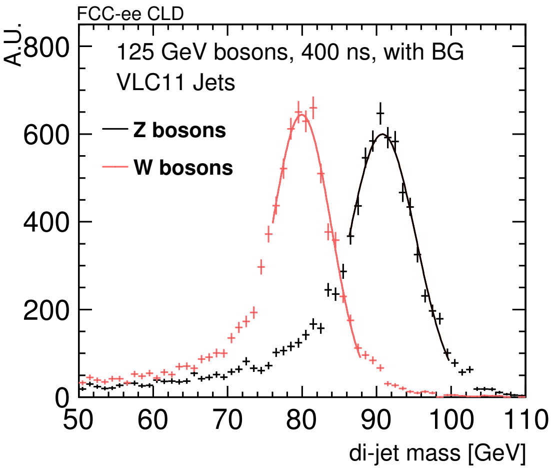
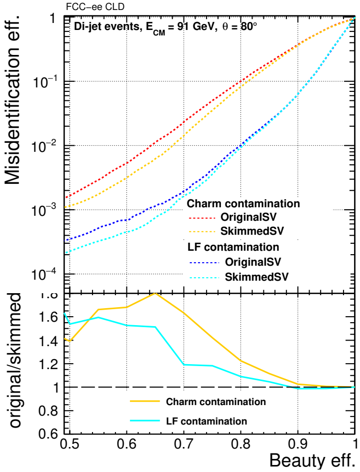


Jets

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 the **full sim demonstration by B. Francois**

Software Configuration Baseline

- **CLDConfig** repository collection for Simulation and Reconstruction configuration files
- Rein in the multitude of configuration files flying around with fixes due to fluidity of Key4hep in the last months.
- Repository to fix things centrally and publicize, and a place for questions.

Full Simulation with DDSim

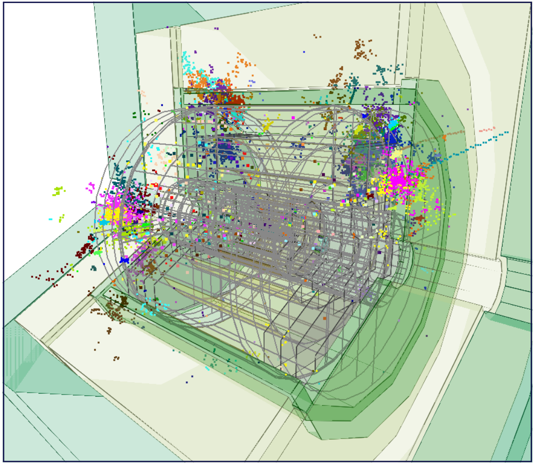
- Using `ddsim` and the CLD specific steering file
  - 30 mrad crossing angle
  - configuration of sensitive detectors, particularly Scintillator HCal (Birks' Law), and silicon tracking sensors
  - Physics list, simulation parameters (e.g., stepper, range cut), additional particles

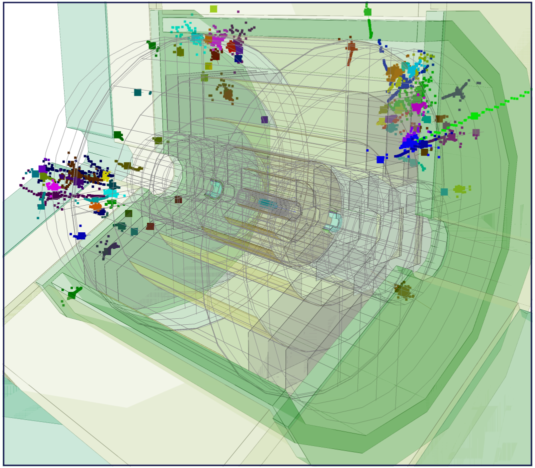
```
source /cvmfs/sw.hsf.org/key4hep/setup.sh
git clone https://github.com/Key4hep/CLDConfig
cd CLDConfig/
ddsim --compactFile $K4GEO/FCCee/CLD/compact/CLD_o2_v05/CLD_o2_v05.xml \
      --inputFiles ../test/yyxyev_000.stdhep \
      --numberOfEvents 3 \
      --steeringFile cld_steer.py \
      --outputFile 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 cldReconstruction.py`
  - Input and output in EDM4hep

Event Displays





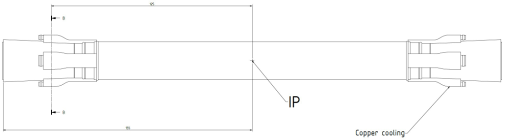
CLD_02_v05

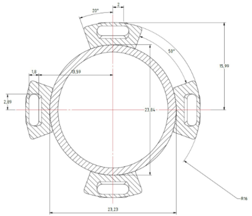
- Modifications for the vertex detector to fit with the new design for the innermost beampipe, including liquid cooling of the beampipe
- Fixed wrong number and size of modules in the last ring of the last inner tracker endcap
- Fixed some small overlaps
- Removed HOM absorber, which is no longer needed for low impedance beampipe

New Beampipe

- New beam pipe design **(cf. MDI session)**. Figures from [7]
- Only using primitive volumes available in Geant4 and TGeo, no CAD created pieces here
  - Conical chamber is conical, no circular to ellipse volume

[mm]	Cyl R_{min}	Cyl R_{max}	Cyl L	Cone R_{min}
v02	10	11.2	125	11
v05	**10**	**11.7**	**90**	**12**



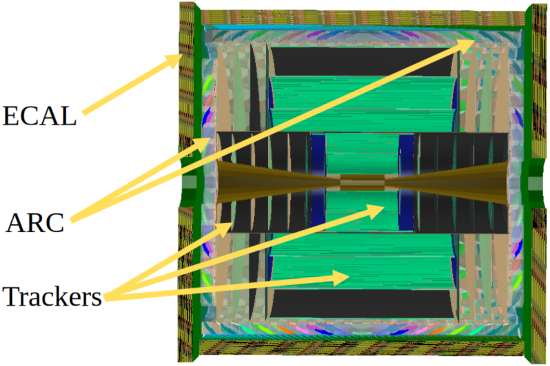


CLD_o2_v06: Coming to the next Key4hep release

- Modified position and dimensions of the LumiCal
  - LumiCal always centered on the outgoing beam line
- Move from $Z = 1074$ mm to $Z' = 1074$ mm (along outgoing beam pipe, also modified X position)
- Increase outer radius from 112 mm to 115 mm

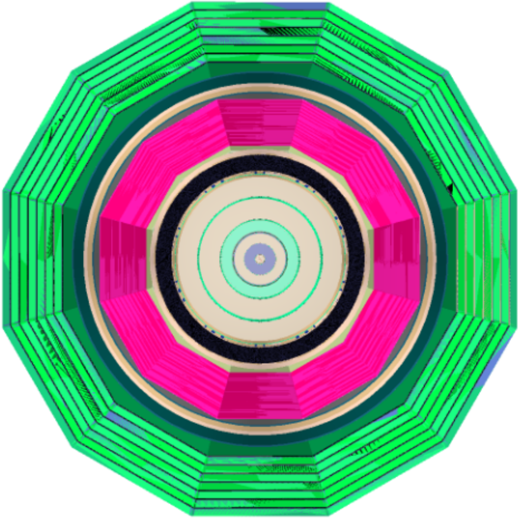
CLD_o3_v01

- Same as CLD_02_v05, except
- Array of RICH Cells (ARC) particle ID detector
  implementation by A. Tolosa Delgado
- Reduced tracker sizes to fit RICH cells before the ECal
- Need to finalise the tracker sizes, understand impact on coverage and resolution



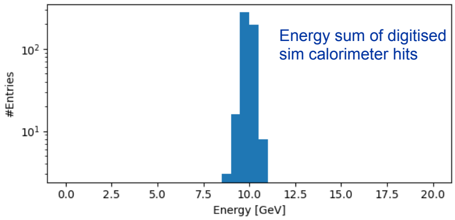
CLD_o4_v05

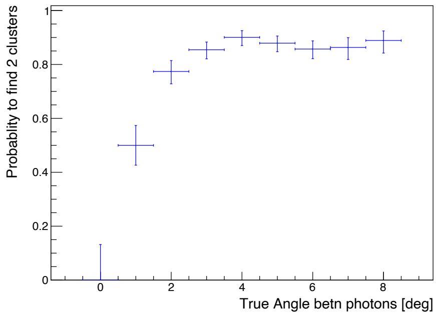
- Same as CLD_02_v05, except
- ECal Barrel replaced by LAr
- HCal, Solenoid, Yoke moved outwards by ≈40 cm
- Testing PandoraPFA for LAr, making interfaces more generic



PandoraPFA Reconstruction for LAr

- Reconstructing photon clusters in the LAr ECal with PandoraPFA [5]
- Single particle(below), and two particle separation (right)





Future Plans

- Mechanical engineering study for the integration of new beampipe and support tube design (A. Gaddi)
- Tracking studies: efficiencies, performance, layout, physics (L. Reichenbach, G. Sadowski, J. Andrea, Z. El Bitar)
  - Integrate with ACTS reconstruction package
- Finalise additional options
- Update material budget and coverage figures
- Provide full simulation samples for those interested

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 → so far only rough estimate of additional material; re-evaluate material estimates in general
- 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 → so far only rough estimate of additional material; re-evaluate material estimates in general
- Further optimisation of the tracker configuration → 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 [8]
  - Or for the more speculative approach: Chromatic calorimetry with *Quantum Dots* [9]?

Luminosity detectors:

- Further background studies
- Inclusion of the detailed 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
- Integrate ARC detector in reconstruction

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

Thanks and Acknowledgements

Thanks to my colleagues
J. Carceller, L. Reichenbach, P. Roloff, S. Sasikumar, A. Tolosa Delgado
for contributing material to these slides!

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References

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[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.

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[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] Manuela Boscolo, Fabrizio Palla, et al. "The FCC-ee interaction region, design and integration of the machine elements and detectors, machine induced backgrounds and key performance indicators (FCC note)". In: (2023). DOI: 10.17181/w4kws-rne05. URL: https://new-cds.cern.ch/doi/10.17181/w4kws-rne05.

[8] 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/.

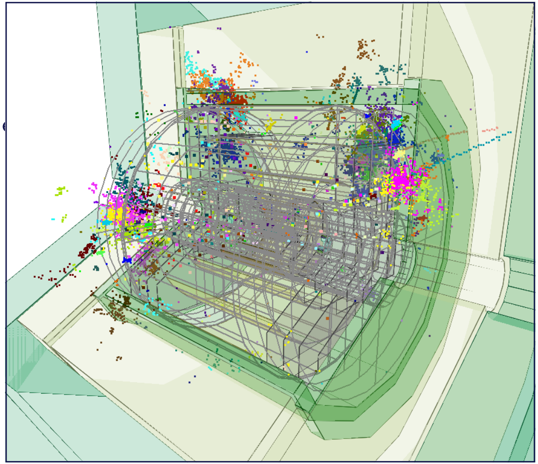
[9] M. Doser. *Quantum detectors for (low and high energy) particle physics*. 2022. URL: https://indico.cern.ch/event/1152324/.

Thank you for your attention!

Backup Slides

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. . .