

ILD/CLD rationale and full-sim based studies

FCC Physics Workshop 2025

Jan 13-17, CERN

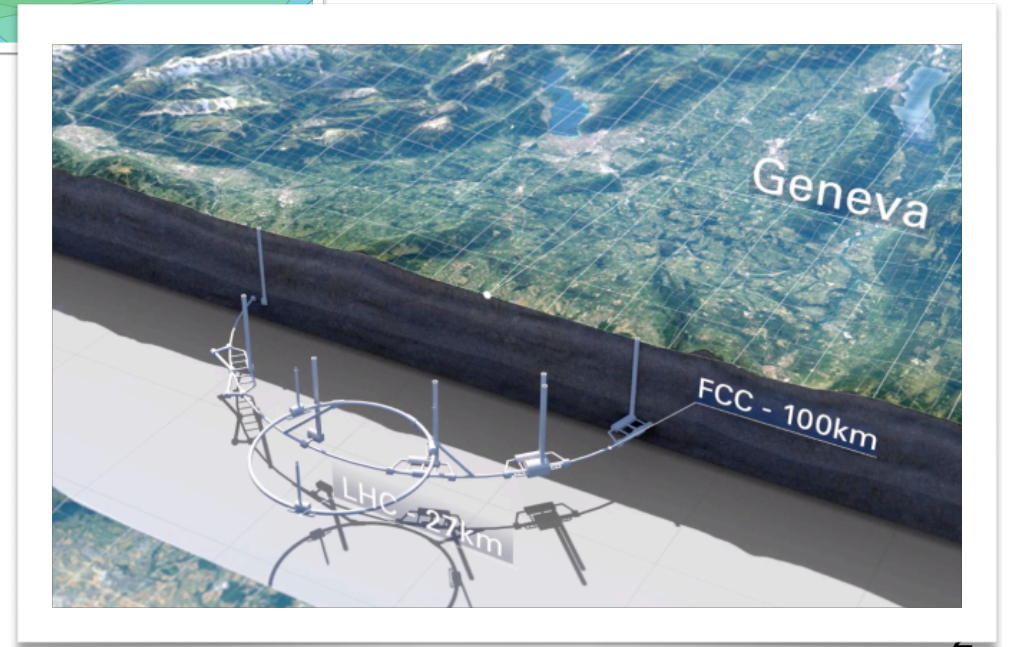
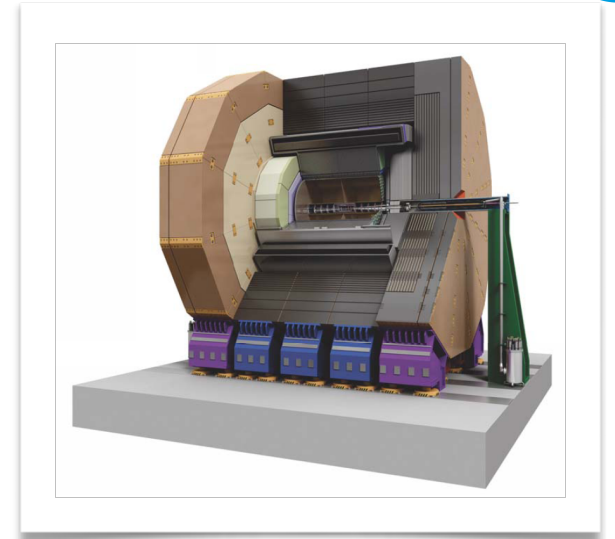
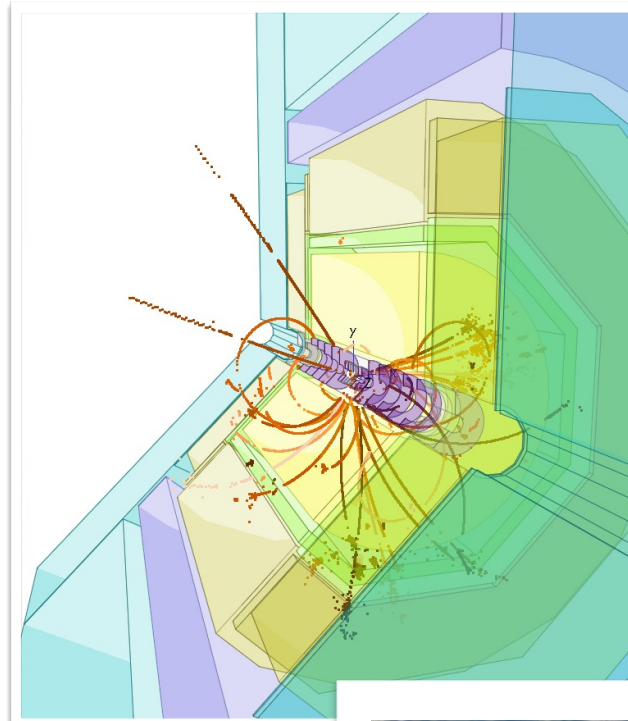
Frank Gaede, DESY



Outline



- Rationale of ILD (and CLD)
 - Relation ILD-CLD
- Key4hep and DD4hep detector models
- CLD/ILD detector variants for FCCee studies
- Some recent results and ongoing work on
 - Full Simulation studies and Reconstruction
- Summary

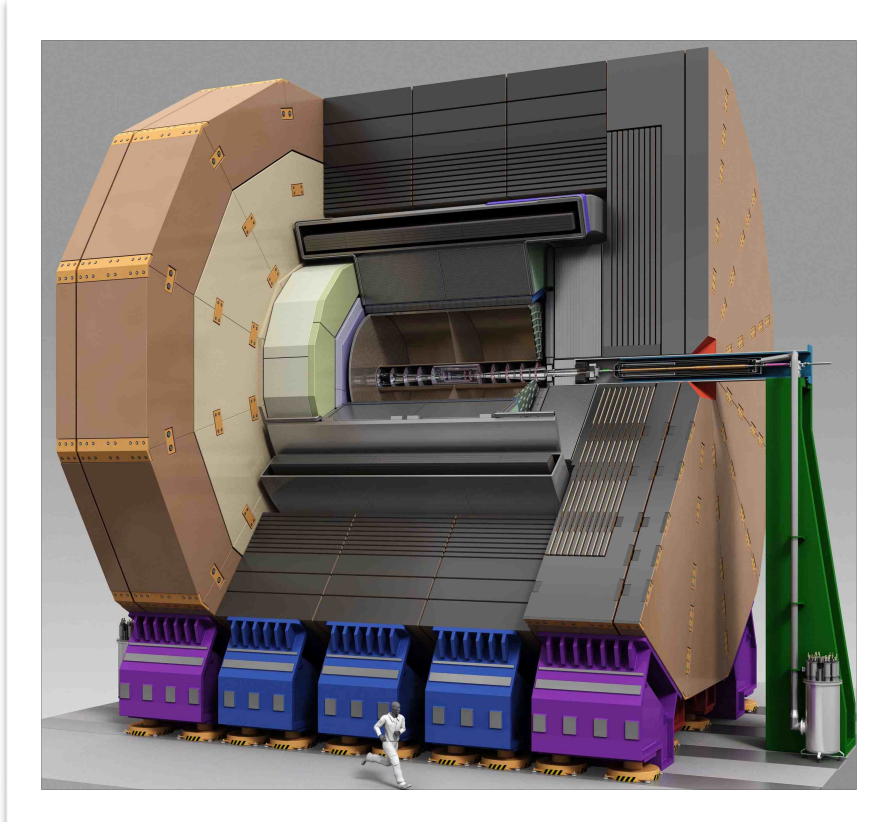
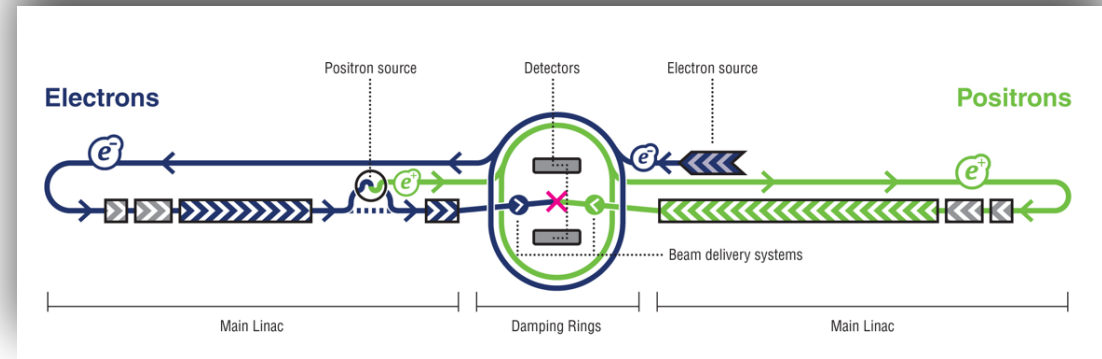


Rationale of the ILD detector

A fully optimised detector concept for the ILC

ILC

- a linear e⁺e⁻ collider at **250-500 GeV** (up to 1 TeV) with super conduction RF technology
- was going to be build in Japan - now a potential candidate for 'plan B'

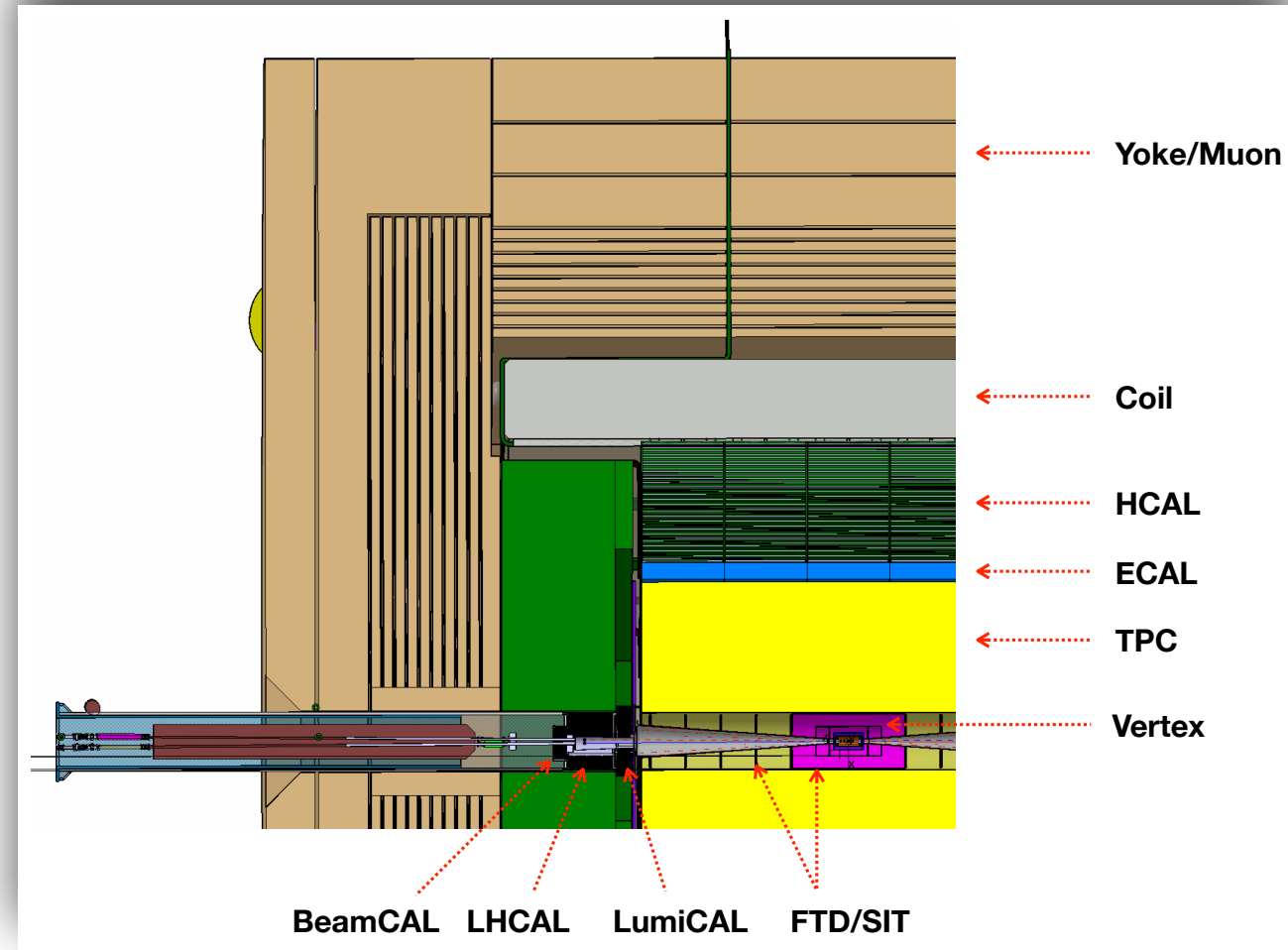


- **ILD** is one of two detector concepts for the ILC
- optimised for **PFA** at the ILC energies, w/
 - highly granular calorimeters
 - excellent tracking resolution
 - excellent vertex resolution
 - low material budget (in the trackers)
- **CLD** is closely related (see later)

Rationale of the ILD detector

And its sub-detectors

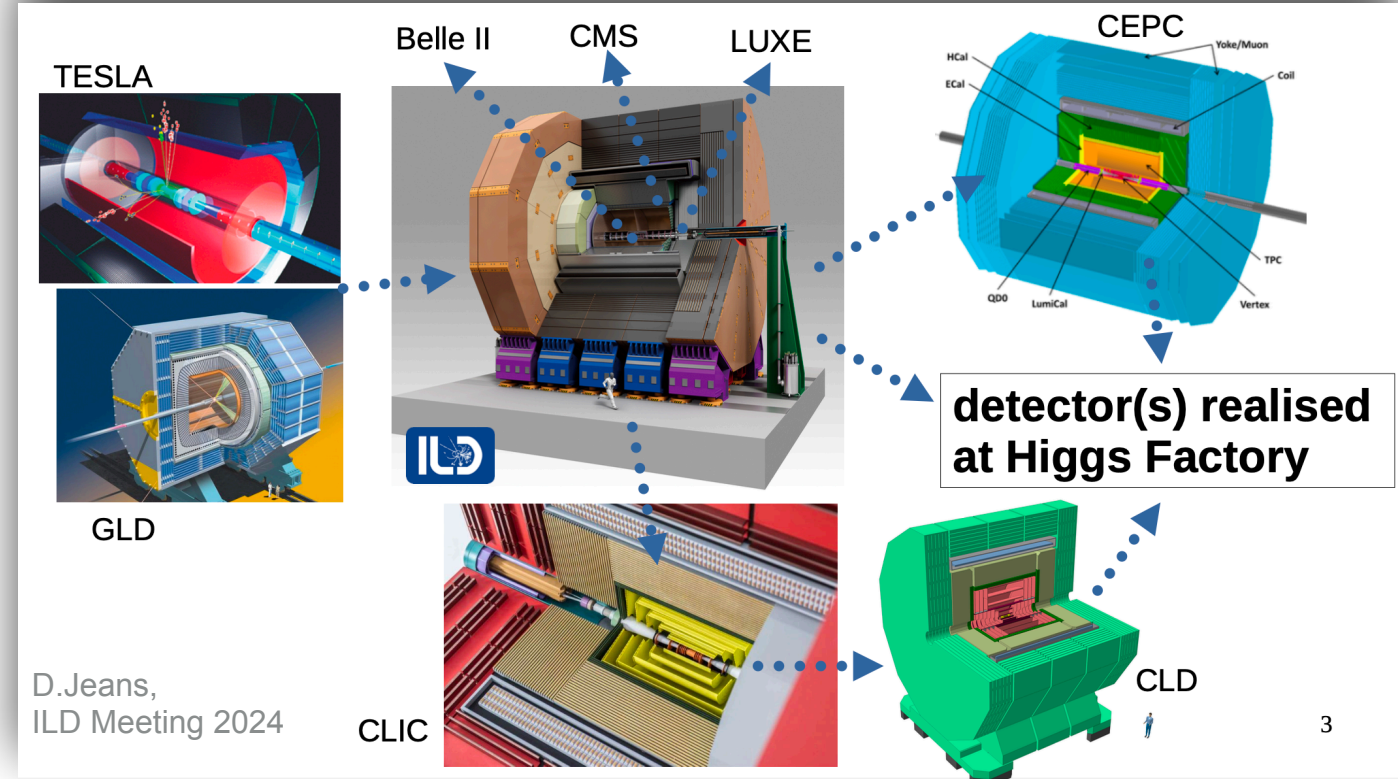
- high precision and low material tracking system
 - inner Si-tracking (VTX, SIT, FTD) - $\sigma_{point} = 3,5,7\mu m$
 - TPC w/ 220 layers + SET $\sigma_{point} = 7\mu m$
- highly granular calorimeters:
 - ECal, 20 layers, (SiW or SciW), $5 \times 5mm^2$ ($5 \times 45mm^2$)
 - HCal, 48 layers (SciFe or RPC-Fe) $3 \times 3cm^2$ ($1 \times 1cm^2$)
- inside 3.5 T B-field
- forward calorimeters
 - LumiCal, LHCal and BeamCal



CLD and ILD

closely related detector concepts

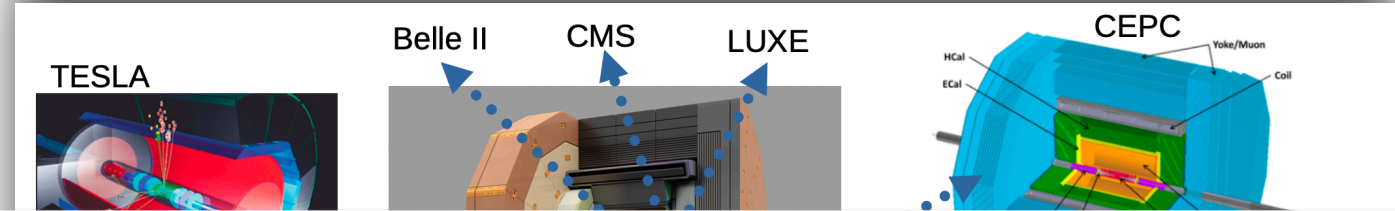
- both detectors are defined by their main CALICE imaging calorimeters:
 - ECal and HCal optimised for PFA with very high granularity
- major difference: large **Si-Tracker vs TPC**
- and of course many differences in size, thickness, MDI, ...



CLD and ILD

closely related detector concepts

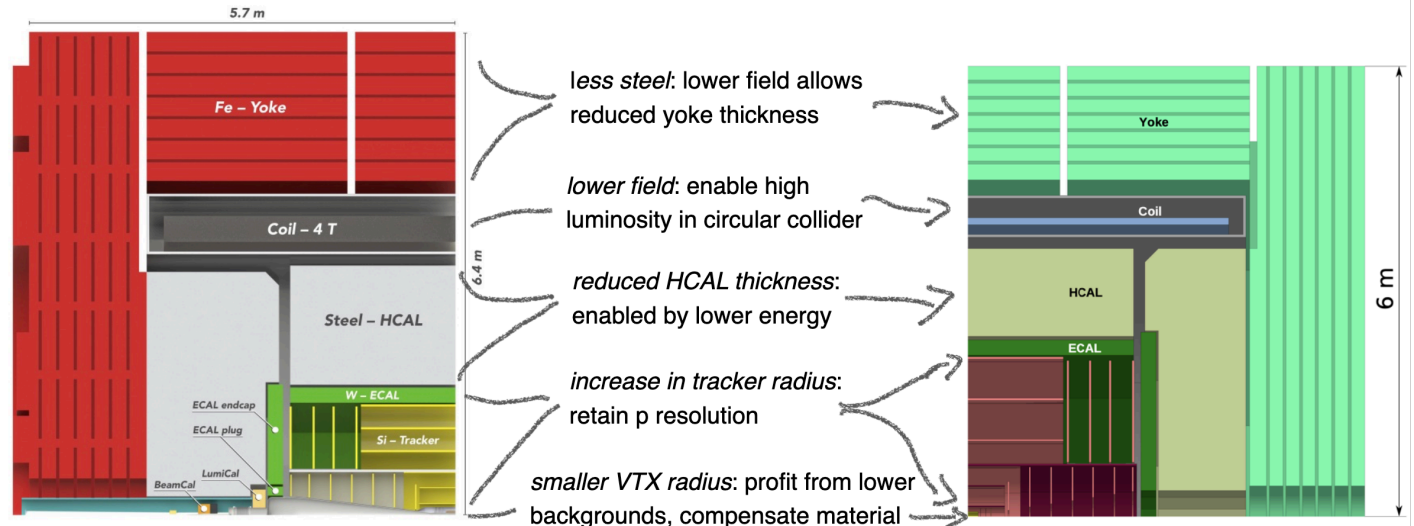
- both detectors are defined by their main CALICE **imaging calorimeters**:
 - ECal and HCal optimised for PFA with very high granularity
 - major difference: large **Si-Tracker vs TPC**
 - and of course many differences in size, thickness, MDI, ...
 - **CLD** is the well established **evolution of CLICdp optimised for FCCee**
- complete full simulation and **reconstruction software chain available in Key4hep for both**



From LCs to FCCee

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
Evolving from CLIC to CLD



Linear Collider Detectors - FCC Week, November 2020

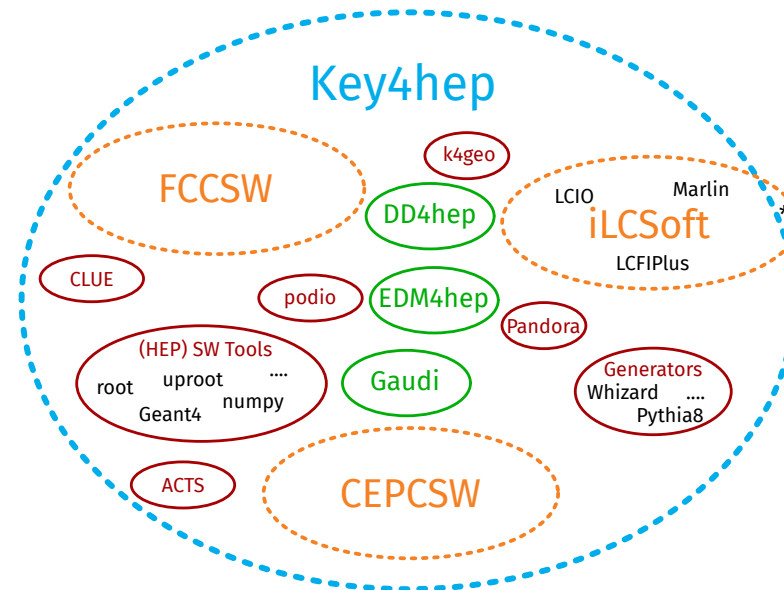
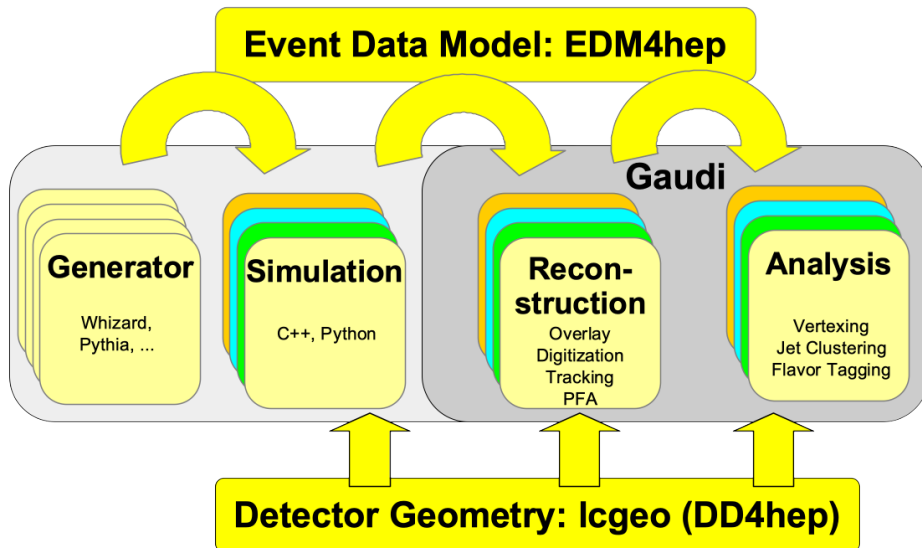
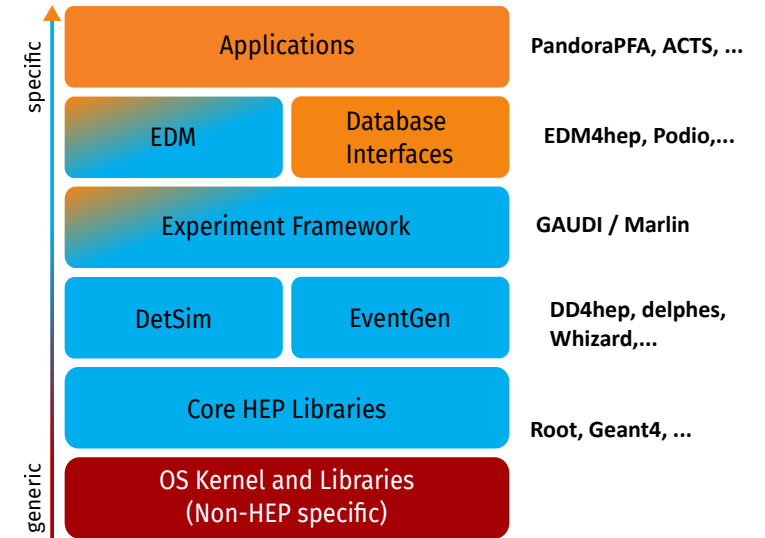
Frank Simon (fsimon@mpp.mpg.de)

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Key4hep

the turnkey software stack for FCC and all other future colliders

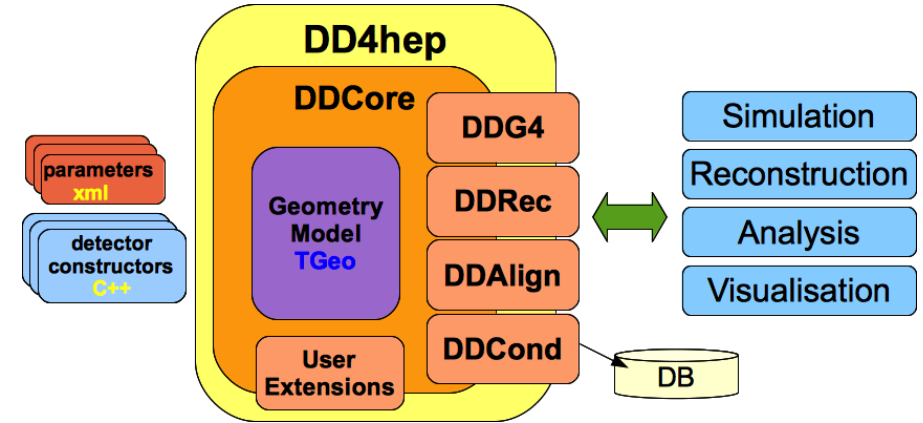
- HEP community decided 5 years ago to develop a **common turnkey software stack** – for future collider studies
- create a software ecosystem integrating in an **optimal way the best software components** to provide a **ready-to-use full-fledged solution** for data processing of (future collider) **HEP** experiments
- involved communities/contributors: CEPC, CLIC, EIC, FCCee, FCChh, ILC, LUXE, Muon Collider ...



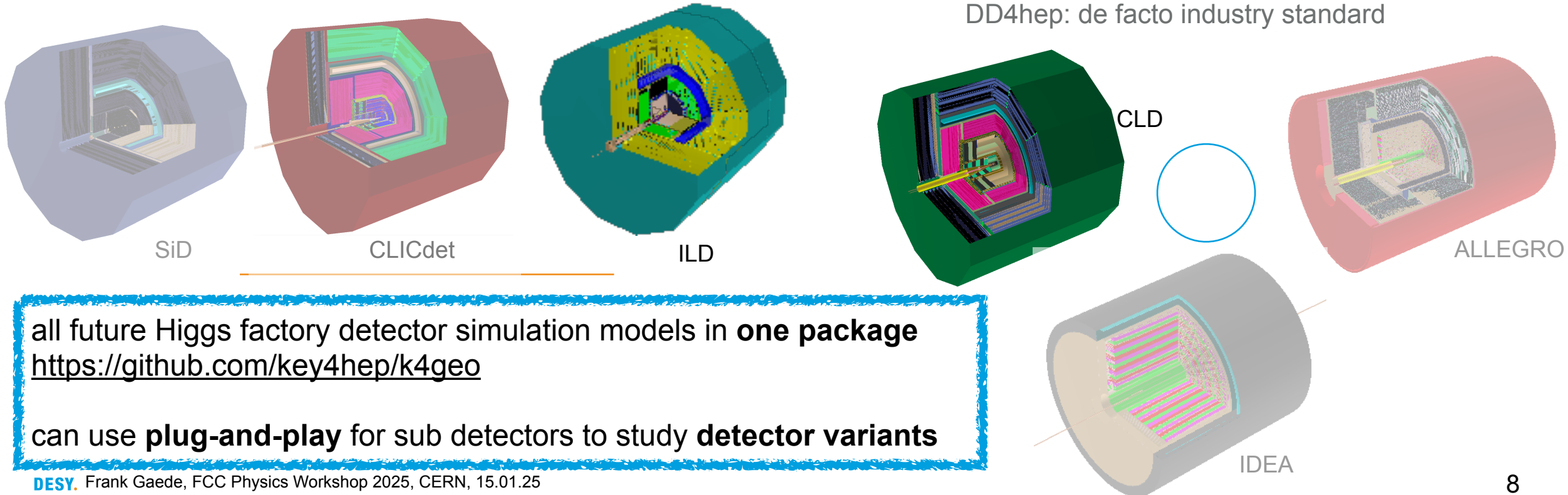
DD4hep geometry toolkit

defining the detector geometry and different views on it

- supporting the full life cycle of the experiment
- **single source** of information for full **simulation, reconstruction, conditions, alignment, visualisation and analysis**
 - used by CEPC, CLIC, CMS, EIC, FCC, ILC, LHCb, ...



DD4hep: de facto industry standard



all future Higgs factory detector simulation models in **one package**
<https://github.com/key4hep/k4geo>
 can use **plug-and-play** for sub detectors to study **detector variants**

ILD/CLD have very large reconstruction code base

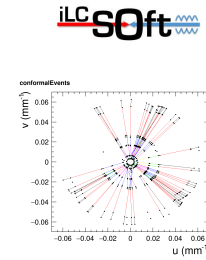
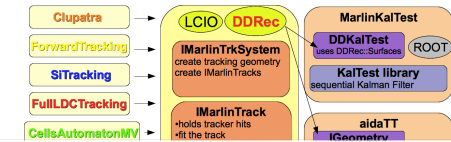
Developed over >15 years for (linear) lepton colliders

- **track reconstruction**
 - generic API for fitting algorithms
 - large number of pattern recognition algorithms
- **particle flow algorithms**
 - PandoraPFA ans Arbor, AprilPFA
- **high level reconstruction**
 - jet finding, flavor tagging, PID, TOF,...

Tracking in iLCSoft

pattern recognition and Kalman-Filter

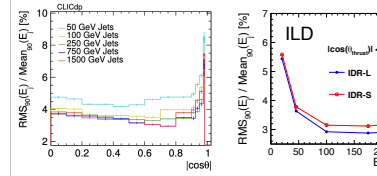
- generic tracking API MarlinTrk based on DDRec material surfaces



Particle Flow Algorithms

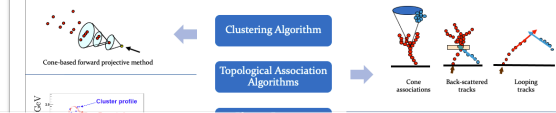
highly granular calorimeter reconstruction

- all current detector concepts for LC are based on highly granular calorimeters
- optimised for the Particle Flow Algorithm
- **PandoraPFA** is the de facto standard for ILD, SiD and CLICdp
- alternative PFA algorithms exist and offer the possibility to cross check
- Arbor (CEPC), April (SDHCa)

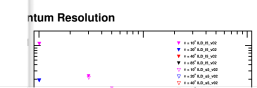


DESY, Frank Gaede, LCWS 2021, 17.03.21

Pandora Algorithms

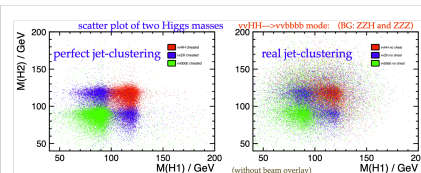
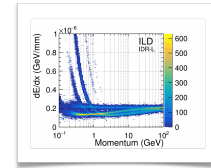
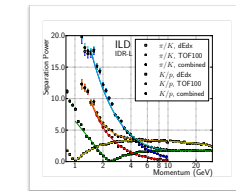
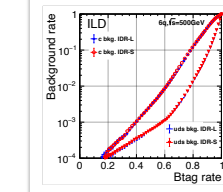
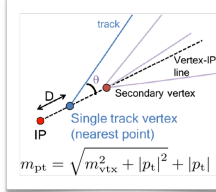


efficiencies and codes



High Level Reconstruction

analysing the Particle Flow Objects



$\delta\lambda_{HHH}$ improves by 40% w/ perfect jet clustering

DESY, Frank Gaede, LCWS 2021, 17.03.21

- **High-Level reconstruction** algorithms are crucial to achieve the ultimate physics reach of detectors
- vertex finding and flavor tagging: **LCFIPlus**
- PID tools: dE/dx , TOF, shower shapes,...
- Jet clustering: Durham, Valencia, ...

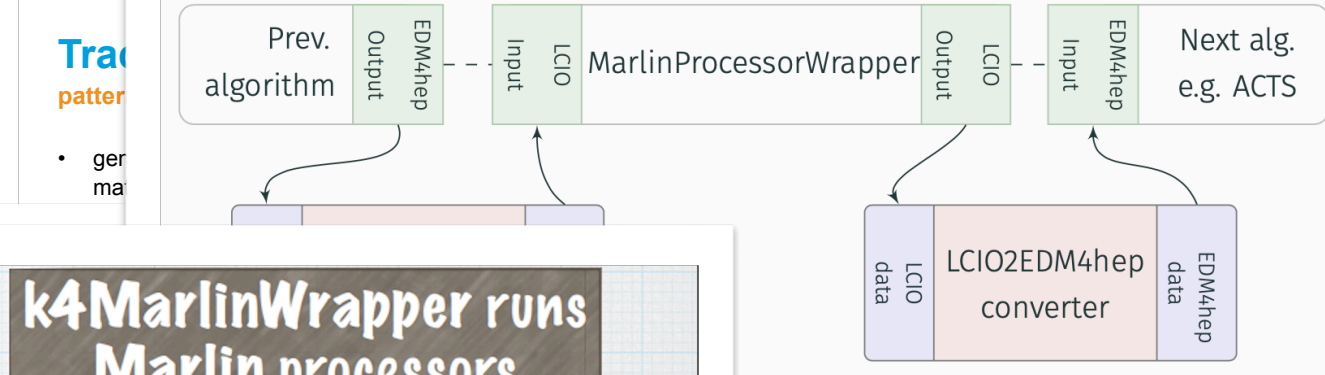
very active field of development
 • already good set of tools available
 • further improvement in HLR tools often directly impacts the final physics performance

ILD/CLD have very large reconstruction code base

Developed over >15 years for (linear) lepton colliders

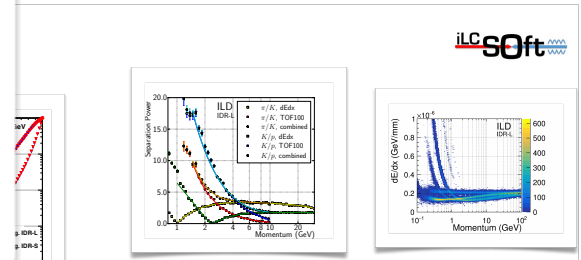
- **track reconstruction**
 - generic API for fitting algorithms
 - large number of pattern recognition algorithms
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 - PandoraPFA ans Arbor, AprilPFA
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 - jet finding, flavor tagging, PID, TOF,...

can re-use use these for FCCee detector variants in Key4hep via MarlinWrapper



hep

k4MarlinWrapper runs Marlin processors As Gaudi algorithms.



- **High-Level reconstruction** algorithms are crucial to achieve the ultimate physics reach of detectors
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• very active field of development
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CLD and its variant(s)

studying options and develop algorithms

- the **standard CLD detector** model - with all Si-tracker and FCC specific MDI region, CLD_o2_v06

FCC March 25, 2024 / FCC US WS A. Sailer – The CLD Detector Concept 5 / 33

Detector for FCCee

General purpose detector for Particle Flow reconstruction [1]

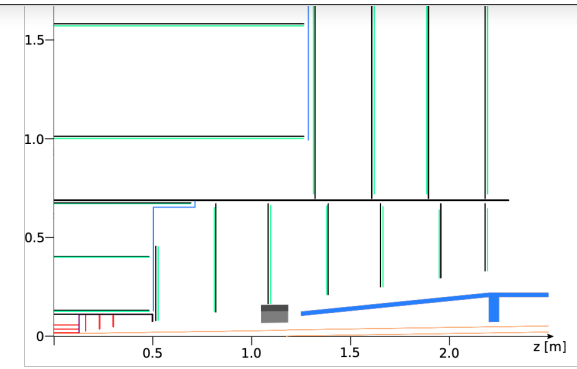
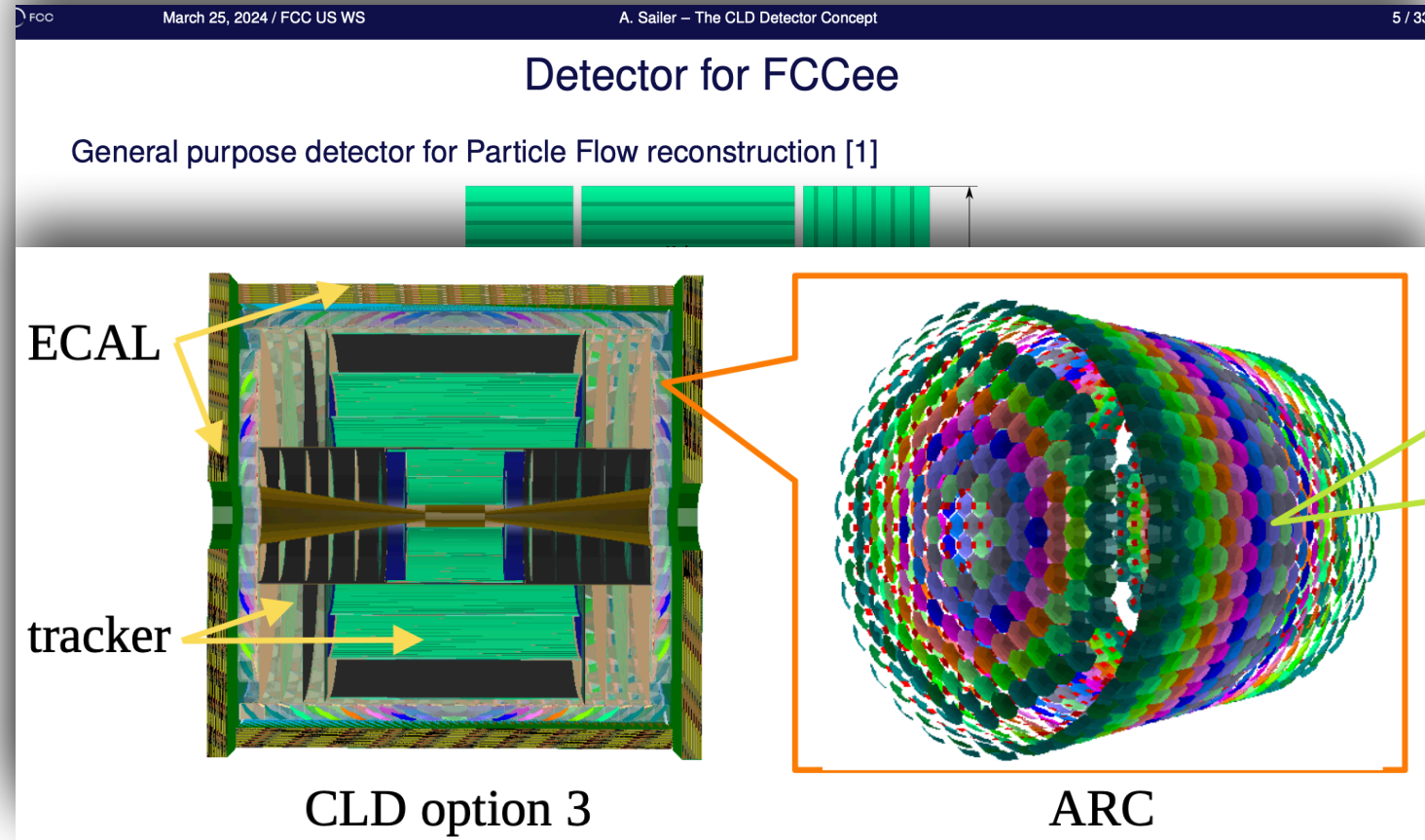
- ▶ Steel-Scintillator HCal with 3 cm cell-size
- ▶ Silicon-Tungsten ECal with 5 mm cell-size
- ▶ Silicon Tracker, mostly 50 μm pitch strips
- ▶ Vertex Detector with 25 μm pixels
- ▶ Superconducting Solenoid of 2 T
- ▶ Iron Yoke with RPCs for Muon ID

CLD Si-Tracking and MDI

CLD and its variant(s)

studying options and develop algorithms

- the **standard CLD detector** model - with all Si-tracker and FCC specific MDI region, CLD_o2_v06
- a CLD variant with the **ARC** and a **slightly reduced tracking volume**, CLD_o3_v01
- study excellent PID performance - and necessary trade-offs for tracking and PFA ...



CLD and its variant(s)

studying options and develop algorithms

- the **standard CLD detector** model - with all Si-tracker and FCC specific MDI region, CLD_o2_v06
- a CLD variant with the **ARC** and a **slightly reduced tracking volume**, CLD_o3_v01
- study excellent PID performance - and necessary trade-offs for tracking and PFA ...
- and also a **CLD-Alegro hybrid** with a LAr-Ecal in order to adapt **PandoraPFA** for the LAr calorimeter, CLD_o4_v05 ...

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Detector for FCCee

General purpose detector for Particle Flow reconstruction [1]

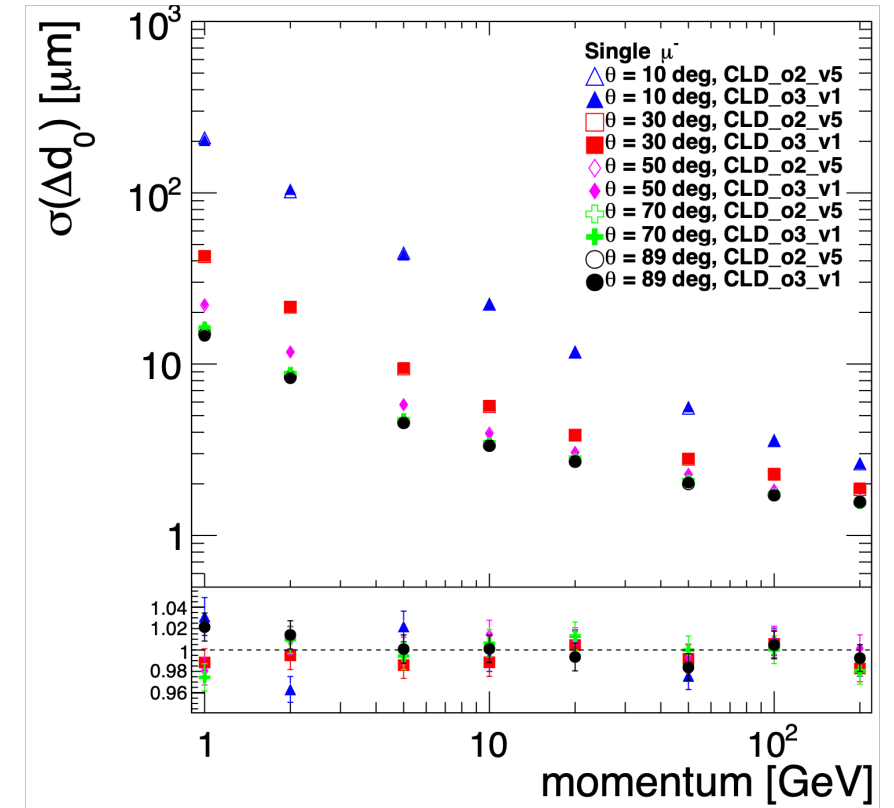
The diagram illustrates the detector layout for FCCee. It features a central **tracker** region, flanked by **ECAL** (Electromagnetic Calorimeter) sections. A large, multi-layered spherical structure labeled **ARC** (Active Recoil Calorimeter) is positioned to the right. A detailed cross-section of the ARC is shown below, with the following layers and dimensions:

- 1st layer (presampler) no Pb: 2.12 cm
- cryostat: 4.94 cm
- active gap (noble liquid): 210 cm
- absorber: 40 cm
- read-out electrode: 256 cm
- 270 cm (total length)
- 5 cm (gap)
- 10 cm (gap)

Studying tracking performance for CLD

sub-detector variants

- using full simulation (MarlinWrapper) and tracking performance scripts (EDM4hep) to study and understand effects of
 - sub detector variants and modifications
- more **realistic** beam pipe w/ more material and smaller radius results in **better impact parameter resolution** (VXD r0 13/17.5)
- **reduced tracking volume (ARC)** results in
 - 10-15% **reduced momentum resolution** (lever arm)
 - ~unchanged **impact parameter resolution**

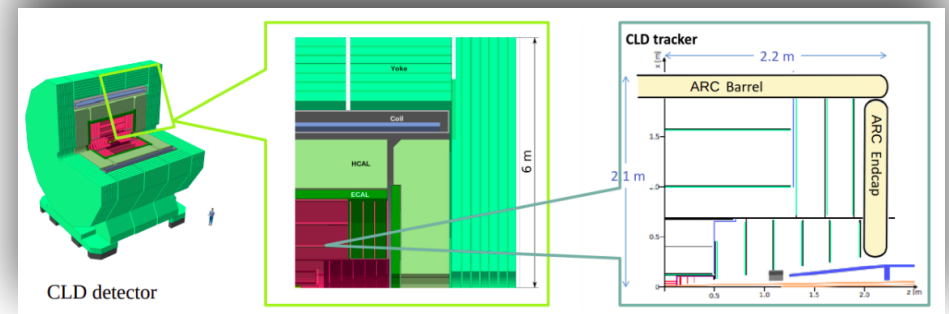


CLD_o2_v05

- BeamPipe radius: 10 mm
- BeamPipe material: AlBeMet 0.35 mm + paraffin 1 mm + AlBeMet 0.35 mm
- BeamPipe thickness: 1.7 mm + 5 μm gold
- $X/X_0 = 0.61\%$ \Rightarrow + 33% material budget

CLD_o1_v04

- BeamPipe radius: 15 mm
- BeamPipe material: Beryllium
- BeamPipe thickness: 1.2 mm + 5 μm gold
- $X/X_0 = 0.45\%$



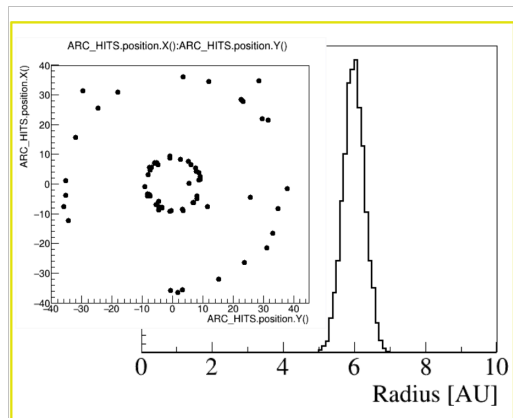
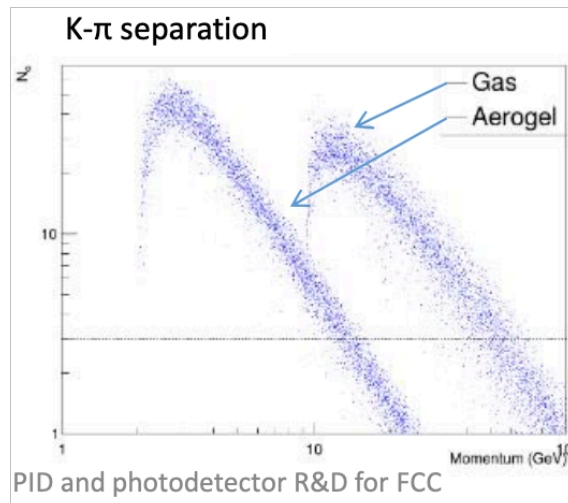
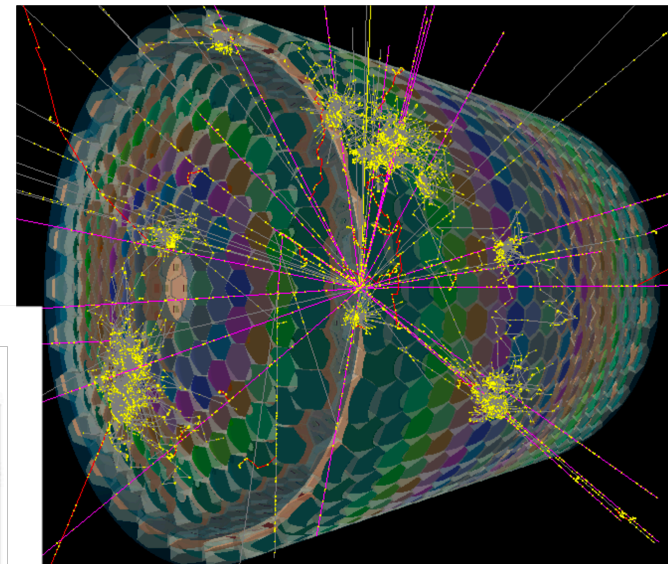
ParticleID performance with the ARC

a novel GAUDI algorithm in Key4hep

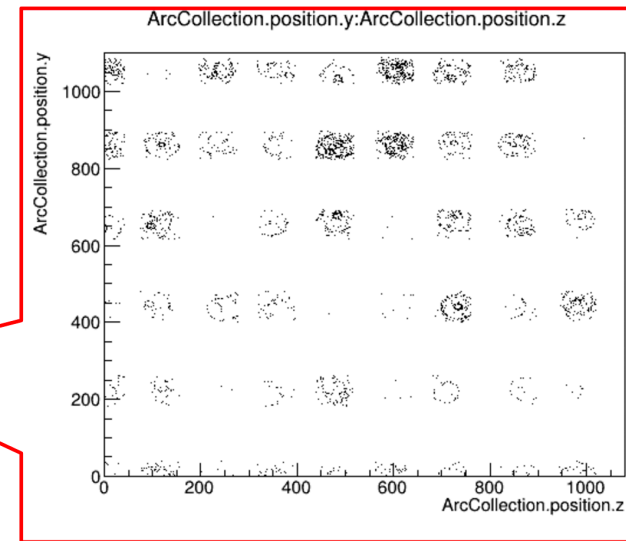
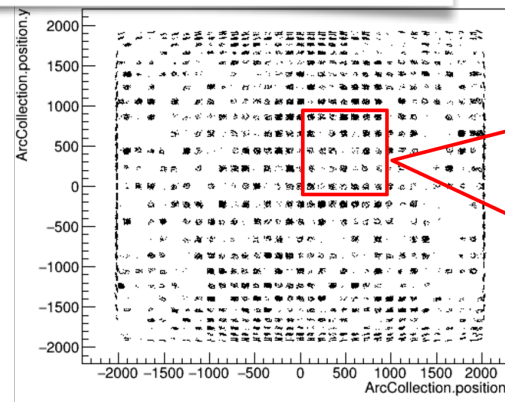
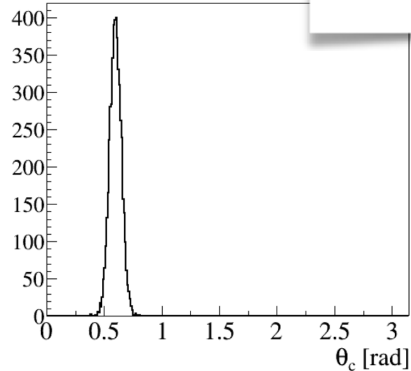
A. Tolosa Delgado et al.

- can simulate full events in CLD w/ ARC with dddim (DD4hep)
- standalone reconstruction w/ inverse ray-tracing exists for single cell
 - should provide excellent K-pi separation from 2-50 GeV
- work in progress ...

see [talk by Serena Pezzulo](#) tomorrow



Inverse ray-tracing

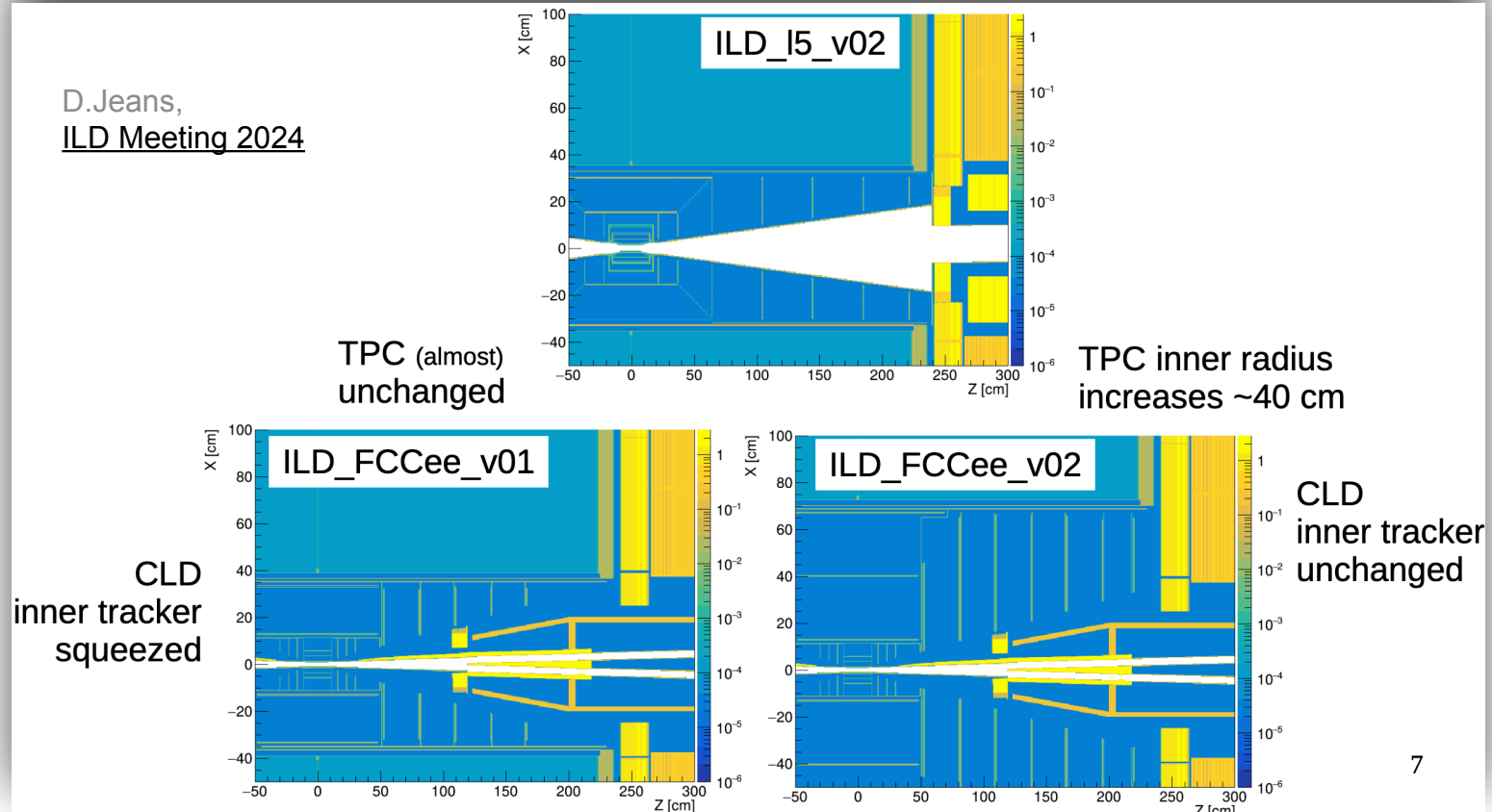


Sagittal cut of the detector (events on the endcaps are compressed in Z, not visible in this projection)

ILD variants for FCCee

study individual evolution steps

- **ILC baseline of ILD:** TPC, inner Si-Tracking, SET, SiW Ecal, SciFeHCal
- **ILD for FCCee - v01:** TPC, inner and fwd tracking from CLD (squeezed), standard FCC-MDI region
- **ILD for FCCee - v02:** TPC - larger inner_r , inner and fwd tracking from CLD, standard FCC-MDI region



can use these models to study:

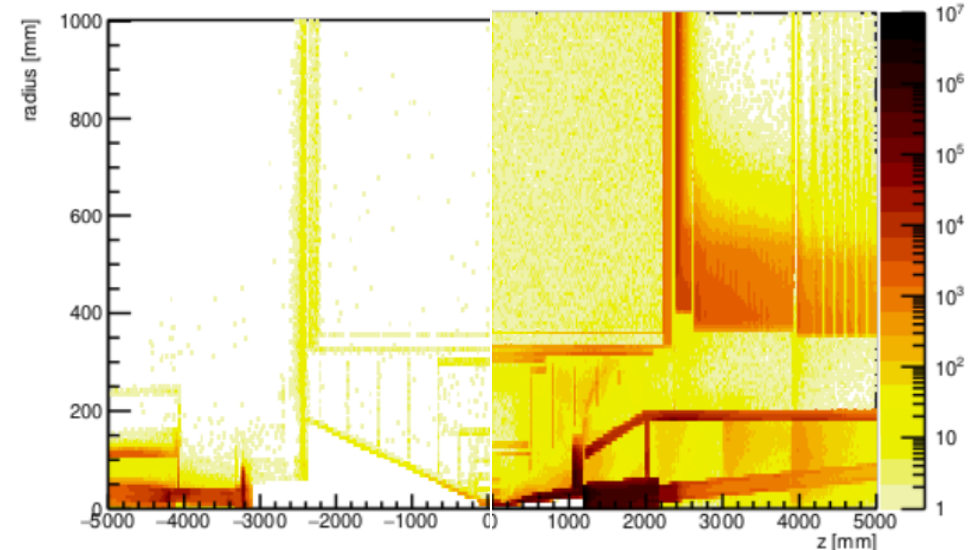
- background at FCC
- tradeoff between larger/smaller TPC
- does a TPC work in principle
- ...

Can a TPC work at FCCee (91 GeV) ?

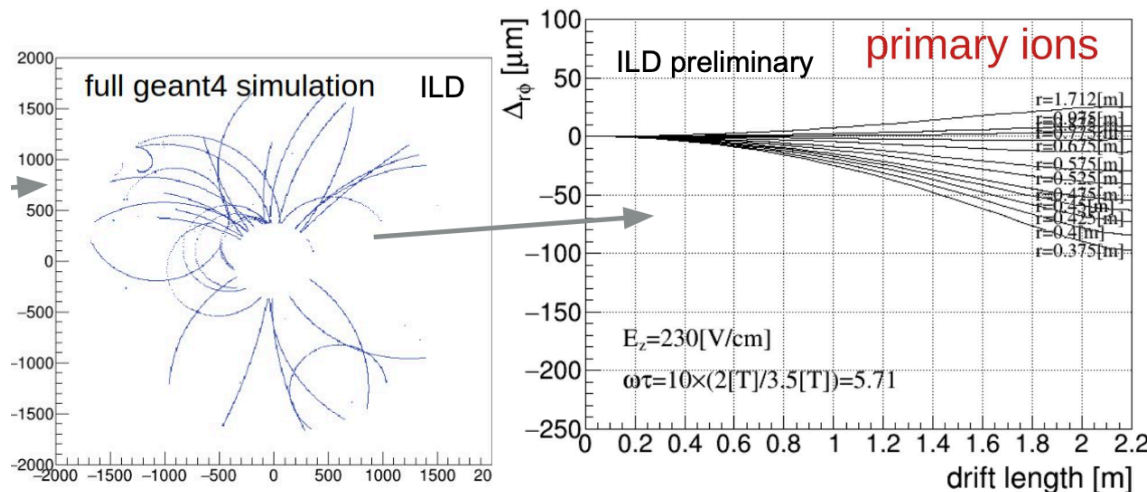
D.Jeans et al.

Study w/ full simulation in ddsim (DDG4) and GunieaPig

- simulate events in TPC at FCCee (91 GeV) from
 - e+e- physics events: $\sim 10^{10}$ ions $\rightarrow 100 \mu\text{m}$ distortions
 - beam induced background: $\sim 2 \times 10^{12}$ ions $\rightarrow 20 \text{ mm}$ distortions (!)
- a TPC also at TeraZ might be feasible - yet further studies needed:
 - mitigation strategies for drift distortions (corrections, redesign MDI elements?, ...)
 - stability of distortions wrt time, operating conditions, ...



MCP particle endpoints at FCCee 91 GeV from beam bg in ILClike (left) and CLDlike (right) ILD



Collider	FCCee-91	FCCee-240	ILC-250
Detector model	ILD_15_v11γ	ILD_15_v11γ	ILD_15_v05
average BX frequency	30 MHz	800 kHz	6.6 kHz
primary ions / BX	270 k	800 k	450 k
primary ions in TPC at any time	1.8×10^{12}	1.4×10^{11}	6.5×10^8
average primary ion charge density nC/m ³	6.8	0.54	0.0025

- primary ion density in TPC - compared to ILC-250:
 - 2500 (200) x higher at FCCee 91 GeV (240)
 - dominated by beam background

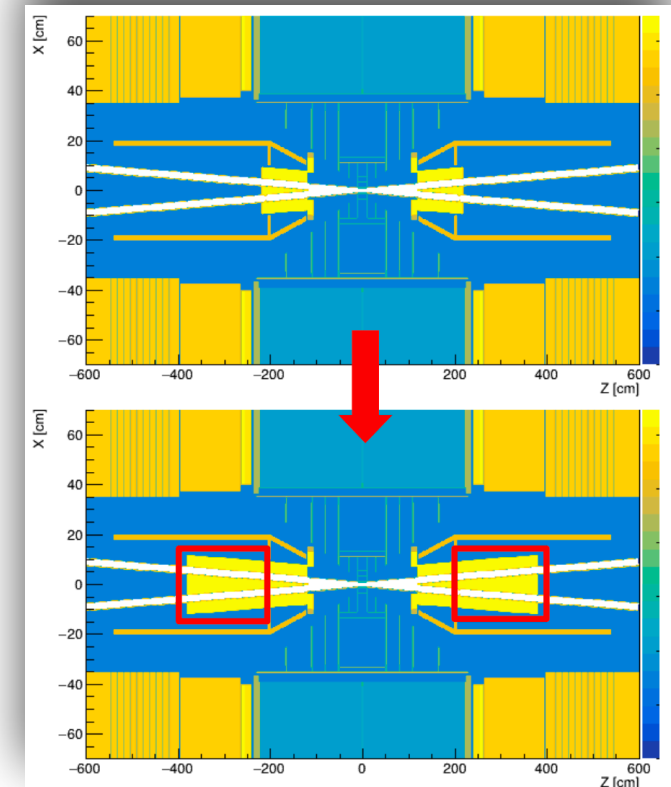
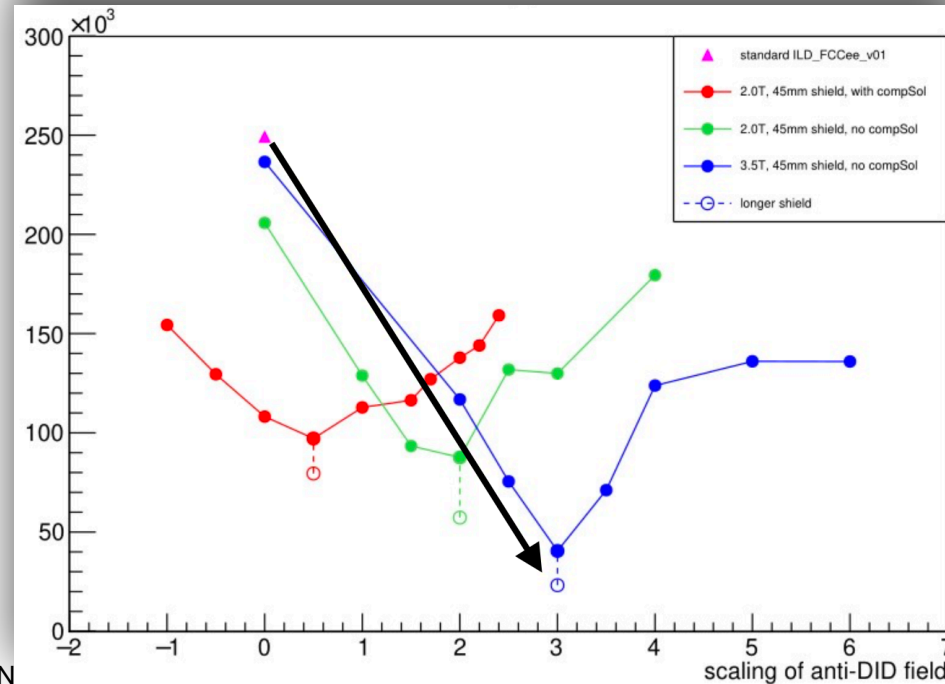
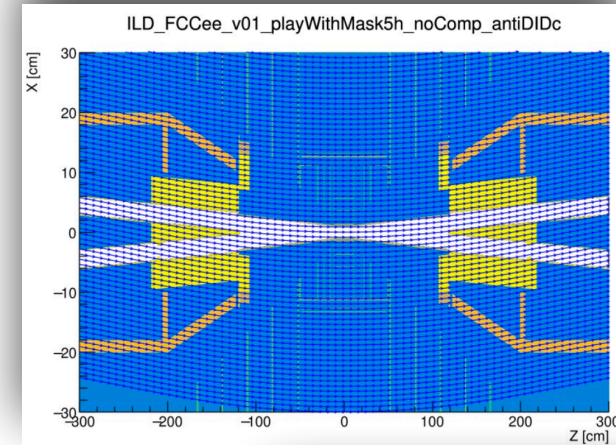
TPC background can be mitigated

By up to an order of magnitude

- additional anti-DID field
- thicker and longer shield after lumi cal
- larger 3.5 T magnetic field
 - engineering design/verification pending

see talk by V.Schwan
this morning

- potentially yet better numbers with v02, i.e. larger inner radius of TPC
 - to be studied ...
- engineering level details in inner forward region are important to be simulated

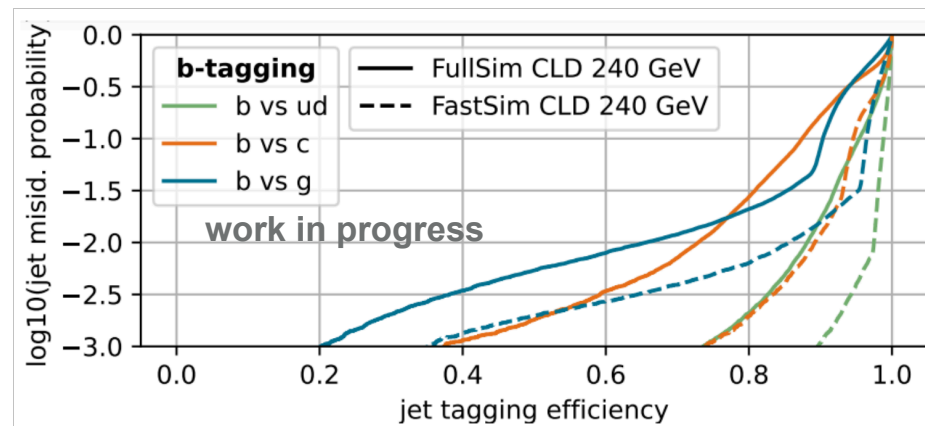
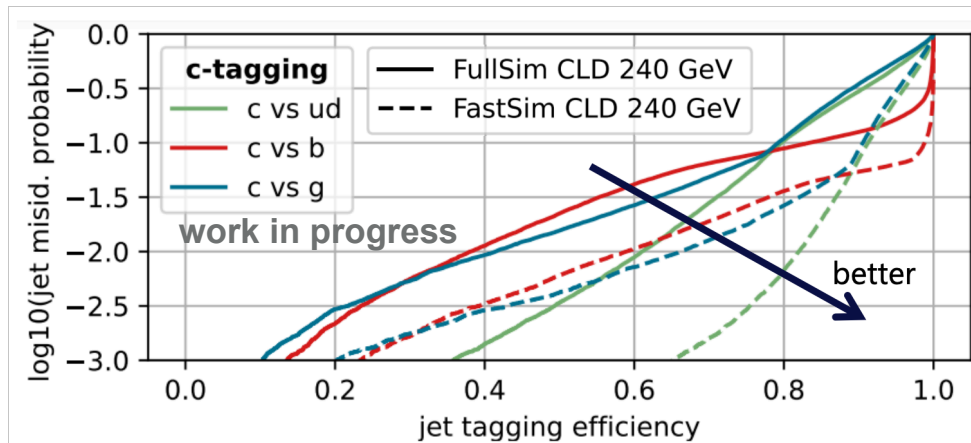
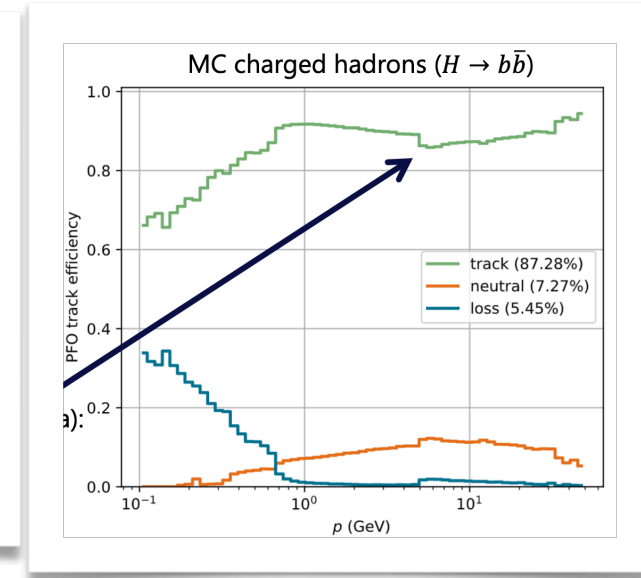
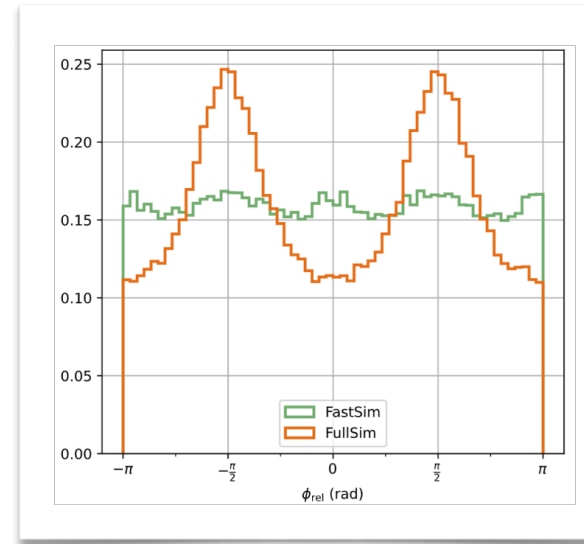


Full simulation is important

demonstrated here for flavour tagging with CLD

S.Aumiller

- training a PartTransformer for CLD w/
 - Delphes and Fullsim samples
- observe differences in extra neutrals due to
 - split clusters in real algorithm and due to tracks intentionally dropped as no cluster found
- leads to significant differences in tagging

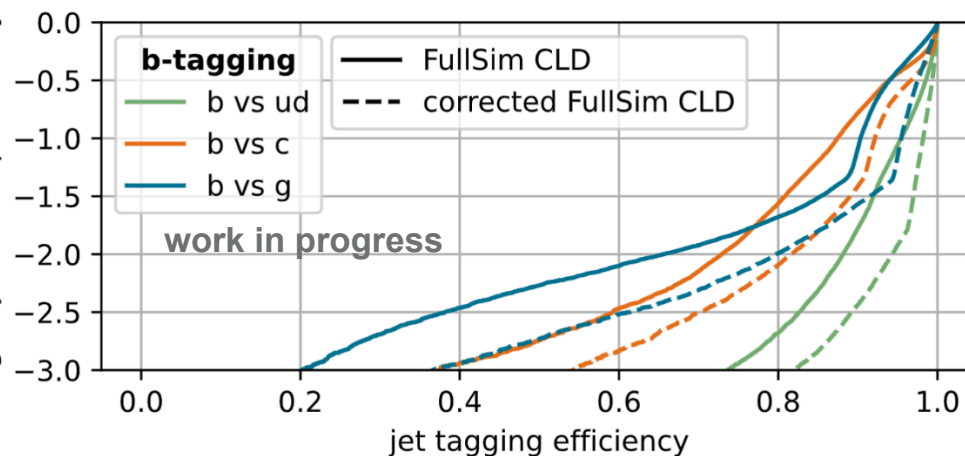
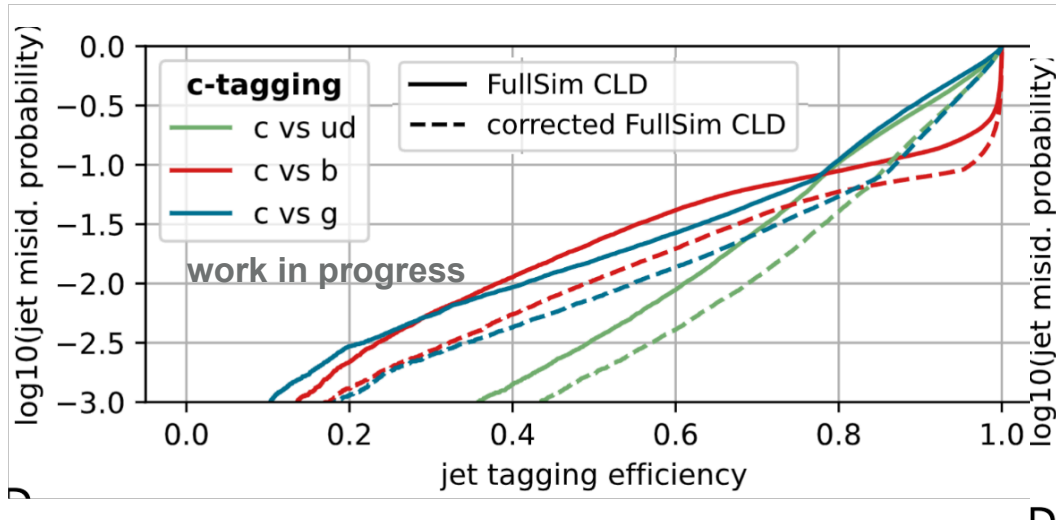
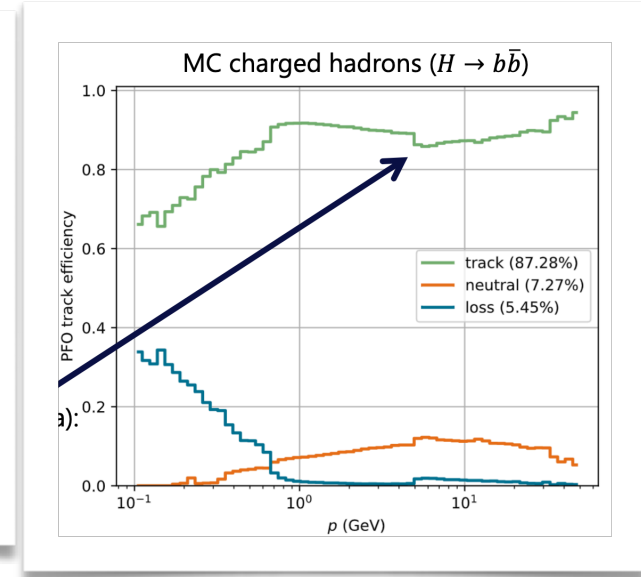
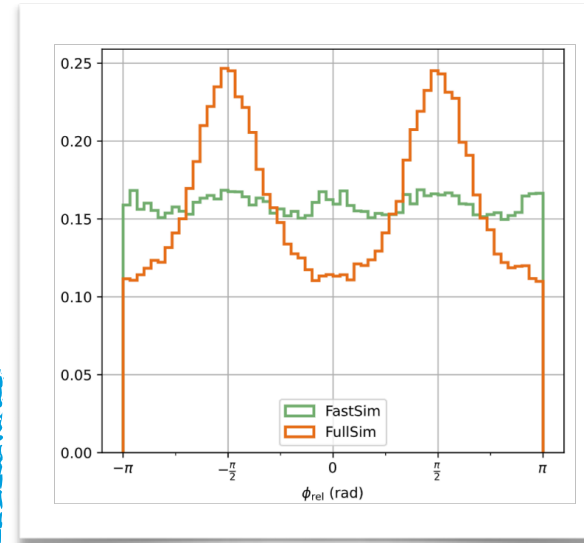


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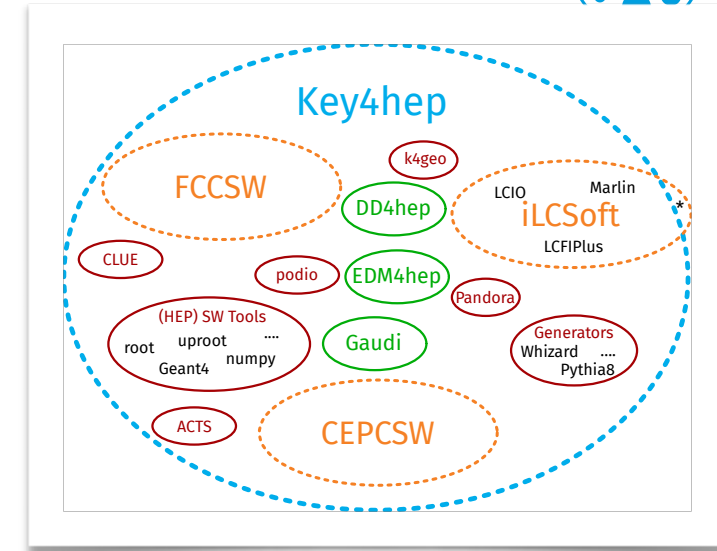
S.Aumiller

- training a PartTransformer for CLD w/
 - Delphes and Fullsim samples
- observe differences in extra neutrals due to
 - can recuperate some of the flavour tag performance with better reconstruction
 - here cheating w/ MCTruth for demonstration



Summary

- ILD and CLD are closely related detector concepts, with **highly granular calorimeters**, partly common inner Si-tracking and either all-Si large tracker or a TPC
- complete reconstruction code for both is available in **Key4hep**
- flexibility of DD4hep allows to have a number of variants, e.g.
 - CLD w/ ARC or a CLD w/ LAr calorimeter
 - ILD w/ CLD inner tracking and TPC
- reconstruction code for new sub detectors under development
- **CLD/ILD ideal platform to study potential detectors for FCCee**
- for ILD ongoing work to establish whether and how a TPC can be operated at the FCCee (Z-Pole running)
 - recent studies show room for improvement wrt. backgrounds



CLD/ILD'

