FCC-ee detectors: overview

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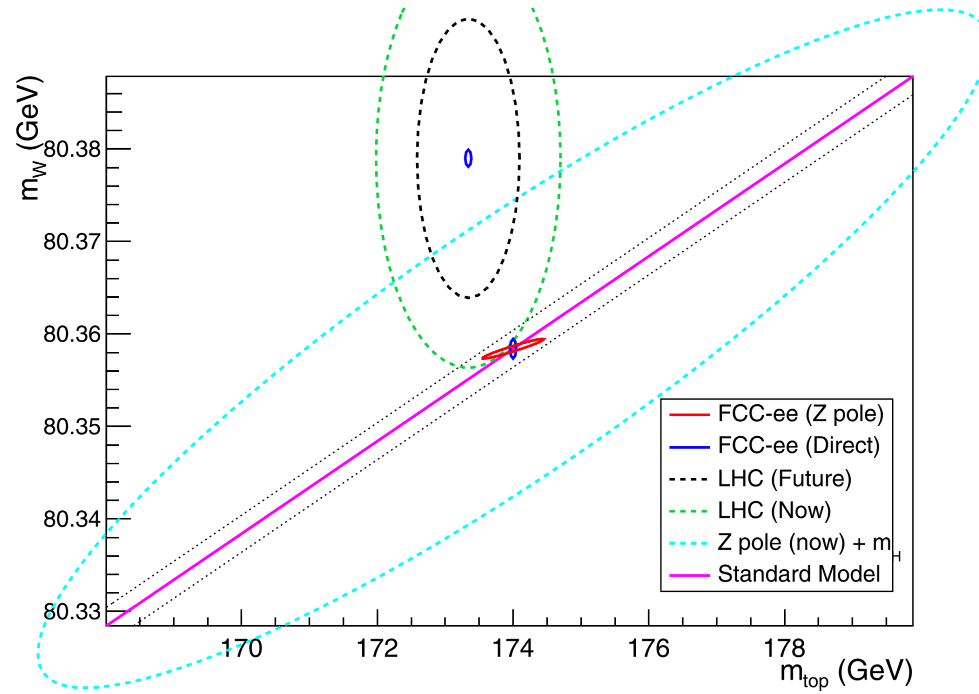
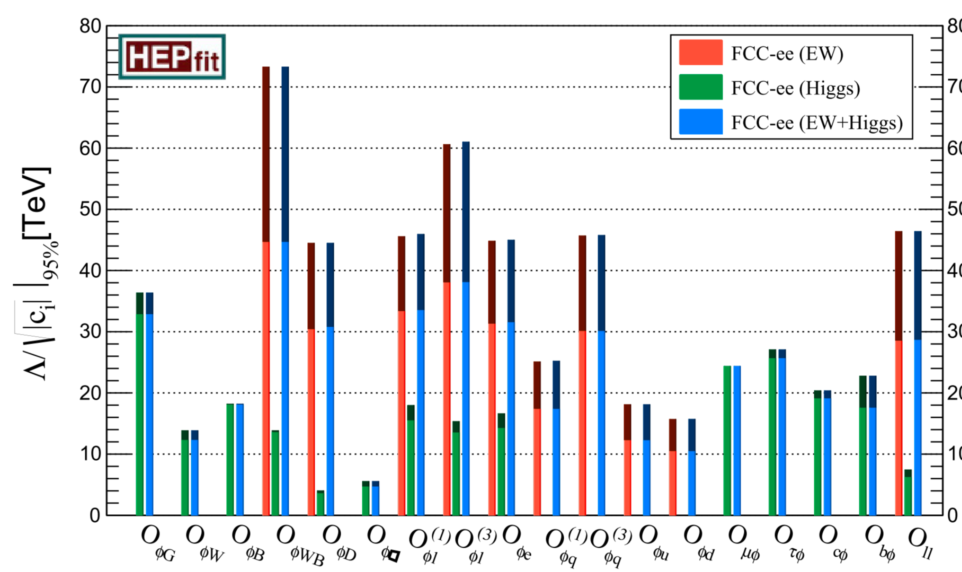
Introduction

- Overview of detectors:
  - **CLD and IDEA** discussed in FCC-ee Conceptual Design Report (CDR)
  - Complementary choices for these benchmark detectors
  - Focusing on **what has been done so far** (dedicated talks will discuss opportunities as well)
- References:
  - FCC-ee CDR
  - CLD detector paper: https://arxiv.org/abs/1911.12230
  - IDEA: Presentations at FCC-ee workshop 2020, ICHEP 2020

What physics?

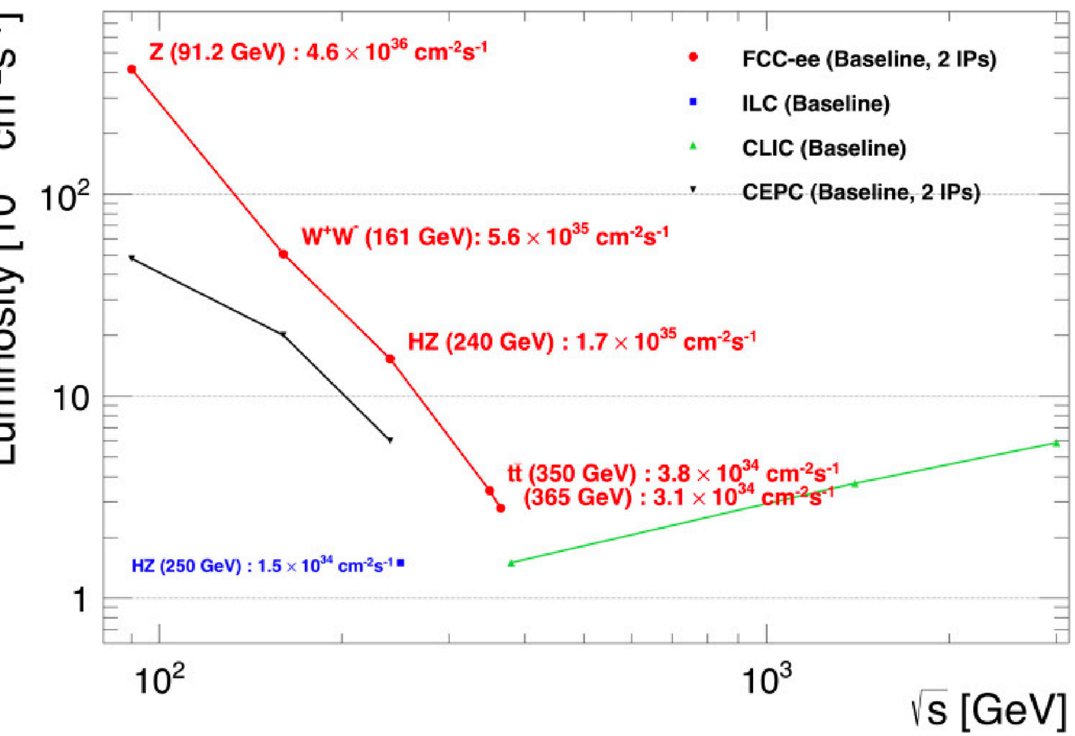
- $\sin^2 \theta_W^{\text{eff}}$ mainly from $A_{\text{FB}}^{\mu\mu}$
- m_W and width at $o(1\ \text{MeV})$
- m_{top} and width at $o(10 - 50\ \text{MeV})$
- Auxiliary measurements ($\alpha_{\text{QED}}(m_Z^2)$, Z boson mass and width, $\alpha_S^2(m_Z^2)$)
- Model-independent Γ_H, Higgs couplings and Higgs to invisible
- BSM models (ALPs, dark photon, light dark matter, ...)





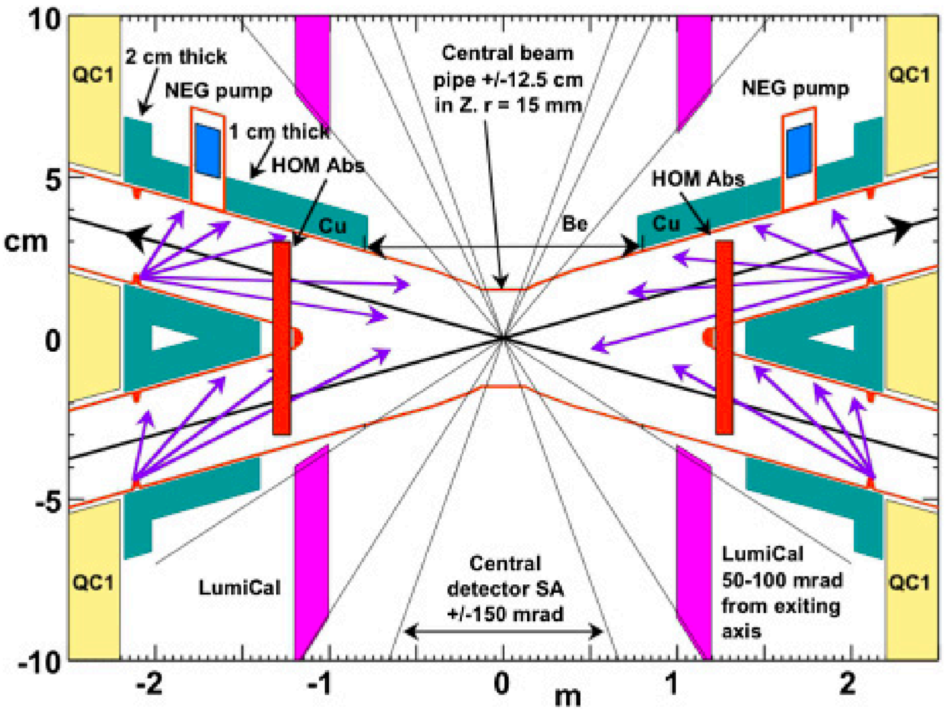
Machine plan

- **5×10^{12} Z, 10^8 WW pairs, 10^6 Higgs** bosons and **10^6 top pairs** expected.
- Different **running conditions** depending on beam energy



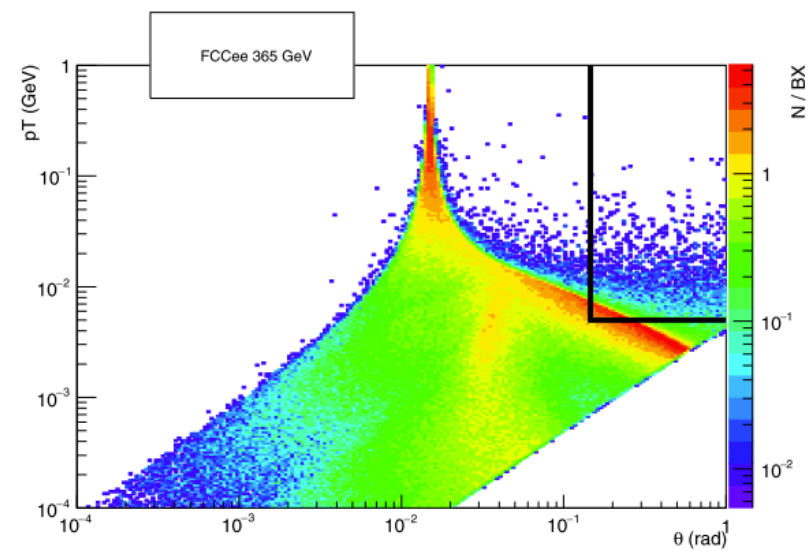
- **Synchrotron radiation losses** kept at 50 MW/beam.
- High-current/low RF at the Z pole, small-current/high RF voltage for $t\bar{t}$
- Bunch spacing ranging from **20 ns (Z) to 7 μs (top)**
- Crab-waist collision scheme guarantees high luminosity.

Collision point and machine requirements



- Large (30 mrad) crossing angle between beams + low beam emittance $\Longrightarrow$ detector **magnetic field** 2 T max
- Machine-detector interface structure (large angle + shielding + compensating magnets + luminometer) limit **detector acceptance to ±150 mrad**.

- Residual **synchrotron radiation** and **incoherent pair creation** drive ID and VTX detectors occupancy.



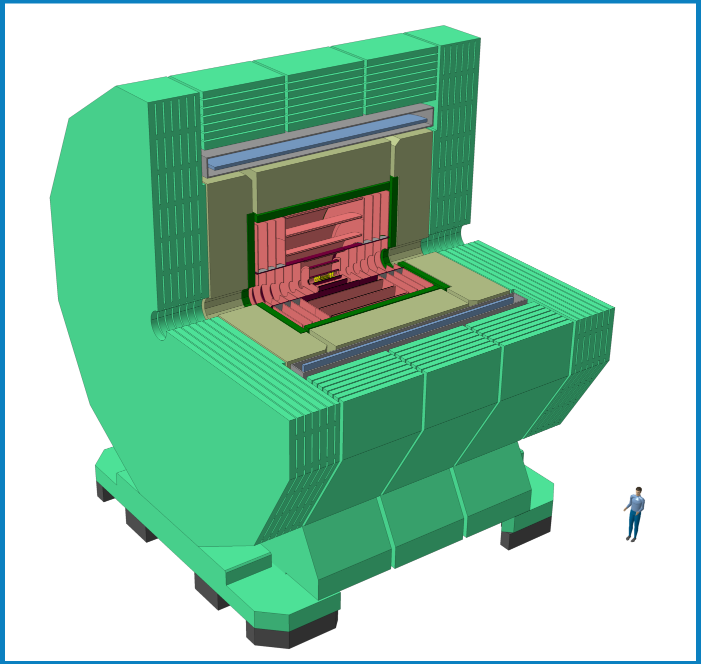
Physics requirements

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$ $\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	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)

- Very good momentum resolution.
- Very good vertex resolution.
- Excellent Hadronic calorimetry.
- Good, but not extreme, EM calorimetry
- Good tau identification capabilities and ability for polarisation measurements, very good PID.

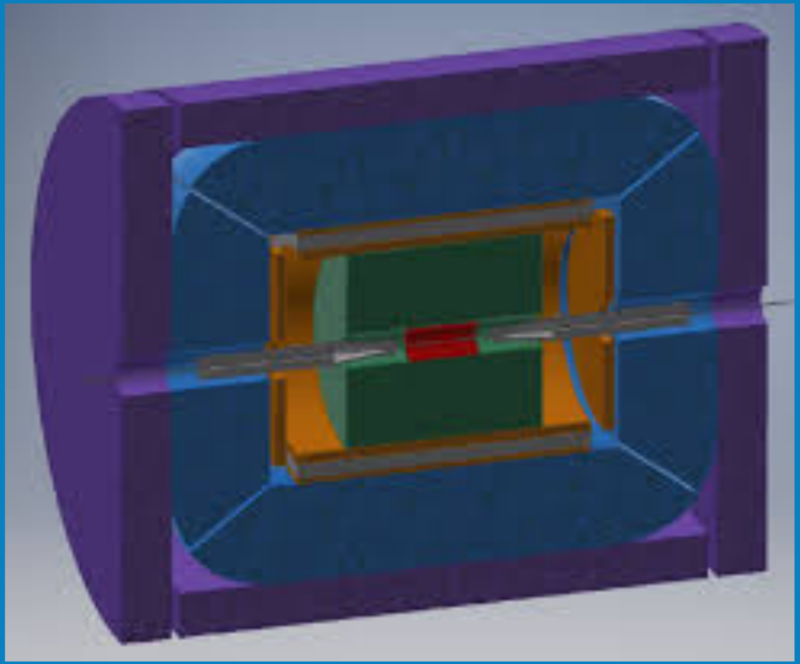
The detectors

CLD
(CLIC-like detector)



2 T solenoid **outside calo**
Full silicon tracker
SiW high-granularity EM Calo
Sci-steel high-granularity HAD Calo
RPC-based Muon detector

IDEA
(International Detector for Ep Accelerators)

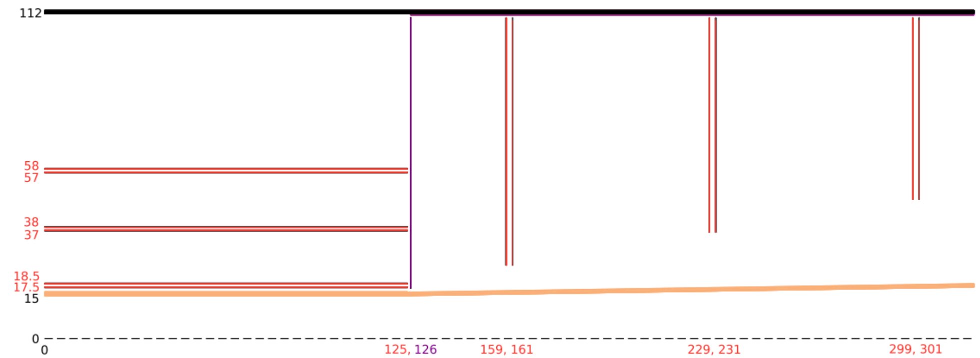


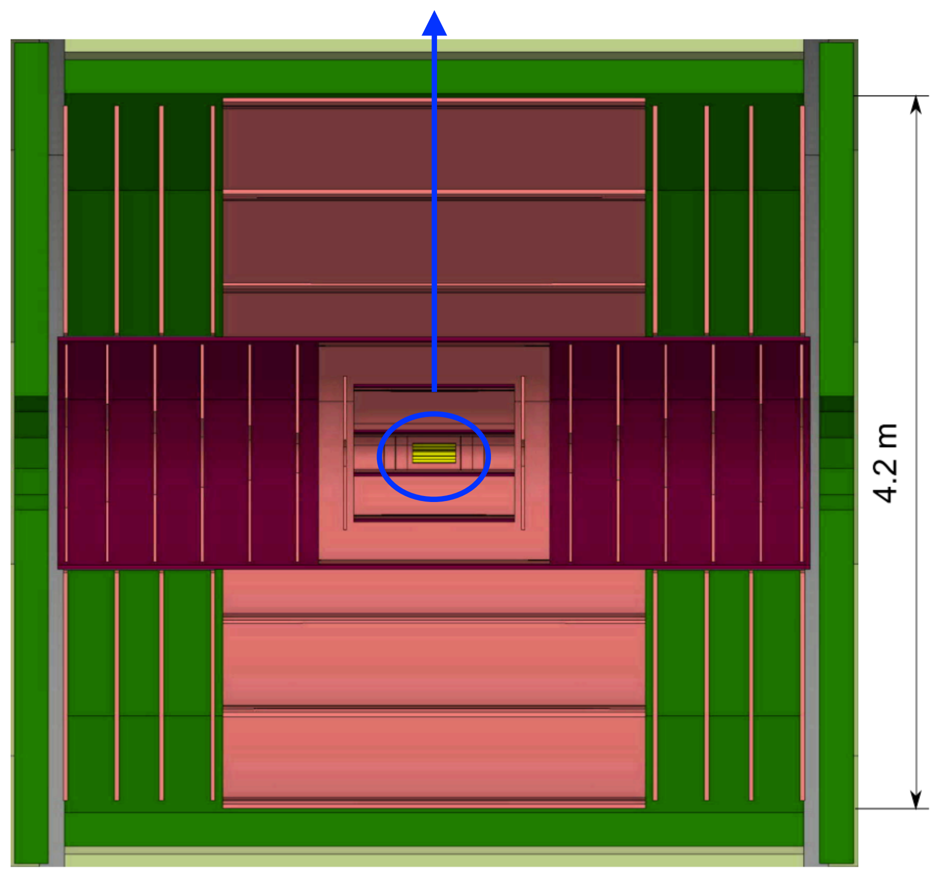
2 T thin solenoid within calo
Si vertex detector
Tracking with ultra light drift chamber
Dual Readout Calorimeter + pre-shower
MPGD (μRwell) based Muon detector

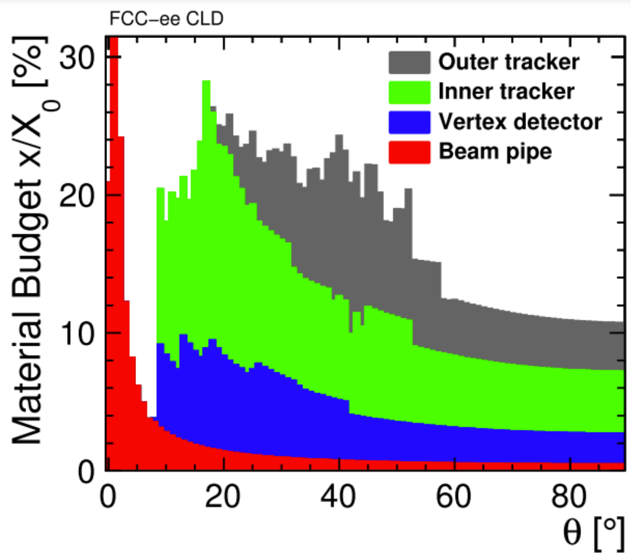
CLD - Vertexing and tracking

VTX:
- Pixel size 25x25 μm^2 - 50 μm sensor thickness - aiming at 3 μm resolution
- Material and cooling benchmarked on ALICE ITS LS2 upgrade design (MAPS)
- Occupancy dominated by IPC - higher at the Z pole and below 1% (Safety factor 5 - 10 μs readout window)
- Power dissipation: 40 mW/cm^2 - water cooled

ID:
- Single point resolution 7x90 μm^2 - 5x5 μm^2 in 1st layer.
- Inner tracker: Barrel 3 layers, end-cap 7 discs.
- Outer tracker: Barrel 3 layers, end-cap 4 discs.

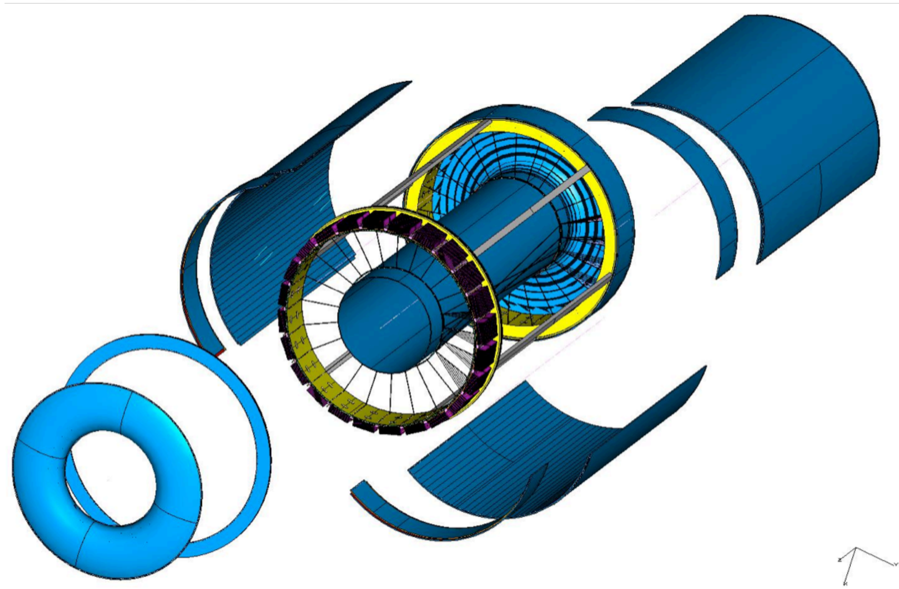




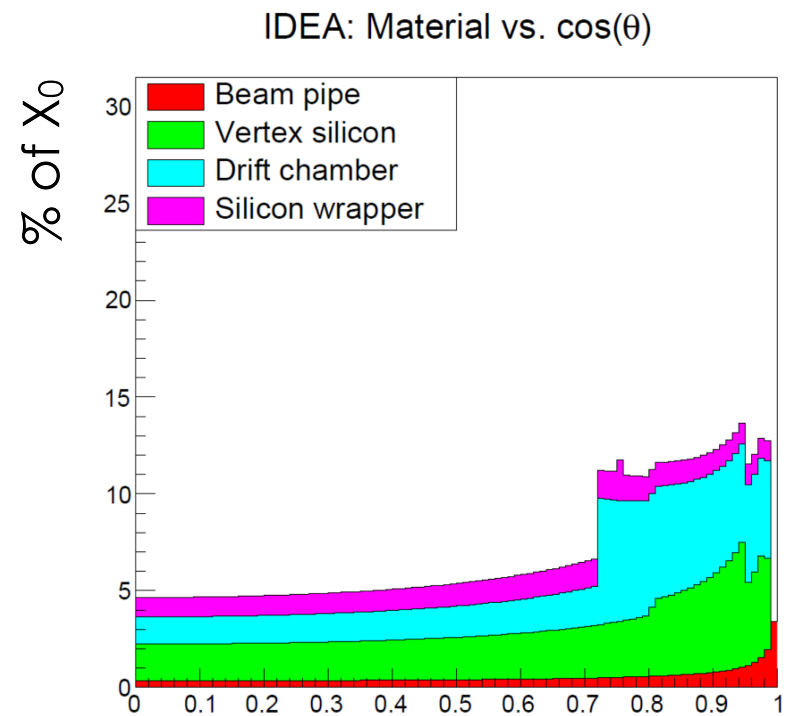


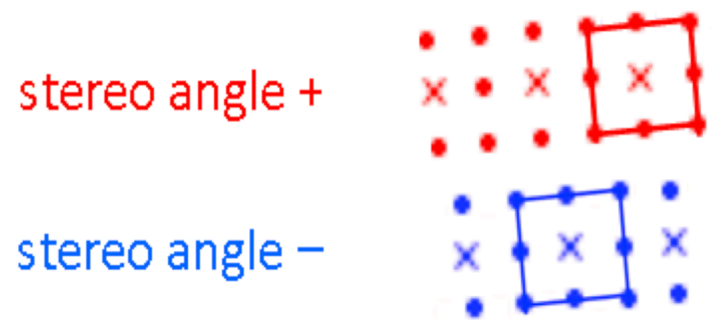
IDEA - Vertexing and tracking

- VTX similar to CLD
- Tracking with drift chamber (similar in concept to MEG II chamber)
  - Minimising multiple scattering, adding only 2% X_0 to material in front of calorimeter
  - R_{in} = 35 cm, R_{out} = 200 cm, L = 400 cm, drift time o(300 ns)
  - 90% He - 10% iC_4H_{10} - max drift time 360 ns, Stereo angle 30°
  - Cluster counting (12.5 cm^{-1} clusters) improves spacial resolution and dE/dx measurement
  - Single point precision (with cluster counting) better than ~ 100 μm.



See here for more details





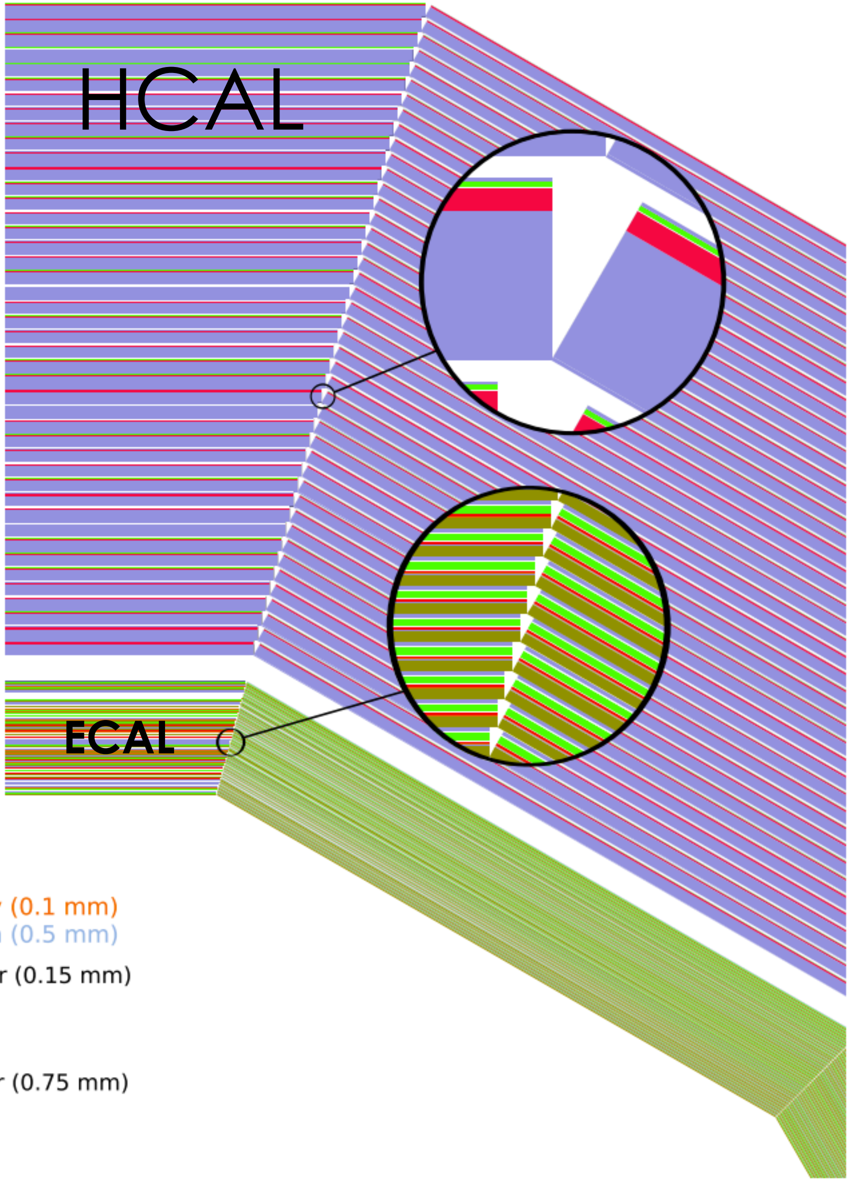
x-y view

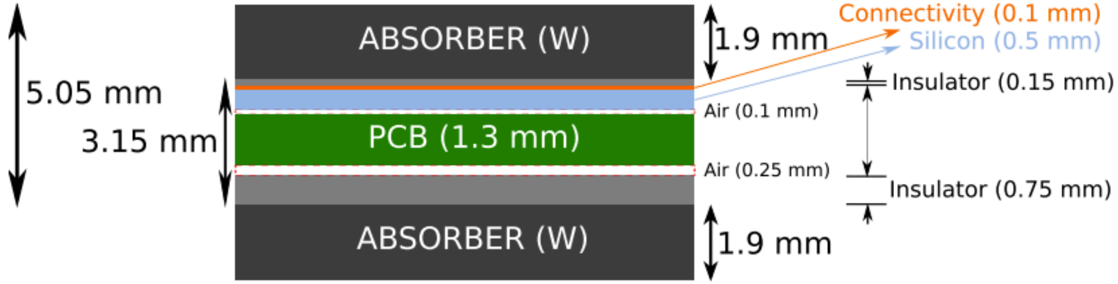
CLD - Calorimeters

- Calorimetry optimised for particle flow

ECAL (CDR numbers - See here for optimisation studies):
- Cell size 5x5 mm² with Si-W
- 40 layers - 5.05 mm thickness each
- Total 20 cm, 22 X_0, ~ 1 λ_I
- No power pulsing - cooling is an issue - part of the optimisation process.

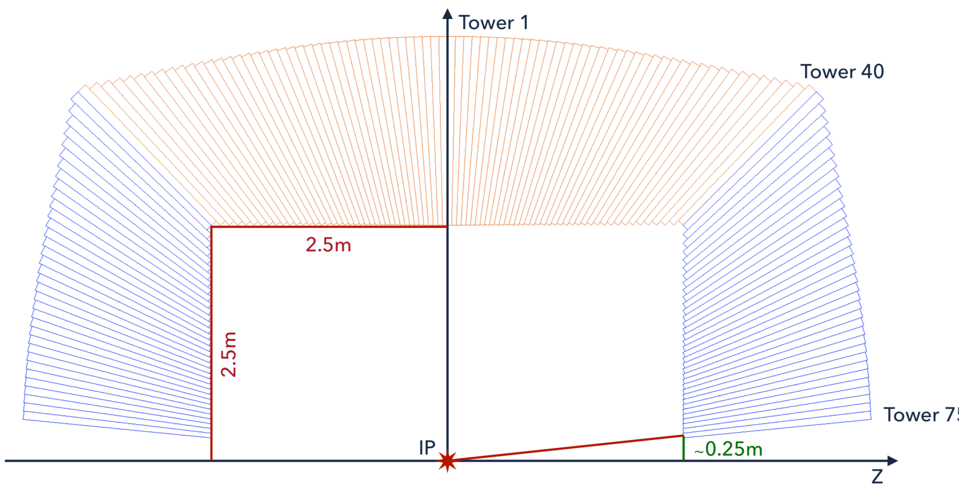
HCAL:
- Cell size 30x30 mm² scintillator-steel
- 44 layers - 26.5 thickness each
- Total 117 cm, 5.5 λ_I

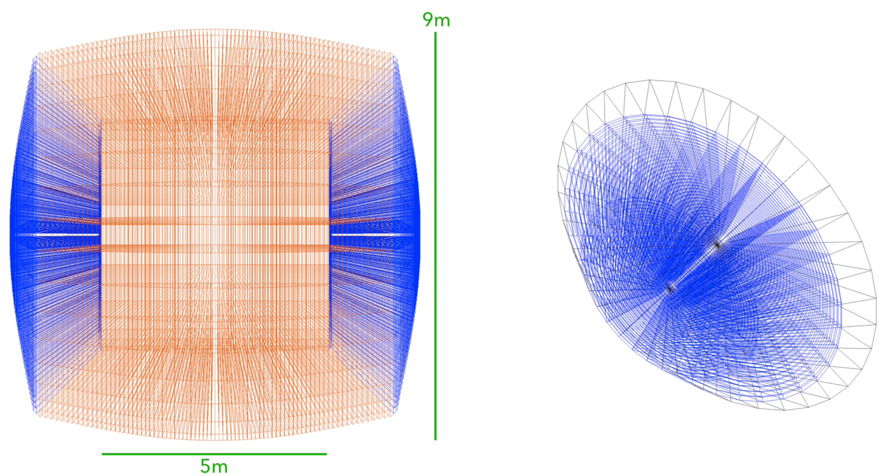


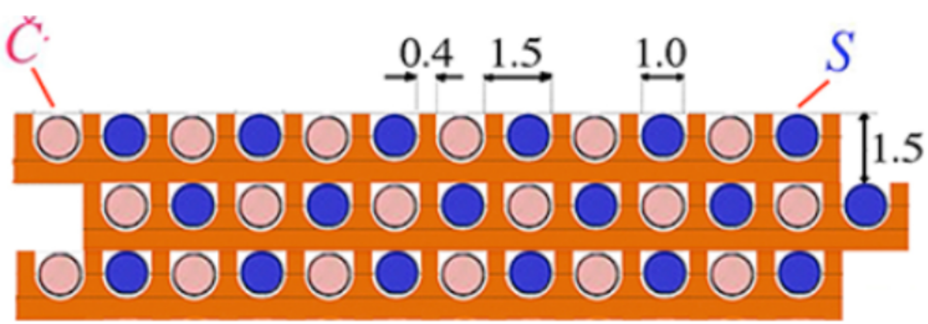


IDEA - Calorimetry+preshower

- Preshower under optimisation, using μ-RWELL - aim: provide one last tracking point, help for π_0 identification.
- Single calorimeter, with **1.5 mm fiber pitch** and Cherenkov/Scintillation dual-readout.
    - For details about dual-readout, see here
- No mechanical **longitudinal segmentation**, ~ 7 λ_I length.
- Good **EM intrinsic** energy resolution, excellent **hadronic** resolution







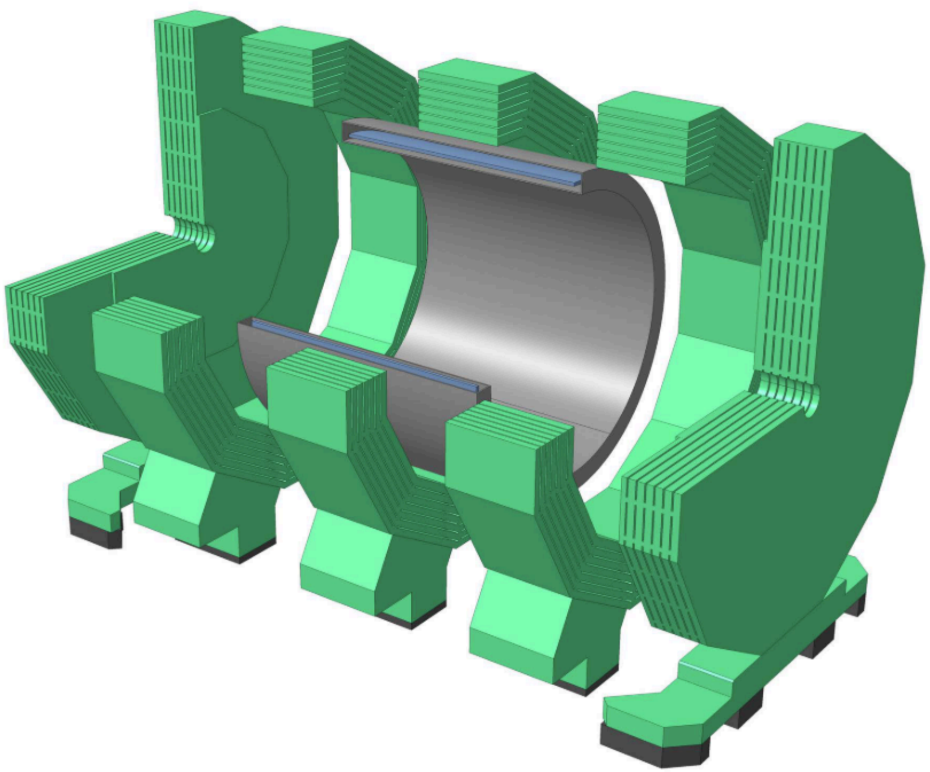
Magnet and muon system

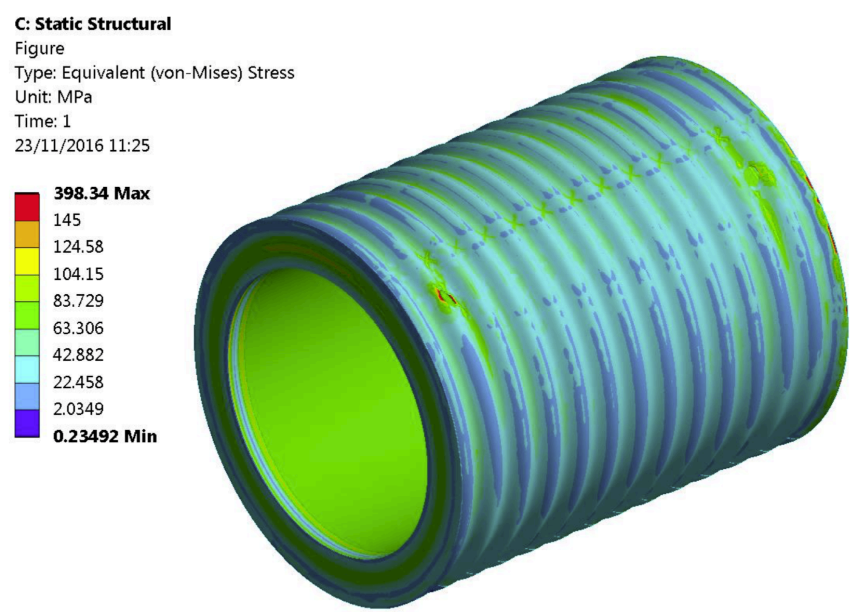
CLD:

- 2 T superconducting solenoid **outside calorimeters**, I = 20-30 kA, 0.7 λ_I
- Return yoke field barrel ~ 1 T
- Muon spectrometer **based on RPC** - performance based on a 30x30 mm^2 cell size

IDEA:

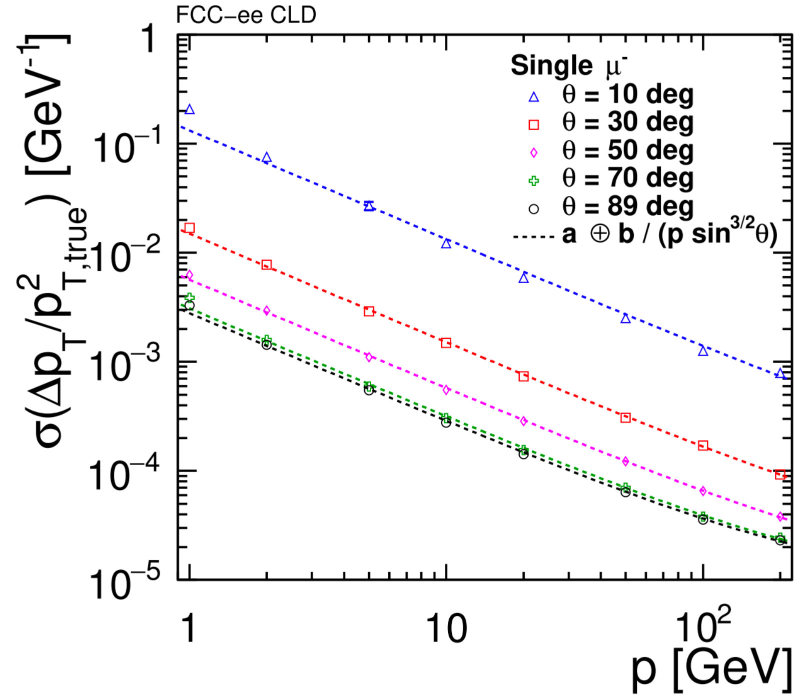
- Thin superconducting solenoid within the calorimeter volume (0.46 X_0 cold mass, 0.28 X_0 cryostat)
- Current design: NbTi/Cu conductor + high strength aluminum for cryostat - 8 ton total
- Muon spectrometer using μ-RWELL

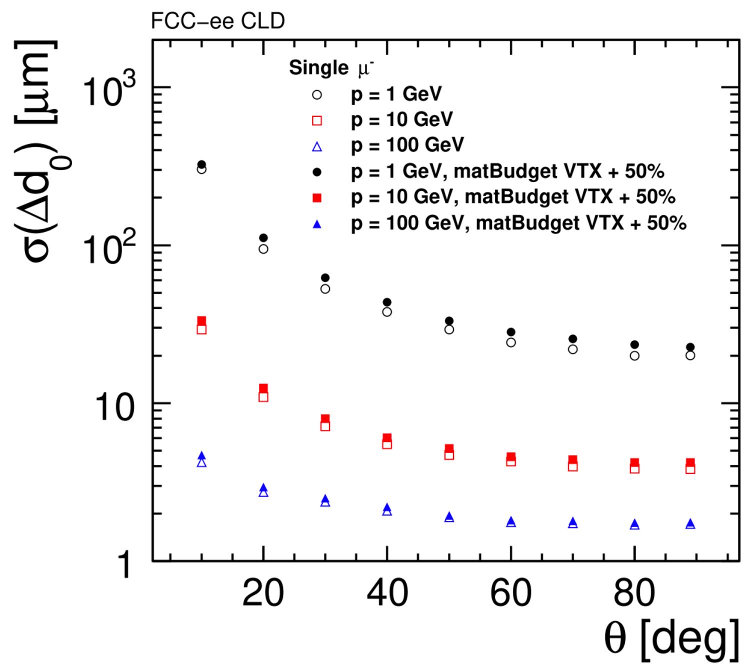


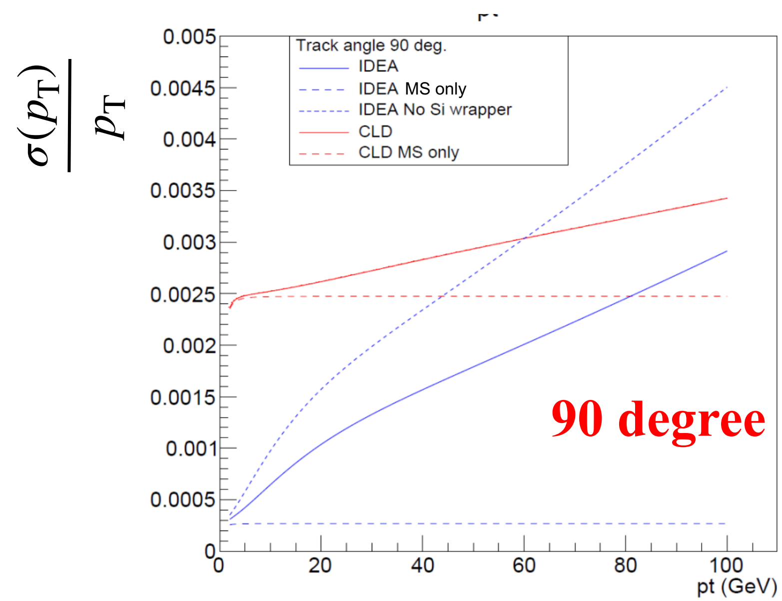


Tracking performance

- IP resolution $o(10\ \mu m)$ for CLD, similar for IDEA
- Very low amount of material in IDEA minimising Multiple Scattering (MS).
- Interesting range $20\ \text{GeV} < p < 80\ \text{GeV}$ (in, e.g., ZH production)







Single particle (calo) response

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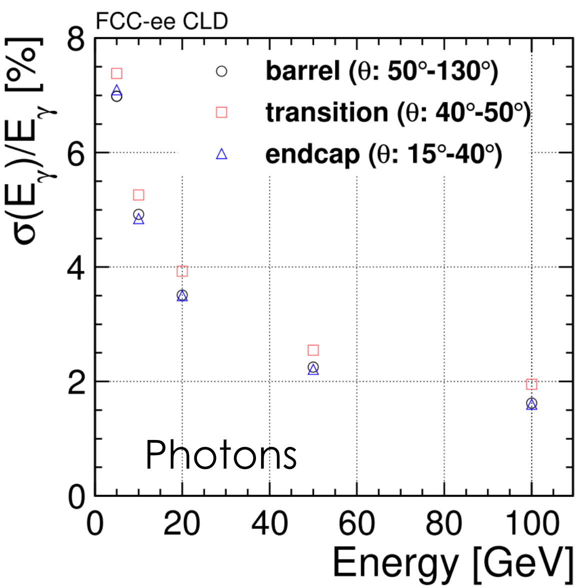
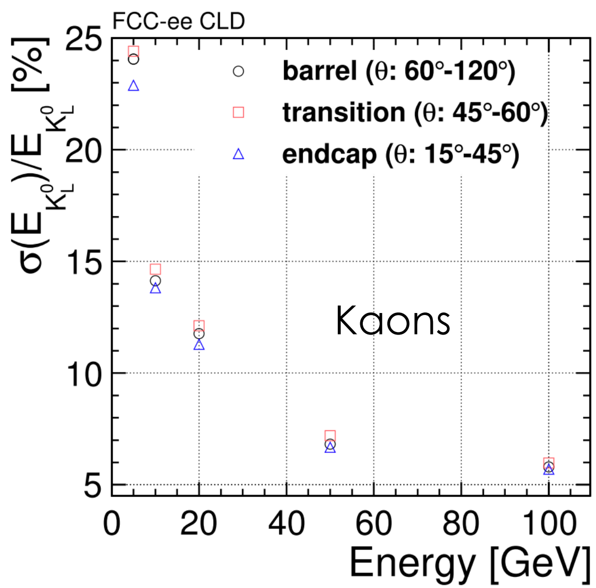
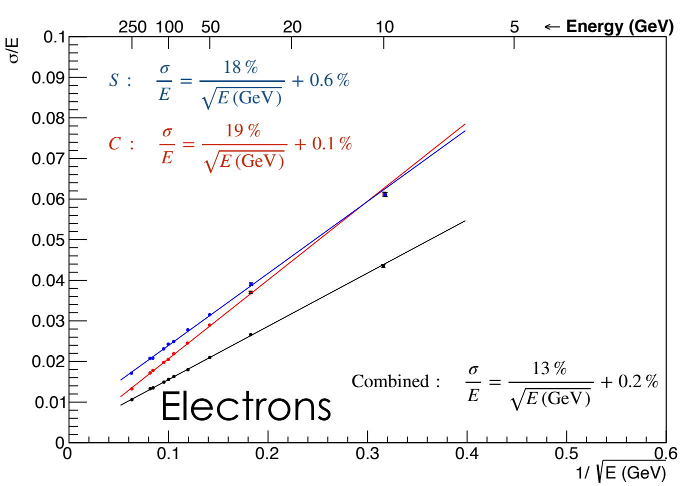
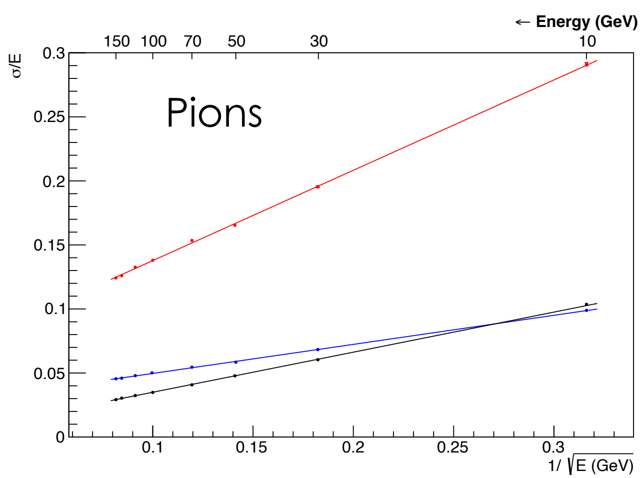
CLD - Full detector simulation

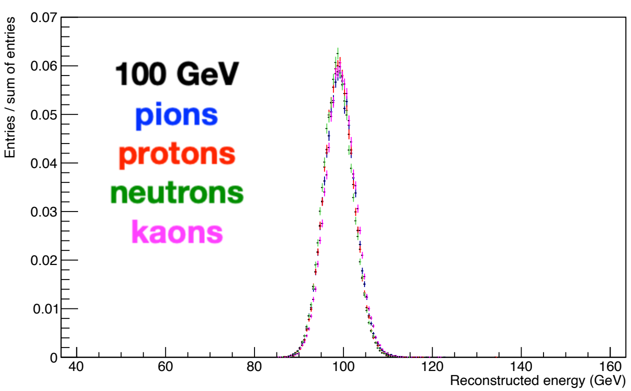




- Calo response to neutral particles (relevant for PF) compared to that of electrons and pions
  - However, dual-readout response is hadron-independent





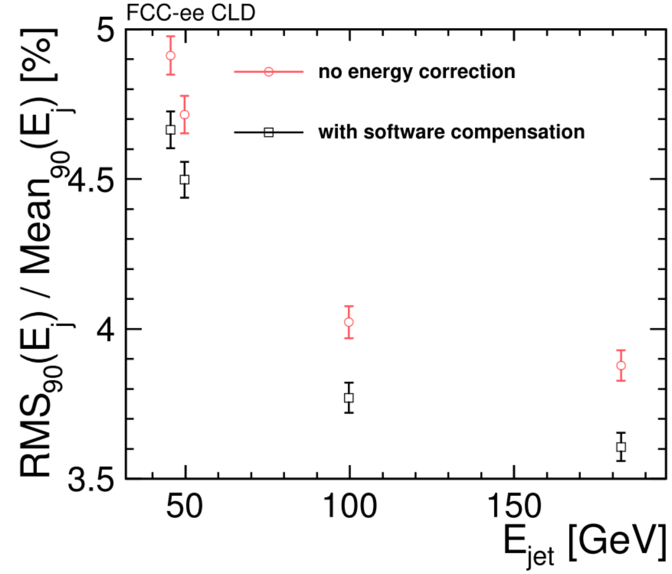


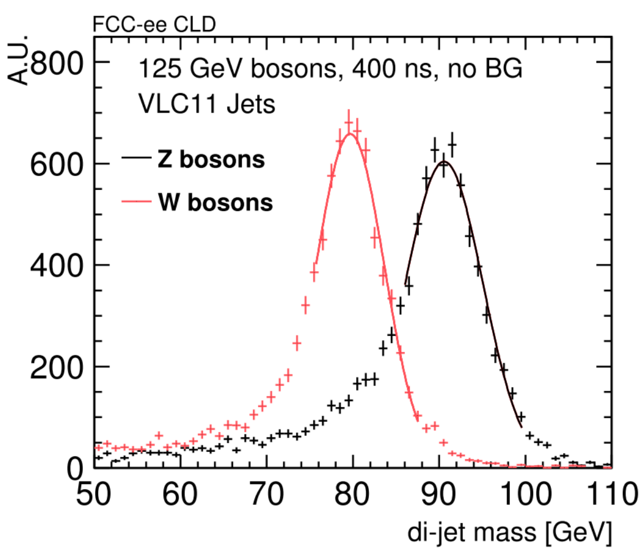
IDEA - Calo only simulation

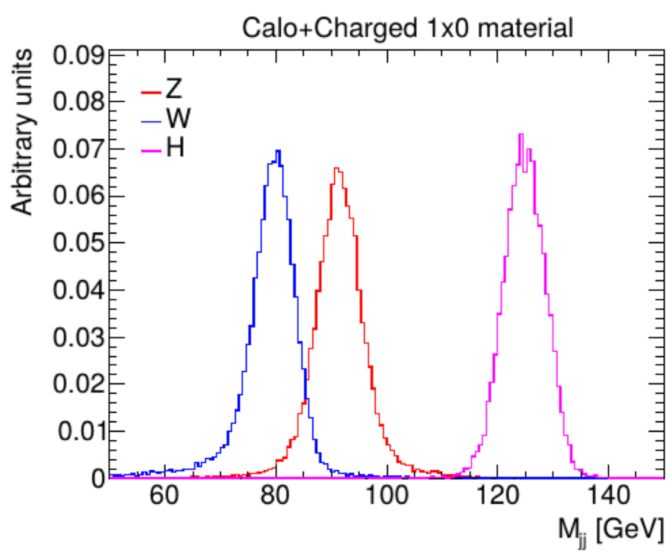
Performance (jets)

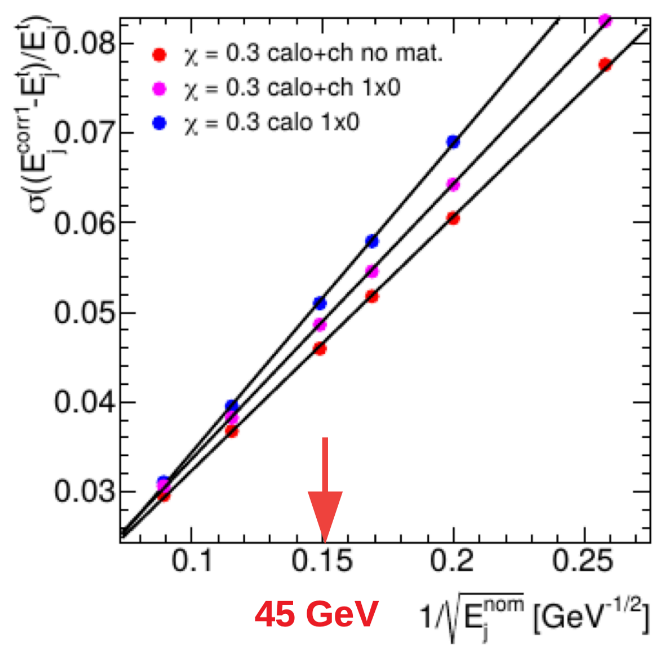
- CLD: particle flow (non optimised) + dedicated software compensation corrections (on or off)
- IDEA: pure calorimetric measurement compared with a “track aided” calibration
- Full collision events used

$$e^+e^- \rightarrow ZH \rightarrow jj\tilde{\chi}_0^1\tilde{\chi}_0^1$$
$$e^+e^- \rightarrow WW \rightarrow jj\mu\nu$$
$$e^+e^- \rightarrow ZH \rightarrow \nu\nu bb$$



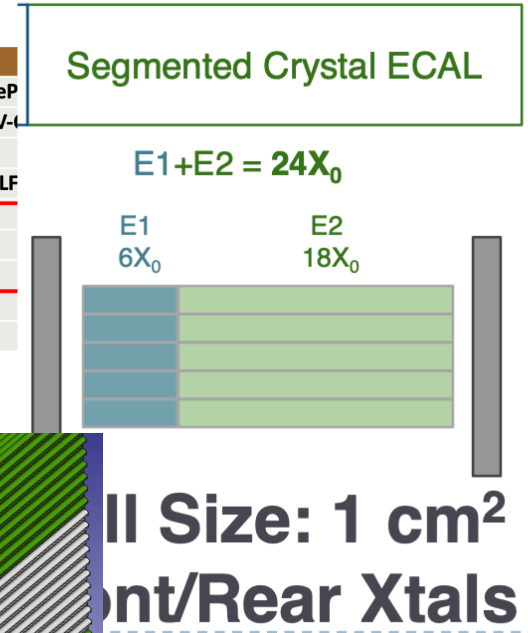


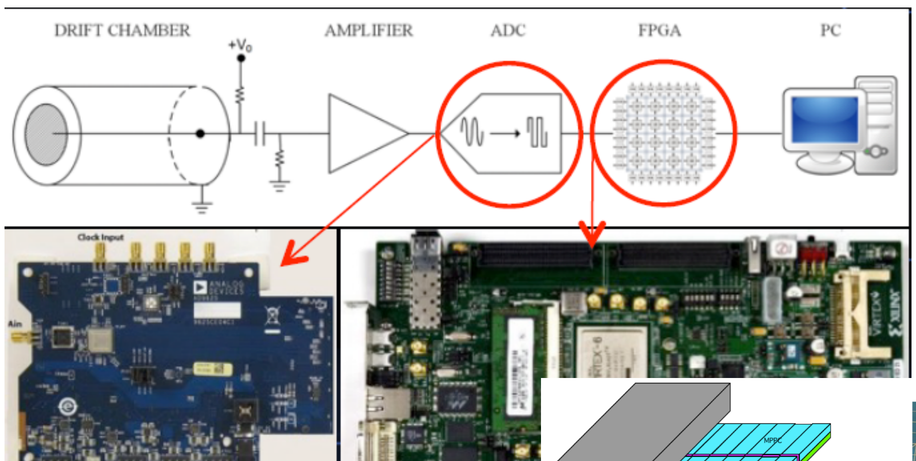


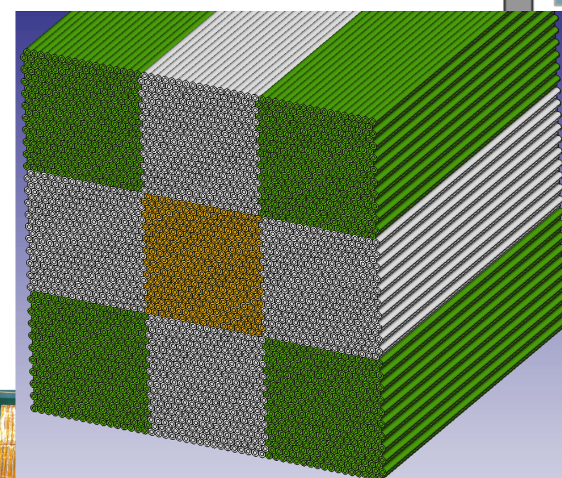


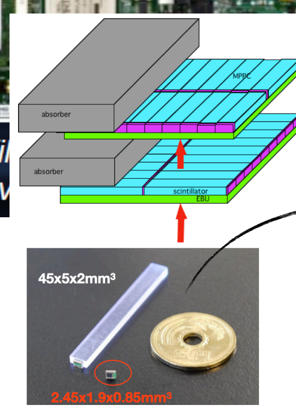
Ongoing R&D

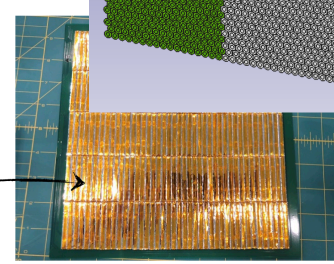
Silicon sensor R&D	Hybrid	SoI		CMOS Monolthitic			
Demonstrator	CLICpix	Cracov	CLIPS (CLIC)	ALICE investigator	CLICTD	Malta/Monopix	ATLASpix(Mu3eP
Sensor	planar	planar	planar	HR-CMOS standard	HR-CMOS modified process		HV-(
Connection to readout electronics	bump bonding	SoI	SoI	momolithic	monolthitic	monolithic	monolitic
ASIC technology (nm)	65	200	200	180(TJ)	180 (TJ)	180(TJ)/150(LF)	180(AMS)/150(LF
Thickness (μm)	50 / 200	300 / 500	100 / 500	100	50 / 100	100	60
Pitch/cell size (μm x μm)	25 x 25	30 x 30	20 x 20	28 x 28	30 x 300	36 x 36	40 x 130
Hit resolution (μm)	9 / 3.5	5/2		4		4	12
Time resolution (ns)				6		< 10	5
Max NIEL (1 MeV neq/cm2)/TID (Mrad)	$O(10^{16})$/Grad			$O(10^{15})$/300			$O(10^{15})$/100

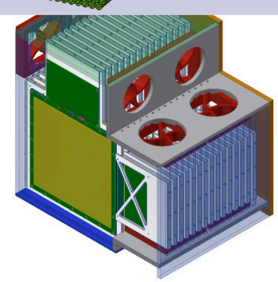










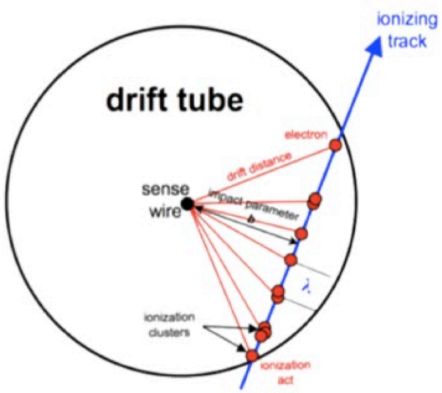


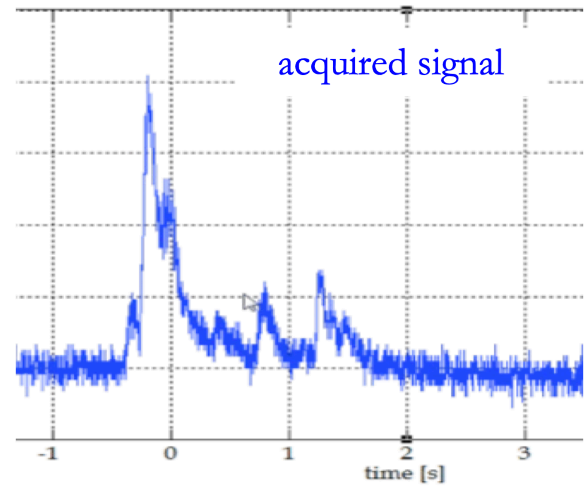
Summary

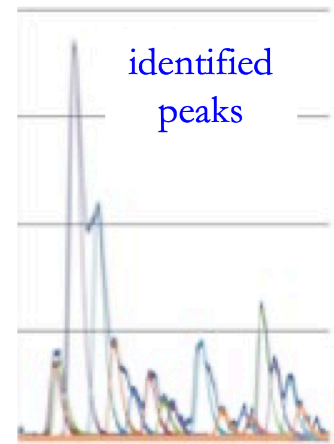
- FCC-ee CDR discusses in some detail **two benchmark detectors** using **different philosophies**:
  - **CLD:** all silicon ID, PF-optimised calo. **IDEA:** drift chamber + dual readout calo.
  - Status of sub-detectors R&D **varies a lot across the board** - in some case profiting from previous work on linear colliders or other experiments (e.g. MEG)
  - Satisfactory performance achieved on **simulation and test beam**
    - …and **full simulation** available for physics studies.
- **Lots of opportunities** - see next talks.
  - …especially if more than 2 interaction points are considered

Backup

DCH - Cluster Counting

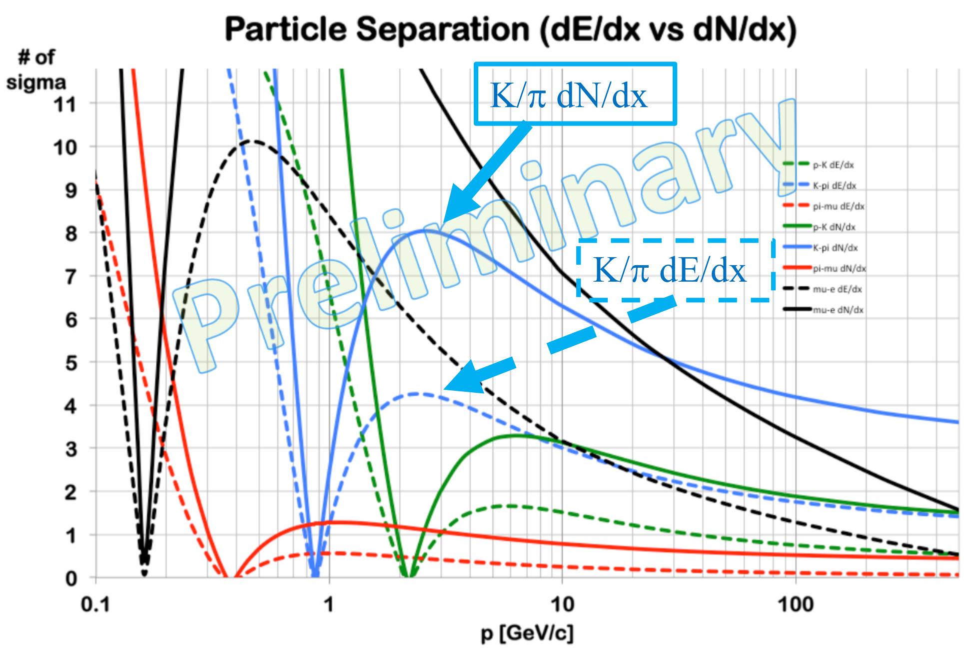






dE/dx

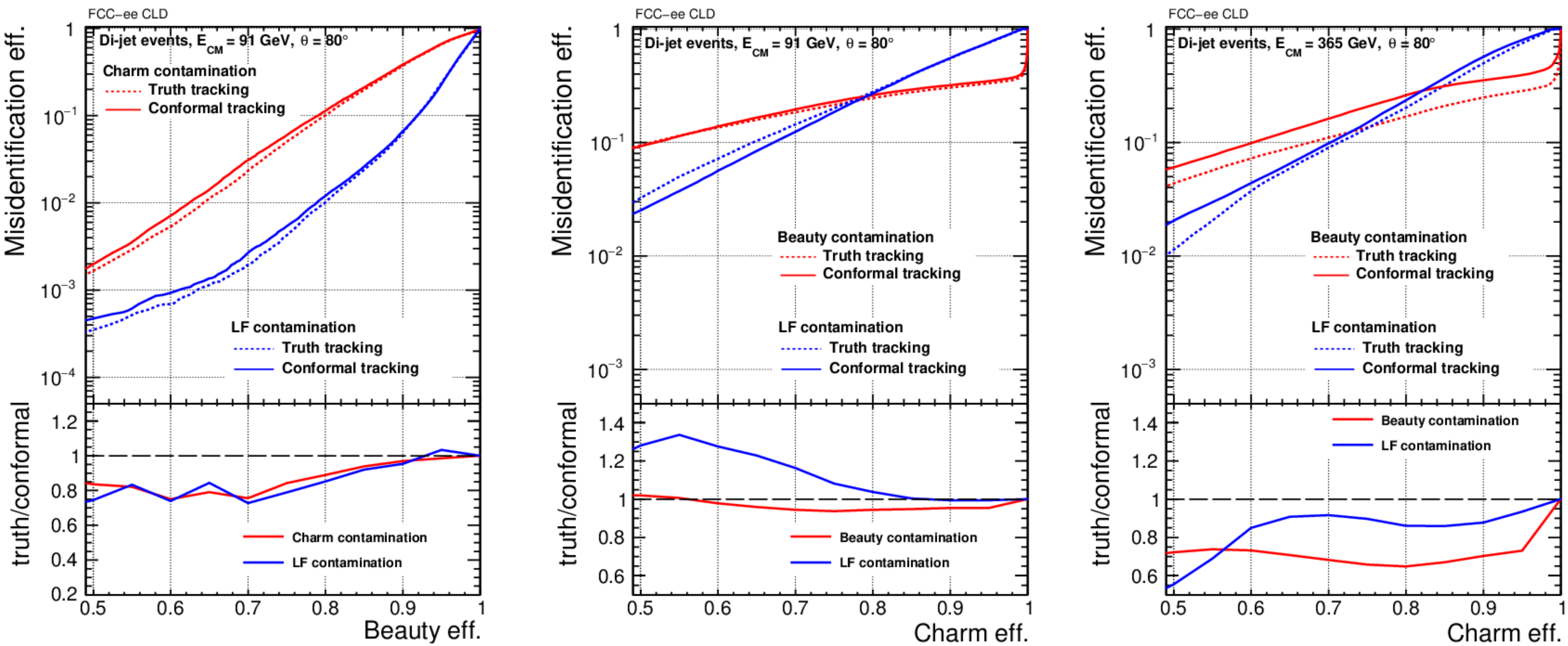
dN_{cl}/dx



- He-based gas mixtures + fast electronics -> Access to the number of ionisation clusters produced. Can measure dN/dx (better than dE/dx for truncated mean)
- Need fast electronics (1 GHz sampling)
  - Impact on readout strategy in terms of bandwidth required.

Performance (flavour tagging)

- Performance evaluated at Z pole and top pair production threshold. Results using truth tracking and reconstruction to decouple detector effects from algorithmic effects.

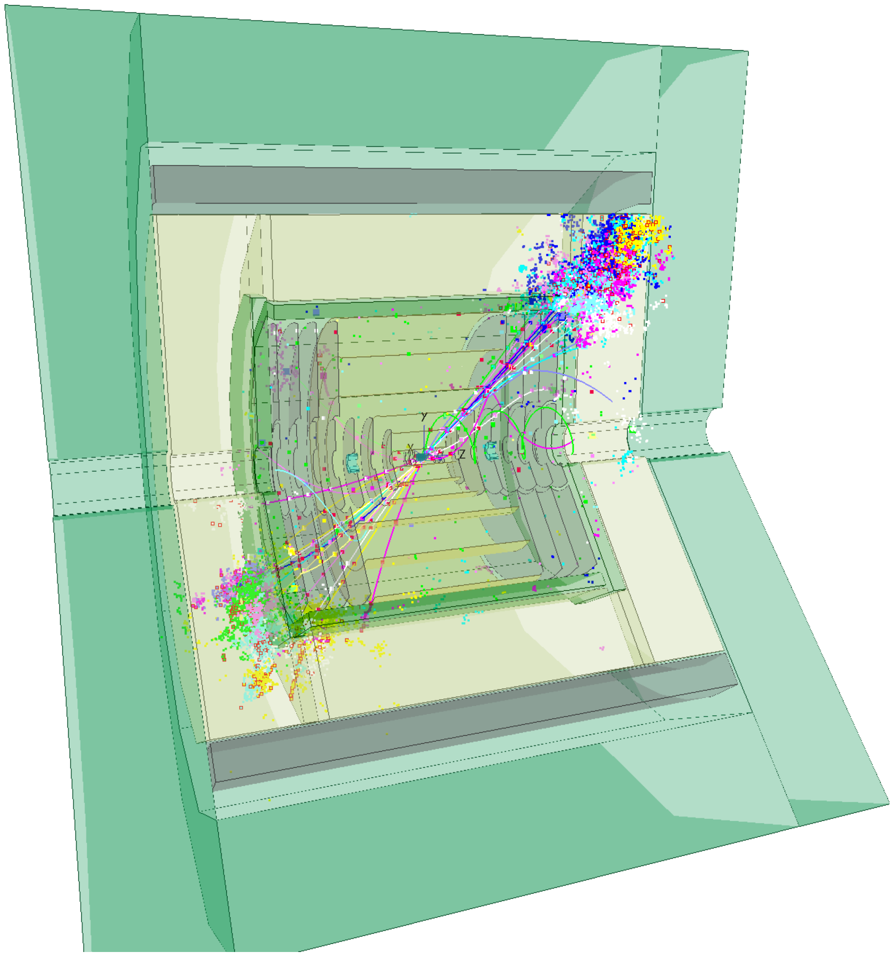


Readout

- Z pole: Z produced at ~**100 kHz** rate + 30 kHz $\gamma\gamma \rightarrow \text{hadrons}$.
  - VTX (IDEA and CLD similar): bandwidth **dominated by IPC** (750 hits assuming 1 μs integration time) - 6 GB/s (13 bit encoding)
  - CLD tracking: similar bandwidth to VTX expected (1 μs integration time - 10 GB/s)
  - IDEA drift chamber - full pulse shape ~ 1TB/s, dominated by IPC, reduced to 30 GB/s (dominated by Z) after FPGA feature extraction for cluster counting.
  - Total IDEA throughput ~ 100 GB/s.
- Assuming current technology, numbers need to be reduced by a factor 5-10 for permanent storage.

Simulation status

- CLD - full detector simulation exists (geometry in DD4Hep and used for performance studies in https://arxiv.org/abs/1911.12230)
- IDEA - G4 implementation of sub detector geometries exist - but not a combined one
  - Geometry of Calo and preshower being migrated to DD4Hep for use within FCCee framework.
  - Most performance studies based on standalone G4 simulation
- Delphes parameterisations of detector response exist for both detectors.



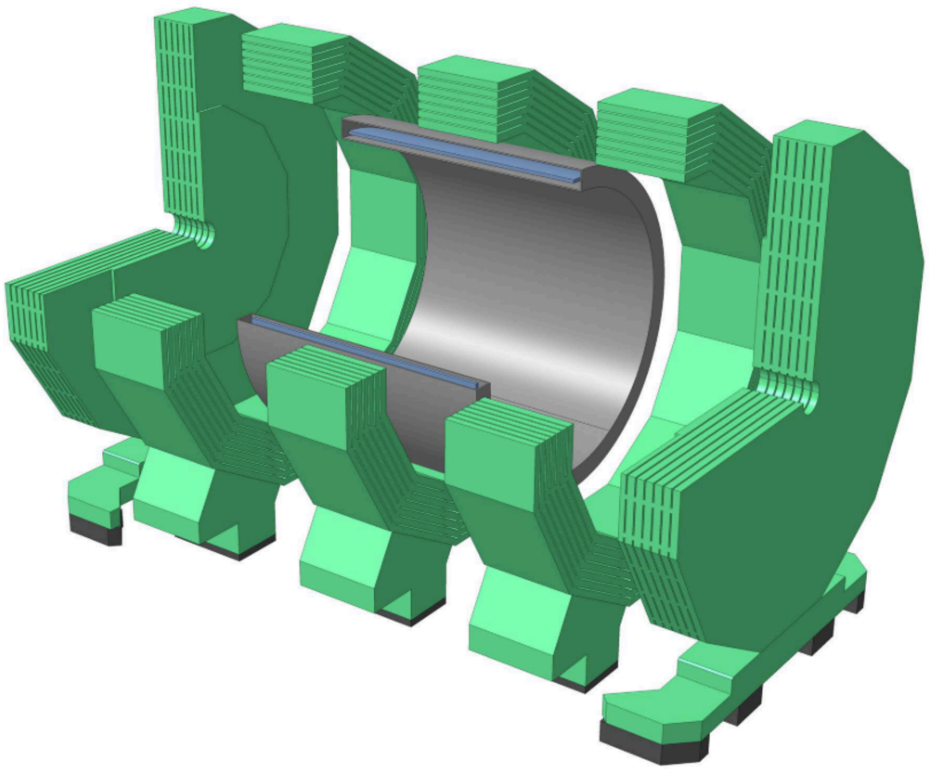
CLICDet Vs CLD

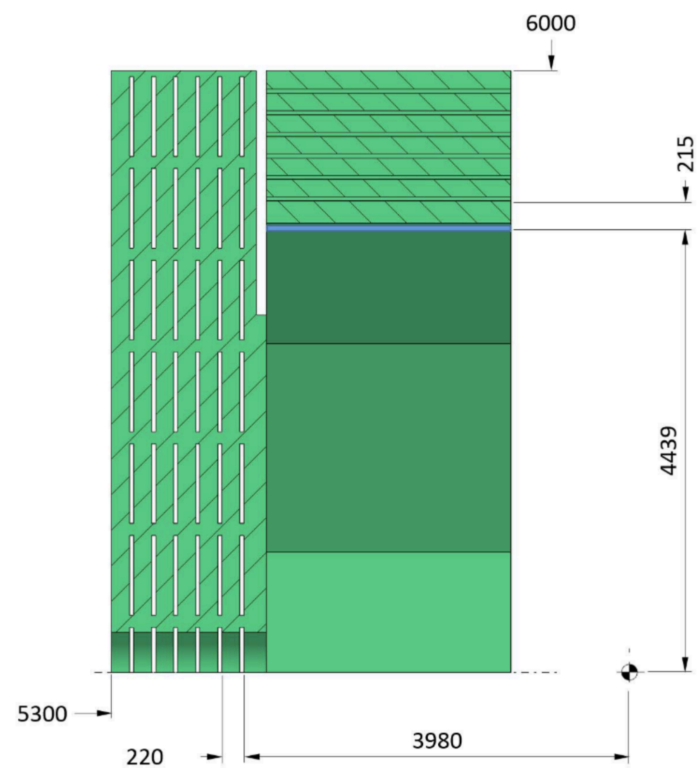
- Main changes to CLICDet:
  - Magnetic field from 4 to 2 T to avoid blowing up the beam
  - As a consequence, ID outer radius increased
  - Change in the maximum CM energy
    - Shorter HCAL (7.5 $\lambda_I \rightarrow$ 5.5 λ_I)

Concept	CLICdet	CLD
Vertex inner radius [mm]	31	17.5
Vertex outer radius [mm]	60	58
Tracker technology	Silicon	Silicon
Tracker half length [m]	2.2	2.2
Tracker inner radius [m]	0.127	0.127
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]	2.54	2.54
HCAL endcap z_{max} [m]	4.13	3.71
HCAL endcap r_{min} [mm]	250	340
HCAL endcap r_{max} [m]	3.25	3.57
HCAL ring z_{min} [m]	2.36	2.35
HCAL ring z_{max} [m]	2.54	2.54
HCAL ring r_{min} [m]	1.73	2.48
HCAL ring r_{max} [m]	3.25	3.57
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

CLD - Magnet and muon system

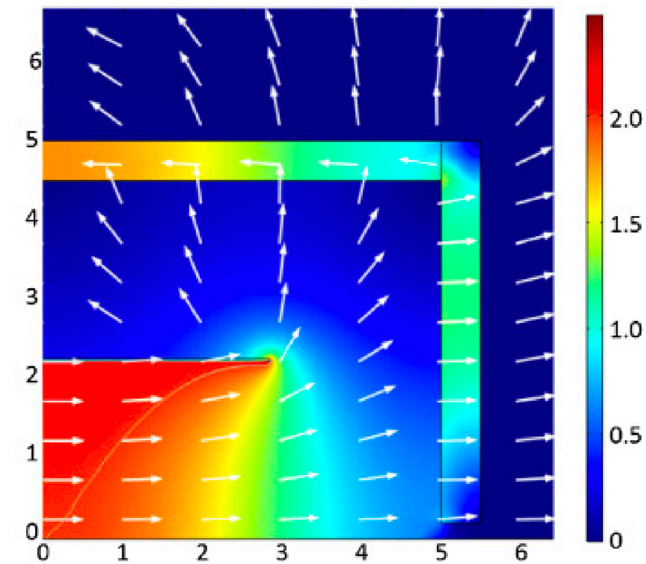
- 2 T superconducting solenoid **outside calorimeters**, I = 20-30 kA, 0.7 λ_I
- Return yoke field barrel ~ 1 T
- Muon spectrometer **based on RPC** - performance based on a 30x30 mm^2 cell size

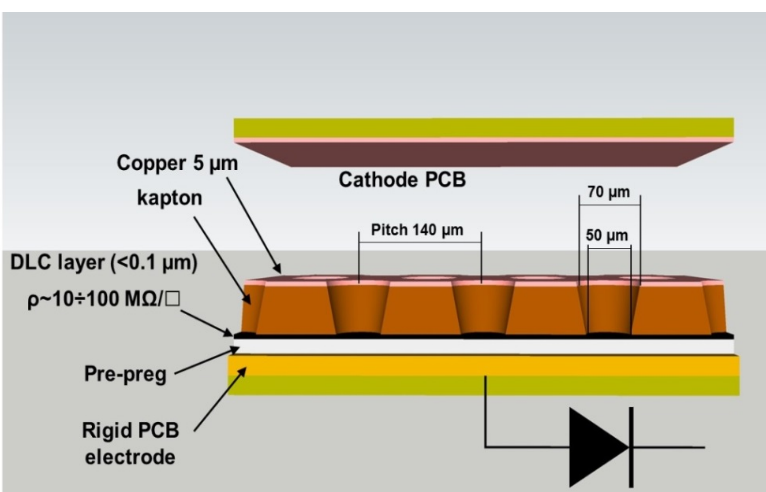


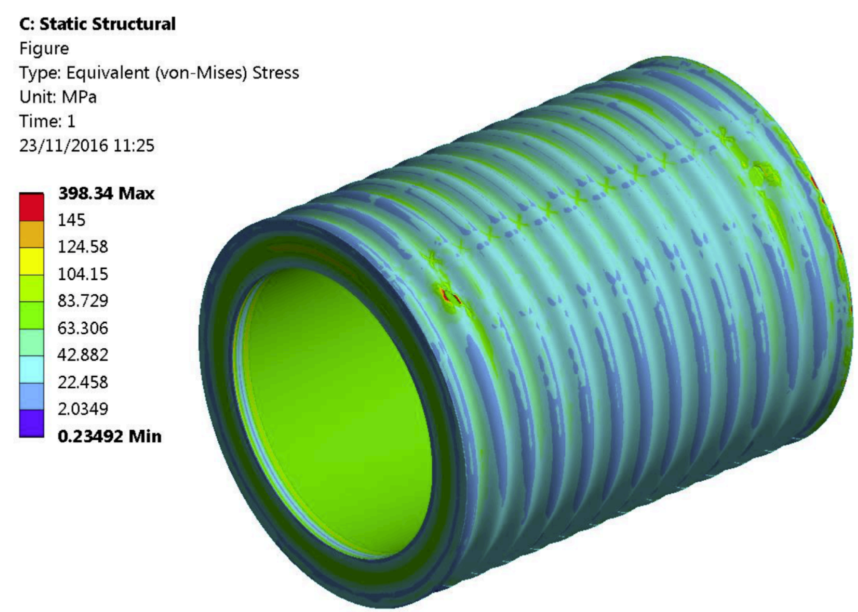


IDEA - Magnet and muon system

- Thin superconducting solenoid within the calorimeter volume (0.46 X_0 cold mass, 0.28 X_0 cryostat)
  - Current design: NbTi/Cu conductor + high strength aluminum for cryostat - 8 ton total
- Muon spectrometer using μ-RWELL



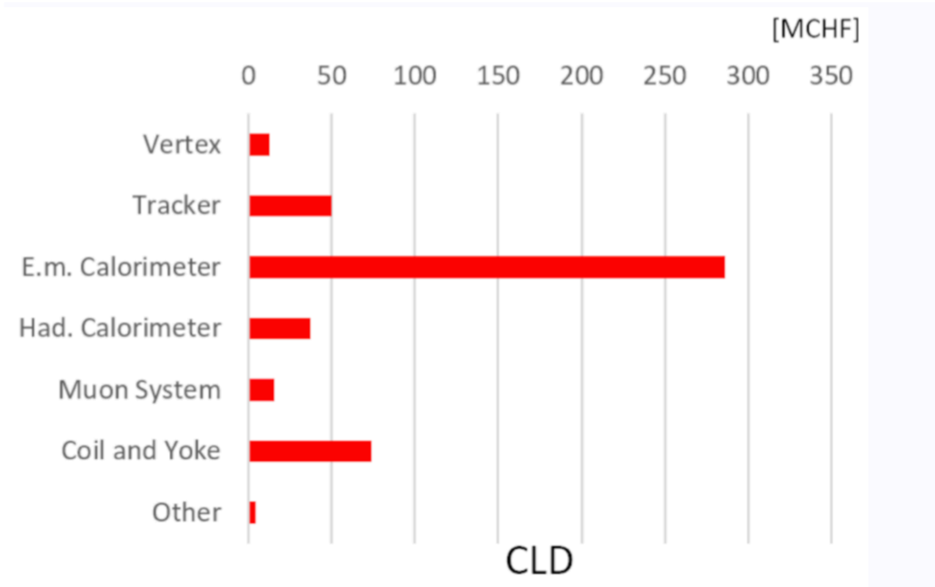




Miscellanea

- CLD VTX and ID detector assumes 40 mW/cm^2 and water cooling (no power-pulsing like CLICDet)
- CLD ECAL (based on ILD/CALICE design): with no power pulsing 200-400 kW expected.
- CLD: Occupancy of VTX dominated by IPC and similar at the different energy points. Expected at the permille level (10 μs time readout - safety factor 5), even lower in the inner tracker.
- IDEA: Occupancy of drift chamber expected o(1%), not considered to be a problem.

Costs



From CLD presentation at FCC workshop January 2020

- IDEA: total cost dominated by DR calorimeter (currently estimated ~ 150 Meuro