NIELS BOHR INSTITUTE
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FCC-ee Detector Concepts

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Lyon meeting: *Prospectives IP2I 2023 sur Futur Collisioneurs FCC*

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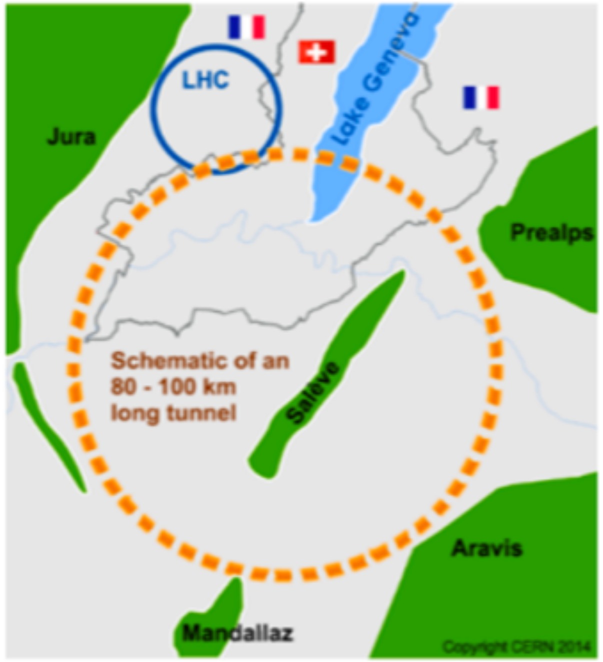
Gratefully acknowleging colleagues from whom material has been borrowed and not in all cases properly referenced

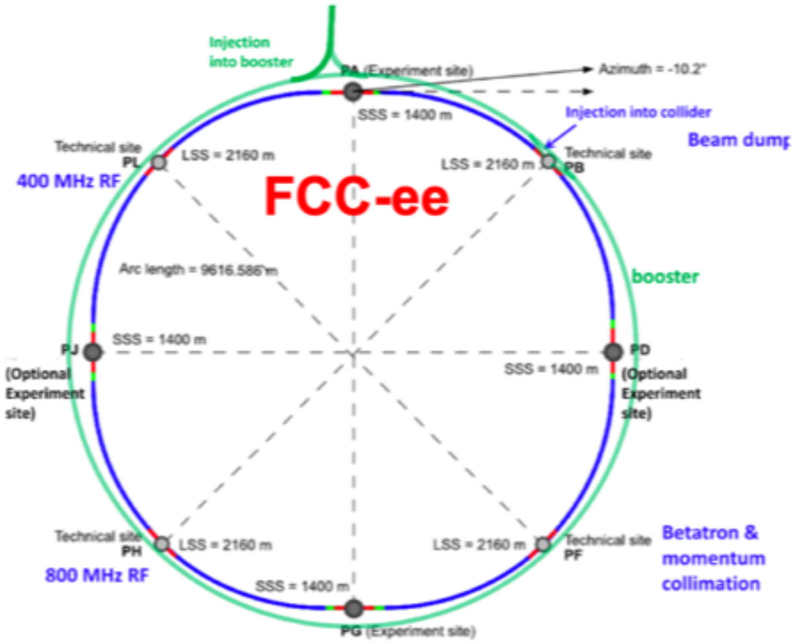
Introduction and Detector Requirements

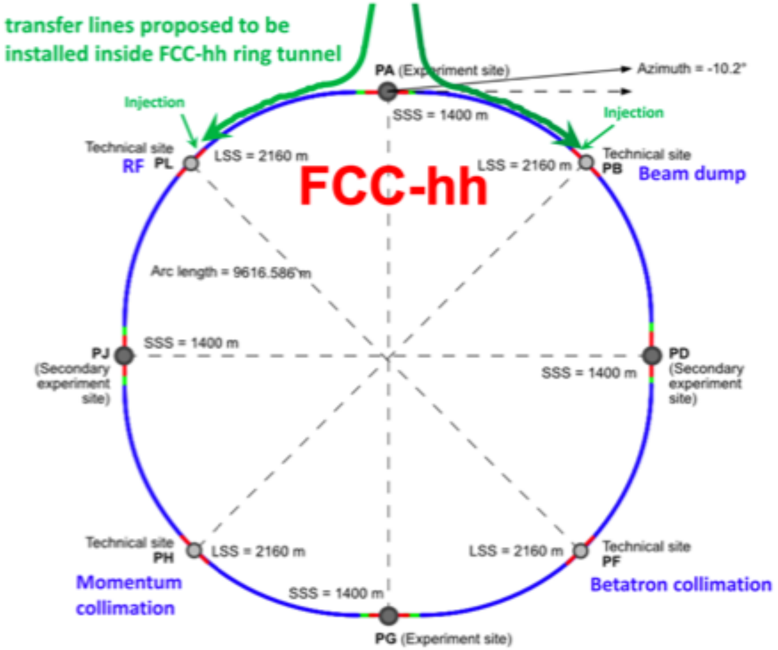
The FCC integrated program inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program

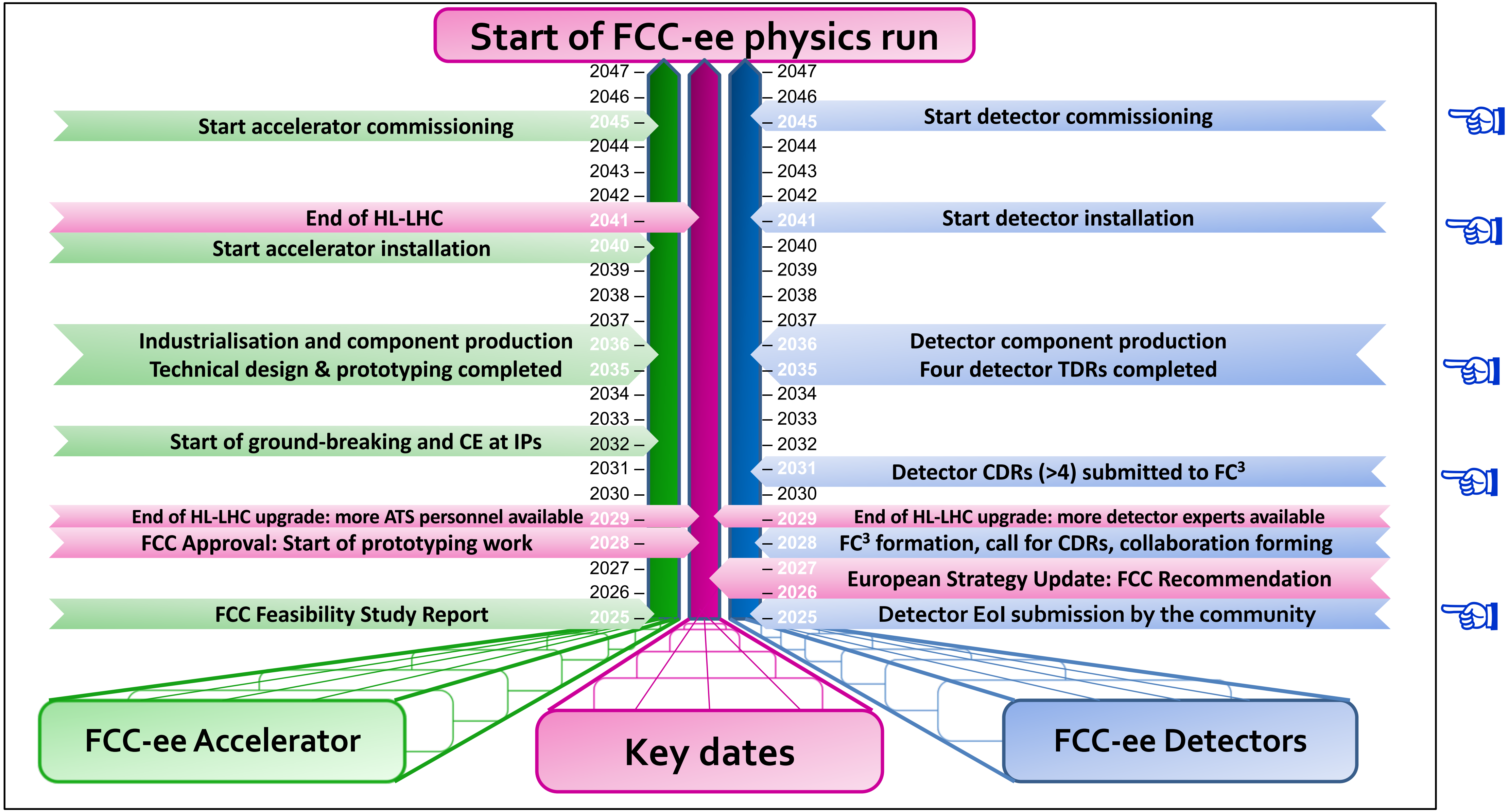






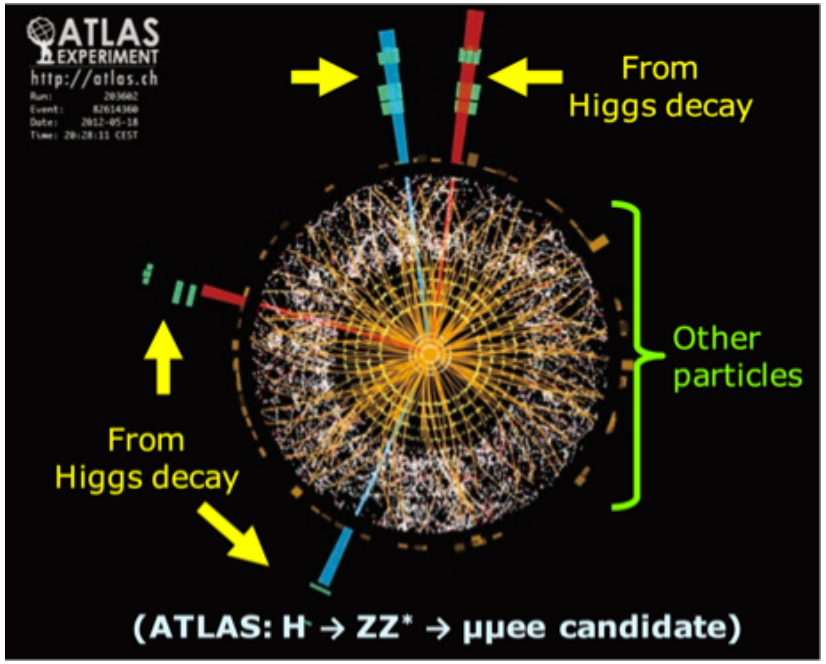
2020 - 2040 | **2045 - 2060** | **2070 - 2090++**

Current FCC-ee Project Timeline

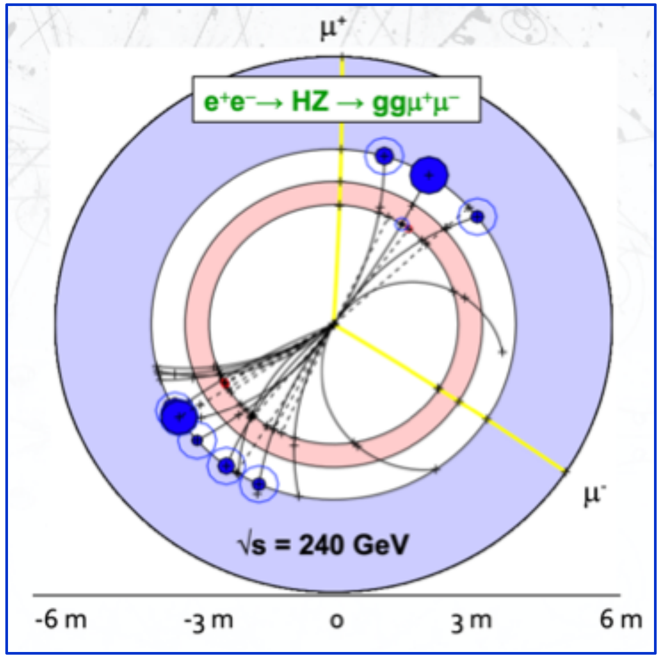


Prelude: pp vs. e^+e^-

Higgs event in pp



Higgs event in e^+e^-



pp: look for striking signal in large background

- High rates of QCD backgrounds
  - ➢ Complex triggering schemes
  - ➢ High levels of radiation
- High cross-sections for coloured states
- High-energy circular pp colliders feasible
  - ➢ Large mass reach ➞ direct exploration
- S/B ≈ 10^{-10} before trigger; S/B ≈ 0.1 after trigger

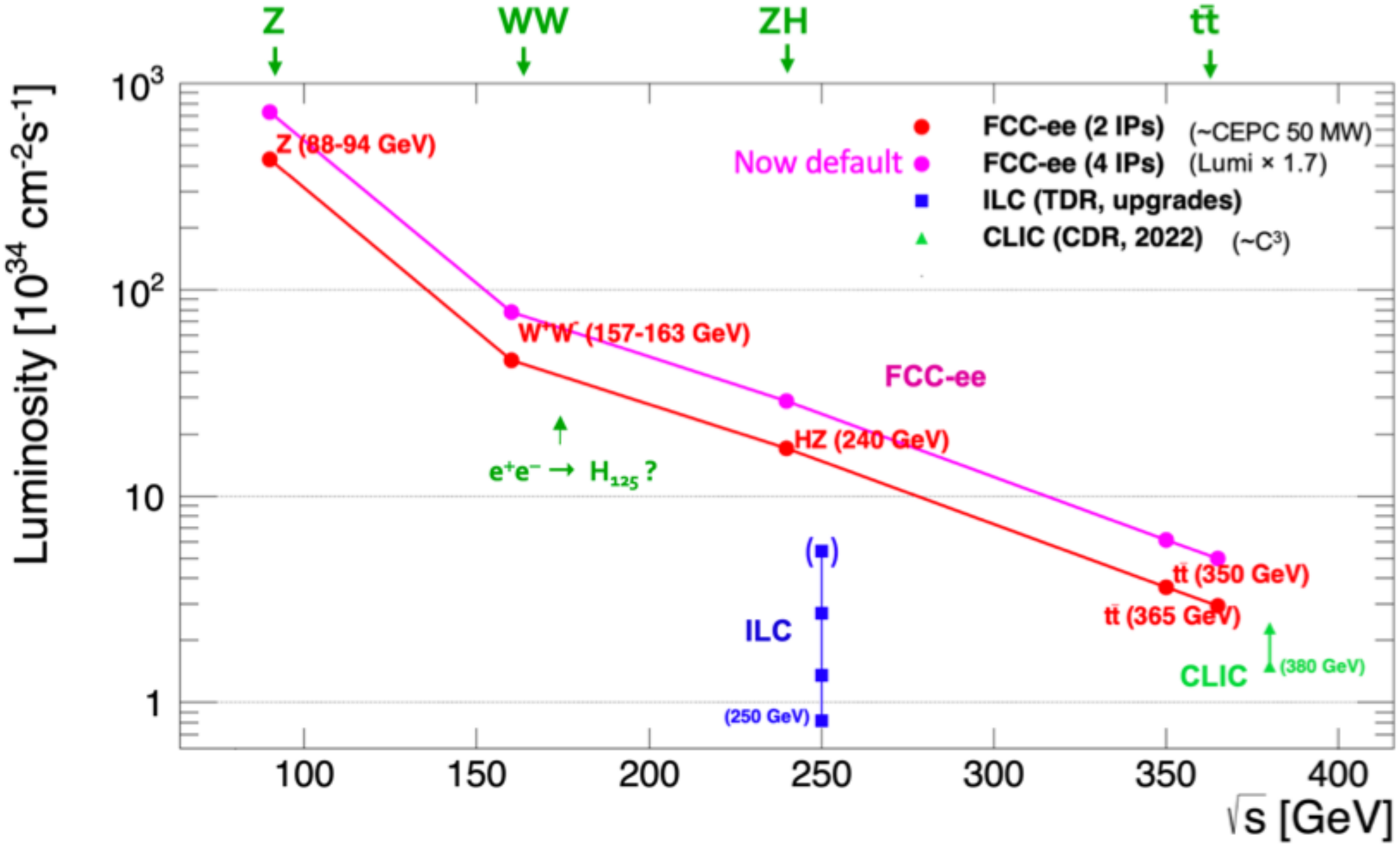
e^+e^-: detect everything; measure precisely

- Clean experimental environment
  - ➢ Trigger-less readout
  - ➢ Low radiation levels
- Superiour sensitivity for electro-weak states
- Limited direct mass reach
- S/B ≈ 1 ➞ precision measurement
  - ➢ Exploration via precision

FCC-ee Luminosity and Event Rates

Numbers of events in 15 years, tuned to maximise the physics outcome

						$\sqrt{s}$ uncertainty
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	2×10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s} \sim 365$ GeV	5 years	2×10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	6×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 50 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	3×10^8	$e^+e^- \to W^+W^-$	LEP x 10^3	< 200 keV
[s-channel H	$\sqrt{s} = 125$ GeV	5? years	~7000	$e^+e^- \to H_{125}$]	Never done	< 100 keV



FCC-ee: ultimate precison with

- **~100 000 Z / second (!)**
  - 1 Z / second at LEP
- **~ 10 000 W / hour**
  - 20 000 W in 5 years at LEP
- **~ 1 500 Higgs bosons / day**
  - $\mathcal{O}(10)$ times more than ILC
- **~ 1 500 top quarks / day**

The Challenge – High Precision Measurements

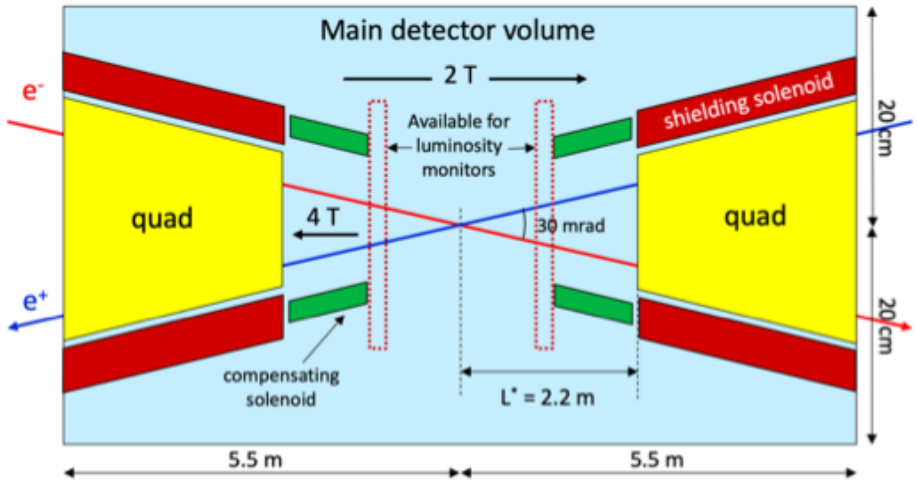
Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

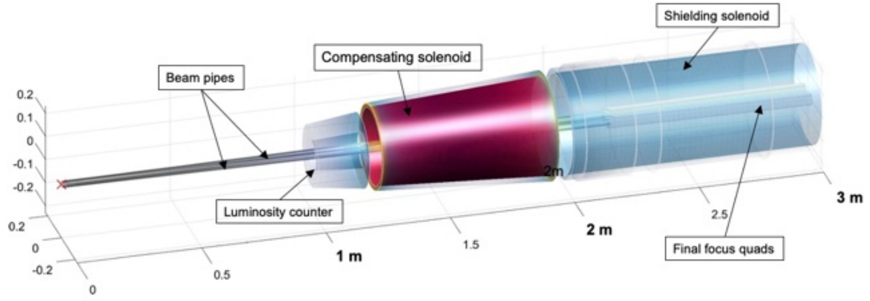
- FCC-ee EWPO measurements with unprecedented statistical precision
  - e.g. 6 x 10^{12} hadronic Z decays at Z-pole
  - **Statistical precision** for EWPOs measured at the Z-pole is **typically 500 times smaller than the current uncertainties**
- ☞ Systematic uncertainty dominant!
- ☞ Can achieve indirect sensitivity to new physics up to a scale $\Lambda_{\text{new physics}}$ of 70 TeV
- We therefore require:
  - Better control of parametric uncertainties, e.g. PDFs, α_s,m_t,m_H
  - Higher order theoretical computations, e.g. N…NLO
  - **Minimizing detector systematics**

Experimental Challenges

- 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla (at Z-peak operation)
  - Tightly packed MDI (Machine Detector Interface)
- ”Continuous” beams (no bunch trains); bunch spacing down to $\lesssim$ 20 ns
  - Power management and cooling (no power pulsing as possible for linear colliders)
- Extremely high luminosities
  - High statistical precision -- control of systematics down to $10^{-6} – 10^{-5}$ level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics: ”Big Data”
- Physics events at up to 100 kHz
  - Detector response ($\lesssim$ 1 µs) to minimise dead-time and event overlaps
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - At the same time, keep low material budget: minimise mass of electronics, cables, cooling, …
- More physics challenges
  - Luminosity measurement to 10^{-4} – luminometer acceptance to $\mathcal{O}$(1 µm) level
  - Detector acceptance to $\sim 10^{-5}$ – acceptance definition to $\mathcal{O}$(10 µrad), hermeticity (no cracks!)
  - Precise momentum measurement via continous resonant depolarisation (RDP) measurement $\Rightarrow$ e.g. 50 keV (1 ppm) at the Z pole
  - Stability of momentum measuremet – stability of magnetic field wrt E_{cm} (10^{-6})

Central part of detector volume – top view





FCC-ee Physics Programme

"Higgs Factory" Programme

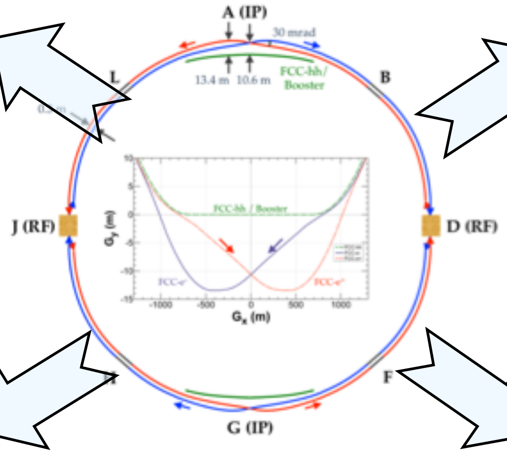
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

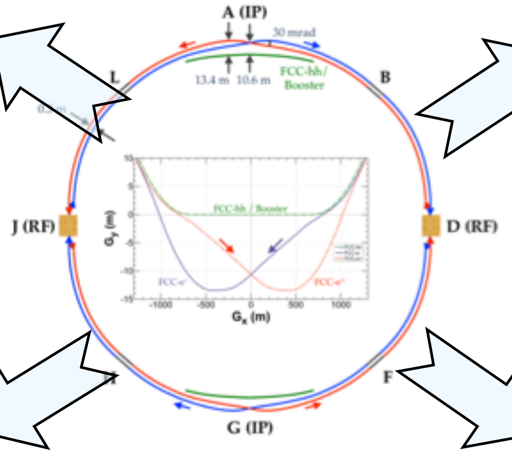
Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes – LLPs

FCC-ee Detector Requirements

"Higgs Factory" Programme
- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD
- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.

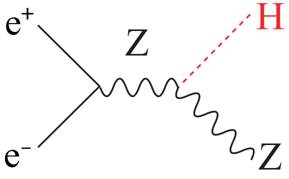


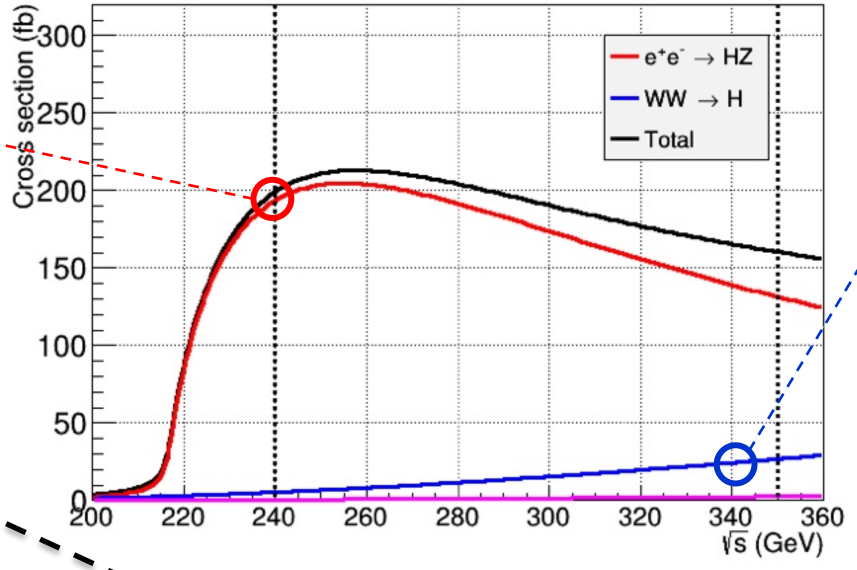
Heavy Flavour Programme
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs
Benchmark signature: Z → νN, with N decaying late
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

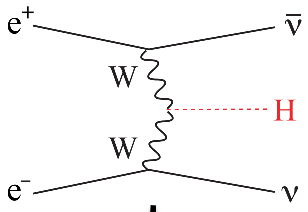
Higgs Factory: Higgs Production and Decay

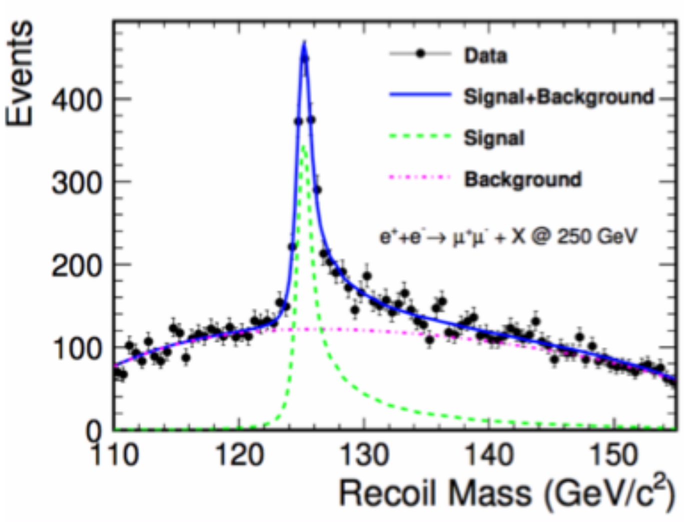
Higgs-strahlung

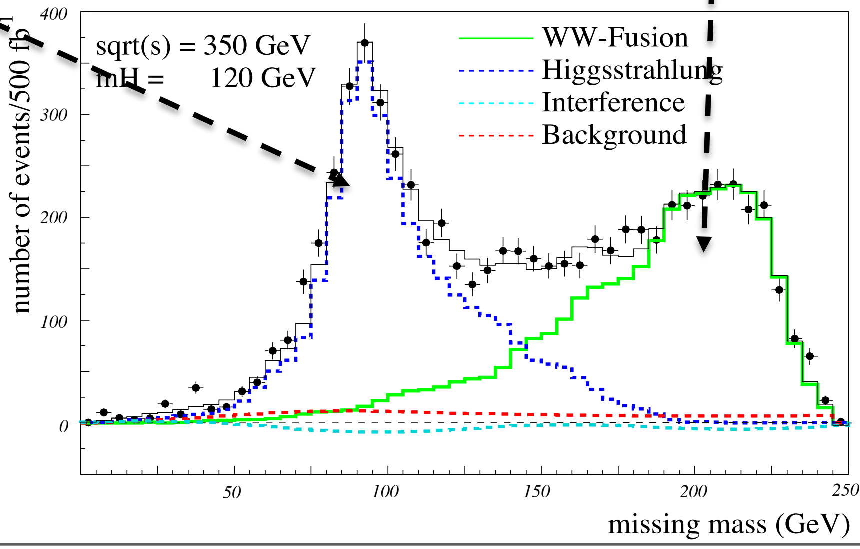




Boson fusion



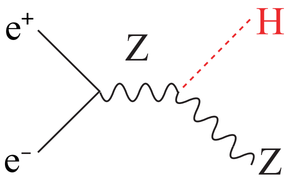


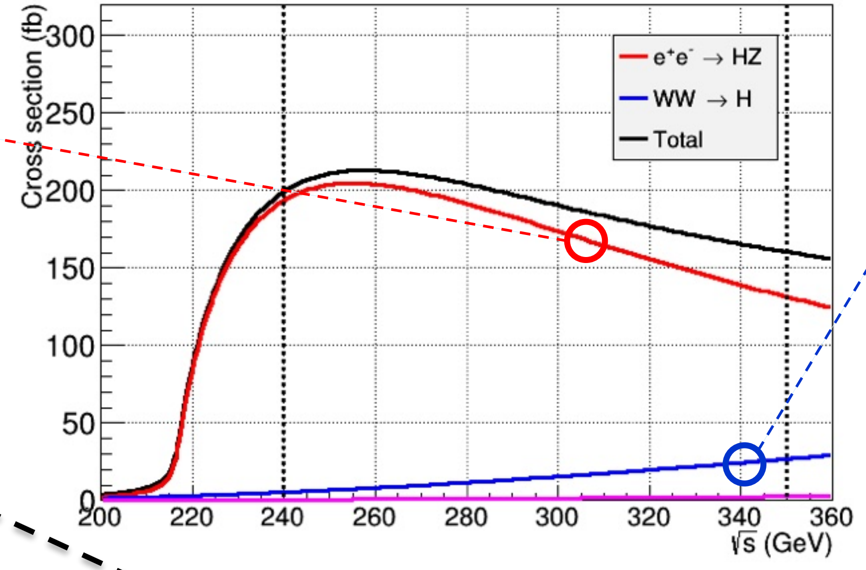


M_H = 125 GeV	SM BF
bb	56.1%
WW*	23.1%
gg	8.2%
ττ	6.3%
ZZ*	2.6%
cc	2.9%
γγ	0.2%
Zγ	0.15%
ss	0.1%
μμ	0.02%

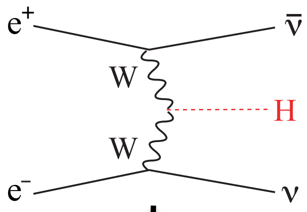
Higgs Factory: Higgs Production and Decay

Higgs-strahlung





Boson fusion



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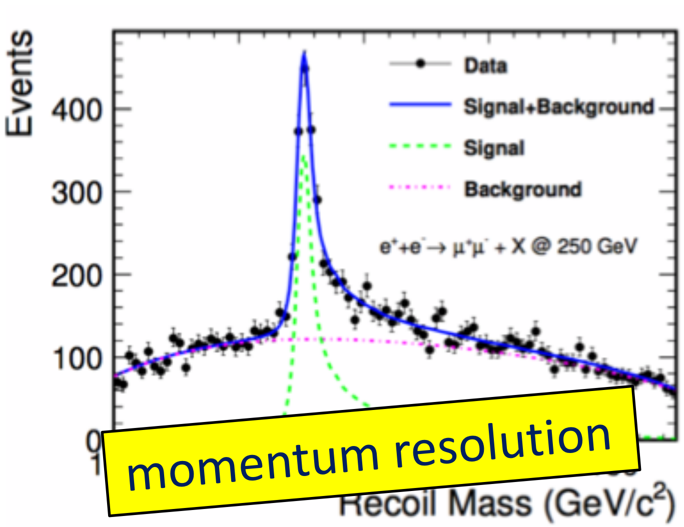
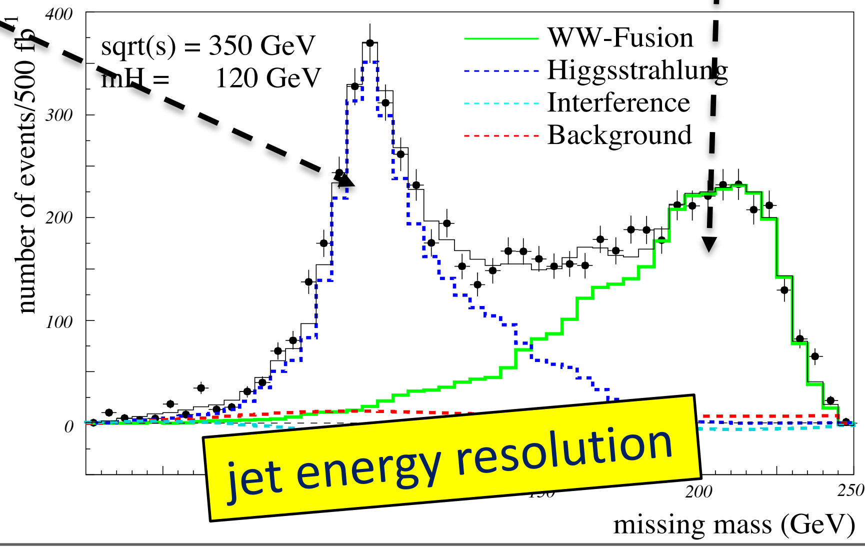
flavour tagging



momentum resolution



jet energy resolution

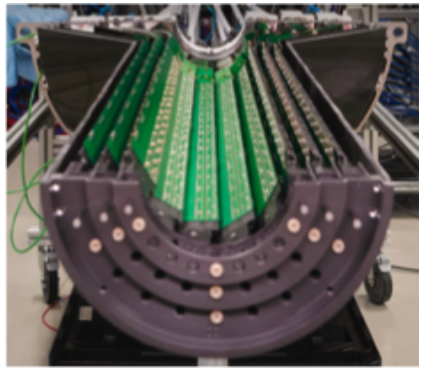
Detector elementss and technologies

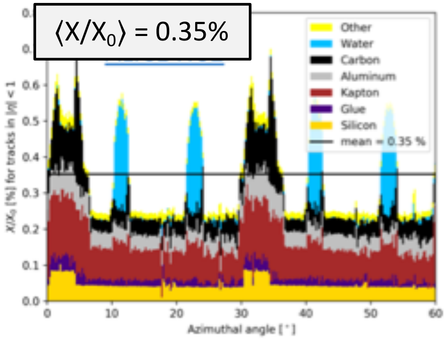
Vertex Detector

- Measurement of impact parameter, reconstruction of secondary vertices, flavour tagging, lifetime measurements
- Very strong development
  - **Lighter, more precise, closer**

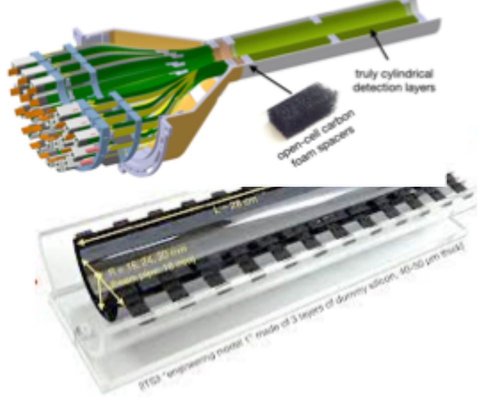
Strong ALICE Vertex detector development

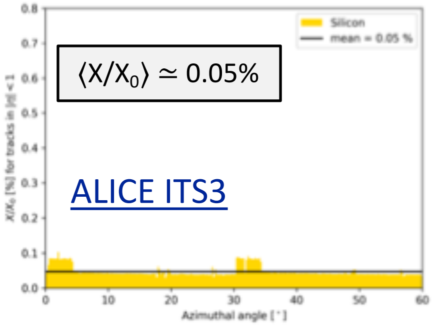
ITS2: installed in 2021





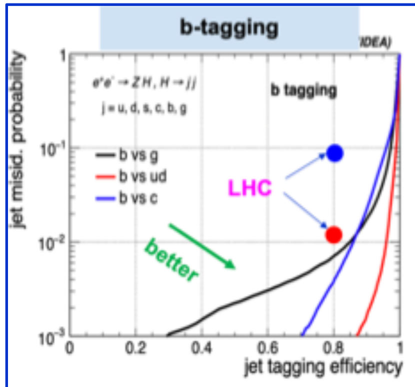
ITS3: installation 2027/2028



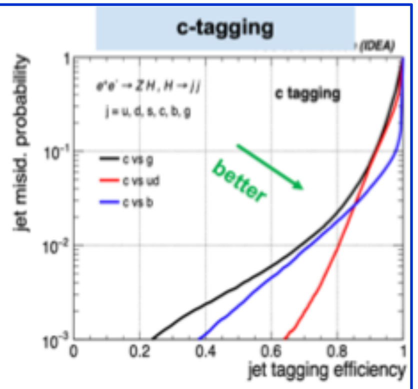


- Many conditions/requirements common between ALICE and FCC-ee
  - Moderate radiation environments
  - No need for picosecond timing
  - High resolution and low multiple scattering is key

- Heavy flavour tagging results (simulation)
  - ML based: large lifetimes, displaced vertices/tracks, large track multiplicity, non-isolated e/μ



WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.1%	2%
Medium	80%	0.7%	<0.1%	0.3%



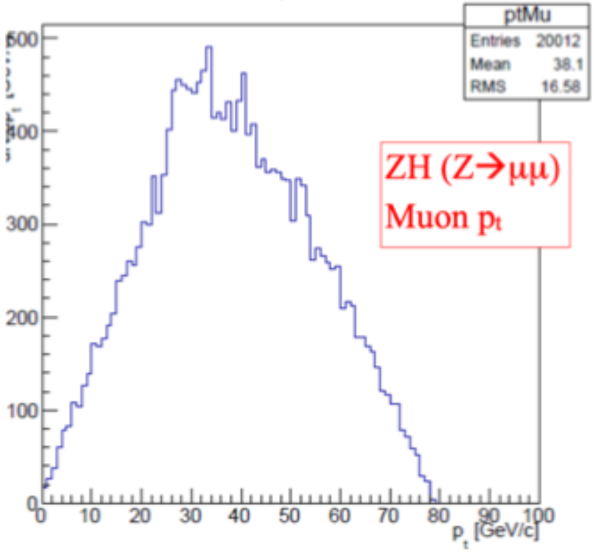
WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

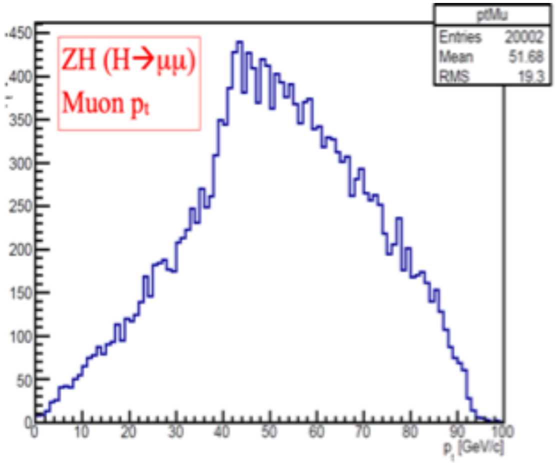
Very substantial improvement wrt LHC

ML-based - ParticleNet
F.Bedeschi, M.Selvaggi, L.Goukas, EPJ C 82 646 (2022) link

Tracking Systems - Momentum measurement

Particles from Higgs production process are generally of rather low momentum





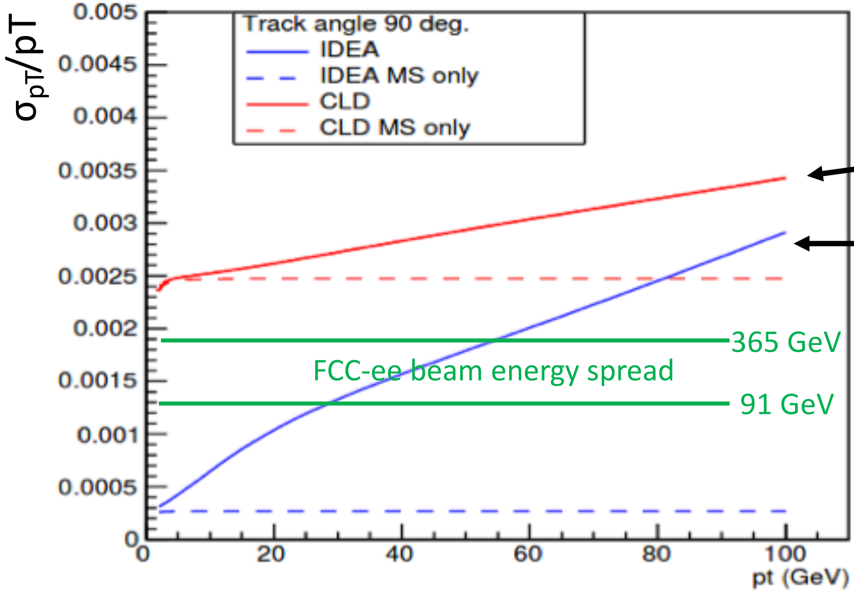
Momentum resolution tends to be multiple scattering dominated

⇒ Asymptotic resolution not reached

$$\sigma(p_T)/p_T^2 = a \oplus \frac{b}{p \sin\theta}$$

b → mult.scat

a → resolution



CLD: All-Si tracker with total material budget of 11%

IDEA: Drift Chamber as main tracking device with a material budget of 1.6%. Supplemented by VTX and Silicon "wrapper" surrounding drift chamber.

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0 \sin\theta}}$$

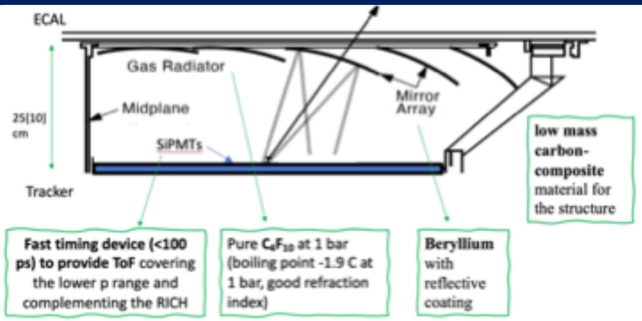
Thinning of Si sensors helps (only) as √ of thickness

⇒ Detector transparency more important than asymptotic resolution ⇐

https://doi.org/10.1016/j.nima.2018.08.078

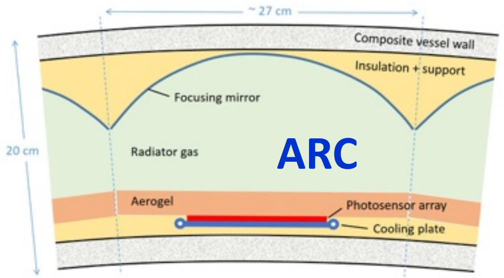
Particle Identification

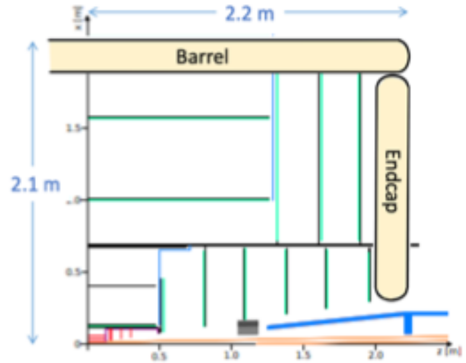
- **PID capabilities across a wide momentum range** is essential for flavour studies; will enhance overall physics reach
  - Example: important mode for CP-violation studies $B^0_s \to D^\pm_s K^\mp$ → require K/π separation over wide momentum range to suppress same topology $B^0_s \to D^\pm_s \pi^\mp$
- **E.g. IDEA drift chamber** promises >3σ π/K separation up to 50-100 GeV
  - Cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of $\delta T \lesssim 0.5$ ns
- **Time of flight (TOF) alone** δT of ~10 ps over 2 m (LGAD)
  - could give 3σ π/K separation up to ~5 GeV
- **Alternative approaches**, in particular (gaseous) **RICH** counters are also investigated (e.g. A pressurized RICH Detector – **ARC**)
  - → could give 3σ π/K separation from 5 GeV to ~80 GeV

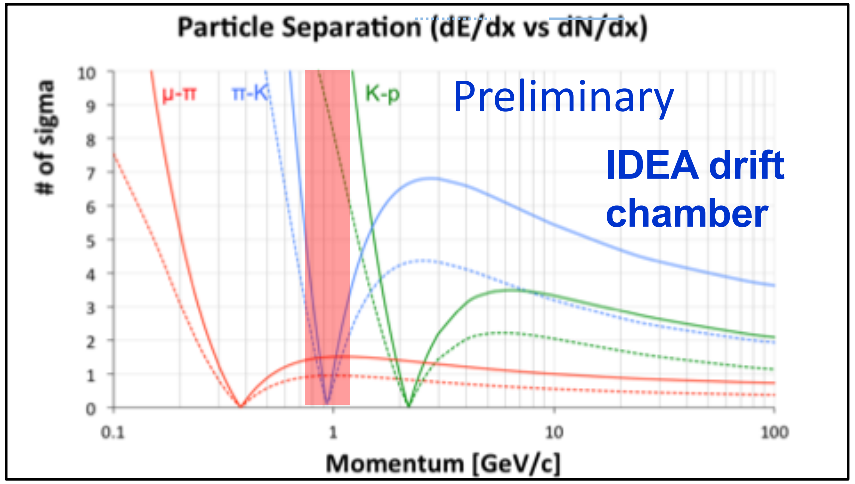


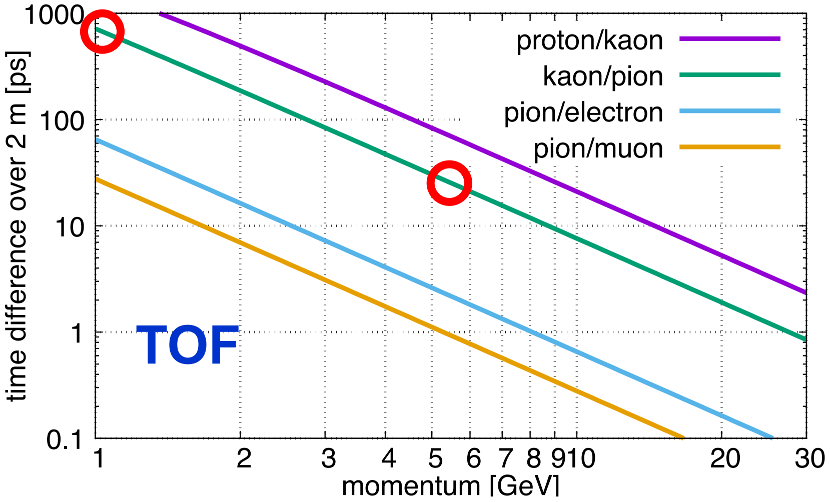
FCC Workshop, Feb. 2022

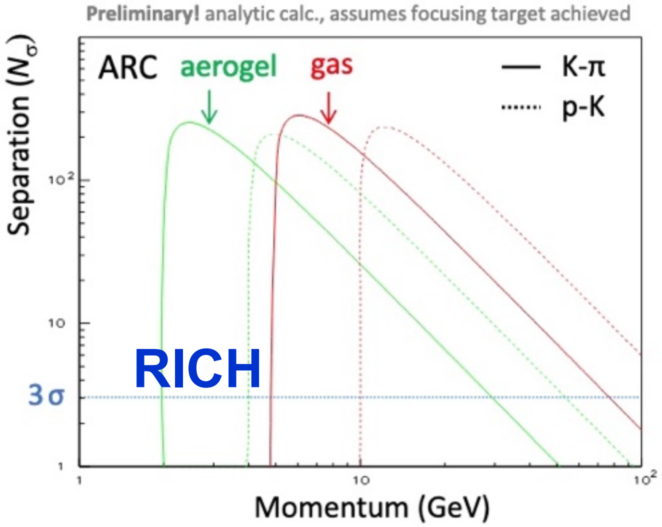
Possible RICH layout in an FCC-ee experiment











Calorimetry – Jet Energy Resolution

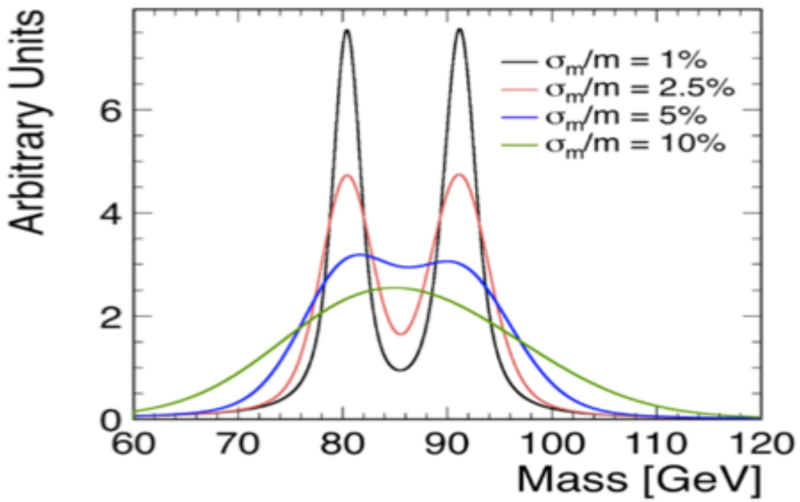
Energy coverage < 300 GeV : $22\ X_0$, 7λ
Precise jet angular resolution

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

⇒ **Mass reconstruction from jet pairs**

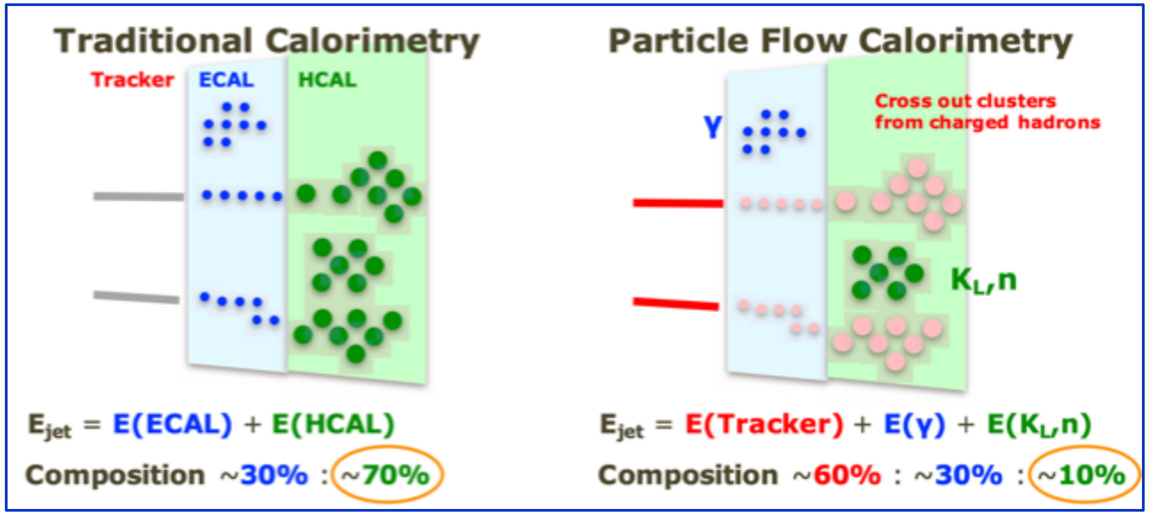
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to ννH
- HZ → 4 jets, tt events (6 jets), etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons



How to reach jet energy resolutions of 3-4% at 50 GeV:

- **Highly granular calorimetes**
- **Particle Flow Analysis techniques**
- The above possibly combined with techniques to correct for non-compensation (e/h ≠ 1), e.g. *dual readout*



High granularity !
Possibly combined with dual readout

Calorimetry

Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [45,20]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3 – 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5 – 6 % [30,50]	3 – 4 % [50]

Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists.

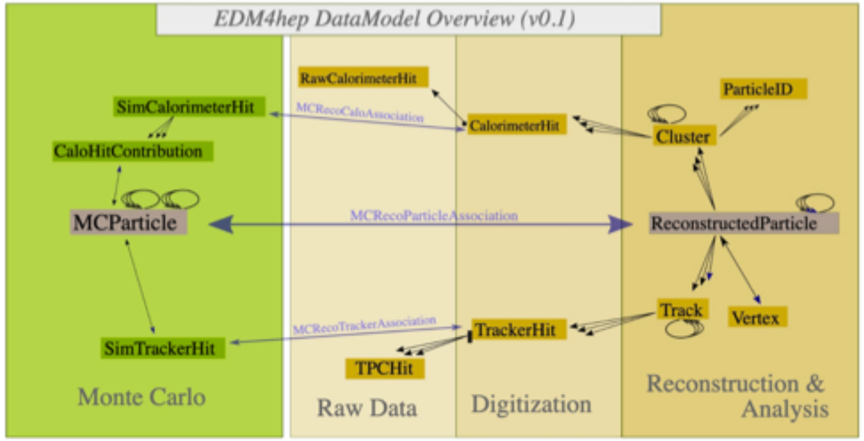
For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

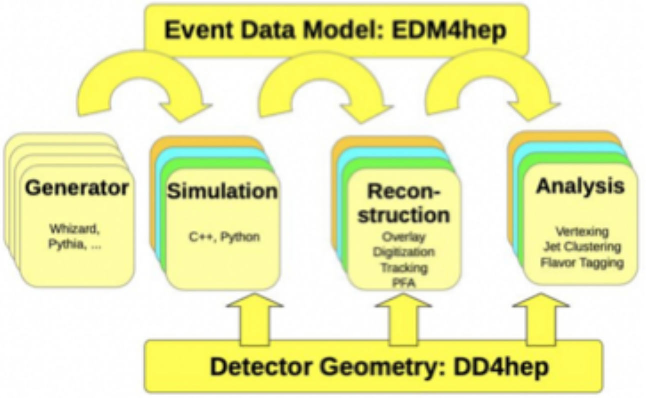
- **Excellent Jet resolution:** ≈ 30%/√E
- **ECAL resolution:** Higgs physics ≈ 15%/√E; but for heavy flavour programme better resolution beneficial → 8%/√E → 3%/√E
- **Fine segmentation for PF algorithm** and powerful **γ/π^0 separation** and measurement
- **Other concerns:** Operational stability, cost, …
- **Optimisation ongoing for all technologies:** Choice of materials, segmentation, read-out, …

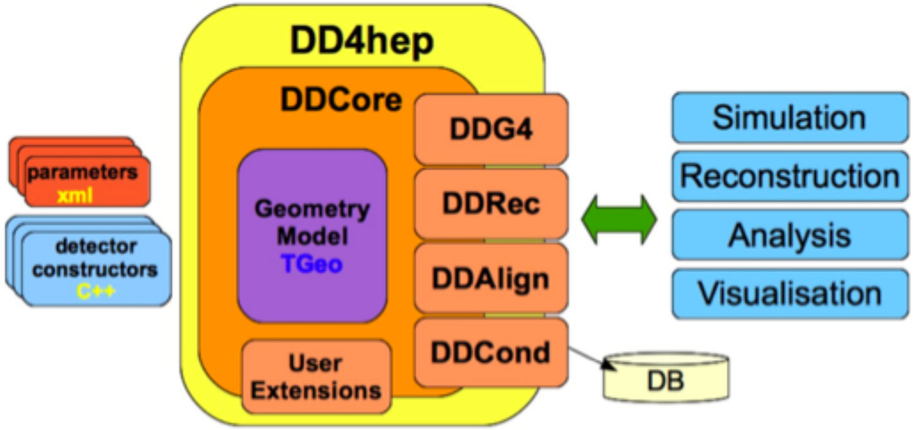
Software - Brief Overview

FCC Software System in a Nutshell

- FCC Software fully relies on **Key4hep**
  - Framework aimed at supporting all future collider studies
  - Centrally provides a set of useful HEP packages in a consistent stack
- **edm4hep** data format, relying on podio
- Chains of algorithms (Gen, Sim, Digi, Reco) orchestrated with Gaudi
- Detector description based on **DD4hep**
  - Generic detector description supporting full life cycle of experiment
  - Complete description
    - Geometry, material properties, readout, alignment, calibration, …
  - From user perspective
    - C++ for generic geometry structure construction
    - XML configuration for detector parameters
  - Facilitates **sub-detector combination**
    - Plug-and-play





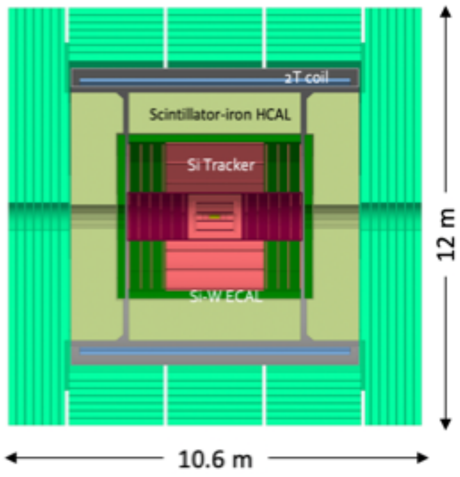


Material from and more details by Brieuc Francois in link

Proto Detectors

FCC-ee Proto Detectors - Overview

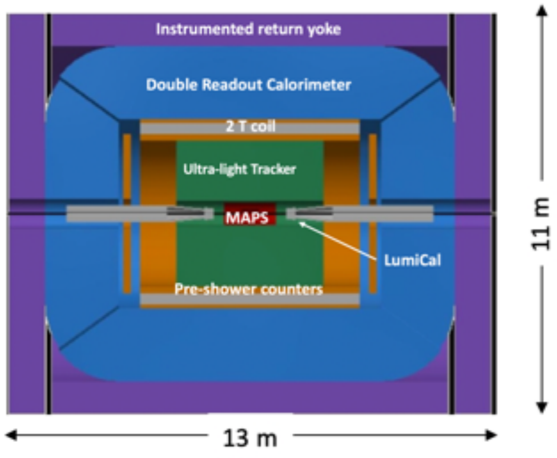
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker; CALICE-like calorimetry; large coil, muon system
- Engineering and R&D needed for
  - reduction of tracker material budget
  - operation with continous beam (no power pulsing: cooling of Si sensors for tracking + calorimetry)
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: timing and/or RICH?
  - …

CDR

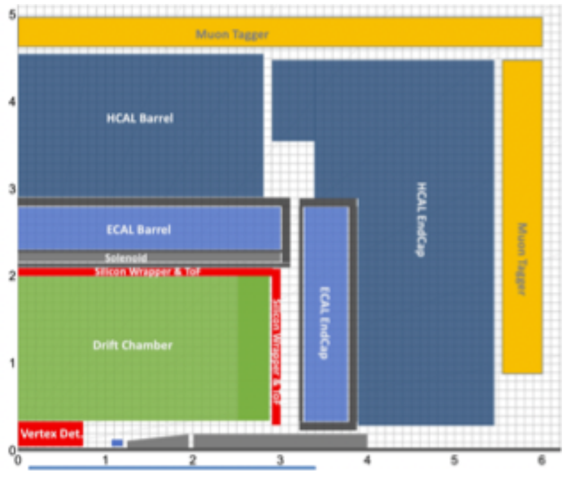
IDEA



- Less established design
  - But still ~15y history: ILC 4^{th} Concept
- Si vtx detector; ultra light drift chamber w powerfull PID; compact, light coil; monolitic dual readout calorimeter; muon system
  - Possibly augmented by crystal ECAL
- Active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based

new

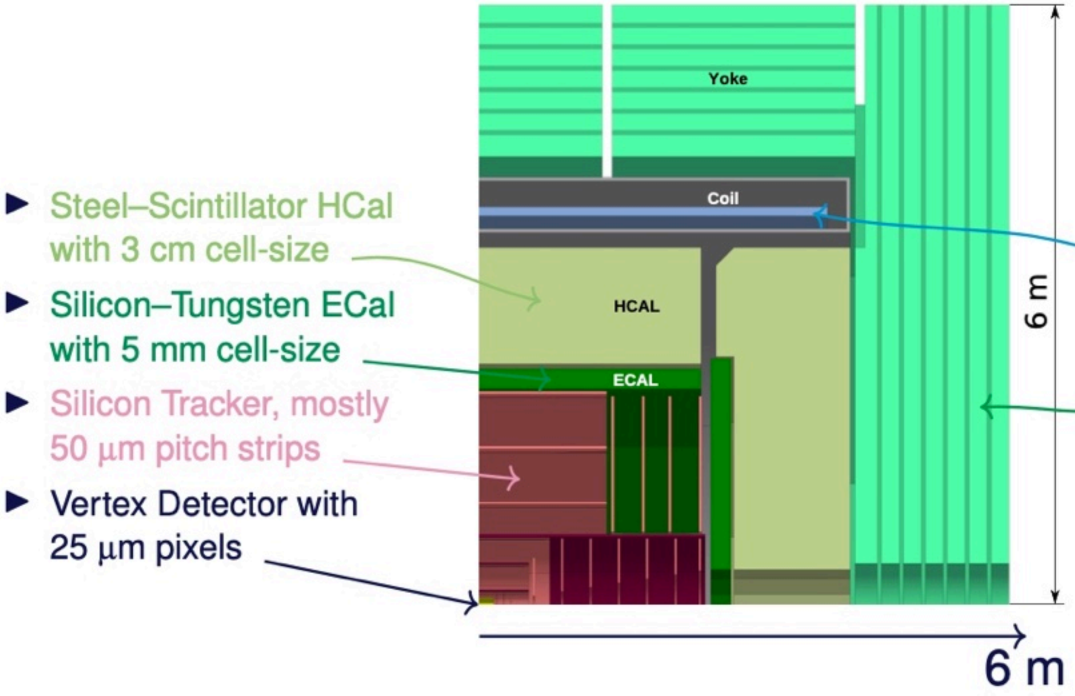


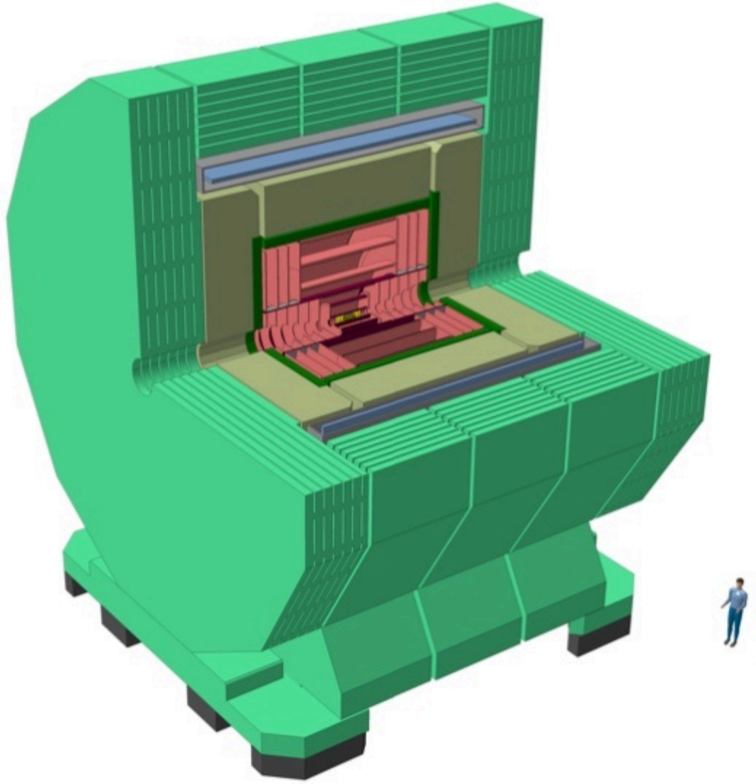
- A design in its infancy
- High granularity Noble Liquid ECAL is core
  - Pb+LAr (or denser W+LCr)
- Drift chamber; CALICE-like HCAL; muon system.
- Coil inside same cryostat as LAr, possibly outside ECAL
- Active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

CLD Detector Concept

General purpose detector for Particle Flow reconstruction

- development of CLICdp detector concept developed for CLIC



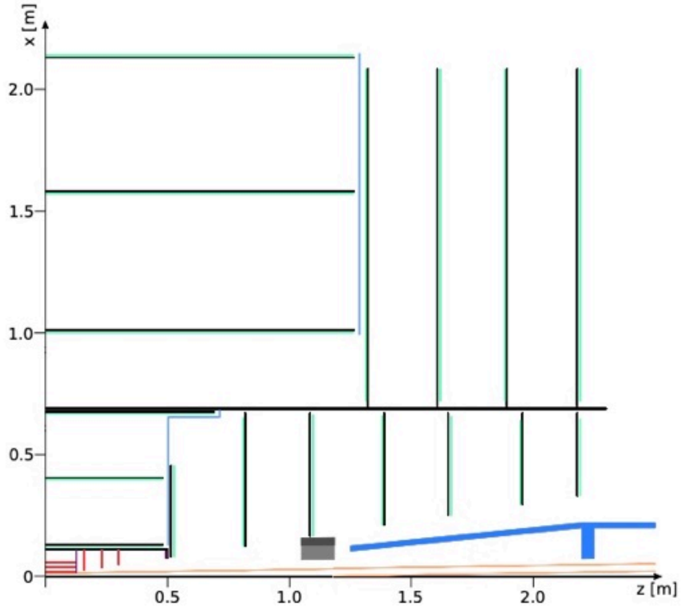


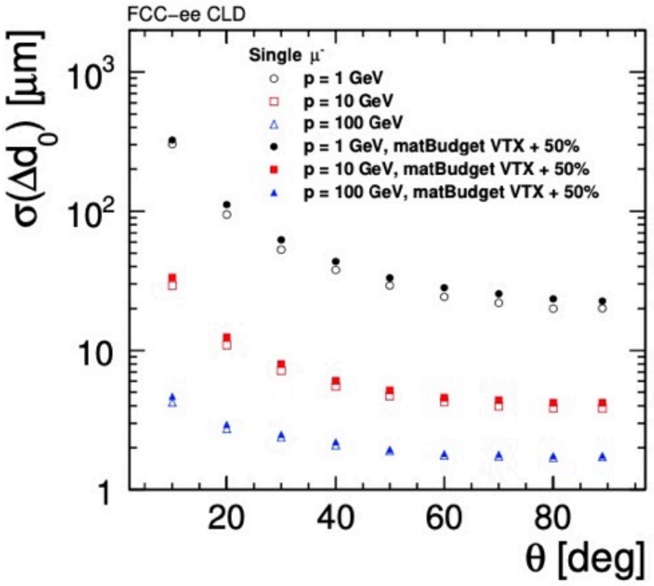
https://arxiv.org/abs/1911.12230 and FCC CDS vol. 2

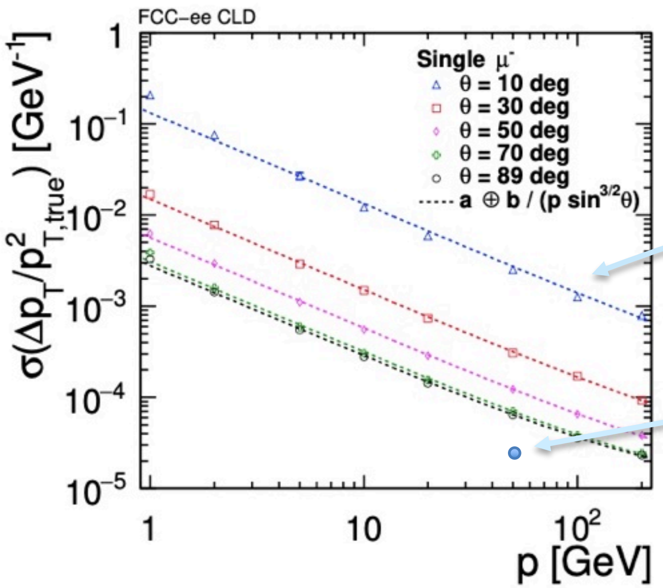
2 Tesla solenoidal field (solenoid ourside calorimetry, R=3.7m, L=7.4 m)
Return yoke contains muon system with 6 (7 in barrel) equidistant layers

CLD Vertex Detector and Si Tracker

- Silicon vertex detector: precise impact parameter measurement/vertex reconstruction
  - 25 x 25 µm pixels, 50 µm thickness, 3 µm single point resolution
  - Double layers (0.3% X_0 per detection layer), R_{in} = 17.5 mm (-> 12.5 mm with new beam pipe)
- Inner and Outer Silicon Tracker
  - 3 short and 3 long barrel layers, 7 inner and 4 outer endcaps
  - 200 µm sensor thickness, pixels for inner tracker disk, elsewhere strips
  - At least 8 hits for θ > 8.5°
  - Material budget: 1.1 – 2.2 % X_0 per layer (including overlaps)

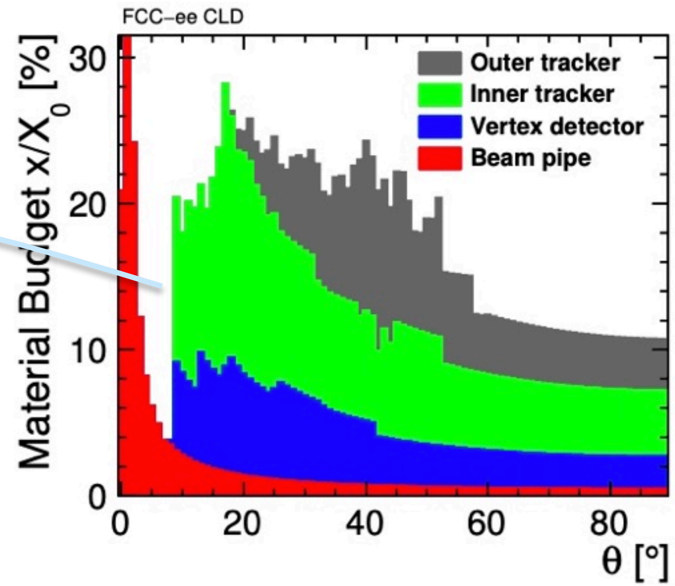






Multiple scattering limited
→ lighter Si tracker!?

$\sigma_{p_T}/p_T \simeq 1.5 \times 10^{-3}$ @ 50GeV (BES)

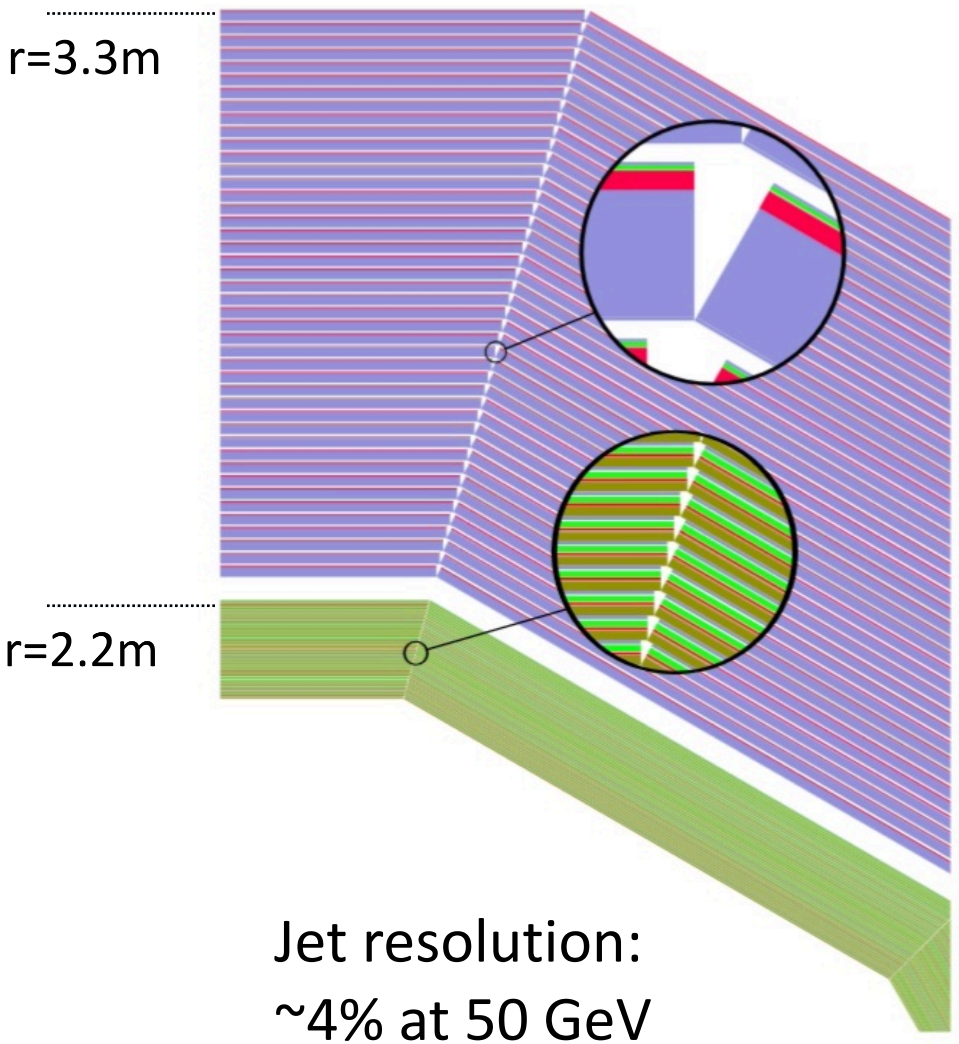


CLD Calorimetry

- ECAL (Si/W)
  - 40 layers, 1.9 mm tungsten absorber, 22 X_0
  - 0.5 mm thick Si sensors with 5 x 5 mm^2 granularity
  - ECAL optimisation studies

$$\frac{\sigma}{E} \approx \frac{16\,\%}{\sqrt{E}}$$

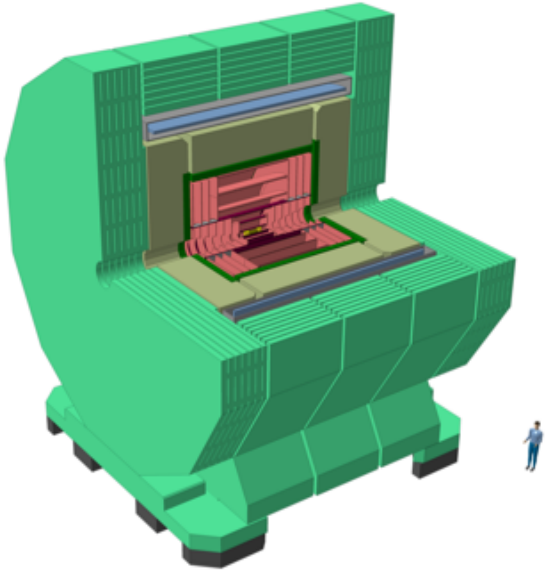
- HCAL (Scintillator/Steel)
  - 44 layers, 19 mm steel absorber, 5.5 (+1) λ
  - 3 mm thick scintillator tiles with 30 x 30 mm^2 granularity



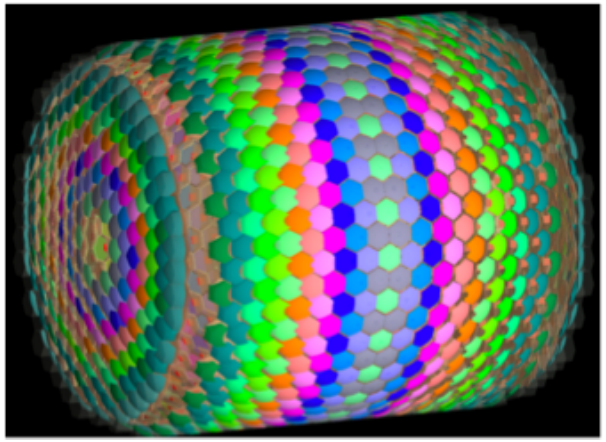
Jet resolution:
~4% at 50 GeV

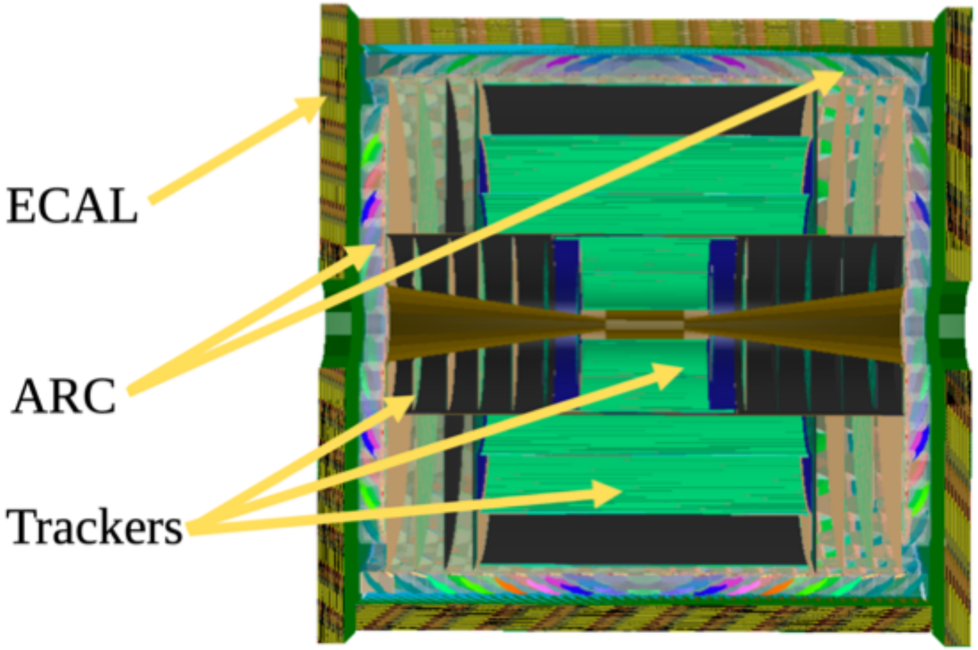
CLD Software Implementation Status

- All CLD sub-detectors implemented in DD4hep
- Full simulation + reconstruction workflow available
  - Simulation through ddsim
  - Reconstruction through *Marlin*
    - Background overlay, digitization, conformalTracking, ParticleFlow (PandoraPFA), vertexing, and flavour tagging
    - Inhereted from ILD/CLICdet
- *Marlin* reconstruction based on LCIO data format but can be integrated in EDM4hep Gaudi workflows through *MarlinWrappers* + data format translation



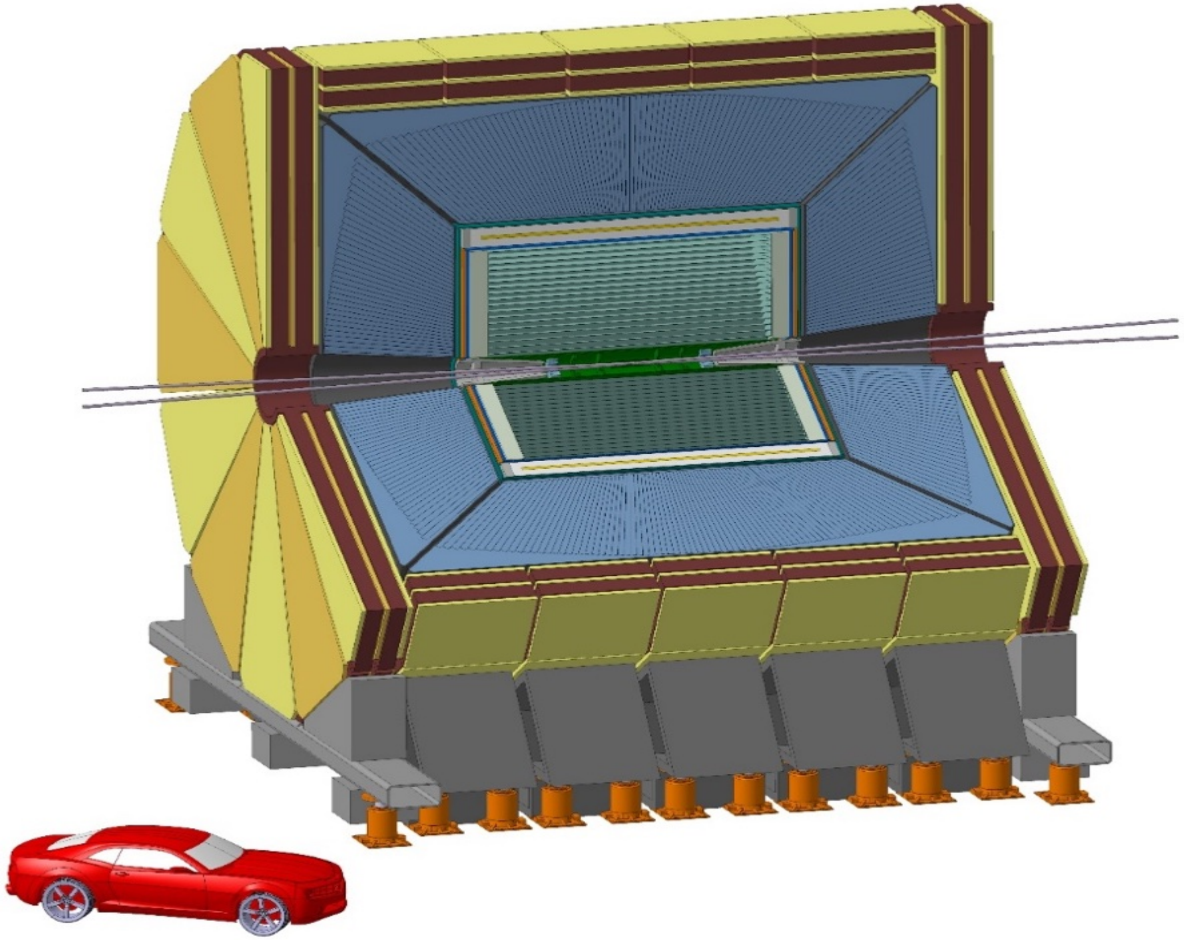
- RICH ARC detector finding its way into CLD full simulation





IDEA Detector Concept

IDEA, Innovative Detector for e^+e^- accelerator



FCC CDR vol. 2

Designed specifically for circular e^+e^- collider (FCC/CEPC)

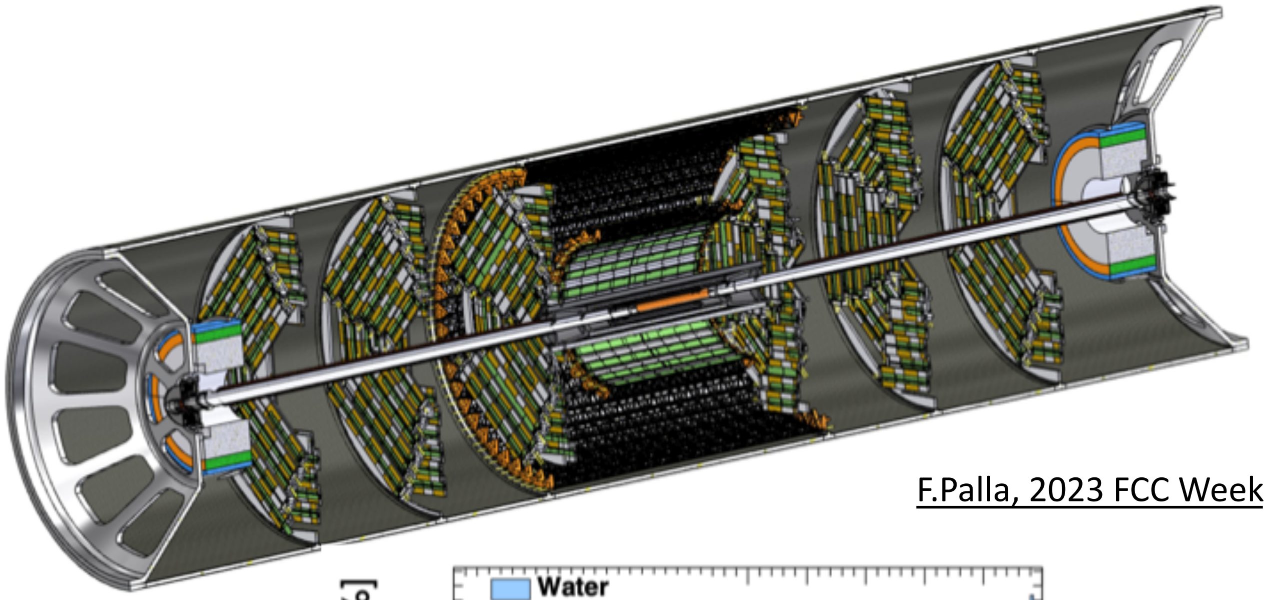
- Silicon vertex detector
  - 5 MAPS layers, 17-340 mm
- Short-drift, ultra-light wire chamber
  - 112 layers, L= 400 cm, R = 35-200 cm
- Silicon ”wrapper”
  - Precise spacepoint measurement in front of calorimeter
- Thin and light solenoid coil inside calorimeter system
  - Coil: 2 Tesla, R = 2.1-2.4 m
  - 0.76 X_0 , 0.19 λ_{int}
- Dual-readout calorimeter
  - 2 m depth, 7 λ_{int}
  - Particle flow reconstruction
  - Option: crystal ECAL (in front of coil) for better EM resolution
  - If no crystals: pre-shower detector in front of DR calorimeter
- Muon system
  - 3 layers of µ-RWELL detectors in return yoke

IDEA Vertex Detector

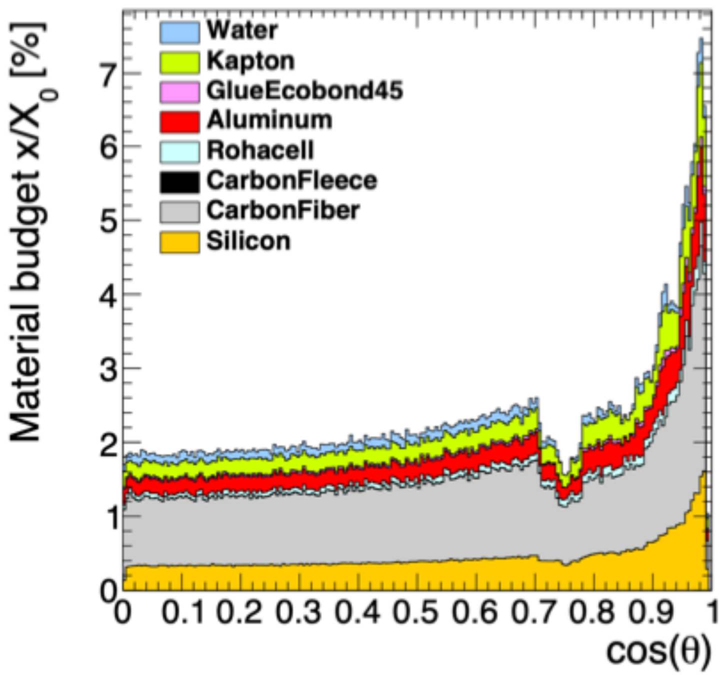
Vertex detector

Inspired by Belle II (and ALICE ITS) based on DMAPS technology, using ARCADIA R&D program

- Inner Vertex Detector
  - Modules of 25 x 25 µm pixel size, 50 µm thick
  - 3 barrel layers at 13.7, 22.7, 33 mm
    - 0.3% X_0 per layer
  - Point resolution of ~3 mm
- Outer Vertex Detector
  - Modules of 50 x 150 µm pixel size, 50 µm thick
  - 2 barrel layers at 130, 315 mm, 2 x 3 disk layers
    - 1% X_0 per layer
- Performance
  - Efficiency of ~100%
  - Extremely low fake hit rate

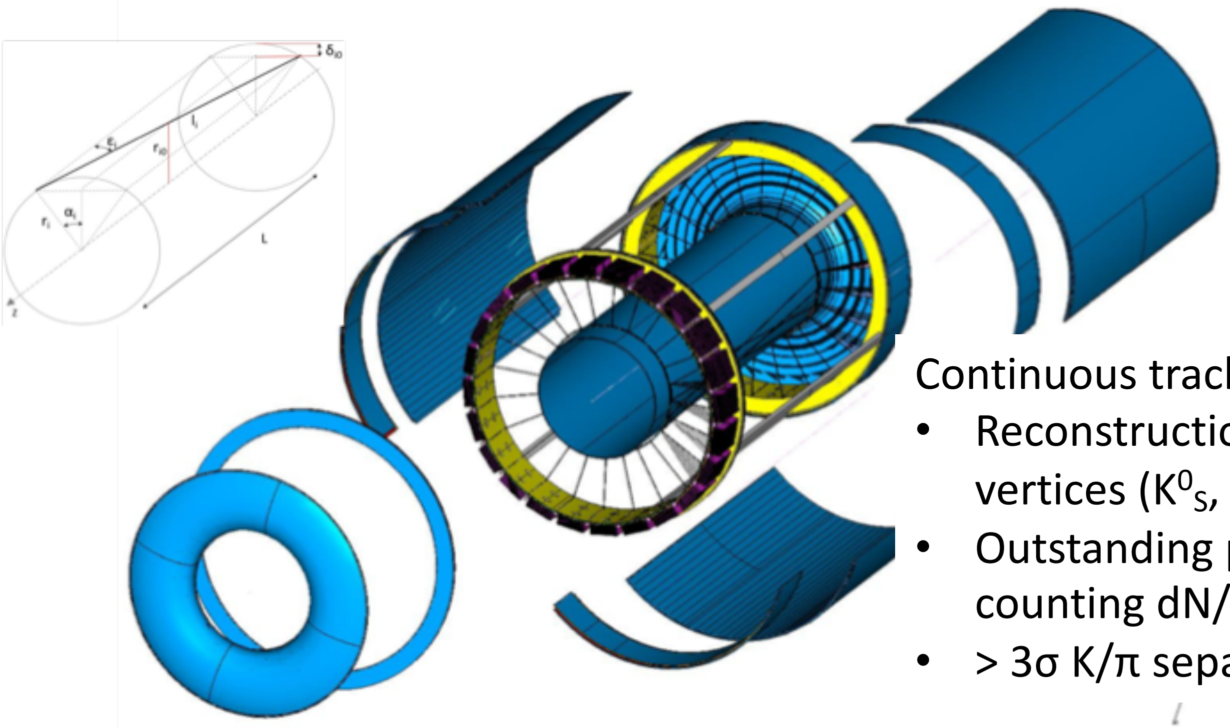


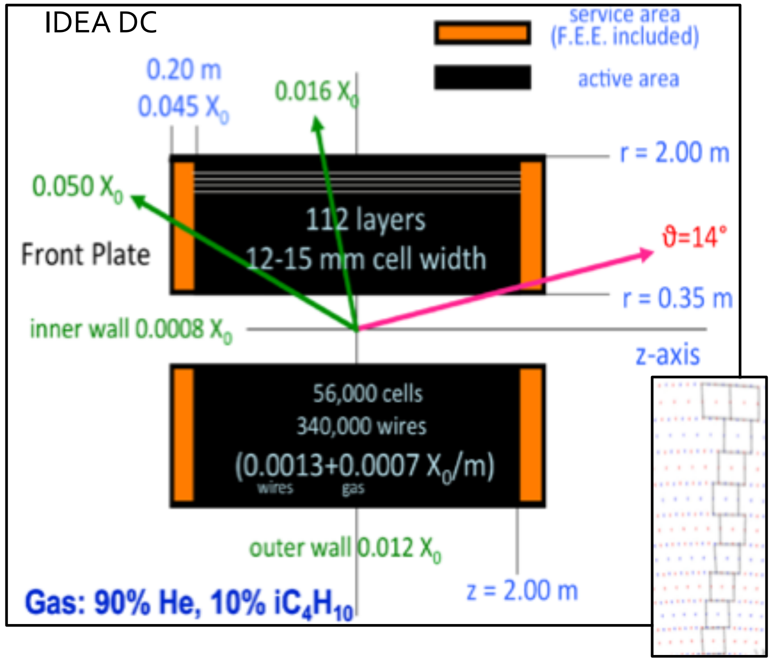
F.Palla, 2023 FCC Week



Extremely transparent Drift Chamber

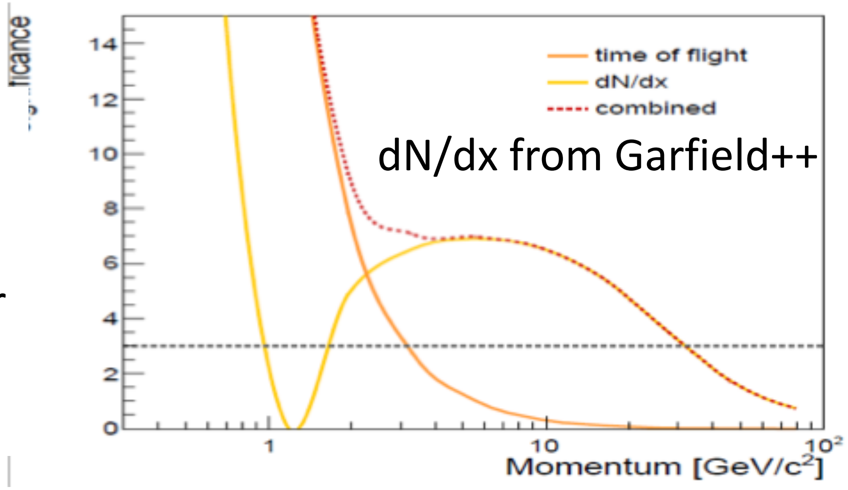
- Gas: 90% He – 10% iC_4H_{10}
- Radius: 0.35 – 200 m
- Total thickness: 1.6% of X_0 at 90°
  - Tungsten wires dominant contributor
- 112 layers for each 15° azimuthal sector
- Max drift time: 350 ns



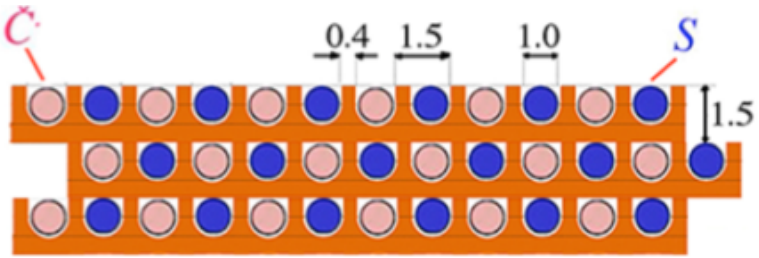


Continuous tracking:

- Reconstruction of far-detached vertices (K^0_S, Λ, BSM, LLPs)
- Outstanding particle ID via cluster counting dN/dx or dE/dx
- > 3σ K/π separation up to 35 GeV



Dual Readout Calorimetry



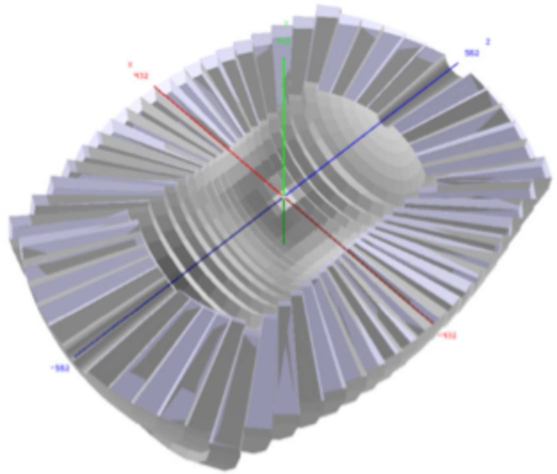
- Scintillation fibres
- Cherenkov fibres

- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (C)
- Calibrate both signals with e⁻
- Unfold event by event f_{em} to obtain corrected energy

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

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

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with: } \chi = \frac{1-(h/e)_S}{1-(h/e)_C}$$



Full GEANT4 simulation:

Single hadron:

$$\frac{\sigma}{E} = \frac{31\%}{\sqrt{E}} + 0.4\%$$

Electromagnetic:

$$\frac{\sigma}{E} = \frac{13.0\%}{\sqrt{E}} + 0.2\%$$

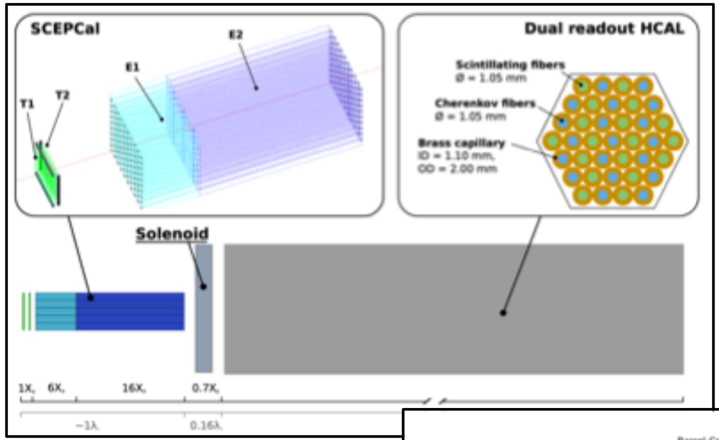
Crystal option:

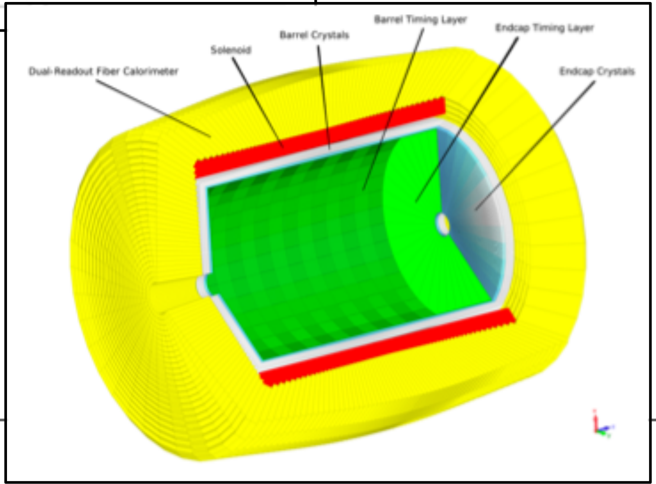
20 cm $PbWO_4$

$$\frac{\sigma}{E} \approx \frac{3\%}{\sqrt{E}}$$

Crystal option

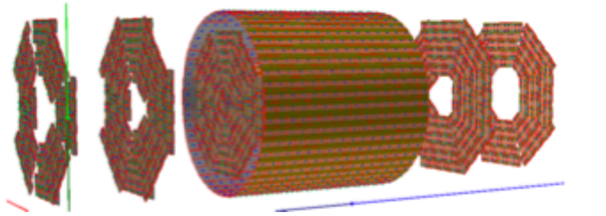
- Crystal ECAL in front of DR fibre calorimeter
- PbWO crystals – two longitudinal layers
  - 10 × 10 × [50 (front) + 150 (rear)] mm^3
  - Dual readout via separation of light spectrum (S vs. C)
- $\sigma_{EM} \approx 3\% / \sqrt{E}$



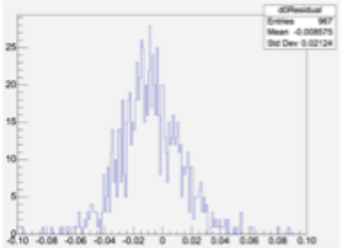


IDEA Software Implementation Status

- Detailed DD4hep implementation of vertex detector being finalized
  - Sim, Digi, and Reco available
  - Silicon wrapper will be implemented based on the same detector builders

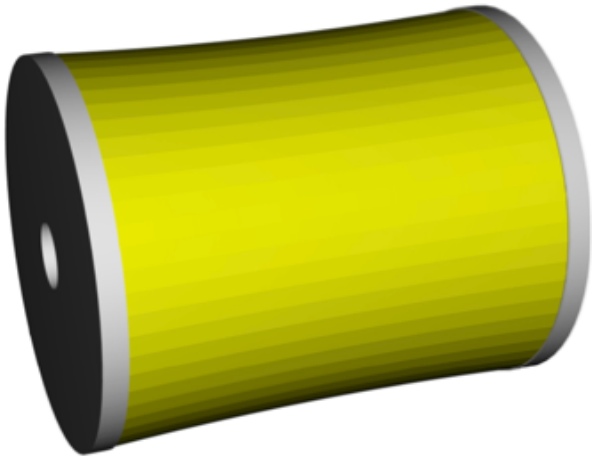


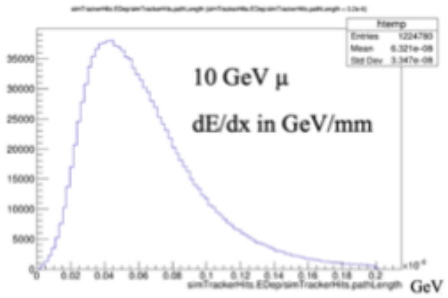
A.Ilg, FCC Week 2023



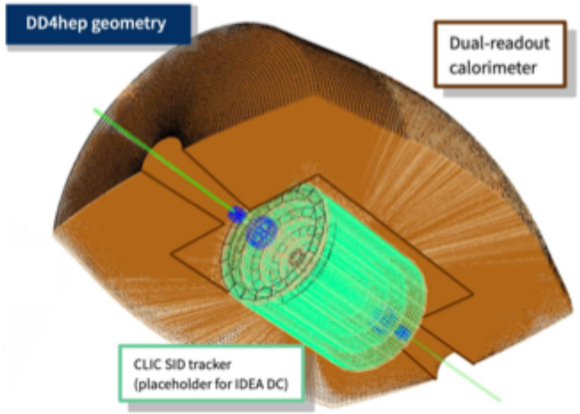
D_0 resolution in mm.

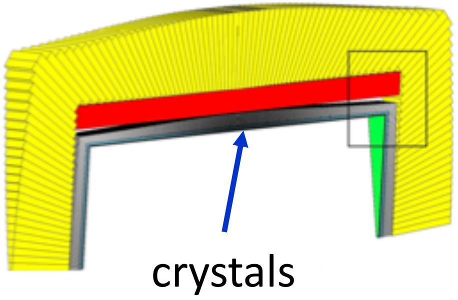
- Drift Chamber
  - Originally implemented in in plain Geant
  - Detailed DD4hep implementation under debugging and validation
    - Carbon fibre/Cu walls, sense + field wires, Au coating, Gas:He_90Isob_10
  - Next steps
    - Implementation of DCH reconstruction into Key4hep
    - Implementation of combined VXD + DCH tracking
      - Options: MarlinTracker, ACTS, ILD approach, BES III solution, native DCH tracking algorithm, …





- Dual readout calorimeter fully implemented in key4hep
  - Geometry, simulation, digitization, reconstruction
  - Next steps: integrate geometry in central repository, CPU optimisation
- Crystal ECAL detector description implemented in DD4hep
  - WIP: port code to central dual-readout repositiry, digi, reco, ParticleFlow





Noble-Liquid ECAL Based Detector Concept

- Vertex Detector
  - MAPS or DMAPS possibly with timing layer (LGAD)
  - Possibly ALICE ITS3 like?
- Drift Chamber
  - ± 2.5 m active
- Silicon wrapper + ToF:
  - MAPS or DMAPS possibly with timing (LGAD)
- High Granularity ECAL
  - Noble Liquid + Pb or W
  - Particle Flow reconstruction
- Solenoid B=2T outside ECAL, sharing cryostat with ECAL
  - Light solenoid coil = 0.75 X_0
  - Low-material cryostat < 0.1 X_0
- High Granularity HCAL / Iron yoke
  - Scintillator + Iron (particle flow reconstruction)
    - SiPMs directly on scintillators or
    - TileCal: WS fibres, SiPMs outside
- Muon System
  - Drift chambers, RPC, Micromegas

M.Aleksa @ FCC Week, 2022

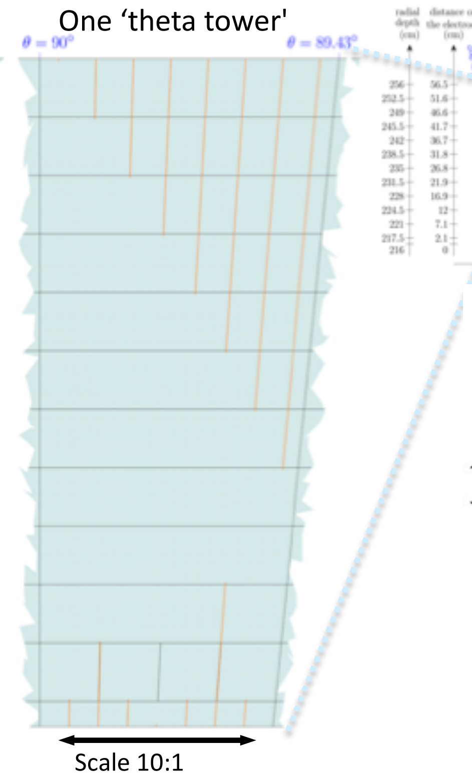
High Granularity Noble-Liquid Calorimeter

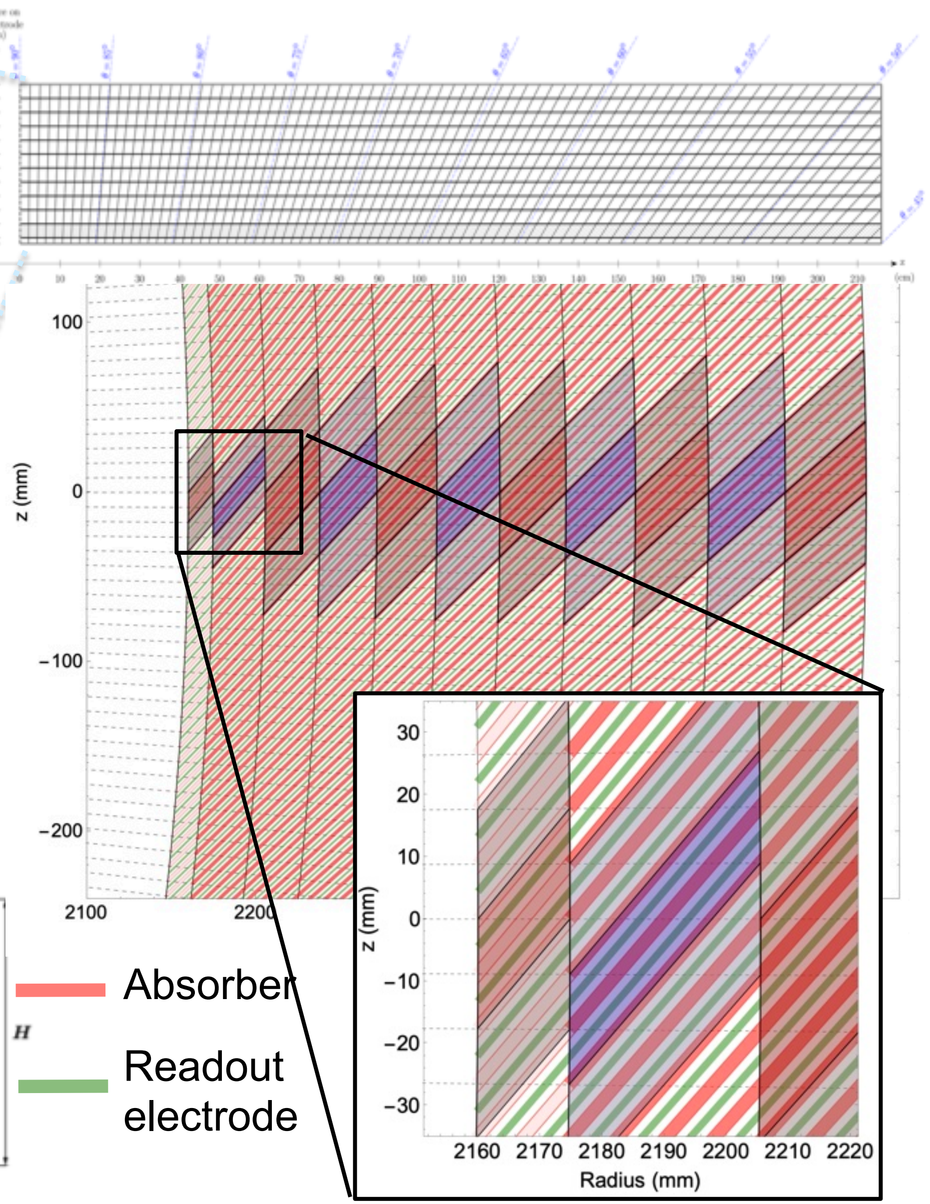
Baseline design

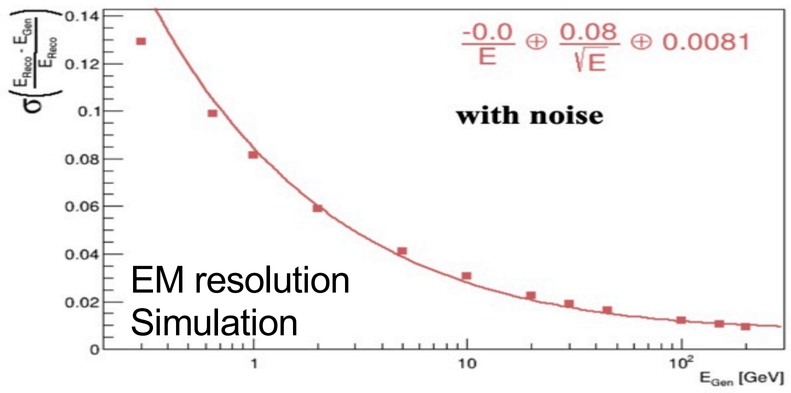
- 1536 straight inclined (50.4°) 1.8mm Pb absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm LAr gaps
- 40 cm deep (≈ 22 X_0)
- Segmentation:
  - 11 longitudinal compartments
  - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells
  - $\Delta\phi$ = 8 mrad

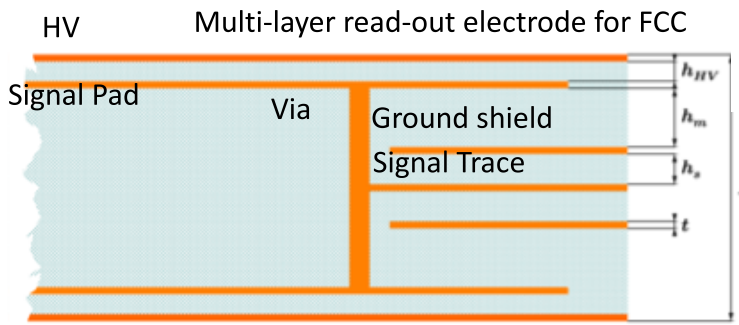
Possible options

- LKr or Lar, W or Pb absorbers
- Absorbers with growing thickness
- Al or carbon fibre cryostat
- Warm or cold electronics





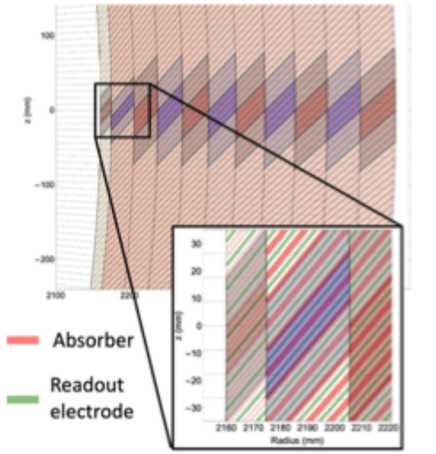


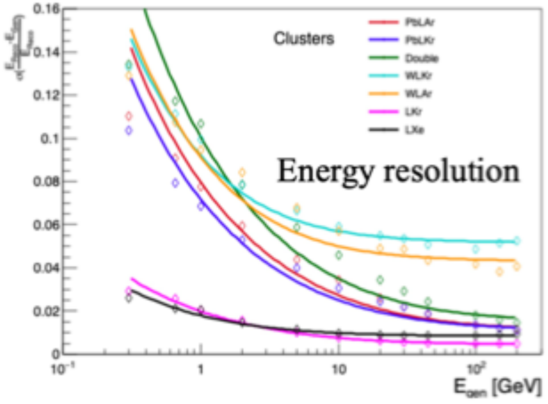


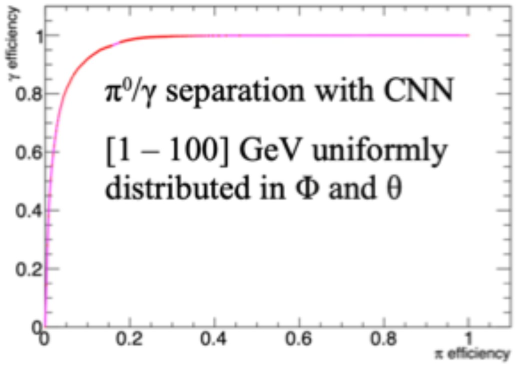
Software Implementation Status

Current detector description in DD4hep

- Simplified VXD (CLD), to be updated to the detailed IDEA one
- Simplified drift chamber (no tracking available)
- **ECAL barrel fully implemented in Key4hep**
  - Inclined absorber plates that can be made trapezoidal
  - Cryostat, services, and solenoid material budget included
  - Calibration, noise, and clustering available as edm4hep native to Gaudi algorithms
  - Plug-and-play complant
    - Automatic rescaling upon geometry changes
  - First performance studies performed
  - Need Particle Flow to optimize granularity, requires tracks
    - Temperary hack: prepared detector config with CLD + LAr ECAL
    - Working on PandoraPFA integration
- ECAL endcaps under validation







B.Francois @ FCCWeek, 2023

Outlook

- FCC-ee has an enormous physics potential
  - Unprecedented factory for Z, W and Higgs bosons; for top, beauty, and charm quarks; and for tau leptons
  - Possibly also factory for BSM particles !!
- Instrumentation to fully exploit the physics potential is challenging and exciting
  - FCC-ee can host (up to) four experimental collaborations
- For next ESUPP, need to demonstrate that experimental challenge can be met by several Detector Concepts
- Work currently ongoing on three proto detectors
  - CLD, IDEA, Noble Liquid ECAL based concept (recently named Allegro)
- Work ongoing to implement proto detectors and their sub-detectors fully into Key4hep framework
  - Framework allows study of alternate detector configurations via plug-and-play

- Mailing lists:

  FCC-PED-DetectorConcepts@cern.ch

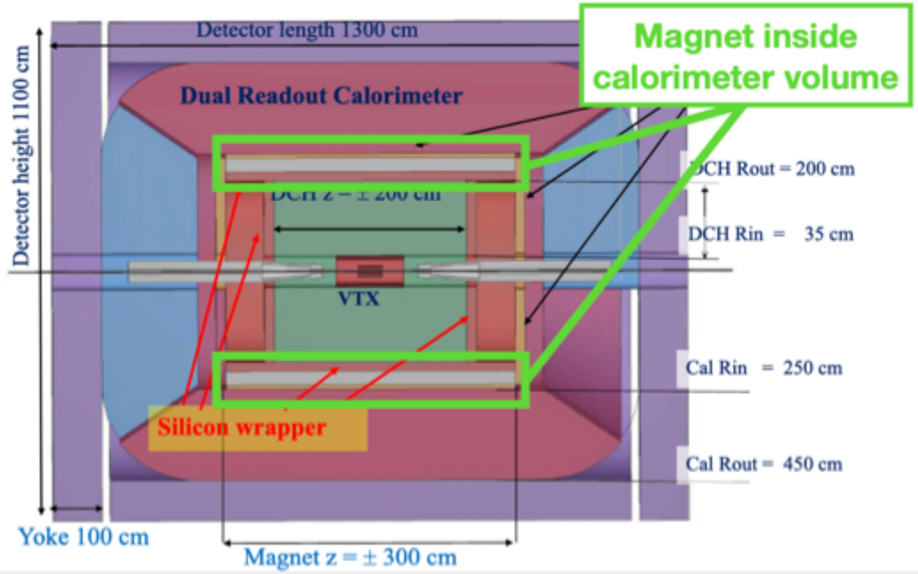
  FCC-PED-SoftwareAndComputing@cern.ch

Extras

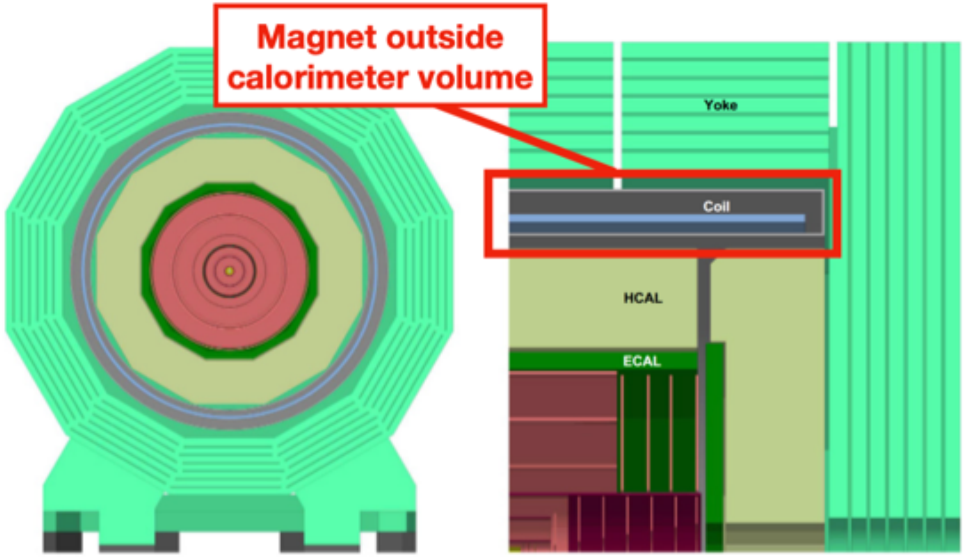
Solenoid Magnet

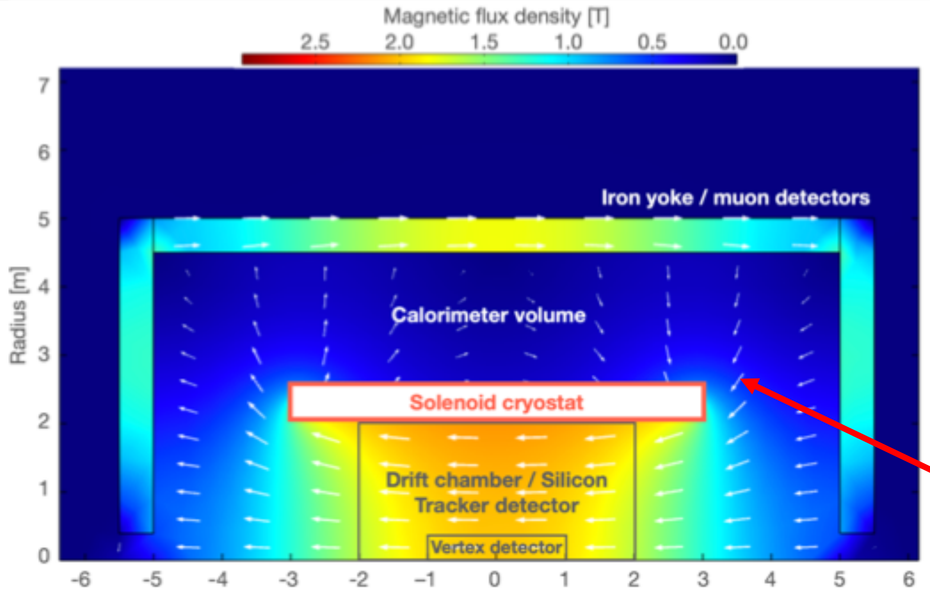
Nikkie Deelen,, FCC Workshop Feb. 2022

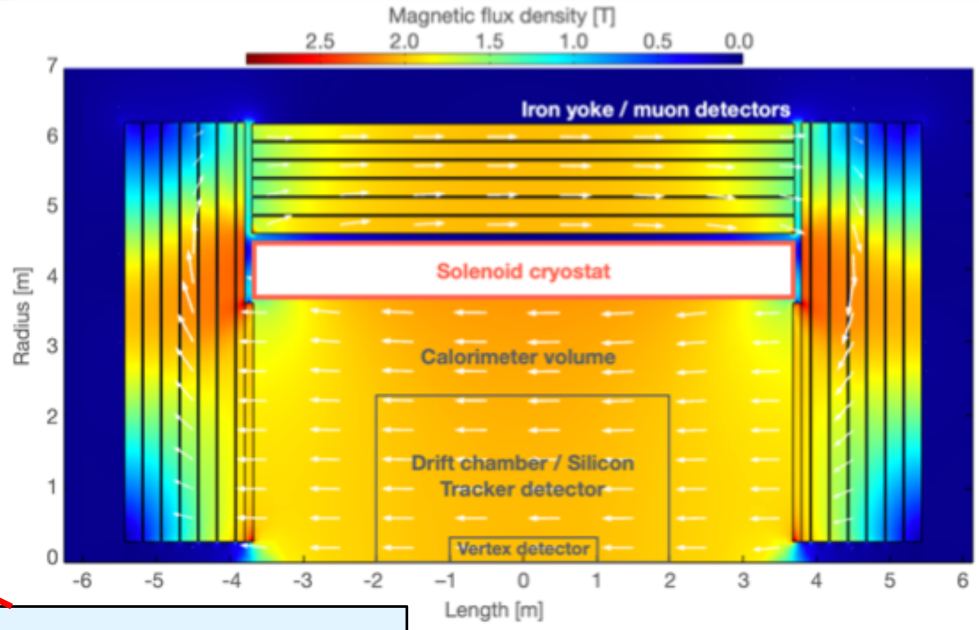
International Detector for Electron-positron Accelerators



CLIC-Like Detector







Transparency of the cold mass: 0.76 X_0
Energy density: ~14 kJ/kg [2]

For crystal IDEA:
- Hybrid solution; coil between ECAL and HCAL