The IDEA detector concept for FCC-ee

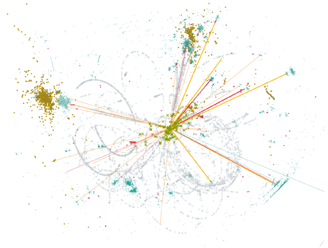
2025 European Physical Society Conference on High Energy Physics

Armin Ilg[1]

on behalf of the IDEA Study Group and FCC

[1]University of Zürich

07.07.2025



Circular collider with 90.7 km circumference machine to serve HEP for the rest of the century

The Future Circular Collider (FCC) integrated programme

University of Zurich[UZH]

Circular collider with 90.7 km circumference machine to serve HEP for the rest of the century

FCC-ee: e^+e^- collisions at highest luminosities $\rightarrow$ *intensity frontier* $\leftarrow$ **Focus on this!**

FCC-hh: *hh* collisions at $\sqrt{s} \geq 84\,\text{TeV}$ $\rightarrow$ *energy frontier*

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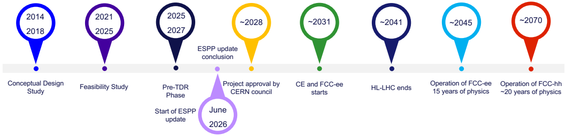

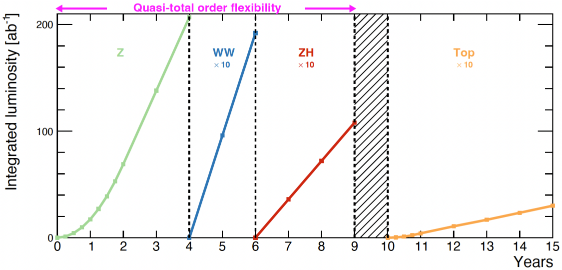

Baseline operation model for FCC-ee [2]

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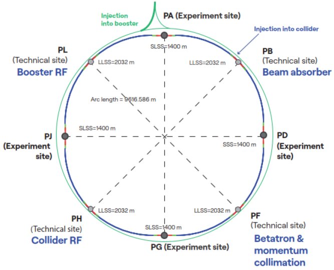
FCC-hh: *hh* collisions at $\sqrt{s} \geq 84$ TeV → *energy frontier*



FCC-ee layout with four collision points and four technical insertions [1]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$!
H: $1.78 \cdot 10^6$ HZ, 125k WW → H
Top: $1.9 \cdot 10^6$ $t\bar{t}$

University of Zurich[UZH]

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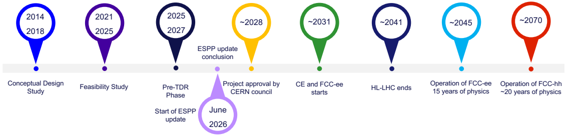

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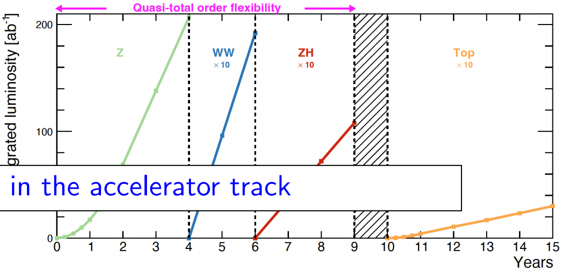
FCC-hh: ... *frontier*

See S. Kostoglou's talk today at 14:24 in the accelerator track



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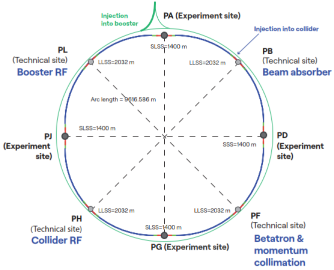

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Beam pipe and vertexing

Example: $B^0 \rightarrow K^{*0}\tau^+\tau^-$, BR improvement from $\mathcal{O}(10^{-3})$ down to SM value of 10^{-7} [3]

- Material budget of beam pipe $< 0.5\%\ X_0$
- Material budget of vertex $< 1\%$

$\rightarrow$ $\sigma_{d_0} = 3 \oplus 15/(p \sin^{3/2}\theta)\mu\text{m}$

Light and precise vertex detector

FCC-ee detector requirements in a nutshell

University of Zurich[UZH]

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Example: δM_{H} down to 4 MeV, $\delta\Gamma_{\mathrm{Z}}$ down to 15 keV [4]

$\rightarrow \quad \sigma_p/p < 0.1\,\%$ for $\mathcal{O}(50)$GeV tracks

Example: $H \rightarrow s\bar{s}$ [5], $b \rightarrow s\nu\bar{\nu}$

$\rightarrow \quad 3\sigma\ K/\pi$ separation for $p < 40$ GeV

Superb momentum resolution
Strong particle identification capabilities

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Superb momentum resolution

Strong particle identification capabilities

Electromagnetic calorimeter

Example: $Z \to \nu_e\bar{\nu}_e$ coupling [6], $B_s \to D_s K$

$\to$ $\sigma_E/E = 3\,\%/\sqrt{E}$

Example: τ polarisation [7]

$\to$ $\Delta x \times \Delta y = 2 \times 2\,\text{mm}^2$

High granularity and tiny EM resolution

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High granularity and tiny EM resolution

Hadronic calorimeter

Example: $H \to s\bar{s}/c\bar{c}$ [8]

$\to$ $\sigma_E/E = 30\,\%/\sqrt{E}$

$\to$ $\Delta x \times \Delta y = 2 \times 2\,\text{mm}^2$

High granularity, good hadronic resolution

FCC-ee detector requirements in a nutshell

Beam p … **(PID)**

Example … down to

from $\mathcal{O}($ …

- Mat … s
- Mat …

$\rightarrow$ σ_{d_0} … /

Light an … *es*

	Aggressive	Conservative	Comments
Beampipe	$X/X_0 < 0.5\%$	$X/X_0 < 1\%$	$B \to K^*\tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15\,/\,(p \sin^{3/2}\theta)\,\mu m$ $X/X_0 < 1\%$	–	$B \to K^*\tau\tau$ R_c
	$\delta L = 5\,\text{ppm}$	–	$\delta\tau_\tau < 10\,\text{ppm}$
Tracking	$\sigma_p/p < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\sigma_p/p < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4\,\text{MeV}$ $\delta\Gamma_Z = 15\,\text{keV}$ $Z \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1\,\text{mrad}$	$\delta\Gamma_Z(\text{BES}) < 10\,\text{keV}$
ECAL	$\sigma_E/E = 3\%/\sqrt{E}$	$\sigma_E/E = 10\%/\sqrt{E}$	$Z \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y =$ $2 \times 2\,\text{mm}^2$	$\Delta x \times \Delta y =$ $5 \times 5\,\text{mm}^2$	τ polarisation boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100\,\mu\text{m}$, $\delta R_{\text{min}} = 10\,\mu\text{m}\ (\theta = 20°)$	In-situ constraint with dilepton/diphoton events	alignment tolerance for $\delta\mathcal{L} = 10^{-5}$ with $\gamma\gamma$ events
HCAL	$\sigma_E/E = 30\%/\sqrt{E}$	$\sigma_E/E = 50\%/\sqrt{E}$	$H \to s\bar{s}, c\bar{c}, gg$, invisible HNLs
	$\Delta x \times \Delta y =$ $2 \times 2\,\text{mm}^2$	$\Delta x \times \Delta y =$ $20 \times 20\,\text{mm}^2$	$H \to s\bar{s}, c\bar{c}, gg$
Muons	low momentum ($p < 1\,\text{GeV}$) ID	–	$B_s \to \nu\bar{\nu}$
Particle ID	$3\,\sigma$ K/π $p < 40\,\text{GeV}$	$3\,\sigma$ K/π $p < 30\,\text{GeV}$	$H \to s\bar{s}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100\,\mu\text{m}$, $\delta R_{\text{min}} = 1\,\mu\text{m}$ acceptance 50–100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$e^+e^- \to \gamma\gamma$ $e^+e^- \to e^+e^-\tau^+\tau^-(c\bar{c})$

FCC-ee detector requirements [2]

Electron …

Example …

$\rightarrow$ $\sigma_E/$ …

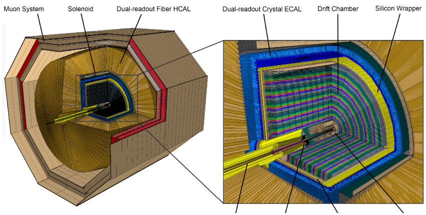
Example …

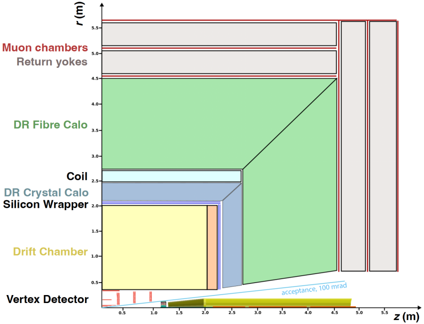
$\rightarrow$ Δx … *ion*

High granularity and tiny EM resolution

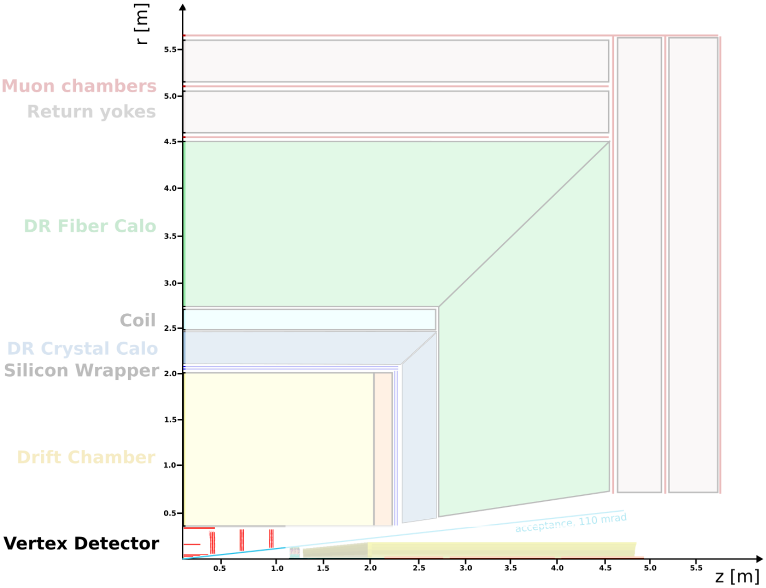
- **Vertex detector** of monolithic active pixel sensors
    - MAPS → Minimal mat. budget, small resolution
    - Air-cooled → Minimal mat. budget
- **Drift chamber** with cluster counting
    - Ultra-light, up to 112 track hits with $\sigma_{xy} \approx 100\,\mu\text{m}$
    - $dN_{\text{ion.}}/dx$ for PID
- **Silicon wrapper** for precise last track hit
    - Momentum resolution, precise ruler for acceptance
    - Potentially with $\mathcal{O}(\leq 100\,\text{ps})$ timing for PID
- **Dual readout crystal ECAL**
    - DR: Measures EM *and* hadr. shower components
    - Highly-segmented
    - Before the **HTS solenoid**, up to 3 T

    → Ultimate EM resolution
- **Dual readout fibre HCAL** complementing ECAL
- ≥ 3 layers of μ-RWELL **muon detectors**





IDEA arXiv note: 2502.21223


r [m]
Muon chambers
Return yokes
DR Fiber Calo
Coil
DR Crystal Calo
Silicon Wrapper
Drift Chamber
Vertex Detector
acceptance, 110 mrad
z [m]
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

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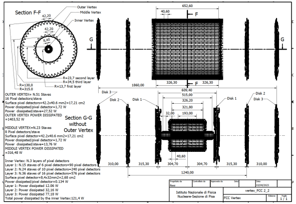
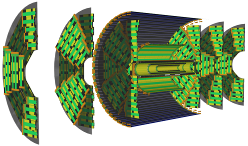
- 3 inner barrels (ARCADIA [9], $25\times25\,\mu m^2$ pitch)
- 2 outer barrels and 3 disks (ATLASPix3 [10], $50\times150\,\mu m^2$)

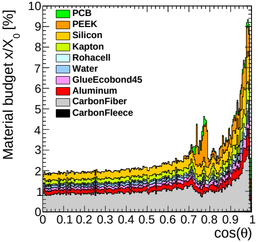
→ Integrated into MDI [11]

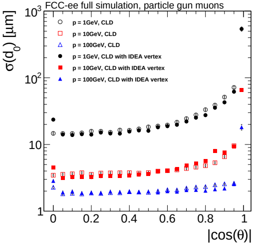


IDEA vertex design [12]



DD4hep implementation [13]

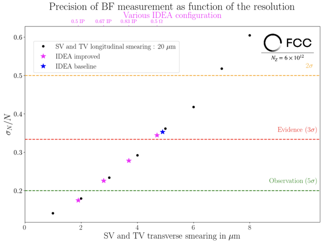




Vertex material budget (top) and transv. IP reso. assuming 3 μm resolution in inner vertex (bottom)

- $B^0 \to K^{*0}\tau^+\tau^-$ not observed yet, limit of BR $< \mathcal{O}(10^{-3}\text{–}10^{-4})$
- SM value at 10^{-7}, strongly enhanced in many BSM theories!

→ Three-prong τ decays allow event kin. and B^0 mass reco



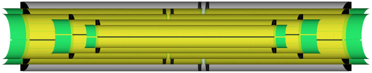
Fast sim. study of $B^0 \to K^{*0}\tau^+\tau^-$ in IDEA [3]

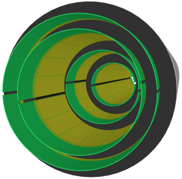
→ Need to improve IP resolutions by ≈ 40% to measure down to SM expectation

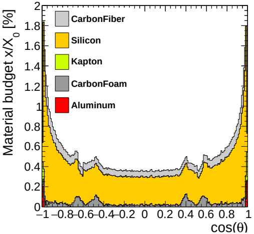
Vertex detector – Going ultra-light and close

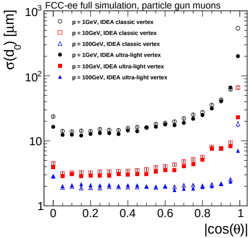
Ultra-light inner vertex

- ALICE ITS3-like design
- 4 layers to ensure ≥ 3 hits
- Extended forward coverage
  - $\rightarrow$ Two sensors in z in 3rd/4th layer

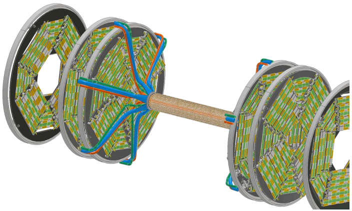




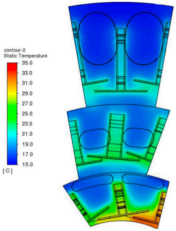




Ultra-light inner vertex material budget (top) and resulting IP resolution (bottom)



Piping studies (G. Ammirabile)



Air-cooling simulation @ Perugia+Pisa

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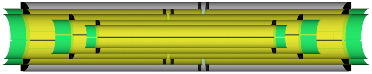

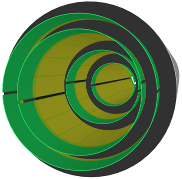

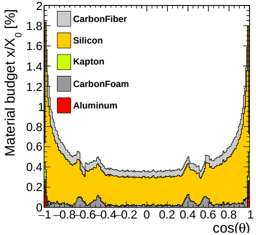

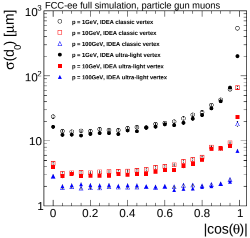

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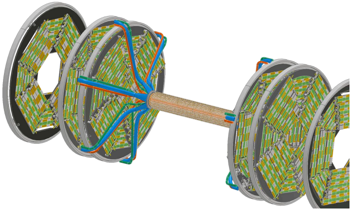

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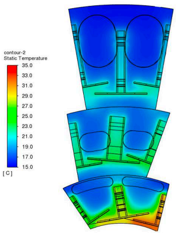

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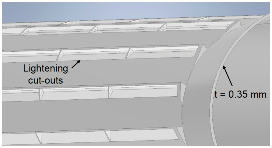

First design effort to move to $r = 11.7$ mm (G. Ammirabile)

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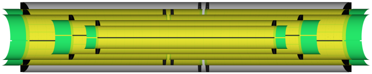

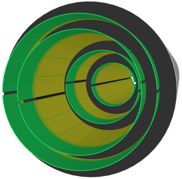

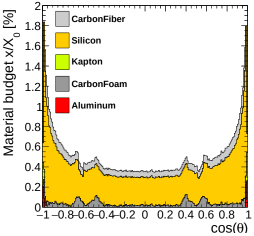

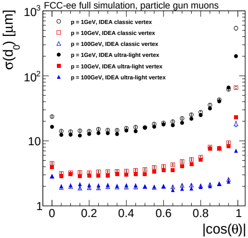

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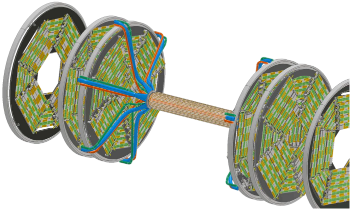

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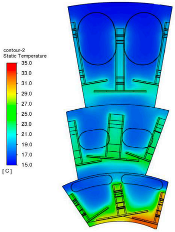

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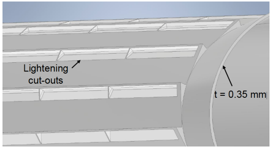

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Also improve outer barrel and disk resolutions?

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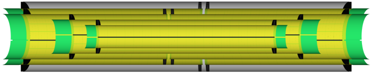
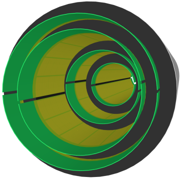
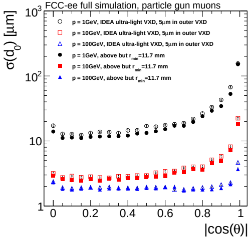
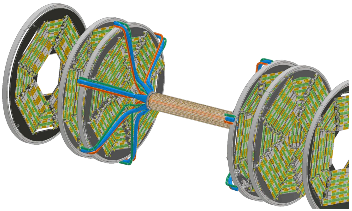






IP resolution with an ultra-light inner vertex, $r_{\text{min}} = 11.7$ mm, and 5 μm resolution in outer vertex barrels and disks



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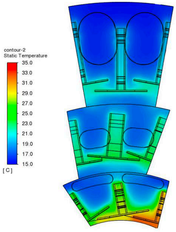
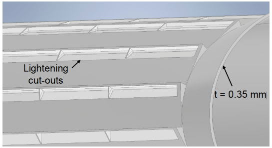


Air-cooling simulation @ Perugia+Pisa

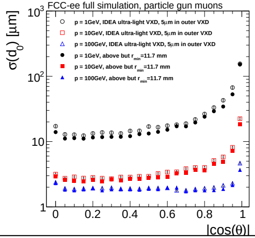


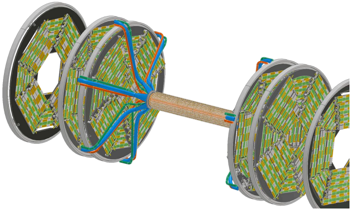
First design effort to move to $r = 11.7$ mm (G. Ammirabile)

Also improve outer barrel and disk resolutions?

Ultra-light inner vertex

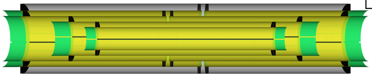
- ALICE ITS3-like design
- 4 layers to ensure ≥ 3 hits
- Extended forward coverage
  - → Two sensors in z in 3rd/4th layer

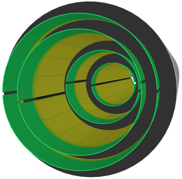




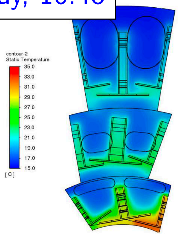
...ing studies (G. Ammirabile)

F. Palla's talk on Tuesday, 16:48

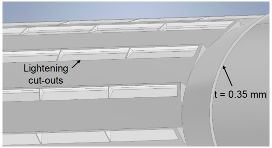




$r_{\mathrm{min}} = 11.7\,\mathrm{mm}$, and $5\,\mu\mathrm{m}$ resolution in outer vertex barrels and disks

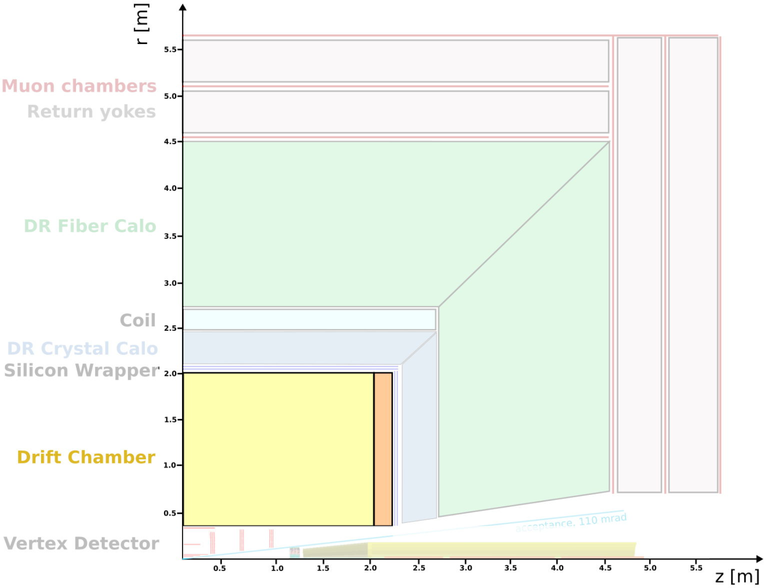


Air-cooling simulation @ Perugia+Pisa



First design effort to move to $r = 11.7\,\mathrm{mm}$ (G. Ammirabile)

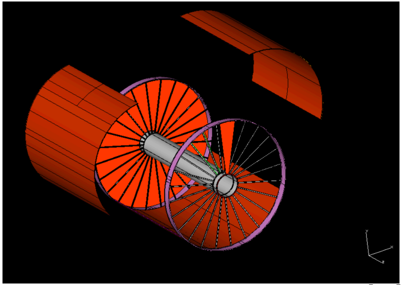
Also improve outer barrel and disk resolutions?


r [m]
Muon chambers
Return yokes
DR Fiber Calo
Coil
DR Crystal Calo
Silicon Wrapper
Drift Chamber
Vertex Detector
acceptance, 110 mrad
z [m]
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

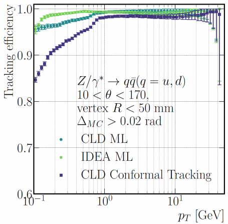
Drift chamber – Design and performance

University of Zurich[UZH]

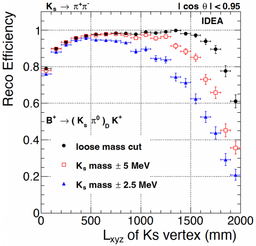
- $35 < r < 200\,\text{cm}$, $|z| < 200\,\text{cm}$, 1.6 % to 5.0 % of X_0
- Cylindrical carbon fibre walls
- 112 hyperboloidal layers filled with gas (90% He, 10% H_4C_{10}) $\rightarrow$ $\sigma_{xy} \approx 100\,\mu\text{m}$
    - 350k wires in total



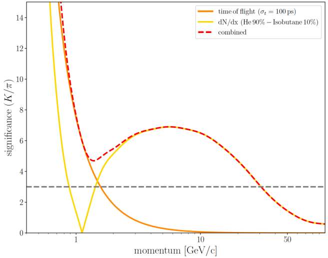
Schematic drawing of mech. structure [12]



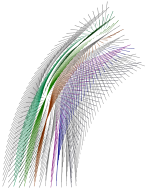
ML tracking [14]



K_s eff. in $B^+ \rightarrow (K_s\pi^0)_D K^+$ [2]



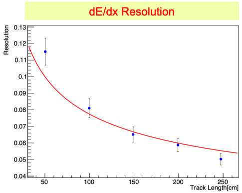
K/π separation in fast sim [12]

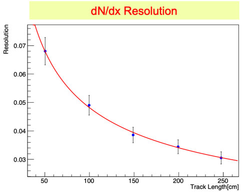


DC wires in full sim [15]

Next steps: Track reco and realistic digitizer in full sim.

Drift chamber – R&D

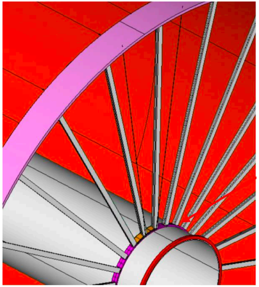


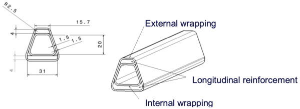


dE/dx resolution dependence on the track length $L^{-0.37}$ dN/dx resolution dependence on the track length $L^{-0.5}$

~ 2 times improvement in the resolution using dN/dx method

Setup of drift tubes in 180 GeV/c muon test beam





- 50 cm spoke prototype (full length 165 cm)

→ 6× lighter carbon foam core

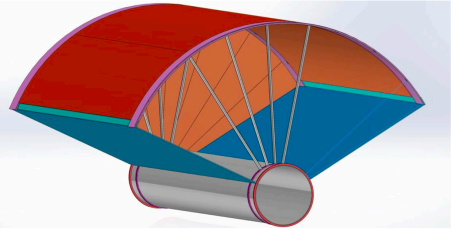
Full-size drift chamber prototype

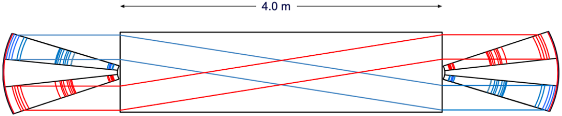
- 8 spokes, internal ring, 1/3 outer ring/panel, 1400 wires in total

→ To test mech. and electrostatic stability

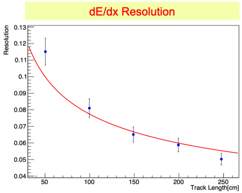
- Wire tests have started (1 km W and CF)

All figures Courtesy of M. Primavera

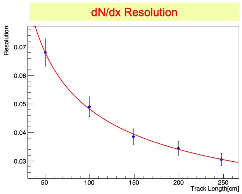




Drift chamber – R&D



dE/dx resolution dependence on the track length $L^{-0.37}$

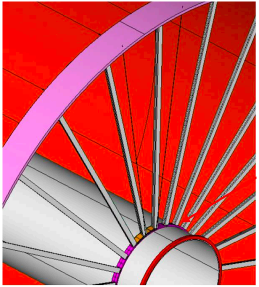


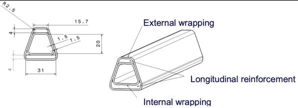
dN/dx resolution dependence on the track length $L^{-0.5}$

~ 2 times improvement in the resolution using dN/dx method

Setup of drift tubes in 1

Check out W. Elmetenawee's talk on Wed. 18:47





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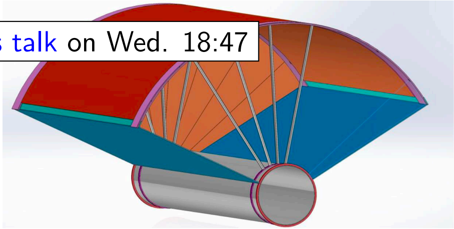
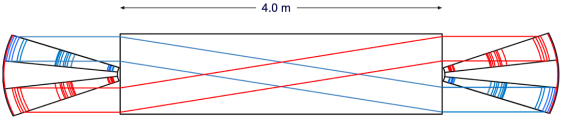
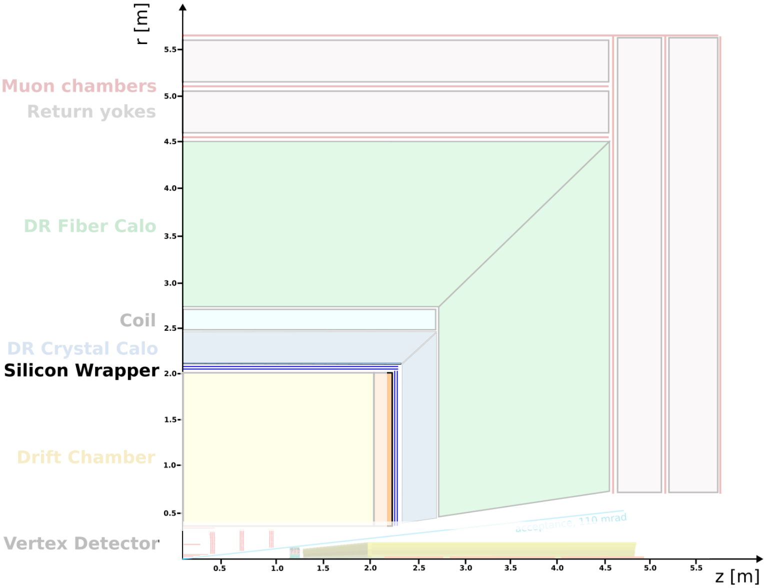
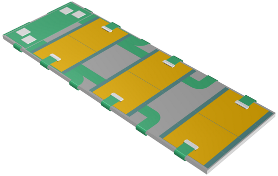




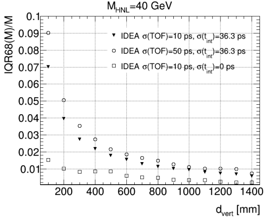

r [m]
Muon chambers
Return yokes
DR Fiber Calo
Coil
DR Crystal Calo
Silicon Wrapper
Drift Chamber
Vertex Detector
acceptance, 110 mrad
z [m]

Silicon wrapper – Requirements, challenges, detector R&D

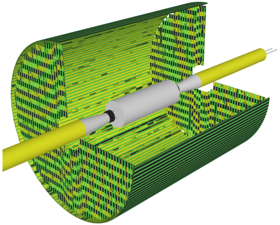
- Two barrel layers and disks per side
  - Barrel: Tiles of ATLASPix3-sized sensors, outer vertex flex and cooling
  - Disks: Inspired by CMS ETL [16]
  - ≥ 1 hit down to $|\cos\theta| < 0.989$
- Silicon microstrip, LGADs, or MAPS?
  - $\mathcal{O}(10\,\mu\text{m})$ for momentum resolution, complementing DCH in forward region
  - Precise and stable ruler for the detector acceptance definition ($< \mathcal{O}(10\,\mu\text{rad})$)
  - Potentially σ_t of $\mathcal{O}(\leq 100\,\text{ps})$ for PID



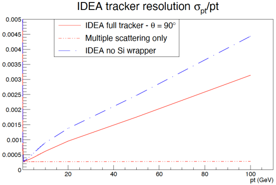
Tile proposed for CEPC [17, 18]



Relative mass resolution on HNL as a function of its flight distance [2]



Complete silicon wrapper in DD4hep



Silicon wrapper impact on momentum resolution [12]

Silicon wrapper – Requirements, challenges, detector R&D

University of Zurich[UZH]

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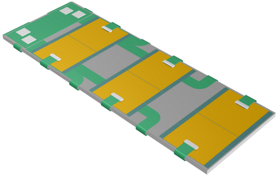
  - Potentially σ_t of $\mathcal{O}(\leq 100\,\text{ps})$ for PID

Next design iteration

- $\mathcal{O}(100\,\text{m}^2)$ area
  - $\rightarrow$ One layer/disk design to minimise area
- Barrel: Develop support structure on top of drift chamber with sensors facing IP
- D-shaped half-disks supported by DCH



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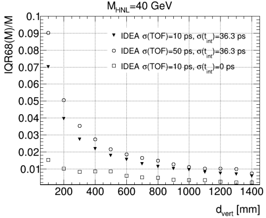

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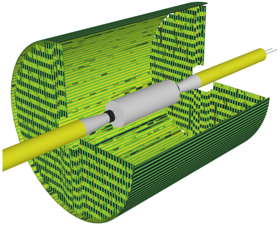

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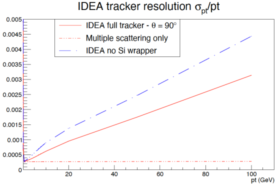

Silicon wrapper impact on momentum resolution [12]

- Two barrel layers and disks per side
  - Barrel: Tiles of ATLASPix3-sized sensors, outer vertex flex and cooling
  - Disks: Inspired by CMS ETL [16]
  - ≥ 1 hit ...
- Silic...

Estimate hit rate from physics and beam backgrounds
→ Influences technology choice

  - $\mathcal{O}(10\,\mu\text{m})$ for momentum resolution, complementing DCH in forward region
  - Precise and stable ruler for the detector acceptance definition ($< \mathcal{O}(10\,\mu\text{rad})$)
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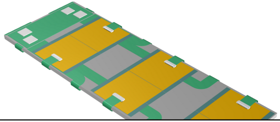
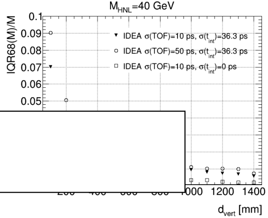


[17, 18]



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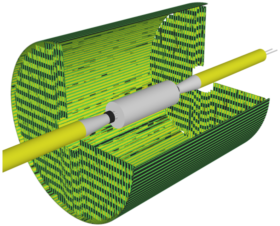

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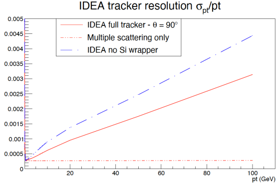

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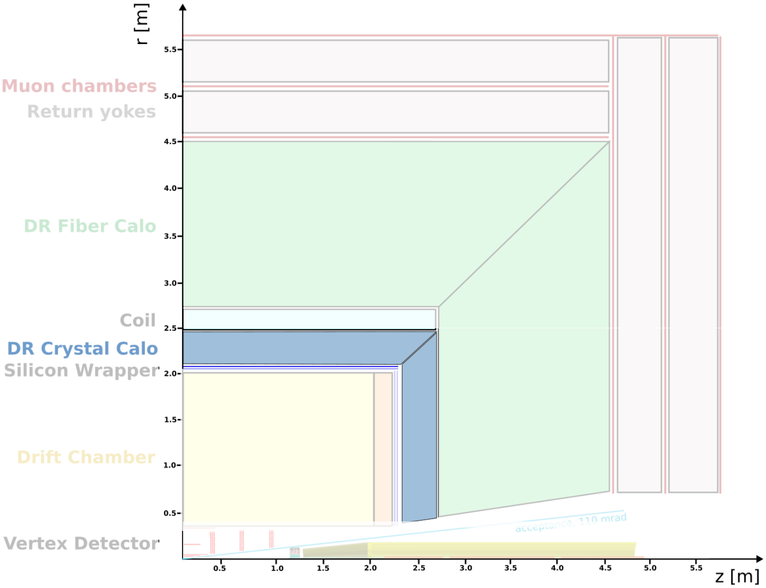
r [m]
Muon chambers
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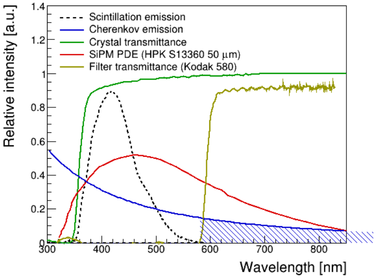
Silicon Wrapper
Drift Chamber
Vertex Detector
acceptance, 110 mrad
z [m]
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

Dual readout crystal ECAL – Design and performance

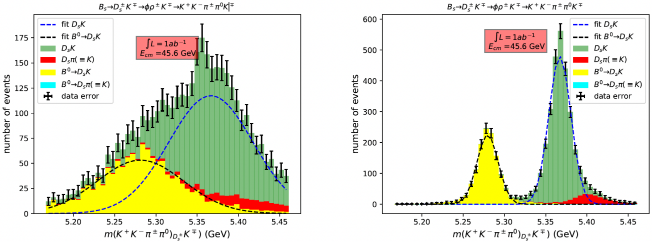
University of Zurich[UZH]

- Improved EM resolution, target $\sigma/E = 3\%/\sqrt{E}$
- Longitudinally segmented $PbWO_4$ crystals, front/rear sections

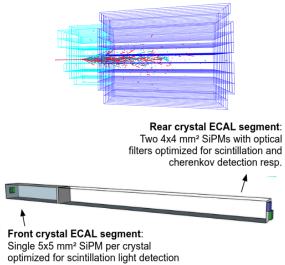


Relative intensity in $PbWO_4$ [12]

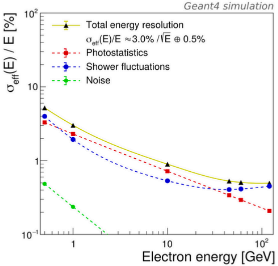
- Two layers of fast scintillating LYSO crystals in front



$B_s \to D_s K \to \phi(KK)\pi K$ (IDEA fast sim [2])



DR crystal ECAL stack [12]



Resolution in Geant4 [12]

Dual readout crystal ECAL – R&D

$PbWO_4$ or BGO/BSO?

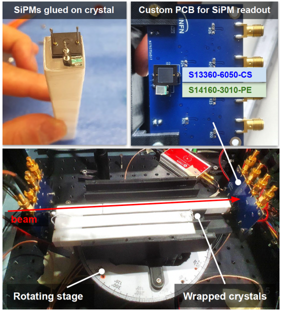
- BGO/BSO with peak at 480 nm
- Higher light yield

→ Harder to filter out scintillation photons

- Slower decay time (100's of ns)

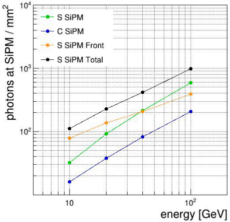
→ Separate scintillation/Cherenkov with timing

All figures courtesy of R. Hirosky, M. Lucchini



2024 CERN H6 test beam

Testing single-crystal to measure Sci and Cherenkov light photon yields



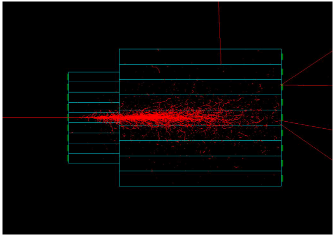
Light yields in $PbWO_4$

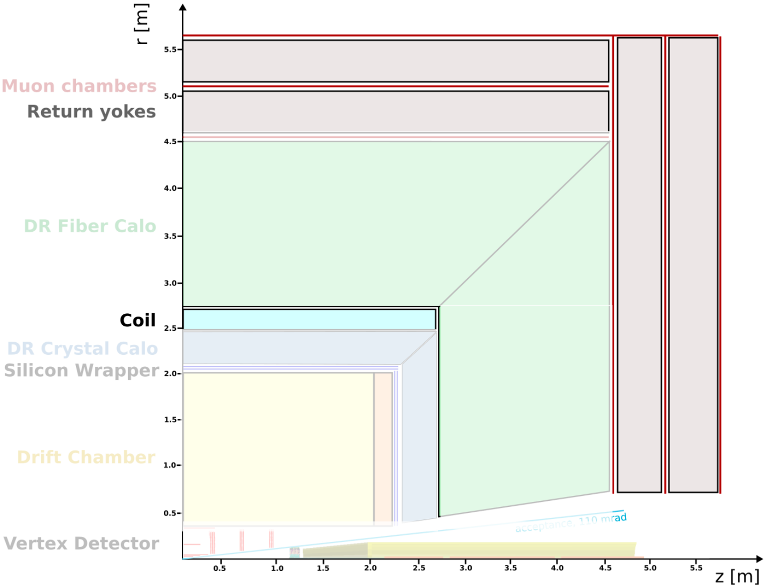
→ Defines SiPM/filter specifications

- Also angular dependence measured

- Prototype of 9×9 $PbWO_4$ crystals

→ Target Fall 2025 TB




r [m]
Muon chambers
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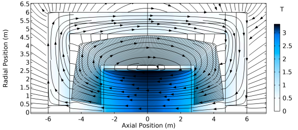
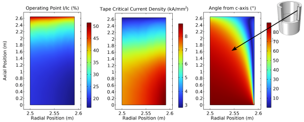
Silicon Wrapper
Drift Chamber
Vertex Detector
acceptance, 110 mrad
z [m]
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

HTS solenoid – Detector R&D

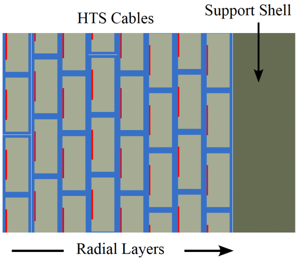
- Solenoid now outside ECAL → Less transparency is ok
- Aluminium-stabilised NbTi detector magnets not commercially available anymore!
- Low temperature ($< 5\,\mathrm{K}$) means large energy consumption and liquid helium inventory
  - → High-temperature superconducting (HTS) solenoid!
- $T_{\mathrm{op.}}$ 20 K currently assumed, up to 50 K to be considered
- $|B|$ limited to 2 T at the Z pole, but can go up to 3 T for runs beyond Z pole



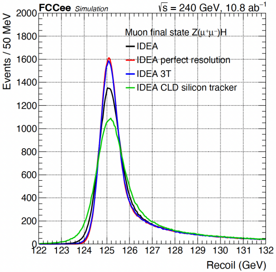
Magnetic fields in 3 T HTS solenoid [12]

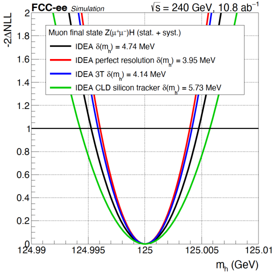


Simulated map of properties [12]

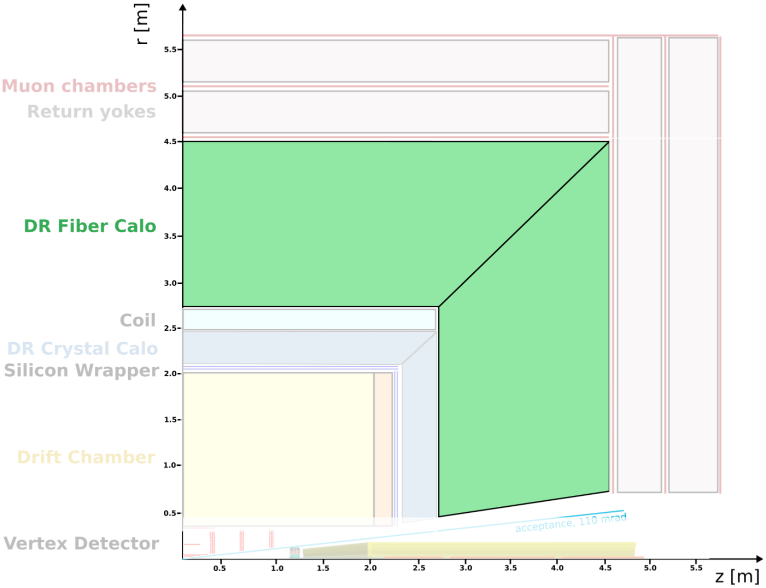


Sketch of conductor assembly. [12]





Impact of 3 T on m_H [2]


r [m]
5.5
5.0
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1.5
1.0
0.5
Muon chambers
Return yokes
DR Fiber Calo
Coil
DR Crystal Calo
Silicon Wrapper
Drift Chamber
Vertex Detector
acceptance, 110 mrad
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
z [m]

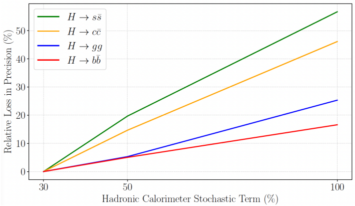
Dual readout fibre HCAL – Requirements and challenges

- Alternating scintillating and clear (→ Cherenkov) fibres in metal tubes (act as absorbers)

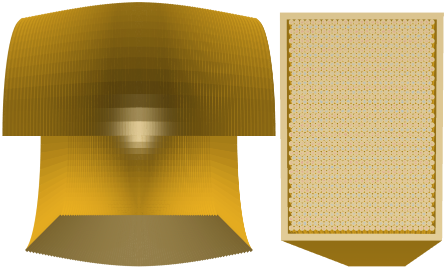
→ Stacked to form hexagonal pattern

→ Forming trapezoidal towers pointing to IP

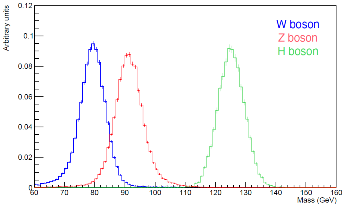
- $\approx 30\,\%/\sqrt{E}$ standalone hadr. resolution
- Capillary tubes 70 million individual tubes
  - High computing and memory demands
  - Granularity to be retuned given crystal ECAL in front



HCAL impact on Higgs couplings. [2]

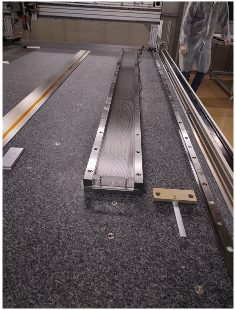


Fibre HCAL barrel in DD4hep. [12]



m_{reco} for jet-jet resonances using only GEANT4 DR fibre calo, excl. semileptonic b decays [19]

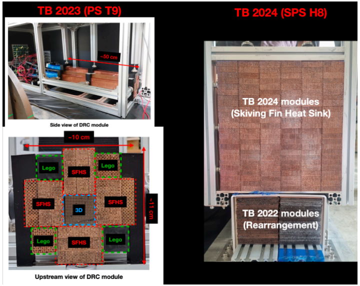
Dual readout fibre HCAL – Detector R&D



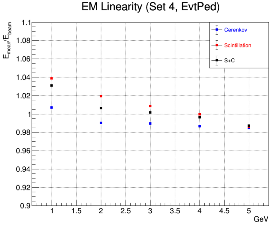
High precision assembly tool [12]

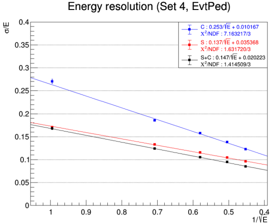
Method	Cu (%)	fibers (%)	Air (%)	X_0 (cm)	λ_I (cm)	Sampling fraction (%)
Ideal	65.1	34.9	0	2.16	21.16	S(4.02) C(4.54)
Machining	54.1	32.7	13.2	2.59	25.10	S(4.48) C(5.07)
SFHS	48.1	33.6	18.3	2.91	27.77	S(5.10) C(5.77)
3D printing / drilling	57.8	34.9	7.3	2.43	23.54	S(4.48) C(5.06)

Alternative mechanical options. [12]



Left: 3D metal printing prototype, right: skiving fin heat sink, bottom right: groove machining technique [12]





DR fibre calo perf. in a low energy positron beam. [20]

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University of Zurich[UZH]

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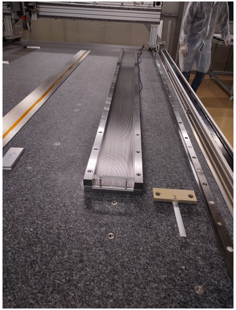

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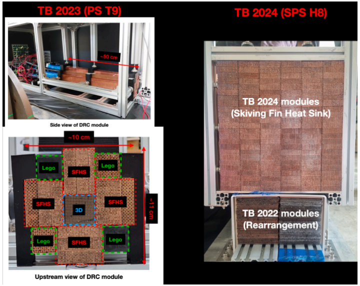

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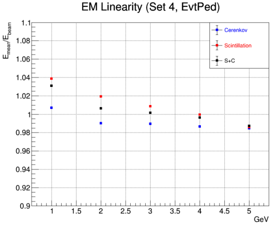

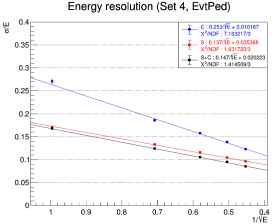

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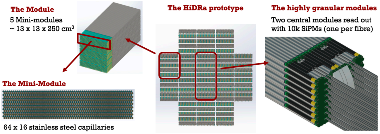
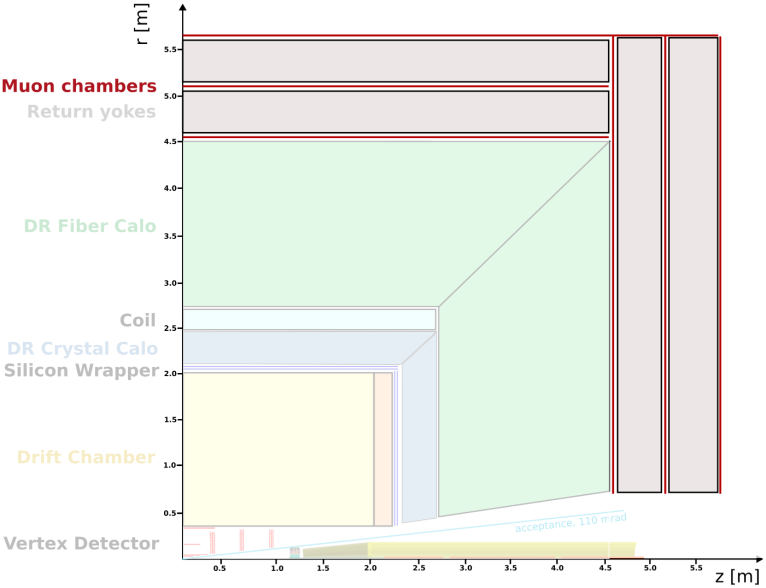


HiDRa prototype [12] → TB 09.25!

Outlook:

- Study timing SiPMs for long. segm.
  - → Access to jet substructure
- Fibres with different refrective indices


r [m]
Muon chambers
Return yokes
DR Fiber Calo
Coil
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Silicon Wrapper
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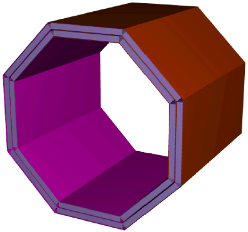
Vertex Detector
acceptance, 110 mrad
z [m]
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

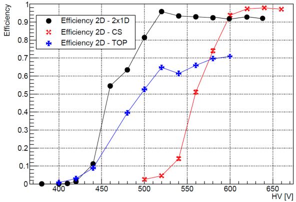
- $\sigma_p(\mu)$ driven by tracker, but...
  - → need high-purity and efficient identification
  - → need to catch hadronic shower tails not contained in HCAL
- Independent μ tracking could, however, be relevant for LLP searches!
  - Not part of IDEA: Proposal to instrument cavern walls

IDEA muon detector design

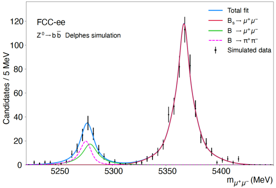
- Barrel and endcaps, ≥ 3 layers
- μ-RWELL tiles of $50 \times 50\,\text{cm}^2$, overlap to avoid dead areas



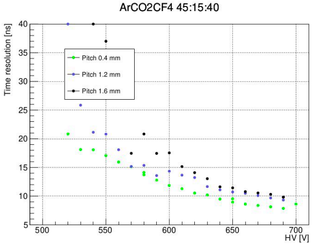
IDEA muon barrel in DD4hep full simulation [12]



2D layouts comparison. CS: capacitiy sharing anode [21], TOP: 1D R&O + strip-patterned top electrode. [12]



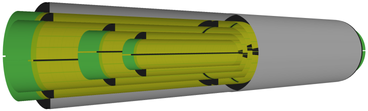
Impact of misidentified pions in $B/B_s \to \mu^+\mu^-$ [2]

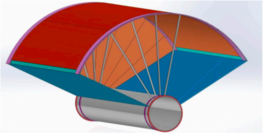


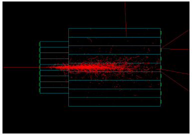
Timing performance in TB with TIGER front-end. Courtesy of R. Farinelli

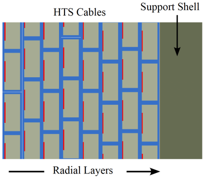
University of Zurich[UZH]

- Pushing possible FCC-ee detector performance to the limits
- Using many novel and innovative detector systems









Conclusions – an Innovative Detector for $\mathbf{E}^{+}e^{-}$ Accelerator

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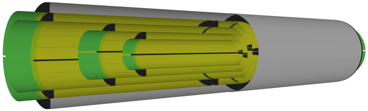

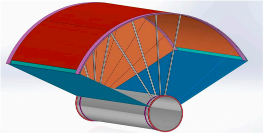

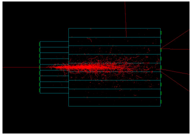

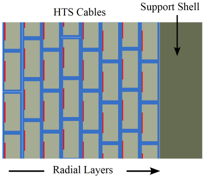

Conclusions – an Innovative Detector for E^+e^- Accelerator

University of Zurich[UZH]

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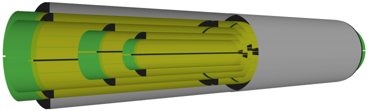
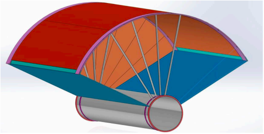
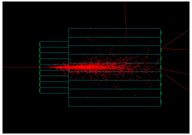
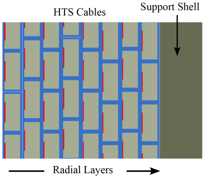
  - → Not the end but the beginning of the story!









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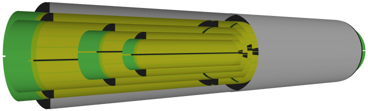

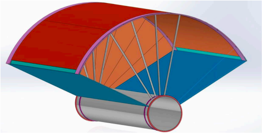

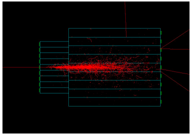

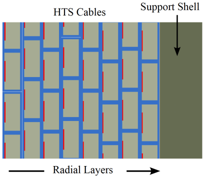

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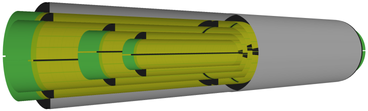

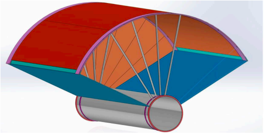

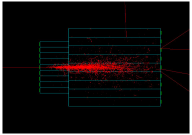

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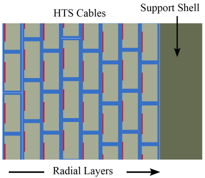

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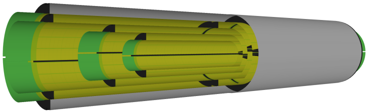

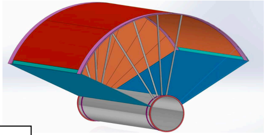

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IDEA Study Group open for collaboration!

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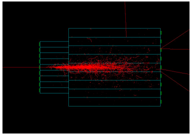

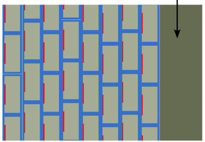

Thanks to the whole IDEA Study Group!

https://arxiv.org/abs/2502.21223

M. Abbrescia[1], S. Ajmal[2], N. Akchurin[3], M. Al-Thakeel[4], M. Alviggi[5], G. Ammirabile[7], A. Andreazza[74], B. Argiento[5], E. Auffray[36], P. Azzi[6], P. Azzurri[7], N. Bacchetta[6,30], A. Bacci[8], G. Baldinelli[2], R. Bartek[9], F. Bedeschi[7], L. Bellagamba[10], A. Benaglia[11], G. Bencivenni[12], M. Bertani[12], M. Biglietti[13], G. Bilei[2], D. Boccanfuso[14], L. Borriello[14], A. Bortone[53], D. Boscherini[10], M. Boscolo[12], F. Bosi[7], A. Braghieri[15], S. Braibant[4], F. Brizioli[2], G. Broggi[73,36], A. Burdyko[16], S. Busatto[17], M. Caccia[16], Y. Cai[4], M. Campajola[5], L. Capriotti[18], E. Carquin[19], C. Cecchi[20], P. Cenci[2], F. Cetorelli[21], D. Chiappara[22], F. Chiapponi[4], G. Chiarello[23], W. Chung[25], S. Ciarlantini [22], A. Ciarma[12], G. Cibinetto[26], F. Cirotto[5], M. Cobal[27], A. Coccaro[28], F. Conventi [29], T. Croci[2], G. Cummings[30], F. Cuna[31], M. D'Alfonso[24], B. D'Anzi[1], M. Da Rocha Rolo[53], A. D'Avanzo[5], N. De Filippis[32], M. De Gerone[28], E. De Lucia[12], G. De Nardo[5], E. Delfrate[33], M. Della Pietra[5], A. De Vita[36,22], E. Di Fiore[26], C. Di Fraia[5], B. Di Micco[13], R. Di Nardo[34], A. Dominguez[9], A. D'Onofrio[14], I. Drebot[8], W. Elmetenawee[31], S. Eno[35], L. Fanò[20], A. Farilla[13], R. Farinelli[10], M. Farino[25], L. Favilla[37], Y. Feng[3], R. Ferrari[15], F. Ferro[28], A. Fondacci[2], H. Fox[38], M. Francesconi[14], B. Francois[36], F. Fransesini[12], A. Frasca[75,36], Y. Gao[39], D. Garcia[36], I. Garzia[18], S. Gascon-Shotkin[40], M. Gatta[12], G. Gaudino[37], G. Gaudio[15], P. Giacomelli[10], S. Giagu[41], M. Giovannetti[12], P. Giubilato[22], E. Gorini[42], S. Gramigna[43], F. Grancagnolo[44], S. Grancagnolo[42], F. G. Gravili[42], M. Greco[59], L. Guan[45], G. Guerrieri[36], R. Hirosky[46], J. Hirschauer[30], G. Iakovidis[47], P. Iengo[36], A. Ilg[48], M. Iodice[13], A. Iorio[5], V. Izzo[14], A. Jung[49], H. Khanpour[50], M. Kim[51], S. Ko[52], L. Lavezzi[53], A. Ledovskoy[46], K. Lee[54], S.W. Lee[55], S. Lee[3], J.S.H. Lee[56], Y. Lee[56], G. Lerner[36], A. Loeschcke Centeno[57], M. Louka[1], M. Lucchini[21], A. Lusiani[58], C. Madrid[3], M. Maggiora[59], G. Manco[15], E. Manoni[2], L. Marafatto[27], S. Mariotto[60], G. Martelli[2], S. Mattiazzo[22], F. Melendi[26], L. Meng[38], A. Messineo[61], G. Mezzadri[62], A. Miccoli[44], M. Migliorati[41], P. Miller[35], S. Moneta[2], G. Morello[12], A. Morozzi[2], F. Moscatelli[63], L. Nasella[33], G. Nigrelli[73,36], S. Pacetti[20], F. Palla [7], M. Panareo[42], O. Panella[2], G. Panizzo[27], P. Paolucci[14], A. Pareti[64], F. Parodi[65], D. Passeri[20], C. Paus[24], L. Pezzotti[10], M. Piccini[2], M. Pinamonti[27], L. Pintucci[27], G. Polesello[15], M. Poli Lener[12], A. Polini[10], M. Primavera[44], F. Procacci[31], L. Ratti[64], E. Robutti[28], M. Rossetti Conti[66], L. Rossi[60], E. Rossi[5], F. Salvatore[57], R. Santoro[16], J. Scamardella[14], C. Schiavi[65], M. Scodeggio[26], G. Sekhniaidze[14], M. Selvaggi[36], B. Singhal[9], M. Sorbi[60], S. Sorti[60], M. Statera [66], G. Tassielli[67], R. Tenchini[7], L. Toffolin[27], L. Toffolin[68], C. Tully[25], R. Turra[8], C. Turrioni[2], F. Ustuner[69], N. Valle[15], A. Ventura[42], I. Vivarelli[4], I. Watson[56], J. Wyss[70], H.D. Yoo[71], S. Yu[9], D. Yu[72], A. Zingaretti[6]

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[2] W. Bartmann, et al., *Future Circular Collider Feasibility Study Report Volume 1: Physics and Experiments*, 2025. http://cds.cern.ch/record/2928193.

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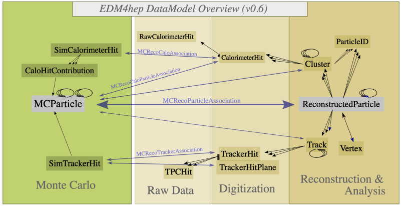
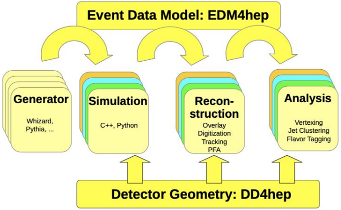
Co-project Manager: Magnus Mager, magnus.mager@cern.chds.

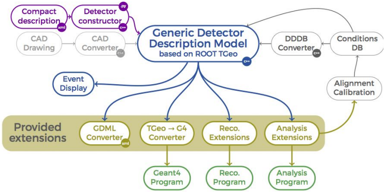
The common software vision: Key4hep

Key4hep is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis

- Event data model: EDM4hep for exchange among framework components
  - Podio as underlying tool, for different collision environments
  - Including truth information
- Data processing framework: Gaudi
- Geometry description: DD4hep, ability to include CAD files
- Package manager: Spack: `source /cvmfs/sw.hsf.org/Key4hep/setup.sh`







FCC-ee detector *concepts* (modulo some variations)

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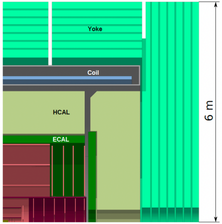
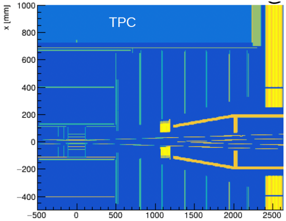
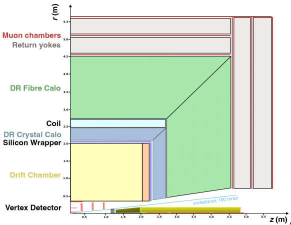


CLD [22, 23]



ILD [24, 25]



IDEA [12]

ALLEGRO [26]

- Light silicon vertex detector using monolithic active pixel sensors (MAPS)

CLD:
- Si tracker
- dE/dx + ARC (?)
- CALICE-like highly-granular ECAL/ HCAL
- Solenoid coil outside calorimeter system

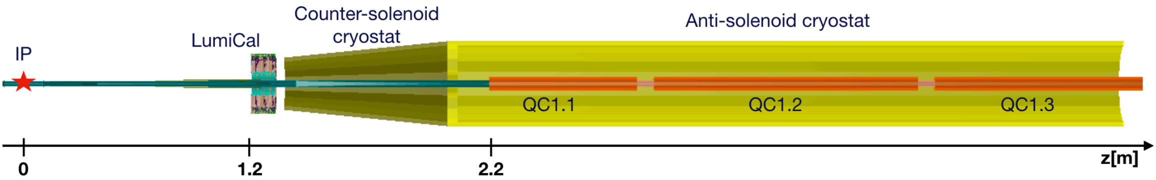
ILD:
- Si tracker + time projection chamber
- Si or ECAL with T.O.F
- CALICE-like highly-granular ECAL/ HCAL
- Solenoid coil outside calorimeter system

IDEA:
- Ultra-light drift chamber with d$N_{\text{ion.}}$/dx
- Si layer with T.O.F
- Dual-readout crystal ECAL
- Light solenoid up to 3 T
- DR fibre HCAL

ALLEGRO:
- DC/SciFi/Straw tubes
- Si layer with T.O.F
- Noble liquid ECAL, Pb/W+LAr or W+LKr
- Solenoid in same cryostat as ECAL
- TileCal HCAL

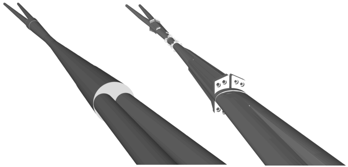
- Muon system in return yoke, pretty much det. concept independent (e.g. μ-RWELL in IDEA)

Machine-detector interface and luminosity calorimeter

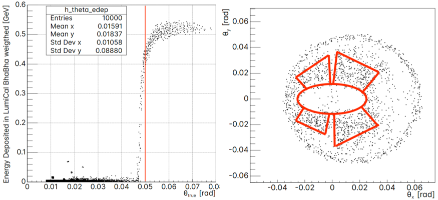


MDI design in full simulation (MDI Note [11])

- Central beam pipe
  - $r_{\text{inner}} = 10\,\text{mm}$ and $r_{\text{outer}} = 11.7\,\text{mm}$
  - AlBeMet162, $0.68\,\%X_0$
- SiW sandwich lumical at $z = 1074\,\text{mm}$
  - Limiting detector acceptance to $\geq 110\,\text{mrad}$



Shape-based (left) and CAD beam pipe (right) [15]



Energy deposits from Bhabha pairs in the lumical (Z pole) [11]

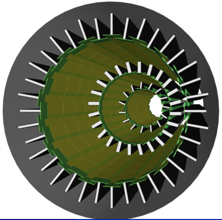
With accurate sensor peripheries, on-detector services, support structures

Classic inner vertex design

- 3 layers of ARCADIA staves, $r_{\min} = 13.7\,\text{mm}$, $\sigma_{\phi,z} = 3\,\mu\text{m}$

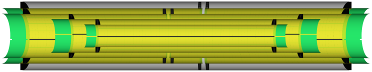
→ 1st layer on beam pipe?

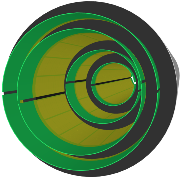
- Detailed sensor peripheries allowed to fix cracks in coverage



Ultra-light inner vertex

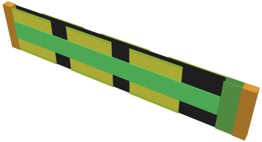
- ALICE ITS3-like design
- 4 layers to ensure ≥ 3 hits
- Extended forward coverage
  → Two sensors in z in 3rd/4th layer

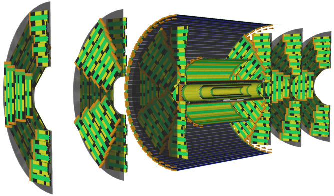




Outer vertex and disks

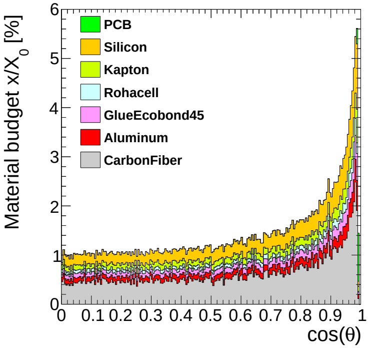
- ATLASPix3 quads, $150 \times 50\,\mu\text{m}^2$ pitch
- 2 barrel layers, 3 disks



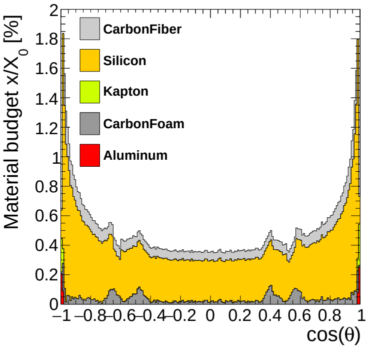


Vertex detector – material budget

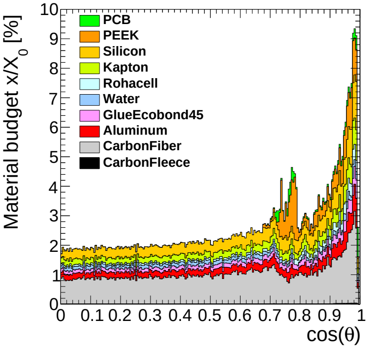
Classic inner vertex design



Ultra-light inner vertex

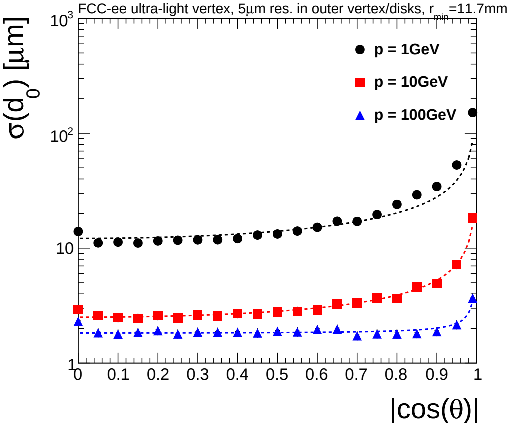


Classic inner vertex + outer vertex + disks



Ultra-light inner vertex to reduce material budget by almost factor of three

Using Conformal tracking [27] by inserting IDEA vertex into CLD (*: See appendix)



- CLD vertex detector already gives decent impact parameter resolution
- IDEA vertex has lighter, single-hit layers
  - No hit in first layer at $\cos\theta = 0$
- Using curved, wafer-scale sensors similar to ALICE ITS3 (mat. budget reduction of ≈ 3)
- Improving resolution of fourth and fifth barrel layer and disks to 5 µm
- Moving first layer to $r = 11.7\,\mathrm{mm}$ (instead of 13.7), cooling by beam pipe

- Impact parameter resolution in transverse direction of $\sigma_{d_0} \approx 1.8 \bigoplus \frac{12\,\mu\mathrm{m\,GeV}}{p\sin^{3/2}\theta}$ reachable
  - Similar numbers in σ_{z_0}

Digitisation: Gaussian smearing, but work towards more detailed digitisation ongoing

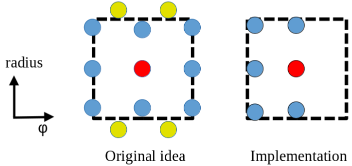
Geometry

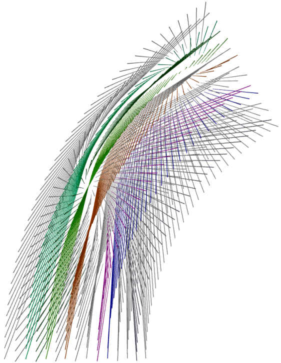
- $35 < r < 200\,\text{cm}$, $|z| < 200\,\text{cm}$, $1.6\,\%$ to $5.0\,\%$ of X_0
- Cylindrical carbon fibre walls
- 112 hyperboloidal layers filled with gas (90% He, 10% H_4C_{10})
  - Include all wires with stereo angle, sensitive volume definition
  - 350k wires in total
- Native Geant4/Garfield++ simulation existing demonstrating PID capabilities [30]

Digitisation

- EDM4hep data extension to store digitised hits
- Digitisation: Smearing of hit positions, estimating cluster count for PID according to [28]

→ Working now on a more realistic digitizer with full waveform (check out effort at CEPC by G. Zhao [29])



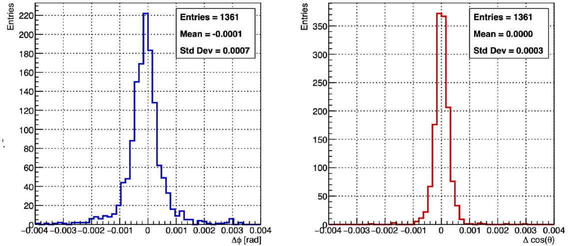


Drift chamber wires [15]

University of Zurich[UZH]

Algorithmic reconstruction using Genfit2

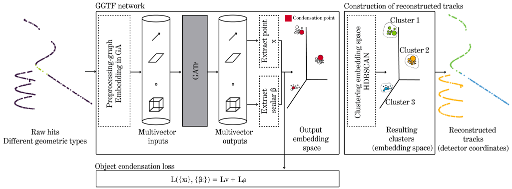
- Providing track representation, track-fitting algorithms and graphic visualization
- Relying on ground truth

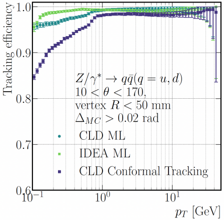


Vertex + drift chamber reco, $E = 5\,\mathrm{GeV}$, θ between 15° and 80°, A. de Vita @ FCC Week 2025

ML-based track reconstruction

- GNN, detector agnostic
- Track refitting to be done still



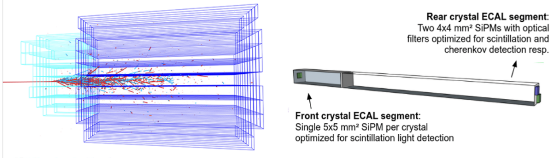


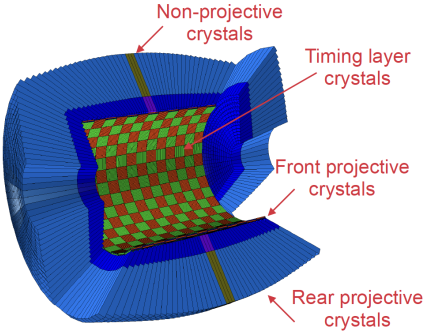
Tracking efficiency [14]

Dual readout crystal ECAL

Is now the baseline in IDEA_o2

- Improved EM resolution, target $\sigma/E = 3\%/\sqrt{E}$
- Longitudinally segmented $PbWO_4$ crystals with front/rear sections
- DR through two dedicated SiPMs on rear section
- Two layers of fast scintillating LYSO crystals in front

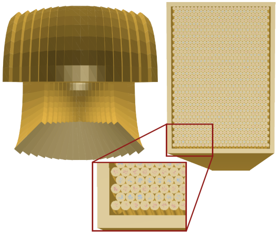




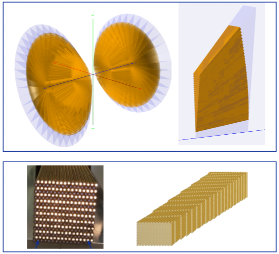
[12] and L. Pezzotti @ 8th FCC Physics Workshop

Dual readout fibre HCAL

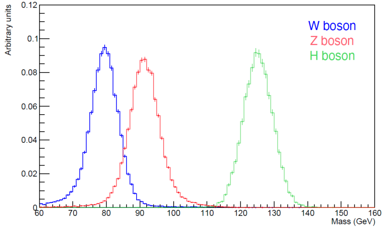
- Alternating scintillating and clear ($\rightarrow$ Cherenkov) fibres in metal tubes (act as absorbers)
  - $\rightarrow$ Stacked to form hexagonal pattern
  - $\rightarrow$ Forming trapezoidal towers pointing to IP
- $\approx 30\,\%/\sqrt{E}$ standalone hadr. resolution
- Capillary tubes 70 million individual tubes
  - High computing and memory demands
  - Granularity to be retuned given new crystal ECAL in front



Barrel geometry [12]

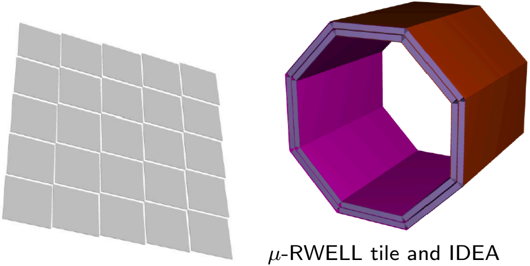


Endcap geometry [12]



Reco mass for three jet-jet resonances using GEANT4 DR fibre calo only, excl. semileptonic b decays [19]

- Versatile, generic detector constructor (was also previously used for pre-shower)
- IDEA: cylindrical barrel and two endcaps, ≥ 3 layers
- μ-RWELL tiles of $50 \times 50\,\mathrm{cm}^2$, overlap to avoid dead areas
- Simple Gaussian smearing digitisation



μ-RWELL tile and IDEA muon detector barrel [12]

Track reconstruction using conformal tracking

For CLD, simply use conformal tracking [27] (see talk by Leonhard)

For IDEA, eventually use

- ACTS tracking (talk by Samuel) → Not yet available for IDEA
- Genfit2 tracking or ML tracking (talk by Andrea) → Track refitting not yet done

For the moment simply insert IDEA vertex detector into CLD_o2_v05 and use conformal tracking!

Necessary changes

- Removing first Inner Tracker barrel layer ($r = 127$ mm)
- Removing first and second Inner Tracker disks ($r = 79.5$ and 123.5 mm)
- Unchanged conformal tracking max. distance (CT_MAX_DIST) and *MinClustersOnTrack*

Nota bene

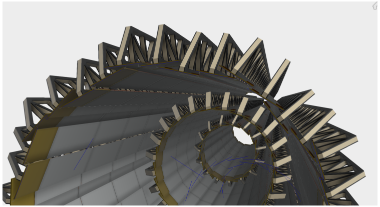
- Tracking performance should be much better with drift chamber and silicon wrapper
- Assume spatial resolution of $3\,\mu$m for inner vertex barrel (same as CLD), and $14\,\mu\text{m} \times 43\,\mu$m for outer barrel and disks (CLD: vertex endcap: $3\,\mu$m, inner tracker endcap: $5\,\mu$m or $7 \times 90\,\mu$m)

Not perfect, but works, reasonably meaningful for impact parameter resolution comparison

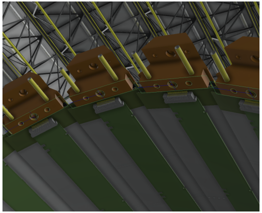
IDEA vertex detector design

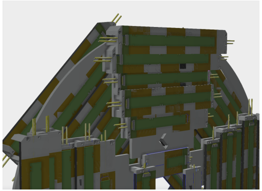
University of Zurich[UZH]

Vertex detector design by INFN-Pisa, integration in MDI by INFN-LNF

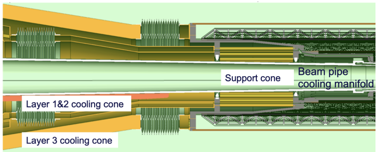


Inner vertex barrel with dual modules of ARCADIA, air-cooled → $\lesssim 50\,\mathrm{mW\,cm^{-2}}$

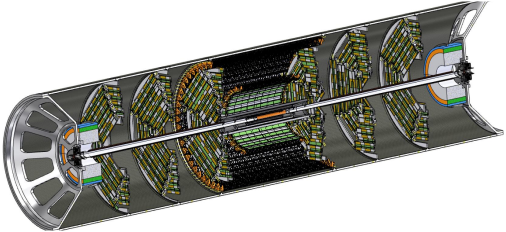




Outer vertex barrel and disks using quad ATLASPix3 DMAPS with $150 \times 50\,\mu\mathrm{m}^2$ pixels, water-cooled

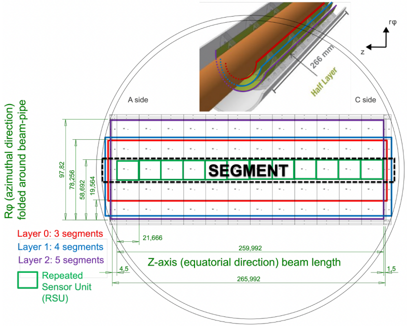


Inner vertex support and cooling cones, first air cooling and transient mechanical analysis results promising

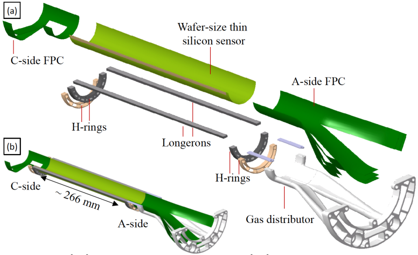


Support tube holding lumical, vertex and beam pipe

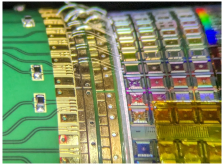
- Three layers of wafer-scale 65 nm MAPS
- Building blocks are Repeated Sensor Units (RSUs) that are stitched together
  - 12 RSUs in z direction
  - 3, 4 or 5 segments around ϕ
- Data transmission in sensor along z
- Metal layer for distribution of power
- Endcaps on sides for powering and readout
- Air-cooling from one side



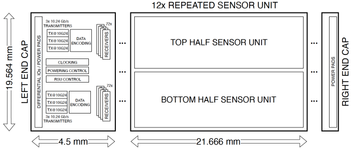
Wafer stitching plan [32]



Exploded (a) and assembled (b) ITS3 half-layer[32]



Wire bonds from sensor to FPCs [32]



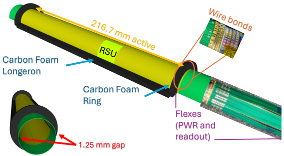
Block diagram of sensor segment [32]

Ultra-light inner vertex concept for FCC-ee

University of Zurich[UZH]

Layer 1 and 2: $r = 13.7, 20.35\,\mathrm{mm}$

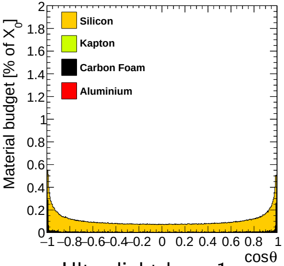
- 10 and 13 repeated sensor units long $\rightarrow |\cos(\theta)| < 0.992/0.99$
- Peripheries, gap between half-barrels $\rightarrow$ Rotation in ϕ to fill gaps
- Readout and power from both sides



Layer 1 layout

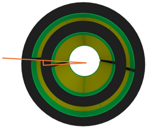
Layer 3 and 4: $r = 27, 33.65\,\mathrm{mm}$

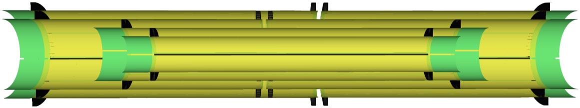
- Two sensors per side, readout only on sides, power on sides and centre (power wire)
- 8 (10) RSUs on +z (-z) side for layer 3, inverted for layer 4
  $\rightarrow |\cos(\theta)| < 0.991/0.986$



Ultra-light layer 1

Assume 50 µm of Si + 16 µm of Si-equivalent (metal layer along sensor)


Layer 1+2 front


Longitudinal cross section of all four layers

$0.075\%\ X_0$ at $\cos(\theta) = 0$

$\rightarrow > 3$ improvement!