



FCC Detector Concepts

Martin Aleksa

on behalf of the FCC Detector Concepts Group

- Introduction Detector Requirements
- Proto Detectors
- Organisation – Detector R&D

Based on:

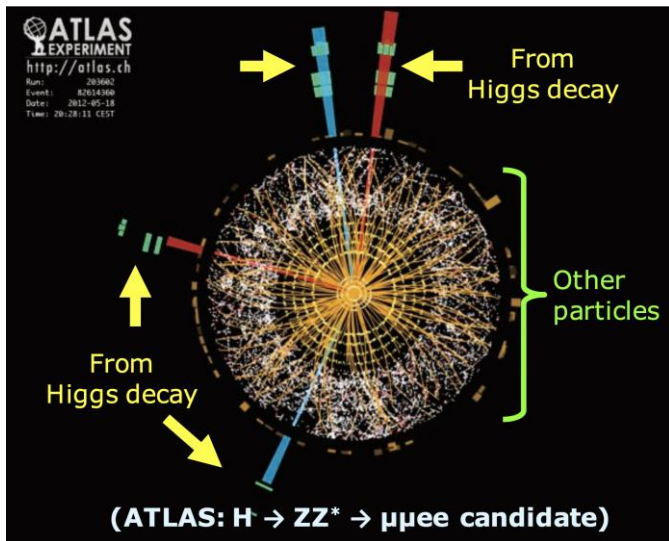
- FCC Week in Paris (<https://indico.cern.ch/event/1064327/>)
- 6th FCC Physics Workshop in Krakow (<https://indico.cern.ch/event/1176398/>)
- Talk by P. Janot at December 2022 CERN SPC Meeting
- [Presentation by M. Dam](#) at EP R&D Day 2022



Introduction & Detector Requirements

Introduction – pp versus e^+e^-

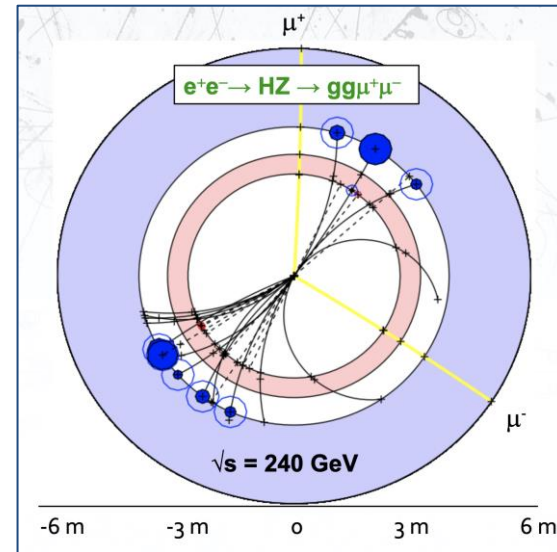
Higgs event in pp



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 → exploration
- $S/B \approx 10^{-10}$ without trigger, $S/B \approx 0.1$ with trigger

Higgs event in e^+e^-



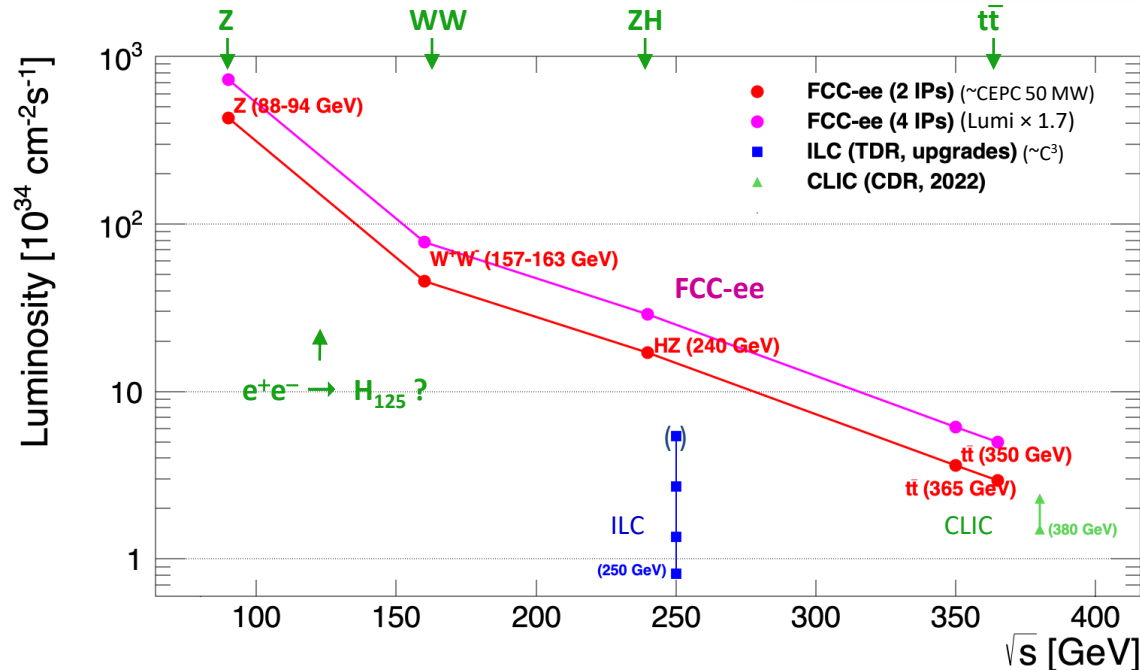
e^+e^- : detect everything; measure precisely

- Clean experimental environment
 - Trigger-less readout
 - Low radiation levels
- Superior sensitivity for electro-weak states
- Limited direct mass reach
- $S/B \approx 1 \rightarrow$ measurement

e^+e^- Collider Options

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

| | | | | | | |
|----------------------|-------------------------|----------|--------------------|-------------------------------|-------------------|------------------------------|
| ZH maximum | $\sqrt{s} \sim 240$ GeV | 3 years | 2×10^6 | $e^+e^- \rightarrow ZH$ | Never done | \sqrt{s} uncertainty 2 MeV |
| $t\bar{t}$ threshold | $\sqrt{s} \sim 365$ GeV | 5 years | 2×10^6 | $e^+e^- \rightarrow t\bar{t}$ | Never done | 5 MeV |
| Z peak | $\sqrt{s} \sim 91$ GeV | 4 years | 6×10^{12} | $e^+e^- \rightarrow Z$ | LEP $\times 10^5$ | < 50 keV |
| WW threshold+ | $\sqrt{s} \geq 161$ GeV | 2 years | 3×10^8 | $e^+e^- \rightarrow W^+W^-$ | LEP $\times 10^3$ | < 200 keV |
| [s-channel H | $\sqrt{s} = 125$ GeV | 5? years | ~ 8000 | $e^+e^- \rightarrow H_{125}$ | Never done | < 100 keV |



FCC-ee: ultimate precision with

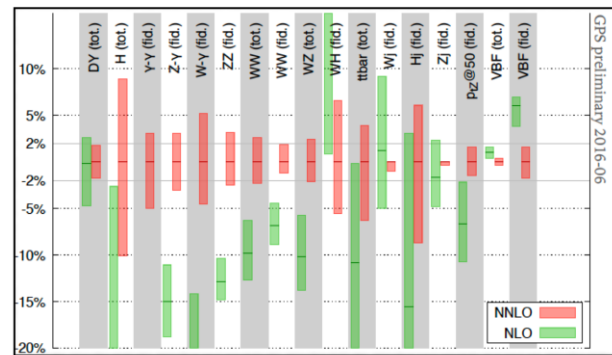
- **$\sim 100\,000$ Z / second (!)**
 - 1 Z / second at LEP
 - **$\sim 10\,000$ W / hour**
 - 20 000 W in 5 years at LEP
 - **$\sim 1\,500$ Higgs bosons / day**
 - 10-20 times more than ILC
 - **$\sim 1\,500$ top quarks / day**
- ... in each detector

The Challenge – High Precision Measurements

| Observable | present value \pm 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 |
| $\sin^2 \theta_W^{\text{eff}} (\times 10^6)$ | 231480 ± 160 | 2 | 2.4 | from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration |
| $1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$ | 128952 ± 14 | 3 | small | from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate |
| $R_\ell^Z (\times 10^3)$ | 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 |
| $\sigma_{\text{had}}^0 (\times 10^3)$ (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 |
| $A_{FB,0}^b (\times 10^4)$ | 992 ± 16 | 0.02 | 1-3 | b-quark asymmetry at Z pole from jet charge |
| $A_{FB}^{\text{pol},\tau} (\times 10^4)$ | 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 |
| $\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$ | 1.2 ± 0.3 | 0.8 | small | ratio of invis. to leptonic in radiative Z returns |
| ttZ couplings | $\pm 30\%$ | 17 | small | From $t\bar{t}$ threshold scan QCD errors dominate |
| | | 45 | small | From $t\bar{t}$ threshold scan QCD errors dominate |
| | | 0.10 | small | From $t\bar{t}$ threshold scan QCD errors dominate |
| | | 0.5 – 1.5 % | small | From $\sqrt{s} = 365$ GeV run |

→ see physics talk later in this session

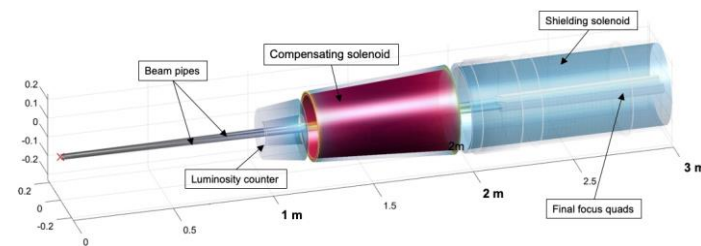
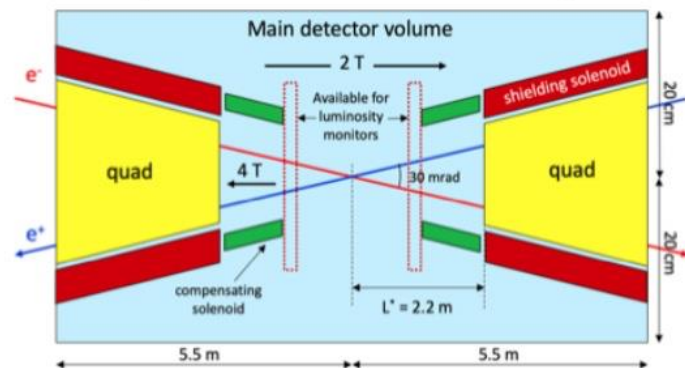
- **FCC-ee EWPO measurements with unprecedented statistical precision**
 - e.g. 6×10^{12} hadronic Z decays at Z-pole
 - **Statistical precision** for EWPOs measured at the Z-pole is **typically 500 times smaller than the current uncertainties**
- **→ Systematic uncertainty dominant!**
- **→ Can achieve 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
 - Access to phase-space limited regions + understand correlations among bins in distributions
 - **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 ≤ 20 ns
 - Power management and cooling (no power pulsing as possible for linear coll.)
- **Extremely high luminosities**
 - High statistical precision – control of systematics down to 10^{-6} 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 $\lesssim 1$ μ s 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**
 - Absolute luminosity measurement to 10^{-4} – luminometer acceptance to $\mathcal{O}(1 \mu\text{m})$ level
 - Detector acceptance to $\sim 10^{-5}$ – acceptance definition to few micro-radians, hermeticity (no cracks!)
 - Precise momentum measurement through quasi-continuous resonant depolarisation (RDP) measurements \rightarrow e.g. 50 keV at the Z pole
 - Stability of momentum measurement – stability of magnetic field wrt E_{cm} (10^{-6})

Central part of detector volume – top view



FCC-ee Physics Programme

"Higgs Factory" Programme

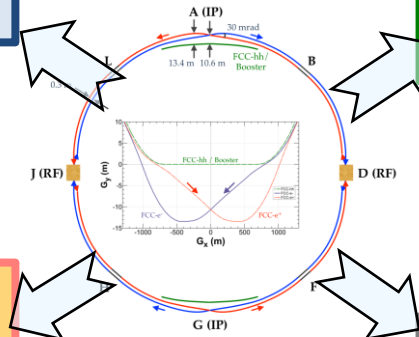
- At two energies, 240 and 365 GeV, collect in total
 - 1.2M HZ events and 75k WW \rightarrow H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s} =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

Ultra Precise EW Programme & QCD

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

- 6×10^{12} Z and 3×10^8 WW
 - $m_Z, \Gamma_Z, \Gamma_{inv}, \sin^2\theta_W^{eff}, R_\ell^Z, R_b, \alpha_s, m_W, \Gamma_W, \dots$
- 2×10^6 tt
 - $m_{top}, \Gamma_{top},$ EW couplings

Indirect sensitivity to new phys. up to $\Lambda = 70$ TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} $\tau\tau$
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. $b \rightarrow s\tau\tau$, 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

Courtesy M. Dam

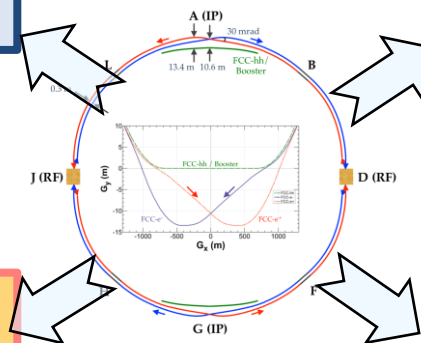
FCC-ee Detector Requirements

"Higgs Factory" Programme

- Momentum resol. at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with $\mathcal{O}(10^{-3})$ 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. $\Gamma_{\text{had}}/\Gamma_\ell$) to 10^{-5}
- Momentum resolution "as good as we can get it"
 - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from $\mu\mu$)
- Stability of B-field to 10^{-6} : stability of v_s meas.



Heavy Flavour Programme

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

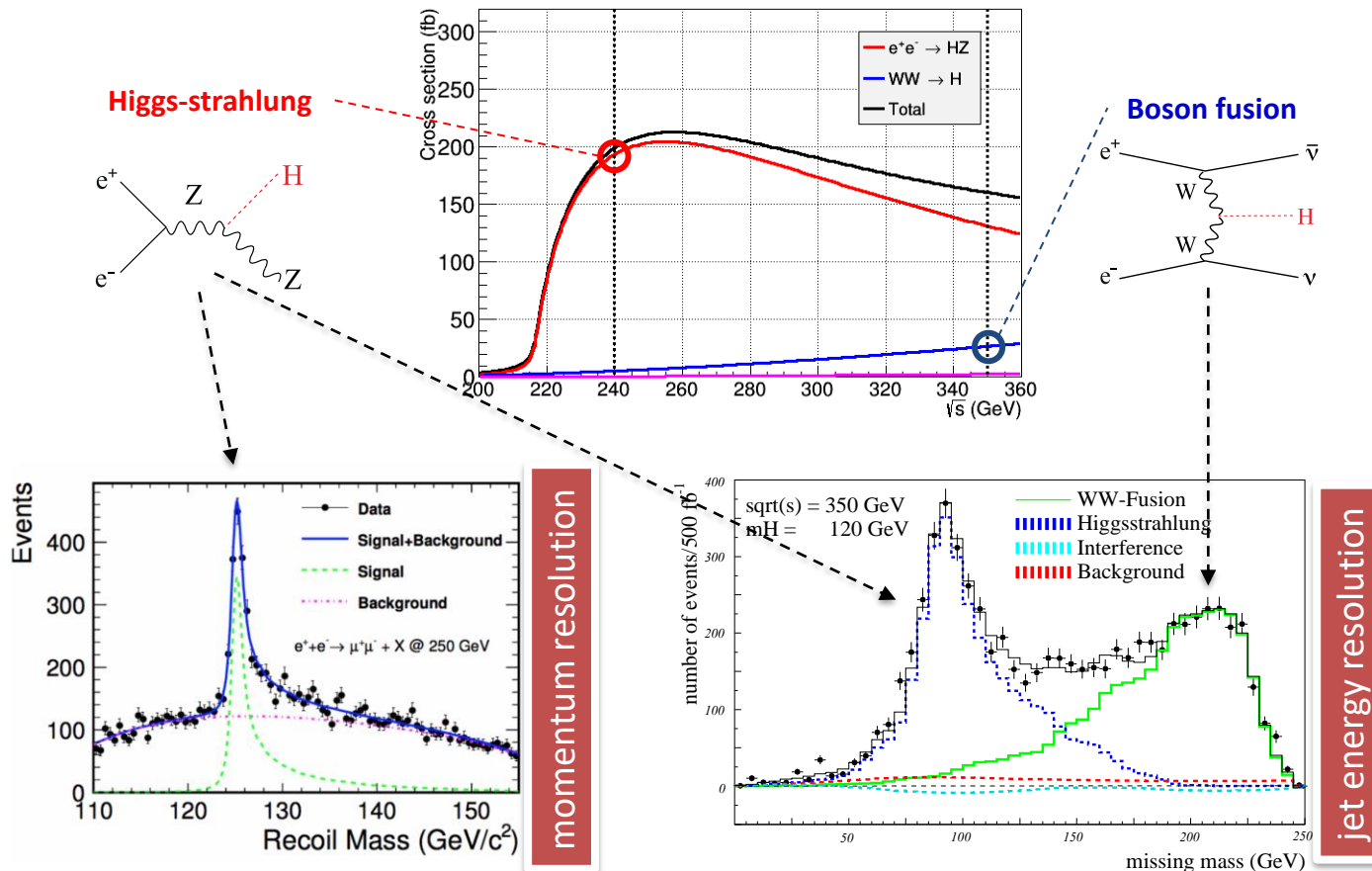
Feebly Coupled Particles - LLPs

Benchmark signature: $Z \rightarrow \nu N$, with N decaying late

- Sensitivity to far detached vertices (mm \rightarrow m)
 - Tracking: more layers, continuous tracking
 - Calorimetry: granularity, tracking capability
- Large decay lengths \Rightarrow extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

Courtesy M. Dam

Higgs Factory: Higgs Production and Decay



| $M_H = 125$ GeV | SM BF |
|--------------------|-------|
| bb | 56.1% |
| WW* | 23.1% |
| gg | 8.2% |
| $\tau\tau$ | 6.3% |
| ZZ* | 2.6% |
| cc | 2.9% |
| $\gamma\gamma$ | 0.2% |
| Z γ | 0.15% |
| ss | 0.1% |
| $\mu\mu$ | 0.02% |

flavour tagging

Vertex Detector and Tracking

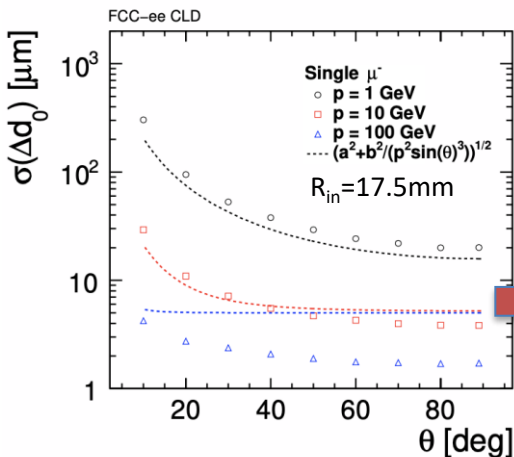
Flavour Tagging:
Impact parameter
"design goal"...

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2} \theta}$$

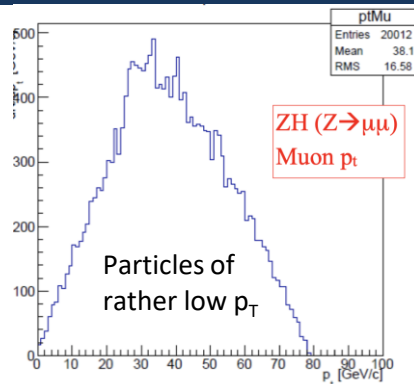
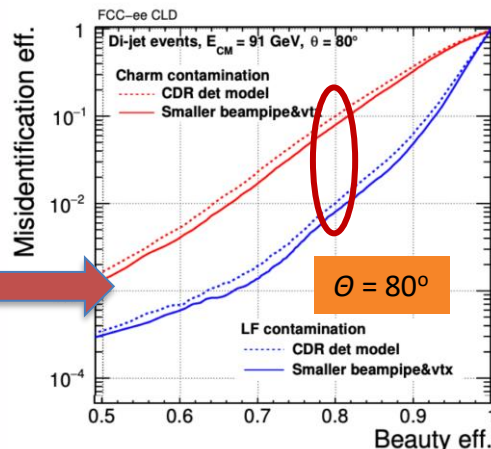
$a \simeq 5 \mu\text{m}; \quad b \simeq 15 \mu\text{m GeV}$

arXiv:1911.12230

e.g. CLD flavour tagging



b-tagging



→ **Momentum resolution**
multiple scattering dominated

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

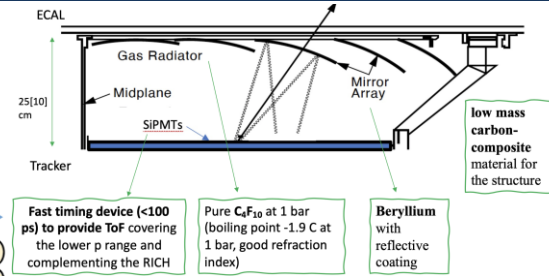
$$\frac{\Delta p_T}{p_T} \Big|_{m.s.} \approx \frac{0.0136 \text{ GeV}/c}{0.3\beta B_0 L_0} \sqrt{\frac{d_{tot}}{X_0 \sin \theta}}$$

- **Flavour tagging – Vertex Detector: Lighter, more precise (smaller pixel size), closer to IP**
- **Momentum Resolution – Tracking Detector: The lighter the better**

| | r beam pipe | 1 st VTX layer |
|--------|-------------|---------------------------|
| ILC | 12 mm | 14 mm |
| CLIC | 29 mm | 31 mm |
| FCC-ee | 10 mm | 12 mm |

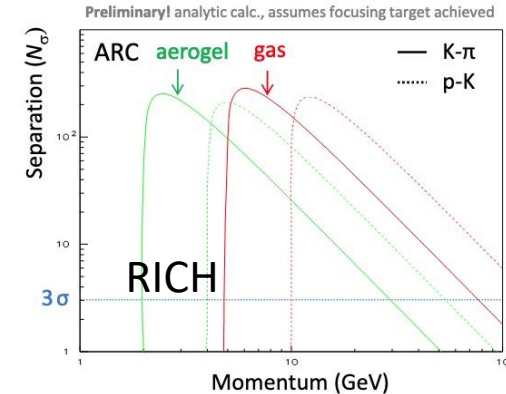
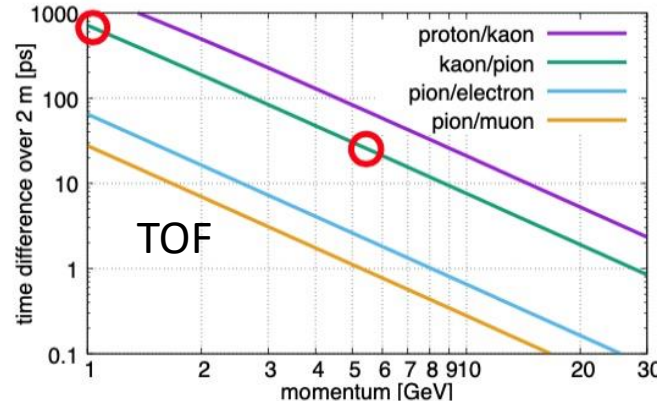
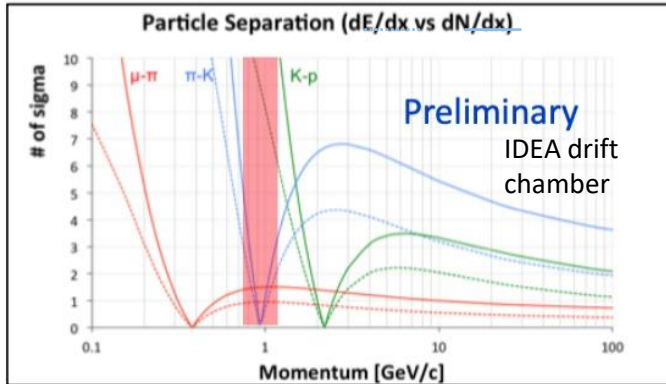
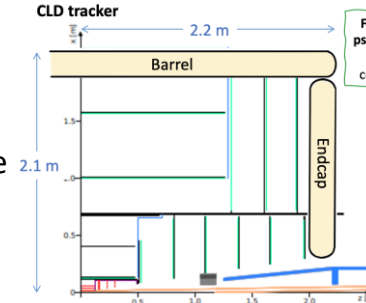
Particle Identification

- PID capabilities across a wide momentum range** is essential for flavour studies and will enhance overall physics reach
 - Example: important mode for CP-violation studies $B_s^0 \rightarrow D_s^\pm K^\mp \rightarrow$ require K/π separation over wide momentum range to suppress same topology $B_s^0 \rightarrow D_s^\pm \pi^\mp$
- E.g. IDEA drift chamber** promises $>3\sigma$ π/K separation all the way up to 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, TORCH)
 - 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)
 - \rightarrow 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 : $22 X_0, 7\lambda$

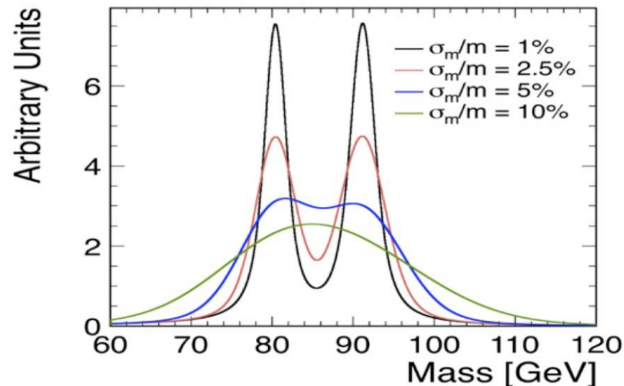
Precise jet angular resolution

Jet energy: $\sigma(E_{\text{jet}})/E_{\text{jet}} \approx 30\% / \sqrt{E} [\text{GeV}]$?

⇒ **Mass reconstruction from jet pairs**

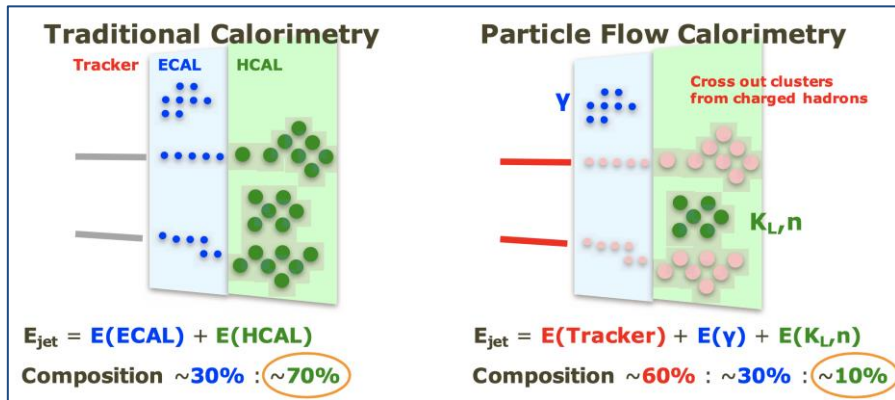
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to $\nu\nu H$
- $HZ \rightarrow 4$ jets, $t\bar{t}$ events (6 jets), etc.
- At $\sigma E/E \approx 30\% / \sqrt{E} [\text{GeV}]$, detector resolution is comparable to natural widths of W and Z bosons



How to achieve jet energy resolutions of $\sim 3\text{-}4\%$ at 50 GeV:

- **Highly granular calorimeters**
- **Particle Flow reconstruction and possibly in addition techniques to correct non-compensation ($e/h \neq 1$), e.g. dual read-out**



→ High granularity and/or dual read-out

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] | $\approx 6\%$? | 4 % [20] |
| Highly granular Noble liquid based ECAL & Scintillator based HCAL | 8 – 10 % [24,27,46] | < 1 % [24,27,47] | $\approx 40\%$ [27,28] | $\approx 6\%$? | 3 – 4 % ? |
| Dual-readout Fibre calorimeter | 11 % [48] | < 1 % [48] | $\approx 30\%$ [48] | 4 – 5 % [49] | 3 – 4 % ? |
| Hybrid crystal and Dual-readout calorimeter | 3 % [30] | < 1 % [30] | $\approx 26\%$ [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>

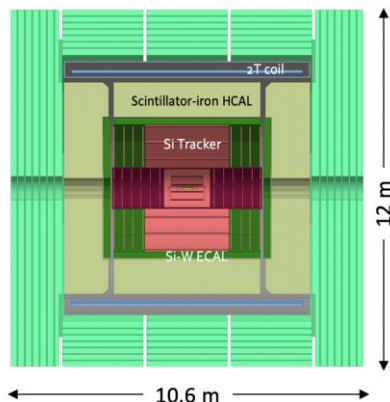
- **Excellent Jet resolution:** $\approx 30\%/ \sqrt{E}$
- **ECAL resolution:** Higgs physics $\approx 15\%/ \sqrt{E}$; but for heavy flavour programme better resolution beneficial $\rightarrow 8\%/ \sqrt{E} \rightarrow 3\%/ \sqrt{E}$
- **Fine segmentation for PF algorithm** and powerful γ/π^0 separation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



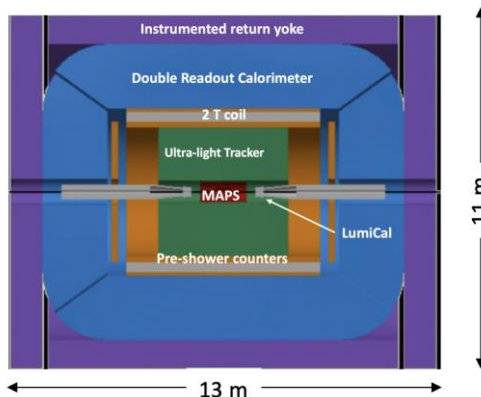
Proto Detectors

FCC-ee Proto Detectors – Overview

CLD

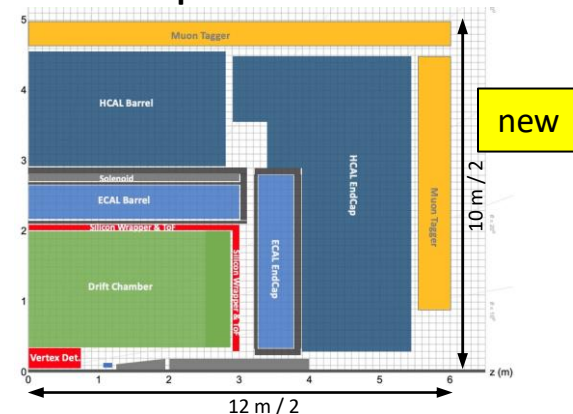


IDEA



- A bit less established design
 - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
 - Possibly augmented by crystal ECAL
- Muon system
- Very active community
 - Prototype designs, test beam campaigns, ...

Noble Liquid ECAL based

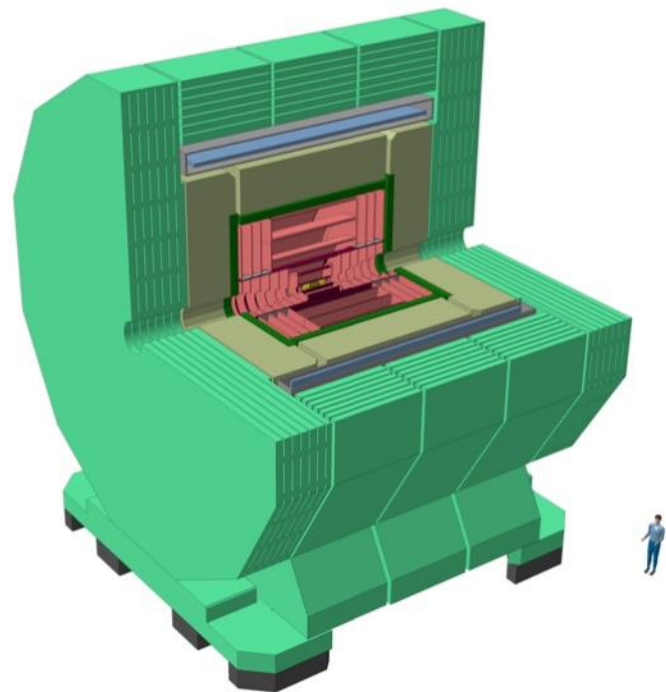
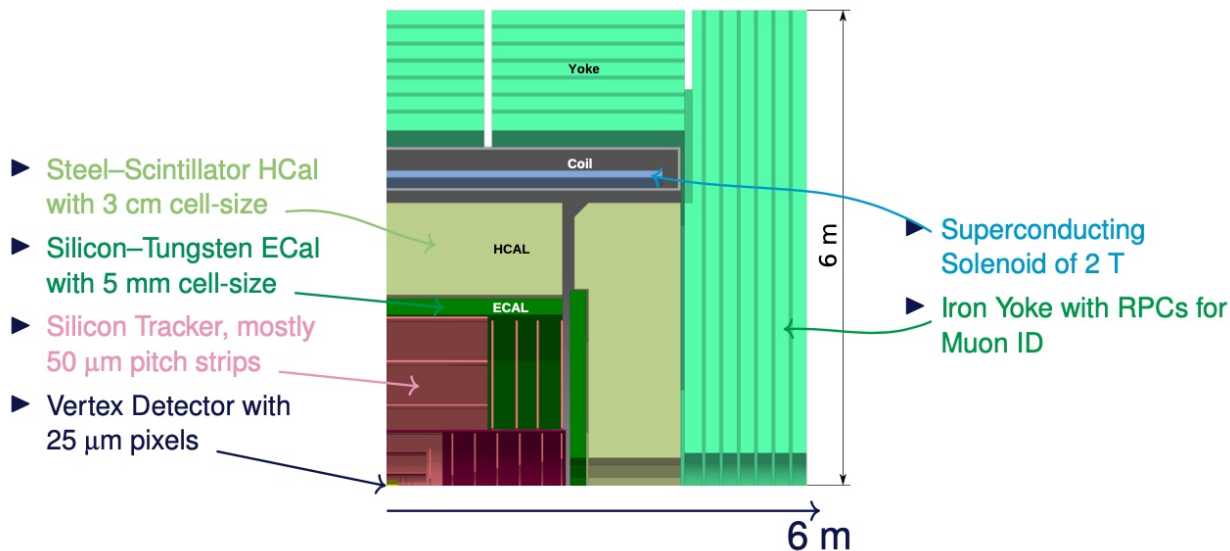


- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
 - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
 - Readout electrodes, feed-throughs, electronics, light cryostat, ...
 - Software & performance studies

FCC-ee CDR: <https://link.springer.com/article/10.1140/epjst/e2019-900045-4>

CLD Detector Concept

General purpose detector for Particle Flow reconstruction
(based on the work for a detector at CLIC)



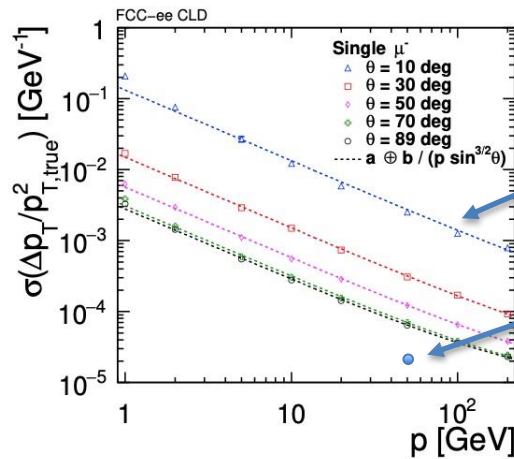
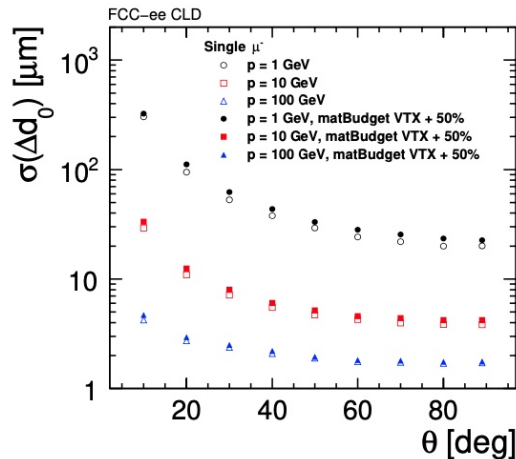
2 Tesla Solenoid Field (solenoid $r=3.7\text{m}$, $L=7.4\text{m}$)

Return yoke contains muon system with 6 equidistant layers

<https://arxiv.org/abs/1911.12230>

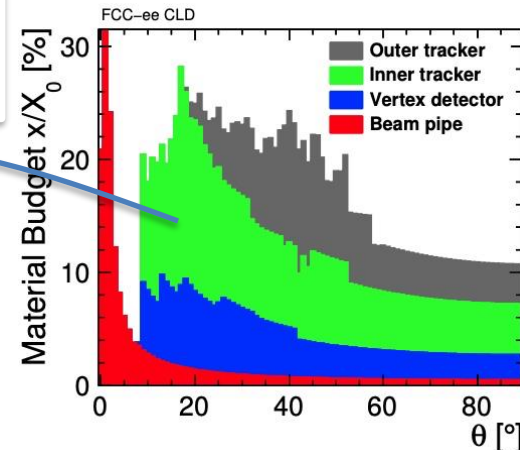
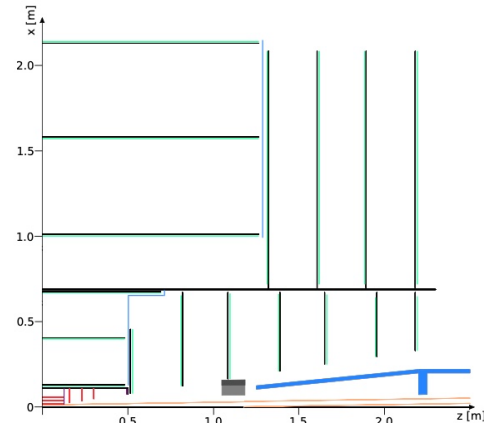
CLD Vertex Detector and Si Tracker

- **Silicon vertex detector:** precise vertex reconstruction
 - $25 \times 25 \mu\text{m}^2$ pixels, $3 \mu\text{m}$ single point resolution, $50 \mu\text{m}$ silicon thickness
 - Double layers ($0.3 \% X_0$ per detection layer), $R_{\text{in}} = 17.5 \text{ mm}$
- **Inner and Outer Tracker**
 - 3 short and 3 long barrel layers, 7 inner and 4 outer endcaps
 - $200 \mu\text{m}$ Silicon thickness, $50 \mu\text{m} \times 0.3 \text{ mm}$ cell size, $7 \mu\text{m} \times 90 \mu\text{m}$ single point resolution (except first inner tracker disk, $5 \times 5 \mu\text{m}^2$)
 - At least 8 hits for $\theta > 8.5^\circ$
 - Material budget: $1.1 \% - 2.2 \% X_0$ per layer (including overlaps)
 - Some studies for re-scaling were done, $R_{\text{max}} \in (2.1, 2.0, 1.9, 1.8)$



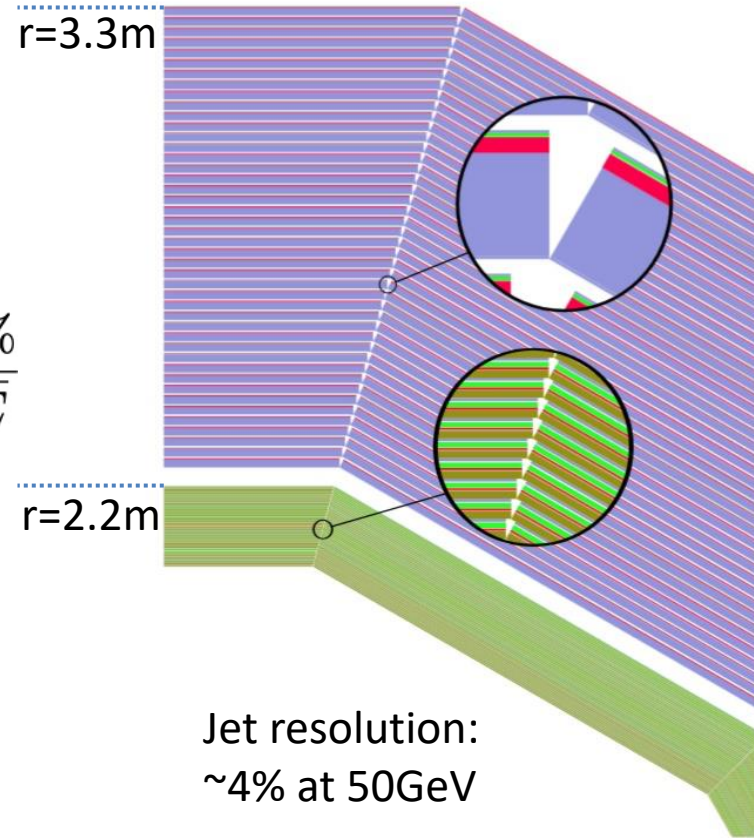
Multiple scattering limited
→ lighter Si tracker!?

$$\sigma_{pT}/p_T \approx 10^{-3} \text{ @ } 50 \text{ GeV}$$



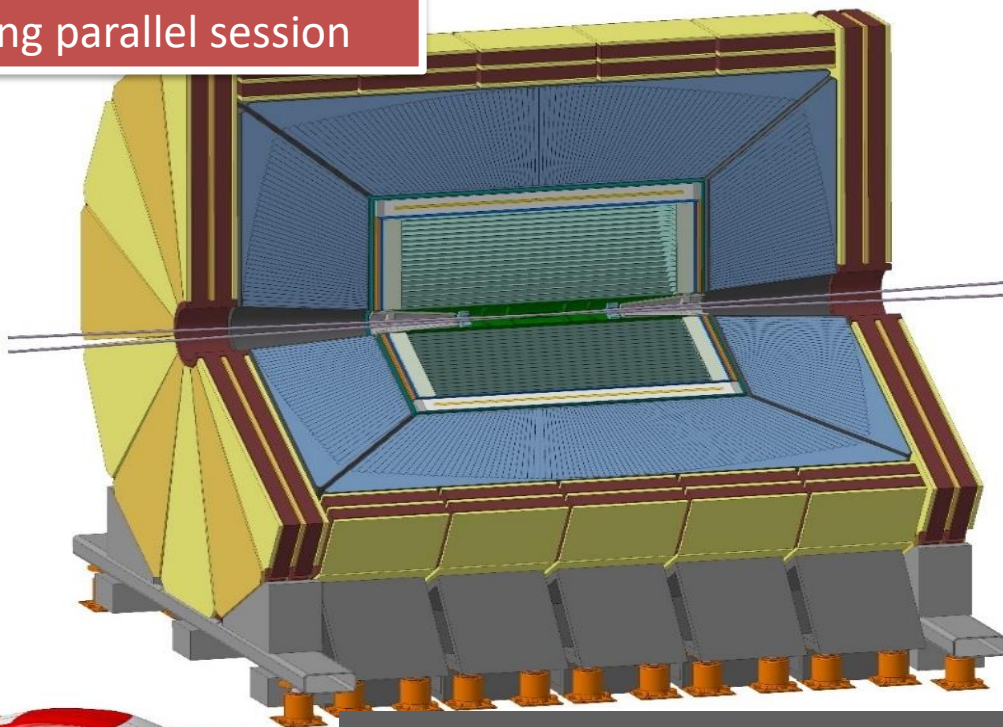
CLD Calorimetry

- ECal (Si/W)
 - 40 layers, 1.9 mm tungsten absorber, $22 X_0$
 - 0.5 mm thick silicon sensors with $5 \times 5 \text{ mm}^2$ granularity
 - ECal optimisation studies $\frac{\sigma}{E} \approx \frac{16\%}{\sqrt{E}}$
- HCal (Scintillator/Steel)
 - 44 layers, 19 mm steel absorber, $5.5 (+1) \lambda$
 - 3 mm thick scintillator tiles with $3 \times 3 \text{ cm}^2$ granularity



IDEA Detector Concept

→ See talks in the Tuesday morning parallel session



IDEA concept (proposed in FCC CDR)
Innovative DETector for e^+e^- Accelerator

New, innovative concept

- Silicon vertex detector
 - 5MAPS layers, $R=1.7-34\text{cm}$
- Short-drift, ultra-light wire chamber
 - 112 layers, $L=4\text{m}$, $R=35-200\text{cm}$
- Silicon wrapper
- Thin and light solenoid coil inside calorimeter system (see back-up)
 - Coil: 2T, $R=2.1-2.4\text{m}$
 - $0.76X_0$, $0.16\lambda_{\text{int}}$
- Dual-readout calorimeter
 - 2m depth, $7\lambda_{\text{int}}$
 - Particle flow reconstruction
 - Option: crystal calorimeter in front for better EM resolution
- Muon system made of 3 layers of μ -RWELL detectors in the return yoke (see back-up)

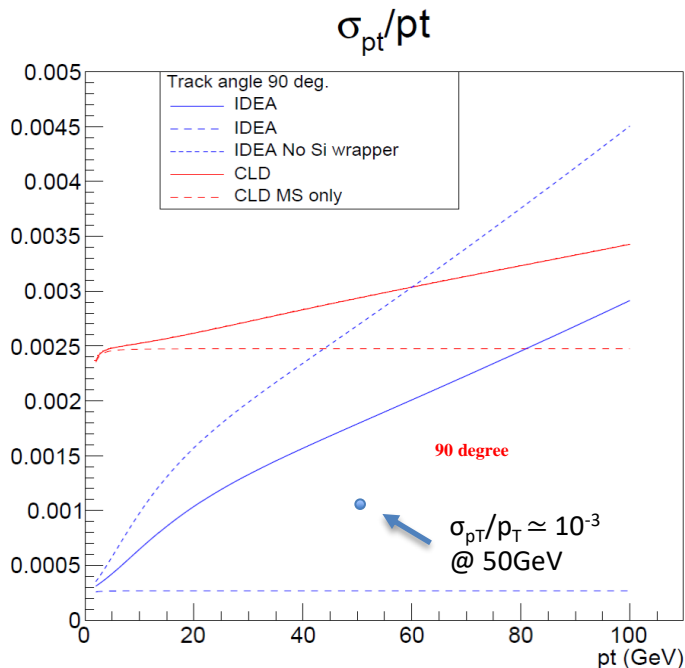
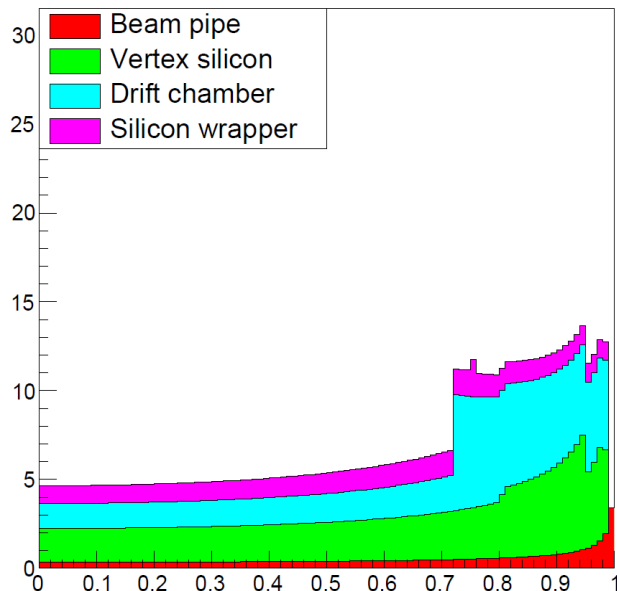
<https://pos.sissa.it/390/877/pdf>

Vertex Detector & Momentum Measurement

Tracker: Z or H decay muons in ZH events have rather low p_T

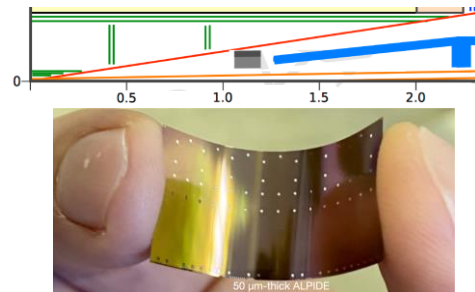
- Transparency more important than asymptotic resol. → minimize material!
- Very light vertex detector and drift chamber (see next slide and back-up)

IDEA: Material vs. $\cos(\theta)$



Vertex Detector: Inspired by Belle II based on MAPS technology, using the ARCADIA R&D program

- 5MAPS layers, pixels $20 \times 20 \mu m^2$
- Light
 - Inner layers: $0.3\% X_0/\text{layer}$
 - Outer layers: $1\% X_0/\text{layer}$
- Performance:
 - Point resolution of ~ 3 mm
 - Efficiency of $\sim 100\%$
 - Extremely low fake rate hit rate

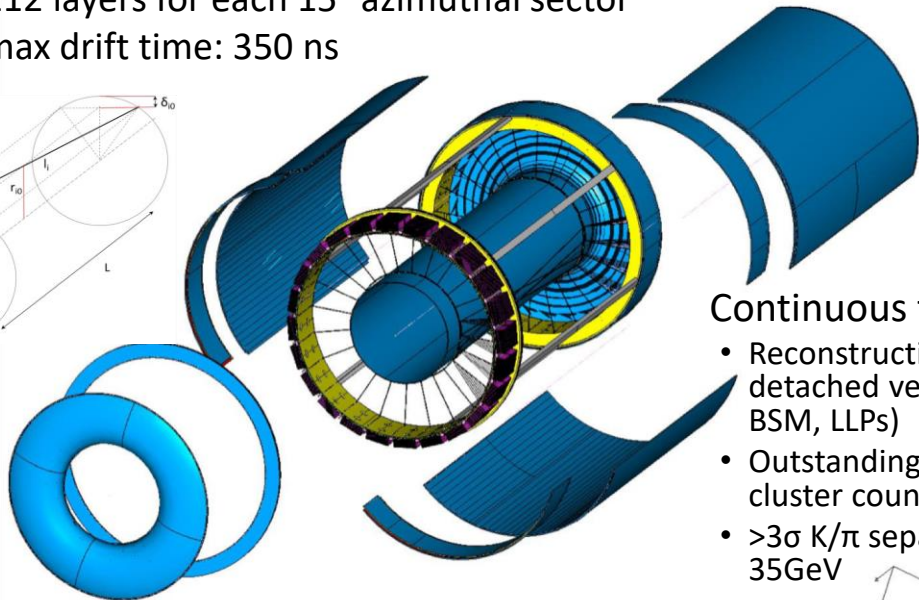
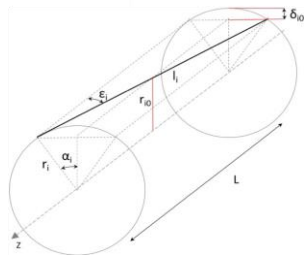


Courtesy of Magnus Mager, CERN

Drift Chamber

IDEA: Extremely transparent Drift Chamber

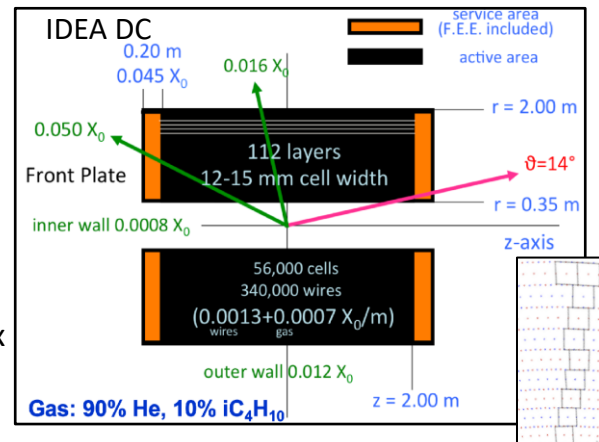
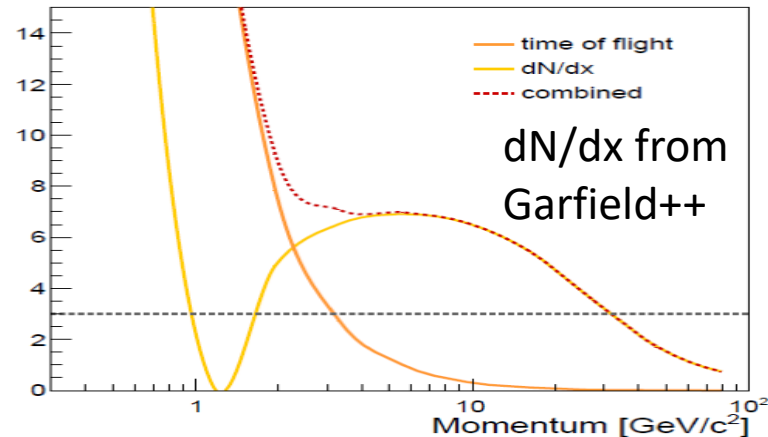
- Gas: 90% He – 10% iC_4H_{10}
- Radius 0.35 – 2.00m
- Total thickness: 1.6% of X_0 at 90°
 - Tungsten wires dominant contribution
- 112 layers for each 15° azimuthal sector
- max drift time: 350 ns



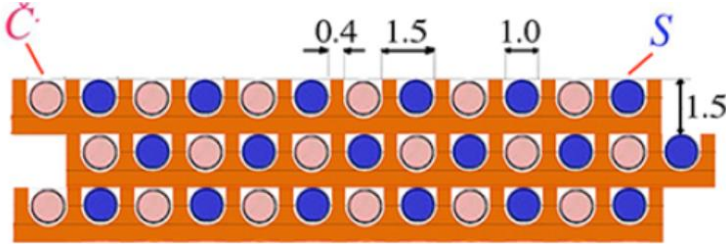
Continuous tracking:

- Reconstruction of far-detached vertices (K_s^0 , Λ , BSM, LLPs)
- Outstanding part. ID via cluster count. dN/dx or dE/dx
- $>3\sigma$ K/ π separation up to 35GeV

significance

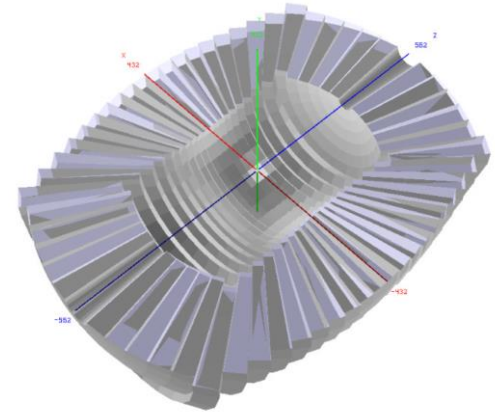


Dual Readout Calorimetry

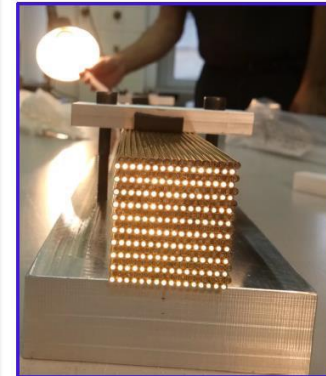


Alternate

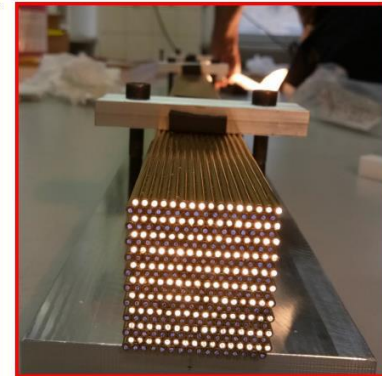
- Scintillation fibres
- Cherenkov fibres



Newer DR calorimeter (bucatini calorimeter)



Scintillation fibers



Cherenkov fibers

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

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

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

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

Full GEANT4 simulation:

hadronic:

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

electromagnetic:

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

Crystal option:

$$20\text{cm PbWO}_4 \quad \frac{\sigma}{E} \approx \frac{3\%}{\sqrt{E}}$$

Noble-Liquid ECAL Based Detector Concept



Vertex Detector:

- MAPS or DMAPS possibly with timing layer (LGAD)
- Possibly ALICE 3 like?

Drift Chamber ($\pm 2.5\text{m}$ active)

Silicon Wrapper + ToF:

- MAPS or DMAPS possibly with timing layer (LGAD)
- ## High Granularity ECAL:
- Noble liquid + Pb or W
 - Particle Flow reconstruction

Solenoid $B=2\text{T}$, sharing cryostat with ECAL, outside ECAL

- Light solenoid coil $\approx 0.76 X_0$ (see back-up)
- Low-material cryostat $< 0.1 X_0$ (see back-up)

High Granularity HCAL / Iron Yoke:

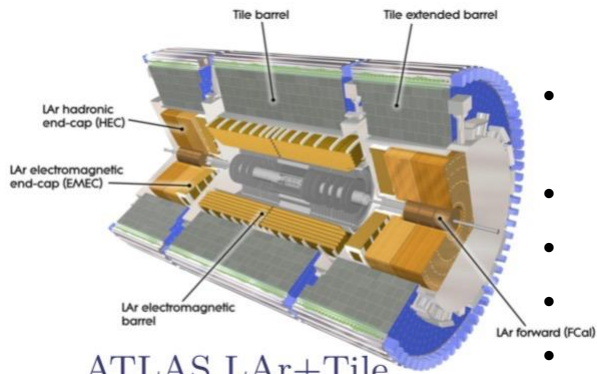
- Scintillator + Iron (particle flow reconstruction)
- SiPMs directly on Scintillator or
- TileCal: WS fibres, SiPMs outside

Muon Tagger:

- Drift chambers, RPC, MicroMegas

See [talk](#) at [FCC Week 2022](#) in Paris

FCC Calorimetry

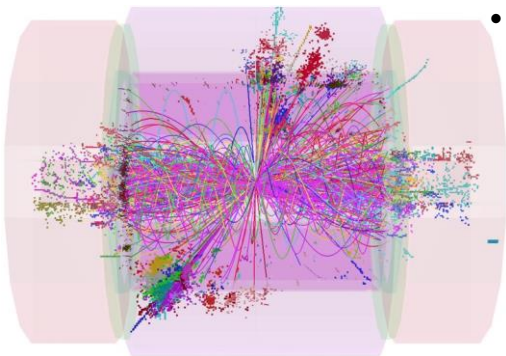


ATLAS LAr+Tile

arXiv:1305.4551

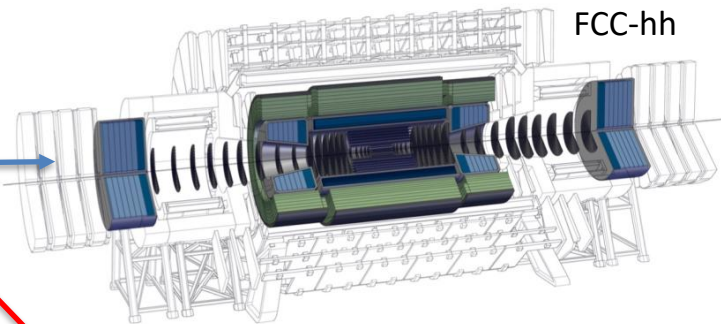
- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

- High granularity
 - Pile-up rejection
 - Particle flow
 - 3D/4D/5D imaging

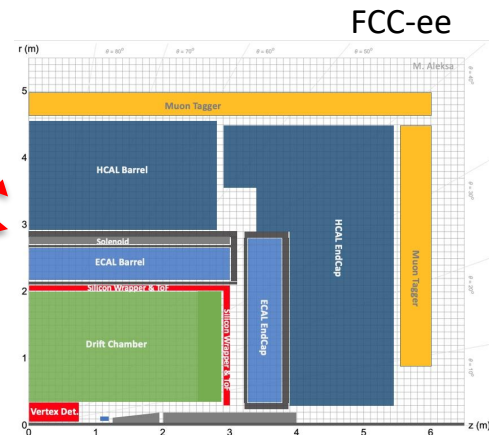


CLIC Detector

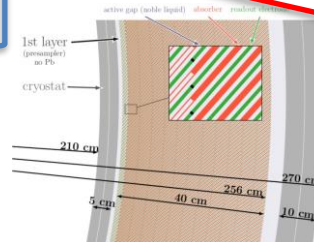
FCC Calorimetry



FCC-hh



FCC-ee



FCC-hh Calorimetry studies have been published at <https://arxiv.org/abs/1912.09962>

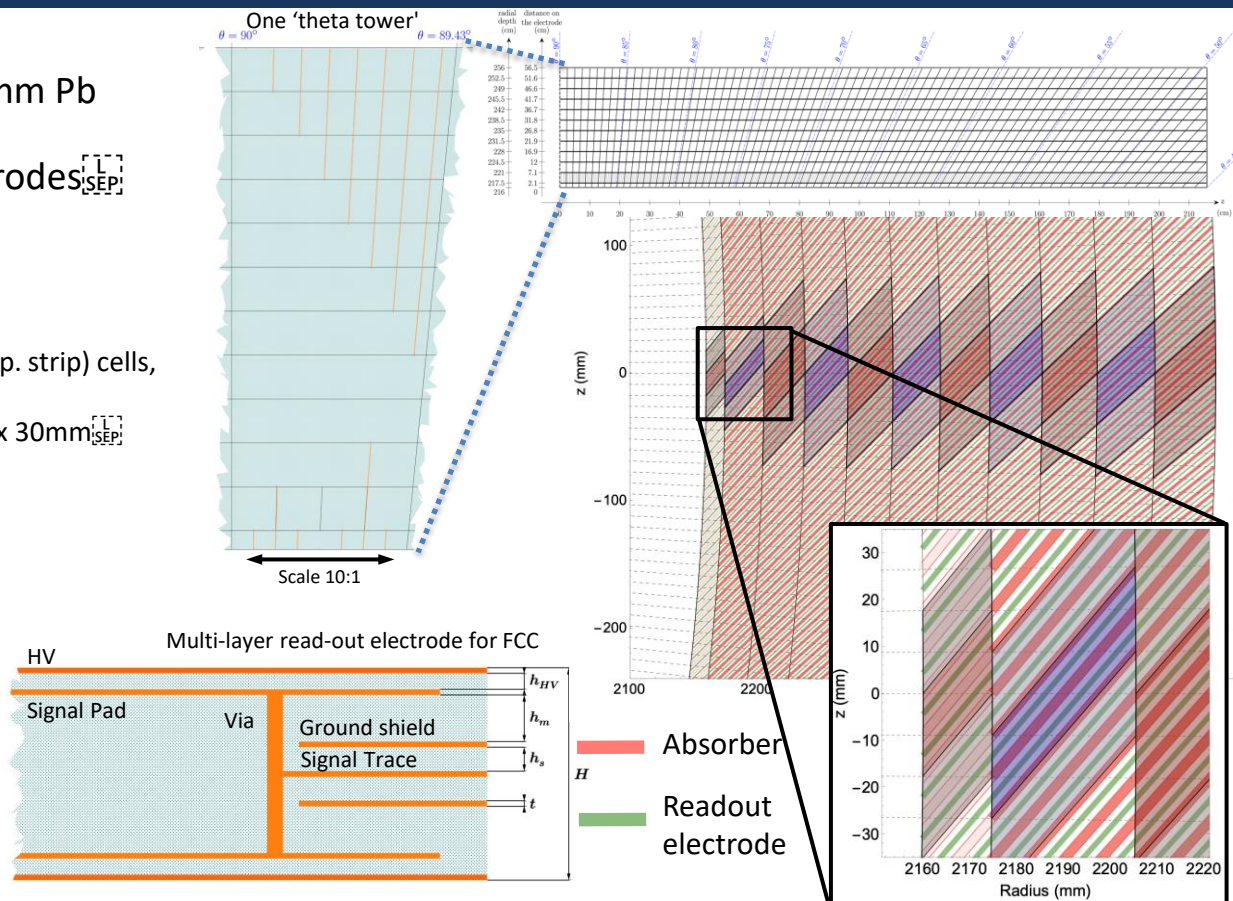
High Granularity Noble-Liquid Calorimeter

Baseline design

- 1536 straight inclined (50.4°) 1.8mm Pb absorber plates_[SEP]
- Multi-layer PCBs as readout electrodes_[SEP]
- 1.2 – 2.4mm LAr gaps_[SEP]
- 40cm deep ($\approx 22 X_0$)_[SEP]
- Segmentation:
 - $\Delta\theta = 10$ (2.5) mrad for regular (1st comp. strip) cells,
 - $\Delta\phi = 8$ mrad
 - \rightarrow cell size in strips: 5.4mm x 17.8mm x 30mm_[SEP]
- 11 longitudinal compartments_[SEP]
- Implemented in FCC-SW Fullsim

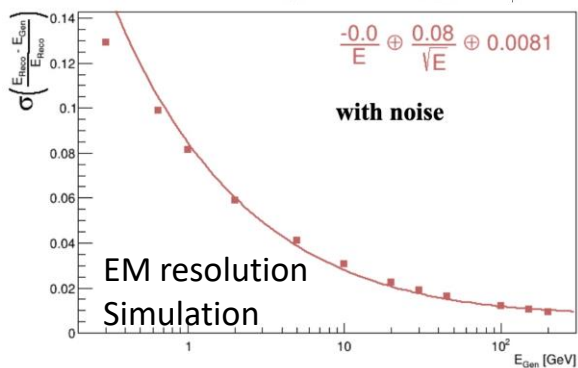
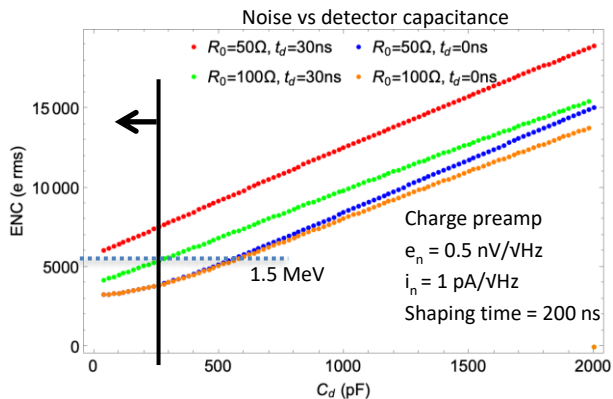
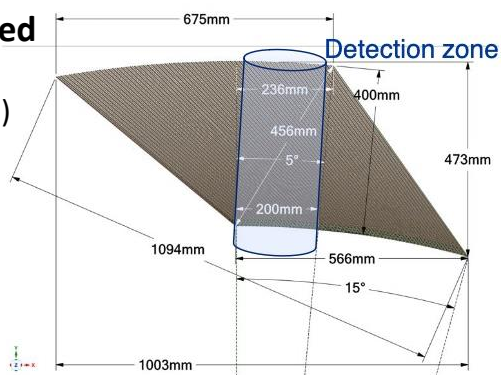
Possible Options

- LKr or LAr, W or Pb absorbers,
- Absorbers with growing thickn.
- Granularity optimization
- Al or carbon fibre cryostat
- Warm or cold electronics



Challenges: Resolution, Noise and Crosstalk

- **EM resolution** with sampling term of 8 to 9%
- **Noise vs cross-talk challenge:** traces need to be shielded to minimize cross-talk → grounded shields increase detector capacitance and hence noise → need to find best compromise – **prototype electrode produced & measured**
 - **Noise** of < 1.5 MeV per cell for warm electronics and transmission lines of $R_0 = 100 \Omega$ and $\tau = 200 \text{ ns}$ ($C_d \leq 250 \text{ pF}$)
 - → MIP S/N > 5 reached for all layers
 - **Cross-talk** of < 1% for shaping times $\tau \geq 20 \text{ ns}$
- **Next steps: Further optimization, then ≈ 64 absorber test module for testbeam measurements**



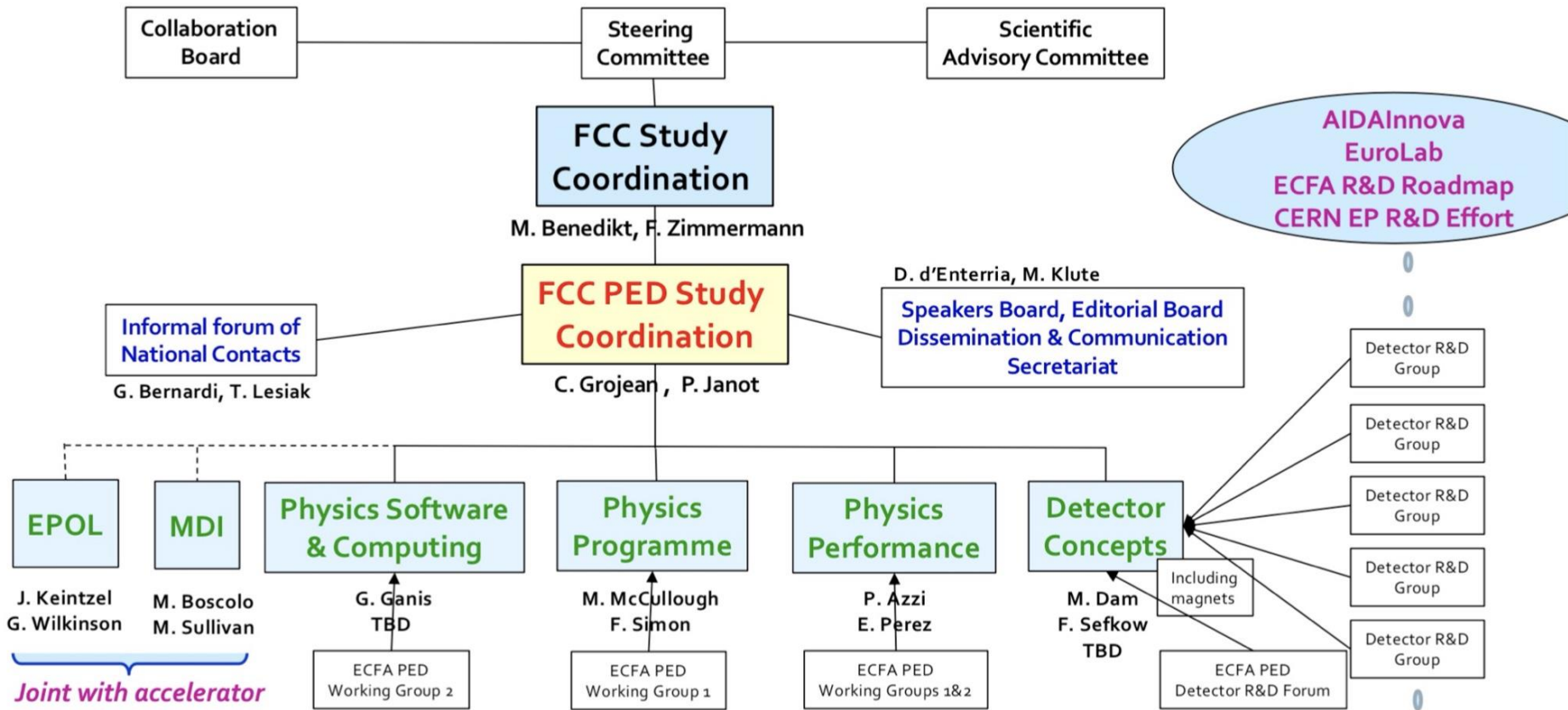
Simulated cross-talk 2 shields < 1% for $\tau \geq 20 \text{ ns}$ confirmed by measurements on prototype

| Cross-talk (%) | Cell 1 | Cell 2 | Cell 3 | Cell 4 | Cell 5 | Cell 6 |
|---------------------|--------|--------|--------|--------|--------|--------|
| Shaping time (ns) ↓ | | | | | | |
| No shaper | 0.54 | 0.85 | 0.85 | 2.31 | 2.62 | 9.11 |
| 20 | 0.03 | 0.04 | 0.01 | 0.09 | 0.11 | 0.75 |
| 50 | 0.01 | 0.02 | 0.0 | 0.04 | 0.05 | 0.37 |
| 100 | 0.01 | 0.01 | 0.0 | 0.02 | 0.03 | 0.23 |
| 150 | 0.0 | 0.01 | 0.0 | 0.02 | 0.02 | 0.18 |
| 200 | 0.0 | 0.01 | 0.0 | 0.01 | 0.02 | 0.15 |
| 300 | 0.0 | 0.0 | 0.0 | 0.01 | 0.01 | 0.13 |



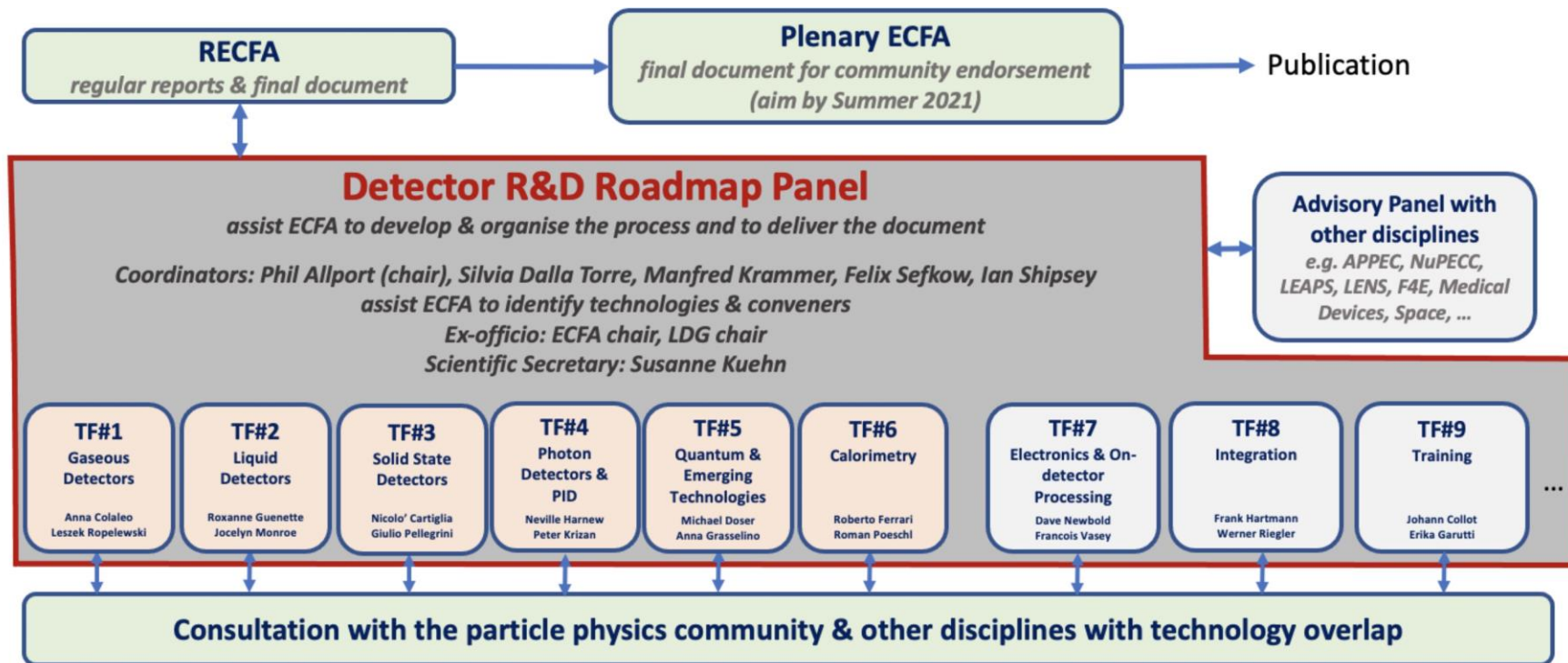
FCC Organisation & Detector R&D

The International FCC Organization



ECFA Detector Roadmap Implementation

<https://indico.cern.ch/event/957057/>



- Focus on the technical aspects given the EPPSU process as input.
- Development of a matrix, where for each Task Force the identified future science programmes that they will need to address in terms of the main technology challenges to be met and estimate the lead-time over which the required detector R&D programmes may be expected to extend.
- Create a time-ordered R&D requirements roadmap in terms of key capabilities not currently achievable.

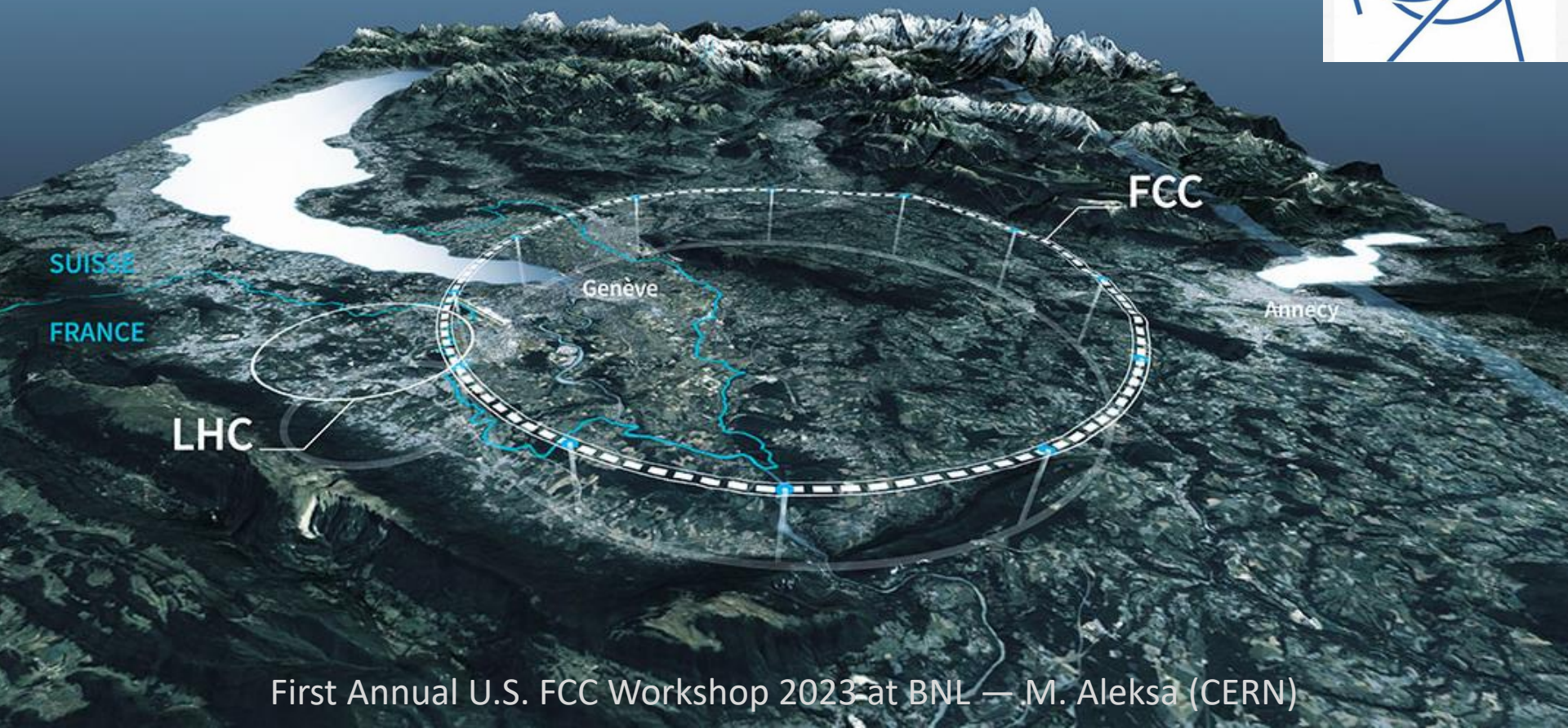
30

Conclusions

- 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
 - Full exploitation of physics potential via N "general purpose" experiments, possibly complemented by M dedicated experiments (e.g. heavy flavour) $\rightarrow N+M \leq 4$
- For next ESPP, need to propose detector concepts that meet the experimental challenge
- Detector Concepts working group formed last year (e-group: FCC-PED-DetectorConcepts), monthly meetings: <https://indico.cern.ch/category/15054/>
- Detector R&D for FCC-ee is a rich field totally orthogonal to challenges at HL-LHC or DUNE!
- Strong European effort (ECFA) on setting up Detector R&D Collaborations
- Many interesting questions and research topics ahead of us!
- We are all looking forward to a fruitful collaboration towards the approval of the project in 2028, and the proposal of four detectors in ~2032!!



Thank You for Your Attention!



First Annual U.S. FCC Workshop 2023 at BNL — M. Aleksa (CERN)



BACK-UP

Ultra-Thin Solenoid Magnet R&D at CERN

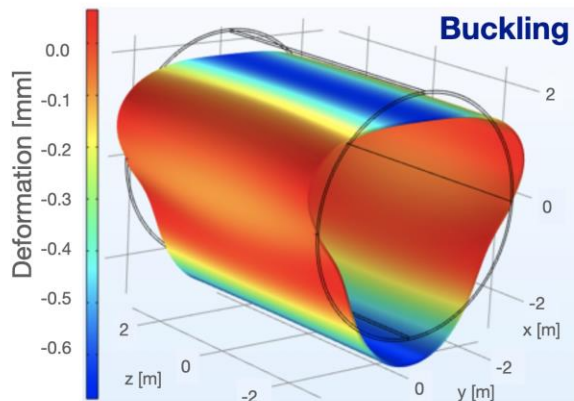
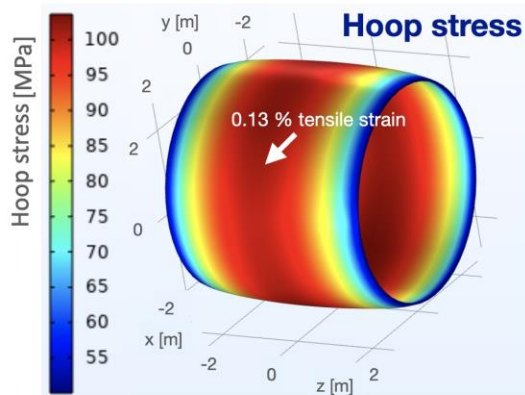
Thin solenoid magnet ($R=2.2\text{m}$) as developed for IDEA inside calorimeter cryostat (inside or outside ECAL)

- Support cylinder with thickness of 12 mm
- Support cylinder material: aluminium 5083

Transparency of the cold mass: $0.76 X_0$
Energy density: $\sim 14 \text{ kJ/kg}$ [2]

- First mechanical analysis is promising

| | Conductor | Support | |
|-----------------|---------------------|------------------|------|
| Parameter | Value | Value | Unit |
| Material | Ni-doped aluminium | Aluminium 5083 | |
| Yield strength | 147 (with NbTi) [3] | 209 @ 4.2 K [4] | MPa |
| Young's modulus | 75×10^3 | 81×10^3 | MPa |



- Peak von Mises stress: **105 MPa**
- Peak tensile strain: **0.13 %**
- Peak shear stress: **0.5 MPa**
- Buckling of coil with simple (**pessimistic**) support, max. deformation: **0.7 mm**

See presentation by N. Deelen on this WS!

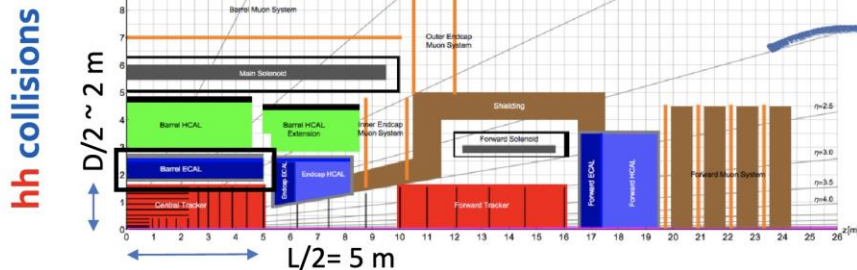
Thin Cryostats R&D at CERN

Thin cryostats (carbon fibre or honeycomb) under study, see presentation by M. Soledad

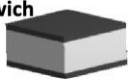
Presentation by M. Soledad at EP R&D Day, 2021

Baseline geometry, FCC-hh LAr barrel ECAL :

The aluminium cryostat is 5 cm thick, representing 56 % of X_0 at $\eta=0$



Sandwich



Skin [0,45,-45,90]_s
Core : Al Honeycomb
Skin [0,45,-45,90]_s

Radiation length X_0 [mm]
Al = 88.9
HM CFRP = 260
Honeycomb Al = 6000

| Criteria: Safety Factor = 2 | Honeycomb Al | | | | Solid shell | | | |
|-----------------------------|--------------|-------|-------|------|-------------|------|------|------|
| | HM CFRP | | Al | | HM CFRP | | Al | |
| | OWC | ICC | OWC | ICC | OWC | ICC | OWC | ICC |
| Material budget X/X_0 | 0.03 | 0.043 | 0.094 | 0.17 | 0.092 | 0.12 | 0.34 | 0.44 |
| X_0 % savings | -68% | -75% | REF | REF | -2% | -29% | 262% | 159% |
| Skin Th. [mm] | 3.2 | 4.8 | 3.9 | 7.5 | | | | |
| Core Th. [mm] | 32 | 38 | 40 | 40 | | | | |
| Total Th. [mm] | 38.4 | 47.6 | 47.8 | 55 | 24 | 30.4 | 30 | 39 |
| Thickness % savings | -20% | -13% | REF | REF | -50% | -45% | -37% | -29% |

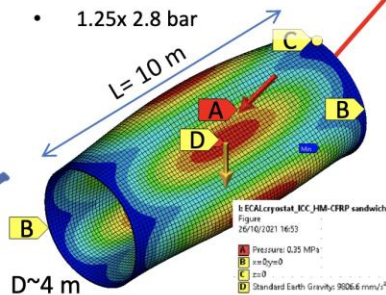
Outer warm cylinder (OWC)
Insulation vacuum
Outer cold cylinder (OCC)
LAr ECAL
Inner cold cylinder (ICC)
Inner warm cylinder (IWC)

Minimum material budget

Buckling resistance

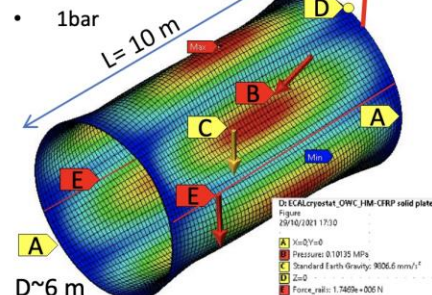
FEM loads ICC:

- 1.25x 2.8 bar



FEM loads OWC:

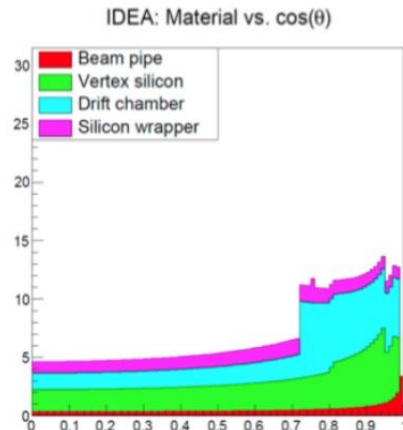
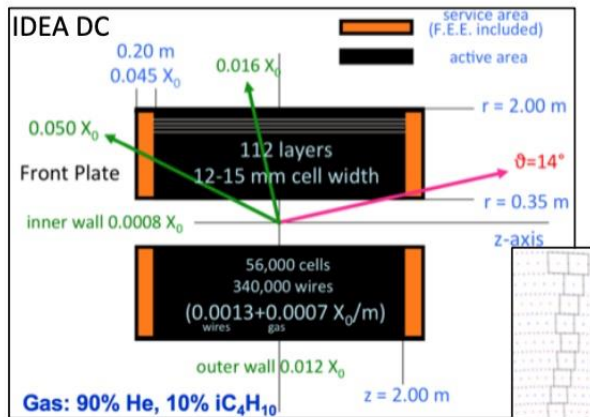
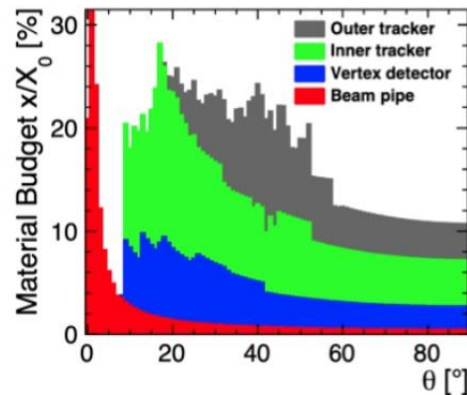
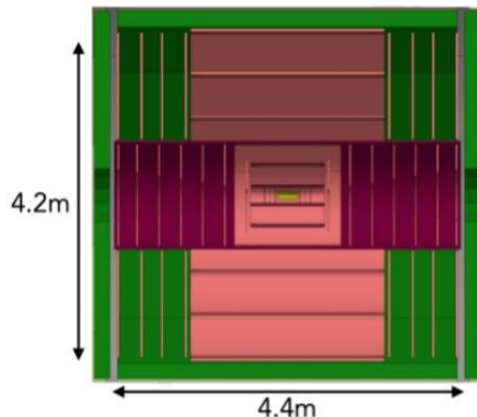
- 1bar



Tracking for FCC-ee

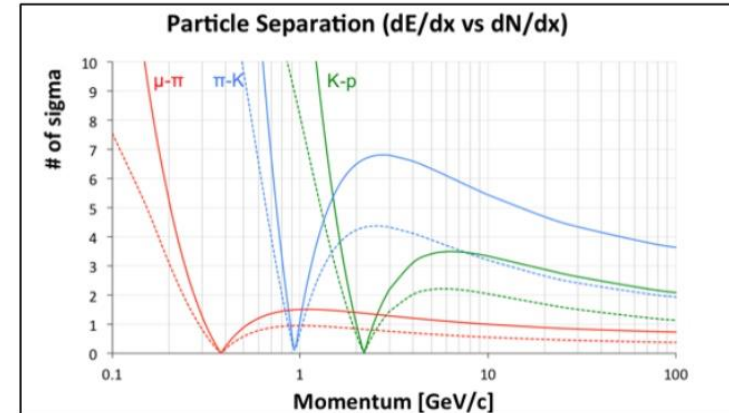
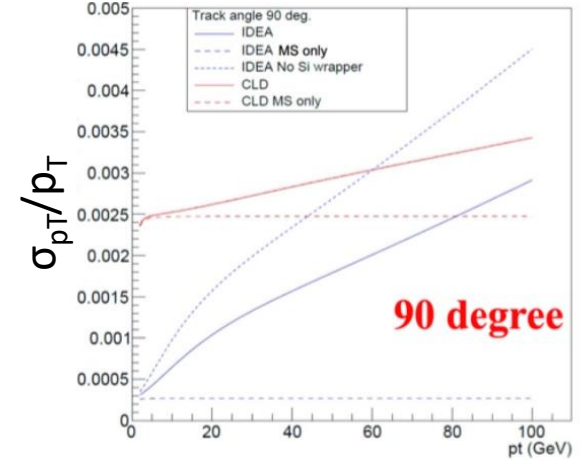
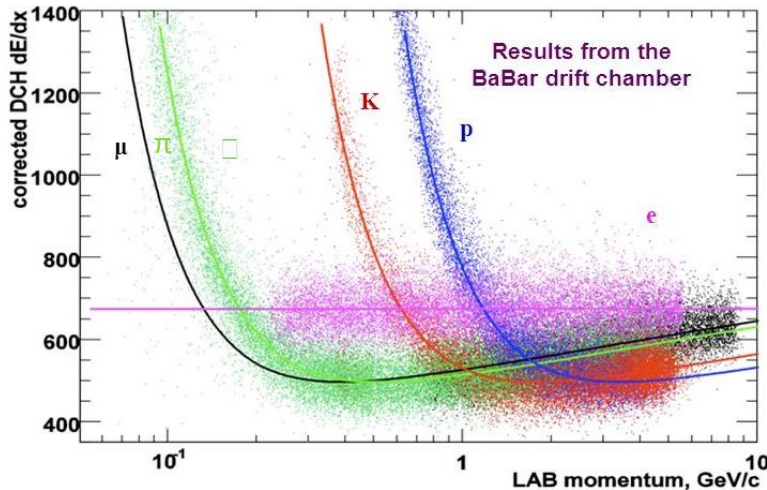
Two solutions under study

- **CLD:** All silicon pixel (innermost) + strips
 - Inner: 3 (7) barrel (fwd) layers ($1\% X_0$ each)
 - Outer: 3 (4) barrel (fwd) layers ($1\% X_0$ each)
 - Separated by support tube ($2.5\% X_0$)
- **IDEA:** Extremely transparent Drift Chamber
 - GAS: 90% He – 10% iC_4H_{10}
 - Radius 0.35 – 2.00 m
 - Total thickness: 1.6% of X_0 at 90°
 - Tungsten wires dominant contribution
 - Full system includes Si VTX and Si “wrapper”
- **What about a TPC?**
 - Very high physics rate (70 kHz), field limited to 2T
 - Considered for CEPC, but having difficulties...



Drift Chamber

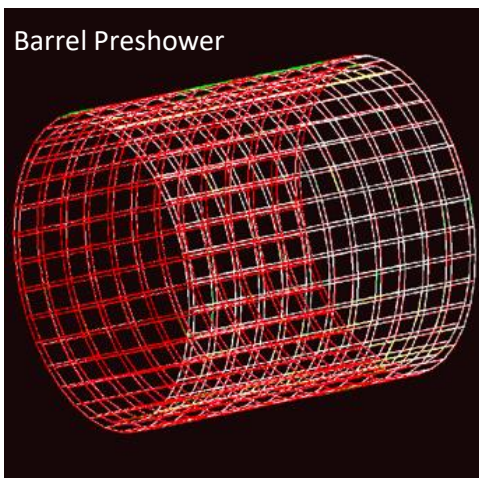
- **Drift chamber (gaseous tracker) advantages**
 - Extremely transparent: minimal multiple scattering and secondary interactions
 - Continuous tracking: reconstruction of far-detached vertices
 - K_S^0 , Λ , BSM long-lived particles (LLPs)
 - Particle separation via dE/dx or cluster counting (dN/dx)
 - dE/dx much exploited in LEP analyses



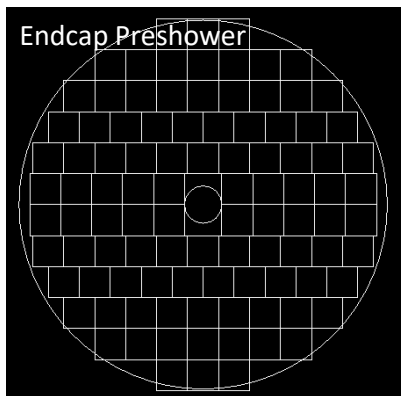
IDEA: Preshower and Muon Detector

Preshower Detector

- High resolution before the magnet to improve cluster reconstruction
- Efficiency > 98%
- Space Resolution < 100 mm
- Mass production
- Optimization of FEE channels/cost



Similar design for the Muon detector



Similar design for the Muon detector

Muon Detector

- Identifies muons and detects LLPs
- Efficiency > 98%
- Space Resolution < 400 mm
- Mass production
- Optimization of FEE channels/cost

Detector technology:

μ -RWELL, 50x50 cm² 2D tiles to cover more than 4330 m²

- **Preshower:**
 - pitch = 0.4 mm
 - FEE capacitance = 70 pF
 - 1.5 million channels
- **Muon Detector:**
 - pitch = 1.5 mm
 - FEE capacitance = 270 pF
 - 5 million channels

IDEA: μ -RWELL Technology

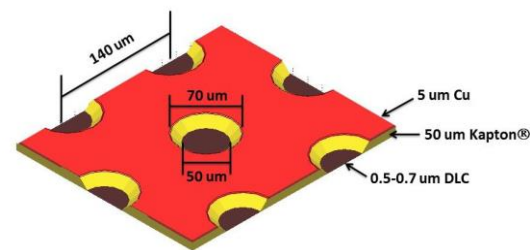
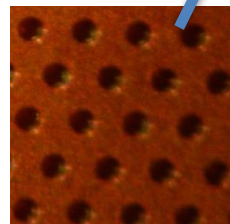
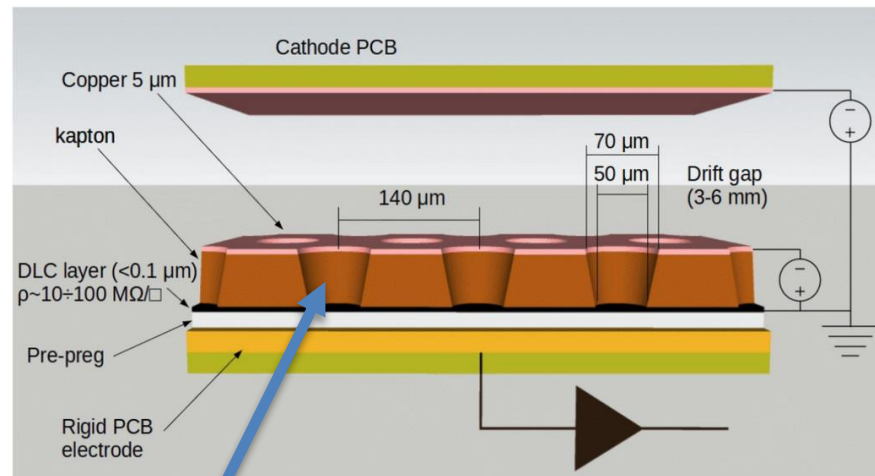
The μ -RWELL is composed of only two elements:

- μ -RWELL_PCB
- drift/cathode PCB defining the gas gap

μ -RWELL_PCB = amplification-stage \oplus resistive stage \oplus readout PCB

μ -RWELL operation:

- A charged particle ionises the gas between the two detector elements
- Primary electrons drift towards the μ -RWELL_PCB (anode) where they are multiplied, while ions drift to the cathode
- The signal is induced capacitively, through the DLC layer, to the readout PCB
- HV is applied between the Anode and Cathode PCB electrodes
- HV is also applied to the copper layer on the top of the kapton foil, providing the amplification field



(*) G. Bencivenni et al., "The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD", 2015_JINST_10_P02008)

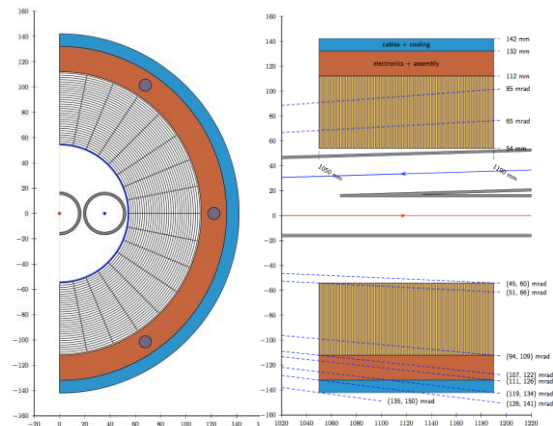
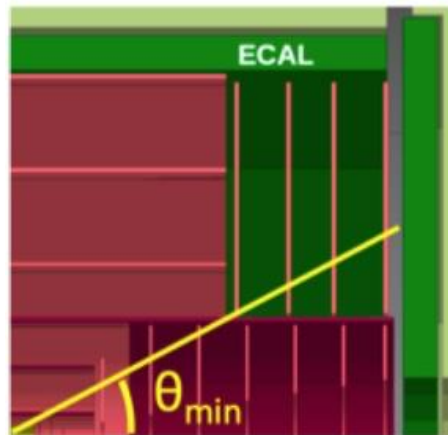
FCC-ee: Center of Mass Energy and Luminosity Measurement

- **Need to know $\langle \nu_s \rangle$ precisely**

- Key systematics for all mass measurements, and all EW observables.
- FCC-ee, Z peak and WW threshold: exquisite precision on $\langle \nu_s \rangle$ (100 keV at the Z, 300 keV at WW) thanks to quasi-continuous resonant depolarisation (RDP) measurements
 - Exploits the relation between the number of spin precessions per turn of transversely polarised e^\pm and their energy
 - Very powerful, unique to circular machines - allows a meas. of M_Z to 100 keV

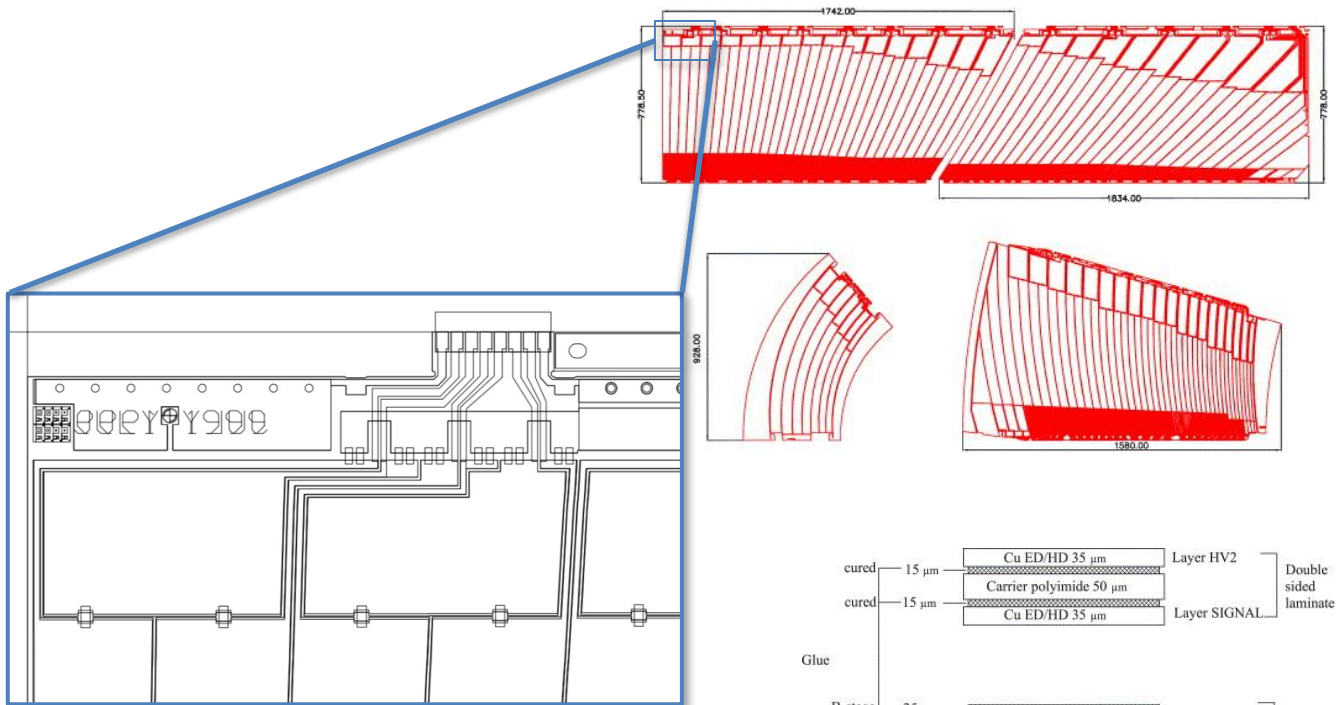
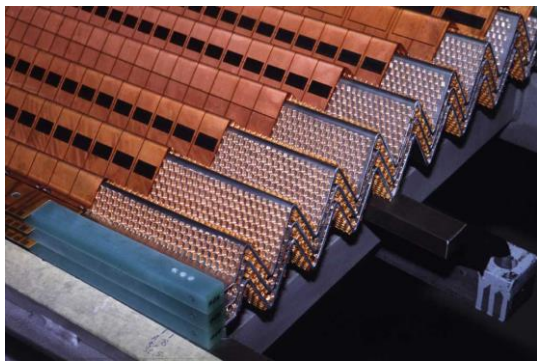
- **Luminosity Measurement: ambitious goals:**

- Absolute luminosity measurement to $\lesssim 10^{-4}$
- Relative luminosity (energy-to-energy point) to $\lesssim 10^{-5}$
- Inter-channel normalisation (e.g. $\mu\mu$ /multi-hadronic) to $\lesssim 10^{-5}$
- Luminosity measurement using low-angle Bhabha scattering, large angle $e^+e^- \rightarrow \gamma\gamma$ and $Z \rightarrow ll$
 - Requiring extremely high precision on acceptance boundaries
 - $O(1 \mu\text{m})$ and $O(50 \mu\text{rad})!$ \rightarrow Very challenging!!



Granularity – What are the Limits in ATLAS LAr?

- In the ATLAS LAr calorimeter electrodes have 3 layers that are glued together ($\sim 275\mu\text{m}$ thick)
 - 2 HV layers on the outside
 - 1 signal layer in the middle
- \rightarrow All cells have to be connected with fine signal traces (2-3mm) to the edges of the electrodes
 - Front layer read at inner radius
 - Middle and back layer read at outer radius
- \rightarrow limits lateral and longitudinal granularity
- \rightarrow maximum 3 long. layers

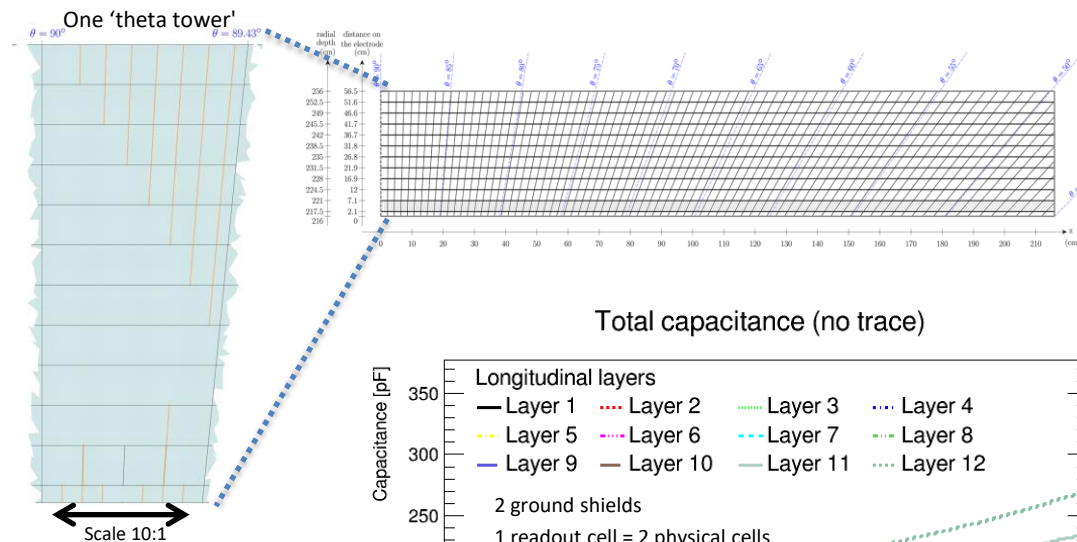


\rightarrow O(200k) read-out cells – particle flow reconstruction possible, but not optimal

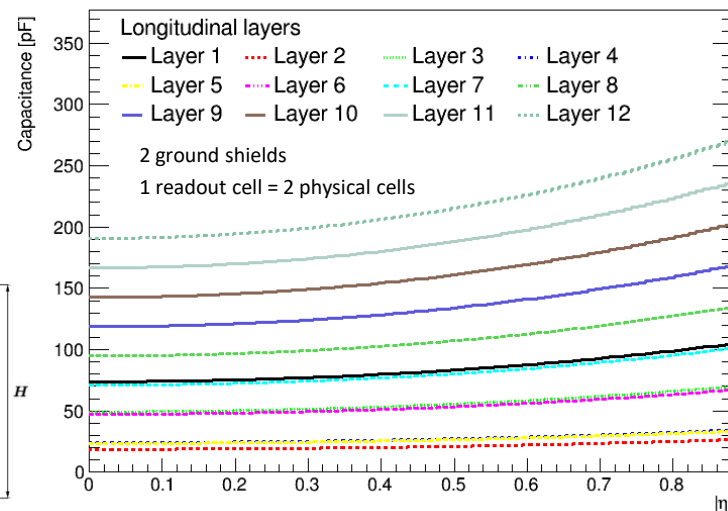
Noble-Liquid Calo: How to Achieve High Granularity?

Realize electrodes as multi-layer PCBs (1.2mm thick), 7 layers

- HV and read-out
- Signal traces (width w_t) in dedicated signal layer connected with vias to the signal pads
- Traces shielded by ground-shields (width w_s) forming 50 Ω – 80 Ω transmission lines
- \rightarrow capacitance between shields and signal pads C_s will add to the detector capacitance via the gap C_d
- $\rightarrow C_{cell} = C_s + C_d \approx 25 - 300\text{pF}$
- The higher the granularity the more shields are necessary $\rightarrow C_s$ increases, C_d decreases (smaller cells)

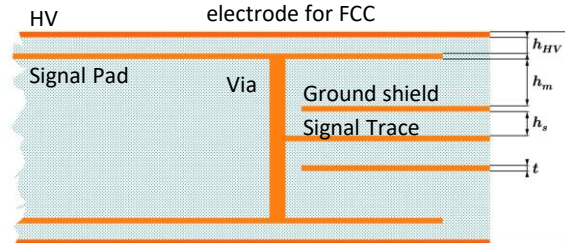
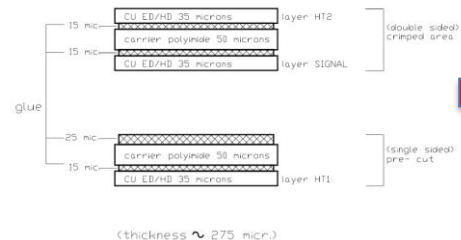


Total capacitance (no trace)

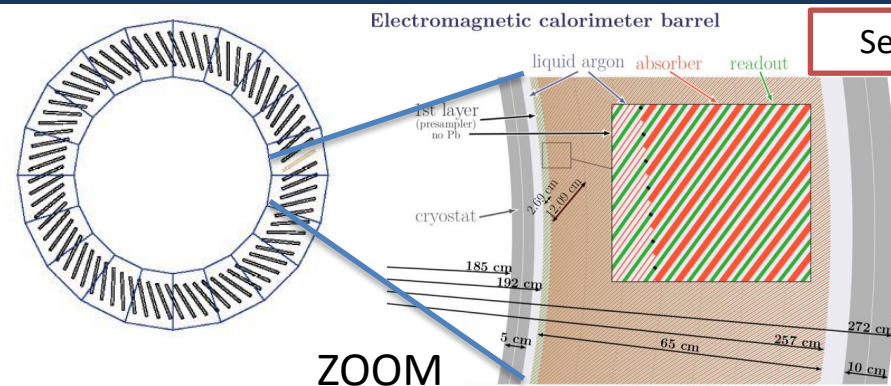


ATLAS electrode

Multi-layer read-out electrode for FCC

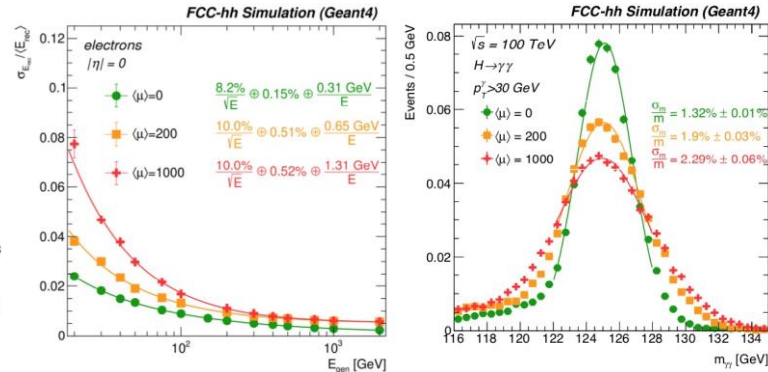


Reminder – FCC-hh Electromagnetic Calorimeter (ECAL)

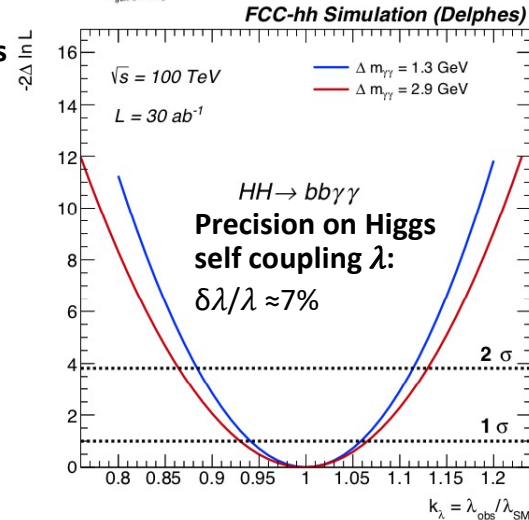


See [arXiv paper](#)

- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\phi = 0.009$;

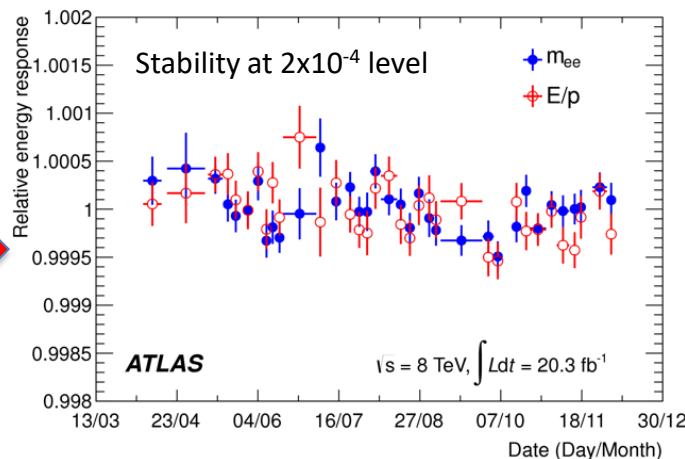
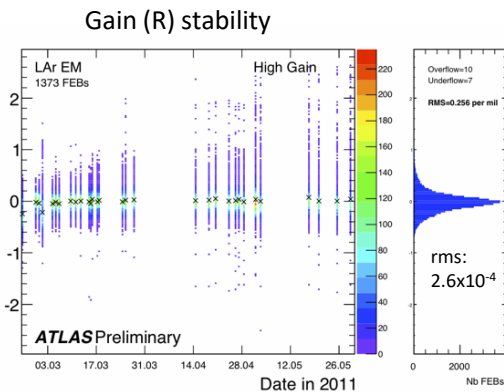
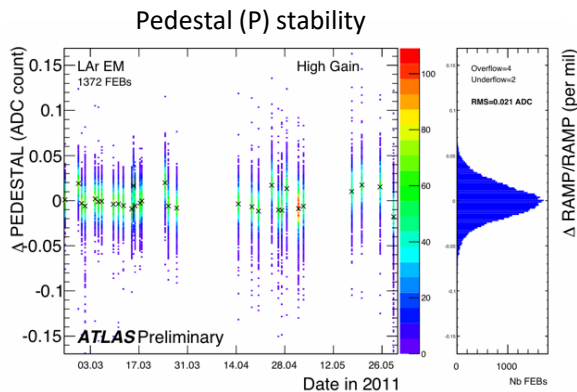


- **CDR Reference Detector (2019): Performance & radiation considerations → LAr ECAL, Pb absorbers**
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
 - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$, first layer $\Delta\eta=0.0025$),
 - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
 - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
 - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
 - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
 - Sampling term $\leq 10\%/\sqrt{E}$, only ≈ 300 MeV electronics noise despite multilayer electrodes
 - Impact of in-time pile-up at $\langle\mu\rangle = 1000$ of ≈ 1.3 GeV pile-up noise (no in-time pile-up suppression)
 - → Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)
- **Since 2019 adapting this calorimeter to FCC-ee**



Example – Stability of ATLAS LAr Energy Scale

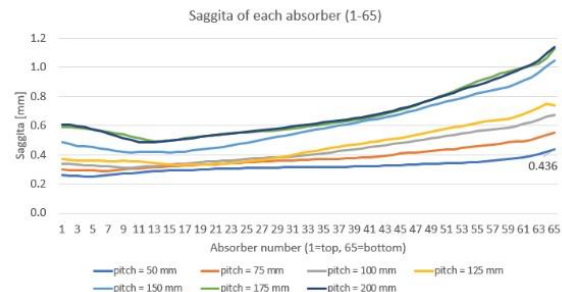
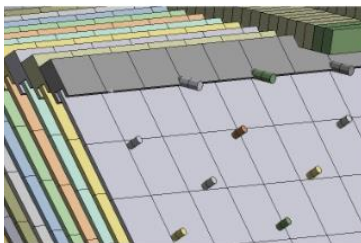
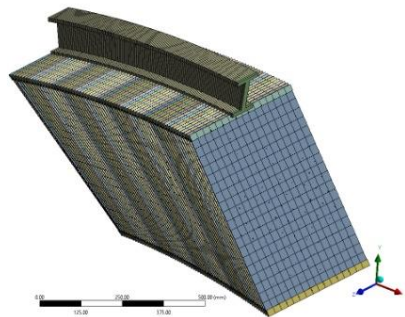
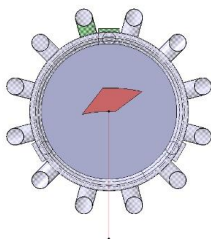
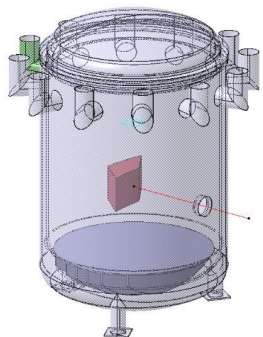
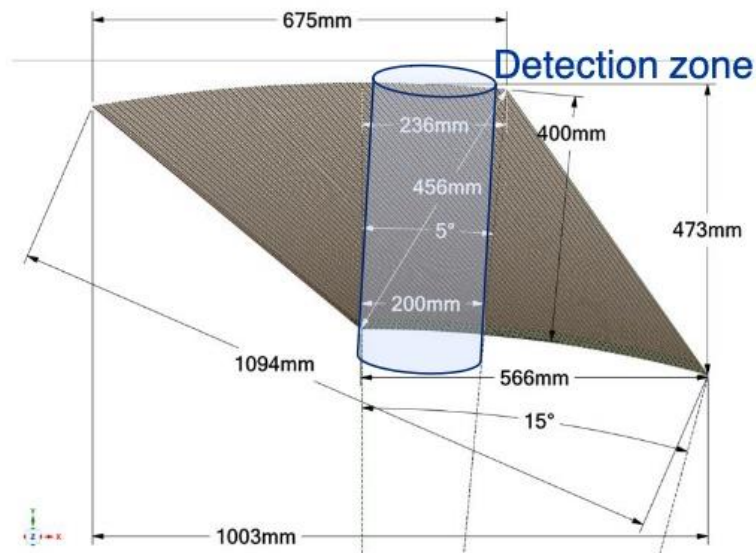
- **Noble-liquid calorimetry:** High intrinsic stability (see gain and pedestal stability)
 - Pedestal stability < 100 keV (!)
 - Gain stability 2.6×10^{-4}
- These parameters are monitored in daily calibration runs \rightarrow constants are updated when necessary (about once a month)
- \rightarrow Leading to high stability of the energy scale of 2×10^{-4} , monitored by invariant mass m_{ee} ($Z \rightarrow ee$ events) and E/p



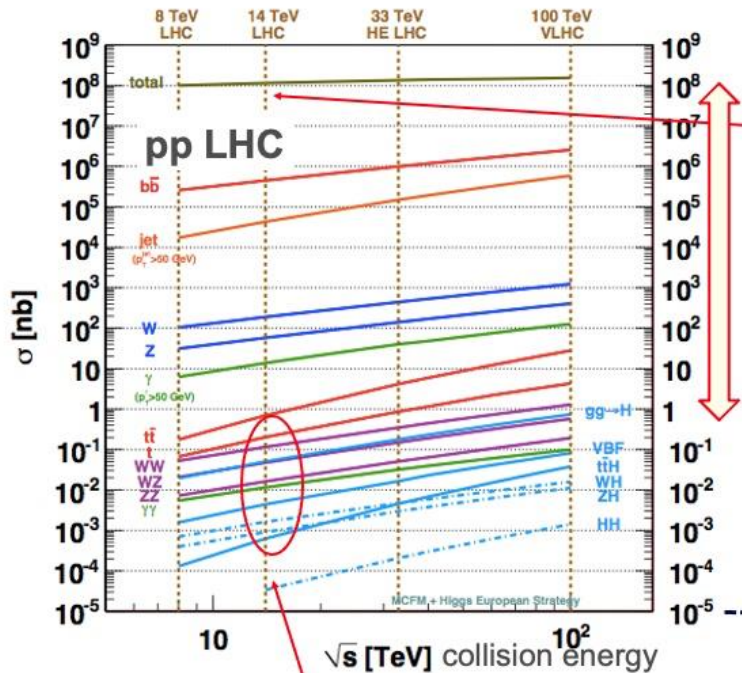
Noble-Liquid Calo: Next Step – Testbeam Module

- Mechanical design of testbeam module (64 absorbers) has started
- Finite element calculations including
 - Rings and G10 bars
 - Absorbers and electrodes as shell (2D) elements using layers
 - Distance pins
 - Six M5 beams join electrodes and absorbers in each side (inner-outer)
- In parallel work on finding/adapting testbeam cryostat
- Plan to produce testmodule in the next four years

The cryostat available to make the test beam is the CRRP-00563.

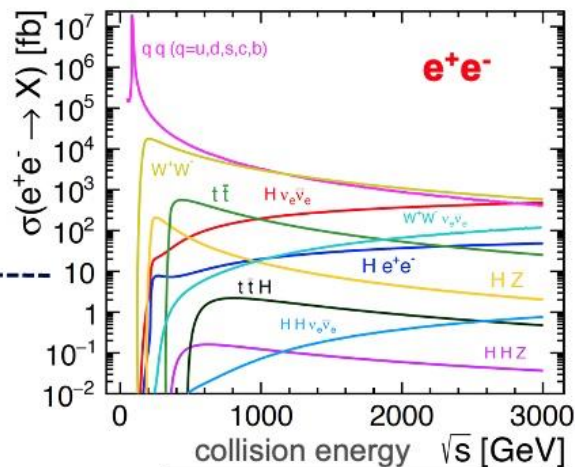


e^+e^- vs. pp Collisions – Cross Section Comparison



LHC total cross section
factor > 100 million !!

In e^+e^- collisions the total cross section \sim
equals the electroweak cross section.



e^+e^- events are "clean"

At LHC, much of the interesting physics needs
to be found among a huge number of collisions



A 100 TeV Hadron Collider – FCC-hh

FCC-hh Parameter Table

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

| Parameter | Unit | LHC | HL-LHC | HE-LHC | FCC-hh |
|---|--|---------|-----------|--------|--------|
| E_{cm} | TeV | 14 | 14 | 27 | 100 |
| Circumference | km | 26.7 | 26.7 | 26.7 | 97.8 |
| Peak \mathcal{L} , nominal (ultimate) | $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ | 1 (2) | 5 (7.5) | 16 | 30 |
| Bunch spacing | ns | 25 | 25 | 25 | 25 |
| Number of bunches | | 2808 | 2760 | 2808 | 10600 |
| Goal $\int \mathcal{L}$ | ab^{-1} | 0.3 | 3 | 10 | 30 |
| σ_{inel} [331] | mb | 80 | 80 | 86 | 103 |
| σ_{tot} [331] | mb | 108 | 108 | 120 | 150 |
| BC rate | MHz | 31.6 | 31.0 | 31.6 | 32.5 |
| Peak pp collision rate | GHz | 0.8 | 4 | 14 | 31 |
| Peak av. PU events/BC, nominal (ultimate) | | 25 (50) | 130 (200) | 435 | 950 |
| Rms luminous region σ_z | mm | 45 | 57 | 57 | 49 |
| Line PU density | mm^{-1} | 0.2 | 1.0 | 3.2 | 8.1 |
| Time PU density | ps^{-1} | 0.1 | 0.29 | 0.97 | 2.43 |
| $dN_{ch}/d\eta _{\eta=0}$ [331] | | 6.0 | 6.0 | 7.2 | 10.2 |
| Charged tracks per collision N_{ch} [331] | | 70 | 70 | 85 | 122 |
| Rate of charged tracks | GHz | 59 | 297 | 1234 | 3942 |
| $\langle p_T \rangle$ [331] | GeV/c | 0.56 | 0.56 | 0.6 | 0.7 |
| Bending radius for $\langle p_T \rangle$ at B=4 T | cm | 47 | 47 | 49 | 59 |

- $E_{cm} = 100 \text{ TeV}$
- $\sim 100 \text{ km}$ circumference
- $\mathcal{L} = 30 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- $\int \mathcal{L} = 30 \text{ ab}^{-1}$
- 31 GHz pp collisions
- Pile-up $\langle \mu \rangle \approx 1000$
- 4 THz of charged tracks

See lecture by M. Benedikt

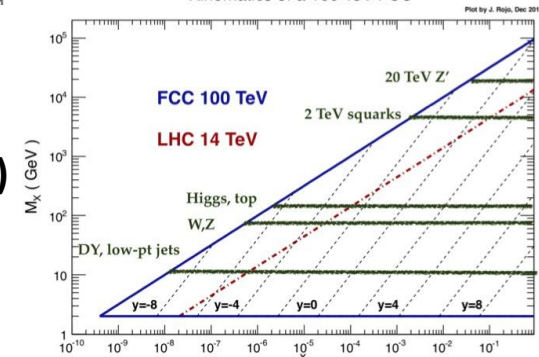
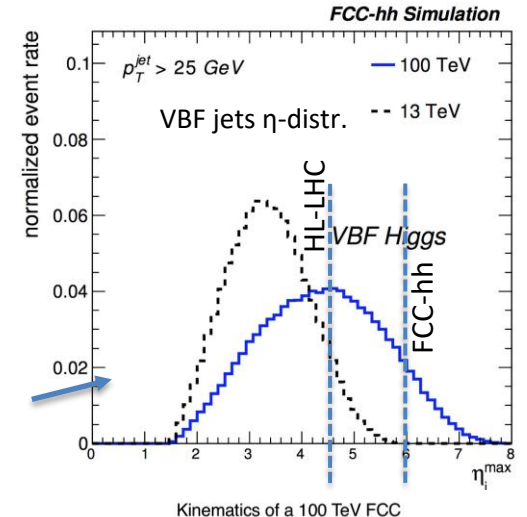
Parameter Table

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

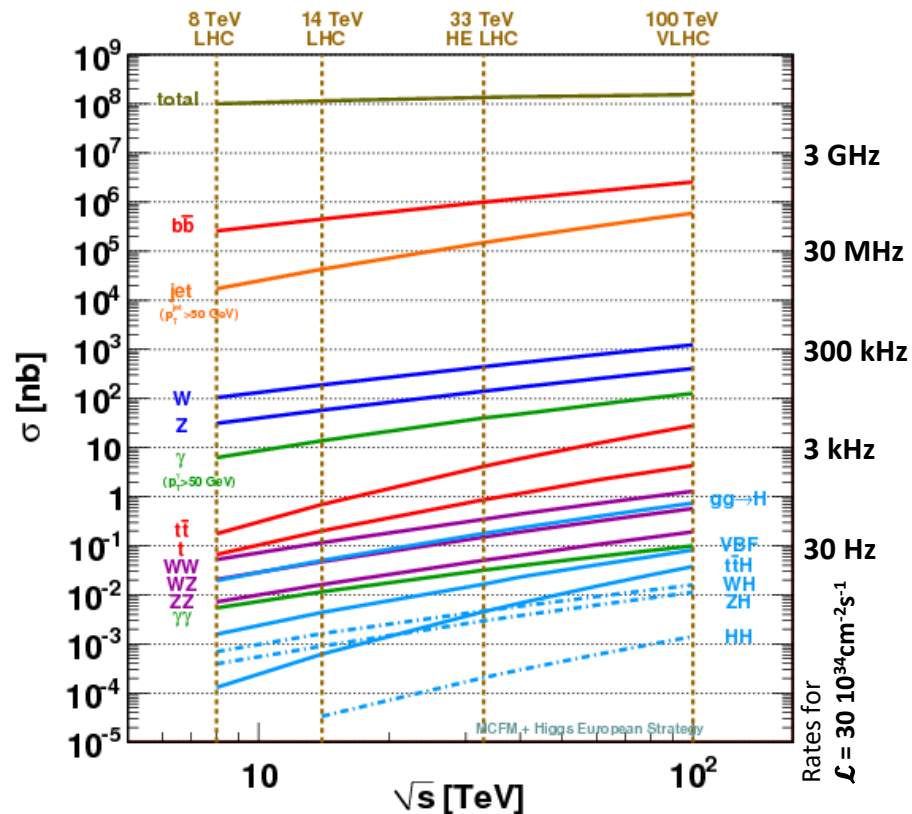
| Parameter | Unit | LHC | HL-LHC | HE-LHC | FCC-hh |
|---|---------------------------|------|--------|--------|-----------|
| Total number of pp collisions | 10^{16} | 2.6 | 26 | 91 | 324 |
| Charged part. flux at 2.5 cm, est.(FLUKA) | GHz cm^{-2} | 0.1 | 0.7 | 2.7 | 8.4 (10) |
| 1 MeV-neq fluence at 2.5 cm, est.(FLUKA) | 10^{16} cm^{-2} | 0.4 | 3.9 | 16.8 | 84.3 (60) |
| Total ionising dose at 2.5 cm, est.(FLUKA) | MGy | 1.3 | 13 | 54 | 270 (300) |
| $dE/d\eta _{\eta=5}$ [331] | GeV | 316 | 316 | 427 | 765 |
| $dP/d\eta _{\eta=5}$ | kW | 0.04 | 0.2 | 1.0 | 4.0 |
| 90% $b\bar{b}$ $p_T^b > 30 \text{ GeV}/c$ [332] | $ \eta <$ | 3 | 3 | 3.3 | 4.5 |
| VBF jet peak [332] | $ \eta $ | 3.4 | 3.4 | 3.7 | 4.4 |
| 90% VBF jets [332] | $ \eta <$ | 4.5 | 4.5 | 5.0 | 6.0 |
| 90% $H \rightarrow 4l$ [332] | $ \eta <$ | 3.8 | 3.8 | 4.1 | 4.8 |

Unprecedented particle flux and radiation levels

- 10 GHz/cm² charged particles
- $\approx 10^{18} \text{ cm}^{-2}$ 1 MeV-n.eq. fluence for 30ab⁻¹ (first tracker layer, fwd calo)
- “Light” SM particles produced with increased forward boost
 - spreads out particles by 1-1.5 units of rapidity



Cross-Sections for Key Processes



- **Total cross-section and Minimum Bias Multiplicity** show only a **modest increase** from LHC to FCC-hh.
- The **cross-sections for interesting processes, however, increase significantly** (e.g. HH x 50!)
- Higher luminosity to increase statistics \rightarrow pileup of 140 at HL-LHC to **pileup of 1000** at FCC-hh \rightarrow **challenge for triggering and reconstruction**
- $\mathcal{L} = 30 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$:
 - 100MHz of jets $p_T > 50 \text{ GeV}$,
 - 400kHz of Ws,
 - 120kHz of Zs,
 - 11kHz of $t\bar{t}$ bars
 - 200Hz of $gg \rightarrow H$



FCC-hh Detector

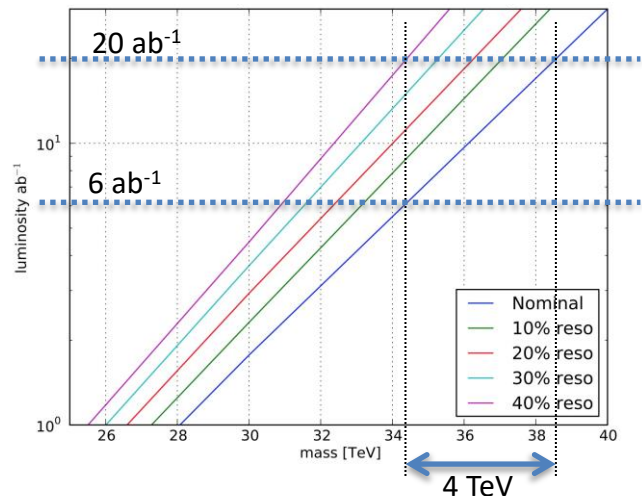
Physics Benchmarks – Detector Requirements

Physics at the $\mathcal{L}\sigma$ -limit

Exploration potential through higher energy, increased statistics, increased precision

Example: Z'_{SSM} discovery

luminosity versus mass for a 5σ discovery



Muon momentum resolution:

- **$\mathcal{O}(5\%)$ at 10TeV.**
- **Compare to 10% at 1TeV spec. at LHC**

Tracking – Resolution degrading with higher momentum!

$$\frac{\Delta p}{p} \propto \frac{\sigma_{\text{pos}} \cdot p}{BL^2}$$

→ Have to improve on

- σ_{pos} : difficult
- Magnetic field B: go from 2T (ATLAS) to 4T (FCC-hh)
- Lever arm L: magnet cost scales with $\approx \text{volume}^{2/3} \rightarrow$ very quickly very expensive

Physics Benchmarks – Detector Requirements

Calorimetry – Improving resolution with higher energy!

Simple shower model: The detectable signal is proportional to the total number of produced signal quanta N (e.g. e^- -ion pair, scintillation photon)

An estimation of the **energy resolution** is given by the **fluctuations** of the number N of produced signal quanta in the active medium (N : Poisson distributed). Need **average energy W** to produce 1 signal quantum.

$$N \approx \frac{E}{W}$$

$$\frac{\sigma(E)}{E} \propto \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{W}{E}}$$

Silicon detectors: $W \approx 3.6\text{eV}$
 Gas detectors: $W \approx 30\text{eV}$
 Plastic scintillators: $W \approx 100\text{eV}$
 Liquid Ar: $W \approx 23.3\text{eV}$
 Scint. crystal NaI: $W \approx 25\text{eV}$
 Scint. crystal PbWO₄: $W \approx 10\text{keV}$

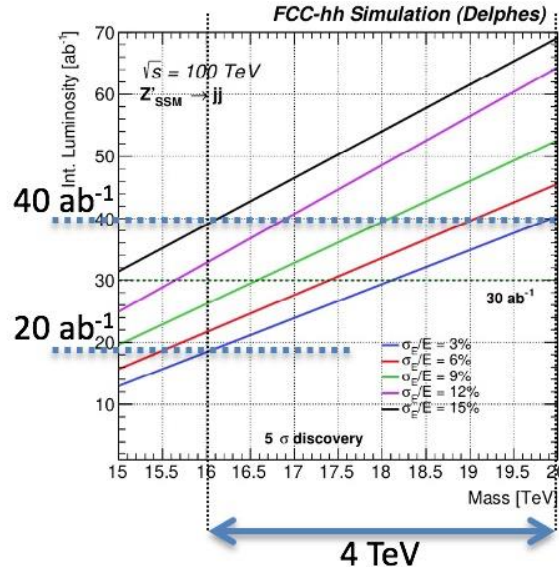
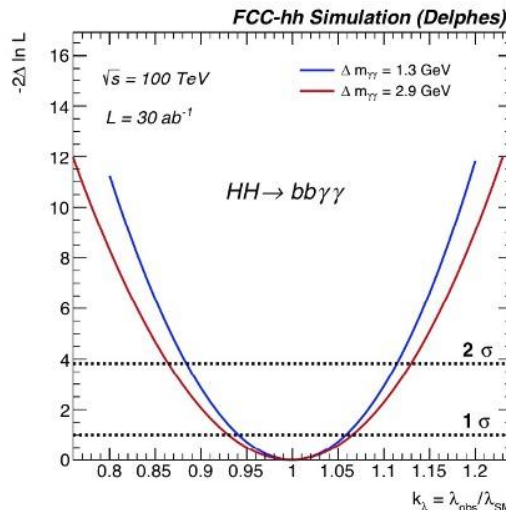
Parametrization of resolution:

$$\frac{\sigma_E(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

stochastic/sampling term
constant term

noise term

Relative resolution improves with $1/E^{1/2}$



Higgs self-coupling $\delta\lambda/\lambda = 7\%$ for $\Delta m_{\gamma\gamma} < 3\text{GeV}$

- **EM-calorimeter resolution**
 sampl. term $a \approx 10\%$ and noise term $b < 1.5\text{GeV}$ (including pile-up)!

Di-jet resonances: HCAL constant term of $c = 3\%$ instead of 15% :
 extend discovery potential by 4TeV (or same disc. pot. for 50% lumi)

- **full shower containment is mandatory!**
- Large HCAL depth ($\sim 12 \lambda_{\text{int}}$)!

Requirements for FCC-hh Detector

- **ID tracking target:** achieve $\sigma_{p_T} / p_T = 10\text{-}20\%$ @ 10 TeV
- **Muon target:** $\sigma_{p_T} / p_T = 5\%$ @ 10 TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)

Used in Delphes
physics simulations

- Constant term of $<1\%$ for the EM calorimeter and $<2\text{-}3\%$ for the HCAL
- **High efficiency vertex reconstruction, b-tagging, τ -tagging, particle ID!**

- Pile-up of $\langle\mu\rangle=1000 \rightarrow 120\mu\text{m}$ mean vertex separation

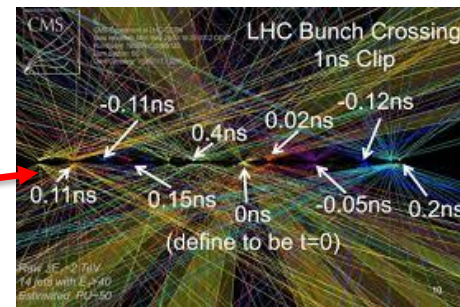
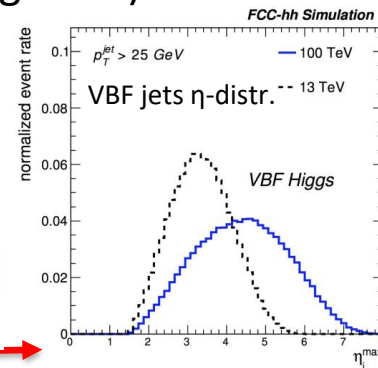
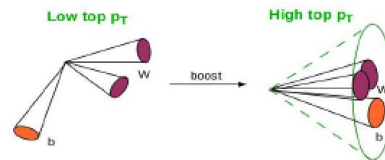
- **High granularity** in tracker and calos (boosted obj.)

- **Pseudorapidity (η) coverage:**

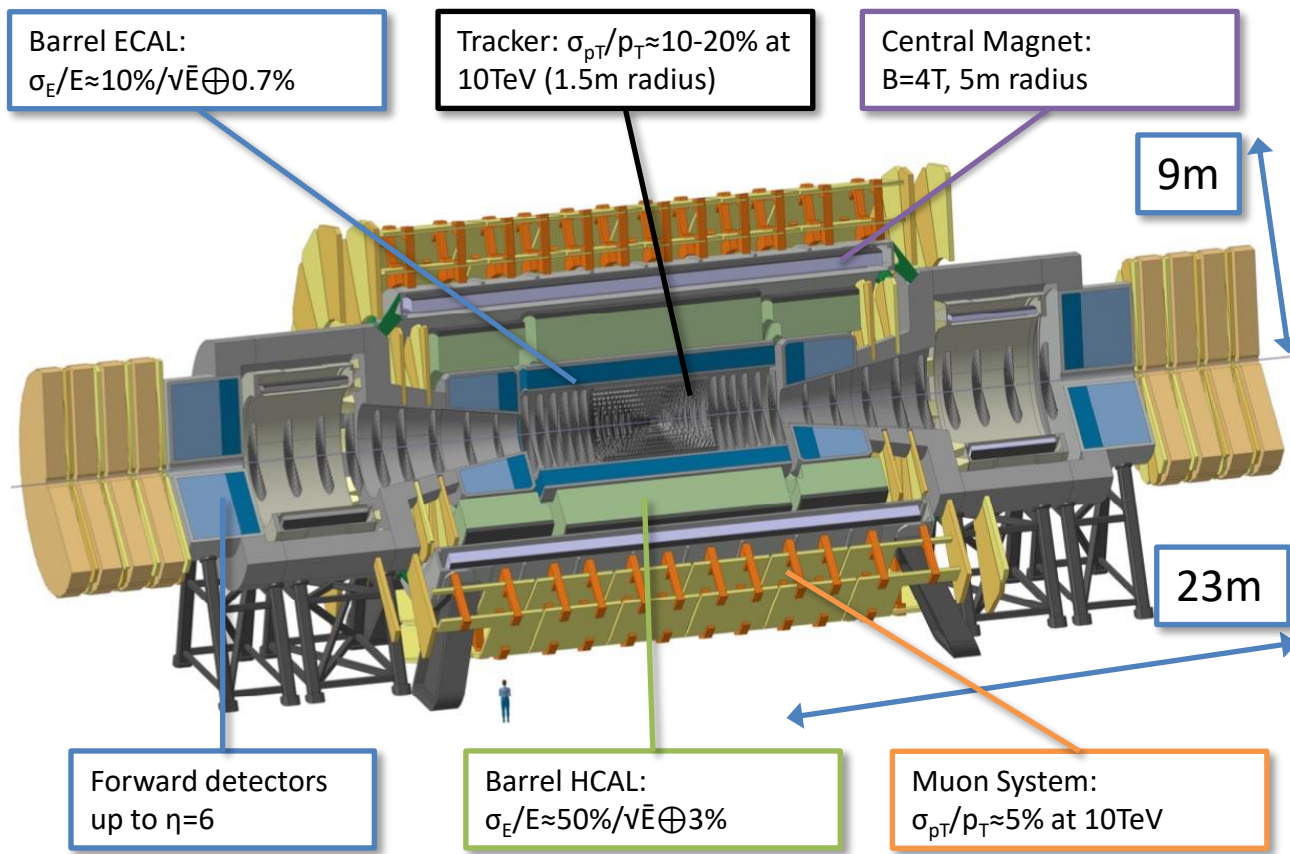
- Precision muon measurement up to $|\eta|<4$
- Precision calorimetry up to $|\eta|<6$

- **\rightarrow Achieve all that at a pile-up of 1000! \rightarrow Granularity & Timing!**

- **On top of that radiation hardness and stability!**

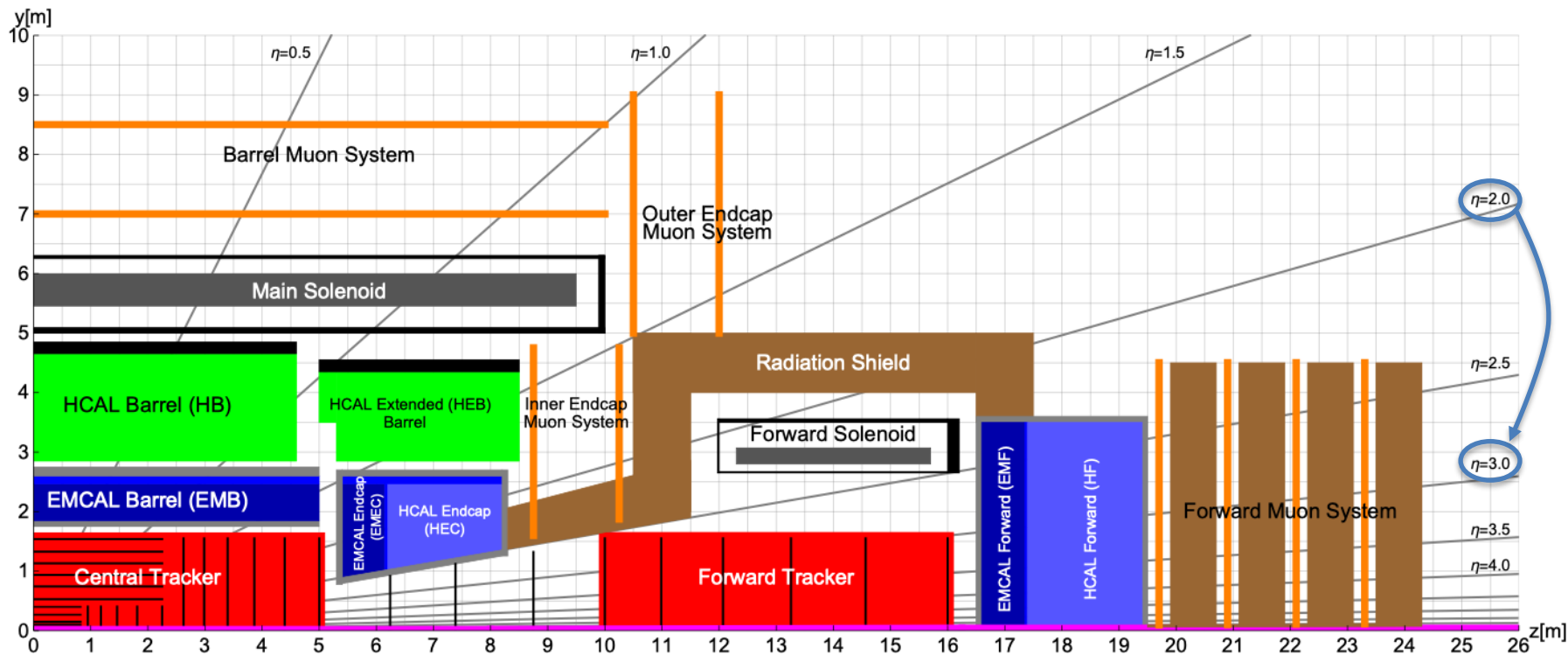


A Possible FCC-hh Detector – Reference Design for CDR



- Converged on **reference design** for an FCC-hh experiment for [FCC CDR](#)
- Goal was to demonstrate, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
 - Input for Delphes physics simulations
 - Radiation simulations
- However, this is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**

Reference Design for CDR

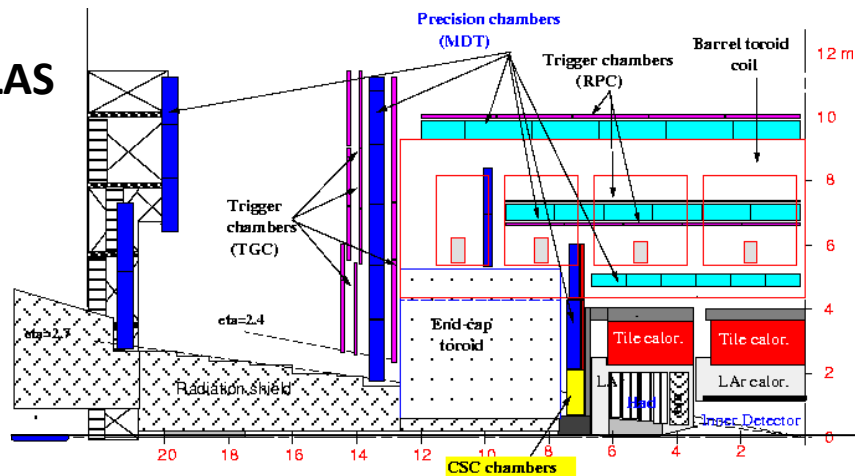


Forward solenoid adds about 1 unit of η with full lever-arm

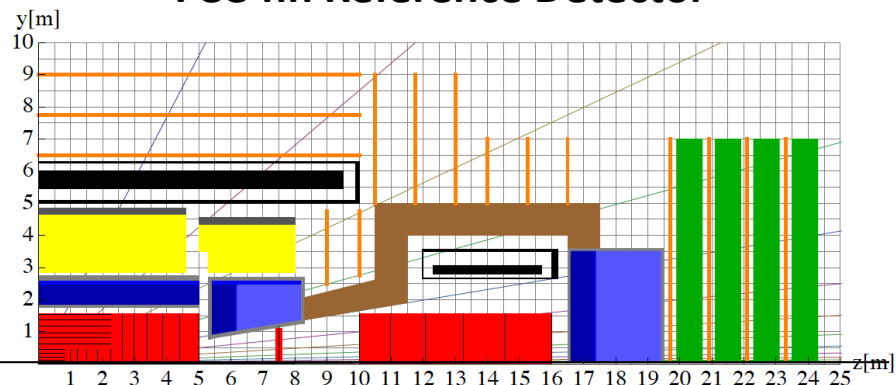
Forward solenoid requires additional radiation shield to connect endcap and forward calorimeter

FCC-hh Detector: Comparison to ATLAS & CMS

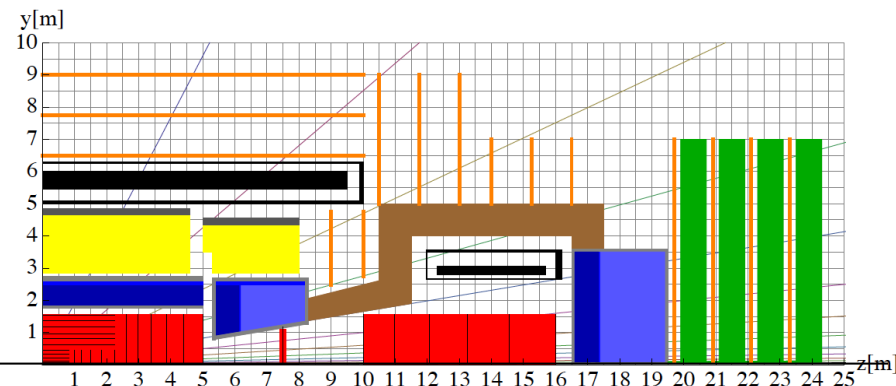
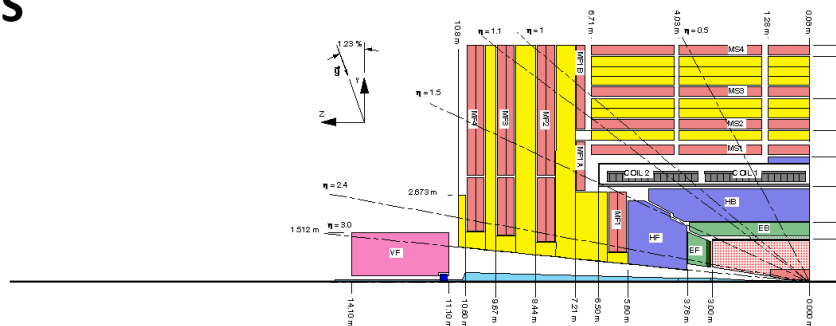
ATLAS



FCC-hh Reference Detector



CMS

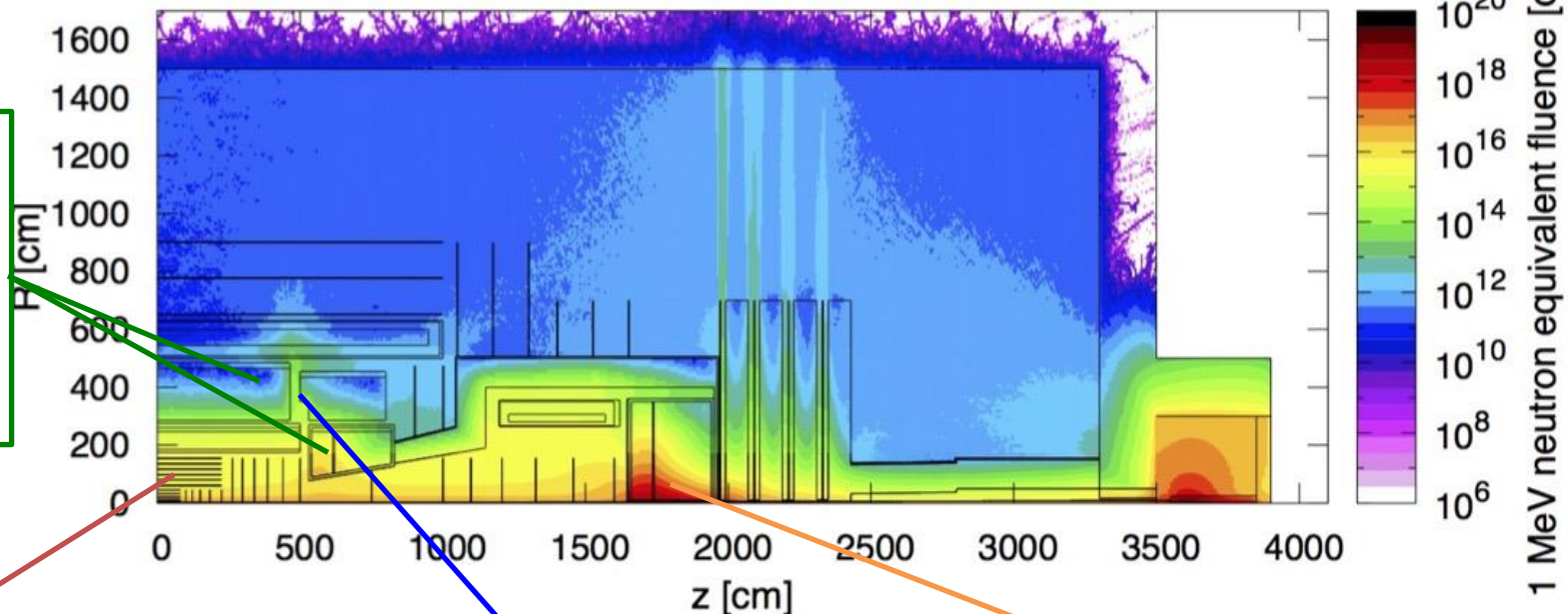


1 MeV Neutron Equivalent Fluence for 30ab⁻¹

Generally ~10-30 times worse than HL-LHC

Exception: Forward calorimeter goes to higher $\eta \rightarrow$ bigger factor

Barrel calorimeter:
EM-cal: $4 \cdot 10^{15} \text{ cm}^{-2}$
HAD-cal: $4 \cdot 10^{14} \text{ cm}^{-2}$
End-cap calorimeter:
EM-cal: $2.5 \cdot 10^{16} \text{ cm}^{-2}$
HAD-cal: $1.5 \cdot 10^{16} \text{ cm}^{-2}$



Central tracker:

- first IB layer (2.5 cm): $\sim 5\text{-}6 \cdot 10^{17} \text{ cm}^{-2}$
- external part: $\sim 5 \cdot 10^{15} \text{ cm}^{-2}$

Calorimeter gap:

from 10^{16} cm^{-2} to 10^{14} cm^{-2}

Forward calorimeters:

$\sim 5 \cdot 10^{18} \text{ cm}^{-2}$ for both the EM and the HAD-cal

FCC-hh Magnet System

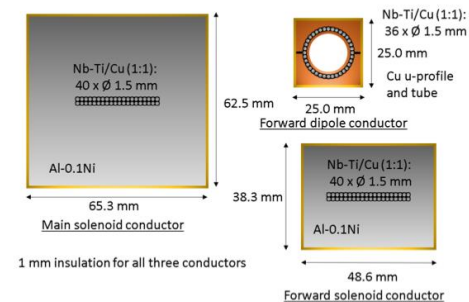
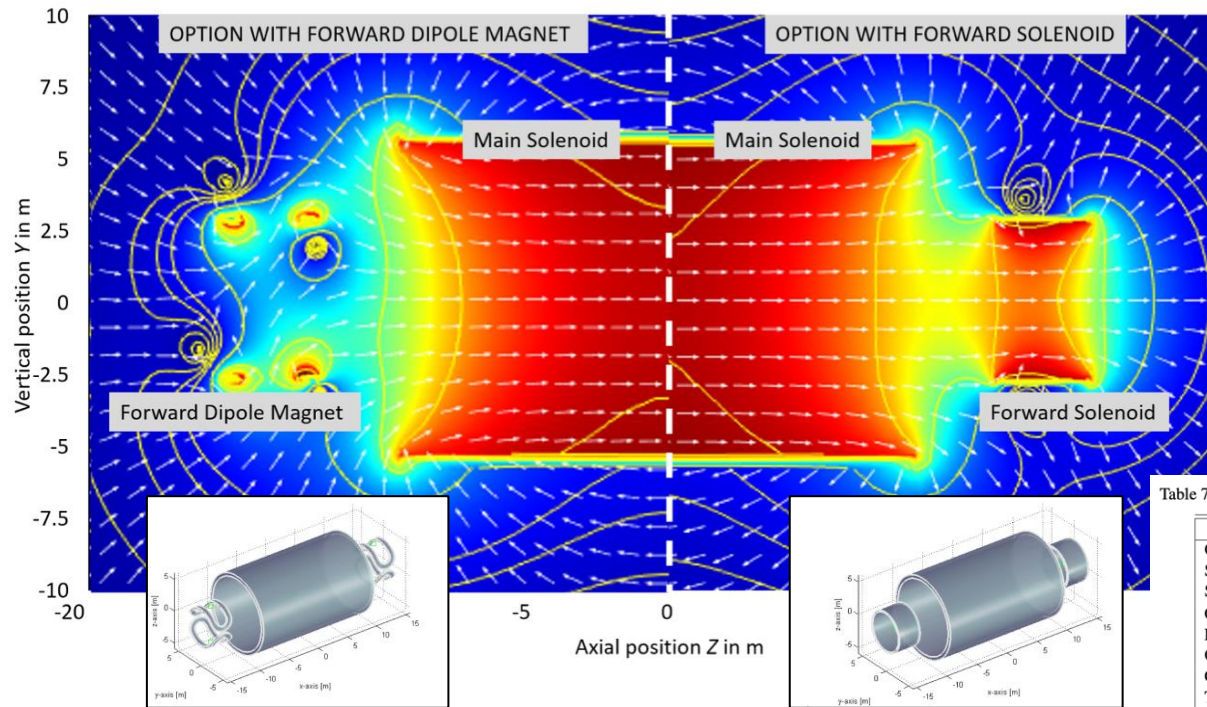


Table 7.2: Main characteristics of the central solenoid, a forward solenoid and a forward dipole magnet.

| | Unit | Main solenoid | Forward solenoid | Forward dipole |
|--------------------------|-------------------|---------------|------------------|----------------|
| Operating current | kA | 30 | 30 | 16 |
| Stored energy | GJ | 12.5 | 0.43 | 0.20 |
| Self-inductance | H | 27.9 | 0.96 | 1.54 |
| Current density | A/mm ² | 7.3 | 16.1 | 25.6 |
| Peak field on conductor | T | 4.5 | 4.5 | 5.9 |
| Operating temperature | K | 4.5 | 4.5 | 4.5 |
| Current sharing temp. | K | 6.5 | 6.5 | 6.2 |
| Temperature margin | K | 2.0 | 2.0 | 1.7 |
| Heat load cold mass | W | 286 | 37 | 50 |
| Heat load thermal shield | W | 5140 | 843 | 1500 |
| Cold mass | t | 1070 | 48 | 114 |
| Vacuum vessel | t | 875 | 32 | 48 |
| Conductor length | km | 84 | 16 | 23 |

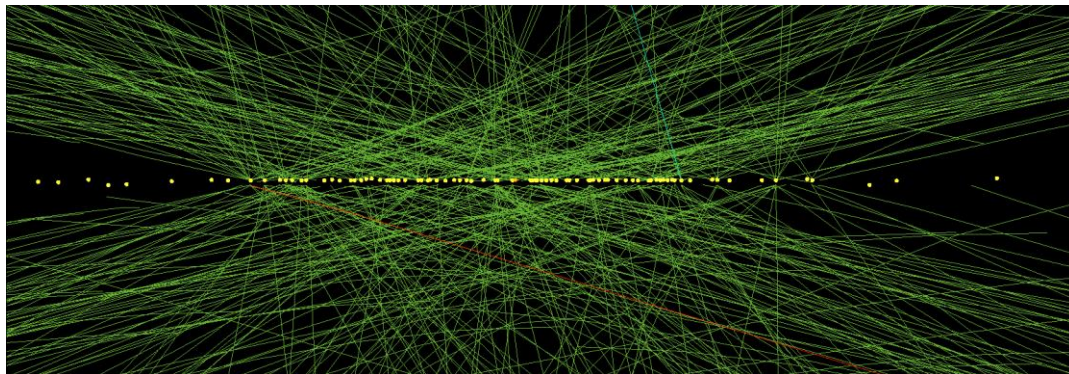
ATLAS Magnet System 2.7 GJ

CMS Magnet System 1.6 GJ

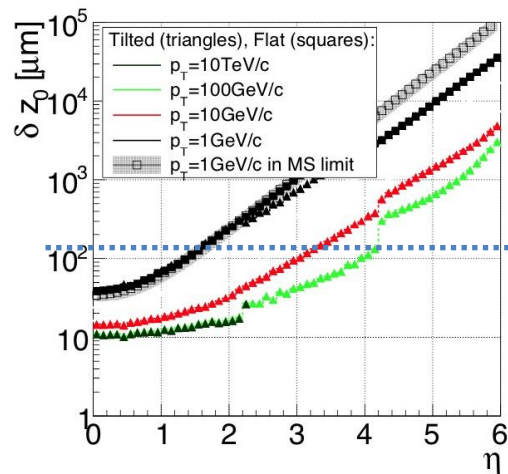
FCC-hh: ~13 GJ, cold mass + cryostat around 2000 tons.

Possible alternative solutions: Ultra-thin solenoid positioned inside the calorimeter (difficulty: muon measurement!)

The Challenge of $\langle\mu\rangle = 1000$ Pile-Up

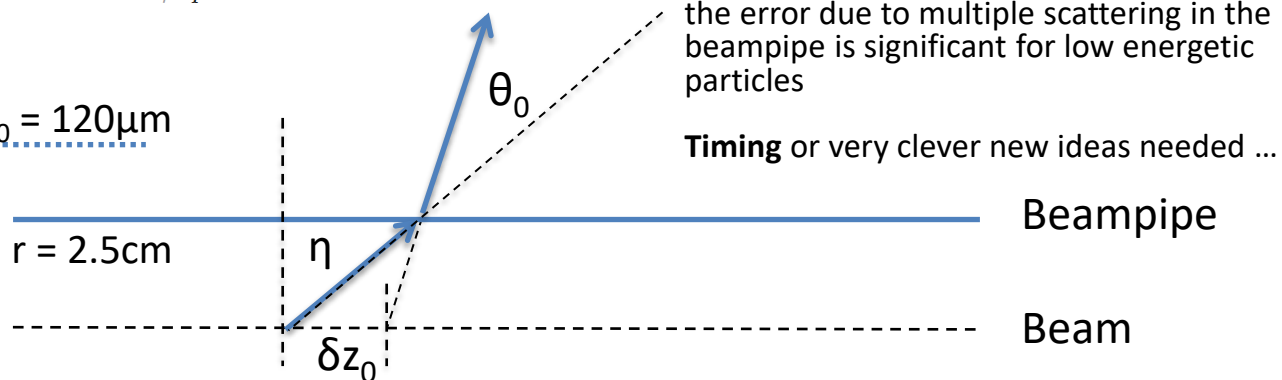


- HL-LHC average distance between vertices at $z=0$ is
 - $\approx 1\text{mm}$ in space and 3ps in time.
- \rightarrow For 6 times higher luminosity and higher c.m. energy at FCC-hh:
 - $\approx 120\text{ }\mu\text{m}$ in space and 0.4ps in time
- \rightarrow **Future trackers will need to use both, position resolution and timing to identify the correct vertex!**



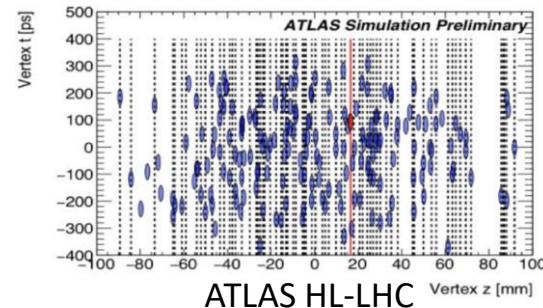
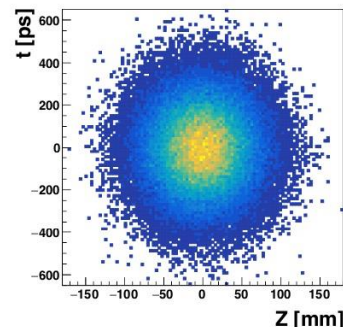
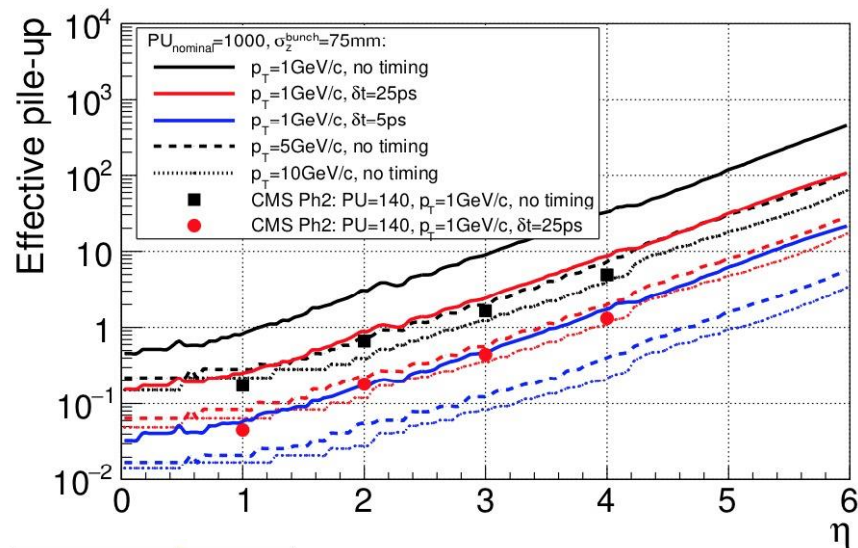
$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta_{cp}} z \sqrt{x/X_0} \left[1 + 0.038 \ln(x/X_0) \right]$$

$$\delta z_0 = 120\text{ }\mu\text{m}$$

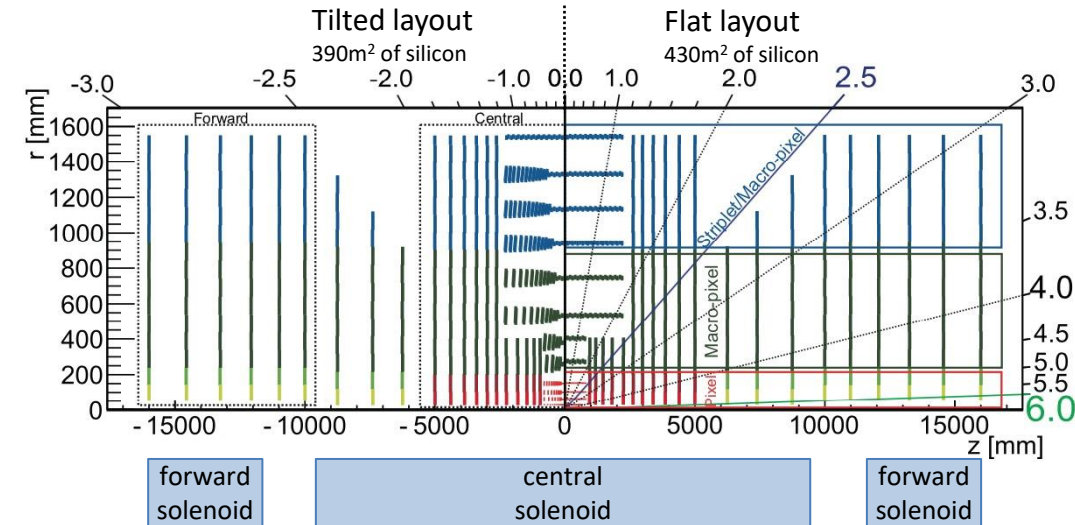


Timing Information for Vertex Reconstruction

- **Goal is to identify the primary vertex!**
- **Effective pile-up:** number of vertices compatible with reconstructed tracks (95%CL)
 - Eff. pile-up = 1: Indication for unambiguous primary vertex identification
- **Example:** eff. pile-up = 1 for $p_T = 5\text{GeV}$:
 - $\eta < |2|$ without timing (---)
 - $\eta < |3.5|$ with 25ps timing accuracy (---)
 - $\eta < |4.5|$ with 5ps timing accuracy (---)
- **→ Very challenging!**



FCC-hh Tracker



Tilted layout:

| | | |
|---|---------------------------------|--|
| $25 \times 50 \mu\text{m}^2$ (1-4th BRL) | $33.3 \times 400 \mu\text{m}^2$ | $33.3 \mu\text{m} \times 1.75 \text{ mm}$ (BRL) |
| $25 \times 50 \mu\text{m}^2$ (1st EC ring) | | $33.3 \mu\text{m} \times 1.75 \text{ mm}$ (EC) |
| $33.3 \times 100 \mu\text{m}^2$ (2nd EC ring) | | $33.3 \mu\text{m} \times 50 \text{ mm}$ (12th BRL layer) |
| $33.3 \times 400 \mu\text{m}^2$ (3-4th EC ring) | | |

Assuming an r - ϕ resolution of
7.5-9.5 μm per detector layer

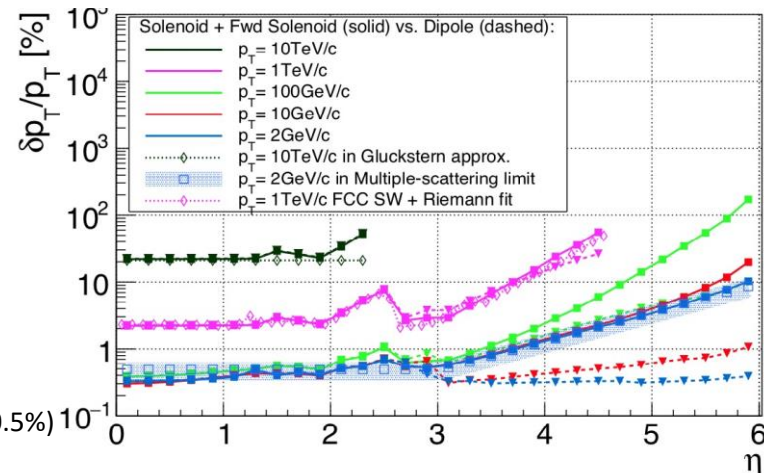
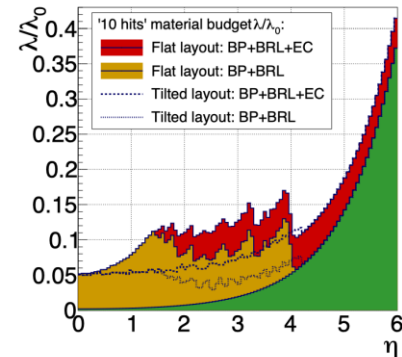
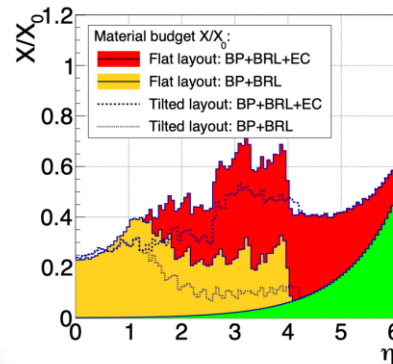
$\delta p_T/p_T \leq 10\%$ for

- $\leq 10 \text{ GeV}/c$ and $\eta \leq 5.8$
- $\leq 1 \text{ TeV}/c$ and $\eta \leq 4.0$

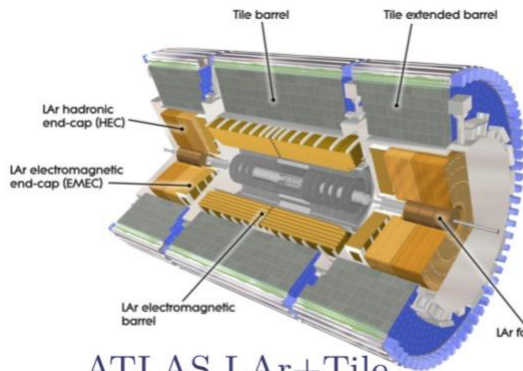
$\delta p_T/p_T = 20\%$ for 10 TeV/c in the central region

Momentum resolution dominated by **multiple scattering** up to 250 GeV (limit at $\delta p_T/p_T = 0.5\%$)

→ **low material tracker!!**

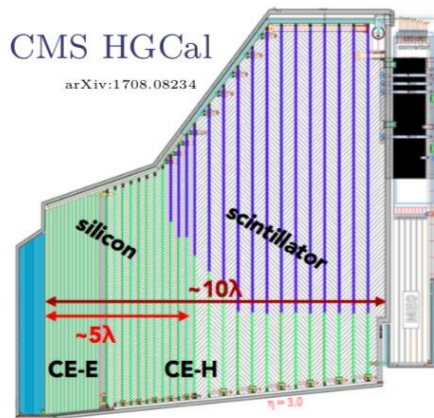


FCC-hh Calorimetry



ATLAS LAr+Tile

arXiv:1305.4551

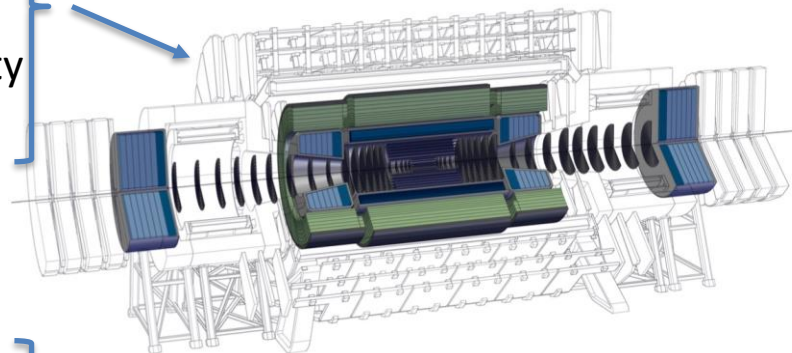


CMS HGCAL

arXiv:1708.08234

- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

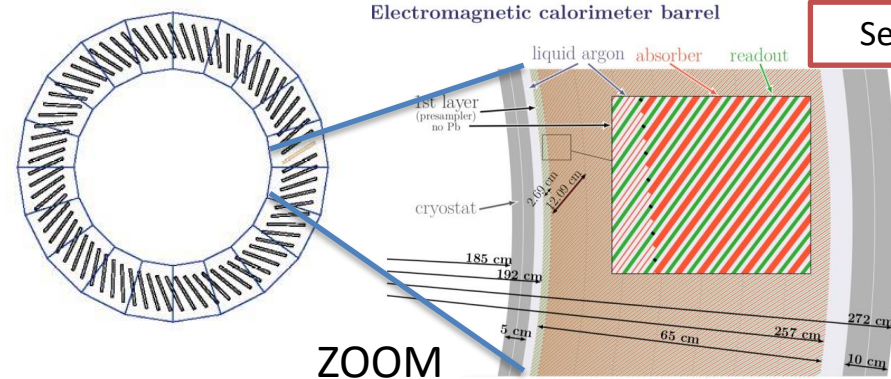
FCC-hh Calorimetry
„conventional calorimetry“
optimized for particle flow



- High granularity
 - Pile-up rejection
 - Particle flow
 - 3D/4D/5D imaging

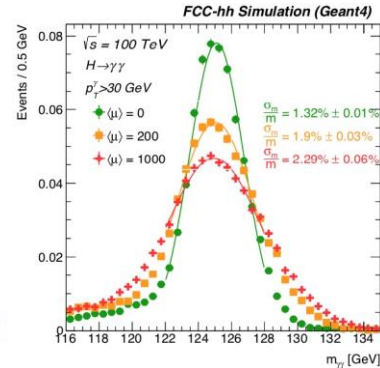
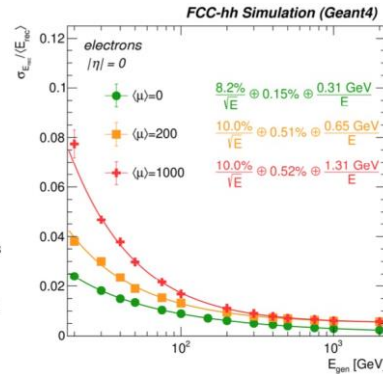
FCC-hh Calorimetry studies have been published at <https://arxiv.org/abs/1912.09962>

Electromagnetic Calorimeter (ECAL)

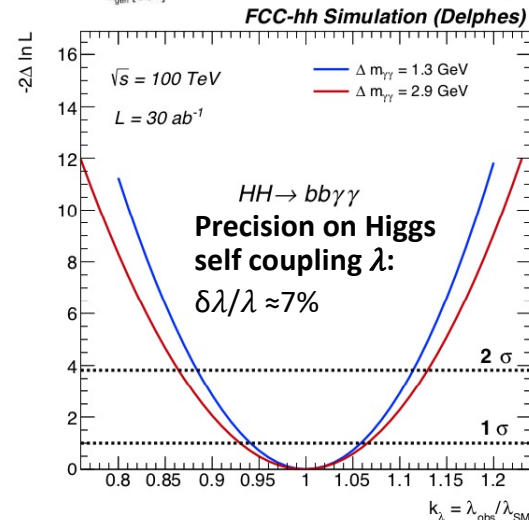


See [arXiv paper](#)

- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\phi = 0.009$;



- **CDR Reference Detector: Performance & radiation considerations \rightarrow LAr ECAL, Pb absorbers**
 - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
 - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$, first layer $\Delta\eta=0.0025$),
 - $\rightarrow \sim 2.5\text{M}$ read-out channels
- Possible only with **straight multilayer electrodes**
 - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
 - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
 - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
 - Sampling term $\leq 10\%/\sqrt{E}$, only ≈ 300 MeV electronics noise despite multilayer electrodes
 - Impact of in-time pile-up at $\langle\mu\rangle = 1000$ of $\approx 1.3\text{GeV}$ pile-up noise (no in-time pile-up suppression)
 - \rightarrow Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)



Hadronic Calorimeter (HCAL)

Barrel HCAL:

- **ATLAS type TileCal optimized for particle flow**
 - Scintillator tiles – steel,
 - Read-out via wavelength shifting fibres and SiPMs
- **Higher granularity** than ATLAS
 - $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
 - 10 instead of 3 longitudinal layers
 - Steel \rightarrow stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout \rightarrow faster, less noise, less space
- Total of 0.3M channels

Combined pion resolution (w/o tracker!):

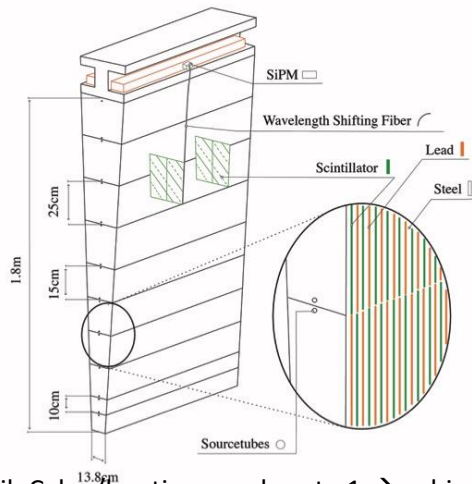
- Simple calibration: $44\%/\sqrt{E}$ to $48\%/\sqrt{E}$
- Calibration using neural network (calo only):
 - Sampling term of $37\%/\sqrt{E}$

Jet resolution:

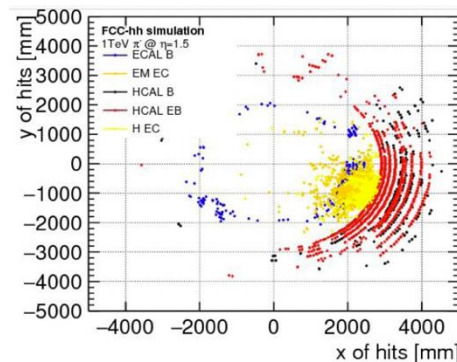
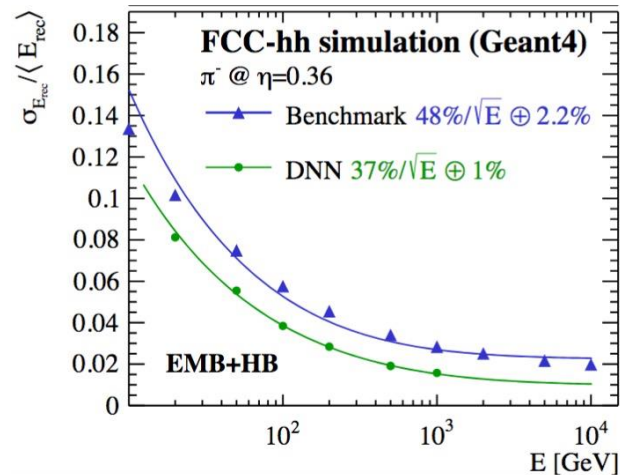
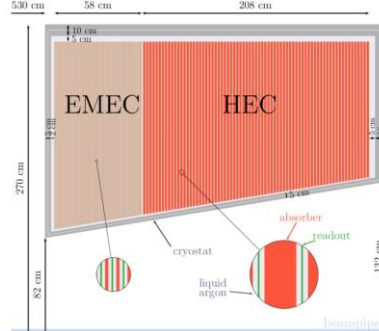
- Jet reconstruction impossible without the tracker @ 4T \rightarrow particle flow.

Endcap HCAL and forward calorimeter:

- Radiation hardness!
- LAr/Cu, LAr/W

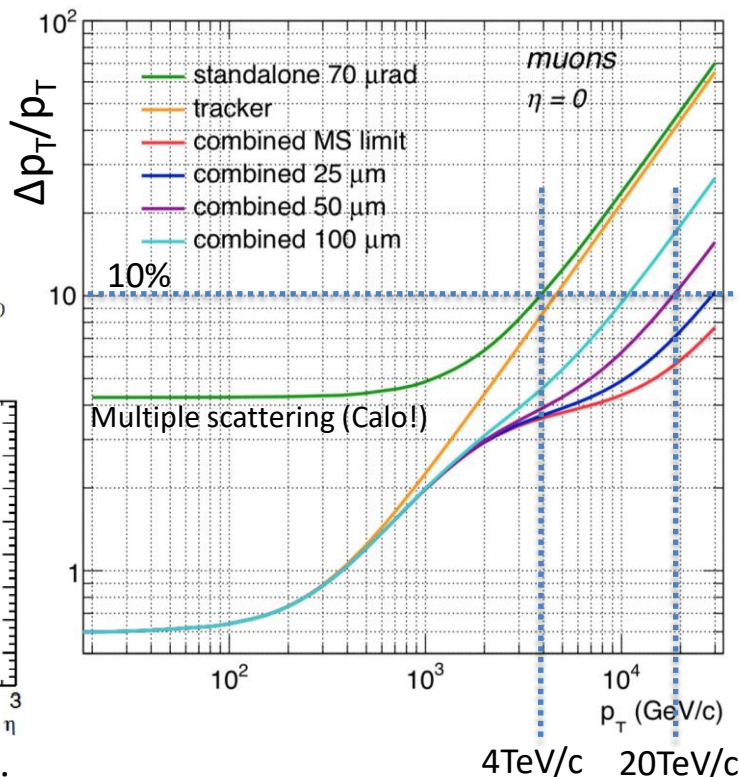
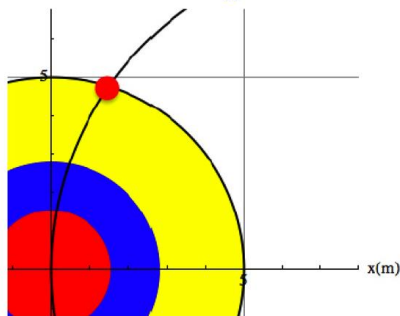


TileCal: e/h ratio very close to 1 \rightarrow achieved using steel absorbers and lead spacers (high Z material)



FCC-hh Muon System

$p_t = 3.9 \text{ GeV}$ enters muon system
 $p_t = 5.5 \text{ GeV}$ leaves coil at 45 degrees

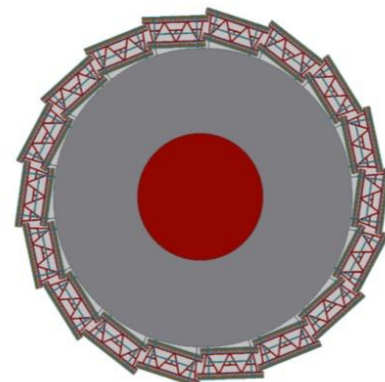


With $50 \mu\text{m}$ position resolution and $70 \mu\text{rad}$ angular resolution we find ($\eta=0$):

- $\leq 10\%$ standalone momentum resolution up to 4 TeV/c
- $\leq 10\%$ combined momentum resolution up to 20 TeV/c

Standalone muon performance not relevant, the task of muon system is **triggering and muon identification!**

Muon rate dominated by c and b decays \rightarrow isolation is crucial for triggering W, Z, t!



Muon barrel: Rates of up to $\sim 500 \text{ Hz/cm}^2$ expected

Muon detection in forward region:

Expected rates up to 500 kHz for $r > 1 \text{ m}$

\rightarrow HL-LHC muon system gas detector technology will work for most of the FCC detector area

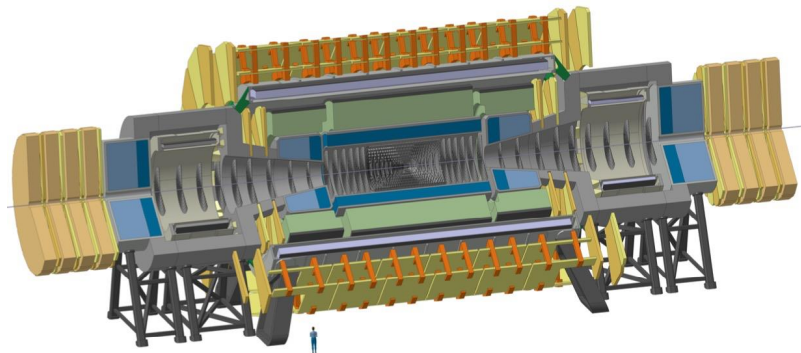
Reading Out Such a Detector → Trigger/DAQ

- **Example ATLAS:**

- ATLAS Phase II calorimetry will be digitized at 40MHz and sent via optical fibers to L1 electronics outside the cavern at 25TByte/s to create the L1 Trigger.
- Muon system will also be read out at 40MHz to produce a L1 Trigger.

- **FCC-hh detector:**

- calorimetry and muon system at 40MHz will result in 200-300 TByte/s, which seems feasible.
- 40MHz readout of the tracker (using zero-suppression) would produce about 800TByte/s.



- **FCC-hh trigger strategy question:**

- Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz?
 - Difficult: 400kHz of W's and 100MHz of jets ($p_T > 50\text{GeV}$)
- Or: un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.