# ALLEGRO
# Noble-Liquid ECAL Based Detector Concept

Martin Aleksa

- Physics Requirements
- Proto Detectors – New Detector Concept
- Noble-Liquid ECAL
- DRD6

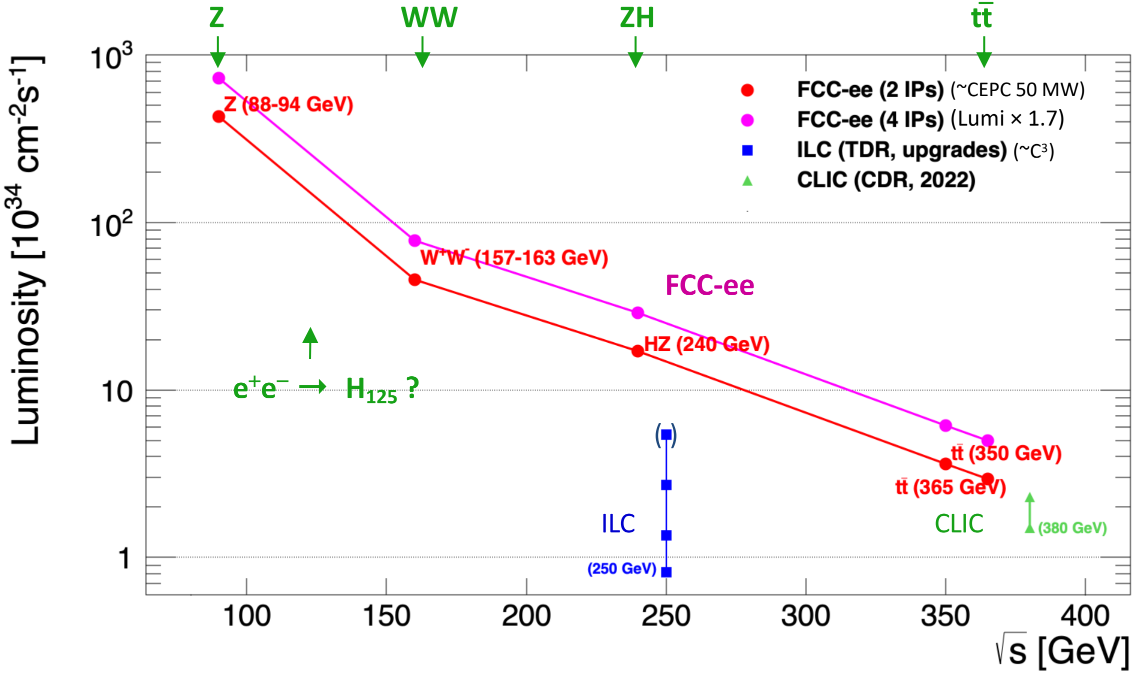
**Based on:**

- First Annual US FCC Workshop at BNL (https://www.bnl.gov/usfccworkshop/)
- FCC Week in London (https://indico.cern.ch/event/1202105/)
- Noble-Liquid Calorimeter Group Meetings (https://indico.cern.ch/category/8922/)

# FCC-ee versus other $e^+e^-$ Collider Options

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

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




**FCC-ee: ultimate precision with**

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

**… in each detector**

→ **FCC-ee EWPO measurements with unprecedented statistical precision**

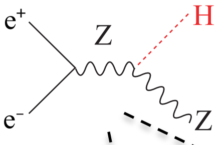
e.g. 6 x $10^{12}$ hadronic Z decays at Z-pole

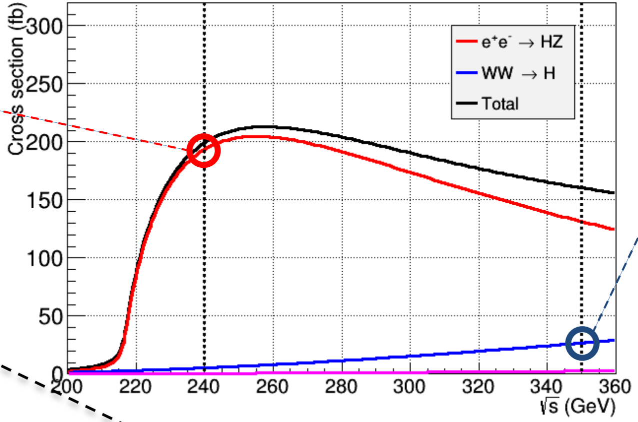
**Statistical precision** for EWPOs measured at the Z-pole is **typically 500 times smaller than the current uncertainties**

→ **Systematic uncertainty dominant!**

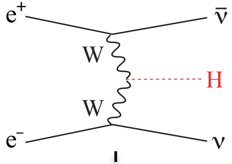
# Higgs Factory: Higgs Production and Decay

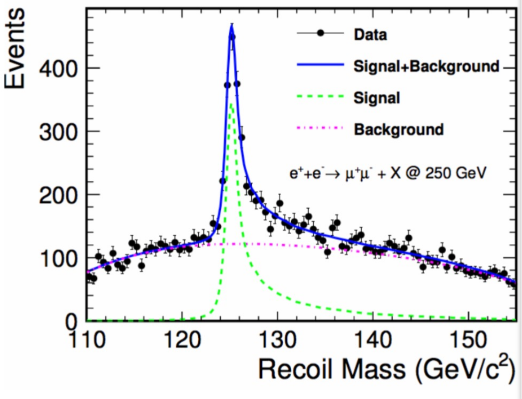
**Higgs-strahlung**



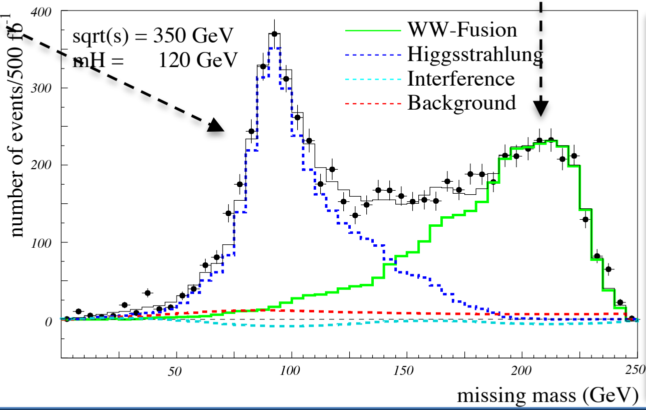




**Boson fusion**




momentum resolution




jet energy resolution

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

flavour tagging

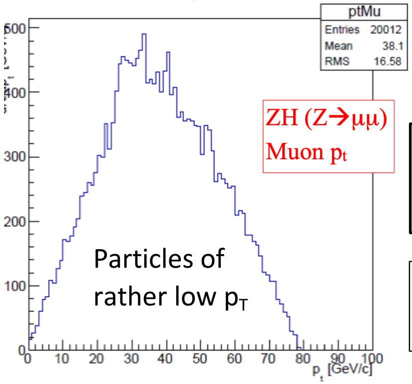
# Vertex Detector and Tracking

**Flavour Tagging:**
Impact parameter "design goal"…

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

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

arXiv:1911.12230

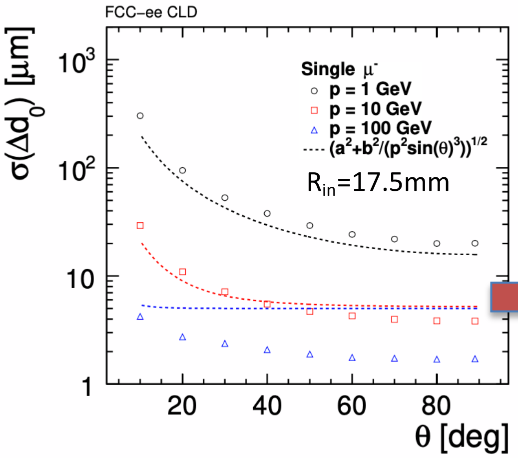



**→ Momentum resolution**
multiple scattering dominated

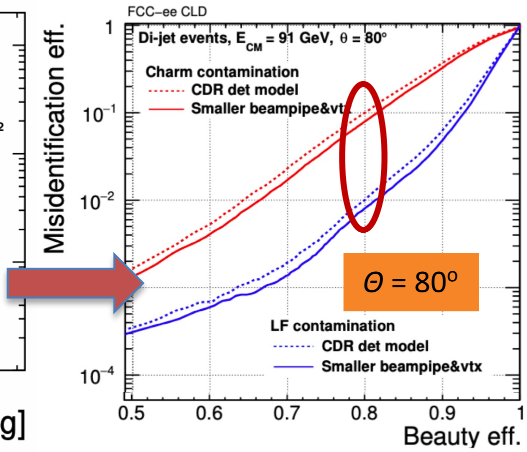
$$\sigma(p_\mathrm{T})/p_\mathrm{T}^2 = a \oplus \frac{b}{p \sin\theta}$$

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

## e.g. CLD flavour tagging




**b-tagging**

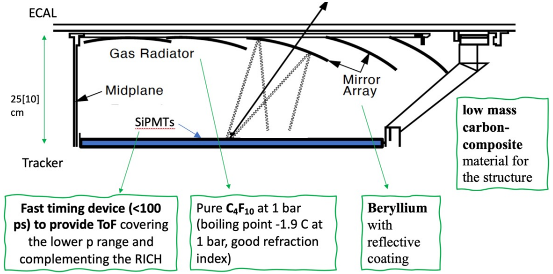



- → **Flavour tagging – Vertex Detector: Lighter, more precise (smaller pixel size), closer to IP**
- → **Momentum Resolution – Tracking Detector: The lighter the better**

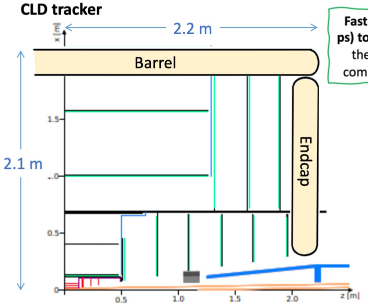
| | r beam pipe | 1st VTX layer |
|---|---|---|
| ILC | 12 mm | 14 mm |
| CLIC | 29 mm | 31 mm |
| FCC-ee | 10 mm | 12 mm |

# Particle Identification

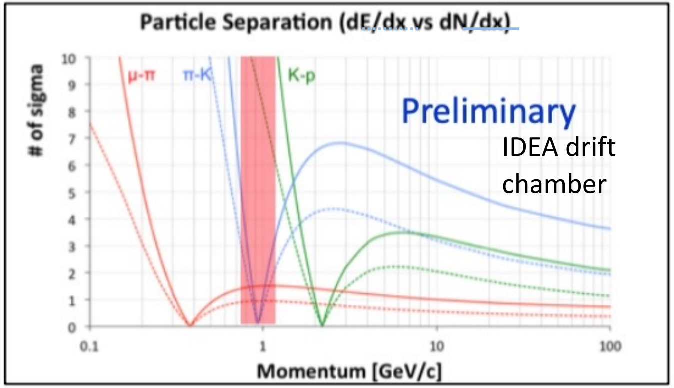
- **PID capabilities across a wide momentum range** is essential for flavour studies and will enhance overall physics reach
  - Example: important mode for CP-violation studies $B^0_S \rightarrow D^{\pm}_S K^{\mp}$ → require K/π separation over wide momentum range to suppress same topology $B^0_S \rightarrow D^{\pm}_S \pi^{\mp}$
- **E.g. IDEA drift chamber** promises >3σ 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)
  - → could give 3σ π/K separation from 5 GeV to ~80 GeV

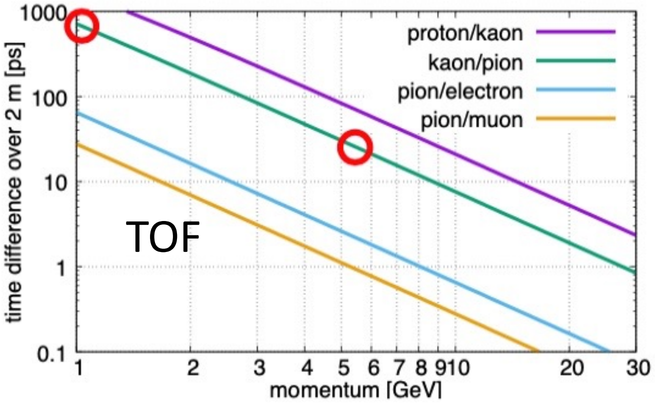


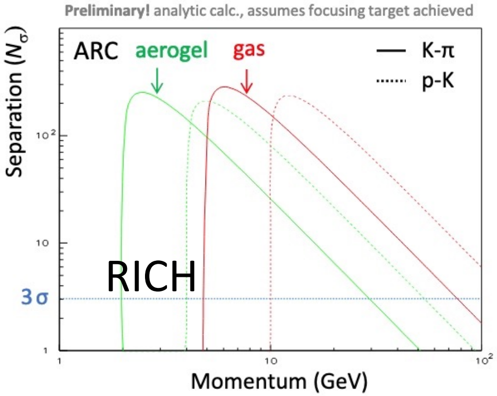

FCC Workshop, Feb. 2022




Possible RICH layout in an FCC-ee experiment



# Calorimetry – Jet Energy Resolution

Energy coverage < 300 GeV : $22\ X_0$, $7\lambda$

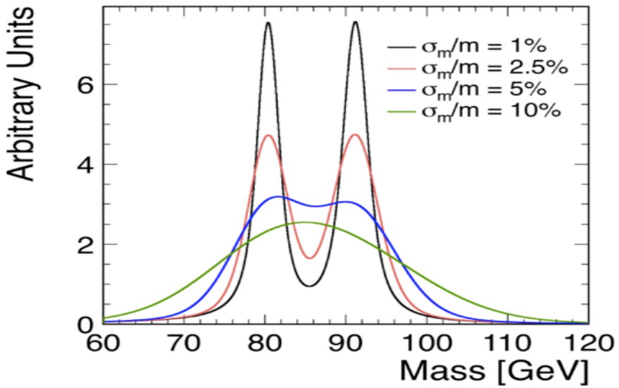
Precise jet angular resolution

Jet energy: $\sigma(E_{jet})/E_{jet} \simeq 30\% / \sqrt{E\,[\mathrm{GeV}]}$ **?**

**⇒ Mass reconstruction from jet pairs**

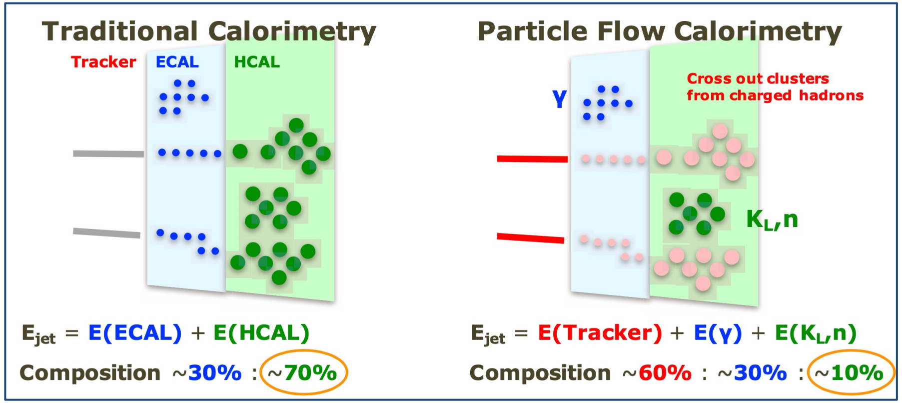
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

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




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

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




**→ High granularity and/or dual read-out**

# Calorimetry

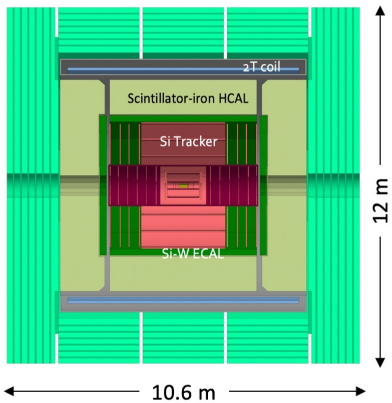
| Detector technology (ECAL & HCAL) | E.m. energy res. stochastic term | E.m. energy res. constant term | ECAL & HCAL had. energy resolution (stoch. term for single had.) | ECAL & HCAL had. energy resolution (for 50 GeV jets) | Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets) |
|---|---|---|---|---|---|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

**Table 1.** Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists. For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

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

# FCC-ee Proto Detectors – Overview

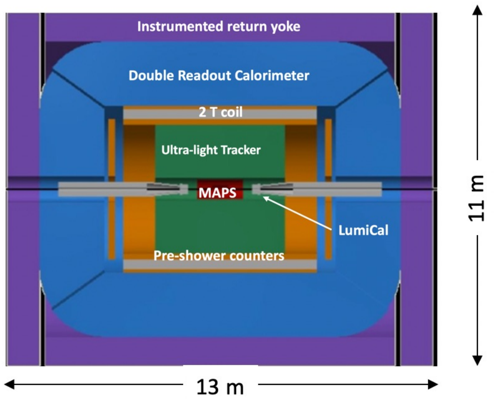
## CLD




- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - $\sigma_p/p$, $\sigma_E/E$
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

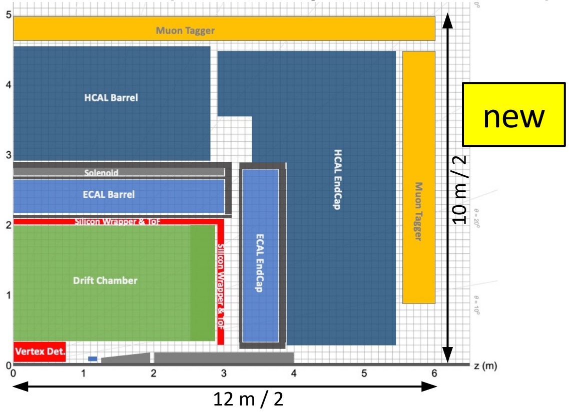
CDR

## 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, …

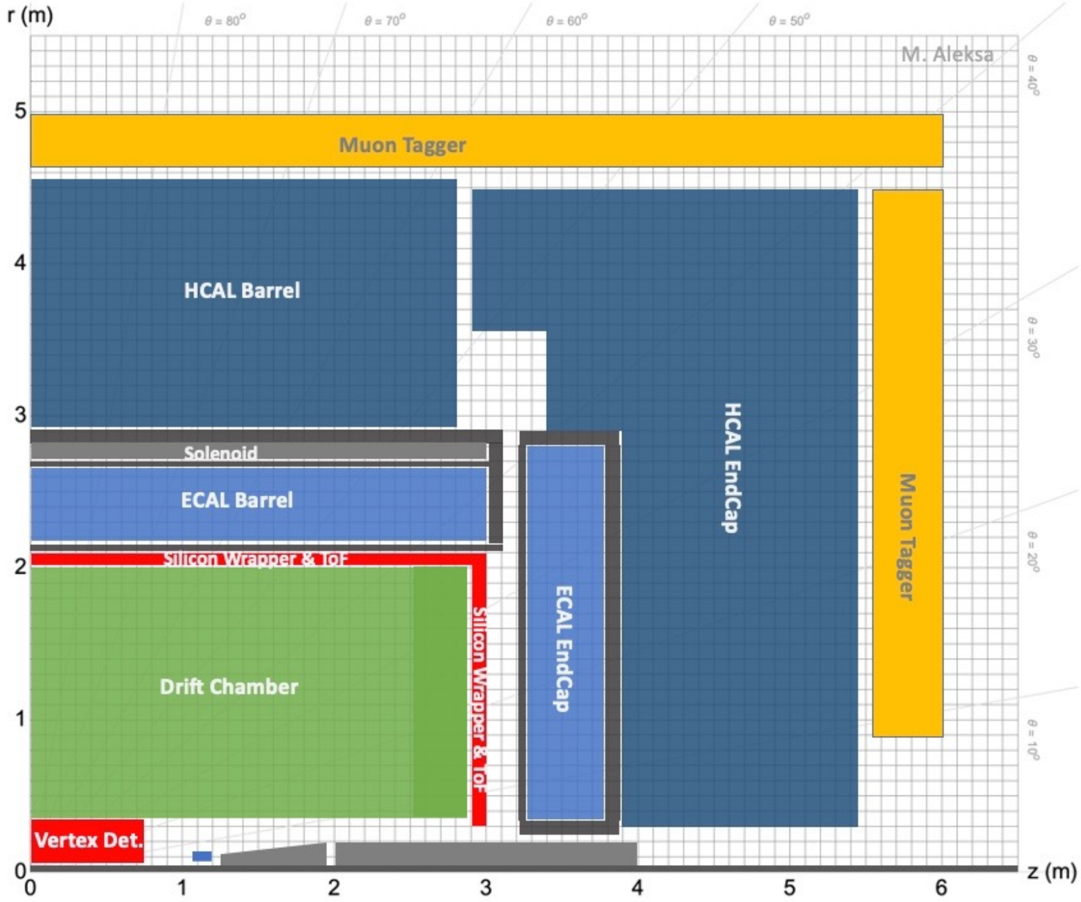
## ALLEGRO (Noble Liquid ECAL based)




- 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

# ALLEGRO Detector Concept




**ALLEGRO**

- **A L**epton co**L**lider **E**xperiment with **G**ranular **R**ead-**O**ut

**Vertex Detector:**

- MAPS or DMAPS possibly with timing layer (LGAD)
- Possibly ALICE 3 like or similar to Belle II VTX upgrade

**Drift Chamber** (±2.5m active) similar to IDEA

**Silicon Wrapper + ToF:**

- MAPS or DMAPS possibly with timing layer (LGAD), Monolithic CMOS (see talk by P. Schwemling this morning)

**High Granularity ECAL:**

- Noble liquid + Pb or W
- Particle Flow reconstruction

**Solenoid B=2T**, sharing cryostat with ECAL, between ECAL and HCAL

- Light solenoid coil ≈ 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

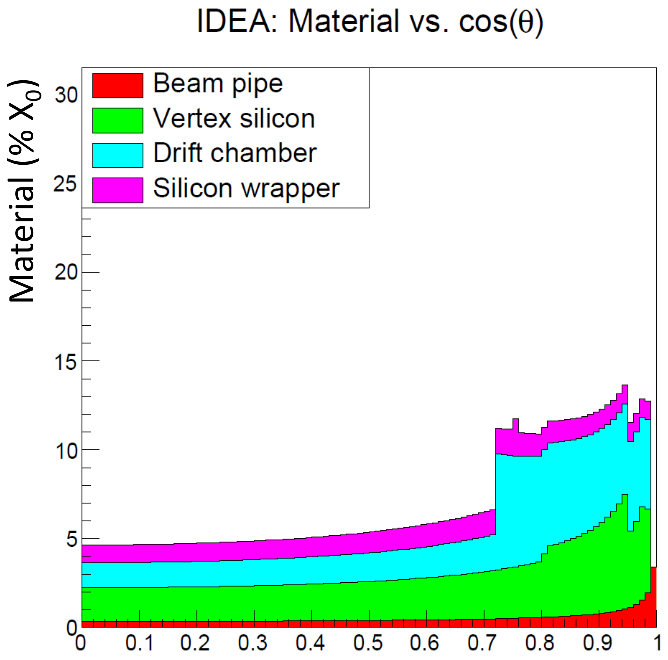
# Vertex Detector & Momentum Measurement

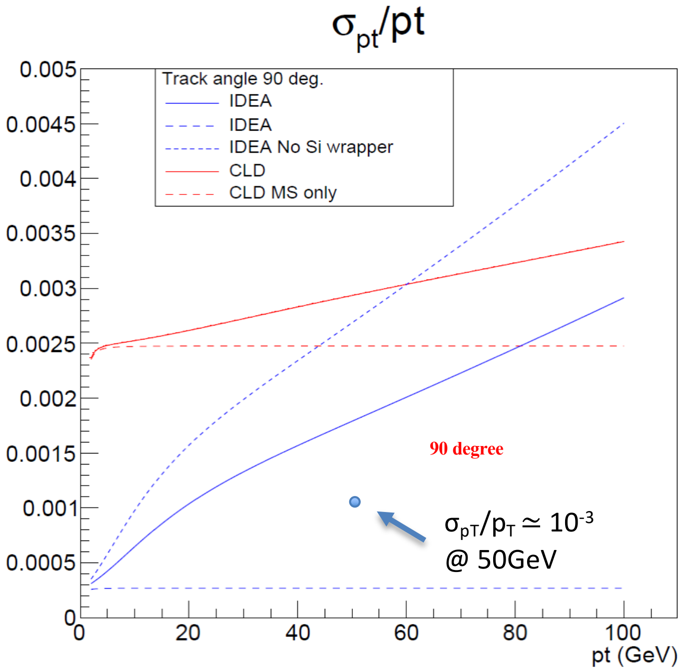
**Starting Point: IDEA Vertex Detector and Drift Chamber**

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

→ Transparency more important than asymptotic resol. → minimize material!

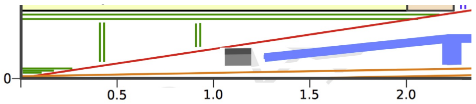
→ Very light vertex detector and drift chamber (see next slide and back-up)

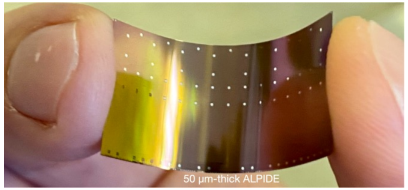



**Vertex Detector:** E.g. similar to Belle II based on Depleted Monolithic Active CMOS

- 5 layers, pixels 33×33 $\mu m^2$
- Light
  - Inner layers: 0.1% $X_0$/layer
  - Outer layers: 0.5 % - 1% $X_0$/layer
- Performance:
  - Impact parameter resolution of ~ 10 µm
  - Efficiency of ~ 95%
  - Extremely low fake rate hit



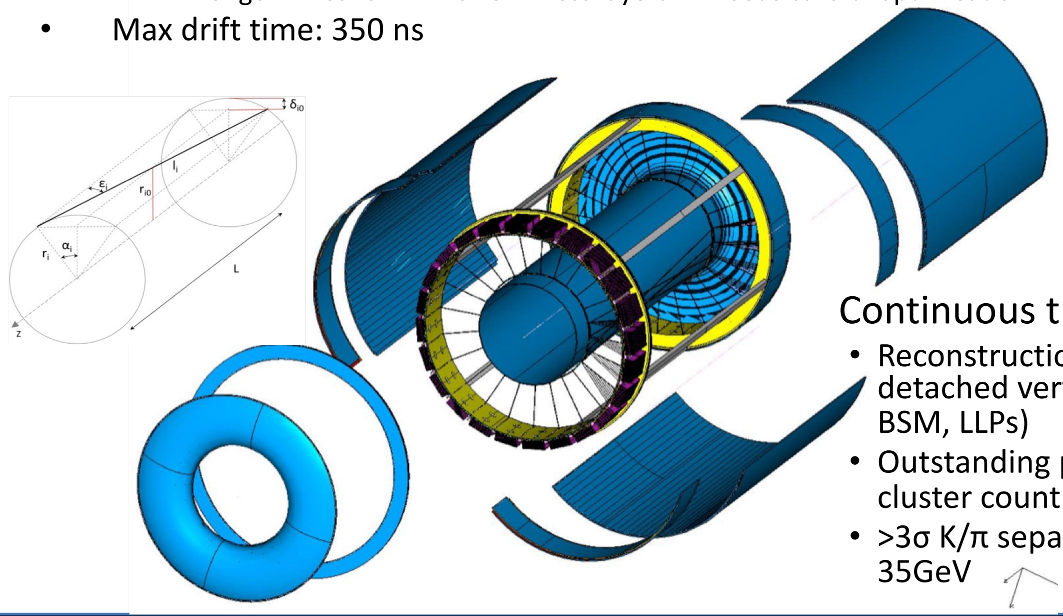

Courtesy of Magnus Mager, CERN

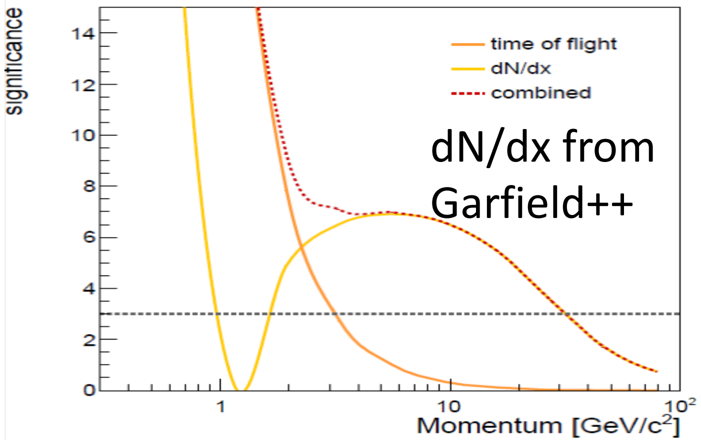
# Drift Chamber – IDEA

**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
  - Longer wires for ALLEGRO → less layers → needs careful optimisation
- Max drift time: 350 ns

See talk by N. De Filippis this morning!

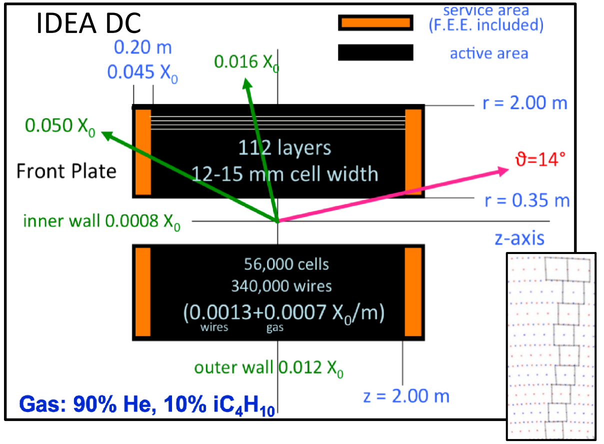




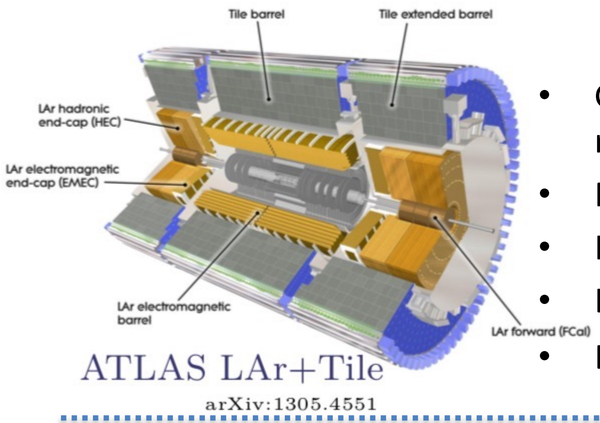

dN/dx from Garfield++

Continuous tracking:

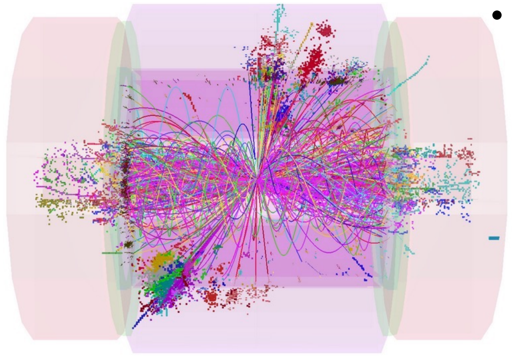
- Reconstruction of far-detached vertices ($K^0_s$, Λ, BSM, LLPs)
- Outstanding part. ID via cluster count. dN/dx or dE/dx
- >3σ K/π separation up to 35GeV



# FCC Calorimetry




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

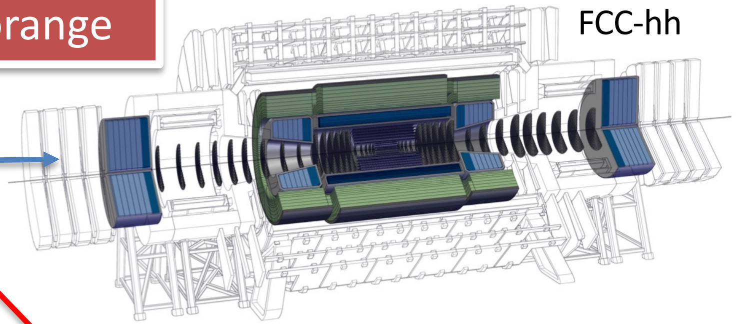


CLIC Detector

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

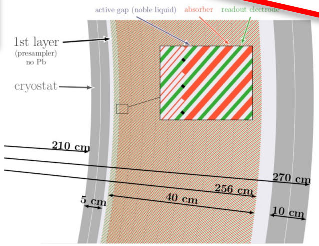
See talk by N. Morange

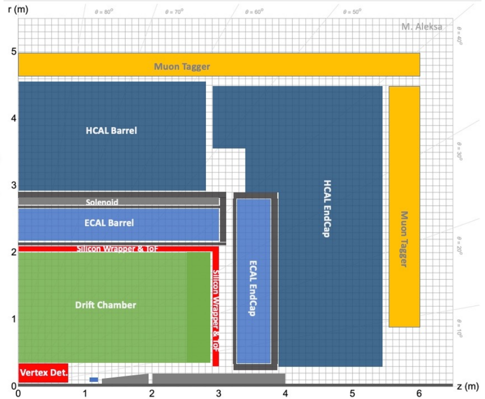
FCC Calorimetry



FCC-hh

FCC-ee



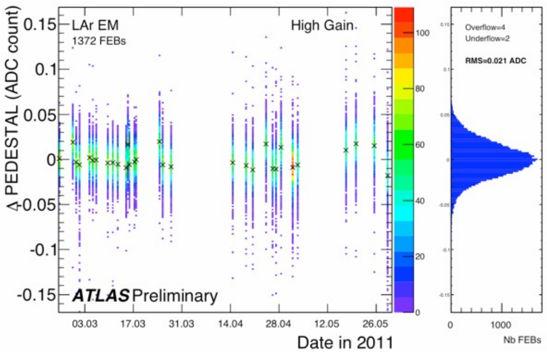




FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

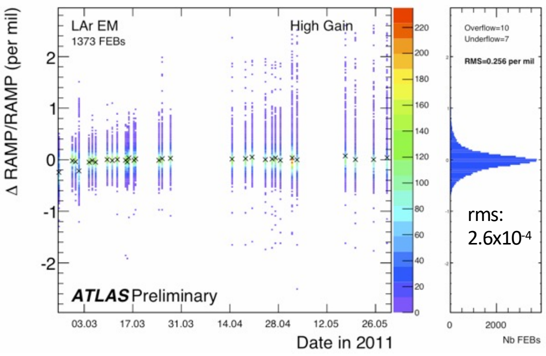
# Example – Stability of ATLAS LAr Energy Scale

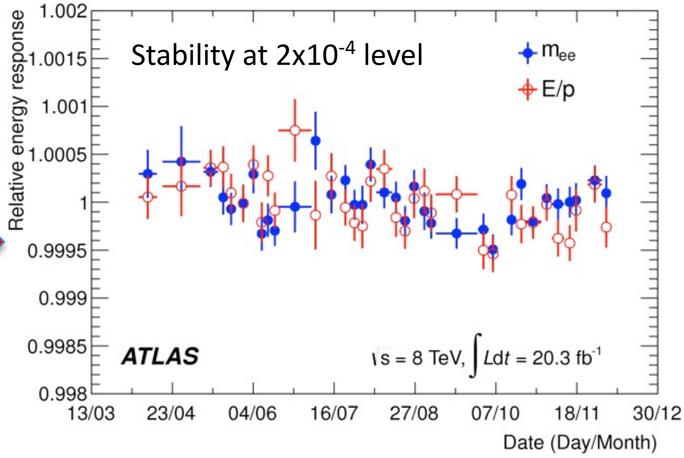
- **Noble-liquid calorimetry:** High intrinsic stability (see gain and pedestal stability)
  - Pedestal stability < 100 keV (!)
  - Gain stability 2.6x$10^{-4}$
- These parameters are monitored in daily calibration runs → constants are updated when necessary (about once a month)
- → Leading to high stability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

Pedestal (P) stability



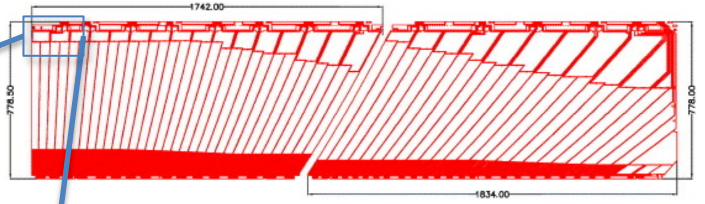

Gain (R) stability

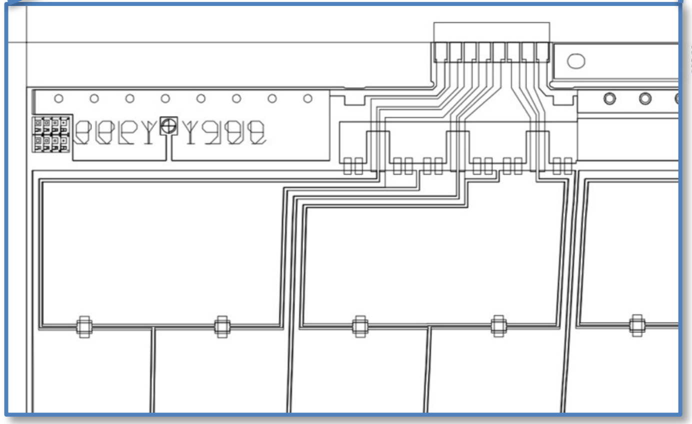


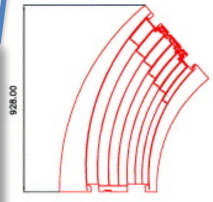



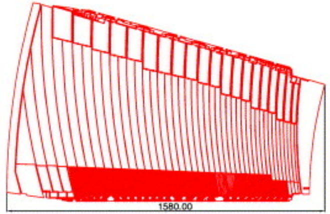
# Granularity – What are the Limits in ATLAS LAr?

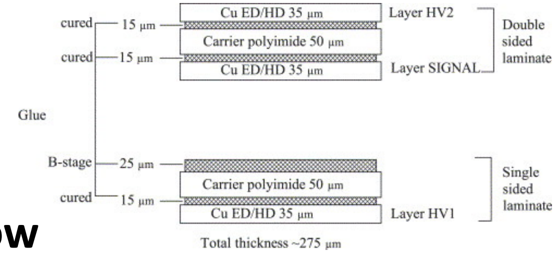
- **In the ATLAS LAr calorimeter** electrodes have 3 layers that are glued together (~275µm thick)
  - 2 HV layers on the outside
  - 1 signal layer in the middle
- → **All cells** have to be connected **with fine signal traces** (2-3mm) to the edges of the electrodes
  - Front layer read at inner radius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

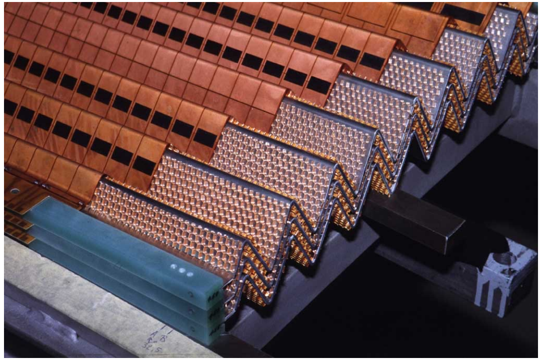




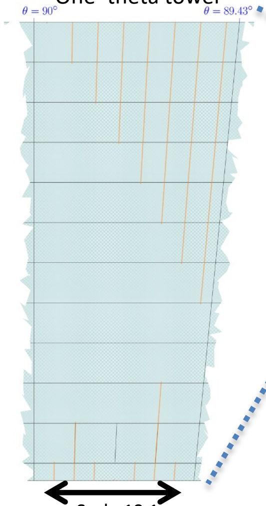
**→ O(200k) read-out cells – particle flow reconstruction possible, but not optimal**

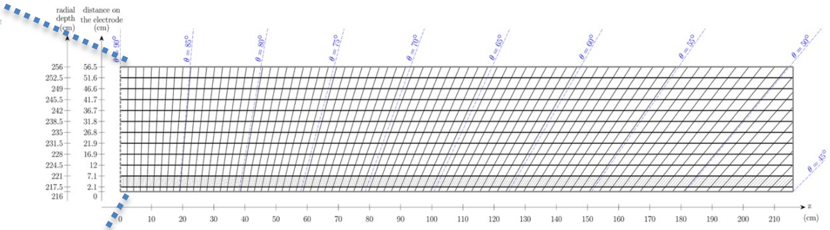
# Noble-Liquid Calo: How to Achieve High Granularity?

**Realize electrodes as multi-layer PCBs ($H$=1.2mm thick), 5 to 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 $w_s$ , dist. $h_s$) forming 50Ω – 80Ω transmission lines
  - Optimizing between 0, 1 or 2 shield layers
- → capacitance between shields and signal pads $C_s$ will add to the detector capacitance via the gap $C_d$
- → $C_{cell} = C_s + C_d \approx 25 – 300$pF
- The higher the granularity the more shields are necessary → $C_s$ increases, $C_d$ decreases (smaller cells)

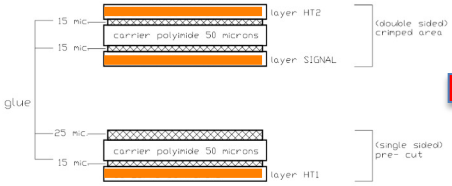
One ‘theta tower'

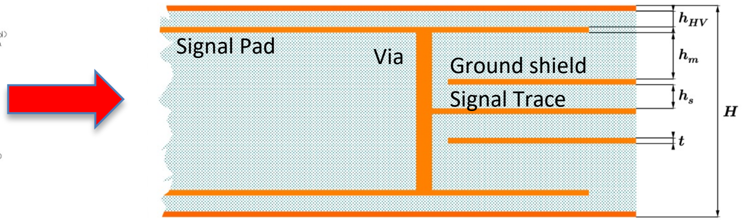


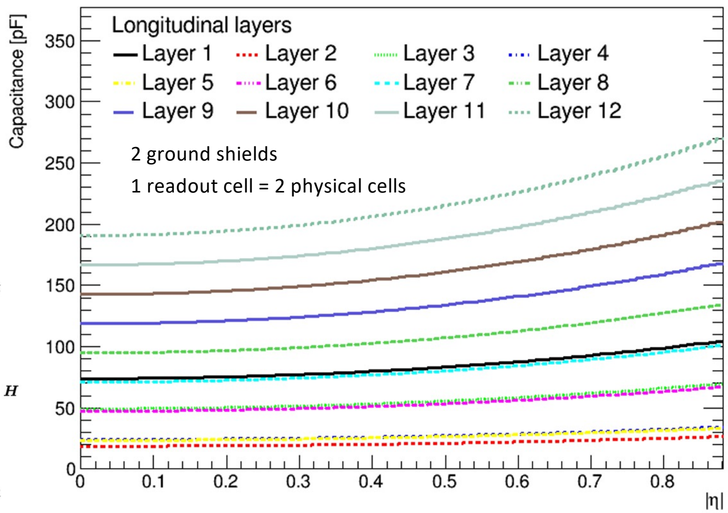
Multi-layer read-out electrode for FCC

ATLAS electrode




Total capacitance (no trace)




**In principle any granularity realisable → cost in cross-talk and noise → careful optimization!**

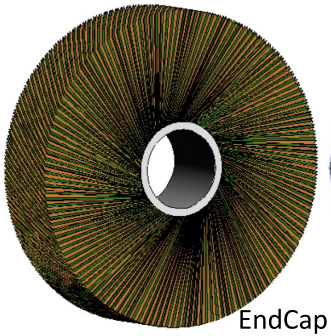
# High Granularity Noble-Liquid Calorimeter

**Baseline design**

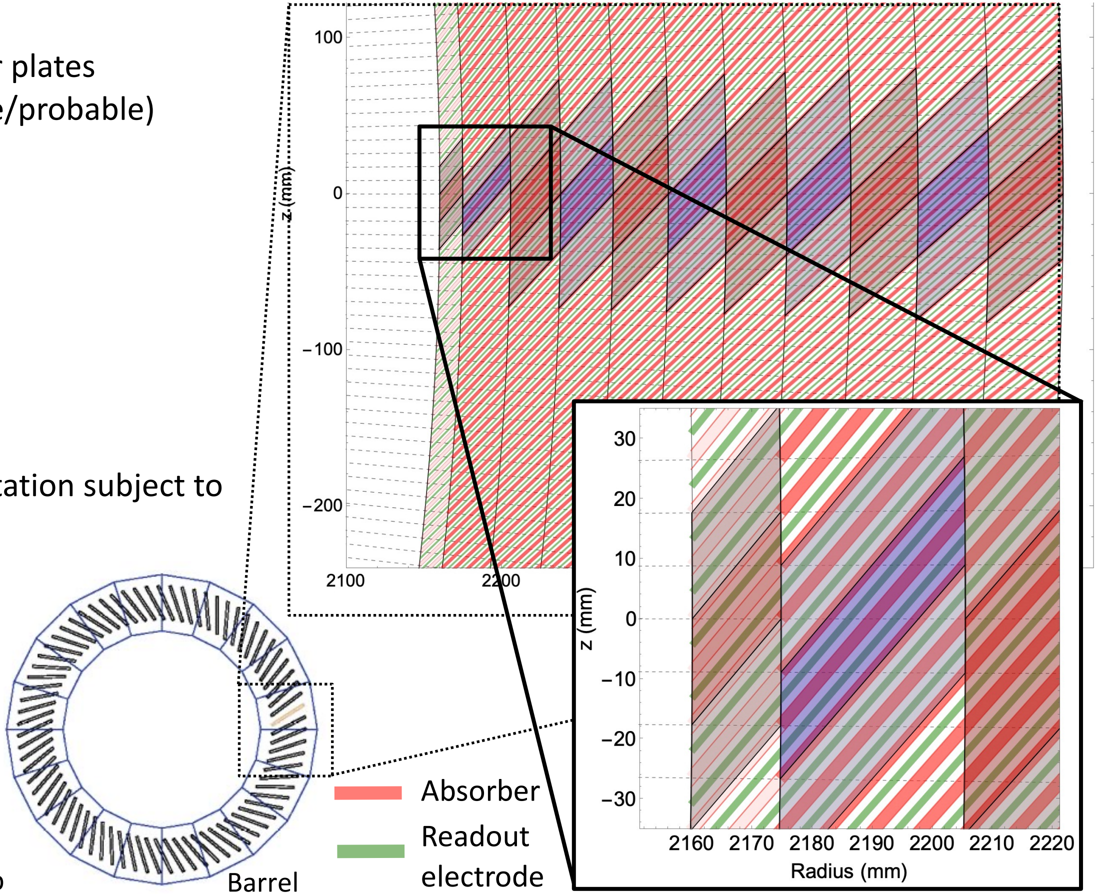
- 1536 straight inclined (50.4°) 1.8mm Pb absorber plates
- $R_i$=216cm, $R_o$=256cm (small adjustments possible/probable)
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm LAr gaps
- 40cm deep (≈ 22 $X_0$)
- Segmentation:
  - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells,
  - $\Delta\phi$ = 8 mrad
  - → cell size in strips: 5.4mm x 17.8mm x 30mm
- 11 longitudinal compartments
- Implemented in FCC-SW Fullsim
- Exact radius and lateral and longitudinal segmentation subject to further optimization!

**Possible Options**

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



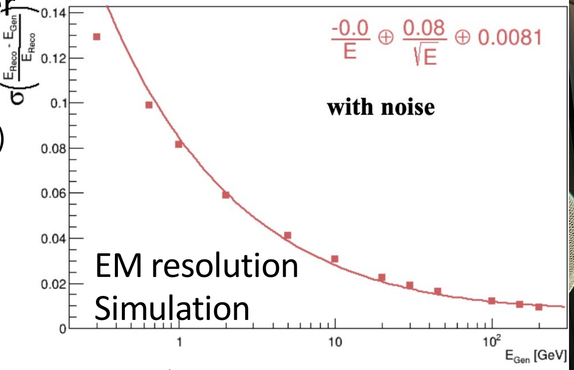
EndCap



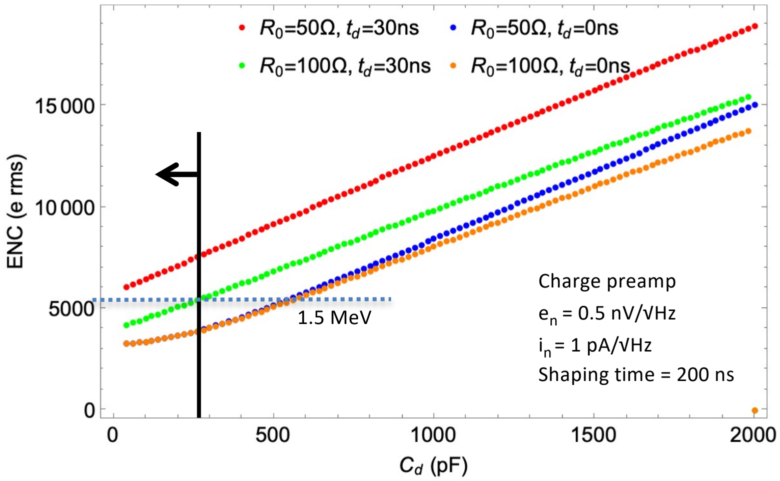

Barrel

# Challenges: Resolution, Noise and Crosstalk

- **Goal: EM resolution** with sampling term of 8-10% or better
  - Further **optimization** under study
    - Increasing sampling fraction,
    - Different absorber geometries (increasing thickness with depth)
    - Other active material (LAr/LKr)

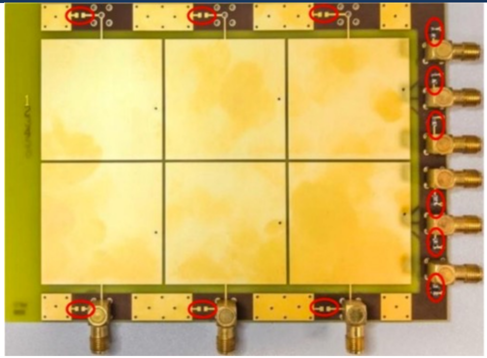


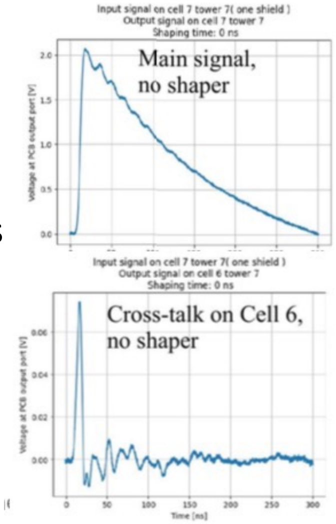

- **Noise vs cross-talk challenge:** traces need to be shielded to minimize cross-talk → grounded shields increase detector capacitance and hence noise → need to find best compromise – **prototype electrode produced & measured**
  - **Noise** of < 1.5 MeV per cell for warm electronics and transmission lines of $R_0$ = 100 Ω and τ = 200 ns ($C_d$ ≤ 250 pF)
    - → **MIP S/N > 5** reached for all layers using **warm electronics**
    - **With cold electronics noise** can be **further improved** substantially

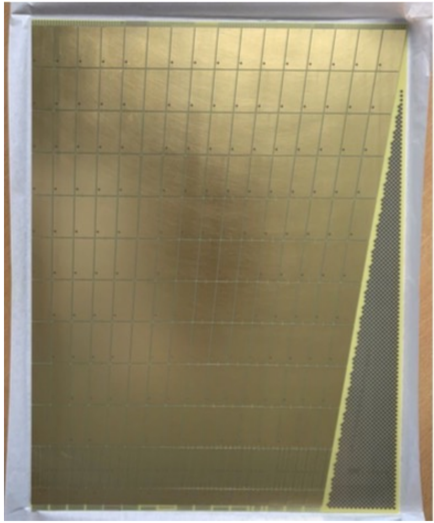



# Prototype Electrodes

- **Small Scale Prototype Electrode** (IJCLab)
  - Detailed measurements of cell properties and cross-talk effects
    - Frequency behaviour
    - Good overall agreement with simulations on large frequency range
- **Larger Scale Prototype Electrode** (CERN)
  - 1:1 scale $\theta$ chunk: 16 towers with different layouts
    - Electrical tests with function generator, scope and software shaper
    - Sub-percent cross-talk easily achievable with > 50 ns shaping
- **New Prototypes Planned at IJCLab and CERN**



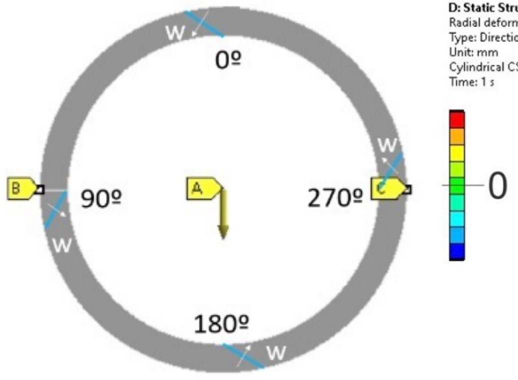


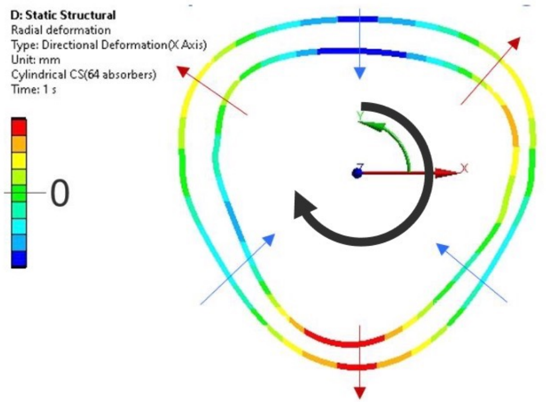



# Noble-Liquid Calorimeter – Mechanical Studies

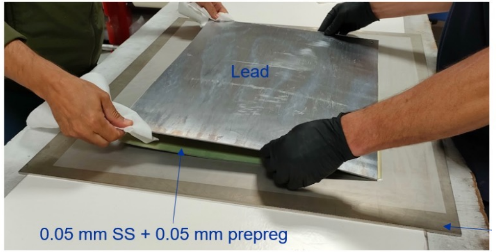
- Started to model **full barrel calorimeter**
- Defining **inner and outer rings** to hold barrel calorimeter
- Defining **spacers** between absorbers and electrodes – optimizing distance
- In order to verify assumed rigidity of absorbers building **feasibility prototype** and perform thermo-mechanical tests

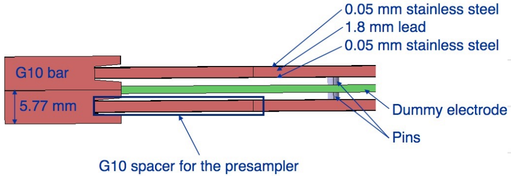
Radial and circumferential displacement of the rings

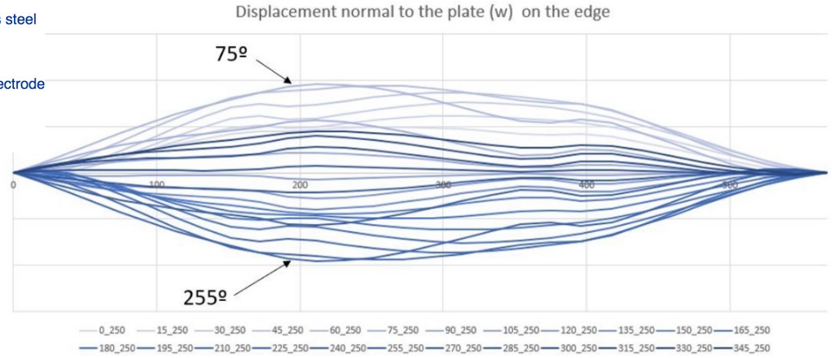




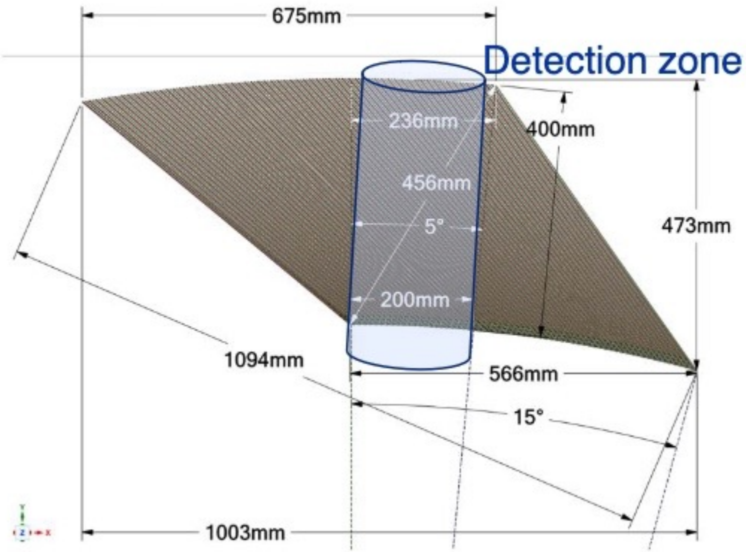


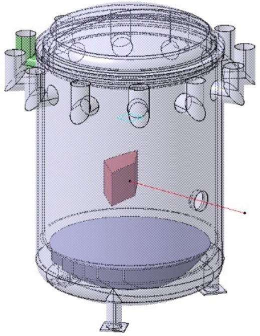



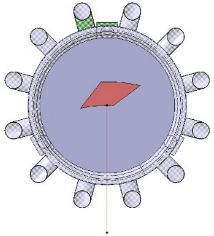
# Noble-Liquid Calorimeter – Testbeam Module

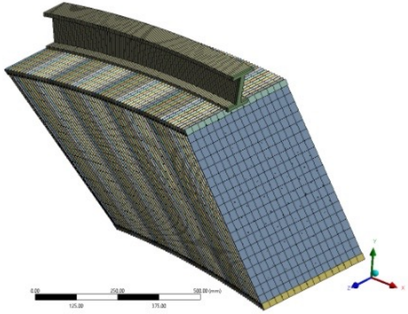
- Mechanical design of **testbeam module** (64 absorbers) has started
- **Finite element calculations** including
  - Rings and G10 bars
  - Absorbers and electrodes as shell (2D) elements using layers
  - Distance pins
  - Six M5 beams join electrodes and absorbers in each side (inner-outer)
- In parallel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

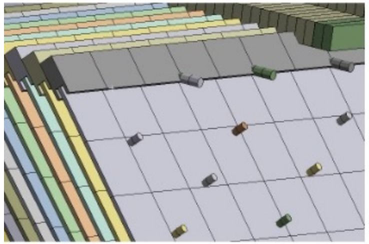


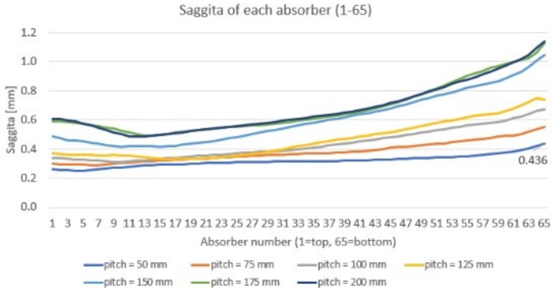

The cryostat available to make the test beam is the CRRP-00563.





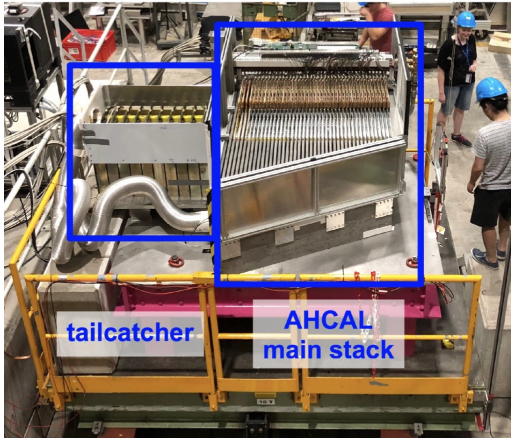




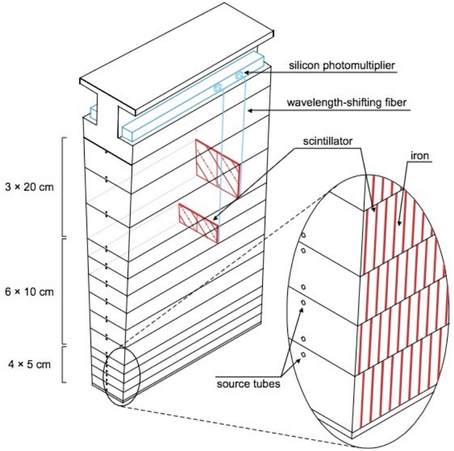


# HCAL for Noble-Liquid Based Concept

- **ATLAS TileCal inspired HCAL** has been implemented into FullSim, other **Sci/Steel options (CALICE like) will also be studied**
- **FCC-ee TileCal** (talk by M. Mlynarikova):
  - 5mm steel absorber plates alternating with 3mm Scint.: 8 - 9.5λ
  - 128 modules in ϕ, 2 tile/module
  - 13 radial layers
  - Δη = 0.025 (grouping 3-4 tiles), Δϕ = 0.025
  - In the FCC-hh design there used to be Pb plates to improve the e/h ratio. Since the HCAL acts as return yoke, these Pb plates have been removed for FCC-ee.
  - 13 layers in depth (smaller cells)
  - FCC-ee TileCal geometry is available in FCCDetectors
  - Work on optimisation of segmentation and reconstruction is in full swing
  - Started testing Sci tile + WLS fibre + SiPM readout
  - ECAL + HCAL performance: Sampling term of ~37% for $\pi^{\pm}$ → excellent starting point for particle flow reconstruction! → further improvement expected




CALICE AHCAL

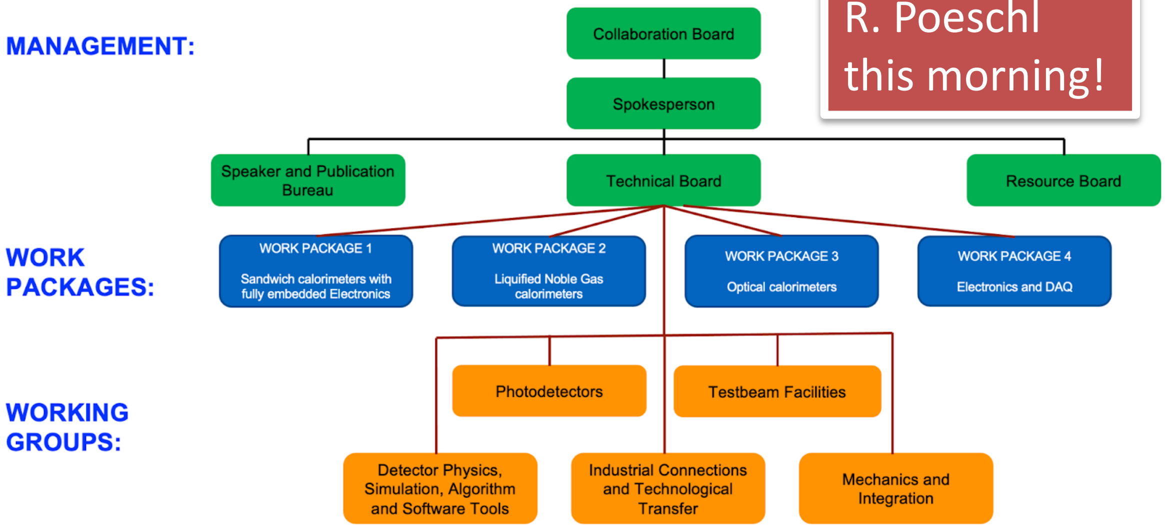



TileCal

# DRD6 Proposal

See talk by R. Poeschl this morning!

- **Detector R&D (DRD) collaborations** being set-up to implement the **ECFA Detector R&D Roadmap**
- **DRD6 on Calorimetry** with 4 work packages and several transversal activities (TB, Materials, SW, …)
  - Noble Liquid Calorimeter R&D part of work area 2 (18 institutes from 7 countries incl. F)
  - TileCal R&D part of work area 3 (7 institutes from 6 countries)
  - CALICE-like AHCAL part of work area 1 (10 institutes from 4 countries incl. F)
- **DRD Proposal** has been submitted, implementation beg. of 2024 (link)
- **Noble Liquid Calorimeter R&D (WP2)** joined by 18 institutes from 7 countries:
  - 5 French participating institutes: IN2P3-IJCLab, IN2P3-APC, IN2P3-CPPM, IN2P3-LPNHE, IN2P3-OMEGA
  - *O*(10-15) FTE expected during the next 5 years

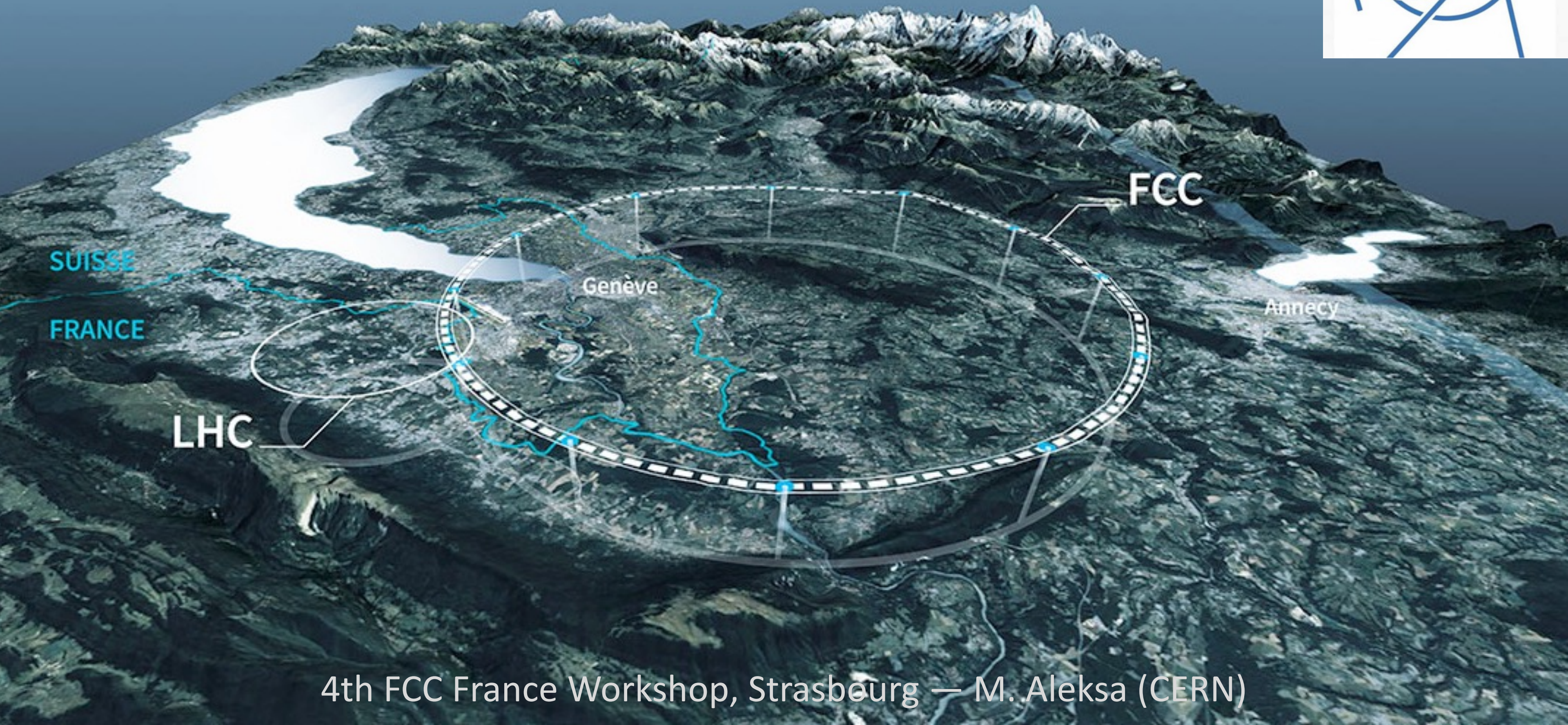



**Work area 2** (noble-liquid calorimetry) **with 4 objectives**:
- Performance studies and optimization, optimization of granularity for particle flow, particle ID and displaced vertices
- Optimisation of read-out electrodes – further prototypes and then production of electrodes for test module
- Read-out electronics: warm electronics versus cold electronics
- Mechanical study of noble-liquid calorimeter in an experiment and design of a module for a testbeam to be built in 2027/2028.

# Conclusions

- A very **active and motivated group** working on the **noble-liquid ECAL** has been forming during the last 4 years → DRD6 work package 2
  - Recent progress on SW and simulation, electrode studies and mechanical studies
  - Many new institutes are joining (now 18 institutes from 7 countries)
  - Planning to build a module for a testbeam in 2027/2028
- **Detector concept ALLEGRO** based on **noble-liquid ECAL** has been proposed – looking for new groups joining
  - ALLEGRO implemented in FCC-SW fullsim
  - Close collaboration with HCAL (DRD6)
  - Reaching out to other groups to join for other detector parts
  - → **Ideal occasion to join ALLEGRO now!**

# Thank You for Your Attention!

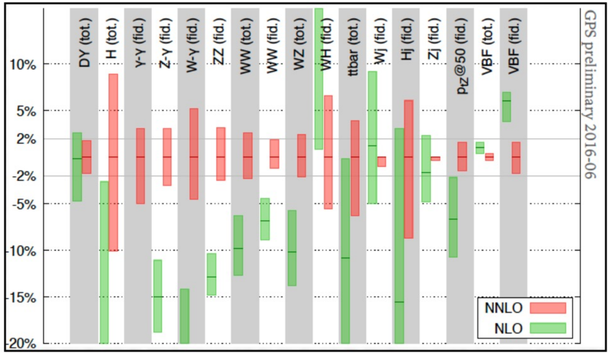


# BACK-UP

# The Challenge – High Precision Measurements

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

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



# FCC-ee Physics Programme

## "Higgs Factory" Programme

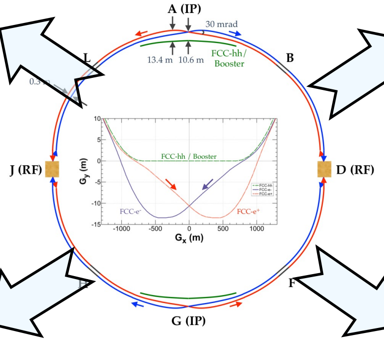
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

## Ultra Precise EW Programme & QCD

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

- $6x10^{12}$ Z and $3x10^{8}$ WW
  - $m_Z$, $\Gamma_Z$, $\Gamma_{inv}$, $\sin^2\theta_W^{eff}$, $R^Z_\ell$, $R_b$, $\alpha_s$, $m_W$, $\Gamma_W$,…
- $2x10^{6}$ tt
  - $m_{top}$, $\Gamma_{top}$, EW couplings

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




## Heavy Flavour Programme

- Enormous statistics: $10^{12}$ bb, cc; $1.7x10^{11}$ ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

## Feebly Coupled Particles - LLPs

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

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

Courtesy M. Dam

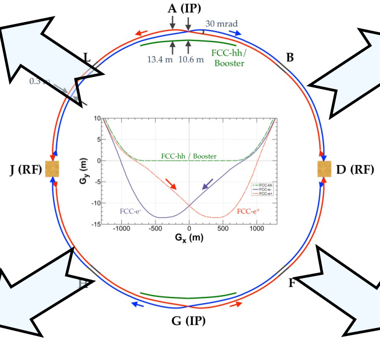
# FCC-ee Detector Requirements

## "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%/$\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

## Ultra Precise EW Programme & QCD

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




## Heavy Flavour Programme

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

Courtesy M. Dam

## Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

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

# PCB Measurement – Simulation Agreement

- **Large Prototype: Improvements on measurement set-up**, better shielding and grounding, now measurements on cells read-out via the front and via the back
- **Improved agreement** between measurements and ANSYS PCB simulations
  - Still discrepancies for no-shaper case – but difficult to measure since set-up will always have some low-pass filtering and attenuate very high frequencies
  - → **Good agreement when shaping applied**
  - → **Cross-talk of < 1%** for shaping times **τ ≥ 20 ns** → might enable us to reduce number of shields

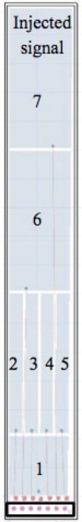
Two shields

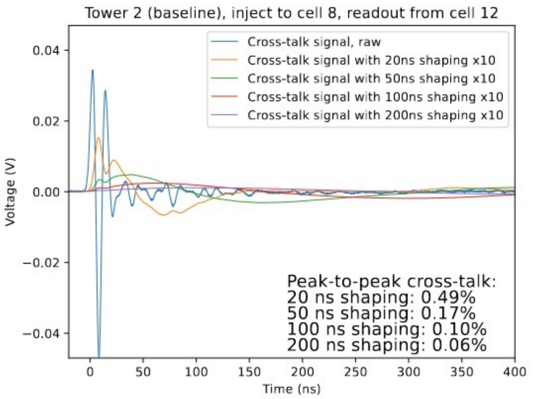
**New measurement**

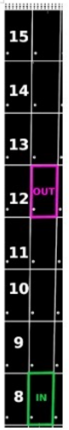
| Cross-talk (%) / Shaping time (ns) ↓ | Cell 1 | Cell 2 | Cell 3 | Cell 4 | Cell 5 | Cell 6 |
|---|---|---|---|---|---|---|
| No shaper | 0.59 | 0.28 | 0.36 | 1.11 | 0.98 | 4.66 |
| 20 | 0.17 | 0.06 | 0.08 | 0.28 | 0.23 | 0.81 |
| 50 | 0.09 | 0.04 | 0.05 | 0.14 | 0.13 | 0.44 |
| 100 | 0.06 | 0.03 | 0.03 | 0.09 | 0.09 | 0.29 |
| 150 | 0.04 | 0.02 | 0.03 | 0.07 | 0.07 | 0.23 |
| 200 | 0.04 | 0.02 | 0.02 | 0.06 | 0.07 | 0.21 |
| 300 | 0.03 | 0.02 | 0.03 | 0.05 | 0.06 | 0.17 |

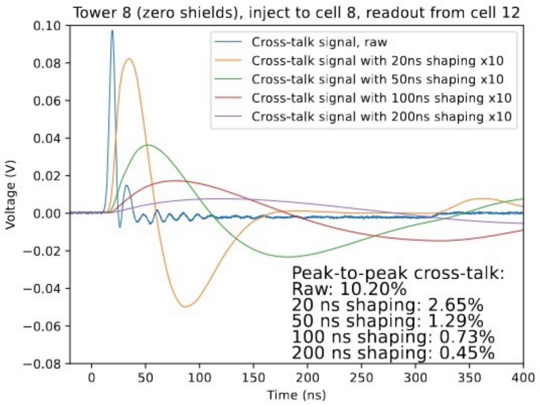
**New simulation**

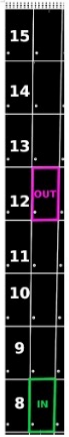
| Cross-talk (%) / Shaping time (ns) ↓ | Cell 1 | Cell 2 | Cell 3 | Cell 4 | Cell 5 | Cell 6 |
|---|---|---|---|---|---|---|
| No shaper | 0.52 | 3.22 | 3.29 | 5.89 | 5.5 | 20.94 |
| 20 | 0.06 | 0.08 | 0.03 | 0.12 | 0.07 | 0.92 |
| 50 | 0.04 | 0.05 | 0.01 | 0.06 | 0.04 | 0.52 |
| 100 | 0.03 | 0.03 | 0.0 | 0.04 | 0.03 | 0.35 |
| 150 | 0.03 | 0.03 | 0.0 | 0.03 | 0.02 | 0.29 |
| 200 | 0.03 | 0.03 | 0.0 | 0.03 | 0.02 | 0.26 |
| 300 | 0.02 | 0.02 | 0.0 | 0.02 | 0.02 | 0.22 |



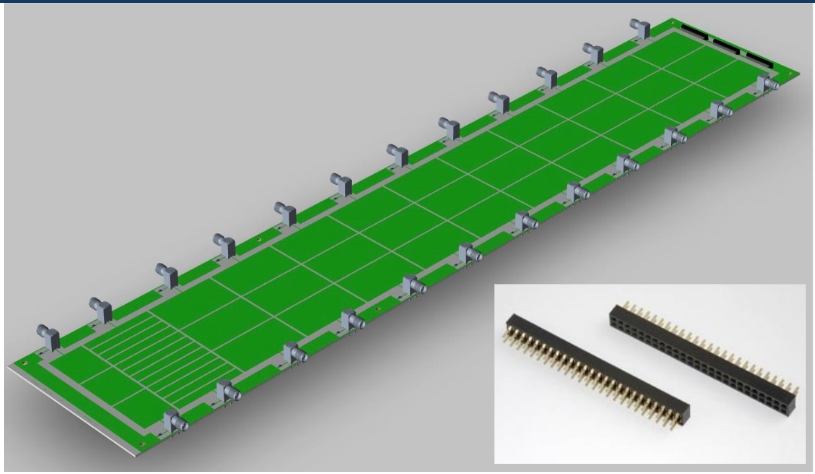



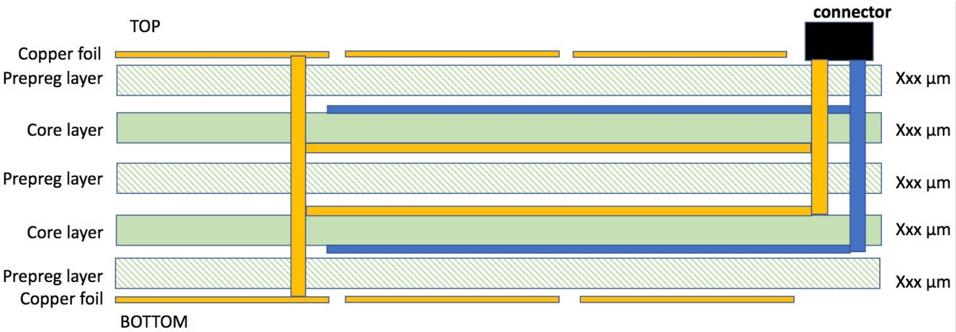



# Further Plans for PCB Prototypes

- **New small prototype** planned without HV layer (IJCLab)
  - Doubled signal traces to have an even number of layers (6)
  - Will include extra shielding strip lines between traces
  - SMA connector for signal injection
  - 3x ANTELEC 2x15 pins connectors for signal reading from the backside
- **New large scale prototype** with connectors planned to be designed and produced end 2023 (CERN)



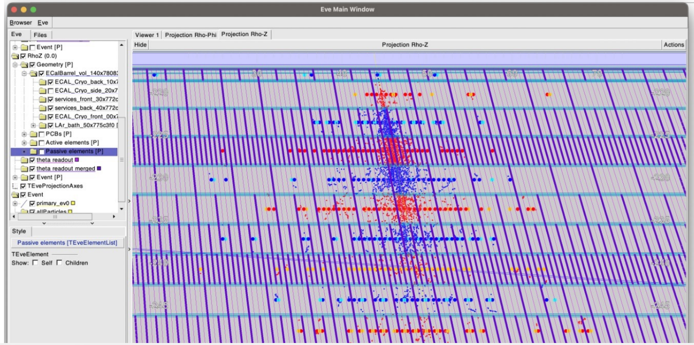


# Software – Digitization & Event Display

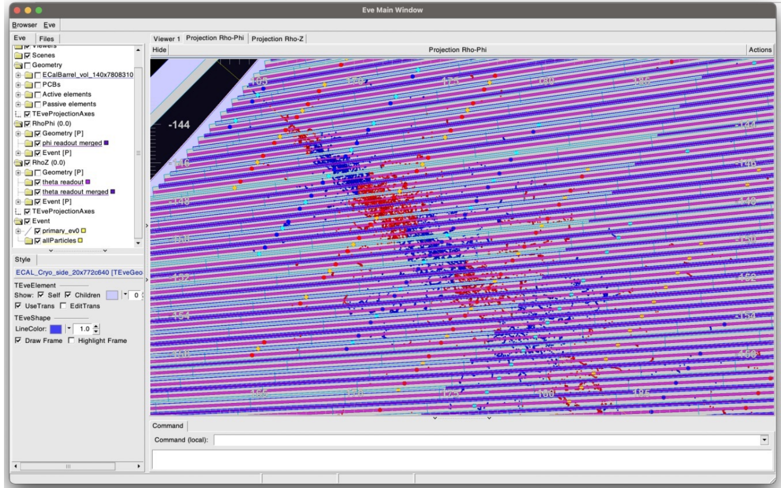
- Work on **digitization of energy deposits**
  - Implementing theta projectivity
  - Proper theta granularity, on a layer-by-layer case
  - Start with a fine grid consistent with cell size of strip compartment, and merge group of adjacent cells in other compartments
  - Display hits and cells before merging and cells after merging on top of the detector geometry
  - Next steps: propagate to clustering, improve user friendliness, phi projectivity,

G. Marchiori, T. Li

Geometry and event display



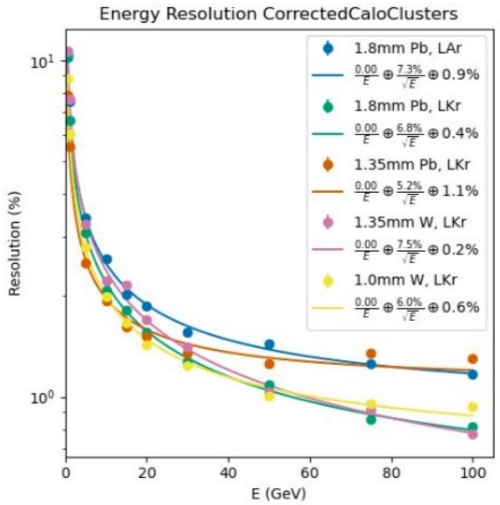

- Same color code as before, not in Rho-Z projection (showing merging of theta cells)
- In this test, merged cells per layer = 4, 8, 2, 1, 8, 4, 2, 1, 4, 2, 1, 8

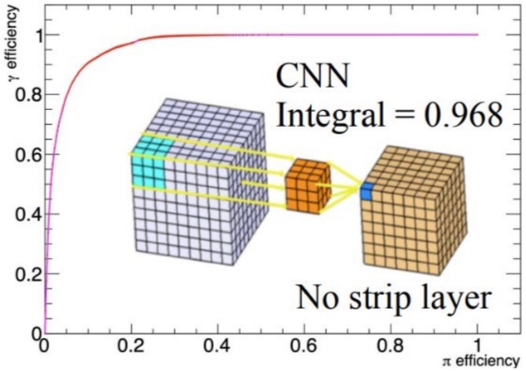



- XY (R-phi) projection, shows merging of modules
- Yellow line: the primary e-
- Blue/red small dots: the hits in even/odd-numbered layers (from hit cellID)
- Blue/red circles: the cells in even/odd-numbered layers before module merging
- Cyan/orange circles: the cells after merging (in this case, N=2 in inner 6 layers and N=1 in outer 6 layers)
- Thick violet lines: the merged readout
- Purple rectangles: the PCB
- Blue lines: absorbers
- Think cyan lines: the active volumes

# Software – Full Simulation

- For **more information** see talk by B. François at the **FCC Week 2023** in London
- **Current detector description in DD4hep**: link
  - Simplified **vertex detector** (CLD), will be updated to the detailed IDEA one
  - Simplified **drift chamber** (no tracking available):
    - Chamber with all wires and the sensitive volume definition from which we can extract SimHits. Digitization being worked on.
  - **ECAL Barrel** fully available in Key4hep
    - Inclined absorber plates that can be made trapezoidal
    - Cryostat, services and solenoid material budget included
    - Calibration, noise and clusterings available as edm4hep native
    - Gaudi algorithms!
    - Plug-and-play compliant
      - Good factorization between xml and cpp builders
      - Automatic rescaling upon geometry changes
    - First performance studies performed
    - Need Particle Flow to optimize granularity, requires tracks
      - Prepared a detector configuration with CLD + LAr ECAL
        - » Temporary hack to exercise the technical machinery
      - PandoraPFA integration on this hybrid detector: Now modifying the detector builder so that all the required information is made available to PandoraPFA.
  - **ECAL Endcaps** under validation



# ECAL + HCAL Performance Studies

- 12 layer LAr + 13 layer TileCal (see [talk by M. Mlynarikova](#))
- Using Benchmark Method
  - Was developed for ATLAS test-beam measurements
  - To be used for hadron simulation when combining ECal and HCal
  - Applies a correction for the energy lost between ECal barrel (EB) and HCal barrel (HB) and calibrates the energy deposits to the hadronic scale
  - Derived using the energy deposited in clusters
  - The total energy:

$$E_{rec}^{bench} = p_0 \cdot E_{EB}^{EM} + p_1 \cdot E_{HB}^{HAD} + p_2 \sqrt{|p_0 \cdot E_{EB}^{last\ layer} \cdot E_{HB}^{first\ layer}|} + p_3 (p_0 \cdot E_{EB}^{EM})^2 + p_4 \cdot E_{EB}^{first\ layer}$$

  - Newly added upstream material (e.g. ECal cryostat) correction $p_4$
  - Benchmark method calibration now available in the k4RecCalorimeter
  - Obtaining sampling term of ~37%
- Using a Boosted Decision Tree (XGBoost)
  - Use only very basic variables - energy per layer, or ratios of energies wrt sum
  - Only running on sliding window clusters
  - The regression target is $E_{truth}/E_{cluster}$
  - Obtaining sampling term ~40% – very promising preliminary result