EP R&D WP3.1 – Noble Liquid Calorimetry

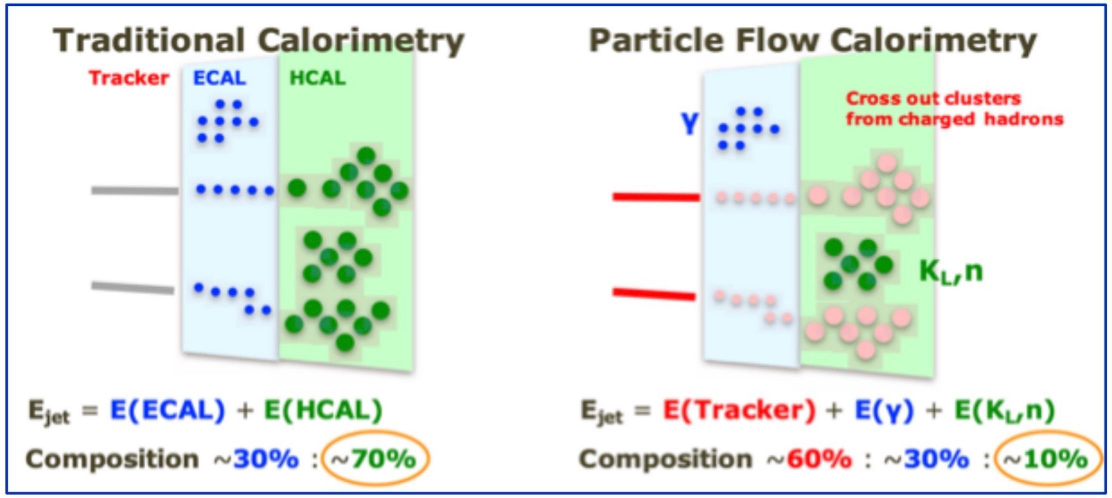
M. Aleksa for EP R&D WP3.1

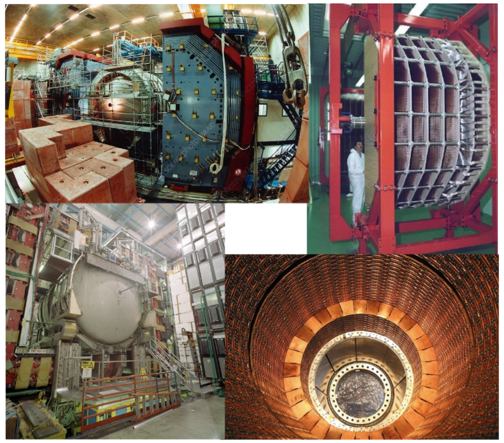
Material used:

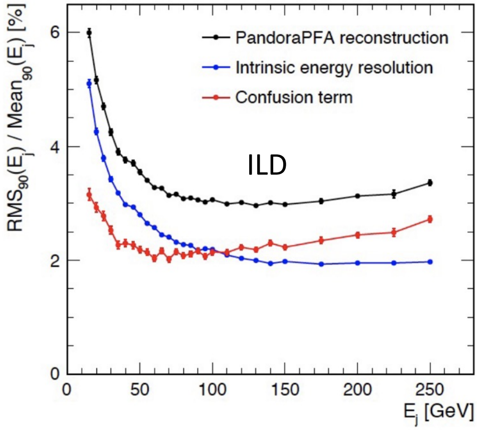
- Monthly Noble-Liquid Calorimetry meetings https://indico.cern.ch/category/8922/
- GranuLAr Workshop https://indico.ijclab.in2p3.fr/event/7664/timetable/#20220406
- Seminar talk by B. François at the EP R&D Seminar

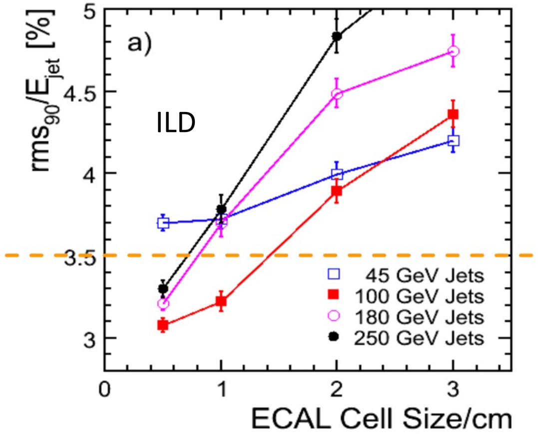
Introduction

- **Noble Liquid Calorimetry** is a key HEP technology
  - Successful operation in D0, H1, NA48/62, ATLAS, …
  - Proposed for several future accelerator facilities
    - FCC-hh, LHeC, FCC-ee, …
  - Extreme radiation hardness, good energy/timing resolution, long term stability, linear response, uniformity, …
- **Excellent jet energy resolution** is achieved with **Particle Flow** reconstruction techniques
  - Requires imaging calorimeters → highly granular (+ small Moliere radius)
- R&D Goal: **design a Noble Liquid calorimeter with imaging capability**
  - → High granularity
  - **Challenging signal extraction!**









GranuLAr Workshop in Paris (April 2022)

https://indico.ijclab.in2p3.fr/event/7664/

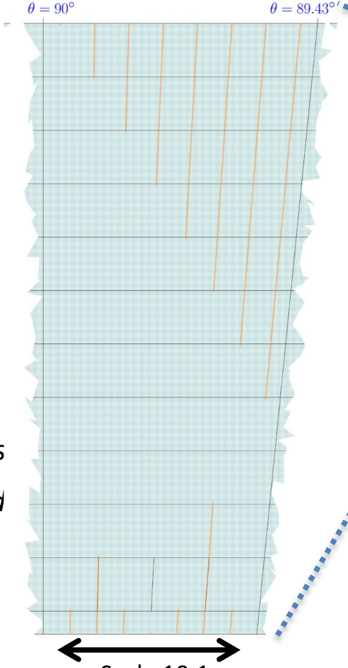
- First ever workshop on noble liquid calorimeter R&D for FCC
  - 26 participants from 9 institutes
  - Meet for the first time in person after 2 years of Zoom meetings
  - Status of the ongoing R&D
  - Experience sharing from long-term ATLAS LAr experts
  - Discussion of our mid-term goals
    - Towards a detector concept
    - Towards a prototype going to testbeam

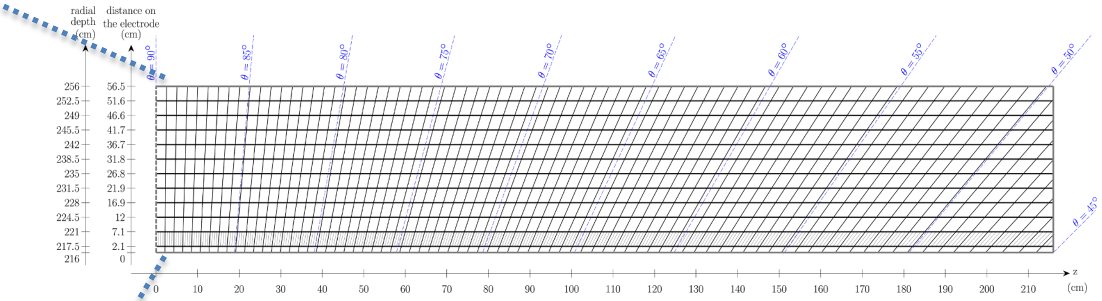
How to Achieve High Granularity?

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

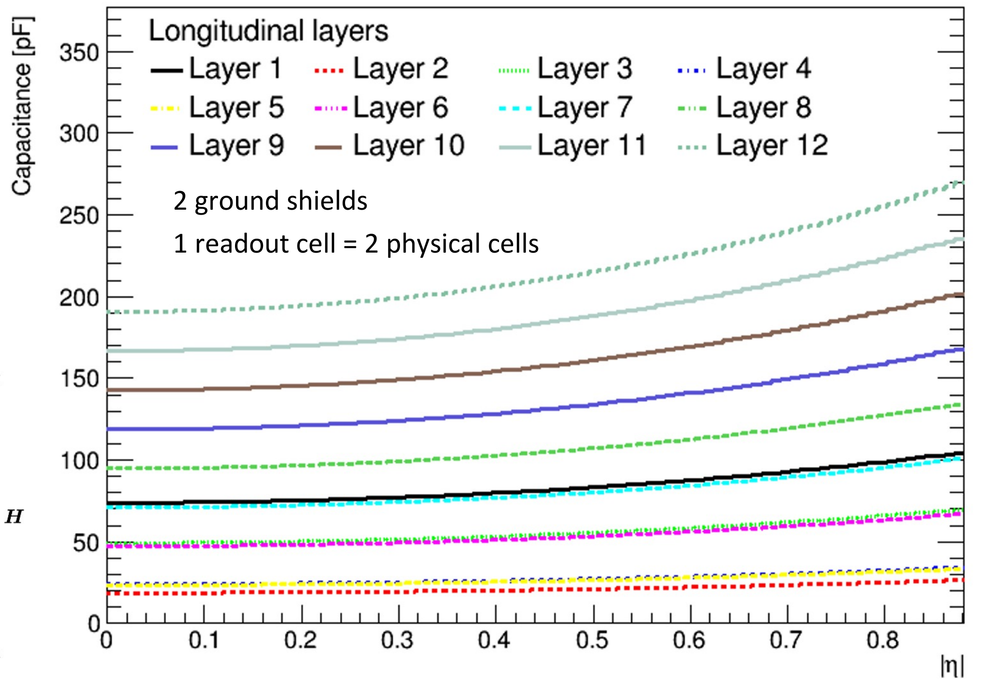
- HV and read-out
- Signal traces (width w_t) in dedicated signal layer connected with vias to the signal pads
- Traces shielded by ground-shields (width w_s) forming 50Ω – 80Ω transmission lines
- → capacitance between shields and signal pads C_s will add to the detector capacitance via the gap C_d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

One 'theta tower'

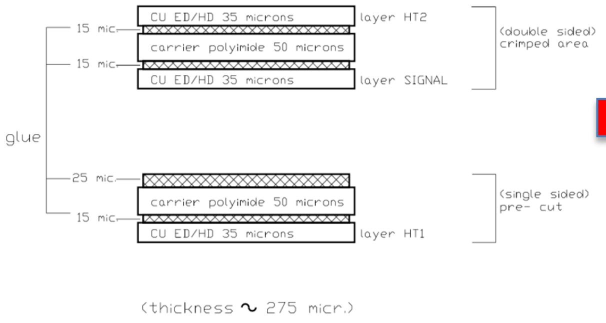




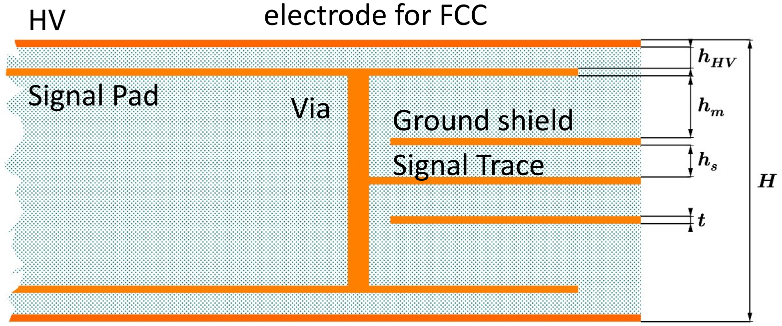
Total capacitance (no trace)



ATLAS electrode



Multi-layer read-out electrode for FCC



Geometry for FCC-ee Experiment

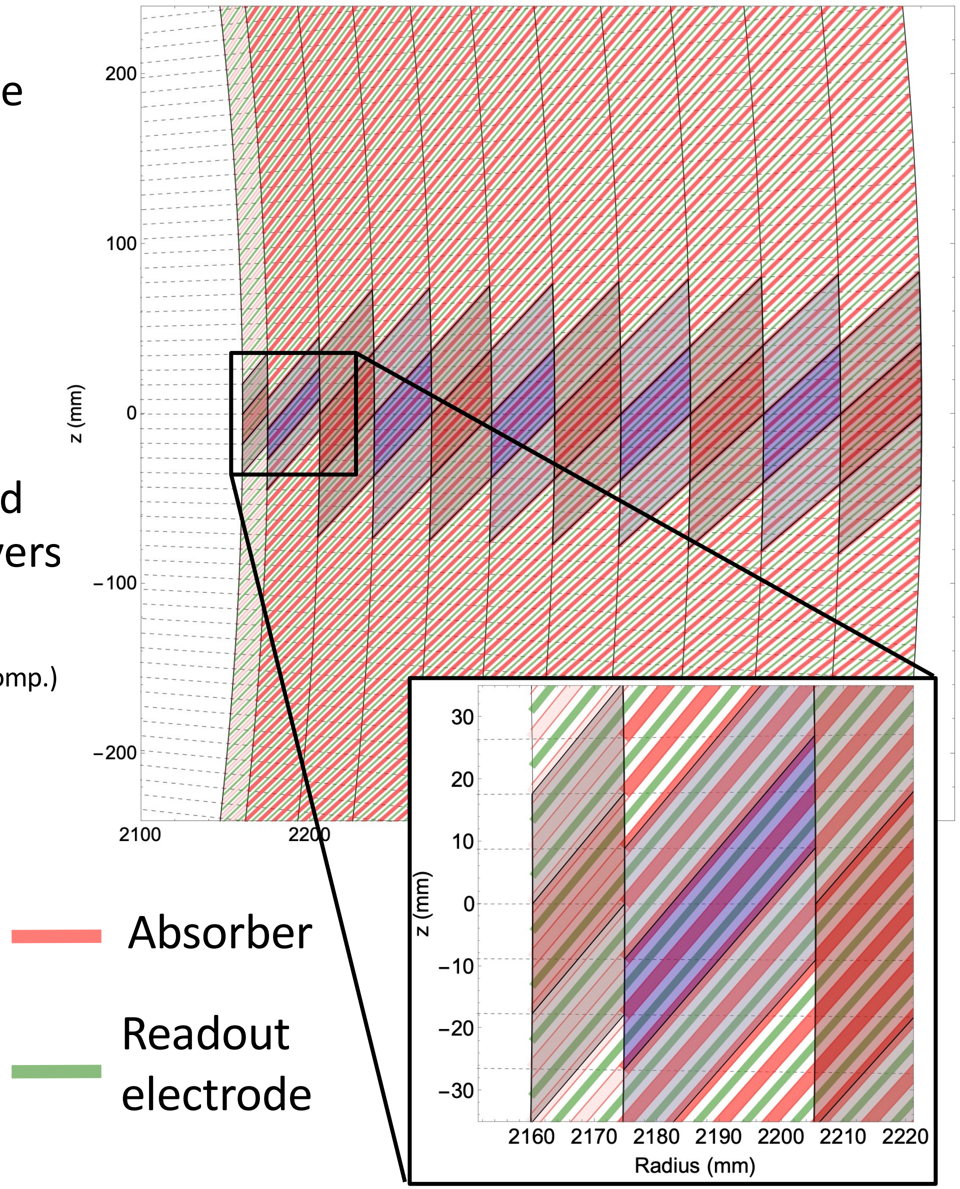
Geometry for FCC-ee ECAL barrel being optimized:

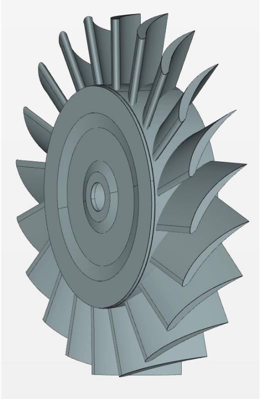
- No Pb/W in the first compartment = presampler (PS) → used to compensate for lost energy upstream
- 1536 absorbers in 2π, flat, no step-increase with r.
- 11 longitudinal compartments
- r_i=2160mm, r_o=2560mm, inclination of absorbers at r_i is α_i=50.381° (α_l depends on r_i and r_o to align cells in ϕ)
  - Radii and other parameters being adjusted to available space
- Cells line up in projective towers in θ and ϕ, add 2 double gaps in the PS and strips (1st and 2nd longitudinal compartment) and 4 double gaps in other layers
  - Strips (2nd comp.): Δϕ x Δθ = 8.2mrad x 2.5mrad = 17.8mm x 5.4mm
  - Other compartments: Δϕ x Δθ = 16.4mrad x 10mrad = 36mm x 22mm$|_{r=2205mm\ (3rd\ comp.)}$
- Readout with 7-layer PCB (FR4), 1.2mm thick
- With LAr/Pb this leads to ~20.5 X_0, $f_{sampl} \approx 1/6$.
- Studies ongoing with other absorbers (Pb/W) and LAr/LKr → leading also to other detector dimensions

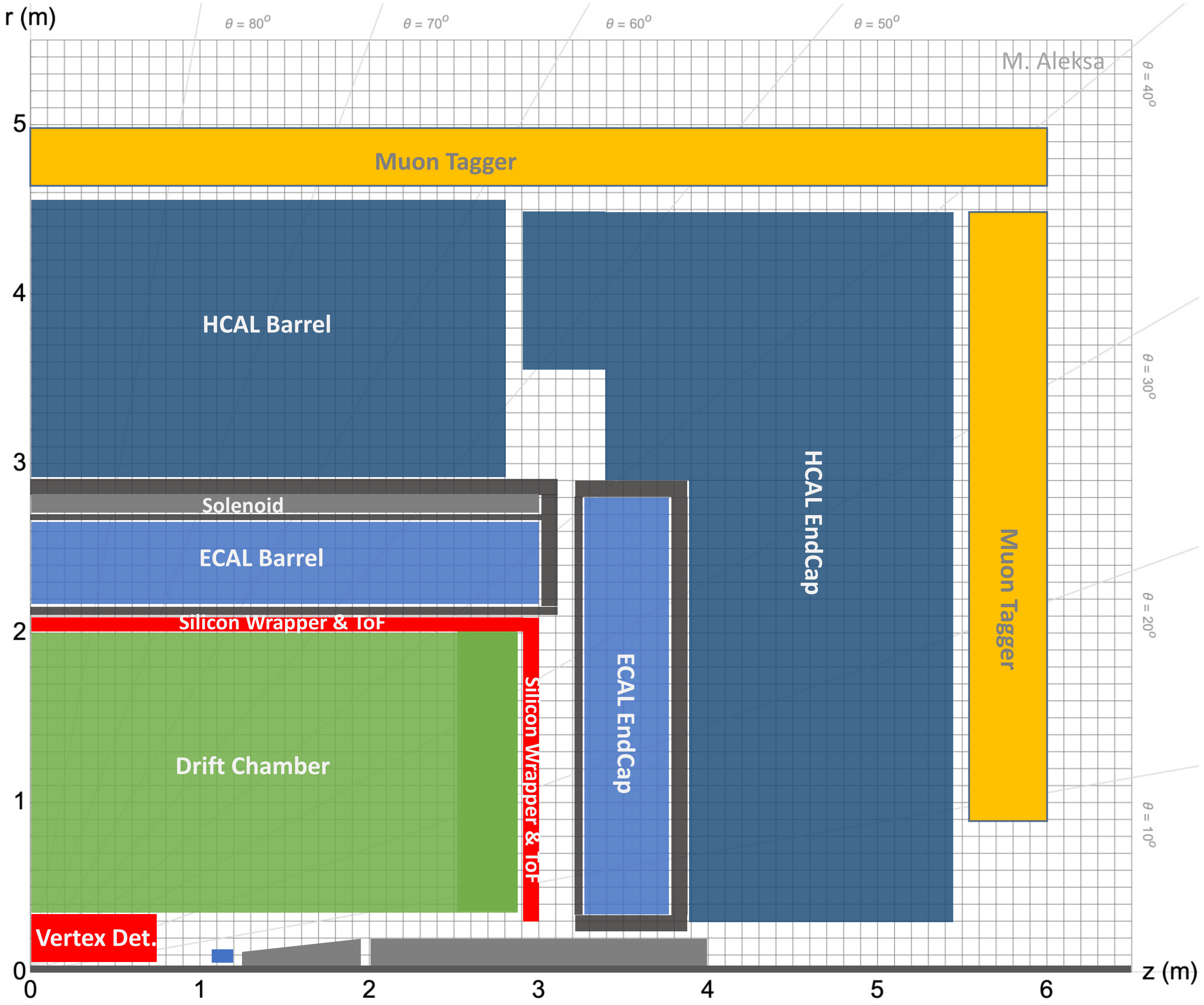
Equivalent geometry for the ECAL endcaps

- Turbine wheel like with radially inclined straight absorbers or parallel plates perpendicular to beam

HCAL endcaps with parallel plates perpendicular to the beam





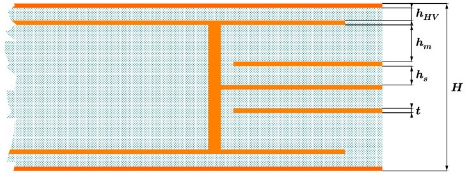


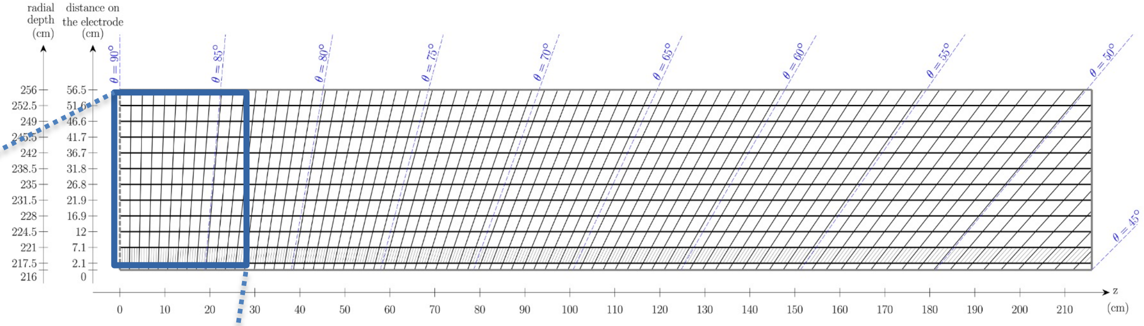
Detector Concept 1a

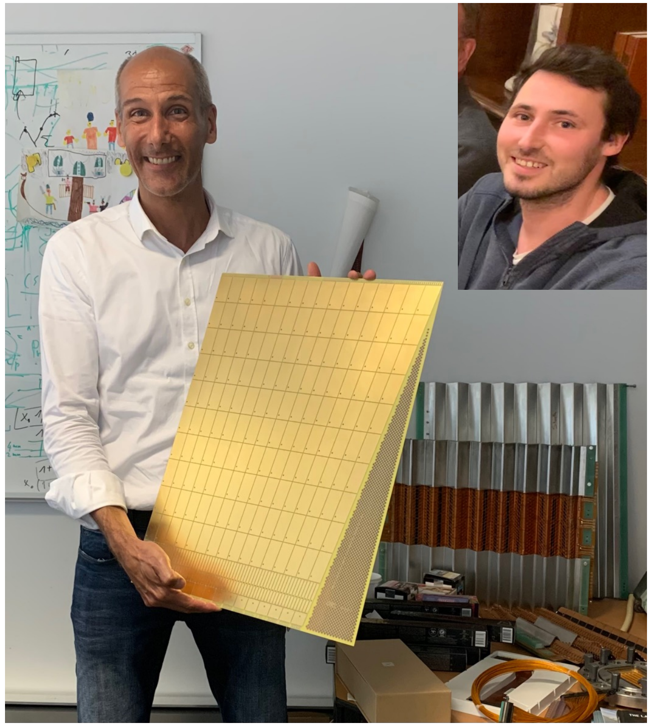
- Vertex Detector:
    - MAPS or DMAPS possibly with timing layer (LGAD)
    - Possibly ALICE 3 like?
- Drift Chamber (±2.5m active)
- Silicon Wrapper + ToF:
    - MAPS or DMAPS possibly with timing layer (LGAD)
- Solenoid B=2T, sharing cryostat with ECAL, outside ECAL
- High Granularity ECAL:
    - Noble liquid + Pb or W
- High Granularity HCAL / Iron Yoke:
    - Scintillator + Iron
        - SiPMs directly on Scintillator or
        - TileCal: WS fibres, SiPMs outside
- Muon Tagger:
    - Drift chambers, RPC, MicroMegas

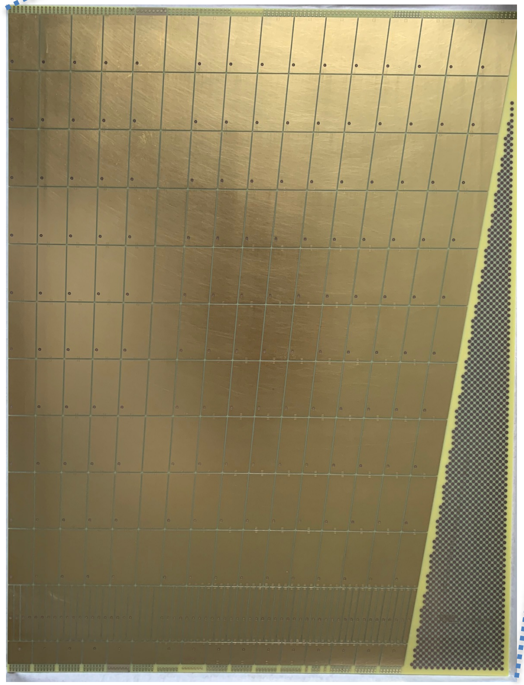
First Electrode Prototype

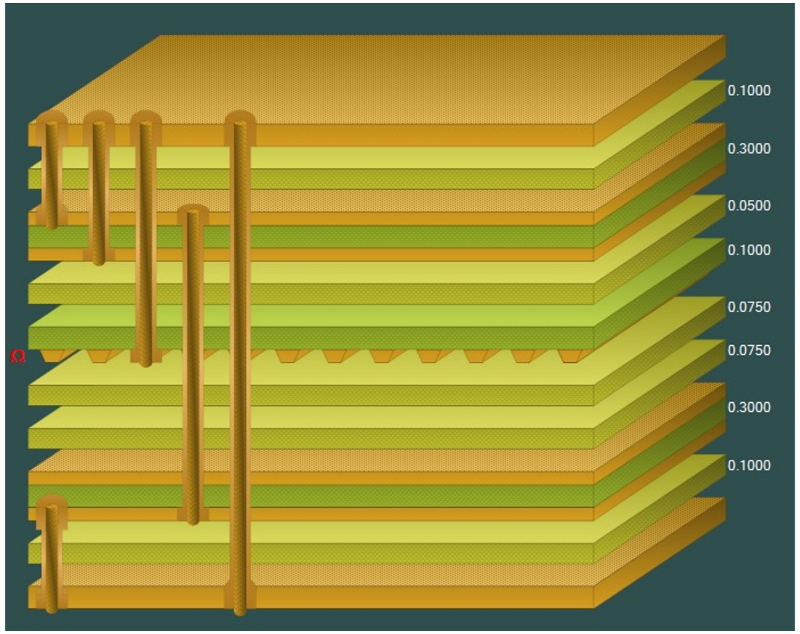
- The first electrode PCB prototype has been designed and produced!
  - Production at the CERN PCB Design office
- Scale 1:1 in the radial direction, 16 theta towers with different scenarios (number of shields, shield width, extraction scheme, …)
- Will be used to validate the concept and cross-check the simulations with several benchmarks







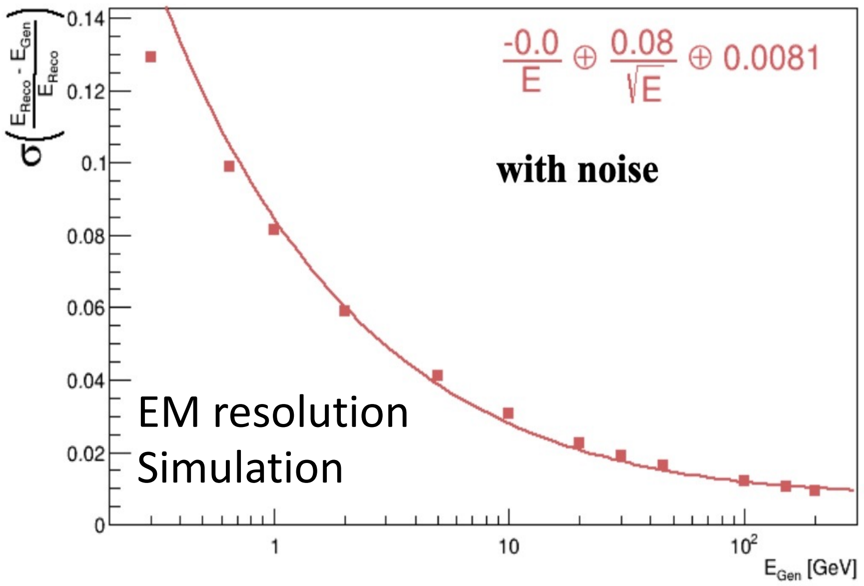




Brieuc François

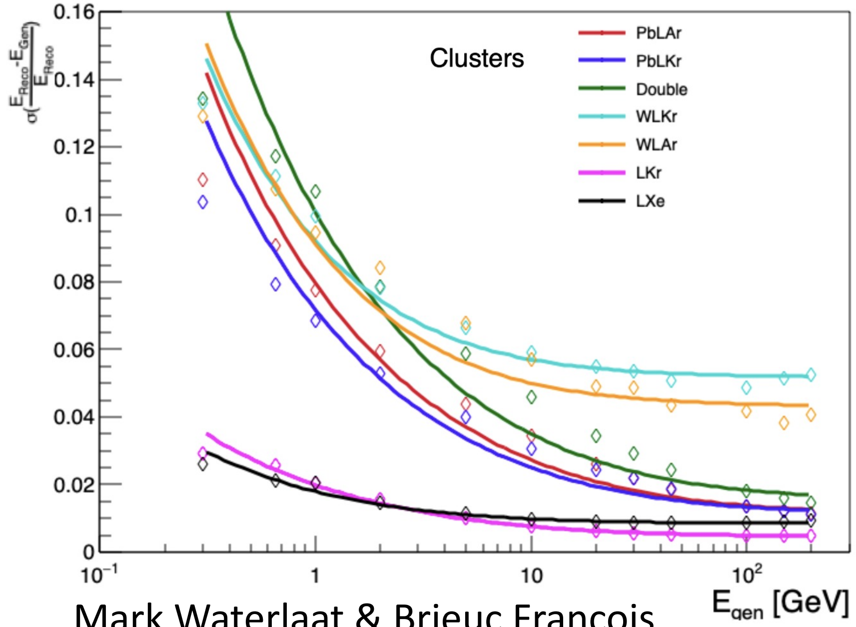
Challenges: Resolution and Noise

- **EM resolution** with sampling term of 8 to 9%
  - Studies with different geometries and different absorber materials and active materials
- **Noise** of < 1.5 MeV per cell for warm electronics and transmission lines of $R_0 = 100\ \Omega$ and $\tau = 200$ ns ($C_d \leq 250$ pF)
  - → MIP S/N > 5 reached for all layers

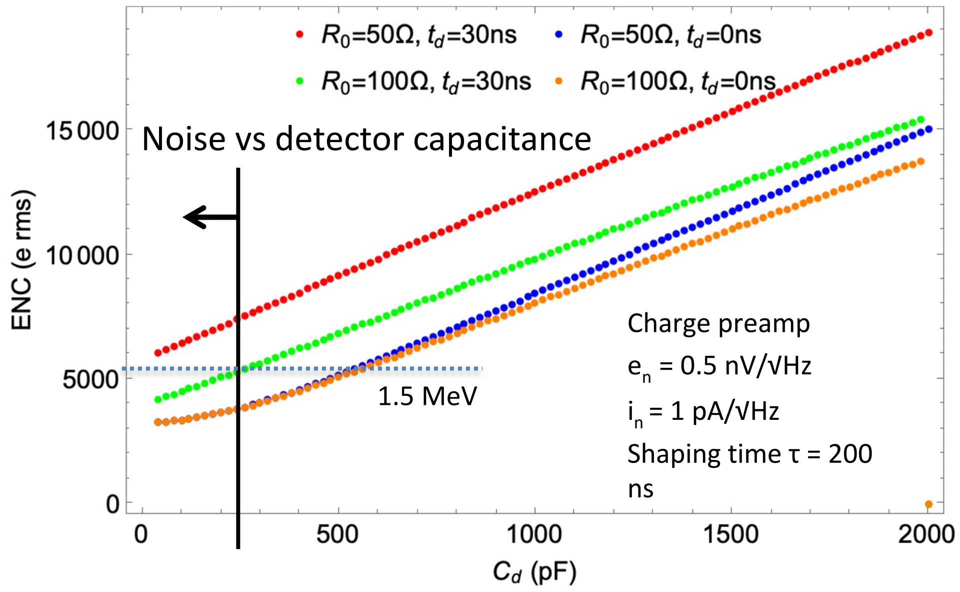


EM resolution Simulation

Brieuc François



Mark Waterlaat & Brieuc François



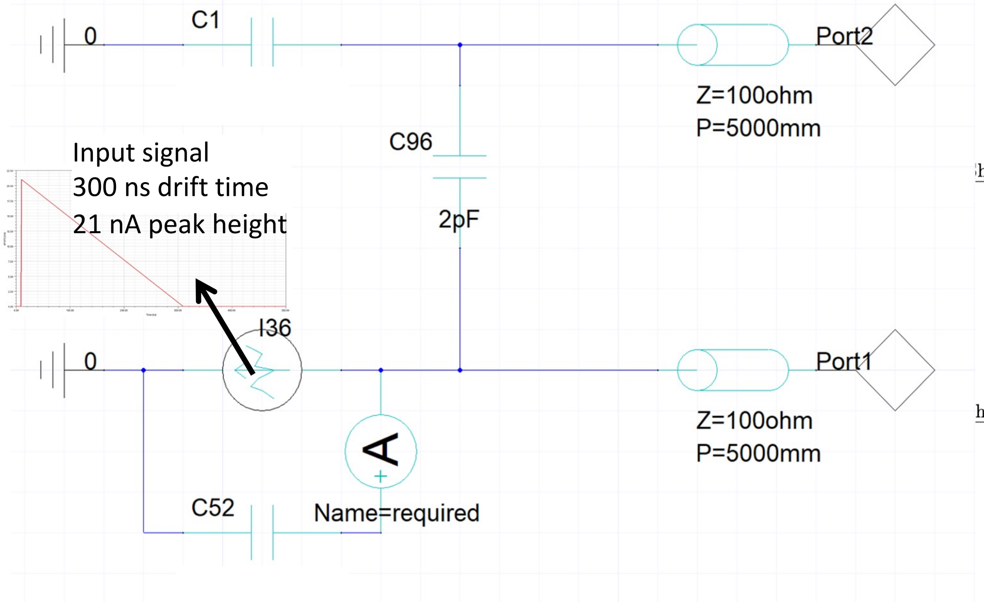
Noise vs detector capacitance

Charge preamp
e_n = 0.5 nV/√Hz
i_n = 1 pA/√Hz
Shaping time τ = 200 ns

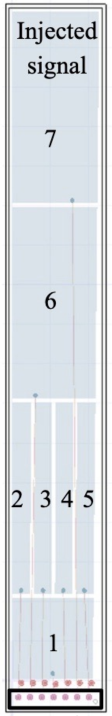
Martin Aleksa

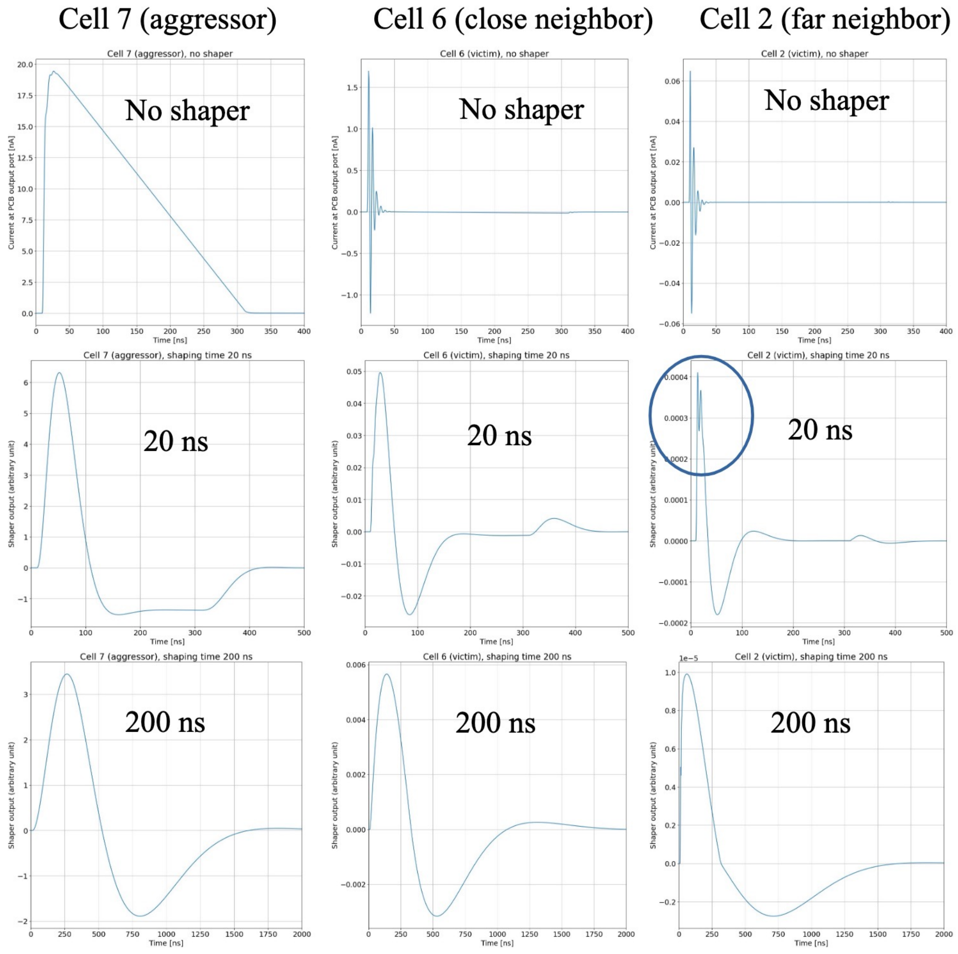
Challenges: Crosstalk

- **Study signal attenuation and x-talk** with Finite Element Method (ANSYS HFSS)
  - PCB ports Scattering parameter (S-matrix) → PSpice equivalent circuits → ANSYS Circuit
- X-talk current has a negative component → drastically lower x-talk values reached with signal integration
  - Without signal shaping:
    - Peak-to-peak x-talk current values for neighbouring cell (7→ 6): 12 % without shield, 6 % with 1 shield, 2 % with two shields
  - With signal shaping CR-RC^2 shaper:
    - **Cross-talk** of < 1% for shaping times τ ≥ 100 ns



Input signal
300 ns drift time
21 nA peak height





Cross-talk including signal shaping

One shield

Cross-talk (%) haping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	1.69	0.71	1.17	2.94	3.86	7.57
20	0.6	0.05	0.08	0.78	1.1	2.5
50	0.28	0.01	0.02	0.36	0.51	1.24
100	0.16	0.0	0.01	0.2	0.29	0.72
150	0.12	0.0	0.0	0.15	0.21	0.54
200	0.1	0.0	0.0	0.13	0.18	0.45
300	0.08	0.0	0.0	0.1	0.14	0.36

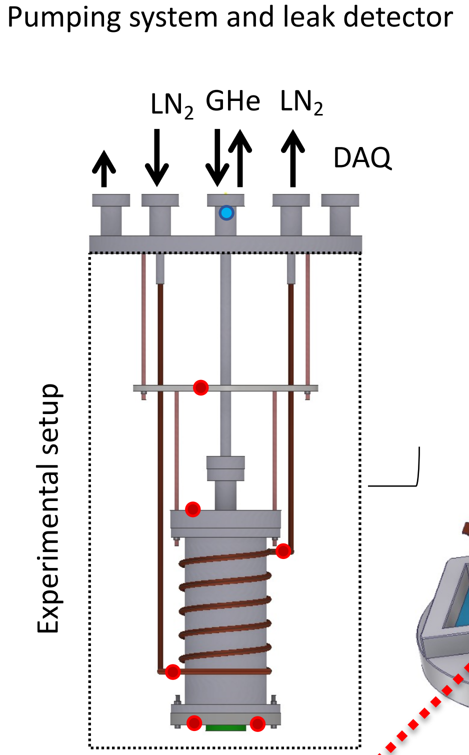
Two shields

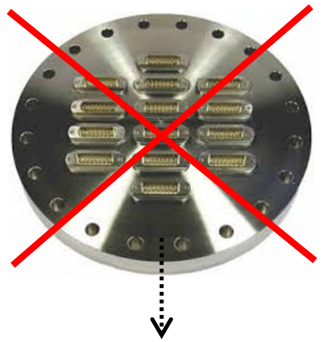
Cross-talk (%) haping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	0.38	0.33	0.74	1.95	1.97	8.71
20	0.02	0.01	0.01	0.11	0.23	0.78
50	0.01	0.0	0.0	0.05	0.11	0.39
100	0.0	0.0	0.0	0.03	0.06	0.24
150	0.0	0.0	0.0	0.02	0.04	0.19
200	0.0	0.0	0.0	0.02	0.04	0.16
300	0.0	0.0	0.0	0.01	0.03	0.14

Brieuc François

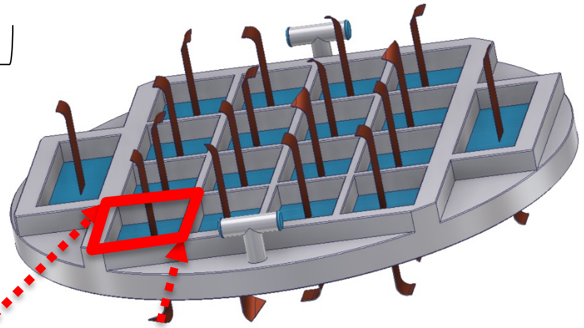
High Density Feedthroughs

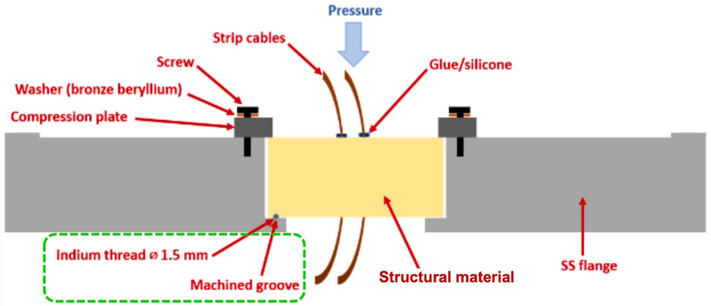
- New generation of noble-liquid calorimeters 10-15 times more granular than ATLAS → more channels to extract from the cryostat (e.g. ECAL barrel ~2 M)
- If the electronics sits outside of the cryostat (warm electronics), one needs high density feedthroughs
- **→ Design of innovative connector-less feedthroughs**
  - High density flange
  - Higher area dedicated to signal extraction
  - → 20 000 wires per feedthrough
- **Reduced size samples development**
  - Testing different 3D-printed epoxy resins as structures with slits allowing the passage of cables
  - Leak and pressure (3.5 bar) tests at 300 and 77 K
  - Already identified a solution surviving several thermal cycles (G10 structure with slits + indium seal + Epo-Tek glued Kapton strip cables)
- **Next step**
  - Full flange design

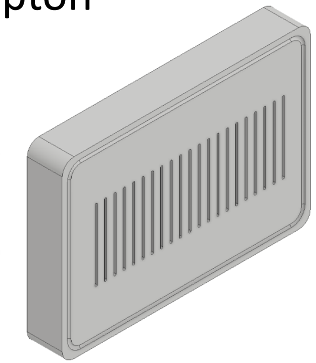


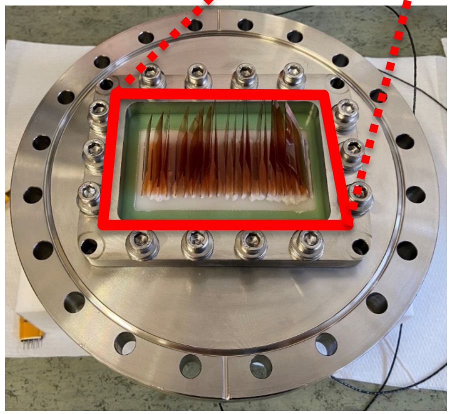


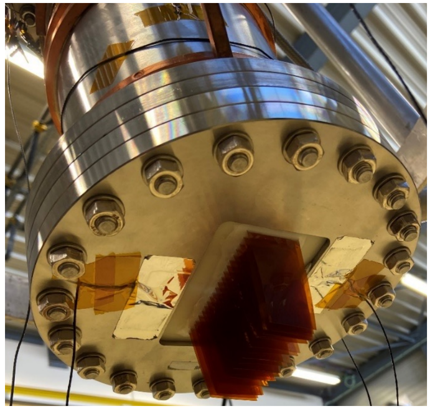
Conceptual high-density flange









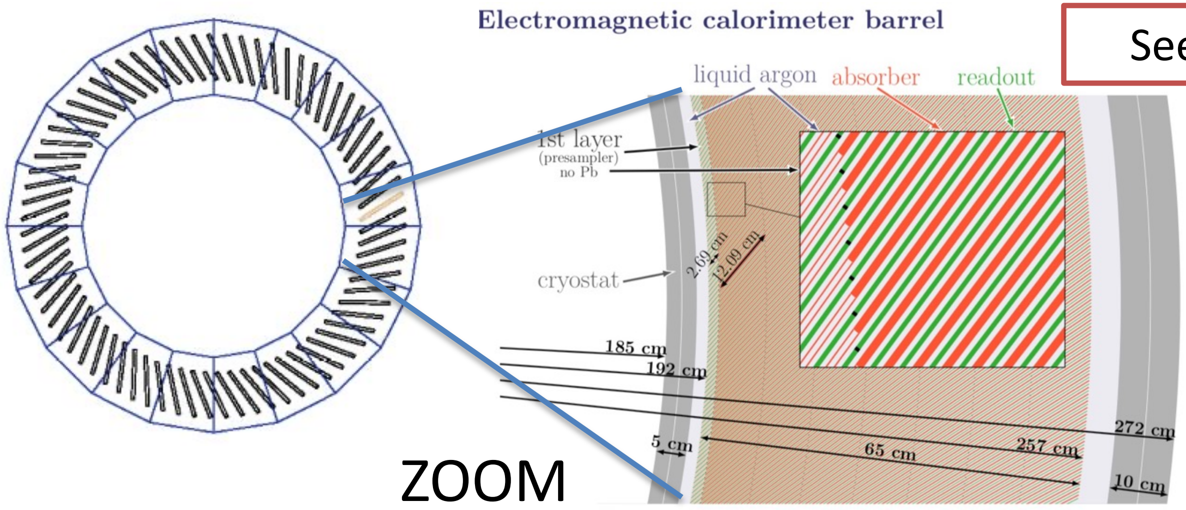


Maria Asuncion Barba Higueras

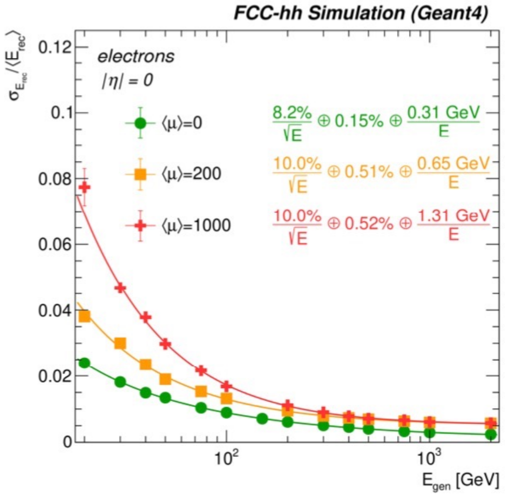
BACK-UP

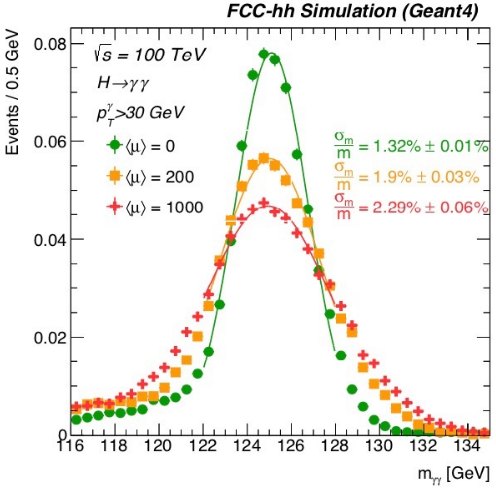
Reminder – FCC-hh Electromagnetic Calorimeter (ECAL)

See [arXiv paper]

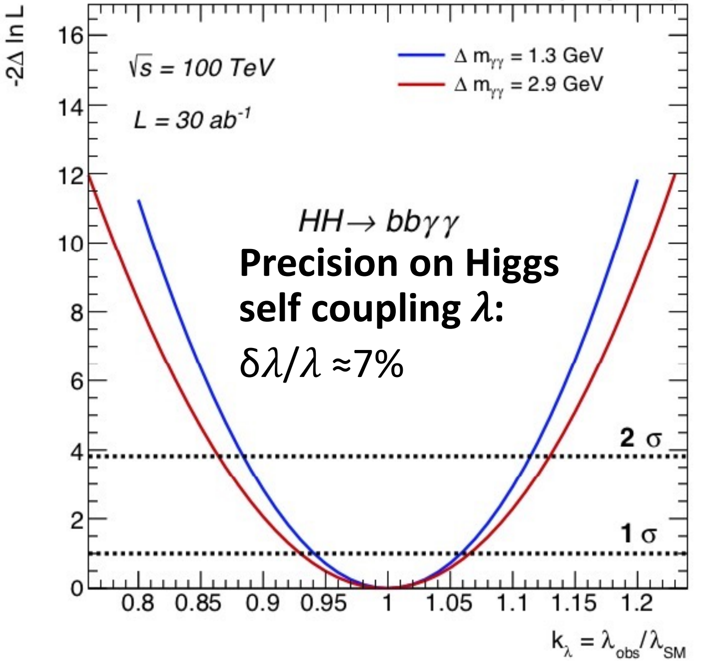


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;



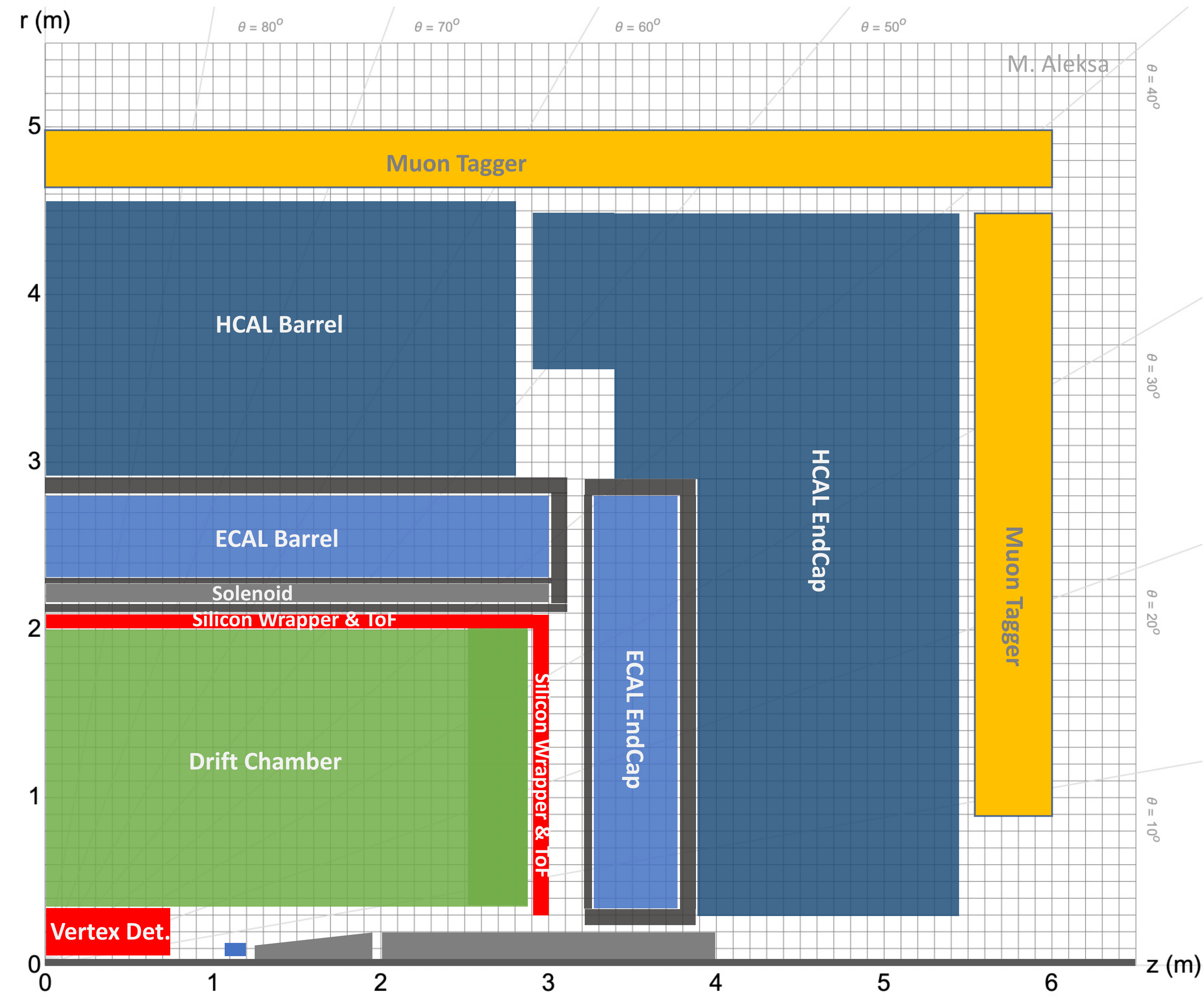


- **CDR Reference Detector (2019): Performance & radiation considerations → LAr ECAL, Pb absorbers**
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$, 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 ≤ $10\%/\sqrt{E}$, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV 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**



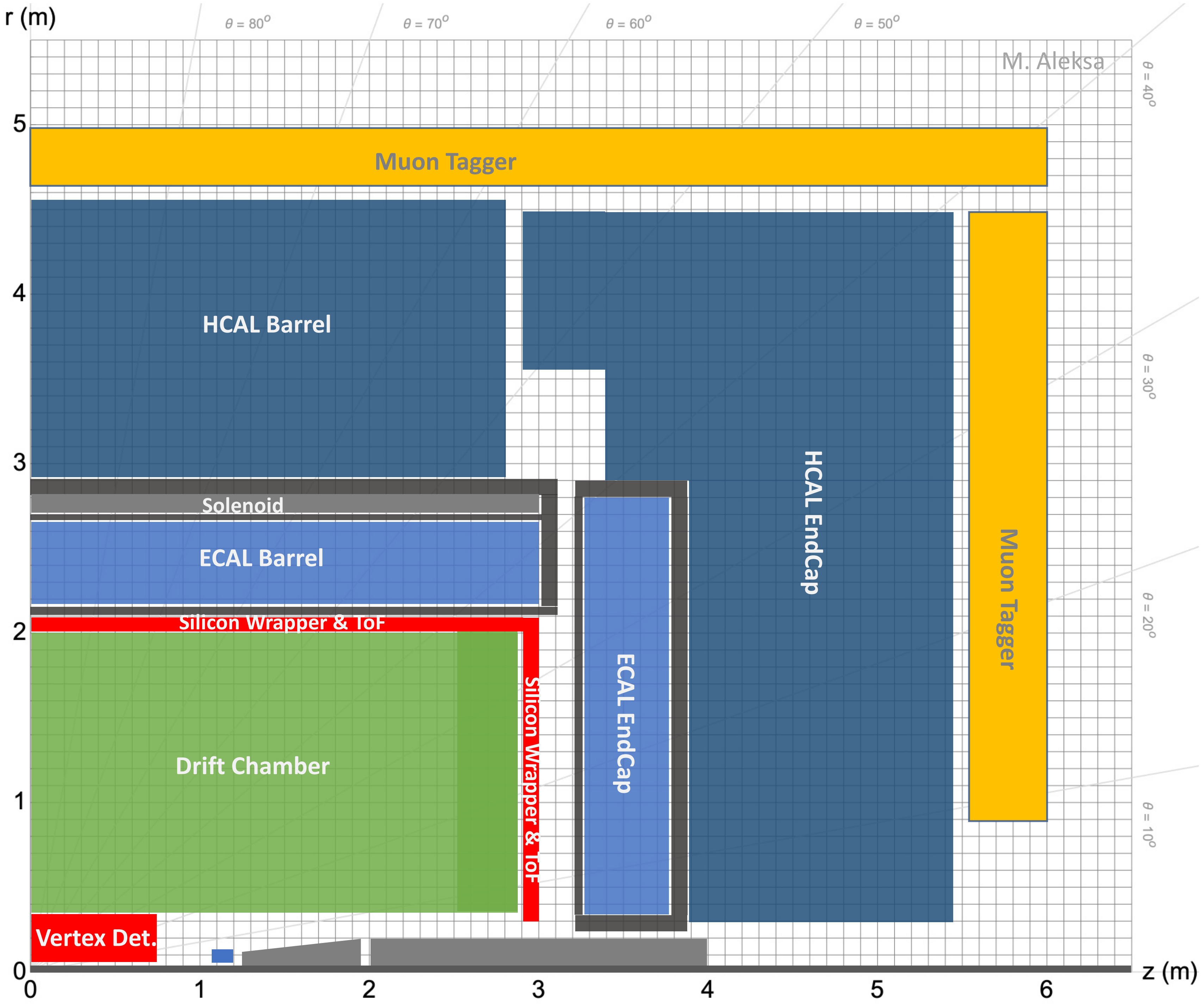
Precision on Higgs self coupling λ:

$\delta\lambda/\lambda \approx 7\%$



Detector Concept 1

- Vertex Detector:
  - MAPS or DMAPS possibly with timing layer (LGAD)
  - Possibly ALICE 3 like?
- Drift Chamber (±2.5m active)
- Silicon Wrapper + ToF:
  - MAPS or DMAPS possibly with timing layer (LGAD)
- Solenoid B=2T, sharing cryostat with ECAL, inside ECAL
- High Granularity ECAL:
  - Noble liquid + Pb or W
- High Granularity HCAL / Iron Yoke:
  - Scintillator + Iron
    - SiPMs directly on Scintillator or
    - TileCal: WS fibres, SiPMs outside
- Muon Tagger:
  - Drift chambers, RPC, MicroMegas



Detector Concept 1a

- Vertex Detector:
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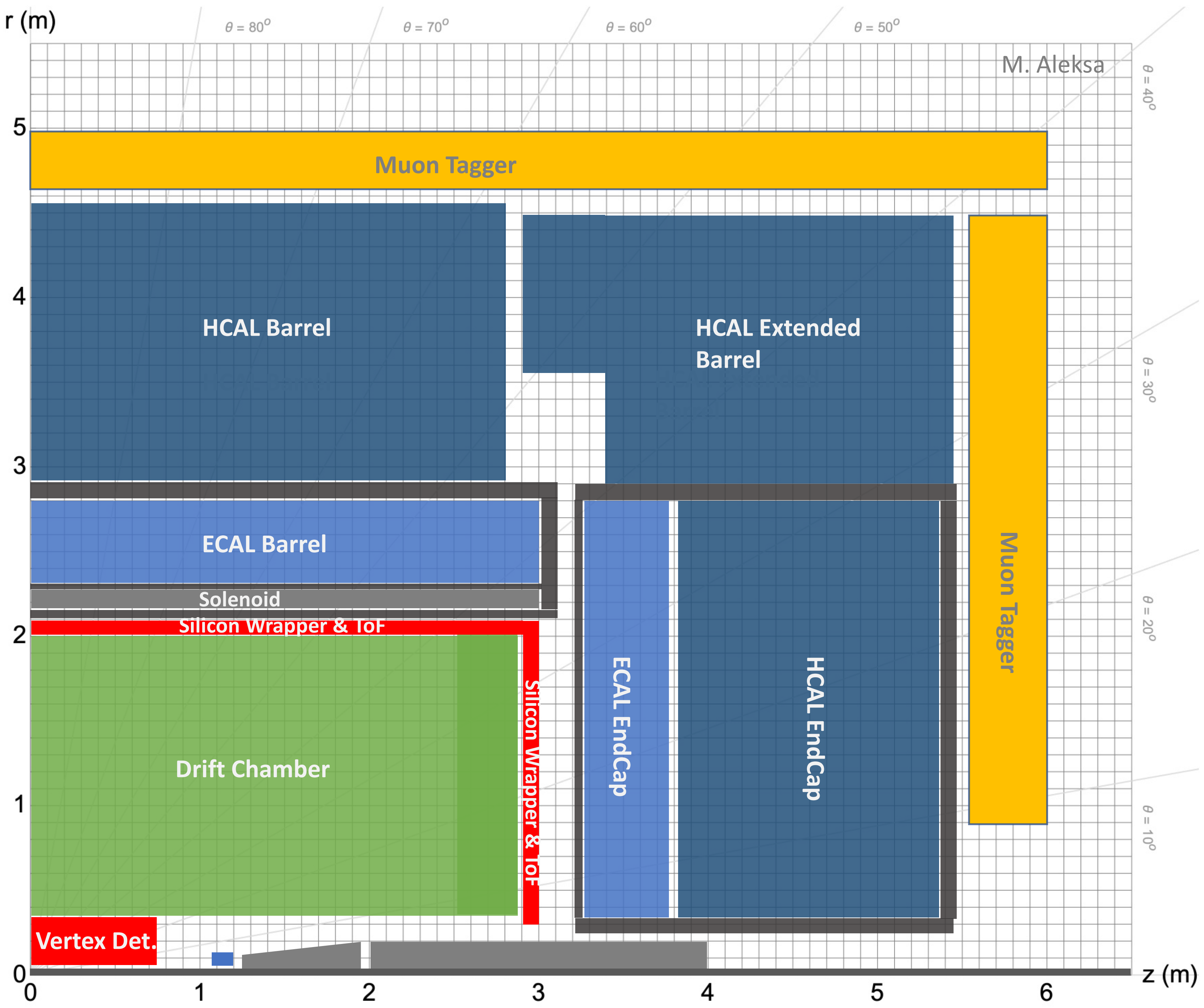
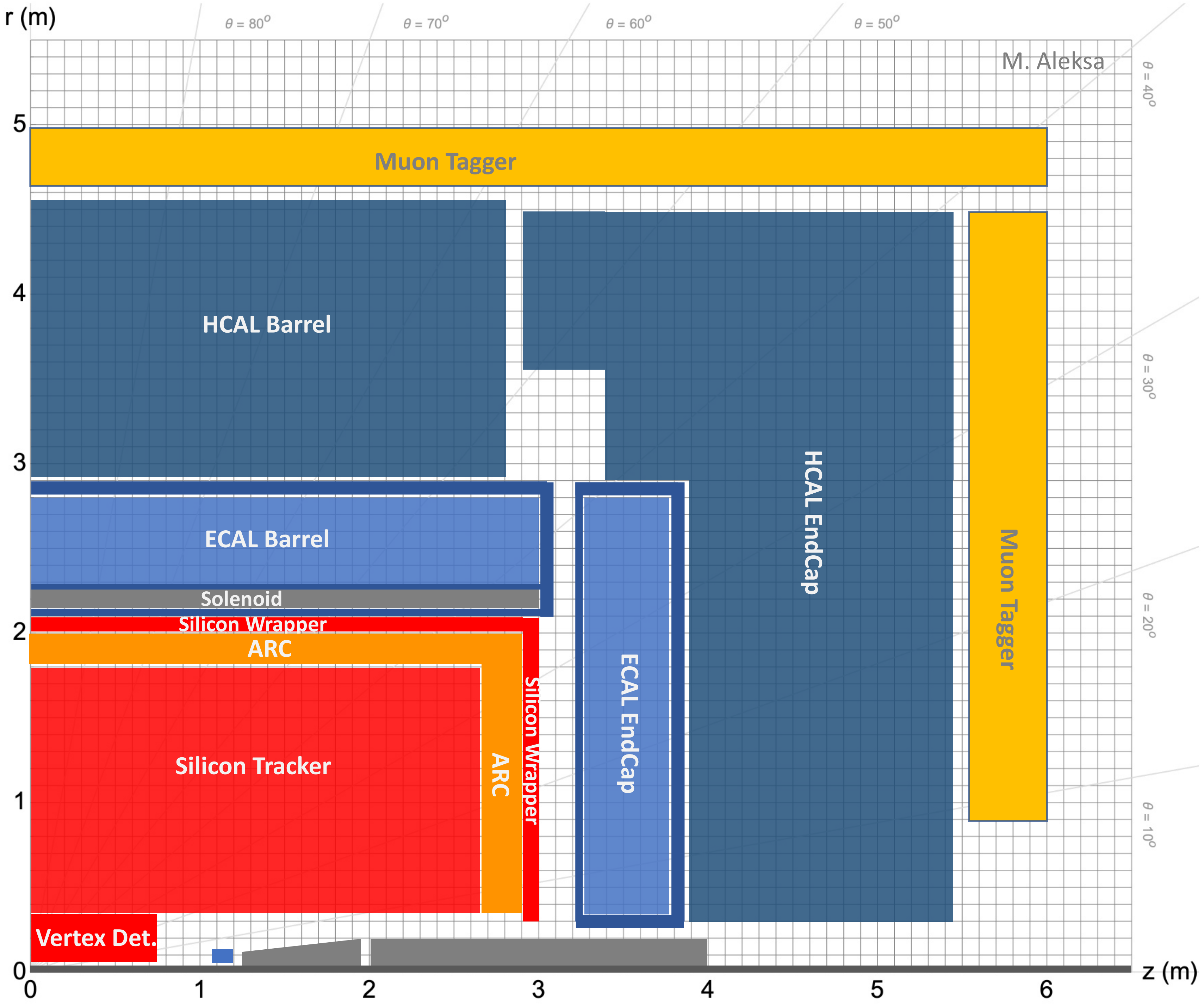
  - Possibly ALICE 3 like?
- Drift Chamber (±2.5m active)
- Silicon Wrapper + ToF:
  - MAPS or DMAPS possibly with timing layer (LGAD)
- Solenoid B=2T, sharing cryostat with ECAL, outside ECAL
- High Granularity ECAL:
  - Noble liquid + Pb or W
- High Granularity HCAL / Iron Yoke:
  - Scintillator + Iron
    - SiPMs directly on Scintillator or
    - TileCal: WS fibres, SiPMs outside
- Muon Tagger:
  - Drift chambers, RPC, MicroMegas



Detector Concept 2

- Vertex Detector:
  - MAPS or DMAPS possibly with timing layer (LGAD)
  - Possibly ALICE 3 like?
- Drift Chamber (±2.5m active)
- Silicon Wrapper + ToF:
  - MAPS or DMAPS possibly with timing layer (LGAD)
- Solenoid B=2T, sharing cryostat with ECAL
- High Granularity ECAL:
  - Noble liquid + Pb or W
- High Granularity HCAL / Iron Yoke:
  - Barrel: Scintillator + Iron
    - SiPMs directly on Scintillator or
    - TileCal: WS fibres, SiPMs outside
  - EndCap: Noble liquid + Copper + iron for the yoke
- Muon Tagger:
  - Drift chambers, RPC, MicroMegas



Detector Concept 3

- Vertex Detector:
  - MAPS, DMAPS
- Silicon Tracker (ALICE 3 like)
- Aerogel RICH Cellular detector (ARC) for PID
- Silicon Wrapper:
  - MAPS, DMAPS
- Solenoid B=2T, sharing cryostat with ECAL
- High Granularity ECAL:
  - Noble liquid + Pb or W
- High Granularity HCAL / Iron Yoke:
  - Scintillator + Iron
    - SiPMs directly on Scintillator or
    - TileCal: WS fibres, SiPMs outside
- Muon Tagger:
  - Drift chambers, RPC, MicroMegas

FCC-ee Physics Programme

”Higgs Factory” Programme

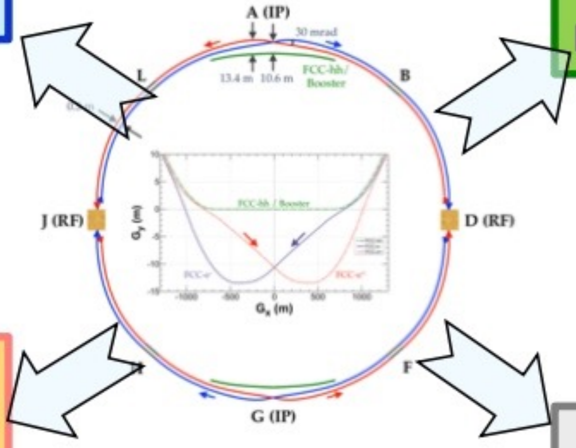
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s} = 125$ GeV

Ultra Precise EW Programme

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

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

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



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays

- CKM matrix, CP measurements, ”flavour anomaly” studies, e.g. b → sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

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

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

Slide courtesy M. Dam

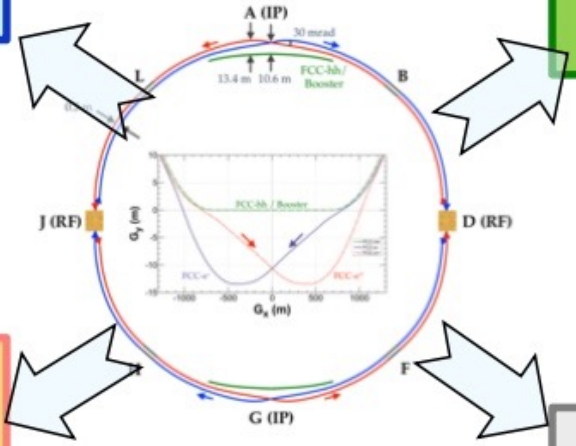
FCC-ee Detector Requirements

”Higgs Factory” Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} 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

- 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 π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

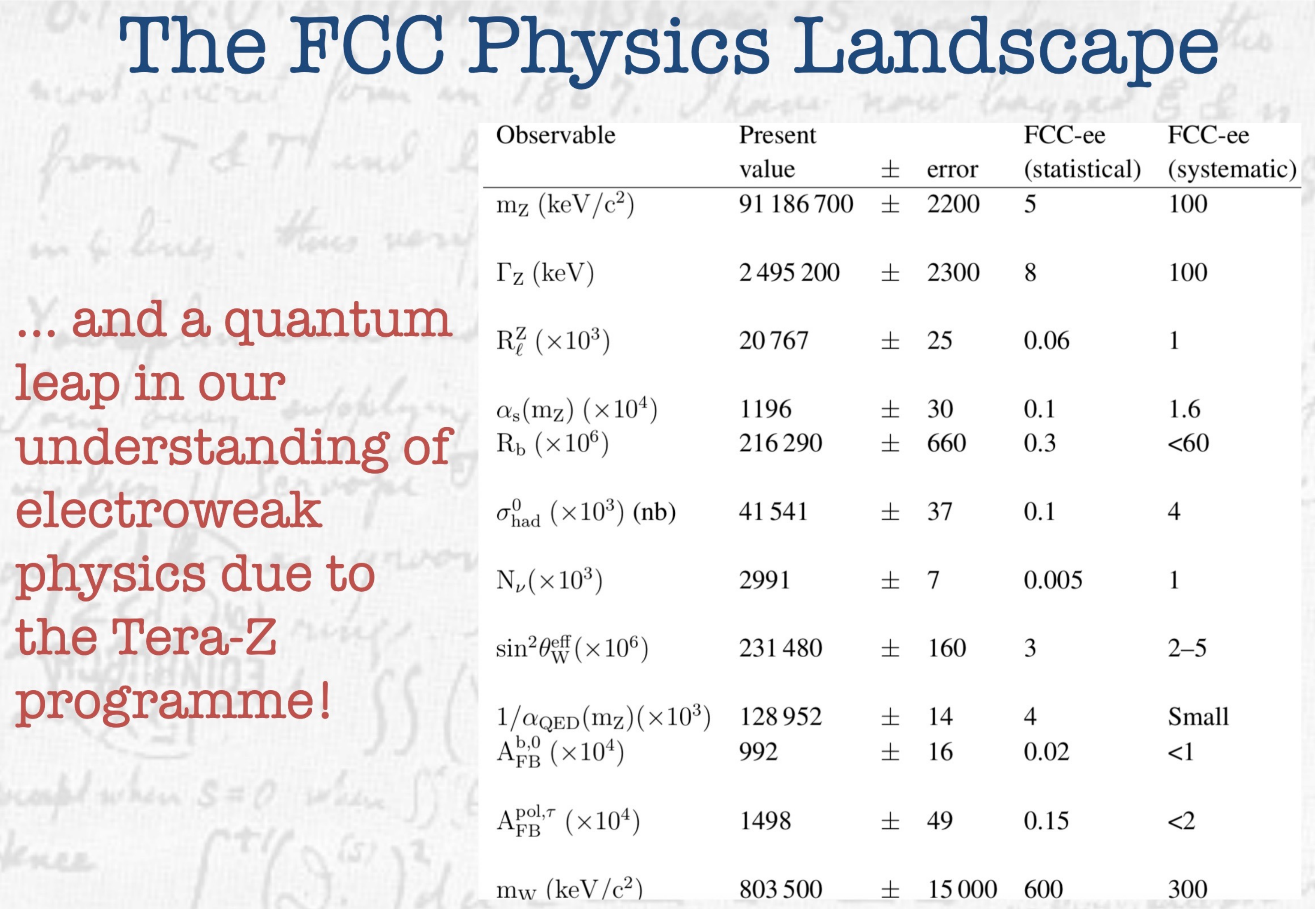
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

Slide courtesy M. Dam

Requirements for Calorimetry in FCC-ee

- **Energy range of particles:**
  - All particles ≤ 182.5 GeV
    - → $22X_0$ and 5-7λ sufficient
  - Measure particles down to < 300 MeV (e.g. photons)
    - → Little material in front of the calorimeter
    - → Low noise (noise term dominant at small energies, $b \ll 300$ MeV)!
- **Jet energy and angular resolutions** via **Particle Flow (PF)** algorithm
  - Jet resolution must be excellent (~ $30\%/\sqrt{E}$) to separate W and Z decays
- **Position resolution of photons / π^0 rejection:** $\sigma_x = \sigma_y = (6\ \mathrm{GeV}/E \oplus 2)$ mm Particle ID:
  - τ decays with collimated final states, separate different decay modes with minimal overlap (e.g. π^0 close to $\pi^\pm$)
- → **Fine segmentation** for PF algorithm and powerful γ/π^0 separation and measurement
- **$10\%/\sqrt{E}$ sufficient for most of the FCC-ee physics programme**, however, **for heavy flavour programme, superior ECAL resolution of a few % could be an advantage** (see e.g. talk by R. Aleksan)
- **On top of that: minimizing the systematic error** (see next slide)

The Challenge – Minimizing the Systematic Error



The FCC Physics Landscape

... and a quantum leap in our understanding of electroweak physics due to the Tera-Z programme!

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)
m_Z (keV/c^2)	91 186 700	±	2200	5	100
Γ_Z (keV)	2 495 200	±	2300	8	100
R_ℓ^Z ($\times 10^3$)	20 767	±	25	0.06	1
$\alpha_s(m_Z)$ ($\times 10^4$)	1196	±	30	0.1	1.6
R_b ($\times 10^6$)	216 290	±	660	0.3	<60
σ^0_{had} ($\times 10^3$) (nb)	41 541	±	37	0.1	4
$N_\nu(\times 10^3)$	2991	±	7	0.005	1
$\sin^2\theta_W^{eff}(\times 10^6)$	231 480	±	160	3	2–5
$1/\alpha_{QED}(m_Z)(\times 10^3)$	128 952	±	14	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	0.02	<1
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498	±	49	0.15	<2
m_W (keV/c^2)	803 500	±	15 000	600	300

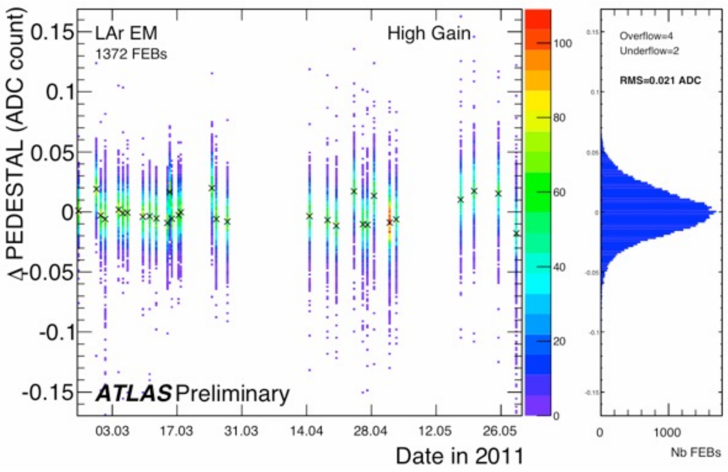
Talk by M. Mccullough on Monday at the FCC-Week (link)

- **FCC-ee EWPO measurements with unprecedented statistical precision**
  - e.g. 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**
  - → Extremely well controlled systematic error
  - → High stability, uniformity and linearity
- **→ Highly granular noble liquid calorimetry is an excellent candidate!!**

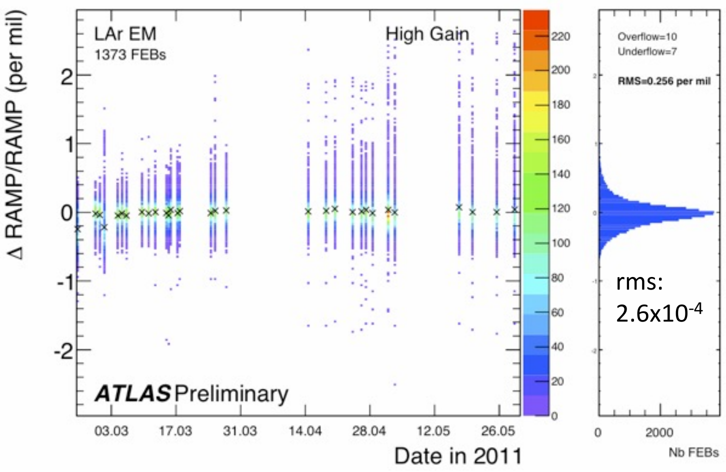
Example – Stability of ATLAS LAr Energy Scale

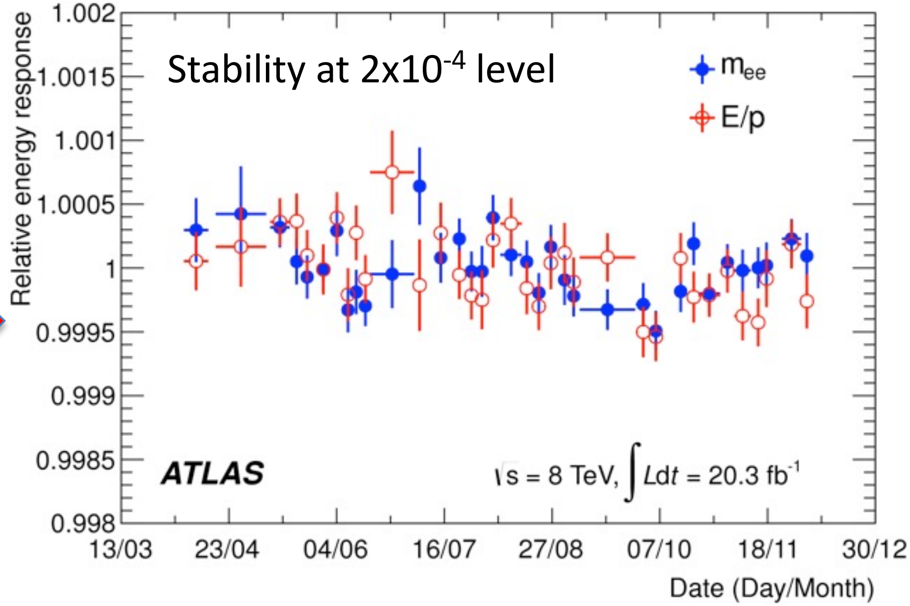
- **Noble-liquid calorimetry:** High intrinsic stability (see gain and pedestal stability)
  - Pedestal stability < 100 keV (!)
  - Gain stability 2.6x10^{-4}
- These parameters are monitored in daily calibration runs → constants are updated when necessary (about once a month)
- → Leading to high stability of the energy scale of 2x10^{-4}, monitored by invariant mass mee (Z→ee events) and E/p

Pedestal (P) stability

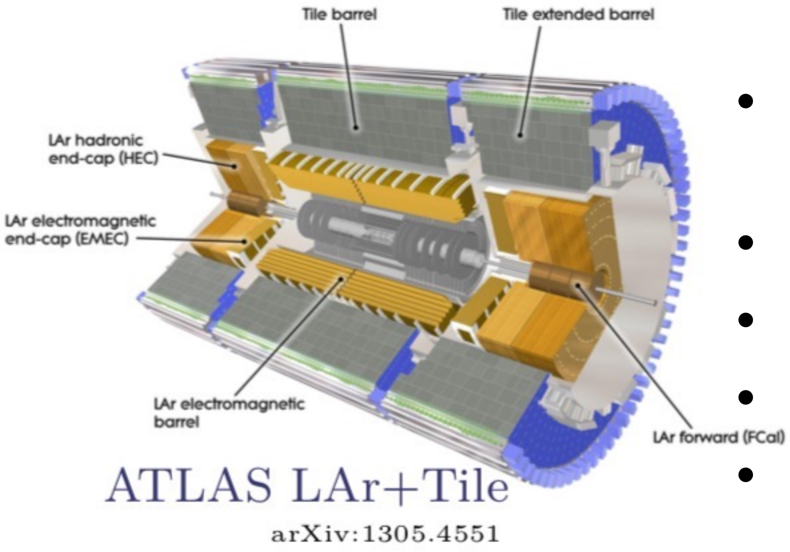


Gain (R) stability





FCC Calorimetry



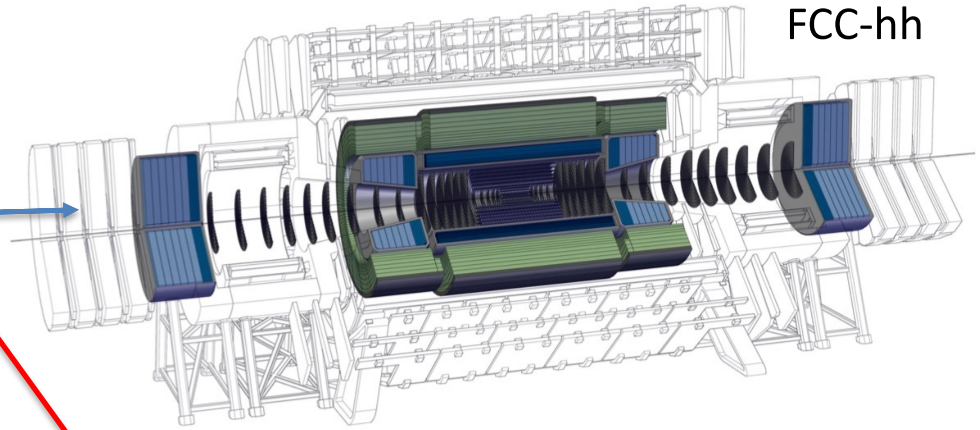
ATLAS LAr+Tile

arXiv:1305.4551

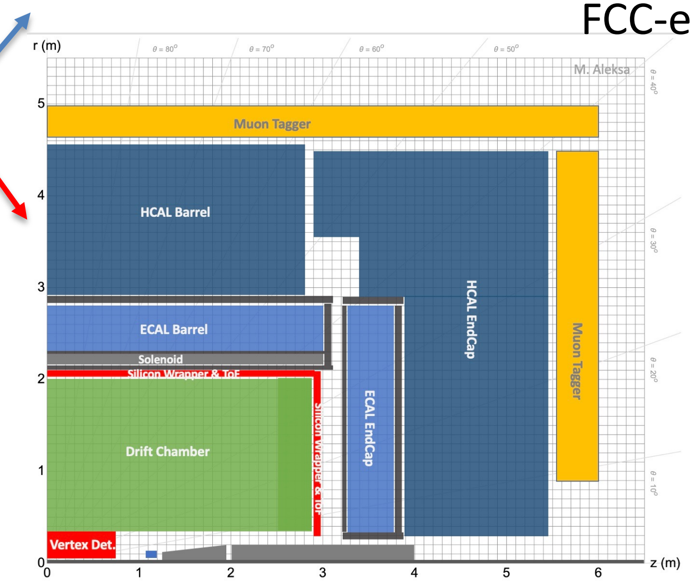
- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

FCC Calorimetry

FCC-hh

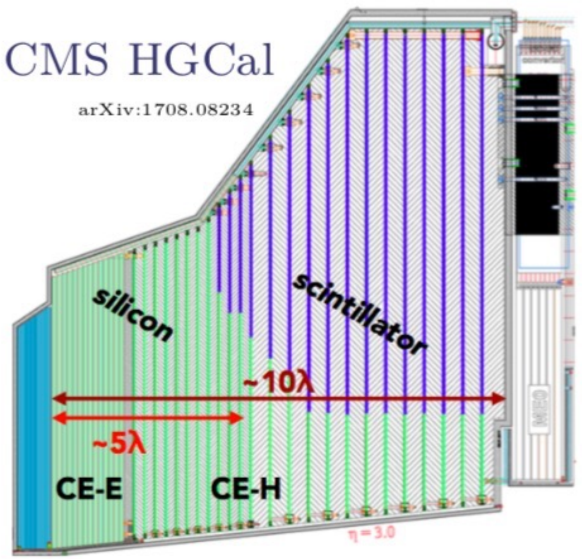


FCC-ee



CMS HGCal

arXiv:1708.08234

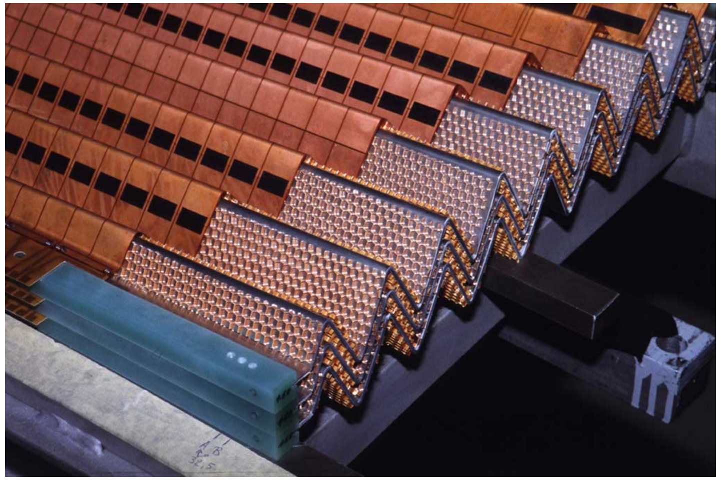


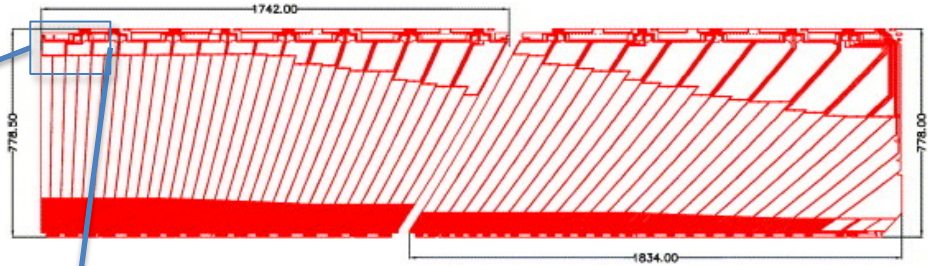
- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

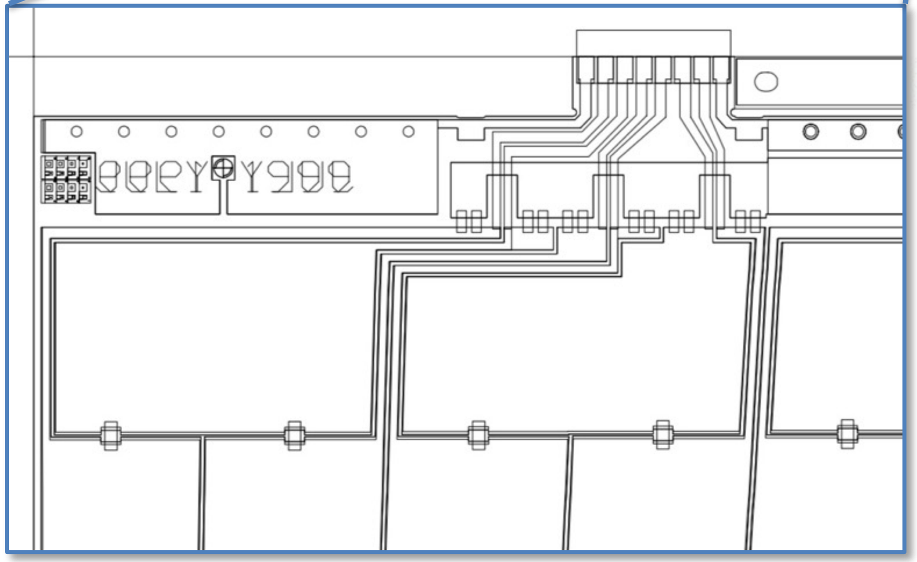
FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

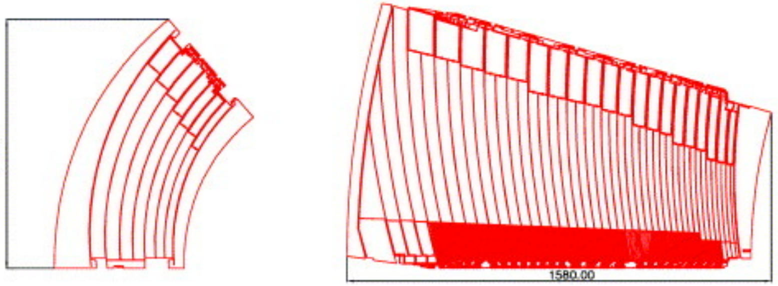
Granularity – What are the Limits in ATLAS LAr?

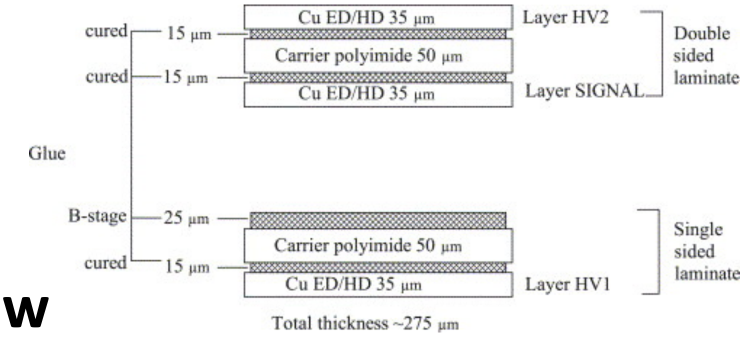
- **In the ATLAS LAr calorimeter** electrodes have 3 layers that are glued together (~275µm thick)
  - 2 HV layers on the outside
  - 1 signal layer in the middle
- → **All cells** have to be connected **with fine signal traces** (2-3mm) to the edges of the electrodes
  - Front layer read at inner radius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

FCC-hh Hadronic Calorimeter Barrel (HCAL)

Barrel HCAL:

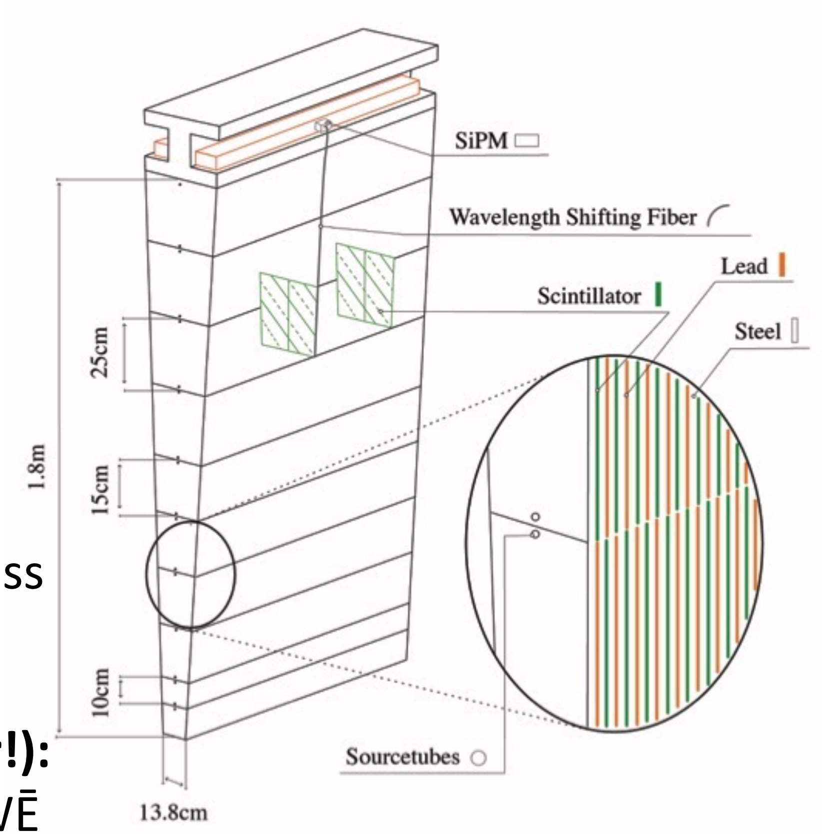
- ATLAS type
  - Scintillator tiles – steel
- **Higher granularity** than ATLAS
  - $\Delta\eta$ x $\Delta\phi$ = 0.025 x 0.025
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels

Combined pion resolution (w/o tracker!):

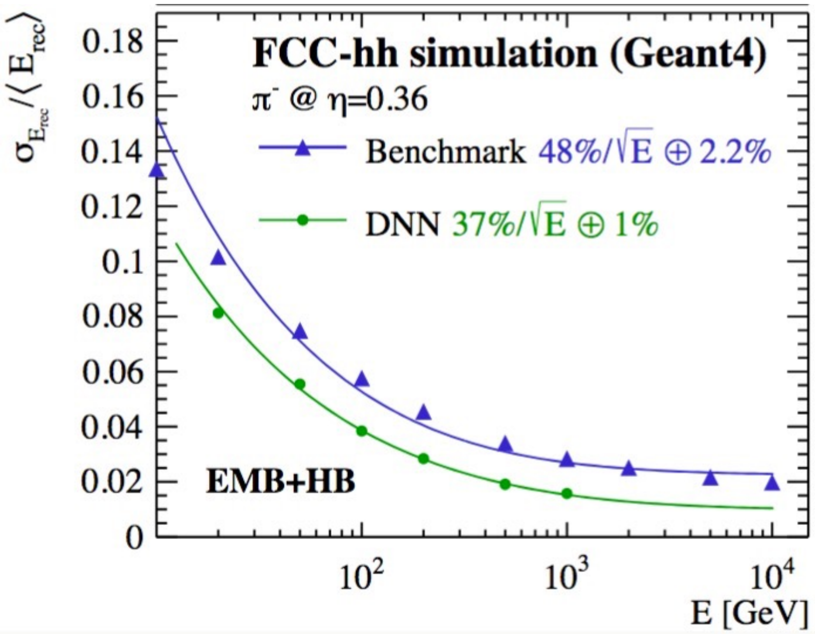
- Simple calibration: $44\%/\sqrt{\bar{E}}$ to $48\%/\sqrt{\bar{E}}$
- Deep neural network (DNN): $37\%/\sqrt{\bar{E}}$

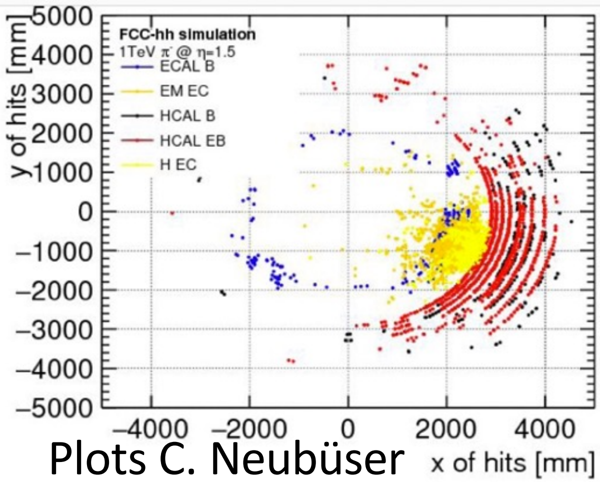
Jet resolution:

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



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

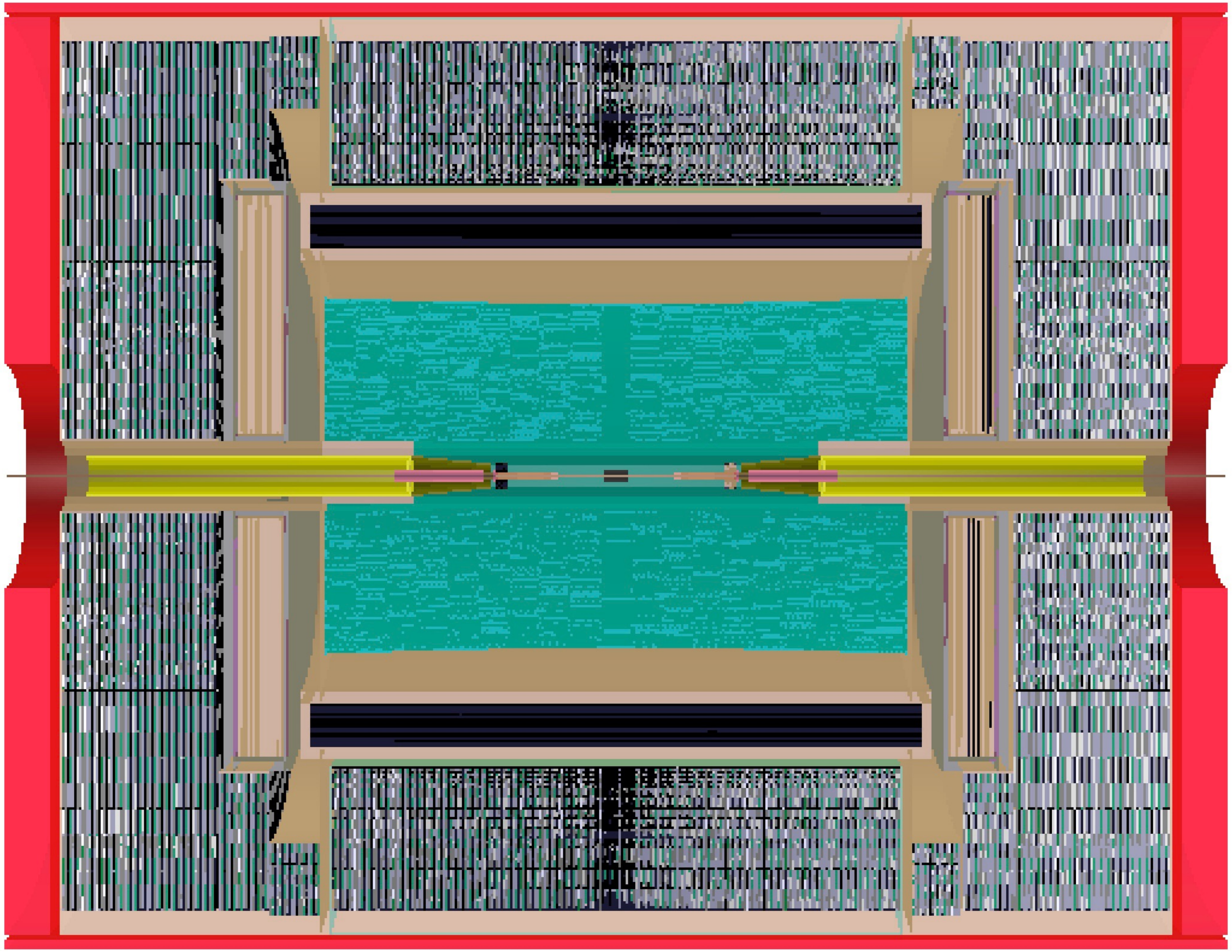




Plots C. Neubüser

Detector Concept 1 Implemented in FCC-SW

- **Detector Concept 1** with noble-liquid ECAL and TileCal HCAL has been implemented into key4hep (J. Faltova link)
- Ready for **plug-n-play** – e.g. simulations with drift chamber or Si tracker are possible …
- **Clustering** can be used from FCC-hh calorimeter (sliding window, topo cluster), also plan to integrate CLUE algorithm (k4Clue, see talk by V. Volkl yesterday, link)
- **Particle flow**: Pandora being made available in key4hep via wrapper (k4pandora, see talk by V. Volkl yesterday, link)



Further Thoughts

- Presented **first ideas of new detector concept** using highly granular noble-liquid calorimeter
- Aimed to include **thin 2T solenoid** in the calorimeter cryostat.
  - Solenoid inside the calorimeter or between ECAL and HCAL
- Currently **scintillator/iron HCAL,** but option with **ECAL and HCAL as noble liquid calorimeter possible**
  - Weight! Might be challenging for cryostat mechanics
- The idea is to **profit** from **detector developments for HL-LHC** (LS3) and **beyond** (e.g. ALICE 3, LHCb Phase-2)
- Thanks to the **modular structure** of the **FCC-SW** different detector concepts can **easily be simulated** and its performance evaluated
  - A first geometry following the above concept has been implemented by Jana Faltova.
- **This is a very new and very promising detector concept! Please come and join us!**