Possible Layouts for an FCC-ee Experiment

M. Aleksa for the Noble-Liquid Calorimetry Group

Material used:

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

For more details on the noble-liquid calorimeter please also see the GranuLAr WS Summary talk by N. Morange in the afternoon!

FCC-ee Physics Programme

”Higgs Factory” Programme

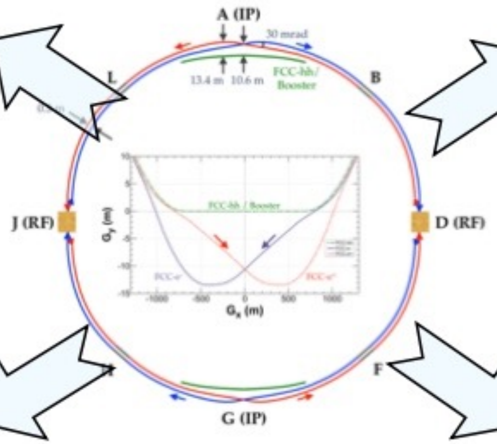
- At two energies, 240 and 365 GeV, collect in total
    - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

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

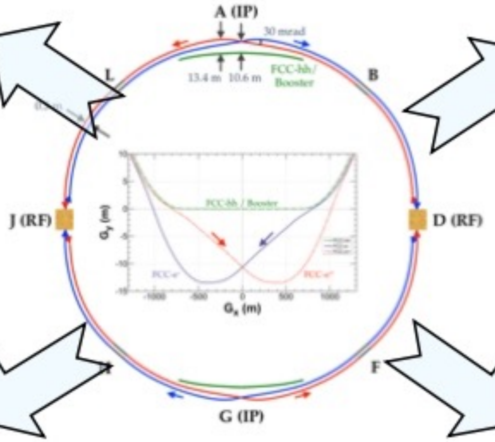
FCC-ee Detector Requirements

”Higgs Factory” Programme

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

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



Heavy Flavour Programme

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

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

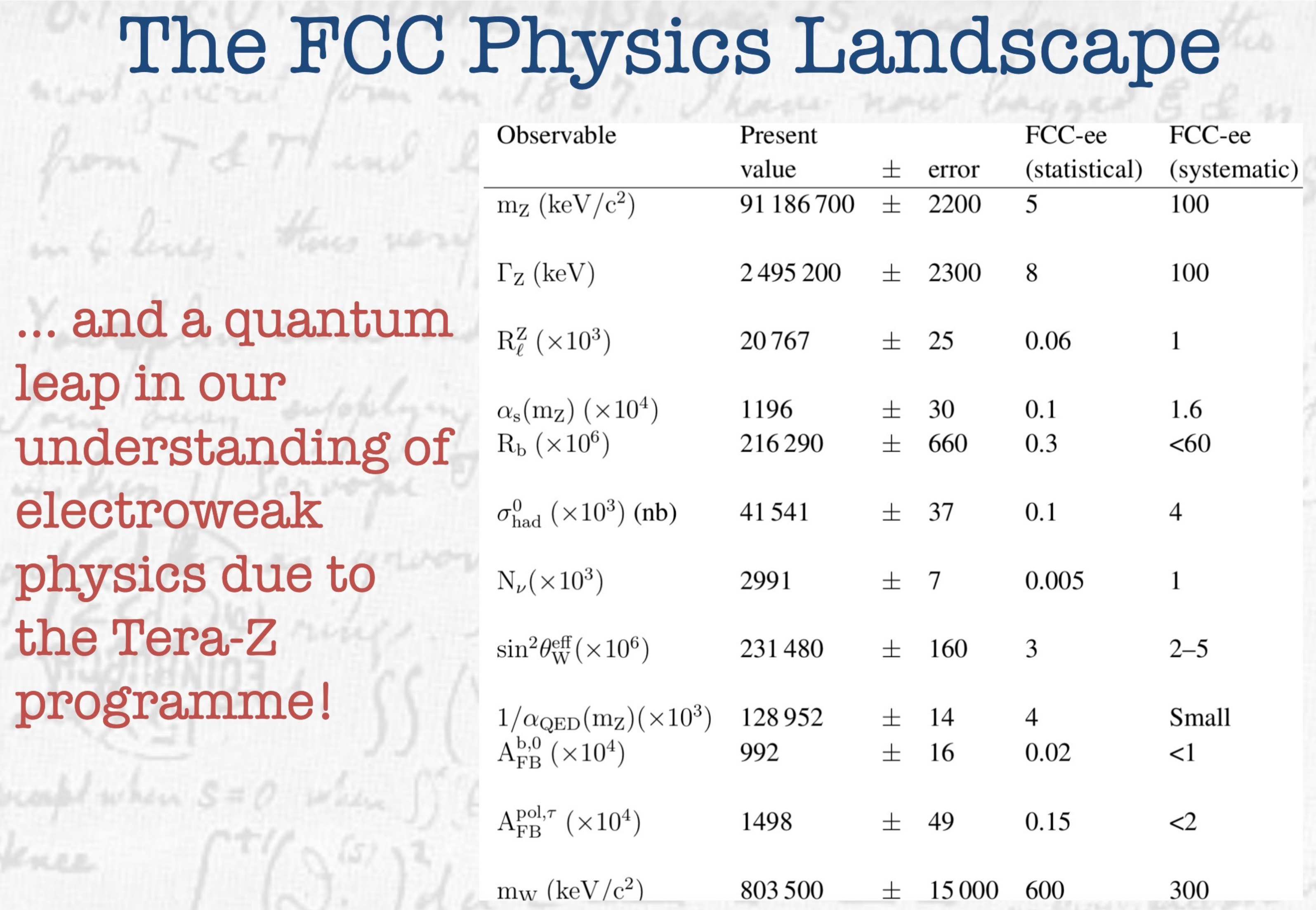
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

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%/√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%/√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 ($\times10^3$)	20 767	±	25	0.06	1
$\alpha_s(m_Z)$ ($\times10^4$)	1196	±	30	0.1	1.6
R_b ($\times10^6$)	216 290	±	660	0.3	<60
σ^0_{had} ($\times10^3$) (nb)	41 541	±	37	0.1	4
N_ν($\times10^3$)	2991	±	7	0.005	1
$\sin^2\theta_W^{eff}$($\times10^6$)	231 480	±	160	3	2–5
$1/\alpha_{QED}(m_Z)$($\times10^3$)	128 952	±	14	4	Small
$A_{FB}^{b,0}$ ($\times10^4$)	992	±	16	0.02	<1
$A_{FB}^{pol,\tau}$ ($\times10^4$)	1498	±	49	0.15	<2
m_W (keV/c^2)	803 500	±	15 000	600	300

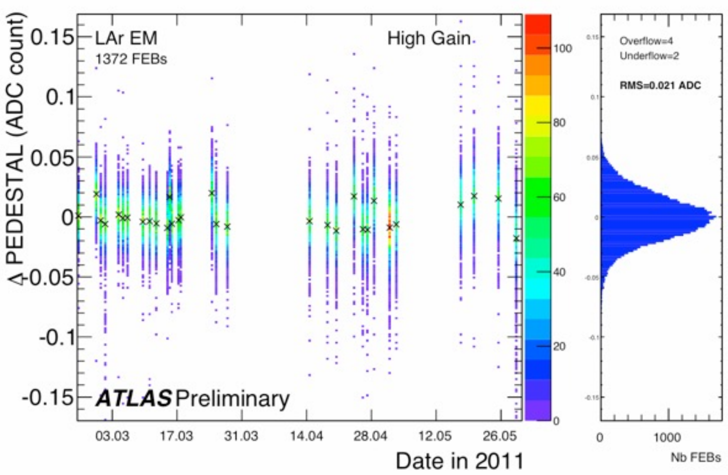
Talk by M. Mccullough on Monday at the FCC-Week (link)

- **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!!**

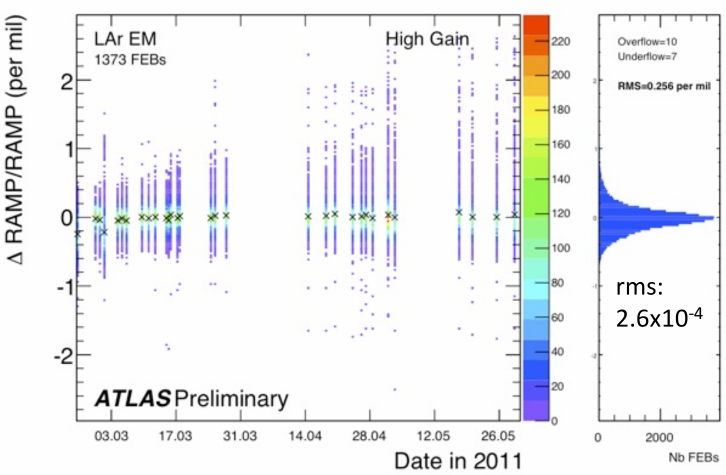
Example – Stability of ATLAS LAr Energy Scale

- **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

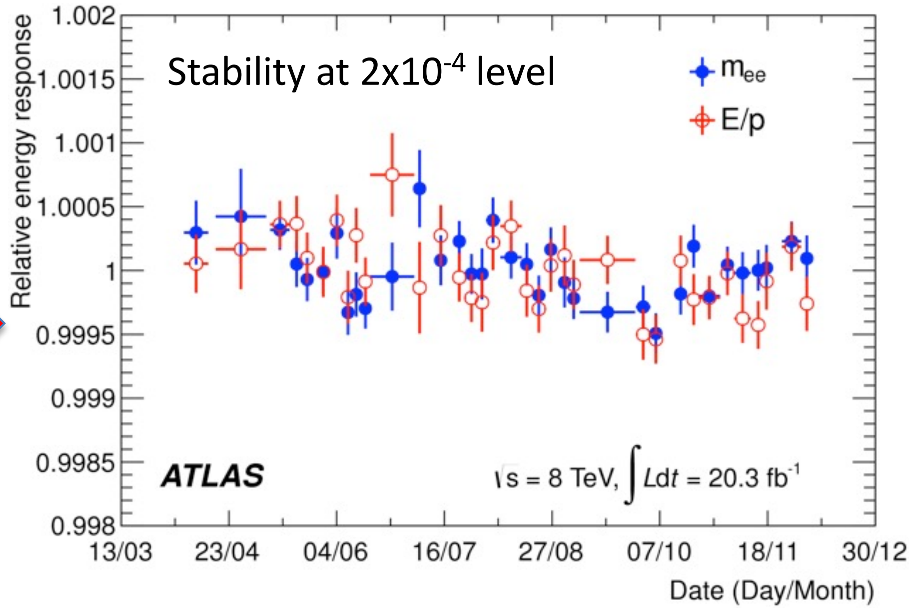
Pedestal (P) stability



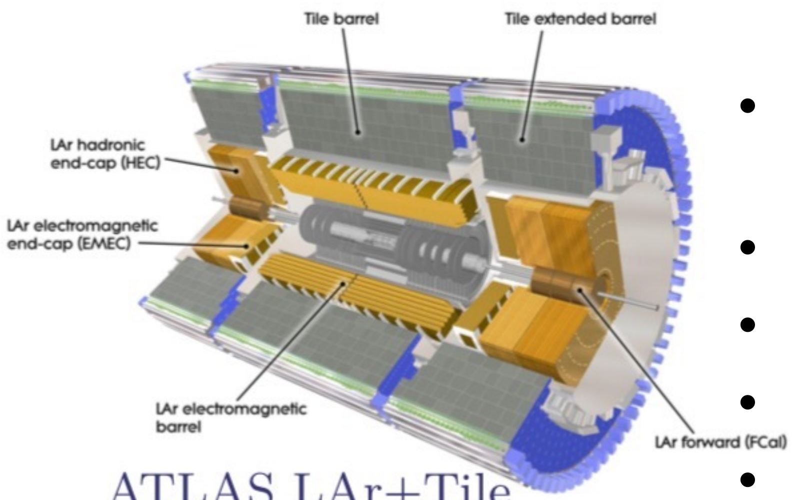
Gain (R) stability



rms:
2.6x10^{-4}

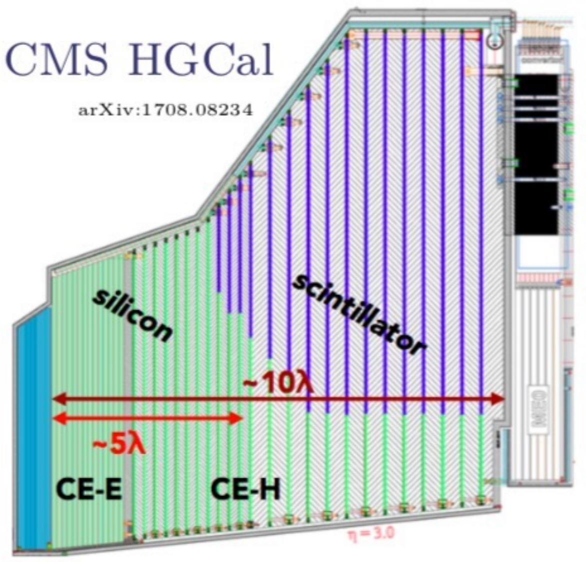

Stability at 2x10^{-4} level

FCC Calorimetry



ATLAS LAr+Tile

arXiv:1305.4551



CMS HGCal

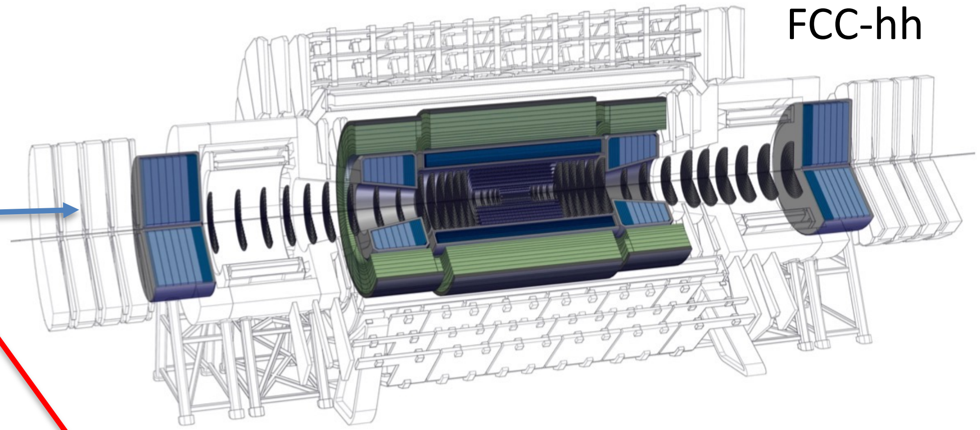
arXiv:1708.08234

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

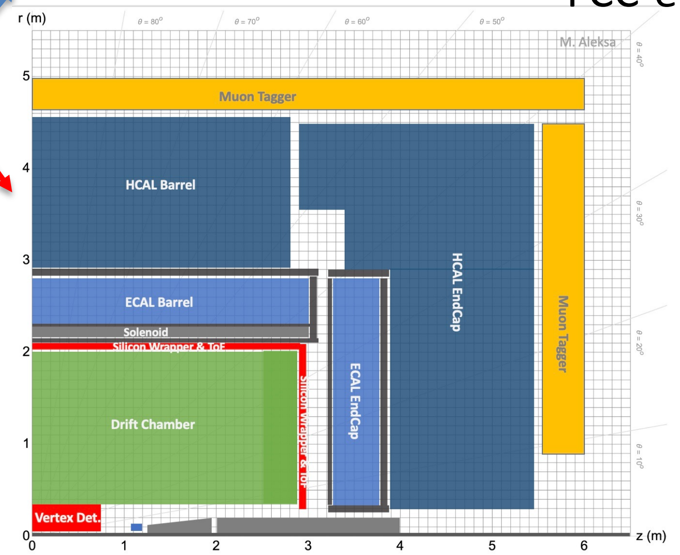
- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

FCC Calorimetry

FCC-hh



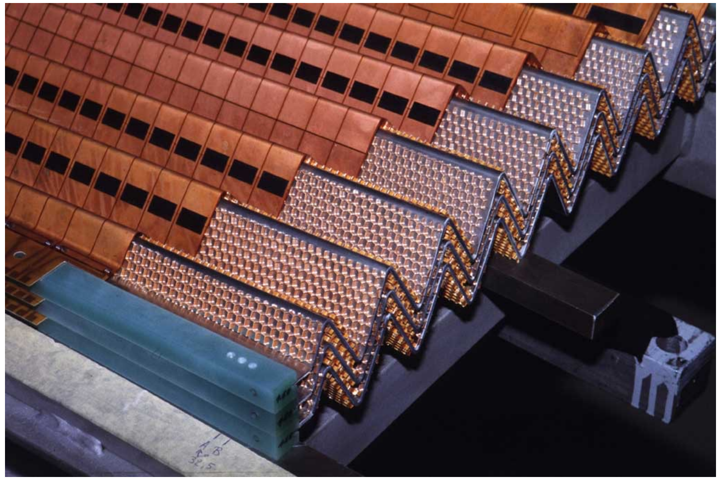
FCC-ee

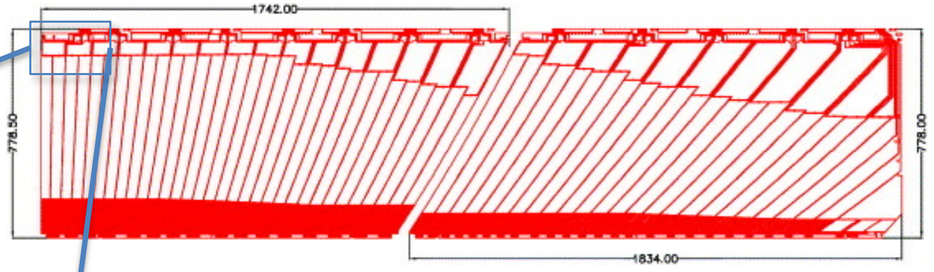


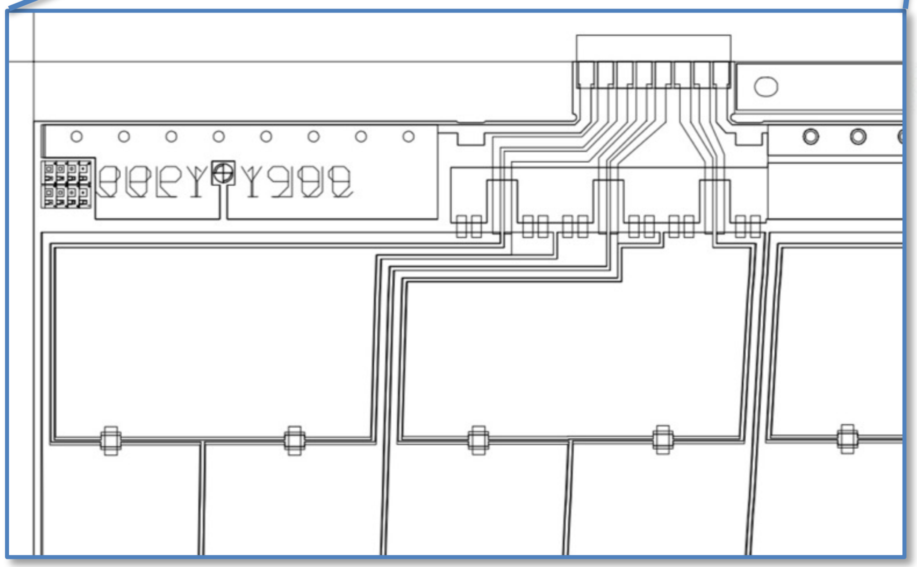
FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

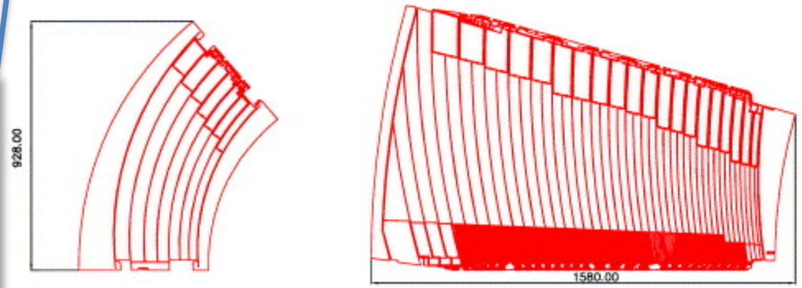
Granularity – What are the Limits in ATLAS LAr?

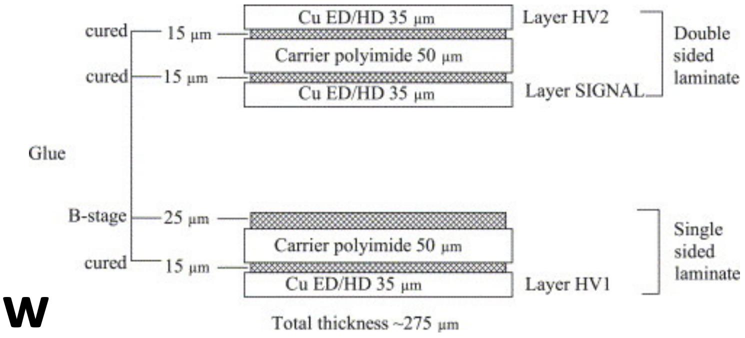
- **In the ATLAS LAr calorimeter** electrodes have 3 layers that are glued together (~275µm thick)
  - 2 HV layers on the outside
  - 1 signal layer in the middle
- → **All cells** have to be connected **with fine signal traces** (2-3mm) to the edges of the electrodes
  - Front layer read at inner radius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









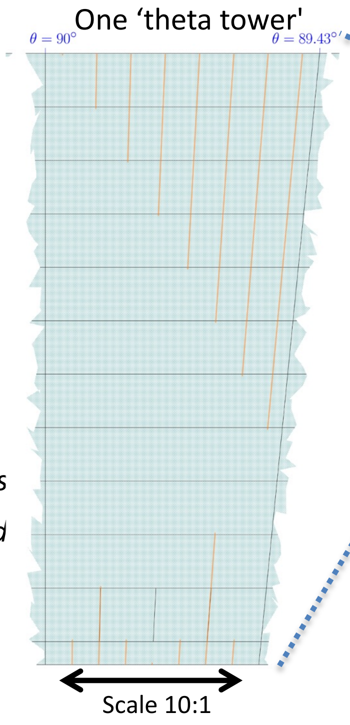


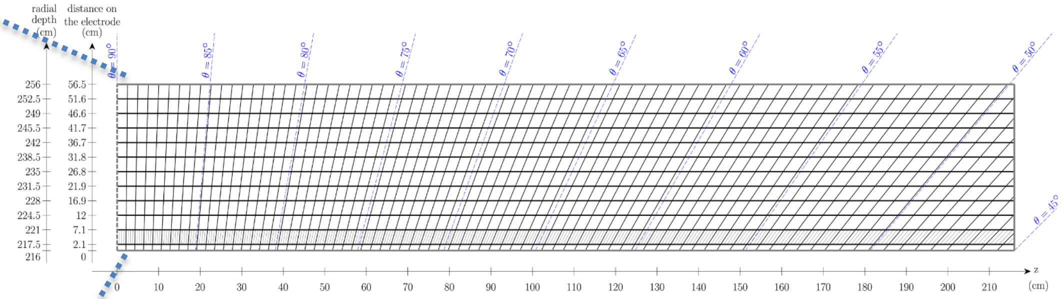
→ O(200k) read-out cells – particle flow reconstruction possible, but not optimal

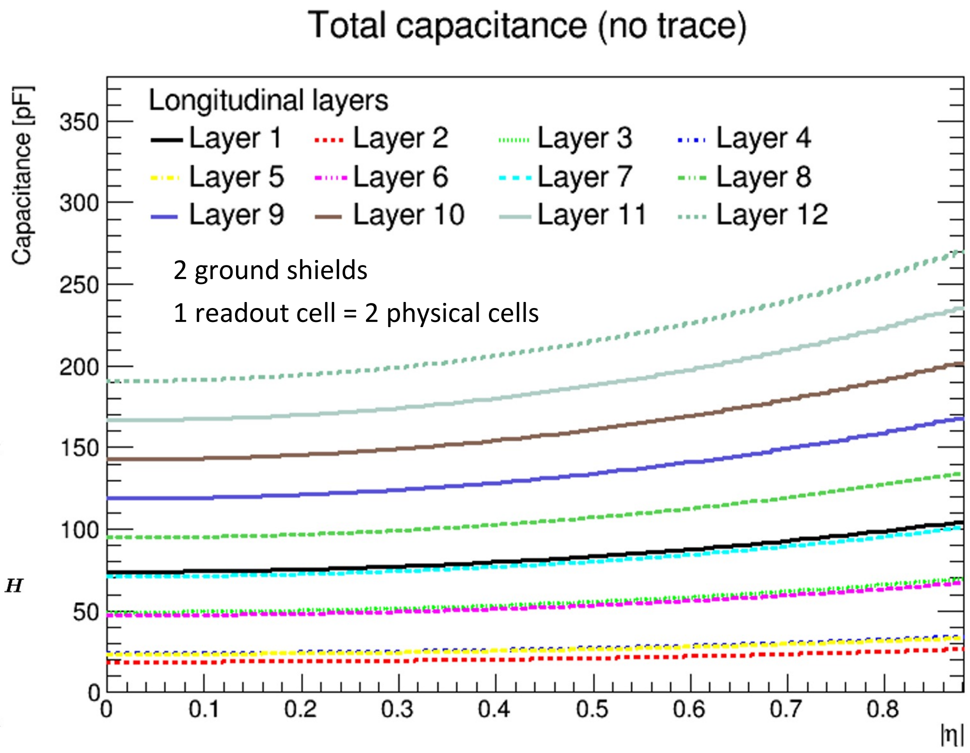
How to Achieve High Granularity?

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

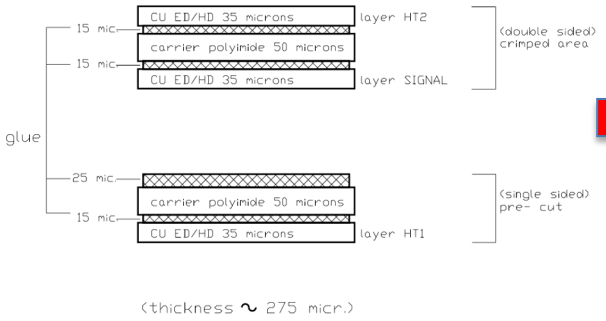
- HV and read-out
- Signal traces (width w_t) in dedicated signal layer connected with vias to the signal pads
- Traces shielded by ground-shields (width w_s) forming 50Ω – 80Ω transmission lines
- → capacitance between shields and signal pads C_s will add to the detector capacitance via the gap C_d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



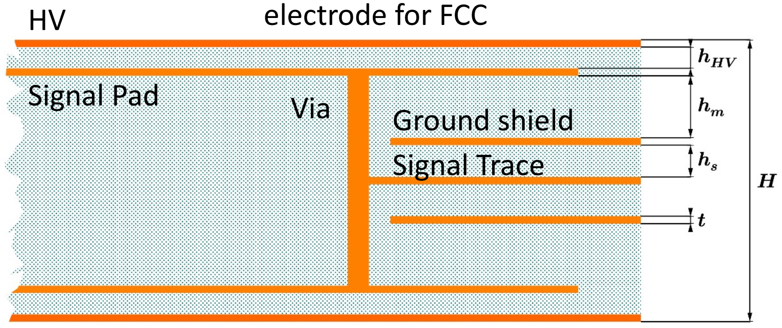




ATLAS electrode

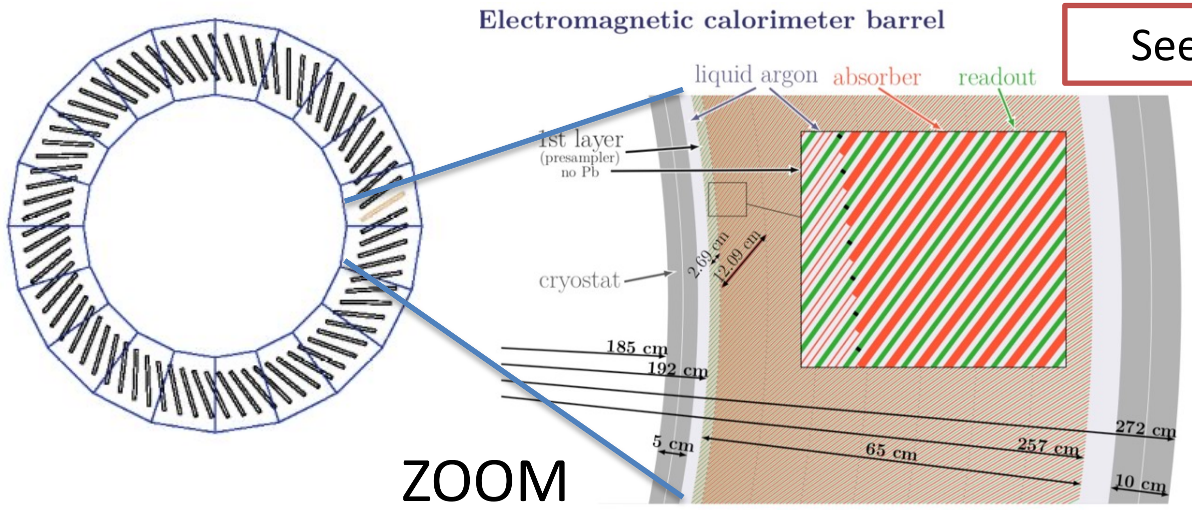


Multi-layer read-out electrode for FCC

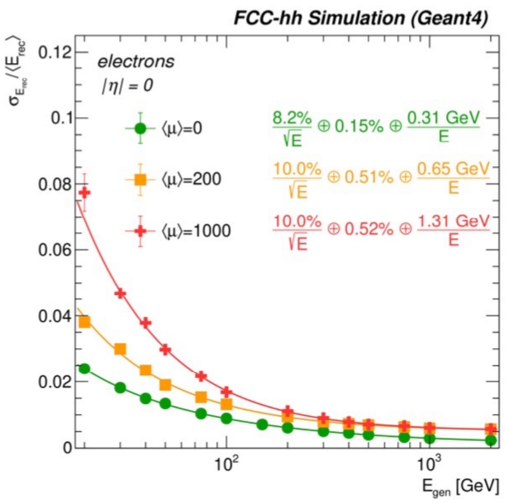


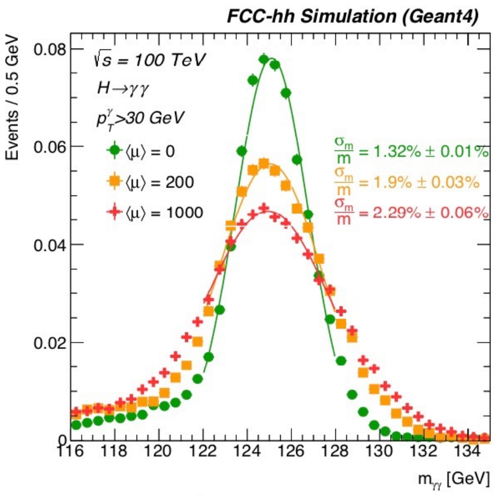
Reminder – FCC-hh Electromagnetic Calorimeter (ECAL)

See [arXiv paper]

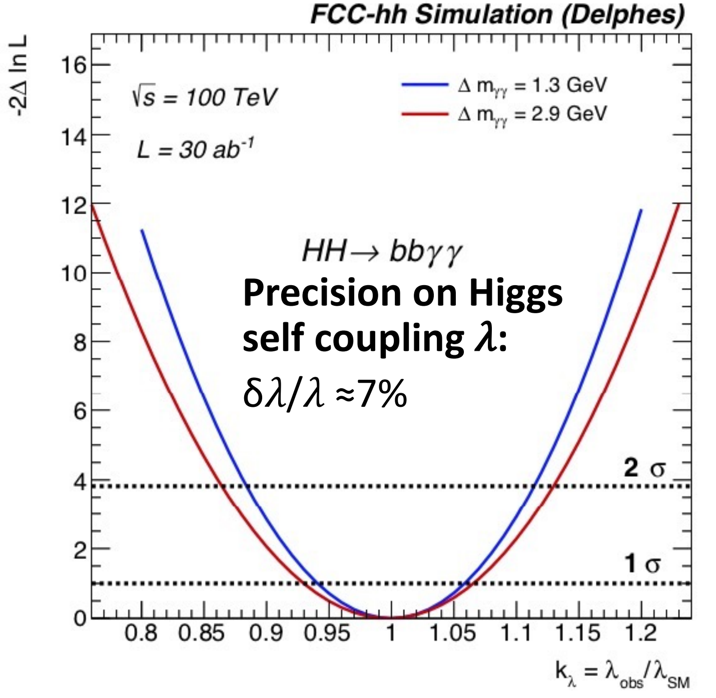


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **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 (Δη x Δϕ = 0.01 x 0.01, first layer Δη=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%/√Ē, 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:

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

Geometry Adjusted to FCC-ee

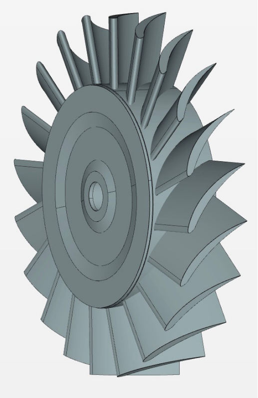
Geometry for FCC-ee ECAL barrel being optimized:

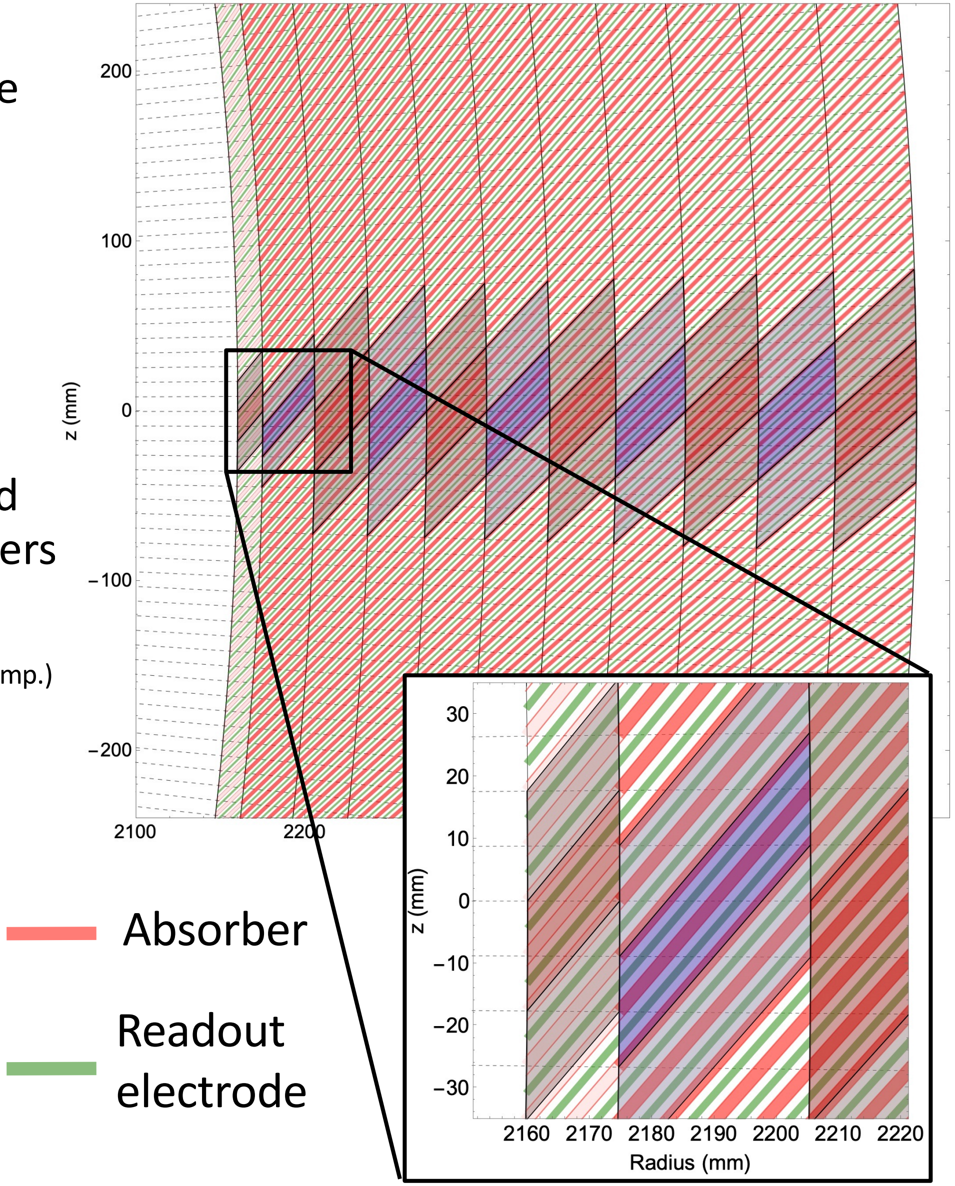
- No Pb/W in the first compartment = presampler (PS) → used to compensate for lost energy upstream
- 1536 absorbers in 2π, flat, no step-increase with r.
- 11 longitudinal compartments
- r_i=2160mm, r_o=2560mm, inclination of absorbers at r_i is α_i=50.381° (α_I depends on r_i and r_o to align cells 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.): $\Delta\phi \times \Delta\theta$ = 8.2mrad x 2.5mrad = 17.8mm x 5.4mm
  - Other compartments: $\Delta\phi \times \Delta\theta$ = 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

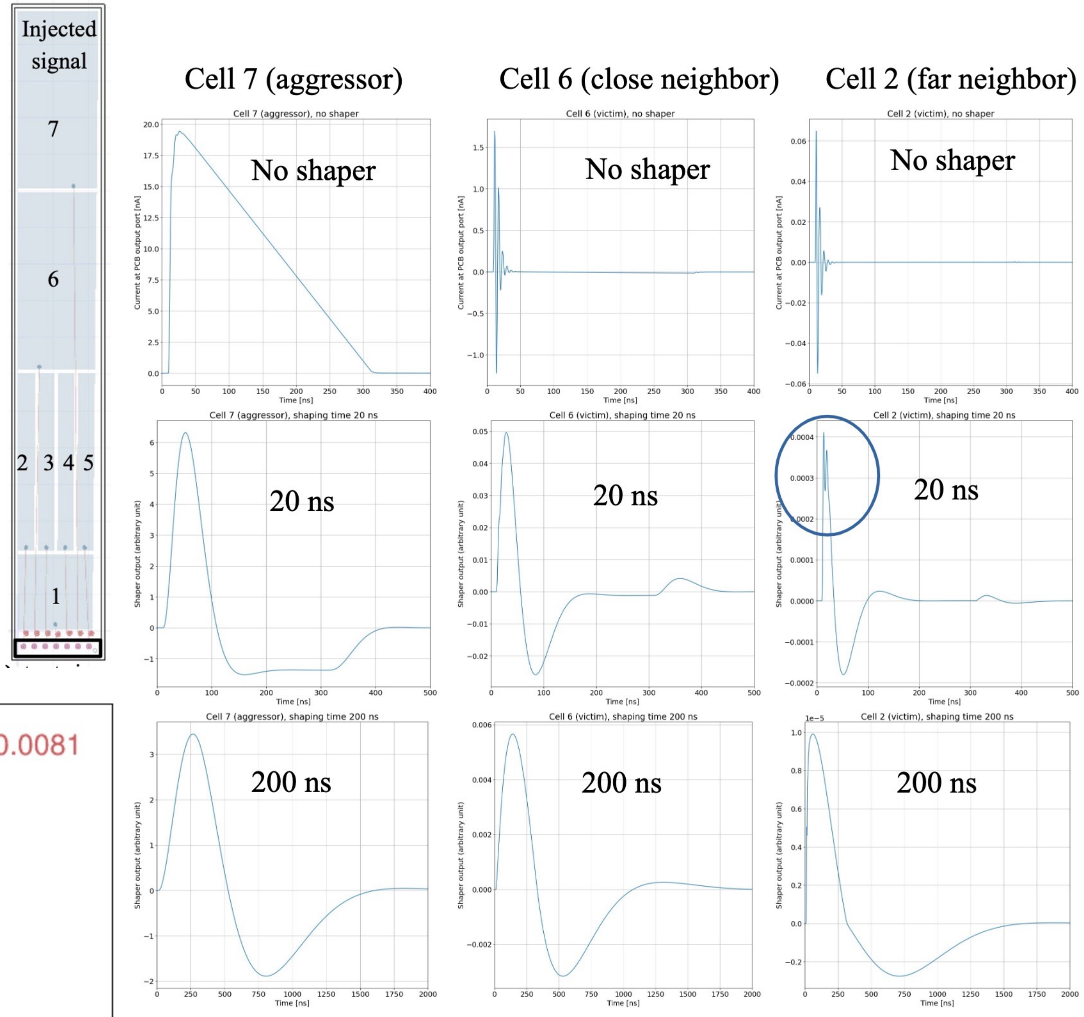
HCAL endcaps with parallel plates perpendicular to the beam

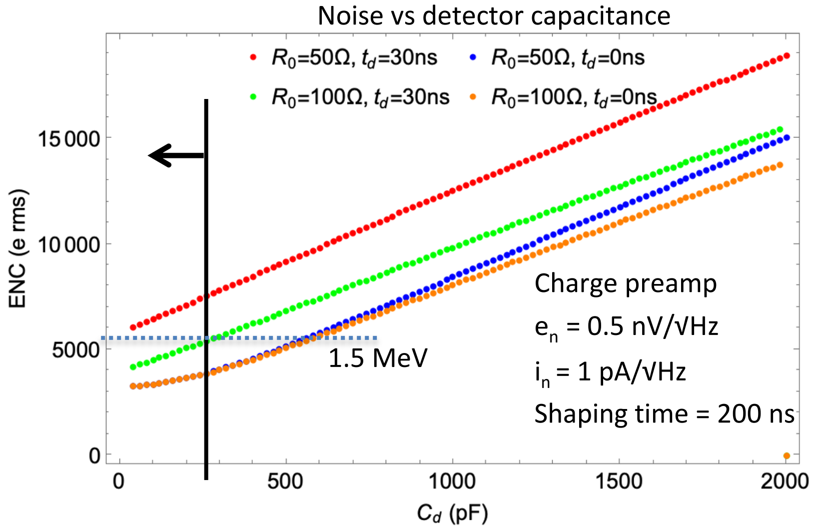


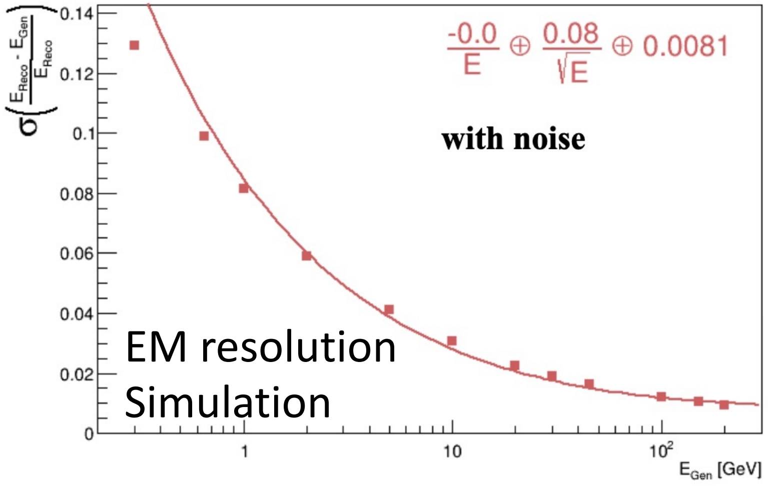


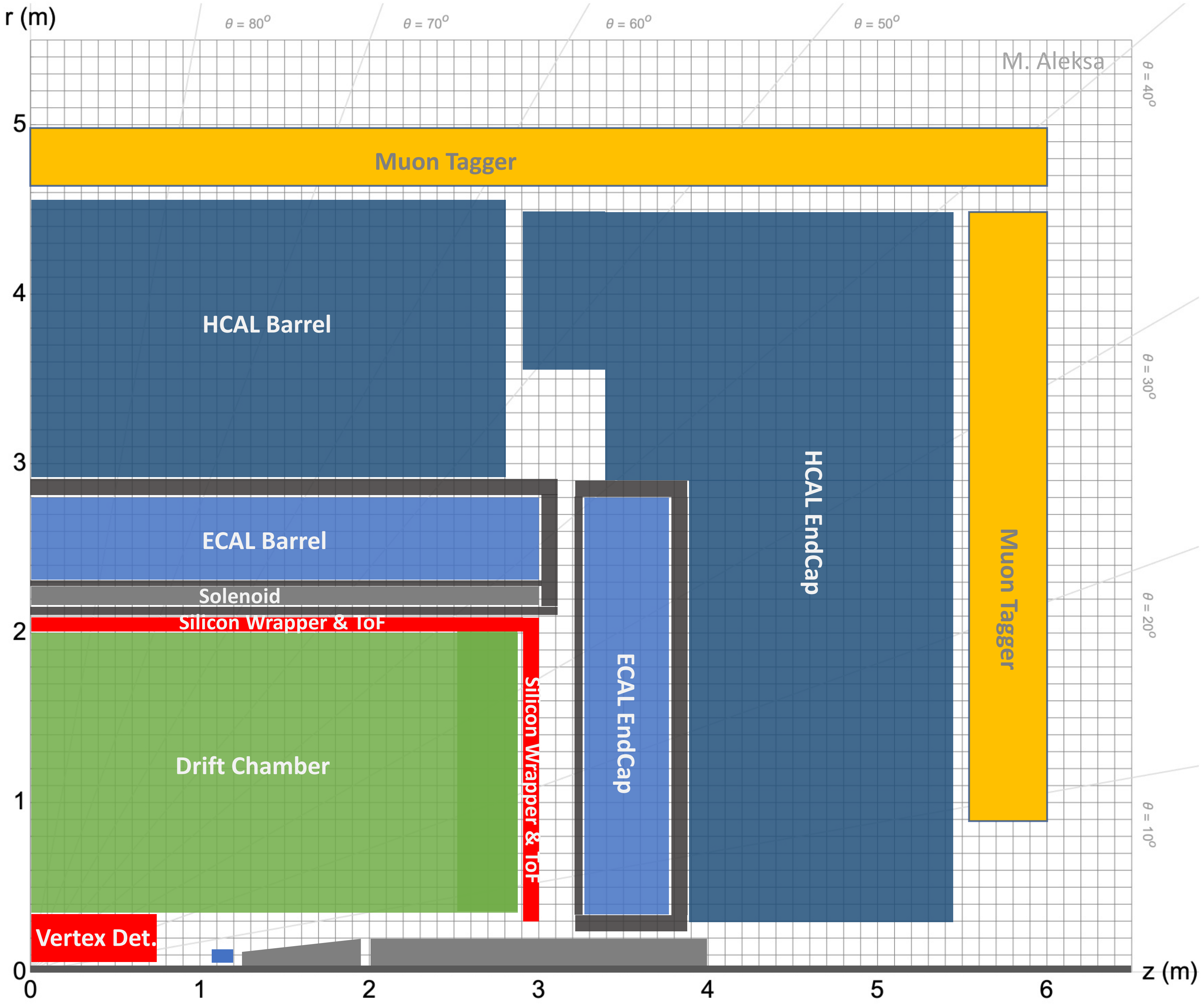
Challenges: Resolution, Noise and Crosstalk

- **EM resolution** with sampling term of 8 to 9%
- **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
- **Cross-talk** of < 1% for shaping times $\tau \geq 100$ ns
- **See talk by N. Morange this afternoon for more details!**



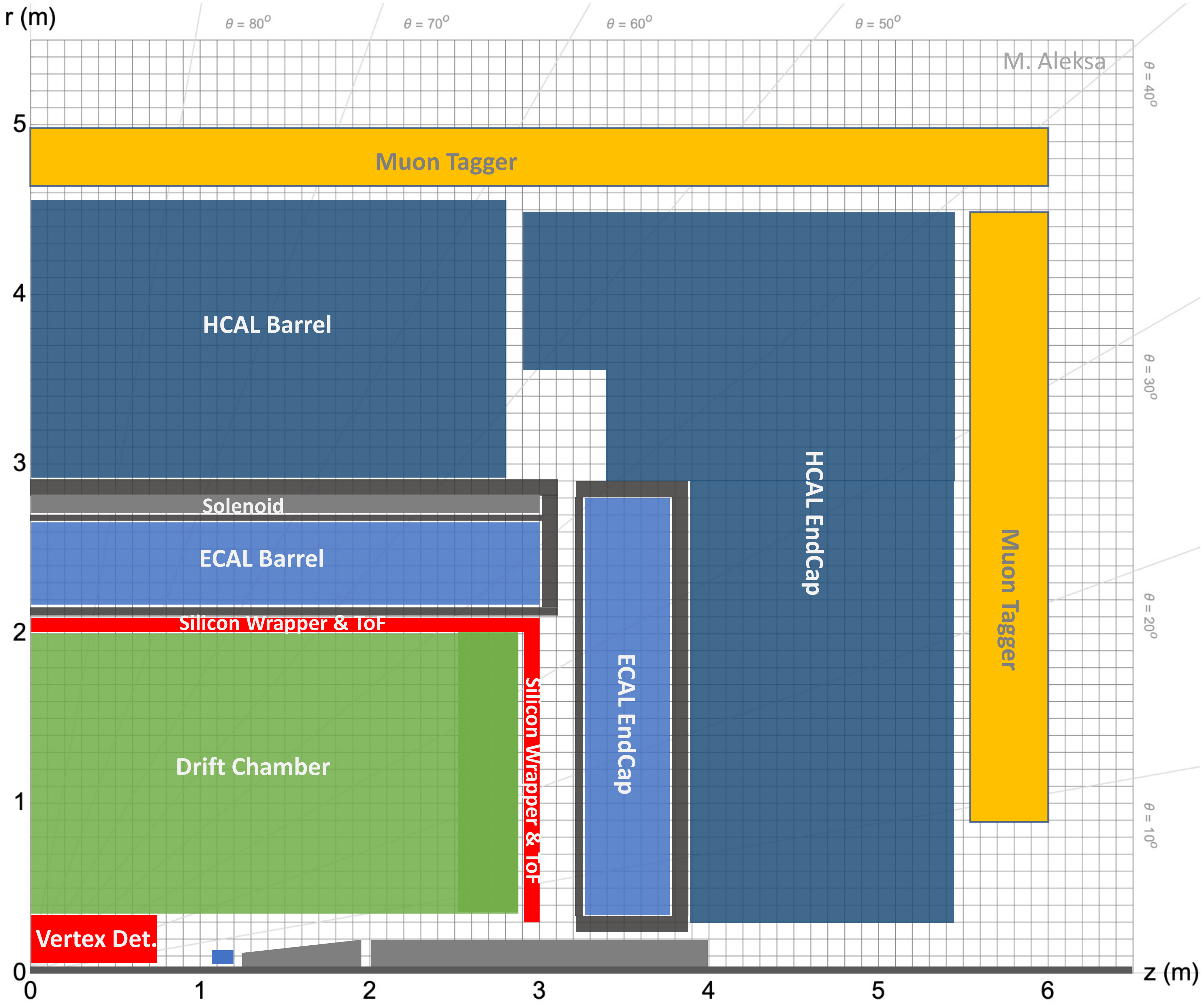






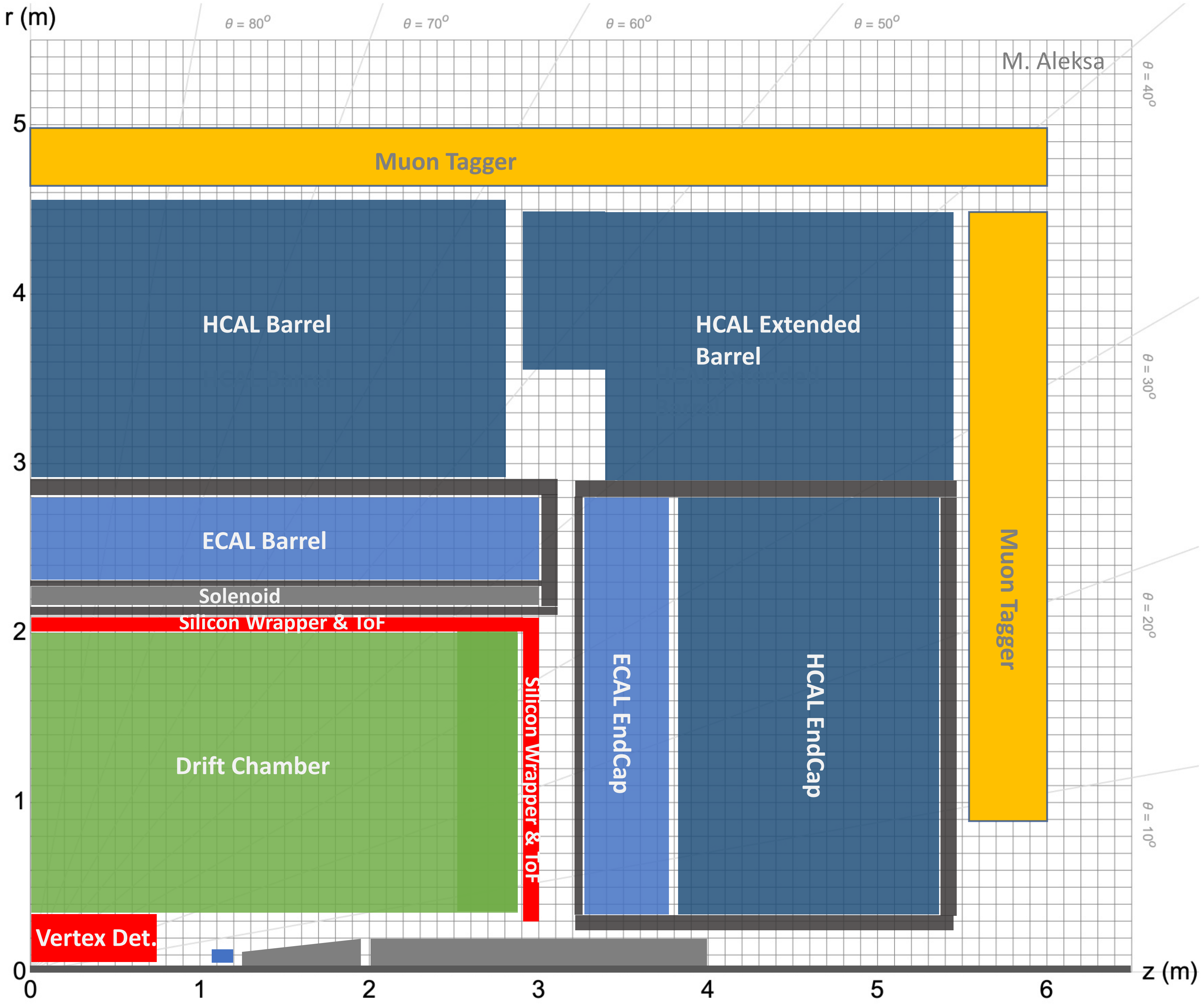
Detector Concept 1

- 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



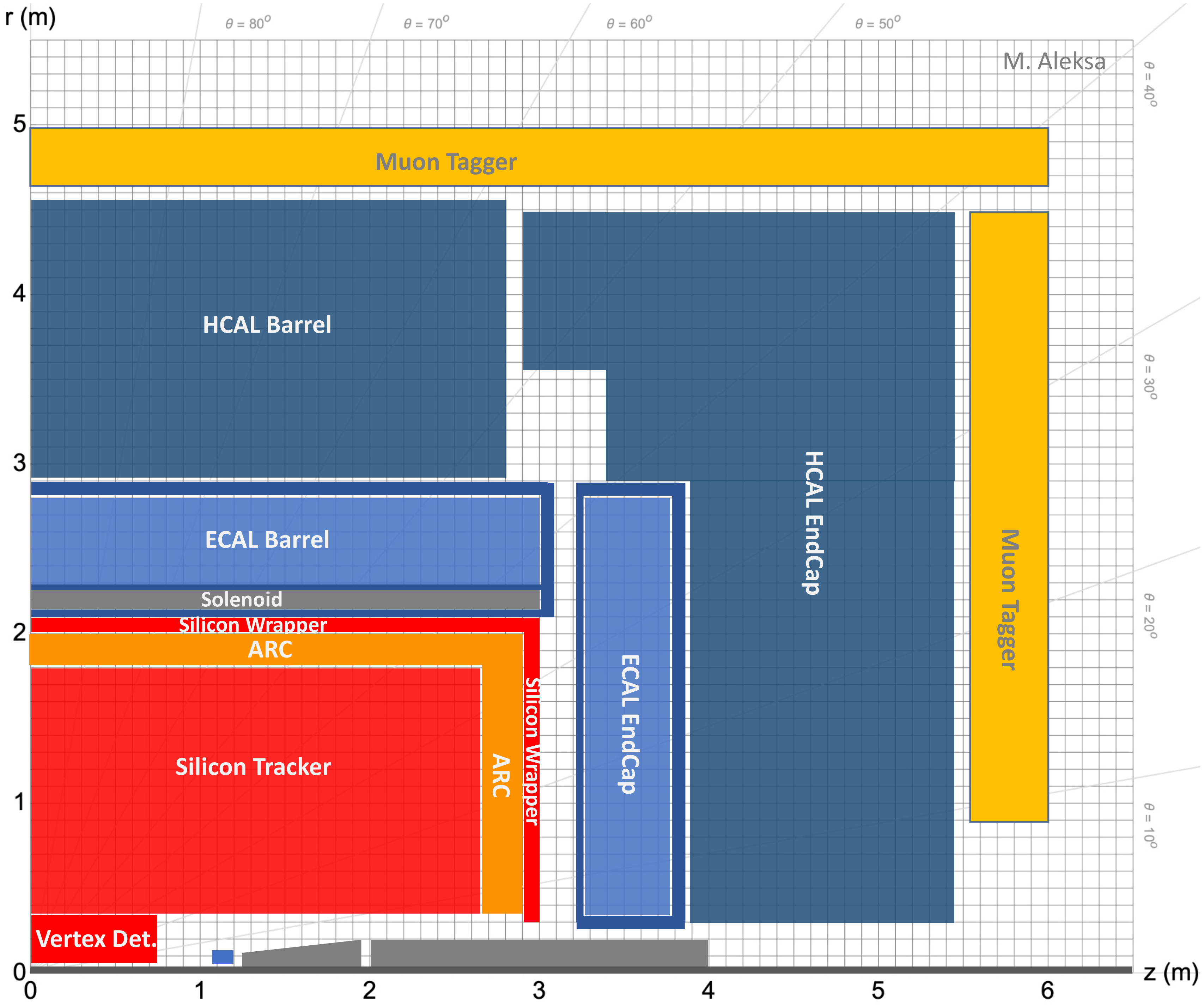
Detector Concept 1a

- Vertex Detector:
  - 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



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

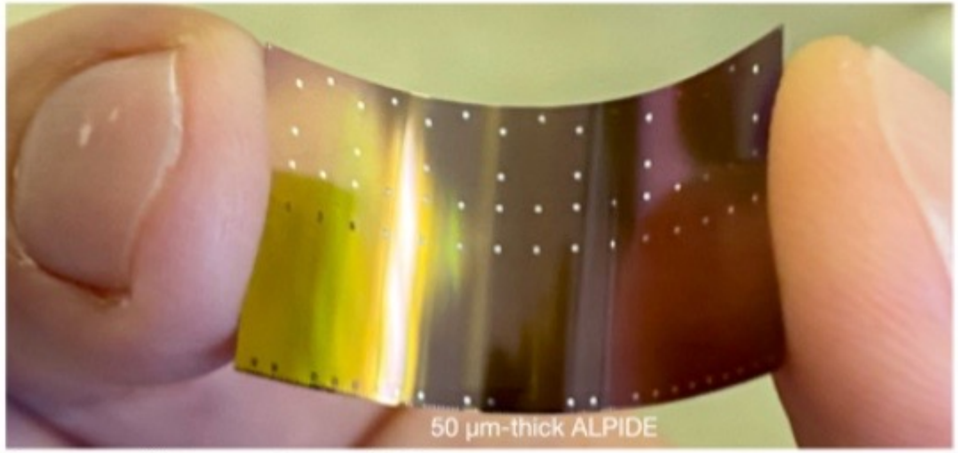


Detector Concept 3

- 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

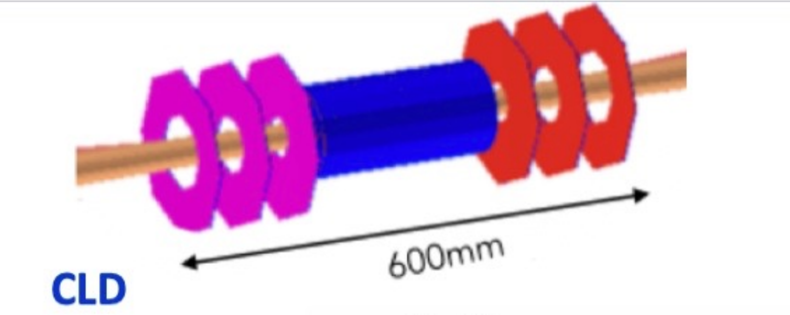
Vertex Detector

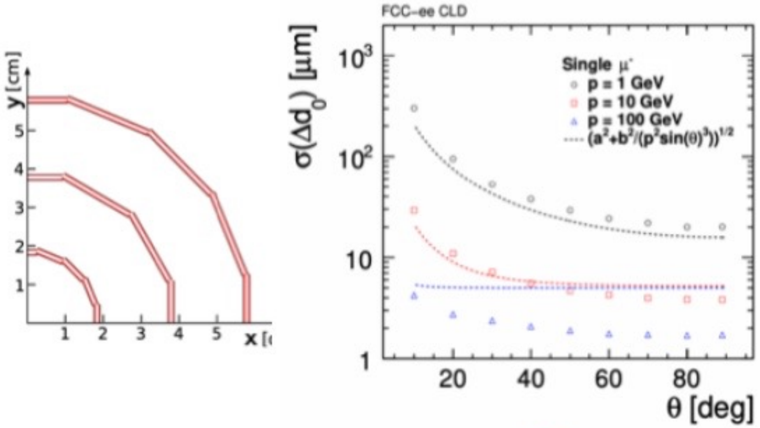
- **Beam pipe radius:**
  - 15 mm (old base line) → 10 mm (new baseline decided after CDR)
- **Thanks to collimators and effective beam-pipe shielding, beam backgrounds are in general negligible**
  - Example: max rate of 10^{-5} hits / mm^2 / BX @ $\sqrt{s}$ = 91.2 GeV
- **Following ongoing rapid technological development**
  - Lighter, more precise, closer, less power

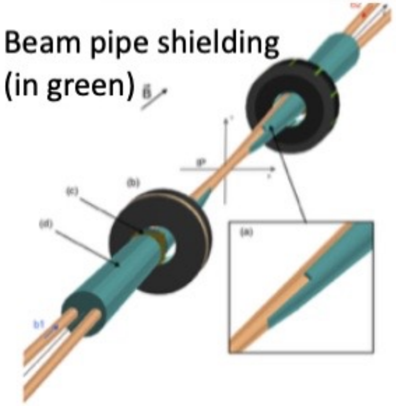


Courtesy of Magnus Mager, CERN

- **Extreme alignment-precision needs for life-time measurements**
  - Ex.: τ lifetime to $\lesssim 10^{-4}$ relative precision ⇒ $\lesssim$ 0.2 µm on flight distance





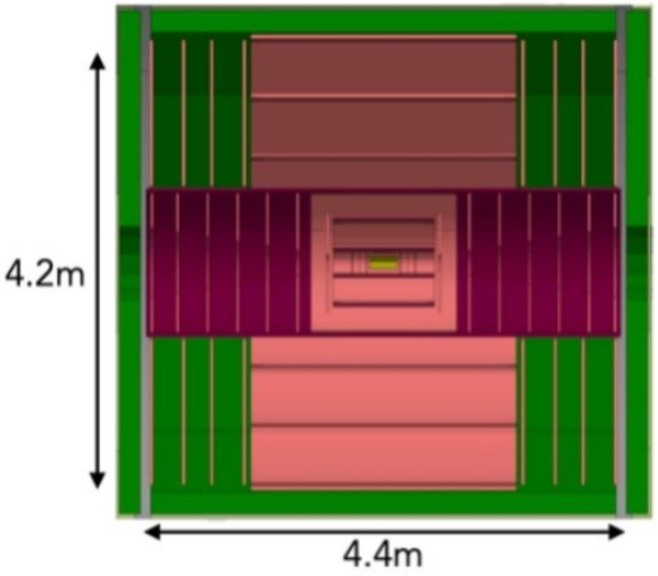


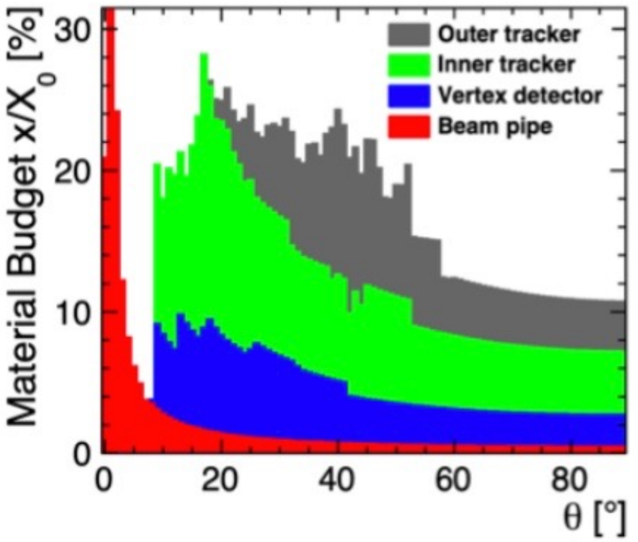
Beam pipe shielding (in green)

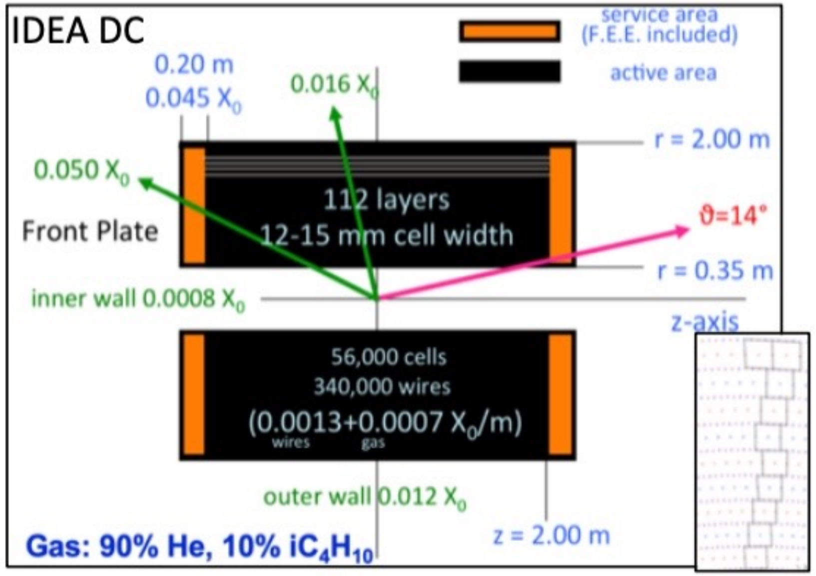
Tracking

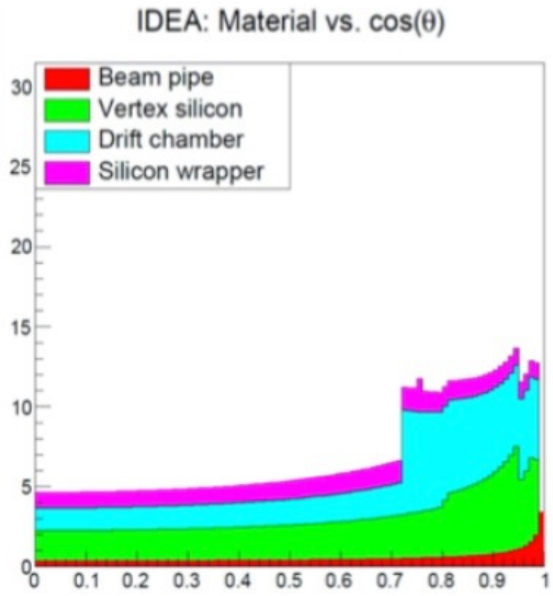
Two solutions under study

- **CLD like (concept 3):** 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 like (concept 1 and 2):** Extremely transparent Drift Chamber (but ±2.5m active area)
  - Longer wires → larger distance
  - Gas: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness (IDEA): 1.6% of X_0 at 90°
    - Tungsten wires dominant contribution
    - → Carbon filaments (with 2µm coating) are being tested



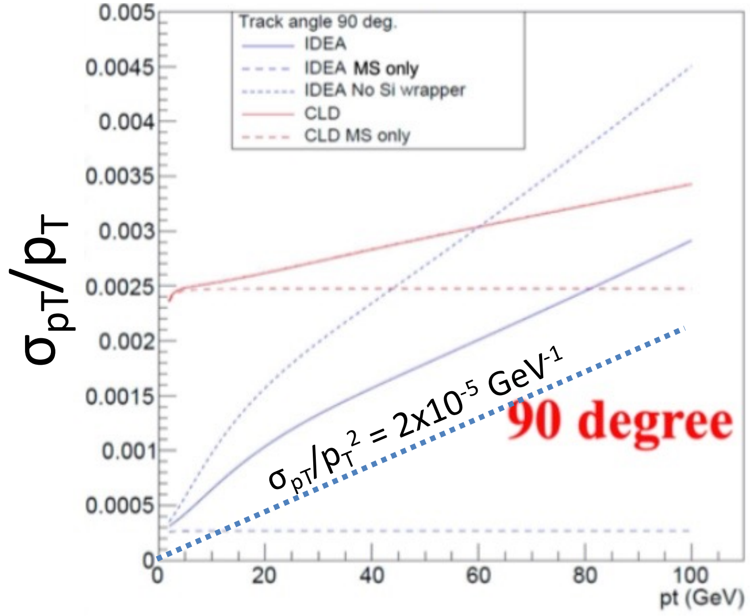


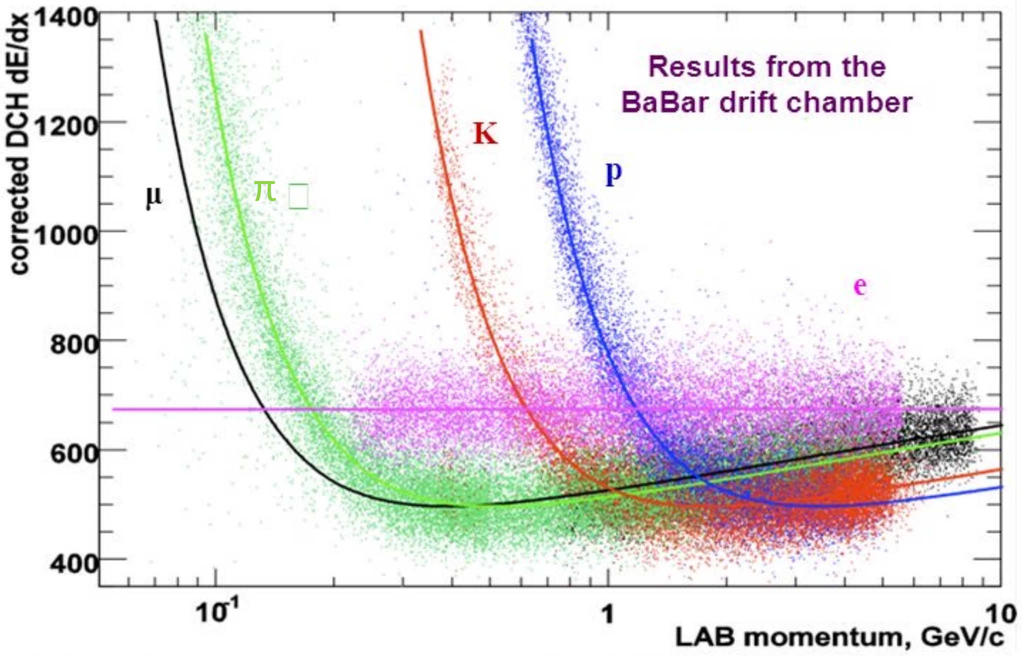


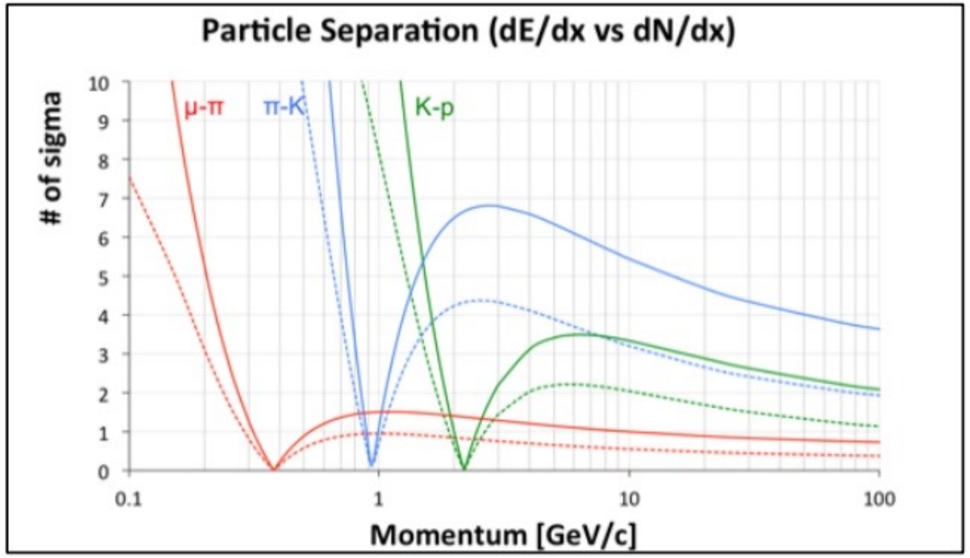


Drift Chamber

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

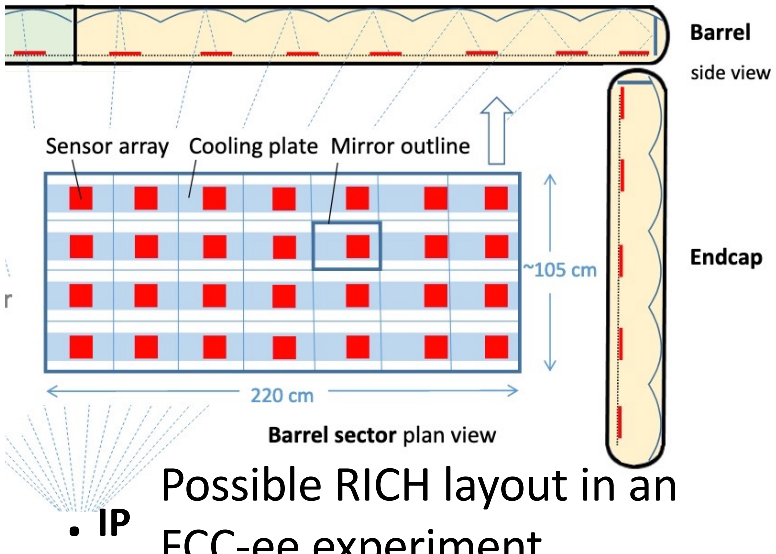




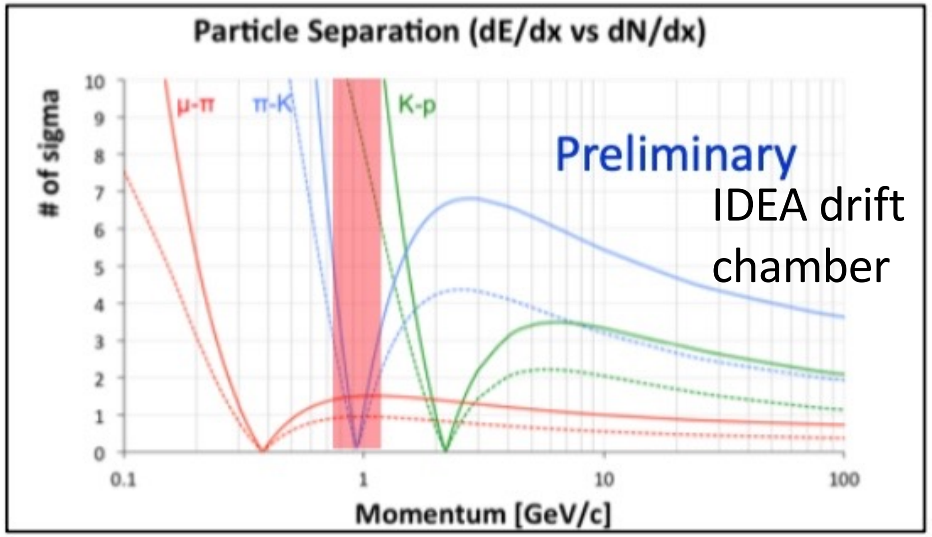


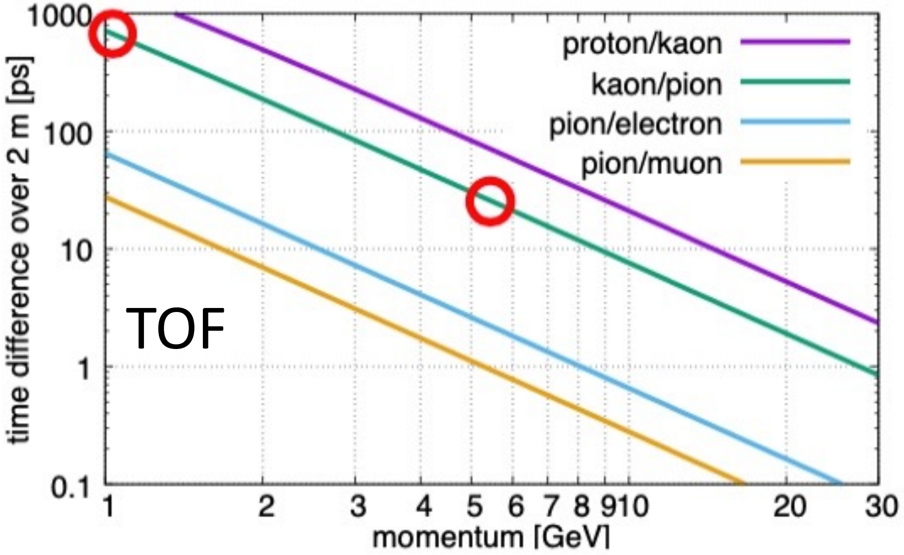
Particle Identification

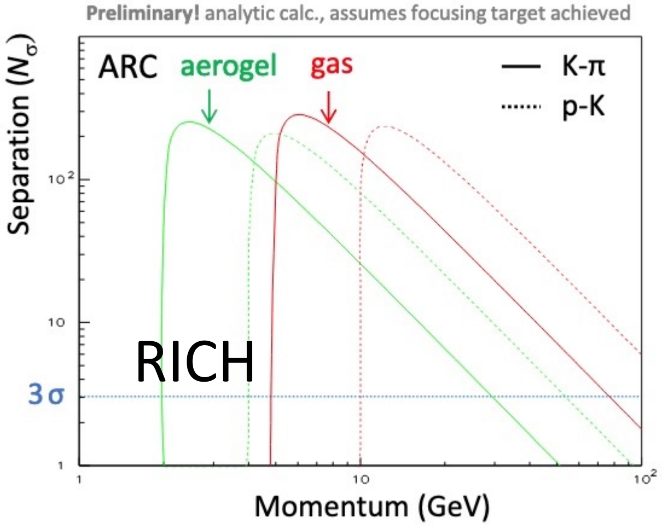
- **PID capabilities across a wide momentum range** is essential for flavour studies and will enhance overall physics reach
  - Example: important mode for CP-violation studies $B^0_S \rightarrow D^{\pm}_S K^{\mp}$
    - Require K/π separation over wide momentum range to suppress same topology $B^0_S \rightarrow D^{\pm}_S \pi^{\mp}$
- **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
  - Example: A pressurized RICH Detector (ARC) as presented at FCC-Week 2021,
  - → could give 3σ π/K separation from 5 GeV to ~80 GeV



Possible RICH layout in an FCC-ee experiment







Solenoid Magnet

Thin solenoid magnet (R=2.2m) as developed for CLD inside calorimeter cryostat (inside or outside ECAL)

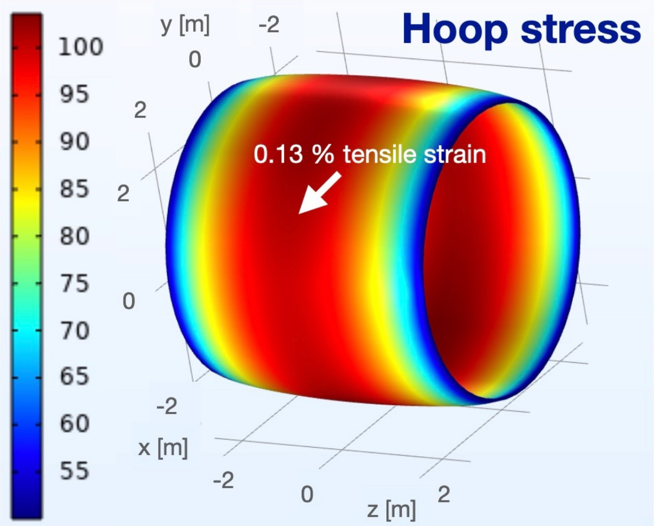
Presentation by N. Deelen at 5th FCC P&E WS

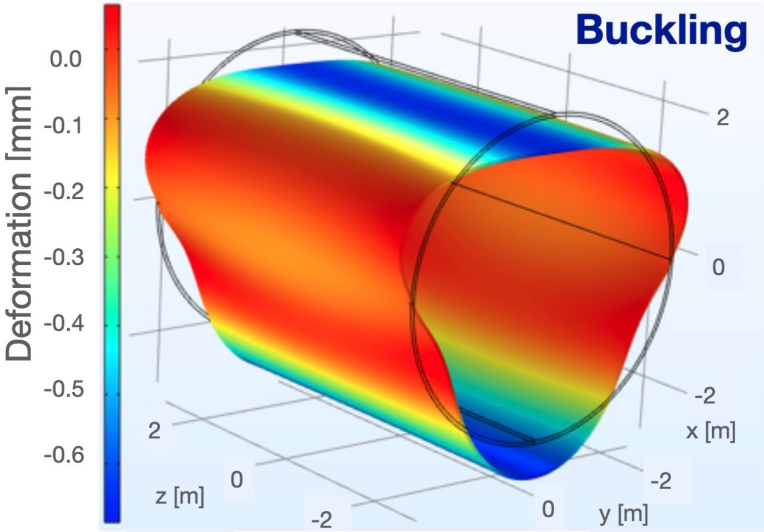
- Support cylinder with thickness of 12 mm
- Support cylinder material: aluminium 5083

Transparency of the cold mass: 0.76 X_0
Energy density: ~14 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 x 10^3	81 x 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

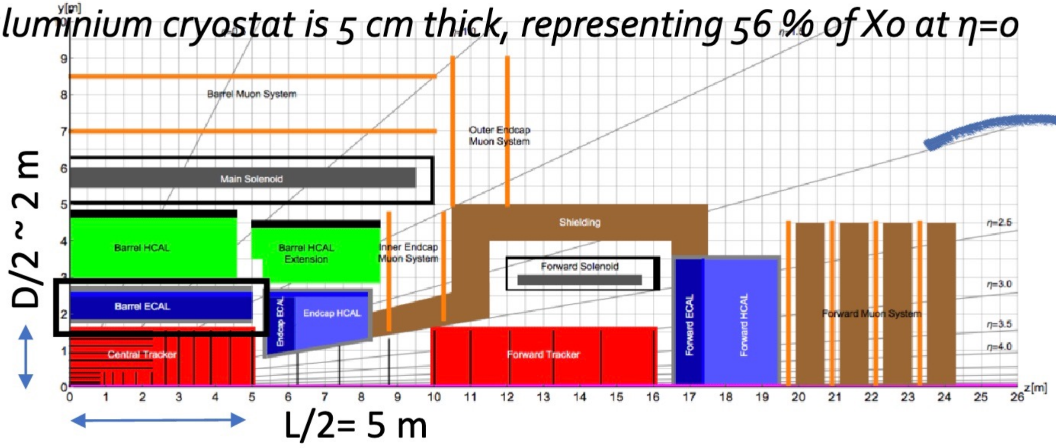
Thin cryostats (carbon fibre or honeycomb) under study, see presentation by M. Soledad

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 Xo at η=o

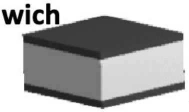
hh collisions



D/2 ~ 2 m

L/2= 5 m

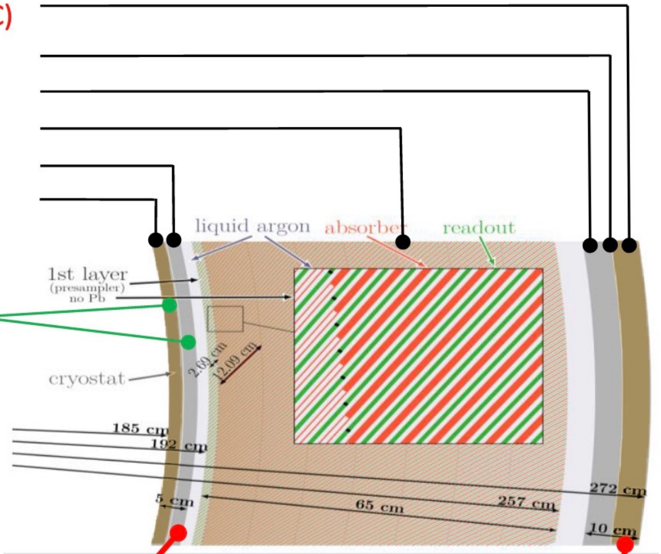
Sandwich



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/Xo	0.03	0.043	0.094	0.17	0.092	0.12	0.34	0.44
Xo % 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%



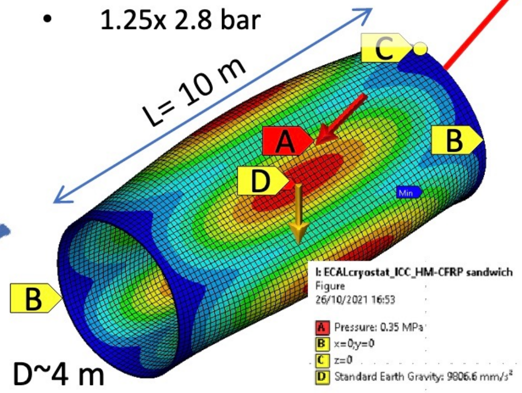
Outer warm cylinder (OWC)
Insulation vacuum
Outer cold cylinder (OCC)
LAr ECAL
Inner cold cylinder (ICC)
Inner warm cylinder (IWC)

Minimum material budget

Buckling resistance

FEM loads ICC:

- 1.25x 2.8 bar

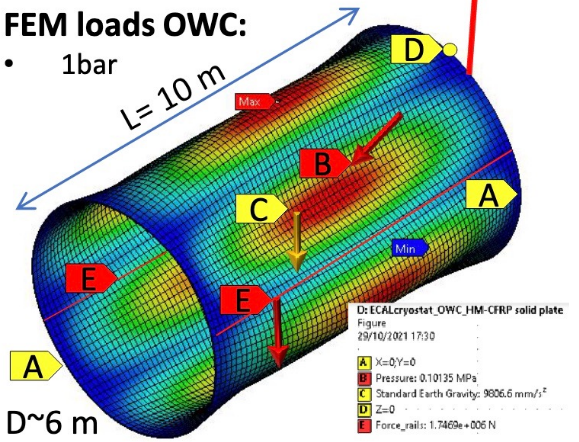


I: ECALcryostat_ICC_HM-CFRP sandwich
Figure
26/10/2021 16:53

A	Pressure: 0.35 MPa
B	x=0;y=0
C	z=0
D	Standard Earth Gravity: 9806.6 mm/s²

FEM loads OWC:

- 1bar

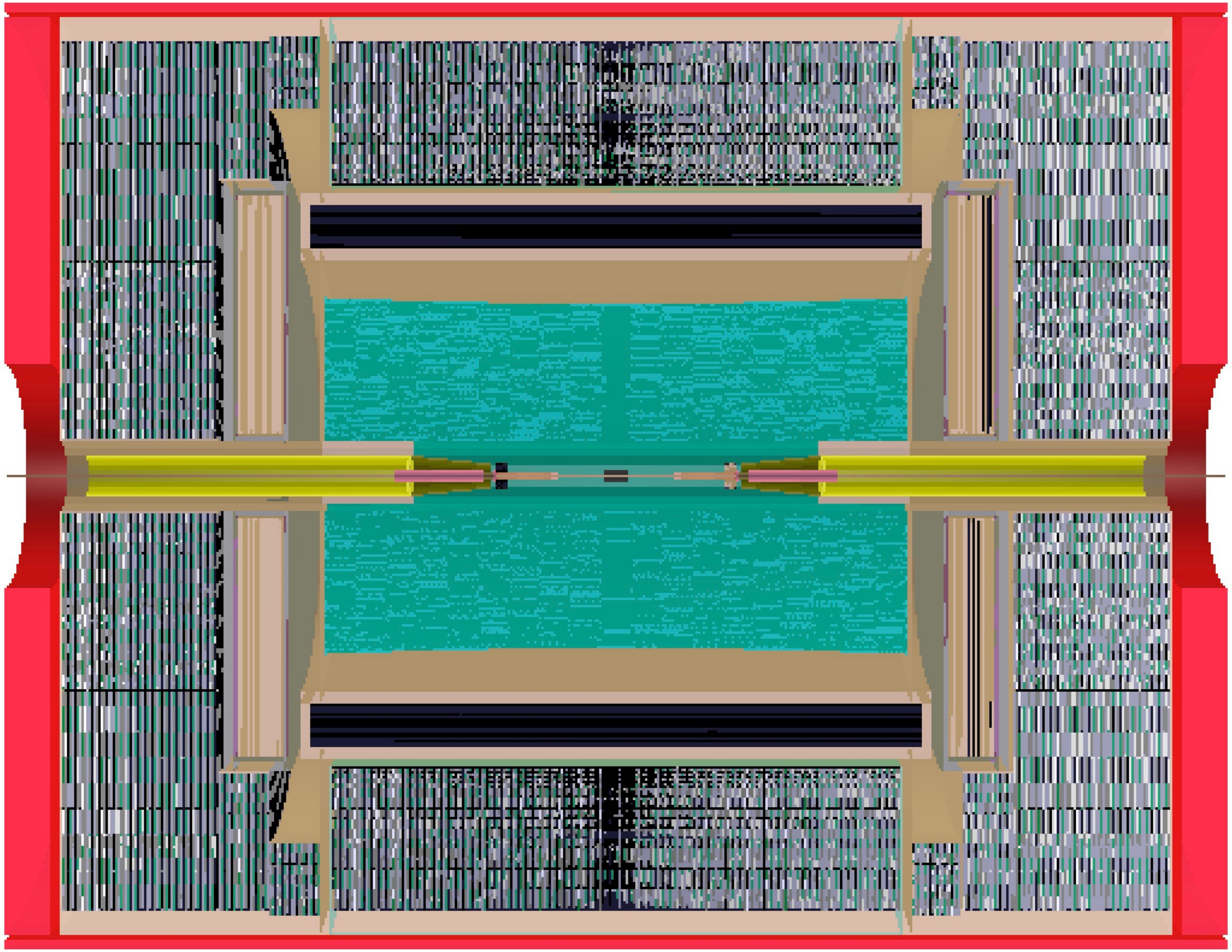


D: ECALcryostat_OWC_HM-CFRP solid plate
Figure
29/10/2021 17:30

A	X=0;Y=0
B	Pressure: 0.10135 MPa
C	Standard Earth Gravity: 9806.6 mm/s²
D	Z=0
E	Force_rails: 1.7469e+006 N

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

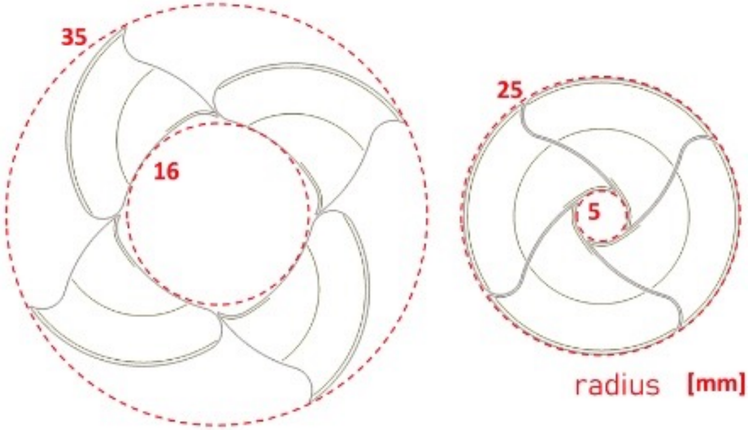
- Presented **first ideas of new detector concept** using highly granular noble-liquid calorimeter
- Aimed to include **thin 2T solenoid** in the calorimeter cryostat.
  - Solenoid inside the calorimeter or between ECAL and HCAL
- Currently **scintillator/iron HCAL,** but option with **ECAL and HCAL 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!**

BACK-UP

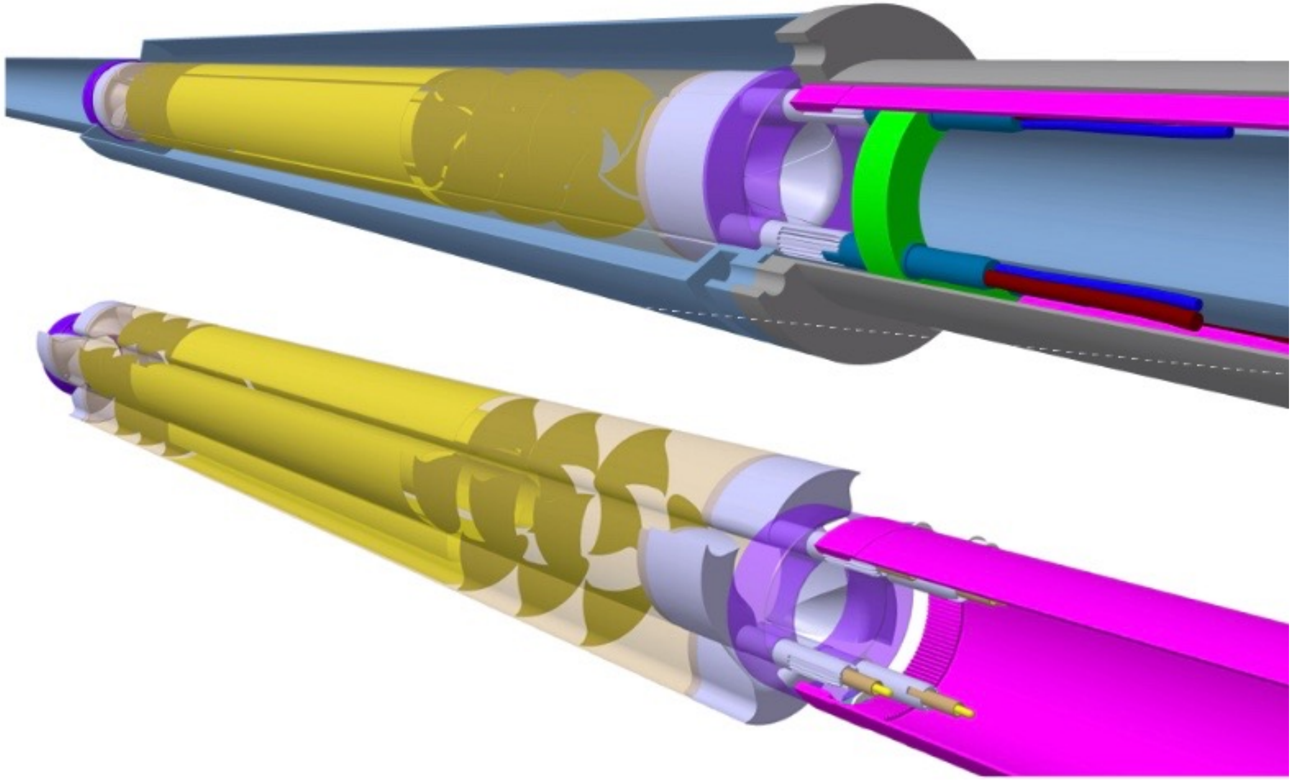
… Coming Even Closer to the Beam?

- **ALICE 3 IRIS vertex detector** (see VCI talk and presentation by C. Gargiulo at GranuLAr WS)
  - Approaching beam to 5mm radius
- FCC-ee will do top-up injection every ~40s → not clear whether fast movement feasible (alignment?)
- Synchrotron radiation needs to be evaluated
- Also higher modes to be checked

Conceptual study for ALICE 3
- wafer-sized, bent MAPS
- rotary petals for secondary vacuum
  - (thin walls to minimise material)
- matching to beampipe parameters
  - (impedance, aperture, ...)
- feed-throughs for power, cooling, data



ALICE 3



FCC-hh Hadronic Calorimeter Barrel (HCAL)

Barrel HCAL:

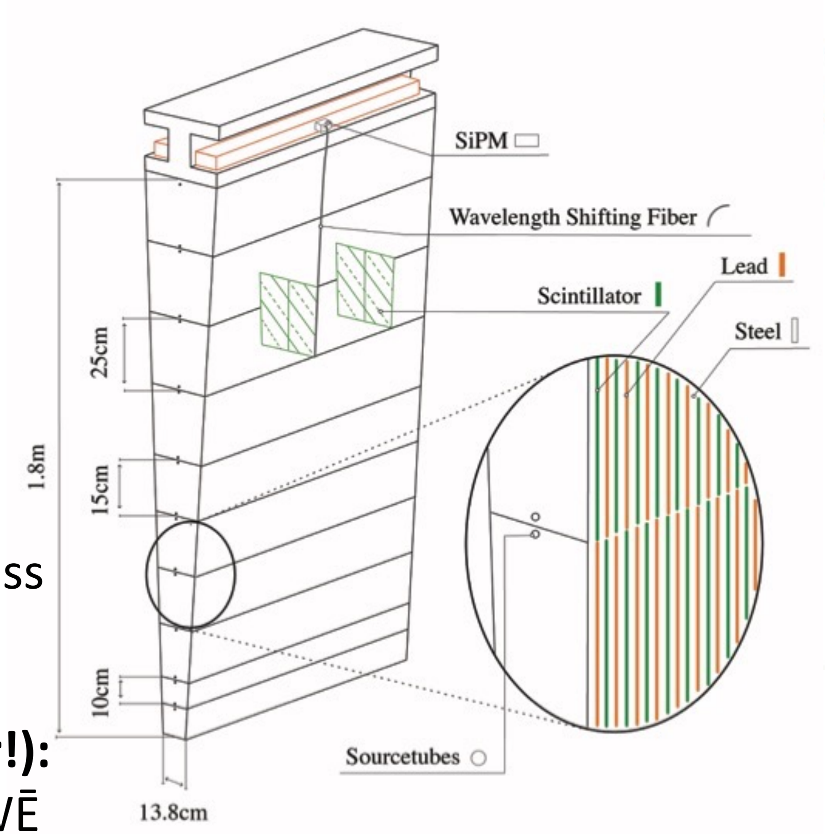
- ATLAS type
  - Scintillator tiles – steel
- **Higher granularity** than ATLAS
  - $\Delta\eta \text{ x } \Delta\phi = 0.025 \text{ x } 0.025$
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less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

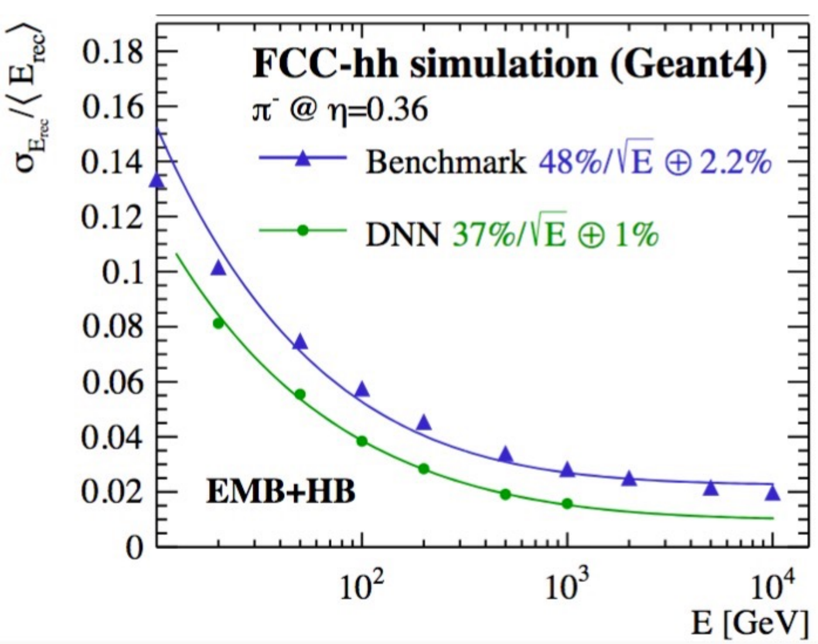
Combined pion resolution (w/o tracker!):

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

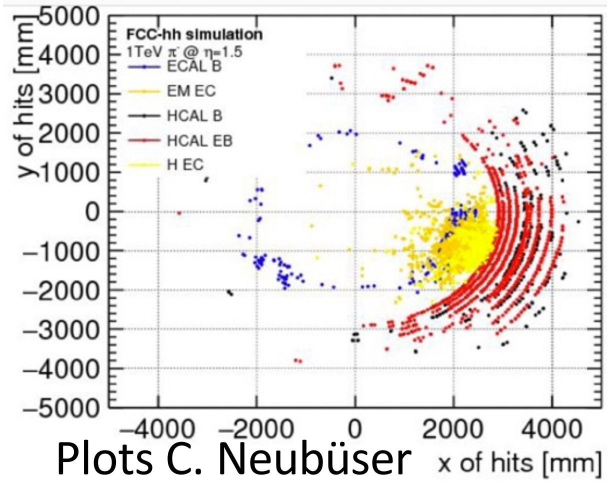
Jet resolution:

- 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