Noble Liquid Calorimetry for a Future FCC-ee Experiment

Brieuc François (CERN) on behalf of the
FCC Noble Liquid Calorimetry group

FCC Physics Workshop
Feb. 9th, 2022

FUTURE
CIRCULAR
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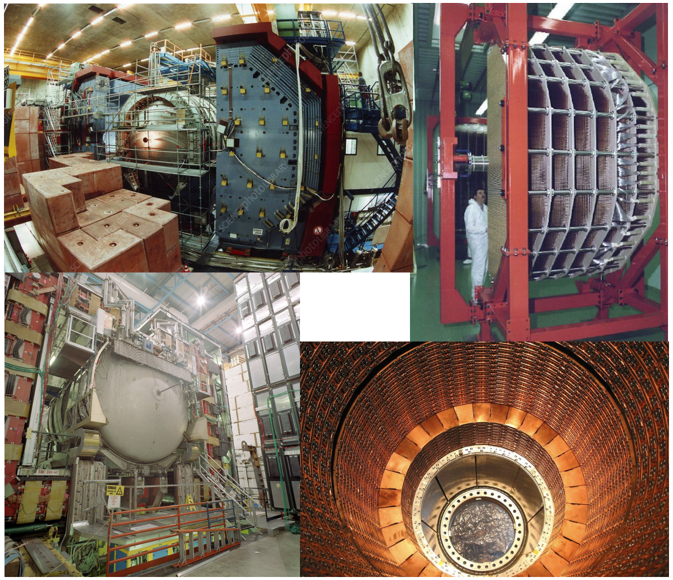
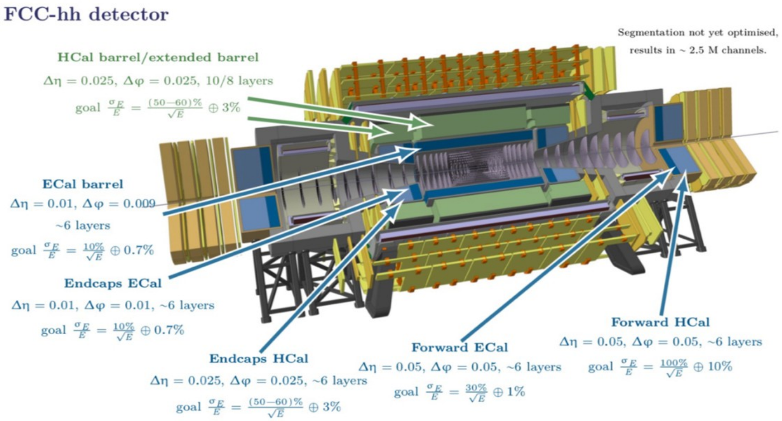
CERN

Outline

- State of the art
  - ATLAS LAr calorimeters
- Future readout electrode and electronics
  - X-talk and noise
- Connector-less feedthroughs
- Light-weight cryostat
- Software and performance studies

Introduction



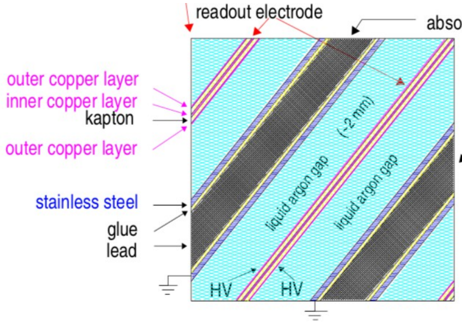


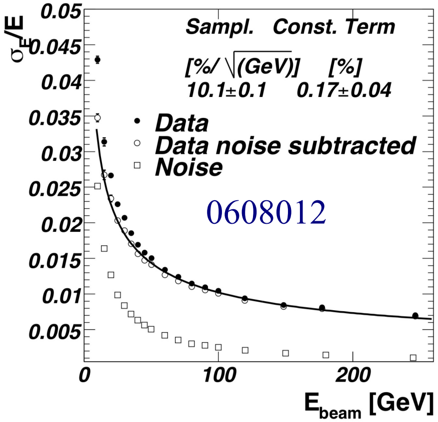
- Noble Liquid Calorimetry is a well proven technology
  - Successful operation in D0, H1, NA48/62, ATLAS, …
- Baseline scenario for FCC-hh ECAL + Hadronic Endcap/Forward and LHeC ECAL
  - Radiation hardness, …
- Why is it also a very interesting option for FCC-ee?
  - Good energy/timing resolution
  - Long term stability, linear response, uniformity
    - **High control over systematics!**
- Important R&D directions for FCC-ee
  - Optimization for particle flow reconstruction on top of conventional calorimetry
    - **Higher granularity**: challenging signal extraction, cross-talk mitigation
  - **Noise reduction**: readout electrode optimization, detailed Front End studies
  - Minimization of radiation length before sensitive area: **light-weight cryostat**

State of the Art

- ATLAS LAr sampling calorimeter: lead absorbers, LAr active gaps, Kapton electrodes with accordion geometry, everything inside a cryostat bath
- Met the designed energy resolution

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.2\%$$





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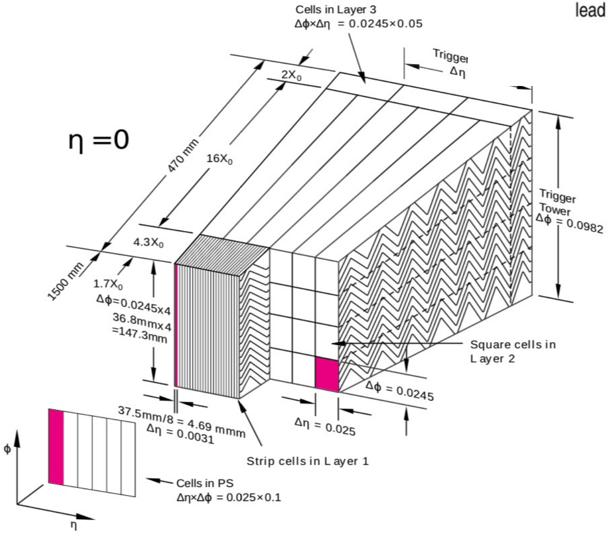

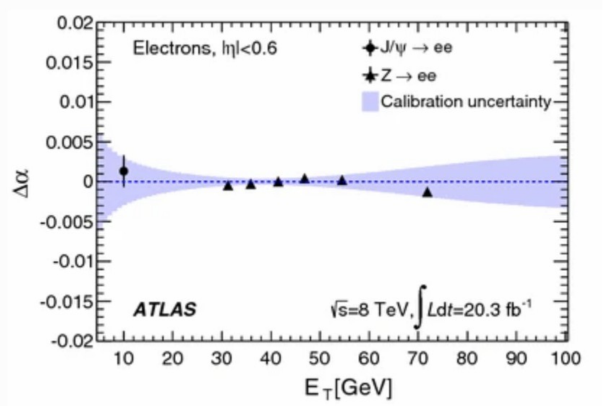

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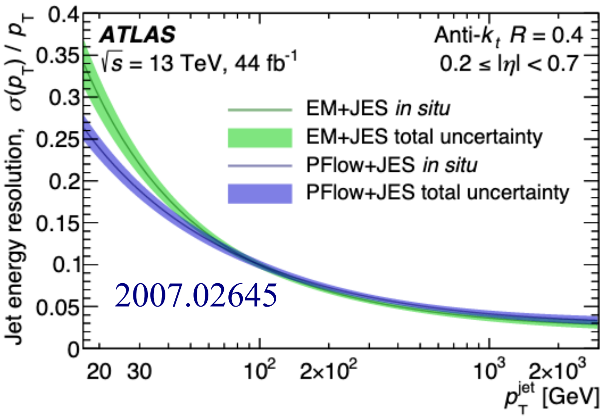
- Linearity: energy scale variation within ~10^{-3} over large E_T range
- Energy response stable at ~10^{-4} level over a year
- Limited Particle flow performances



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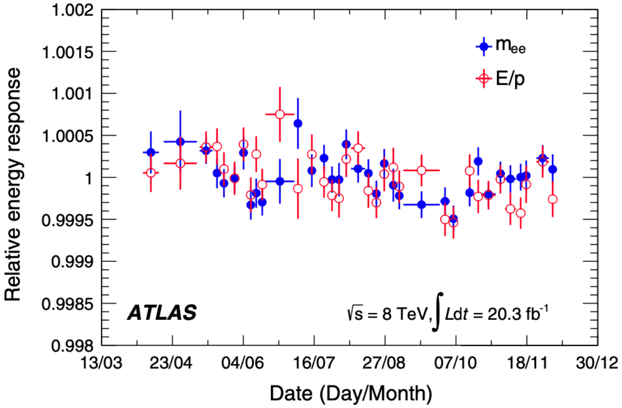
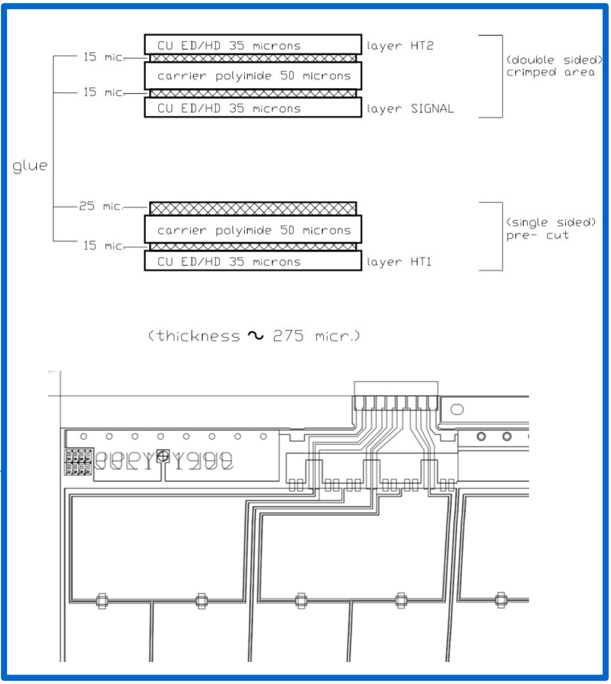
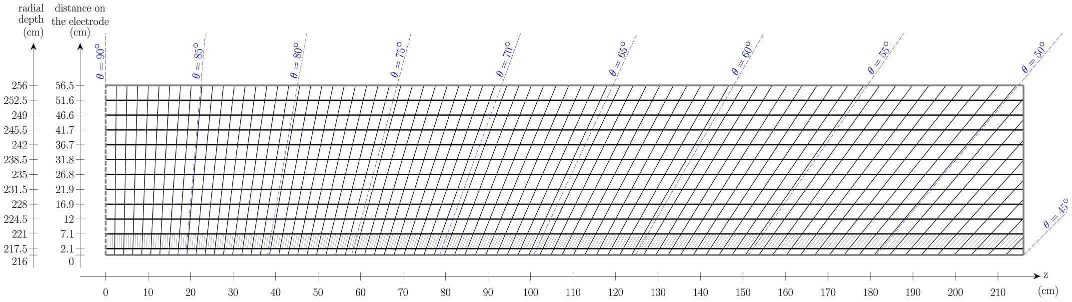


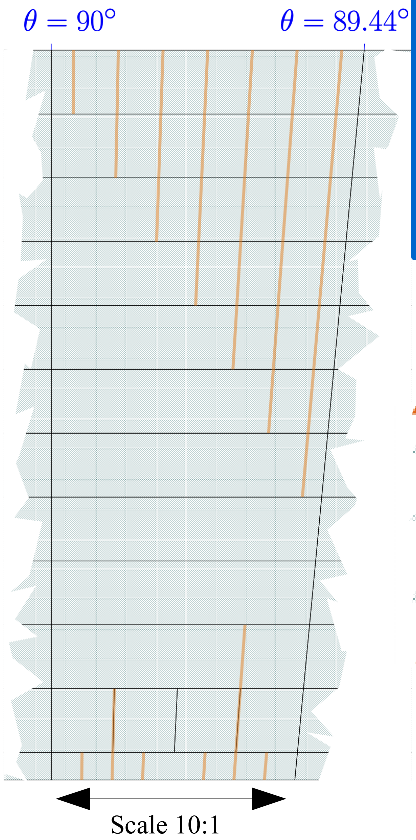
Readout Electrode Design

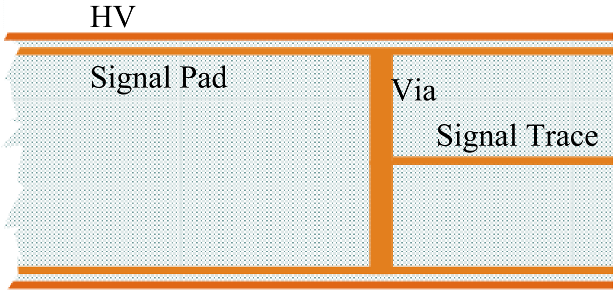
- ATLAS granularity limited by the trace density
    - Only one signal layer → traces routed via the edge of the cells
- Multi-layer PCB electrodes → traces can be routed on a different layer, running beneath other cells
    - FCC-ee design: 12 longitudinal compartments
    - Capacitive coupling between signal trace and other cells signal pads → X-talk has to be studied carefully

ATLAS





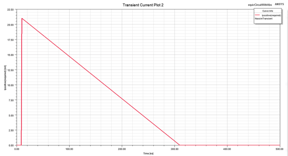




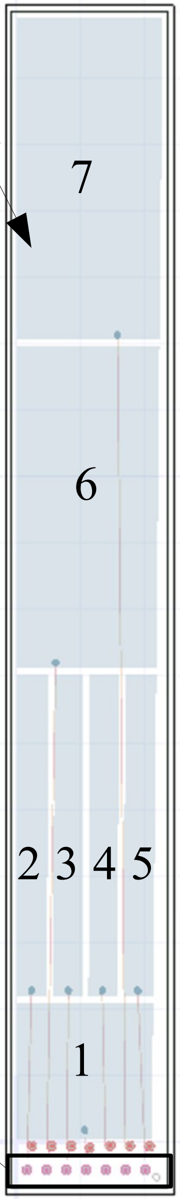
Cross-talk Estimation

- Implementation of a full readout electrode 'theta tower' in FEM tools
  - Ansys HFSS 3D layout → Scattering parameters → equivalent circuit → Ansys circuit for signal studies
  - Capacitive X-talk derived for different ground shield scenarios
    - 0 shield: 12%, 1 shield: 6%, **2 shields: 2% X-talk**
    - Cross-checked with a purely analytical x-talk derivation showing reasonable agreement (slightly lower values)

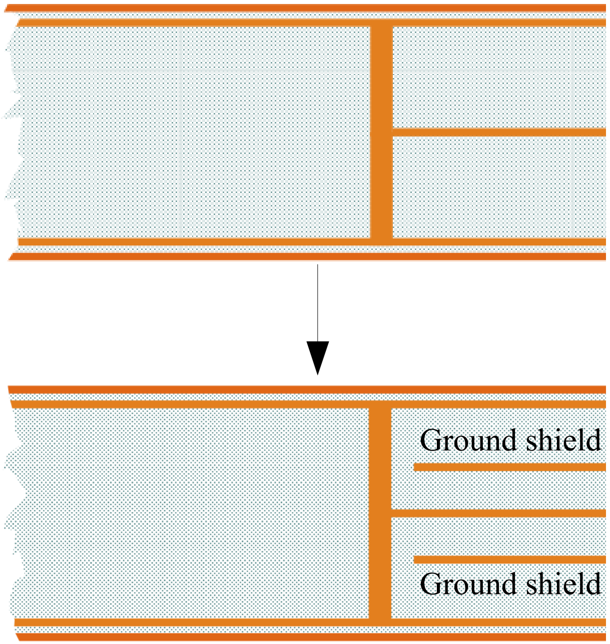
Peak to peak current, real values including shaper should be below



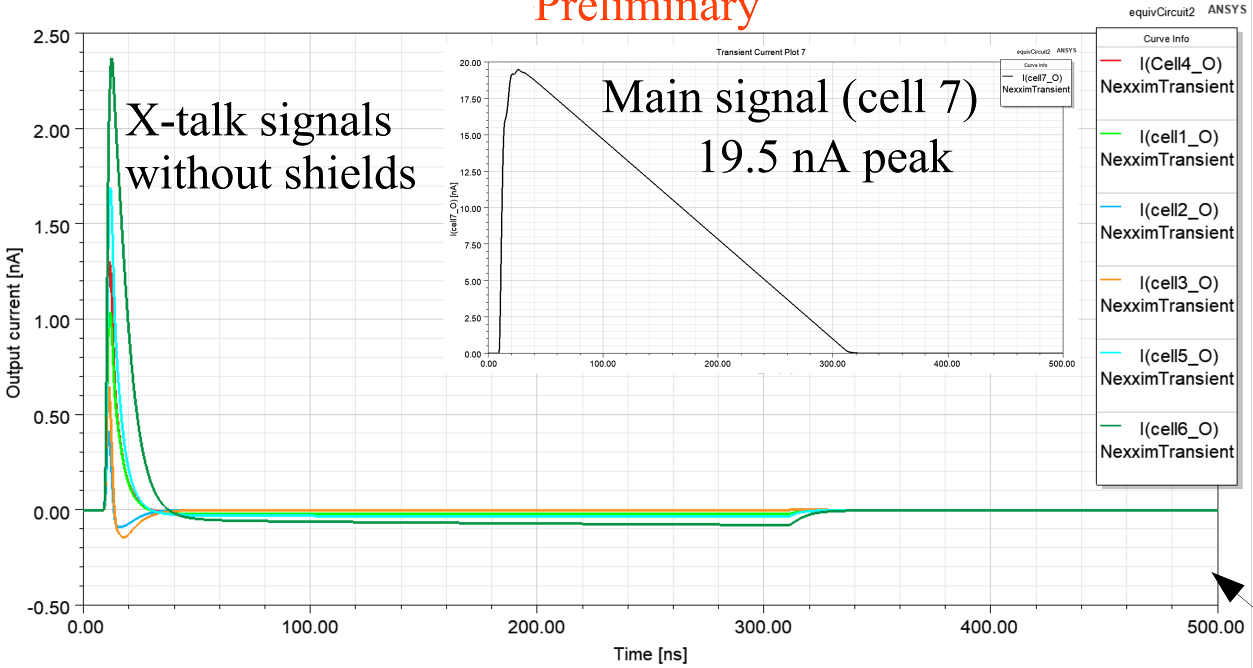
Injected signal Triangular 21 nA peak



Output signals



Preliminary



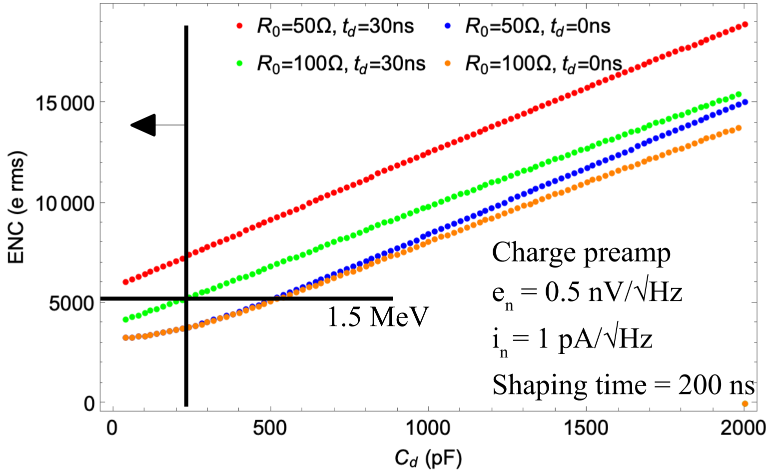
X-talk signals without shields

Main signal (cell 7) 19.5 nA peak

Noise estimation

- The shields increase cell capacitance to ground → noise has to be evaluated precisely
  - Previous noise estimate obtained by scaling ATLAS values to our capacitances
  - New prescription based on a complete readout chain analytical implementation (pre-amplifier and shaper, w/ or w/o transmission line)
    - Many handles to reduce the noise
      - No 'pile-up noise' at FCC-ee → longer shaping time can be envisaged (200 ns here)
      - TL impedance, 'warm' or 'cold' electronics, cell merging scenario, number and width of ground shields, signal extraction scheme, …
    - **MIP signal over noise > 5, per cell, can be achieved!**

Noise vs detector capacitance



1.5 MeV

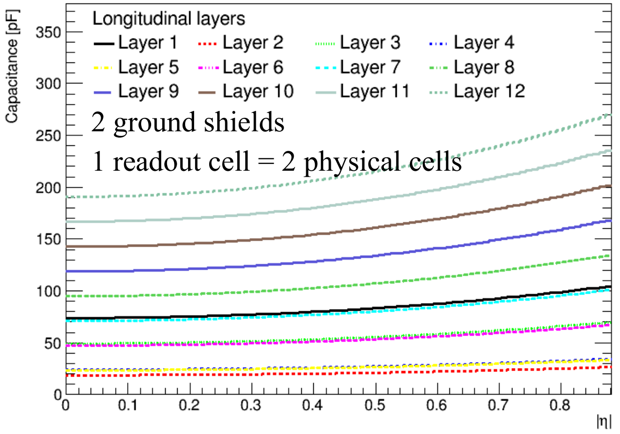
Charge preamp

$e_n = 0.5\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$

$i_n = 1\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$

Shaping time = 200 ns

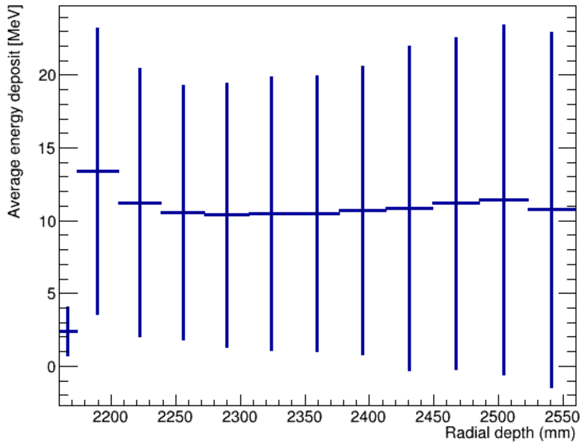
Total capacitance



2 ground shields

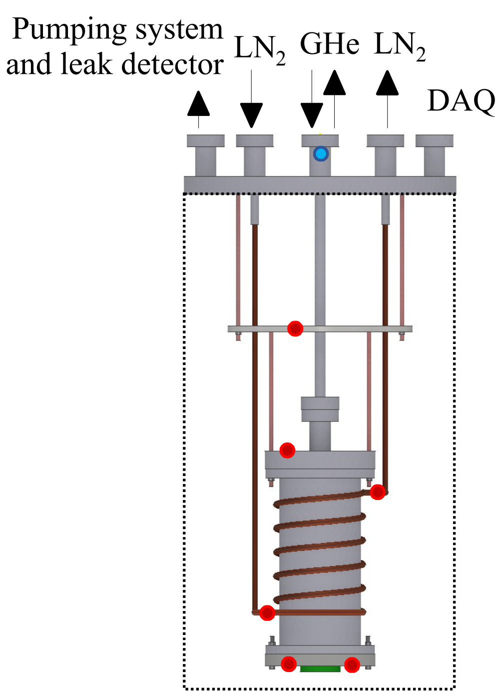
1 readout cell = 2 physical cells

MIP energy deposit per layer

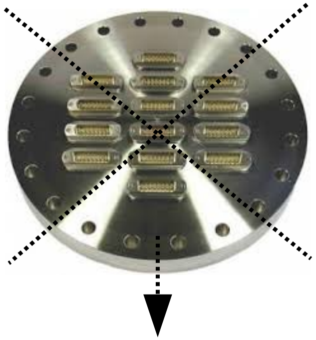


High Density Feedthroughs

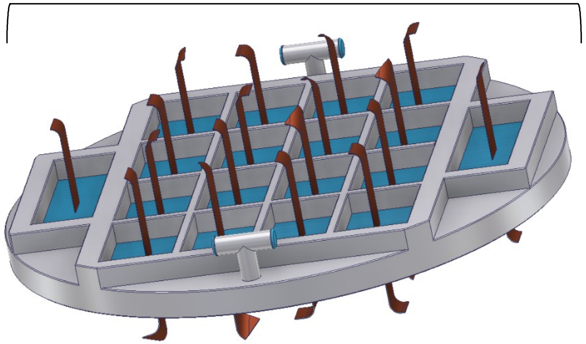
- Factor **10-15** more granular than ATLAS → **more channels to extract from the cryostat** (ECAL barrel ~2 M)
- If the electronics sits outside of the cryostat (warm electronics), one needs high density feedthroughs
- R&D ongoing (CERN) for innovative **connector-less feedthroughs**
  - High density 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 – glued to the flange
    - 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)
- Working now on a full flange design

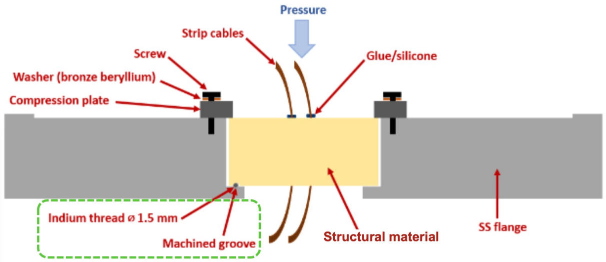


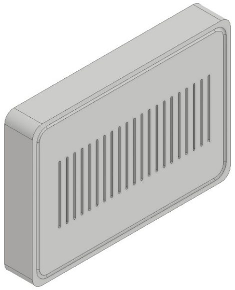
Experimental setup

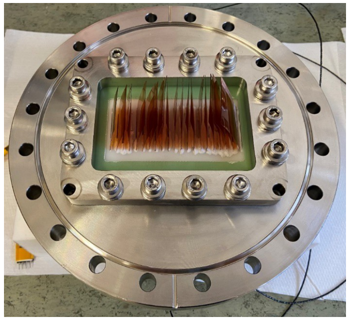


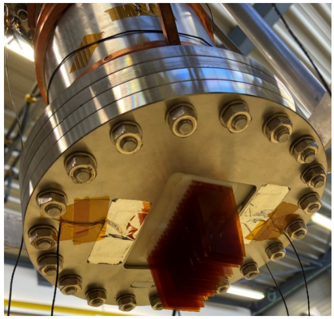
Conceptual high-density flange







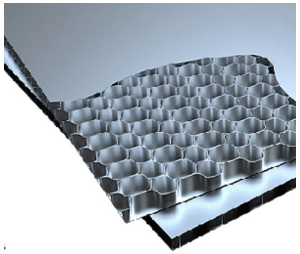


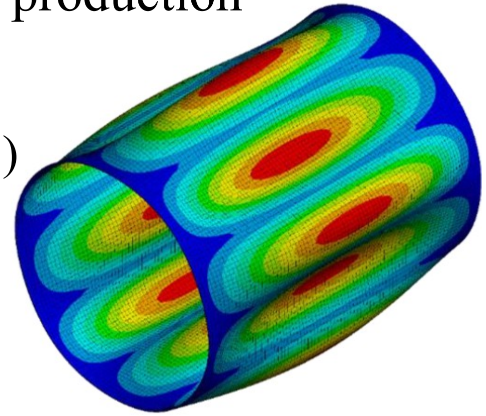


Maria Asuncion Barba Higueras

Lightweight cryostat

- FCC-ee physics program requires to detect very low energy particles (300 MeV) → one has to **minimize dead material budget** before sensitive areas
- Ongoing CERN R&D on **low mass cryostat**
  - Solid (plain) shell or honeycomb sandwich
  - Aluminum or Carbon Fibre Reinforced Polymer (CFRP)
- Small scale CFRP prototype produced and validated (leak-tight at 112 K)!
- Now working on manufacturing process for larger scale production
- Even more to gain w.r.t. material budget
  - Same cryostat for the Calo and the Magnet (as in ATLAS)
  - Thin superconducting solenoid (see next talk!)





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/X0	0.03	0.043	0.094	0.17	0.092	0.12	0.34	0.44
X0 % 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%
	Promising R&D		Baseline		Prototype		ATLAS	

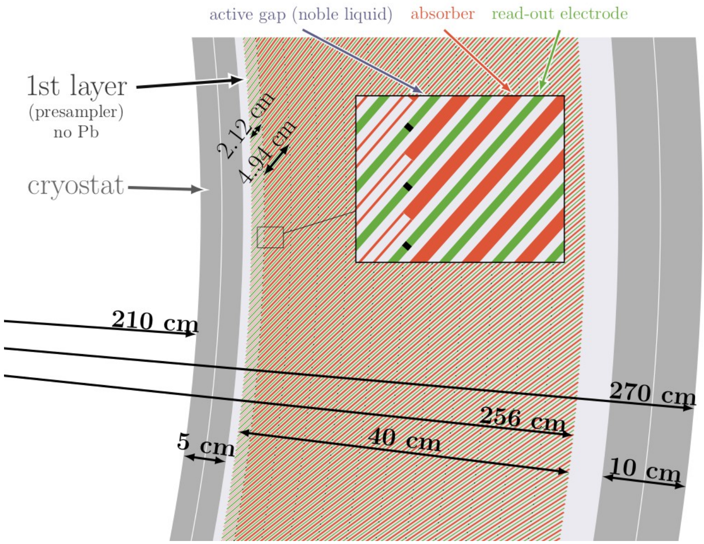
Radiation length X_0[mm]
Al = 88.9
HM CFRP = 260
Honeycomb Al= 6000

CFRP: Carbon Fibre Reinforced Polymer
OWC: Outer Warm Cylinder
ICC: Inner Cold Cylinder
Al: Aluminum

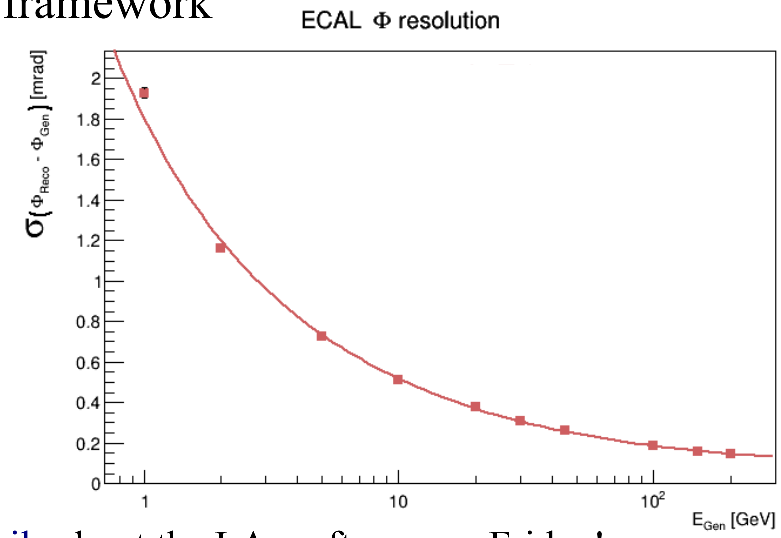
Maria Soledad Molina Gonzalez

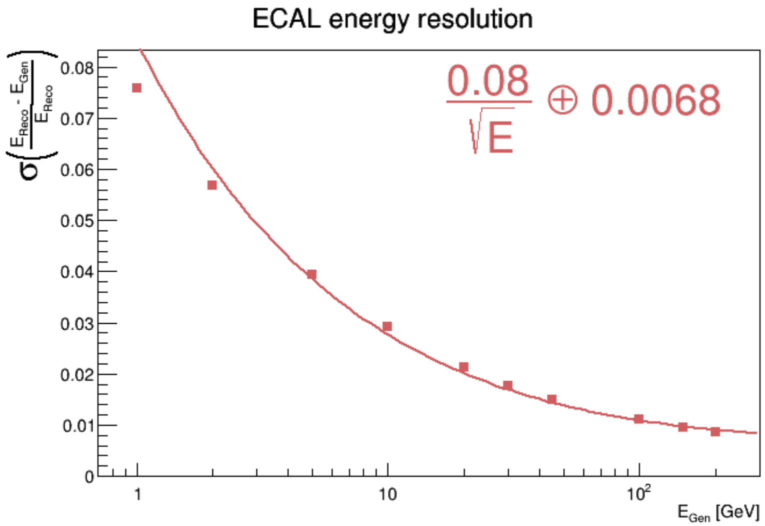
Full Sim & Performance (I)

- The FCC-ee ECAL barrel geometry has been implemented in FCCSW (DD4hep)
  - 12 longitudinal layers
  - Conservative benchmark: 1536 phi cells (2x1.2 mm LAr + 2 mm Pb/Steel + 1.2 mm PCB), inclined plate (50°), Aluminum cryostat, 40 cm depth sensitive area, 22 X_0 in total
  - Typical readout cell size: $\theta \times \Phi \times r \sim 2$ (0.5 strip) x 1.8 x 3 cm^3



- Everything was ported to Key4Hep* (reconstruction, clustering algorithms, dead material corrections, …)
  - First Full Sim performance results produced within this framework



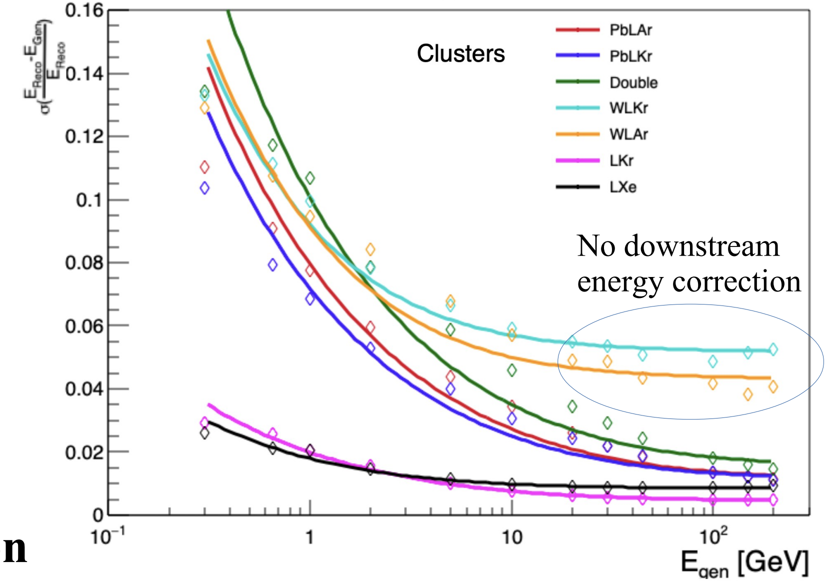


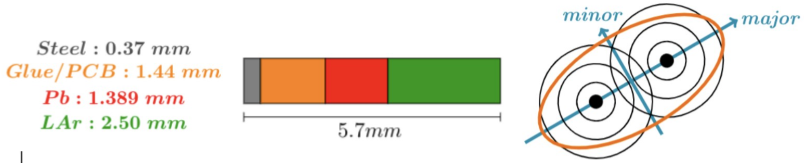
*More details about the LAr software on Friday!

Full Sim & Performance (II)

- Performance studied for **different absorber/Noble Liquid scenarios** with, in most cases:
  - Absorber/sensitive thicknesses kept untouched
  - Calo length adapted to have ~ 22 X_0 in each scenario
- τ polarization measurements ($\sin^2(\theta_W)$ and lepton universality)
  - Precision measurements need **τ final state categorization**
  - Studied in a simplified geometry (concentric cylinders) – no strip layer (pessimistic)
    - LAr + Pb (R_M=4.1 cm), cell size 2 x 2 x 4 cm^3
  - $e^+ e^- \rightarrow Z \rightarrow \tau^+ \tau^-$, one τ forced into μ channel
  - Categorization based on π^0 counting
    - γ/π^0 separation from simple cluster shape variables
  - LKr + W scenario (R_M=2.7 cm) shows better performance on π^0 ID
  - Machine learning approach + inclusion of strip layer will further improve these results

Mark Waterlaat



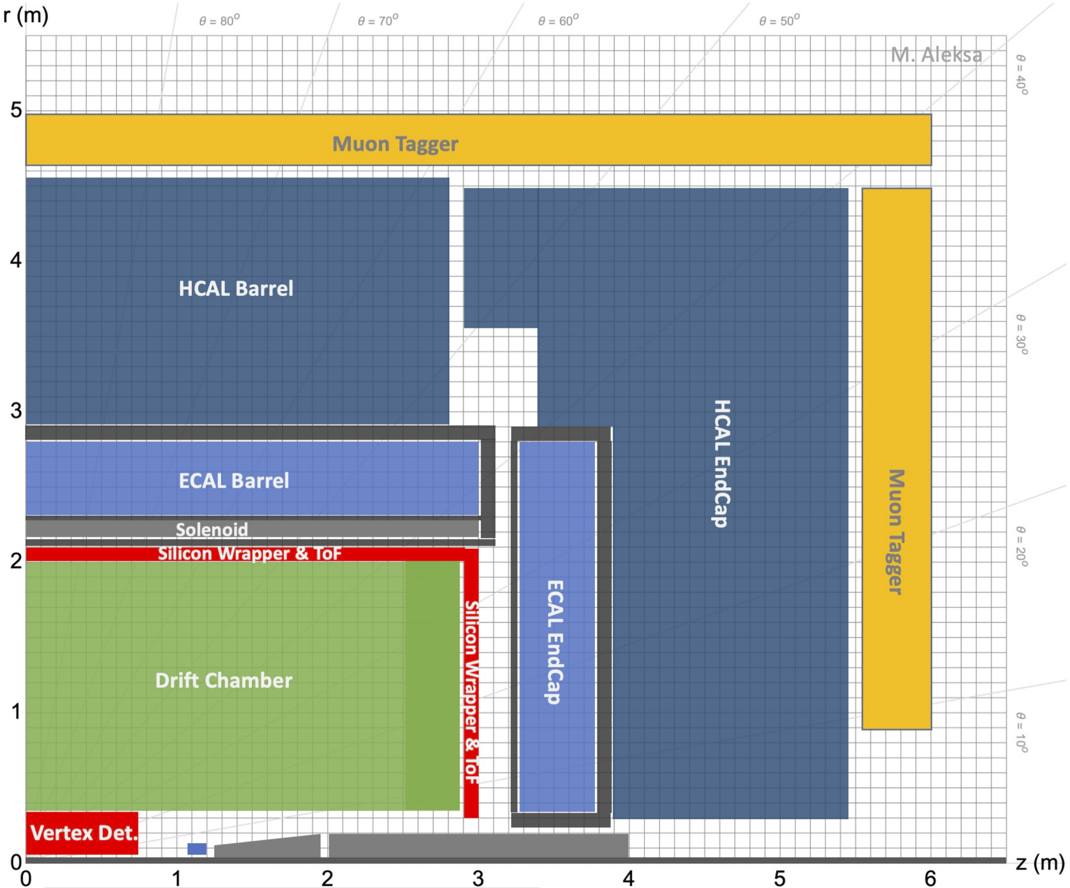


Recon → Gen ↓	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm \pi^0 \nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0 \nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm 3\pi^0 \nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

Katinka Wandall-Christensen and Mogens Dam

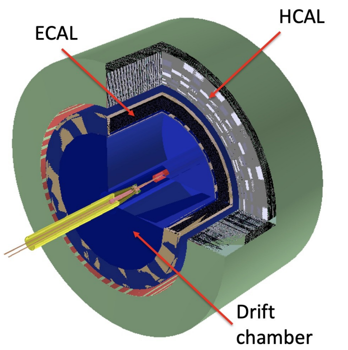
Outlook

- First **PCB prototype** production ongoing
  - Measure cell capacitance, signal attenuation, cross-talk, TL impedance, …
  - Validation of the concept and comparison with simulation results
- Preliminary **full detector concept** under development
  - Will be implemented in FCCSW
- Save the date!
  - **GranuLAr workshop** from 6th to 8th April (starts and ends at noon) at IJCLab – Paris
  - Agenda under construction
- Monthly meeting on Thursday mornings with O(10) people connected and lively discussions!
- A lot of interesting work ahead of us, and a lot of room for significant contribution, **please join**!



Detector Concept

- Vertex Detector:
  - MAPS or DMAPS possibly with timing layer (LGAD)
- Drift Chamber (±2.5m active?) – TPC?
- 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:
  - Scintillator + Iron
    - SiPMs directly on Scintillator or
    - TileCal: WS fibres, SiPMs outside
- Muon Tagger:
  - Drift chambers, RPC, MicroMegas



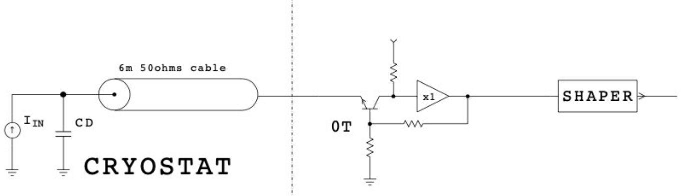
Summary

- Noble Liquid Calorimetry is a key technology for future facilities
- It is presently being ported to high granularity to enhance its Particle Flow Performance
  - PCB design studies show X-talk values ~< 2%
  - MIP S/N of 5 per cell achievable
  - First PCB prototype production ongoing
  - Provided proof of concept for connector-less high channel density feedthroughs
- FCC-ee geometry implemented in FCCSW and ported to Key4Hep
  - First Full Sim performance studies delivered
  - Working on a full detector concept
- Promising R&D
  - Light-weight cryostat
  - Thin magnets

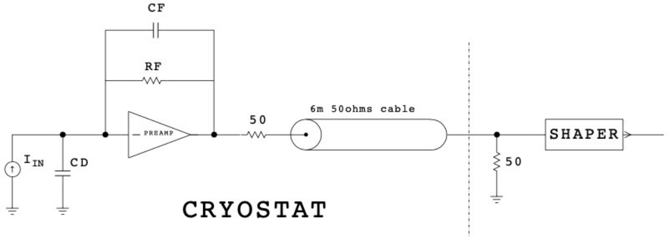
Additional material

Warm or Cold Electronics?

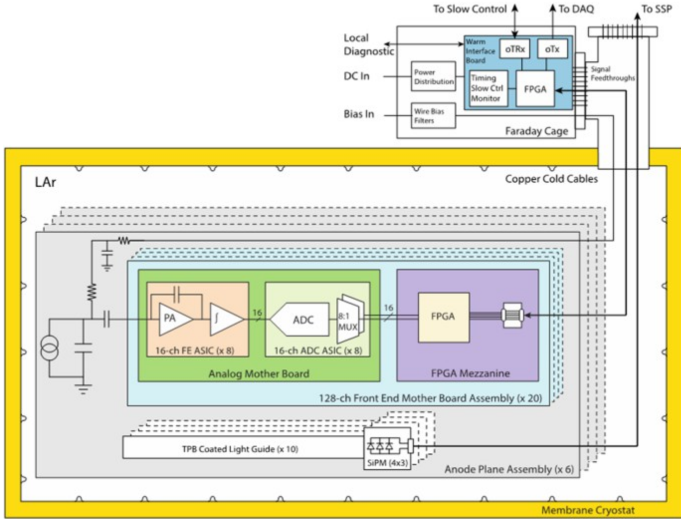
- **Advantages** of placing the front-end inside the cryostat (**cold electronics,** choice for Dune experiment)
  - **Lower noise:** electronics at lower temperature, PA directly connected to the sensor wire (no cable), longer shaping time envisaged
    - Can **easily achieve MIP S/N > 5 per cell**
  - **Eases** the **feedthrough design** (possibility to use optical fibers)
- **Drawbacks**/technical challenges
  - **Difficult maintenance or upgrade** (cryostat opening) → robust electronics + redundancy
  - Minimize **heat dissipation** inside Noble Liquid (low power electronics)
    - Avoid bubbles (electrical breakdown, local change of sampling fraction)
- **Cold electronics is a very interesting option for FCC-ee**
  - Lower radiation + shorter operation time compared to hadron colliders → maintainability and upgradeability less critical
  - Lower electronic noise → ability to detect very low energy particles
- Both options are being considered and studied for now



ATLAS ECAL



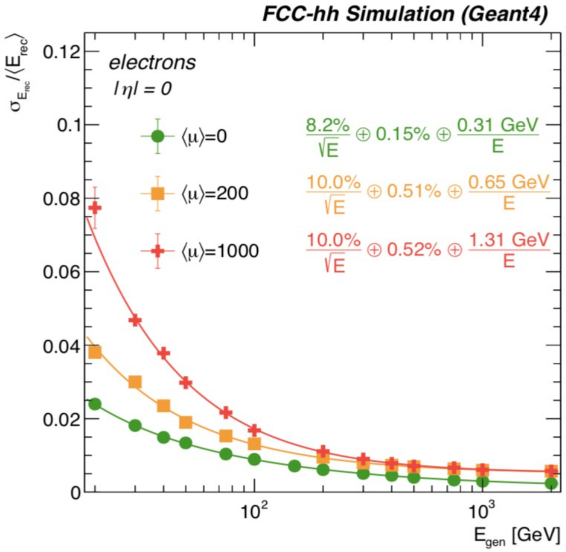
ATLAS Hadronic End Cap



ProtoDUNE

FCC-hh calorimeter

- FCC-hh reference calorimeter inspired by ATLAS Calo and CMS HGCal
    - ECAL, Hadronic Endcap and Forward Calo: LAr/Pb (Cu)
        - Conventional high precision calorimetry made highly granular to allow for 4D imaging and particle flow
        - Barrel ECAL
            - Δη=0.01 (0.0025 strip layer), ΔΦ=0.009, 8 longitudinal layers
            - Meets energy resolution requirements (10%/√E + 0.7%)
    - HCAL Barrel and Extended Barrel: Scintillating tiles/Fe(+Pb) with SiPM
        - Lower radiation behind ECAL barrel, lower cost



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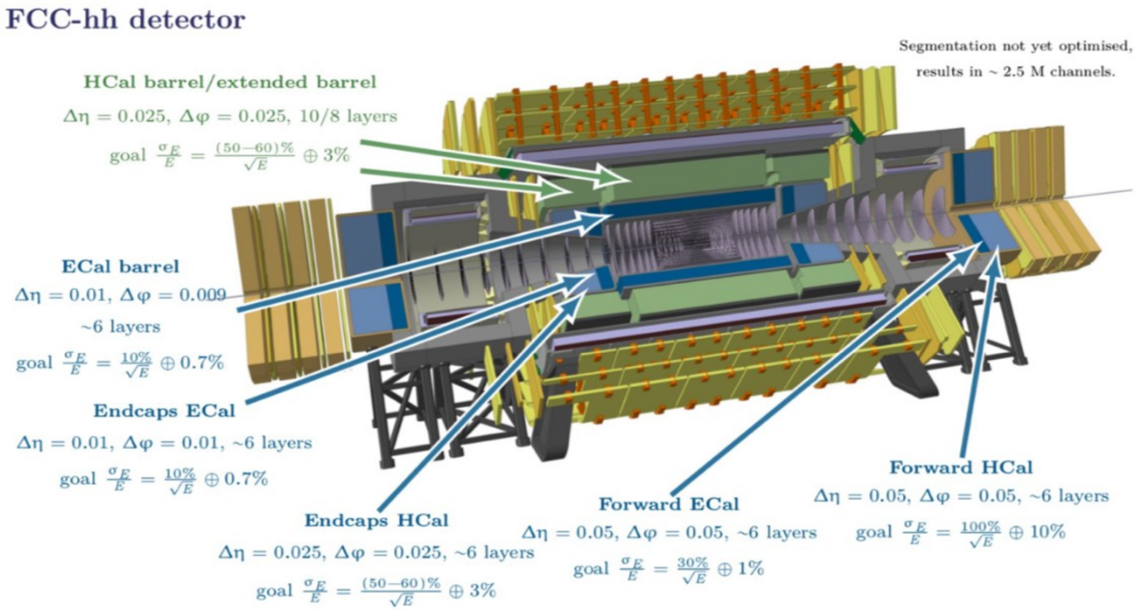
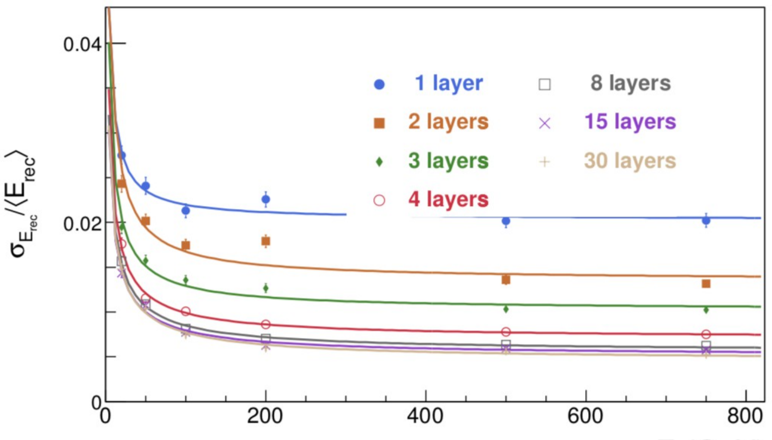

FCC-hh detector

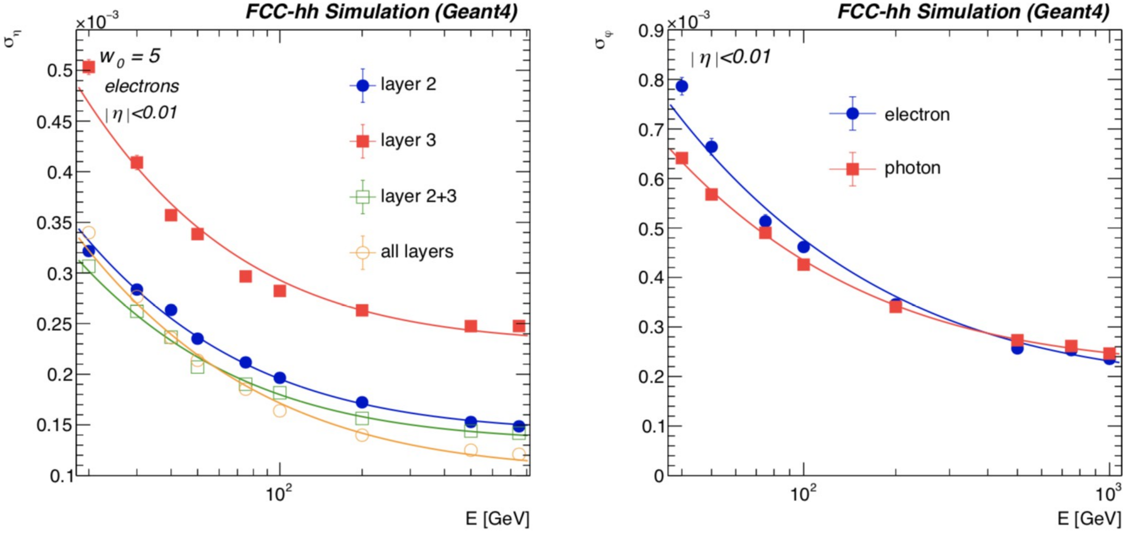
Segmentation not yet optimised, results in ~ 2.5 M channels.



A. Zaborowska

FCC-hh Calorimeter Performance

- Excellent jet energy resolution (30%/√E) needed to separate W and Z decays
    - Already close !
        - 37%/√E achieved for pions in FCC-hh simulations with calo-only information
        - Particle Flow will be used for a more realistic estimation (and will improve)
- Angular resolution



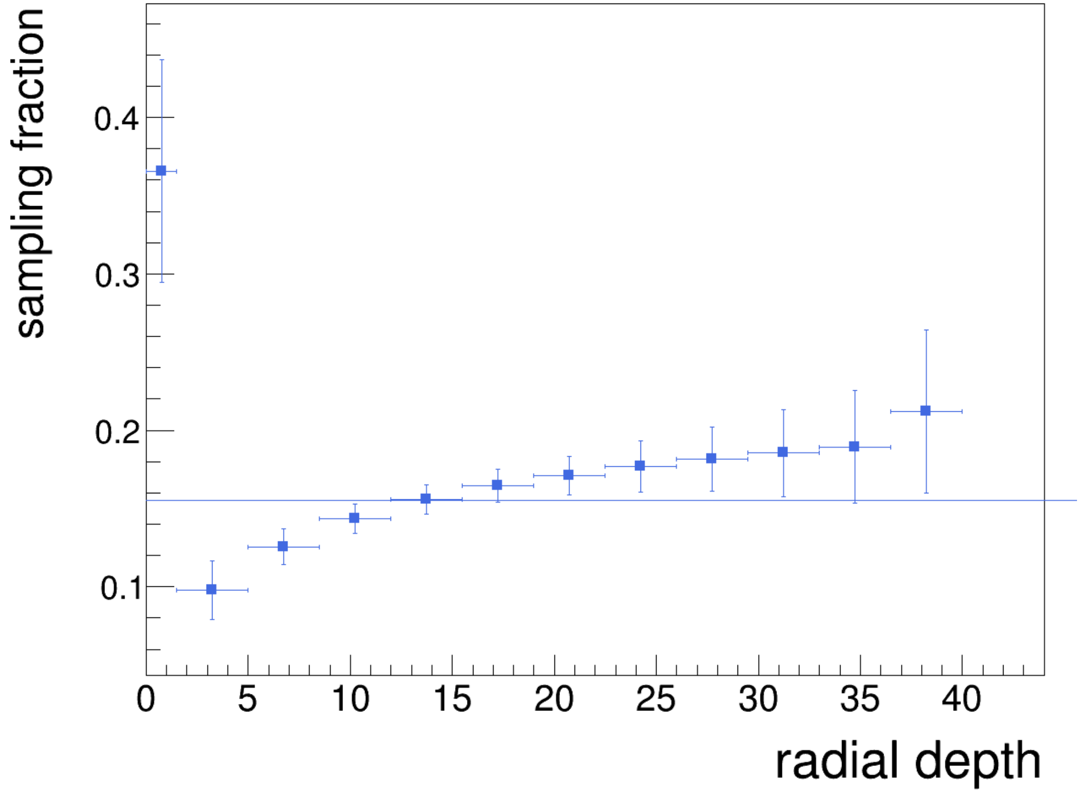
(a)

(b)

Figure 51: (a) Pseudorapidity resolution for two best calorimeter layers: second (red full circles) and third (blue full squares), as well as combined measurements of those two layers (green hollow squares) and from all EMB layers (yellow hollow circles). (b) Azimuthal angle resolution for electrons (blue circles) and photons (red squares).

Sampling fraction

- FCC-ee ECAL barrel sampling fraction per longitudinal layer



Noble Liquid/Absorber study

Absorber	Liquid	Gap size [mm]	Absorber size [mm]	Phi bins	Radial extend [mm]	Radial length 22 X0 [mm]
Pb	LAr	1.239 * 2	1.8	1536, 768, 512, 384, 256	400	
	LAr	3.079 * 2	3.8	768	400	
	LKr	1.239 * 2	1.8	768	400	~337.5
W	LKr	1.239 * 2	1.8	768	~207.5	
	LAr	2.156 * 2	1.8	576	~323.9	
none	LKr (homo)	~4.2	0.001	768	~1034	
	LXe (homo)	~4.2	0.001	768	~647.5	

	Avg sampling fraction
Pb + LAr baseline	0.17
Pb + LKr	0.23
Pb + LAr double	0.17
W + LKr	0.15
W + LAr	0.16
LKr	0.97
LXe	0.97

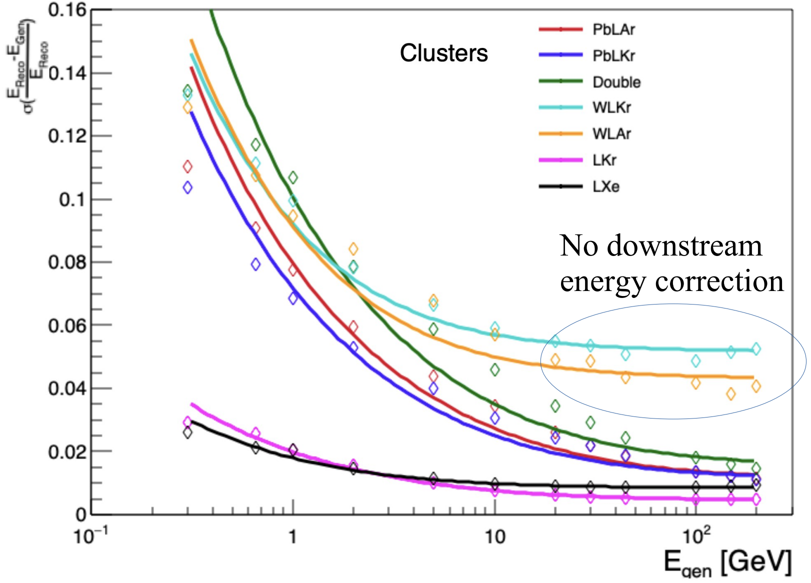
Clusters

	A/E	B/sqrt(E)	C
Pb + LAr	0	0.079	0.011
Pb + LKr	0	0.071	0.011
Double	0	0.099	0.015
W + LKr	0	0.075	0.052
W + LAr	0	0.086	0.041
LKr	0	0.019	0.005
LXe	0	0.016	0.008

Cells

	A/E	B/sqrt(E)	C
Pb + LAr	0	0.077	0.021
Pb + LKr	0	0.070	0.050
Double	0	0.098	0.027
W + LKr	0	0.083	0.050
W + LAr	0	0.085	0.041
LKr	0.004	0	0.008
LXe	0	0.007	0.010

Mark Waterlaat

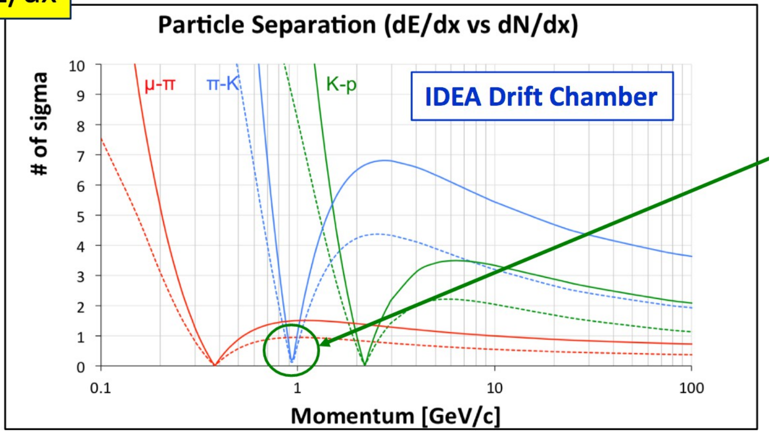


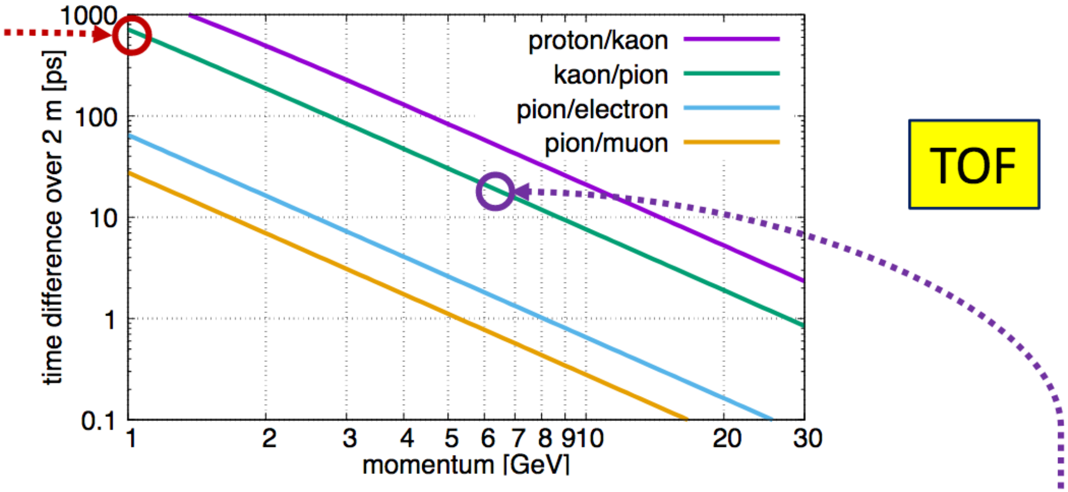
No downstream energy correction

Particle ID

- dE/dx or dN/dx performs very well for particle ID, except in a few points where timing could help (low energy)

dE/dx





TOF

FCC-ee CDR detector concepts

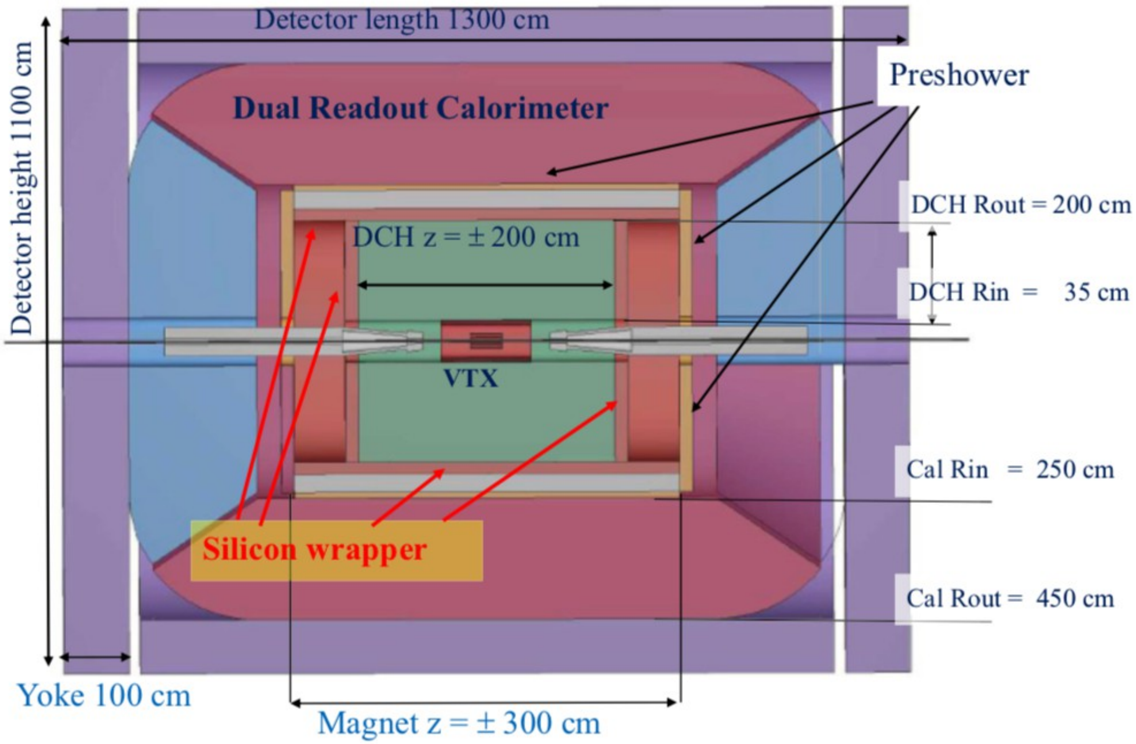
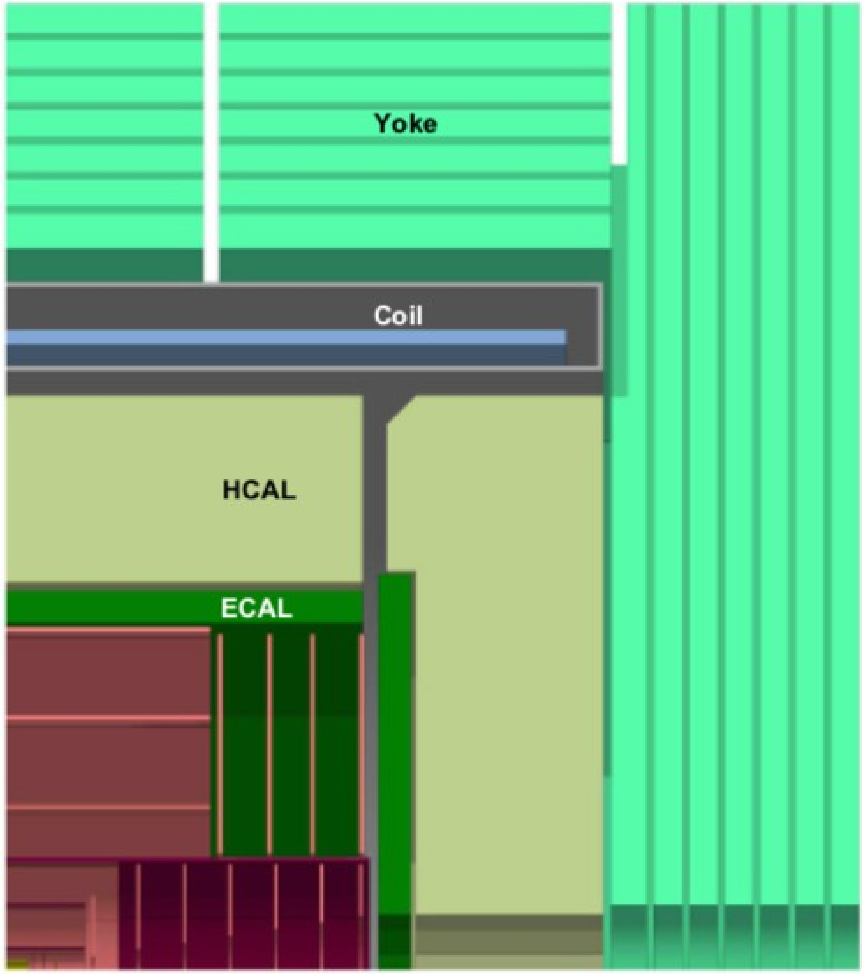


Fig. 7.9. Schematic layout of the IDEA detector.

Hadronic resolution of $\sim 35\%/\sqrt{E}$



CLD (SiW ECAL, Steel scintillaor HCAL)
ECAL $15\%\sqrt{E}$

FCC-ee CLD calorimeter

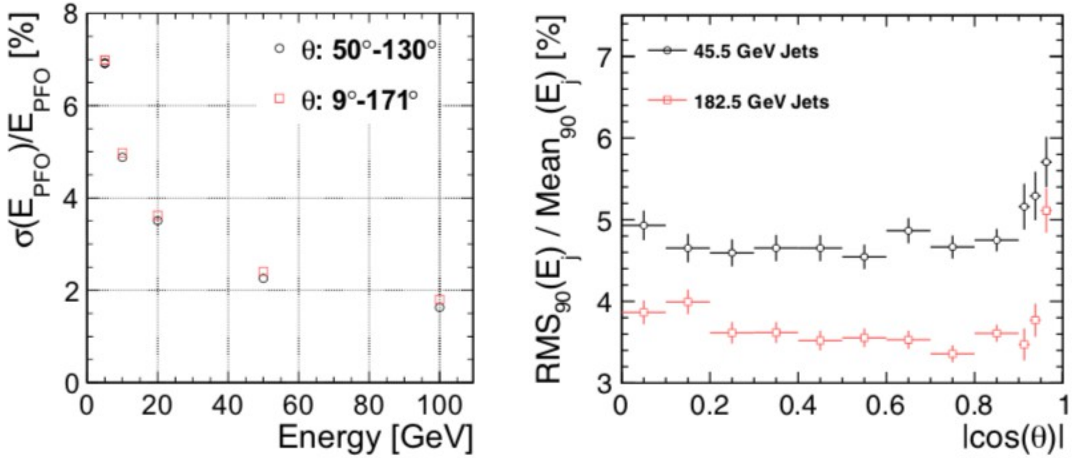


Fig. 7.8. CLD calorimeter performance. Photon energy resolution as a function of energy (left), comparing the barrel region with the full detector acceptance. Jet energy resolution for light quark jets as a function of polar angle (right).

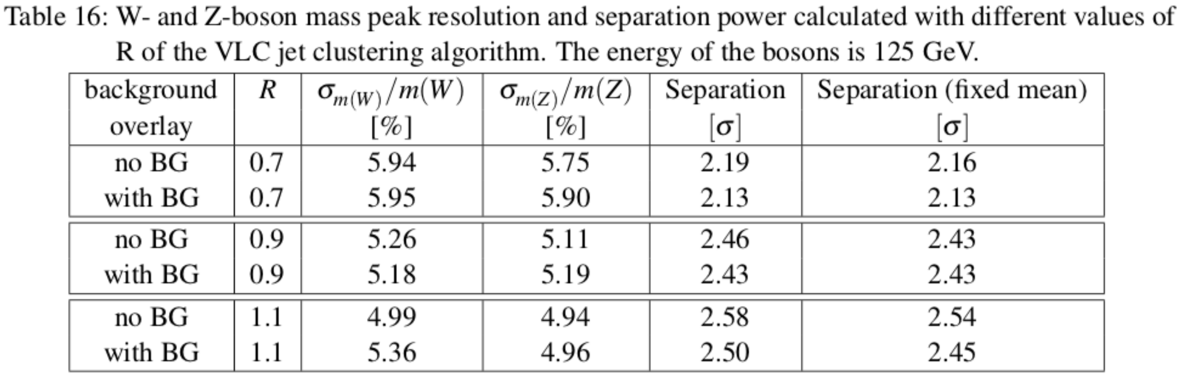
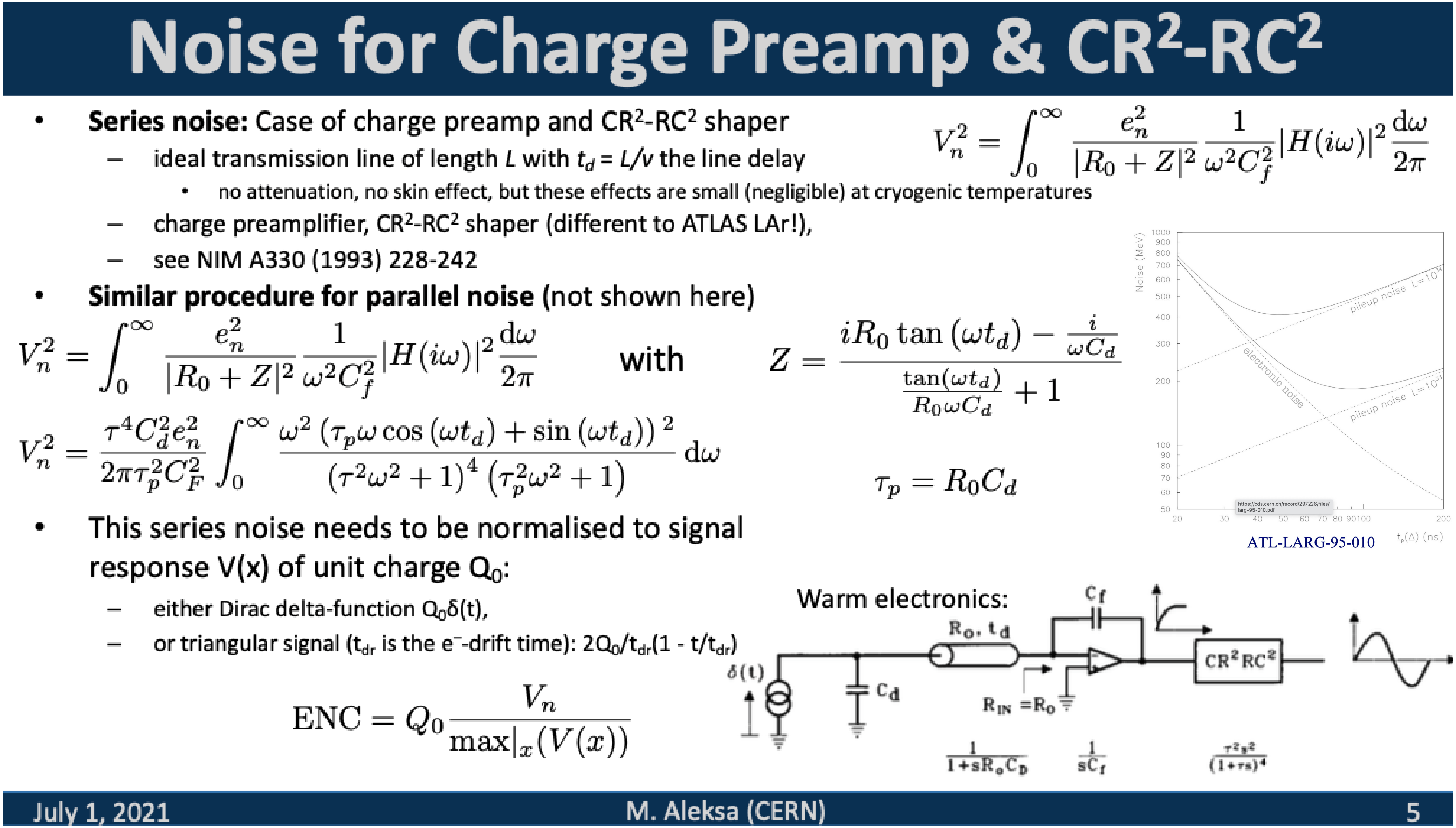


Table 16: W- and Z-boson mass peak resolution and separation power calculated with different values of R of the VLC jet clustering algorithm. The energy of the bosons is 125 GeV.

background overlay	R	$\sigma_{m(W)}/m(W)$ [%]	$\sigma_{m(Z)}/m(Z)$ [%]	Separation [σ]	Separation (fixed mean) [σ]
no BG	0.7	5.94	5.75	2.19	2.16
with BG	0.7	5.95	5.90	2.13	2.13
no BG	0.9	5.26	5.11	2.46	2.43
with BG	0.9	5.18	5.19	2.43	2.43
no BG	1.1	4.99	4.94	2.58	2.54
with BG	1.1	5.36	4.96	2.50	2.45

Noise



Noise for Charge Preamp & CR^2-RC^2

- **Series noise:** Case of charge preamp and CR^2-RC^2 shaper
  - ideal transmission line of length *L* with $t_d = L/v$ the line delay
    - no attenuation, no skin effect, but these effects are small (negligible) at cryogenic temperatures
  - charge preamplifier, CR^2-RC^2 shaper (different to ATLAS LAr!),
  - see NIM A330 (1993) 228-242
- **Similar procedure for parallel noise** (not shown here)

$$V_n^2 = \int_0^\infty \frac{e_n^2}{|R_0+Z|^2}\frac{1}{\omega^2 C_f^2}|H(i\omega)|^2\frac{\mathrm{d}\omega}{2\pi}$$

$$V_n^2 = \int_0^\infty \frac{e_n^2}{|R_0+Z|^2}\frac{1}{\omega^2 C_f^2}|H(i\omega)|^2\frac{\mathrm{d}\omega}{2\pi} \quad \text{with} \quad Z = \frac{iR_0\tan(\omega t_d) - \frac{i}{\omega C_d}}{\frac{\tan(\omega t_d)}{R_0\omega C_d}+1}$$

$$V_n^2 = \frac{\tau^4 C_d^2 e_n^2}{2\pi\tau_p^2 C_F^2}\int_0^\infty \frac{\omega^2\left(\tau_p\omega\cos(\omega t_d)+\sin(\omega t_d)\right)^2}{\left(\tau^2\omega^2+1\right)^4\left(\tau_p^2\omega^2+1\right)}\mathrm{d}\omega \qquad \tau_p = R_0 C_d$$

- This series noise needs to be normalised to signal response V(x) of unit charge Q_0:
  - either Dirac delta-function $Q_0\delta(t)$,
  - or triangular signal (t_{dr} is the e$^-$-drift time): $2Q_0/t_{dr}(1 - t/t_{dr})$

$$\mathrm{ENC} = Q_0\frac{V_n}{\max|_x(V(x))}$$

ATL-LARG-95-010

Warm electronics:

July 1, 2021 M. Aleksa (CERN) 5

Geometry

Geometry Considerations

Adopted geometry proposed by Ronic Ciche in the Dec. meeting (link) – all parameters still to be optimized with performance optimization

- 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.
- r_i=2160mm, r_o=2560mm, inclination of absorbers at r_i is α_i=50.381°
- 11 longitudinal compartments, particle traverses 2 absorbers in 1st comp., 4 in all others
- 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 each other layer
  - 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$|_{\text{r=2205mm (3rd comp.)}}$
- Readout with 7-layer PCB (FR4), 1.2mm thick
- Next pages: tried several absorber compositions and thicknesses, different absorber materials (Pb/W), different active material (LAr/LKr)