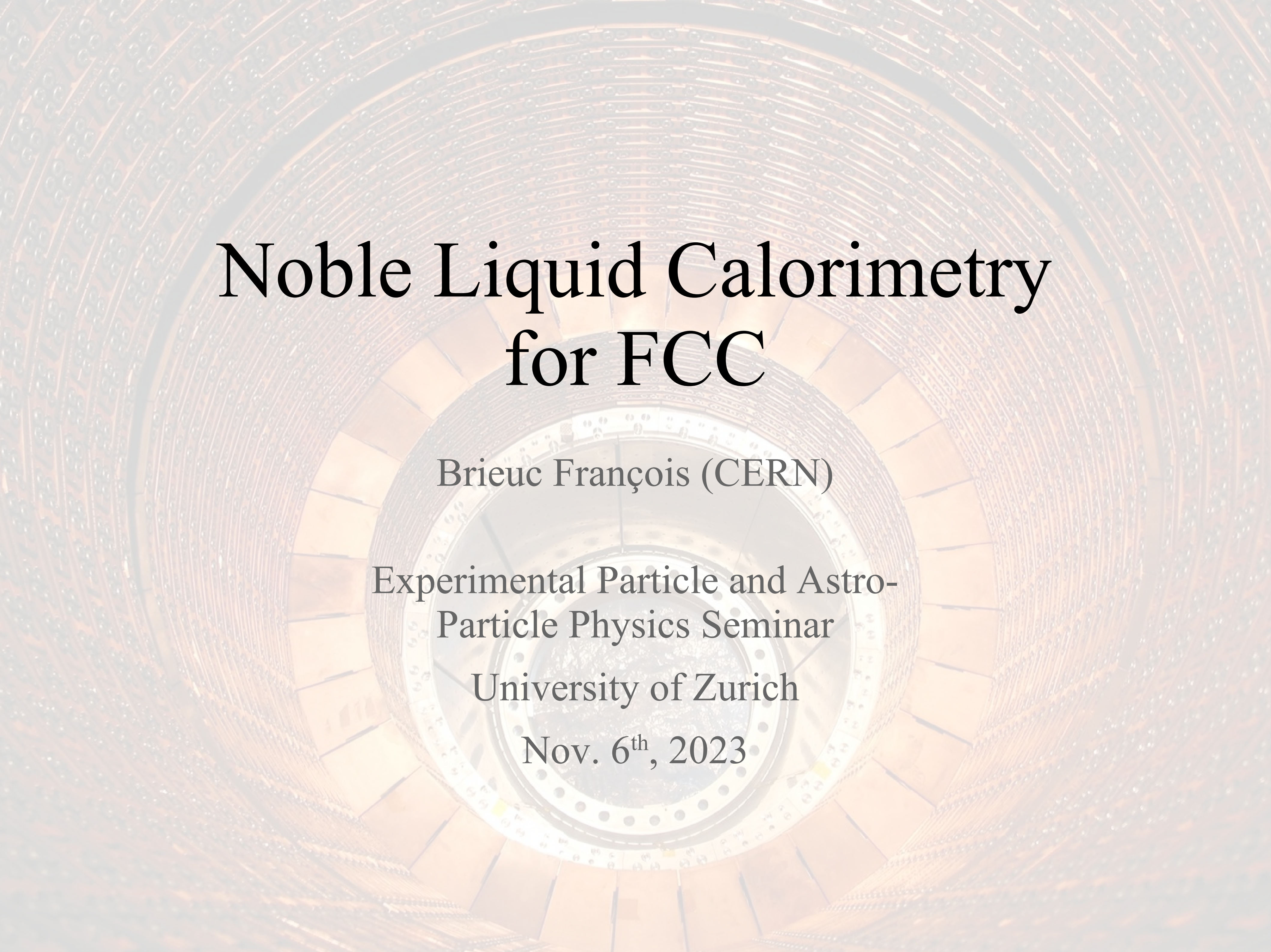


Noble Liquid Calorimetry for FCC

Brieuc François (CERN)

Experimental Particle and Astro-Particle Physics Seminar

University of Zurich

Nov. 6th, 2023

About me

- 2013 – 2017: PhD in CMS, UCLouvain – CP3, Belgium
  - Search for resonant di-Higgs production
  - Model independent search for new physics (Matrix Element Method)
  - b-tagging
  - Tracker detector on-call
- 2017 – 2018: satellite based earth observation, UCLouvain, Earth and life Institute
- 2018 – 2020: Postdoc, Hanyang University (South Korea), based at CERN
  - Search for top-Higgs Flavor Changing Neutral Current
  - Coordination of CMS RPC Trigger activities
- 2020 – 2023: Fellow, CERN
  - R&D for Future Noble Liquid Calorimetry (this talk)
- Feb. 2023 – … : Staff, CERN
  - Coordination of FCC software activities, focus on Detector Full Sim

Content

- Introduction
  - The FCC project
  - Calorimetry
- Noble Liquid Calorimetry R&D
  - Readout electrodes
  - Feedthroughs
  - Cryostat
  - Mechanical studies
- Software studies

Introduction

Dear Santa Claus,

We have been good
these past decades.
Please could you
now bring us

- *a dark matter candidate*
- *an explanation for the fermion masses*
- *an explanation of matter-antimatter asymmetry*
- *an axion, to solve the strong CP problem*
- *a solution to fine tuning the EW scale*
- *a solution to fine tuning the cosmological constant*

Thank you, Particle Physicists

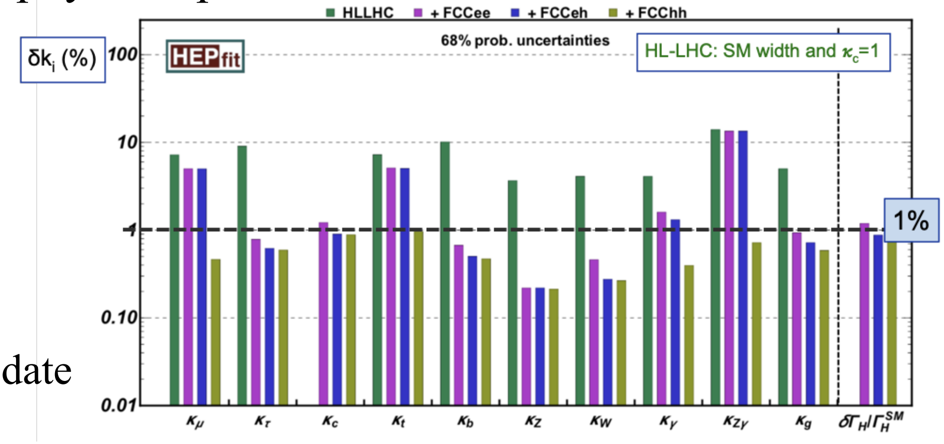
ps: please, no anthropics

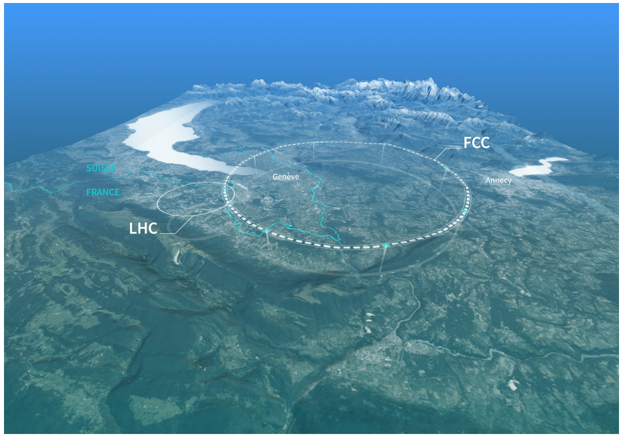
G. Salam, London, FCC week 2023

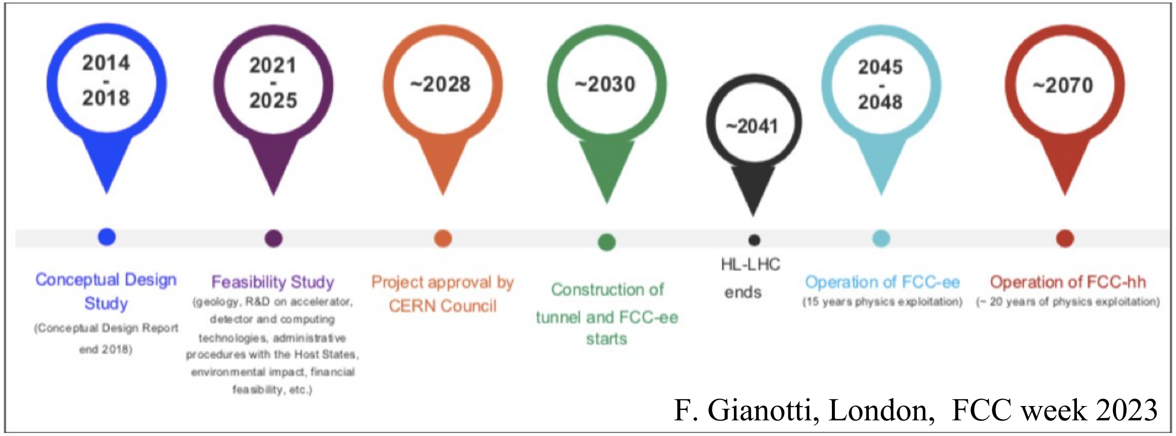
- We have been so far **unlucky** in getting answers to the many **HEP open questions**
  - Hopefully, (HL-)LHC will shed light on some of these answers
  - Regardless, the **next worldwide HEP project** should be prepared **now**
    - Versatile further exploration of Nature
- On the other hand we have been **lucky** in finding a 125 GeV **Higgs boson**
  - A brand new door opened on the most mysterious parts of the Standard Model
  - The 2020 update of the European strategy for particle physics has identified an **electron–positron Higgs factory as the highest priority** collider after the LHC
  - And mandated us to study the feasibility of a **hadron collider at $\sqrt{s} \sim 100$ TeV**

The FCC project

- The CERN based **Future(/Frontier) Circular Collider** (FCC) is one of the proposed project to ensure a smooth continuation of HEP experimental research after HL-LHC
  - ~ **90 km collider** next to the LHC with 4 interaction points (baseline scenario)
  - 1st stage lepton collider (FCC-ee): √s = 90 – 360 GeV, physics operation in 2048 – 2063
    - High luminosity Higgs + EW factory, precision measurement, indirect discovery up to 70 TeV
  - 2nd stage hadron collider (FCC-hh): √s ≥ 100 TeV, physics operation in 2070 – 2095
    - Direct exploration of the next energy frontier
  - Also heavy-ion and possibly e-p/e-ion collisions
  - 150 institutes, 32 companies, 34 countries
  - FCC Conceptual Design Reports
  - Feasibility study report being prepared now
    - Will serve as input to the next European strategy update



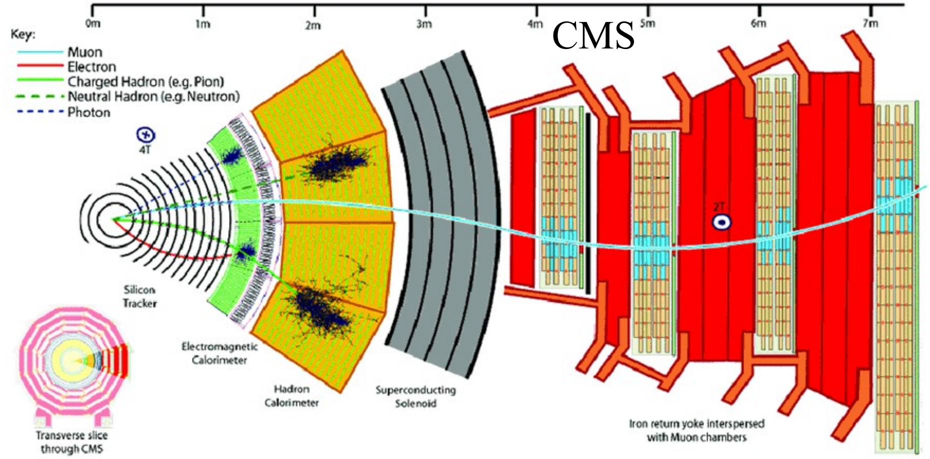


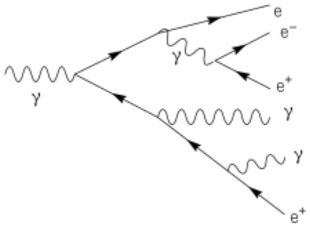


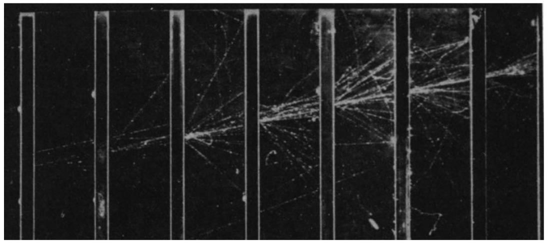
F. Gianotti, London, FCC week 2023

Particle Detection and Calorimetry

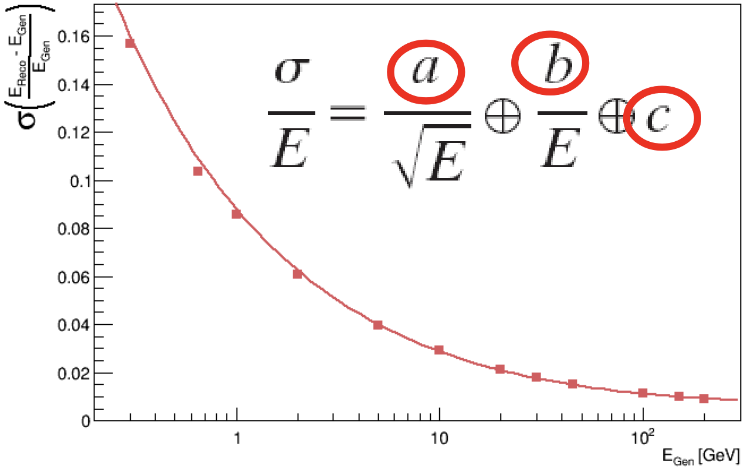
- Each sub-detector has a well identified task
- Sampling calorimetry basics
  - Dense (non-sensitive) absorbers trigger particle showers
  - Only the energy deposited in the sensitive media is read-out
    - Sampling fraction = $\mathbf{E}_{\mathbf{Sensitive}} / \mathbf{E}_{\mathbf{tot}}$
      - “The higher the better”
      - Modulo size/cost + other metrics (PFlow)
- Calorimeter energy resolution can be parametrized
  - a = **sampling term**: depends on the ratio sensitive/non-sensitive
  - b = **noise term**: linked to... the noise (electronics + pile up). Dominates at low energy
  - c = **constant term**: linked to detector non-uniformities, shower leakage, dominates at high energy







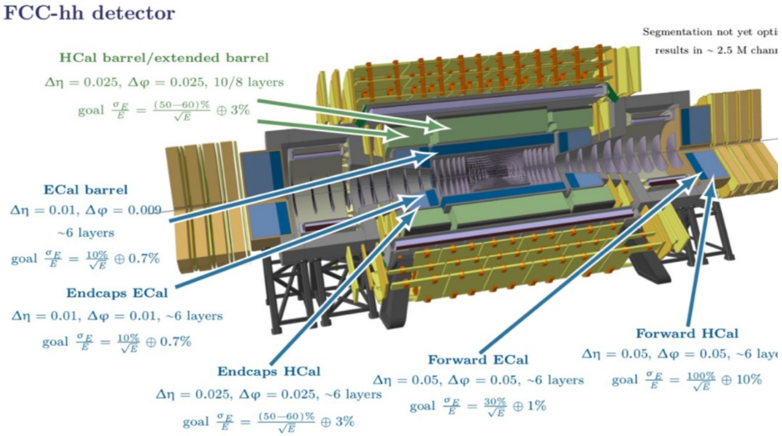
ECAL energy resolution



$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

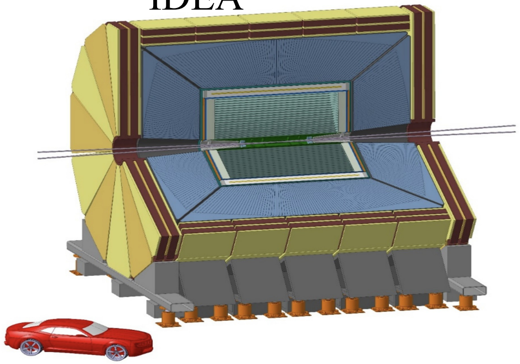
FCC Detectors

- **Large scale HEP experiments** are difficult to reproduce, we usually only get to build a **single facility** → we must **make the best out of it**!
    - Detectors must be optimal, “*Maximize physics outcome per euro spent*”
    - Isn't it too early to start designing FCC Detectors now?
        - First CMS/ATLAS papers on their sub-detectors appeared more than 20 years before operations
- **FCC-hh reference detector established**
    - Silicon Tracker, LAr calorimeters (except barrel HCal Fe/Sci)
- **Three detector proposals for FCC-ee** so far
    - **CLD**: Silicon Tracker, Si-W ECAL, optimized for PFlow
    - **IDEA**: ultra-light gaseous drift chamber, dual readout calorimeter
    - **ALLEGRO**: Noble Liquid ECAL
- Still in the designing/optimization phase

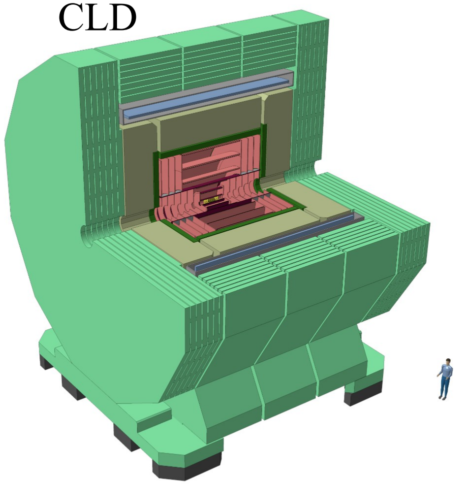


ALLEGRO

IDEA



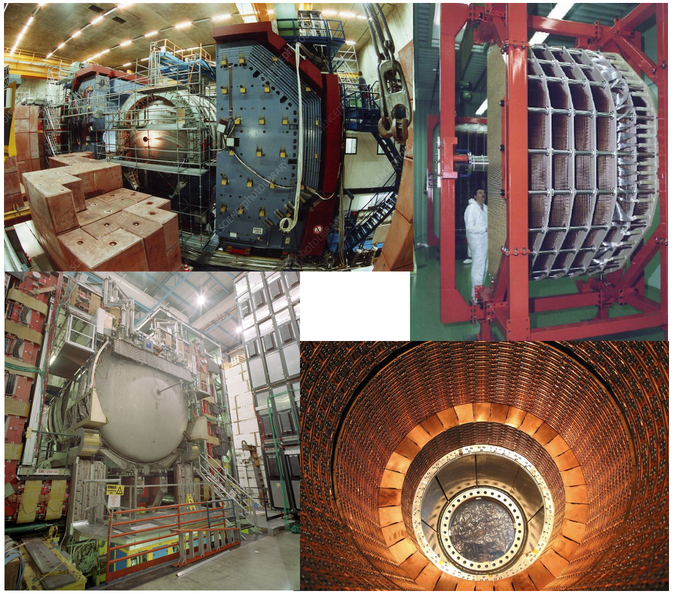
CLD

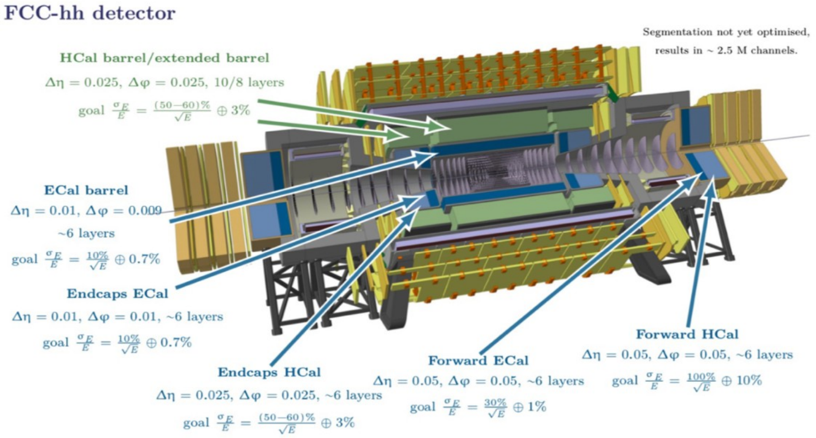


Noble Liquid Calorimetry R&D

Noble Liquid Calorimetry

- **Noble Liquid Calorimetry is a well proven technology**
  - Successful operation in D0, H1, NA48/62, ATLAS
- Suitable for various collider flavors (p-p, e-p, e-e, μμ, fixed target)
- Key features
  - Very good energy/time resolution
  - Radiation hardness
  - Long term stability, linear response, uniformity
    - Easy calibration, high control over systematics
- **Proposed for several future collider experiments**
  - FCC-hh, FCC-ee, LHeC, HIKE, SCTF, …
- R&D ongoing to improve upon the state of the art

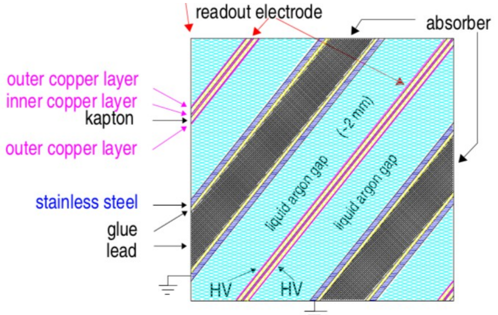


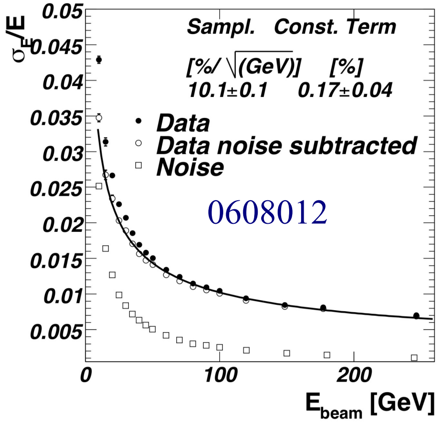


State of the Art

- ATLAS LAr sampling calorimeter: lead absorbers, LAr active gaps, 3-layer Kapton electrodes with accordion geometry, Aluminum cryostat, front-end outside of the cryostat
- 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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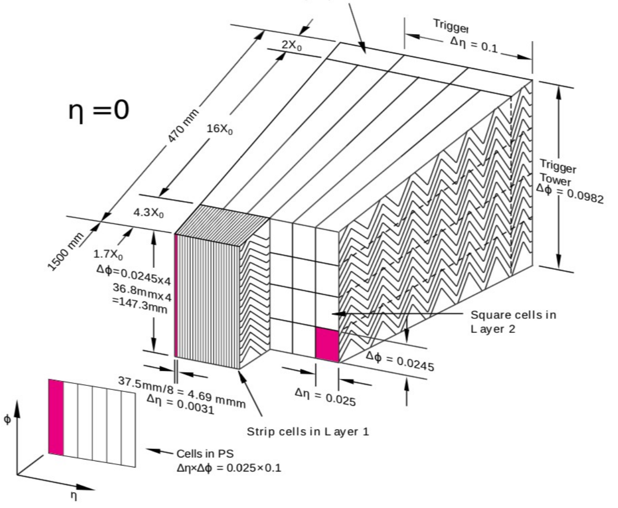

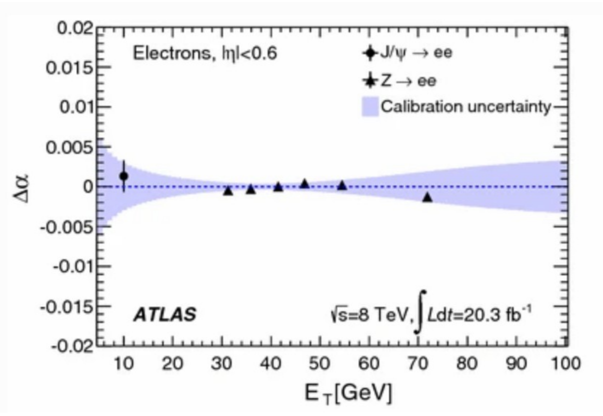

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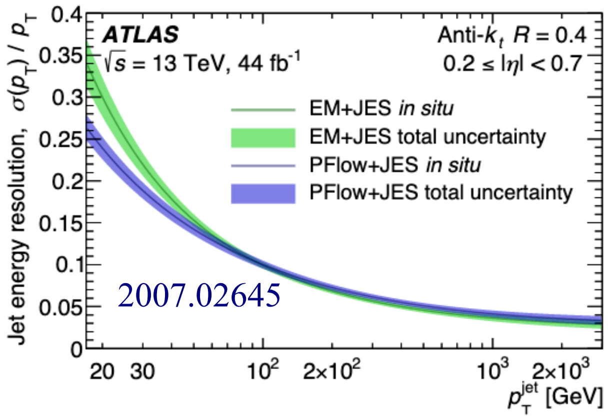
- Linearity: energy scale variation within ~10^{-3} over large E_T range
- Stability: energy response stable at ~10^{-4} level over a year
- Limited particle flow performance



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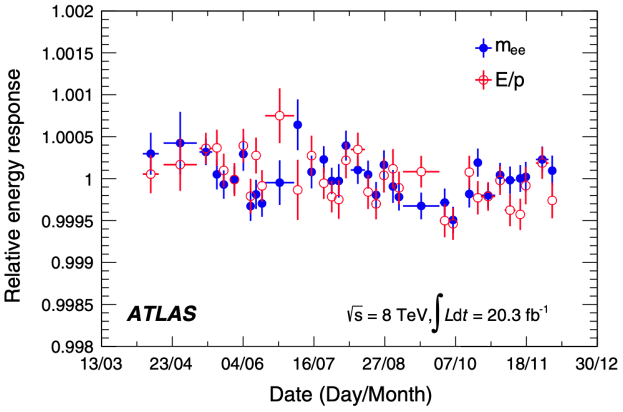
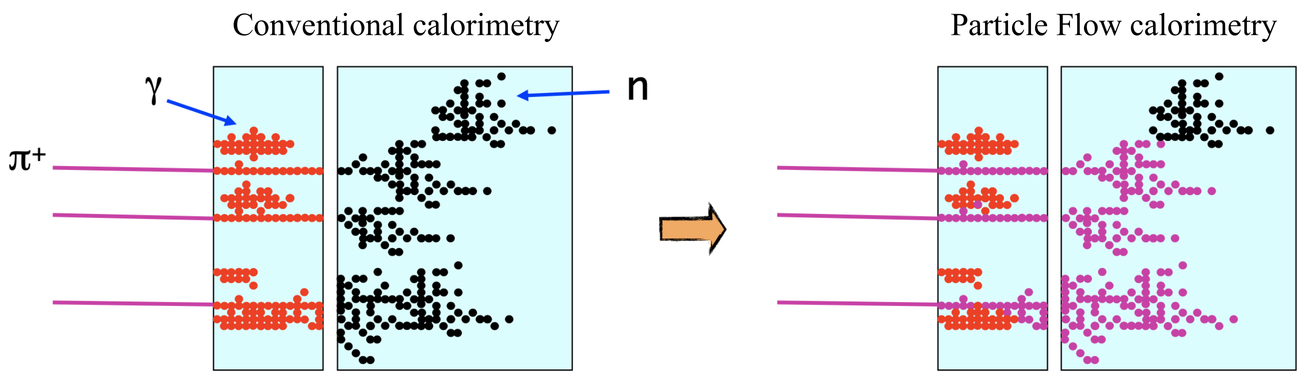


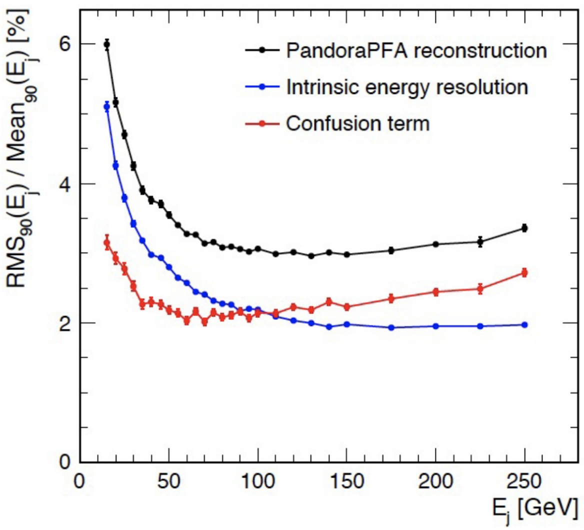
Imaging Calorimeter

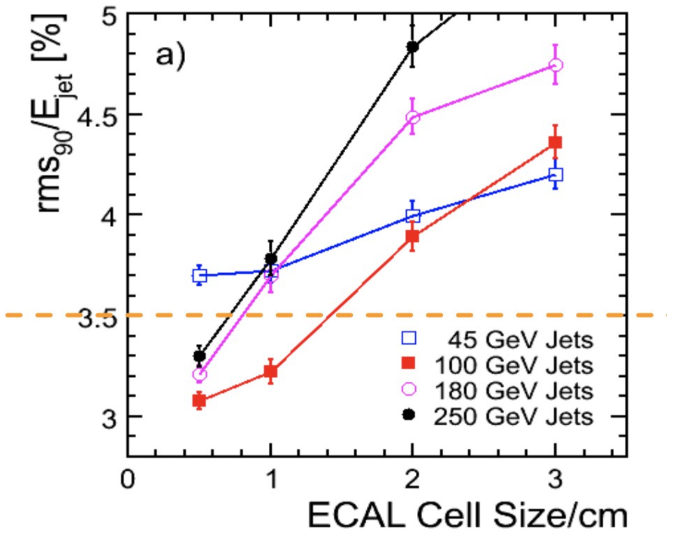


$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

ILD studies

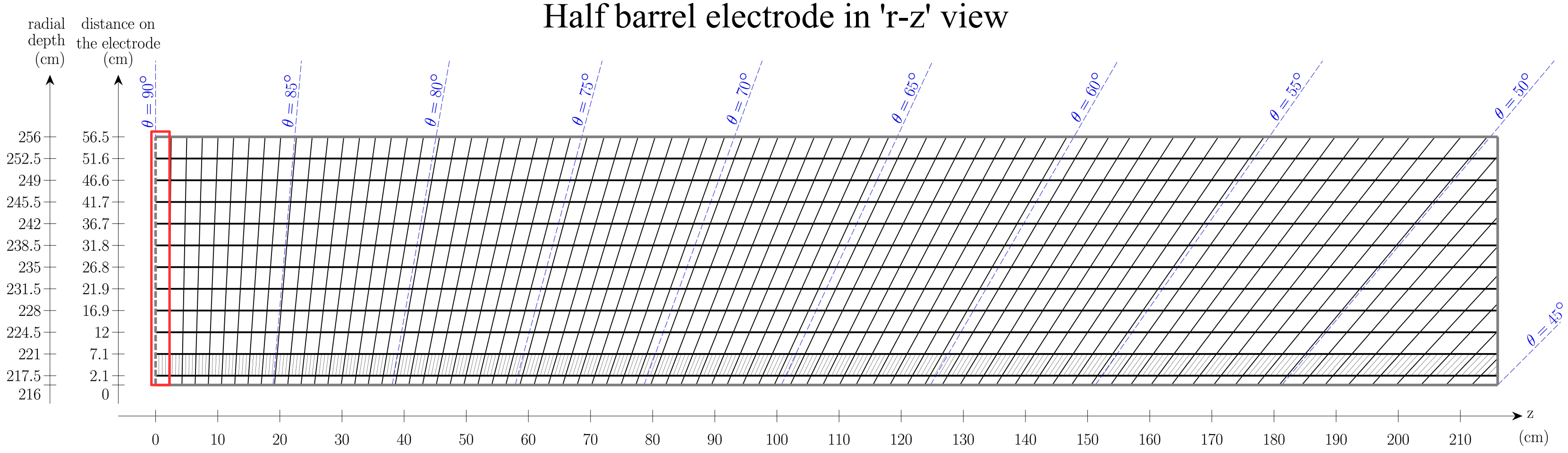




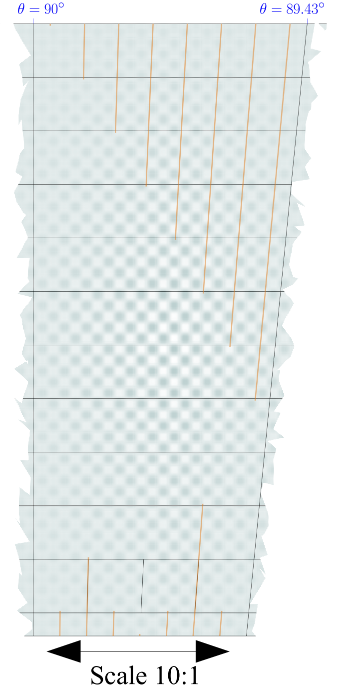
- Excellent relative jet energy resolution can be achieved with Particle Flow → build future detectors with this in mind
  - Need to avoid double counting and wrong merging
  - Calls for an imaging calorimeter
- High granularity! (and small Moliere radius)
  - Requires **finely segmented readout electrodes**
    - **Challenging signal extraction**
      - X-talk, Signal/Noise (S/N), number of cables...

Future Detector Design

Half barrel electrode in 'r-z' view

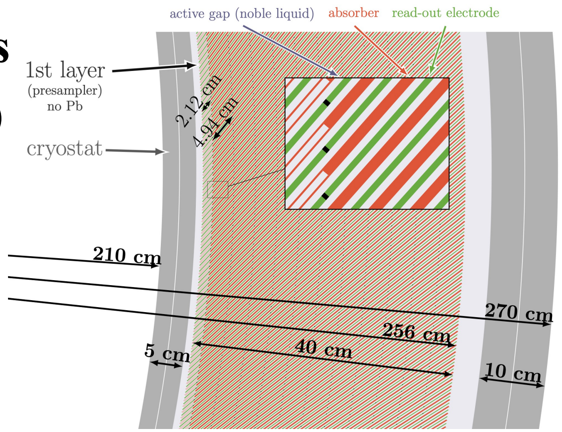


One 'eta tower'



- Propose a geometry with straight inclined plates (instead of accordion)
  - Absorber: Lead or Tungsten (+ steel)
  - Sensitive media: LAr or LKr (or LXe) + PCB readout electrode
- Target **granularity increase** compared to ATLAS
  - Longitudinal (i.e. radial direction): ATLAS = **3 layers** → ~ **12 layers**
  - Pseudo-rapidity: ATLAS **Δη = 0.025 (0.0031 strip)** → **0.01 (0.0025)**
  - Phi granularity
    - Depends on the cell merging scheme of the readout
    - Smallest unit is 'one double gap' i.e. 2π/1536 = 4 mrad
- **Factor 10 to 15 increased granularity** w.r.t. ATLAS implementation

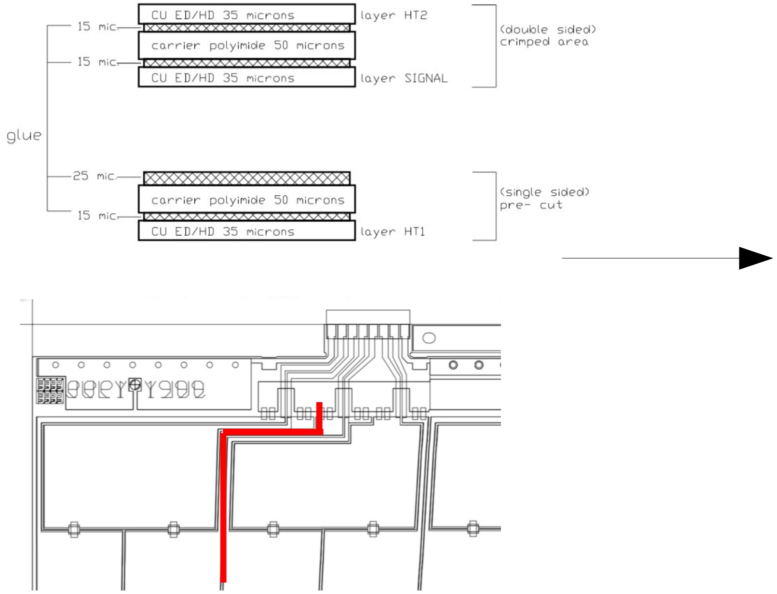
Detector in r-Φ view



Finely Segmented Electrodes

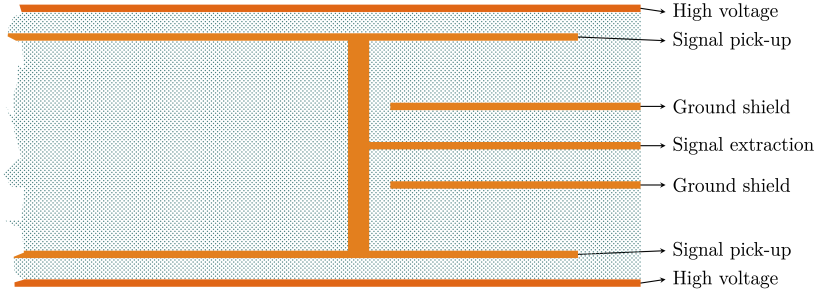
- Most challenging point w.r.t. electrodes: **longitudinal segmentation**
  - Tiny analog signals have to be routed from middle cells outside of the sensitive volume
  - Too many traces to route them in the space between eta towers
    - Solution: 3-layer Kapton → 7-layer PCB with signal traces on a different layer as the pick-up pads
    - EM coupling between trace and other cells → X-talk?
    - Solution: cut the field lines with ground shields
    - Baseline: each trace surrounded by two shields (stripline)
      - Shields increase capa to ground (thus noise) → detailed study needed

ATLAS LAr

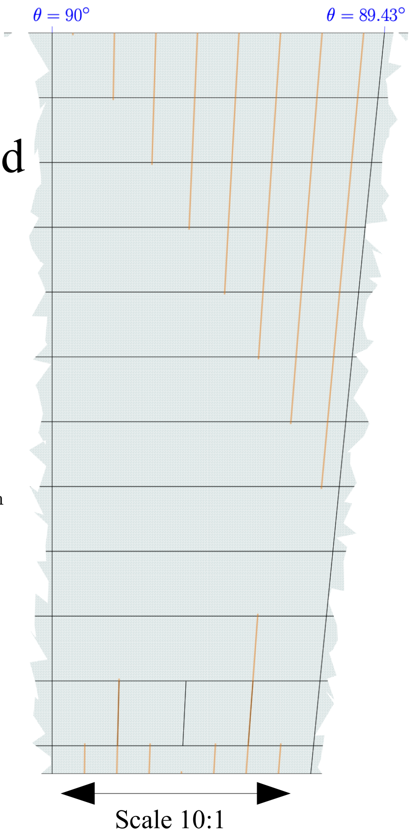


Granular Calo

Readout electrode cross-section

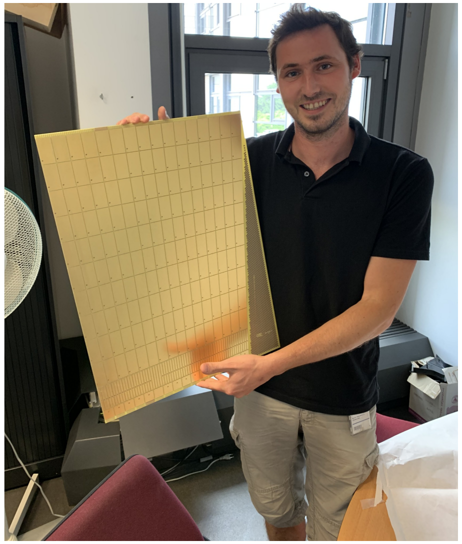


One 'eta tower' seen from top, showing **transmission lines in transparency**



Electrode Studies

- Readout electrode CAD implemented (Cadence)
- Simulation done in ANSYS HFSS 3D Layout
- Real scale electrode prototype produced
  - 16 theta towers to remain within standard dimensions
    - 58 cm x 44 cm x 1.2 mm
    - Towers with ≠ number of shield, shield width, …
  - Electrical tests in the lab with function generator and scope



Simulation workflow

Cadence®

↓

CAD model

↓

ANSYS® HFSS

↓

S-parameters (PSpice model)

↓

ANSYS® Circuit

↓

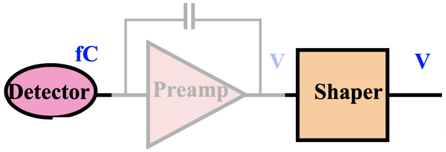
Raw signal

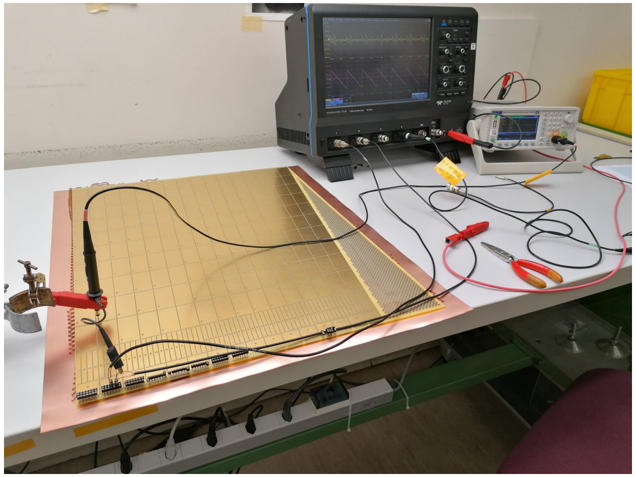
↓

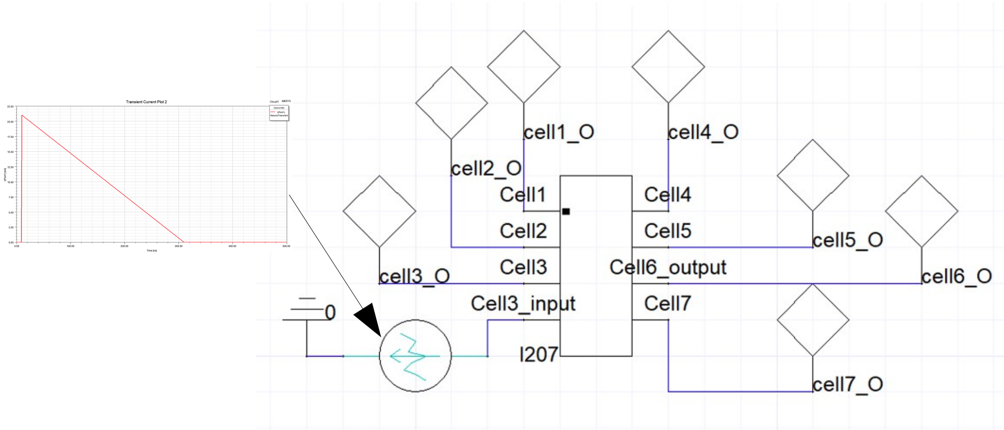
Software shaper (scipy.signal)

↓

Shaped signal



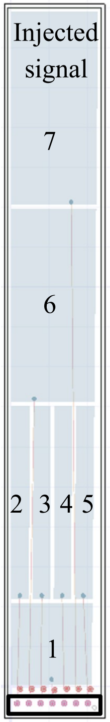




Results

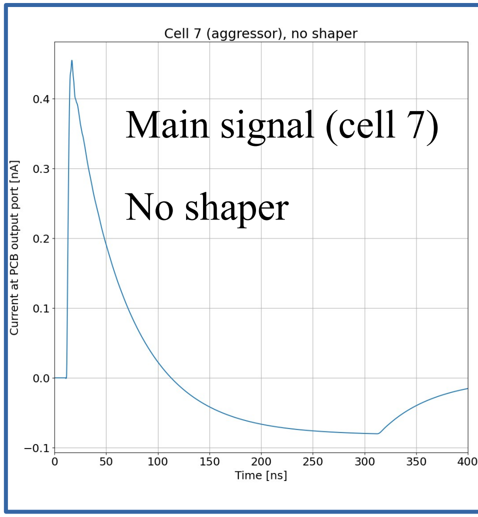
Cross talk for the baseline tower (two shields): signal injected on Cell 7, all inner channels read out

- Reasonable agreement between simulation and measurements after shaping
- **X-talk < 1 % easily achievable** after signal shaping, also true with a single shield!



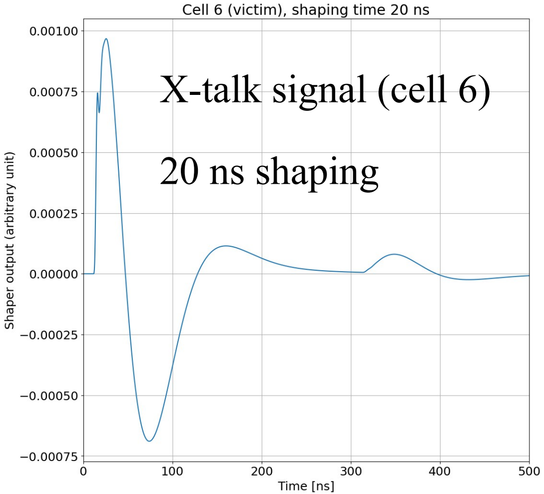
Output signals

Simulation


Cell 7 (aggressor), no shaper

Main signal (cell 7)

No shaper

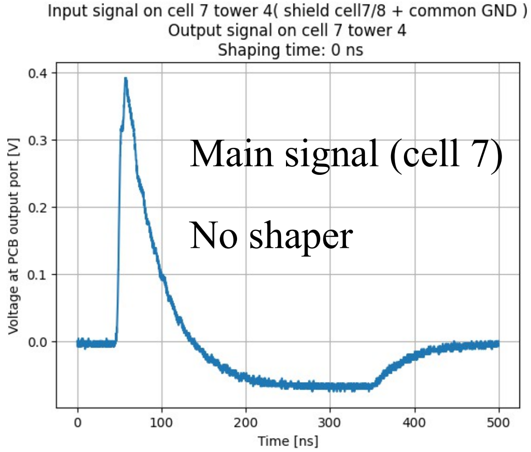

Cell 6 (victim), shaping time 20 ns

X-talk signal (cell 6)

20 ns shaping

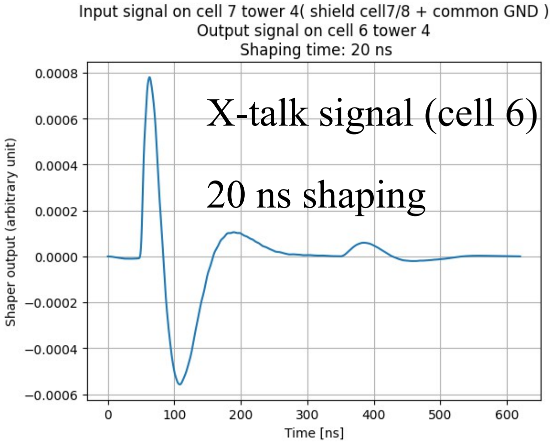
Cross-talk (%) Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	0.52	3.22	3.29	5.89	5.5	20.94
20	0.06	0.08	0.03	0.12	0.07	0.92
50	0.04	0.05	0.01	0.06	0.04	0.52
100	0.03	0.03	0.0	0.04	0.03	0.35
150	0.03	0.03	0.0	0.03	0.02	0.29
200	0.03	0.03	0.0	0.03	0.02	0.26
300	0.02	0.02	0.0	0.02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

Measurement


Input signal on cell 7 tower 4(shield cell7/8 + common GND)
Output signal on cell 7 tower 4
Shaping time: 0 ns

Main signal (cell 7)

No shaper


Input signal on cell 7 tower 4(shield cell7/8 + common GND)
Output signal on cell 6 tower 4
Shaping time: 20 ns

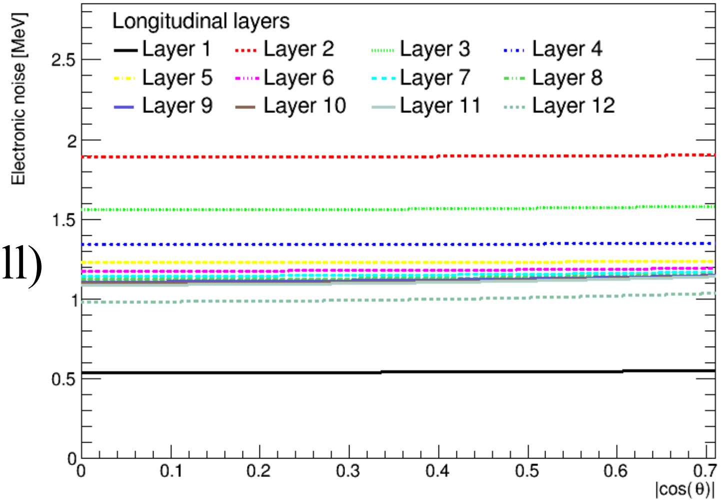
X-talk signal (cell 6)

20 ns shaping

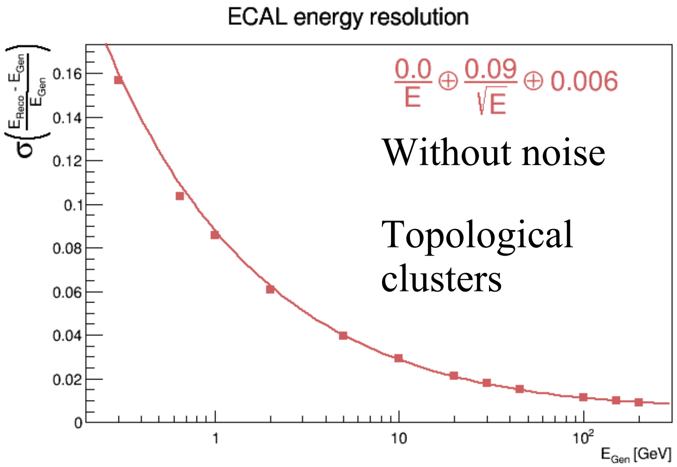
Cross-talk (%) Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	0.59	0.28	0.36	1.11	0.98	4.66
20	0.17	0.06	0.08	0.28	0.23	0.81
50	0.09	0.04	0.05	0.14	0.13	0.44
100	0.06	0.03	0.03	0.09	0.09	0.29
150	0.04	0.02	0.03	0.07	0.07	0.23
200	0.04	0.02	0.02	0.06	0.07	0.21
300	0.03	0.02	0.03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

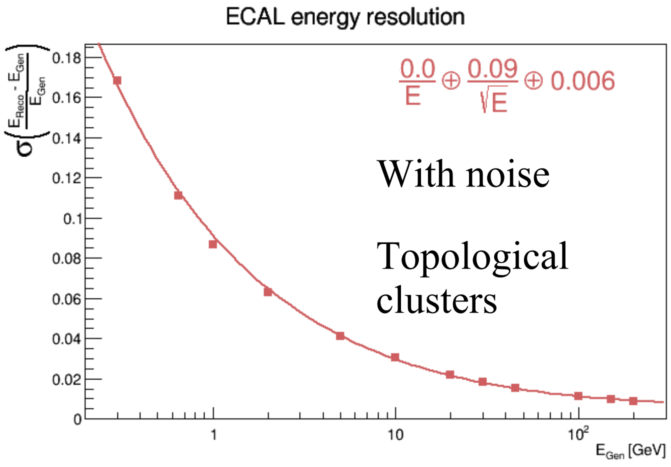
High Granularity Electrode: Noise

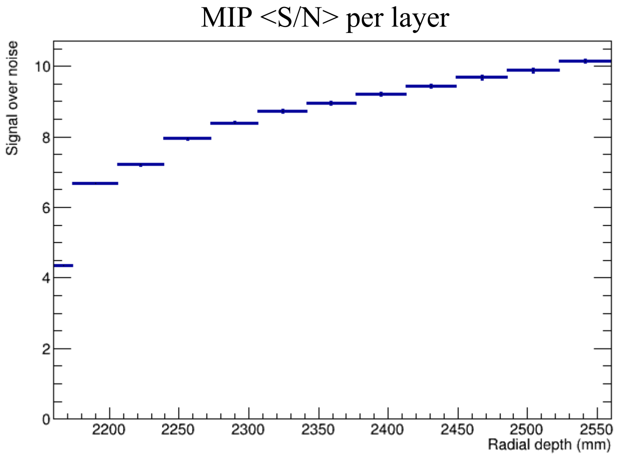
- Electronics noise VS cell capacitance estimated from analytical description of the readout chain
  - Transfer function (Laplace domain) in Mathematica
    - PCB transmission line (+ coaxial cable) + pre-amp + shaper
- Cell capacitance derived from FEM tools (ANSYS Maxwell)
  - 25 - 200 pF depending on the longitudinal layer (2 shields)
  - **0.5 – 2 MeV noise** per cell
- Noise per cell implemented in Full Sim
  - Negligible impact on energy resolution > 1 GeV
  - **MIP S/N > 5** also with warm electronics (next slide)



2 ground shields, 1 readout cell = 2 physical cells, 5 m 100 Ω coax, Charge preamp, e_n = 0.5 nV/√Hz, i_n = 1 pA/√Hz, shaping time = 200 ns



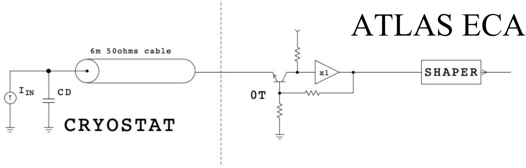




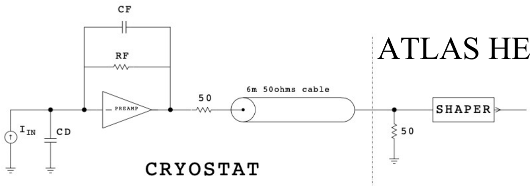
Warm or cold electronics?

- **Electronics** can sit **inside** (cold) **or outside** (warm) the **cryostat**
  - Hybrid solution with only the pre-amplifier inside the noble liquid can also be envisaged
- Noise estimated in both scenarios
  - Cold electronics can bring a **noise reduction factor of *O*(5)**
  - Precise value depends on the final design
    - Transmission line impedance, shaping time, detector capacitance
- All FE electronics inside the cryostat → **easier signal extraction**
  - Analog with cables VS digital with optical fibers
- First trial with HGCROC (CMS HGCAL ASIC) at cold
  - Some adaptation needed but looks promising for first tests
- To be studied:
  - Estimate the impact on the cross-talk (better with cold electronics)
  - **Difficult maintenance**/upgrade with cold electronics: risk assessment and mitigation strategy (redundancy) to be established
  - Estimate impact of **power dissipation inside the noble liquid**

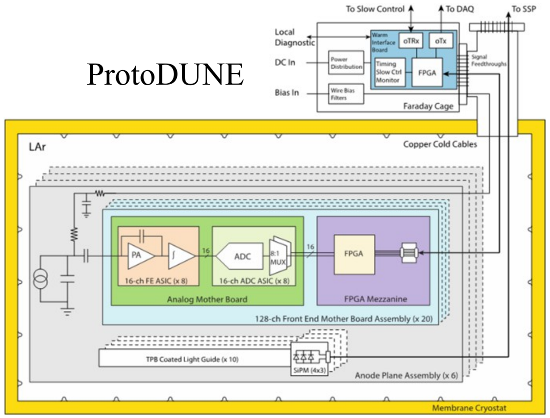
ATLAS ECAL

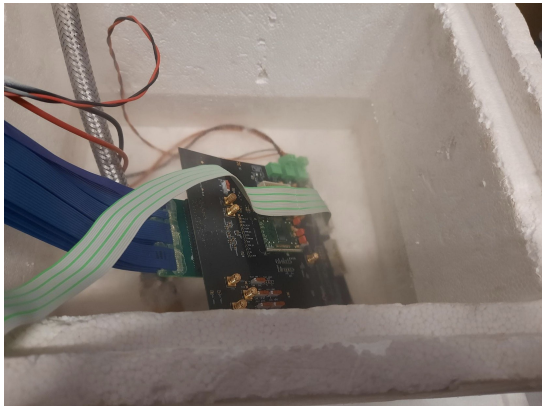


ATLAS HEC



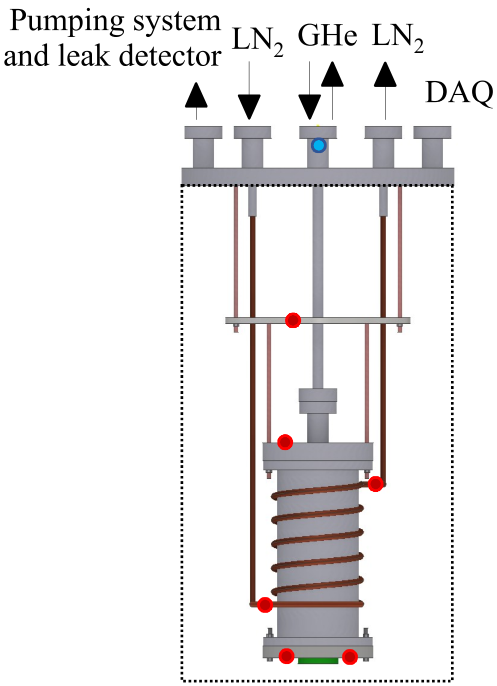
ProtoDUNE



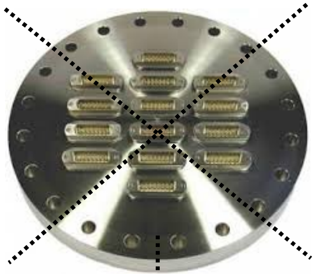


High Density Feedthroughs

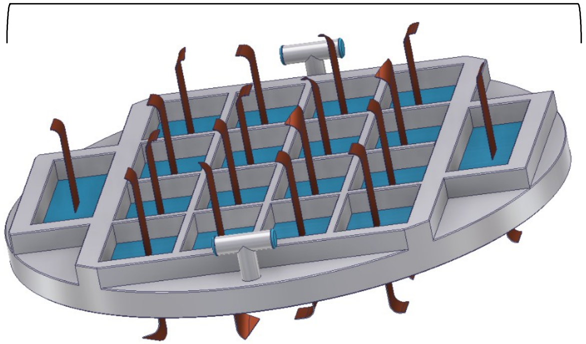
- Factor **10-15** more granular than ATLAS → **more channels to extract** (ECAL barrel ~2 M)
- If the electronics sits outside of the cryostat (warm electronics), one needs high density feedthroughs
- Innovative **connector-less feedthroughs**
  - High density flange
  - Higher area dedicated to signal 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
- **Identified a solution surviving several thermal cycles** (G10 structure with slits + indium seal + Epo-Tek glued Kapton strip cables)
- To be done: design and test a full flange

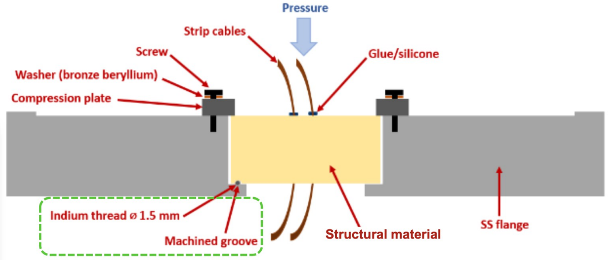


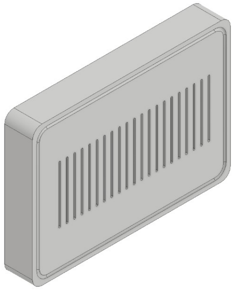
Experimental setup

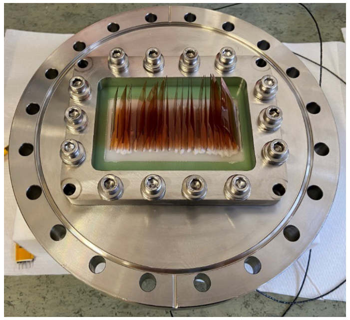


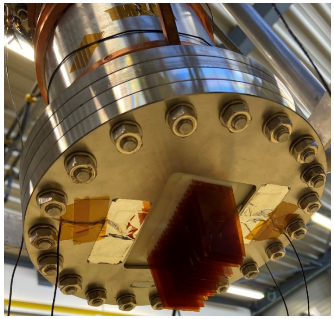
Conceptual high-density flange





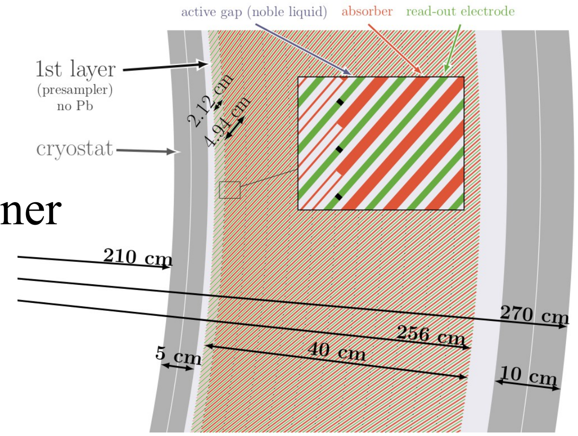






Lightweight Cryostat

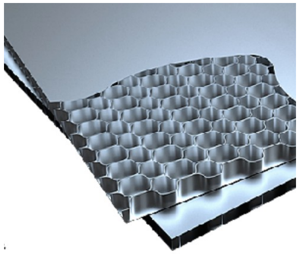
- **Minimizing dead material budget** before sensitive areas is profitable for Particle Flow, energy resolution, low energy particle detection, …
- Ongoing R&D on **low mass cryostat**
  - Solid (plain) shell or honeycomb sandwich
  - Aluminum or Carbon Fibre
  - Up to **factor 10 lower material budget** for Inner Cold Cylinder w.r.t. plain Aluminum
- Small scale CFRP prototype produced and validated (leak-tight at 112 K)
- Next step: establish a large scale manufacturing process




NASA lineless CFRP cryotank

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

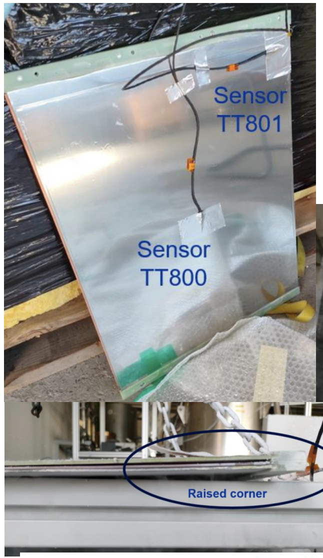
Promising R&D Baseline Prototype ATLAS

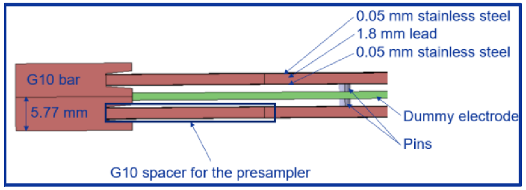


CFRP: Carbon Fibre Reinforced Polymer
OWC: Outer Warm Cylinder
ICC: Inner Cold Cylinder
Al: Aluminum

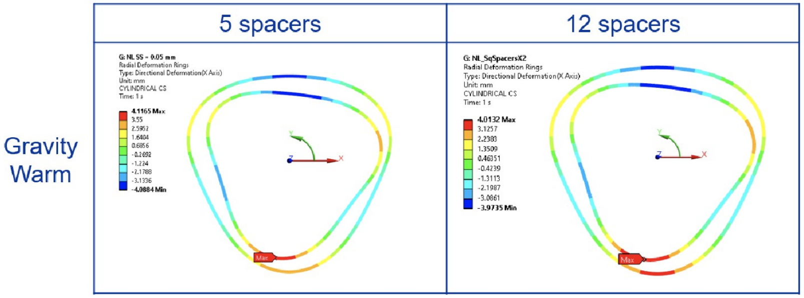
Mechanical Structure

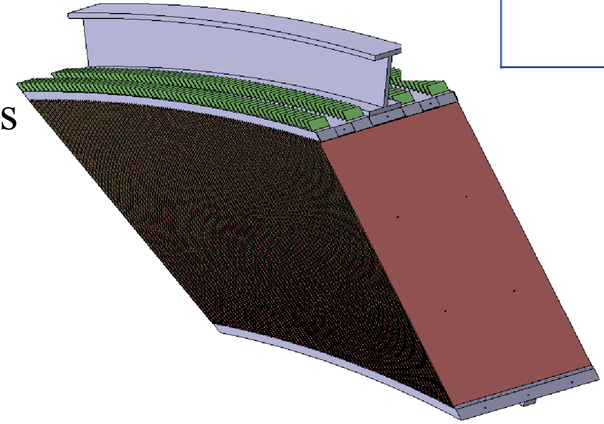
- Mechanical engineering campaign ongoing
  - Design and tuning of the module assembly
    - Test of the module assembly at cold
  - Design of a test beam prototype
    - Support structure with signal extraction
  - Design a solution for the whole ECAL Barrel (~ 100 tons)
    - How to insert and support the modules in a carbon fibre cryostat?
    - Detector integration: how to support it without jeopardizing hermeticity and with good acceptance knowledge?
- Many other things to cover
  - Feasibility for trapezoidal absorbers
  - Design for the endcaps
  - …

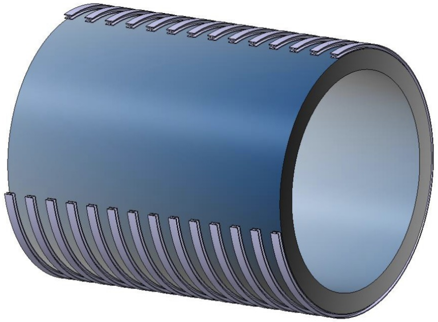




Radial displacements of the rings



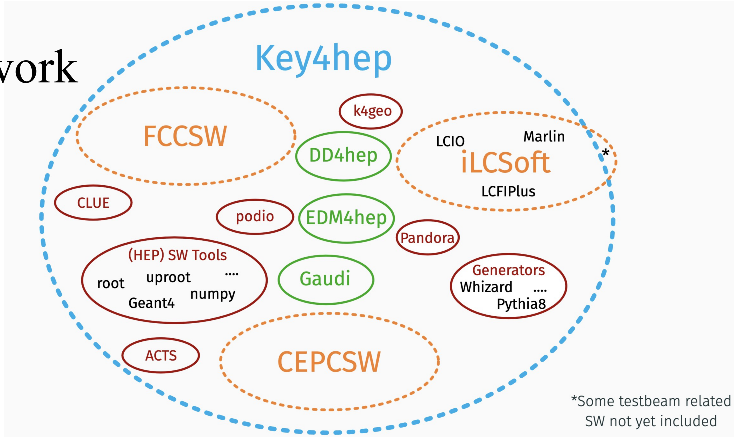




Software Overview

Full sim description of detectors are of utmost importance

- One can not make a prototype for each detector option → needed for **detector optimization**
- Provides inputs for fast/parametrized simulation → **physics reach** of a given facility
- Before the final detector is built, full sim is the only place where **all sub-detectors live together and interact with each other** in a realistic way
- Detector R&D campaigns **span over decades**
  - Need a **stable** and continuously **maintained** software framework
- Future collider studies performed by **small teams**
  - Exploiting **synergies** is a must
- The community agreed on using a common software stack for **all future collider studies**: **Key4hep**

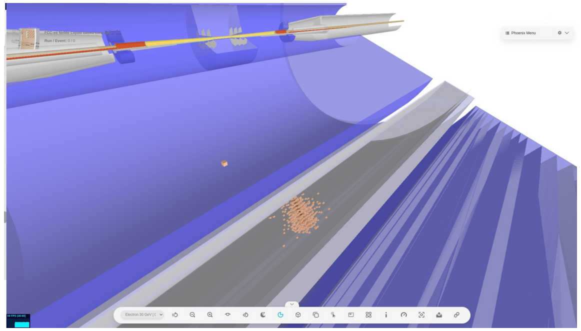


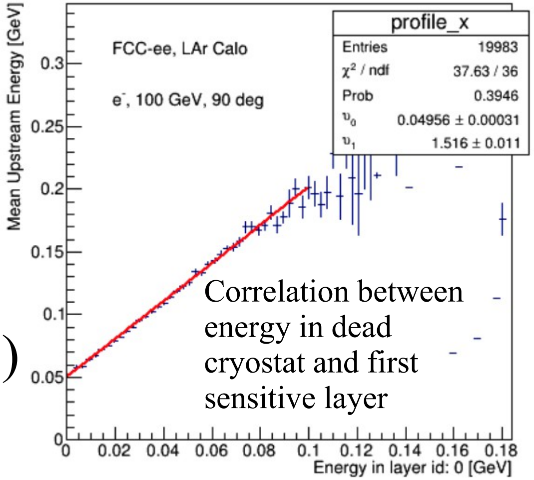
*Some testbeam related SW not yet included

  - Complete set of tools: generation, simulation, reconstruction, analysis
    - State of the art HEP libraries availability: **Spack** (avoid re-inventing the wheel)
  - Common data format: **EDM4hep** (easy sharing)
  - Detector description with **DD4hep** (already used by CMS and LHCb, plug-and-play approach)
  - **Gaudi** orchestration framework (coming from LHCb)

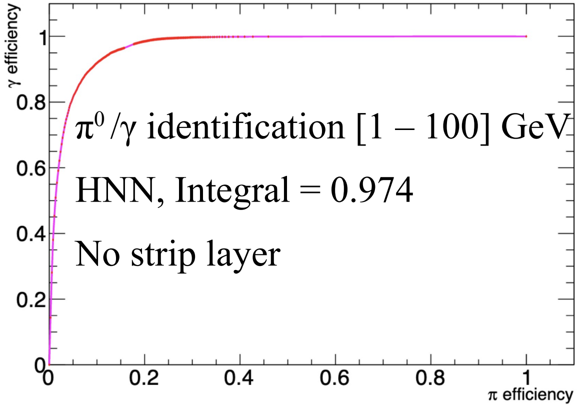
Calorimeter Software Implementation

- Realistic ECAL barrel implemented and validated in DD4hep
    - Endcap being implemented
- First order effects for reconstruction available in Key4hep
    - Sampling fraction, dead material correction, noise, clustering algos
- First performance studies performed
    - **5 – 9 % sampling term** depending on absorber/noble liquid
    - 95 % γ efficiency for 10 % π^0 in the [1 – 100] GeV range
    - **τ final state categorization** (needed for precision measurements)





Correlation between energy in dead cryostat and first sensitive layer

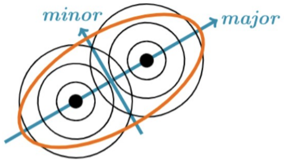


π^0/γ identification [1 – 100] GeV

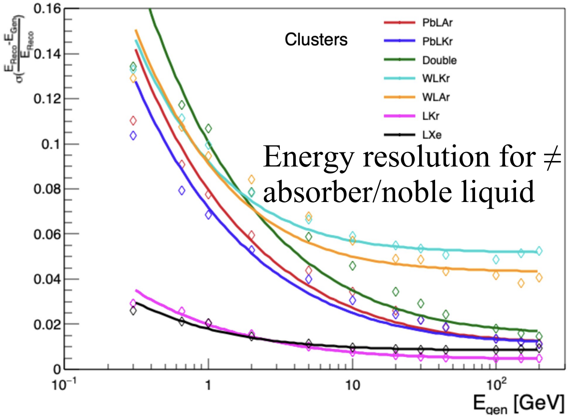
HNN, Integral = 0.974

No strip layer

Steel : 0.37 mm
Glue/PCB : 1.44 mm
Pb : 1.389 mm
LAr : 2.50 mm



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



Energy resolution for ≠ absorber/noble liquid

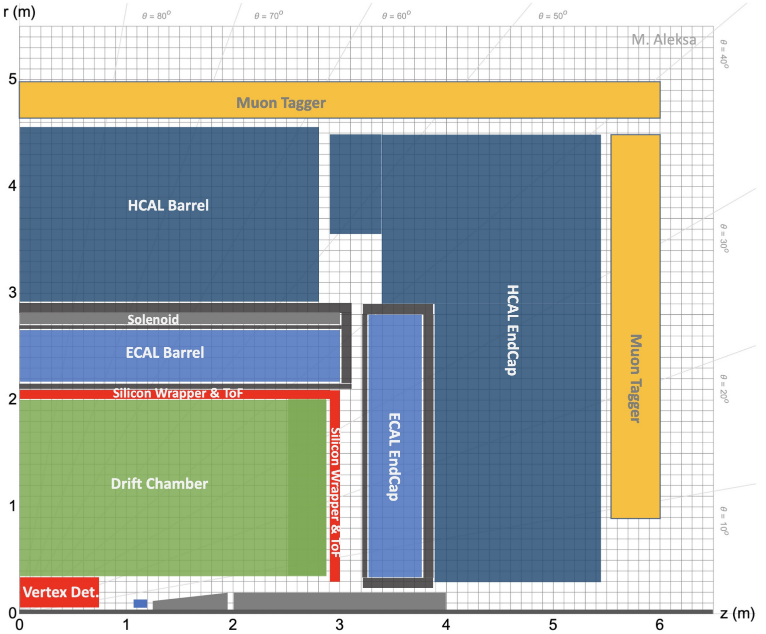
Towards a Full Detector Concept

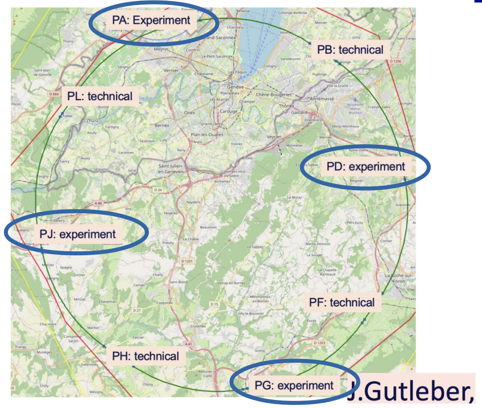
- **Two concepts proposed** for the FCC-ee **CDR**: CLD, IDEA
- **FCC-ee baseline** is now with **4 IP** → we need two more!
  - Currently also working on a **full detector concept** for **FCC-ee, ALLEGRO** (A Lepton coLlider Experiment with highly GRanular calorimetry Read-Out)

Main components for the baseline scenario (still evolving)

- Tracker: Drift Chamber (low rates, relaxed triggering needs)
- Highly granular Noble Liquid ECAL
- Superconducting solenoid after ECAL, sharing same cryostat
- Highly granular HCAL: Scintillator + Iron (return yoke)
- Muon ~~Tracker~~ → Tagger (low momentum → μ_{Pt} from tracker)
- Short term next step:
  - Choose the magnet position (track resolution, particle flow performance, cost)
    - Ensure sufficient guiding of the field lines (stray field)

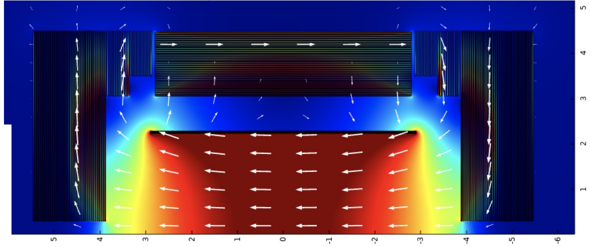
Possible layout for ALLEGRO detector concept



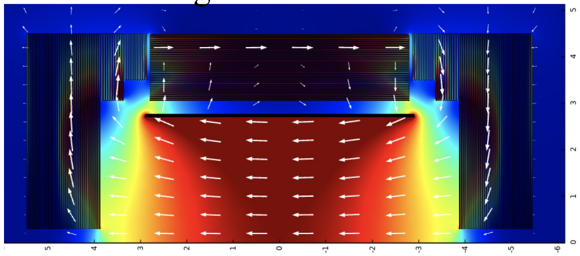


J.Gutleber,

Magnet inside ECAL

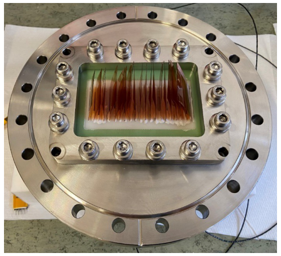


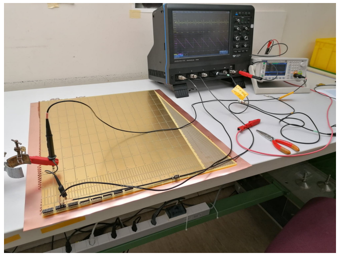
Magnet outside ECAL

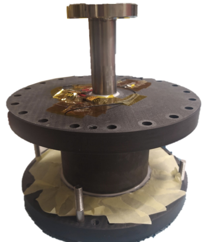


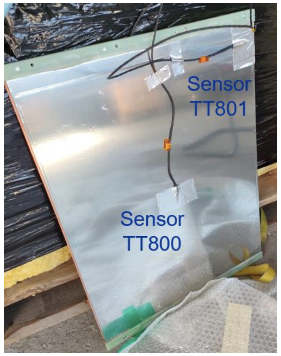
Conclusions

- The FCC integrated program has an immense physics potential
- One has to prepare detectors able to make the best out of those data, exploiting new technologies
- Noble Liquid calorimeters are proposed both for FCC-ee and FCC-hh
- The technology is being adapted for 4/5D calorimetry while preserving its excellent conventional calorimetry properties
- We are now highly confident that it can be done
  - MIP <S/N> > 5 can be achieved (also with warm electronics)
  - High granularity electrodes produced and tested
    - Cross-talk ~ 1% easily achievable
  - Several options for signal extraction identified
  - Carbon fibre cryostat manufacturing well advanced
- We are at the proof of concept level but all lights are green
  - Moving now to the next stage: **design and build a full module prototype for test beam!**









Thank You!

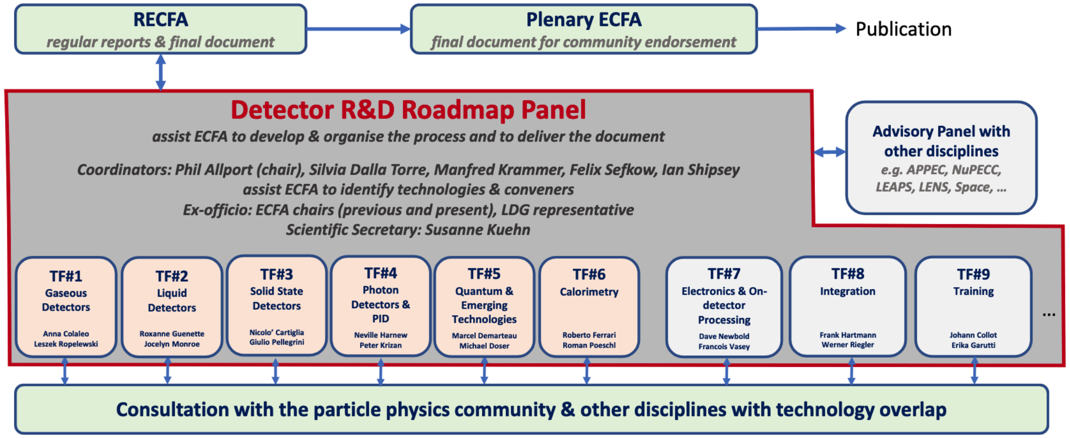
Bibliography

- Calorimeters for the FCC-hh
- Calorimetry at FCC-ee
- Noble liquid calorimetry for a future FCC-ee experiment

Additional material

Support from the Community

- Future Noble Liquid Calorimetry project strongly supported by CERN EP R&D
- Few institute already joined the effort
    - Main contribution (except CERN): IJCLab (Paris), Charles University (Prague)



RECFA
regular reports & final document

Plenary ECFA
final document for community endorsement

Publication

Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document

Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chairs (previous and present), LDG representative
Scientific Secretary: Susanne Kuehn

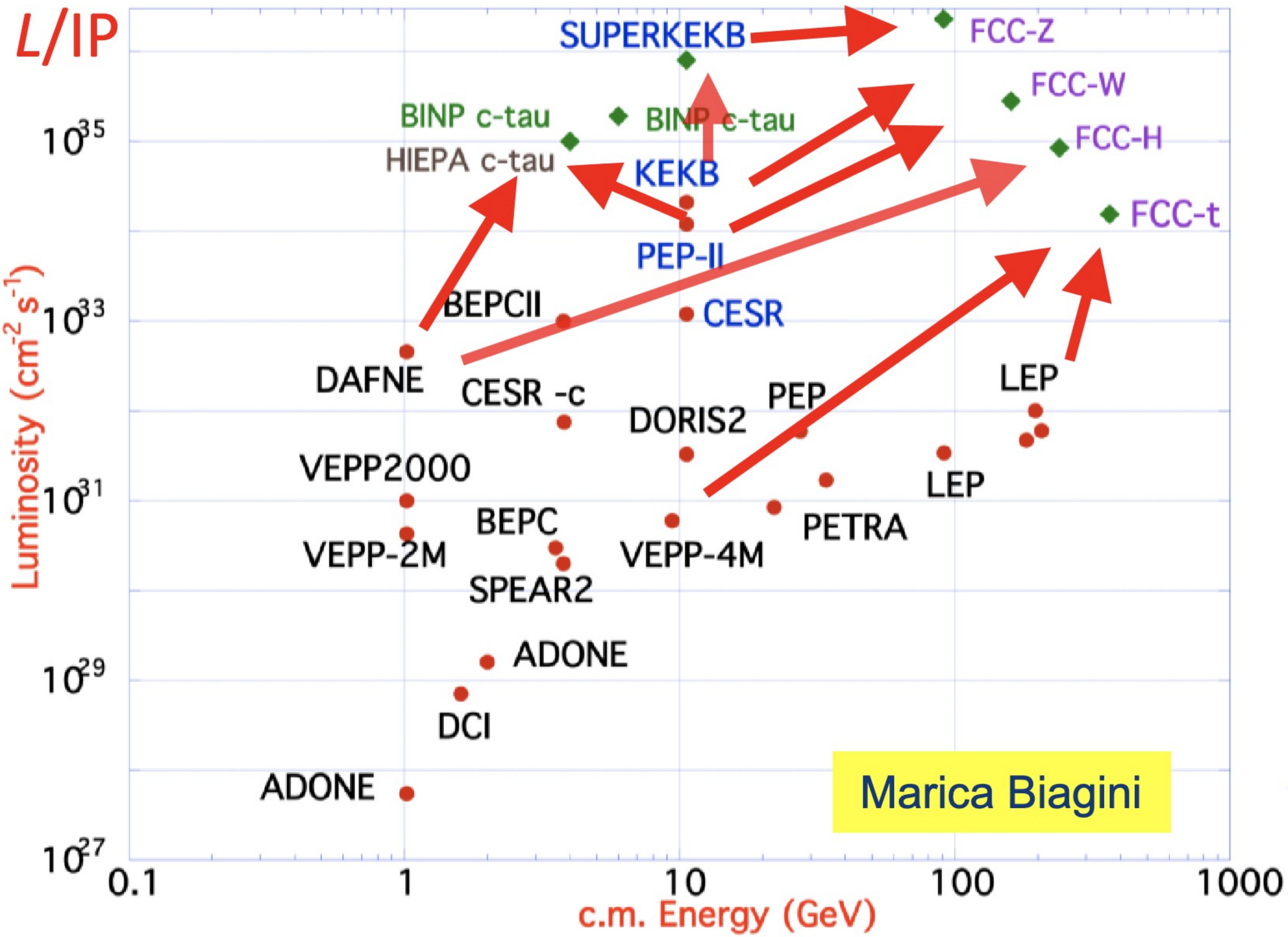
Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, Space, …

TF#1 Gaseous Detectors – Anna Colaleo, Leszek Ropelewski
TF#2 Liquid Detectors – Roxanne Guenette, Jocelyn Monroe
TF#3 Solid State Detectors – Nicolo' Cartiglia, Giulio Pellegrini
TF#4 Photon Detectors & PID – Neville Harnew, Peter Krizan
TF#5 Quantum & Emerging Technologies – Marcel Demarteau, Michael Doser
TF#6 Calorimetry – Roberto Ferrari, Roman Poeschl
TF#7 Electronics & On-detector Processing – Dave Newbold, Francois Vasey
TF#8 Integration – Frank Hartmann, Werner Riegler
TF#9 Training – Johann Collot, Erika Garutti
…

Consultation with the particle physics community & other disciplines with technology overlap

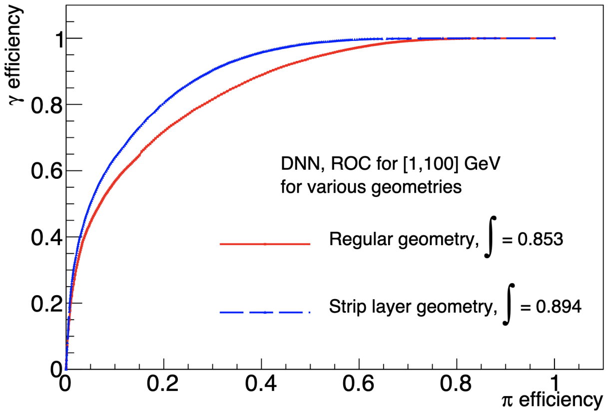
- Currently building proto-collaborations through the **ECFA Detector R&D roadmap** process
    - Mandate: "Identify and describe a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics program in the near and long term."
    - Noble Liquid R&D is fully part of the Calorimetry task force (TF6)
        - Community meeting and R&D roadmap symposium
        - Included in the roadmap document, endorsed by ECFA and the CERN Council
- In parallel, starting to build FCC-ee detector concept proto-collaborations

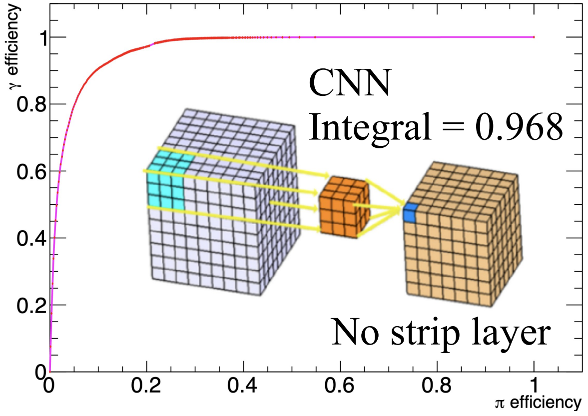
FCC-ee vs Past Lepton Colliders



Particle Identification

- π^0/γ separation studied with different MVA and geometries
  - π^0 and γ particle gun, 100 k events each, [1 – 100] GeV uniformly distributed in Φ and θ, with and without strip layer
  - DNN with ~15 variables
    - No loss of perf. w/ one training for the whole energy range w.r.t. energy specific trainings (parametrized DNN with $E_{Cluster}$)
  - 3D Convolutional NN (CNN) with 10 x 10 x 12 window
    - Tremendous improvement w.r.t. DNN
  - Hybrid NN (**HNN**) with both DNN and CNN
    - **95% γ efficiency for 10% π^0 contamination** for the whole energy range (**no strip layer** + baseline **conservative** geometry)





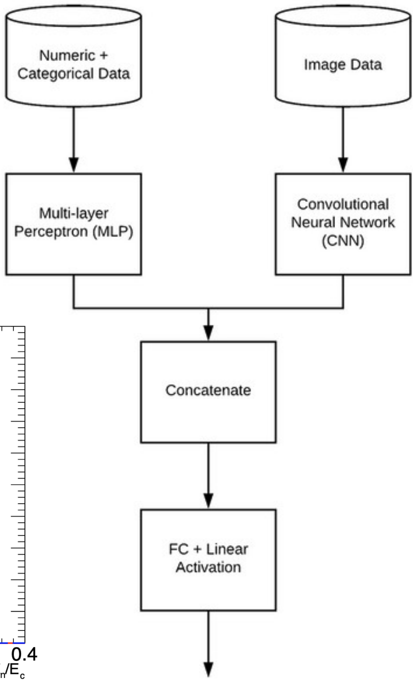

Numeric + Categorical Data

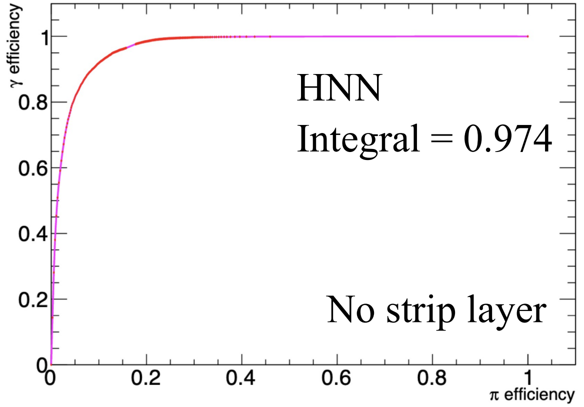
Image Data

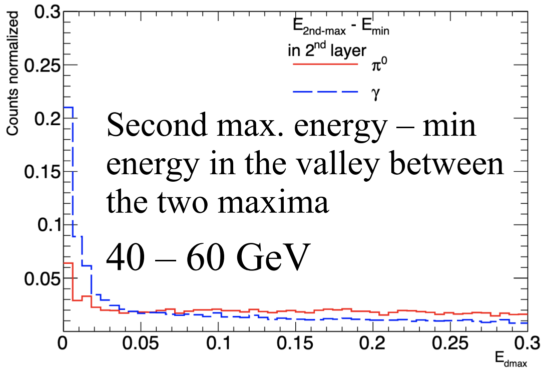
Multi-layer Perceptron (MLP)

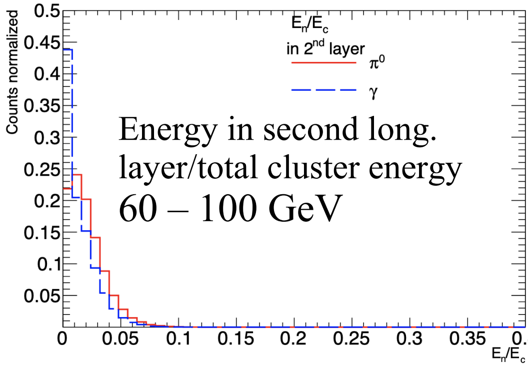
Convolutional Neural Network (CNN)

Concatenate

FC + Linear Activation

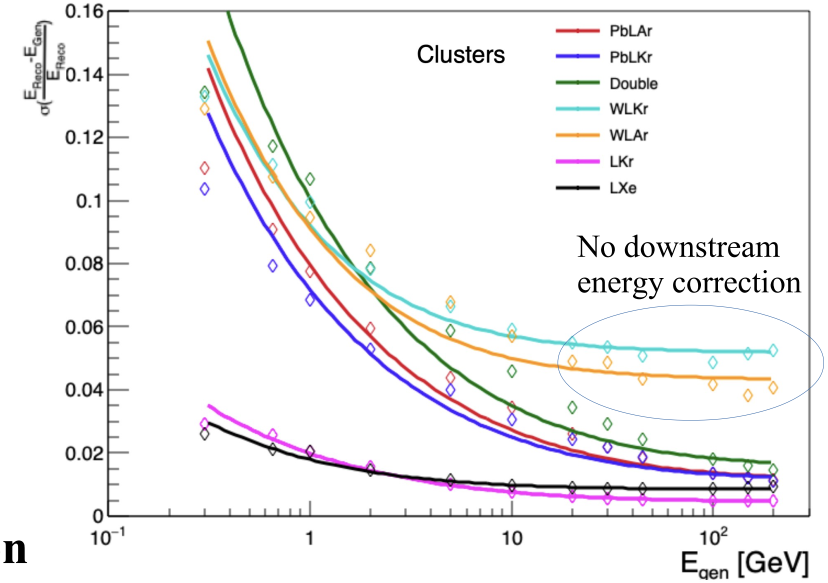






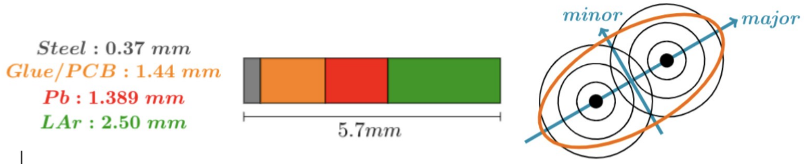
Performance Studies

- 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



No downstream energy correction

- 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



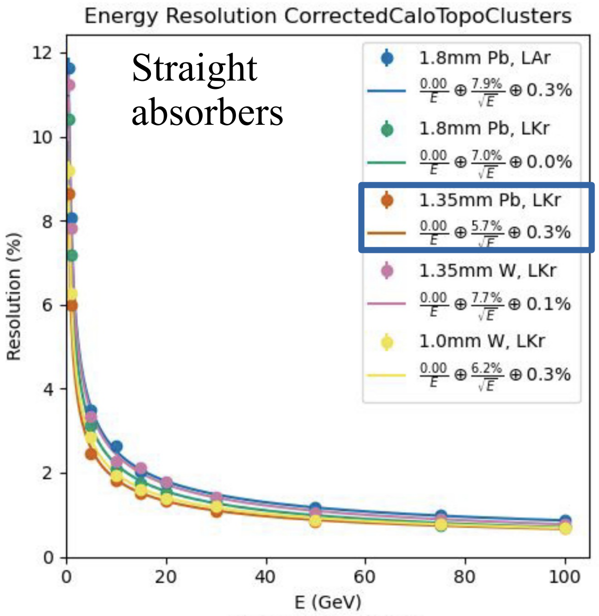
Recon → Gen ↓	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm \pi^0 \nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0 \nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm 3\pi^0 \nu$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

  - 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

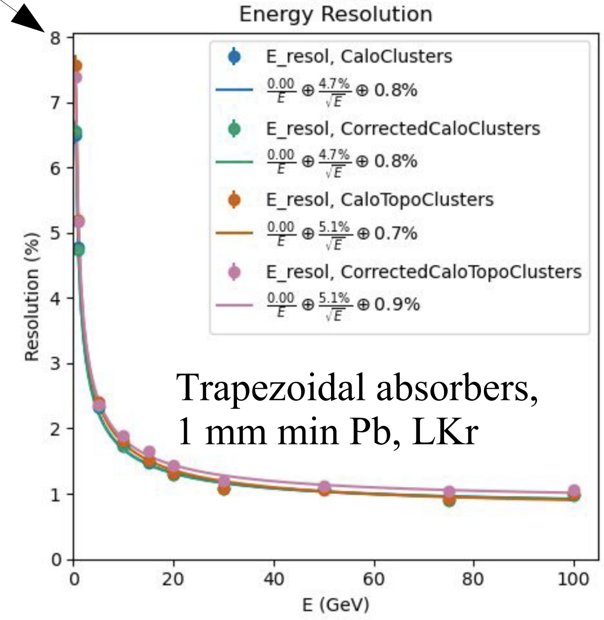
Further Possible Geometries

Other geometries are under consideration

- **LKr** sensitive media
  - Better sampling term: 7% w/o touching absorber, 6% w/ thinner absorbers (keeping same total #X_0's)
- **Trapezoidal absorber** → constant sampling fraction per layer
  - 5% sampling term
  - Easier high voltage distribution
- Thinner Pb absorbers + higher radial extent (not shown here)
  - Increased sampling fraction
- **W absorbers** instead of Pb
  - Smaller R_M and radial extent
- Many handles to bring the **sampling term down to $\mathcal{O}$(5%)!**
  - **Mechanical engineering campaign** started to investigate those options
- Further performance squeezing (esp. constant term) possible through improvement of clustering and calibration (MVA calibration)



Straight absorbers

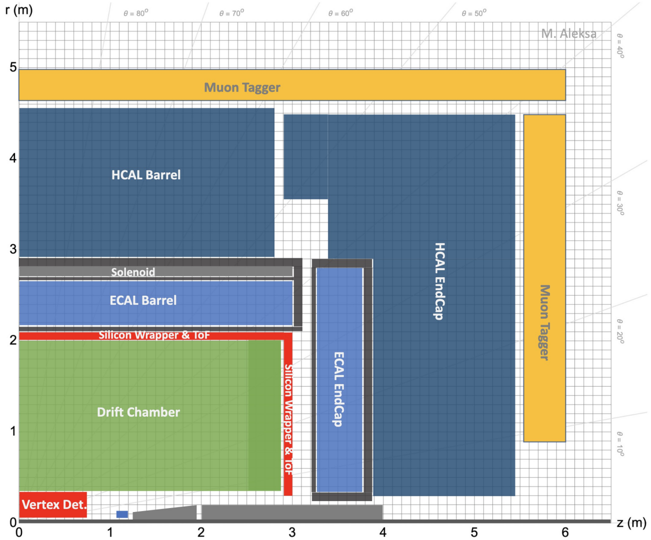


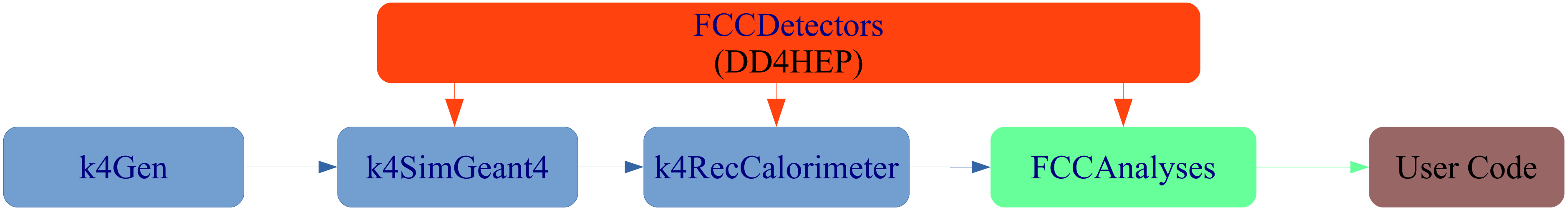
Trapezoidal absorbers, 1 mm min Pb, LKr

Software Implementation

Full simulation in Key4HEP

- Factorized Detector building (DD4HEP): no need to recompile when changing simple detector parameters
- Includes **all the first order effects**: sampling fraction, dead material correction, noise, clustering, …
- Most of the corrections can be automatically derived upon geometry change
- Working on a **complete detector implementation**
  - ECAL endcap and HCAL almost there, tracker from IDEA, muon tagger as sensitive plates for now





FCCDetectors (DD4HEP)

k4Gen → k4SimGeant4 → k4RecCalorimeter → FCCAnalyses → User Code

k4Gen

Monte Carlo Generation

Physics collision or Particle Gun

k4SimGeant4

Detector description

Particle interaction and propagation

Energy deposits

k4RecCalorimeter

Energy deposits per physical cells/readout channel

Noise

Corrections (sampling fraction, dead material correction)

Clusterings

FCCAnalyses

Plain ROOT n-tuple production

High-level variable computation

Originally used to make analysis macros 'dataformat agnostic' but turned out to bring way more!

User Code

Automation

Reco/Gen comparison

Plots!

\+ k4FWCore for Podio services and very generic tools

Gaudi based

X-talk: simulation VS measurement

Comprehensive x-talk measurements with 2, 1 and 0 shields

Preliminary!

Observations from meas.

- Good qualitative behavior
  - Highest x-talk on cell 6
  - The shield mitigate x-talk
  - Cell 4 and 5 show similar values, idem for cell 2 and 3
  - …
- **Confirms that it is easy to get x-talk < 1 %, even without shields!**
- After signal shaping, most of the measured x-talk values are within the same ball-park as the simulated ones
- Quantitative agreement is sometimes poor (especially for small signals or short shaping)

Simulation, 2 shields

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

Measurement, 2 shields

Cross-talk (%) Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	1.66	0.69	0.84	0.78	0.5	2.9
20	0.2	0.07	0.08	0.24	0.21	0.61
50	0.08	0.03	0.03	0.1	0.09	0.28
100	0.04	0.02	0.01	0.06	0.05	0.2
150	0.04	0.02	0.01	0.04	0.04	0.17
200	0.03	0.03	0.01	0.04	0.03	0.15
300	0.02	0.03	0.01	0.03	0.03	0.14

Simulation, 1 shield

Cross-talk (%) Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	2.42	0.82	0.87	3.86	4.14	10.36
20	0.4	0.05	0.04	0.58	0.58	1.72
50	0.18	0.02	0.01	0.26	0.26	0.79
100	0.1	0.01	0.0	0.14	0.14	0.45
150	0.07	0.01	0.0	0.11	0.11	0.34
200	0.06	0.0	0.0	0.09	0.09	0.28
300	0.05	0.0	0.0	0.07	0.07	0.23

Measurement, 1 shield

Cross-talk (%) Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	2.91	1.36	1.5	2.16	1.98	3.59
20	0.62	0.22	0.28	0.52	0.46	0.99
50	0.26	0.08	0.11	0.23	0.2	0.43
100	0.19	0.08	0.09	0.14	0.14	0.27
150	0.17	0.07	0.08	0.12	0.12	0.23
200	0.15	0.08	0.08	0.11	0.11	0.2
300	0.17	0.09	0.09	0.1	0.12	0.16

Simulation, 0 shield

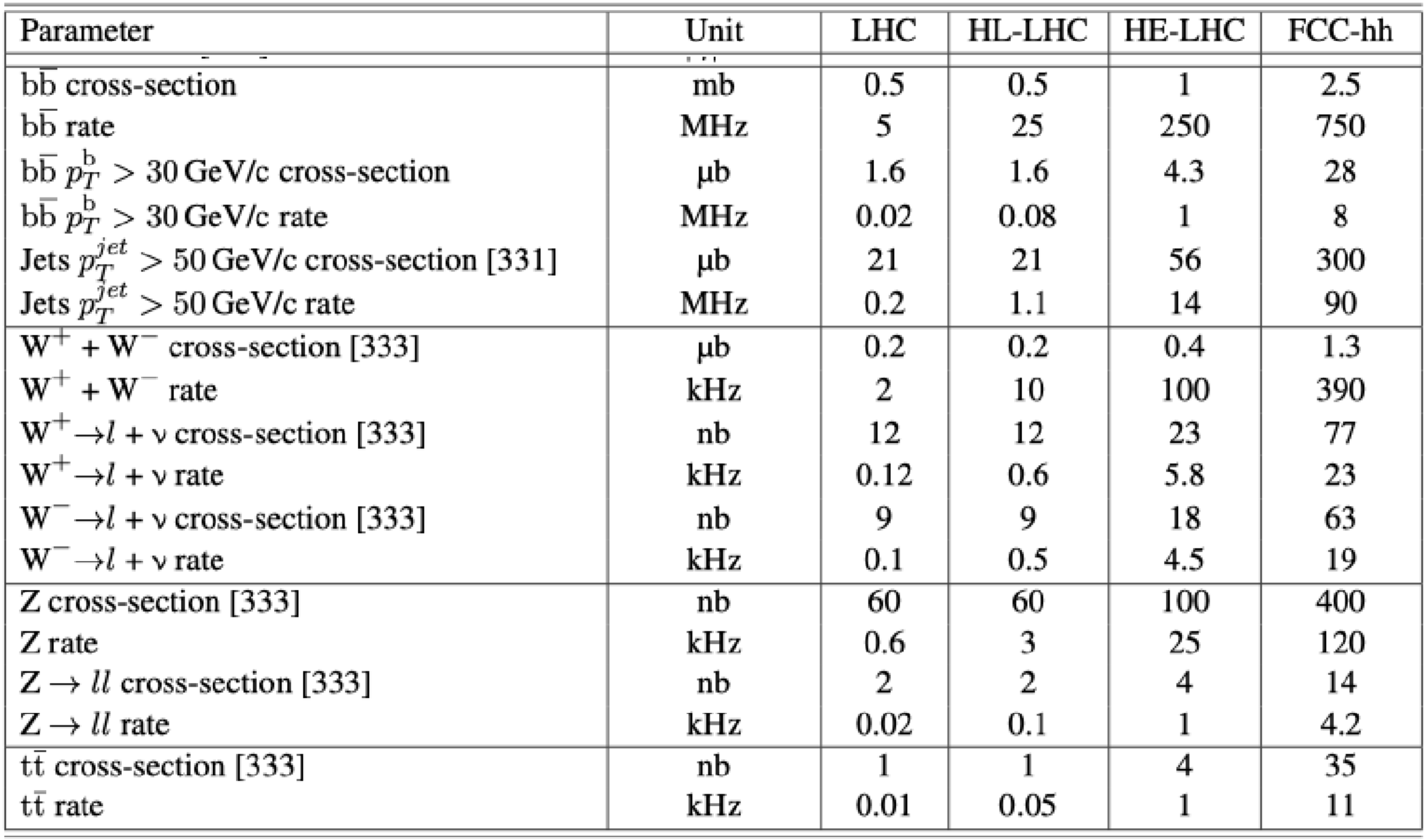
Cross-talk (%) Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	6.27	2.6	3.2	8.75	8.61	15.96
20	0.7	0.1	0.1	0.99	0.92	2.58
50	0.3	0.02	0.02	0.43	0.4	1.14
100	0.17	0.01	0.01	0.24	0.23	0.64
150	0.13	0.01	0.0	0.18	0.17	0.48
200	0.1	0.01	0.0	0.15	0.14	0.4
300	0.08	0.0	0.0	0.12	0.11	0.32

Measurement, 0 shield

Cross-talk (%) Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	3.41	1.35	1.73	2.96	2.79	5.36
20	0.87	0.3	0.45	0.79	0.73	1.49
50	0.36	0.11	0.19	0.35	0.32	0.65
100	0.2	0.05	0.13	0.21	0.19	0.39
150	0.17	0.04	0.11	0.17	0.16	0.32
200	0.14	0.04	0.1	0.14	0.14	0.28
300	0.11	0.03	0.1	0.12	0.12	0.23

FCC-hh Trigger/DAQ

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



Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^b > 30$ GeV/c cross-section	μb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{jet} > 50$ GeV/c cross-section [331]	μb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90
$W^+ + W^-$ cross-section [333]	μb	0.2	0.2	0.4	1.3
$W^+ + W^-$ rate	kHz	2	10	100	390
$W^+ \to l + \nu$ cross-section [333]	nb	12	12	23	77
$W^+ \to l + \nu$ rate	kHz	0.12	0.6	5.8	23
$W^- \to l + \nu$ cross-section [333]	nb	9	9	18	63
$W^- \to l + \nu$ rate	kHz	0.1	0.5	4.5	19
Z cross-section [333]	nb	60	60	100	400
Z rate	kHz	0.6	3	25	120
$Z \to ll$ cross-section [333]	nb	2	2	4	14
$Z \to ll$ rate	kHz	0.02	0.1	1	4.2
$t\bar{t}$ cross-section [333]	nb	1	1	4	35
$t\bar{t}$ rate	kHz	0.01	0.05	1	11

100MHz of jets p_T>50GeV

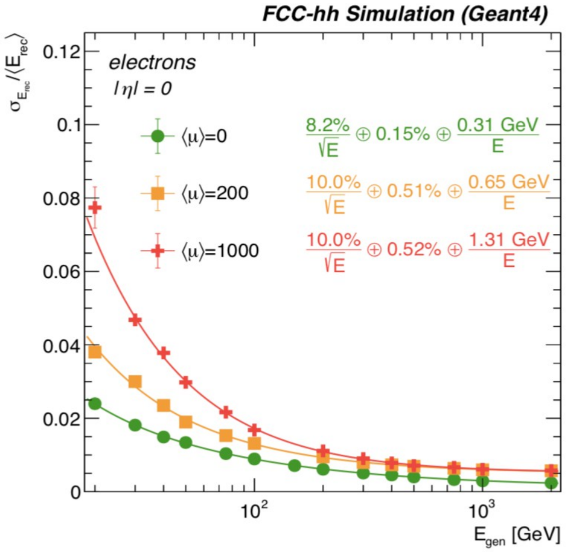
400kHz of Ws

120kHz of Zs

11kHz of Tops

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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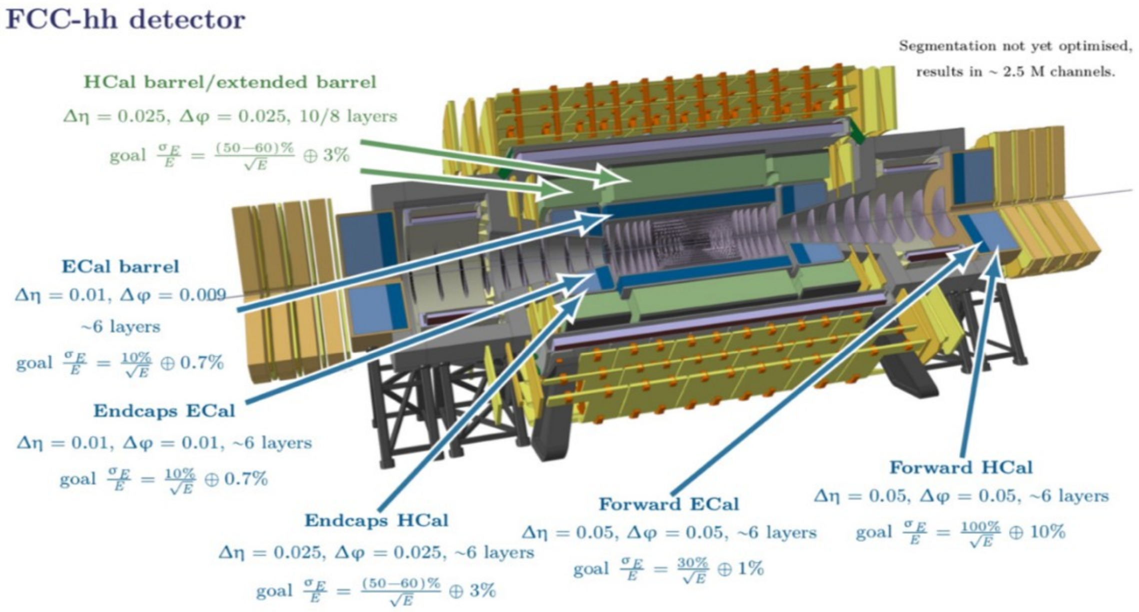
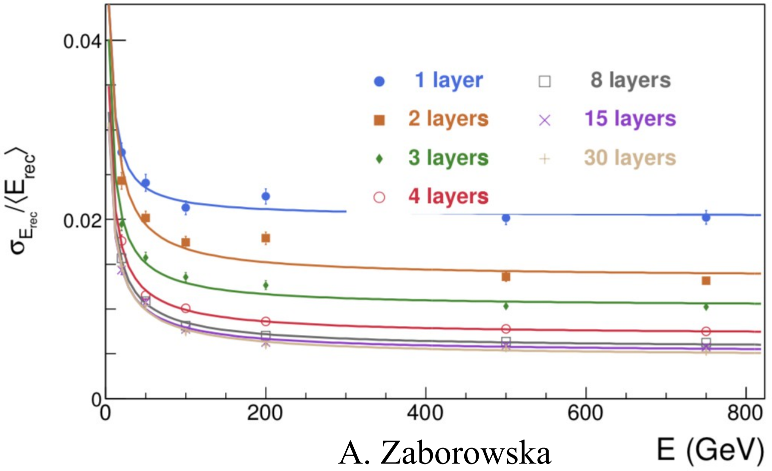
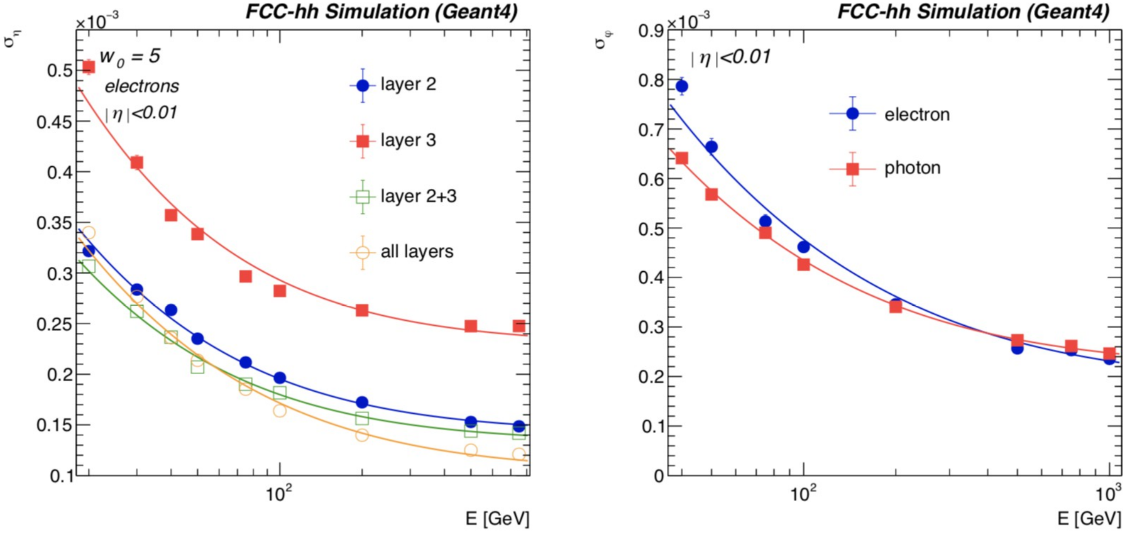




A. Zaborowska

FCC-hh Calorimeter Performance

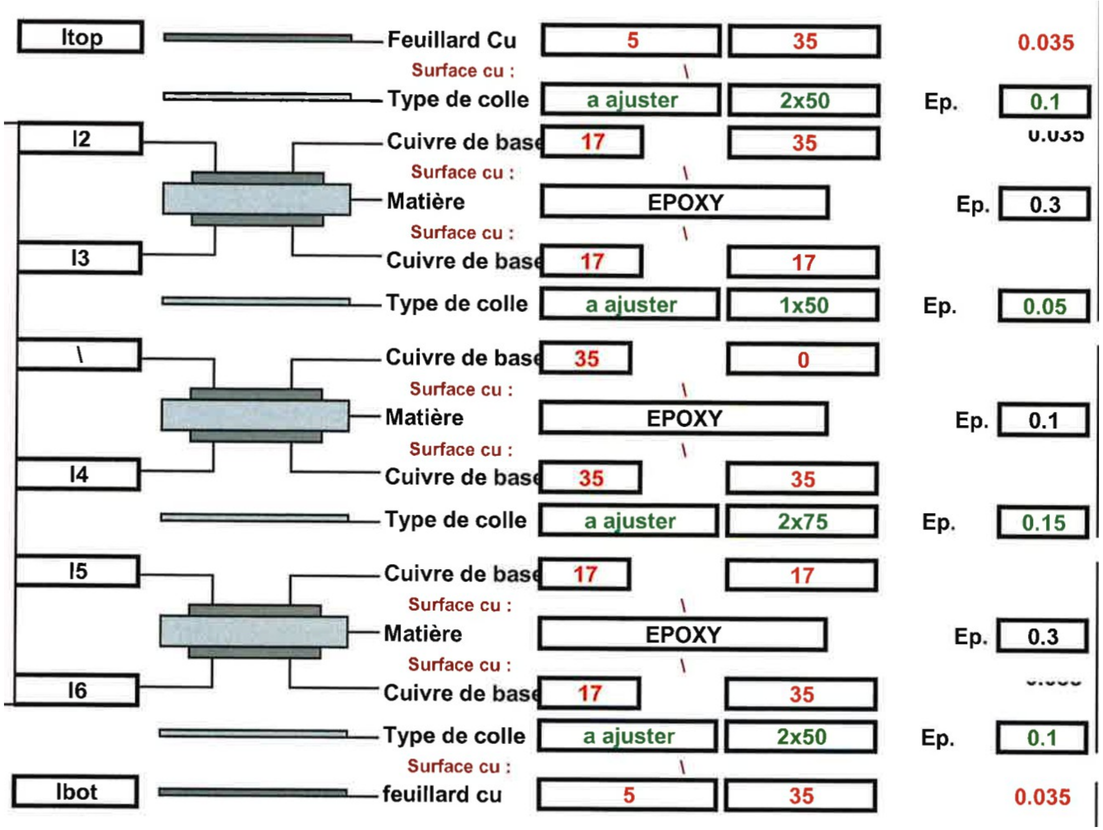
- Excellent jet energy resolution (30%/√E) needed to separate W and Z decays
  - Already close !
    - 37%/√E achieved for pions in FCC-hh simulations with calo-only information
    - Particle Flow will be used for a more realistic estimation (and will improve)
- Angular resolution



(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).

Odd number of layer PCB



Itop	Feuillard Cu	5	35		0.035
	Surface cu :	\			
	Type de colle	a ajuster	2x50	Ep.	0.1
I2	Cuivre de base	17	35		0.035
	Surface cu :	\			
	Matière	EPOXY		Ep.	0.3
	Surface cu :	\			
I3	Cuivre de base	17	17		
	Type de colle	a ajuster	1x50	Ep.	0.05
\	Cuivre de base	35	0		
	Surface cu :	\			
	Matière	EPOXY		Ep.	0.1
	Surface cu :	\			
I4	Cuivre de base	35	35		
	Type de colle	a ajuster	2x75	Ep.	0.15
I5	Cuivre de base	17	17		
	Surface cu :	\			
	Matière	EPOXY		Ep.	0.3
	Surface cu :	\			
I6	Cuivre de base	17	35		
	Type de colle	a ajuster	2x50	Ep.	0.1
	Surface cu :	\			
Ibot	feuillard cu	5	35		0.035

PCB prototype tower list

Tower 1: baseline

Tower 2: baseline

Tower 3: baseline

Tower 4: Additional ground shield between the signal trace from cells 8 and 9

Tower 5: GND plate instead of one via per shield

Tower 6: No via to inject signal directly on the pad

Tower 7: One shield (on l5)

Tower 8: No shield

Tower 9: Doubled width shields

Tower 10: Halved width shields

Tower 11: One shield with doubled width (on l5)

Tower 12: 70 Ohms (signal trace on the shield layer l3, one shield doubled width on l5, nothing on l4)

Tower 13: Outer radius extraction for cells 6 and 7

Tower 14: GND traces between strips (under the anti-etch of Cell 3 to Cell 4)

Tower 15: baseline

Tower 16: baseline

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

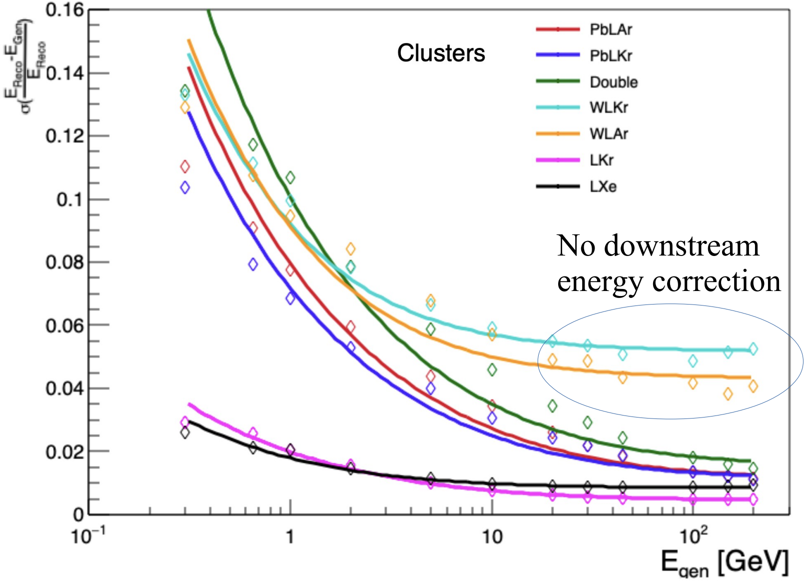
Clusters

	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

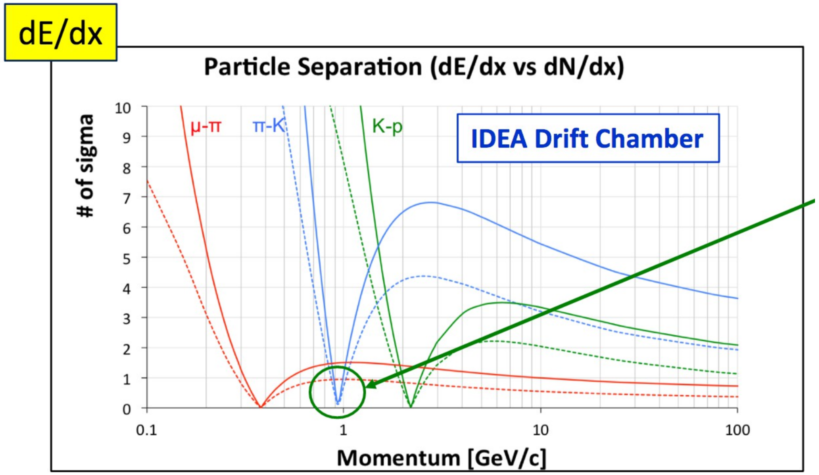
Mark Waterlaat

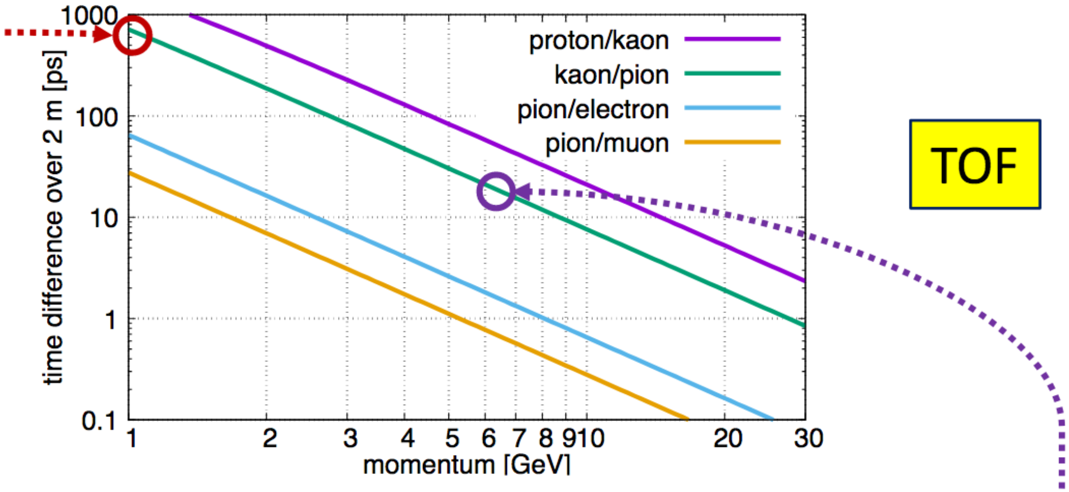


No downstream energy correction

Particle ID

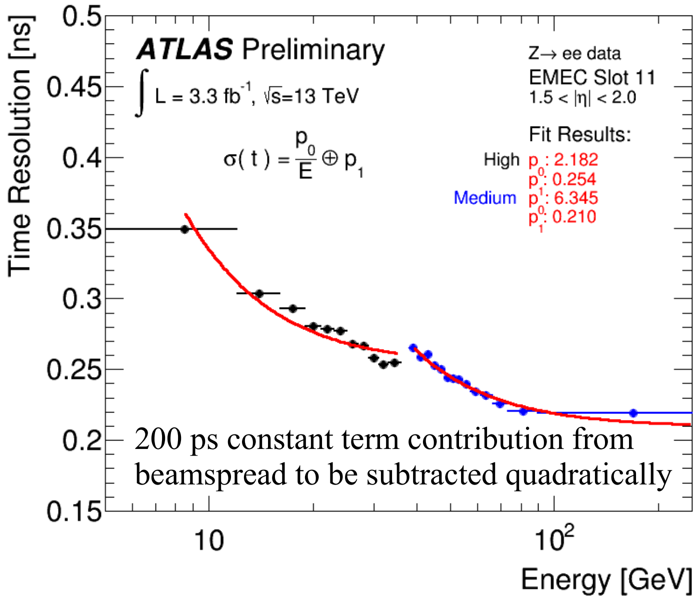
- dE/dx or dN/dx performs very well for particle ID, except in a few points where timing could help (low energy)





Timing

- Timing will play an important role in future colliders (PU removal, particle identification, heavy stable charged particles, …)
- Time resolution achieved by ATLAS
    - ~260 ps for EM showers ≥ 20 GeV, ~130 ps for EM showers ≥ 100 GeV
- **Time resolution needs to be evaluated and optimized with the new designs (and full readout chain)**
    - Depends on the shaping time
        - Which will mainly be driven by noise considerations for lepton colliders
    - Limitations: time-walk, stochastic ionization, cell inter-calibration
    - To be considered with the big (detector) picture in mind
        - Jitter from external sources
        - Do we have dedicated timing layers or not?
        - Do we have dE/dx or dN/dx for particle ID?



200 ps constant term contribution from beamspread to be subtracted quadratically

FCC-ee CLD calorimeter

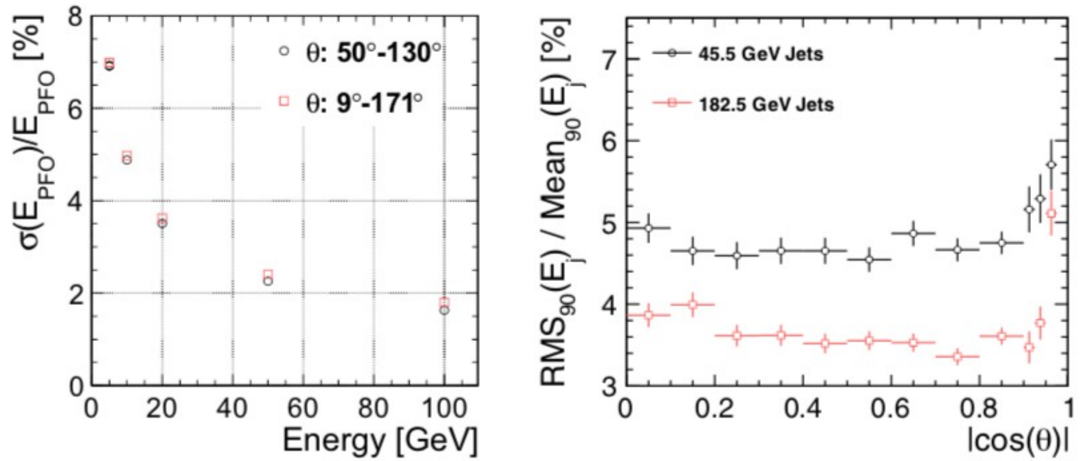


Fig. 7.8. CLD calorimeter performance. Photon energy resolution as a function of energy (left), comparing the barrel region with the full detector acceptance. Jet energy resolution for light quark jets as a function of polar angle (right).

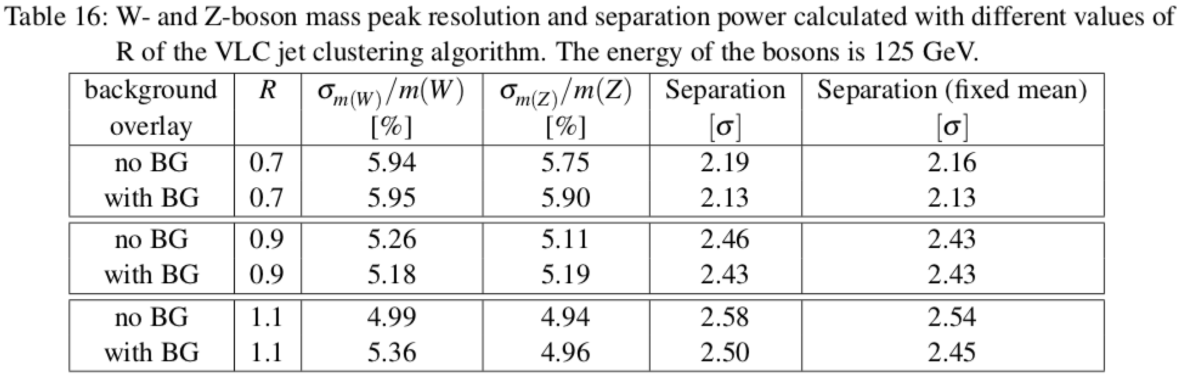
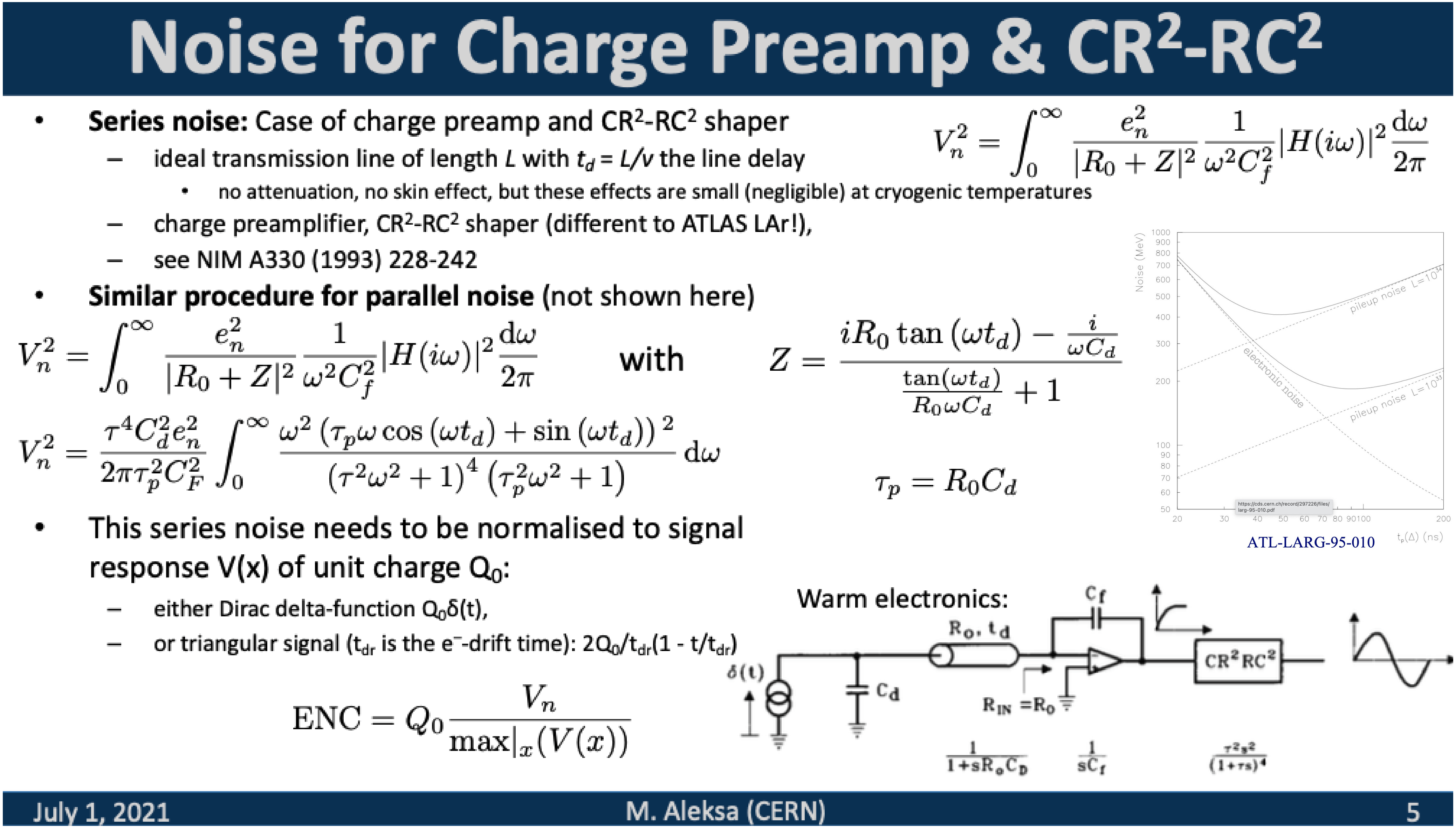


Table 16: W- and Z-boson mass peak resolution and separation power calculated with different values of R of the VLC jet clustering algorithm. The energy of the bosons is 125 GeV.

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 & CR²-RC²

- **Series noise:** Case of charge preamp and CR²-RC² 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, CR²-RC² shaper (different to ATLAS LAr!),
  - see NIM A330 (1993) 228-242

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

- **Similar procedure for parallel noise** (not shown here)

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

with

$$Z = \frac{iR_0\tan(\omega t_d) - \frac{i}{\omega C_d}}{\frac{\tan(\omega t_d)}{R_0\omega C_d}+1}$$

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

$$\tau_p = R_0 C_d$$

ATL-LARG-95-010

- 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): $2Q_0/t_{dr}(1 - t/t_{dr})$

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

Warm electronics:

July 1, 2021 M. Aleksa (CERN) 5