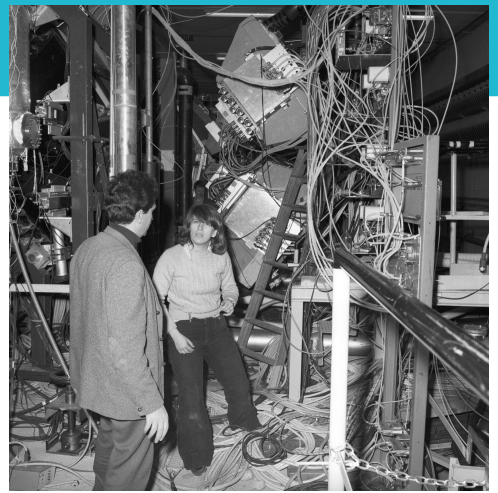
Future Noble liquid gas calo: progress on electrodes R&D

Nicolas **Morange**, *IJCLab*, on behalf of the Allegro team

AIDAInnova Annual meeting, 19/03/2024

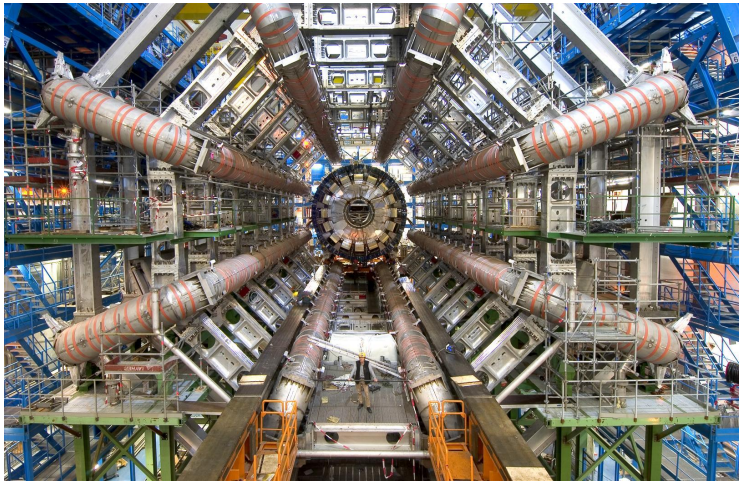
Noble liquid calorimeters



- Decades of success at particle physics experiments: from R806 to ATLAS
  - Mostly LAr, a bit of LKr
- An appealing option for FCC-ee
  - Good energy resolution
  - High(-ish) granularity achievable
  - Linearity, uniformity, long-term stability

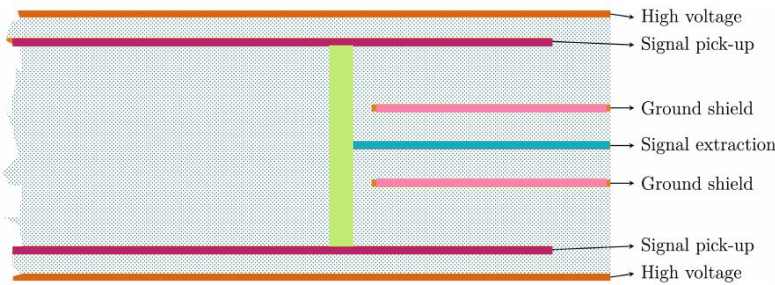
Excellent solution for small systematics

- Lots of interesting studies / R&D to do
  - Optimization for PFlow reconstruction
  - Achieving very low noise
  - Lightweight cryostats to minimize X_0
  - Designing for improved energy resolution



Granularity of Noble Liquid Calorimeters

- Calo design:
  - granularity of the calorimeter
    ⇔ granularity of the electrodes
- ATLAS: copper/kapton electrode
  - traces to read out middle cells take real estate on back layer
  - cannot really increase granularity
- FCC-ee requirements
  - High jet energy resolution needed
  - Particle flow algorithms take advantage of much finer granularity
- **Solution for Noble Liquid calo for FCC**
  - Multi-layer PCB to route signals inside



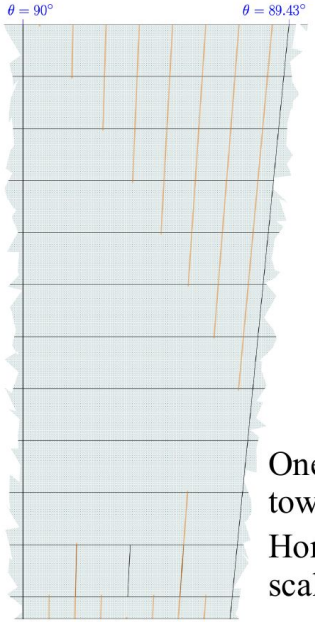
High granularity electrodes

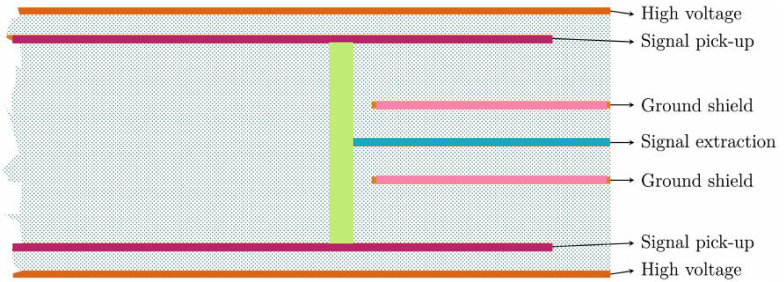
Aiming for ~ ×10 ATLAS granularity

- High granularity required for better PFlow performance (few million cells)
- >6 compartments to compensate LAr gap widening

Implementation: multi-layer PCBs

- 7-layer PCB
  - Signal collection on **readout planes**
  - Transmission through **via**
  - Signal extraction on **trace**
  - **Ground shields** to mitigate cross-talk
- Challenges
  - Trade-off capacitance (noise) / cross-talk
  - Maximum density of signal traces ?
- Studies on simulations and prototypes





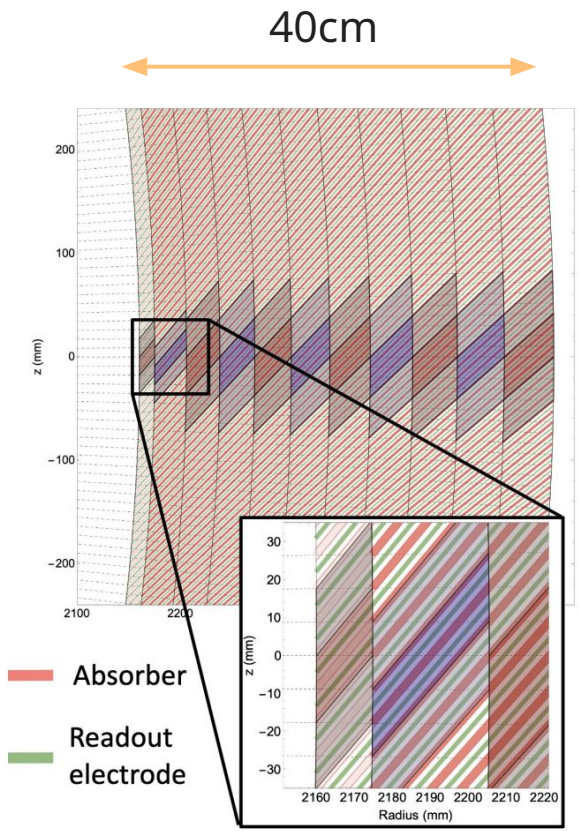
Allegro Barrel Design

Design driven by the solution used for electrodes

- 1536 **straight inclined** (50°) 1.8mm **Pb** absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm **LAr** gaps (**LKr** seriously considered)
- 40cm deep (22 X_0)
- $\Delta\theta$ = 10 (2.5) mrad for regular (strip) cells, $\Delta\phi$ = 8 mrad,
  12 longitudinal layers

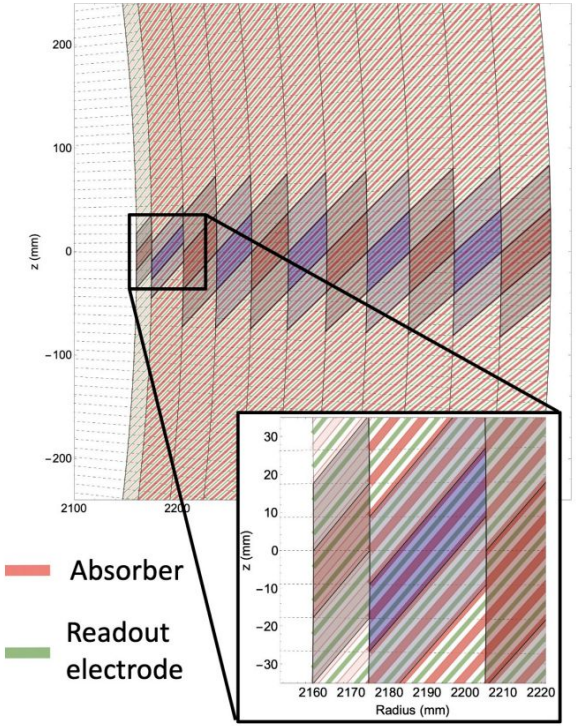
Copper electrodes: lots of flexibility

- Number of layers and granularity of layers fully optimizable
- Projective cells
- ➢ Lots of room for optimisation !

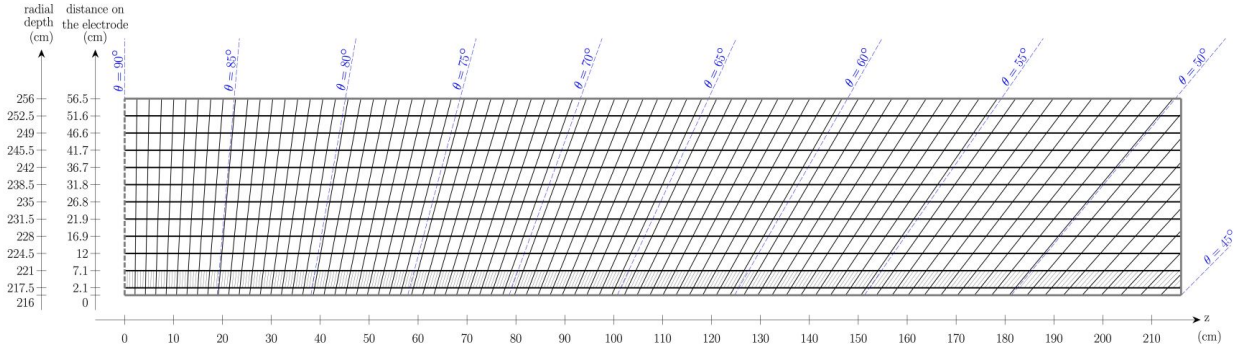


Geometry

Transverse



Longitudinal

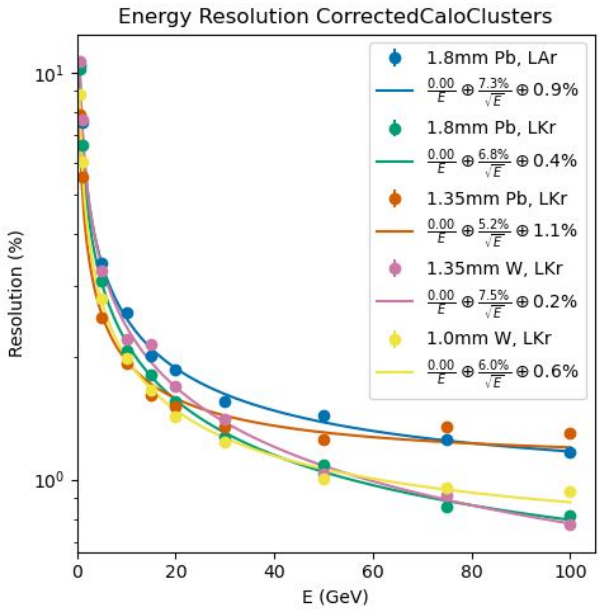


Simulation studies

Role of simulation studies

What is needed from the electrodes to fill the physics goals ?

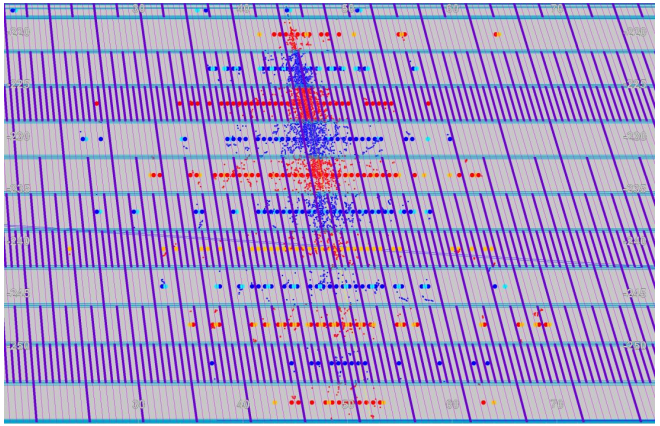
- Understand the required granularity
  - Study photon/pion ID (tau physics)
  - Axion searches
  - Jet energy reconstruction
  - Using 4D imaging techniques, ML, PFlow
- Optimize design for EM resolution
  - Electron and photon resolutions
  - Pions, b-physics
  - gap size, sampling fraction, active and passive material…



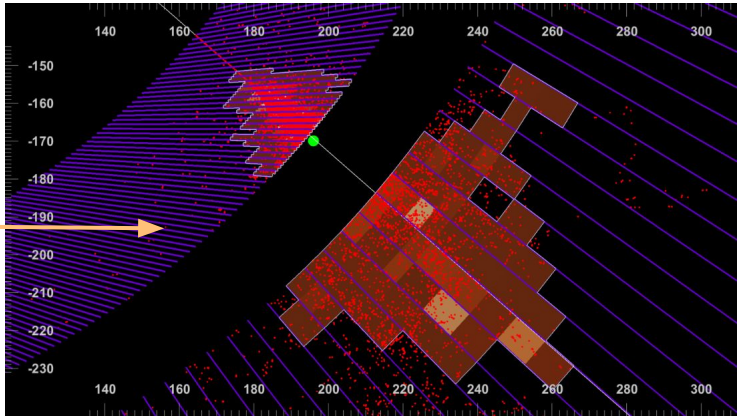
Simulation studies in key4hep

Lots of ground work in 2023 !

- Correct cells geometry was used in simulation but not in digi/reco
  - Now proper θ/ϕ positions used consistently everywhere
  - Much more flexible fullsim geometry:
    - Can easily change cells and layers sizes
    - Can adapt the granularity per layer



- Improvements in clustering
  - Topo-clustering and fixed-size clusters adapted to new geometry
  - Super nice tool to visualize showers and clusters
  - Topo-clustering using ECal+HCal

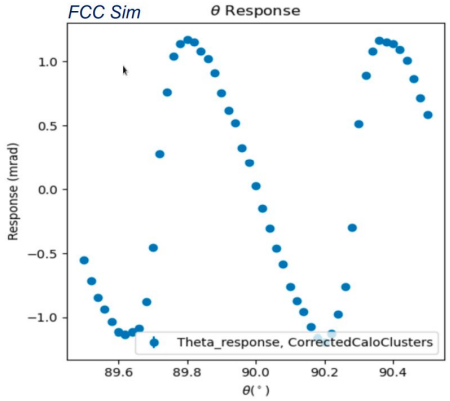


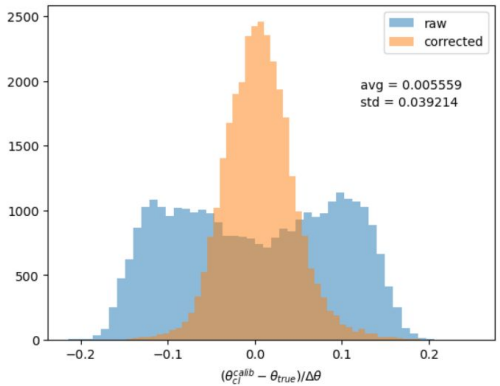
- Technical work
  - Follow FCC software evolution (k4geo)

Simulation studies: towards simu of calo performance

Ground work done this year enables performance optimization based on physics

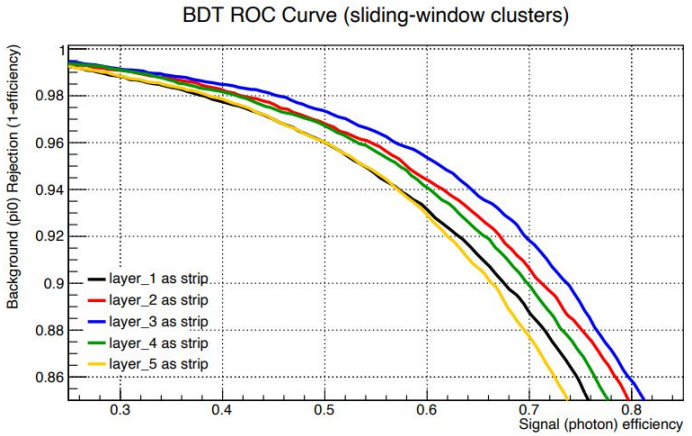
- Finer levels of energy calibration
  - "Rediscovery" of S-shape effects
  - Attempt corrections using log(E) weighting and MVA technique
- Towards cluster pointing reconstruction
  - Accurate position calibration per layer needed
  - Then extrapolate from barycenters



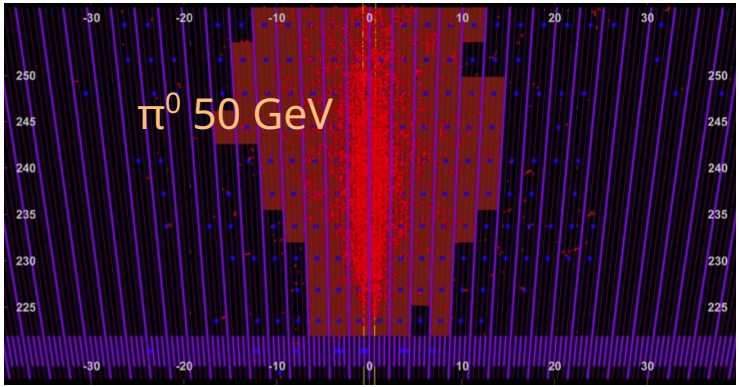


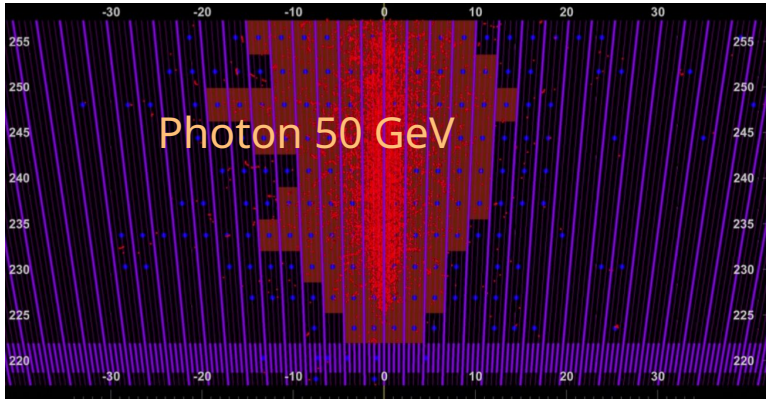
Simulation studies: Optimization of cell sizes

- Studies of photon / π^0 separation
  - Computations of shower shapes
  - Event displays show that position of "strip" layer is probably not correct
  - Preliminary studies (simple BDT) confirm the large room for improvement



- Implementation of cross-talk effects in simu ongoing
  - Necessary for accurate shower shape variables

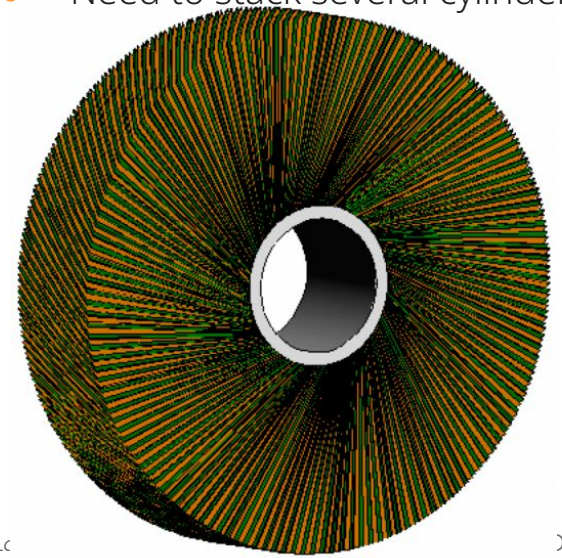




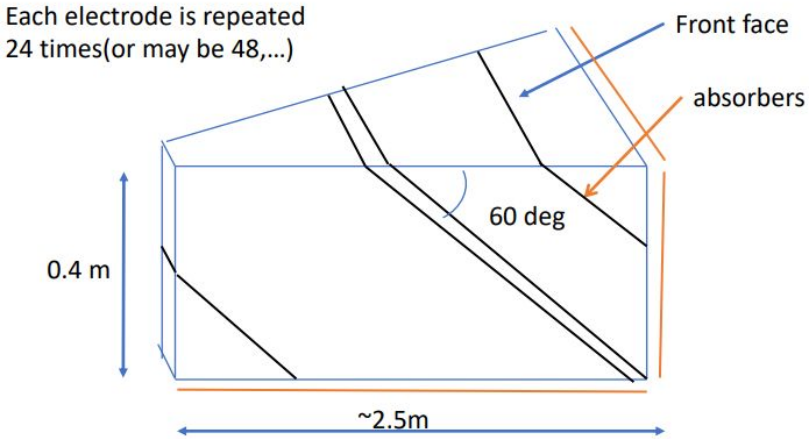
Designs for the endcaps: first ideas

Endcaps designs more complex than that of the barrel: very preliminary ideas !

- "Turbine" design
  - More similar to barrel design
  - Symmetric in ϕ
  - Issue: increase in the size of the Noble liquid gaps
  - Need to stack several cylinders



- XY / Pie wedge designs
  - Less symmetry in ϕ
  - Increase of LAr gaps under control
  - Many types of electrodes to draw and produce

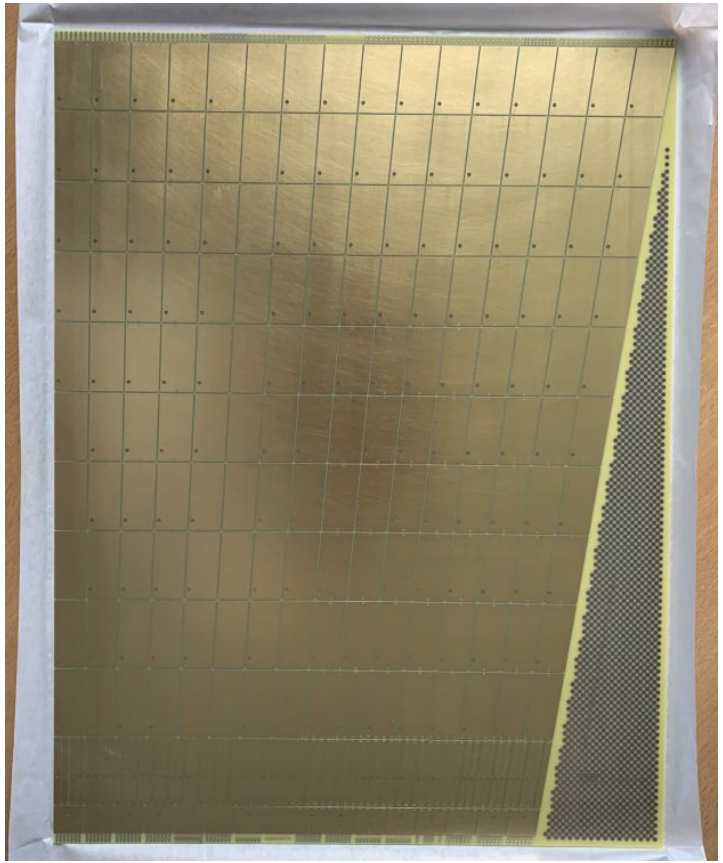


R&D on electrodes

Readout electrodes prototypes

Can we fill the physics goals, and what are the tradeoffs ?

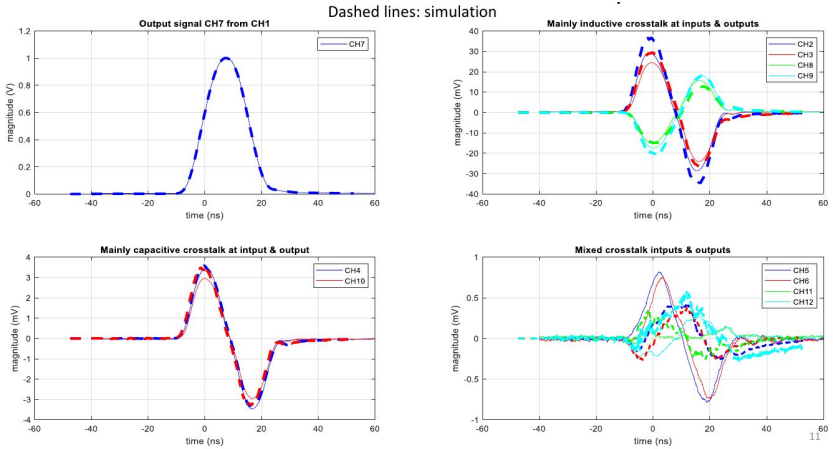
- Design questions
  - Achieving the optimal granularity as given by physics simulations
  - Minimise noise (aim for photons down to 300 MeV and S/N>5 for MIP)
  - Keep cross-talk at per-mille level
  - (noise and cross-talk depend on assumptions on readout electronics)
- Technical questions
  - Connectors to readout the signals
  - Design of HV layer, including resistors
  - Readout everything at the back

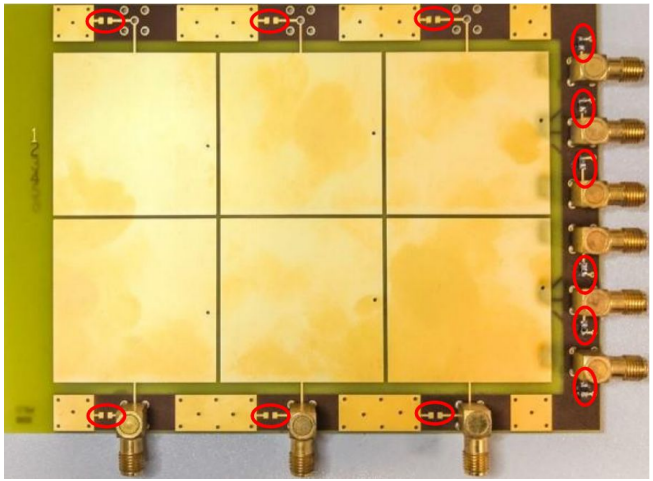


Prototype 2022-2023 @ IJCLab

Small-scale prototype designed for precision tests

- Detailed understanding of signal propagation and cross-talk effects
  - Cross-talk has capacitive but also inductive components
- Building knowledge of Sigrity simulation tool
  - Very good agreement with measurements after tuning !
- Fruitful discussions with PCB manufacturer to understand practical limitations of our design

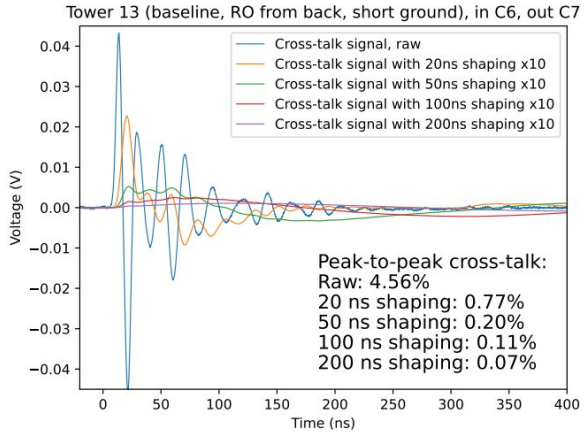


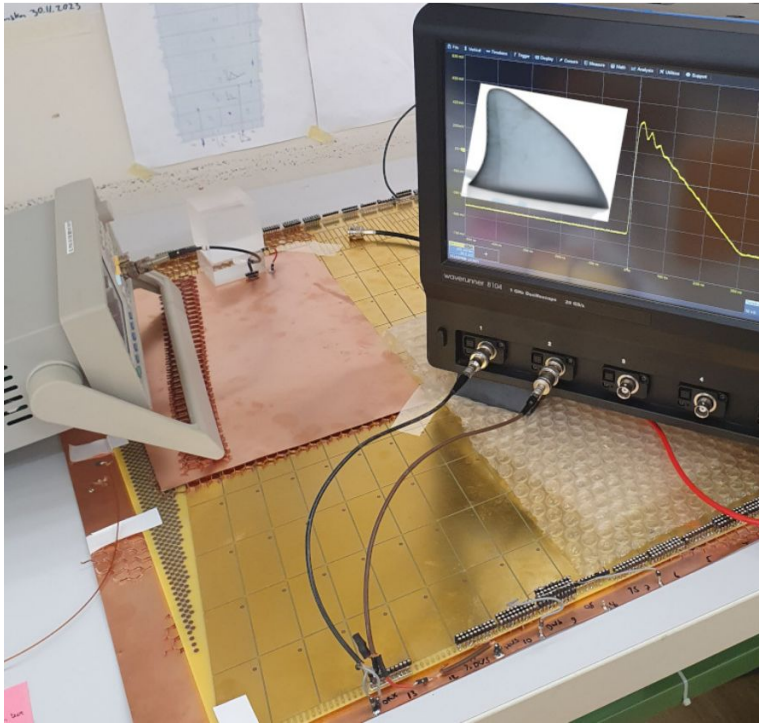


Electrode measurements @ CERN

Full scale electrode !

- Took quite some time and effort to achieve good measurements
  - Fruitful collaboration with IJCLab
  - Proper grounding, terminations, short cables…
- Extraction of cross-talks
  - Impact of shielding and of shaping time
  - Few per-mille easily achievable

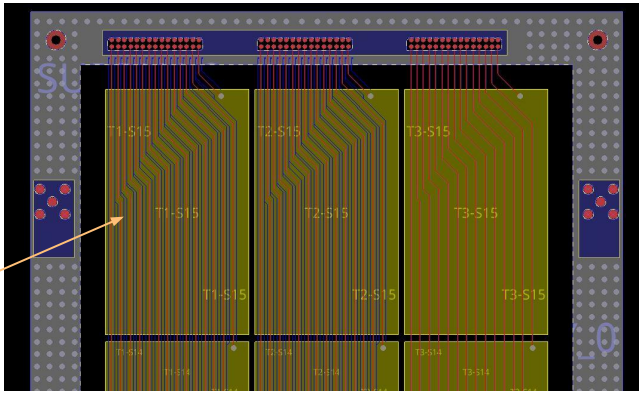


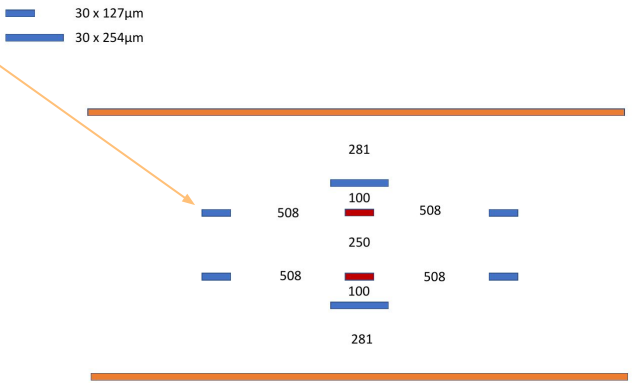


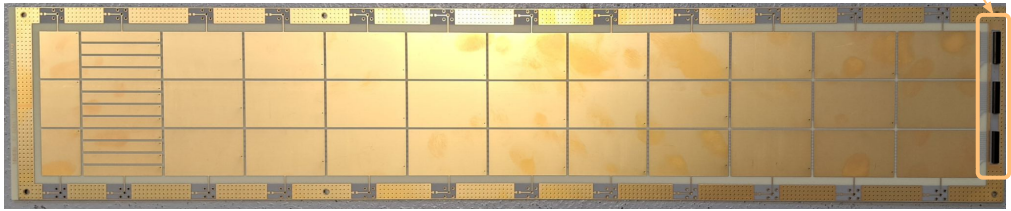
Prototyope 2024 @ IJCLab

Learning from the previous generation

- Next prototype at IJCLab
  - All layers, 3 towers
  - **Readout all cells at the back**
    - Best for material budget in calo, worst for cross-talk
  - Study options for **additional shielding**
  - **Connectors** for easy readout/injection
  - Possibility to merge several PCBs
  - Received January 2024





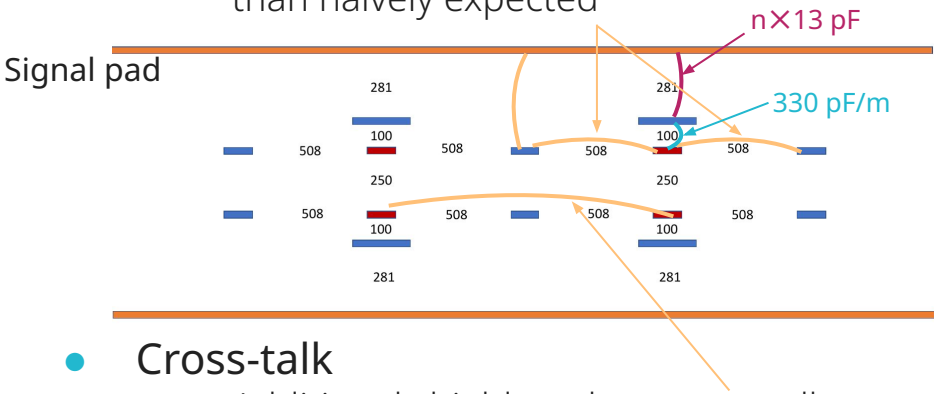


Prototyope 2024 @ IJCLab: first measurements

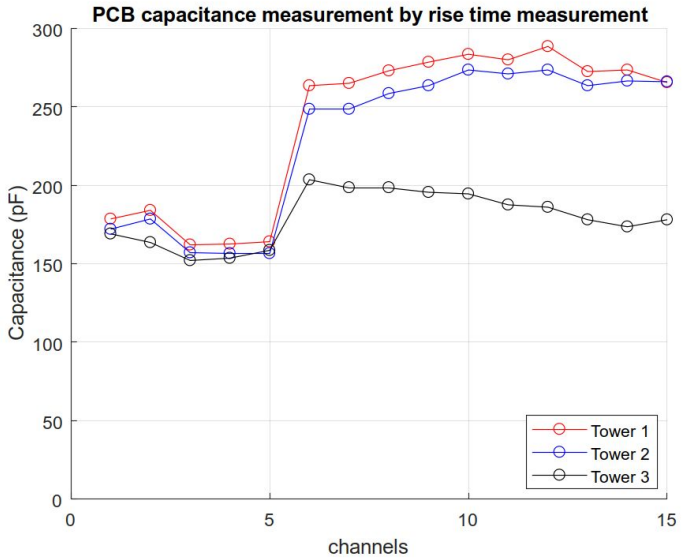
- Measurement of capacitances
  - Done at ~10kHz with capacimeter and ~10MHz with a RC setup (rise-time)
  - In agreement with each other
  - Impact of additional shielding larger than naively expected

Remember: capacitance means noise !

$$N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$



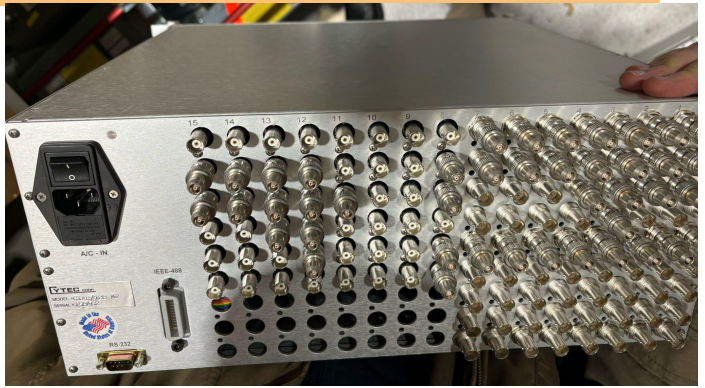
- Cross-talk
  - Additional shields reduce cross-talk capacitance
  - Confirm capacitive and inductive components of the cross-talk



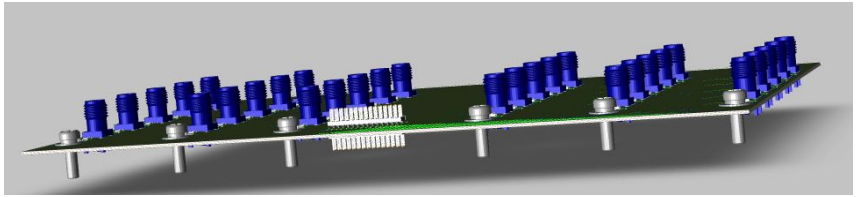
Towards automated measurements

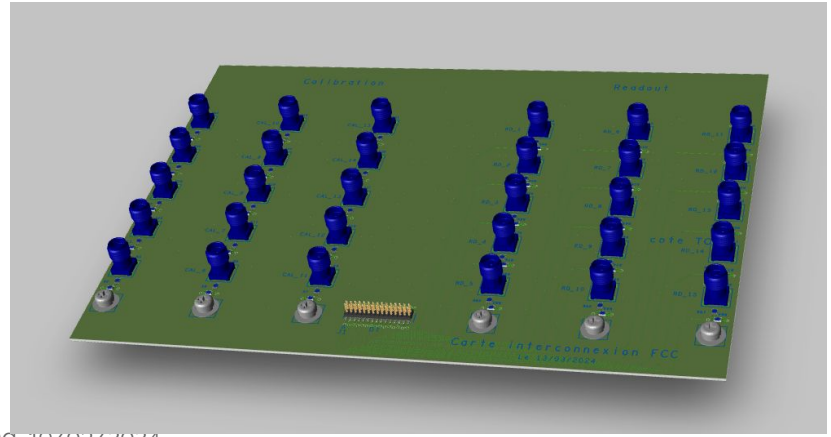
Getting the full measurement matrix “by hand” is quite tedious

- Setting up automated setup
  - Fanout board to go from connector to SMAs
  - Multiplexer crate to route signals to oscilloscope
  - Can also inject calibration signal through the connector
  - Can connect 2 electrodes together



- Status
  - Design of fanout board well advanced
  - Old multiplexer crate borrowed from ATLAS LAr





Conclusions

Even if milestone has been achieved in 2023, work on Noble liquid gas calo electrodes continue

- Simulations
  - Road to as accurate simu as possible to inform the design is long !
  - Great progress achieved in 2023
  - Expect conclusions from granularity optimisation studies in 2024
  - Other aspects of simulation progressing towards physics performance evaluation

- Electrode prototypes
  - Previous generation of prototypes very successful at demonstrating the concept
  - New electrode @ IJClab: validate detailed understanding on realistic scale electrode and demonstrate scaling up of measurements system
  - Next steps @ CERN: new full-scale prototype