Dual-Readout Fibre-Sampling Calorimeter for next lepton collider

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on behalf of the
IDEA Dual-Readout Calorimeter Collaboration

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FCC-ee calorimeters

- 100 kHz event rate, no background events
  - $\Rightarrow$ need to reconstruct all the final states, including the hadronic ones
  - $\Rightarrow$ need very good jet performances
- Need to resolve $Z \rightarrow qq$ from $W \rightarrow qq \Rightarrow$ target goal: $\sigma/E = 30\%/\sqrt{E}$
- For most channels $10\% - 15\%/\sqrt{E}$ is good for EM resolution
  - Higgs mass from $Z(ee)H$ comparable to $Z(\mu\mu)H$ if EM resolution $\lesssim 3\%/\sqrt{E}$

Dual readout for hadronic calorimeters

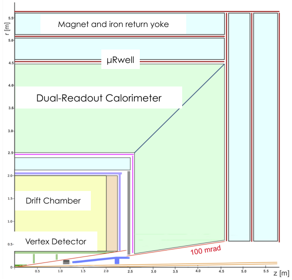
20-year-long experimental programme established the proof-of-principle

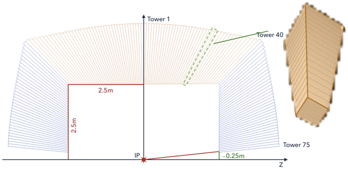
- A sizeable fraction of the particles produced in a hadronic shower are $\pi^0 \to \gamma\gamma$
- Different response to EM (e) or hadronic (h) components: usually $h/e < 1$
- Electromagnetic fraction f_{em} (30-70%) depends on the energy of the primary
  - $\Rightarrow$ non-linear calorimeter response to hadrons
- $\langle f_{em} \rangle$ fluctuations largely determine energy resolution
  - $\Rightarrow$ Measure the two components separately (dual readout)
- Dual readout works because h/e is constant and measurable from test-beams:
  - Use materials with very different h/e: e.g. scintillating and Cherenkov fibres
  - $\Rightarrow$ Linear detector, event-by-event correction for $\langle f_{em} \rangle$ fluctuations, symmetric response

- Silicon VTX detector plus ultra-low material drift chamber
- Thin solenoid in front of the calorimeter

Single, dual-readout calorimeter for EM and HAD calorimetry

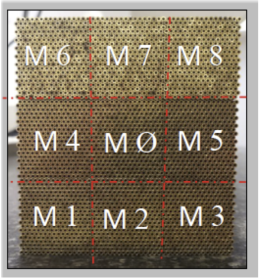
- Option with dedicated crystal ECAL in front
- O(100M) fibres embedded in steel tubes, read by SiPM
- Signals from 8 SiPMs grouped to reduce the number of channels to be read out
- No longitudinal segmentation out of the box
- High transverse granularity, excellent angular resolution
- Full simulation available, integration with DD4hep ongoing

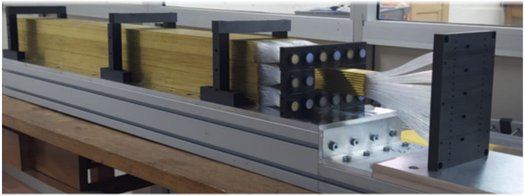




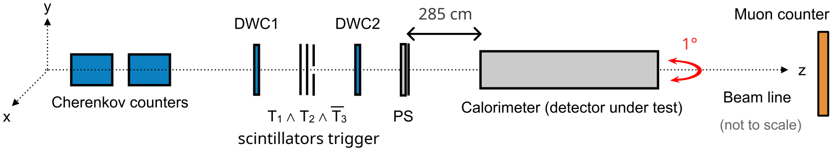
Test beam 2021: bucatini calorimeter

- Brass capillary tubes (Albion Alloys) as absorber and optical fibres as active material
- $100 \times 10 \times 10\,\mathrm{cm}^3$, efficient containment of electromagnetic showers (94% at 100 GeV)
- 9x320 capillary tubes, using Cherenkov and scintillating fibres
- Molière radius: 23.8 mm, radiation length: 22.7 mm
- Central module: each fibre read by SiPM (Hamamatsu S14160-1315 PS)
- Simultaneous readout via high-gain and low-gain amplifier chains, with Caen A5202 (Citiroc1A readout chip)





Test beam 2021: setup

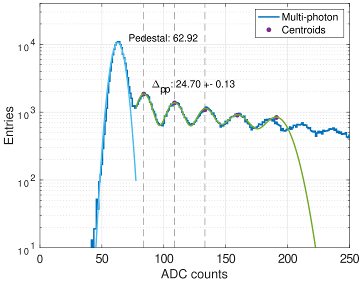


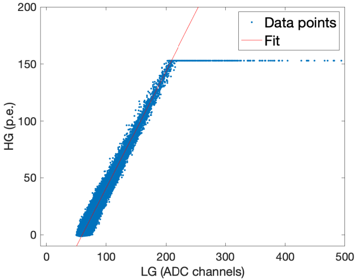
Several issues:

- Positron beam highly contaminated with hadrons
- Preshower placed far from front face of calorimeter due to access restrictions: induced shower lateral leakage
- Calorimeter tilted by 1° to avoid channeling effects
    - Not sufficient: dependence of the overall signal on the beam impact position

Test beam 2021: calibration

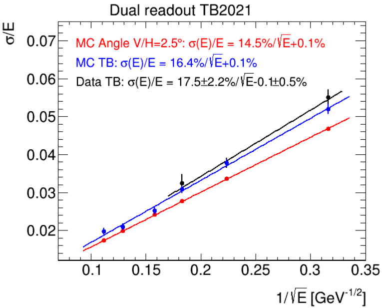
- Calibration of the high-gain ADC to photoelectrons with multi-photon spectrum
- Low-gain intercalibrated with high-gain
- Modules equalised using 20 GeV electrons hitting the center of each module
- 48 (277) photoelectrons per GeV in Cherenkov (Scintillating) fibre
- Large distance between the preshower and the calorimeter
  - Need dedicated correction for the lateral leakage
  - Limit the resolution

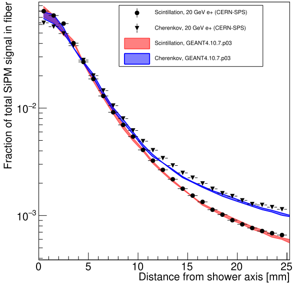




Test beam 2021: results

- Careful position-dependent corrections are needed since the tilt is only in one direction
- Linearity of the energy measurement was found to be within 1%
- Resolution limited by the PS-induced leakage
- Max energy 30 GeV due to poor beam purity
- Data sampling term: $17.5 \pm 2.2\%$, quite reproduced by MC
- MC without the PS-induced leakage and larger tilt: 14.5%
- Very good agreement data/MC for the energy profile

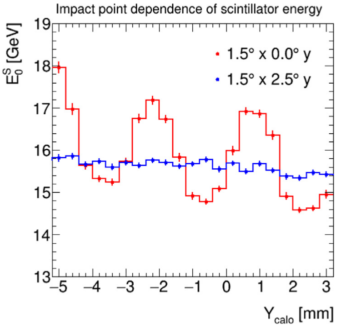


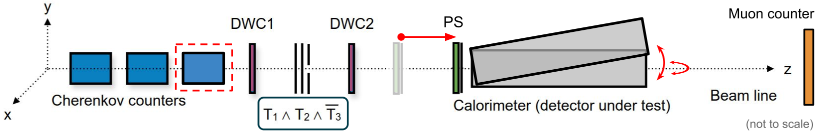


Test beam 2023: bucatini again

Same bucatini calorimeter, improved setup:

- Positron beam with improved purity
- Added third Cherenkov counter
- New, properly working delay wire chamber
- Preshower closer to calorimeter 15.5 mm
- Allowed for horizontal rotation of the prototype, vertical tilt

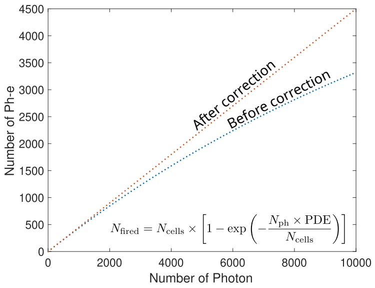


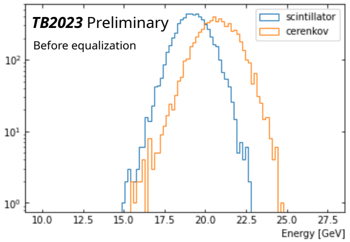


Preliminary results, paper in preparation

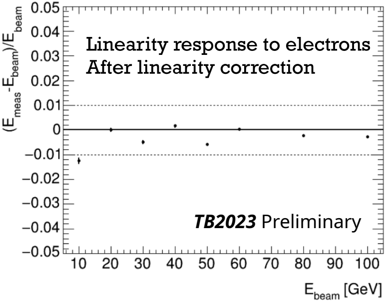
Test beam 2023: particle level calibration

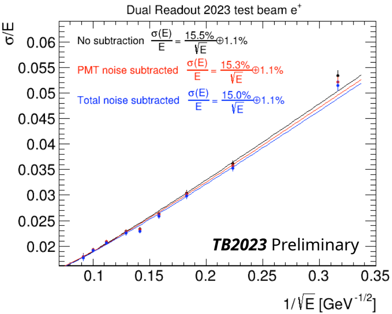
- Linearity at high-energy improved correcting for the non-linearity of the SiPM (e.g. the same cell cannot be fired twice)
  - 700 photoelectrons (10% occupancy, SiPM has 7284 cells), corresponding to 2 GeV in a single fibre ⇒ 5% non-linearity
- Cherenkov and scintillating responses have been equalised
- Positron energy is computed separately for Cherenkov and scintillating, as a linear combination of 8 PMT signals, preshower and sum of SiPMs, using run at 20 GeV
- Final energy as simple average of the two components





Test beam 2023: preliminary results

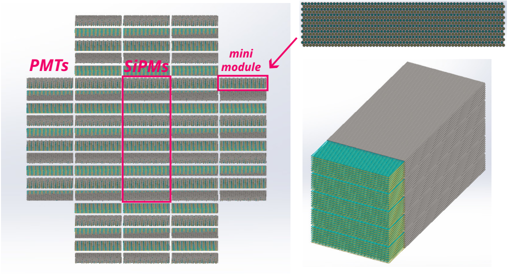




- Good linearity over the whole energy range
- Promising resolution, in agreement with simulations.
  - Difference in the constant term mostly due to spread in beam energy
  - Working on a better understanding of the noise

HiDRa project

- High-resolution, highly granular Dual-Readout Calorimeter: prototype for hadronic shower containment made with steel (slightly worse resolution than brass) capillaries and scintillating/Cherenkov fibres
- $250 \times 65 \times 65\,\mathrm{cm}^3$ made with 80 minimodules with $64 \times 16 = 1024$ capillaries each
- Group signals from eight same-type fibres by analogue summing
- 10240 SiPMs: challenging to fit all the SiPMs on the back side

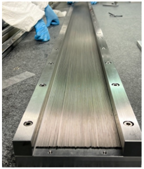


HiDRa aims to identify a scalable and cost-effective solution to build a dual-readout calorimeter for IDEA

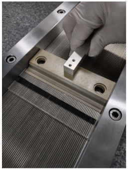
With HiDRa we are investigating an assembly procedure

Tube selection: thickness, straightness, length, internal diameter

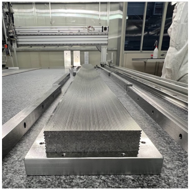
Stacking layers of tube



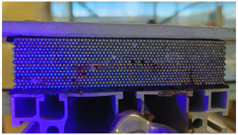
Glue dispensing and alignment



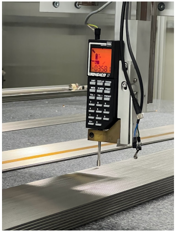
Mini-module



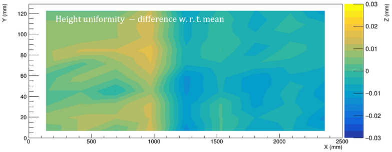
Fiber loaded



Semi-automatic system for planarity measurement

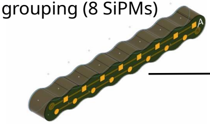


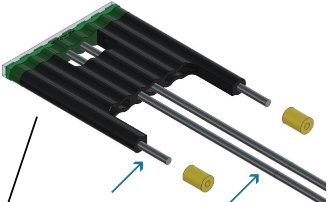
O (10 µm) precision on mini-module height



Custom design, very compact, limited space

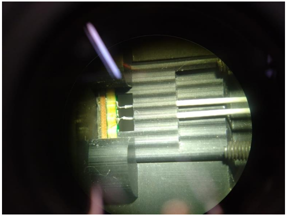
mini FE-board with integrated grouping (8 SiPMs)



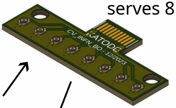


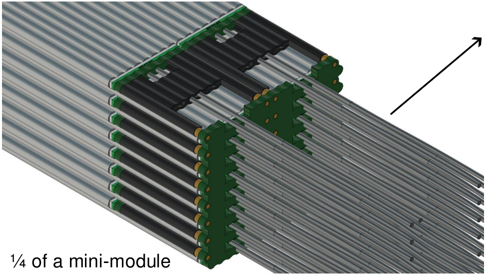
Metal rod

Coaxial cables



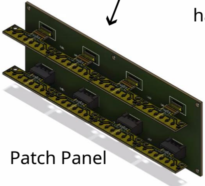
Bridge board: serves 8 SiPM-bars





¼ of a mini-module

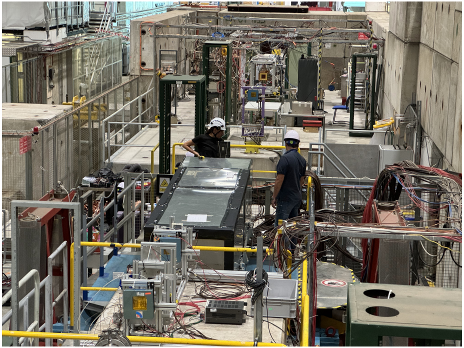
A5202-Board: serves half-minimodule



Patch Panel

Test beam 2024: Drago prototype

- HiDRa prototype instrumented only with PMTs
- 36 minimodules, organised in 12 rows, 3 columns each (∼50% HiDRa)



Positron, muon, pion data analysis is ongoing

Digital SiPM

Analog SiPM:

- Cells connected to common readout
- Analog sum of charged pulses
- Analog output signal

Digital SiPM:

- Made of Single-Photon Avalanche Diodes (SPAD array) and CMOS electronics
- Each diode is a digital switch
- Digital sum of detected photons, incorporate TDC
- Digital data output: number of photons, time stamp
- Possible to implement advanced features as SPAD masking to reduce noise

With digital SiPM there is no need for analogue signal post-processing: no need for grouping

Summary

Highly granular dual-readout calorimeters are promising candidates

- intrinsically linear response to hadrons
- fine segmentation (can be exploited by modern software techniques)

Successful test beam campaigns with bucatini EM prototype [2021 test beam paper]

- Developed an equalisation and calibration procedure
- Improved simulation tuning
- Good agreement with MC, including lateral profile
- Good EM energy resolution, $15\%/\sqrt{E}$

First test beam with the HiDRa hadronic prototype

Not covered here:

- Machine learning application of the high-granularity (e.g. tau identification)
- Longitudinal segmentation with timing
- Dual readout with crystals