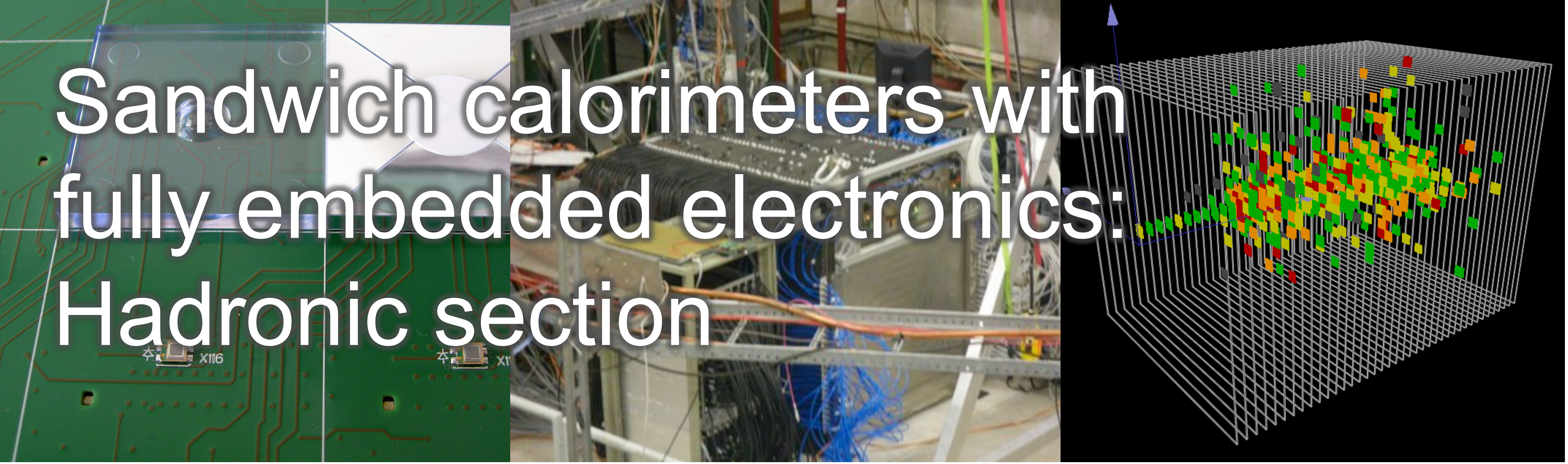


Sandwich calorimeters with fully embedded electronics: Hadronic section

Katja Krüger (DESY)

ECFA Detector R&D Roadmap Task Force 6: Calorimetry Community Meeting
12 January 2023

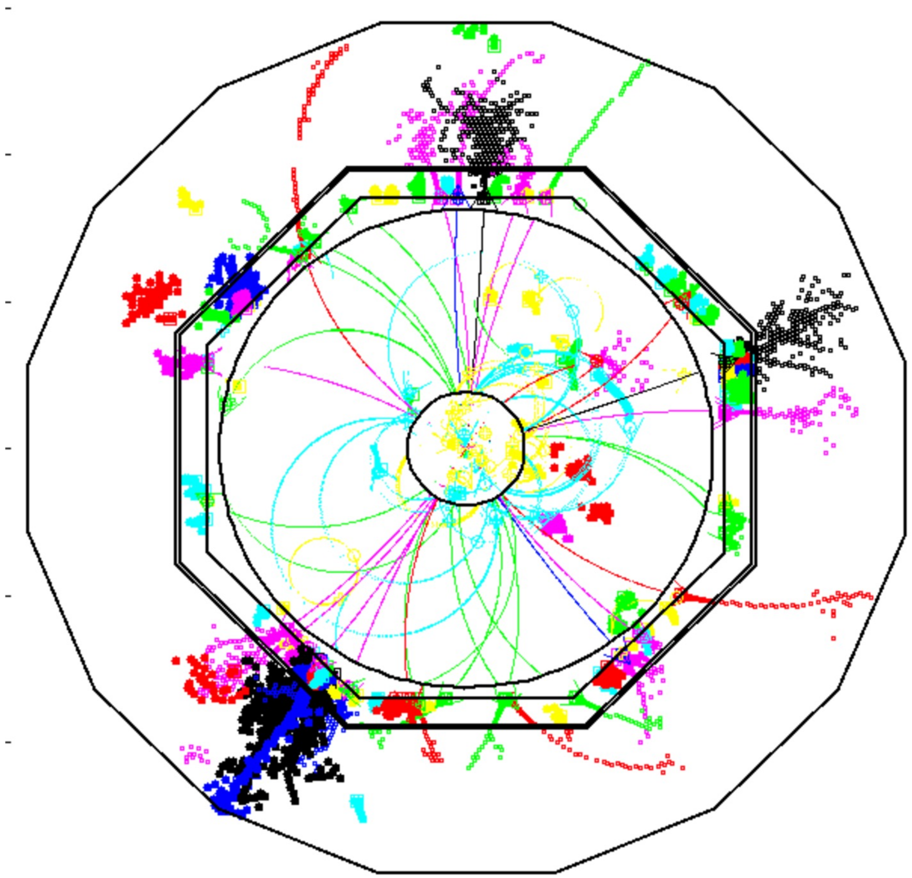
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Intro

Requirements for the Hadronic Section

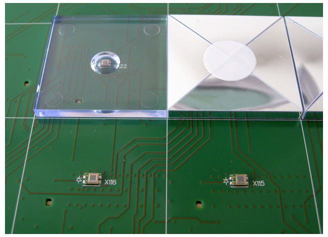
Differences and common aspects with EM section

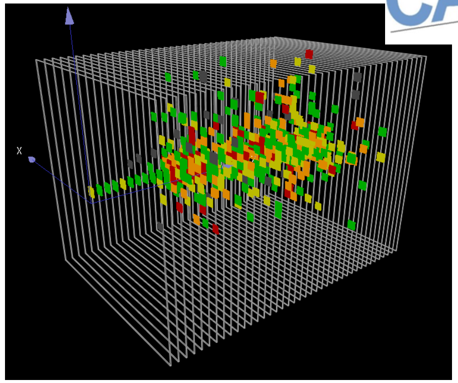
- Hadronic sections have **larger volume** than EM sections, and similar or higher number of layers
  → Larger area to be covered
  → Cost/area is more important
- Some **requirements are less stringent** than for EM section
  - Smaller channel density
  - Compactness not as critical
  - Hadronic energy distributed over large volume and many channels, with large flucutations: less sensitive to single-cell precision
- Many **similar challenges**:
  - Integration
  - Industrialisation of production, QC
  - Cooling
  - Considerations in terms of power pulsing vs. continuous running
  - …

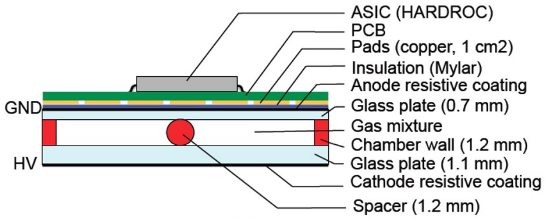


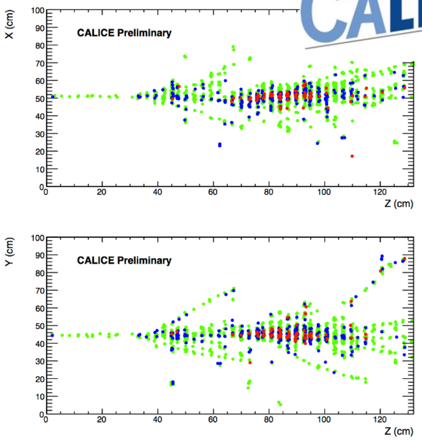
Detection Technologies for the Hadronic Section

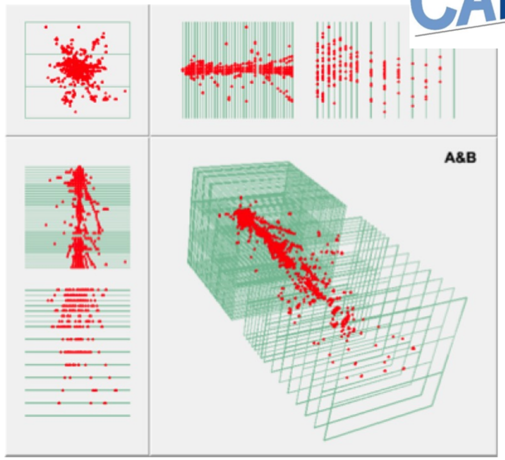
	Optical Readout	Gaseous Readout	
Technology	Plastic scintillator tiles	RPCs / µMegas / GEMs	
Readout concept	Analog	Semi-Digital	Digital
HCAL prototype	AHCAL Physics & technological prototype	SDHCAL Technological prototype	DHCAL Physics prototype











State of the Art

SDHCAL Technological Prototype

Achievements in Beam Tests

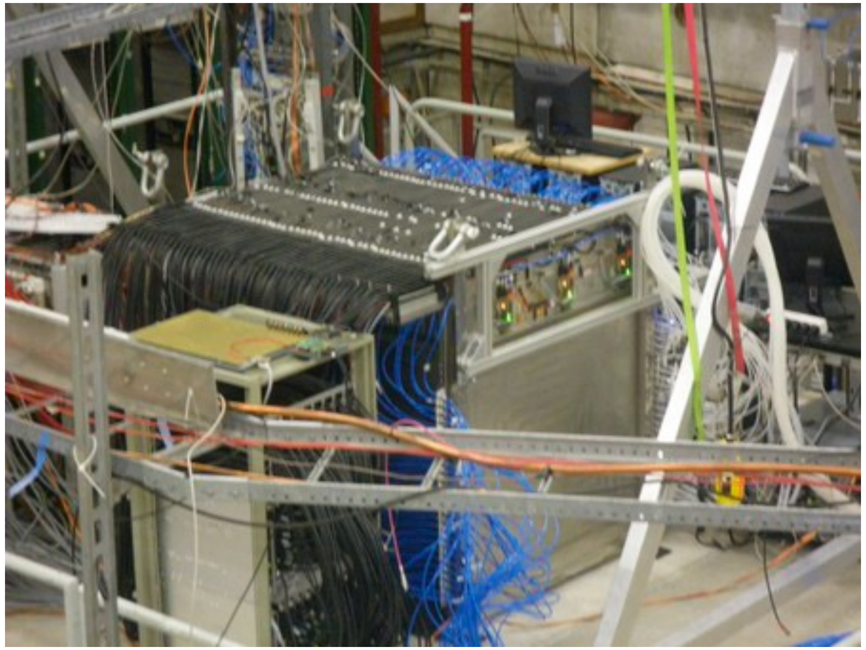
1*1*1 m^3 prototype based on RPCs with 1 cm^2 pads

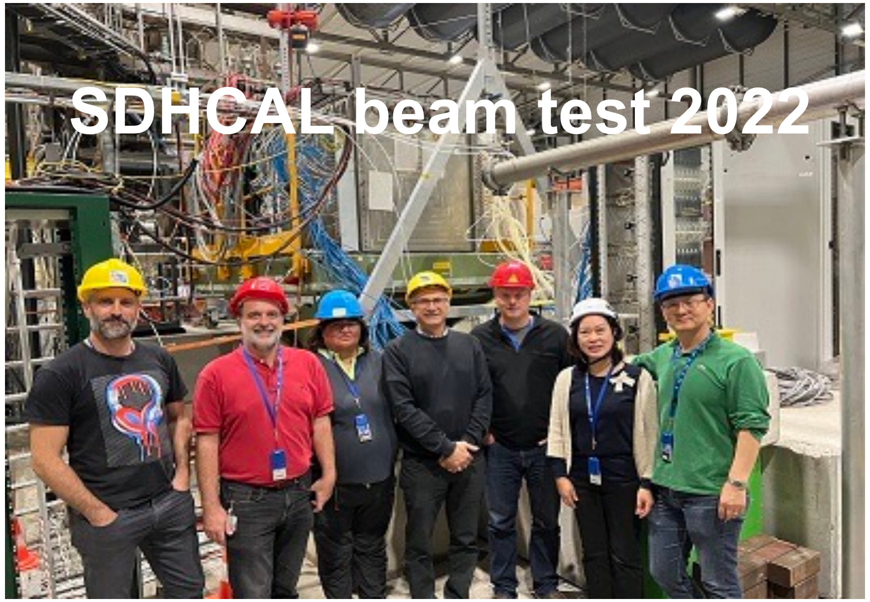
- 48 layers with ~440.000 channels
- built 2011

Successfully operated in many beam tests 2012 – 2022

- publications on operation, energy reconstruction, simulation

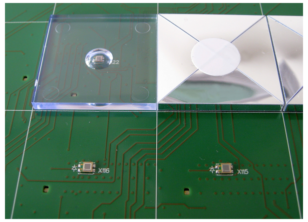
Tested also with a few µMegas layers





AHCAL technological prototypes

Achievements in Beam Tests



AHCAL prototype for ILC

- 0.72*0.72*1 m^3 prototype based 3*3*0.3 cm^3 scintillator tiles
- 38 layers with ~22.000 channels
- built 2017-2018

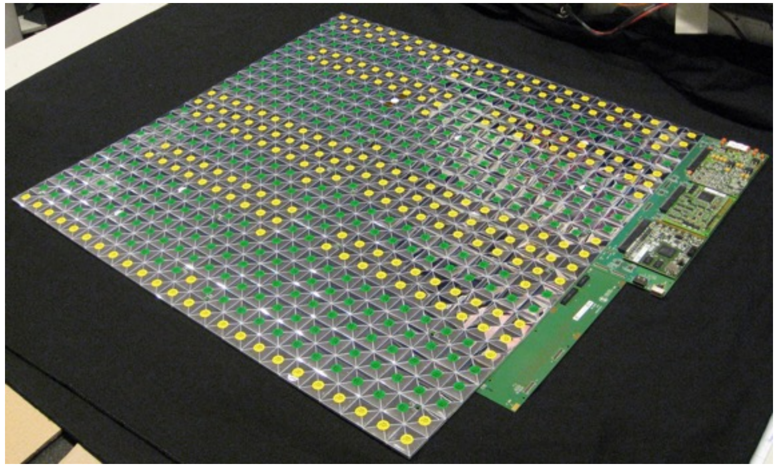
Several successful beam tests 2018 – 2022

- First publication on construction & operation

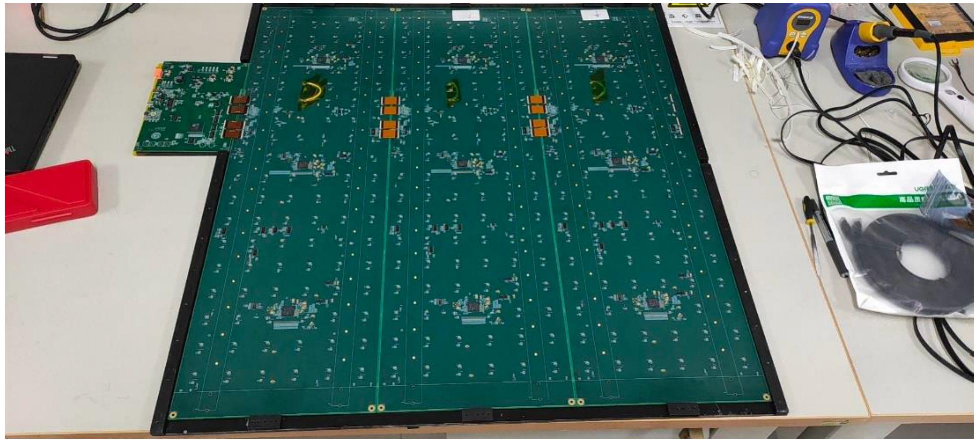
AHCAL prototype for CEPC

- 0.72*0.72*1 m^3 prototype based 4*4*0.3 cm^3 scintillator tiles
- 43 layers with ~14.000 channels
- built 2021-2022

Successful first beam test in 2022

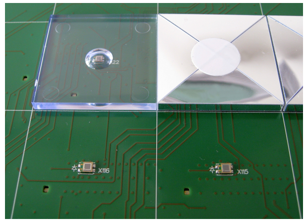


Both prototypes use electronics developed for ILC (power pulsing)



AHCAL technological prototypes

Achievements in Beam Tests



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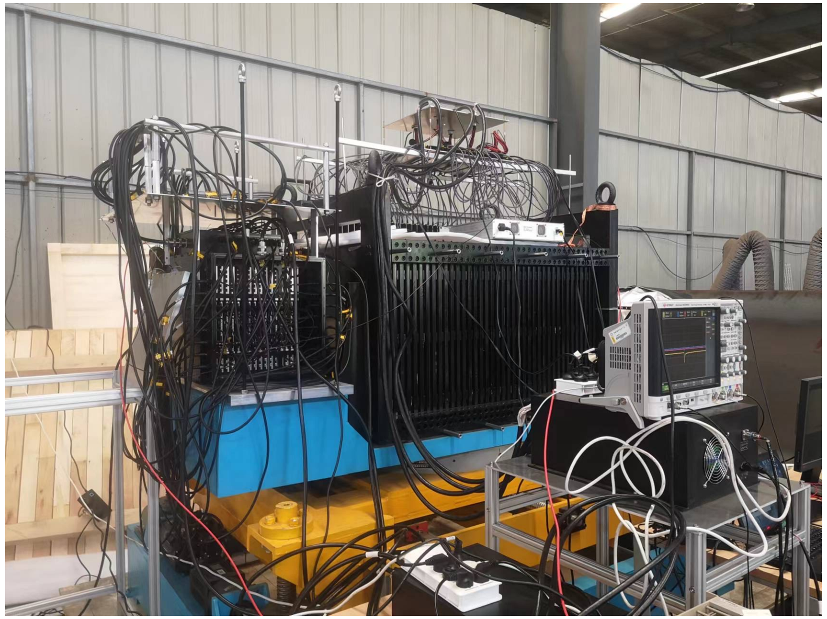
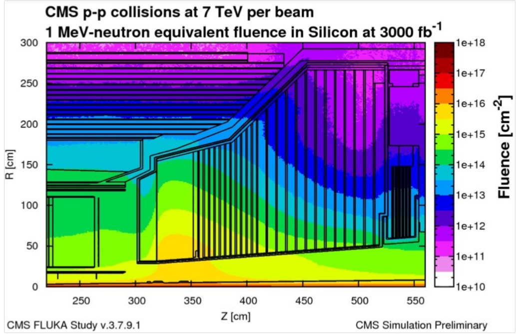


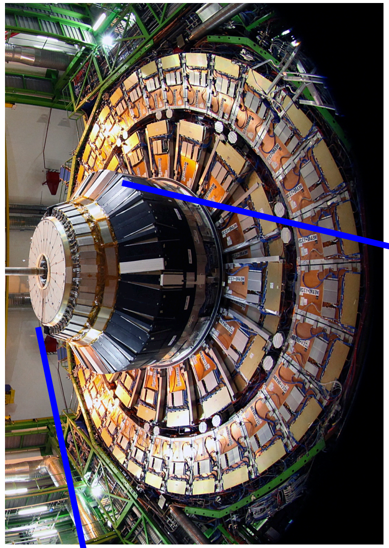
CMS HGCAL

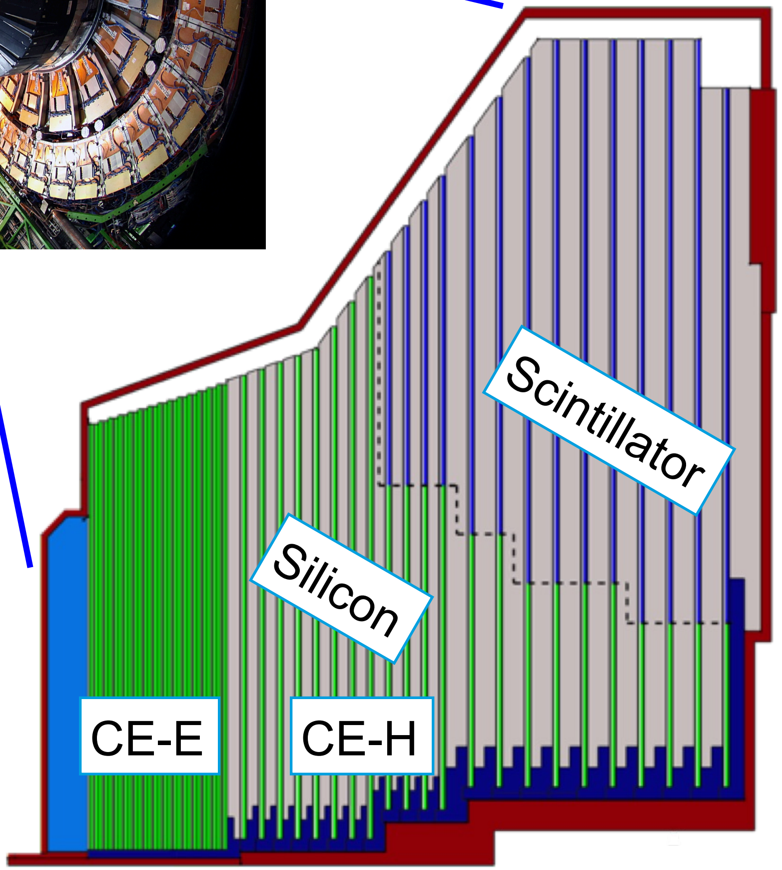
High granularity for HL-LHC

- CMS calorimeter endcap will be replaced for HL-LHC by **H**igh-**G**ranularity **cal**orimeter
    - High granularity for pile-up rejection & particle flow
- Synergy with high granularity calorimeter concepts developed for electron-positron colliders
    - silicon in the front and close to the beam pipe
    - scintillator tiles wherever radiation levels allow
        - ~400 m^2 in ~4000 boards
        - ~240k scintillator channels, 4-30 cm^2 cell size
- New challenges compared to e+e-
    - Radiation levels
    - Operation at -35º C → CO_2 cooling
    - Data rates, continuous running
- Needs to be ready for installation in 2026/27
    - Transition from R&D phase to production ongoing
    - Setting up full production and assembly infrastructure

Valuable experience for the construction of a highly granular calorimeter as part of any future collider detector







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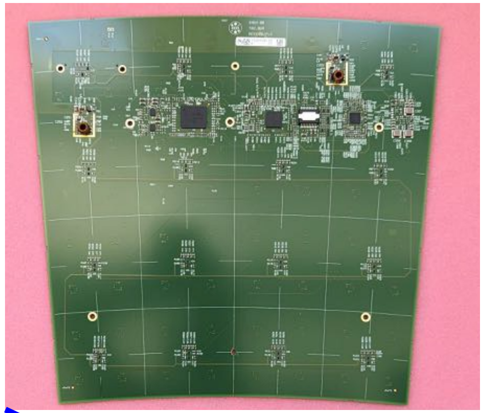
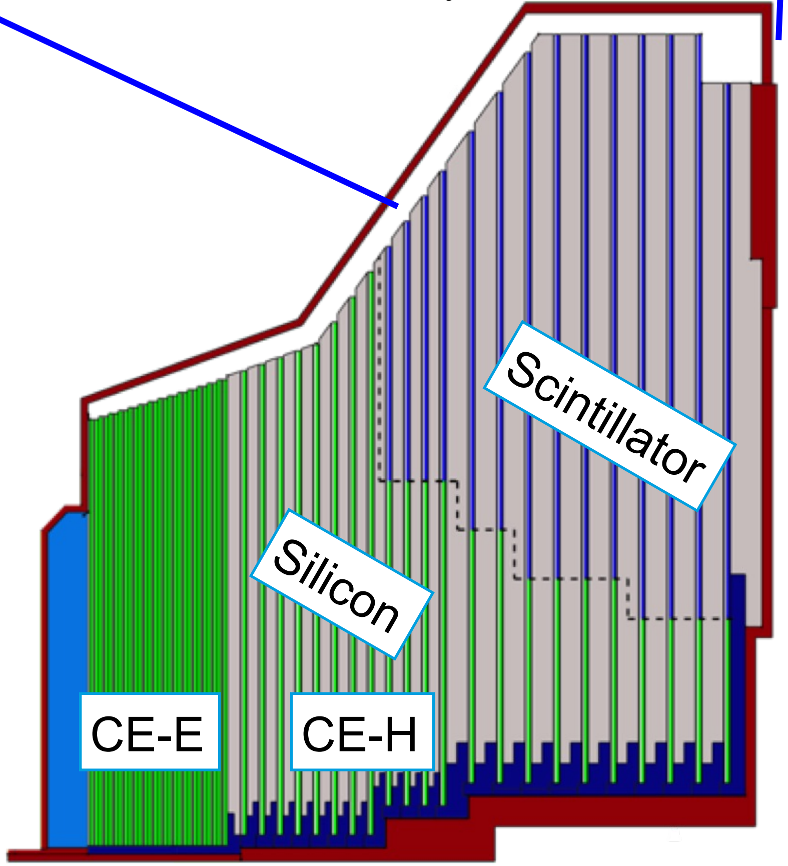


Dummy scintillator module



Plans

Relevant objectives

- DRDT 6.2 - Develop high-granular calorimeters with multi-dimensional read-out for optimised use of particle flow methods.
- DRDT 6.3 - Develop calorimeters for extreme radiation, rate and pile-up environments.

Calorimeters based on Gaseous Readout

R&D Need	Main direction	Target facilities	Related DRDT
Scalability of technology	Large area PCBs with robust interconnection, large scale precise absorber structures	ILC, FCC-ee, CLIC, FCC-hh	6.2, 6.3
Rate capability	Semi-conductive Glass RPC	FCC-hh	6.3
Control of pad multiplicity	Avoid/reduce double counting on cell edges	ILC, FCC-ee, CLIC, FCC-hh	6.2, 6.3

Table 6.3: Overview of main R&D needs and corresponding directions of development for calorimeters based on gaseous readout connected to facilities and DRDTs.

Calorimeters based on Optical Readout

R&D Need	Main Directions	Target facilities	Related DRDT
Optimisation of Photon detectors	Novel SiPMs with large spectral sensitivity and high-band semiconductors for higher radiation tolerance, Digital SiPMs	ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.2, 6.3
Novel crystal technologies	Co-doped garnet crystal fibres	HL-LHC, ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.1, 6.2, 6.3
Longitudinal information	Longitudinal segmen-tation of crystals, z-position from timing	HL-LHC, ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.1, 6.2, 6.3
Novel plastic scintillators	Radiation hardness, implementation of dual readout	ILC, FCC-ee, CLIC, FCC-hh, Muon Collider	6.2, 6.3

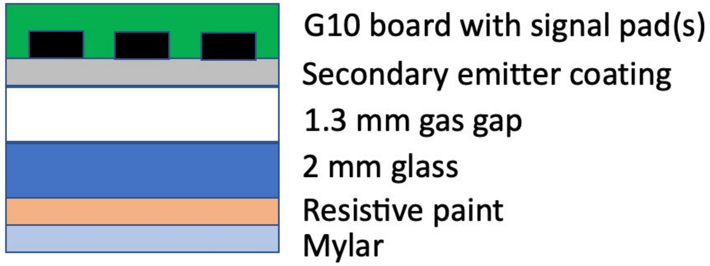
Table 6.4: Overview of main R&D needs and corresponding directions of development for calorimeters based on Optical Readout connected to facilities and DRDTs.

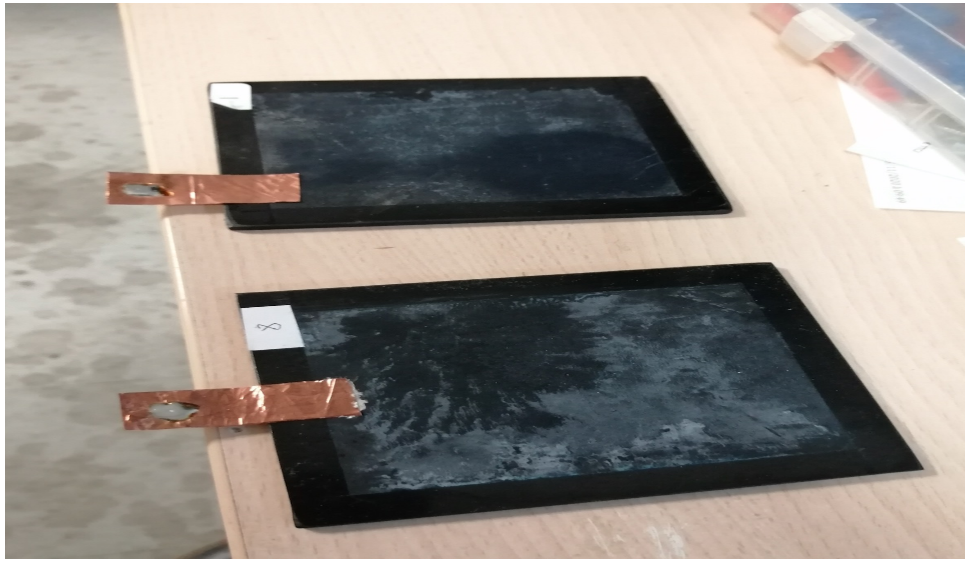
- For more details see also afternoon session
- **Synergies with TF4** (Particle Identification and Photon Detectors)

Gaseous Readout Technologies: main R&D needs

Detection technology

- Environment-friendly gases
  - **Strong synergies with TF1** (Gaseous Detectors)
    - Special focus here on use in environment of hadronic showers
  - Option being investigated: Hybrid (1 glass) RPCs
    - Add layer of secondary emitter to ease requirements on charge multiplication in gas gap
    - Status: first promising results, more studies needed
- Rate capability
  - Rate capability of RPC is limited by resistivity of the electrodes
    - Low resistivity needed for high rates
  - Option being investigated: thermoplastic with low bulk resistivity ($10^{11\text{-}12}$ Ω.cm achieved for PVdF, $10^{8\text{-}9}$ Ω.cm for PEEK)
    - Status:
      - First small test detectors: too high resistivity (PVdF), homogeneity issues (PEEK)
      - More studies needed
  - Other options: semi-conductive glass RPCs
  - Important ingredient: low noise electronics
  - Collaboration with industry needed



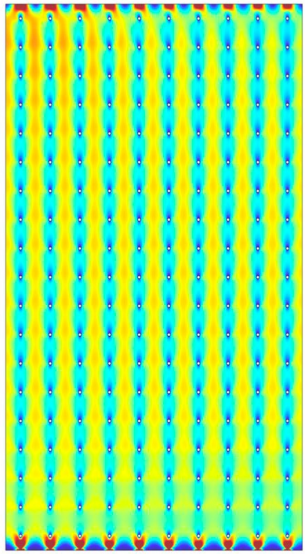


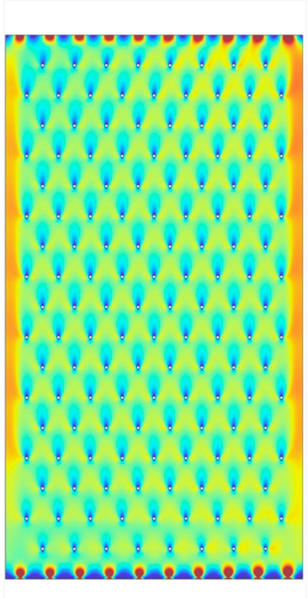
Gaseous Readout Technologies: main R&D needs

Scalability I

Large layers of several m^2 are challenging in several aspects, especially for good signal homogeneity across the whole area

- Homogeneous gas distribution needed
  - Status: optimising detector layout (spacers, …), studies ongoing
- Reproducibility of RPC construction
  - Controlled spacers, uniformity of the colloidal coating, …
  - Effect can be reduced by optimising the threshold to reduce the impact of the gain difference due to the detector geometrical inhomogeneity
- Precise mechanics
  - Develop procedures to build and assemble absorber structure with needed precision at reasonable cost
  - Status: large prototype built with electron beam welding; further studies and optimization of absorber structure desirable





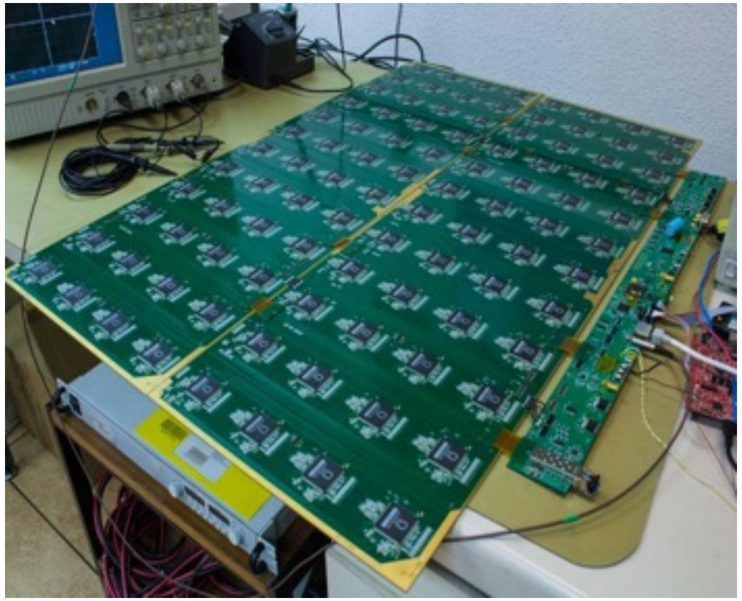
Gaseous Readout Technologies: main R&D needs

Scalability II

Large layers of several m^2 are challenging in several aspects, especially for good signal homogeneity across the whole area

- Large area PCBs
  - Inhomogeneous signals observed at PCB boundaries
    - Can be reduced by using larger PCBs
  - Large area PCBs would reduce the number of components to handle
  - Status: produced PCBs of ~1m length
  - For full detector: industry
  - Shorter term: prototyping capabilities in labs (CERN) needed

  - Also relevant to other readout technologies

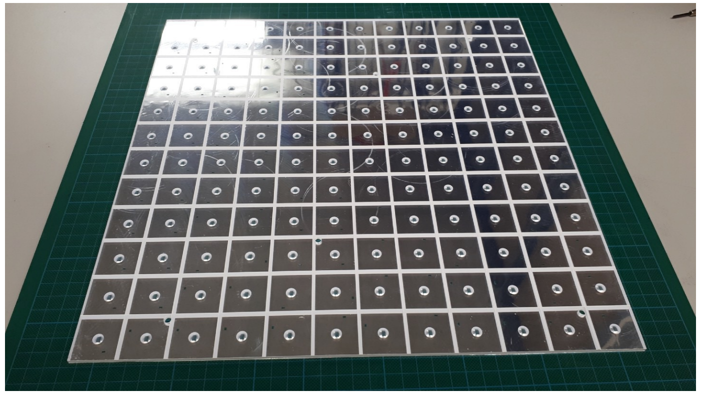


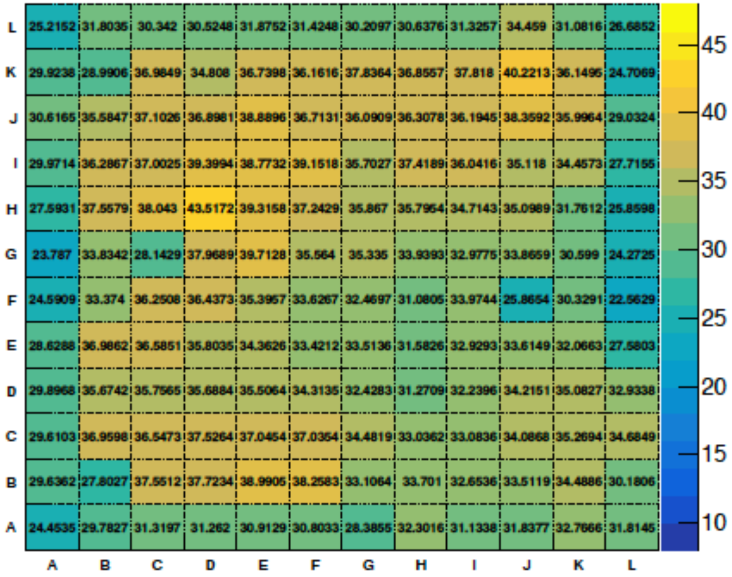
Optical Readout Technologies: main R&D needs

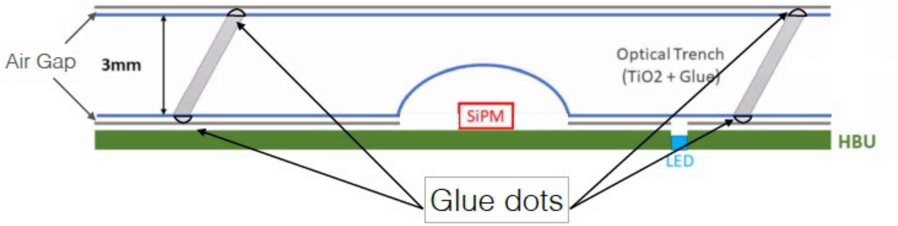
Scalability III

Hadronic section of a full collider detector will require two orders of magnitude more tiles than AHCAL prototype, one order more than CMS HGCAL

- Megatiles would allow larger units for mechanical assembly
- Challenge: reach good uniformity while keeping the cell-to-cell light cross talk small
- Status:
  - Several generations of Megatiles produced, reaching reasonable uniformity and light yield
  - Plan to build a large layer and include it in the AHCAL prototype







Common R&D topics for Gaseous and Optical Readout

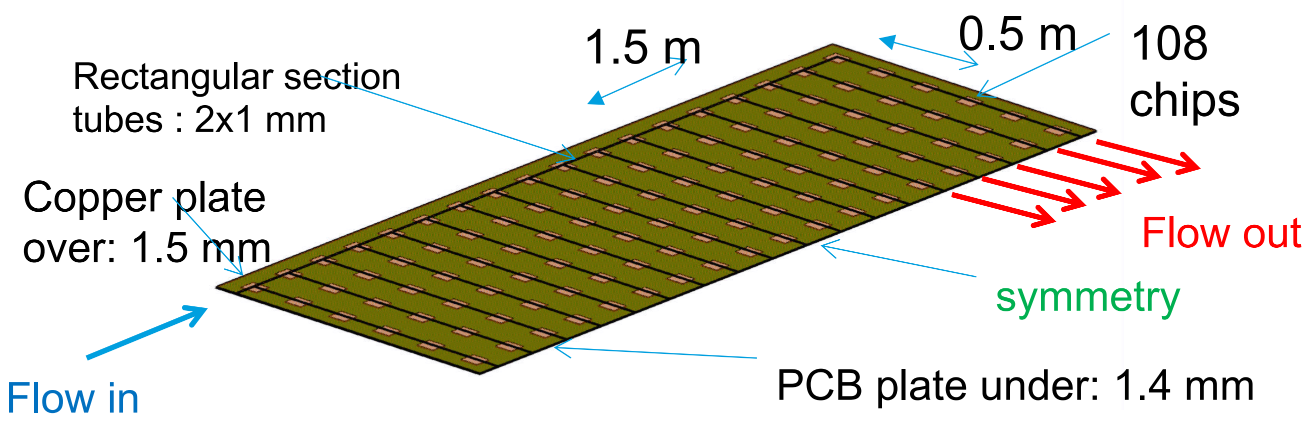
Integration & Readout Electronics

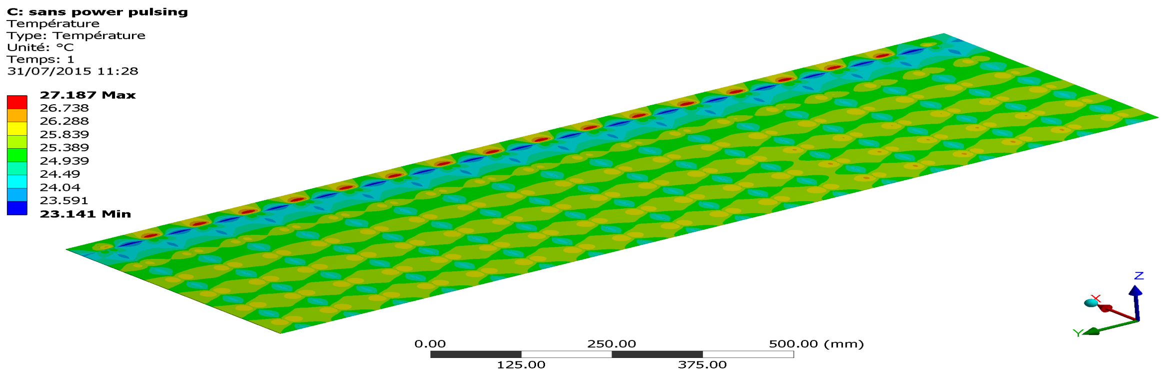
- Large number of channels of highly granular hadron calorimeter sections make electronics embedded in the active layer essential
- The details of the integration and readout concept depend on the environment
  - Linear e+e-: Low rate, low radiation, power pulsing
  - Circular e+e-: High rate, low radiation, continuous power
  - Hadron collider: very high rate, high radiation, continuous power
- Dedicated embedded very-frontend readout ASICs
  - **Synergies with TF7 (Electronics and Data Processing)**
  - Can profit a lot from synergies between calorimeter concepts
  - Linear e+e-: HARDROC (RPC), SPIROC (SiPMs), SKIROC (Si), …
  - Circular e+e-: KLauS (SiPM), PETIROC as starting block (RPC)
  - Hadron collider: HGCROC (Si and SiPM)
- Depending on data rates, several stages of data concentration and selection might be needed
  - For existing concepts: work on miniaturization ongoing
    - AHCAL plans to exploit synergies with SiW ECAL developments of interface boards
  - For other future applications: will likely need dedicated studies
    - FCCee: Need **simulation** to estimate impact of high rate Z pole running on data rates and readout needs
  - Interesting field for new concepts like DNNs on ASICs (implemented for HGCAL)

Common R&D topics: Gaseous and Optical Readout

Continuous running, active cooling

- For circular e+e- (and hadron) colliders, readout ASICs will need to run continuously
- Higher power consumption will likely require cooling within the active layers
  - **Need to study impact in simulation**
    - Started for SDHCAL
  - Need to develop a suitable cooling (that introduces minimal non-homogeneity)
  - Test it in prototypes, both for SDHCAL and AHCAL

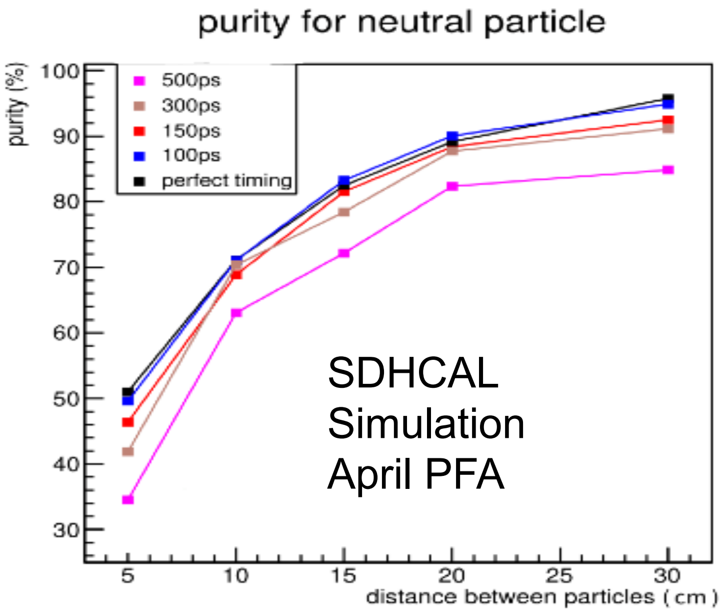


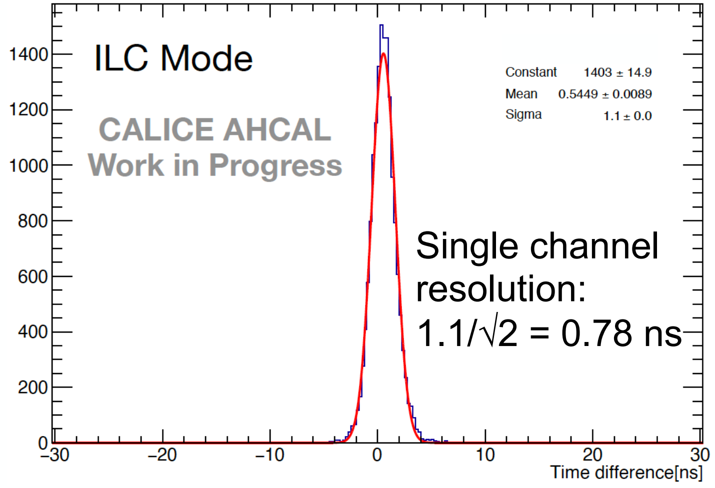


Common R&D topics: Gaseous and Optical Readout

Timing

- Precise hit time measurement can be beneficial in several areas
- In high rate environments, interesting for pile-up rejection
- Could use “time” as additional information in particle flow algorithms to improve 2-particle separation
  - **Simulation studies needed** to determine what resolution is really needed
    - Might depend on detector and on algorithm
  - Status: first studies for SDHCAL and April PFA
- Particle ID with time-of-flight:
  - needs very good resolution O(10-30 ps)
- Current calorimeter prototypes reach O(1 ns) for MIP hits
- The technologies have a lot of potential for better time resolution
  - RPC: multi-gap RPCs have demonstrated ~60ps for MIP hits
    - Plan: build a timing layer for SDHCAL, more effort needed on electronics developments
  - Scintillator: tiles/strips with high light yield reach ~30 ps resolution for MIP hits
    - Requires small tiles, crystal scintillator
- Also readout electronics contributes to time resolution → synergies with TF7



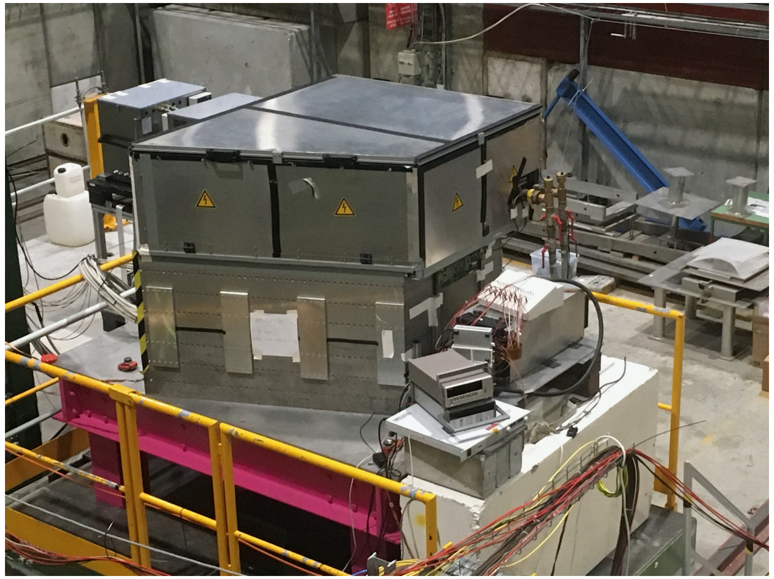


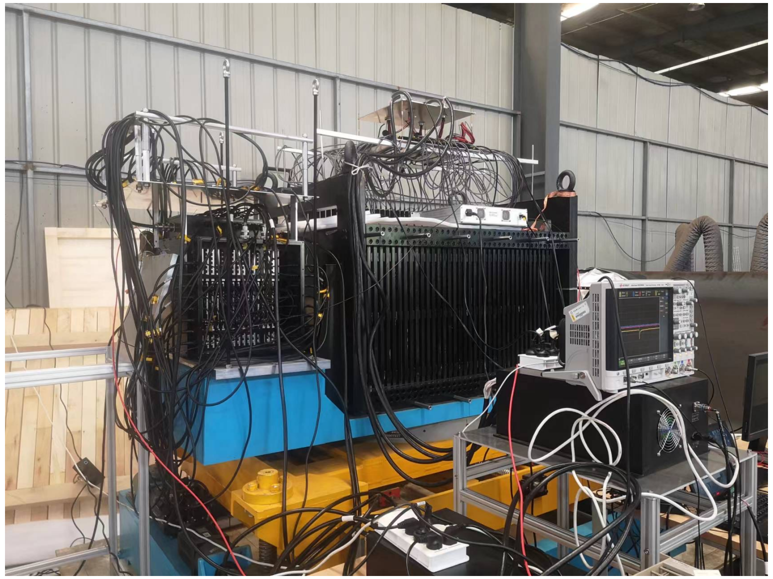
Beam tests of calorimeter systems

Putting it all together

In order to determine the capabilities of a calorimeter concept, we need to test the complete system of EM section and hadronic section (and tail catcher)

- For the large CALICE prototypes of the concepts for the hadronic section, these tests have just started
  - Very limited data for SiW ECAL together with SDHCAL or AHCAL
  - 2 weeks of data taking in 2022 for Sci ECAL + AHCAL (CEPC prototypes)
- More beam tests planned in the coming years
- Data can not only be used to determine calorimeter energy resolution, but also provide important input to other areas
  - Tuning of particle flow algorithms
  - Tuning of hadronic shower models, in Geant4 or with fast generative approaches (ML)





Summary

- Highly granular hadronic sections foreseen and under study for lepton and hadron colliders
- Some challenges specific to the technology being addressed
  - Gaseous: rate capability, scalability
  - Optical: see also afternoon session
  - Synergies with TF1 and TF4
- Common challenges, to be addressed in the coming years
  - Integration & Readout electronics → synergies with TF7
  - Continuous running & active cooling
  - Timing
- Optimisation depends on software: simulation tools, particle flow algorithms, detector concept full simulation models, …
- Testing the developed technologies in beam is essential

Thank you!

Backup

Publications

AHCAL

- Physics prototype
  - **Construction and Commissioning of the CALICE Analog Hadron Calorimeter Prototype**, C. Adloff et al., JINST 5 (2010) P05004; e-print: arXiv:1003.2662
  - **Electromagnetic response of a highly granular hadronic calorimeter**, C. Adloff et al., JINST 6 (2011) P04003; e-print: arXiv:1012.4343
  - **Hadronic energy resolution of a highly granular scintillator-steel calorimeter using software compensation techniques**, C. Adloff et al., JINST 7 (2012) P09017; e-print: arXiv:1207.4210
  - **Track segments in hadronic showers in a highly granular scintillator-steel hadron calorimeter**, C. Adloff et al., JINST 8 (2013) P09001; e-print: arXiv:1305.7027
  - **Validation of GEANT4 Monte Carlo Models with a Highly Granular Scintillator-Steel Hadron Calorimeter**, C. Adloff et al., JINST 8 (2013) P07005; e-print: arXiv:1306.3037
  - **Pion and proton showers in the CALICE scintillator-steel analogue hadron calorimeter**, B. Bilki et al., JINST 10 (2015) P04014; e-print: arXiv:1412.2653
  - **Hadron shower decomposition in the highly granular CALICE analogue hadron calorimeter**, G. Eigen et al., JINST 11 (2016) P06013; e-print: arXiv:1602.08578
  - **Shower development of particles with momenta from 1 to 10 GeV in the CALICE Scintillator-Tungsten HCAL**, C. Adloff et al., JINST 9 (2014) P01004; e-print: arXiv:1311.3505
  - **Shower development of particles with momenta from 15 GeV to 150 GeV in the CALICE scintillator-tungsten hadronic calorimeter**, M. Chefdeville et al., JINST 10 (2015) P12006 ; e-print: arXiv:1509.00617
- Technological prototype
  - **Design, Construction and Commissioning of a Technological Prototype of a Highly Granular SiPM-on-tile Scintillator-Steel Hadronic Calorimeter,** e-Print: 2209.15327 [physics.ins-det]

Publications

SDHCAL

- **Construction and commissioning of a technological prototype of a high-granularity semi-digital hadronic calorimeter**, G. Baulieu et al., JINST 10 (2015) P010039; e-print: arXiv:1506.05316
- **First results of the CALICE SDHCAL technological prototype**, V. Buridon et al., JINST 11 (2016) P04001; e-print: arXiv:1602.02276
- **Resistive Plate Chamber Digitization in a Hadronic Shower Environment**, Z.Deng et al., JINST 11 (2016) P06014; e-print: arXiv:1604.04550
- **Tracking within Hadronic Showers in the CALICE SDHCAL prototype using a Hough Transform Technique**, Z.Deng et al., JINST 12 (2017) P05009; e-print: arXiv:1702.08082
- **Particle identification using Boosted Decision Trees in the Semi-Digital Hadronic Calorimeter prototype**, the CALICE Collaboration, JINST 15 (2020) P10009.
- **Energy reconstruction of hadronic showers at the CERN PS and SPS using the Semi-Digital Hadronic Calorimeter**, the CALICE Collaboration, JINST 17 (2022) P07017
- **Energy reconstruction for a hadronic calorimeter using multivariate data analysis methods**, B. Liu et al., **JINST 14 (2019) 10, P10034**

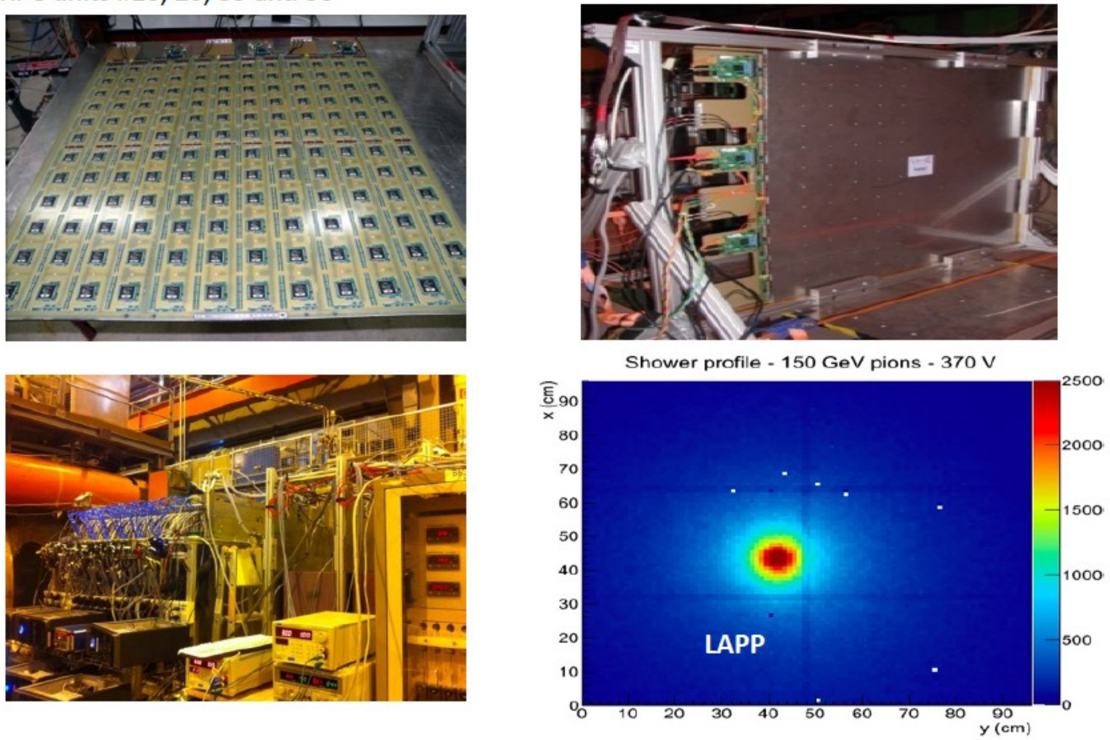
DHCAL

- **DHCAL with Minimal Absorber: Measurements with Positrons**, B. Freund et al., 2016 JINST 11 P05008; e-print: arXiv:1603.01652
- **Analysis of Testbeam Data of the Highly Granular RPC-Steel CALICE Digital Hadron Calorimeter and Validation of Geant4 Monte Carlo Models**, M. Chefdeville et al., NIM A939 (2019) 89-105; e-print: arXiv:1901.08818

Other gaseous technologies

- 4 microMegas layers have been built and tested in the SDHCAL prototype

In addition, within the ANR-Blanc, 4 units of SDHCAL-MM 1m x 1m each were produced, tested in a muon beam. The 4 units of SDHCAL-MM were inserted in the SDHCAL-RPC prototype replacing the RPC units #10, 20, 35 and 50



- First studies also with MicroWell technology

Differences

Linear and Circular Higgs/EW/top factories

- Higgs/EW/top factory options differ in various aspects
- Highest centre-of-mass energy
  - Impacts highest expected particle and jet energies
    → calorimeter thickness, absorber material, granularity
- Beam structure
  - Linear colliders have bunch trains, circular colliders not
    → readout electronics (power pulsing or continuous running), cooling
- High statistics Z pole running at FCC-ee and CEPC
  - Very high rates
    → trigger system, rate capability of the detector technology
  - More interest in detector capabilities for flavour physics
    → b/c tagging, particle ID