French-Italian contribution to **Hadronic Calorimetry** for FCCee

I. LAKTINEH

Many thanks to Piet Verwilligen, Andrea Pareti and Gabriella Gaudio for their help to prepare this talk

French and Italian groups are involved in two innovative HCAL technologies that they propose for future colliders and in particular the FCCee

- ❑ High-granular PFA-based
  France: IP2I, LPCC, OMEGA: RPC-based SDHCAL
  Italy: Bari, Rome, Naples: MPGD-based SDHCAL

  CALICE → DRD1-WP1

- ❑ Dual readout
  Italy: Pavia, Milano, Como

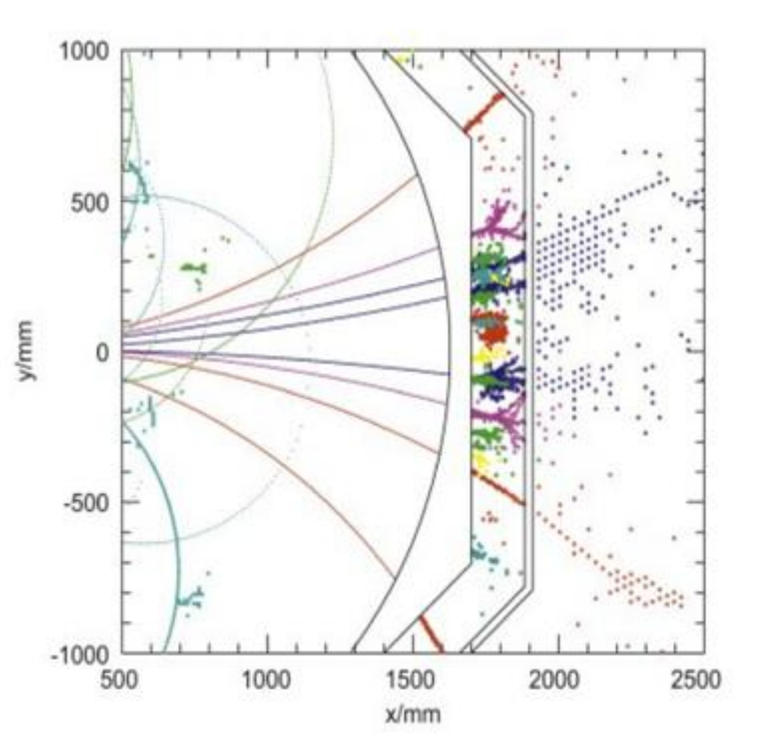
  RD52→ DRD1-WP3

PFA-based granular calorimeters

PFA: Construction of individual particles and estimation of their energy/momentum in the most appropriate sub-detector.

PFA requires the different sub-detectors including calorimeters to be highly granular.

PFA uses the granularity to separate **neutral** from **charged** contributions and exploits the **tracking system** to measure with precision the energy/momentum of charged particles



E_{jet} =	$E_{charged}$ +	E_{γ} +	E_{h0}
fraction	65%	26%	9%

Charged tracks resolution	$\Delta p/p$	~ few10^{-5}
Photon(s) energy resolution	$\Delta E/E$	~ 12% / $\sqrt{E}$
Neutral hadrons energy resolution	$\Delta E/E$	~ 45% / $\sqrt{E}$

Two technologies were developed for hadronic calorimeters : AHCAL & SDHCAL

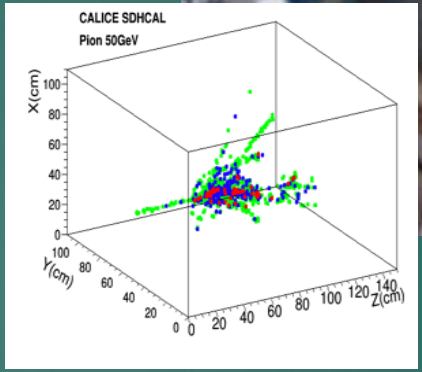
SDHCAL-RPC

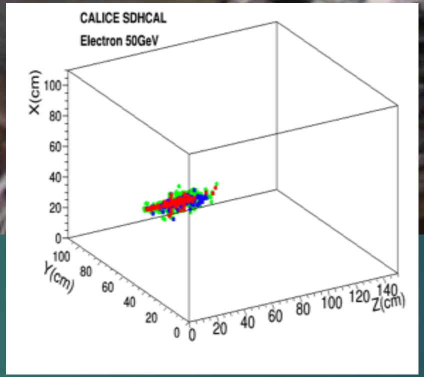
48 layers of 2 cm stainless steel interleaved with planes made of Glass RPC and their embedded readout 2-bit electronics allowing a lateral segmentation of 1 cm^2

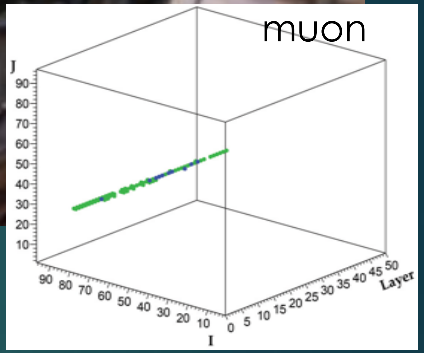
A technological prototype of 48 layers fulfilling all the ILD requirements :

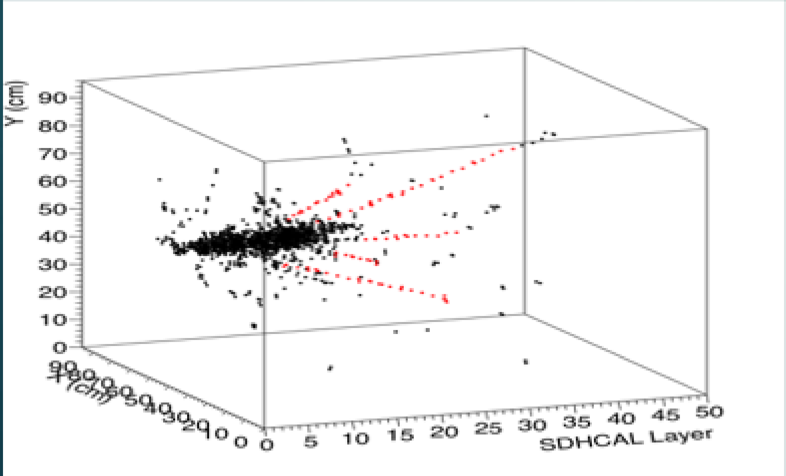
- ➢ compactness
- ➢ self-supporting mechanical structure.
- ➢ Triggerless mode
- ➢ Power-pulsing mode

was built and expensively and successfully tested

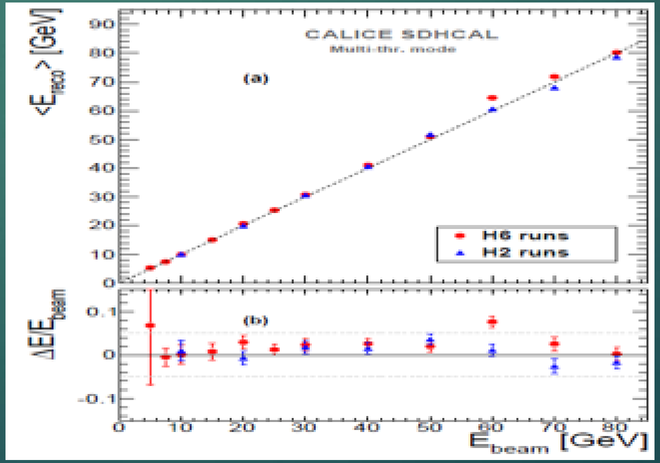


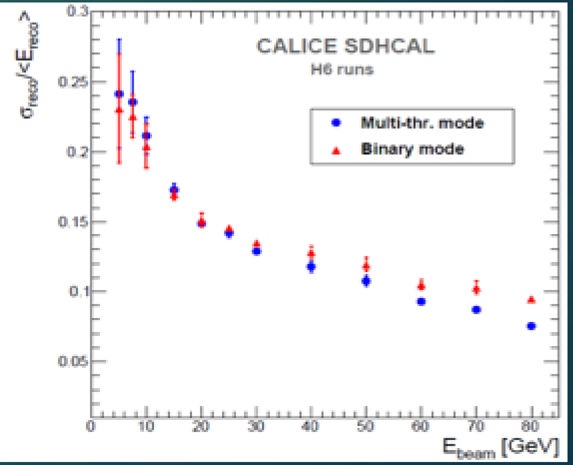






Hough transform tracks to control the



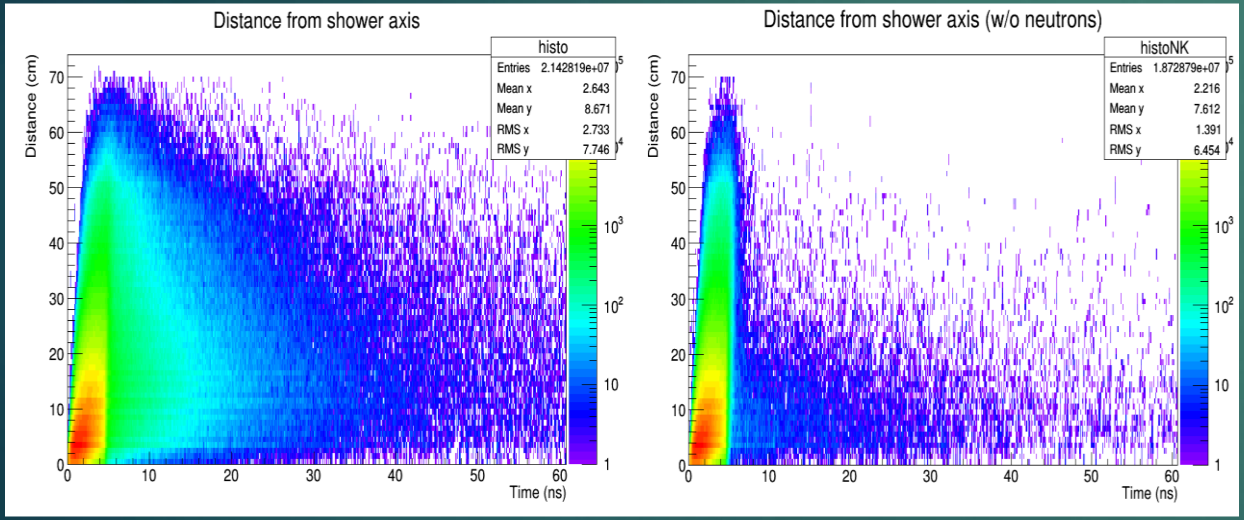


$$E_{rec} = \alpha(N_{tot})\, N_1 + \beta(N_{tot})\, N_2 + \gamma(N_{tot})\, N_3$$

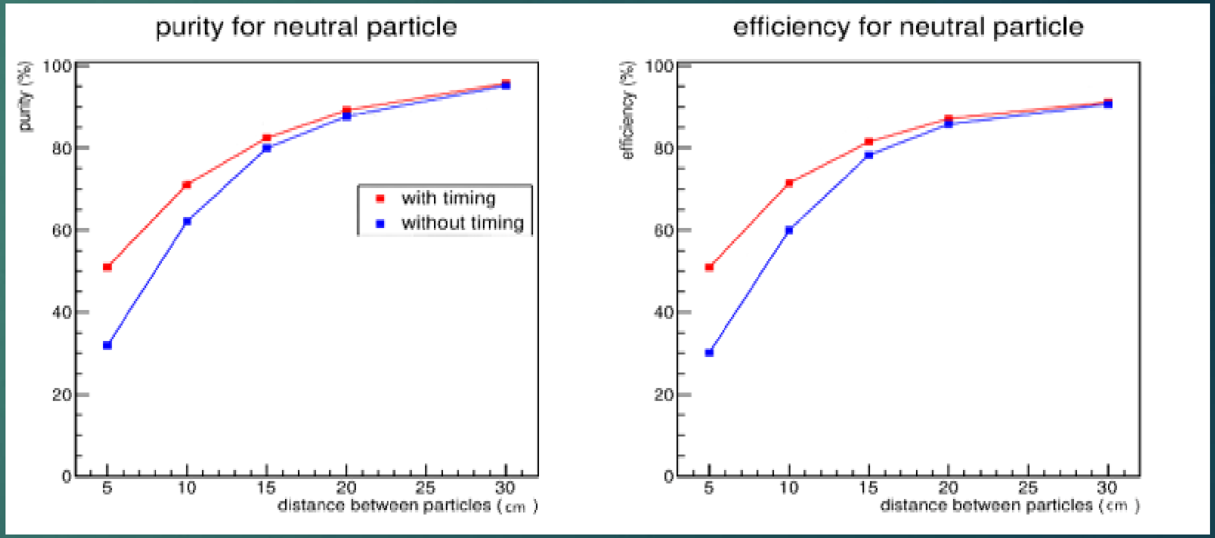
SDHCAL→ T-SDHCAL

- SDHCAL was first developed for **ILC**: low rate and power pulsing
- SDHCAL needs to be adapted to cope with **circular collider** requirements
  - ❑ Continuous readout
  - ❑ Higher rate

In addition, we found that time information could improve significantly hadronic showers separation at lower distances → Powerful tool for PFA



Contribution of delayed neutrons could be separated→ better energy reconstruction and better close-by showers separation

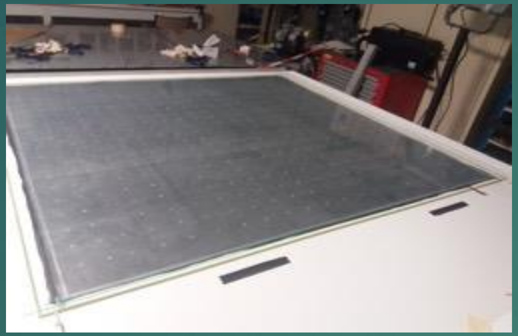


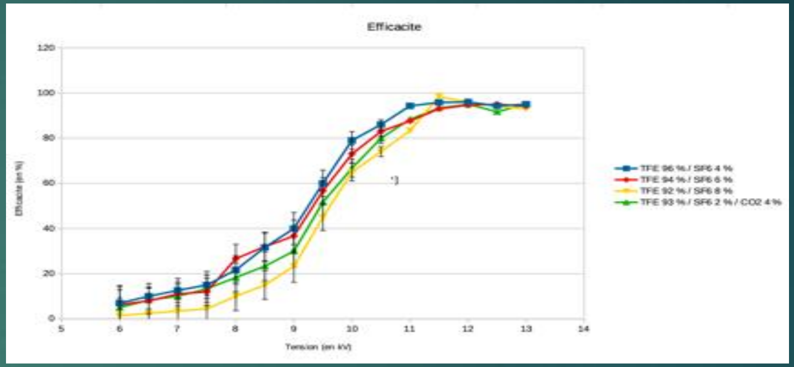
PFA-April extended to include time information improves close-by shower separation

RPC→ MRPC

- MRPC provides excellent time resolution (down to 50-70 ps with 2x4 gpas)
- MRPC has higher detection rate

New way of producing MRPC was developed in Lyon→ easy production, cheap detector

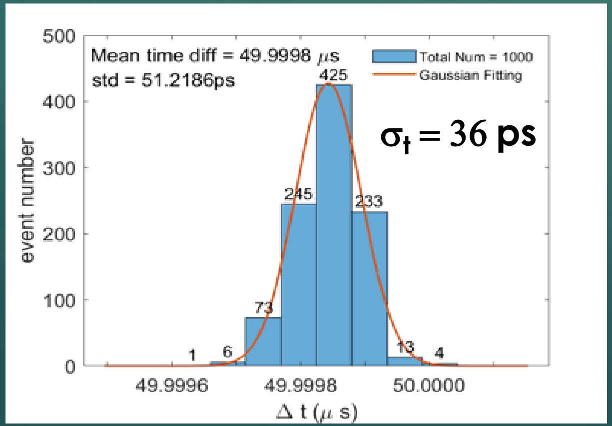


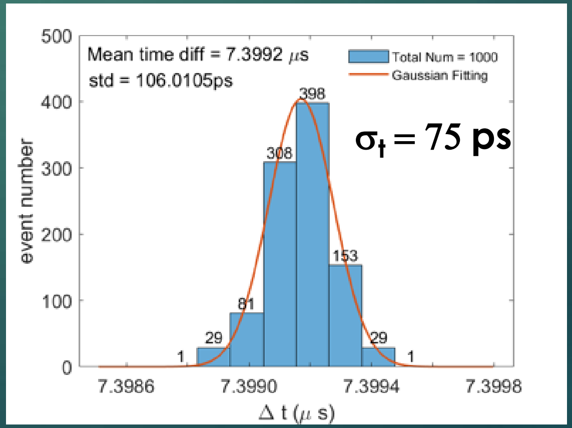


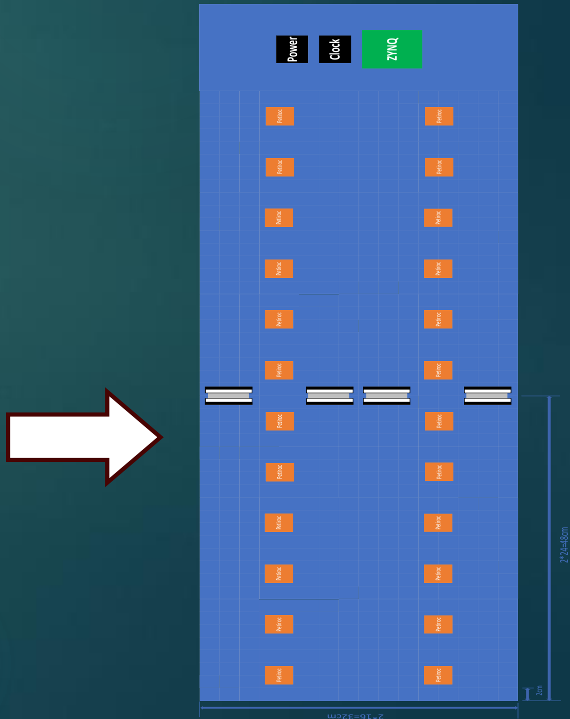
New eco-friendly gases: HFO1234 and NOVEC could replace green glass gases R134a and SF6 currently used.

Electronics:

HR2 (no timing)→ Petiroc (timing + TDC but dead time) →Caloroc (timing + TDC)

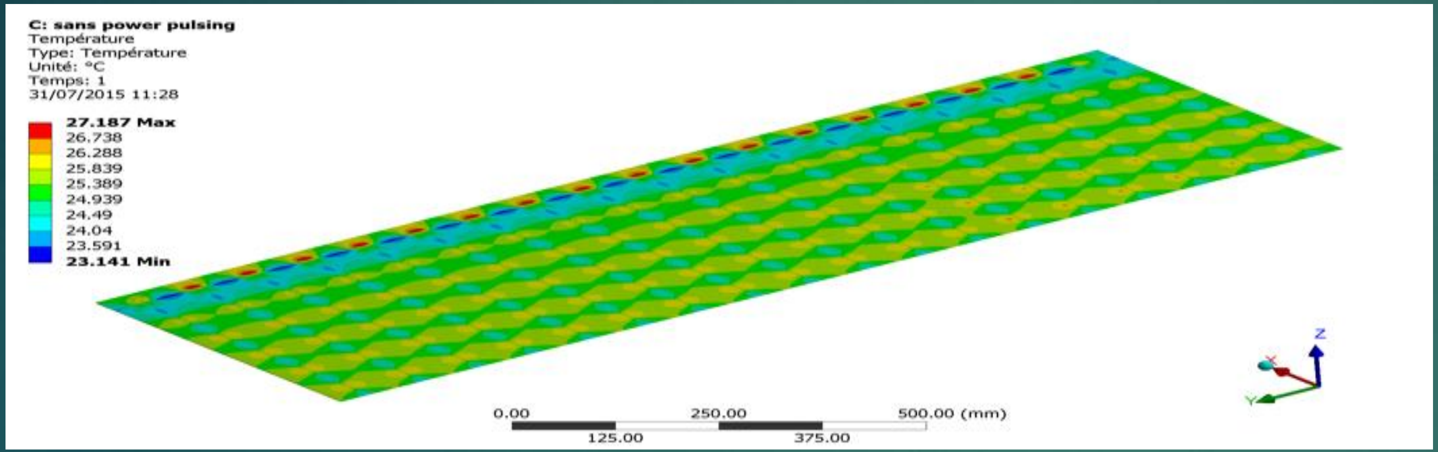






Cooling

Previous studies were performed on HARDROC (full regime) showed efficient heat absorption.
Using water circulating in cooper tubes in contact with the ASICs
We need to re do the studies with the new ASICs and the mechanical structure in mind

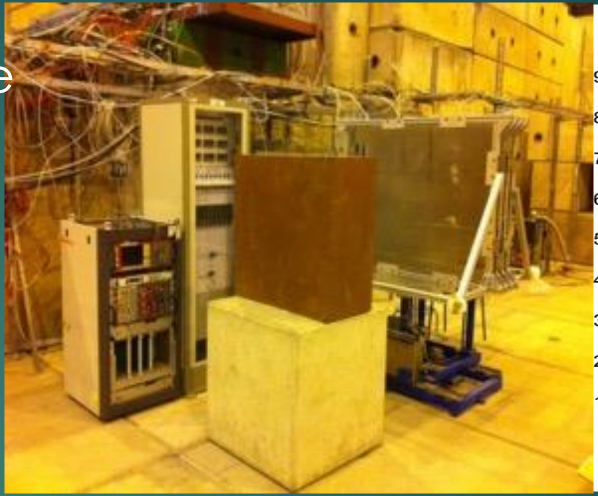


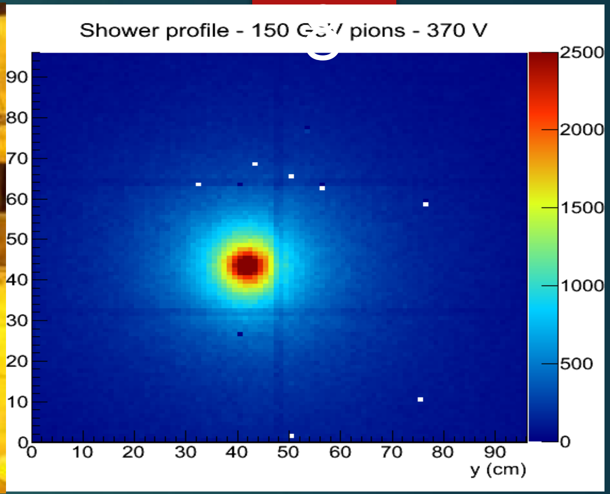
High-rate capability

Low-resistivity glass developed by Tsinghua U.
→ problem with the glass thickness and dimensions
Low-resistive PEEK (10^9 Ω.cm) developed by IP2I-Lyon
→ Some efforts to have better homogeneity is needed

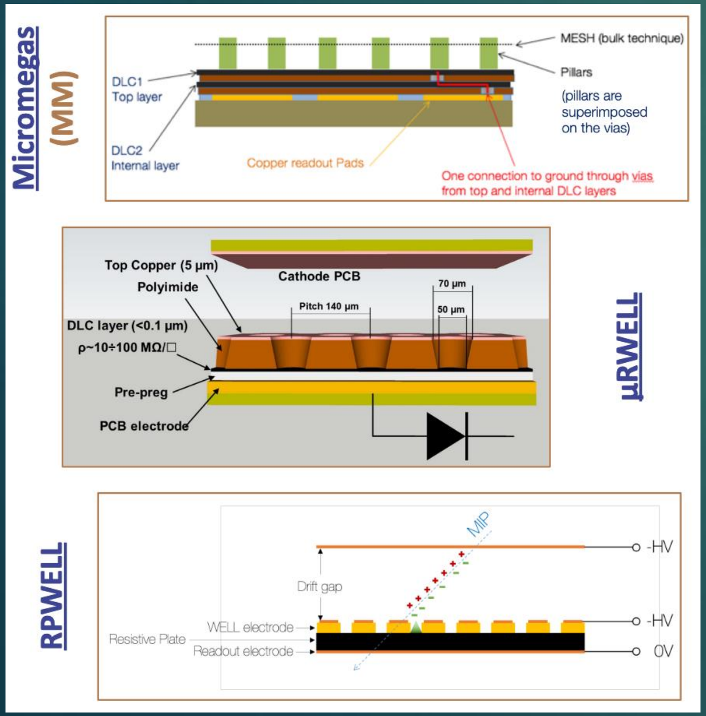
SDHCAL-MPGD

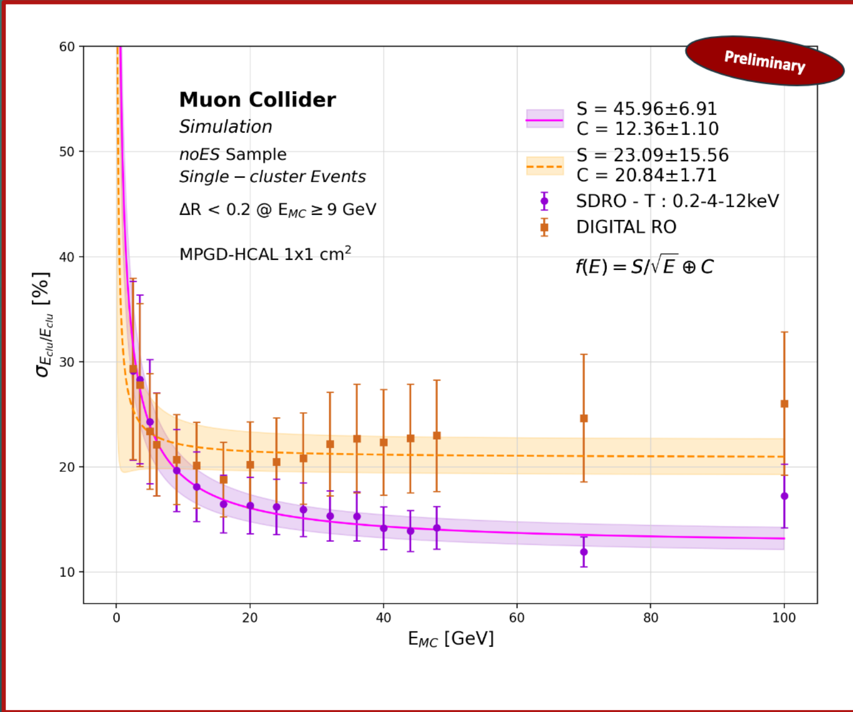
MPGD offers the possibility to operate with high particle rate (> 1 MHz/cm^2) and excellent spatial resolution
First attempt was made with standard MM by LAPP colleagues using a variant of HR (allowing a few fC threshold)





10 years later, the second generation of MPGD using resistive anodes allows robustness against discharges



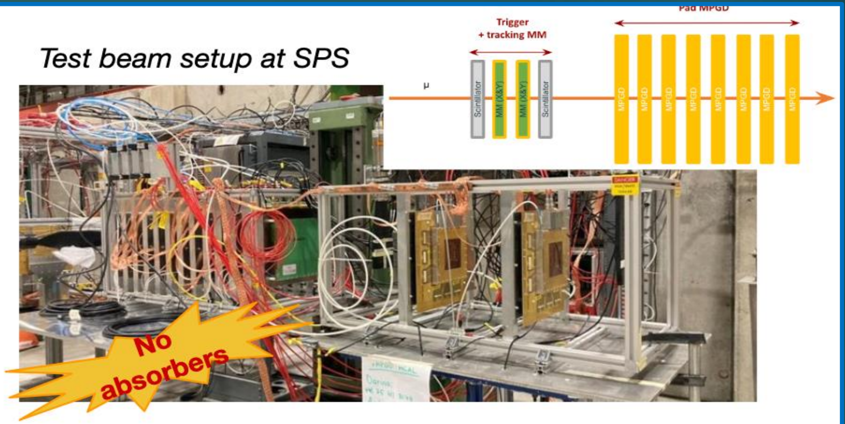


- $\pi^{\pm}$ guns with energy ranging from 2.5 to 100 GeV;
- **only pions not showering in ECAL**;
- reconstruction with Digital RO and SDRO:
  - Thresholds considered for SDRO: 0.2, 4, 12 keV
- fit function $f(E)=S/\sqrt{E}\oplus C$;
- comparable performances below 6 GeV between Digital RO and SDRO
- **Digital RO: saturation at high energies**
- **Overall, better performances of the SDRO**
  - **$\sigma/E = 45.96\%/\sqrt{E}\oplus 12.36\%$**

test beam at SPS (July 2023):

- Tracking: 2 MicroMegas (256 µm-strip)
- Under test: 12 MPGD prototypes
  (7 µRWELL, 4 MicroMegas, 1 RPWELL)
- Gas: **$Ar:CO_2:C_4H_{10}$(93:5:2)** (MicroMegas & RPWELL),
  $Ar:CO_2:CF_4$(45:15:40) (µ-RWELL)
- Particle: O(100) GeV/c **muons**

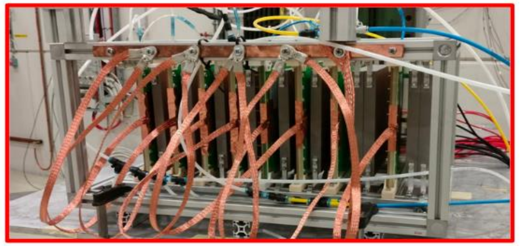
Test beam setup at SPS



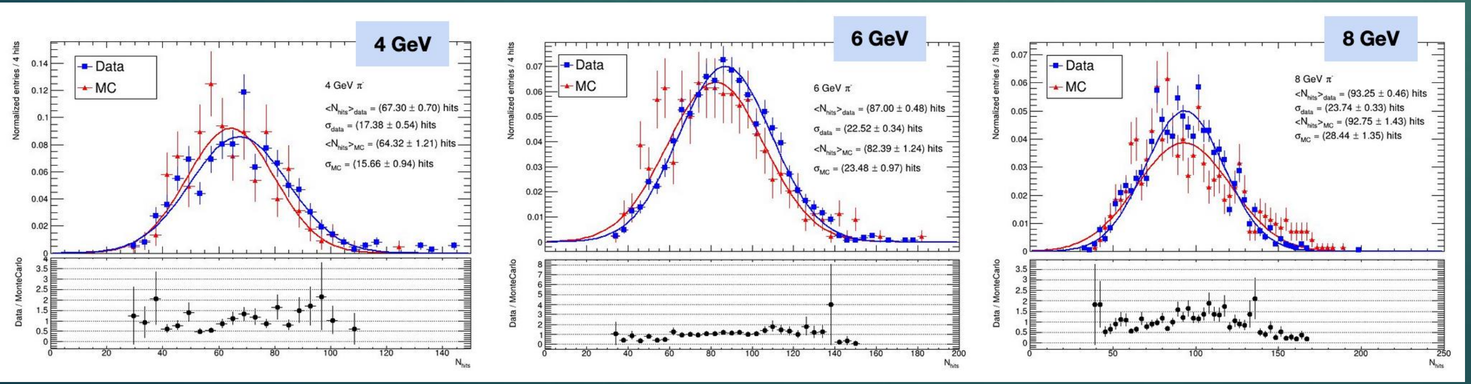
test beam at PS (Aug/Sept 2023):

- Tracking system
- 1 λ_I calorimeter prototype:
  - 8 MPGDs (4µRWELL, 3 MM, 1 RPWELL)
  - First 2 layers of absorbers made of 4cm of Iron instead of 2cm to enhance showers in the first 2 layers
- Pions energy: 2-11 GeV

HCAL Prototype at PS



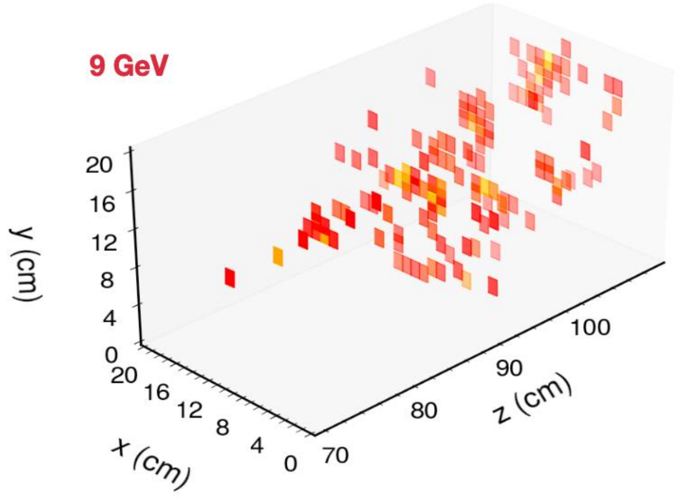
Readout **electronics**: **APV25** front-end chip (analog readout + time information) + **SRS** back-end

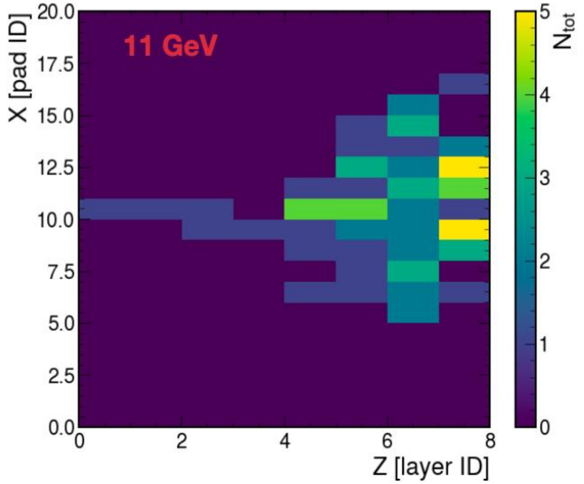


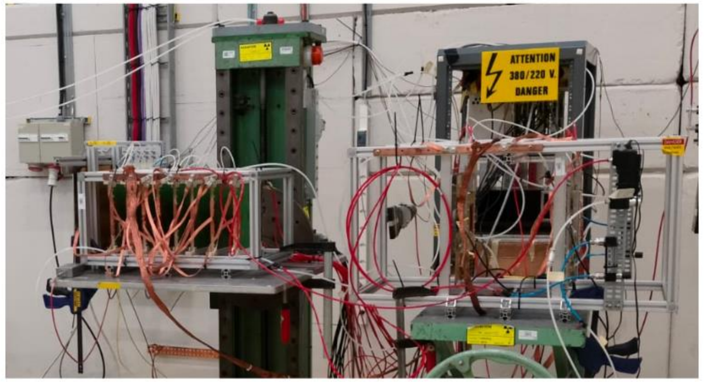
Good agreement in # hits in Testbeam vs GEANT4 MC

INFN 2024 Testbeam

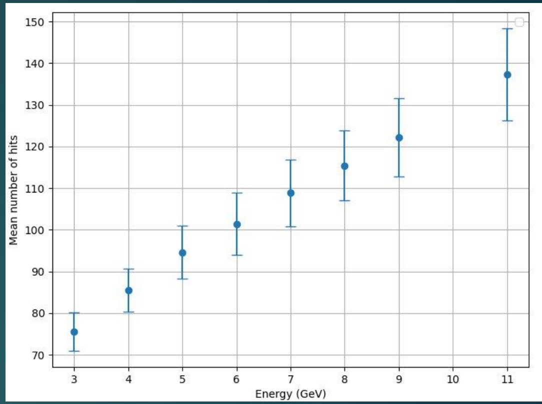
Shower events (2024)







- Consolidating results with present prototypes in two test beams in 2024:
  - SPS (June 26-July10):
    - full efficiency Vs HV curve,
    - response uniformity,
    - timing
  - PS (July 10-24):
    - test of a fully equipped 8 MPGD layers Prototype with pions beam (*E~3-11 GeV*)
    - First trial to run 2 independent APVs/SRS DAQ systems (MPGDHCAL & RHUM) but with the same trigger chain to evaluate the possibility of an offline full event reconstruction and overcome the limits of an APVs/SRS system

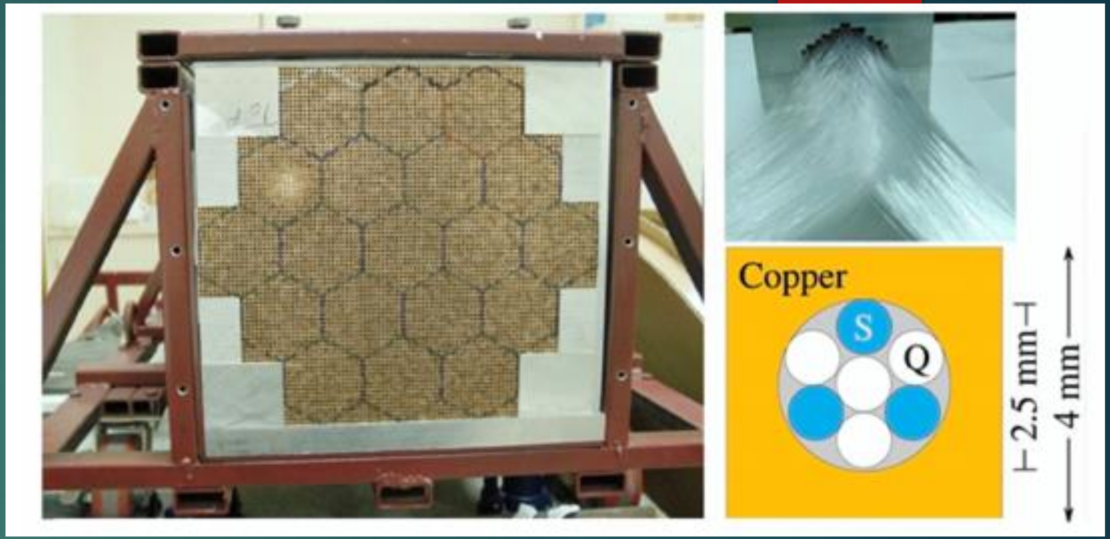


Response Function:
- #hits increases with E
- High E: loss of linearity due to non-full shower containment

Next steps:
- ❑ 50 cm x 50 cm MPGD compatible with the SDHCAL mechanical structure
- ❑ New readout electronics→ discussion to use Claroroc

Dual Readout-based calorimeters

Energy is deposited in two different ways
1) Scintillation light
2) Cerenkov light → relativistic particles
80% of the hadronic component is not relativistic



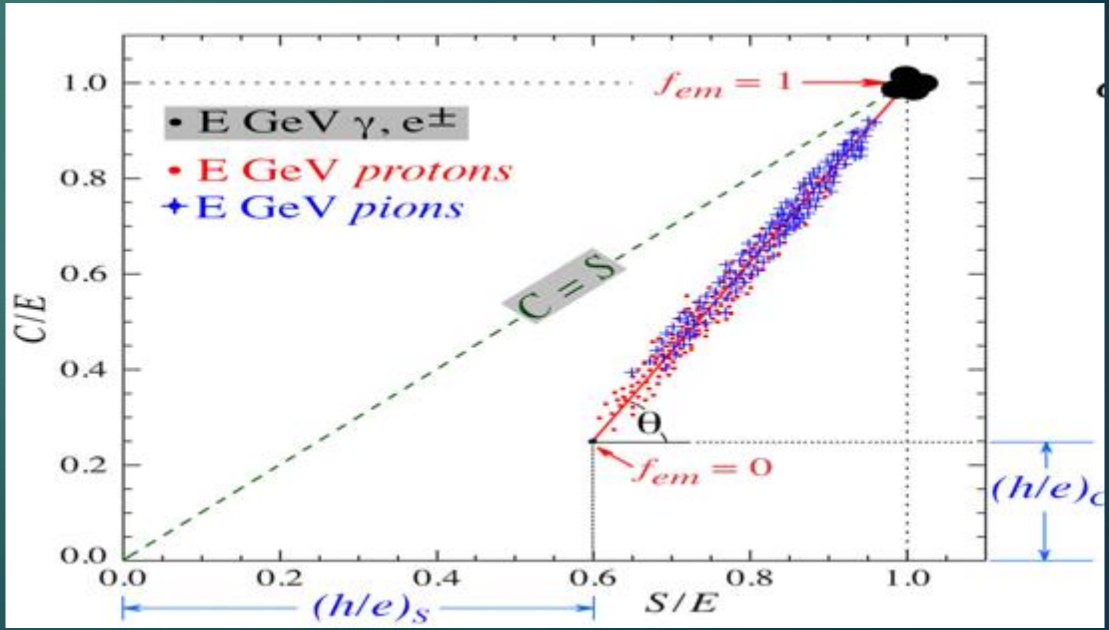
$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$
$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1 - f_{em})\right]$$

If one has $(e/h)_S$ and $(e/h)_C$ then

$$\chi = \frac{1-(h/e)_S}{1-(h/e)_C}$$

X Is independent of E and particle nature

$$E = \frac{S - \chi C}{1 - \chi}$$



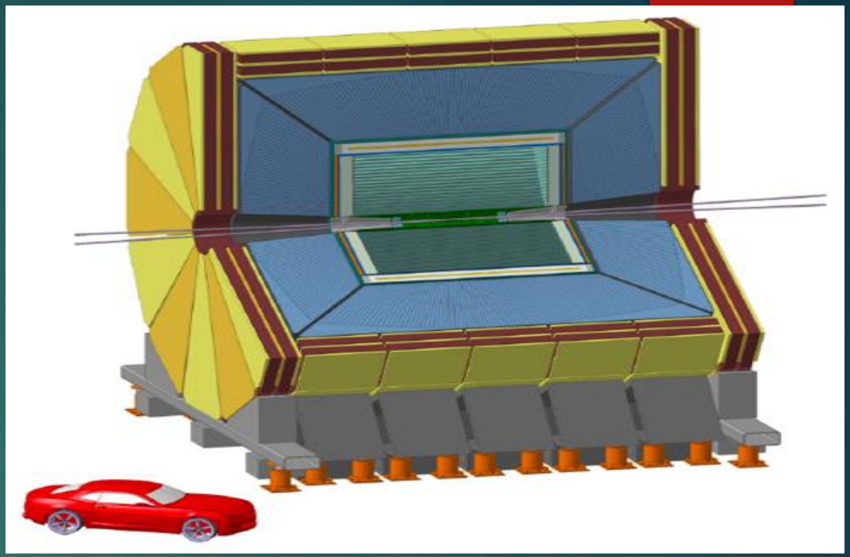
Double Readout technique can use either fibers or crystals

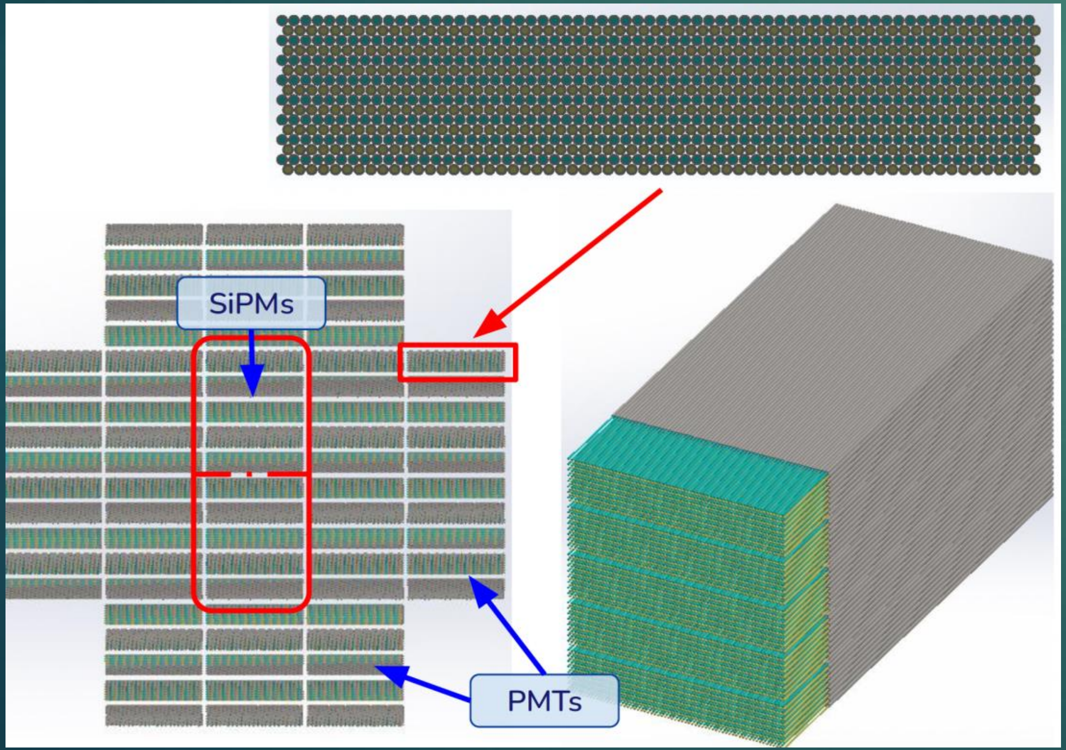
IDEA detector

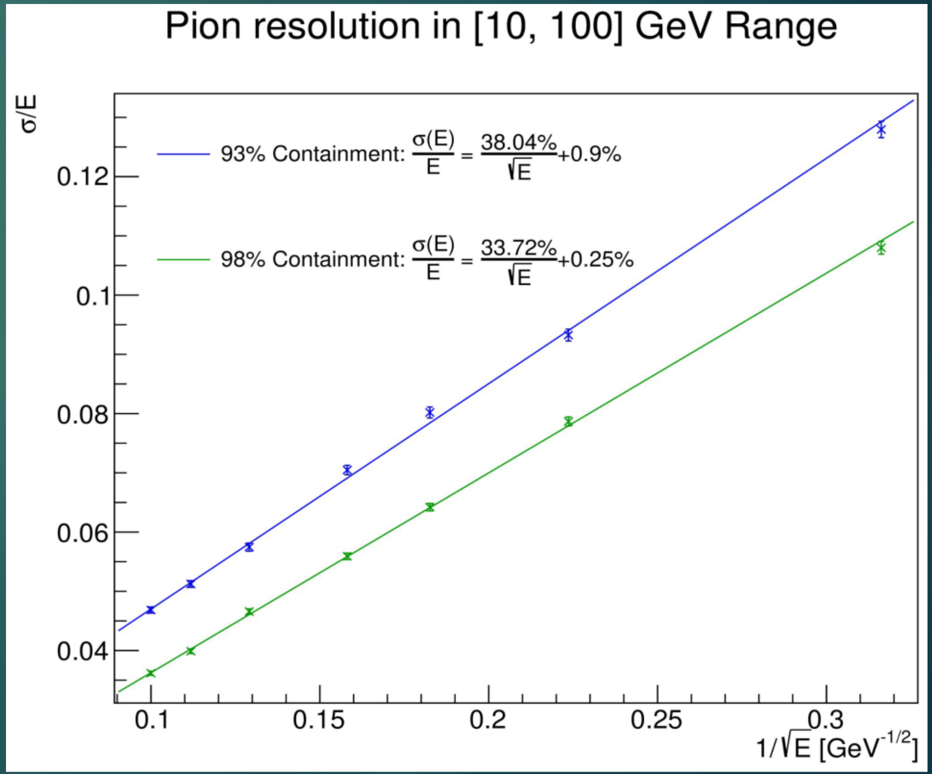
A hadronic-size prototype (HiDRA) is being built with
8 modules each made of 10 mini modules, 250 cm depth each

Each external module read out by two PMTs, one for S
fibres and the other for C fibres (512 fibres each)

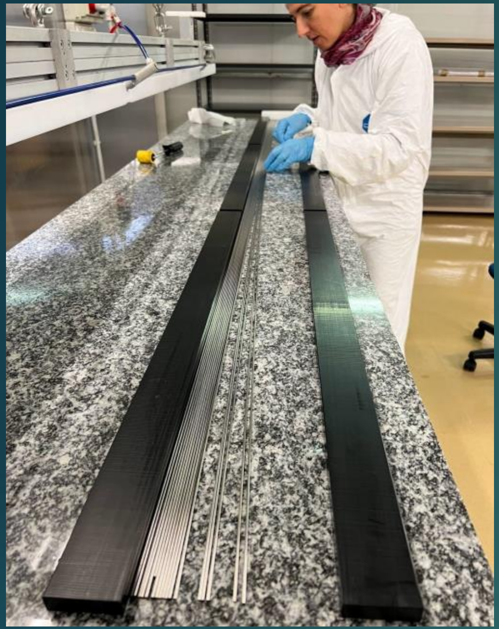
The two central will be equipped with SiPM
This intends to validate the DR concept for future colliders

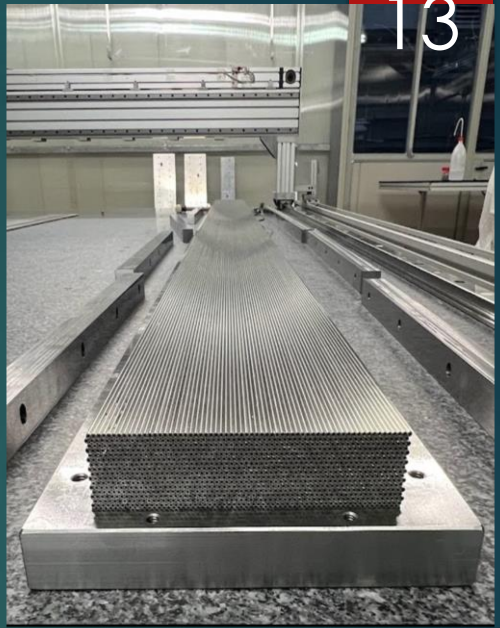
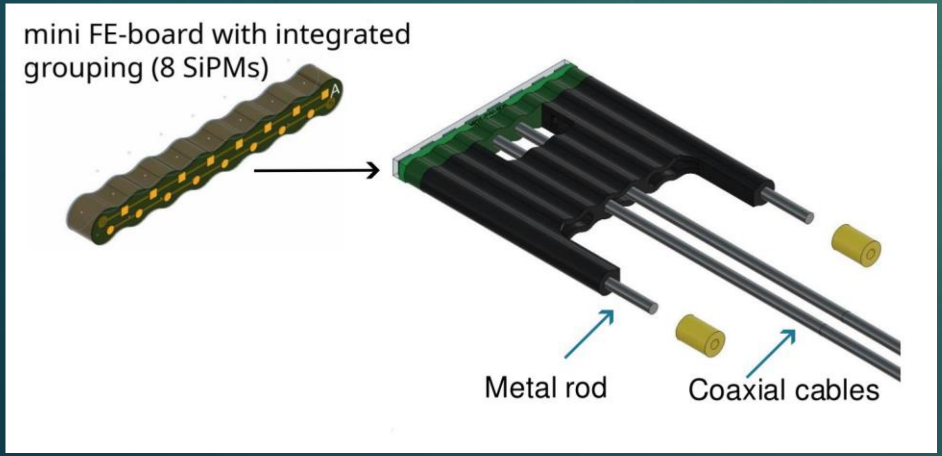


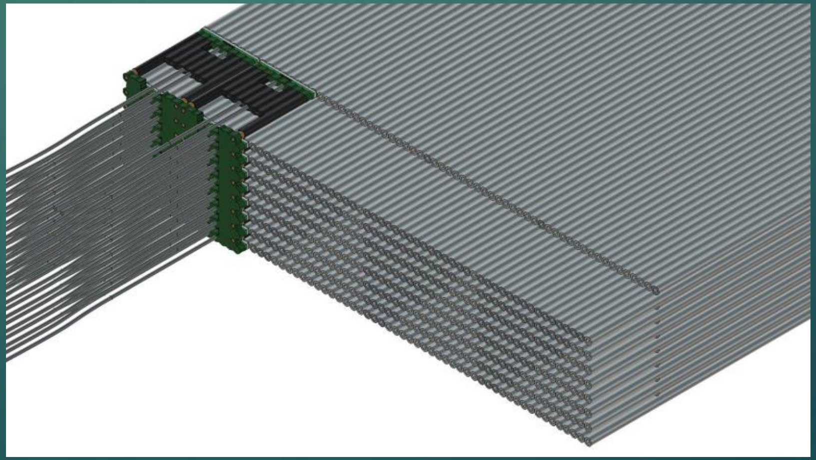




HiDRA Prototype construction : 47/80 are so far assembled



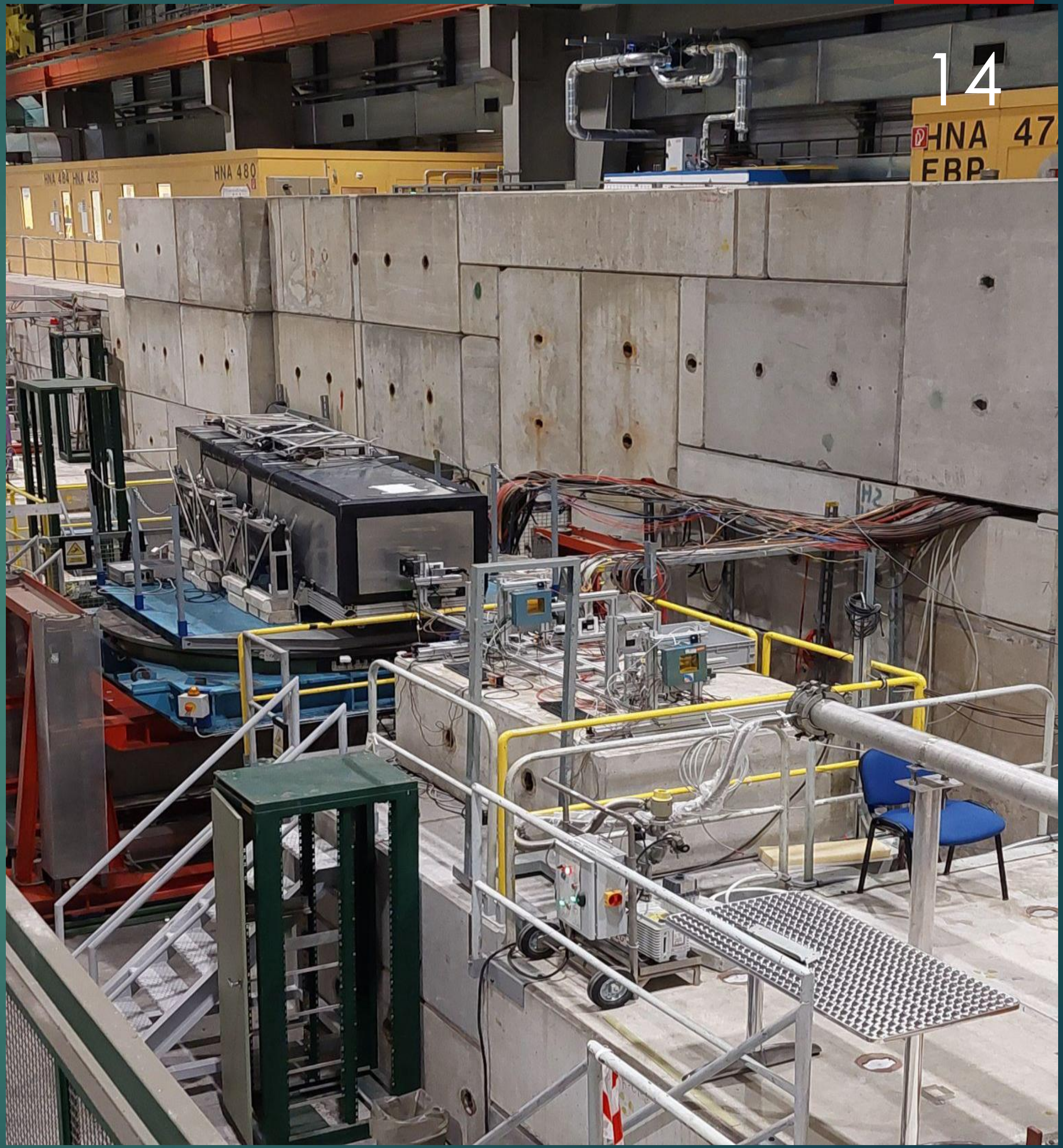



Beam Test 2024

First characterisation of new prototype on beam at the end of August
Partially completed calorimeter with 36/80
modules, using PMT-only readout

12 x 3 modules, ~ 38.4 x 33.9 x 250 cm3
Containment for hadron showers: ~ 87%
(estimated through Geant4 simulation)

TS55	TC55	TS54	TC54	TS53	TC53
TS45	TC45	TS44	TC44	TS43	TC43
TS35	TC35	TS34	TC34	TS33	TC33
TS25	TC25	TS24	TC24	TS23	TC23
TS16	TC16	TS15	TC15	TS14	TC14
TS17	TC17	TS00	TC00	TS13	TC13
TS10	TC10	TS11	TC11	TS12	TC12
TS20	TC20	TS21	TC21	TS22	TC22
TS30	TC30	TS31	TC31	TS32	TC32
TS40	TC40	TS41	TC41	TS42	TC42
TS50	TC50	TS51	TC51	TS52	TC52
TS60	TC60	TS61	TC61	TS62	TC62



Analyses are ongoing.

Personal view on possible HCAL French Italian Collaboration

- DRD6 is the right framework where both communities can work together.
- For the SDHCAL, we all belong to the same WP5 of the DRD1 working on large, high rate capability and efficient gaseous detectors.

What we can do more

- To work on common readout electronics: **timing for instance**
- To develop or improve on the **DAQ** systems
- To collaborate on the **simulation tools** (some issues with hadronic showers in GEANT4)
- Develop **Deep Learning** techniques to better estimate the energy
- Develop **reconstruction codes** (PFA for instance)
- **Exchange students (European network?)**

Many thanks to Piet Verwilligen, Andrea Pareti and Gabriella Gaudio
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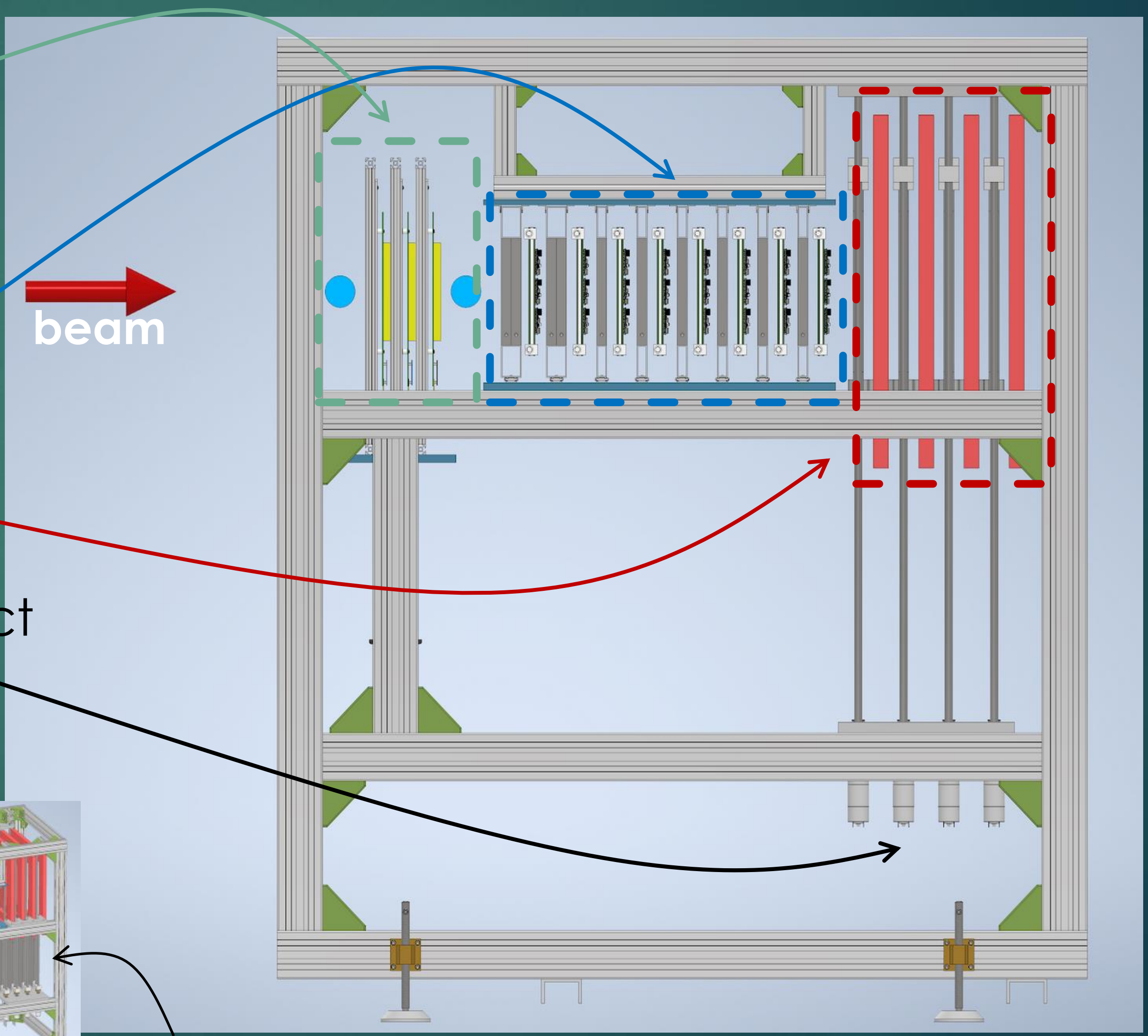
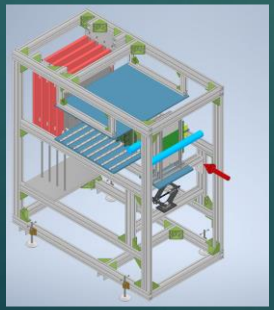
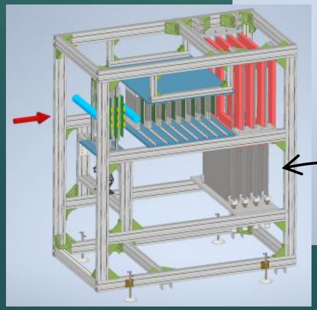
Backup

Preparing for 2025 Testbeams

- Triple-GEM tracker
  - Moveable to scan entire surface
- 1λ with 20x20cm²
  - 8 dets, 8x2cm steel
- 1λ with 50x50cm²
  - 4 dets, 4x4cm steel
- Allows to insert / extract steel absorbers







Absorbers extracted