Key Point on the IN2P3-CALICE activities

SDHCAL

Outline

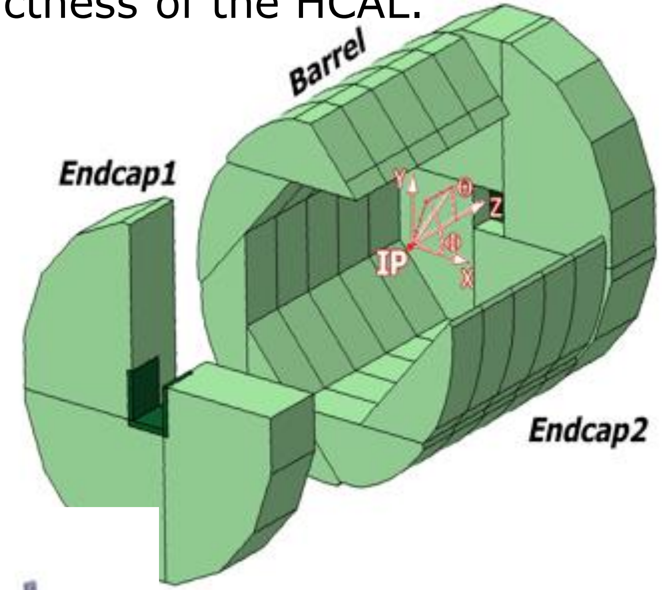
- ❑ SDHCAL prototype goals
- ❑ SDHCAL description
- ❑ Lessons learnt from beam tests
- ❑ SDHCAL and future Higgs factories
- ❑ Spin-off

SDHCAL

The SDHCAL concept is based on exploiting **Gaseous Detectors** potential to build a highly granular hadronic calorimeter allowing to exploit the Particle Flow Algorithms (PFA) performance.

Semi-digital readout was proposed to mitigate the saturation problem allowing better energy reconstruction. **Power-pulsed electronics,** possible in ILC, eliminates the need of active cooling **Self-supporting mechanical** structure servs as absorber increasing the compactness of the HCAL.

The structure proposed for the SDHCAL :
- very compact with negligible dead zones.
- Minimizes barrel / endcap separation (services leaving from the outer radius)

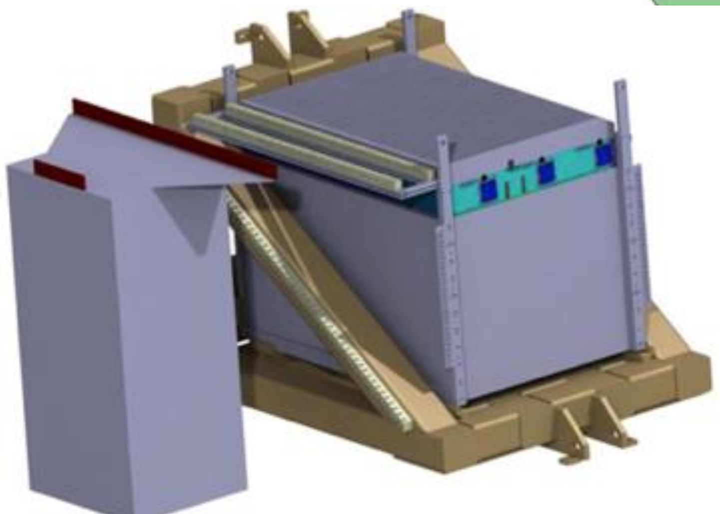


Goals

SDHCAL Technological Prototype should be as much as possible similar to the ILD module and able to study **hadronic showers**

Challenges

-Homogeneity for large detection surfaces
-Thickness of only few mms
-Lateral segmentation of 1 cm X 1 cm
-Services from one side
-Embedded power-cycled electronics
-Self-supporting mechanical structure



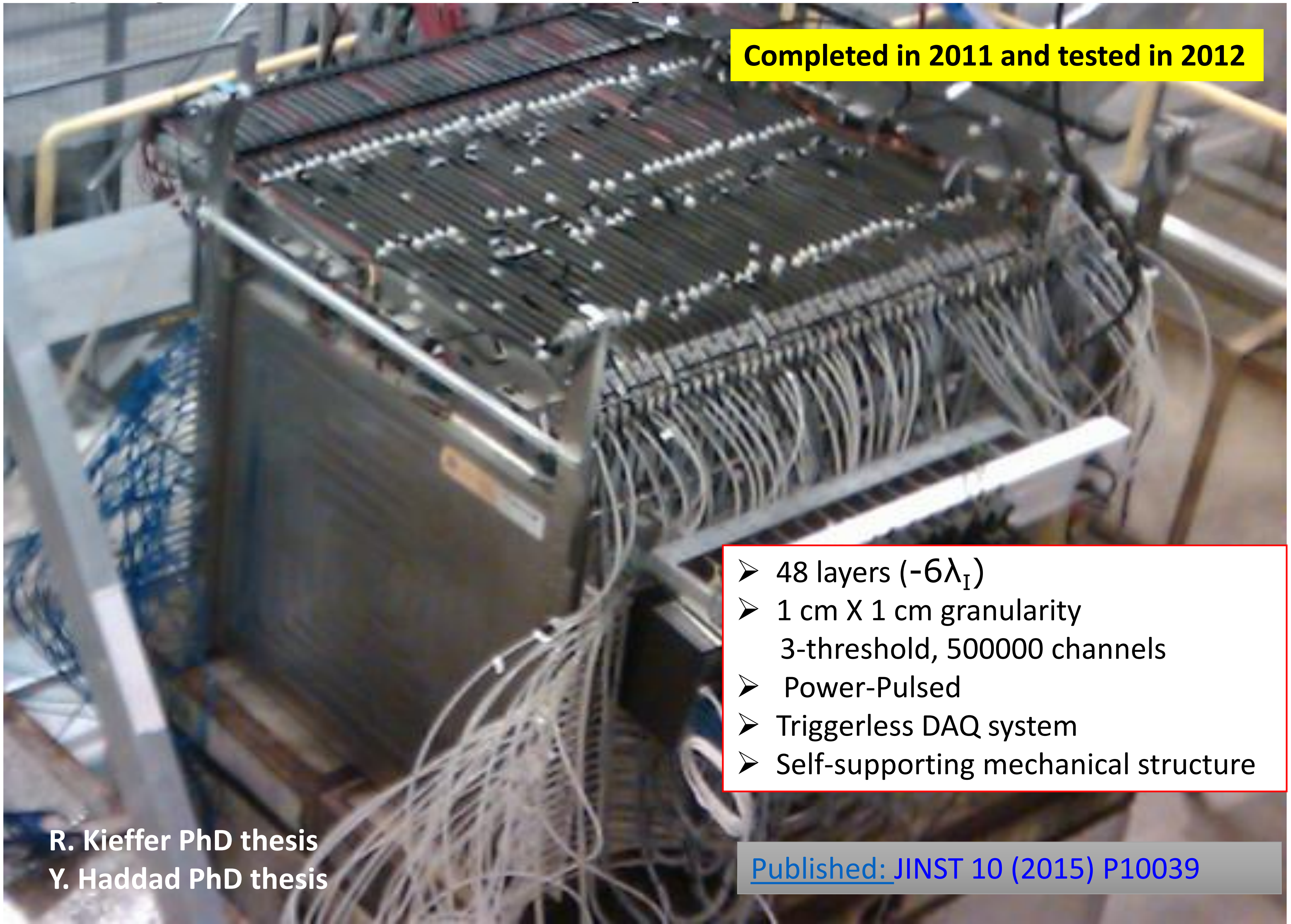
SDHCAL prototype construction

- ✓ 10500 64-ch ASIC were tested and calibrated using a dedicated robot (ASICs layout : 93%).
- ✓ 310 PCBs were produced, cabled and tested. They were assembled by sets of six to make 1m² ASUs
- ✓ 170 DIF, 20 DCC were built and tested.
- ✓ 50 detectors were built and assembled with their electronics into cassettes.
- ✓ Self-supporting mechanical structure.
- ✓ DAQ system using both USB and HTML protocol was developed and used.
- ✓ Full assembly took place at CERN in 2011.

IP2I, LAPP, LLR,
OMEGA
CIEMAT, LLN, Gent

French contribution was essentially funded by
ANR-Blanc DHCAL
Spain: Mechanical structure
Belgium: Services

Completed in 2011 and tested in 2012



- 48 layers ($-6\lambda_I$)
- 1 cm X 1 cm granularity
  3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure

R. Kieffer PhD thesis
Y. Haddad PhD thesis

Published: JINST 10 (2015) P10039

SDHCAL performance

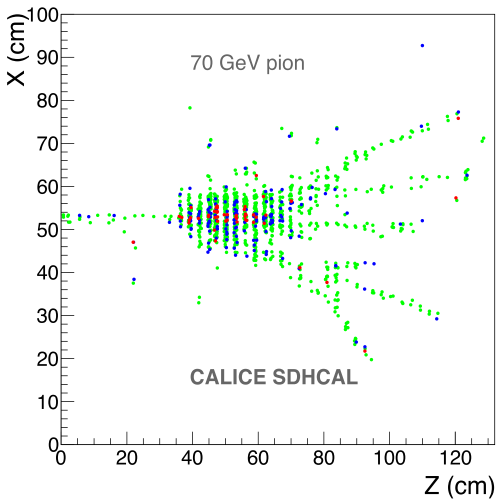
- The SDHCAL prototype was exposed to hadron, muon and electron beams in 2012, 2015 , 2018 and 2022 on PS, H6 and H8 -SPS lines.

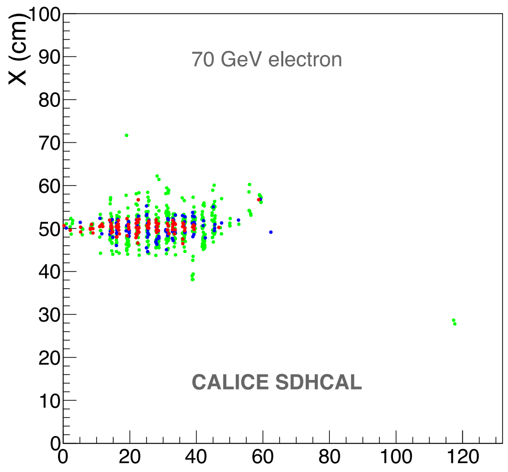
- **Power-pulsing** using the SPS spill structure was used to reduce the power consumption.

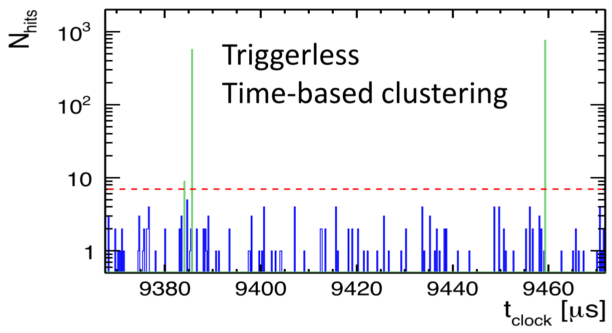
- **Self-triggering** mode is used but external trigger mode is possible

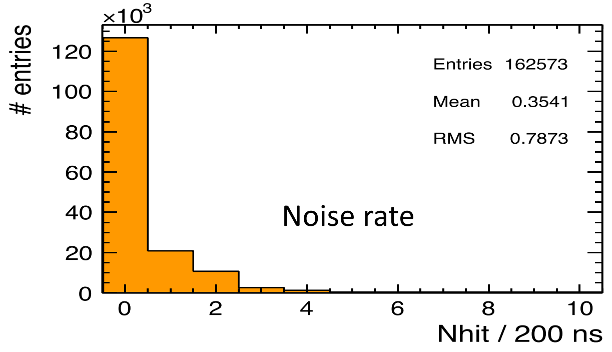
- The threshold information helps to improve on the energy rec. by better accounting for the number of tracks crossing one pad

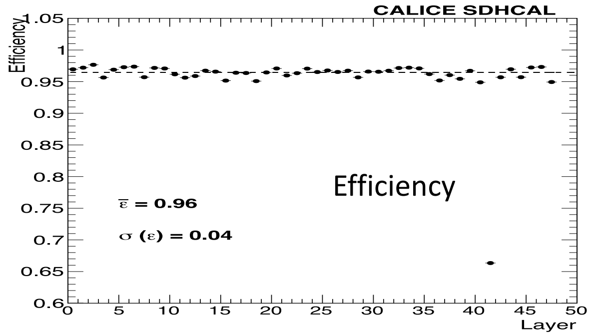
- Data were taken in 2012, 2015, 2017, 2018 and 2022 with continuously improved DAQ system.

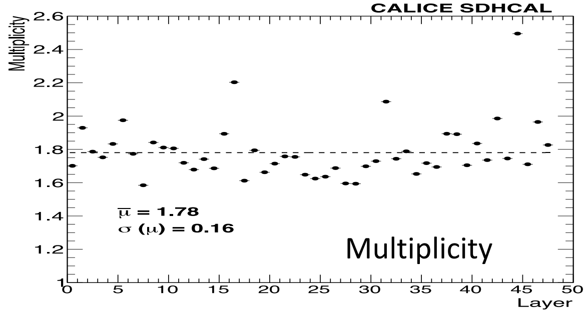




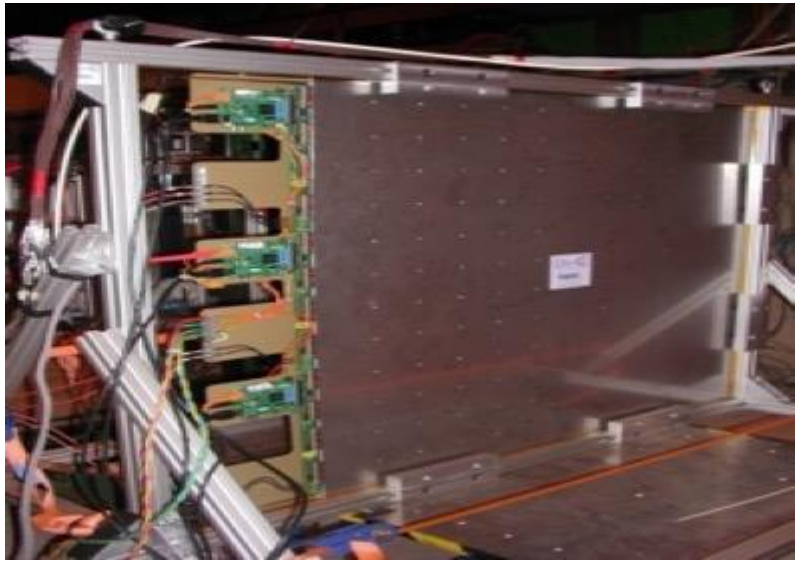


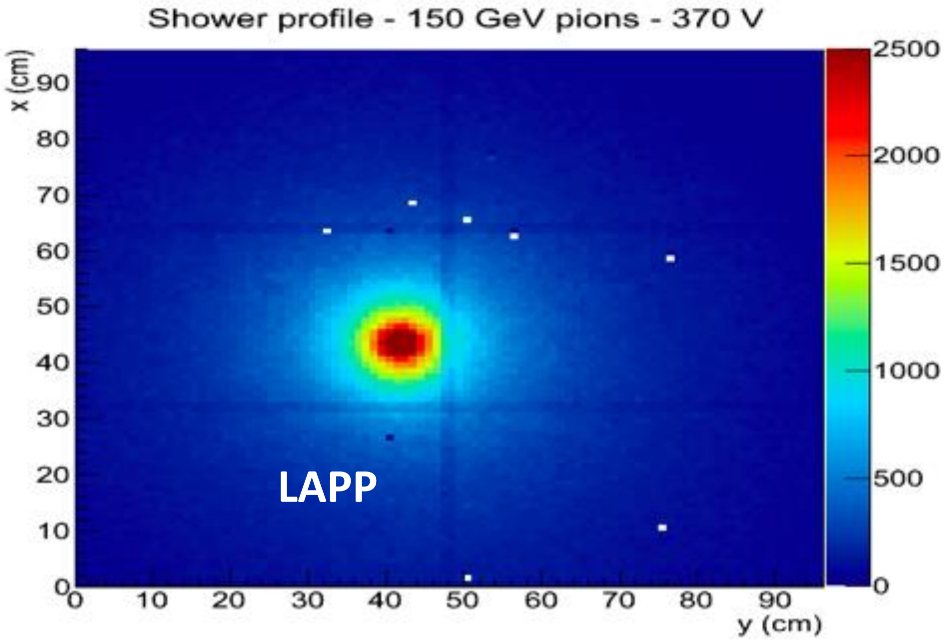






In addition, within the ANR-Blanc, 4 units of SDHCAL-MM 1m x 1m each were produced, tested in a muon beam. The 4 units of SDHCAL-MM were inserted in the SDHCAL-RPC prototype replacing the RPC units #10, 20, 35 and 50





Beam test results

The SDHCAL was the first **technological** prototype developed within the CALICE collaboration.
Beam tests at CERN allowed us

- to validate the concept
- to better understand its different components (GRPC, Front-End and Back-End electronics)
- to continuously improve on the DAQ system to obtain the best performances
- to study hadronic showers

Energy reconstruction

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

N_1= Nb. of pads with first threshold <signal < second threshold

N_2 = Nb. of pads with second threshold <signal < third threshold

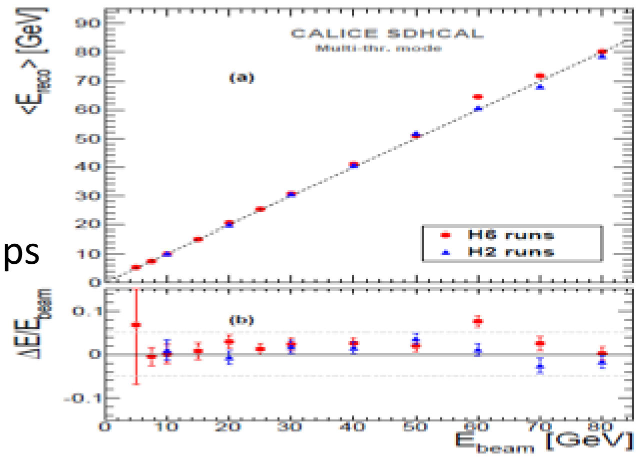
N_3 = Nb. of pads with signal> third threshold

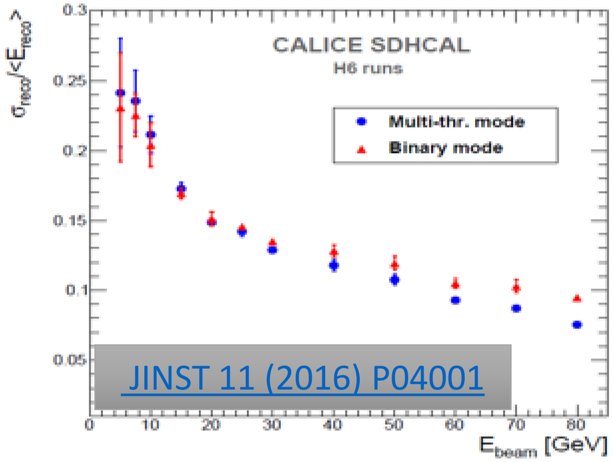
$N_{tot} = N_1 + N_2 + N_3$

α , β , γ are **quadratic functions** of

They are computed by minimizing :

$\chi^2 = (E_{beam} - E_{rec})^2 / E_{beam}$

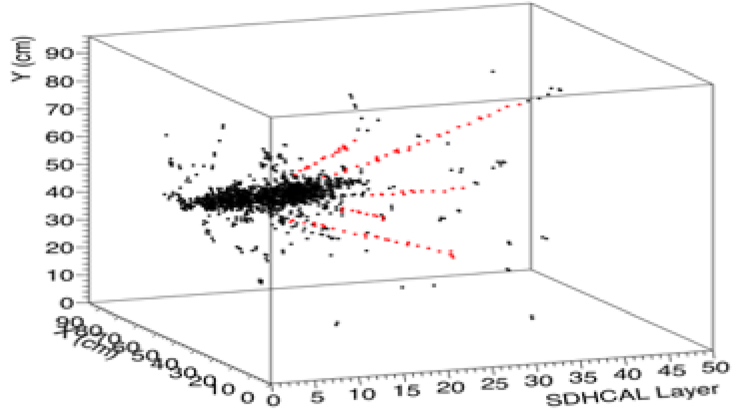


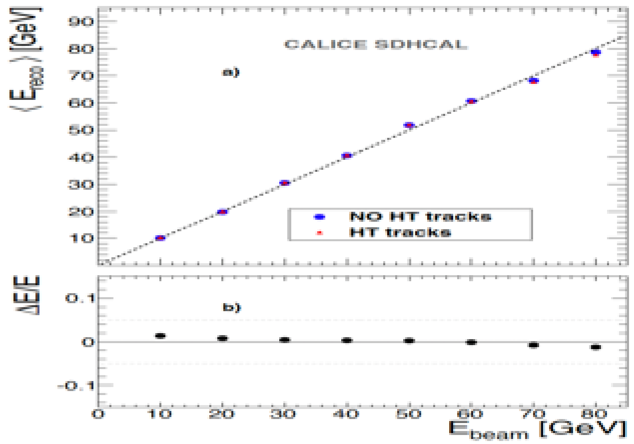


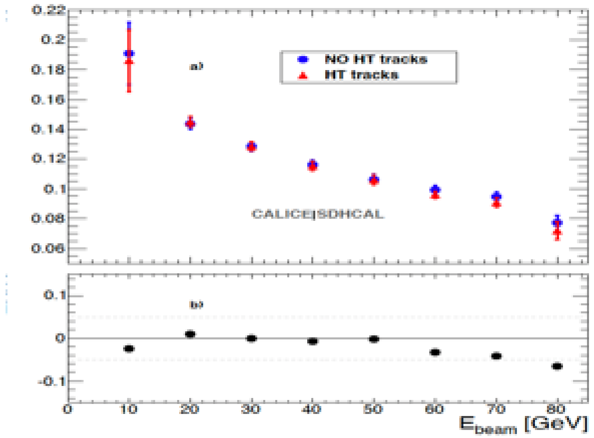
JINST 11 (2016) P04001

Hough-Transform

Track segments reconstruction using 3D-Hough Transform helps to apply different treatment to the hits of these segments.







$E_{rec} = \alpha(N_{tot})\, N'_1 + \beta(N_{tot})\, N'_2 + \gamma(N_{tot})\, N'_3 + c\ N_{HT}$

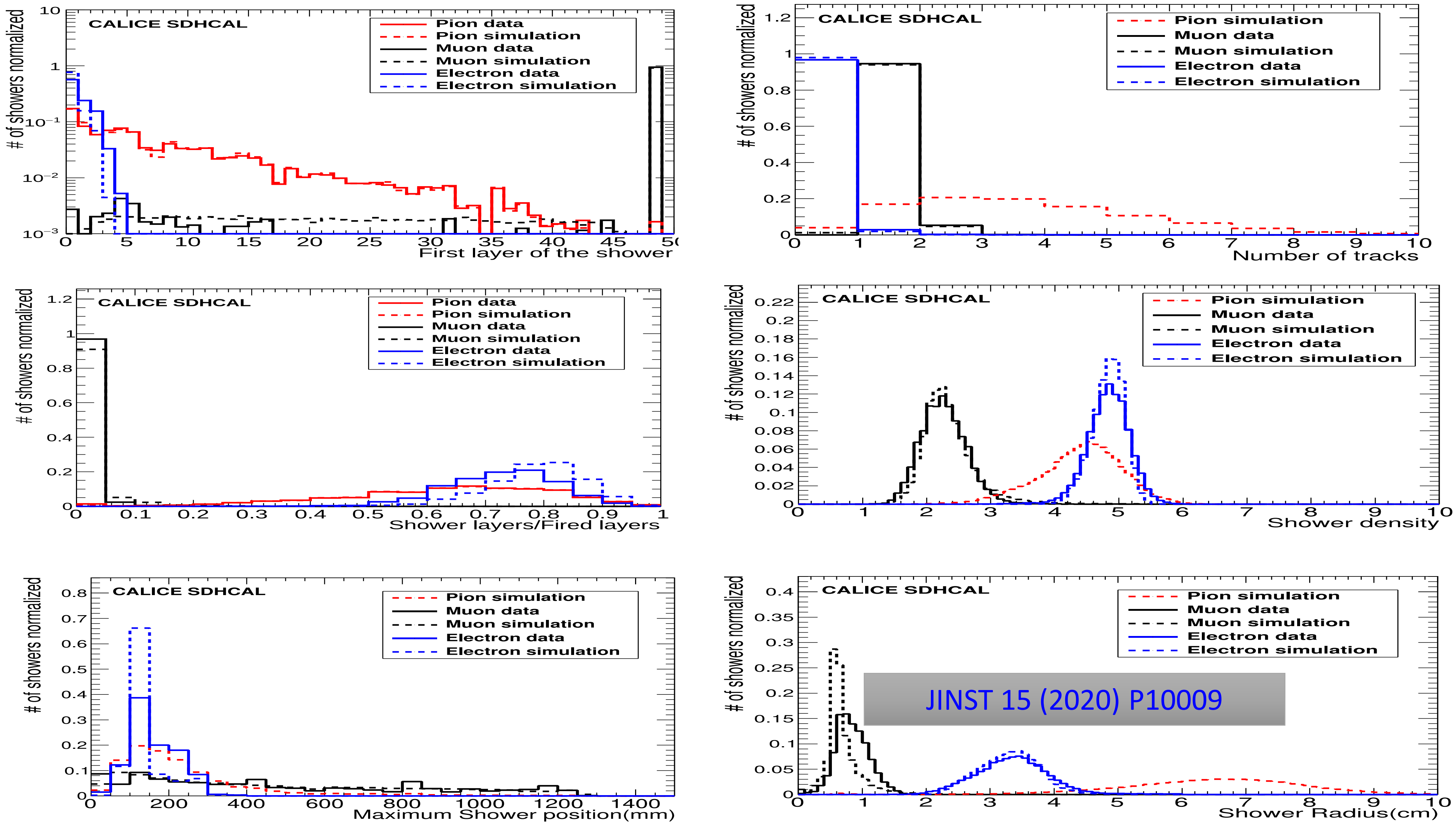
$N_{tot} = N'_1 + N'_2 + N'_3 + N_{HT}$

In addition track segments will be used as in-situ calibration and monitoring tools

JINST 12 (2017) P05009

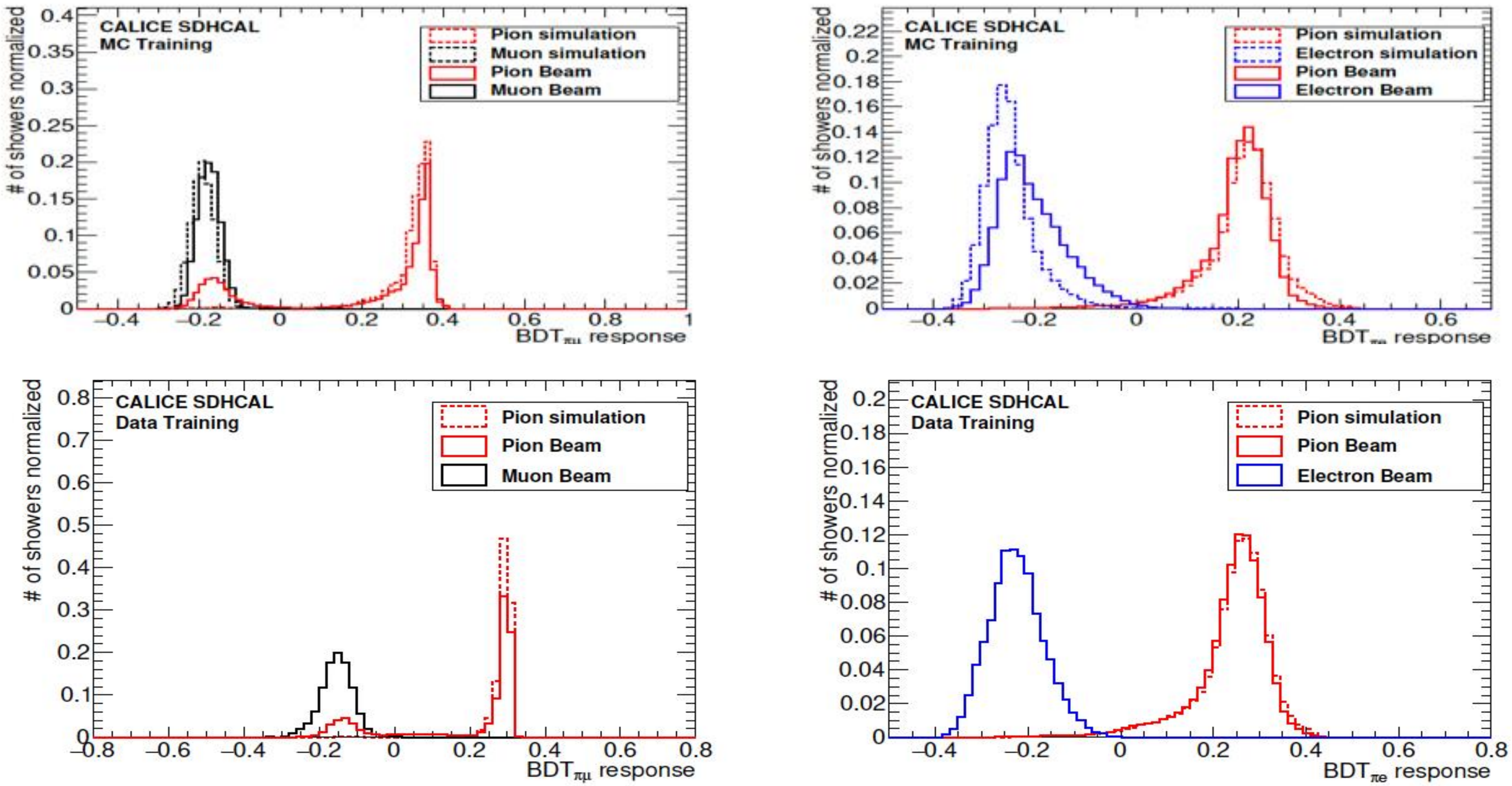
Particle Identification

The high granularity of SDHCAL allows one to discriminate different kinds of particles (pions, electrons and muons)



Particle Identification

The high granularity of SDHCAL allows one to discriminate different kinds of particles (pions, electrons and muons). The discrimination power is well exploited using MVT (BDT in our case)



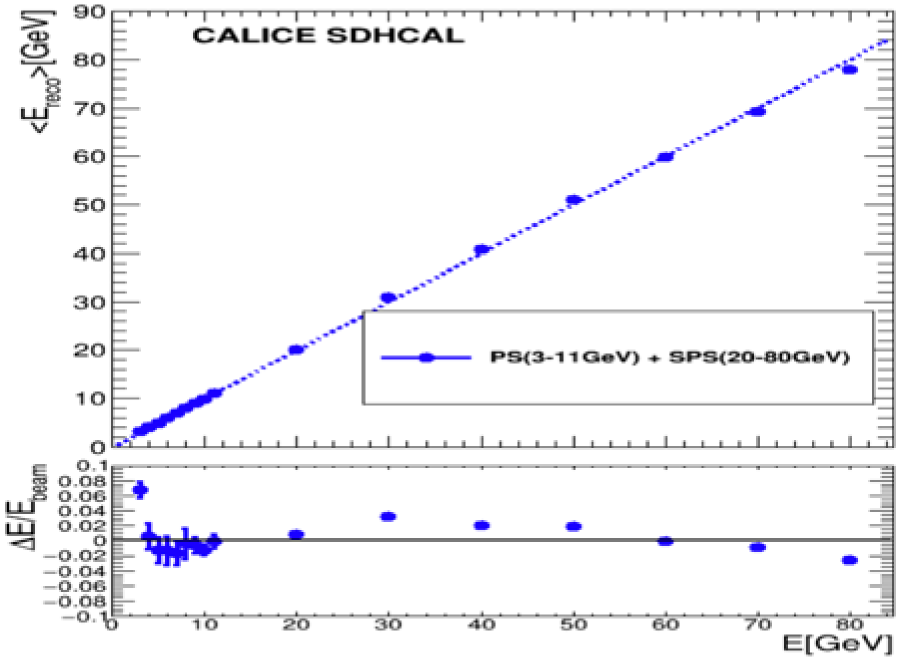
Electron and muon rejection > 99%

B. Liu PhD thesis

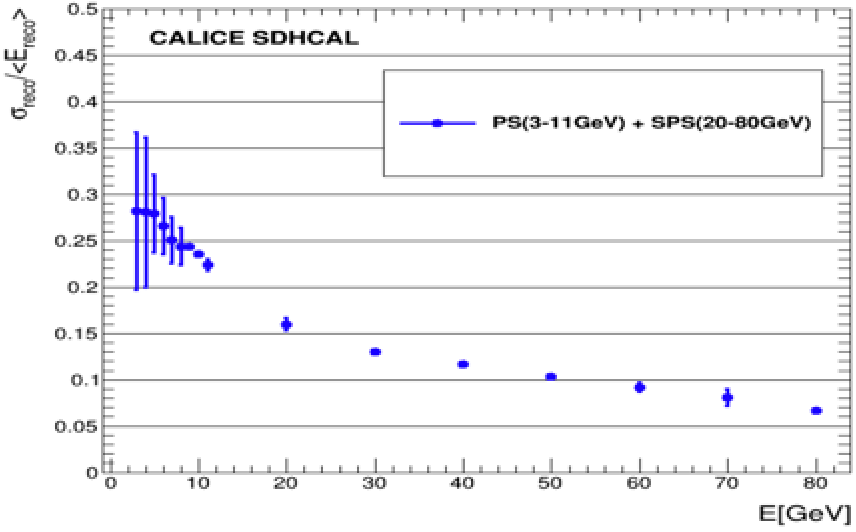
JINST 15 (2020) P10009

Particle Identification & Energy reconstruction

The BDT-based PID technique was also applied to the PS (3-80 GeV) samples



Linearity

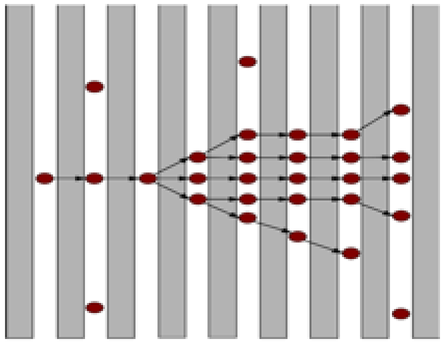


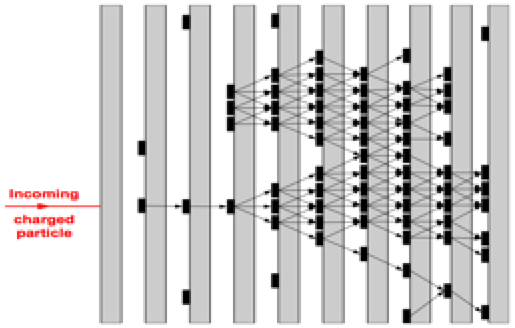
Resolution

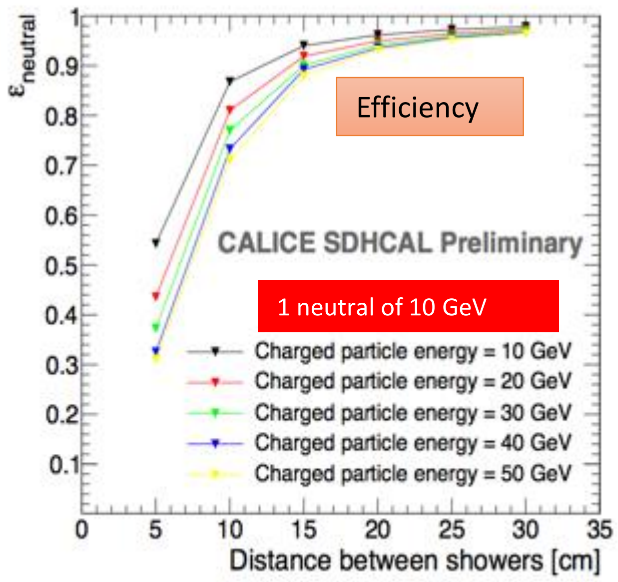
JINST **17** (2022) P07017

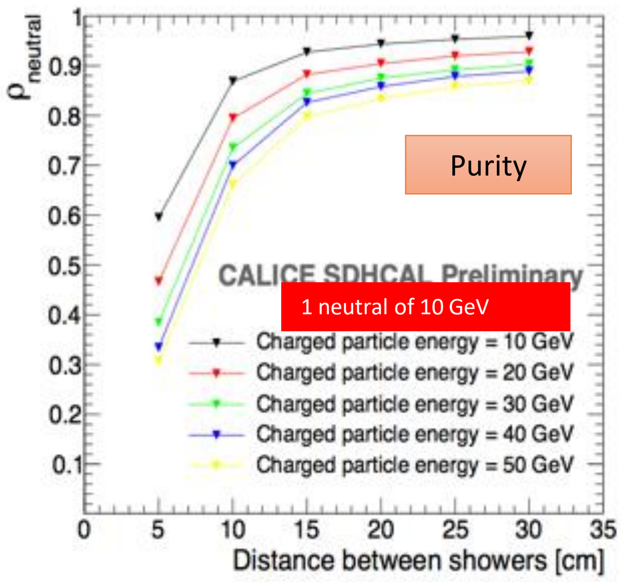
Shower separations

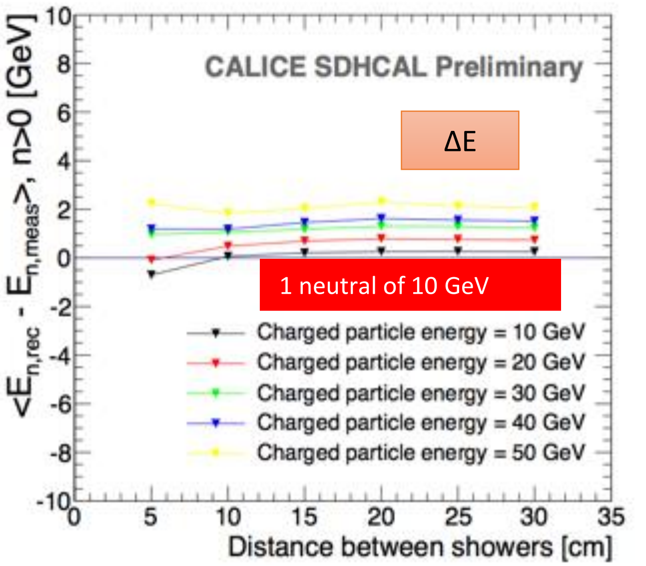
ArborPFA, April algorithms:
they connect hits and then their clusters using distance and orientation information then user tracker information (momentum) to improve on the correction









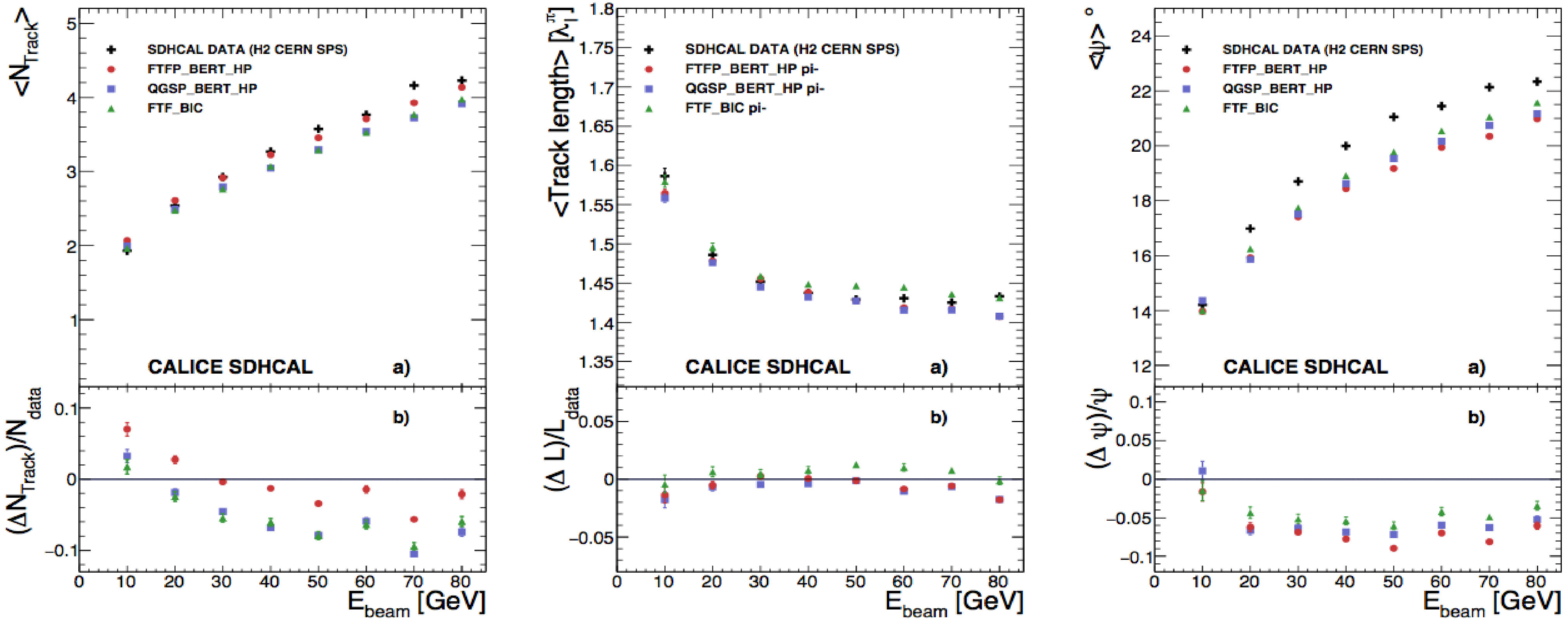


CALICE note CAN054

R. Eté PhD thesis
L. BO (LIO postdoc)

Hadronic shower studies

- The high granularity of SDHCAL provides an excellent probe of hadronic showers.
- Studies of these showers using SDHCAL allow the discrimination of many models.
- A complete digitization of the SDHCAL prototype was developed before using the simulation models.



A. Steen PhD thesis

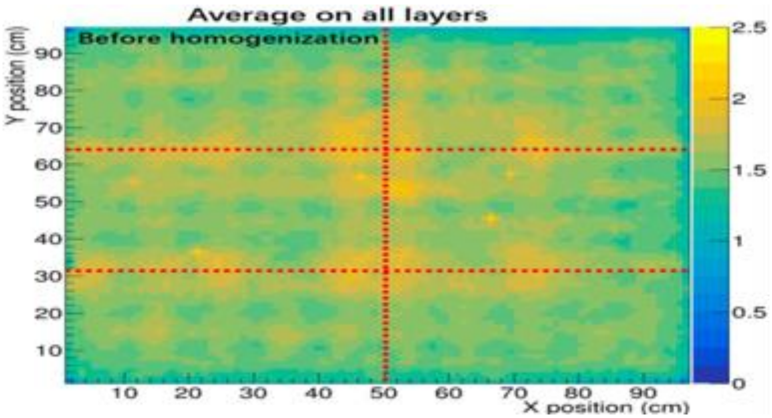
Strong collaboration with GEANT4 Collaboration
(Alberto Ribon defended his HDR in our University)

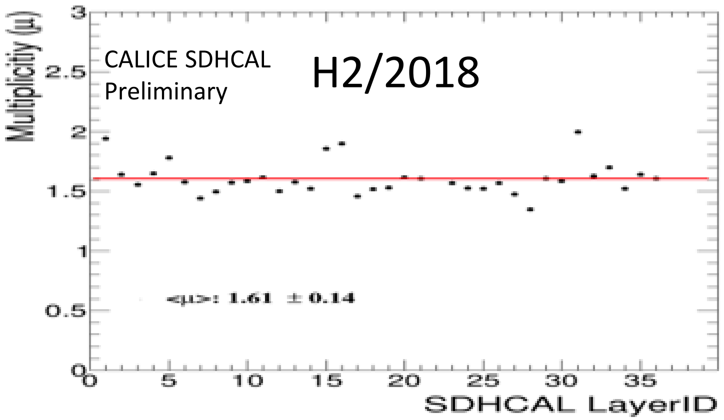
JINS 17 (2016) P06014

Further improvements on the energy reconstruction

Detector homogeneity

The homogeneity of the detector response is important to achieve better energy reconstruction





A new calibration method based on varying the thresholds rather than the electronic gain was found to be powerful. Muon runs with different thresholds Thr1: 0.1-0.42 pC, Thr2: 0.4-5, Thr3:4.7-24) and efficiency and multiplicity were measured for each value. The values of the three thresholds of each ASIC were fixed to obtain same multiplicity (first threshold) and the same efficiency for thr2 and thr3.

$$\varepsilon(t;\bar{q},\delta,\epsilon_0) = \varepsilon_0 \cdot \left(1 - \int_0^t P(q;\bar{q},\delta)dq\right)$$

$$P(q;\bar{q},\delta) = \frac{1}{\Gamma\left(\frac{\bar{q}}{\delta}\right)\delta^{\frac{\bar{q}}{\delta}}}\, q^{\frac{\bar{q}}{\delta}-1}\, e^{-\frac{q}{\delta}}$$

$$\mu(t;f,p,c) = f \cdot t^p + c$$

Further improvements on the energy reconstruction

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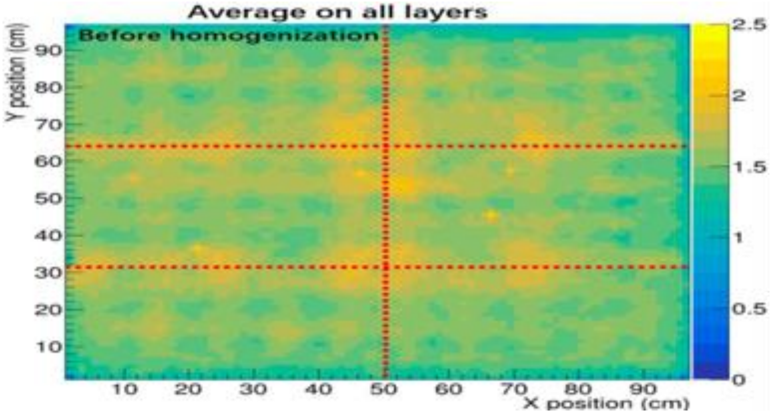

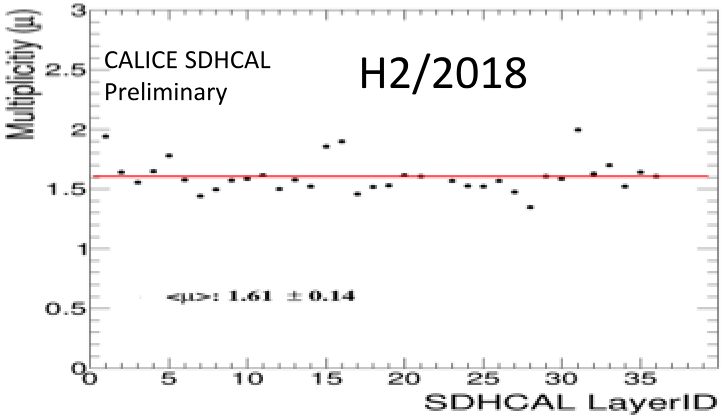

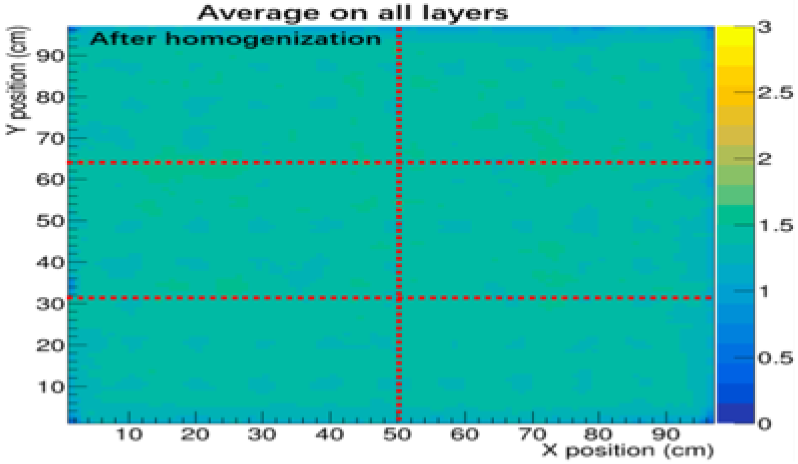

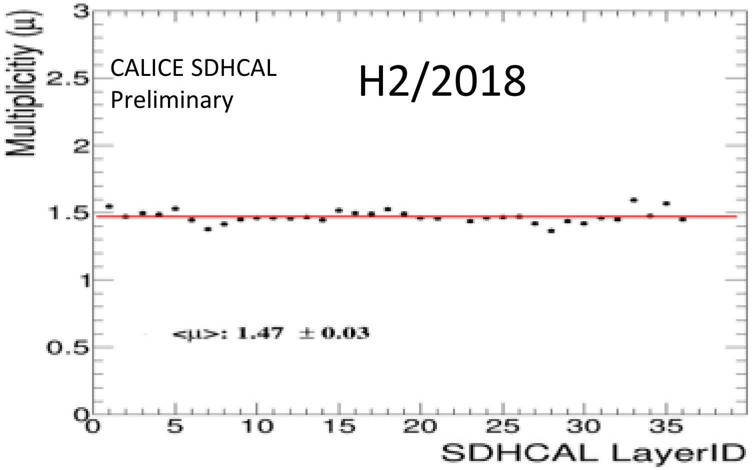

Further improvements on the energy reconstruction

Detector homogeneity

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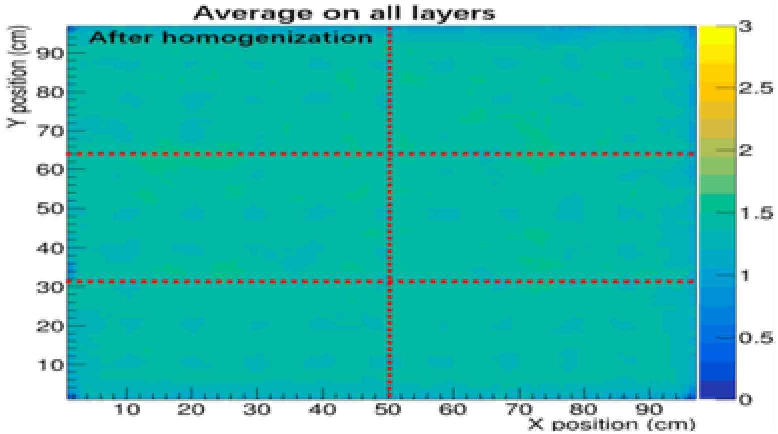
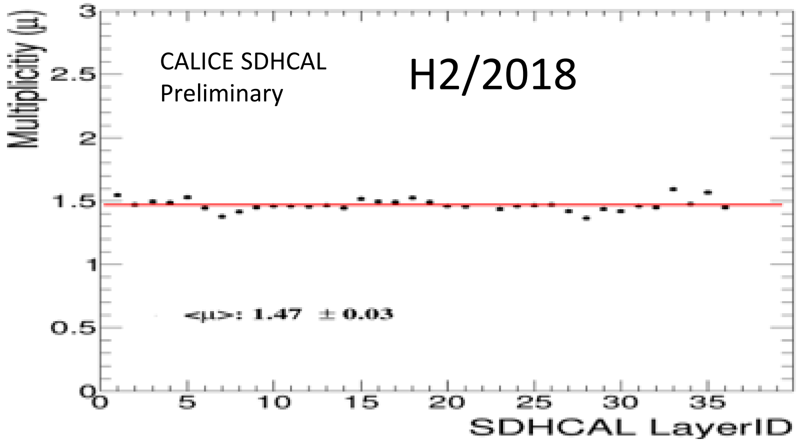
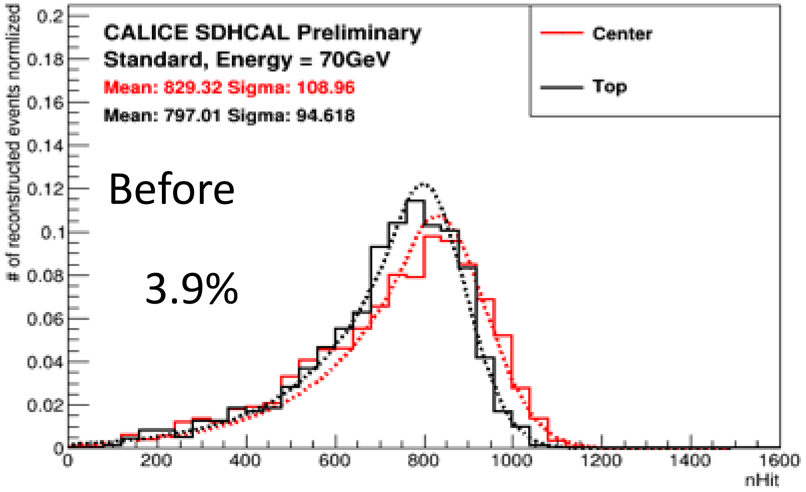
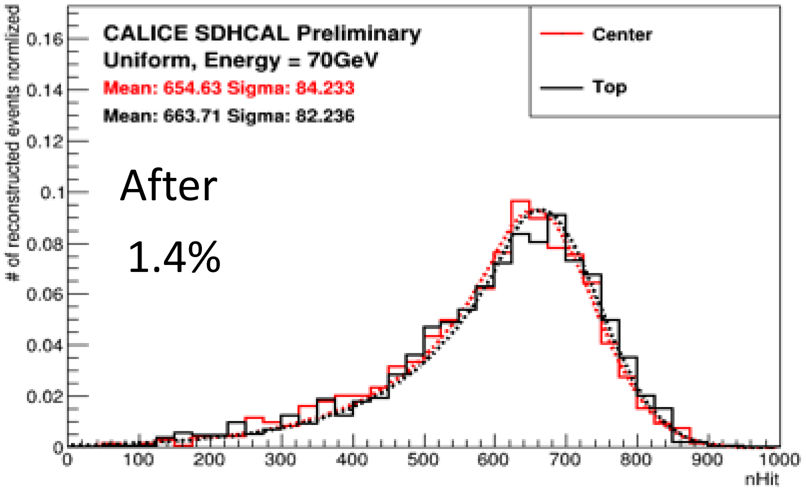








G. Garillot PhD thesis

Monitoring system

A monitoring system (DQM4HEP) developed for the SDHCAL (R. Eté&A. Pingault)
It allows to control

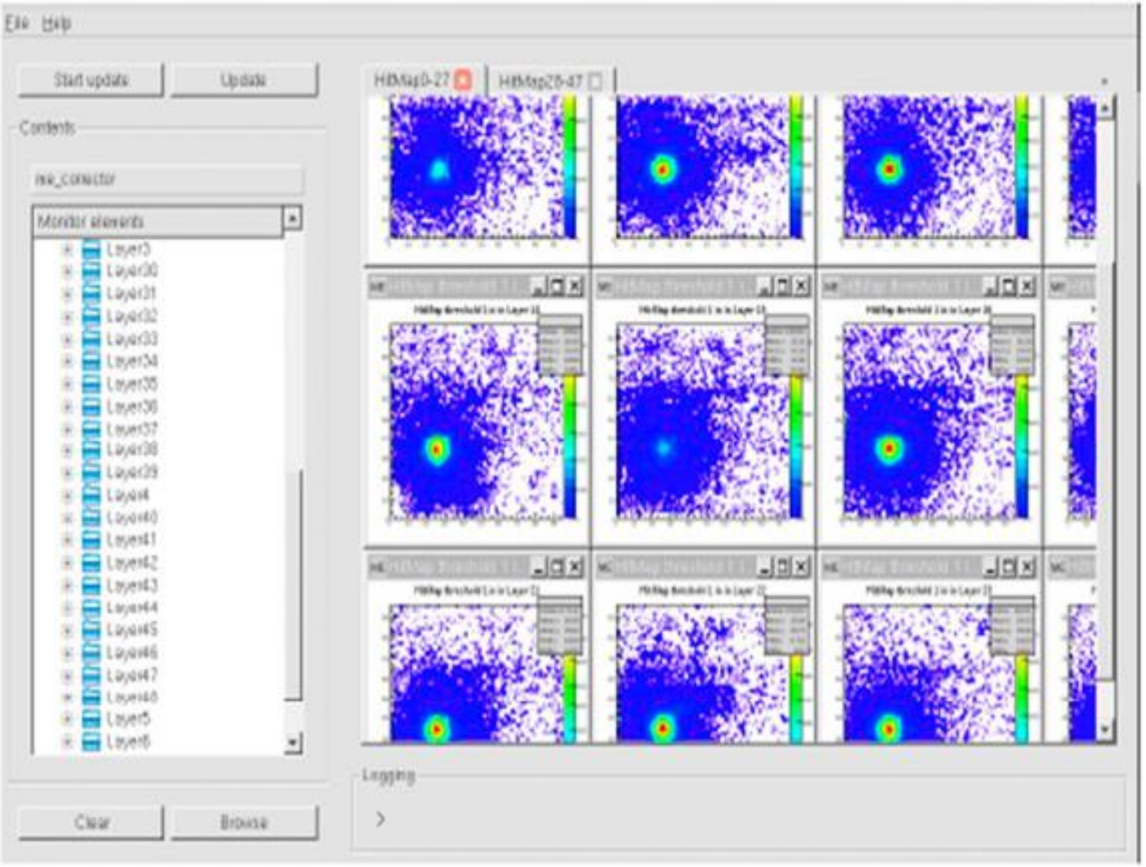
-GRPC efficiencies
-GRPC noise map
-SlowControl (HV, LV, T, P..)

Key points :

- Standalone plugin system (dynamic shared lib loading)
- Event data model/format abstraction

More general features :

- Online analysis (API)
- Streaming tools for event read/write functions
- Distributed system (DIM)
- Data collectors : event and histogram collector servers
- Quality test tools : interface + many template
- Visualisation interfaces (Qt, web)

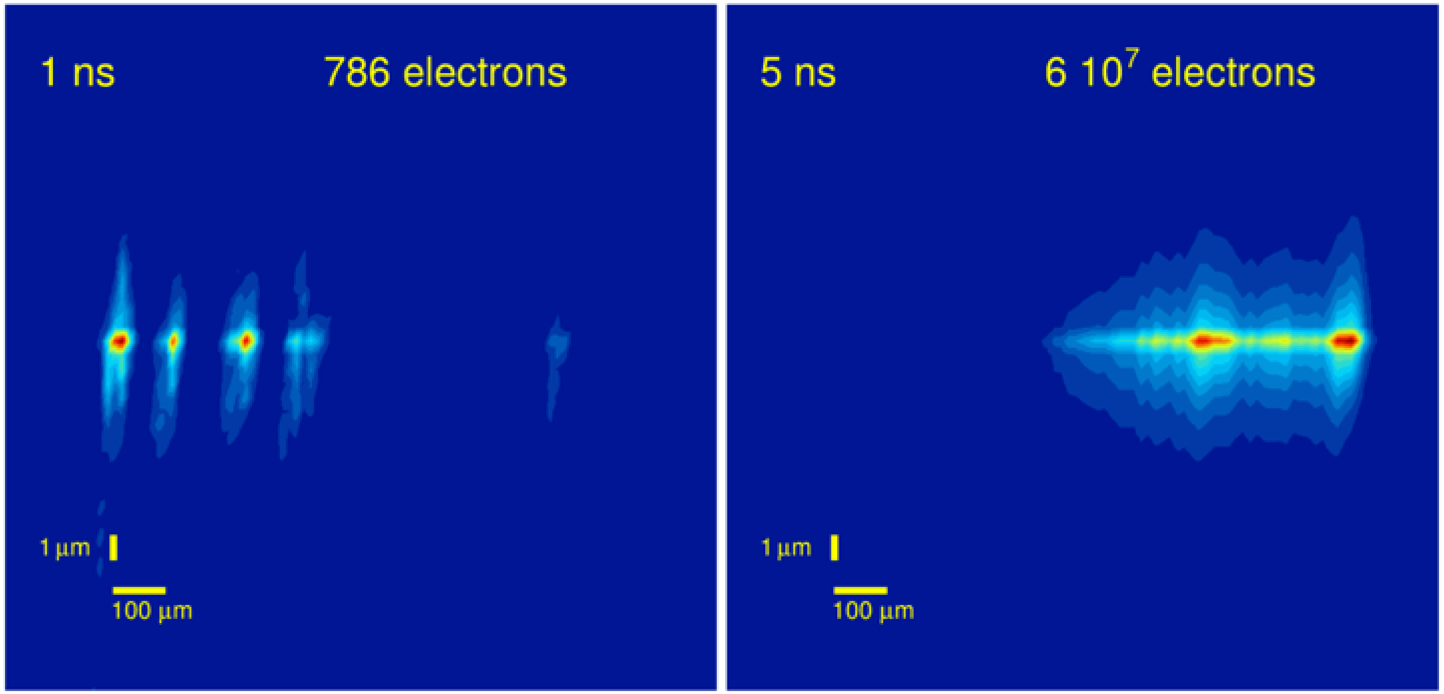


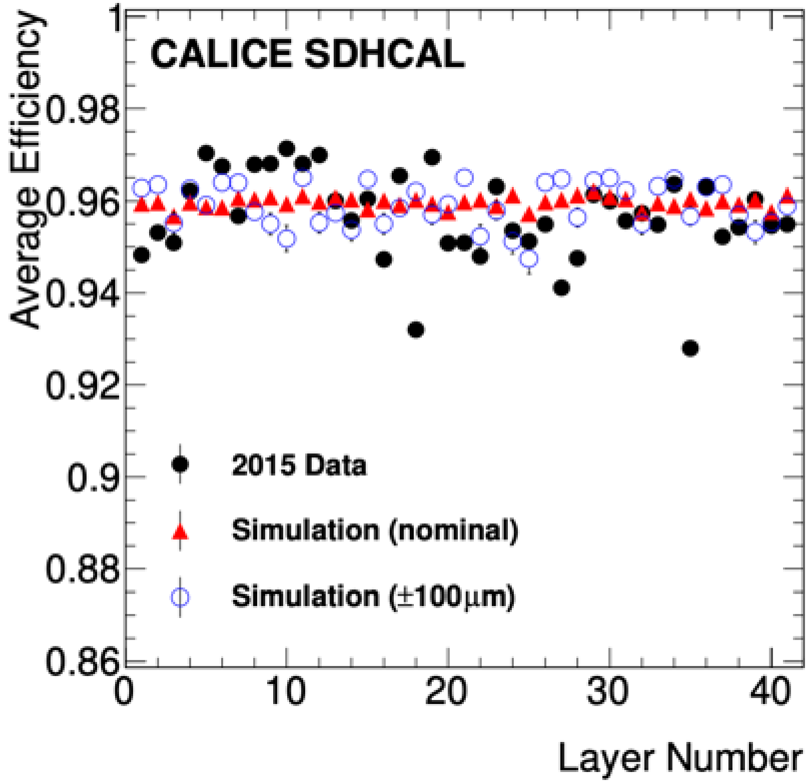
The monitoring system is used by other groups (AHCAL)

Custom digitizer

V. François PhD thesis

We went beyond a simple simulation of the RPC within the SDHCAL





- Modelling the RPC response based on full MC simulation of avalanches
- Analysis of test beam data and comparison with simulations
- Description and stability of a RPC-based calorimeter in electromagnetic and hadronic shower environments. arXiv. https://doi.org/10.48550/arXiv.2207.06291

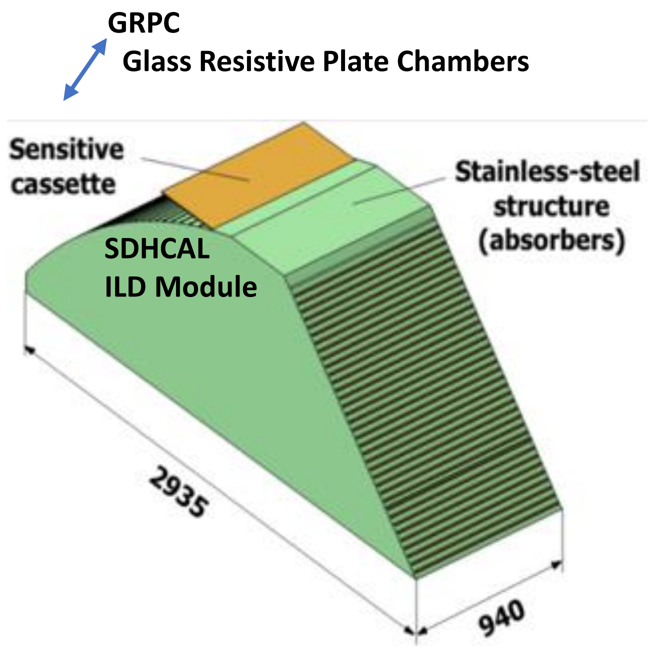
Accepted

SDHCAL R&D towards the future Higgs Factory
ILC, CEPC, FCCee

- Large SDHCAL module
- Timing SDHCAL
- High rate capability

Large SDHCAL module

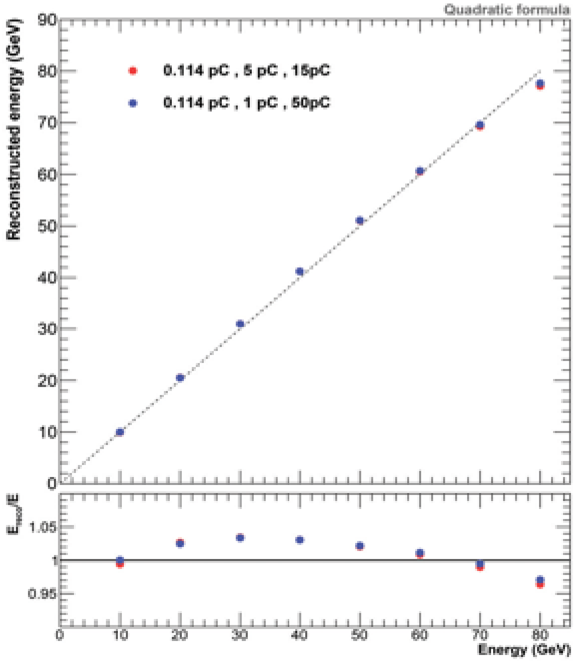
- ❑ Detectors as large as 3m X 1m need to be built
- ❑ Electronic readout should be the most robust with minimal intervention during operation.
- ❑ DAQ system needs to be upgraded to deal with a higher number of chips
- ❑ Mechanical structure to be similar to the final one with minimal dead zones
- ❑ A full description of the SDHCAL with DD4HEP framework

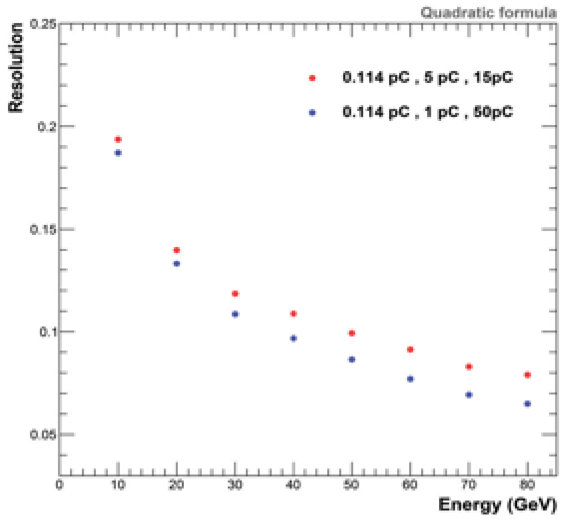


Goal: to build new prototype with a few but large GRPC with the new components

This goal was defended within the CALICE collaboration and the European project AIDA which provides the essential part of the funding to achieve this project.

Large SDHCAL module

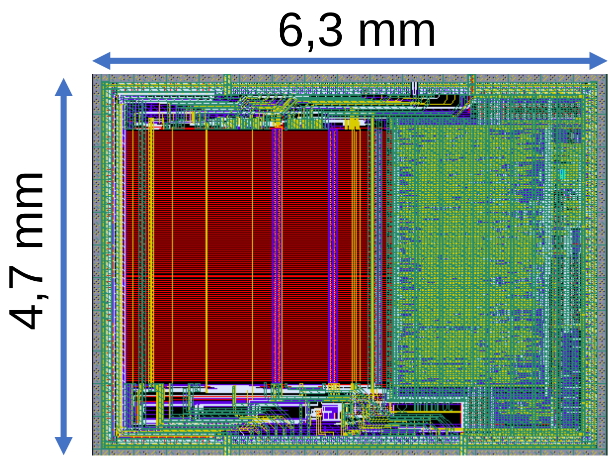




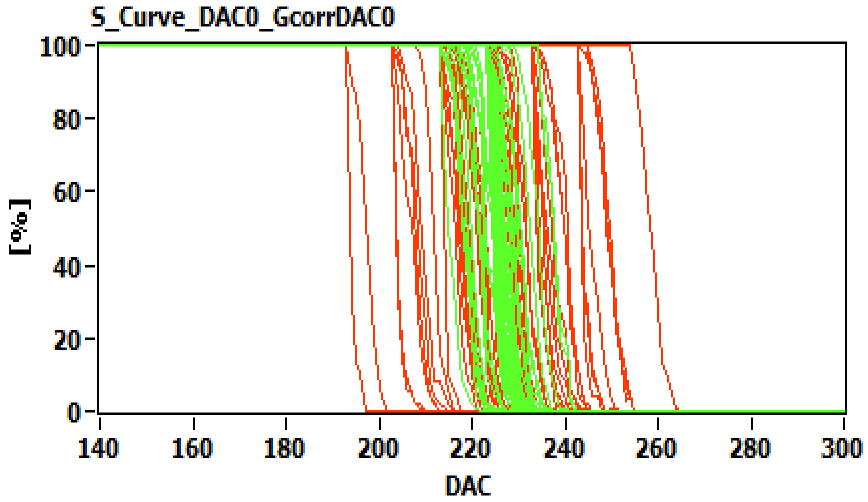
HARDROCR3 main features:

- **Independent channels**
- **Zero suppress**
- Extended dynamic range (**up to 50 pC**)
- **I2C link with triple voting for slow control parameters**
- packaging in QFP208, die size ~30 mm^2
- Consumption increase (internal PLL, I2C)

800 ASICs were produced

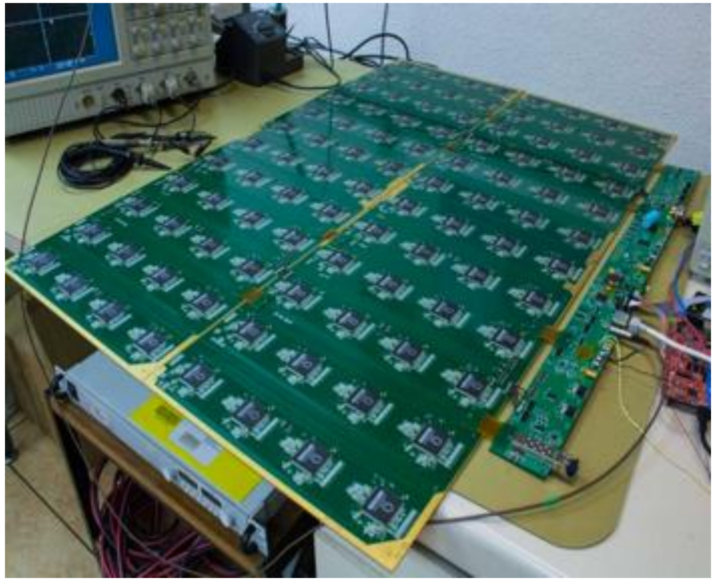


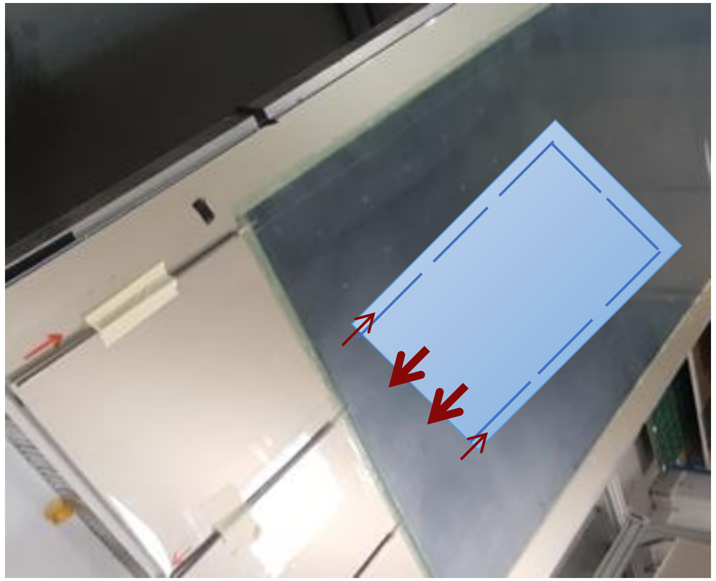
H3B TESTED : 786, Yield : 83.3 %



Large SDHCAL module

- 12 long PCB hosting each 48 ASICs were produced as well as the inter-connecters (to cover up to 4 M^2) by IP2I
- 5 DAQ boards (DIF) conceived and built by CIEMAT
- A mechanical structure to host 4 detectors (as large as 3 m) with a self-supporting structure (Electron Beam welding was used to minimize the dead zones) produced by CIEMAT
- A few large GRPC (2 m x 1 m) detectors were produced with a new gas distribution system at IP2I and
- Improved Master card to communicate with DIFs was conceived and produced by IP2I.





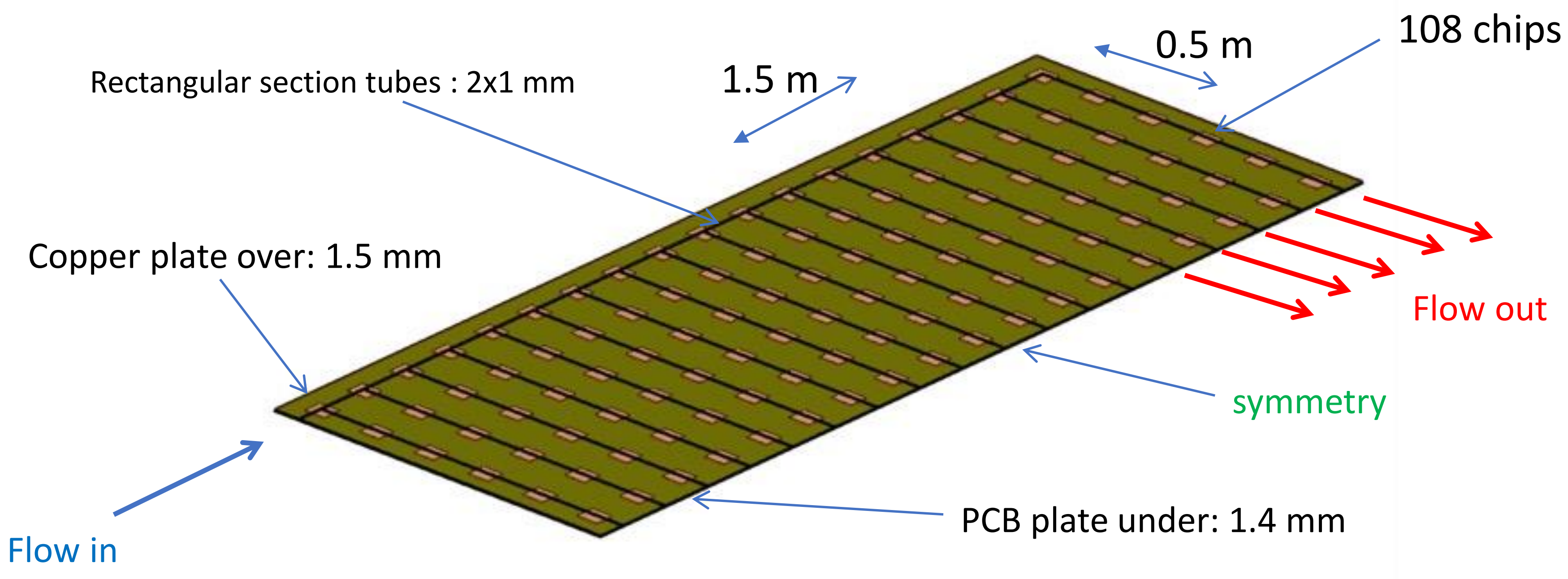
To finish this work , an electronics engineer is needed to take over the work of CIEMAT engineers. This will allow us to validate the concept and test it.

Large SDHCAL module

SDHCAL power consumption and cooling

The duty cycles of CEPC/FCCee are different from that of ILC and no power pulsing is possible.
The power consumption is therefore increased by a factor of 100-200 with respect to ILC and active cooling is needed.
Lyon and Shanghai groups worked on a simple cooling system for SDHCAL based on using water circulating into copper pipes

0.8 mW/chips with power pulsing → 80 mW/chips without power pulsing



Large SDHCAL module

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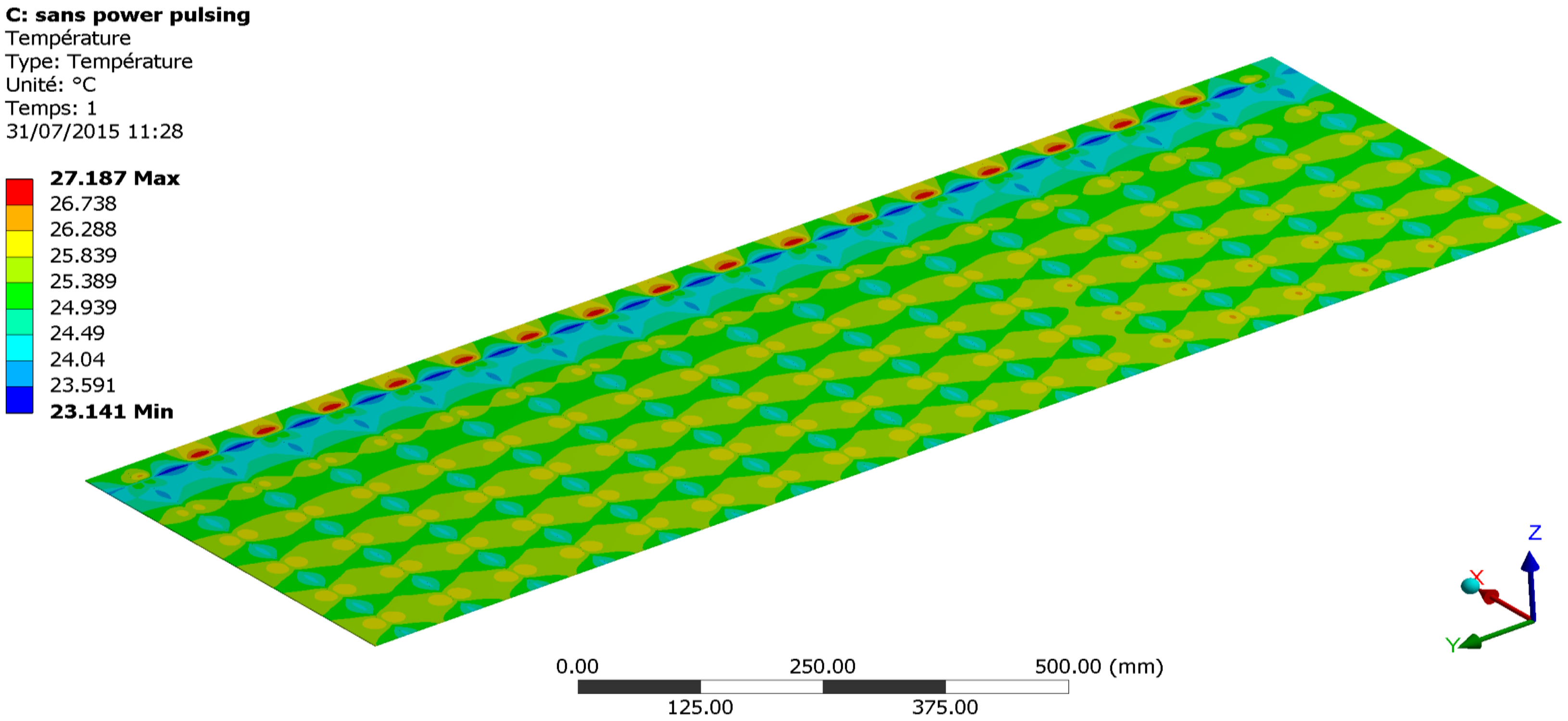
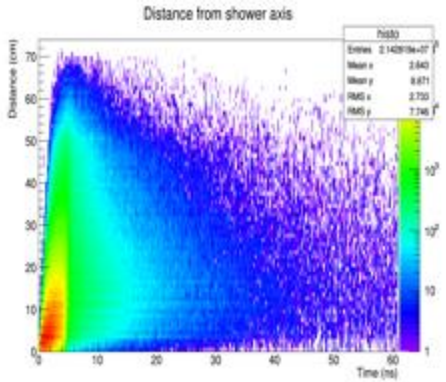
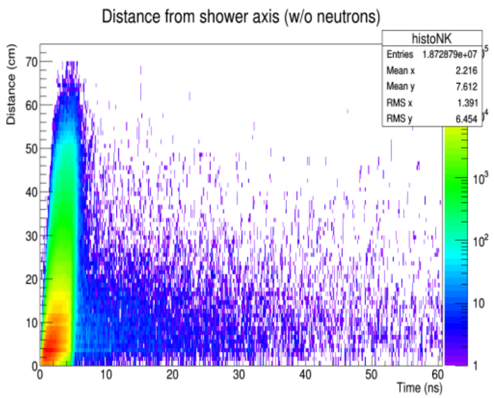


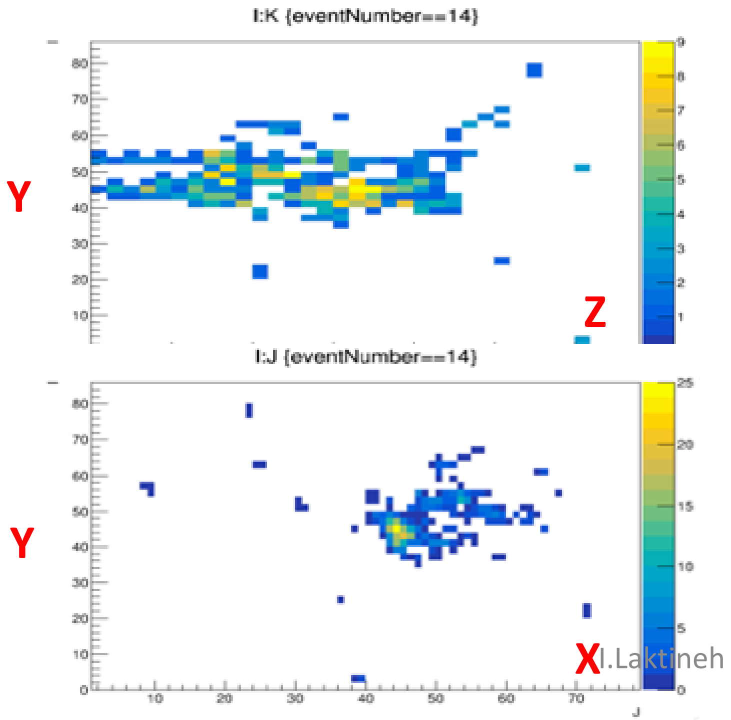
First step towards transforming SDHCAL into T-SDHCAL

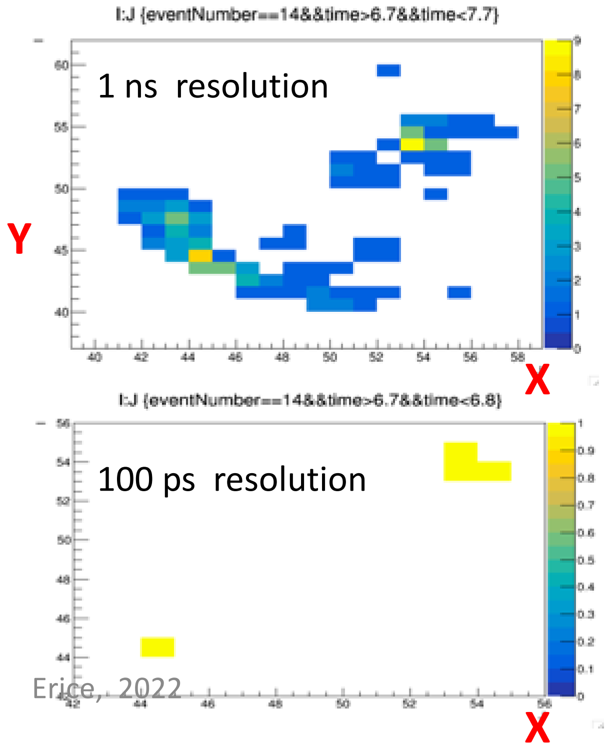
Timing is an important factor to identify delayed neutrons and **better reconstruct their energy**





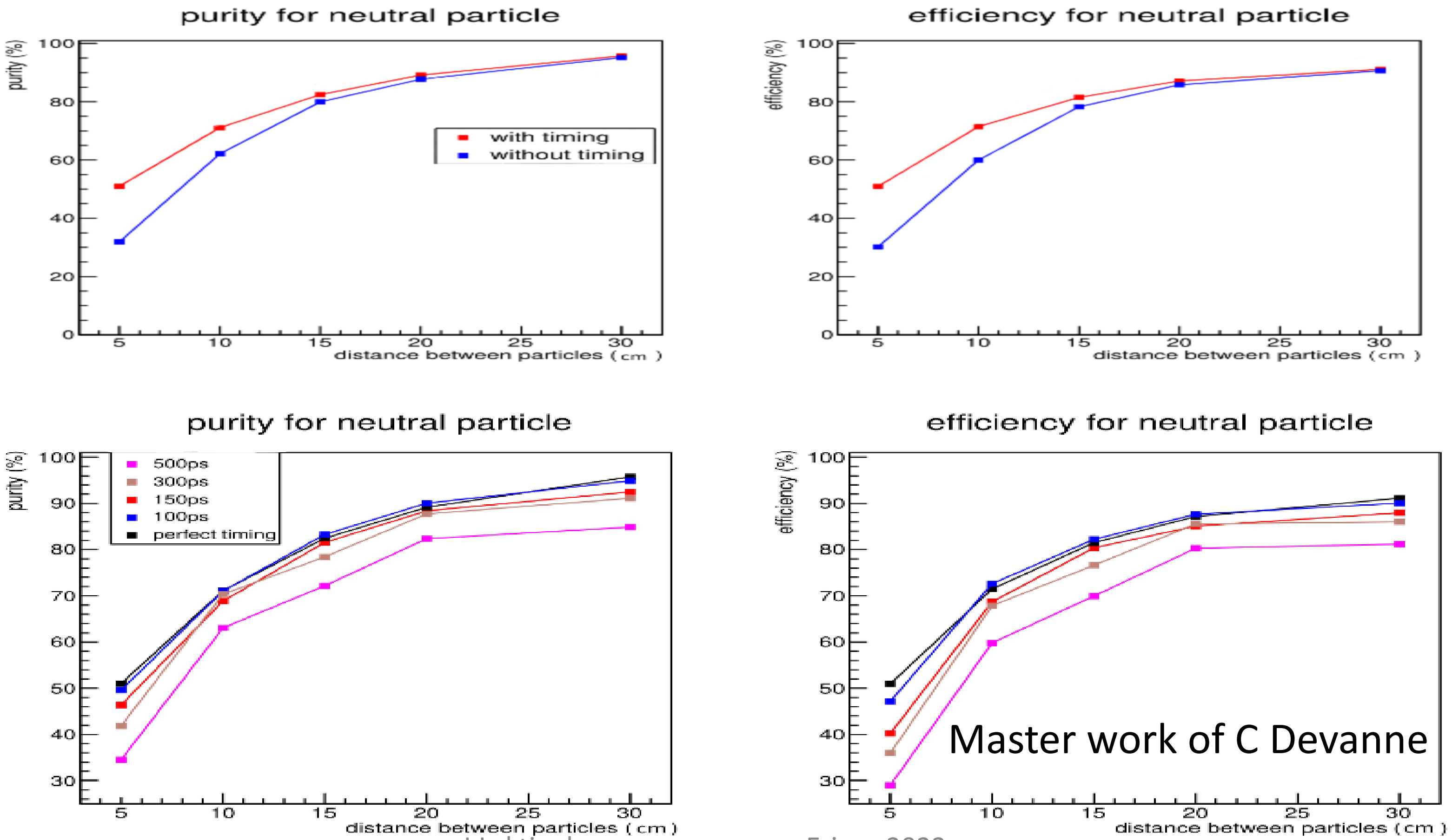
Timing can help to separate close-by showers and reduce the confusion for a better **PFA** application. Example: pi-(20 GeV), K-(10 GeV) separated by 15 cm.





First step towards transforming SDHCAL into T-SDHCAL

Including time information in the simulation to separate hadronic showers (10 GeV neutral particle from 30 GeV charged particle) using techniques similar to ARBOR's ones.



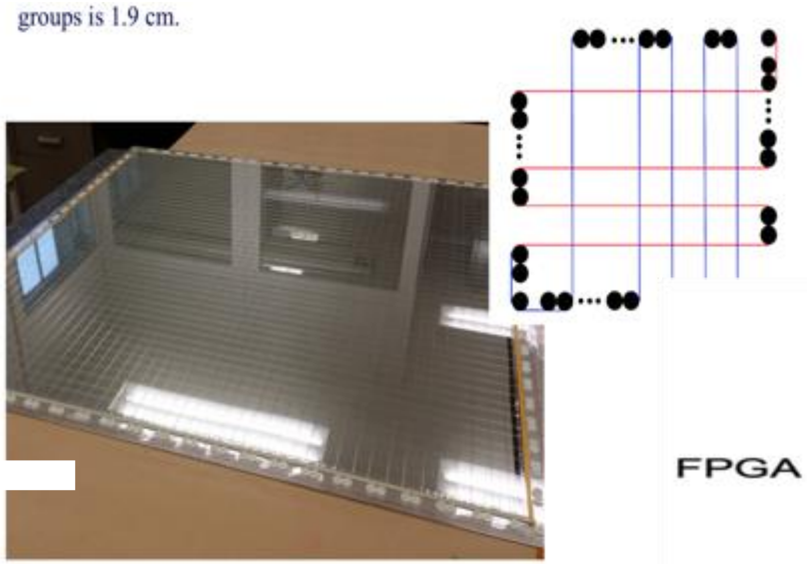
T-SDHCAL

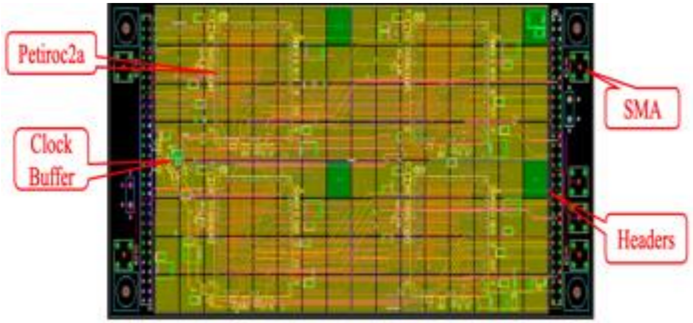
Goal: replace a few layers of SDHCAL by MRPC equipped with time measurement (PETIROC)

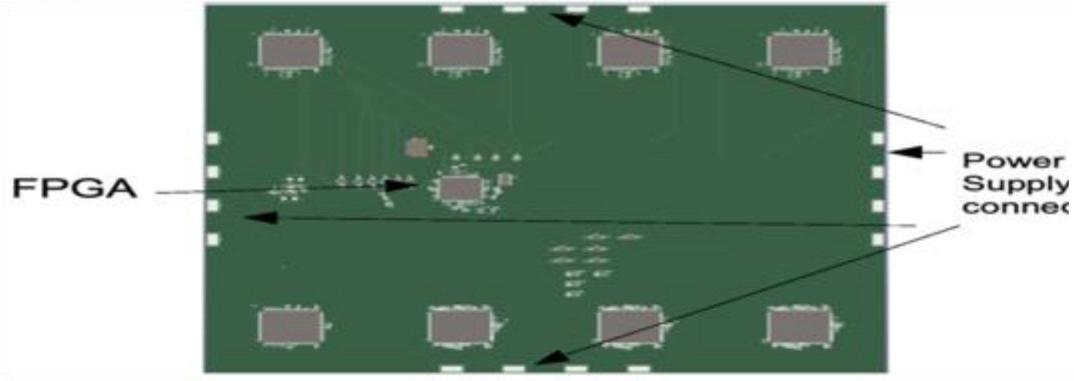
Collaboration with GWNU (S. Korea) and Shanghai (China), Gent (Belgium) and CIEMAT (Spain) within CALICE and **AIDAInnova**

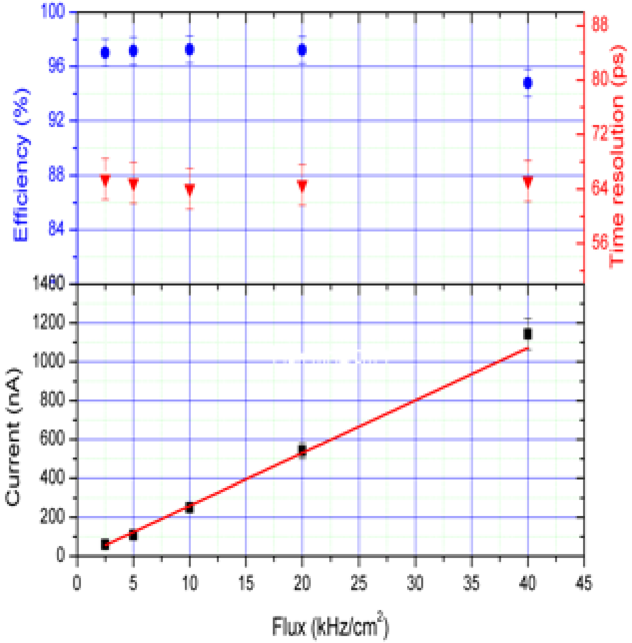
- ❑ MRPC have been produced (**IP2I & GWNU**). A new method developed by IP2I allows the production of such detectors to be greatly simplified
- ❑ A small board hosting 4 and 2 PETIROCs conceived and produced (**SJTU** with the help of **IP2I** and **OMEGA**).
- ❑ A middle board hosting up to 12 PETIROC has been conceived (**IP2I**).

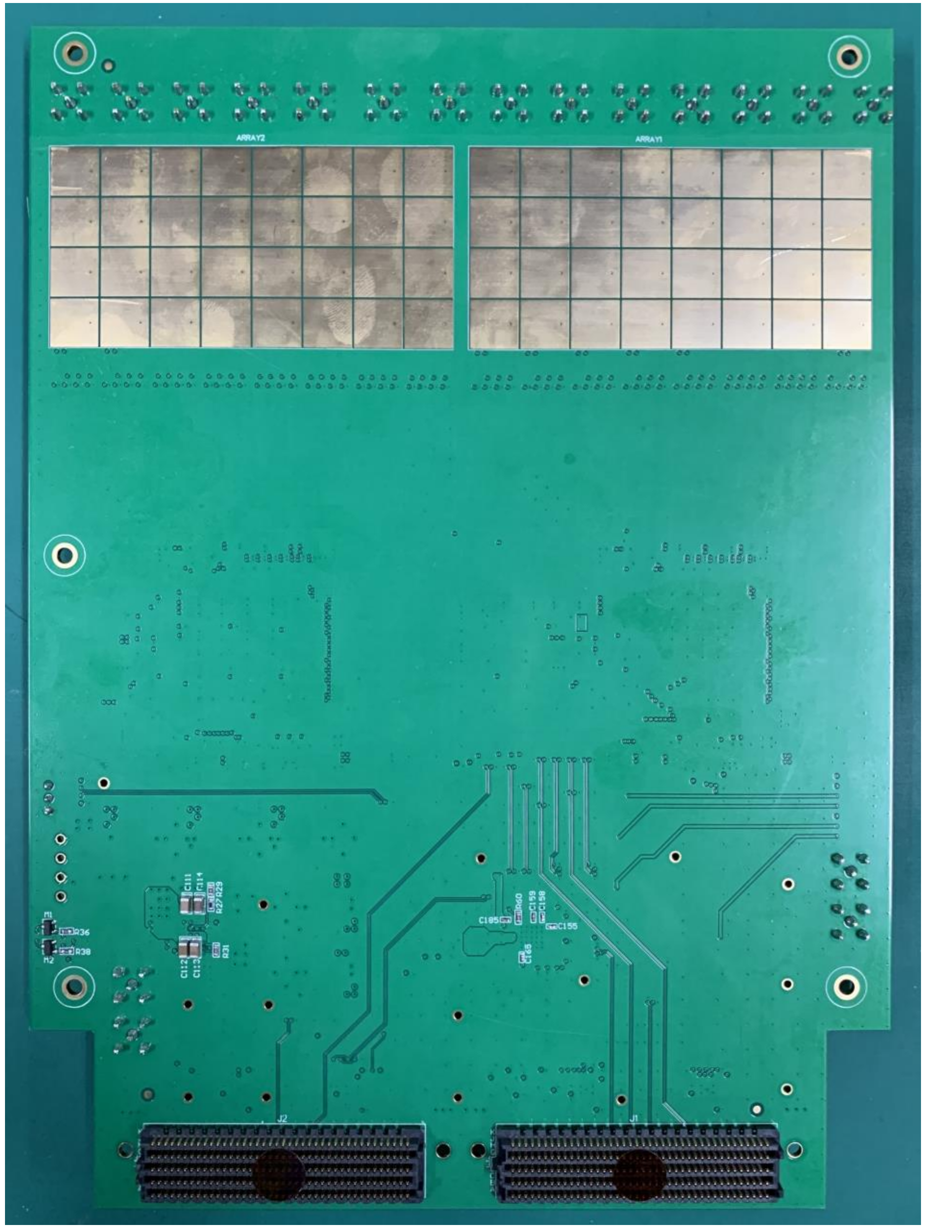
In the two cases the internal TDC of PETIROC will be used to validate the concept but an external TDC will be probably needed to cope with the high rate sin future Higgs factory.

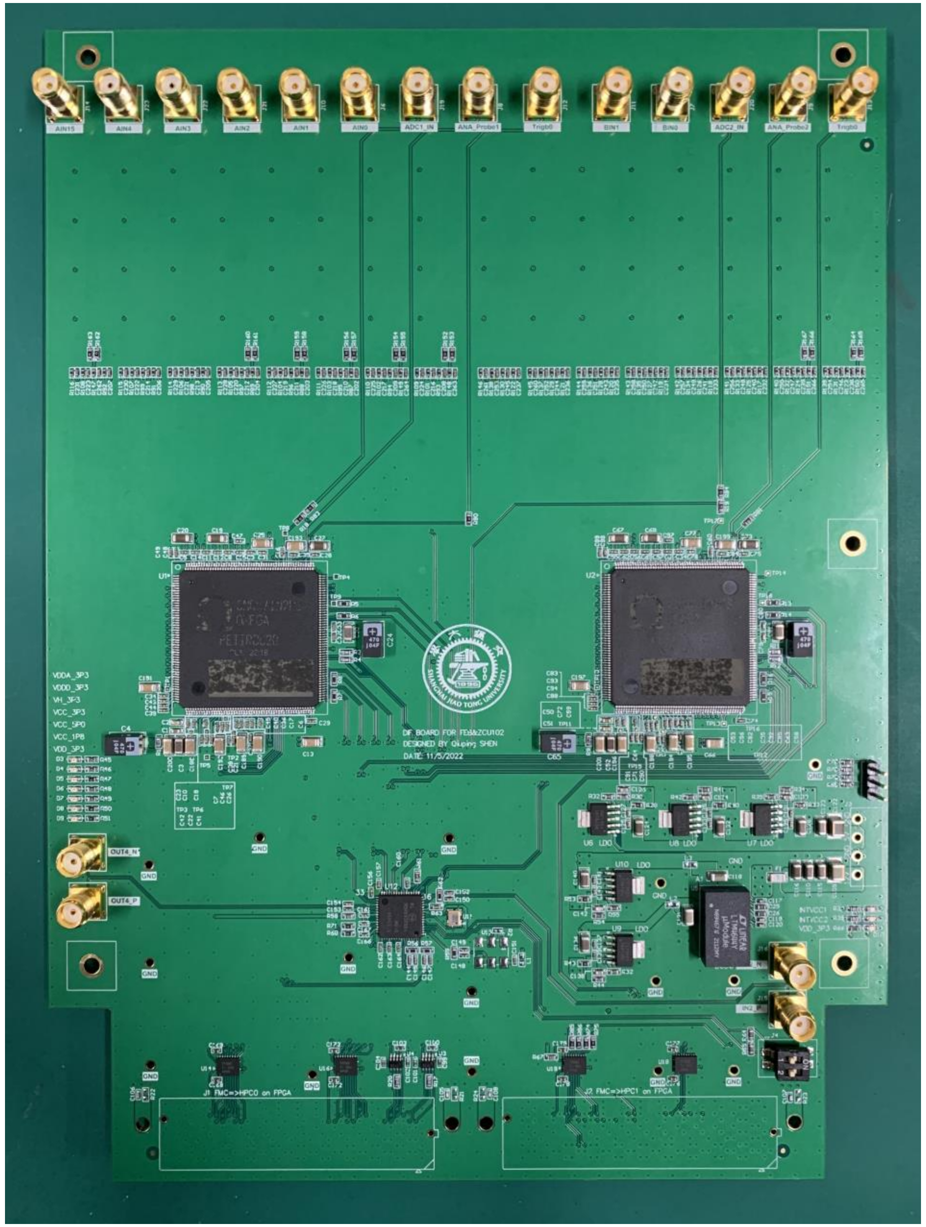


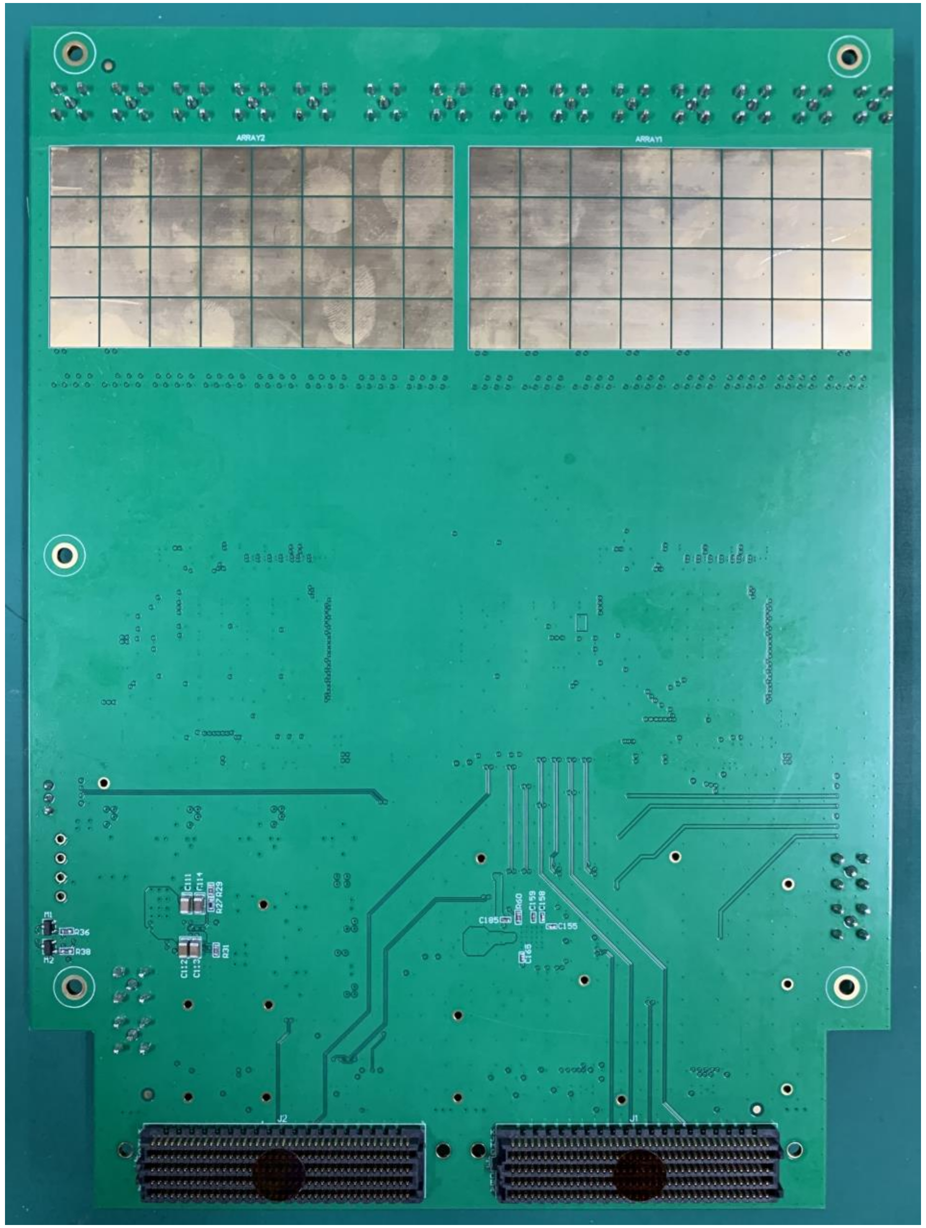


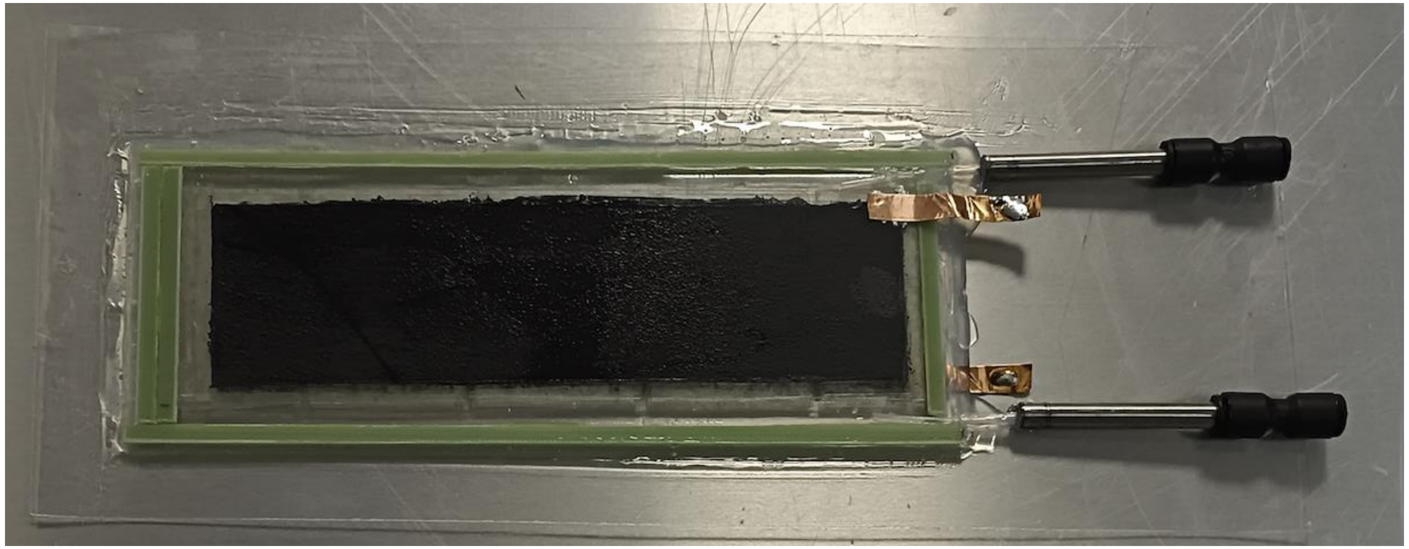












5-gap RPC

More on the time-related development
in the following talk of Yongqi

High-Rate capability

RPC is low-rate capability detector due to the resistive nature of the electrodes. The capability could be increased by developing low resistivity materials. Our R&D started within the CMS-mu upgrade project
Resistive material development benefited from AIDA2020 and LABEX LIO

PVdF and **PEEK** are very stable and chemically inert thermoplastic

-New kind of PVdF developed by IP2I with the help of PolyOne (Germany).
Doped with CNT we achieved a bulk resistivity of $10^{11\text{-}12}$ Ω.cm
-New charged PEEK developed with the help of Krefine (Japan).
Doped with BC a bulk resistivity of $10^{8\text{-}9}$ Ω.cm was achieved.

A few small detectors were made using doped PVdF plates of 2-3 mm thickness.
An excellent efficiency is obtained with cosmic but resisitivity is not low enough for high rate.

Plates made with charged PEEK were produced but homogeneity issues are still there.
More efforts need to be made to finalize this material.
(M)RPC has excellent timing with respect to MPWD

New friendly gases

The CERN gas group (R. Guida& B. Mandelli) has identified friendly gas mixture to replace TFE and SF6.

TFE→ HFO1234ze
SF6→ Nova4710 (not good for Bakelite but ok for GRPC and MRPC)

Work is ongoing to recover the different gases of the mixture (distillation…etc)

We have a common PhD student to work on the new gas mixture for MRPC

Conclusion

- SDHCAL fulfilled all its goals
- An upgrade of `SDHCAL to introduce time information to better separate close-by hadronic showers but also PID has started
- A new proposal called T-SDHCAL will be submitted to DRD6
- We invite also our colleagues working on gas-based calorimetry (DHCAL, MPGD-SDHCAL) to join us as well.