SDHCAL
Status and future

I. Laktineh

For
Gent, CIEMAT,GWNU, IP2I, LPC, OMEGA, SJTU, Tunis. U.

Outline

Status:

SDHCAL technological prototype

- ✓ Short description
- ✓ Energy reconstruction method
- ✓ Improvement with PID techniques
- ✓ Further improvements on energy reconstruction

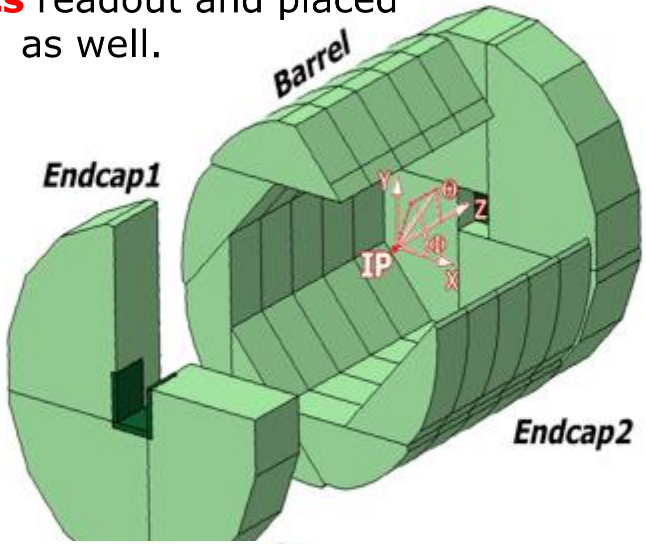
Future:

- ✓ **SDHCAL for ILD@ILC**
- ✓ **SDHCAL for ILD@CEPC**

Summary

SDHCAL

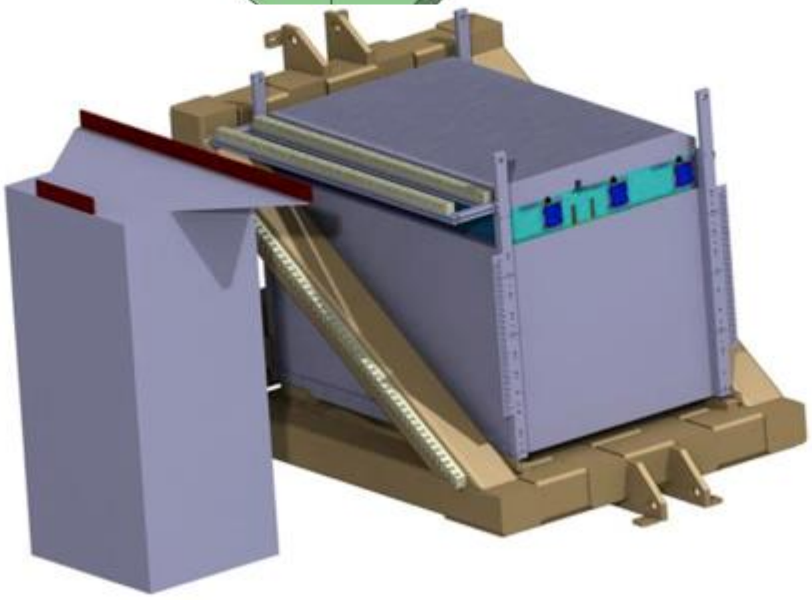
The SDHCAL concept is based on exploiting **Gaseous Detectors** high granularity potential
G.D are equippedwith **semi-digital, power-pulsed electronics** readout and placed
in **self-supporting mechanical** structure to serve as absorber as well.



The structure proposed for the SDHCAL :

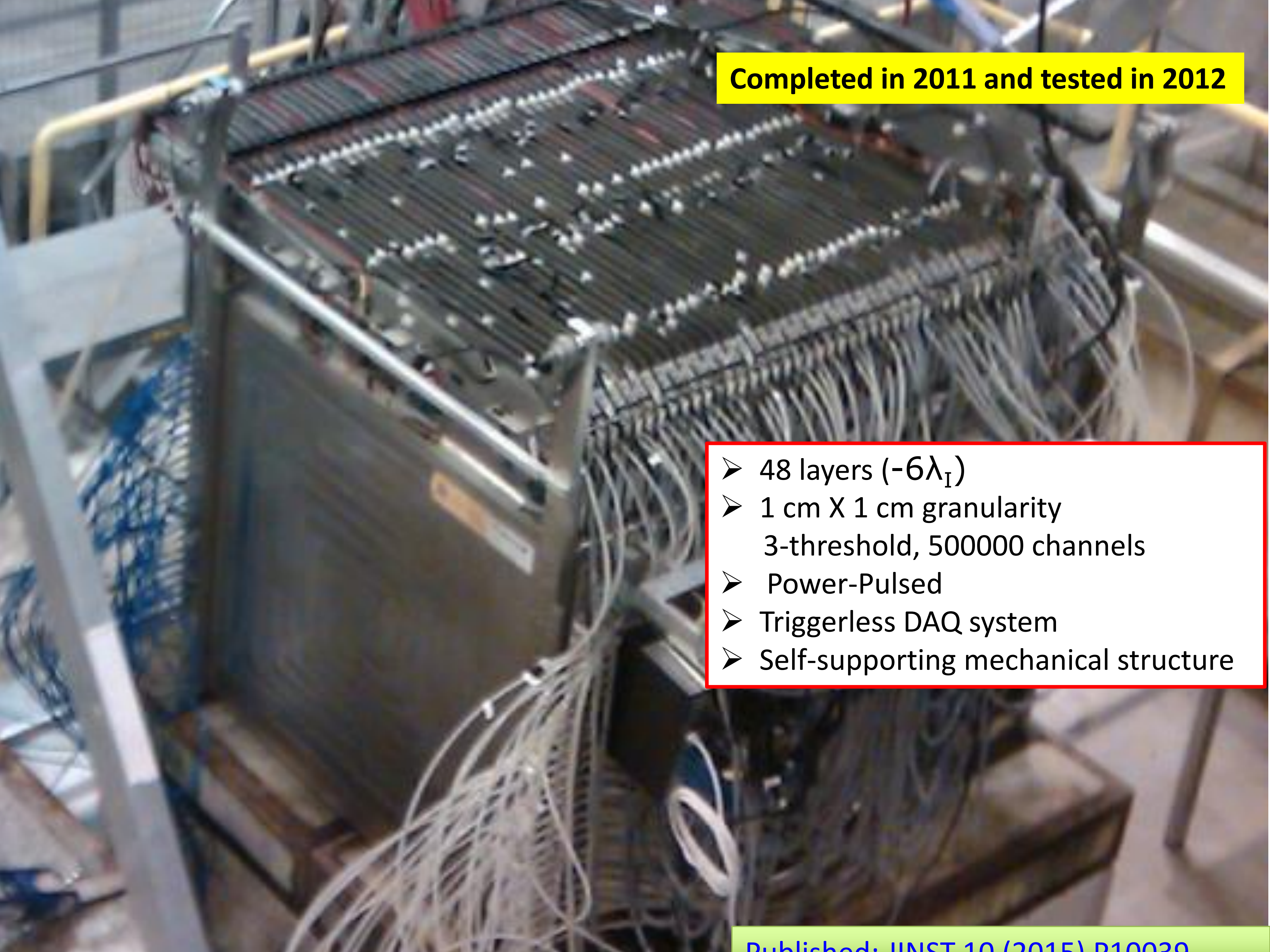
- is very compact with negligible dead zones
- Eliminates projective cracks
- Minimizes barrel / endcap separation
  (services leaving from the outer radius)

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



Challenges

-Homogeneity for large 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

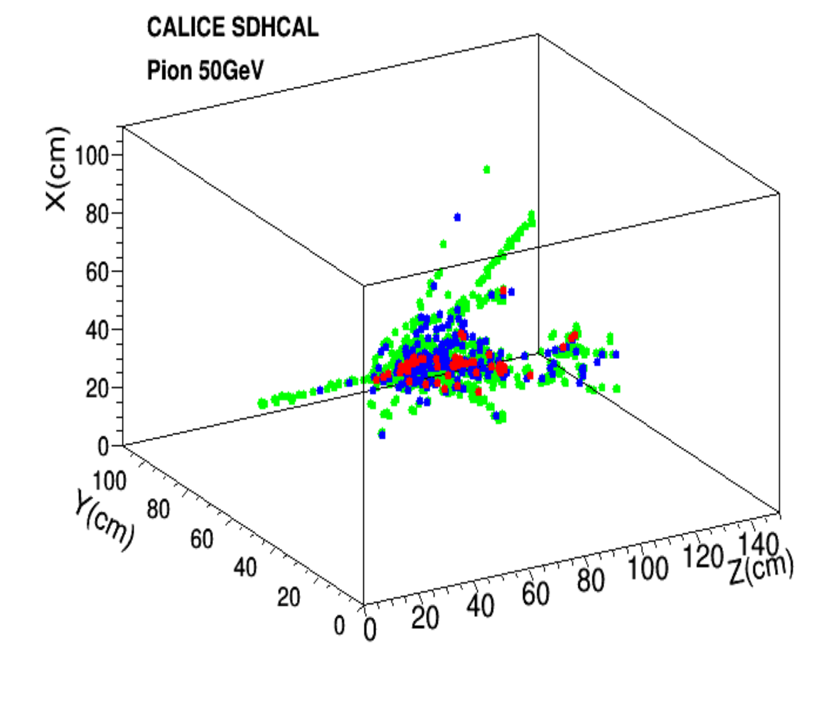


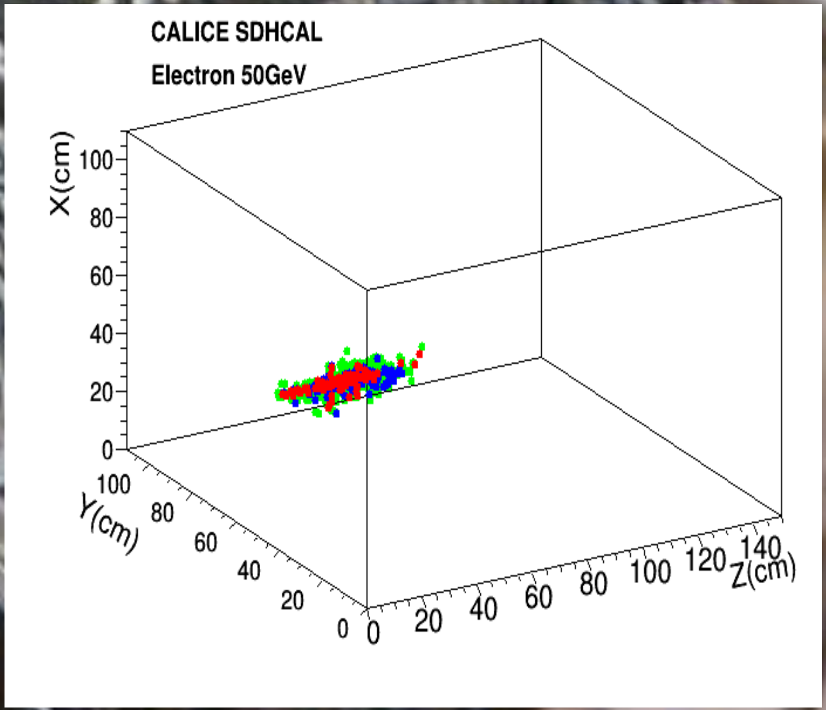
Completed in 2011 and tested in 2012

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

Published: JINST 10 (2015) P10039

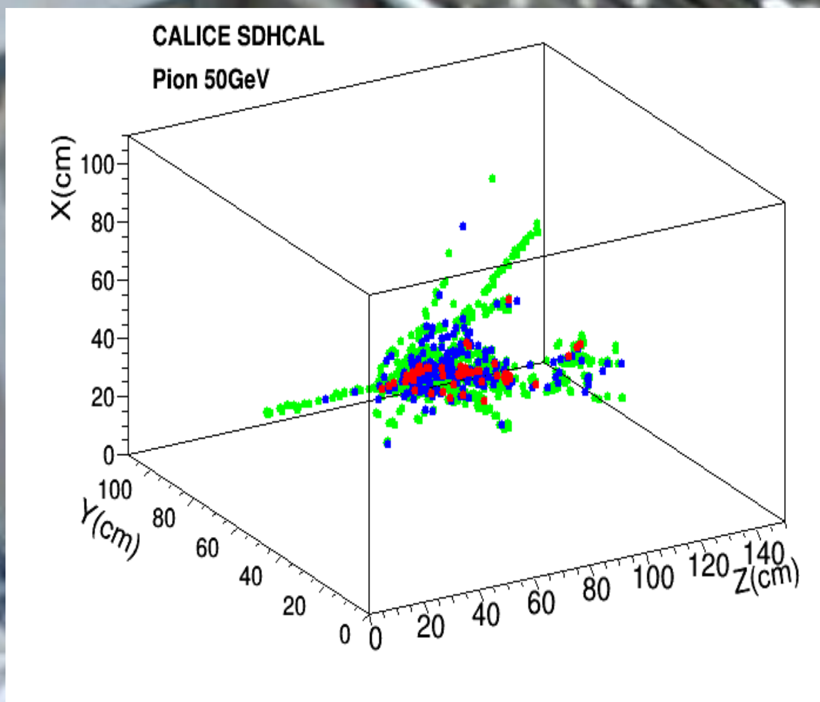
SDHCAL prototype was exposed to beam particles at CERN PS, SPS in 2012, 2015, 2017 and 2018

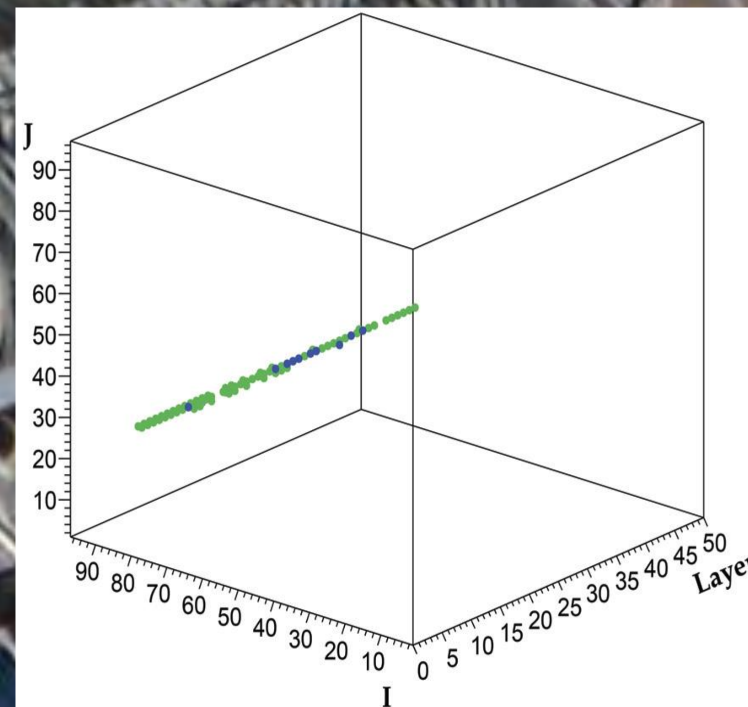




Electron rejection: shower starting after the fourth layer (6 radiation length)

SDHCAL prototype was exposed to beam particles at CERN PS, SPS in 2012, 2015, 2017 and 2018



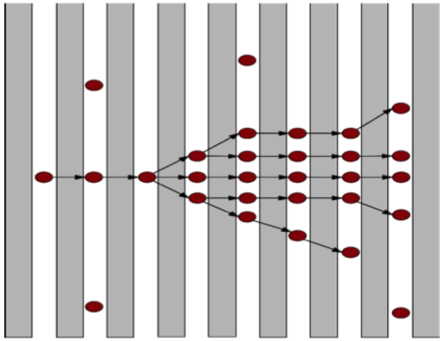


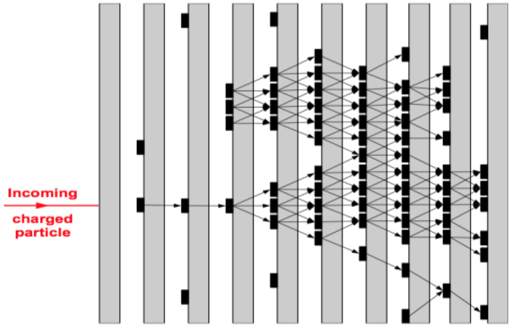
Muon rejection: average number of hits/layer < 2

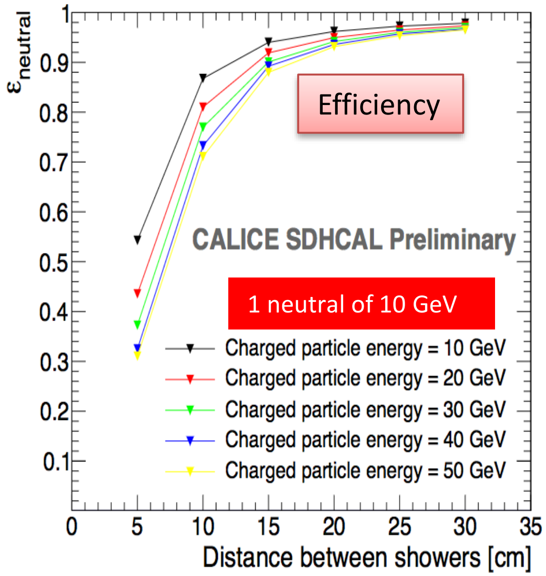
SDHCAL high granularity is conceived for PFA

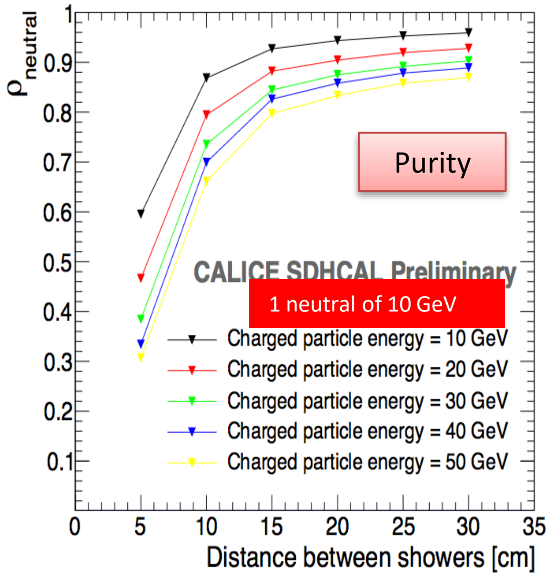
It helps to optimize the connection of hits belonging to the same shower by using first the topology and then the energy information

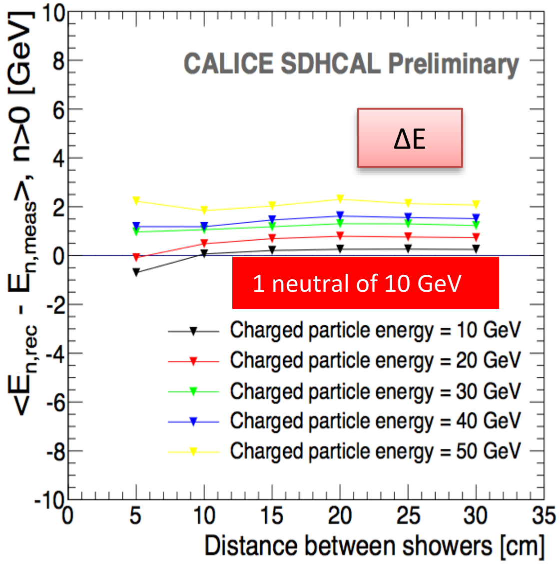
ArborPFA, April algorithms:
It connect hits and then their clusters using distance and orientation information then correct using tracker information (momentum)











CALICE note CAN054

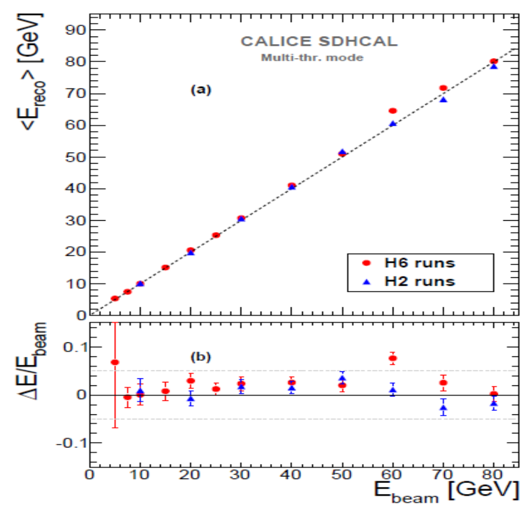
Energy reconstruction

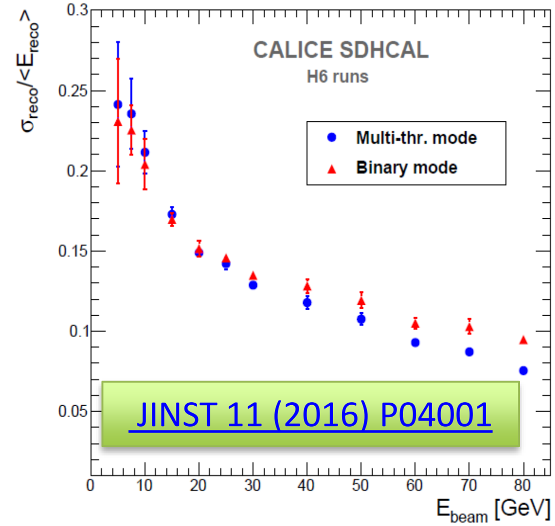
N_1= Nb. of pads with first threshold <signal < second threshold
N_2 = Nb. of pads with second threshold <signal < third threshold
N_3 = Nb. of pads with signal> third threshold

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

α , β , γ are **quadratic functions** of $N_{tot} = N_1 + N_2 + N_3$
They are computed by minimizing :

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

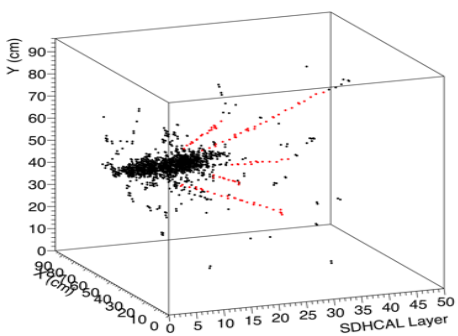


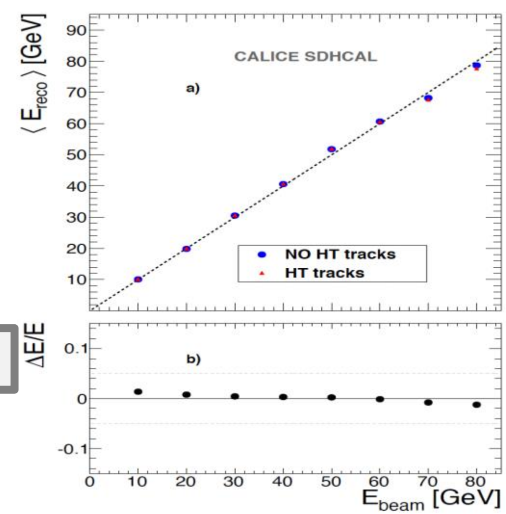


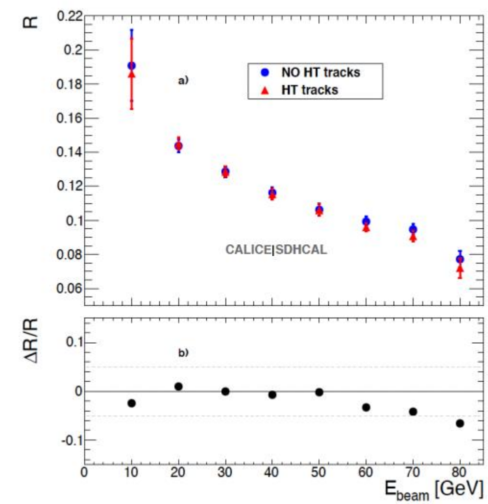
JINST 11 (2016) P04001

Hough-Transform

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







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

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

JINST 12 (2017) P05009

Particle Identification

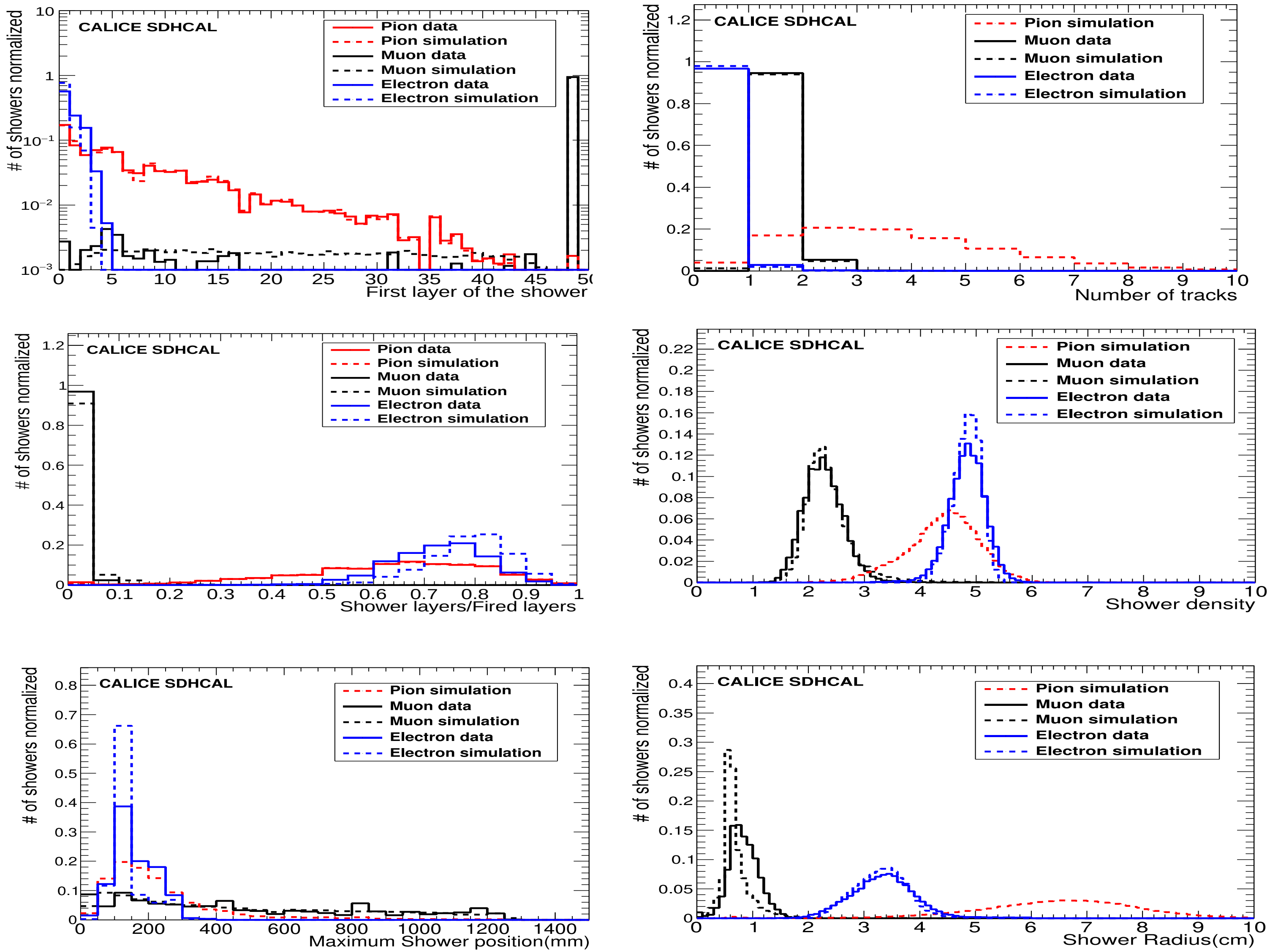
Due to the absence of Cerenkov detectors in front of the SDHCAL, the use of an electron selection (shower starting > d= 6 X_l) was rather powerful but led to an important loss of hadrons (d= 1 λ_l).

To reject electrons and muons without losing hadrons we use the excellent granularity of SDHCAL to discriminate the three species. Several discriminatory variables were selected:

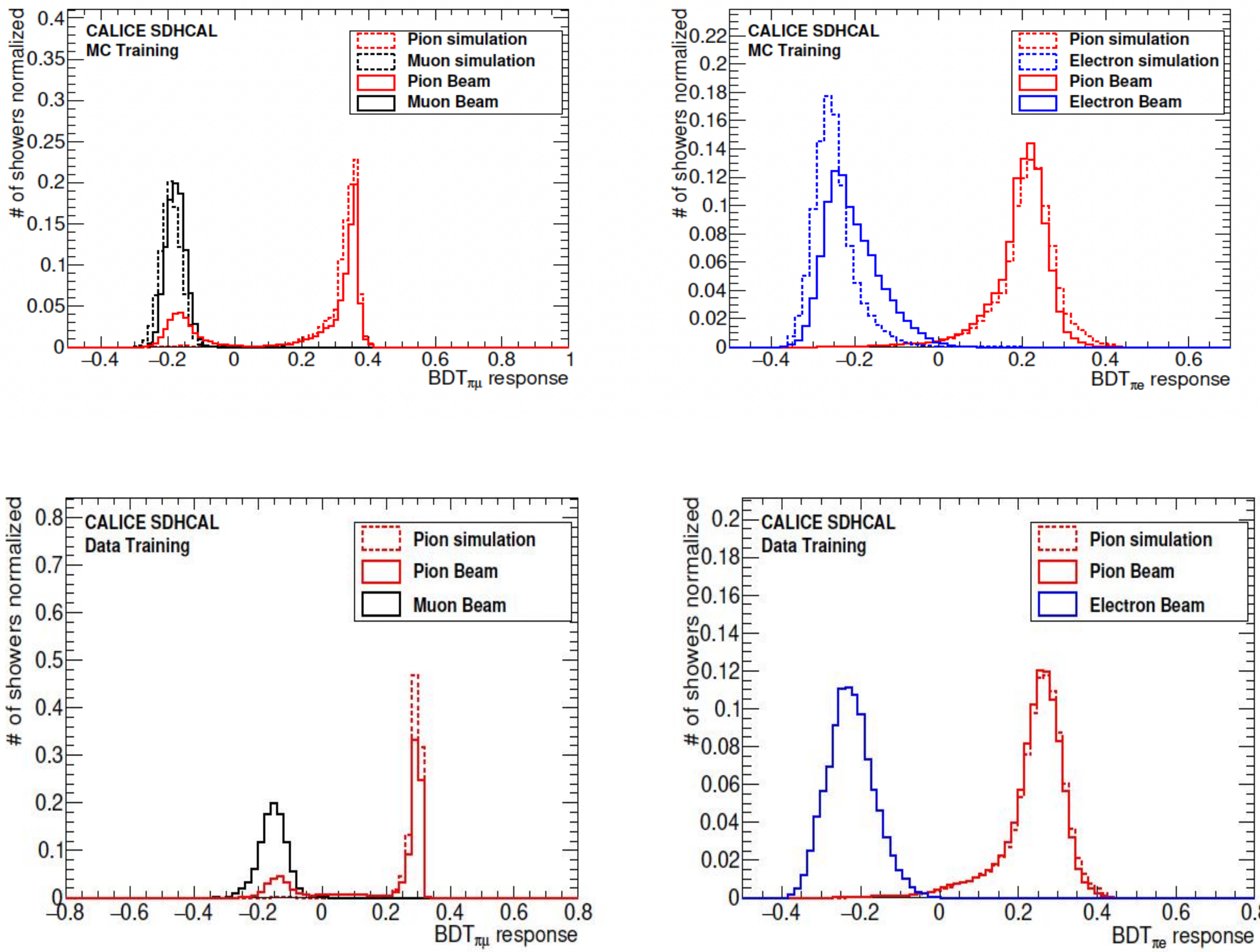
1- First layer of the shower (begin)
2- Number of tracks in the shower (trackMultiplicity)
3- Ratio of shower layers over total fired layers (nSHowerLayer/Nlayers)
4- Shower density (density)
5- Shower radius (radius)
6- Maximum shower position (length)
7- Ratio of N_3/N_{tot}
8- Average number of clusters
….

- BDT technique was used.
- Simulated events of electrons, muons and pions were used for training/validation before to apply to data.
- To avoid a possible bias due to discrepancy between data/simulation of electrons showers in the SDHCAL, pure electrons and muons data events were also used

JINST 15 (2020) P10009



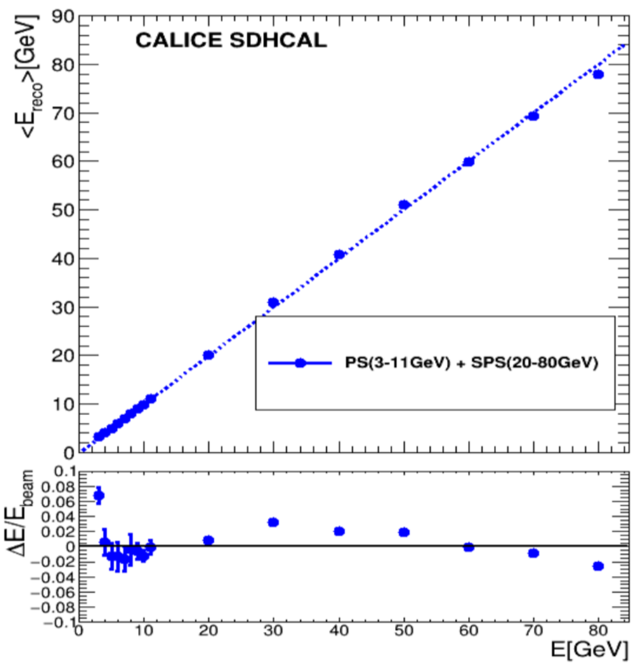
JINST 15 (2020) P10009



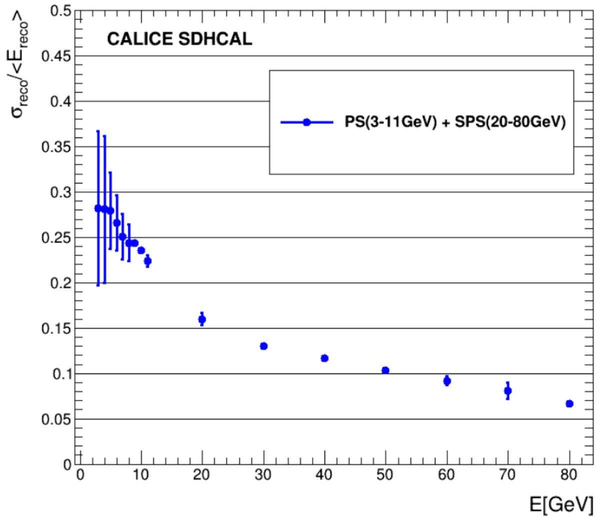
Electron and muon rejection > 99%

Particle Identification & Energy reconstruction

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



Linearity



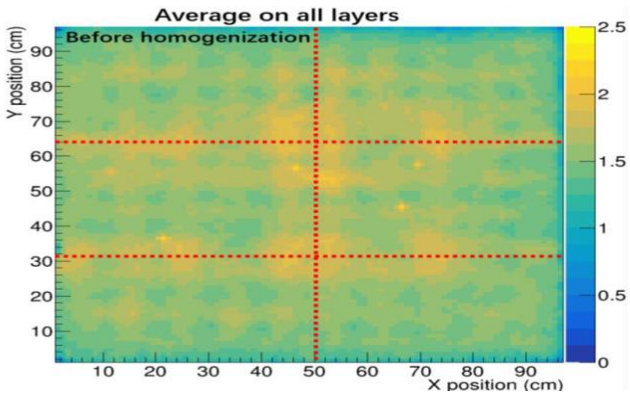
Resolution

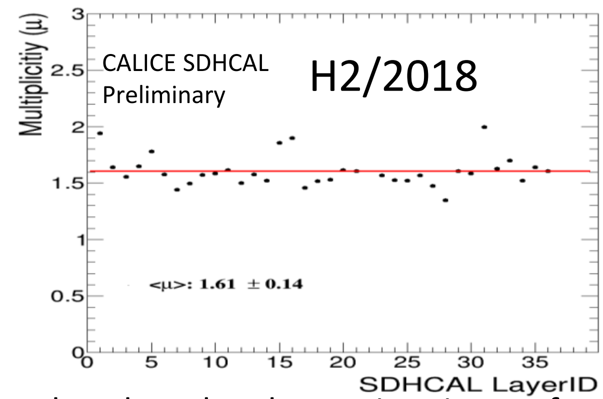
arXiv:2202.09684
Accepted to be published in JINST

Further improvements on the energy reconstruction

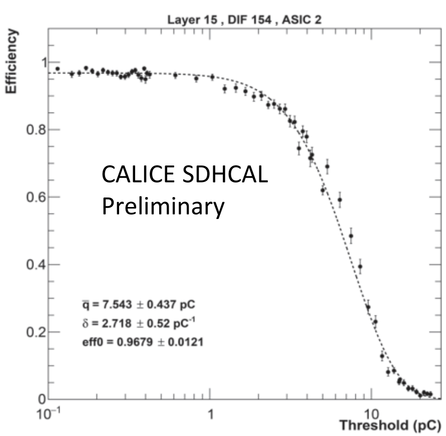
Detector homogeneity

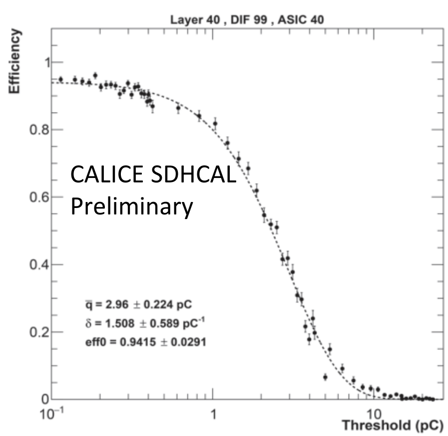
The homogeneity of the detector response is important to achieve better energy reconstruction

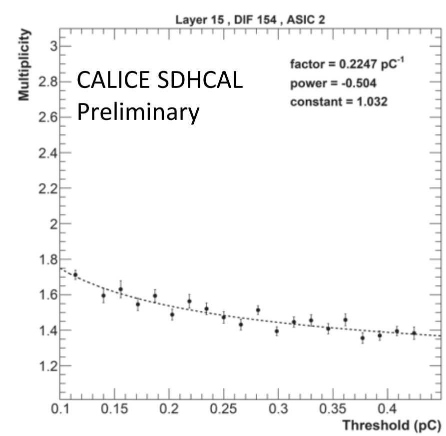


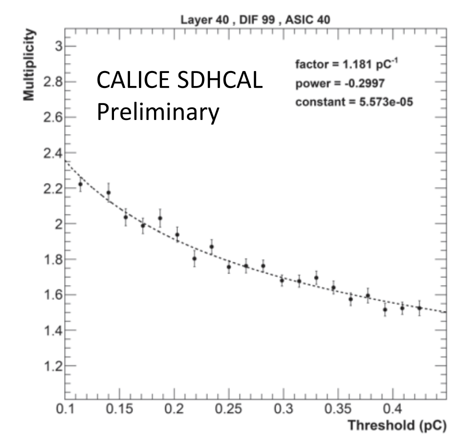


A new calibration method based on varying the thresholds rather than the electronic gain was found to be powerful. Muon runs with different thresholds Thr1: 0.1-0.42 pC, Thr2: 0.4-5, Thr3:4.7-24) and efficiency and multiplicity were measured for each value. The values of the three thresholds of each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





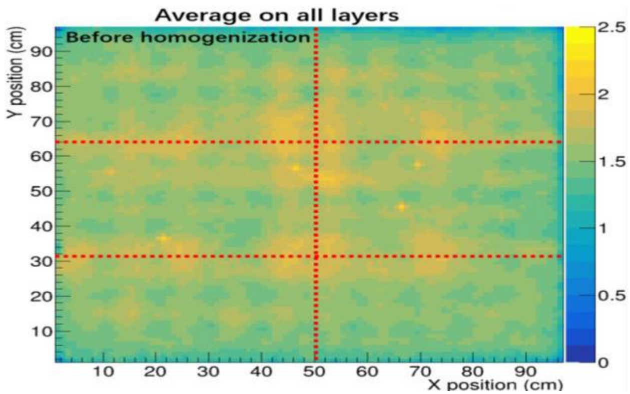


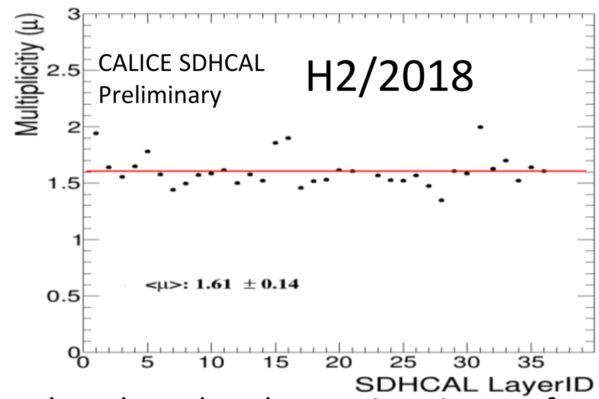


Further improvements on the energy reconstruction

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.

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

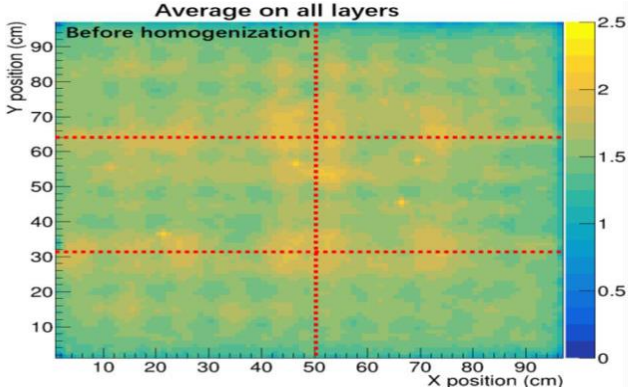
$$P(q;\bar{q},\delta) = \frac{1}{\Gamma\left(\frac{\bar{q}}{\delta}\right)\delta^{\frac{\bar{q}}{\delta}}} q^{\frac{\bar{q}}{\delta}-1} e^{-\frac{q}{\delta}}$$

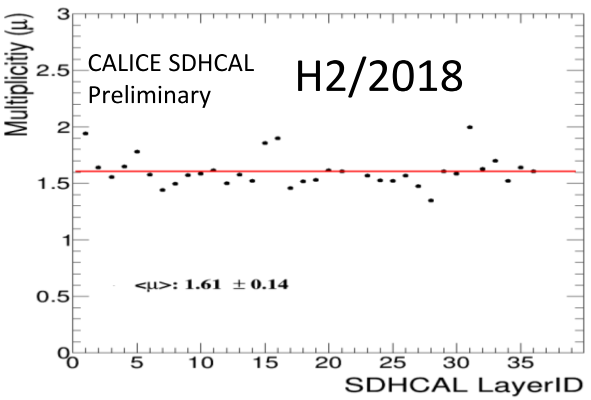
$$\mu(t;f,p,c) = f \cdot t^p + c$$

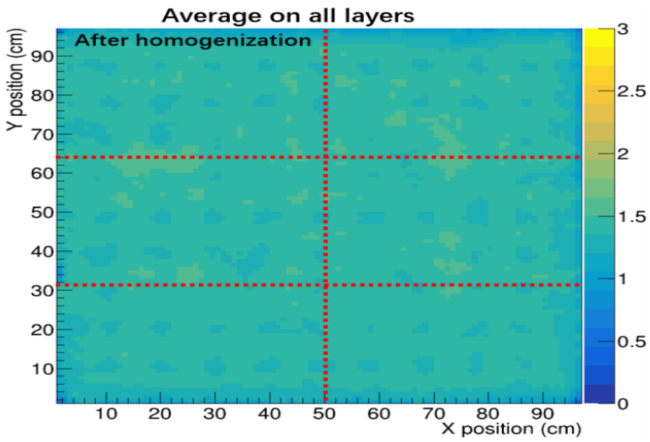
Further improvements on the energy reconstruction

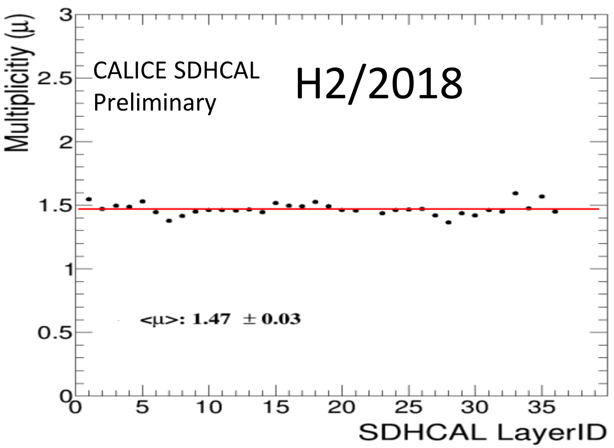
Detector homogeneity

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





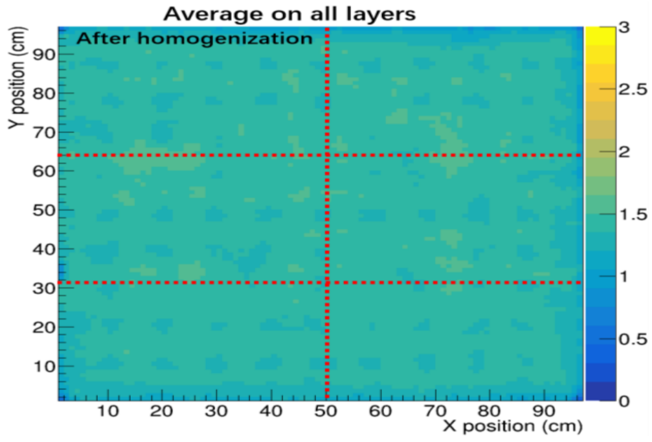


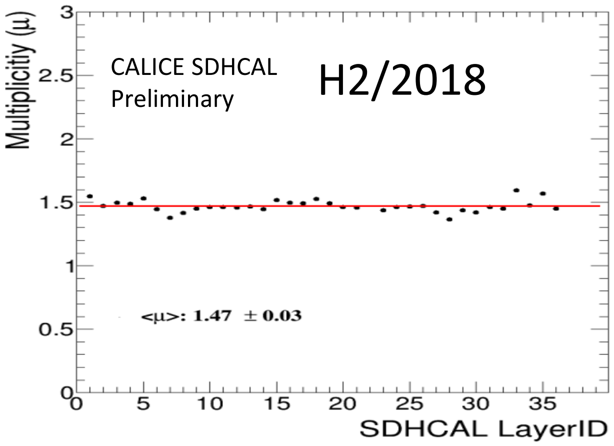


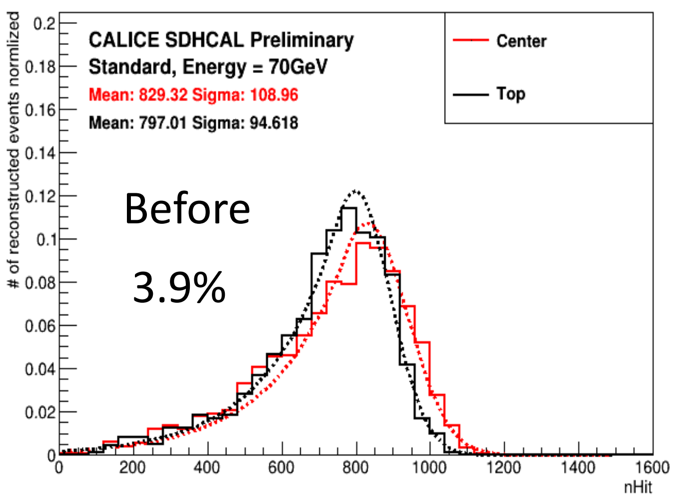
Further improvements on the energy reconstruction

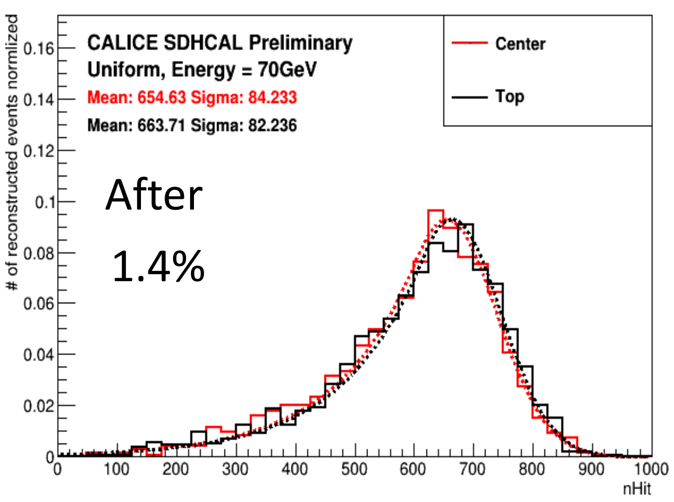
Detector homogeneity

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









We will apply the new method to the data to be collected in 2022

Further improvements on the energy reconstruction

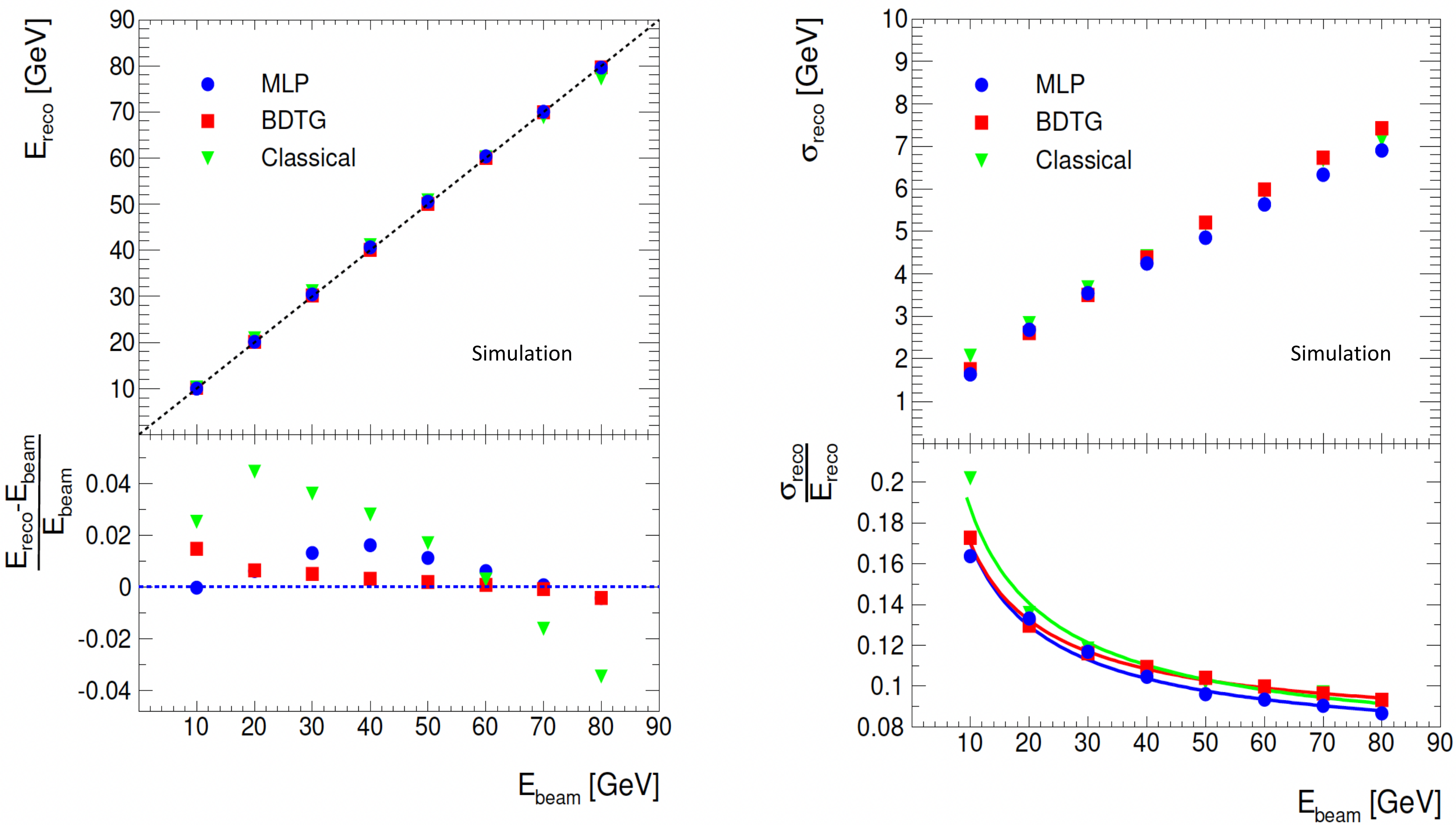
Multi-Variate Techniques

Several MVT methods (NN and BDT) were used to exploit, in addition to N_1, N_2 and N_3, the hadronic shower shape information related to its energy thanks to the high granularity of the SDHCAL

Input Variables	Description
$nHit1$	The number of hits only exceeding the threshold 1
$nHit2$	The number of hits exceeding the threshold 2 but not threshold 3
$nHit3$	The number of hits exceeding the threshold 3
$nHit$	$nHit = nHit1 + nHit2 + nHit3$
$nHough$	Number of hits used to do Hough Transformation
$nCluster$	Number of clusters
$nTrack$	Number of tracks
$nLayer$	Number of layers fired
$Density$	The density of hits
$meanRadius$	Mean of distance between tracks and hits
$InterLayer$	Number of layers when $meanRadius > 5cm$
$begin$	The number of the layer where the shower starts

Further improvements on the energy reconstruction

Several MVT methods were used to exploit in addition to N_1, N_2 and N_3 the **shape information** that is related to the **shower energy** thanks to yhe **high granularity** of SDHCAL. Simulated pion events within SDHCAL were used for this study.



MLP seems to perform better

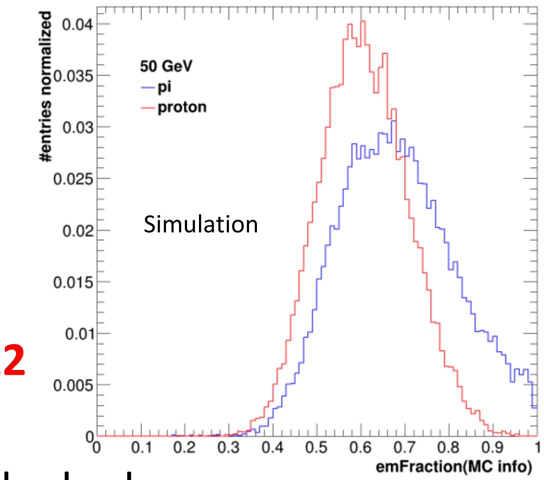
JINST 14, 2019, P10033

Further improvements on PID energy reconstruction

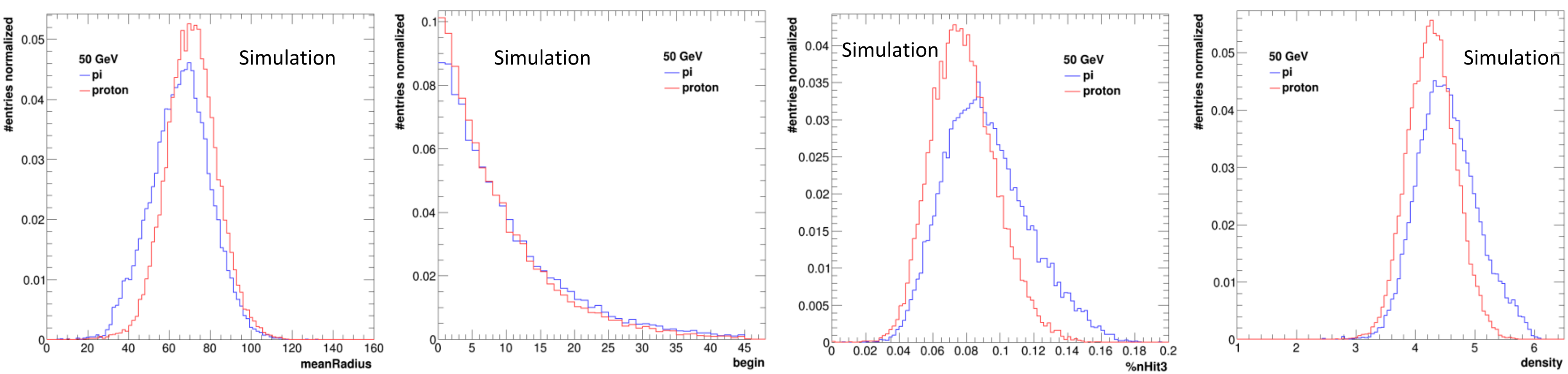
Hadron identification

The energy reconstruction method was applied to hadron events.
No distinction was made between pions and protons or others.
Hadronic showers of pions and protons are not identical.

This is one of the goals of the next TB at CERN in September 2022



Better construction can be made if one can identify the nature f the hadron.

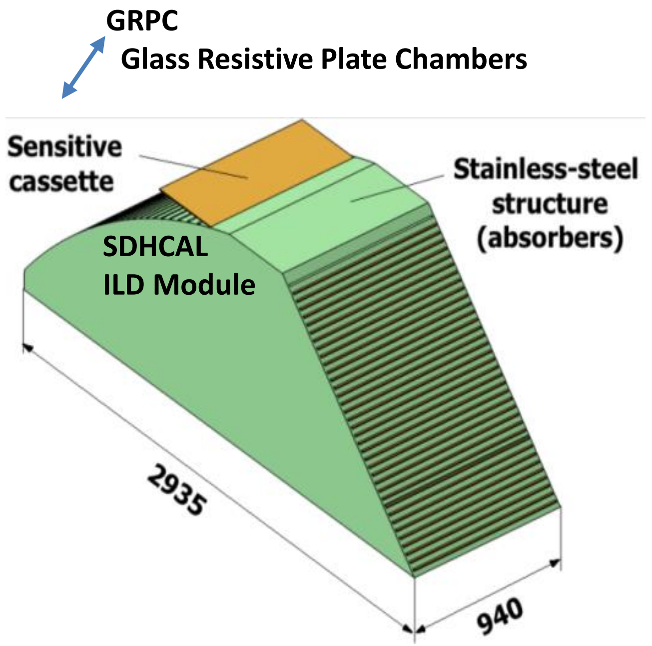


2022 beam test will be dedicated to study pion vs proton and kaon showers using Cerenkov detectors. Then BDT technique will be used to develop hadron PID and then energy construction algorithm with different (α, β, γ) parameters could be used.

SDHCAL-ILD@ILC

SDHCAL R&D towards ILD

- ❑ 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 should be robust and efficient
- ❑ Mechanical structure to be similar to the final one
- ❑ Envisage new features such timing, etc..

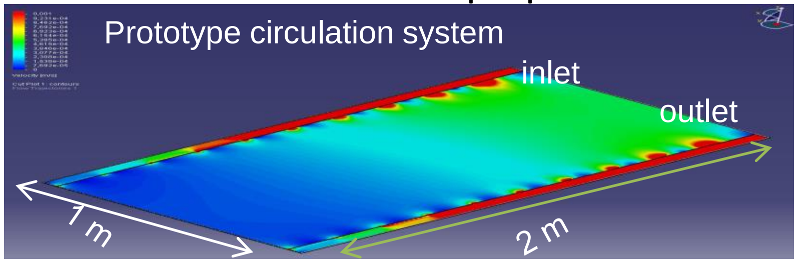


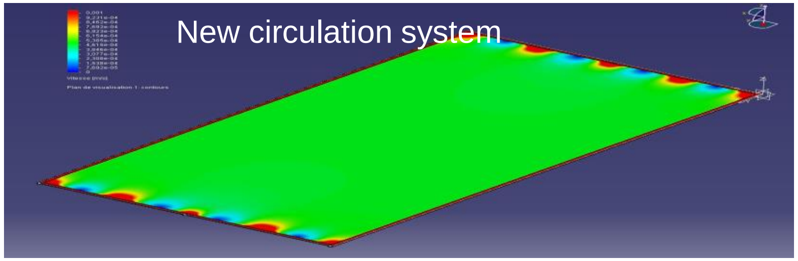
Goal: to build new prototype with few but large GRPC with the new components
→ **ILD Module0**

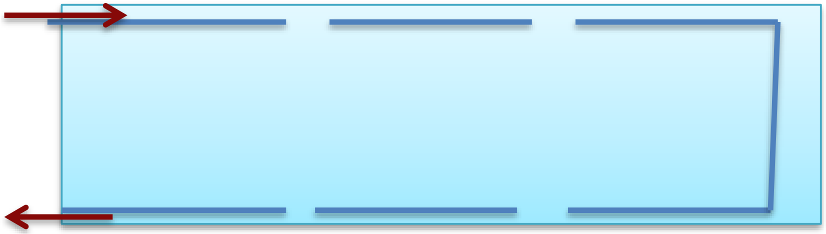
Detector conception

Construction and operation of large GRPC necessitate some improvements with respect to the present scenario.

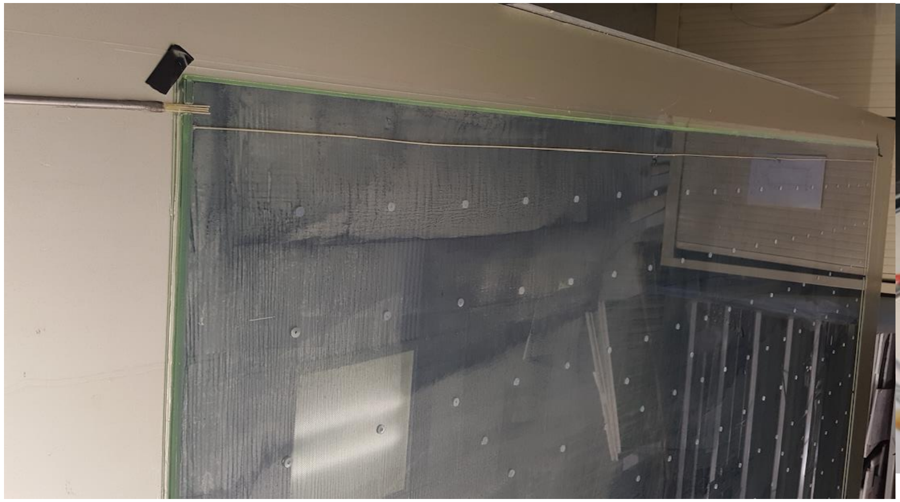
Gas distribution : new scheme is proposed

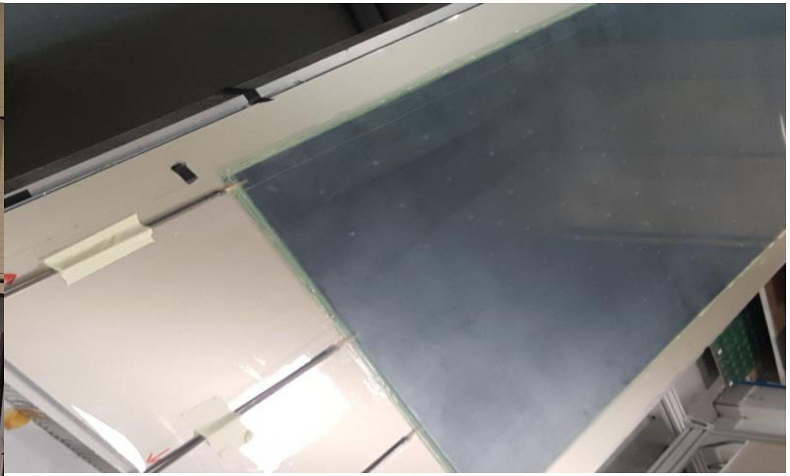






Cassette conception to ensure good contact between the detector and electronics is to be improved



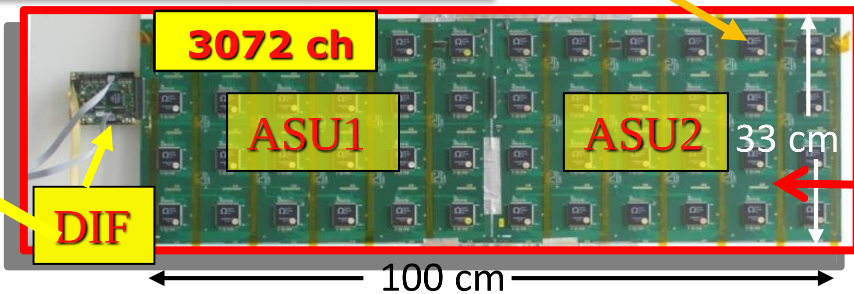


New electronics

Electronics readout for the 1m^3 prototipo

HADROC chip (ASIC)

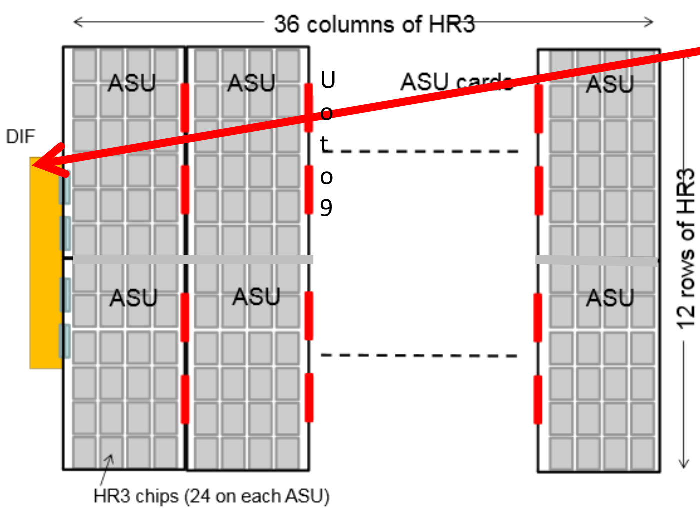
1m^2 board ➔ 6 ASUs hosting 24 ASICs



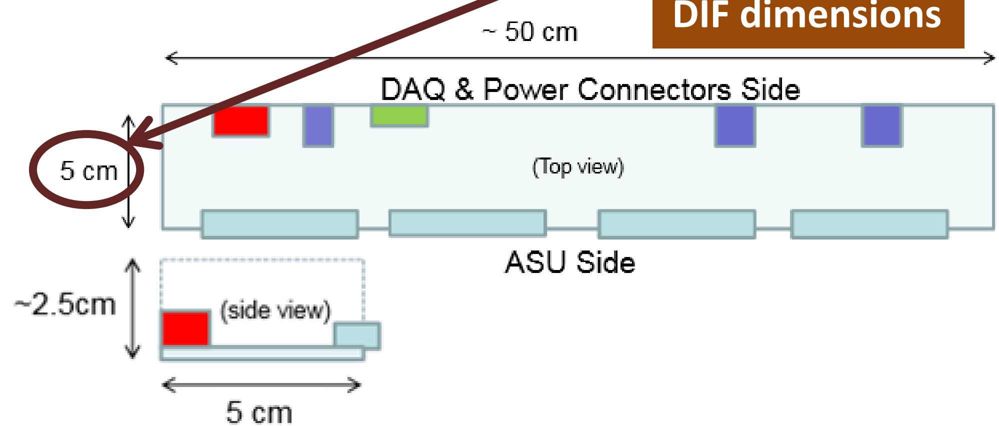
1 DIF (detector InterFace) for 2 ASU (Active Sensor Unit.- PCB+ASICs) ➔ **3 DIFs for ONE 1m2 GRPC detector**

Electronics readout for the final detector

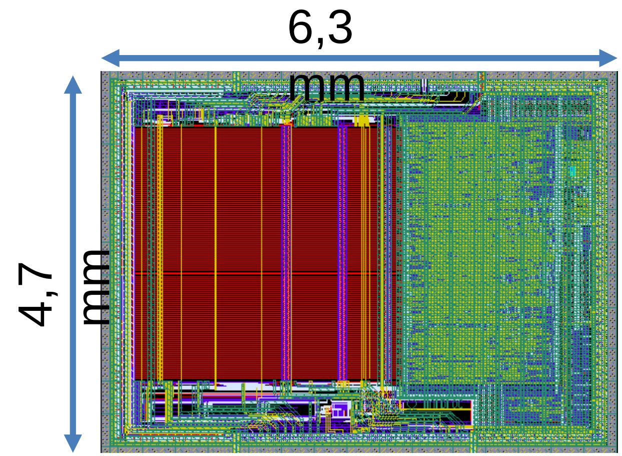
Only **1 DIF per GRPC (any size)** with small dimensions to fit in the **small** space available at the **ILD detector**



DIF dimensions



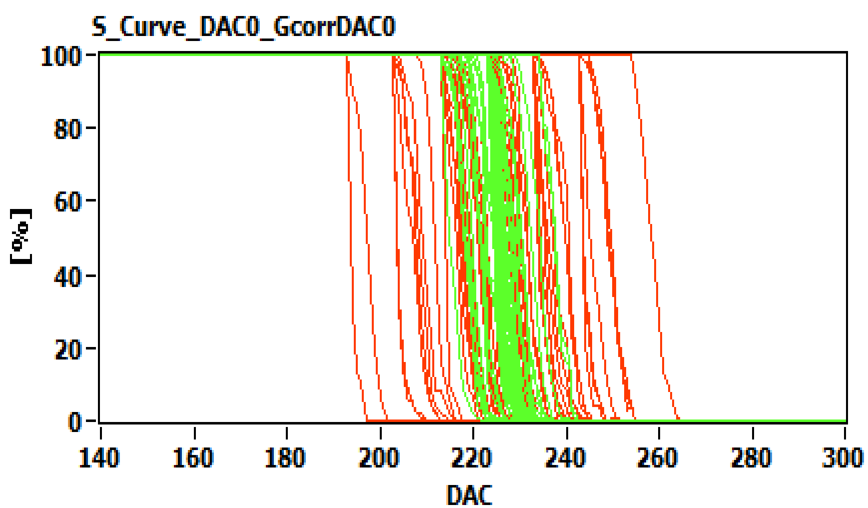
New electronics: ASIC

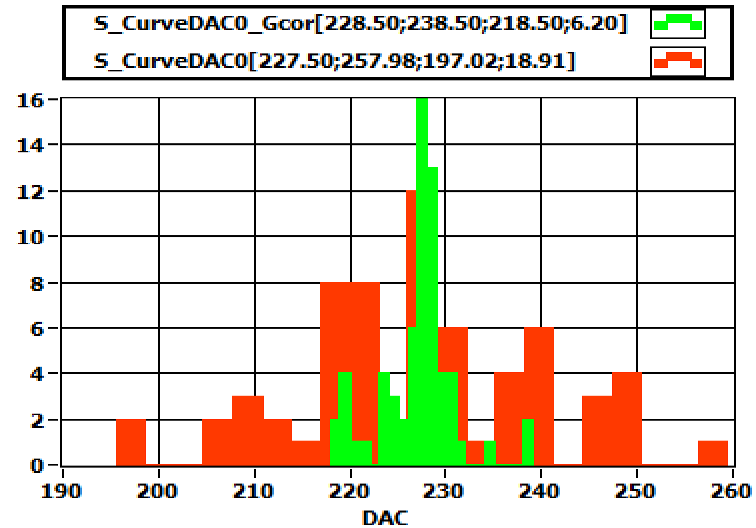


HARDROCR3 main features:

- **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)

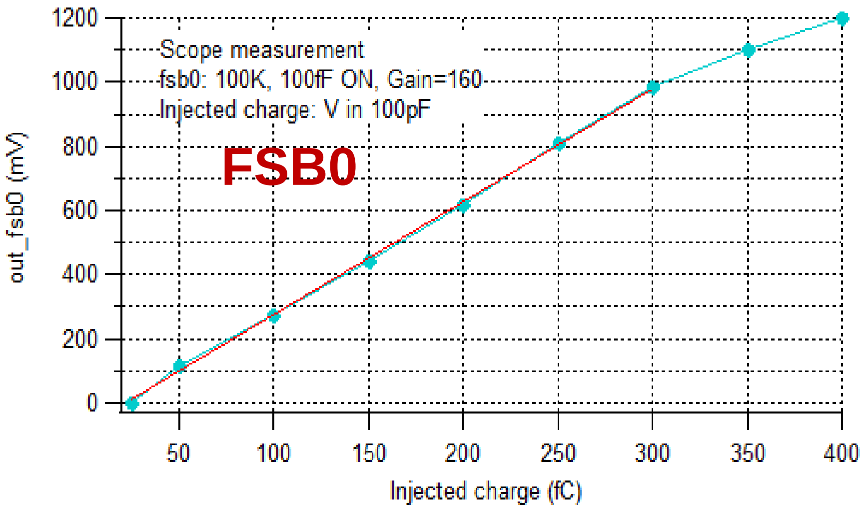
H3B TESTED : 786, Yield : 83.3 %

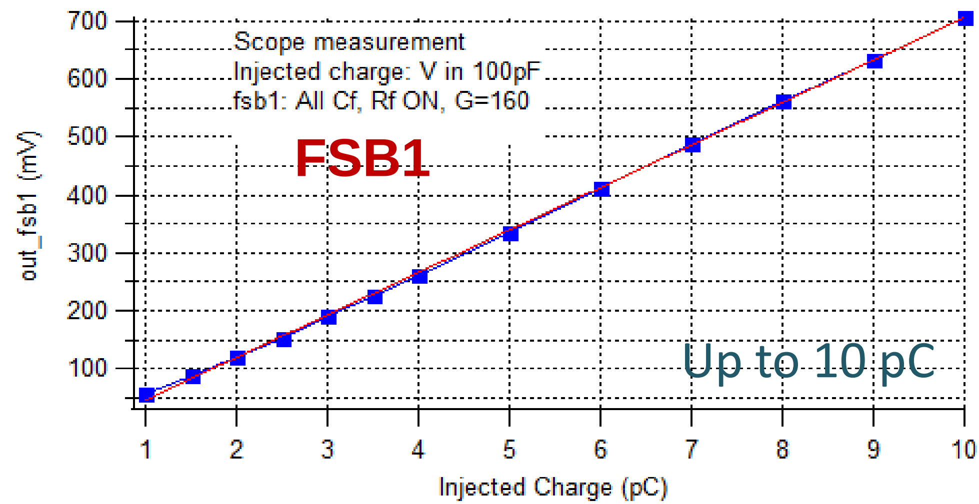


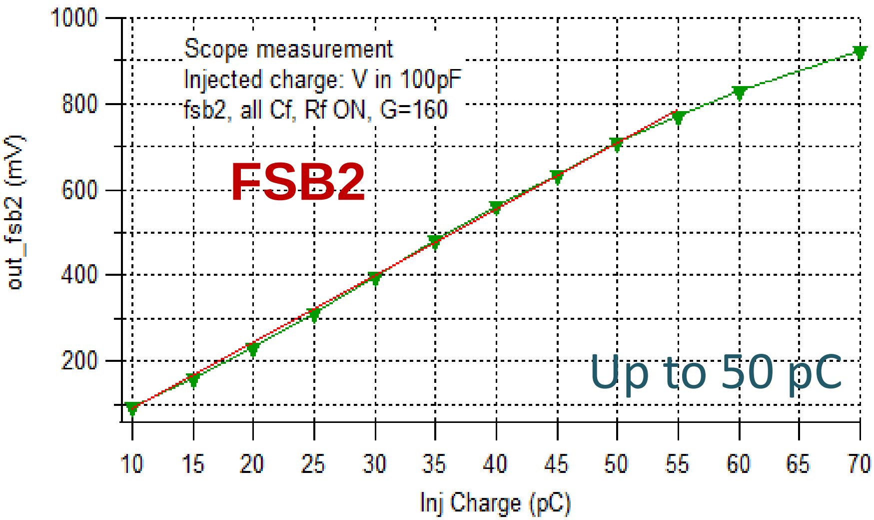


HARDROC3: Analog linearity

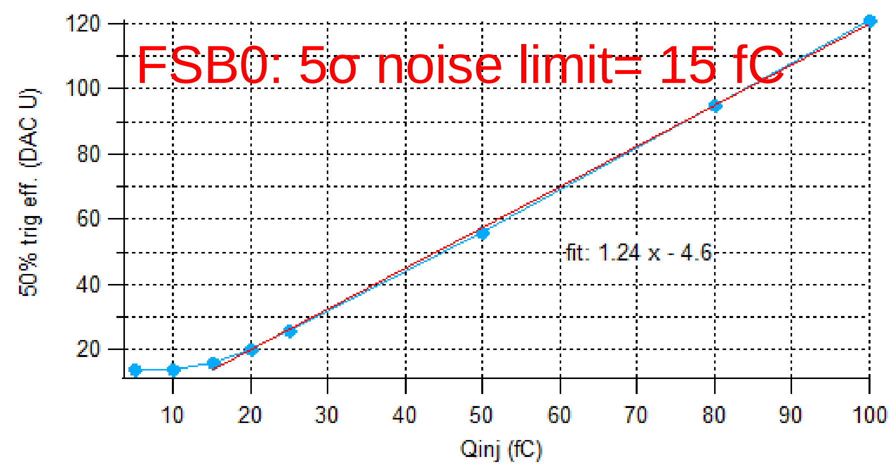
Fast shaper outputs (mV) vs Qinj (fC)







50% trig. Eff. (DAC units) vs Qinj (fC)

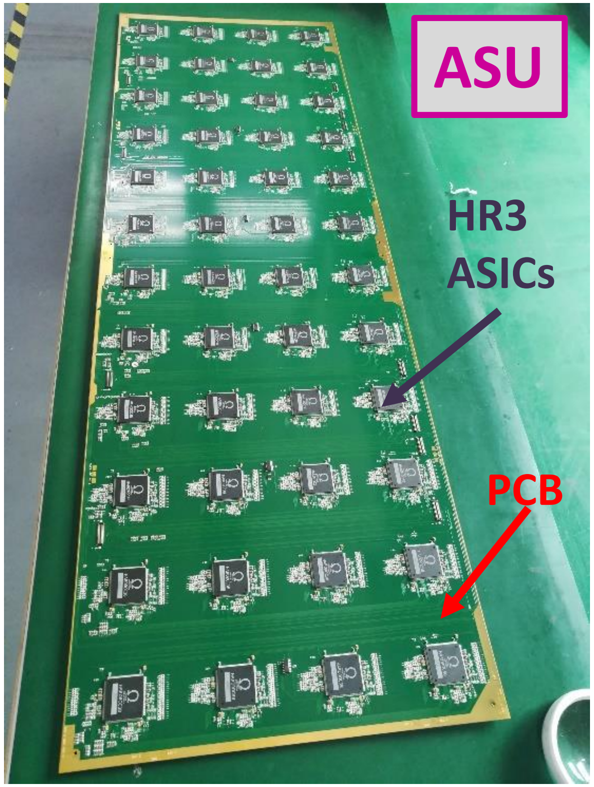


Dynamic range: 15fC - 50 pC

ASU (Active Sensor Unit)

An important challenge is to build a PCB up to 1m length with good planarity to have a homogeneous contact of pads with RPCs in order to guarantee an uniform response along all the detector.

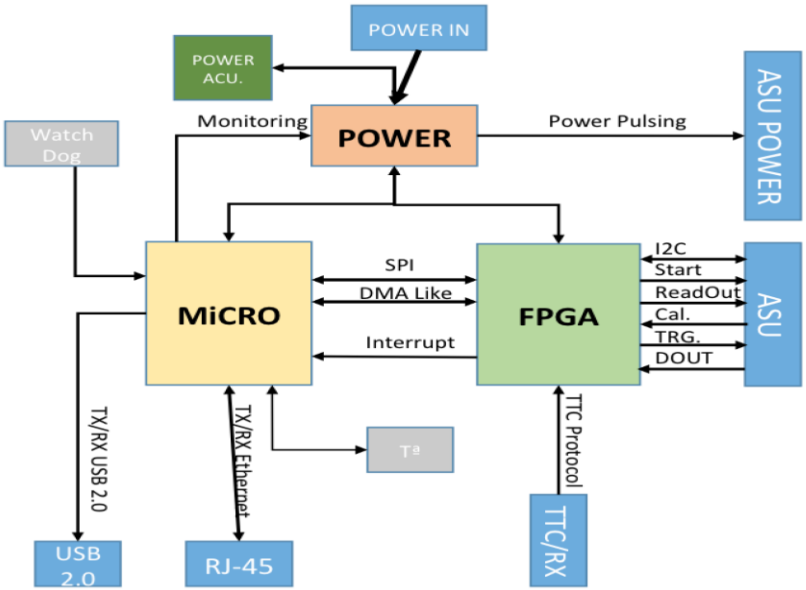
A company was found and ***1x0.33 m2 with 13 layer ASUs*** have been built.



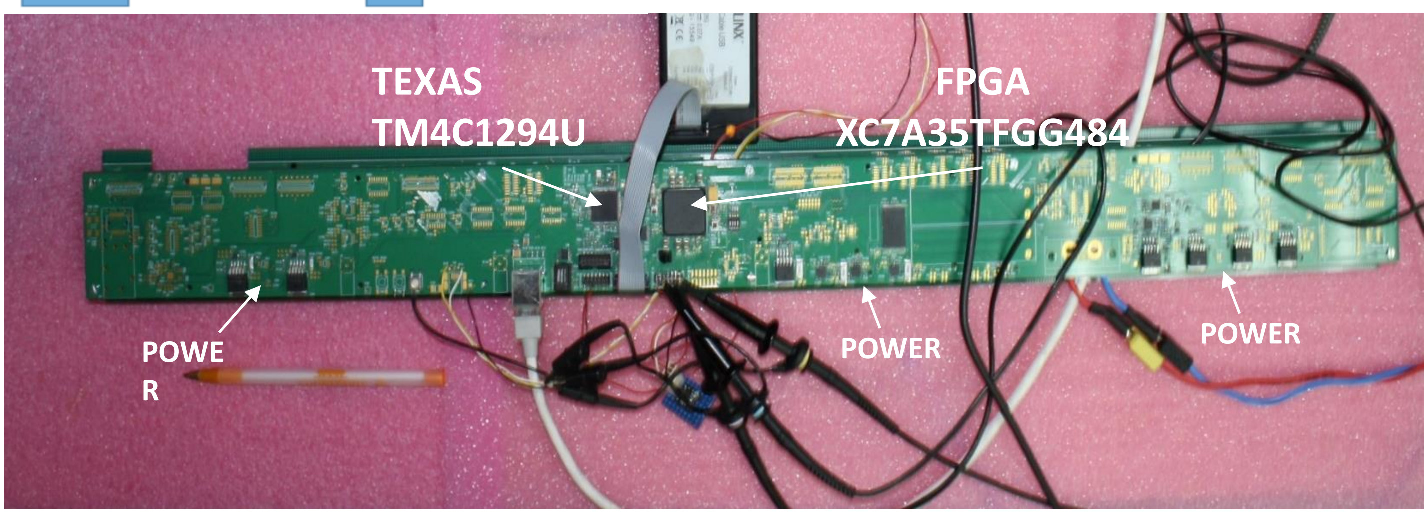
The ASU-ASU (= ASU-DIF) connections also produced

New electronics : DIF

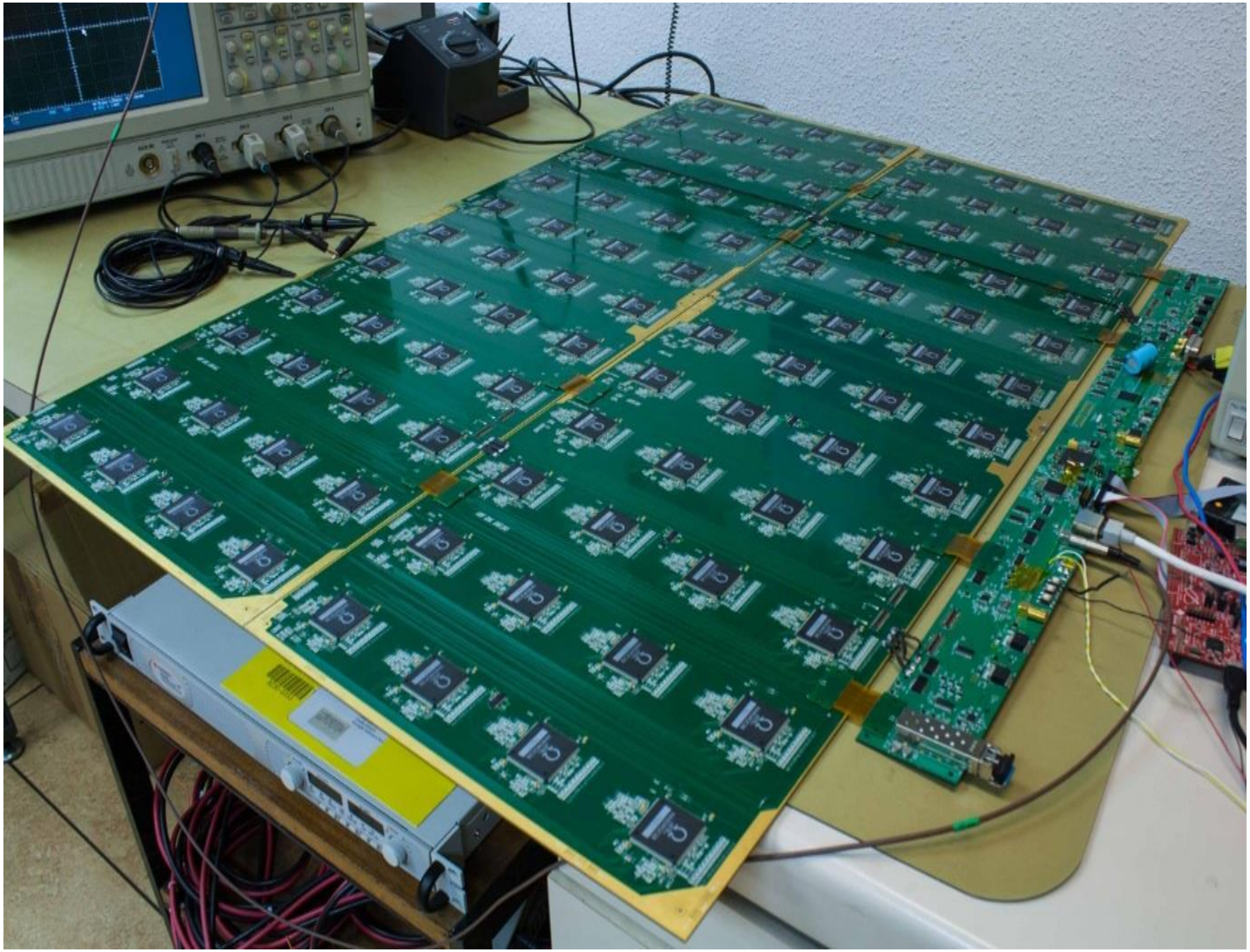
DIF sends DAQ commands (config, clock, trigger) to front-end and transfer their signal data to DAQ. It controls also the ASIC power pulsing



- Only **one DIF per plane** (instead of **three**)
- DIF handle up to **432 HR3 chips** (vs **48 HR2** in previous DIF)
- HR3 **slow control** through **I2C bus (12 IC2 buses).** Keeps also **2 of the old slow control buses as backup & redundancy**.
- **Data transmission to/from DAQ** by **Ethernet**
- **Clock and synchronization** by **TTC** (already used in LHC)
- **93W Peak power supply** with super-capacitors (vs **8.6 W** in previous DIF)
- Spare I/O connectors to the FPGA (i.e. for GBT links)
- Upgrade **USB 1.1** to **USB 2.0**



New readout electronics is being tested
All functionalities seem ok

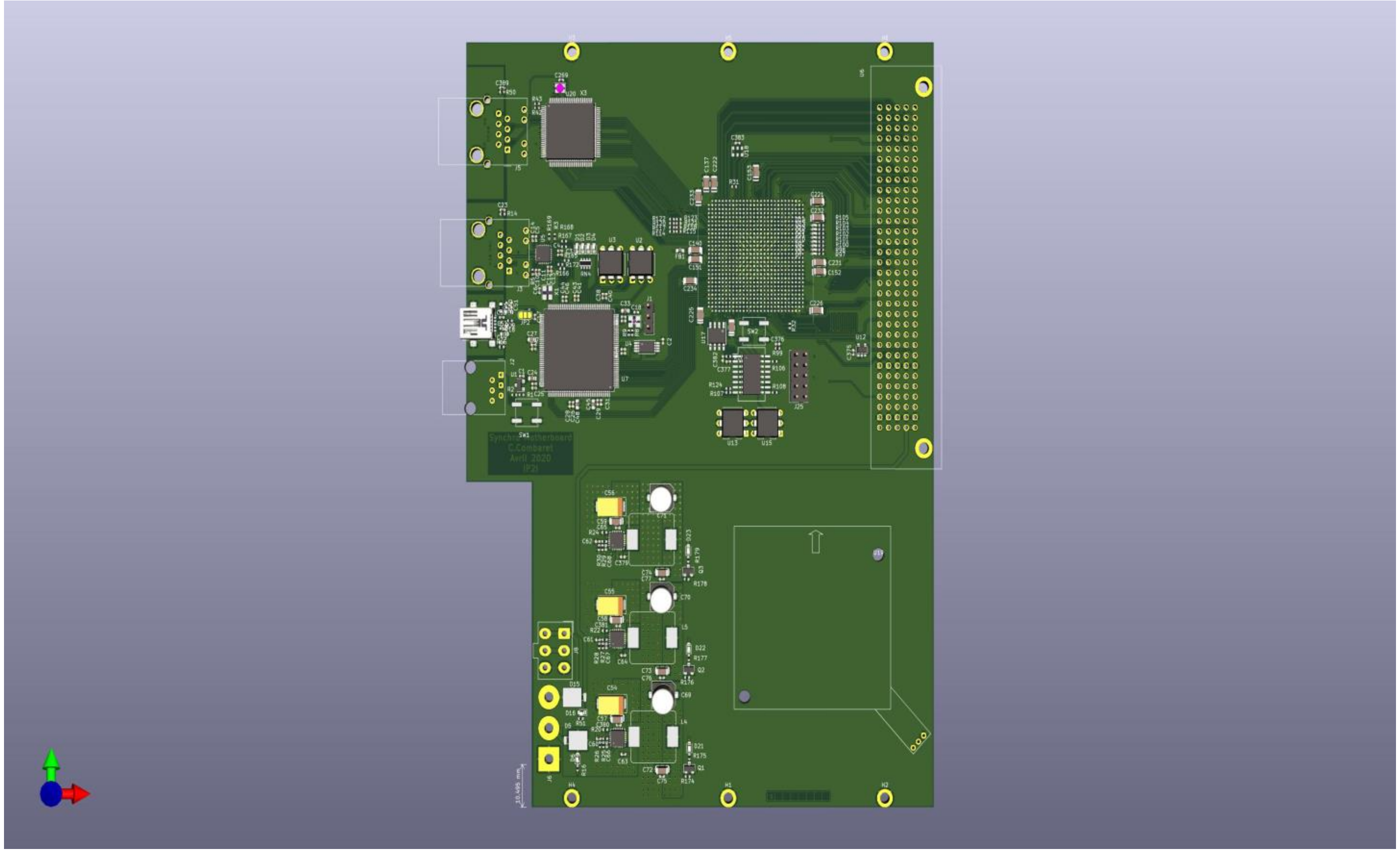


New electronics : DCC

To synchronize several DIFs, a new DAQ board was developed. It contains:

-1 FPGA (cyclone10LP) with 12x5 LVDS links

-Microprocessor (PIC32MZ) interfaced with TCP/IP and with the FPGA for high level operations (calibrations..etc)



Summary of activities related to ILC

SDHCAL is a powerful PFA tool that fulfills all the requirements for ILD@ILC.

All the pieces of a module0 have been developed and successfully tested. If a decision to go for ILC, the construction of module0 is straightforward and will take a short time to be built.

Full construction of SDHCAL for ILC could be achieved easily with the help of industry.

SDHCAL-ILD@CEPC

Strategy followed by the SDHCAL groups

From the beginning the SDHCAL groups were part of the ILD@CEPC proposal.

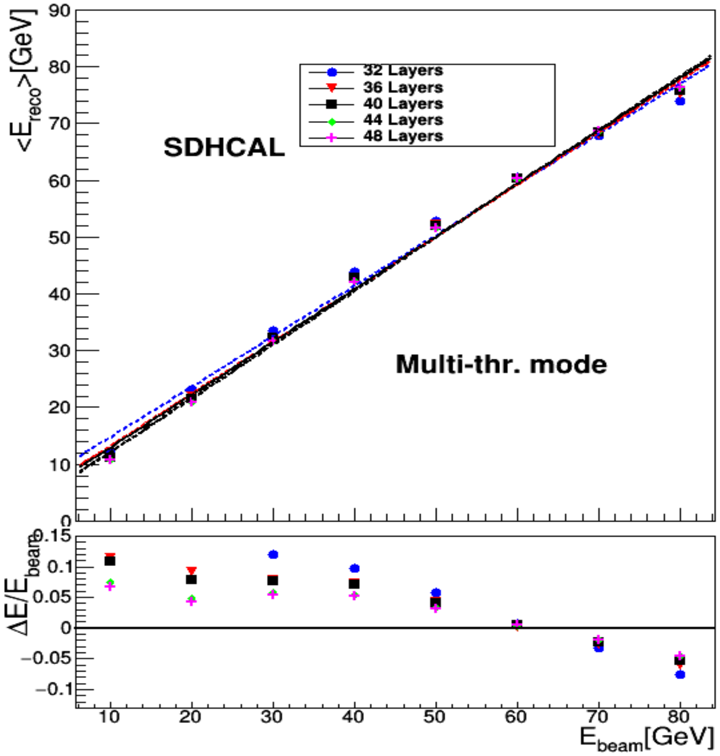
SDHCAL is one of the HCAL baselines and the simulation of physics performance of CEPC is based on SDHCAL performance.

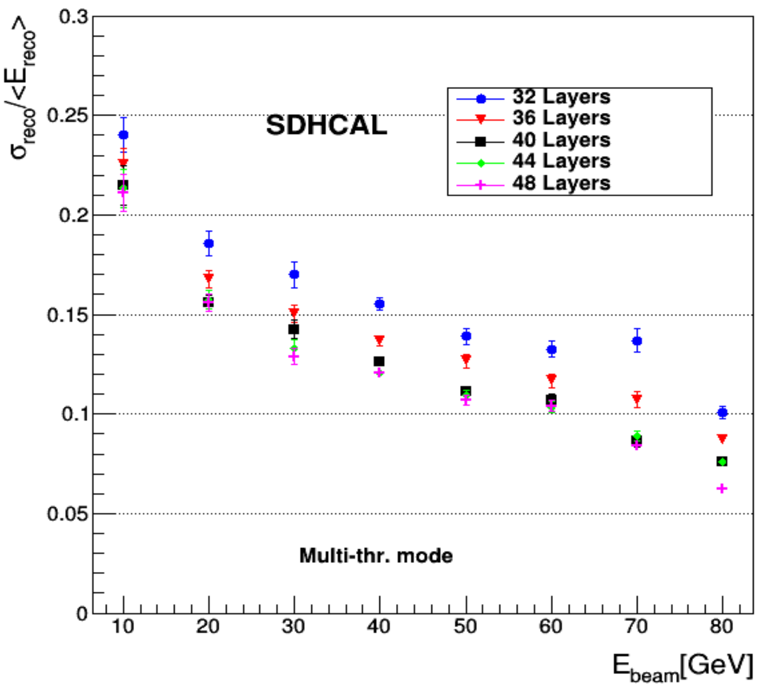
Three important aspects were studied to cope with the constraint of CEPC:

1) SDHCAL depth
2) SDHCAL power consumption and active cooling
3) SDHCAL timing
4) Rate capabilities

SDHCAL depth

Due to L* constraint from CEPC the detector radius is smaller than the one for ILC. This leads to that fact that the depth of the HCAL is smaller than that of ILD@ILC.
The option to **reduce** the number of SDHCAL layers by **4 and 8 and 12 layers** was studied on the simulation and on the **data collected at TB@CERN**.
Reducing by 4 layers seem to have small effects but one can still be efficient with 40 layers



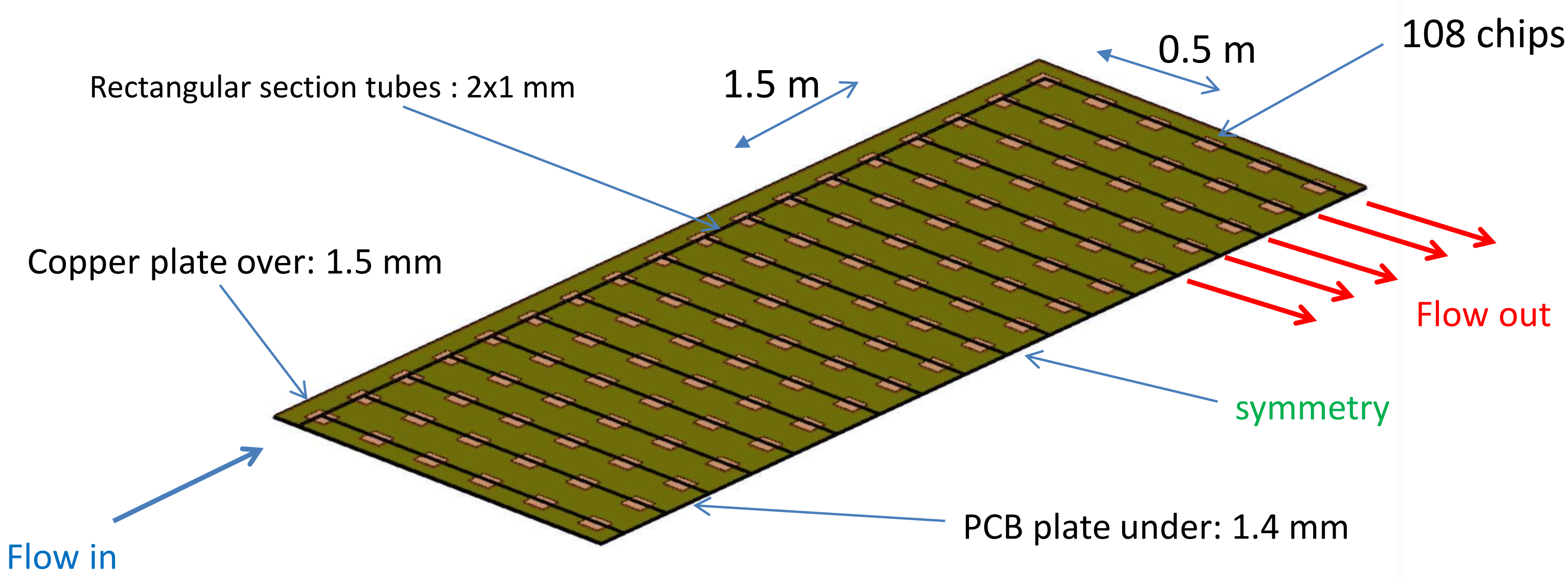


SDHCAL power consumption and cooling

The duty cycle of CEPC is 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

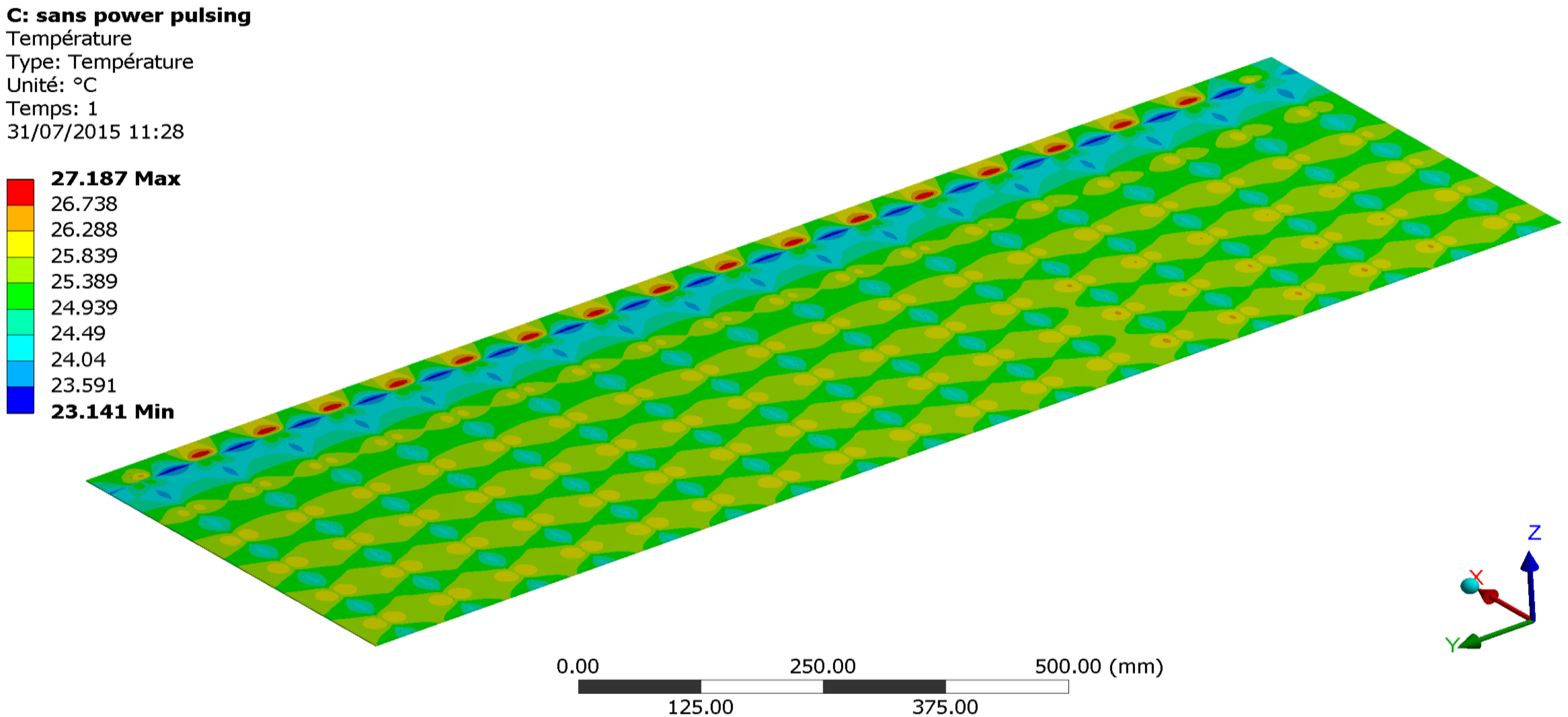


SDHCAL power consumption and cooling

The duty cycle of CEPC is 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

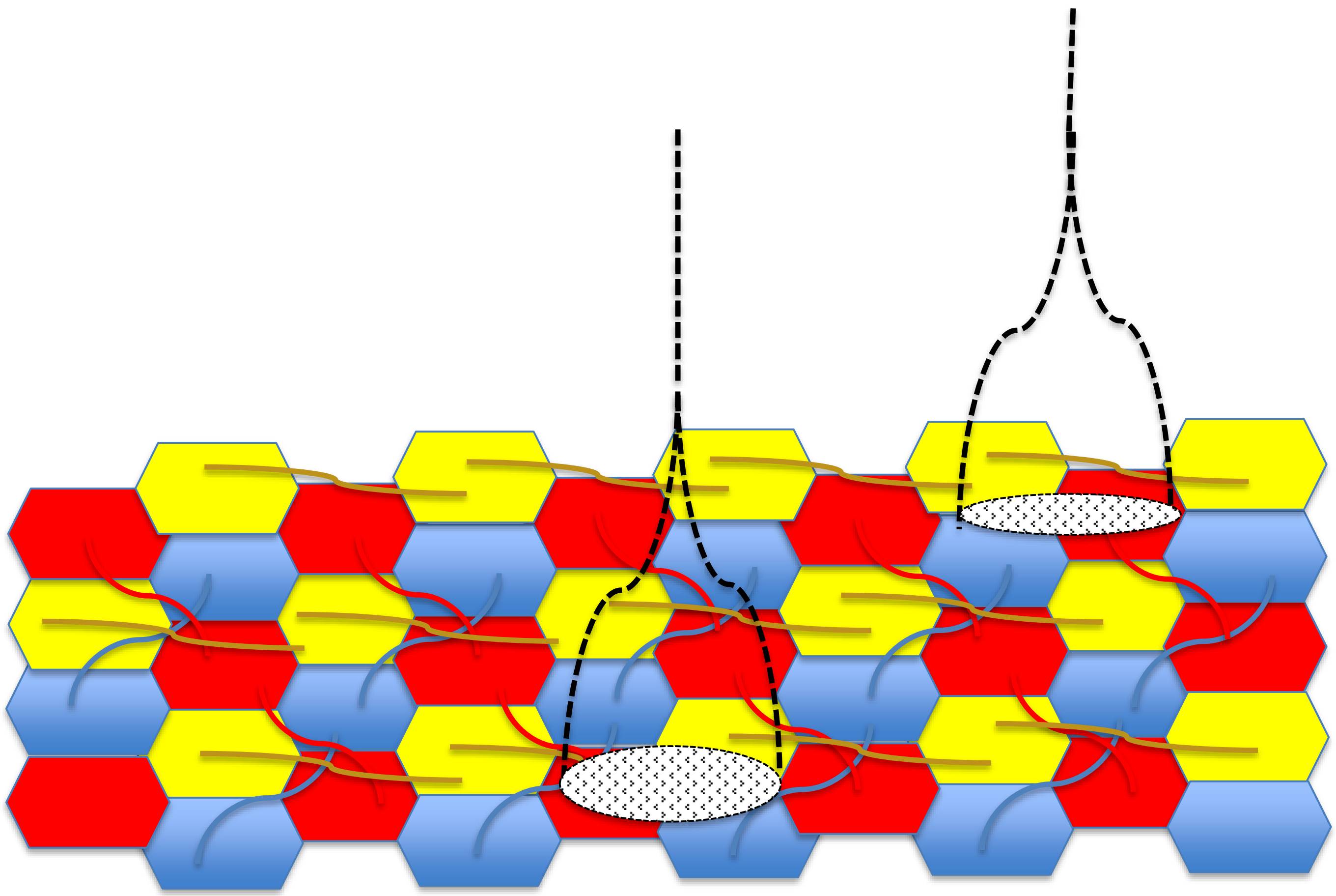
0.8 mW/chips with power pulsing, 80 mW/chips without power pulsing



SDHCAL power consumption and cooling

Other solution is to use the new scheme developed by Lyon group (woven strips) to read out RPC for which a reduction of a factor higher than 30 can be obtained.

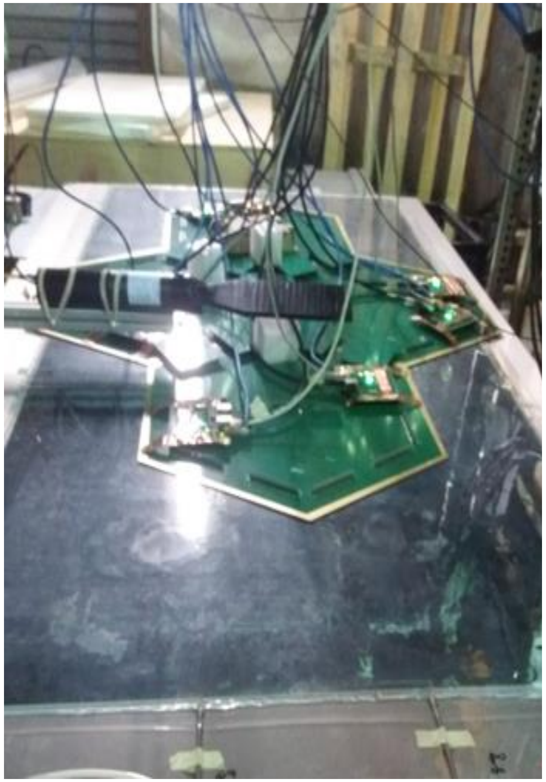
Caveat: This is ok for muon detectors and tail catchers. For SDHCAL a simulation is needed to validate



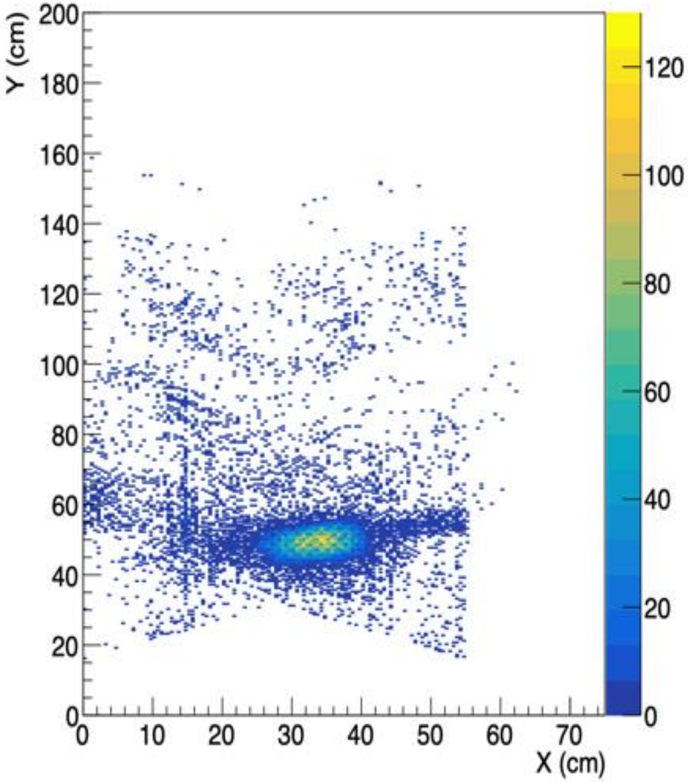
SDHCAL power consumption and cooling

Other solution is to use the new scheme developed by Lyon group (woven strips) to read out RPC for which a reduction of a factor higher than 30 can be obtained.

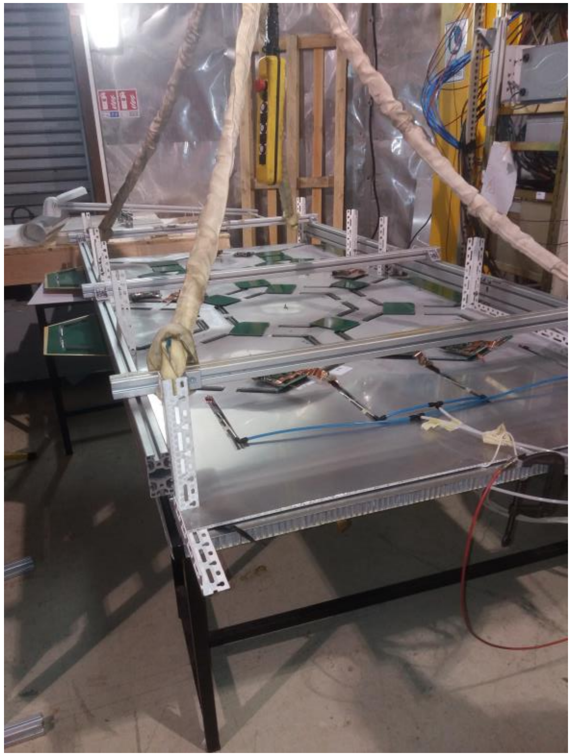
Caveat: This is ok for muon detectors and tail catchers. However to be used in SDHCAL a simulation is needed to validate the concept.



With four PCBs



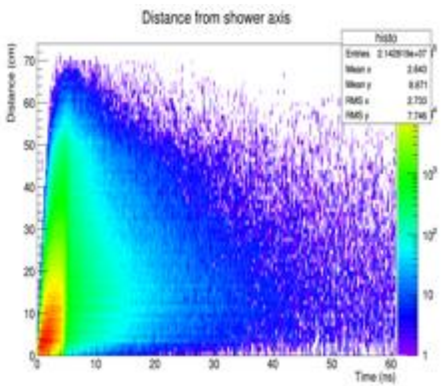
Preliminary results:
Efficiency > 85%

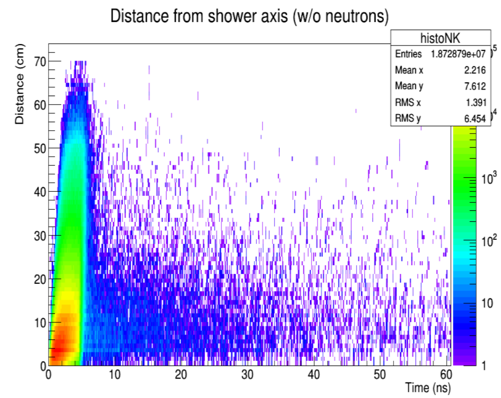


With 10 PCBs

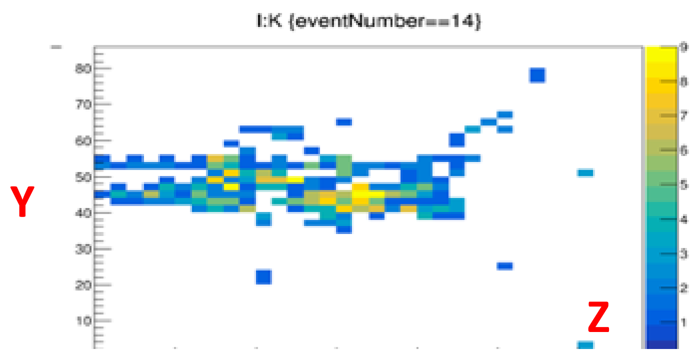
SDHCAL power consumption and cooling

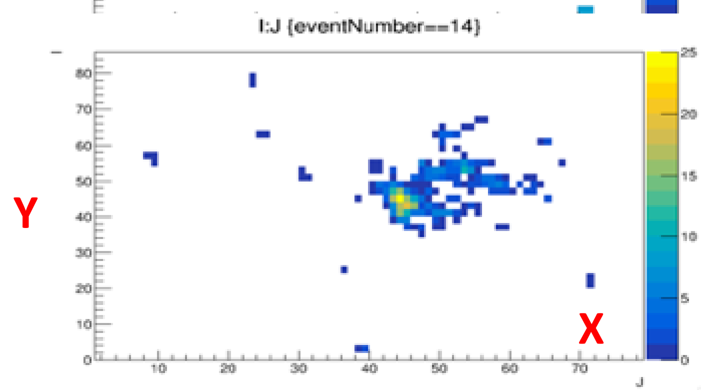
Timing is an important factor to identify delayed neutrons and **better reconstruct their energy**

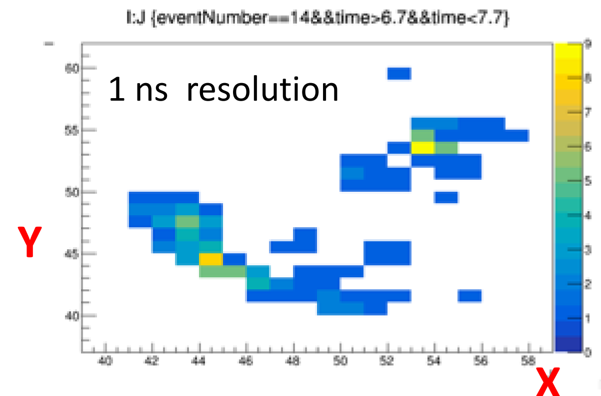


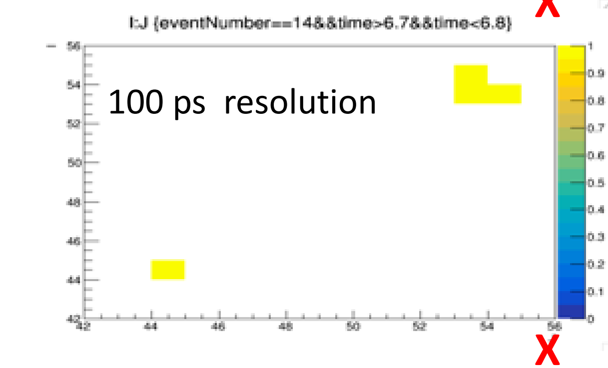


Timing can help to separate close-by showers and reduce the confusion for a better **PFA** application. Example: pi-(20 GeV), K-(10 GeV) separated by 15 cm.



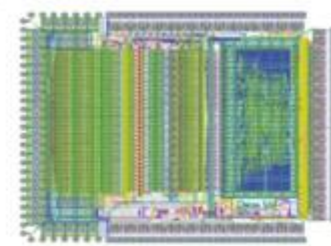




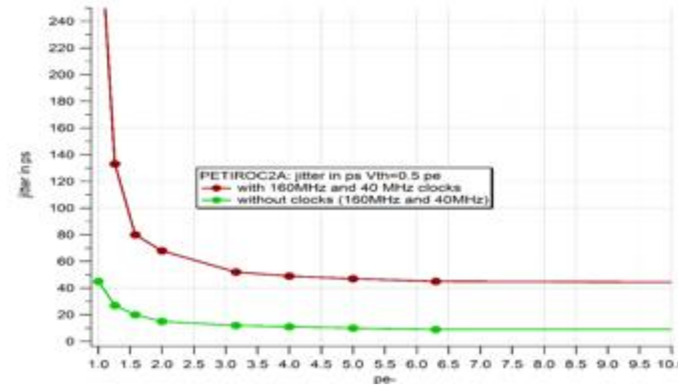


SDHCAL power consumption and cooling

How to achieve an excellent time resolution:

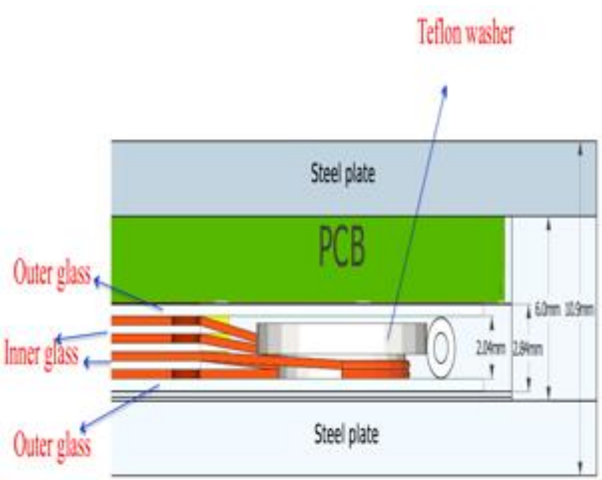


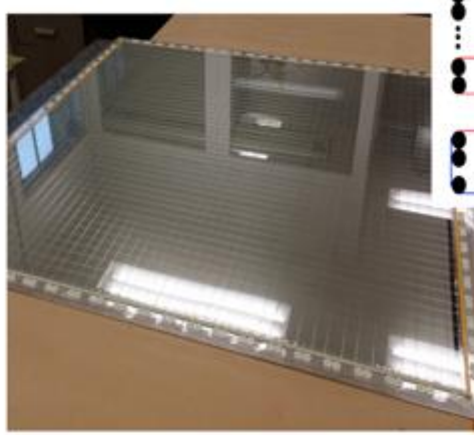
An **ASIC** with a fast preamplifier, precise discriminator and excellent TDC is needed
→**PETIROC** 32-channel, high bandwidth preamp (GBWP> 10 GHz), <3 mW/ch, dual time and charge measurement (Q>50 fC)
jitter < 20 ps rms @ Q>0.3 pC

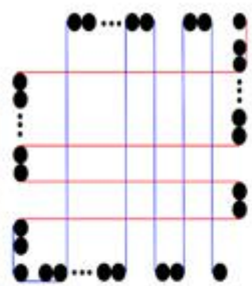


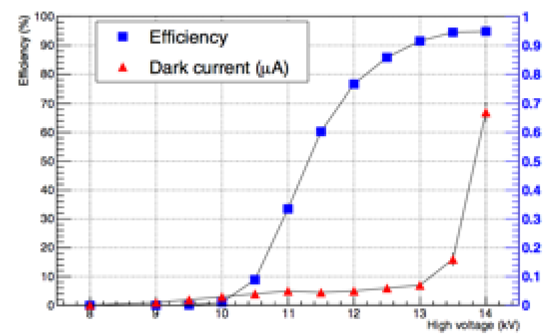
→ TDC either internal or external (delay-line, Vernier,.etc on FP
iRPC CMS upgrade project)

A fast-time **DETECTOR**
→ **MultiGAP** RPC is an excellent candidate.
4-5 gaps of 250 μm each can provide 100 ps tim resolution



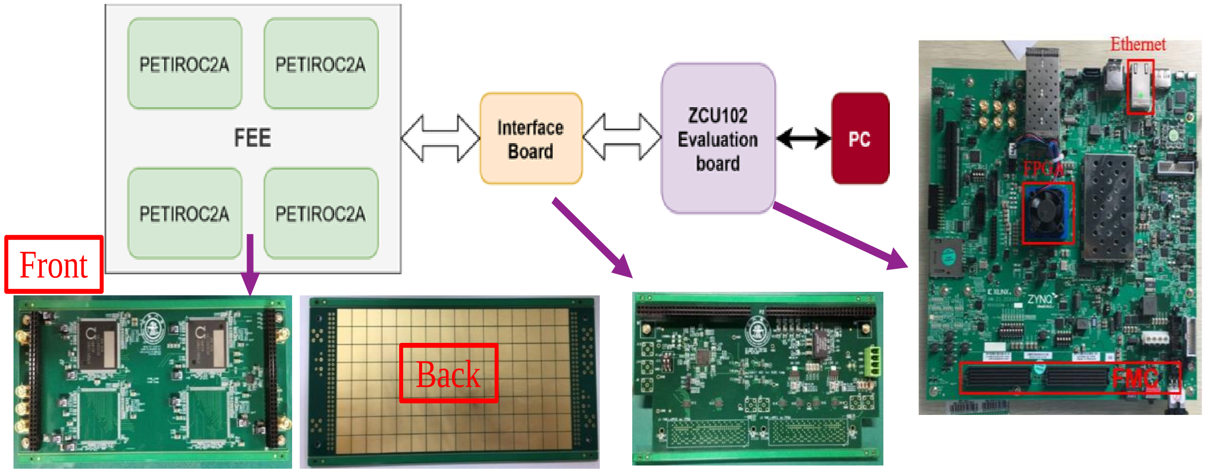






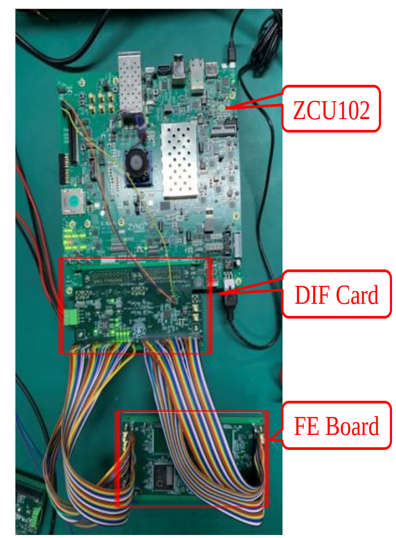
Threshold sets at 114 fC

First step towards transforming SDHCAL into T-SDHCAL



- Front-End Electronics for MRPC readout with high timing resolution
- The system includes a front-end board (FEB), a detector interface card (DIF) and a data acquisition system(DAQ) based on ZCU102.

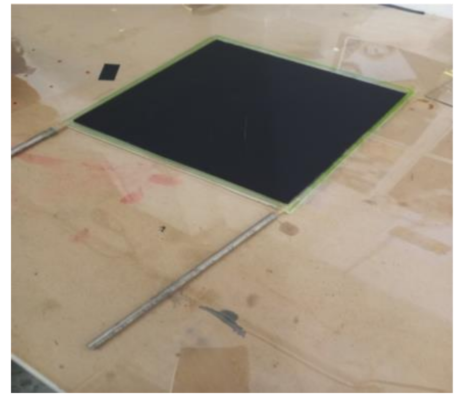
Test System and Setup



First step towards transforming SDHCAL into T-SDHCAL

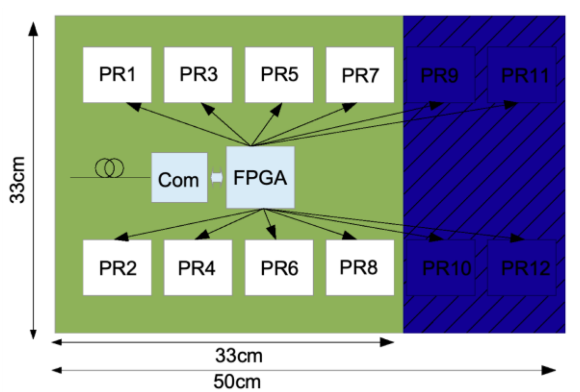
New and easy way of construction MRPC

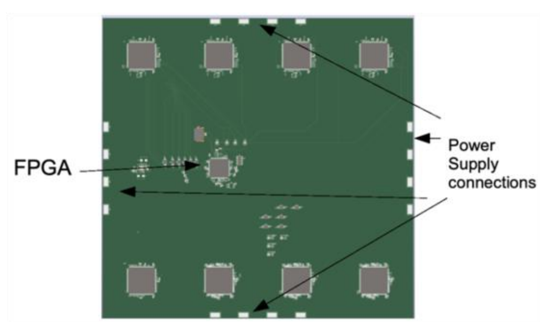
Using thin spacers made of mylar+double face



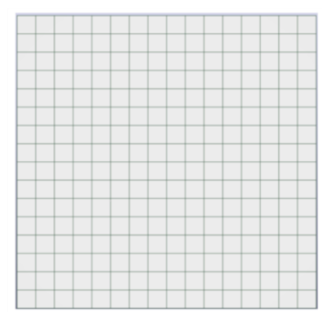
Large timing PCB

- Board with 8 (could be extended to 12) Petircoc2B ASICs
- Pads 2cm x 2cm, 256 channels
- Local FPGA (Xilinx Spartan-6 TQFP) embedded on board





Top view

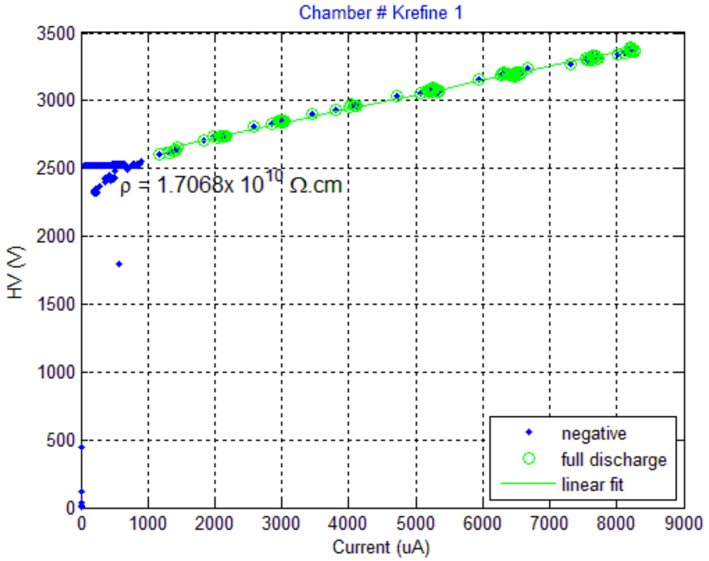


Bttom view

SDHCAL rate capability

GRPC have low rate detection capability (a few hundreds of Hz/cm2)
This is ok for ILC.
For CEPC with 1.5 MHz cycle duty (Higgs factory) this is still ok since the probability to have the same pad fired in one BC (0.7 µs) is about 10^{-5} and the probability to be fired once again before the electric field of the GRPC has reached its full value after a depletion is still small.

In case of Z-run the rate may be a problem, in particular at high eta.
Several scenarios are proposed:
Replace **glass** by other low **resistivity electrodes** leading to higher rate (a factor of 100-1000 higer)→ PEEK doped with nanoparticle



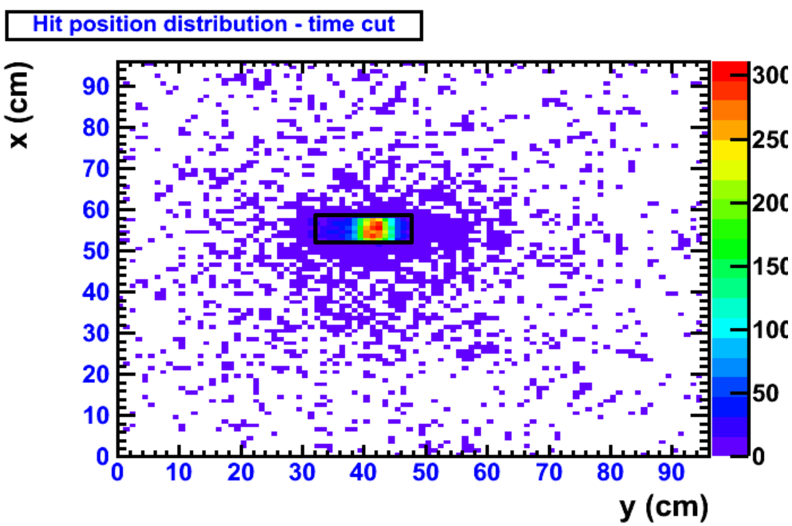
SDHCAL rate capability

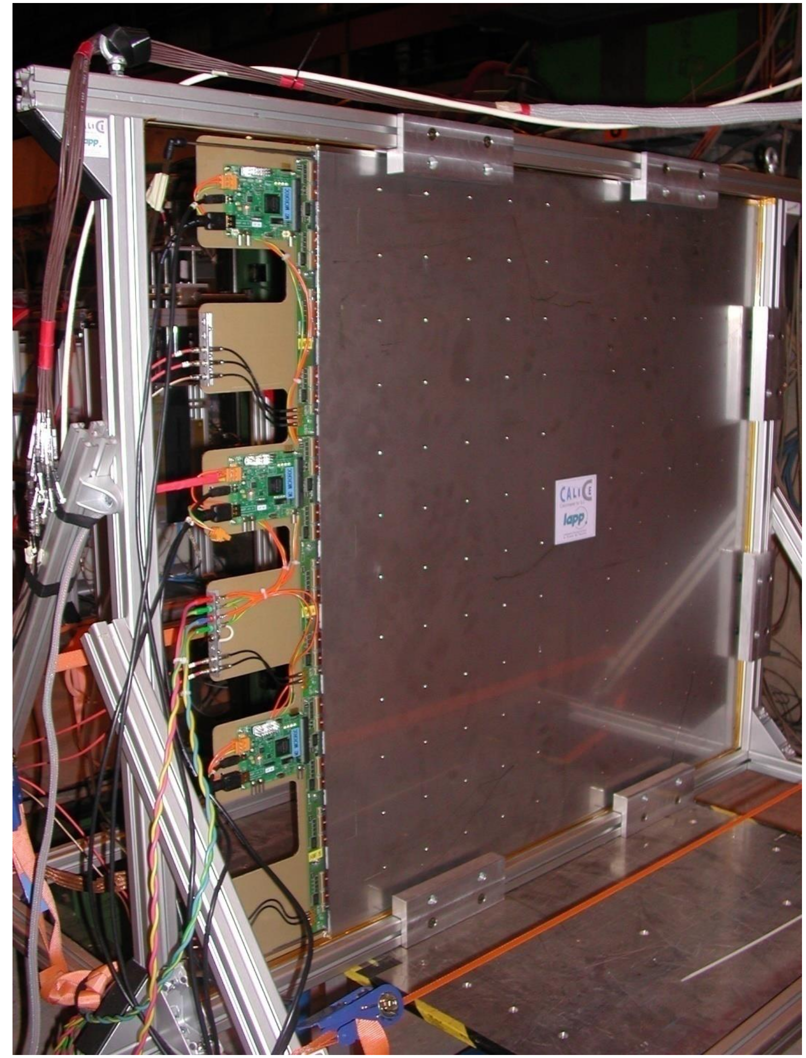
GRPC have low rate detection capability (a few hundreds of Hz/cm2)
This is ok for ILC.
For CEPC with 1.5 MHz cycle duty (Higgs factory) this is still ok since the probability to have the same pad fired in one BC (0.7 μs) is about 10^{-5} and the probability to be fired once again before the electric field of the GRPC has reached its full value after a depletion is still small.

In case of Z-run the rate may be a problem, in particular at high eta.
Another possible scenario is to use **resistive MPGD** such as GEM, MICROMEGAS or μWell in the forward region and RPC in the barrel region.

Tests using **MM in the SDHCAL** along the RPC has already been successfully done.

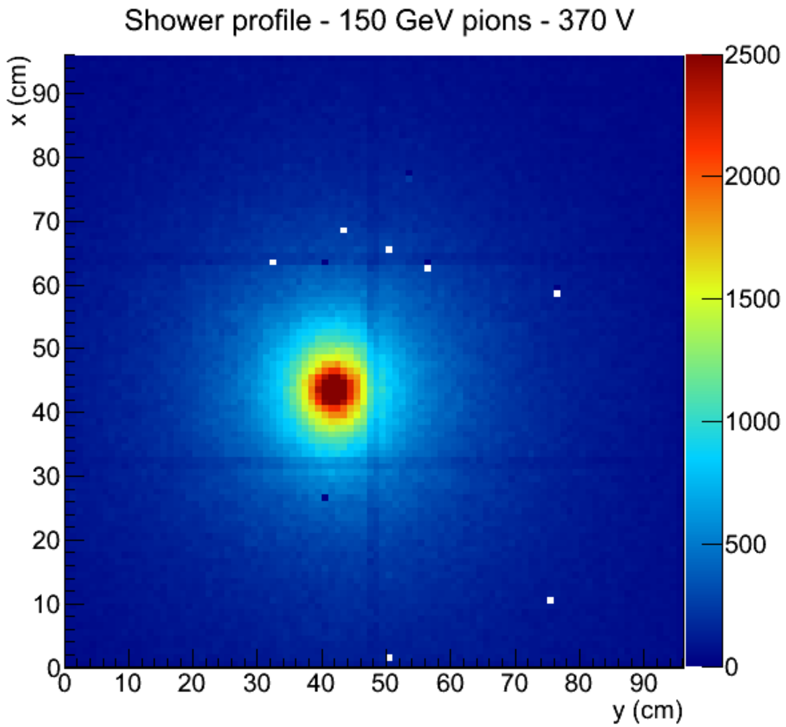
4 units of SDHCAL-MM
1m x 1m each were produced, tested in a muon beam





CNRS-LAPP

The 4 units of SDHCAL-MM were then inserted in the SDHCAL-RPC prototype replacing the RPC units #10, 20, 35 and 50



Additional development with Resistive Micromegas has started to render the SDHCAL-Micromegas more robust against discharges that may happen in the core of the shower.

Similar activities with Thick GEM replacing MM were also initiated.

SDHCAL rate capability

GRPC have low rate detection capability (a few hundreds of Hz/cm2)
This is ok for ILC.
For CEPC with 1.5 MHz cycle duty (Higgs factory) this is still ok since the probability to have the same pad fired in one BC (0.7 μs) is about 10^{-5} and the probability to be fired once again before the electric field of the GRPC has reached its full value after a depletion is still small.

In case of Z-run the rate may be a problem, in particular at high eta. Another possible scenario is to use **resistive MPGD** such as GEM, MICROMEGAS or μWell in the forward region and RPC in the barrel region.

Tests using **MM in the SDHCAL** along the RPC has already been successfully done. Similar tests with **μWell** is being discussed with colleagues from Wiseman Institute.

Still the use of MPGD will not allow to reach excellent time resolution as in the case of MRPC.

Summary of activities related to CEPC

SDHCAL fulfills also the requirements for ILD@CEPC as a Higgs factory but necessitates probably some accommodations for Z factory

SDHCAL-ILD@FCCee

The same logic as the one of CEPC and what can be achieved for CEPC could be for FCCee in principle.

Personal opinion:
When the construction of FCCee (> 2035) there will certainly be many new technologies that are much better than all the existing technologies including SDHCAL.

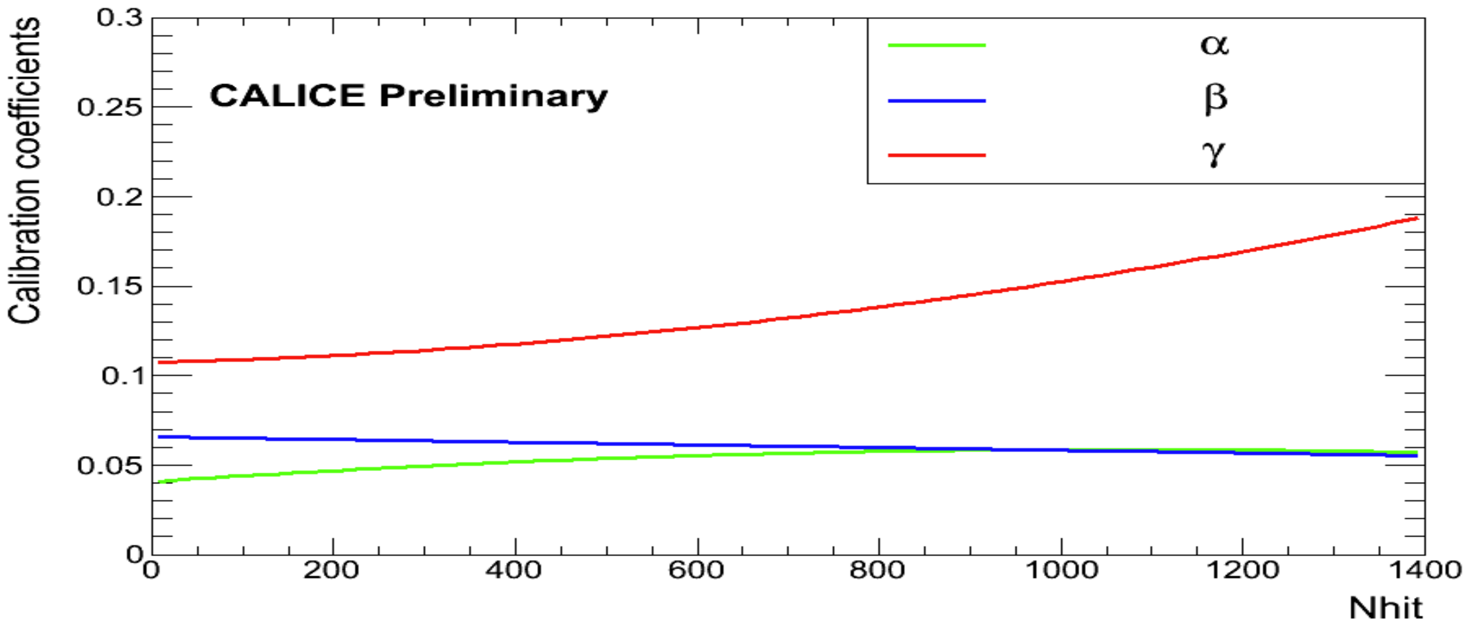
Summary

- SDHCAL concept with its high granularity provides an excellent tool not only to apply PFA by separating nearby showers but also to measure their energy.

- Different techniques were used to measure hadronic shower energy excellent linearity and very good resolution are obtained

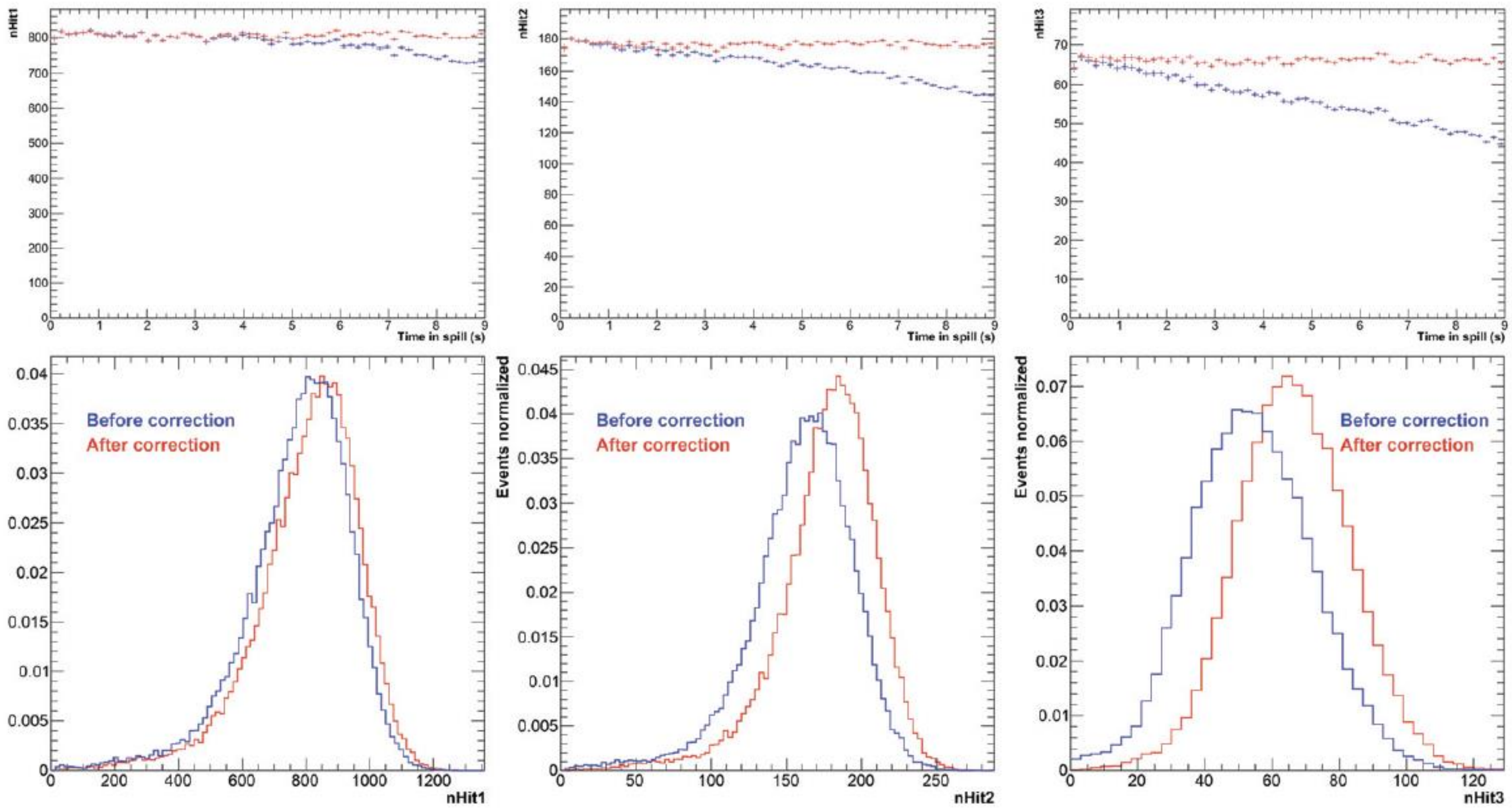
- The exploitation of the hadronic shower shape thanks to the high granularity is an excellent asset to identify particles and then better measure their energy.

- In the future SDHCAL will exploit precise time information using MRPC. The time information will improve on energy reconstruction by separating delayed neutrons contribution and better estimating it.



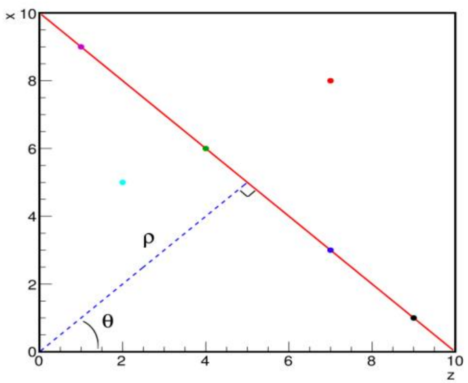
Calibration coefficients
CALICE Preliminary
α
β
γ
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
1000
1200
1400
Nhit

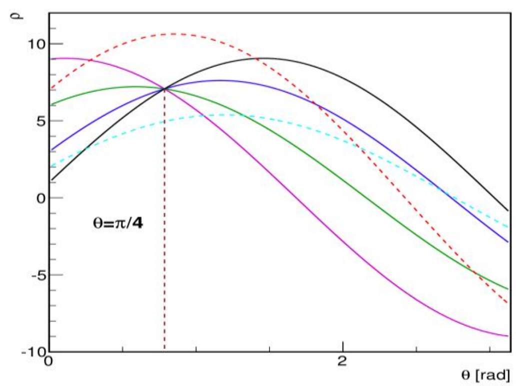
Time correction

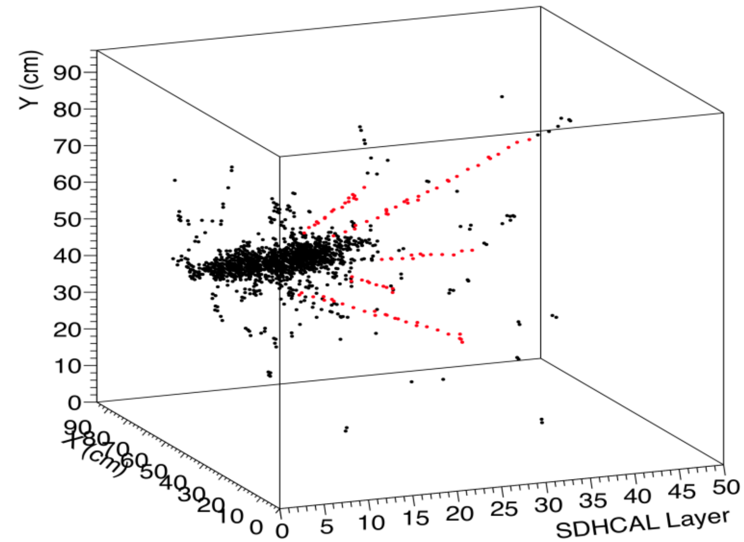


SDHCAL High-granularity impact

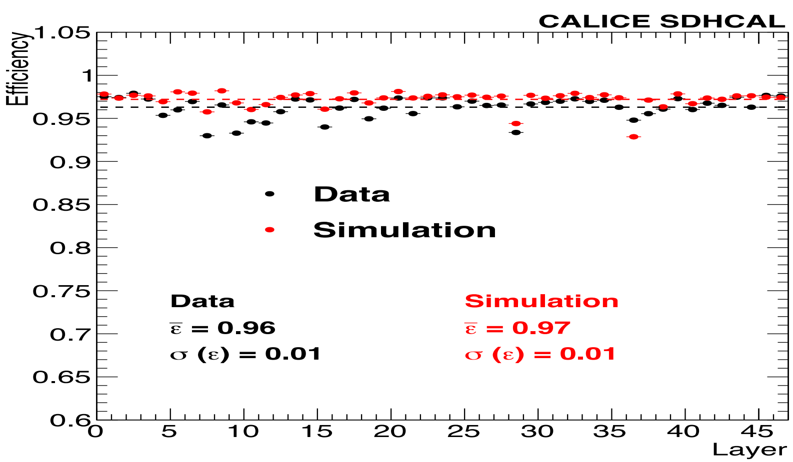
Hough Transform is an example to extract tracks within hadronic showers and to use them to **control the calorimeter in situ**

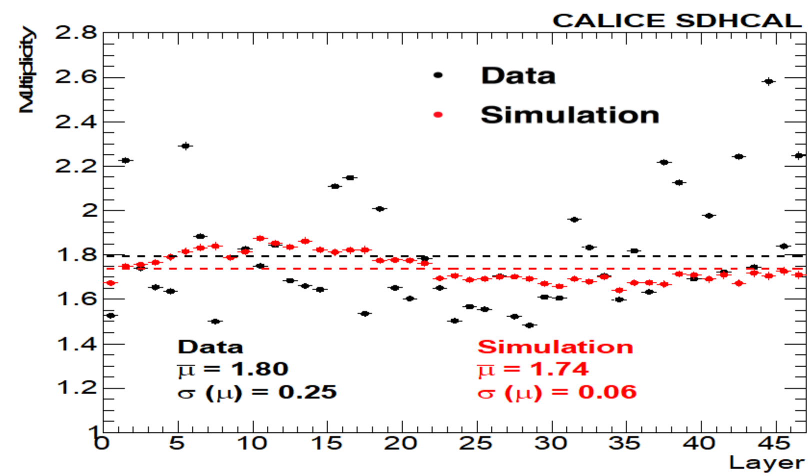






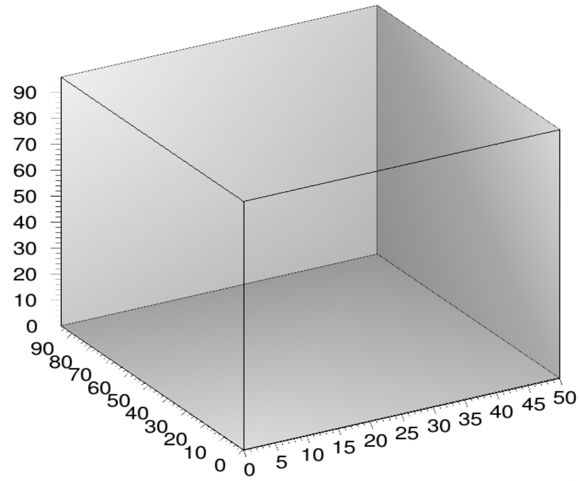
$\rho_{xz} = z \sin(\theta) + x \cos(\theta)$

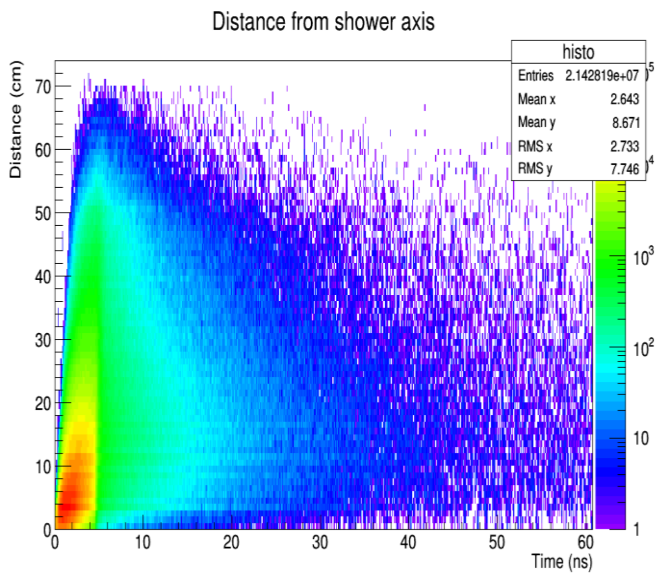


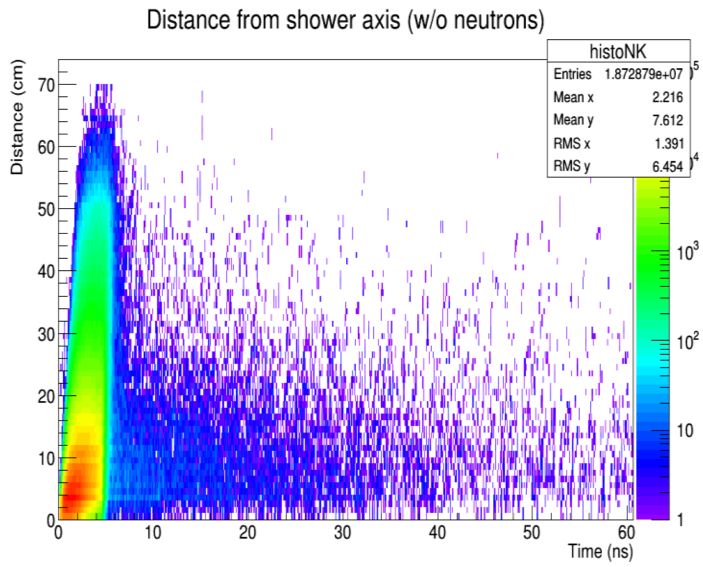


Excellent agreement with efficiency/multiplicity results obtained with cosmic and beam-muons. Excellent agreement data/MC

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







Gas system

Gas recycling is necessary to reduce cost :
-Goal: reduce the gas consumption to reduce the cost.
 -Gas renewal of 5-10% rather than 100%
-Conceived by the CERN gas group