Status of Semi-Digital Hadronic Calorimeter (SDHCAL)

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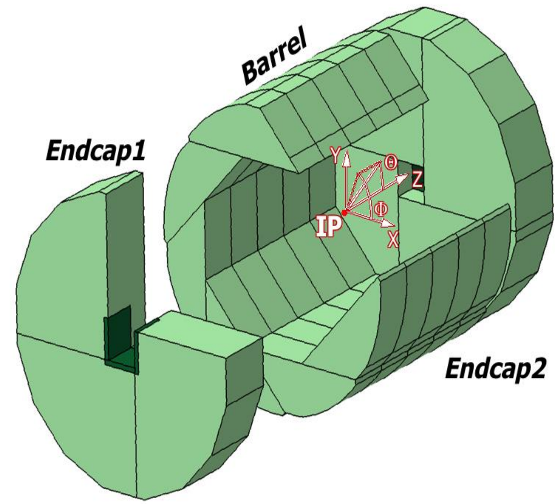
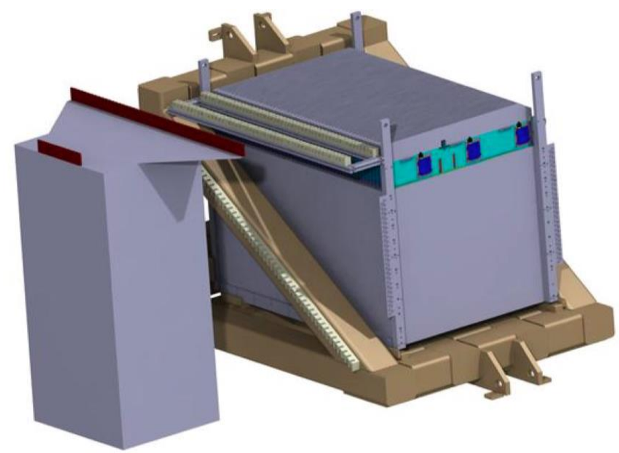
Outline

- SDHCAL Technological Prototype
  - Description
  - Test Beam Results
  - Hadronic Shower Studies
- R&D for Large SDHCAL Modules
  - Detectors
  - Electronics
  - DAQ
  - New Challenges
- Summary and Conclusion

SDHCAL for ILD

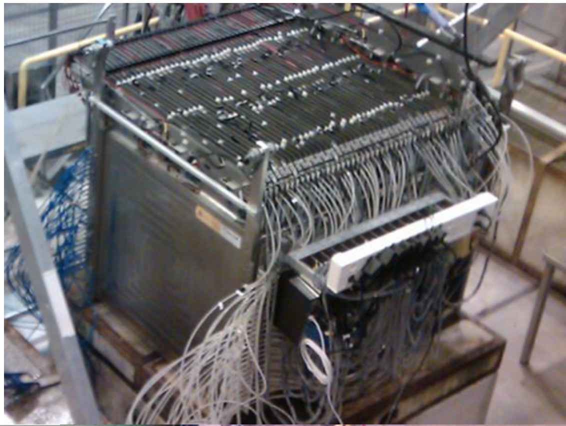
- The **SDHCAL-GRPC** is one of the two HCAL options based on PFA and proposed for **ILD**. Modules are made of 48 RPC chambers (**$6\lambda_I$**), equipped with **semi-digital, power-pulsed electronics** readout and placed in **self-supporting mechanical** structure (stainless steel) to serve as absorber.
- **Proposed structure for SDHCAL-ILD:**
  - Very compact with negligible dead zones
  - Eliminates projective cracks
  - Minimizes barrel and endcap separation
  - SDHCAL prototype should be able to study hadronic showers and very close to ILD module
- **Challenges:**
  - Homogeneity for large surfaces
  - Thickness of only a few mm
  - Lateral segmentation of 1cm X 1cm
  - Services from one side
  - Embedded power-cycled electronics
  - Self-supporting mechanical structure





SDHCAL Prototype Construction

- ✓ 10500 64-ch ASICs were tested and calibrated using a dedicated ASICs layout (93%).
- ✓ 310 PCBs were produced, cabled and tested, assembled by sets of six to make 1m^2 ASUs
- ✓ 170 DIF, 20 DCC were built and tested.
- ✓ 50 detectors were built and assembled with electronics into cassettes.
- ✓ DAQ system using both USB and HTML protocol was developed and used.
- ✓ Self-supporting mechanical structure.
- ✓ Full assembly took place at CERN.



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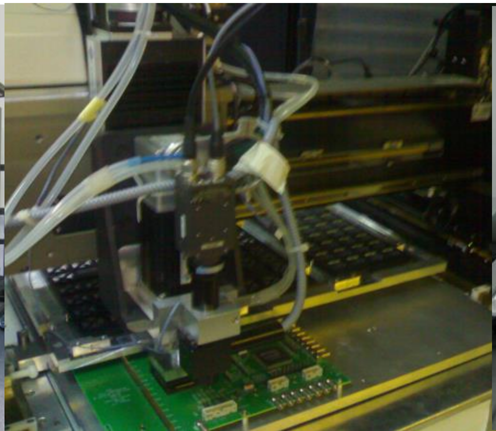
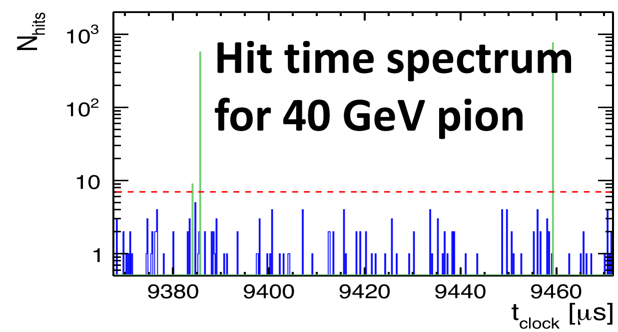
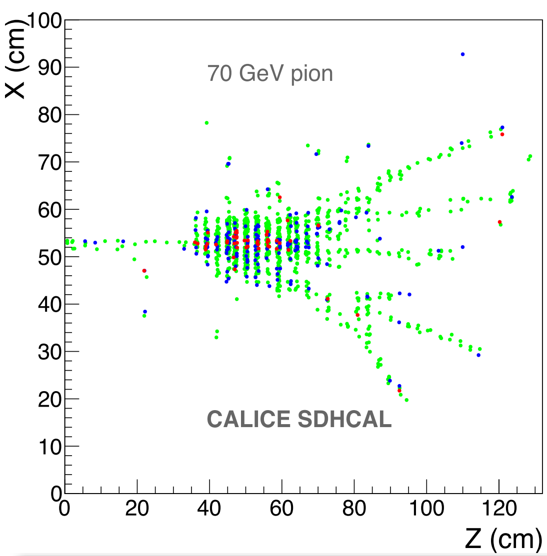
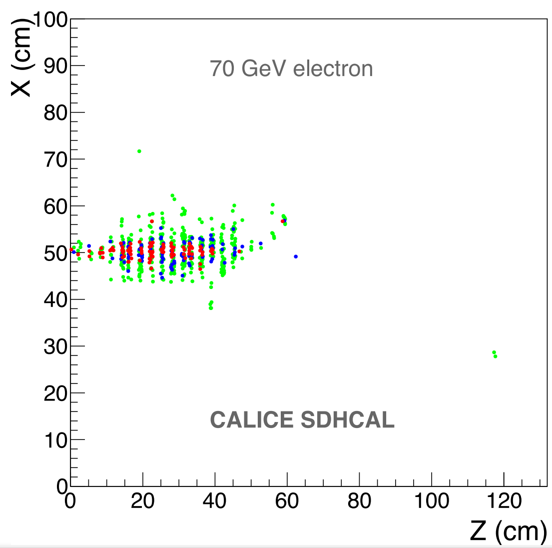


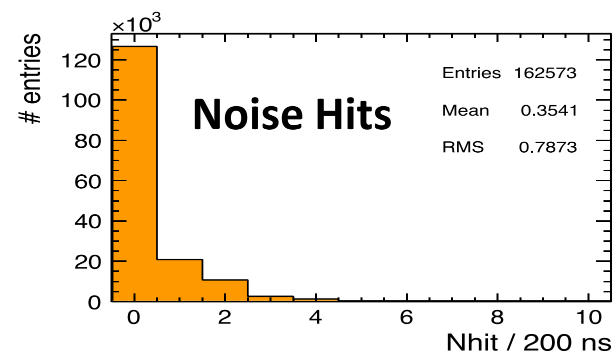
SDHCAL Performance

- The SDHCAL prototype was exposed to hadron, muon and electron beams in 2012, 2015 and 2016 on PS, H2, 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 reconstruction by better accounting for the number of tracks crossing one pad
- New data were taken in 2015, 2016 and 2017 with an improved DAQ system





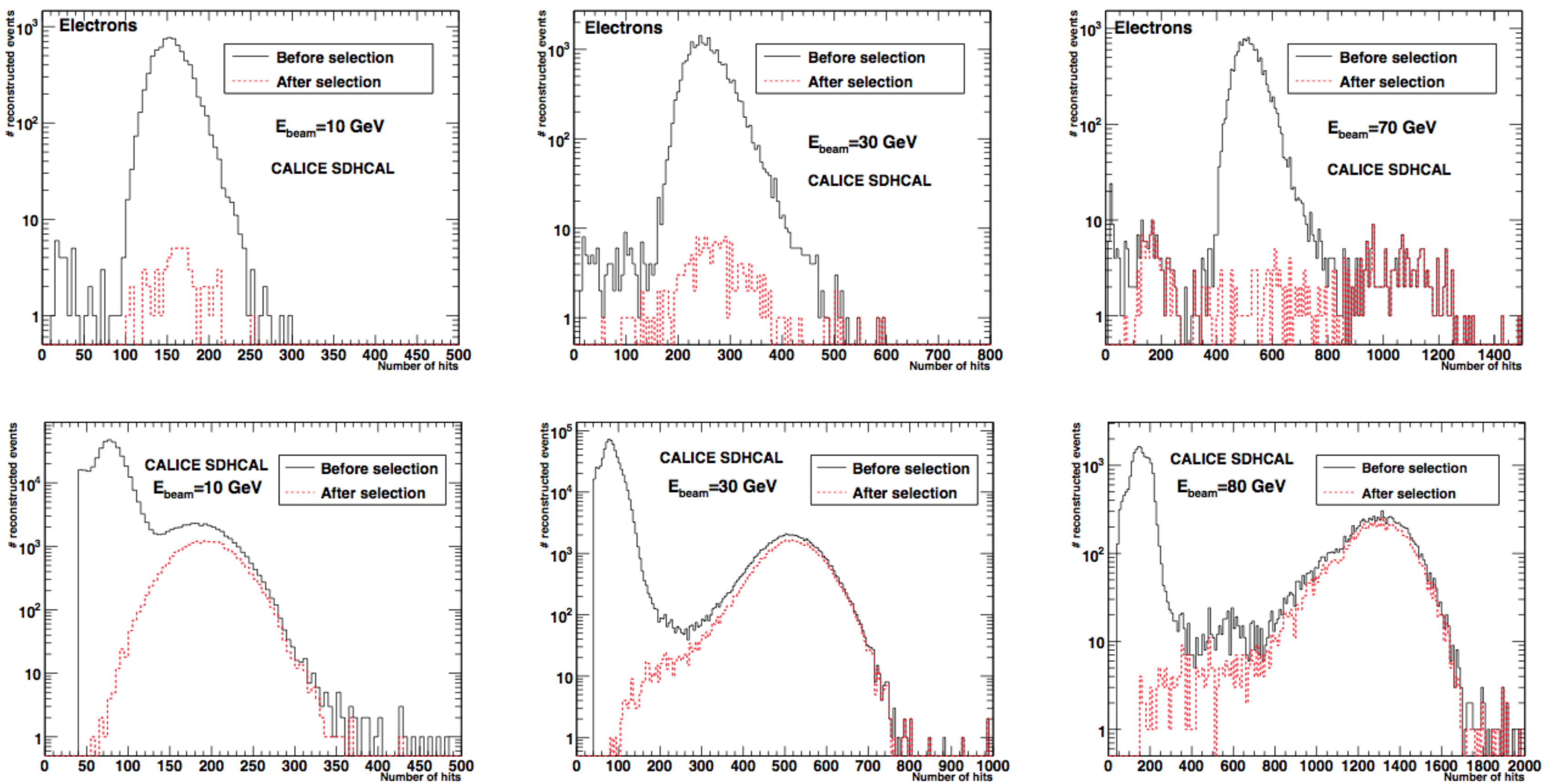




Event Selection of Hadron Beams

Electron rejection	Shower start ≥ 5 or $N_{layer} \geq 30$
Muon rejection	$\frac{N_{hit}}{N_{layer}} > 2.2$
Radiative muon rejection	$\frac{N_{layer} \backslash RMS > 5cm}{N_{layer}} > 20\%$
Neutral rejection	$N_{hit \in First\ 5\ layers} \geq 4$

- No containment selection.
- No Cerenkov detector
- Triggerless mode
- Power pulsed mode



Energy Estimation

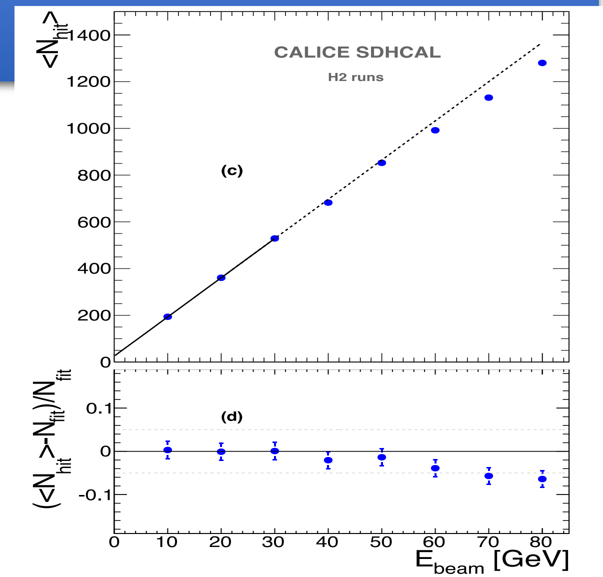
The thresholds weight evolution with the total number of hits obtained by minimizing a χ^2 , $\mathbf{X^2 = (E_{beam}-E_{rec})^2/E_{beam}}$

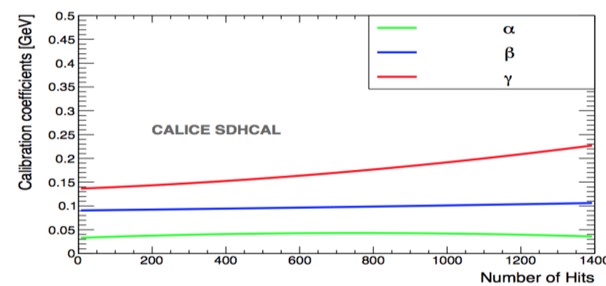
$E_{rec} = \alpha(N_{tot})\, N_1 + \beta(N_{tot})\, N_2 + \gamma(N_{tot})\, N_3$

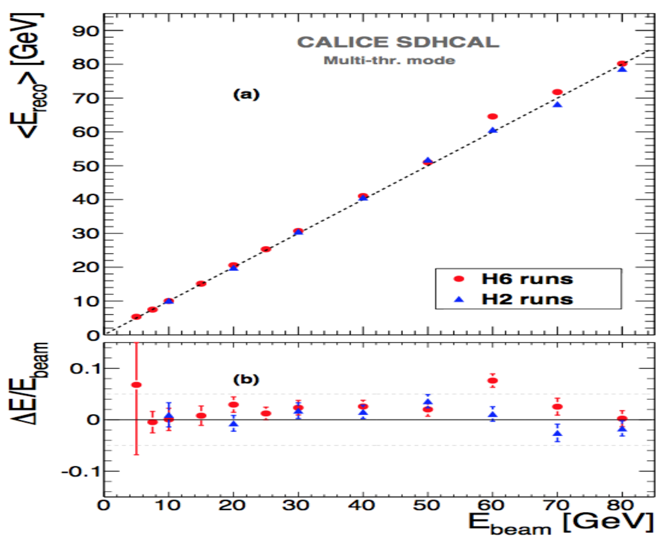
N_1,N_2 and N_3 : exclusive number of hits associated to first, second and third threshold.

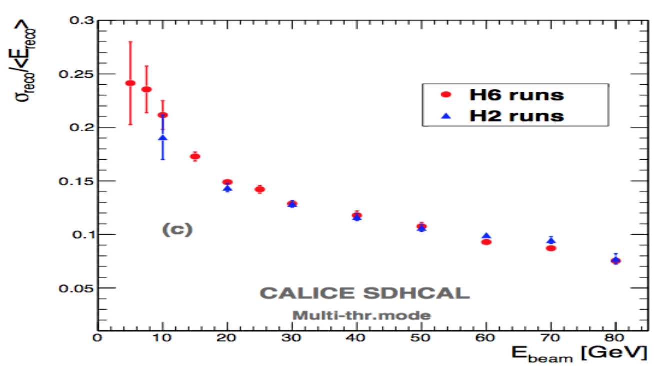
α, β, and γ : quadratic functions of total number of hits (N_{tot})

- Events of H2 runs corresponding to energies : **5, 10, 30 , 60, 80 GeV** were used to fit the 9 parameters.
- Then the energy of hadronic events in both H2(only pions) and H6 (presence of protons)









Energy Estimation

Comparison of semi-digital versus binary readout

E_{rec} (binary) = $C\,N_{tot} + D\,N^2_{tot} + F\,N^3_{tot}$

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

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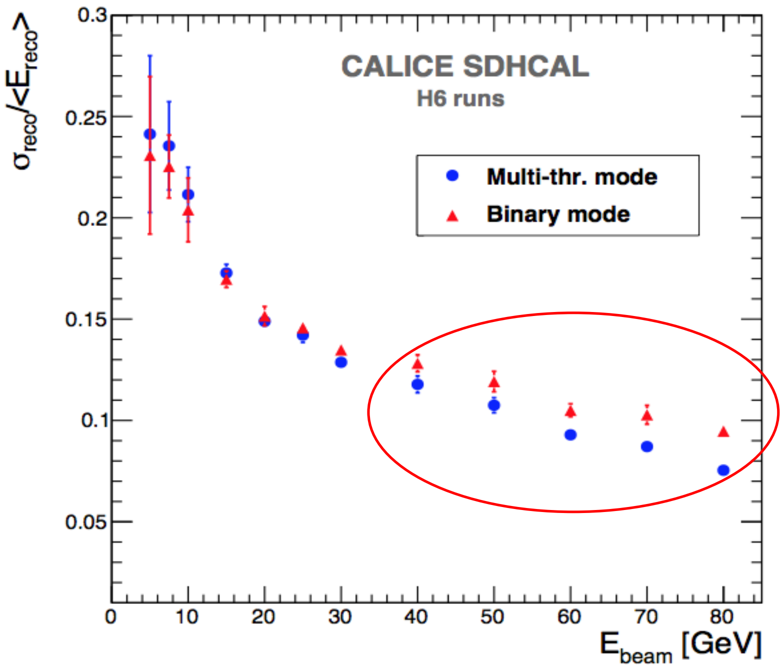

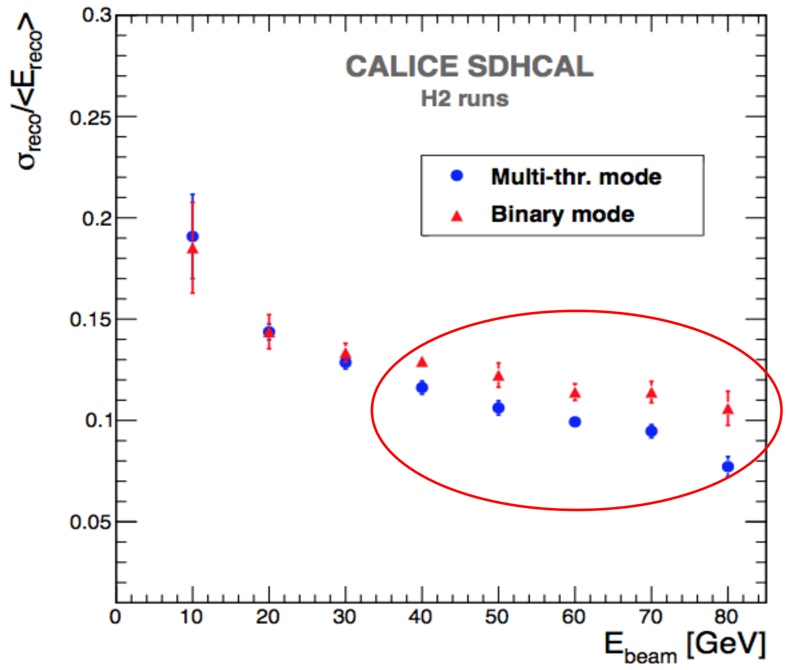

➔ **Substantial improvement for beam energy > ~ 40 GeV**

Data vs MC

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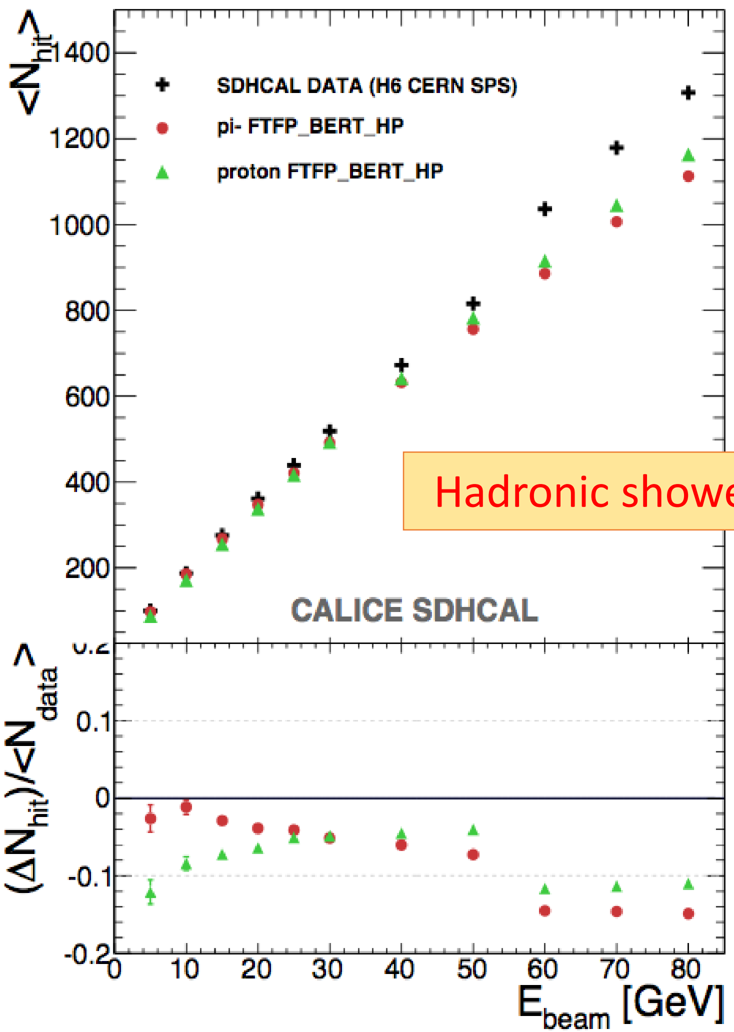
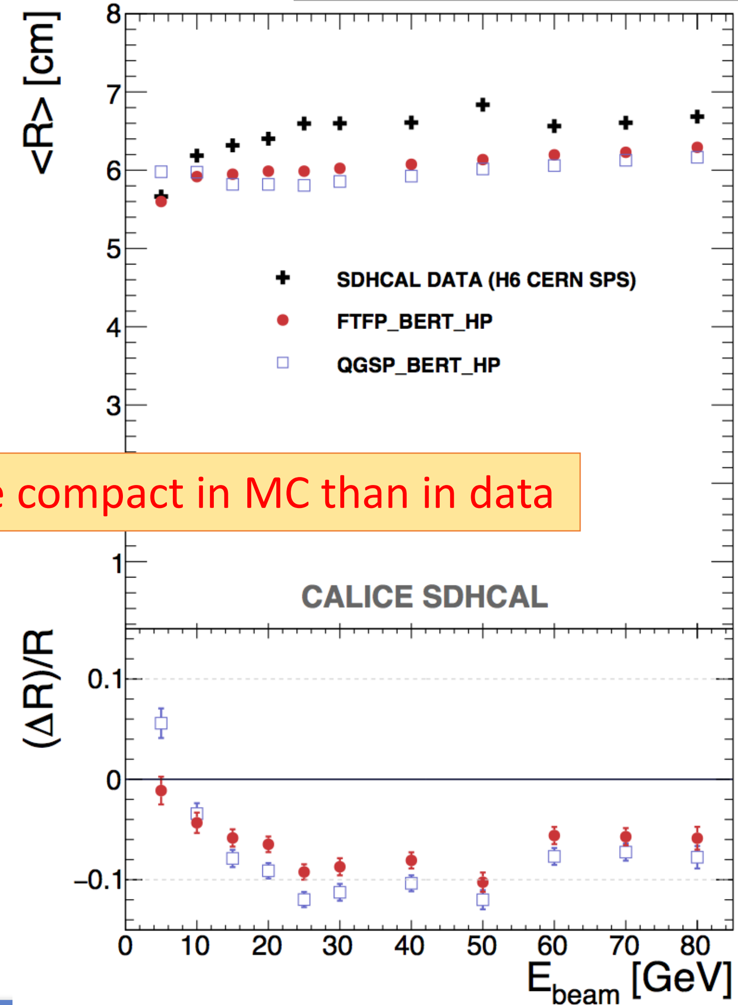




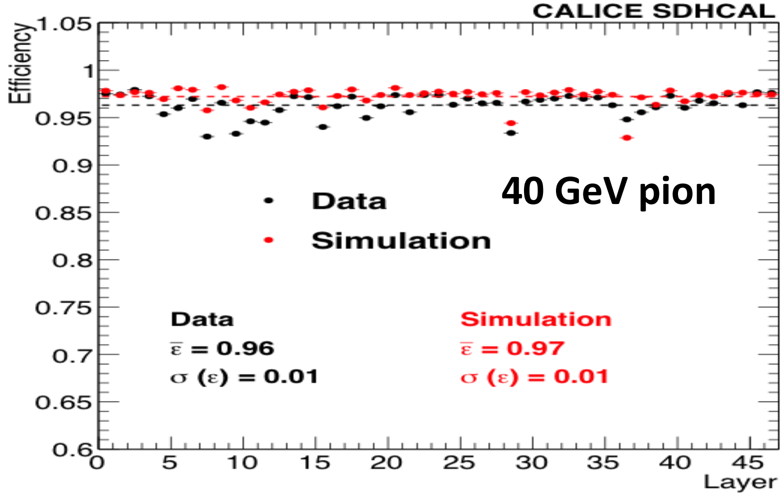
Hadronic shower is more compact in MC than in data

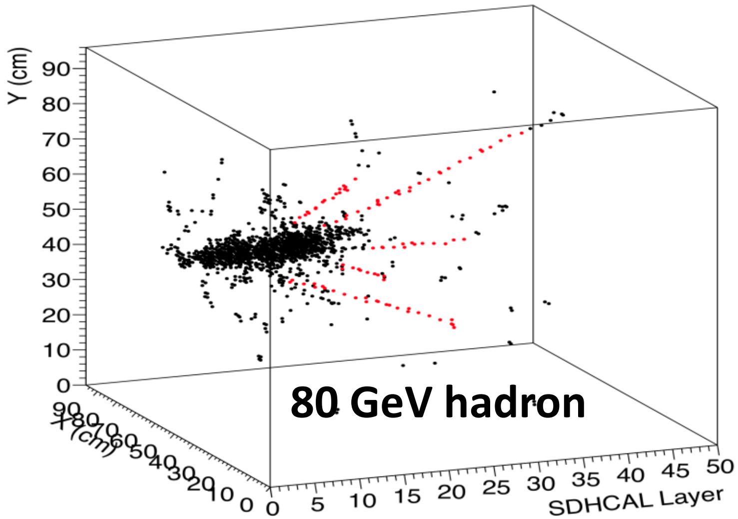
Data vs MC

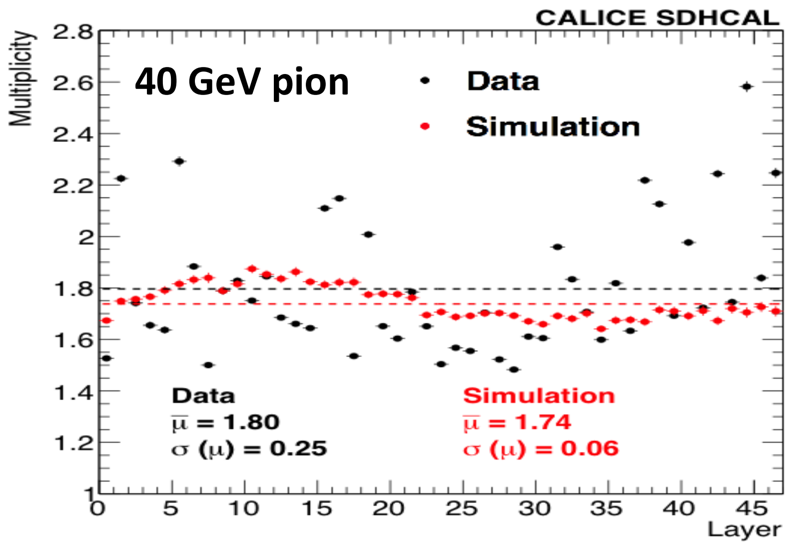
SDHCAL High-granularity impact

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

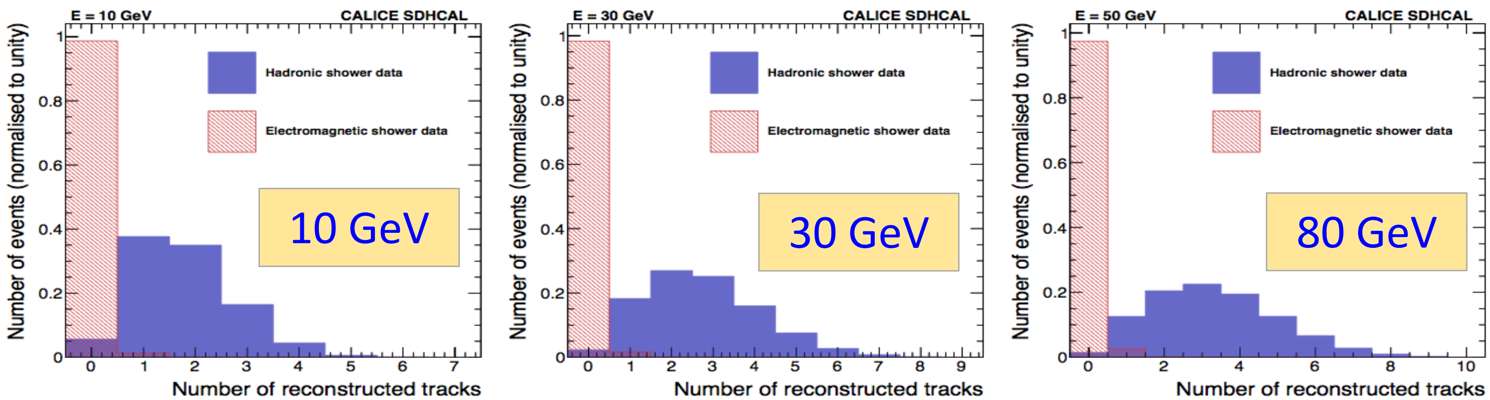
➔ Excellent data/MC agreement for efficiency and multiplicity obtained with cosmic muons and test beam muons.



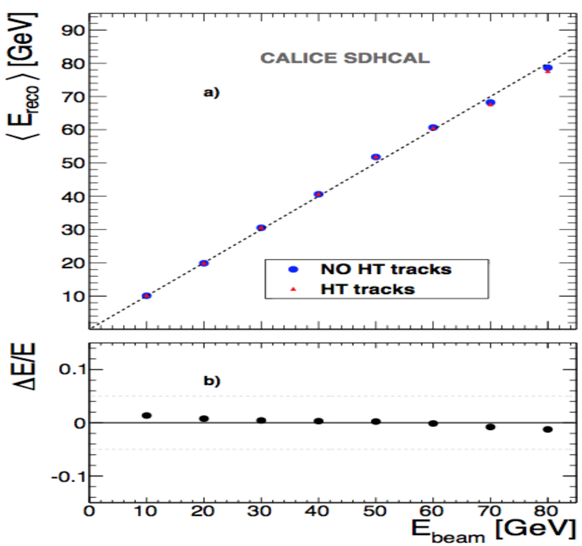


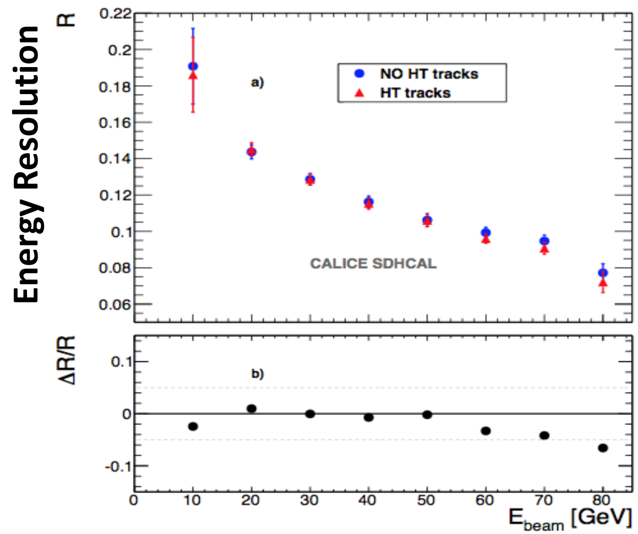


Separation of electron/hadron



It improves on the **energy reconstruction** by dealing with the hits belonging to the track segments independently of their threshold.





The technique could be extended to hadronic showers in magnetic field.

JINST 12 (2017) P05009

Arbor PFA

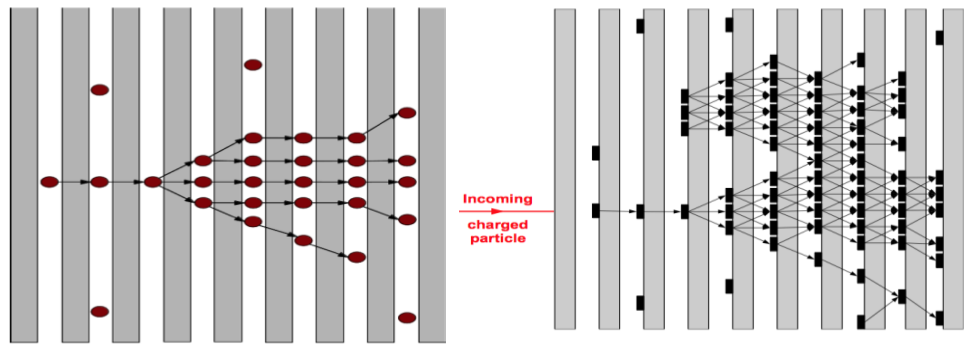
CALICE note CAN054

SDHCAL high granularity is desirable

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

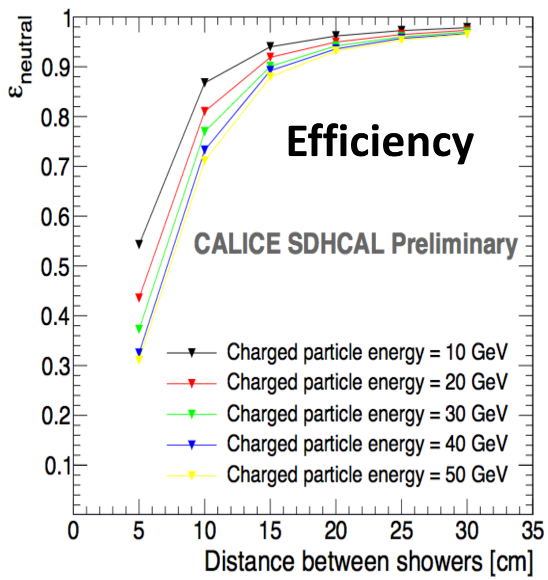
ArborPFA algorithm:

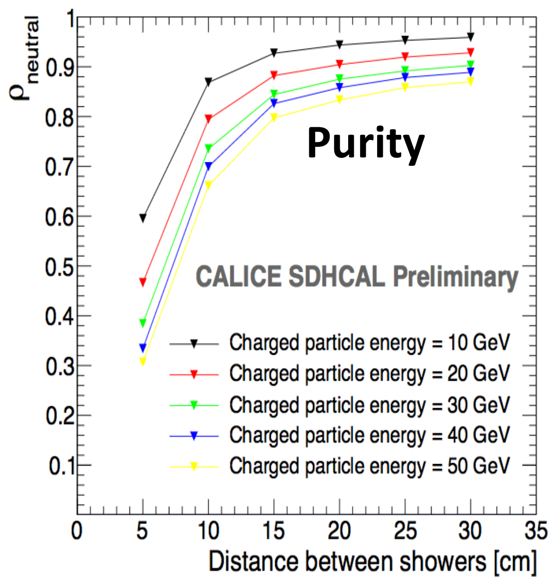
It connects hits and clusters using distance and orientation information, then correct tracker momentum information.

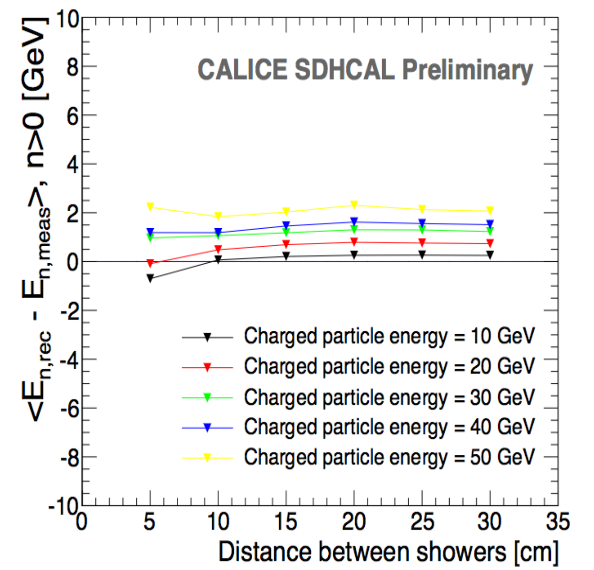


$$\epsilon = \frac{Nhit_{good}}{Nhit_{ini,tot}}$$

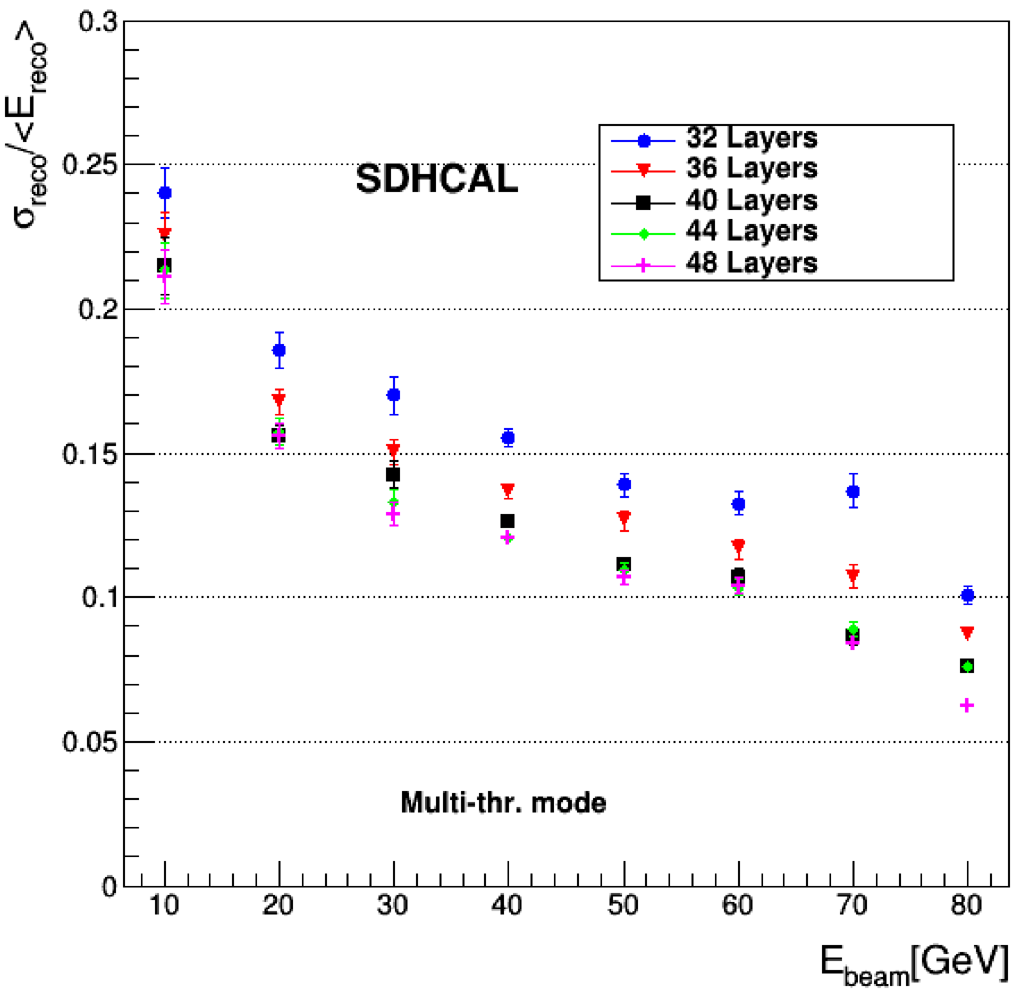
$$\rho = \frac{Nhit_{good}}{Nhit_{rec,tot}}$$

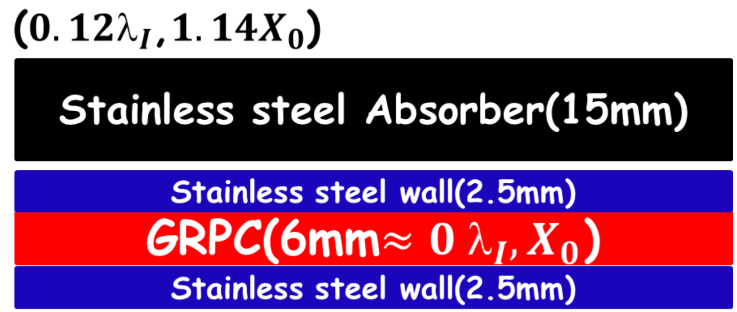






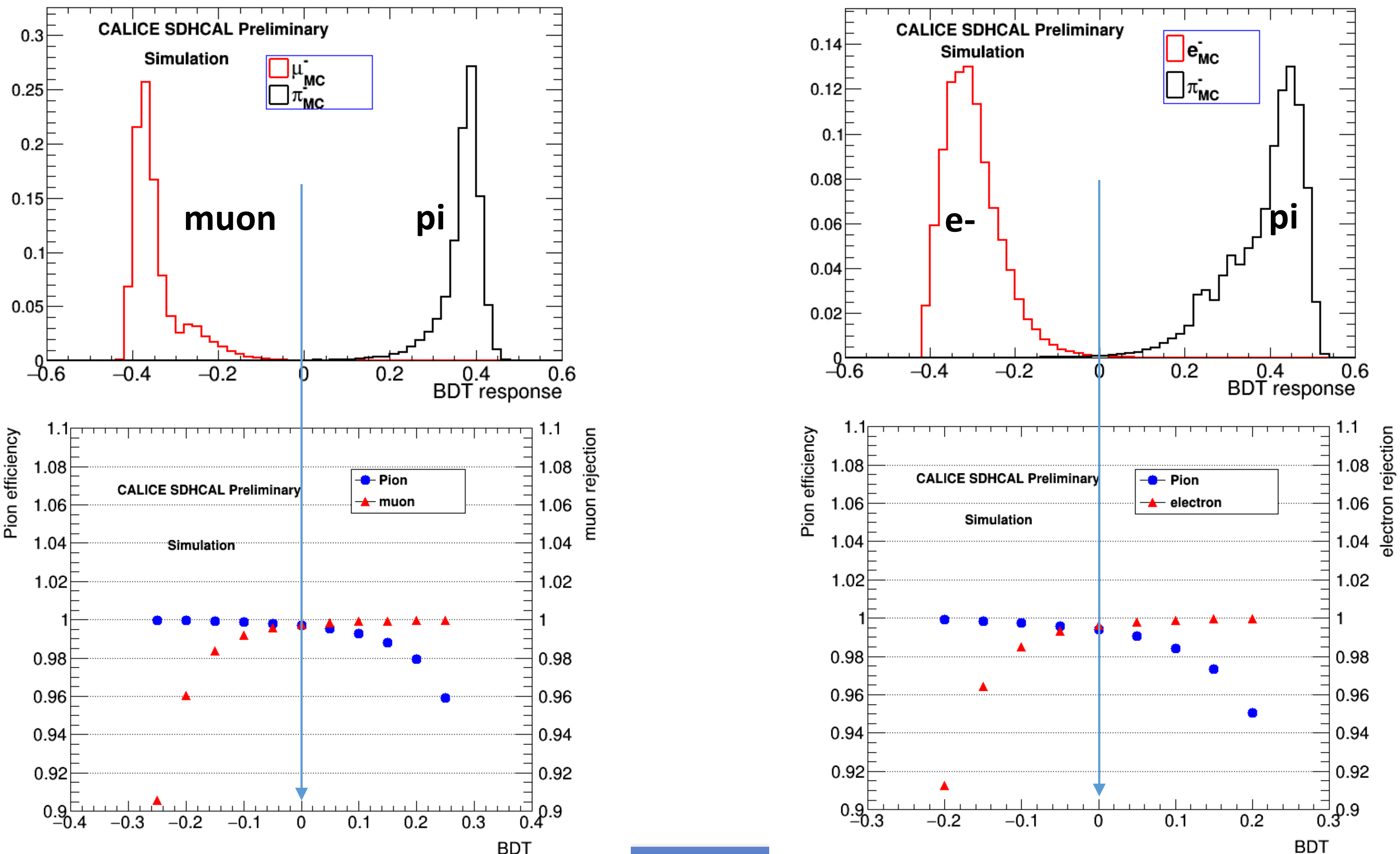
Energy Resolution vs No. of Layers





- ➔SDHCAL has 48 layers which aims for ILC Detector 6mm gRPC + 20mm absorber
- ➔Optimization no. of layers for CEPC at 240GeV
- ➔**40-layer SDHCAL yields decent energy resolution.**

BDT for pion/e, mu Identification



Pion eff. vs Backgrounds eff.

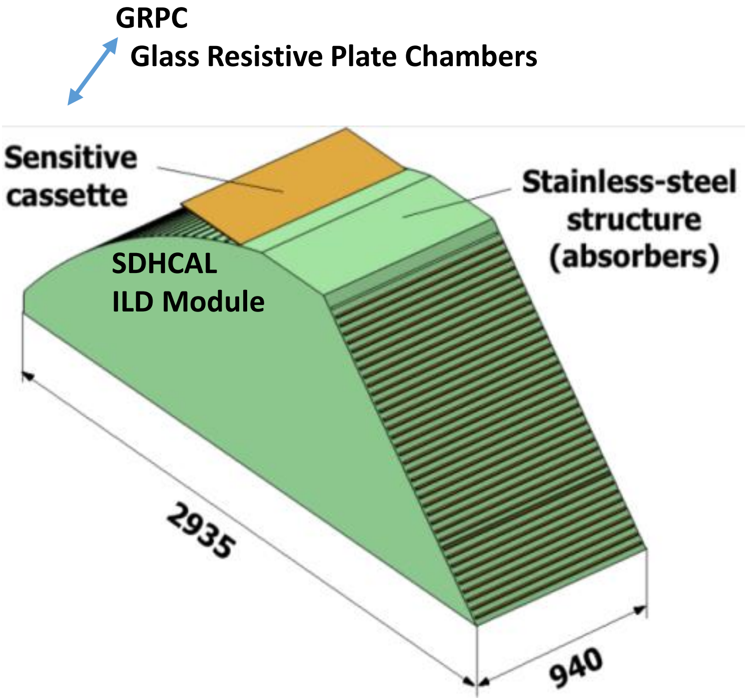
- For same Pion efficiency, we compare electron & muon efficiencies from "simple cut" and "BDT" methods.
- BDT has modest improvement for electron suppression and significant improvement for muon suppression.

Energy	simple cut			BDT		
	eff_{pion}	$eff_{electron}$	eff_{muon}	eff_{pion}	$eff_{electron}$	eff_{muon}
10GeV	55.7%	0.0%	0.1%	55.7%	0.0%	0.0%
20GeV	70.5%	0.0%	0.3%	70.5%	0.0%	0.0%
30GeV	80.9%	0.0%	0.6%	80.9%	0.0%	0.1%
40GeV	87.2%	0.1%	0.6%	87.2%	0.0%	0.1%
50GeV	90.6%	0.1%	0.9%	90.6%	0.1%	0.1%
60GeV	93.0%	0.2%	1.0%	93.0%	0.2%	0.2%
70GeV	94.7%	0.3%	1.2%	94.7%	0.2%	0.2%
80GeV	95.7%	0.3%	1.1%	95.7%	0.2%	0.2%

CALICE note CAN059

SDHCAL for Future Experiements

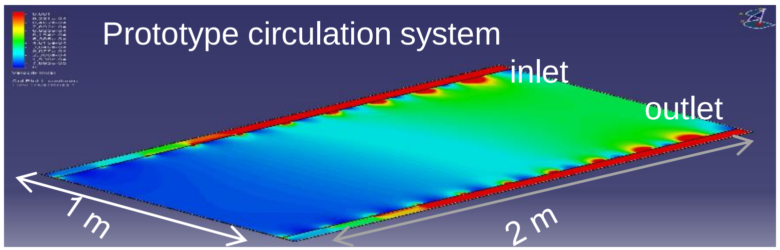
- ❑ Detectors as large as 3m X 1m need to be built
- ❑ Electronic readout should be the most robust with minimal intervention during operation.
- ❑ DAQ system should be robust and efficient
- ❑ Mechanical structure to be similar to the final one
- ❑ Envisage new features such as timing, etc..

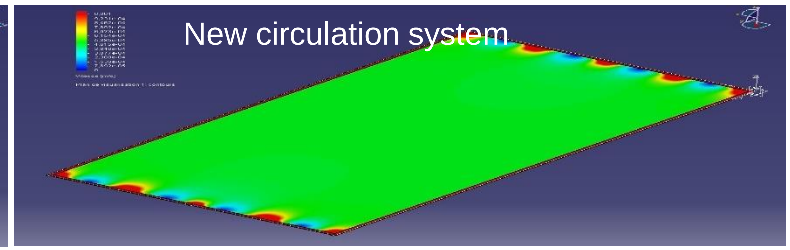


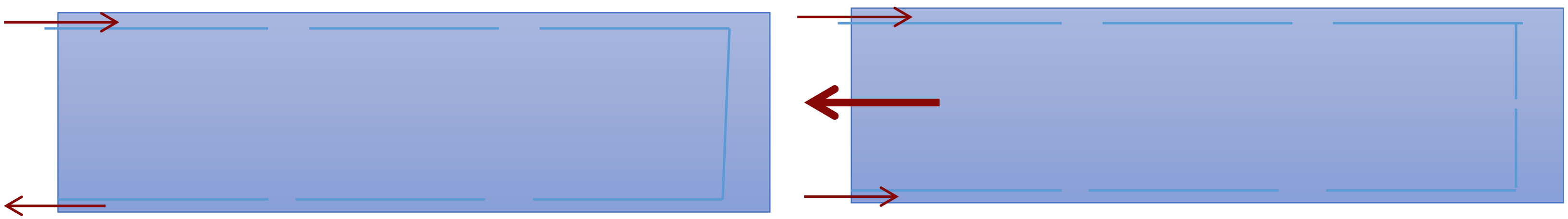
Goal: to build new prototype with few but large GRPC and new components → ILD Module0

Detector Conception

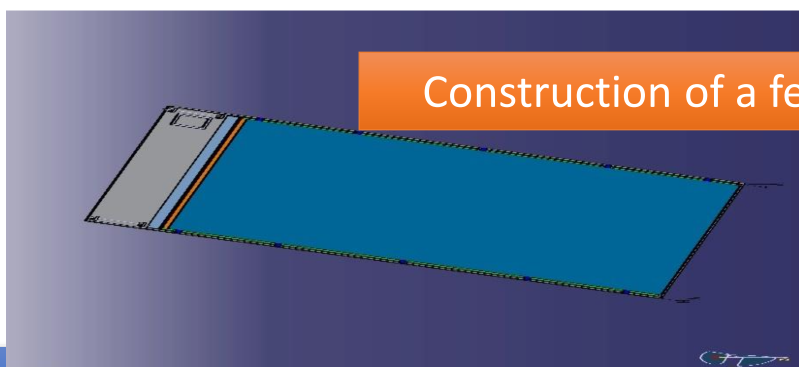
Construction and operation of large GRPC need some improvements with respect to the present scenario. **Gas distribution** : new scheme is proposed



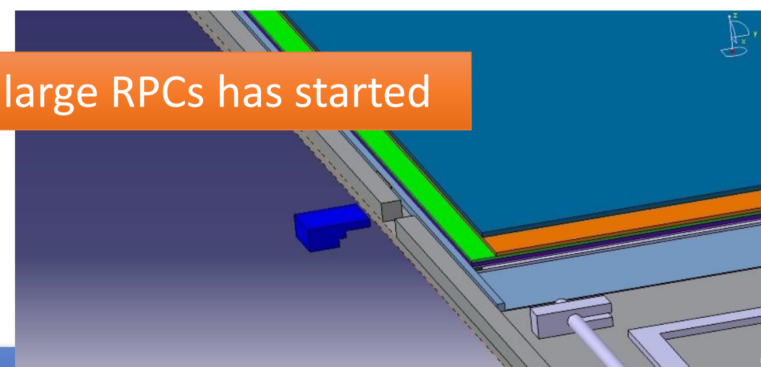




Cassette conception to ensure good contact between the detector and electronics is to be improved



Construction of a few large RPCs has started



New Electronics

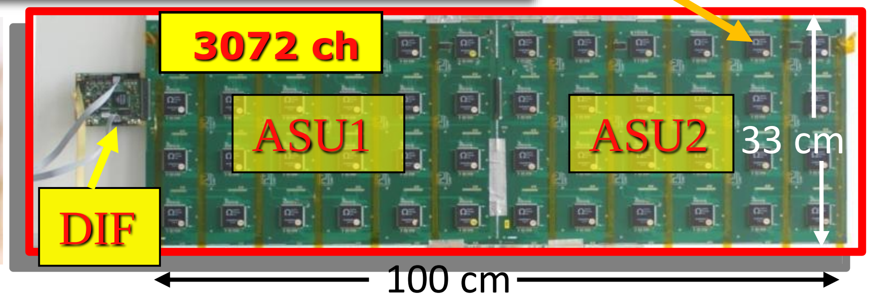
Electronics readout for the 1m³ prototype

HADROC chip (ASIC)

1m² board ➔ 6 ASUs hosting 24 ASICs

USB

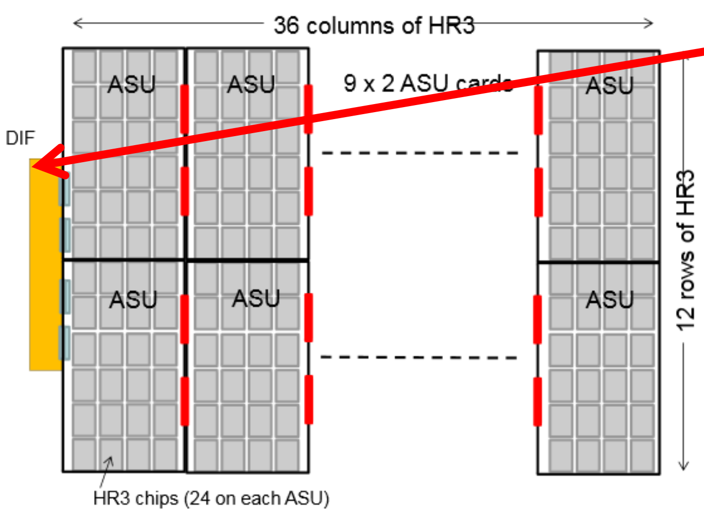
HDMI



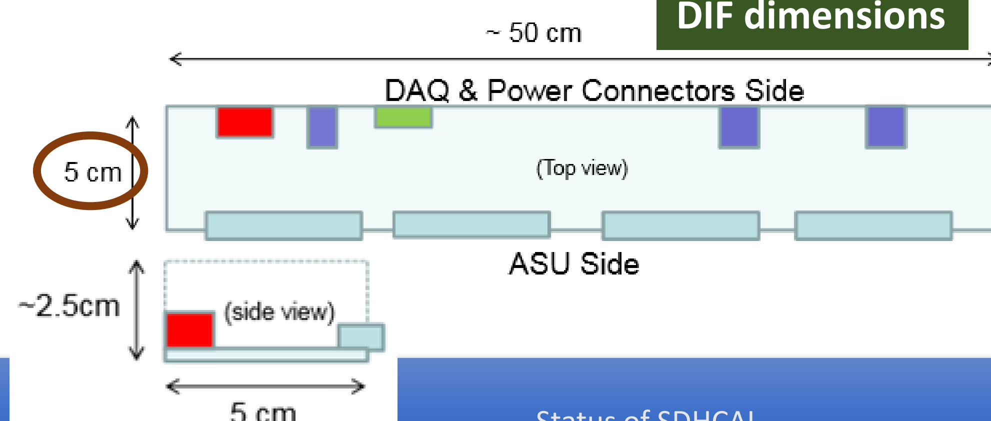
1 DIF (Detector InterFace) for **2 ASU** (Active Sensor Unit.- PCB+ASICs) ➔ **3 DIFs for ONE 1m² GRPC detector**

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**



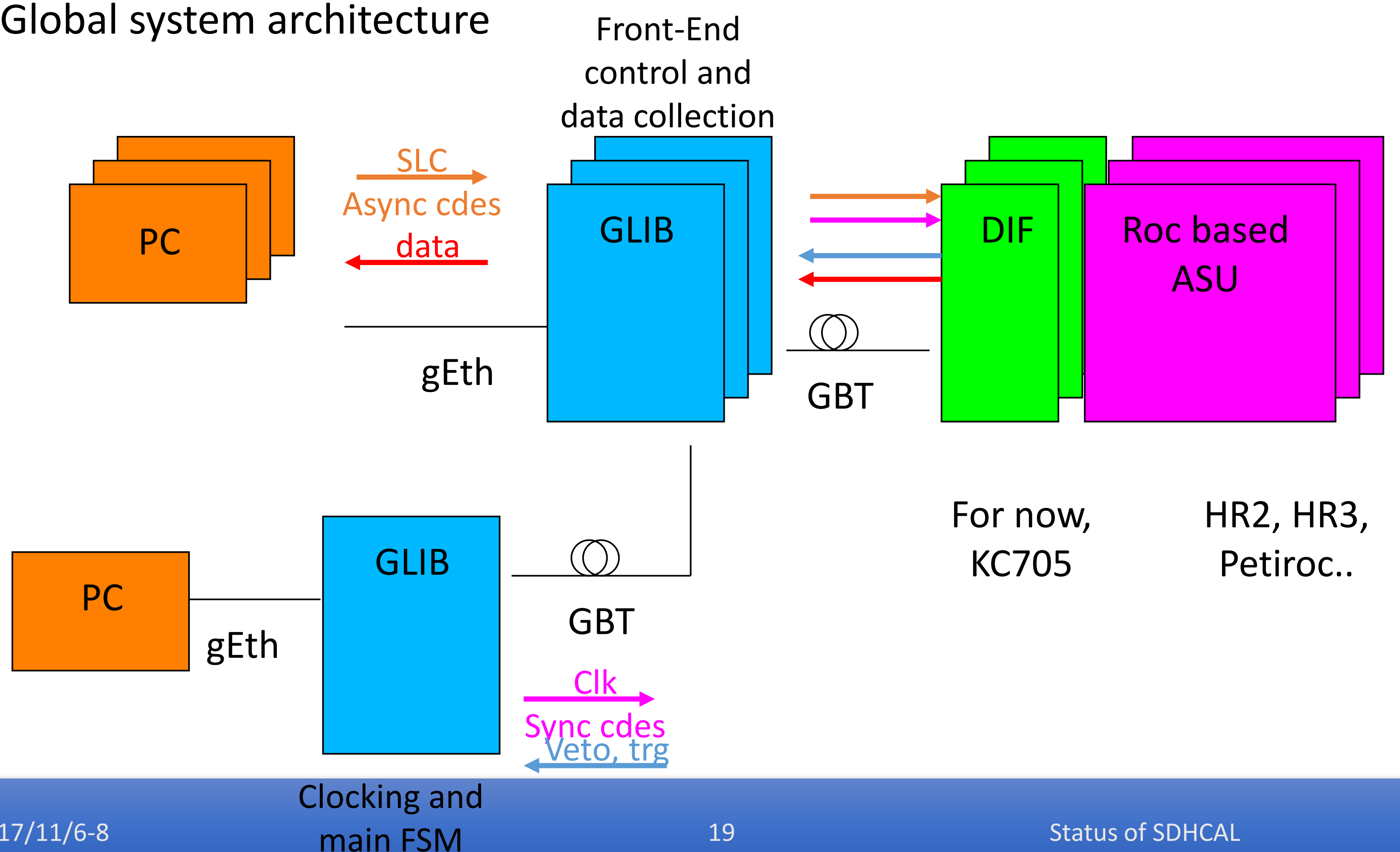
DIF dimensions



DAQ System

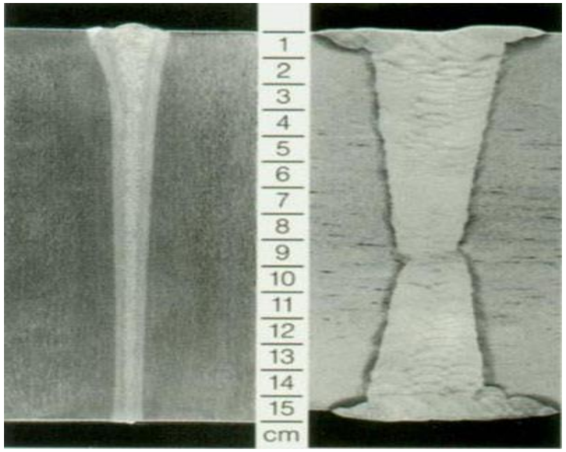
Implementation of a GBT-based communication system for ROC chips. This aims to reach higher performance using robust and well maintained system in the future

Global system architecture



Mechanical Structure

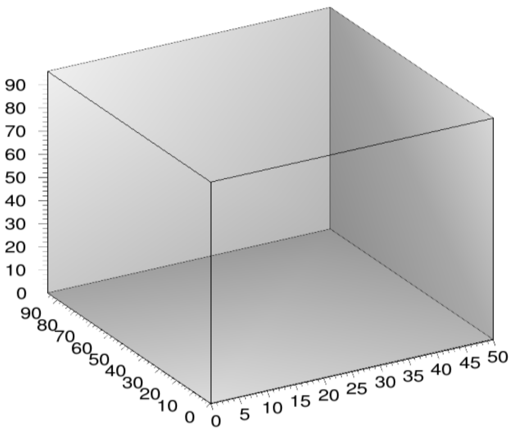
Improvement on the present system is being made by using **Electron Beam Welding** rather than bolts to reduce the deformation and the spacers thickness.

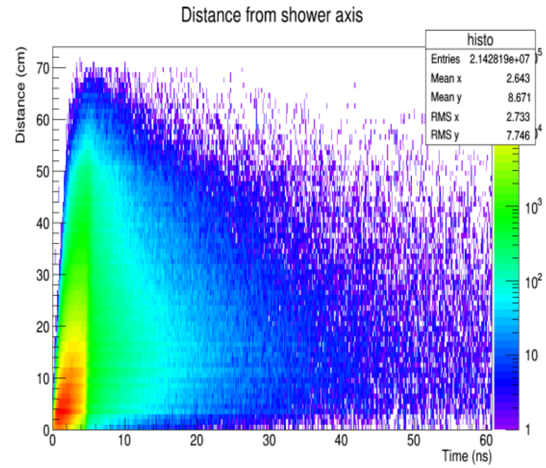


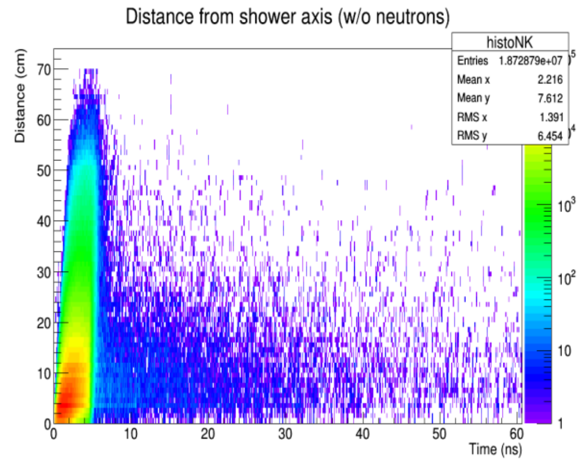
Industrial production of **flat** large absorber plates (3 m X 1 m) by **roller leveling** process

Next Step: Better Timing

Timing could be an important factor to **separate showers** and **better reconstruct their energy**



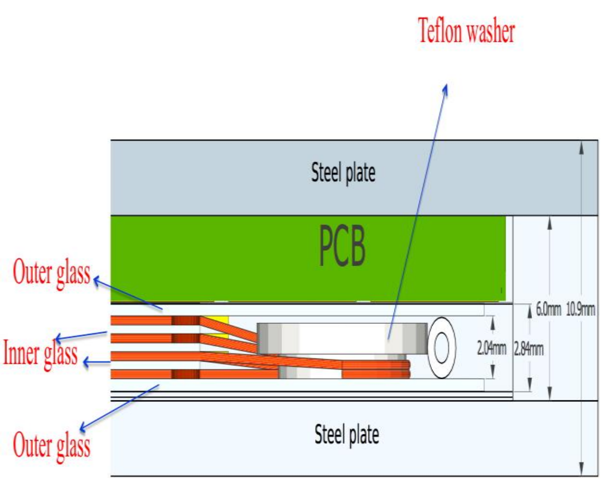


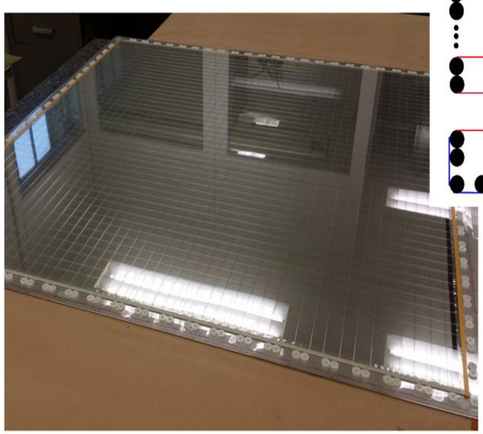


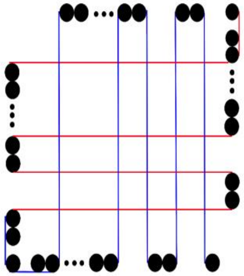
Multi-gap RPC are excellent fast timing detectors

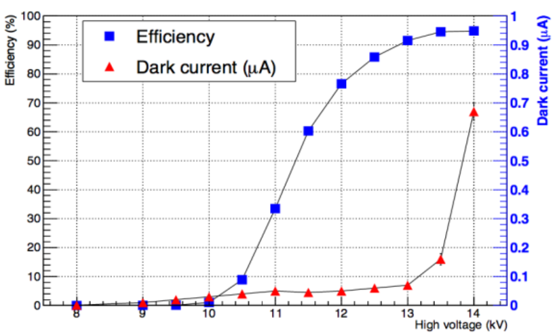
Several MRPC were designed and built . Excellent efficiency when tested with HARDROC ASICs.

Next step use PETIROC (< 20 ps time jitters) to single out neutron contributions.





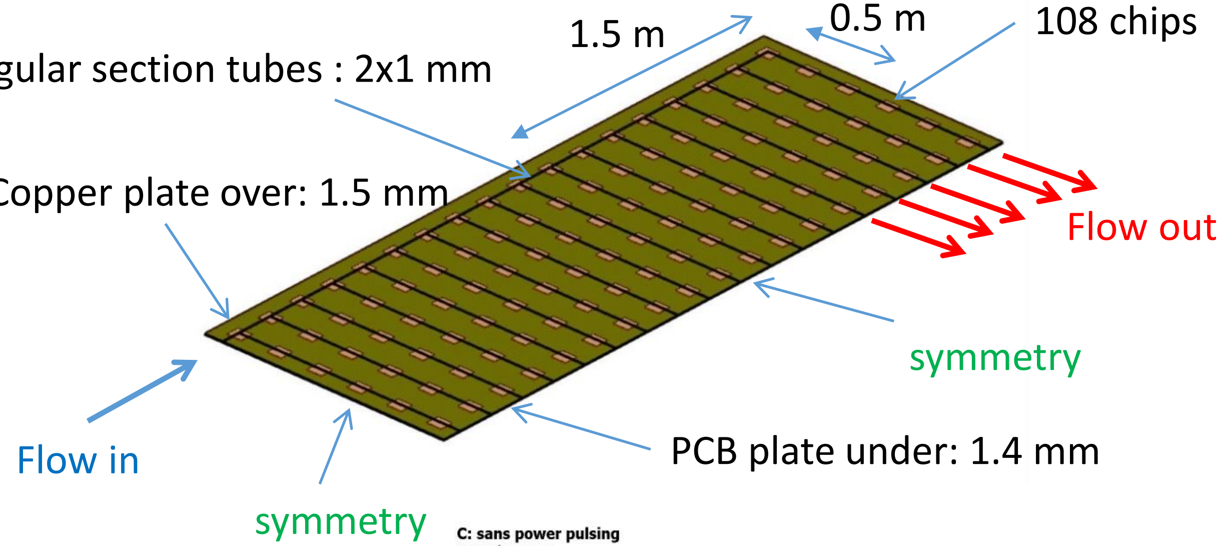




Threshold sets at 114 fC

Next Step: Cooling

Cooling becomes necessary if the power-pulsing scheme is not possible (CEPC project)

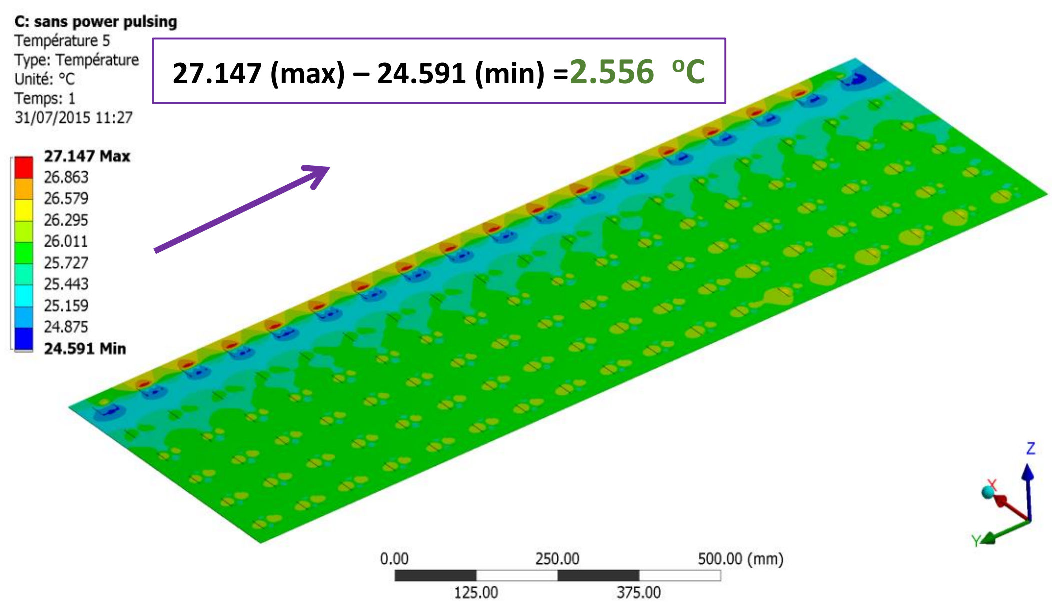


Water cooling :

h = 10000 W/m²/k

Thermal load :

80 mW/chip without power pulsing



Simulation ¼ structure PCB + Chips

Summary and Conclusion

- **SDHCAL (since 2011) is the first technological and still the unique complete prototype built for future experiments.**
- **Results of beam tests validate the concept. Many results are obtained.**
- **There is still a place for improvement by using genuine techniques (Hough Transform, MVA, …)**
- **New prototype is on the rails and in principle could be achieved in 2018.**
- **New features such as timing and cooling will play important role in future colliders R&D.**

Many thanks for great efforts from CALICE SDHCAL working groups !

Backup Slides

Energy Reconstruction

- **Energy reconstruction formula:**

$$E_{reco} = \alpha N_1 + \beta N_2 + \gamma N_3$$

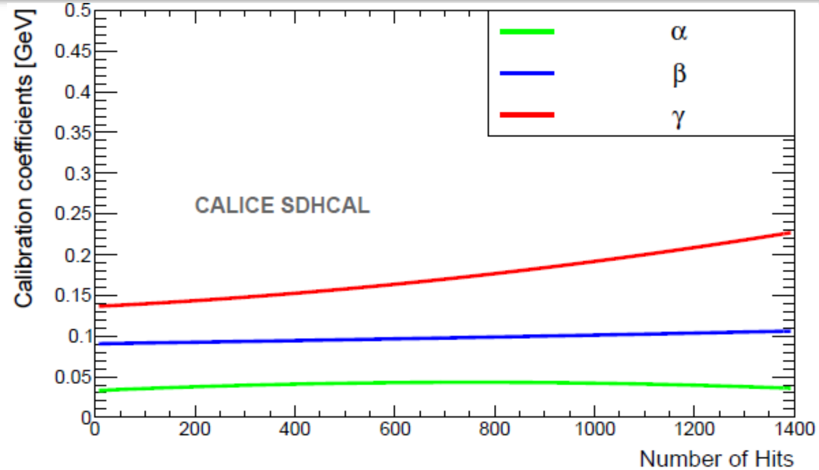
α, β, γ are parameterized as functions of total number of hits(N1+N2+N3)

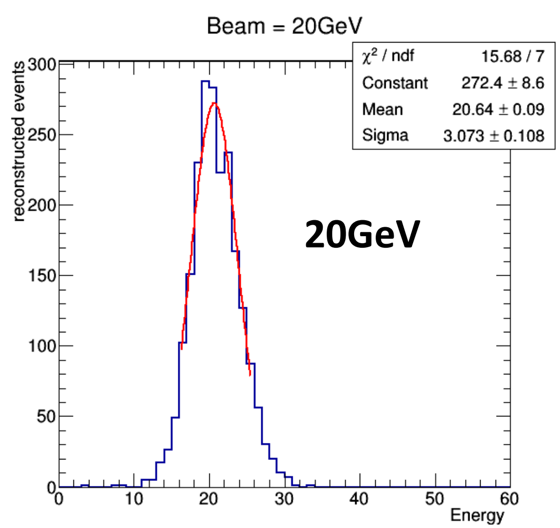
$$\alpha = \alpha_1 + \alpha_2 N_{total} + \alpha_3 N_{total}^2$$
$$\beta = \beta_1 + \beta_2 N_{total} + \beta_3 N_{total}^2$$
$$\gamma = \gamma_1 + \gamma_2 N_{total} + \gamma_3 N_{total}^2$$

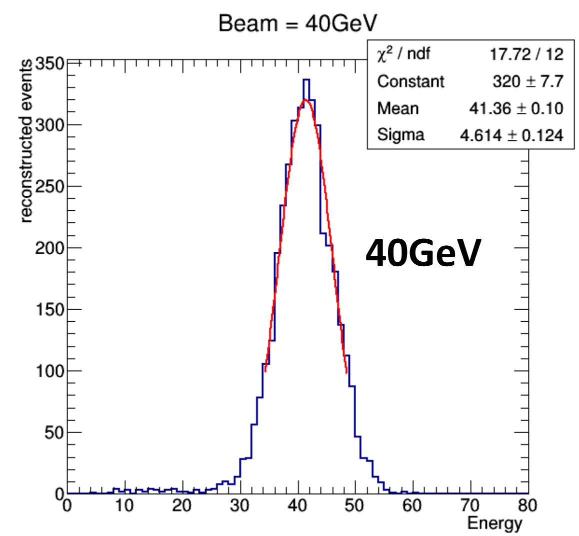
- **optimizer**

$$\chi^2 = \sum_{i=1}^{N} \frac{(E_{beam}^i - E_{reco}^i)^2}{\sigma_i^2}$$

$$\sigma_i = \sqrt{E_{beam}^i}.$$







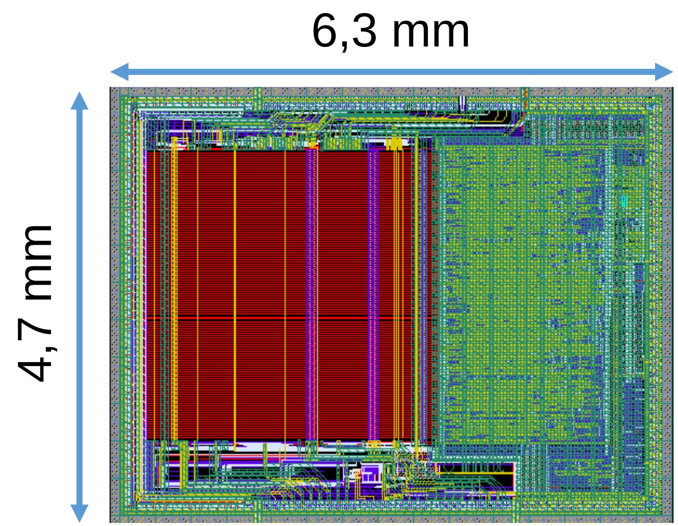
fitted with a Gaussian Function in a 1.5σ range around the mean

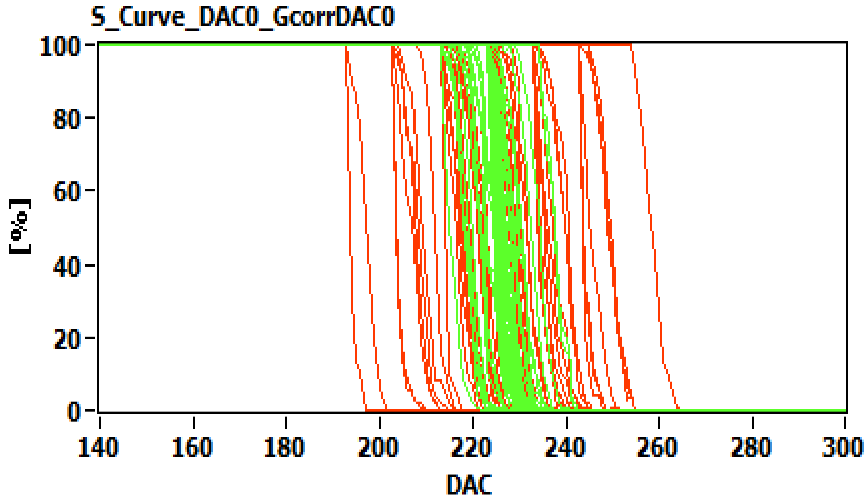
New Electronics: ASIC

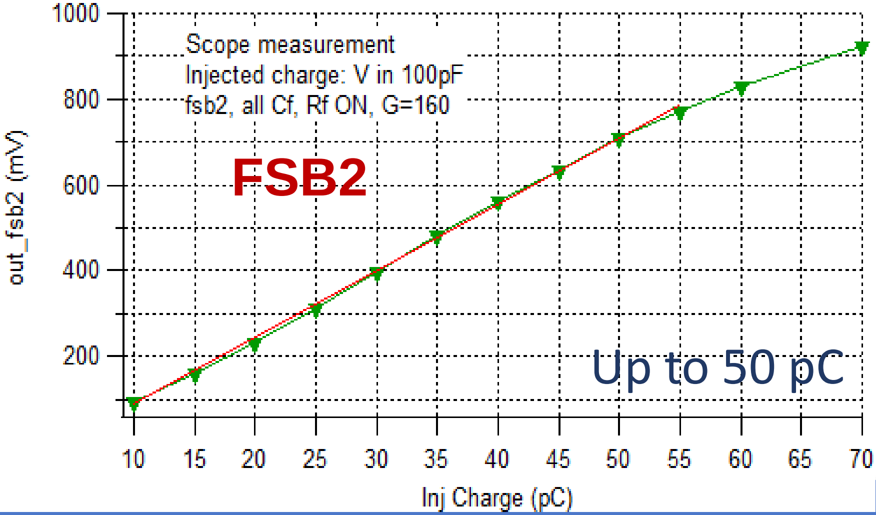
HARDROCR3 main features:

- 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 %







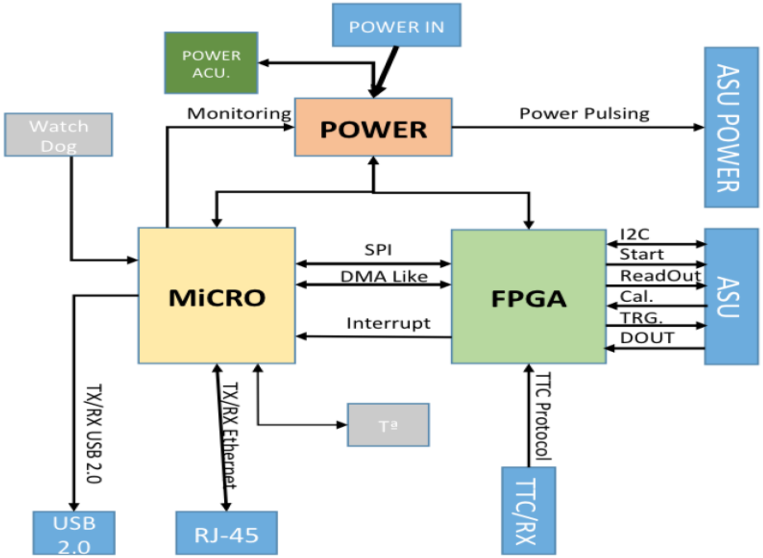
ASU (Active Sensor Unit)

One 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. After investigation in some companies, ***1x0.33 m2 with 13 layer ASUs*** have been built.

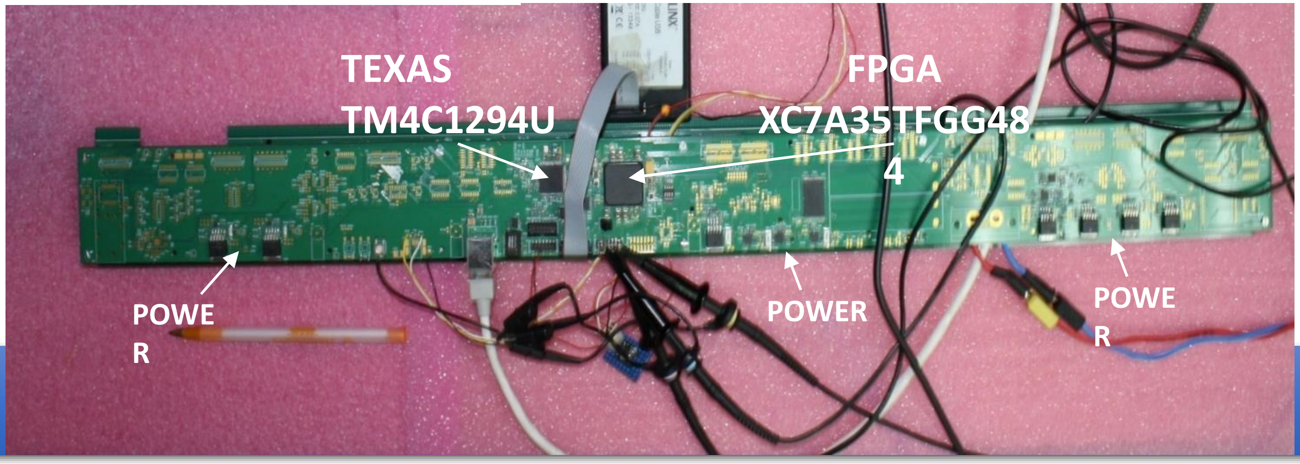
The ASU-ASU (= ASU-DIF) connections also produced

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



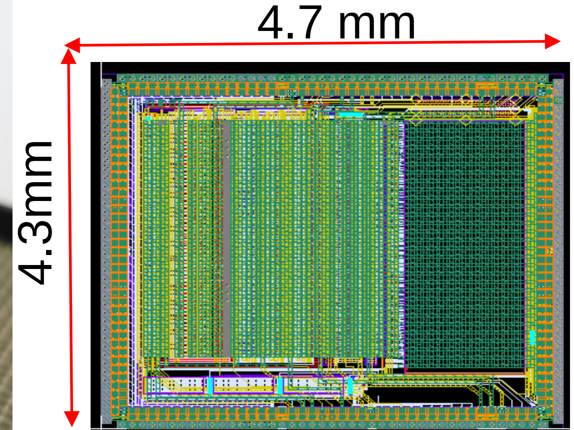
- Only **one DIF per plane** (instead of **three**)
- DIF handle up to **432 HR3 chips** (vs **48 HR2** in previous DIF)
- HR3 **slow control** through **I2C bus (12 IC2 buses).** Keeps also **2 of the old slow control buses as backup & redundancy**.
- **Data transmission to/from DAQ** by **Ethernet**
- **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**



Readout Electronics for RPC

Imad Laktineh (IPNL)

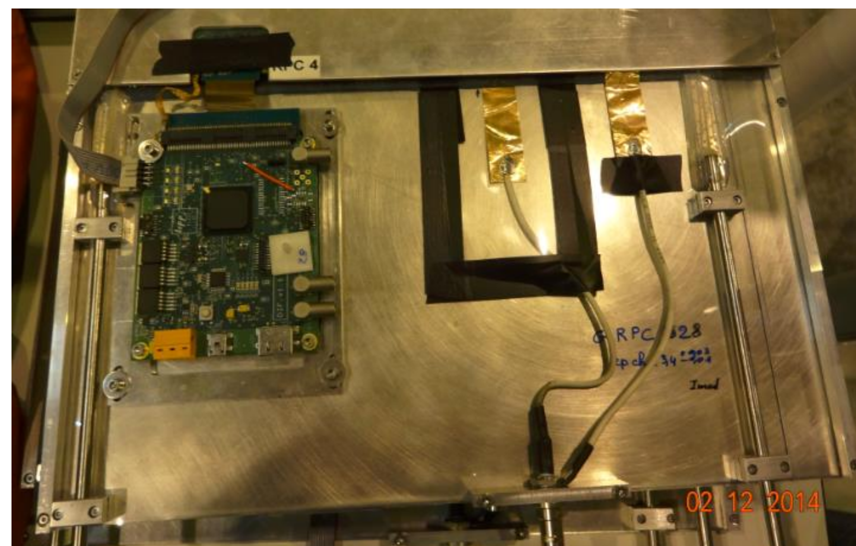
ASICs : HARDROC2
64 channels
Trigger less mode
Memory depth : 127 events
3 thresholds
Range: 10 fC-15 pC
110fC, 5pC, 15pC
Gain correction → uniformity



Printed Circuit Boards (PCB) were designed to reduce the cross-talk with 8-layer structure and buried vias.

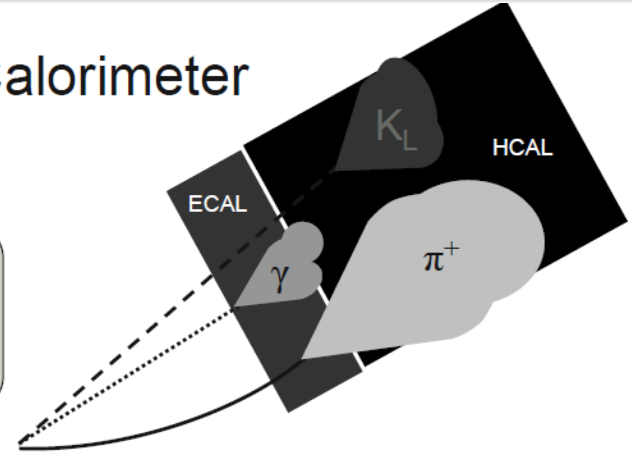
Tiny connectors were used to connect the PCB two by two so the 24X2 ASICs are daisy-chained. $1\times1m^2$ has 6 PCBs and 9216 pads.

DAQ board (DIF) was developed to transmit fast commands and data to/from ASICs.



PFA and Imaging Calorimeter

Particle Flow Algorithms and Imaging Calorimeter



The idea…

Charged particles } measured with the { **Tracker**

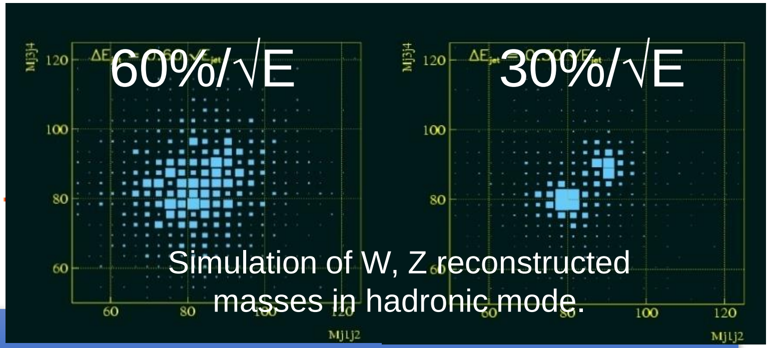
Neutral particles } measured with the { **Calorimeter**

Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion		Required for 30%/√E	$\leq 0.24^2\ E_{jet}$

} 18%/√E

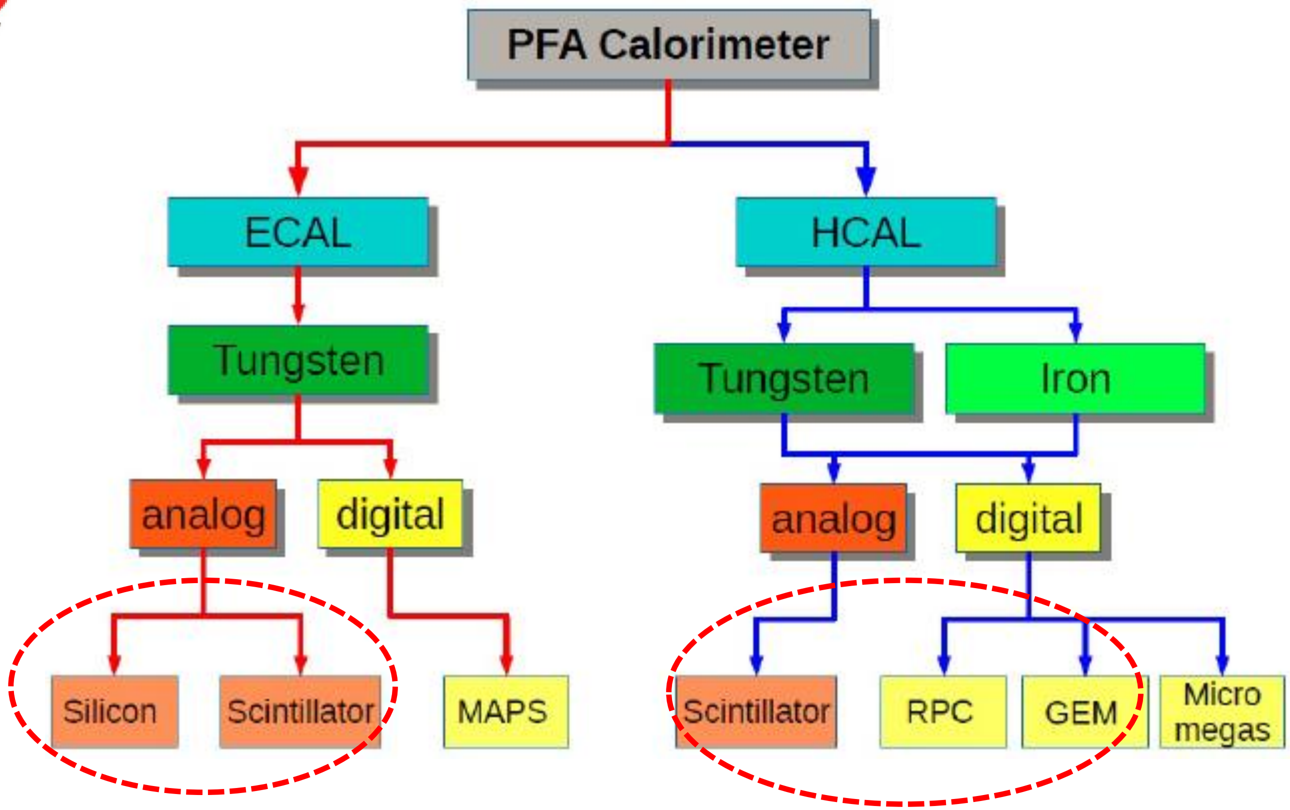
Requirements for detector system

→ Need excellent tracker and high B – field
→ Large R_I of calorimeter
→ Calorimeter inside coil
→ Calorimeter as dense as possible (short X_0, λ_I)
→ Calorimeter with **extremely fine segmentation**



CALICE: Imaging Calorimeter

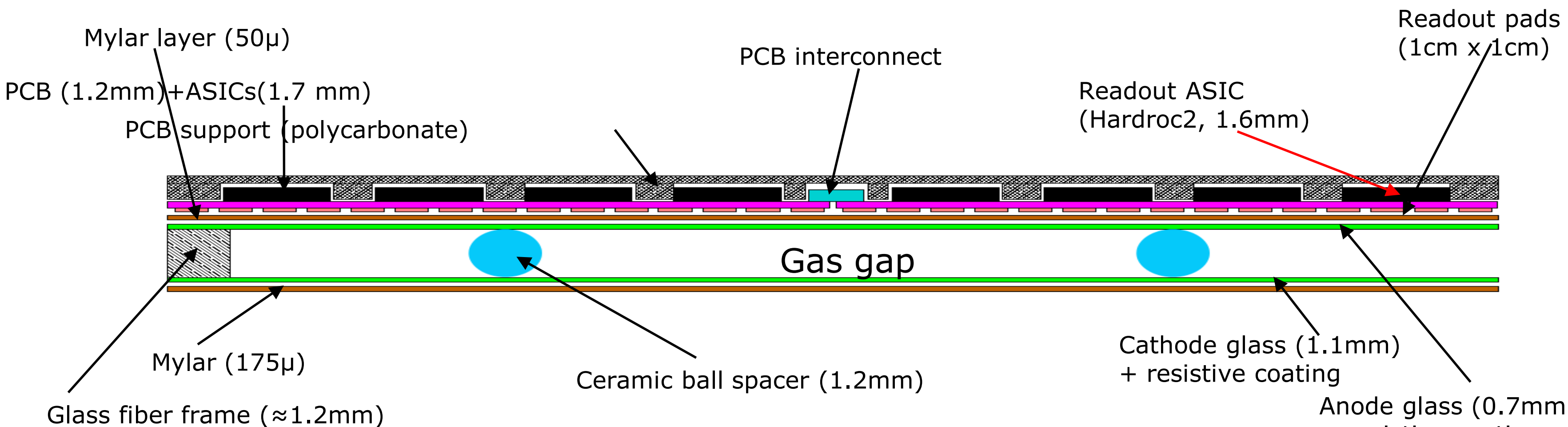
https://twiki.cern.ch/twiki/bin/view/CALICE/CalicePapers



Readout cell size: 144 - 9 cm^2 → 4.5 cm^2 → 1 cm^2 → 0.25 cm^2 → 0.13 cm^2 → 2.5×10^{-5} cm^2

Technology:					
Scintillator + SiPM/MPPC	Scintillator + SiPM/MPPC	Gas detectors Silicon	Silicon	Silicon	Silicon (MAPS)

Schematic of RPC



Ran Han (BISEE)

Haijun Yang (SJTU)

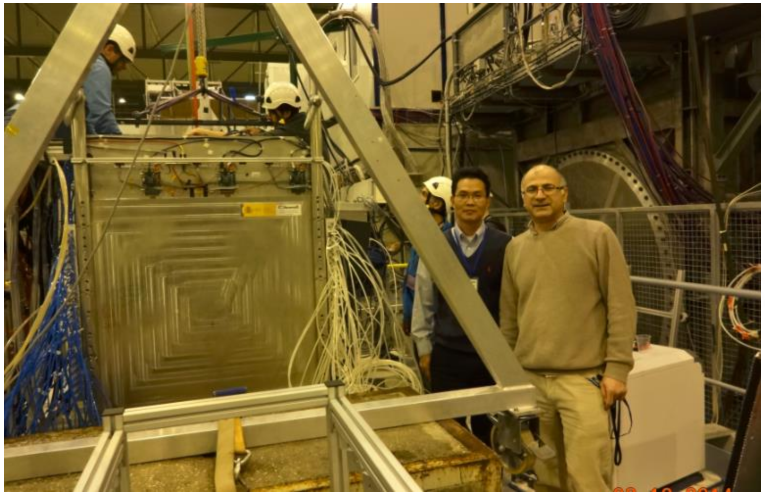
Large area gRPC:

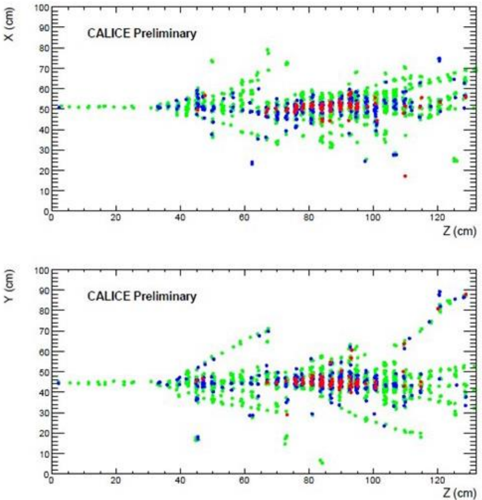
- ✓ Negligible dead zone (tiny ceramic spacers)
- ✓ Large size: 1 × 1 m^2
- ✓ Cost effective
- ✓ Efficient gas distribution system
- ✓ Homogenous resistive coating

DHCAL with RPC

Prototypes of DHCAL based on RPC

- **ANL (J. Repond, L. Xia et.al.)**
  1m^3, 1 threshold, TB at CERN/Fermilab
- **IPNL (I. Laktineh et.al.)**
  1m^3, 3 thresholds, TB at CERN since 2012





80 GeV Pion