# Energy Reconstruction of hadron showers with the CALICE SDHCAL prototype

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# Outline

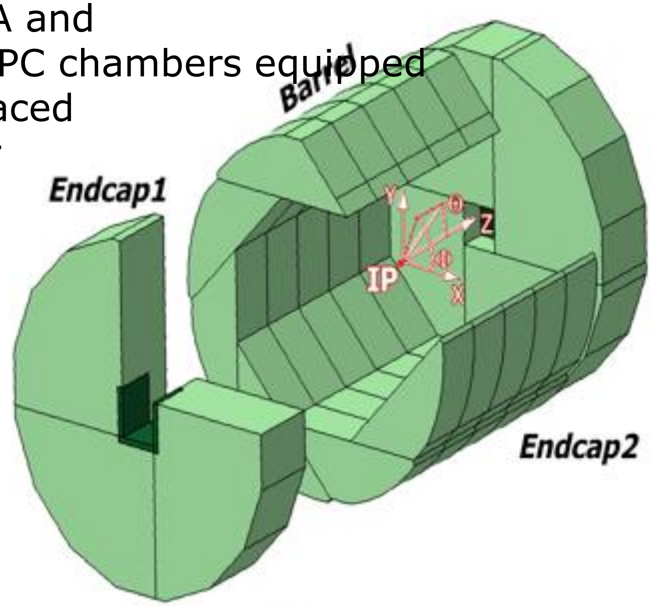
**SDHCAL technological prototype**

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

**Summary**

# SDHCAL

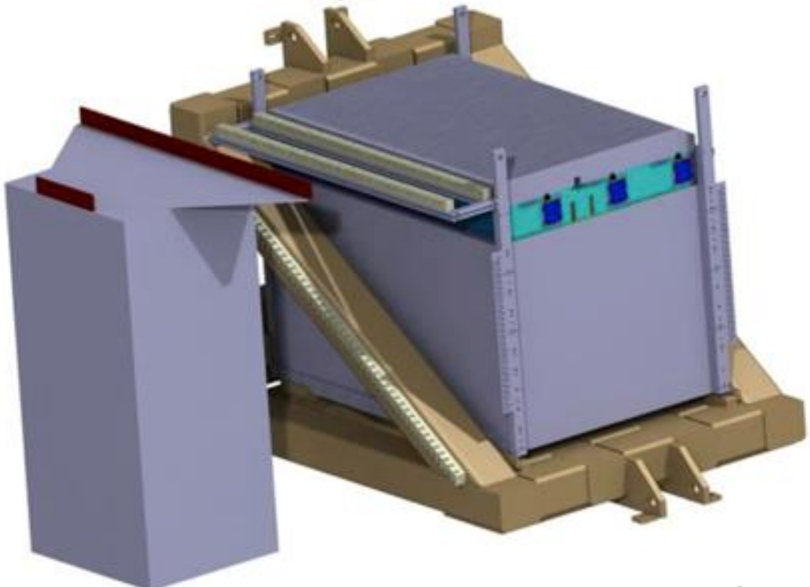
The SDHCAL-GRPC is one of the two HCAL options based on PFA and proposed for **ILD of ILC/CEPC**. Modules are made of 48/40 RPC chambers equipped with **semi-digital, power-pulsed electronics** readout and placed in **self-supporting mechanical** structure to serve as absorber as well.




The structure proposed for the SDHCAL :

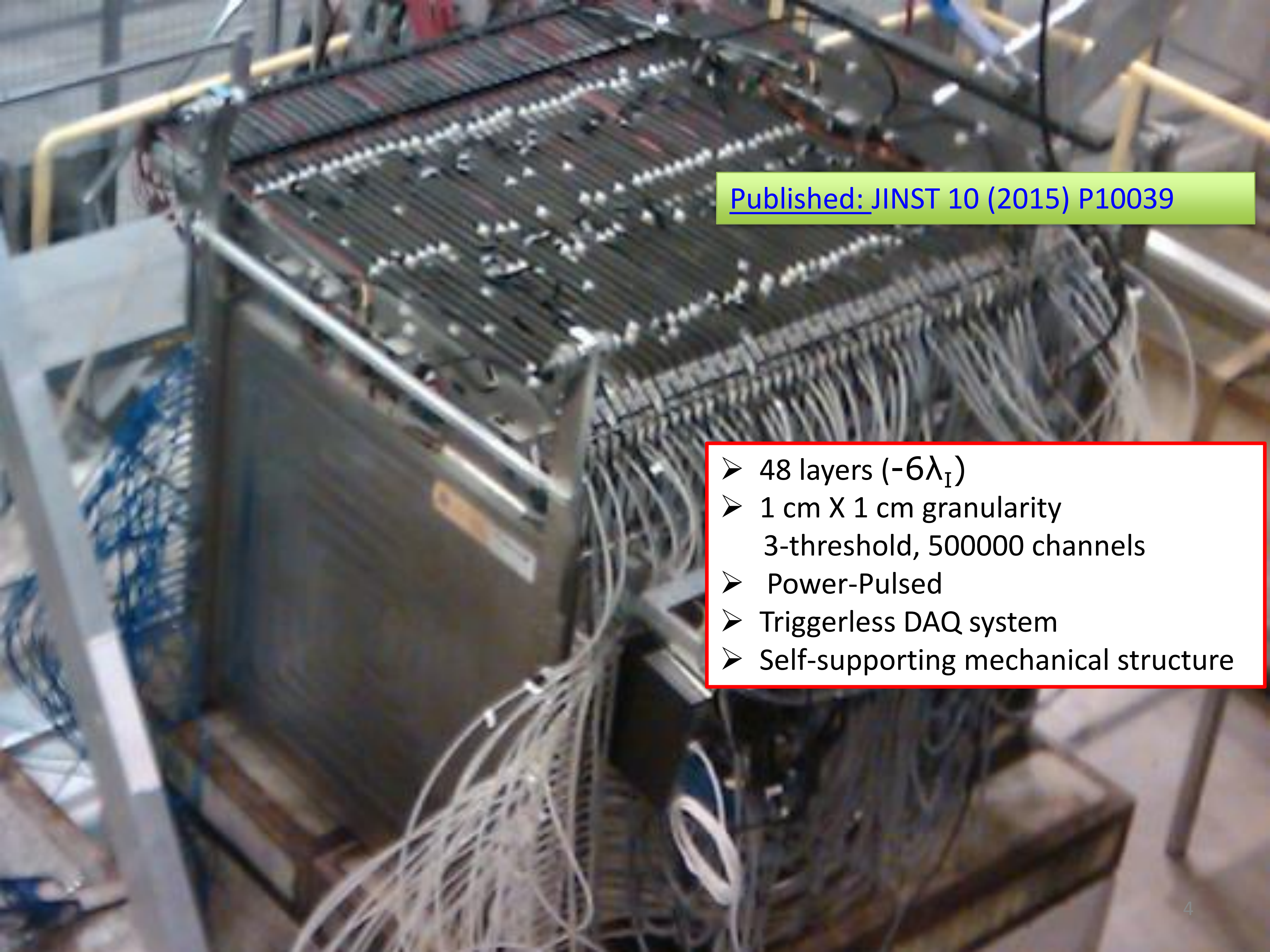
- is very compact with negligible dead zones
- Eliminates projective cracks
- Minimizes barrel / endcap separation (services leaving from the outer radius)

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



## Challenges

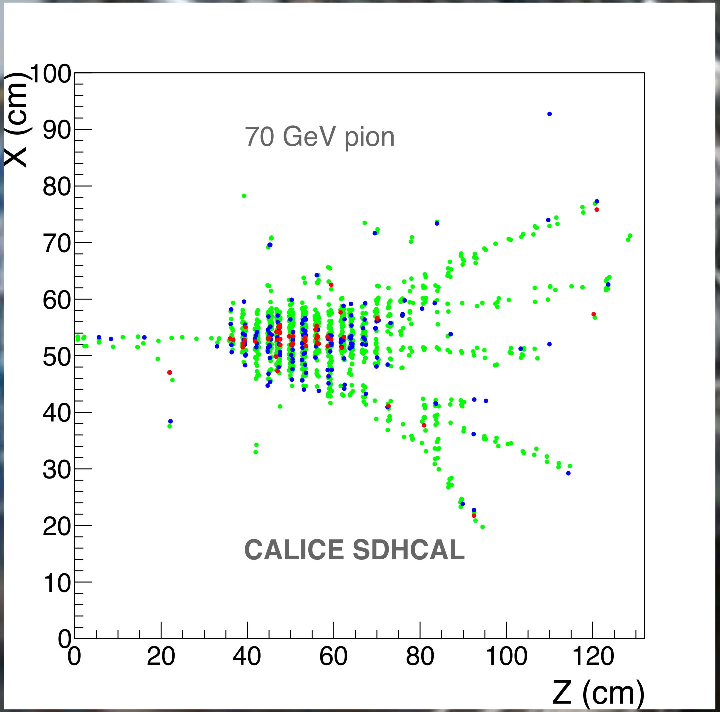
-Homogeneity for large surfaces
-Thickness of only few mms
-Lateral segmentation of 1 cm X 1 cm
-Services from one side
-Embedded power-cycled electronics
-Self-supporting mechanical structure

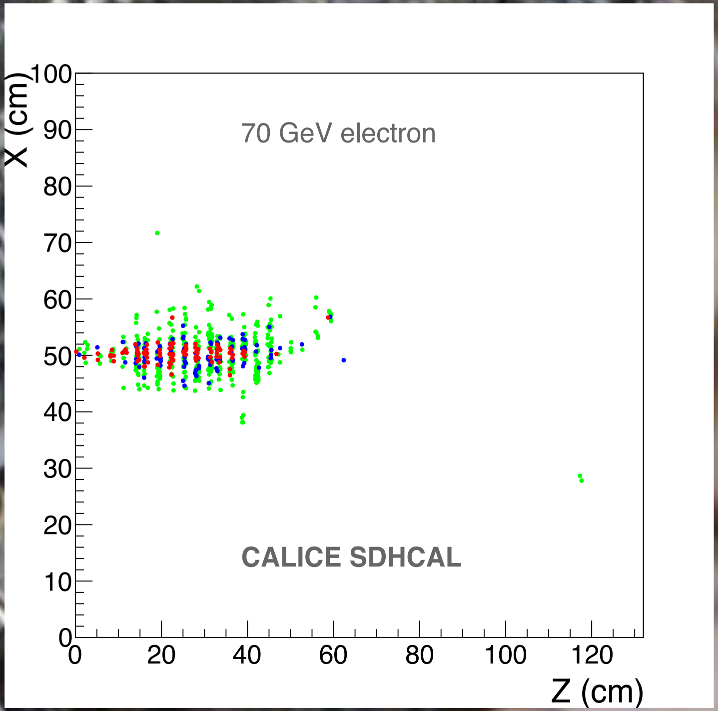


[Published: JINST 10 (2015) P10039]

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

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)

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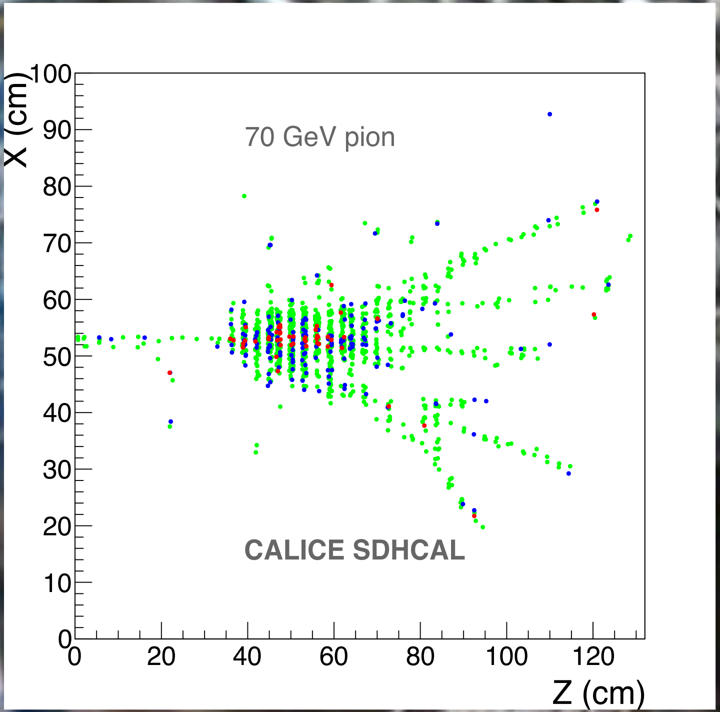
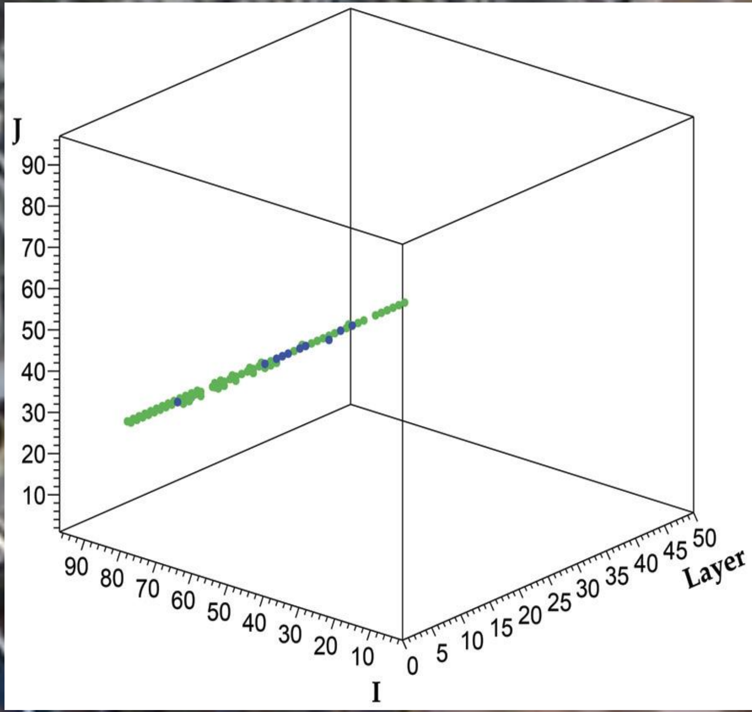


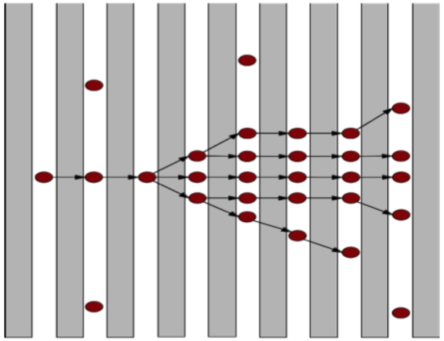

Muon rejection: average number of hits/layer < 2

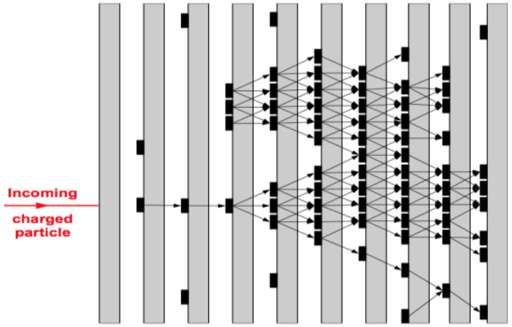
## SDHCAL high granularity is conceived for PFA

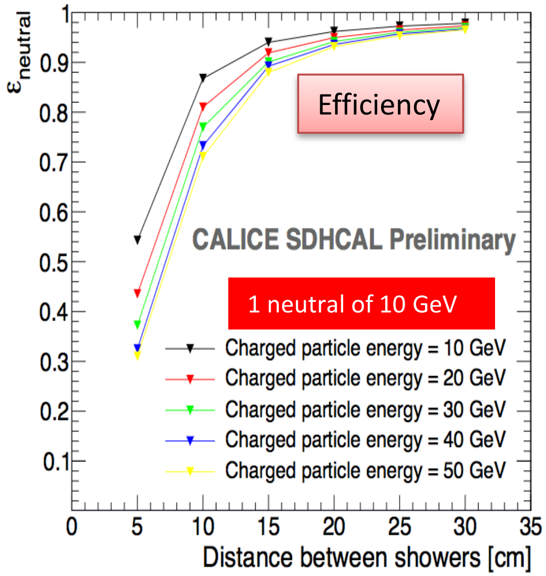
It helps to optimize the connection of hits belonging to the same shower by using first the topology and then the energy information

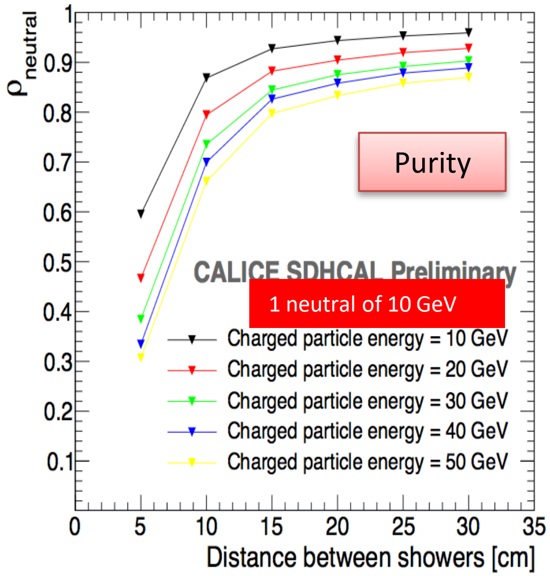
### ArborPFA algorithm*:

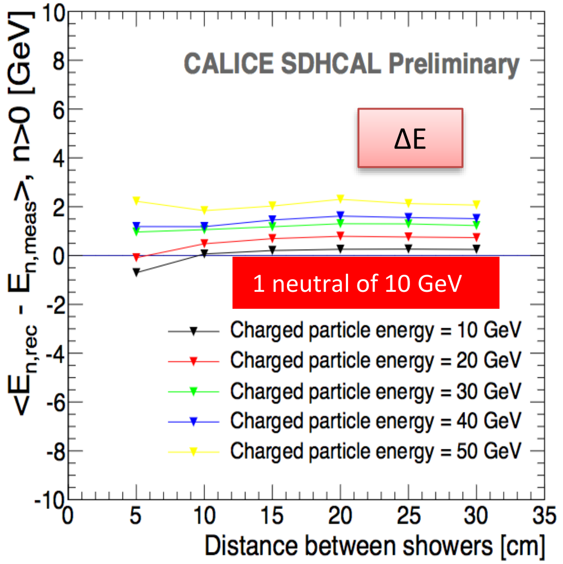
It connect hits and then their clusters using distance and orientation information then correct using tracker information (momentum)






CALICE note CAN054

# 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

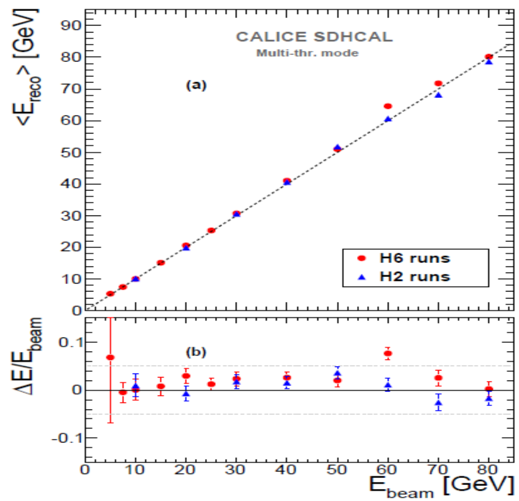
$N_2$ = Nb. of pads with second threshold <signal < third threshold

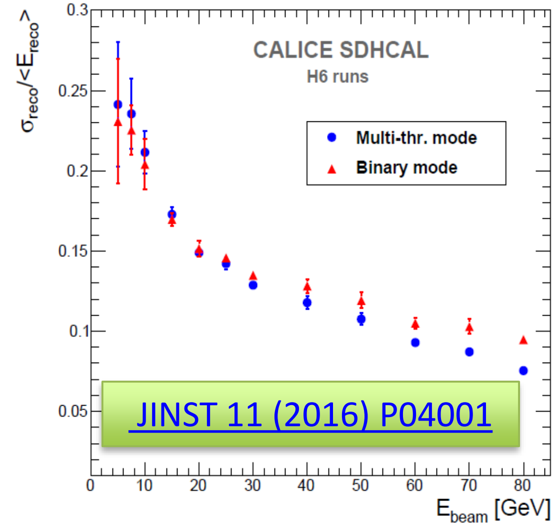
$N_3$ = Nb. of pads with signal> third threshold

$\alpha$, $\beta$, $\gamma$ are **quadratic functions** of $N_{tot} = N_1 + N_2 + N_3$

They are computed by minimizing :

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

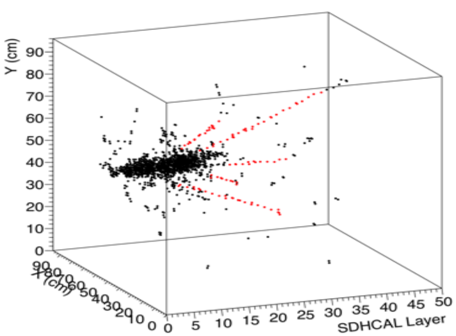


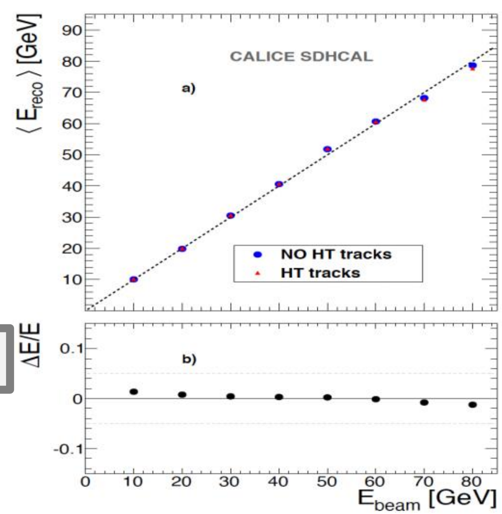



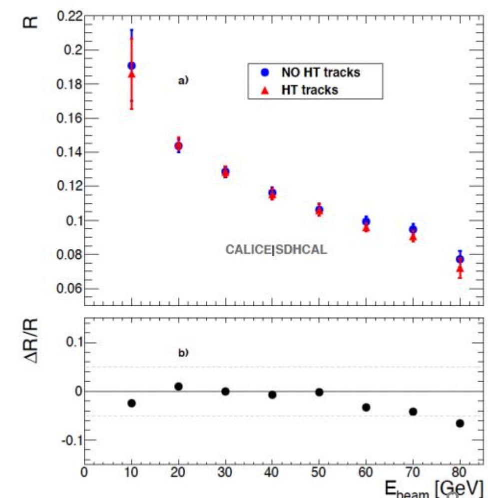

[JINST 11 (2016) P04001]

## 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]

# Energy reconstruction

## Particle Identification

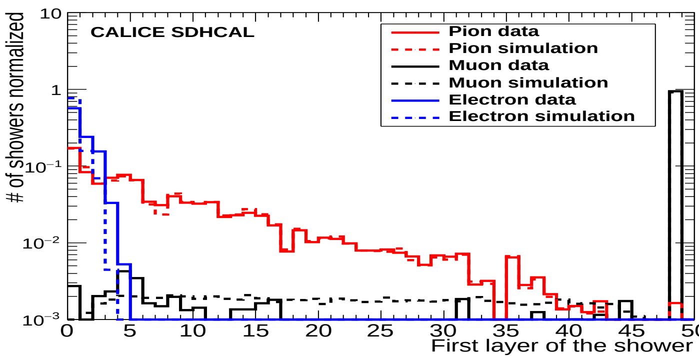
Due to the absence of Cerenkov detectors in front of the SDHCAL, the use of an electron selection (shower starting > d= 6 $X_l$) was rather powerful but led to an important loss of hadrons (d= 1 $\lambda_l$).

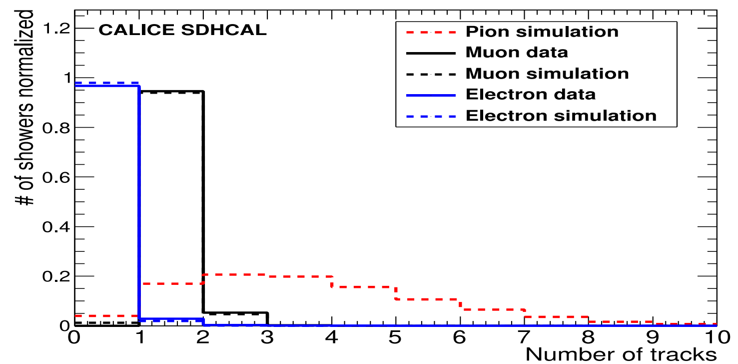
To reject electrons and muons without losing hadrons we use the excellent granularity of SDHCAL to discriminate the three species. Several discriminatory variables were selected:

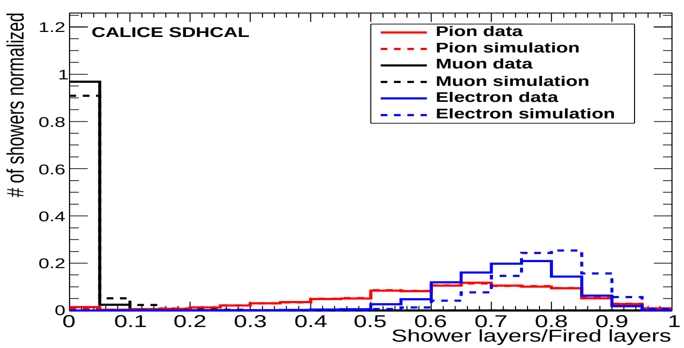
1- First layer of the shower (begin)
2- Number of tracks in the shower (trackMultiplicity)
3- Ratio of shower layers over total fired layers (nSHowerLayer/Nlayers)
4- Shower density (density)
5- Shower radius (radius)
6- Maximum shower position (length)
7- Ratio of $N_3/N_{tot}$
8- Average number of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

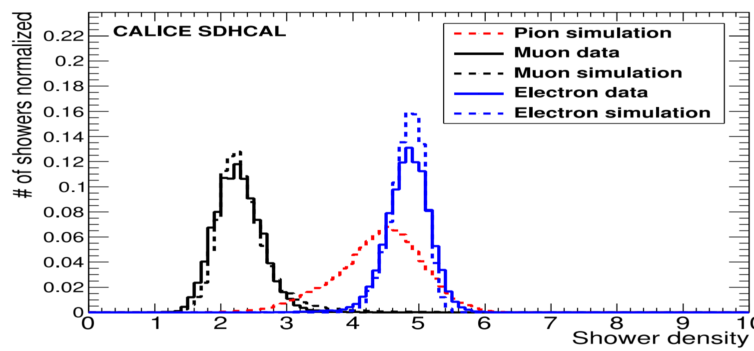
- BDT technique was used.
- Simulated events of electrons, muons and pions were used for training/validation before to apply to data.
- To avoid a possible bias due to discrepancy between data/simulation of electrons showers in the SDHCAL, pure electrons and muons data events were also used

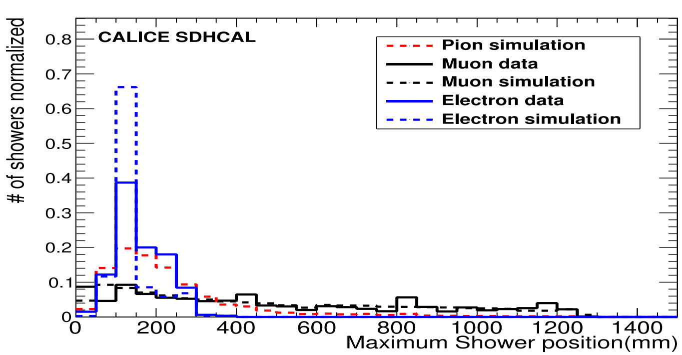
JINST 15 (2020) P10009

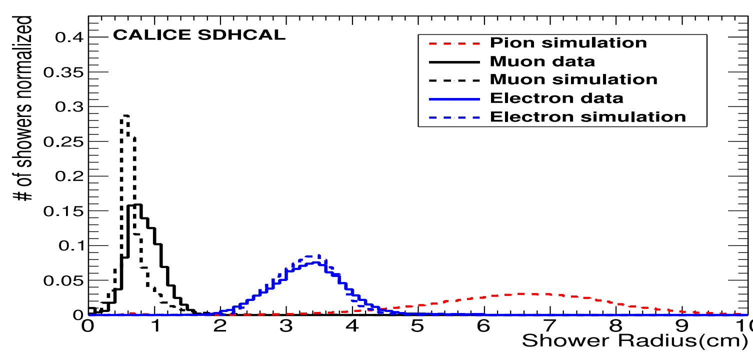


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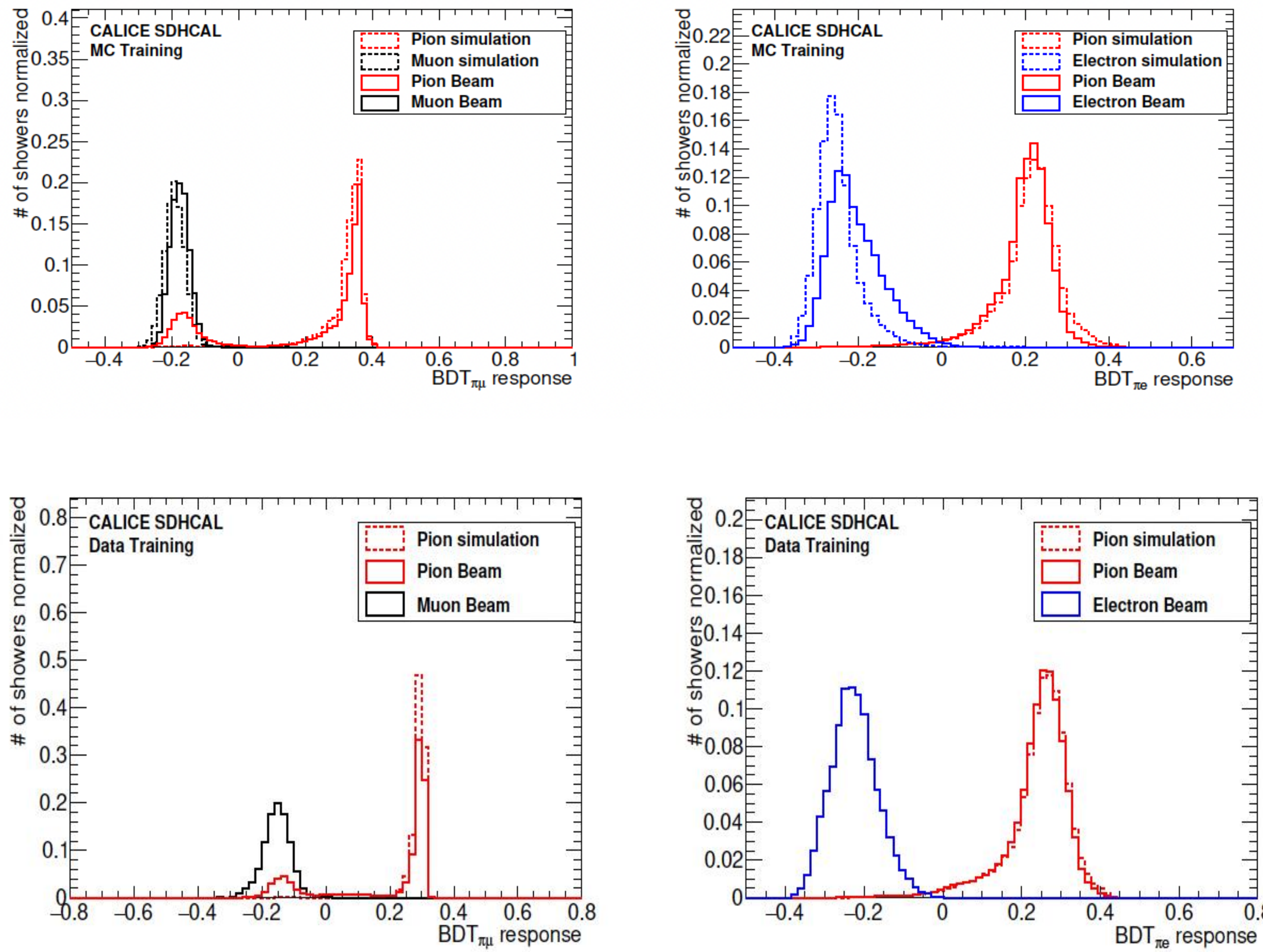


Electron and muon rejection > 99%

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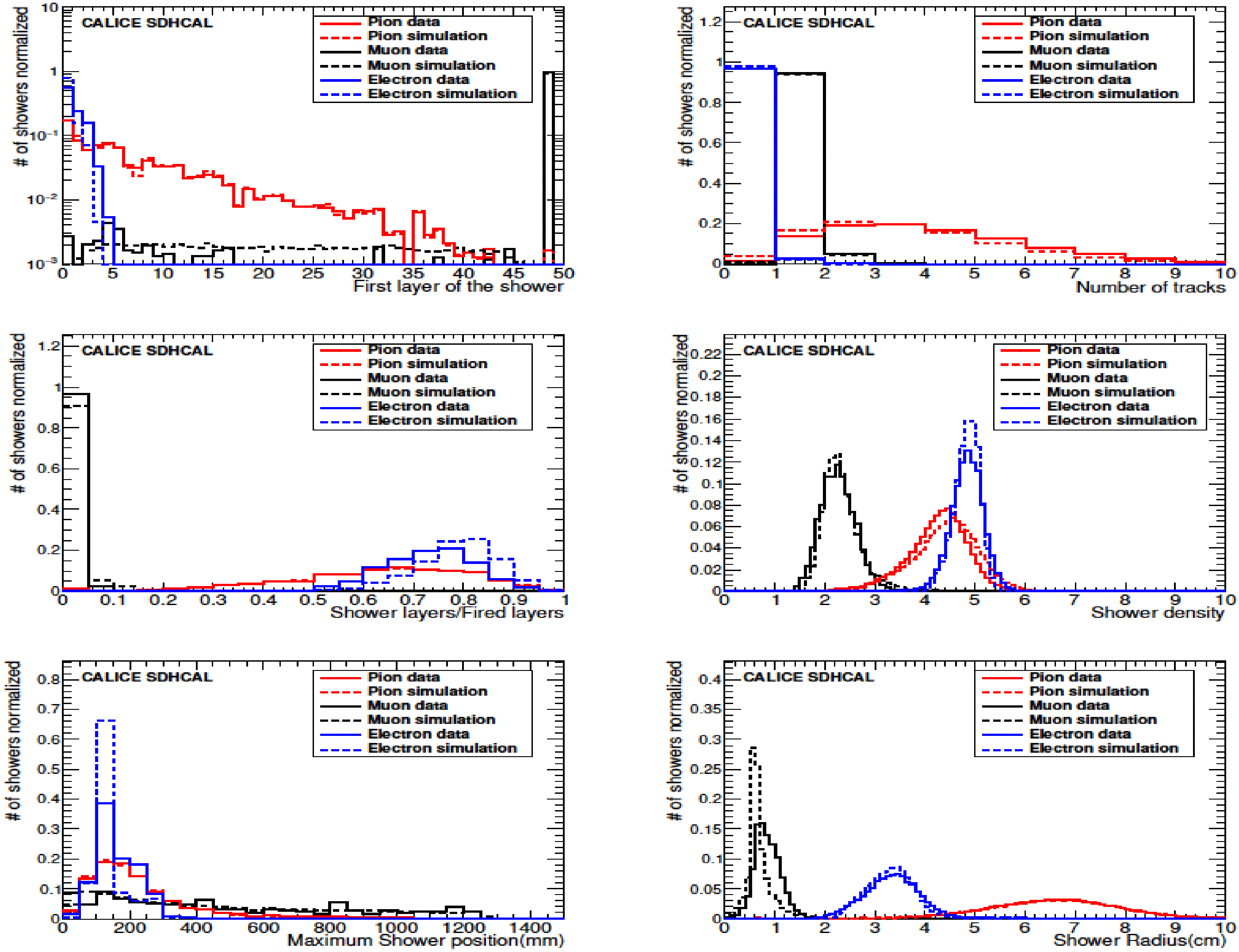
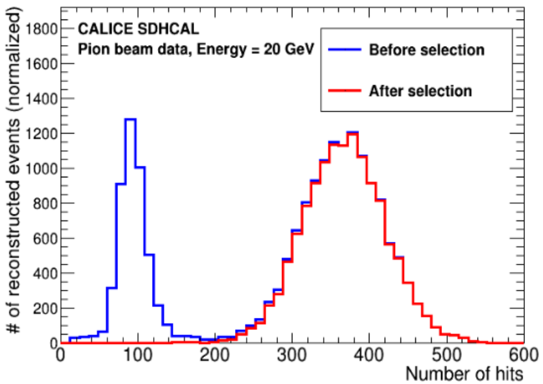
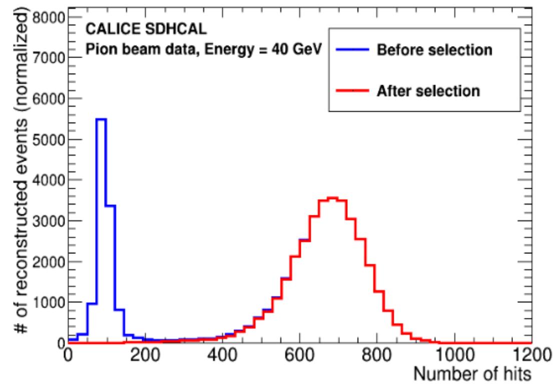
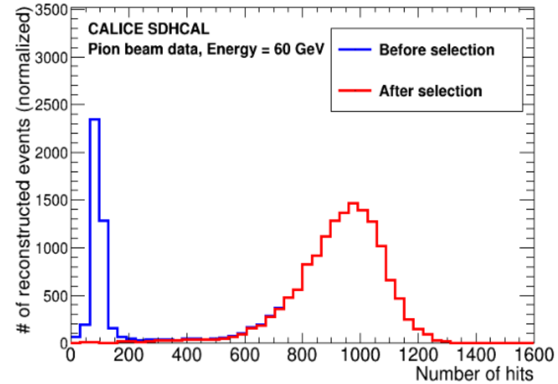



Excellent agreement between data and simulation of pion events.

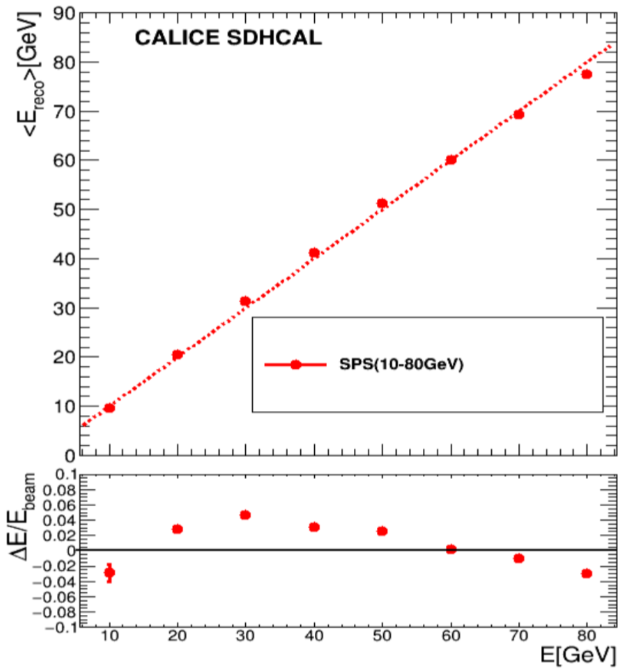
# The BDT-based PID was first applied to the SPS 2015(10-80 GeV) samples

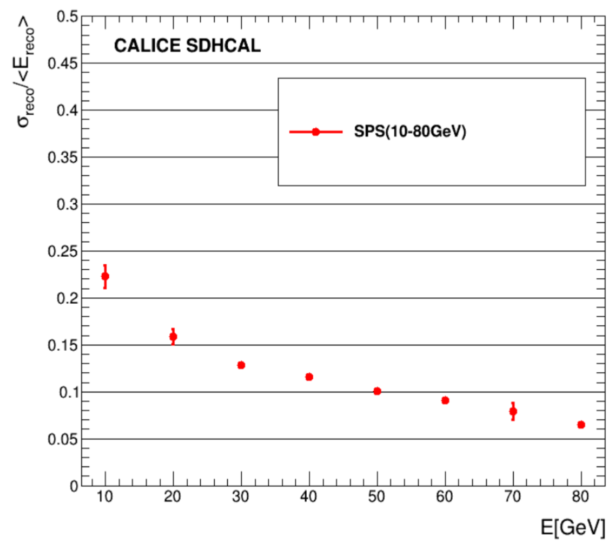



arXiv:2202.09684

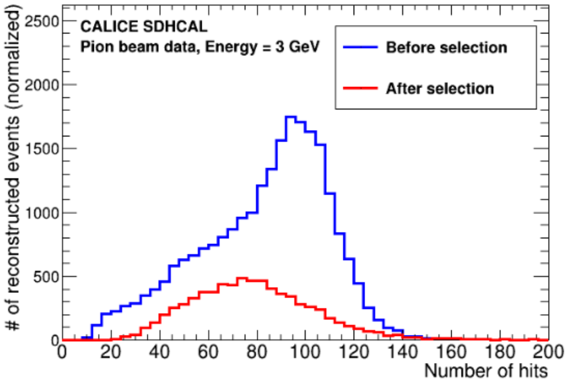


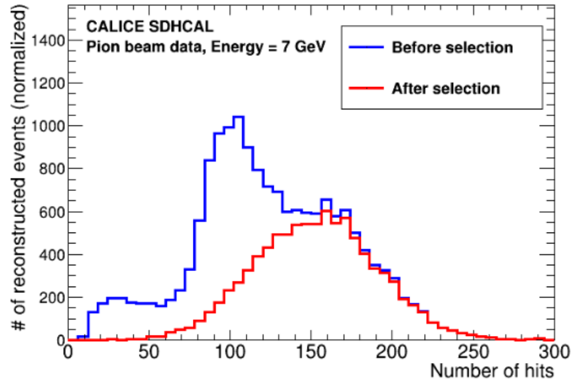



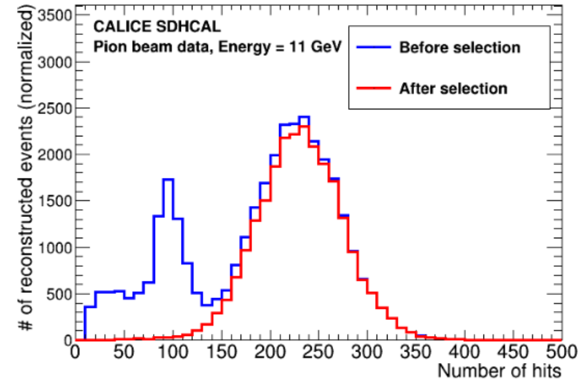

Resolution

Linearity

# The BDT-based PID technique was also applied to the PS (3-12 GeV) samples

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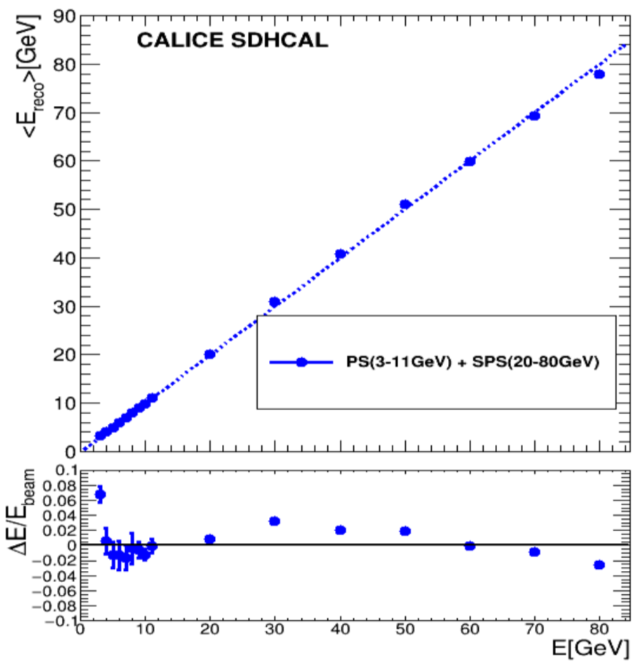
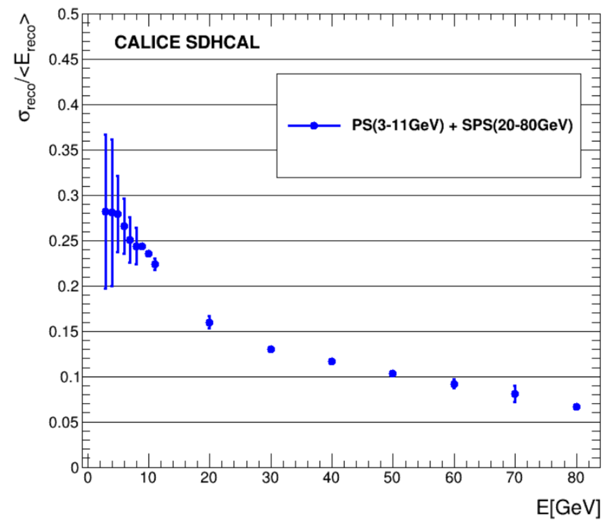
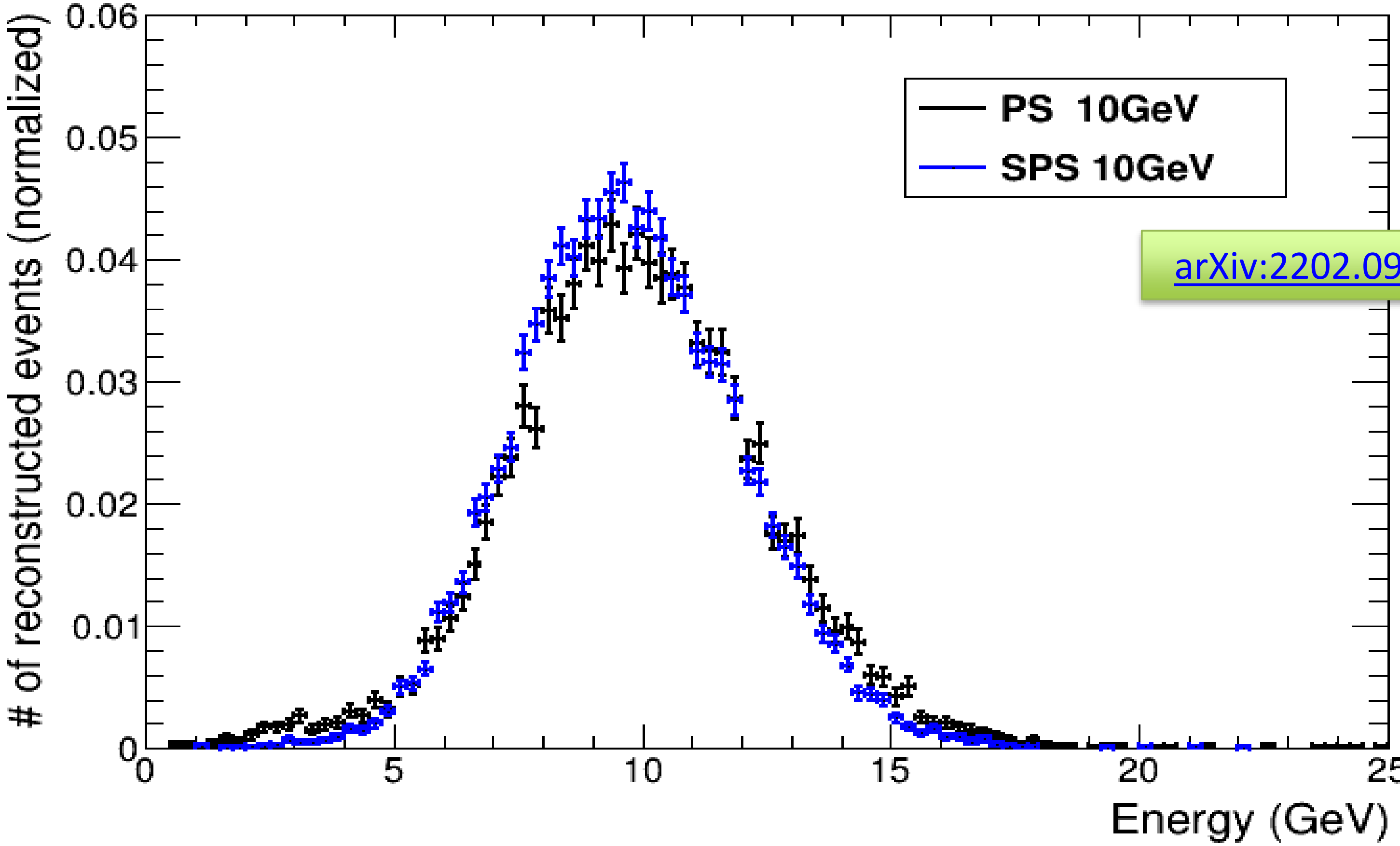



Linearity




Resolution

Comparison of reconstructed energy of 10 GeV PS ( no electron contamination) and 10 GeV SPS (after rejection of electron contamination)

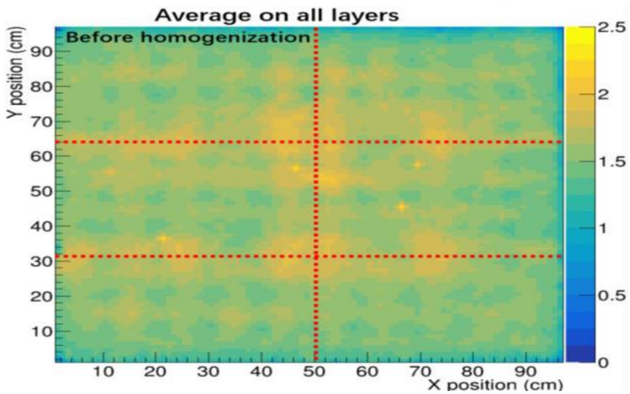


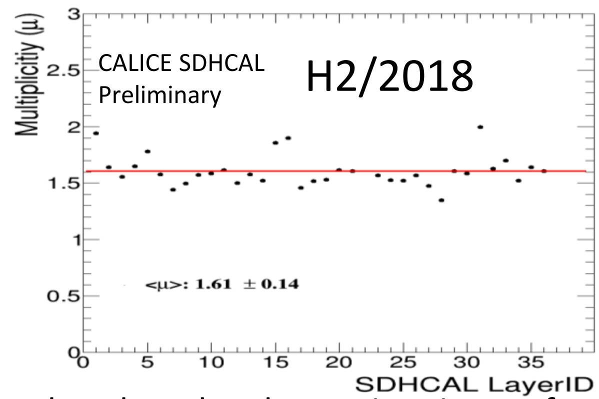

arXiv:2202.09684

# Further improvements on the energy reconstruction

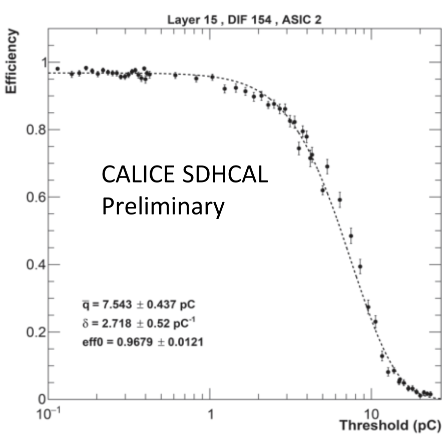
## Detector homogeneity

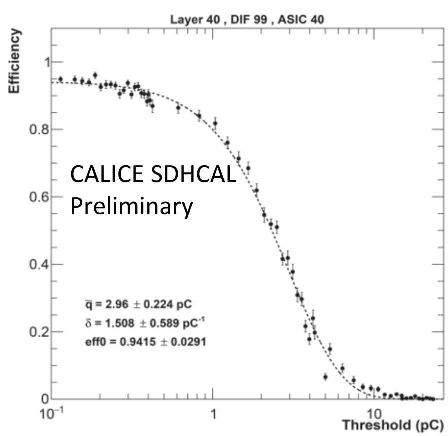
The homogeneity of the detector response is important to achieve better energy reconstruction

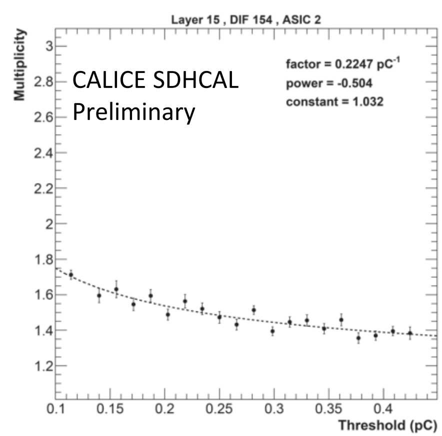


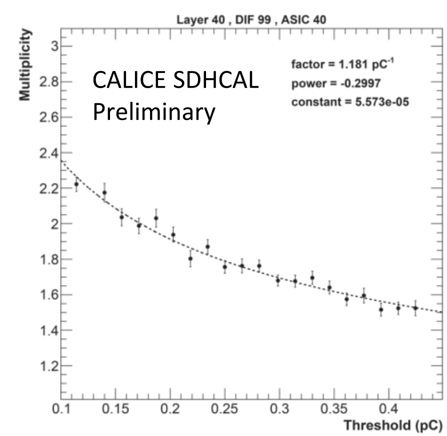




A new calibration method based on varying the thresholds rather than the electronic gain was found to be powerful. Muon runs with different thresholds Thr1: 0.1-0.42 pC, Thr2: 0.4-5, Thr3:4.7-24) and efficiency and multiplicity were measured for each value. The values of the three thresholds of each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



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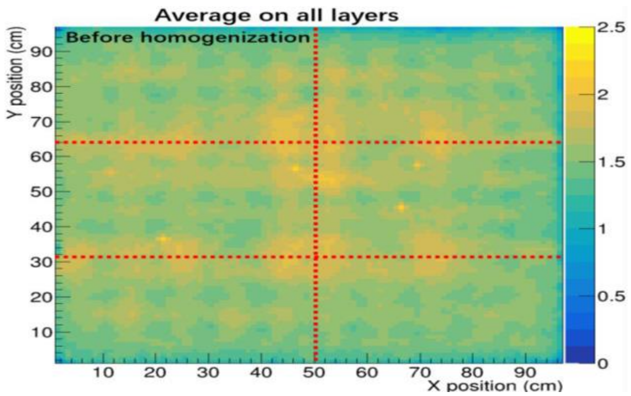


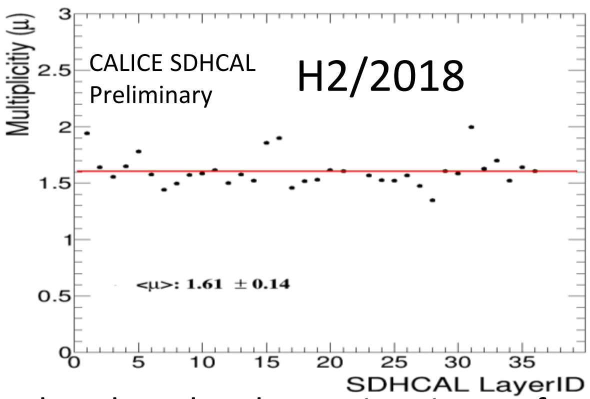


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$$\varepsilon(t;\overline{q},\delta,\epsilon_0) = \varepsilon_0 \cdot \left(1 - \int_0^t P(q;\overline{q},\delta)dq\right)$$

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

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

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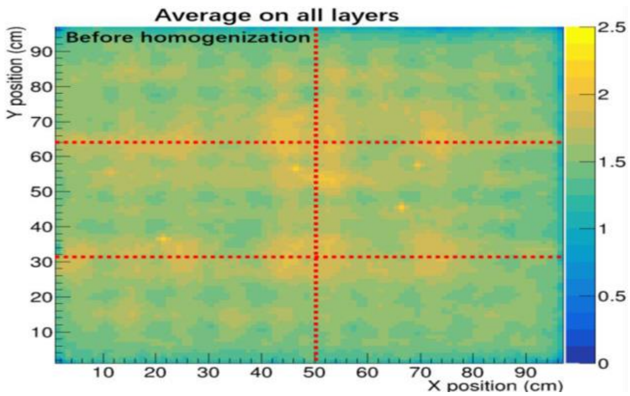


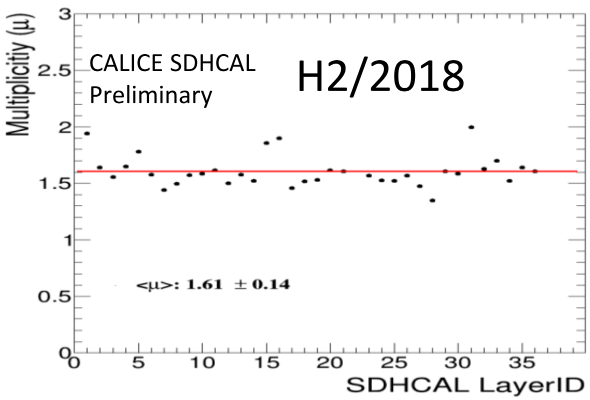


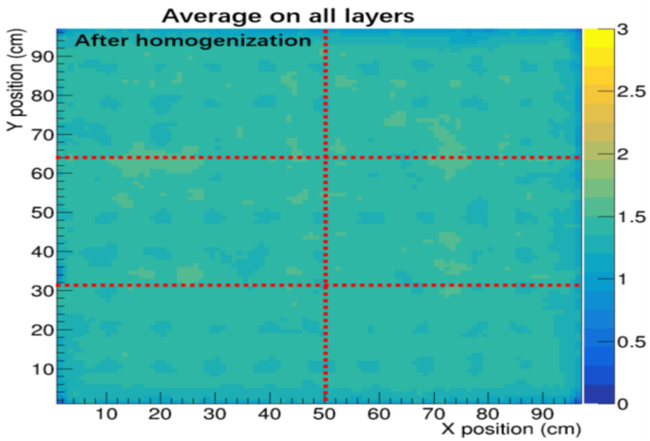


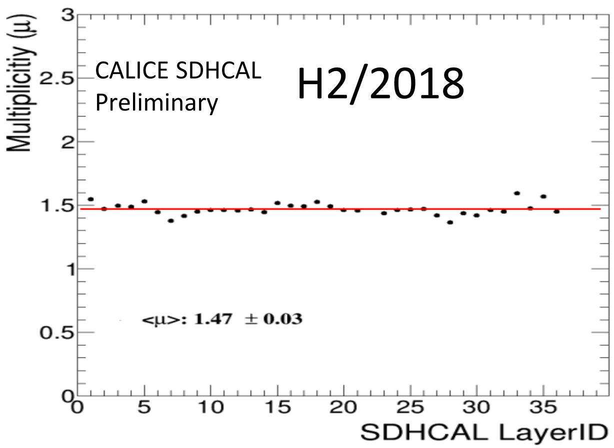

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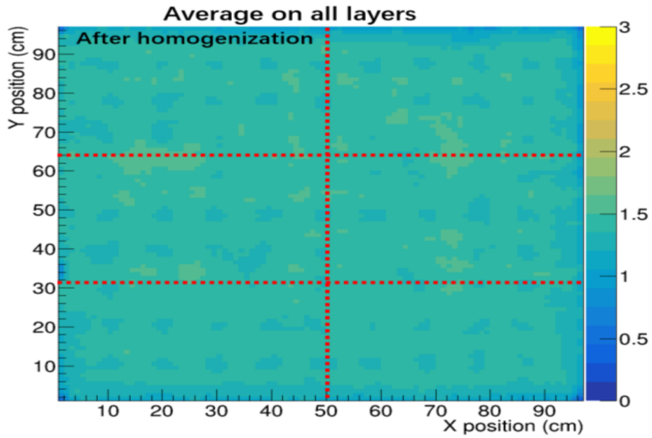
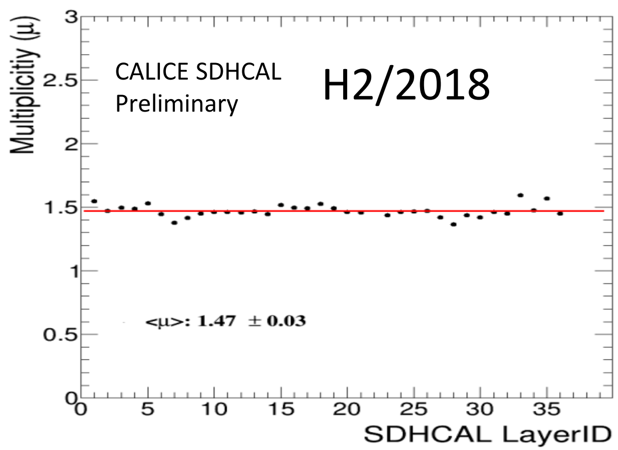
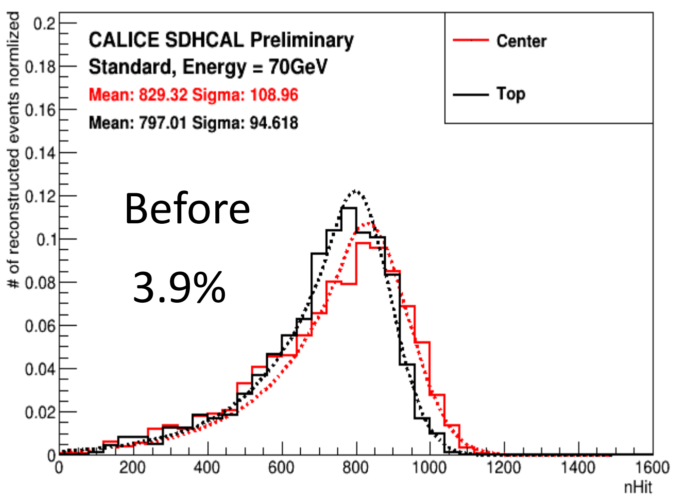
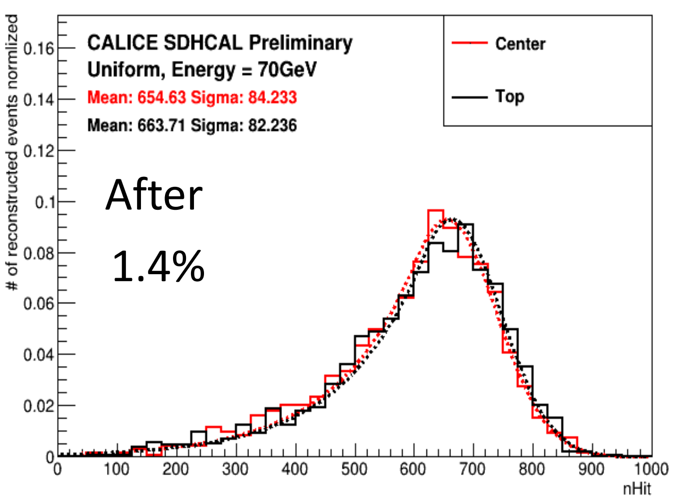



We will apply the new method to the data to be collected in 2022

# Further improvements on the energy reconstruction

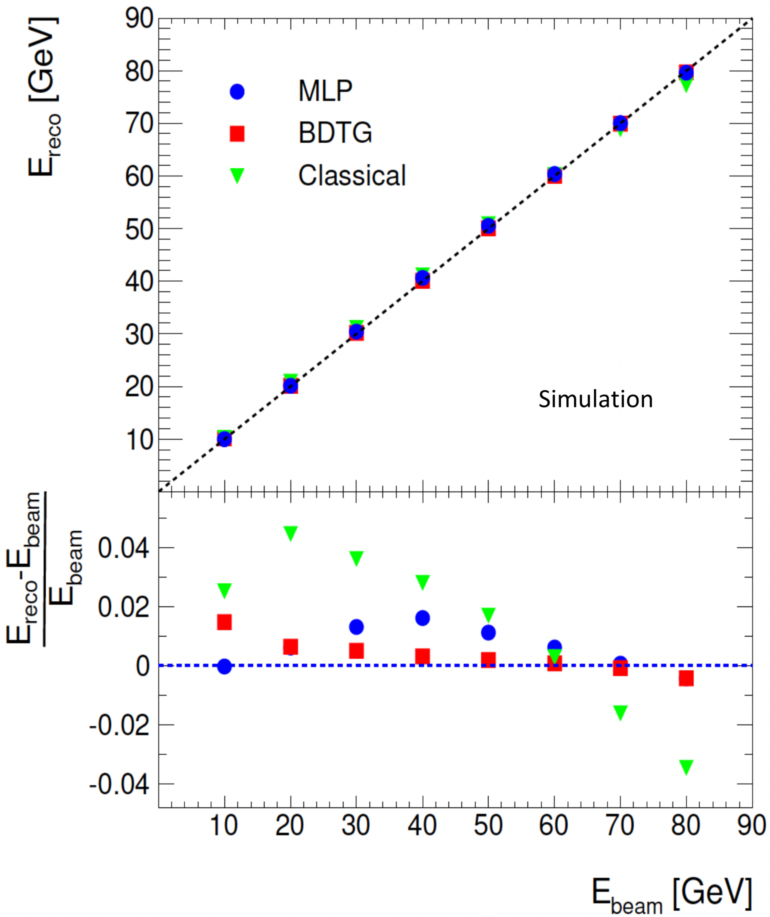
## Multi-Variate Techniques

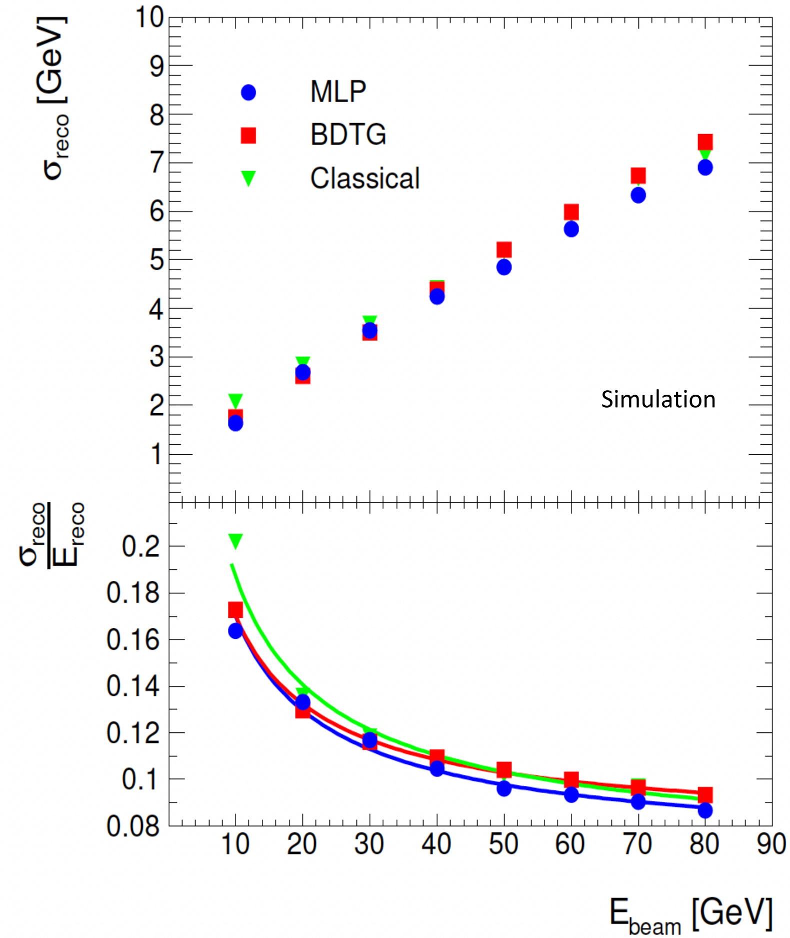
Several MVT methods (NN and BDT) were used to exploit, in addition to $N_1$, $N_2$ and $N_3$, the hadronic shower shape information related to its energy thanks to the high granularity of the SDHCAL

| 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 high granularity of SDHCAL. Simulated pion events within SDHCAL were used for this study.



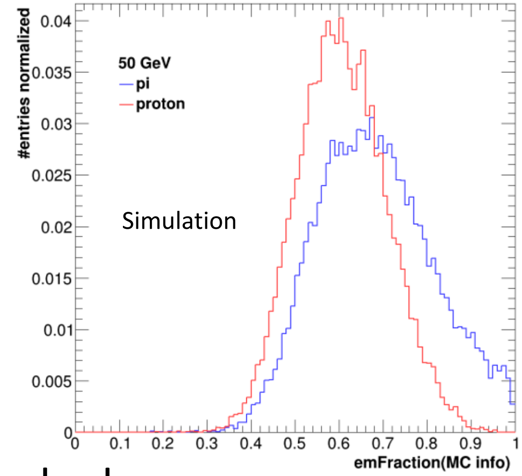

MLP seems to perform better

JINST 14, 2019, P10033

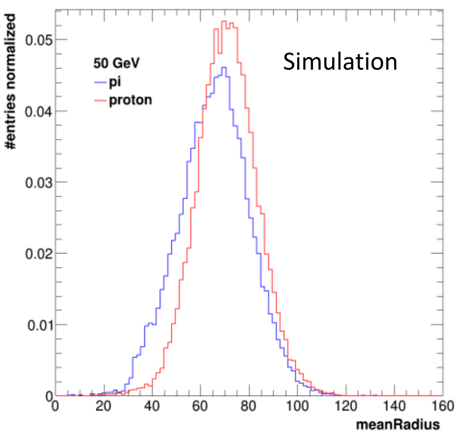
# Further improvements on the energy reconstruction

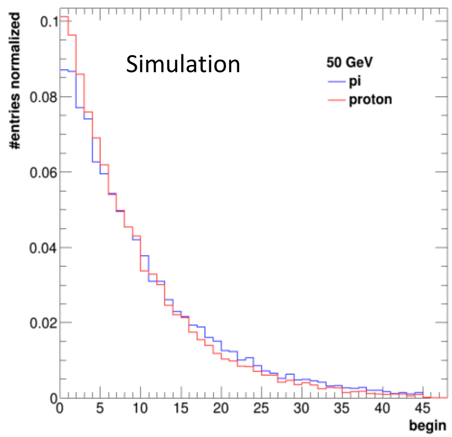
## Hadron identification

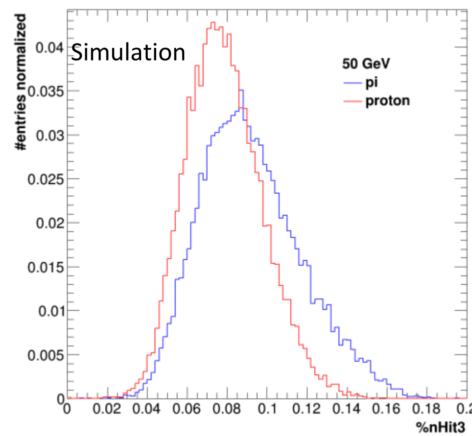
The energy reconstruction method was applied to hadron events.
No distinction was made between pions and protons or others.
Hadronic showers of pions and protons are not identical

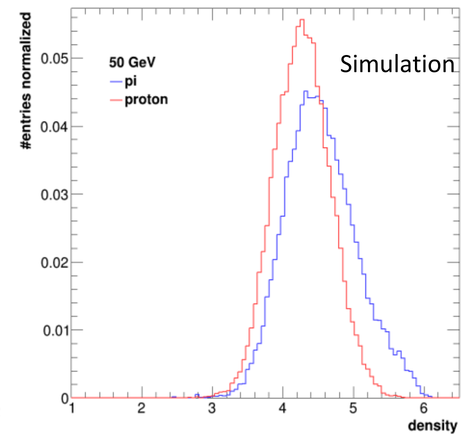



Better construction can be made if one can identify the nature f the hadron.




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 ($\alpha$, $\beta$, $\gamma$) parameters could be used.

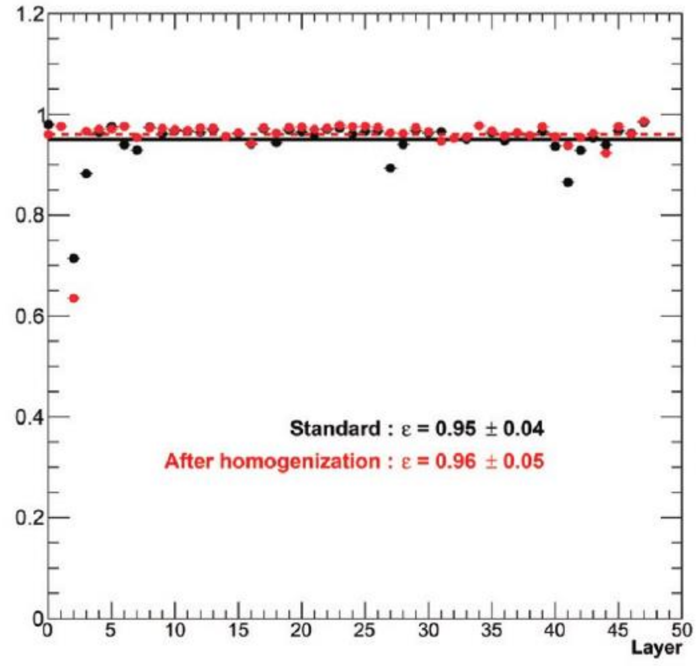
# Summary

- 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

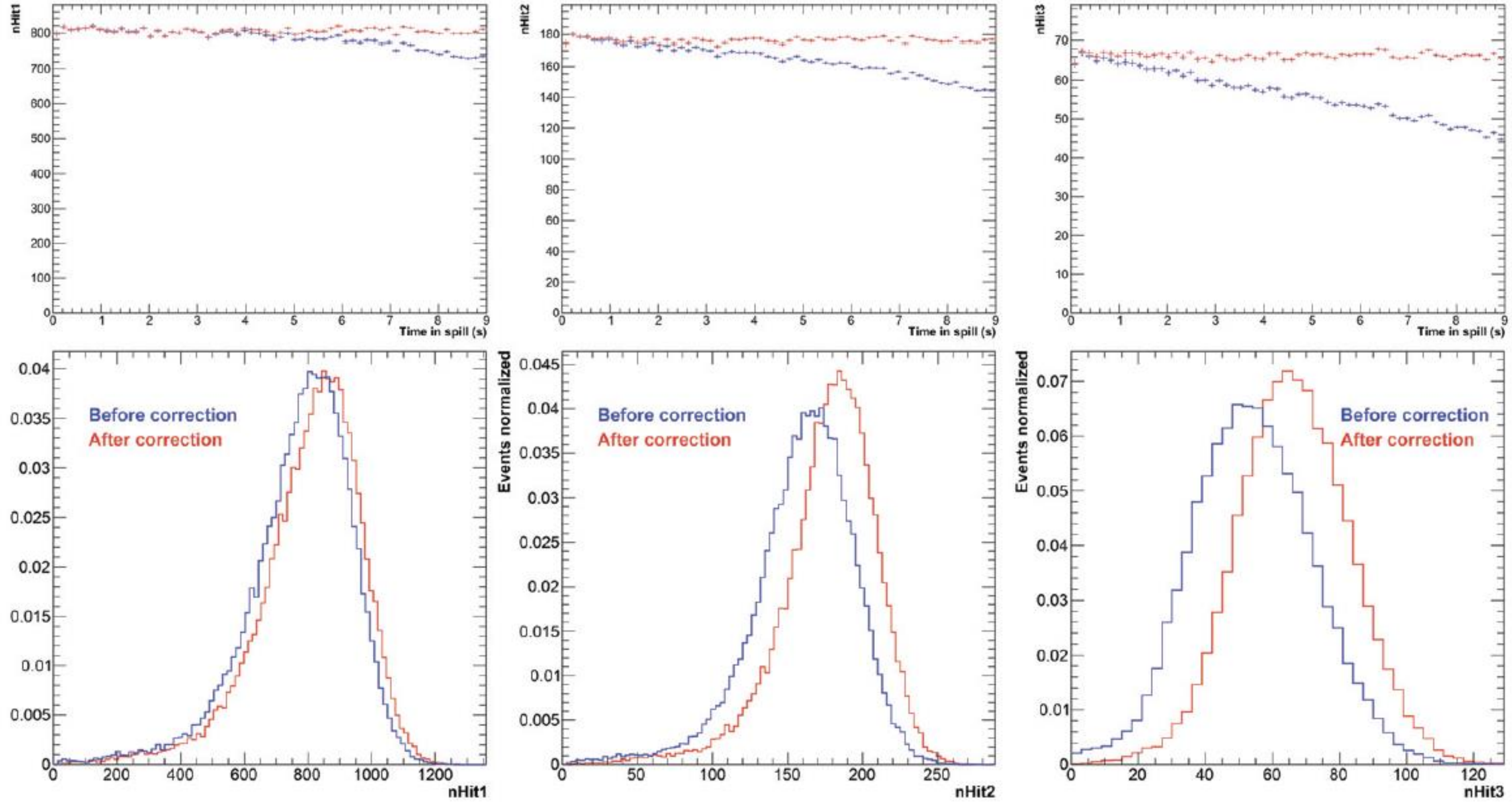
- The  exploitation of the hadronic shower shape thanks to the high granularity is an excellent asset to identify particles and then better measure their energy.

- 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.



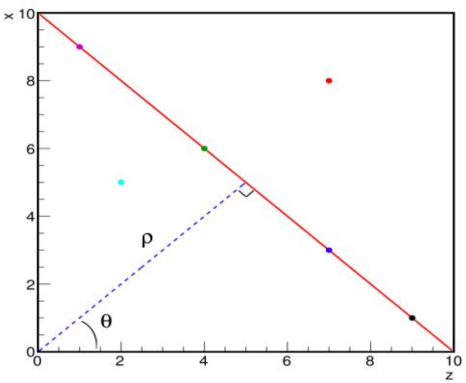
Standard : ε = 0.95 ± 0.04
After homogenization : ε = 0.96 ± 0.05
Layer

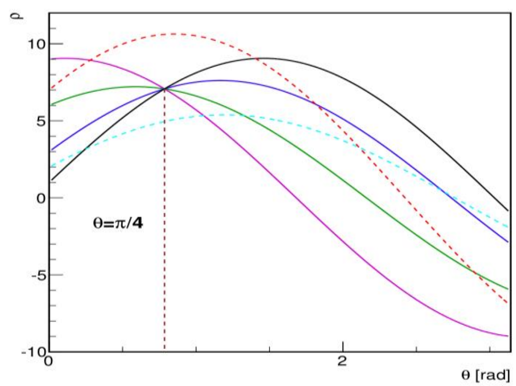
# Time correction

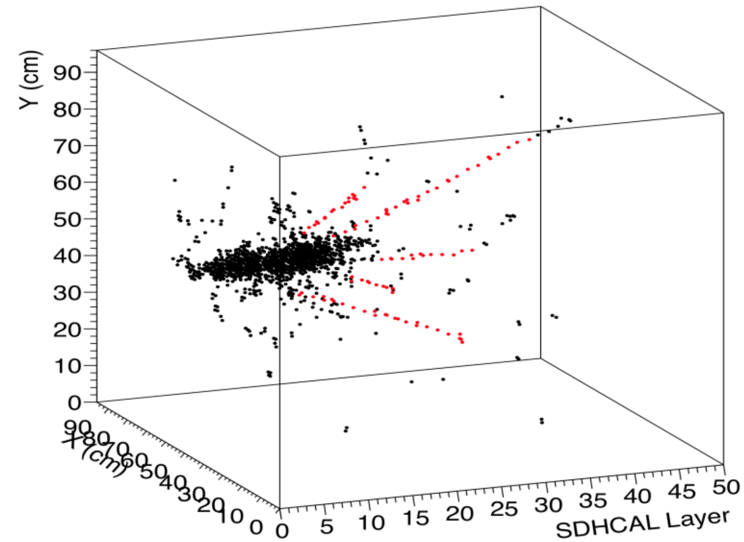


# SDHCAL High-granularity impact

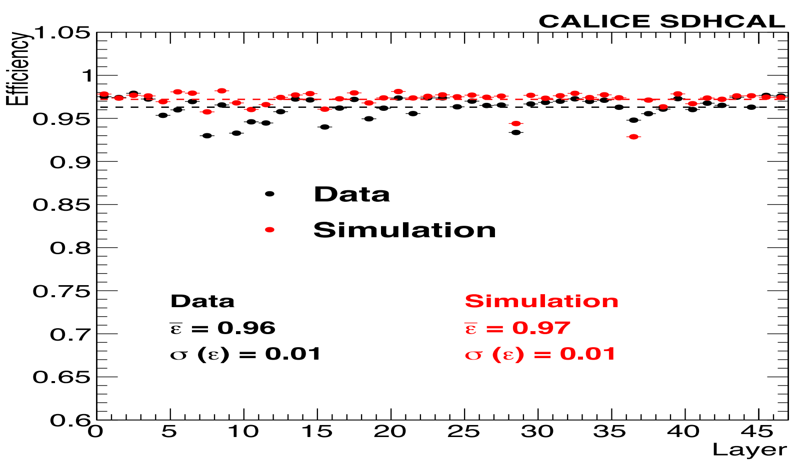
Hough Transform is an example to extract tracks within hadronic showers and to use them to **control the calorimeter in situ**

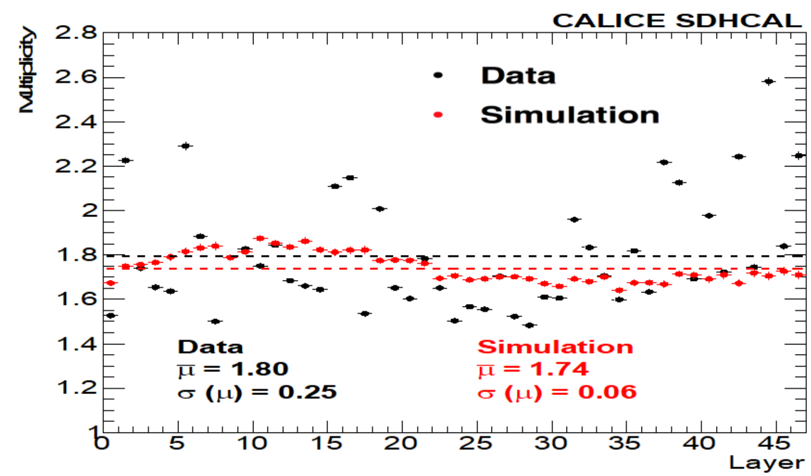


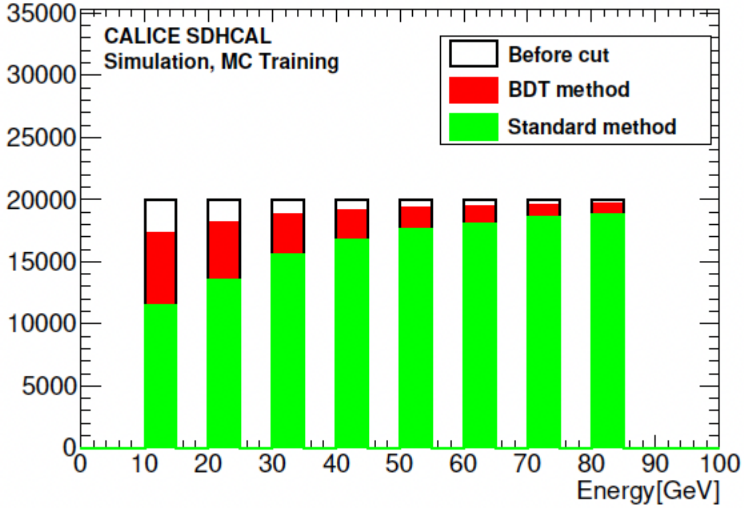



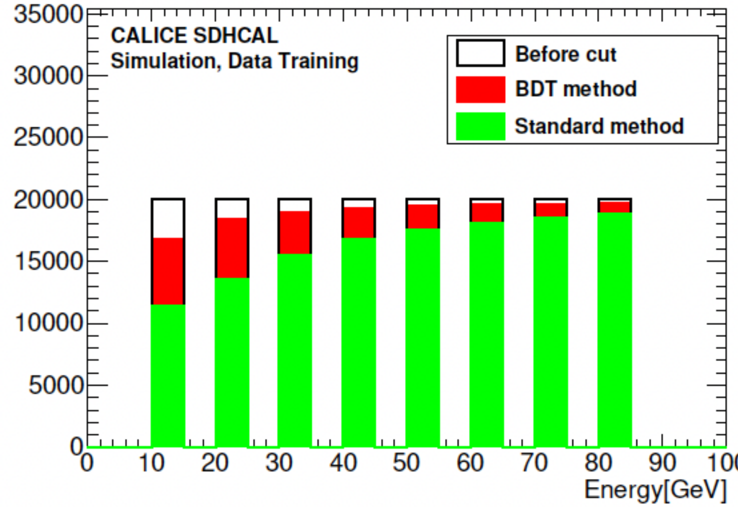

$$\rho_{xz} = z\sin(\theta) + x\cos(\theta)$$




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


35000
30000
25000
20000
15000
10000
5000
0
CALICE SDHCAL
Simulation, MC Training
Before cut
BDT method
Standard method
0
10
20
30
40
50
60
70
80
90
100
Energy[GeV]


35000
30000
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10000
5000
0
CALICE SDHCAL
Simulation, Data Training
Before cut
BDT method
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0
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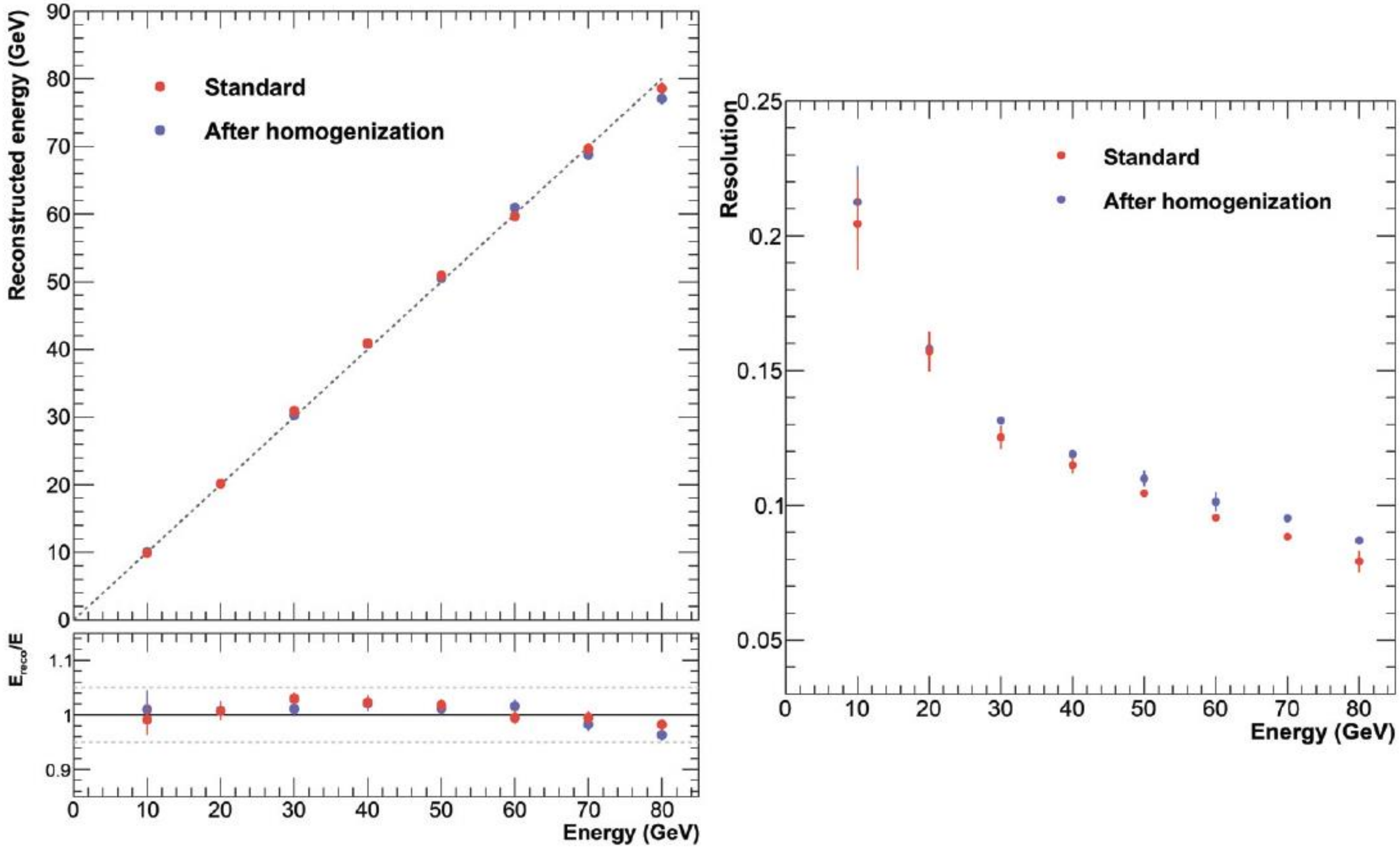
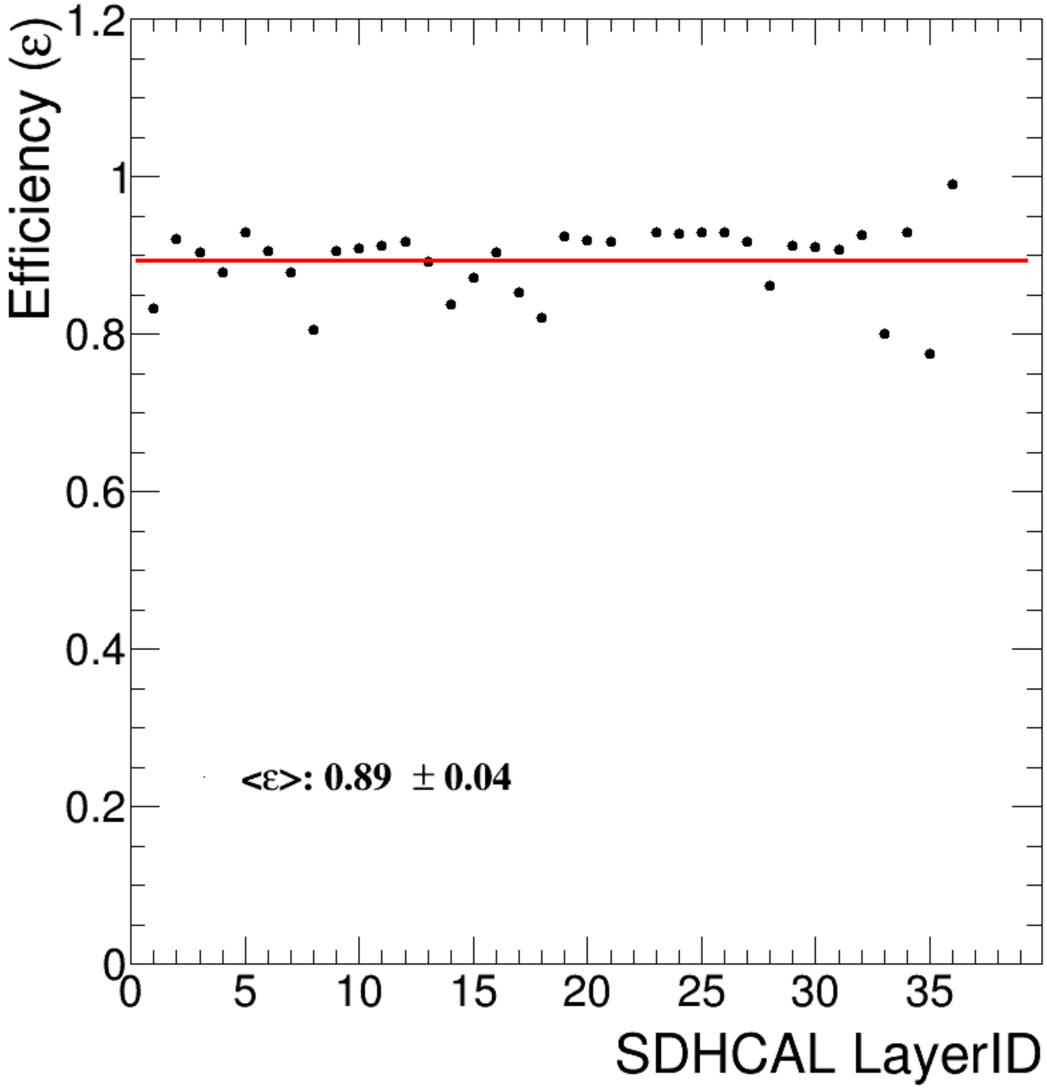
100
Energy[GeV]



Reconstructed energy (GeV)
Standard
After homogenization
$E_{reco}/E$
Energy (GeV)
Resolution
Standard
After homogenization
Energy (GeV)



Efficiency (ε)
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
SDHCAL LayerID
<ε>: 0.89 ± 0.04

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