Hadronic Calorimeters based on Plastic Scintillators and Glass RPCs

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On behalf of the CEPC Calo Group

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Outline

- Introduction: Motivation and Requirements
- Analog HCAL Prototype based on Scintillators
- Semi-Digital HCAL Prototype based on GRPCs
- Test Beam at CERN and Performance Studies
- Summary and Future Plans

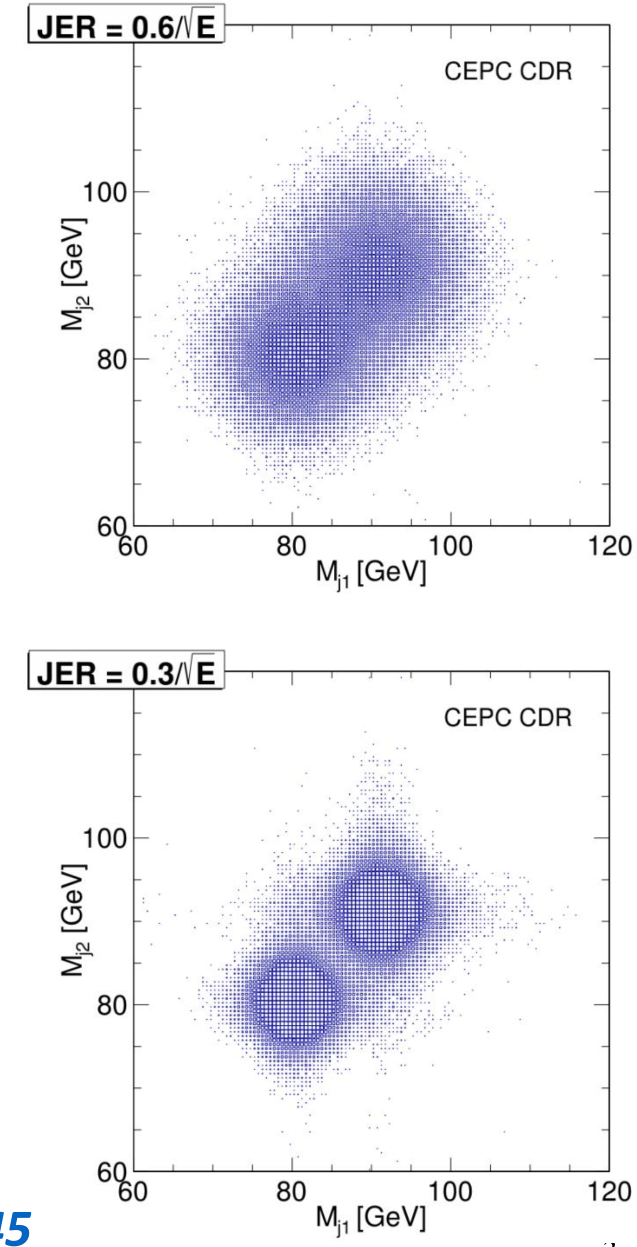
Introduction

CEPC as Higgs/W/Z boson factories

- H/W/Z decay into hadronic final states are dominant, it is crucial to design high granularity calorimetry system to separate them using Particle Flow Algorithm (PFA).
- Required Jet Energy Resolution σ/E: 30%-40%/$\sqrt{E}$

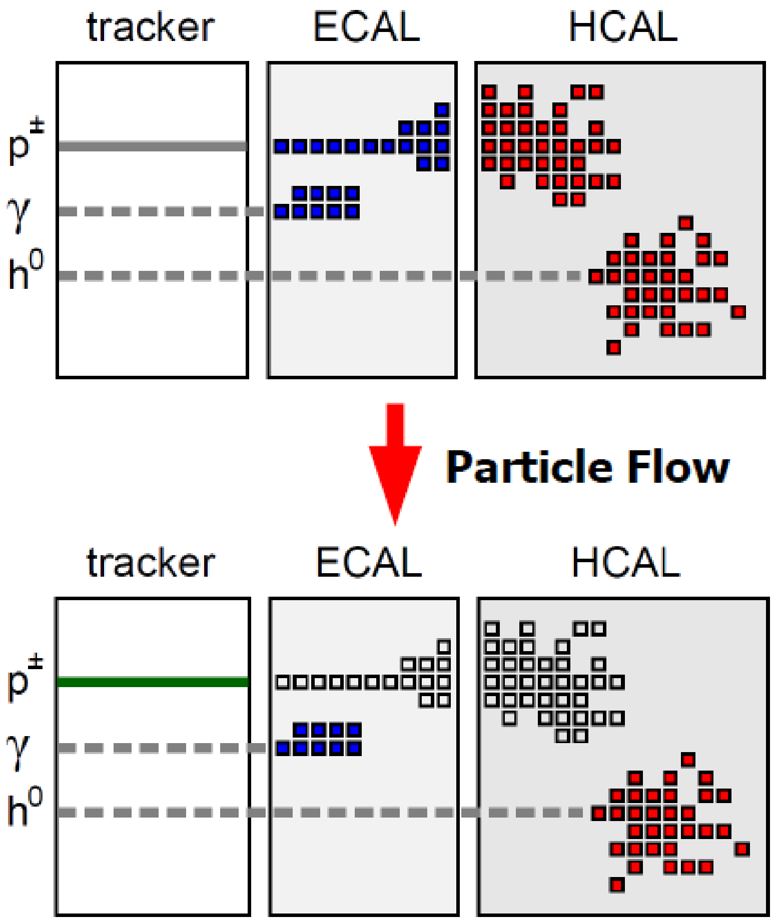
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

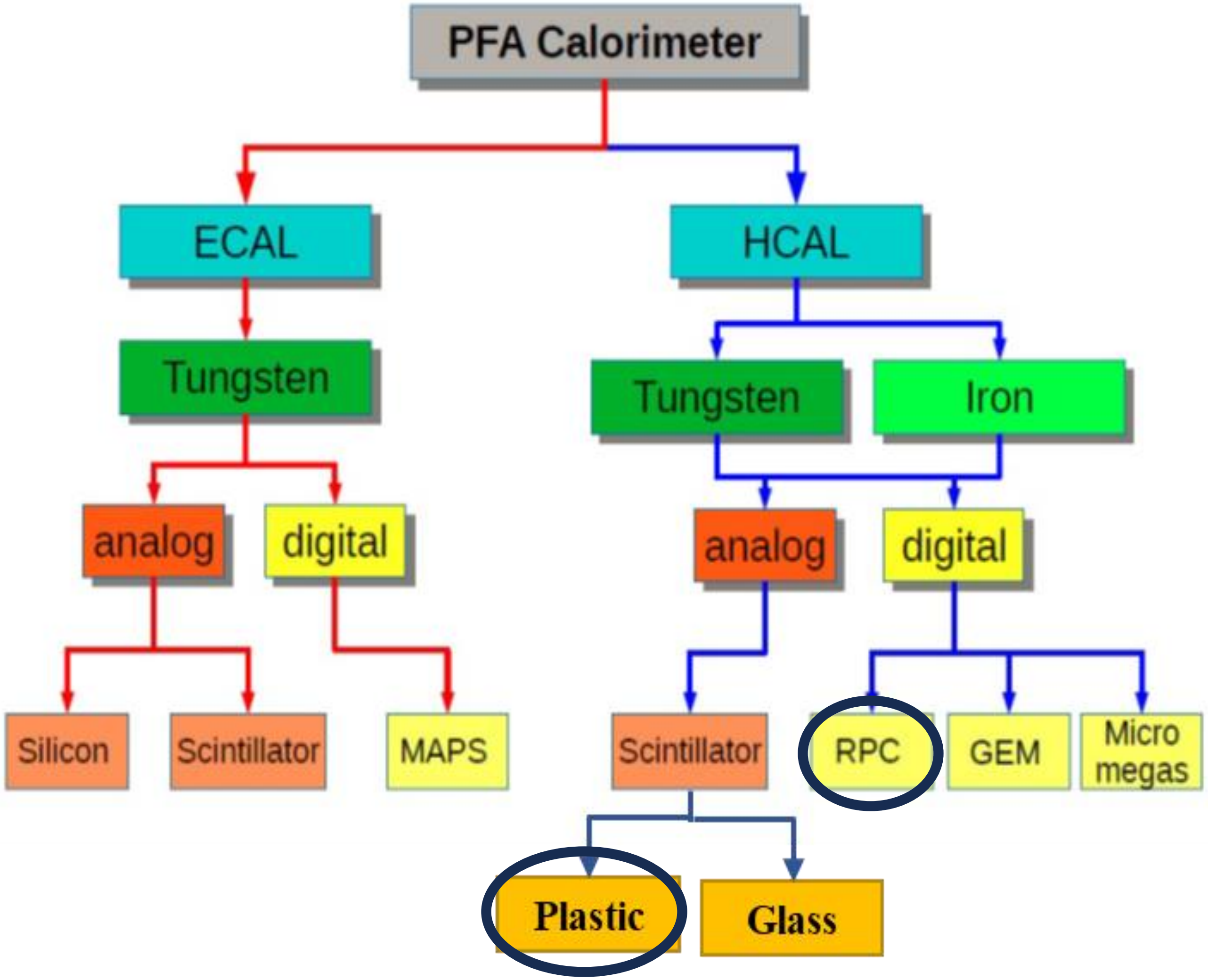
Requirement of CEPC baseline detector



arXiv:1811.10545

Particle Flow Algorithm (PFA)
High granularity Calorimeters





AHCAL based on scintillators
SDHCAL based on glass RPCs

AHCAL Prototype based on Scintillators

❖ Sampling AHCAL

- 40 layers
- Each layer: 72 cm × 72 cm
- Each layer: 18 × 18 = 324 channels

❖ Absorber

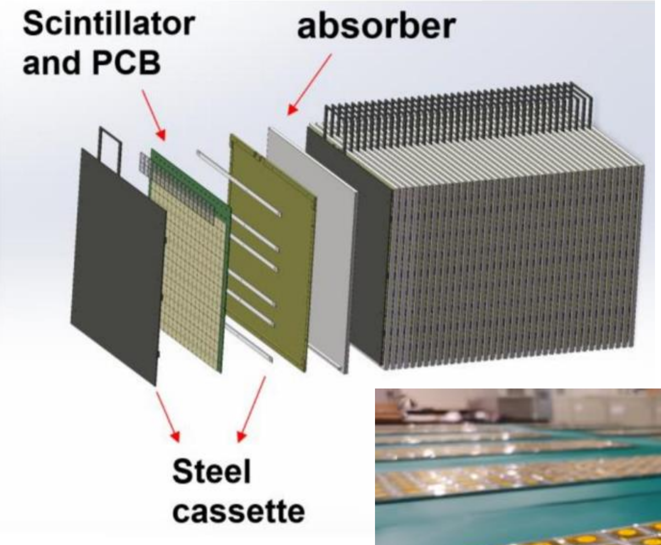
- Iron, 2 cm thickness / layer

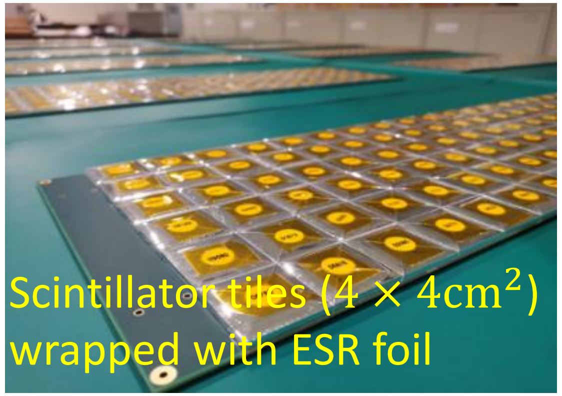
❖ Sensitive Detector

- Scintillator cell size: 40 × 40 × 3 mm^3
- SiPM: HPK S14160-1315 and NDL-22-1515

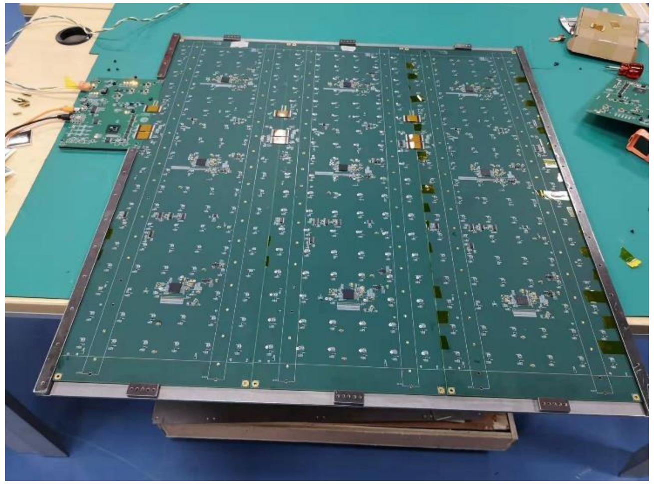
❖ Electronics with analog readout

- SPIROC2E ASIC Chip (36-ch)
- 12960 channels





Scintillator tiles ($4 \times 4cm^2$) wrapped with ESR foil

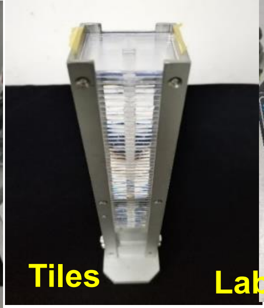


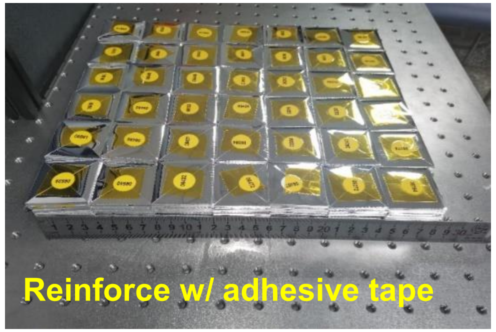
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

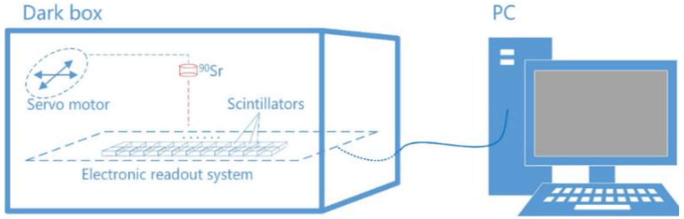
Scintillators Performance Test

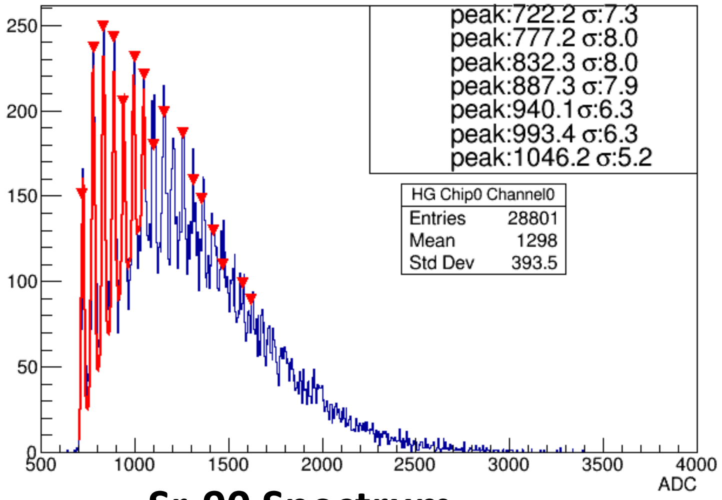
- >15K scintillators are produced with injection molding technique which are wrapped automatically with ESR films
- The batch test platform (with Sr-90)
  - HPK 13360-1325PE SiPM + SPIROC readout
  - 144 channels / batch
  - The light yield is fitted by landau-gauss function

➔ **91.6% of scintillators are within 10% of light yield window**

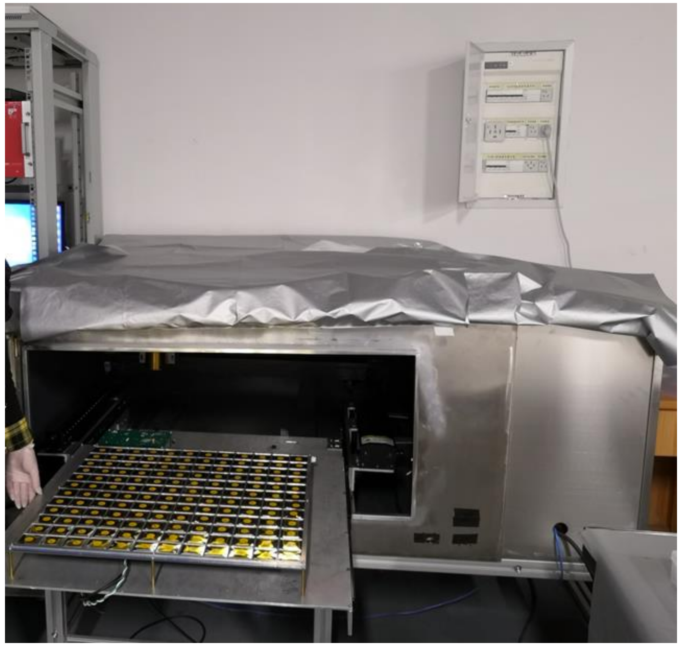




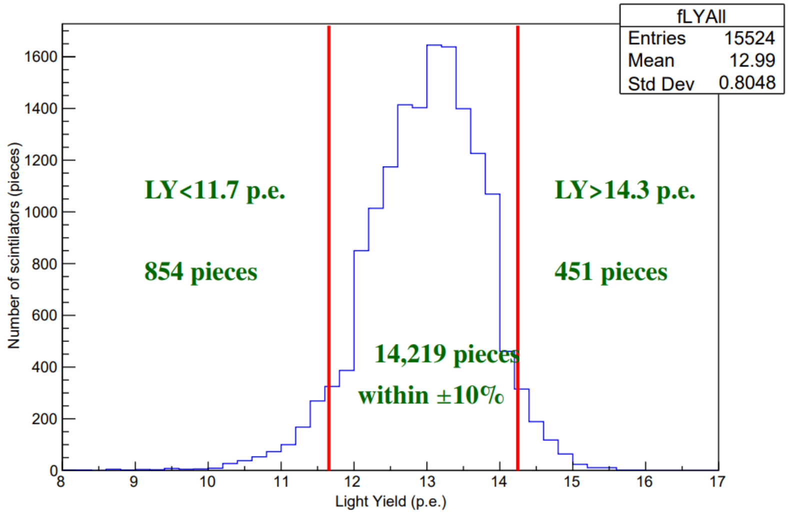




Sr-90 Spectrum



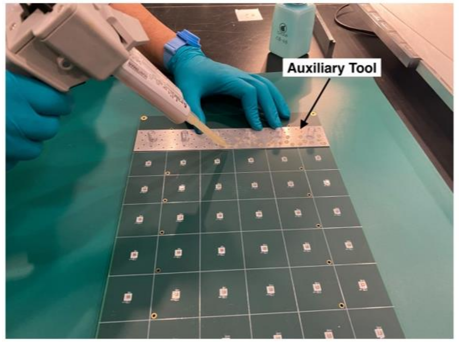
JINST 17 (2022) P05006

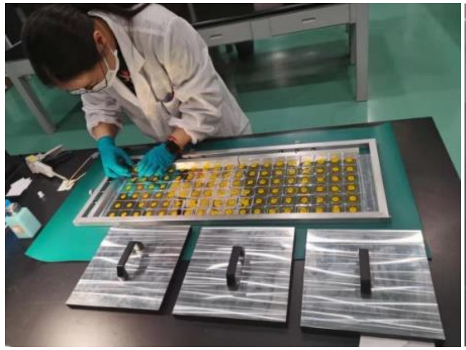


Light yield for all scintillators

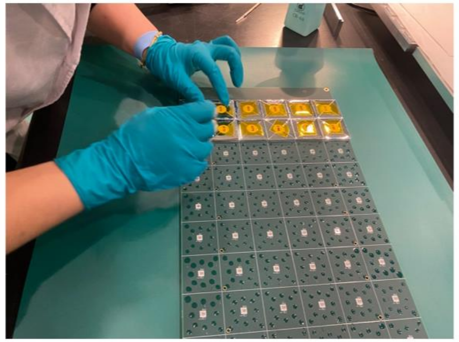
Assembly of Scintillator, SiPM and HBU

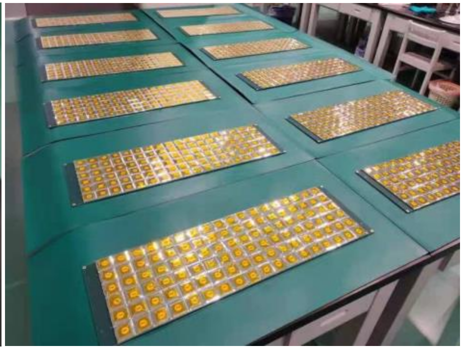
- **Assemble of the AHCAL Prototype (12960-ch, 5-ton)**
  - Assemble the scintillator on HBU with glue
  - Press them with cover plate for solidification
  - Combine 3 HBUs and install in 1 cassette (14.5mm)
  - 40 layers are assembled in the AHCAL prototype
- **38 layers with HPK and 5 layers with NDL SiPM (3 backup)**
- **Assembly completed in August, 2022**



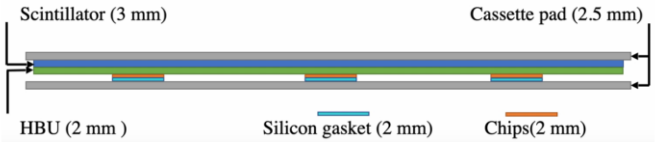


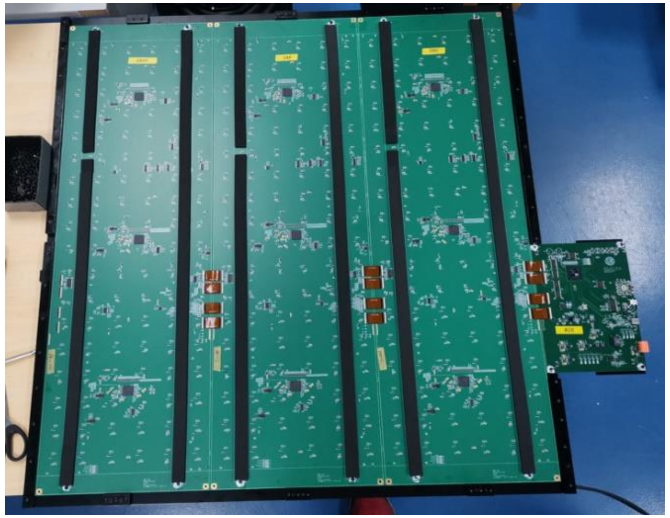
Scintillators on HBU





HBU finished



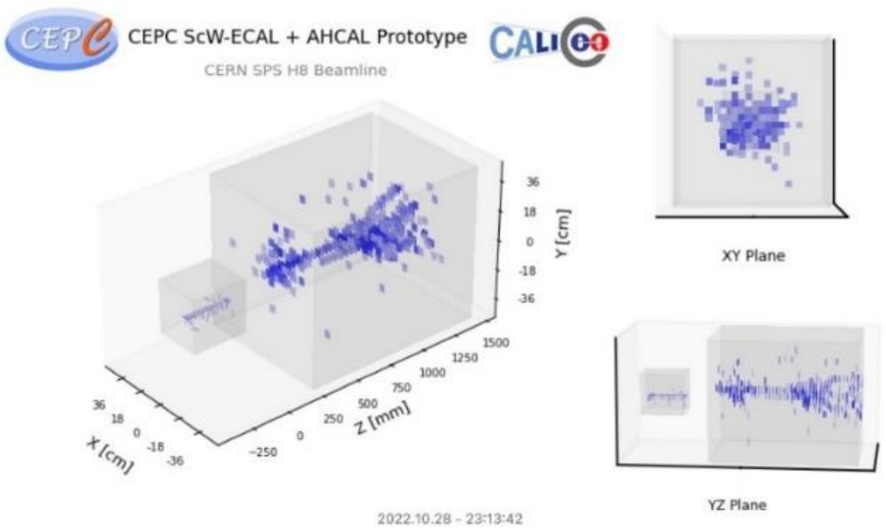


3 HBUs in 1 cassette

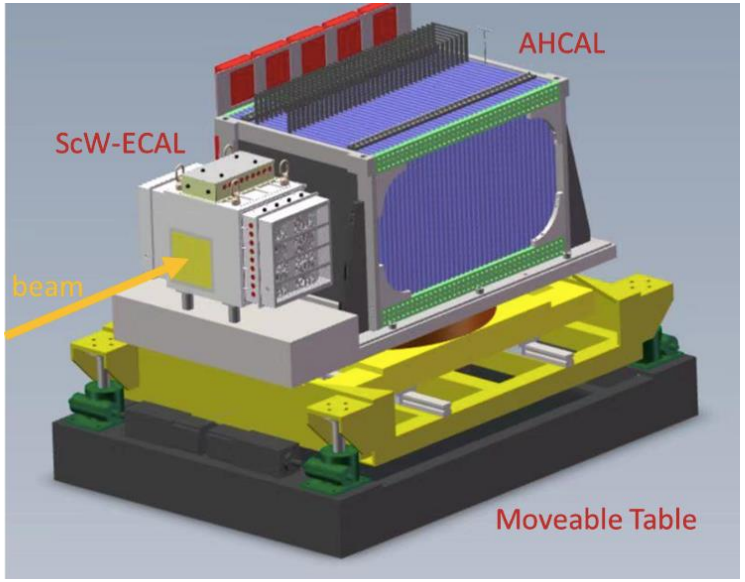
AHCAL with 40 layers

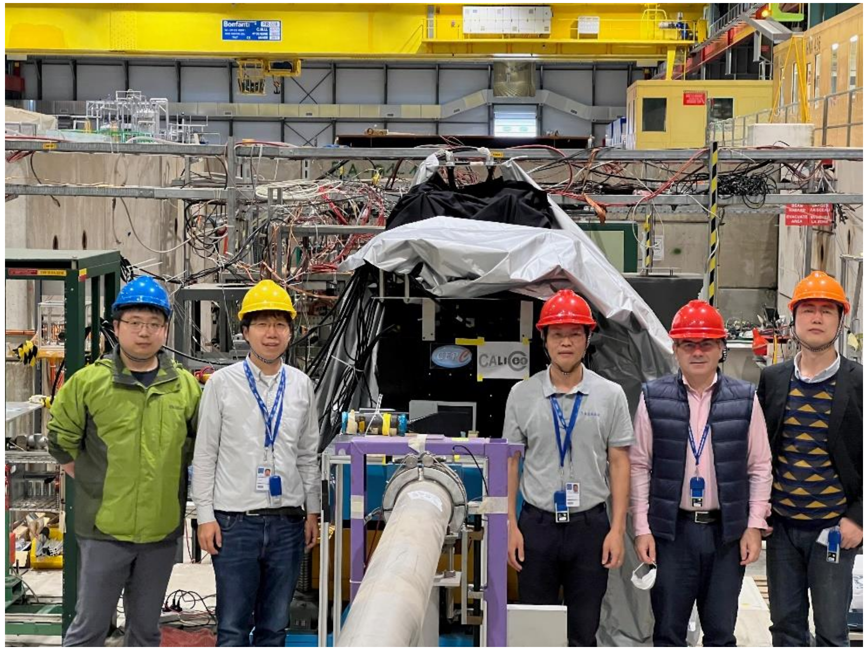
CERN Test Beam in 2022 - 2023

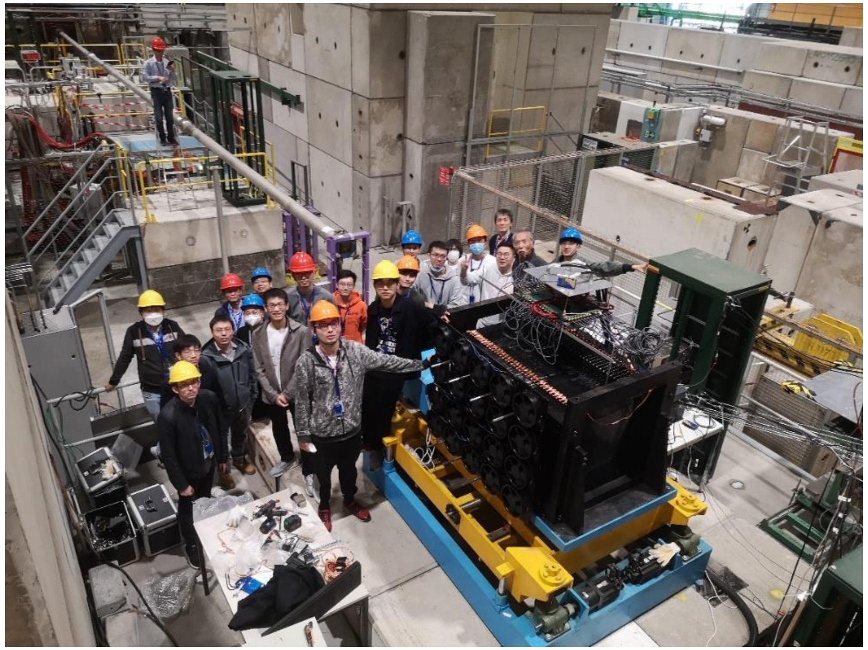
Oct 19 – Nov 2, 2022	Apr 26 – May 10, 2023	May 17 – 31, 2023
SPS H8 beamline	SPS H2 beamline	PS T9 beamline



- **Collected ~60M of test beam data samples**
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 – 250 GeV at SPS
  - Pions: 1 – 15 GeV at PS, 10 – 120 – 150 – 350 GeV at SPS

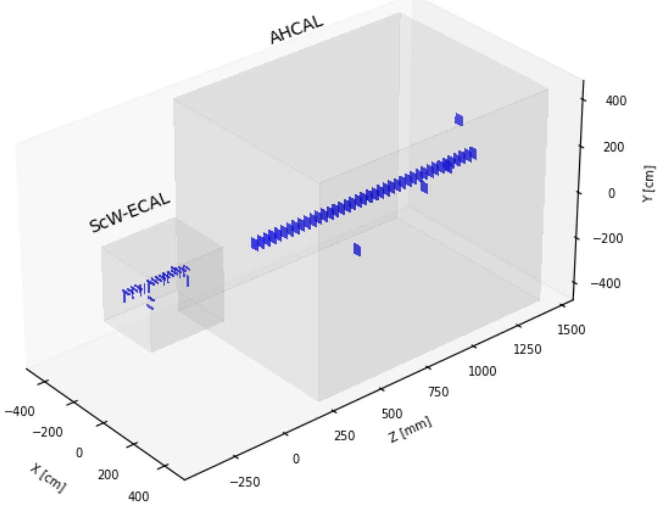


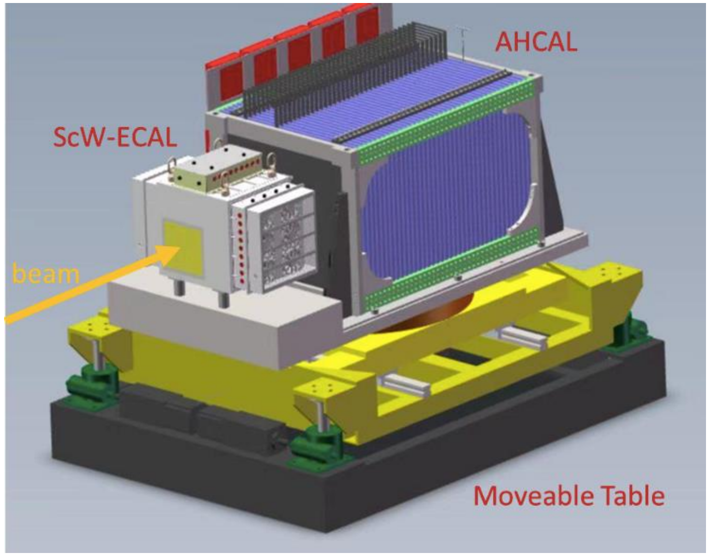




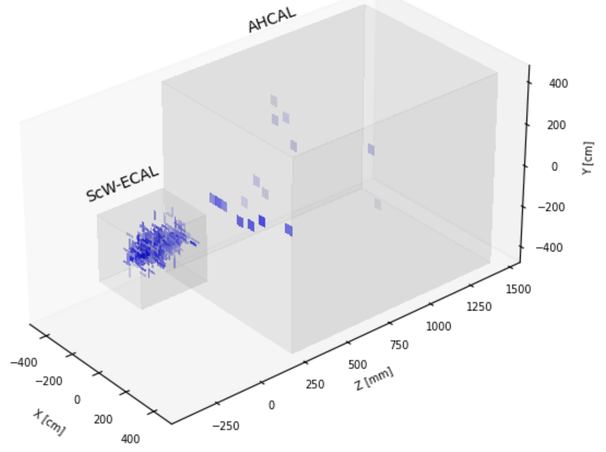
CERN Test Beam in 2022 - 2023

100 GeV mu-

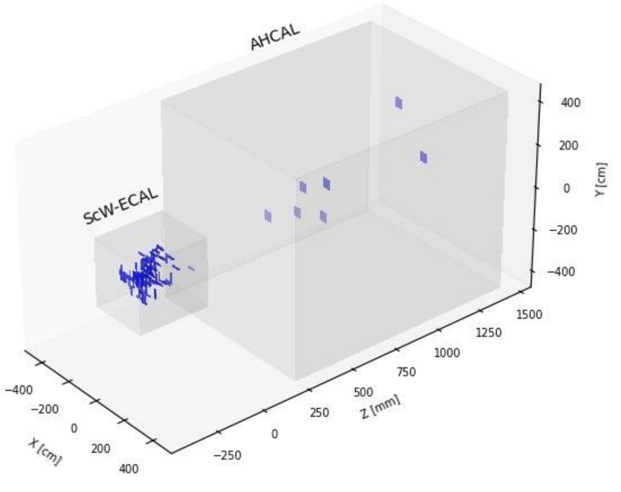




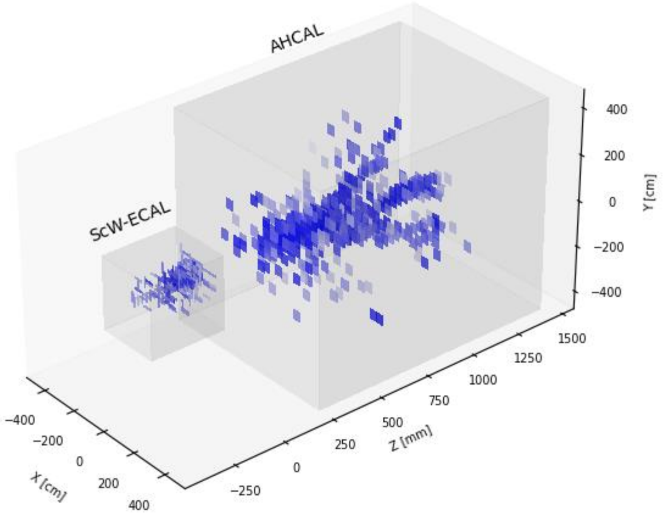
60 GeV electron



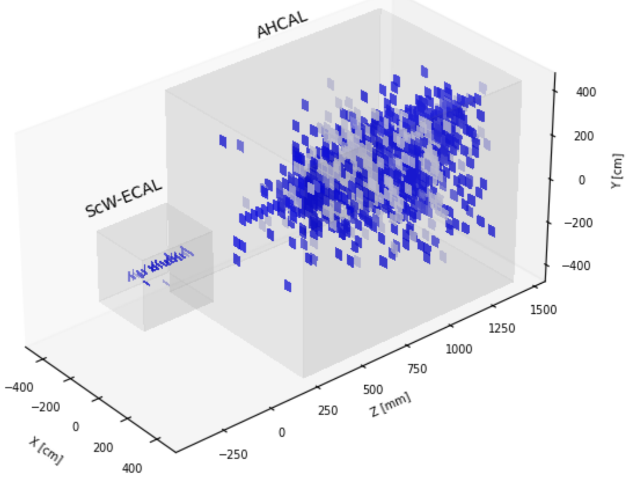
10 GeV negative pion (PS)



60 GeV negative pion (SPS)



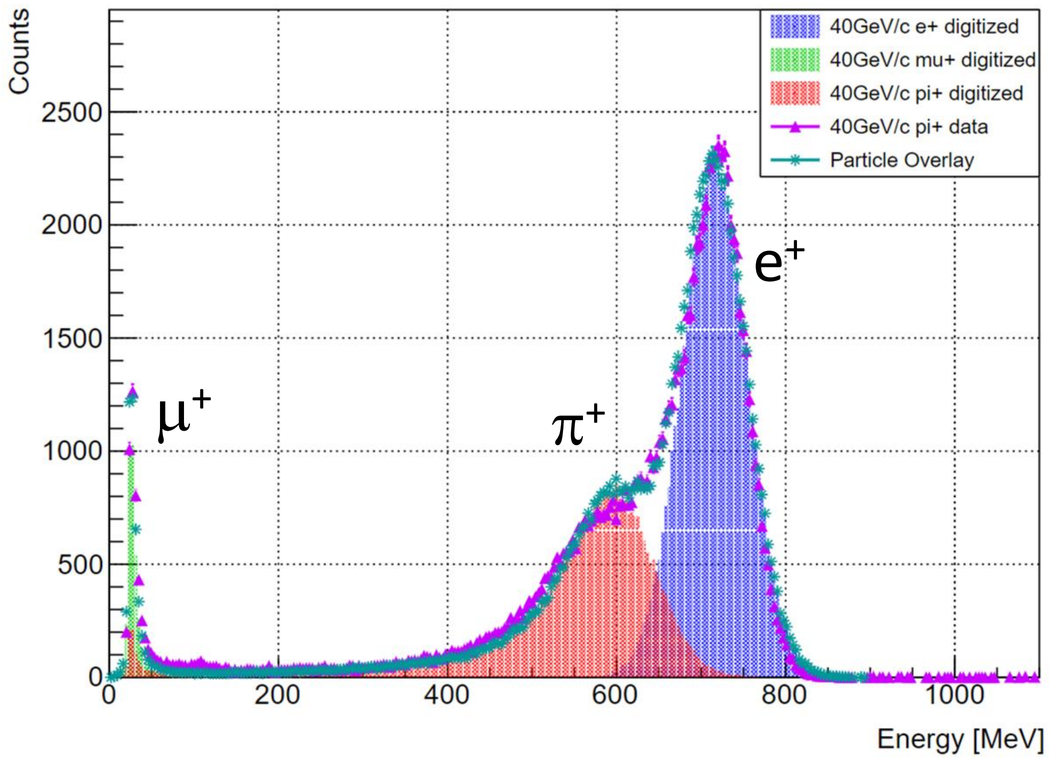
350 GeV negative pion (SPS)



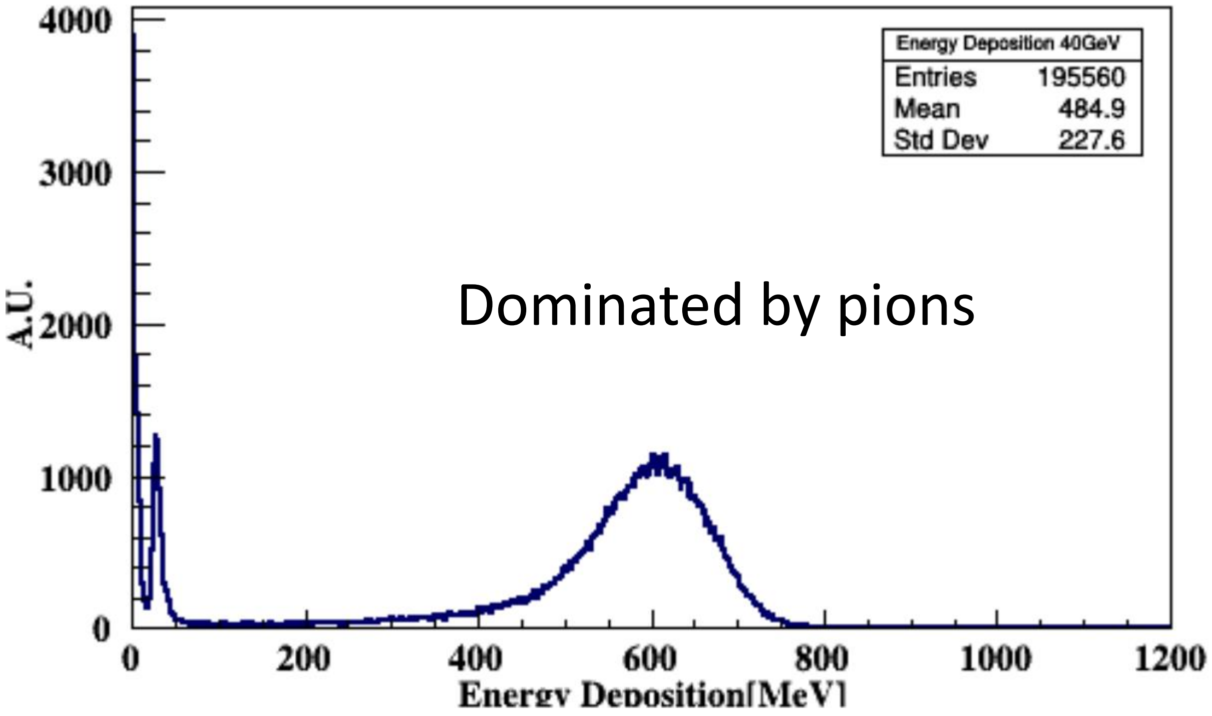
CERN Test Beam in 2022 - 2023

- **Significant beam contamination in SPS-H8 is observed**
  - Mixture of pions, muons, positrons in SPS-H8 beam data
  - Beam purity at SPS-H2 (2023) is significantly better than SPS-H8 (2022)
  - Particle identification techniques developed: to select high-purity data samples

40 GeV π^+ data SPS-H8 (2022)

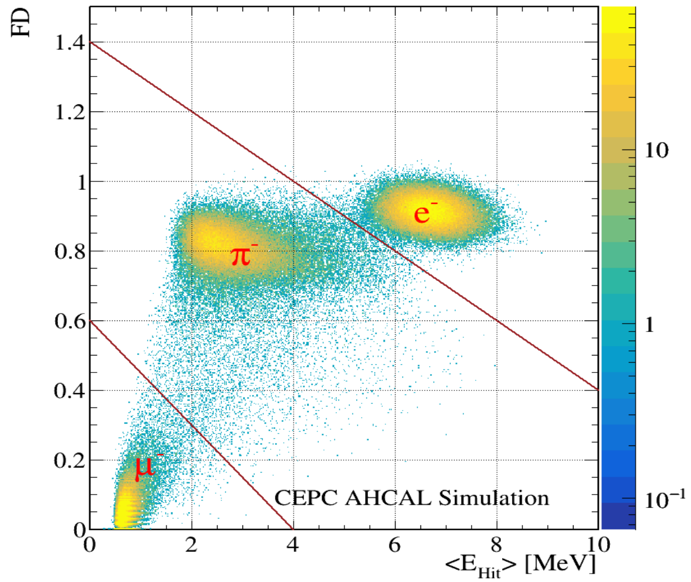


40 GeV π^- data SPS-H2 (2023)



AHCAL: Particle Identification

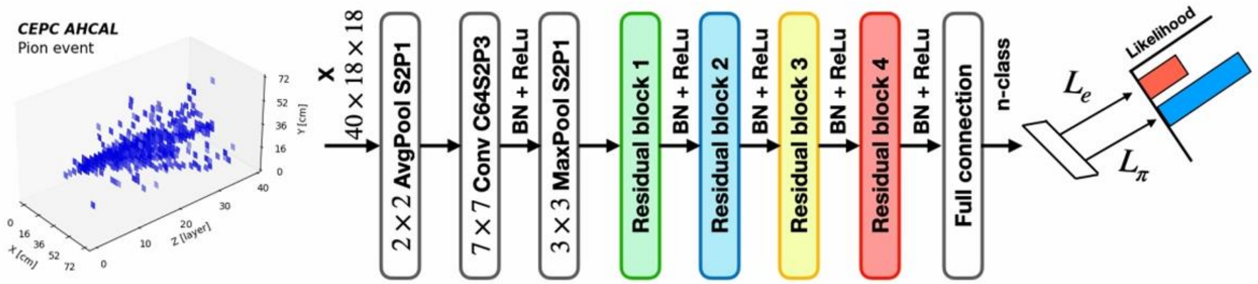
- **PID based on ANN: input tensor of energy deposition per AHCAL tile**
- **ANN is consistent with FD within ~1% level for electron and pion**

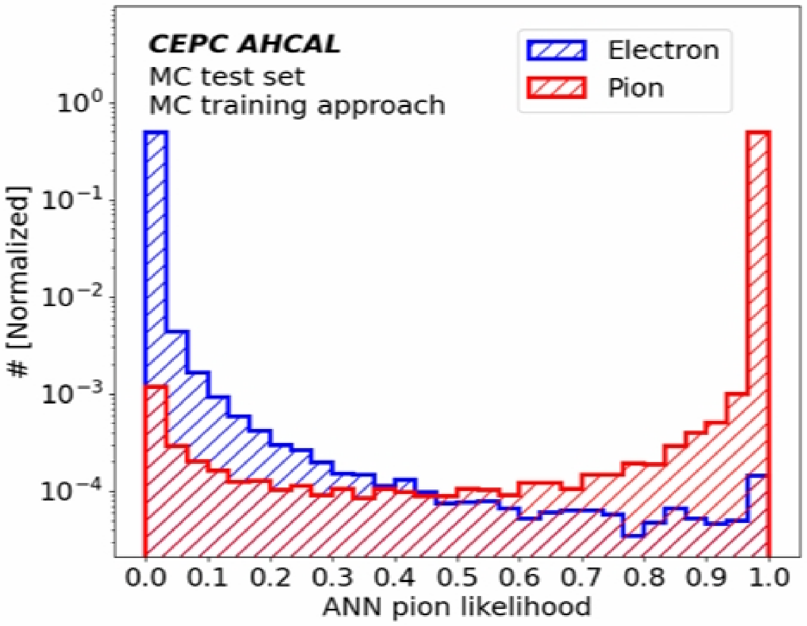


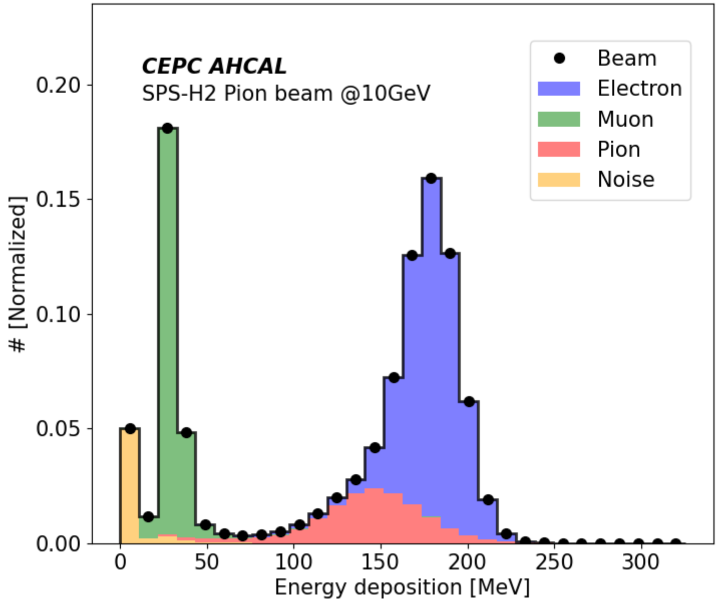
Fractal Dimension (FD): Self-similarity in patterns of particle showers,

$$FD = \left\langle \frac{\log(R_{\alpha,1})}{\log(\alpha)} \right\rangle \text{ where } R_{\alpha,1} = \frac{N_1}{N_\alpha} \text{ and } N_\alpha$$

is number of hits scaled by factor α







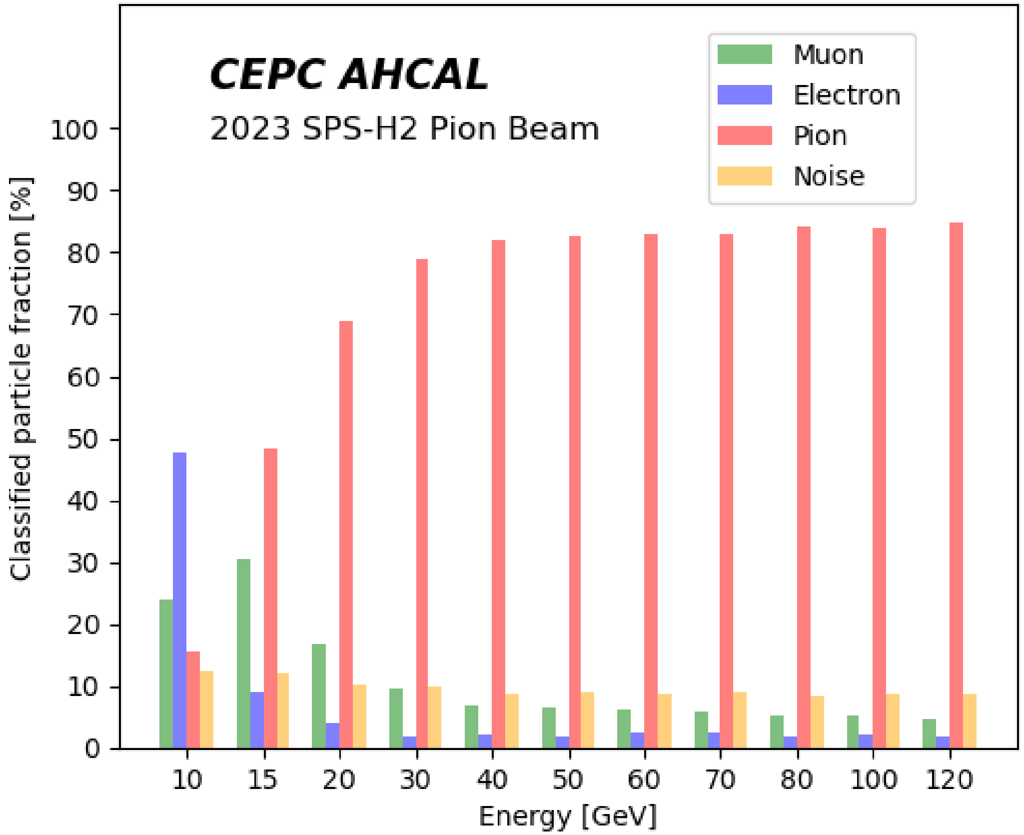
Siyuan Song's thesis work

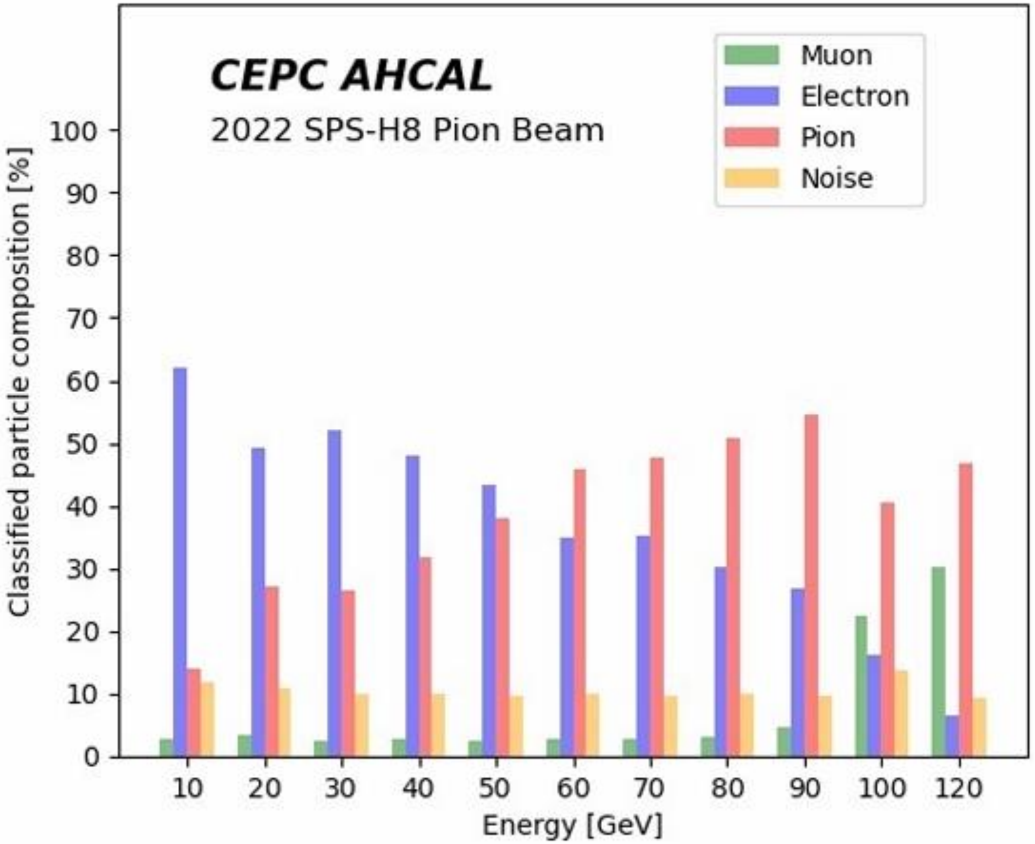
M. Ruan et al., PRL 112, 012001

S. Song et al., JINST 09 (2024) P04033

CERN Test Beam in 2022 - 2023

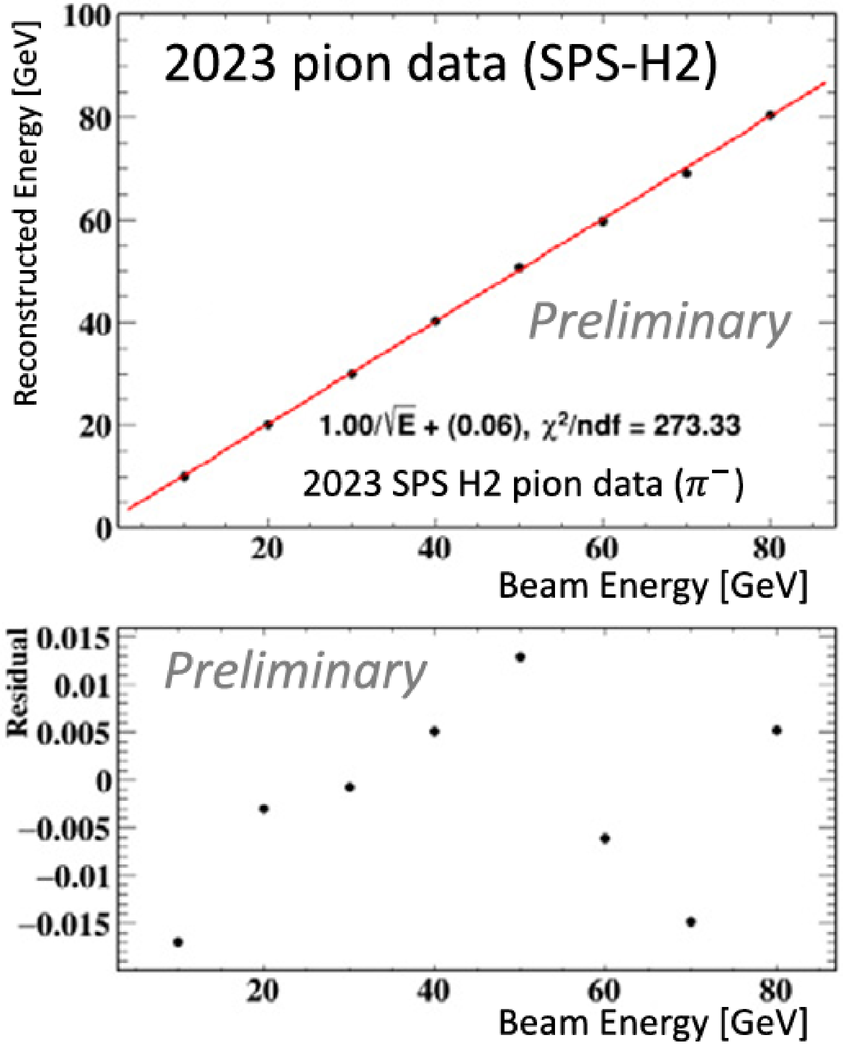
- **Beam composition from SPS-H8 and SPS-H2 beamline**
  - Particle identification techniques developed: to select high-purity data samples
  - SPS-H2 π-: purity is about 80-90% for beam energy $\geq$ 30 GeV
  - SPS-H8 π+: purity is less than 60% with significant contamination from electron



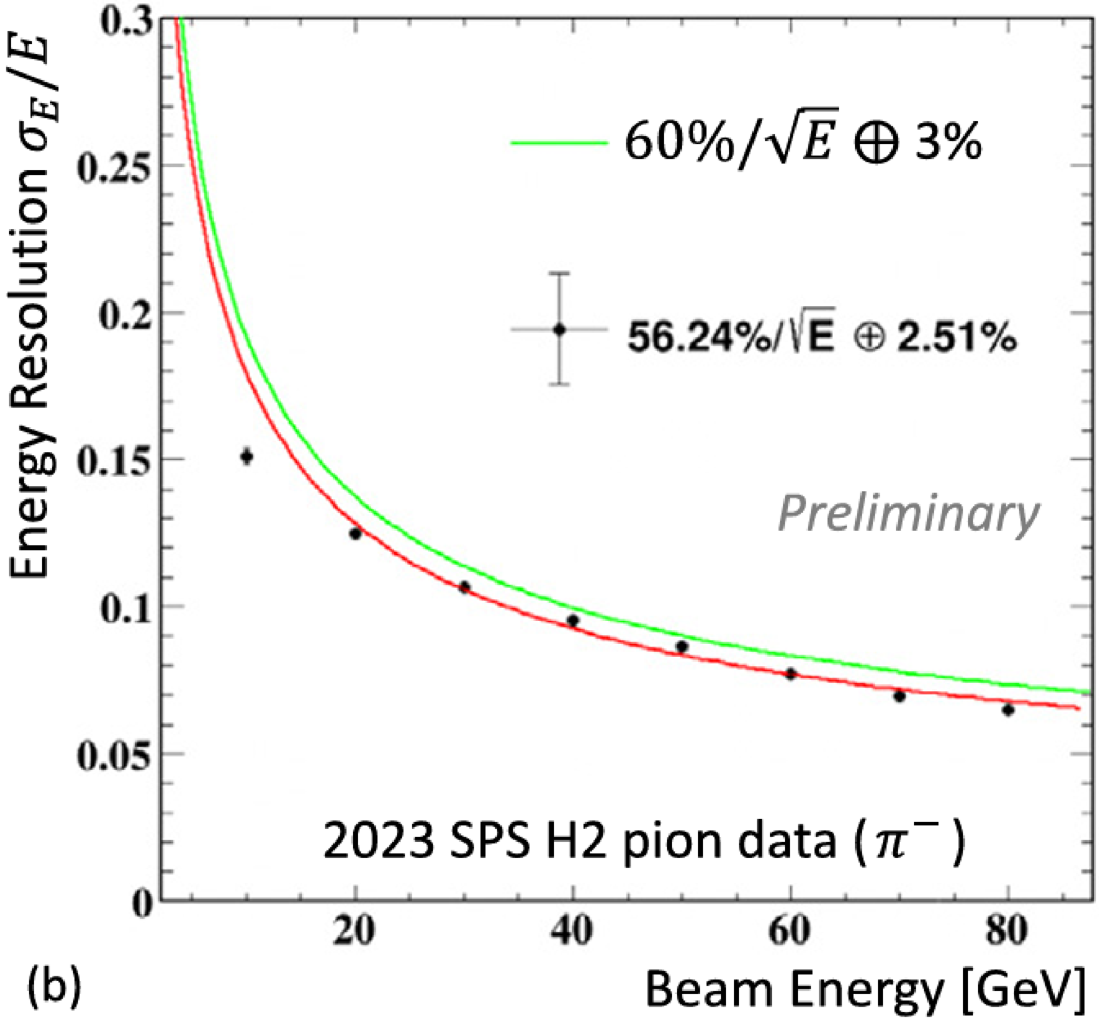


AHCAL: Test Beam Performance

NIMA 1072 (2025) 170191



(a)



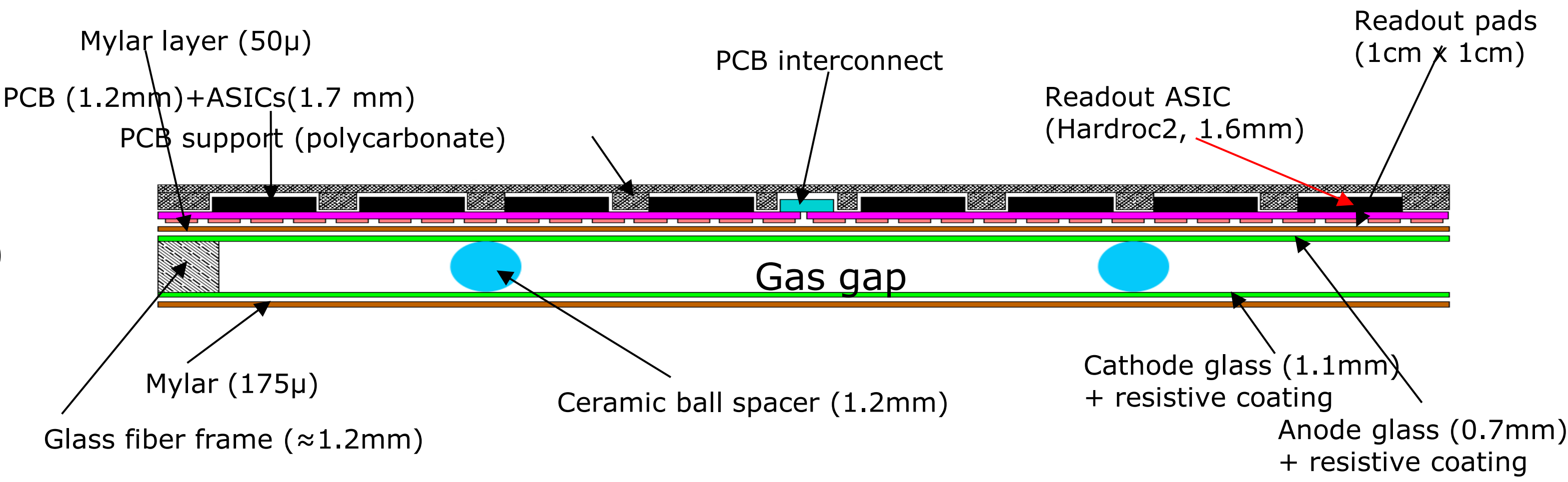
(b)

Rec. Energy Linearity < 1.5%

Hadron Energy Resolution：
$56.2\%/\sqrt{E} \oplus 2.5\%$

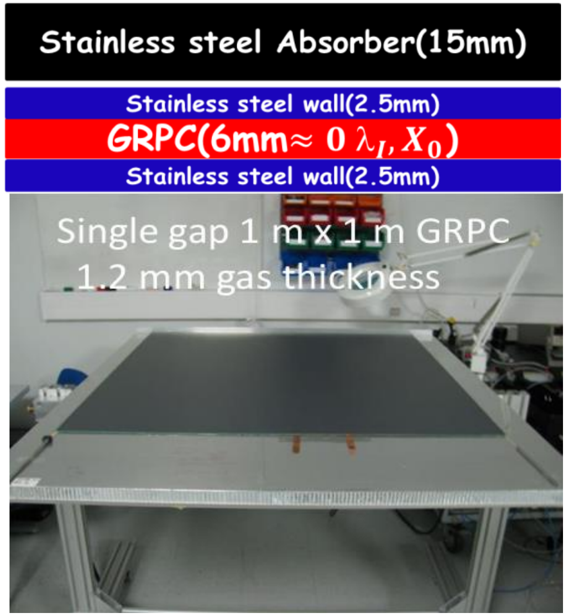
SDHCAL Prototype based on GRPC

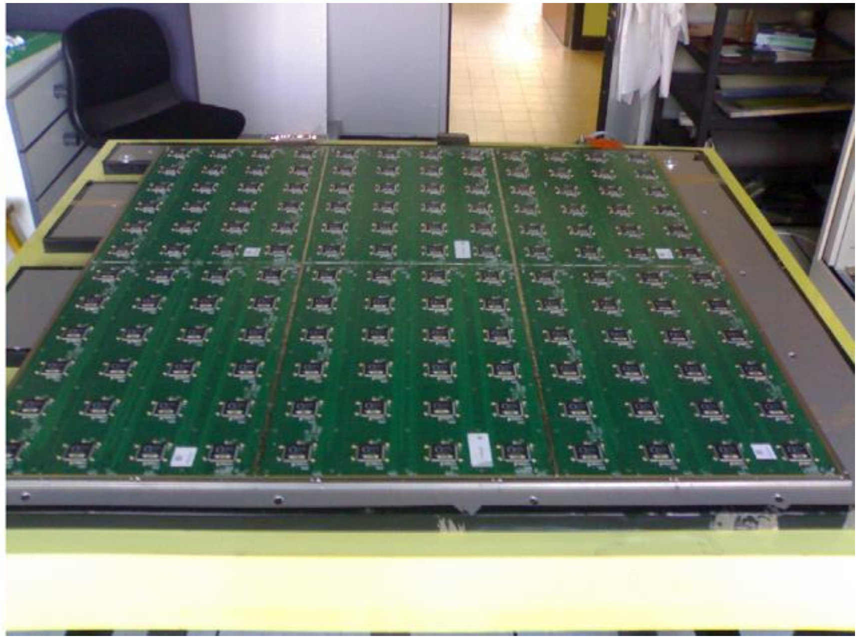
- **Semi-Digital HCAL (SDHCAL)**
  - 48 layers (1m x 1m GRPCs, 6mm)
  - High granularity (1cm x1cm)
  - Three thresholds (64-ch HARDROC)
  - Stainless-steel absorber with self-supporting structure (20mm)
  - Test beam at CERN in 2012, 2015, 2017, 2018 and 2022



JINST10 (2015) P10039

$(0.12\lambda_I, 1.14X_0)$

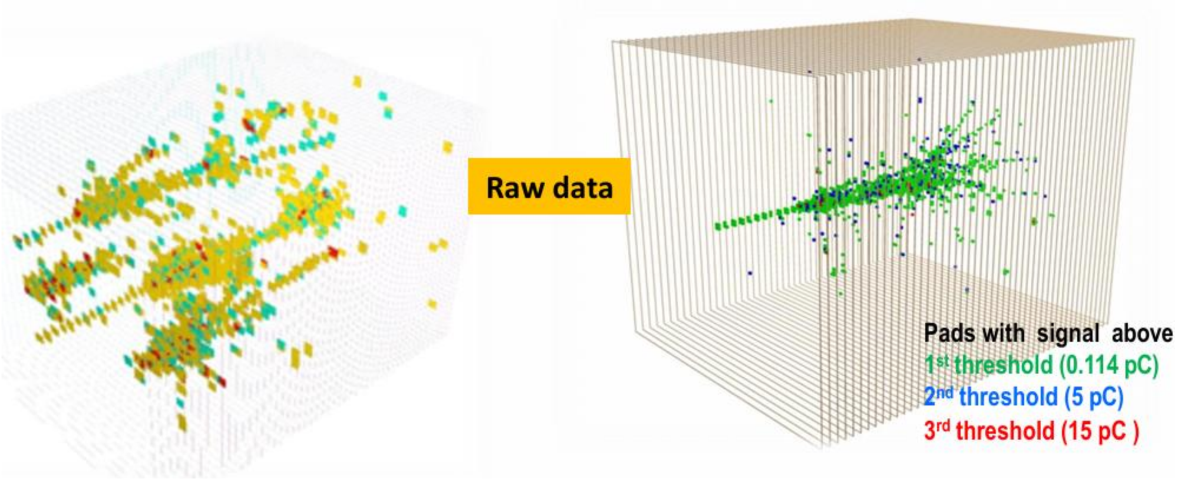


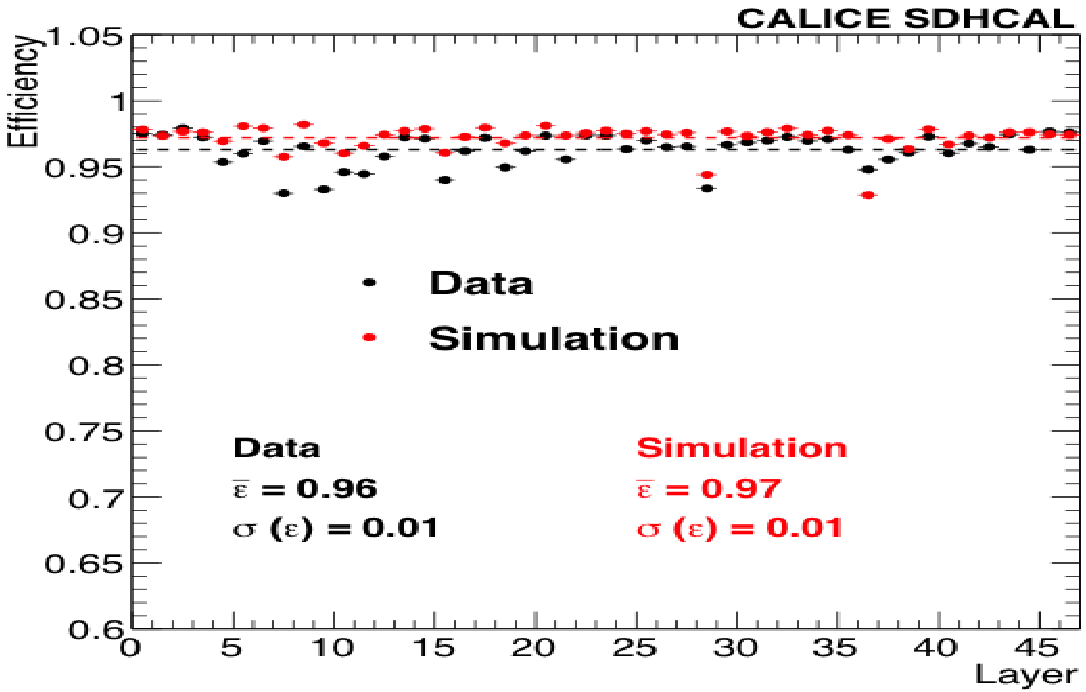


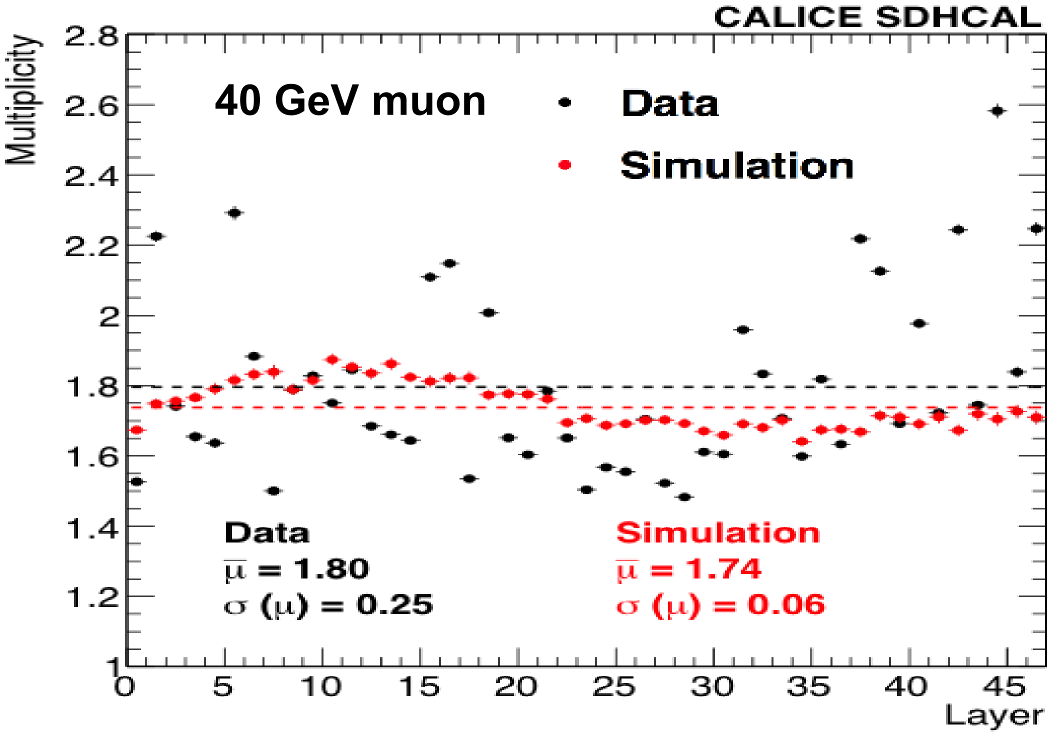
SDHCAL: Efficiency and Multiplicity

➔ SDHCAL Efficiency (Data/MC): 96% / 97%
➔ SDHCAL Multiplicity (Data/MC): 1.8 / 1.74

➔ Good Data and MC agreement for efficiency and multiplicity obtained with cosmic muons and test beam muons.







SDHCAL: Energy Reconstruction

◆ **Energy reconstruction formula:**

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

N_1 = #pads with 1st threshold <signal < 2nd threshold
N_2 = #pads with 2nd threshold <signal < 3rd threshold
N_3 = #pads with signal> 3rd threshold

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

$$\alpha = \alpha_1 + \alpha_2 N_{total} + \alpha_3 N_{total}^2$$

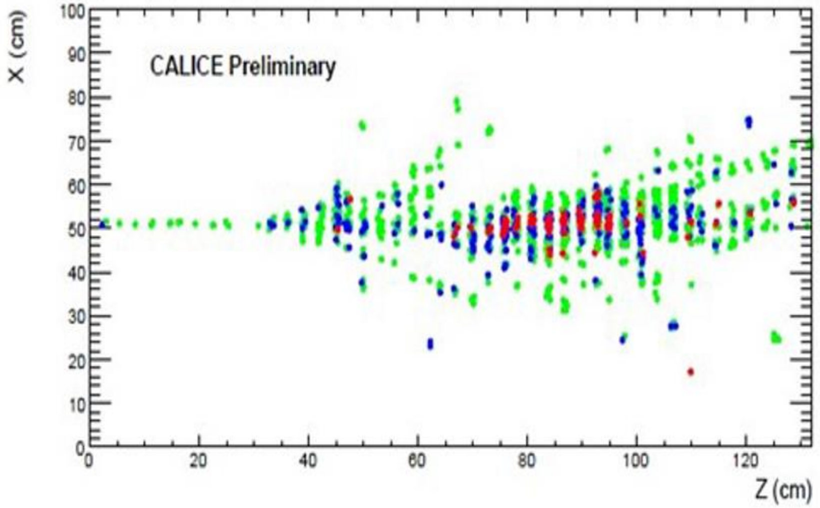
$$\beta = \beta_1 + \beta_2 N_{total} + \beta_3 N_{total}^2$$

$$\gamma = \gamma_1 + \gamma_2 N_{total} + \gamma_3 N_{total}^2$$

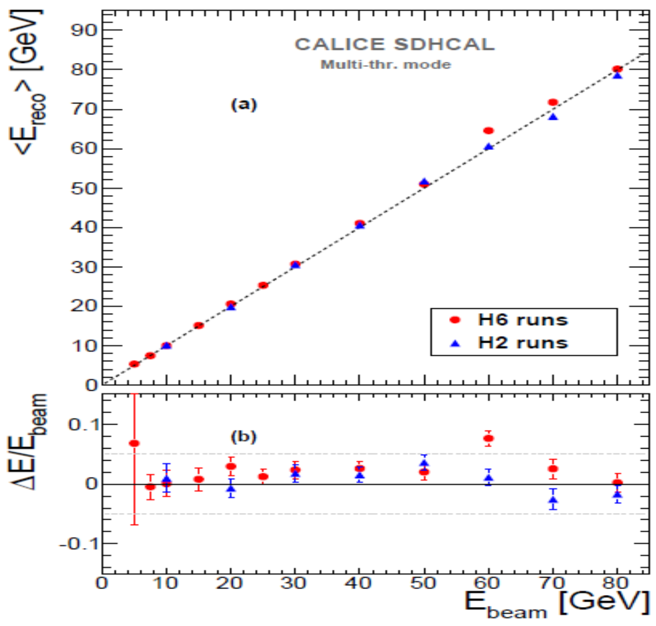
◆ **optimizer**

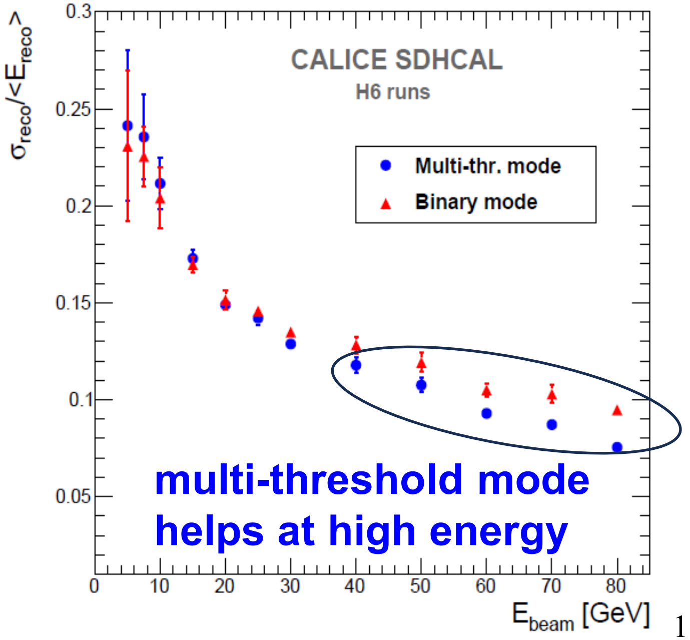
$$\chi^2 = \sum_{i=1}^{N} \frac{(E_{beam}^i - E_{reco}^i)^2}{\sigma_i^2} \quad , \sigma_i = \sqrt{E_{beam}^i}.$$

JINST 10 (2015) P10039
JINST 11 (2016) P04001
JINST 12 (2017) P05009



➢ **80 GeV Pion beam (CERN)**



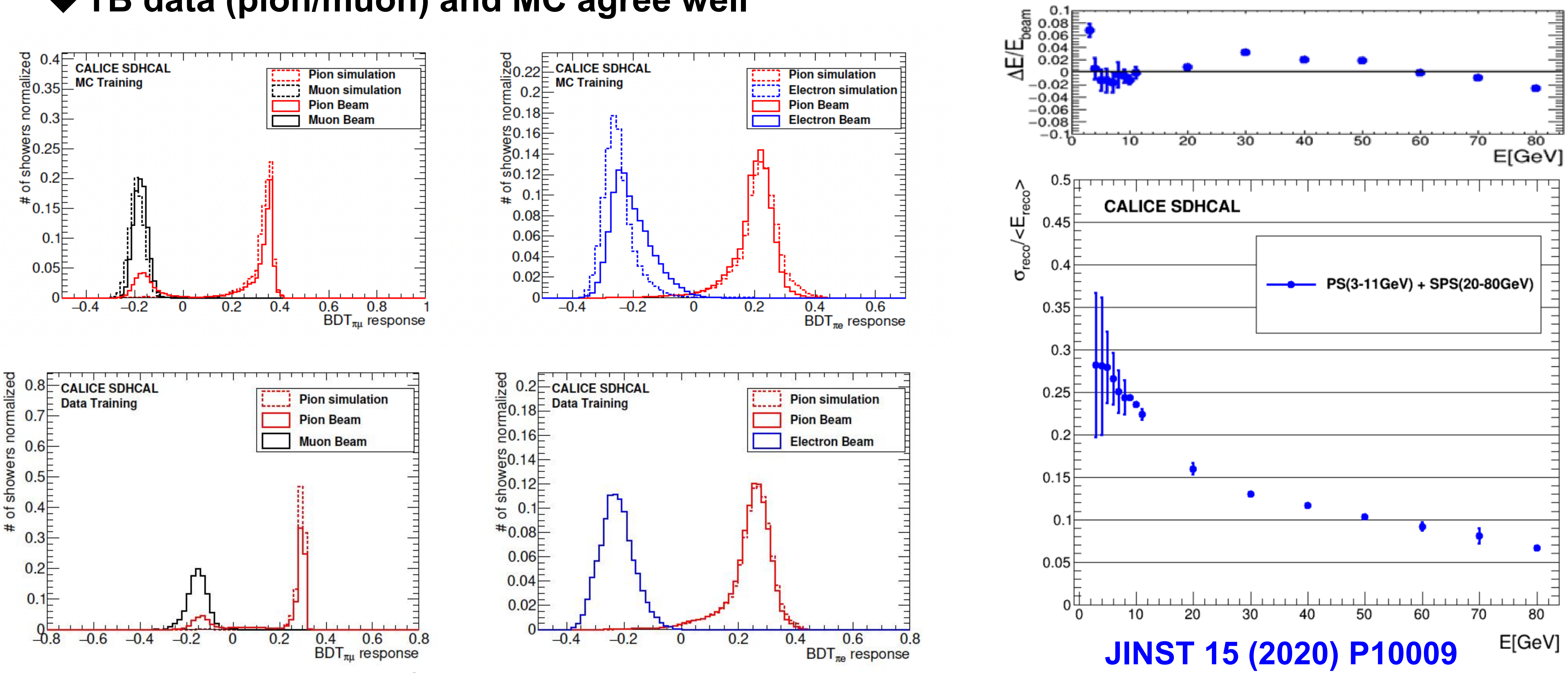


multi-threshold mode helps at high energy

SDHCAL: PID and Energy Resolution

- Using BDT to improve pion, e and muon PID
- Pion eff > 99% with e & muon rejection > 99%
- TB data (pion/muon) and MC agree well

- Energy linearity: < ~3%
- Energy resolution: $65\%/\sqrt{E} \oplus 2.5\%$



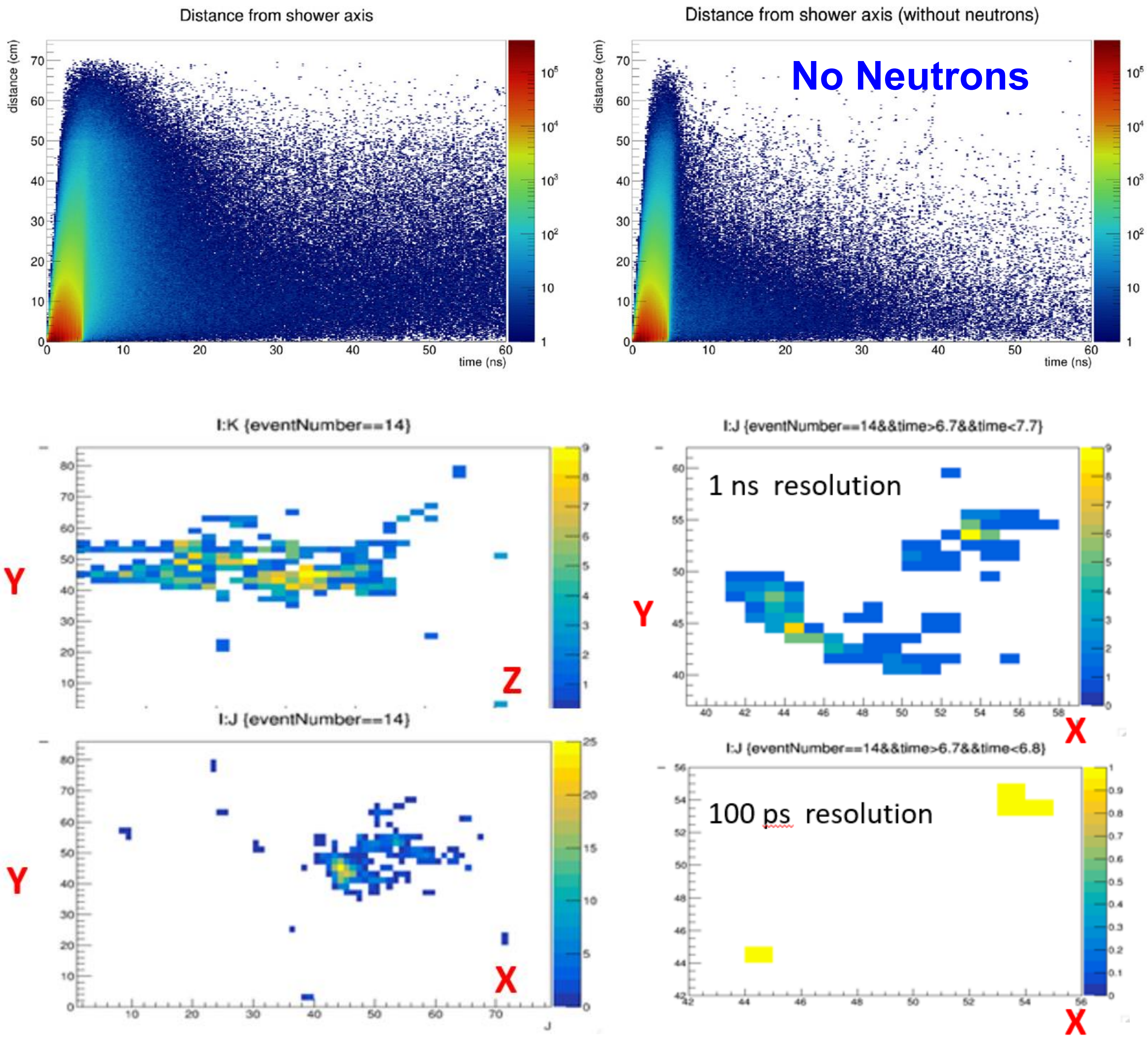
Bing Liu's thesis work

JINST 15 (2020) P10009
JINST 17 (2022) P07017

From SDHCAL to T-SDHCAL (5D)

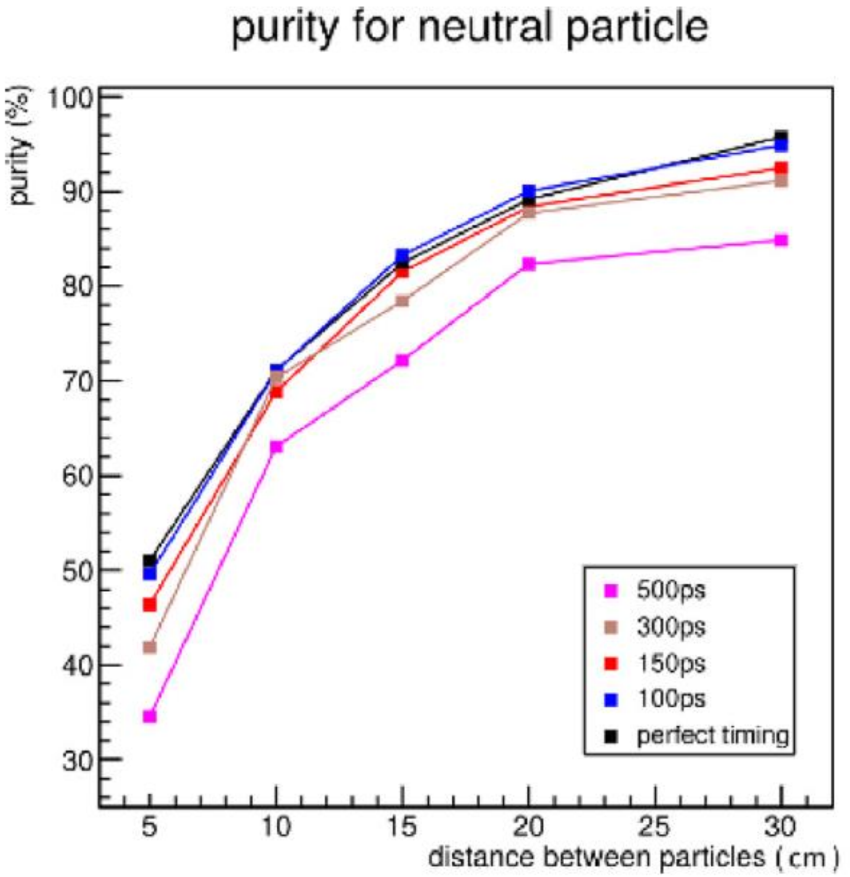
- Hadronic showers have time structure with late components connected to neutron-induced particles
- Time resolution on order of 100 ps to 1 ns results in a sharper distribution of shower core which improve significantly hadronic showers separation at lower distances
- Fast timing info of calorimeter (5D- X,Y,Z,E,T) opens up new possibility in event and object reconstruction
- Lyon-iP2i, IJCLab, CIEMAT, VUB, U. Cordora, GWNU, Yonsei U., SJTU etc.

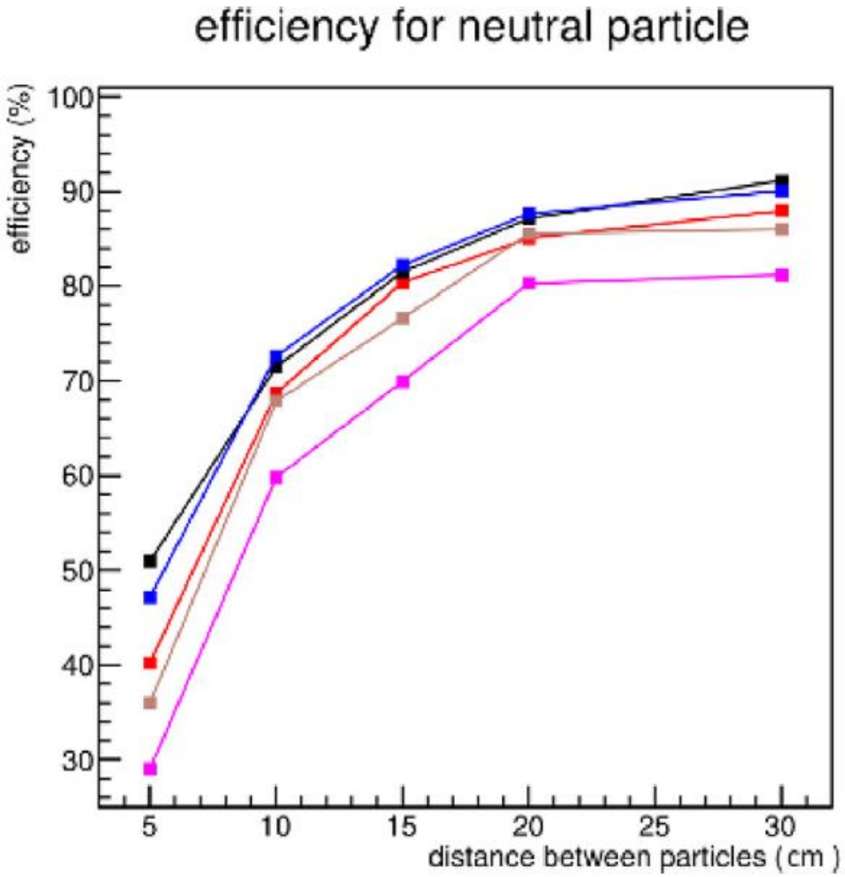
NIMA 1077 (2025) 170520



From SDHCAL to T-SDHCAL (5D)

- Separation of close-by hadronic showers with variant timing resolutions (e.g. 10 GeV neutral and 30GeV charged particle, 100ps – 500ps)
- Timing resolution ~100ps provides descent efficiency & purity of neutral particles



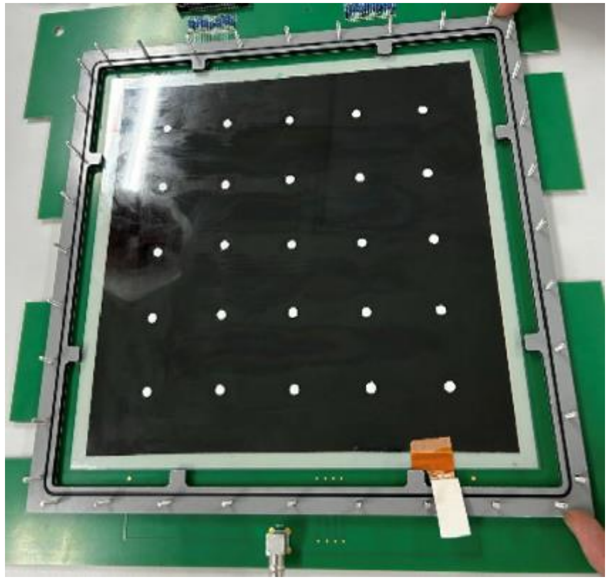


C. Devanne 's thesis work

From SDHCAL to T-SDHCAL (5D)

- Replacing the single-gap RPCs with **multi-gap RPCs (MRPC)**
  → 4-5 gaps of 250 μm each can provide 100 ps timing resolution
- Replacing HARDROC ASIC with a new ASIC (continuous readout + Internal TDC)
  → started with PETIROC (~40ps jitter), aiming for LiROC+PicoTDC
- SDHCAL was firstly developed for ILC, i.e. low rate and power pulsing, needs to be adapted to cope with future circular collider (CEPC, FCC-ee) requirements

Using mylar as spacer

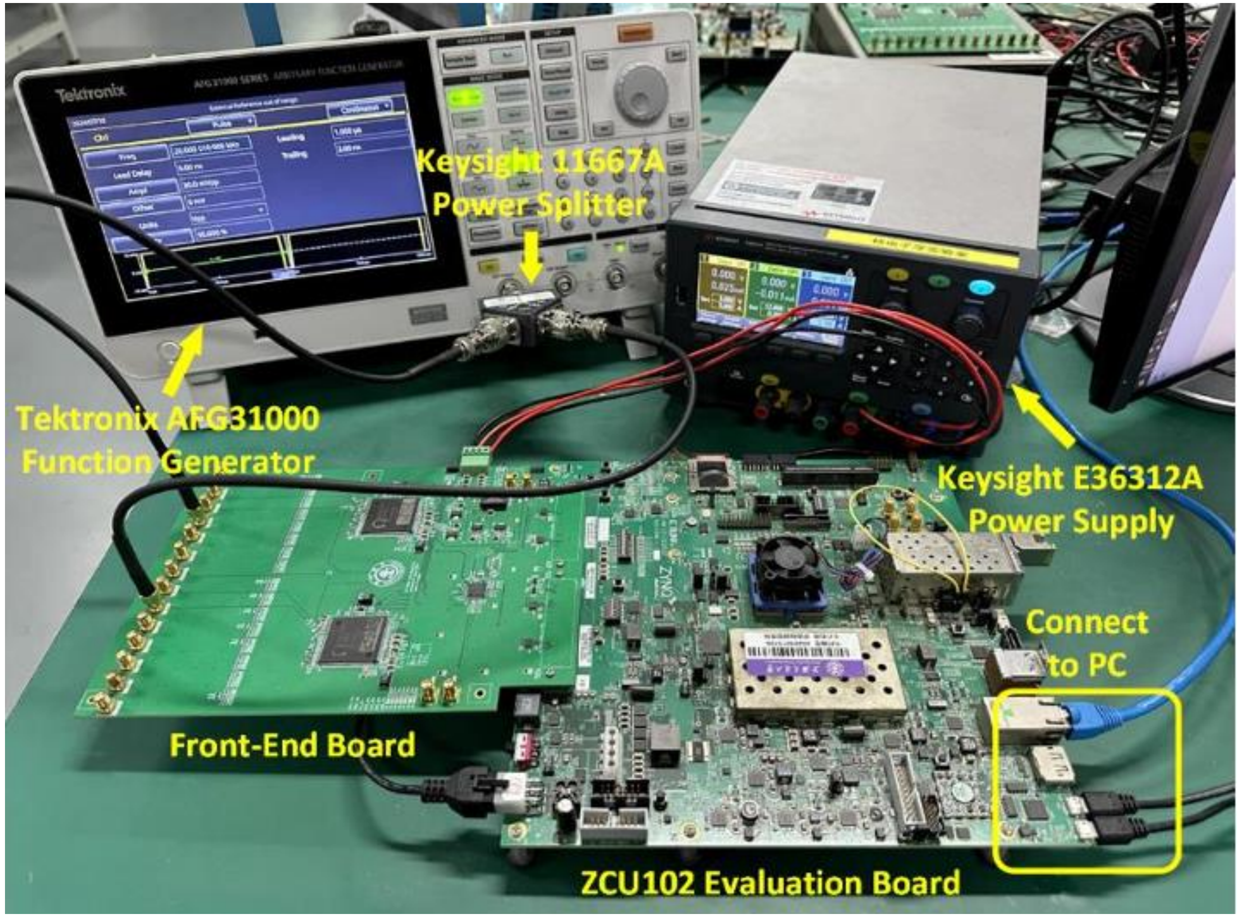


MRPC: 30 x 30 cm^2

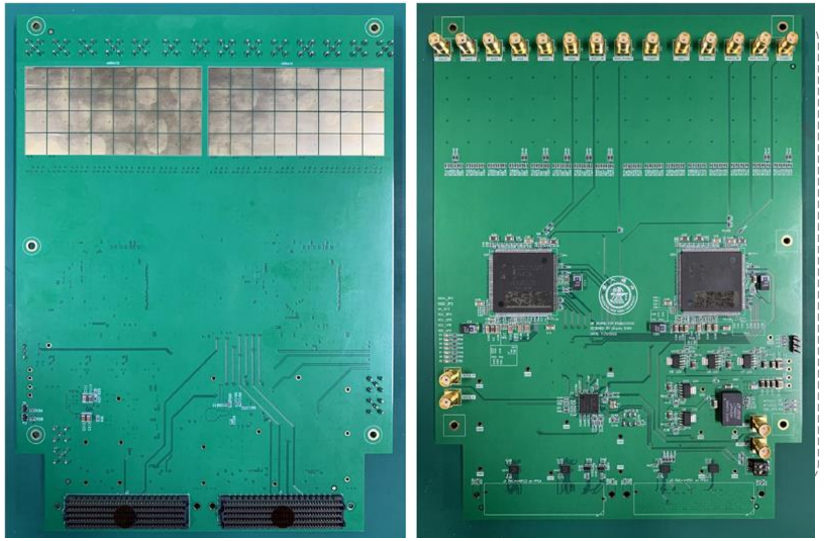
MRPC: 100 x100 cm^2

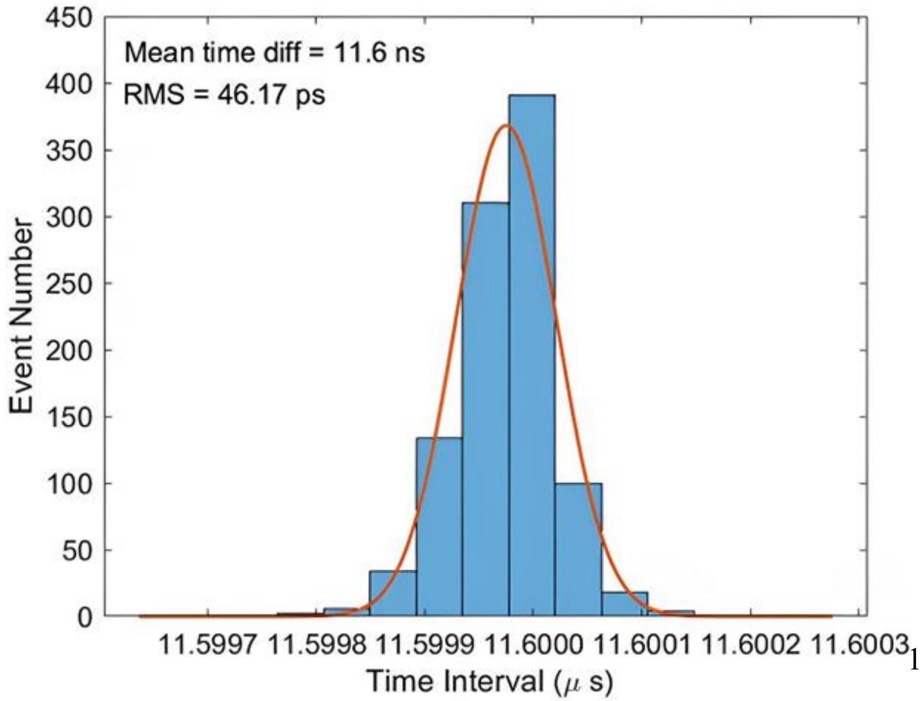
From SDHCAL to T-SDHCAL (5D)

- PETIROC-based readout PCB with 2 ASICs and 64 readout pads. (W. Wu et.al., SJTU)
- Single channel test, time resolution ~46 ps (RMS)



Yongqi Tan's thesis work





Summary and Plan

- **PFA calorimeter prototypes (Scintillators or GRPC based)**
  - Successful beam test campaigns at CERN PS/SPS
  - Collected decent statistics of data samples in the wide energy range
  - Invaluable for detector performance evaluation and shower studies

- **PID and validation studies: preliminary results promising**
  - Particle Identification with machine learning: muons, electrons, pions
  - Prototype simulation + digitization: validation studies with beam data

- **Future: DRD-on-Calorimetry (DRD6 and DRD1) collaboration**
  - Common software, DAQ and beamtest campaigns
  - Ongoing efforts to improve data/MC consistency and for T-SDHCAL (5D)

Thanks for your attention !

Hadronic Calorimeters based on Scintillators and GRPCs

Haijun Yang (SJTU/TDLI)
On behalf of the CEPC Calo Group

Acknowledgement

- Two prototypes are supported by the MOST and NSFC grants
- Successful beam test campaigns at CERN during 2022-2023
- We highly appreciate strong teamwork and enormous support received from CERN, CALICE and EuroLabs


CERN SPS-H2, May 2023


CALICE spokesperson’s visit

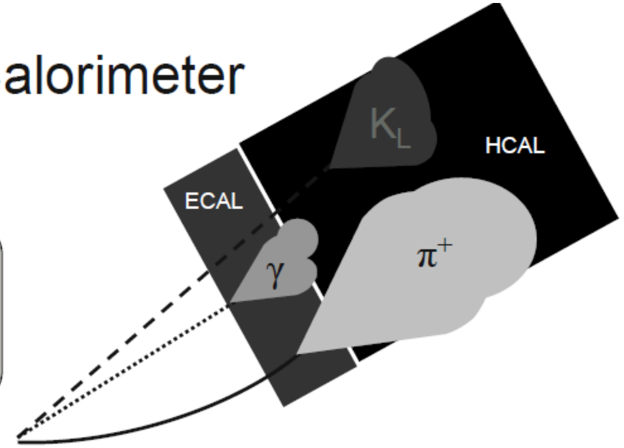

CERN PS-T9, May 2023

Particle Flow Algorithm

Particle Flow Algorithms and Imaging Calorimeter

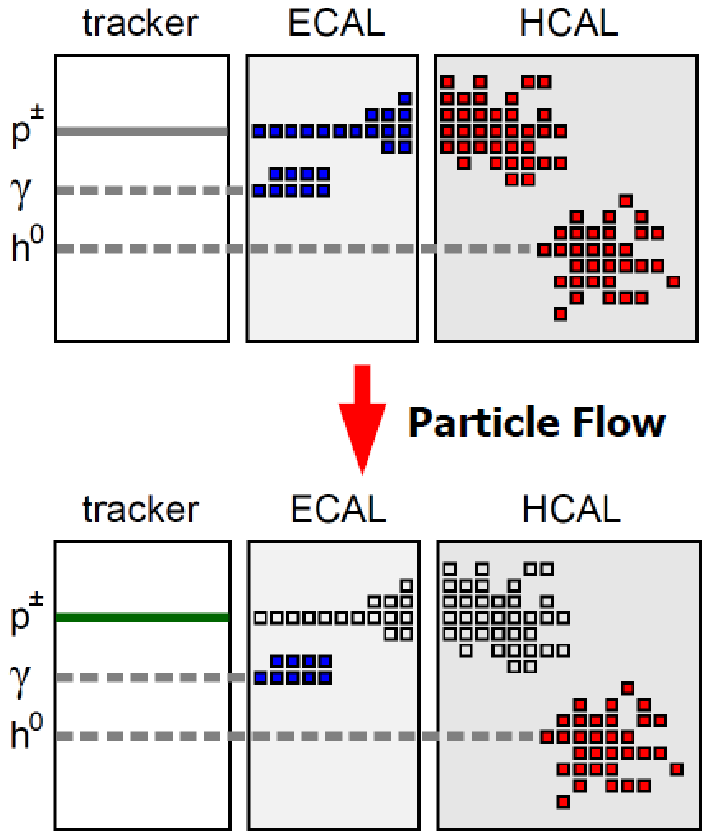
The idea…

Charged particles	measured with the	**Tracker**
Neutral particles		**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



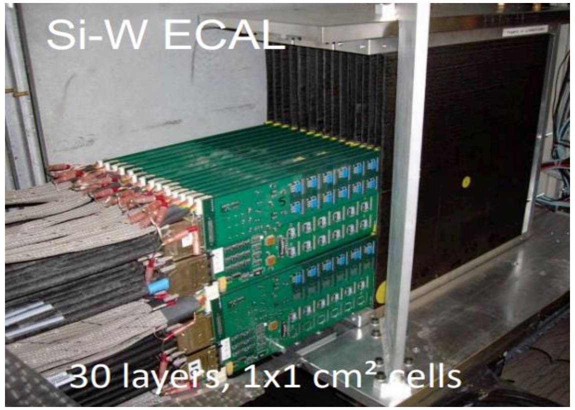
Requirements for detector system

- → Need excellent tracker and high B – field
- → Large R_l of calorimeter
- → Calorimeter inside coil
- → Calorimeter as dense as possible (short X_0, λ_I)

} **thin active medium**

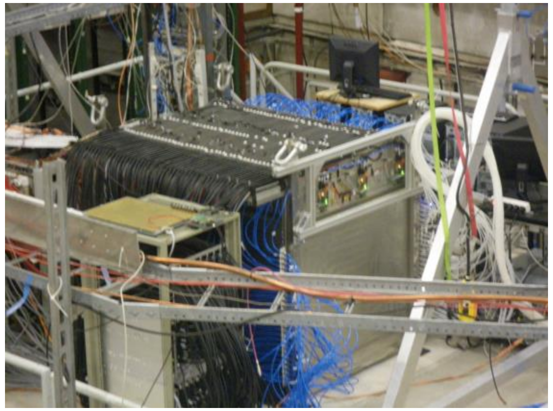
- → Calorimeter with **extremely fine segmentation**

Calorimeters Prototypes for CEPC



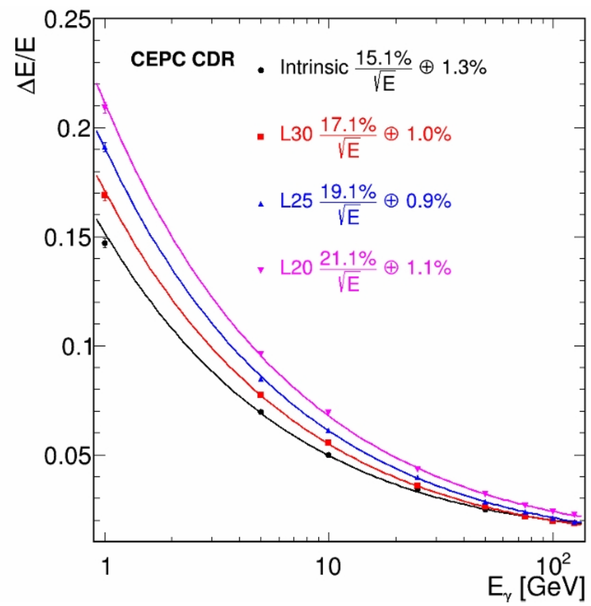
Si-W ECAL, 30 layers, 1x1 cm^2

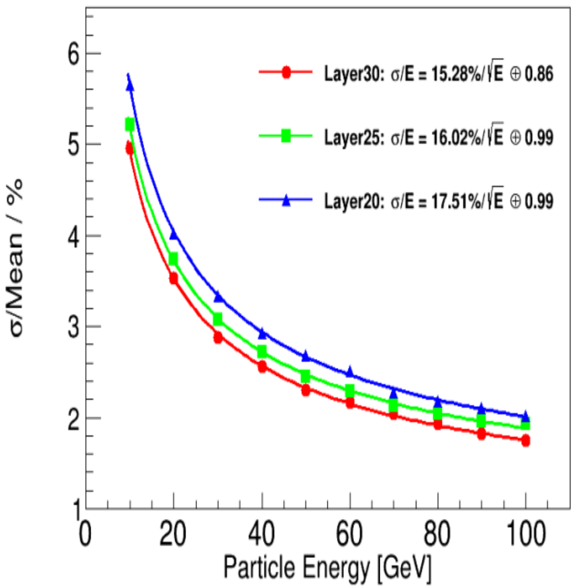
Sci-W ECAL, 32 layers, 5x5 mm^2

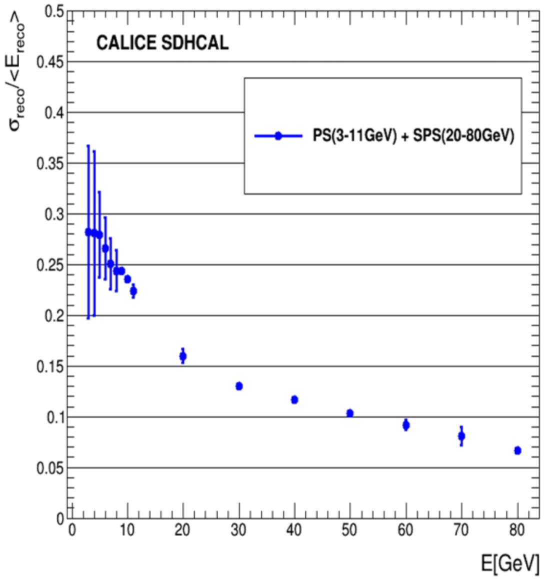


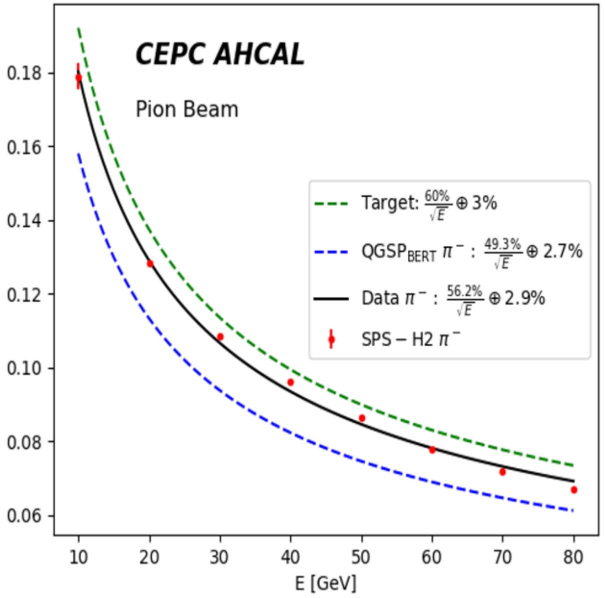
SDHCAL, 48 layers, 1x1 cm^2

AHCAL, 40 layers, 4x4 cm^2



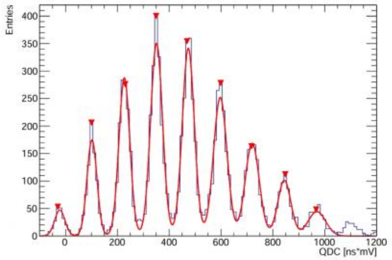






MC Simulation and Digitization

- **Geant4 simulation: detailed geometry of ScW-ECAL and AHCAL prototypes**
- **Digitization: energy depositions (Geant4) → digits in ADC**
  - Same technology: scintillator-SiPM and ASIC in two prototypes
  - Procedure implemented for each readout channel



Geant4 hits: Energy deposition → Scintillator-SiPM: detected photons → SiPM non-linearity → SiPM: p.e. conversion to ADC

MC truth

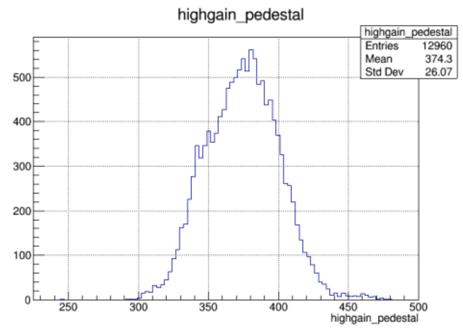
Poisson Distribution based on muon data

SiPM saturation curve from measurements

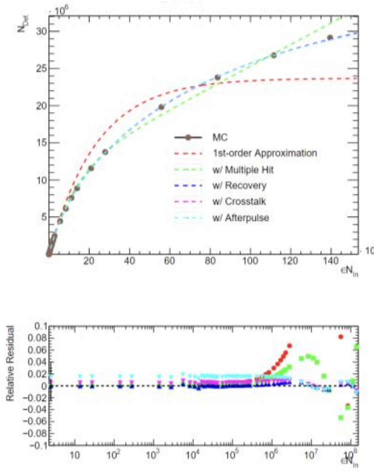
SiPM gain calibration from LED data

Pedestals (Electronics)

Extracted from data

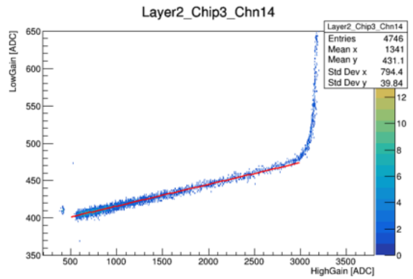


Pedestals (data)



SiPM saturation (data)

ASIC HG-LG ADC (data)



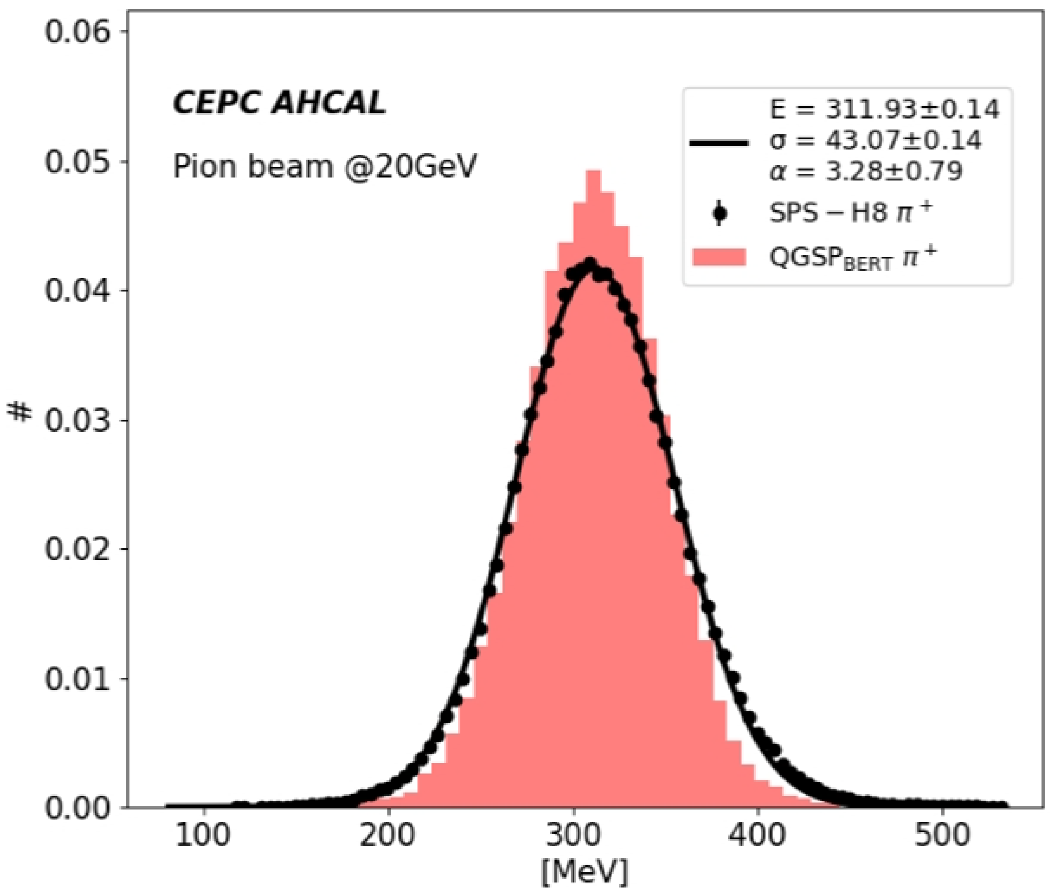
ASIC: ADC in High Gain or Low Gain

SPIROC2E HG-LG slope extracted from beam data

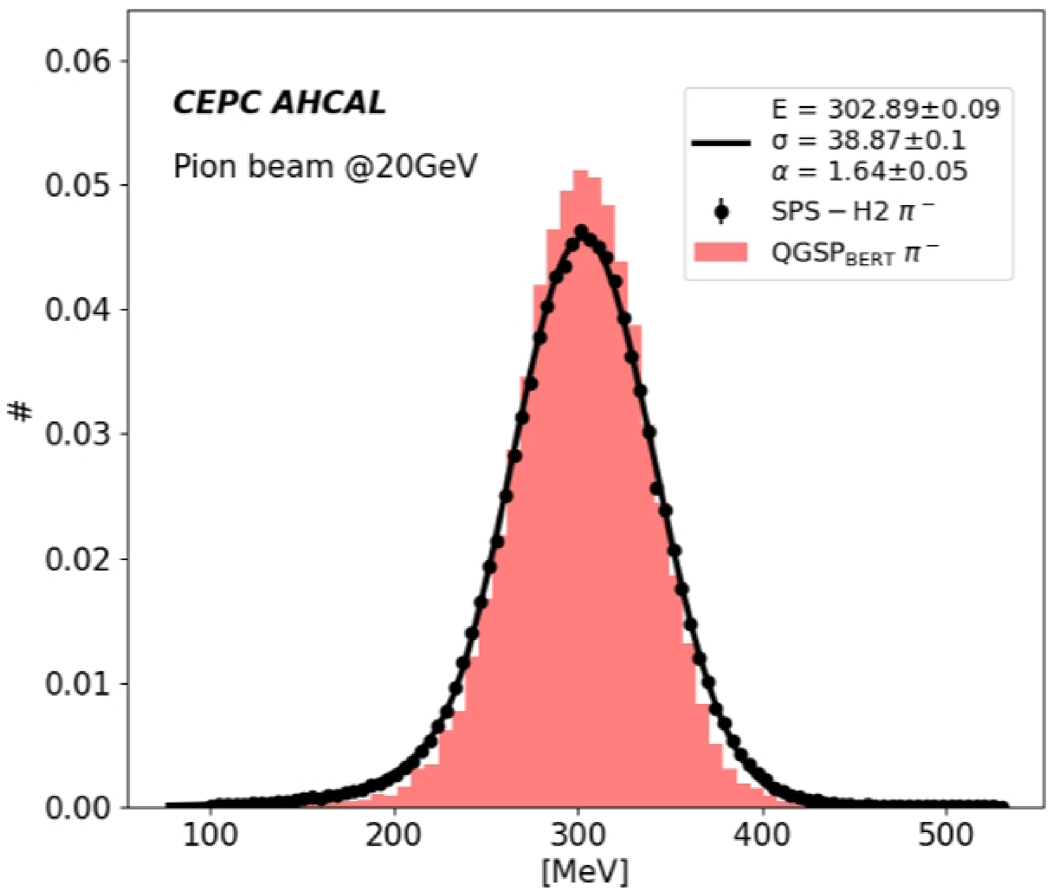
Key: digitization is fully based on calibration data

Marking in Red: based on data

AHCAL Prototype: Pion Data vs MC



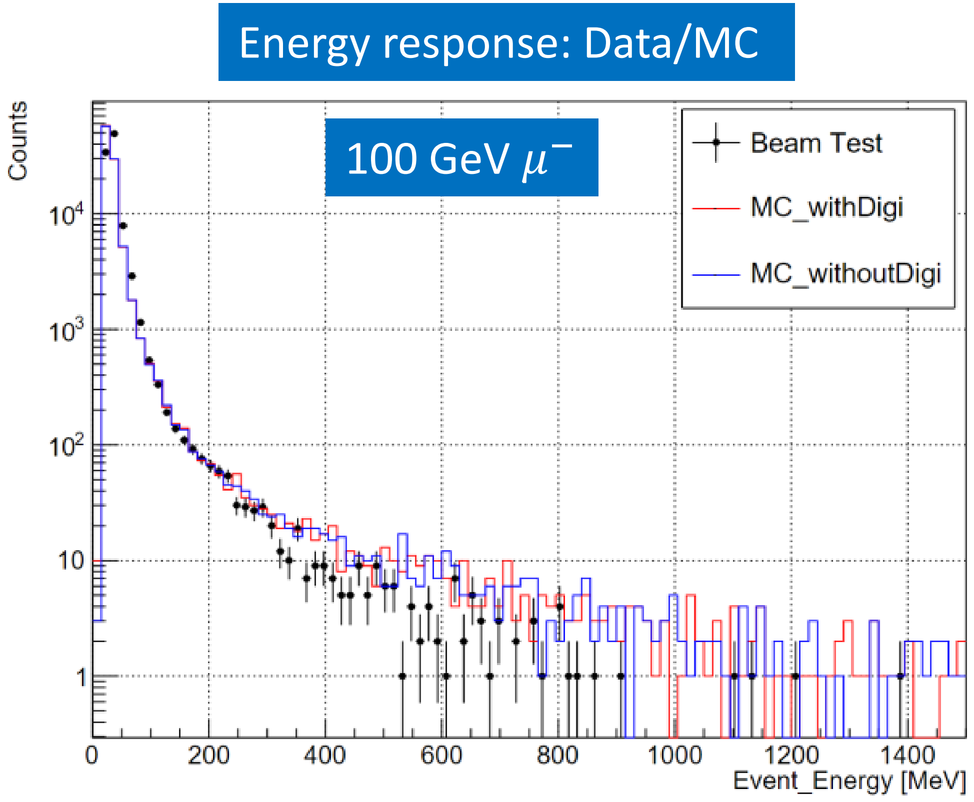
20 GeV π^+ data SPS-H8 (2022)

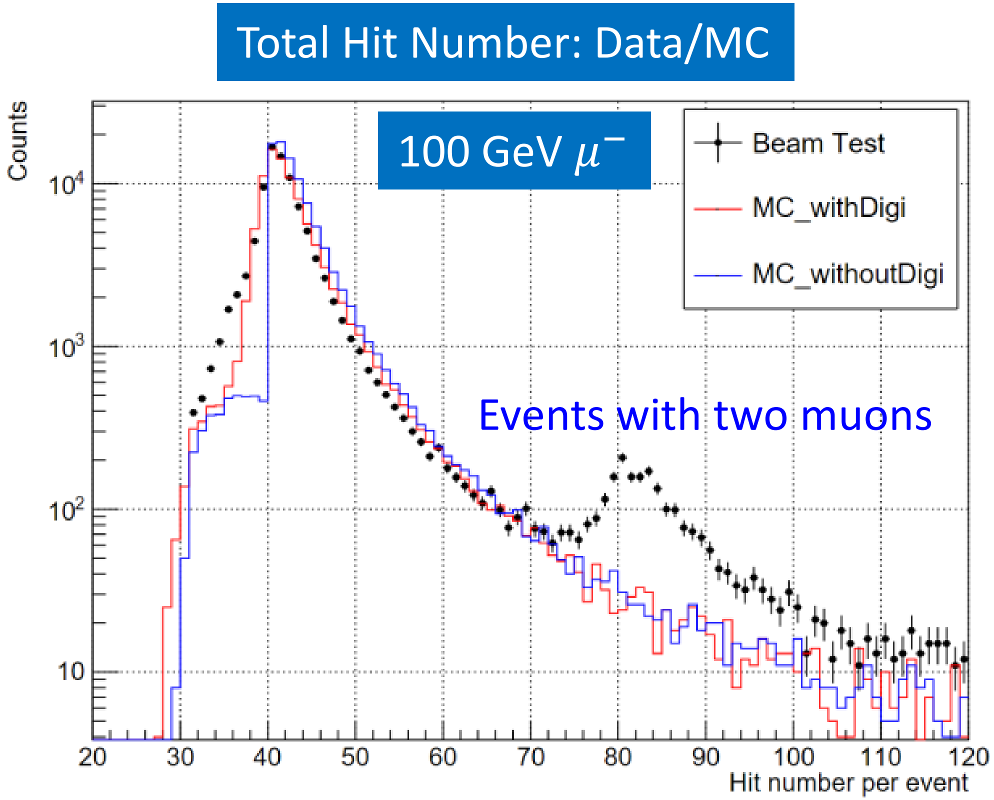


20 GeV π^- data SPS-H2 (2023)

AHCAL Prototype: Muon Data vs MC

- MIP calibration: provide energy scale for each channel
- Crucial inputs for energy reconstruction of electrons and pions





MC is consistent with muon data

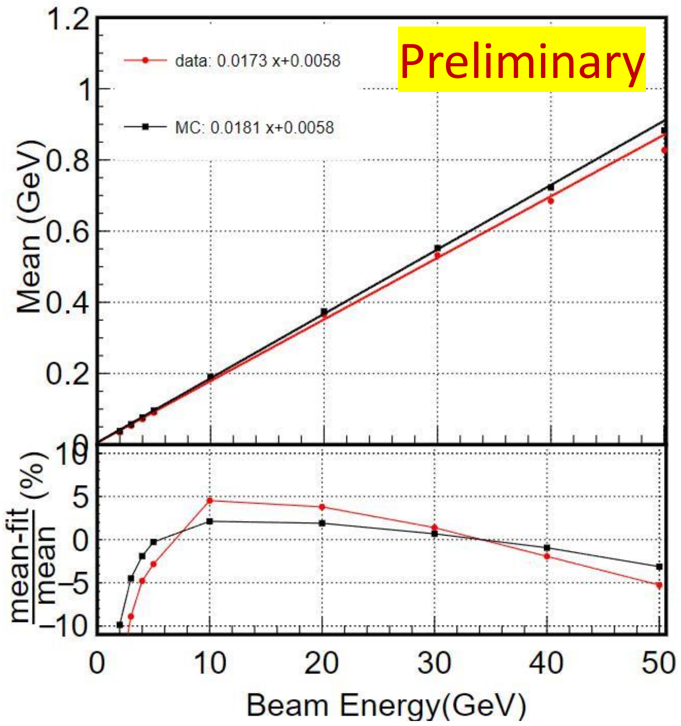
AHCAL Prototype: Electron Data vs MC

- Critical issue: non-linearity effects in SiPM and ASIC (SPIROC2E) with large signals
- Digitization significantly improves MC/data consistency
- But still requires a better digitization model for SiPM+ASIC saturations effects

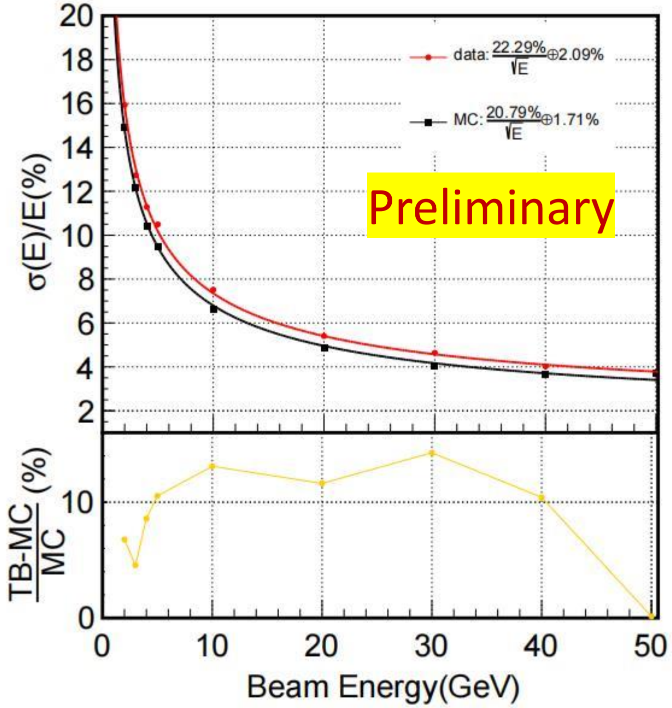
PS-T09 low-energy electron data (1-5 GeV) also included

Data/MC comparisons: ~10% discrepancy in EM response linearity and energy resolution

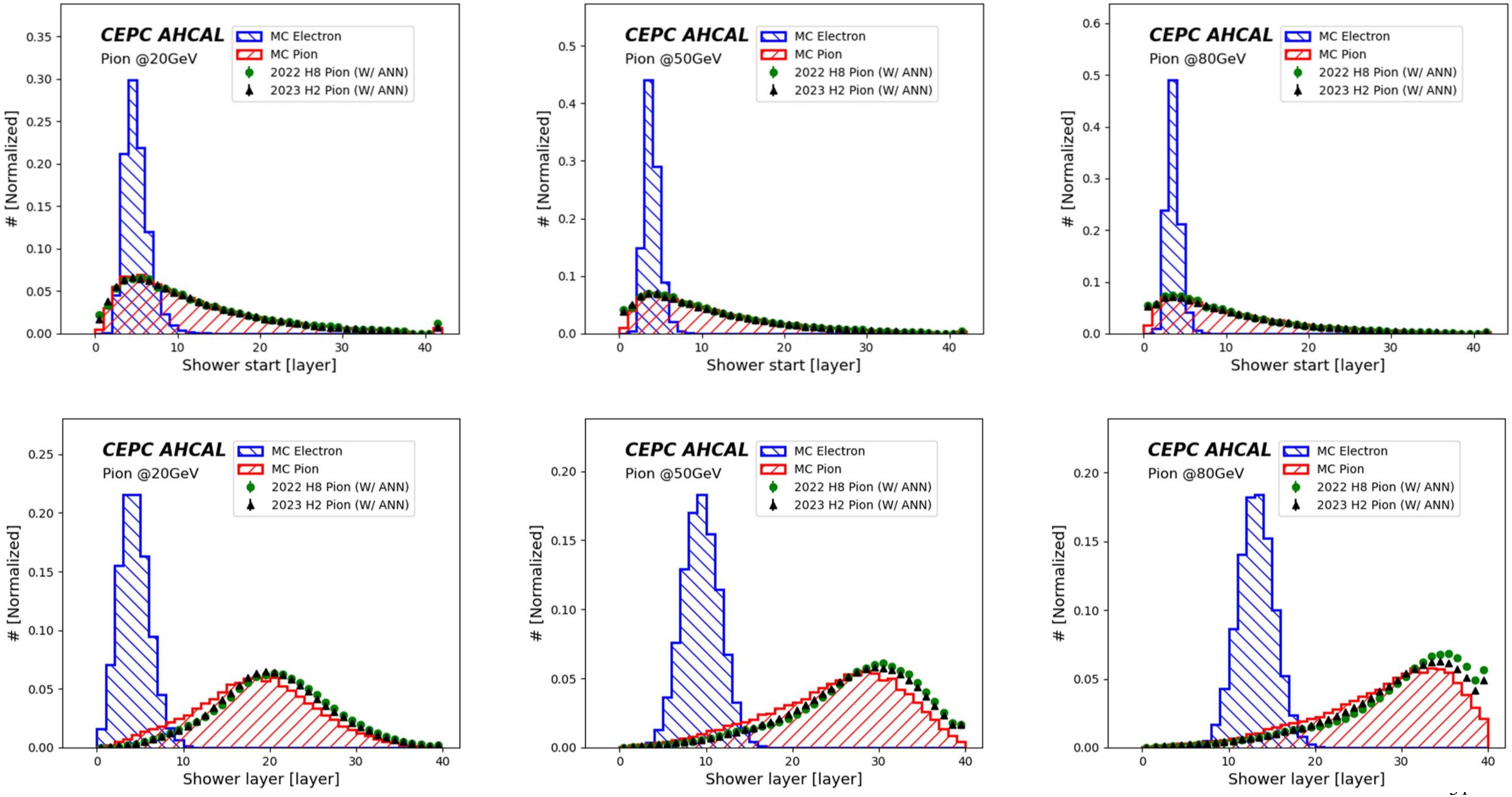
EM response linearity



EM energy resolution

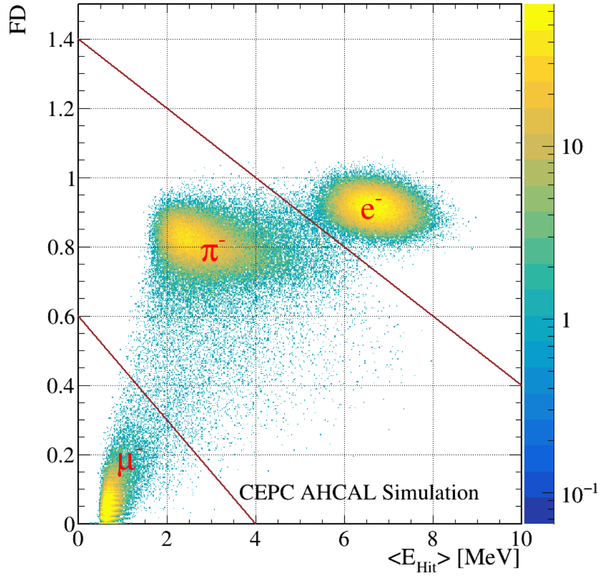


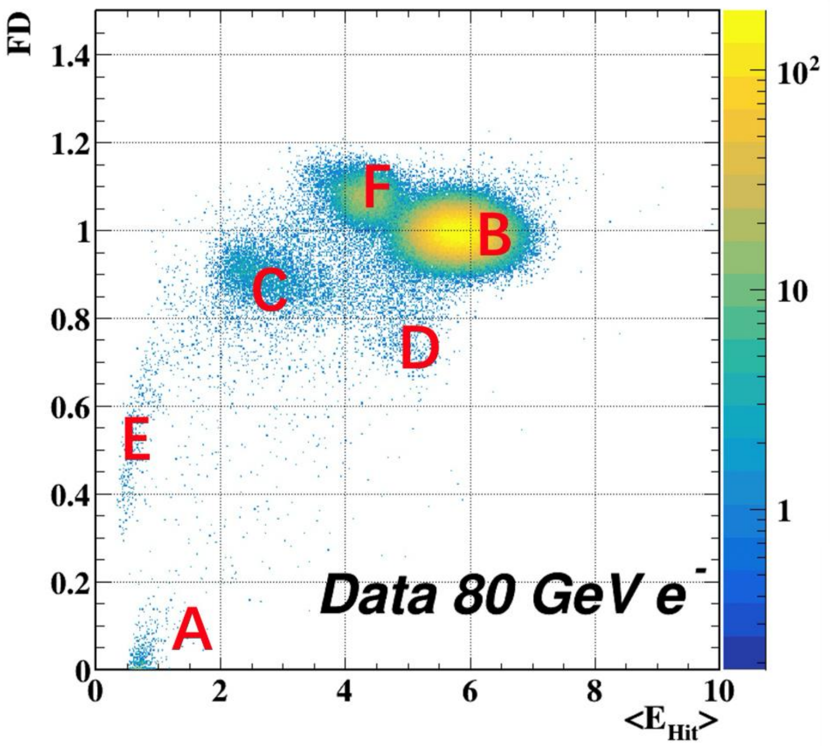
AHCAL Prototype: Pion Data vs MC

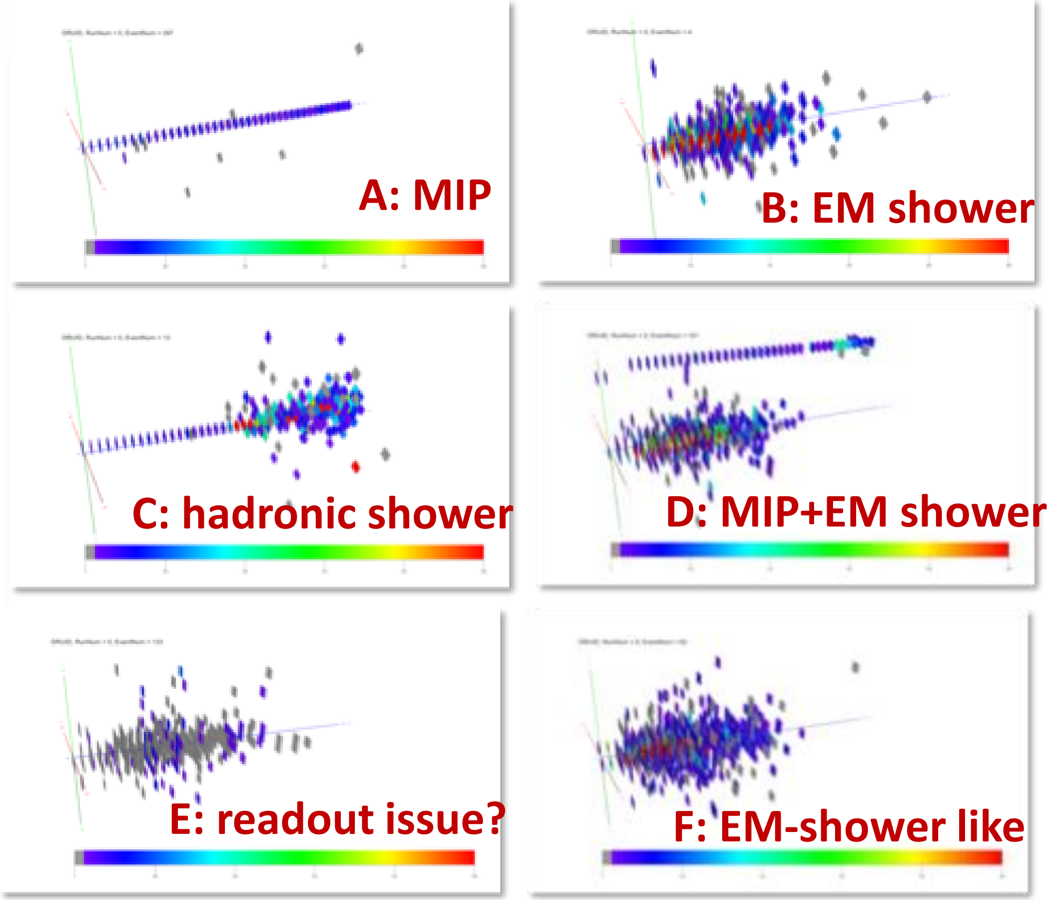


PID based on Fractal Dimension

- **Fractal Dimension (FD)**
  - Self-similarity in patterns of particle showers in the transverse plane
  - $FD = \left\langle \frac{\log(R_{\alpha,1})}{\log(\alpha)} \right\rangle$ where $R_{\alpha,1} = \frac{N_1}{N_\alpha}$ and N_α is number of hits scaled by the factor α

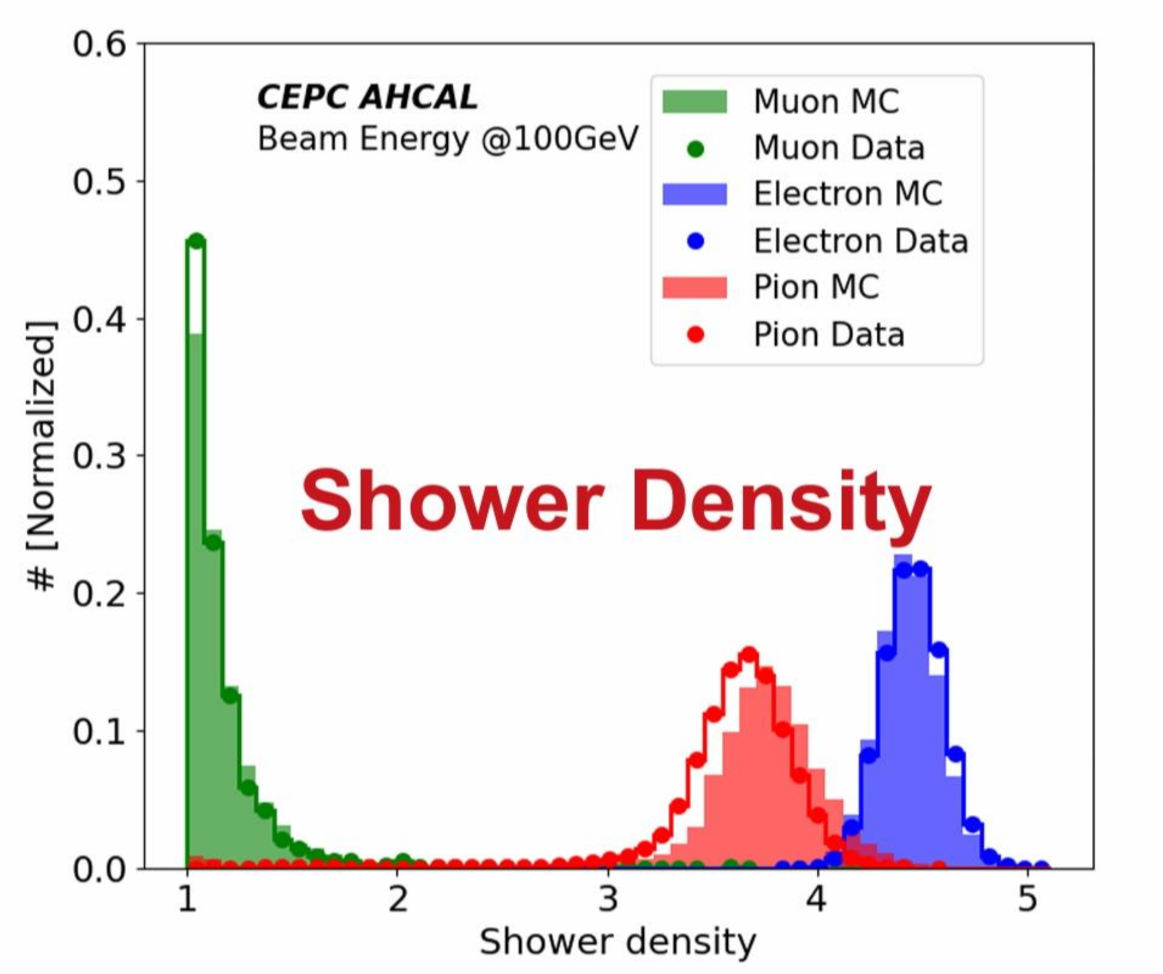


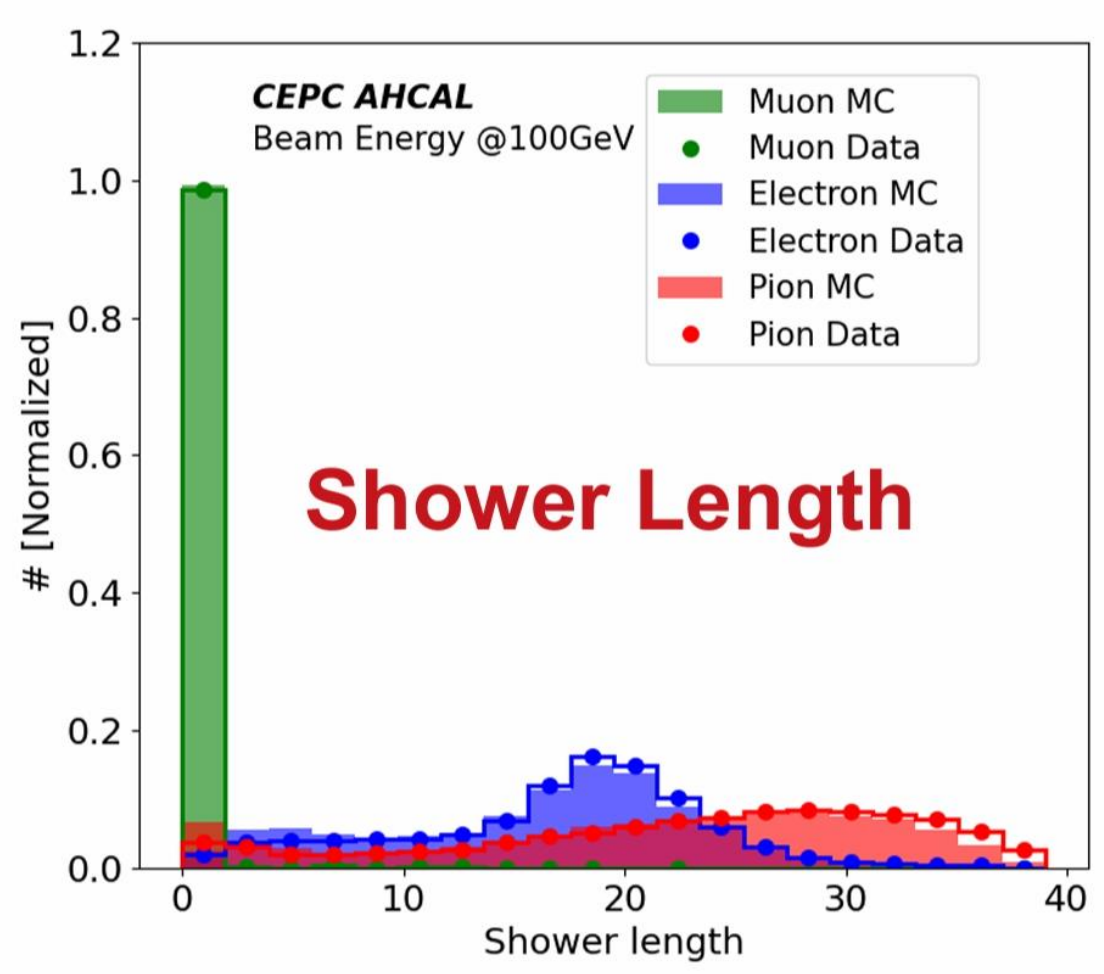




FD methodology based on
M. Ruan et al., Phys. Rev. Lett. 112, 012001

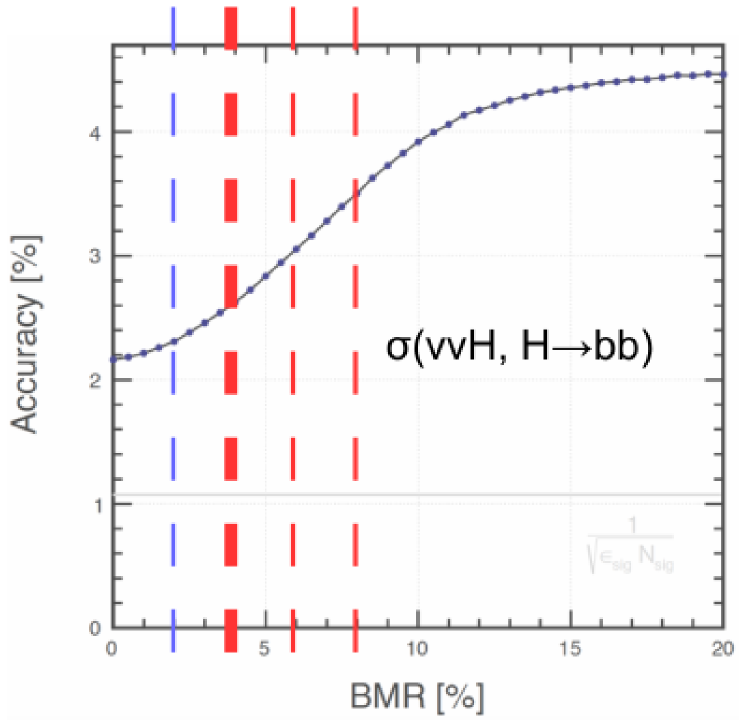
CEPC Detector

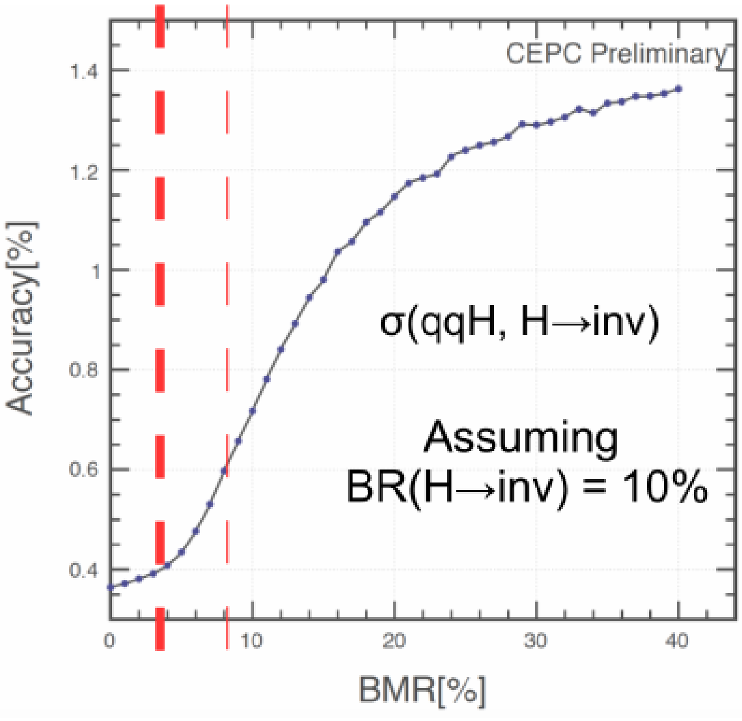


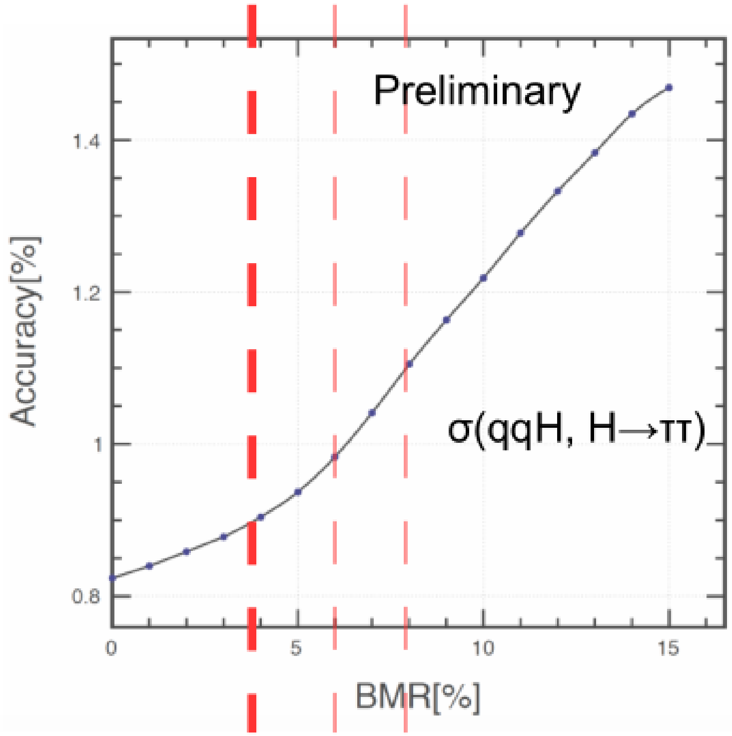


Calorimeters Design and Optimization

Accuracy($\sqrt{S+B}/S$) vs BMR (Boson Mass Resolution)







S: $e^+e^- \to ZH, Z \to \nu\bar{\nu}$
B: $e^+e^- \to \nu\bar{\nu}H$|W fusion

S: $e^+e^- \to ZH$
B: $e^+e^- \to ZZ$

S: $e^+e^- \to ZH$
B: $e^+e^- \to ZZ$

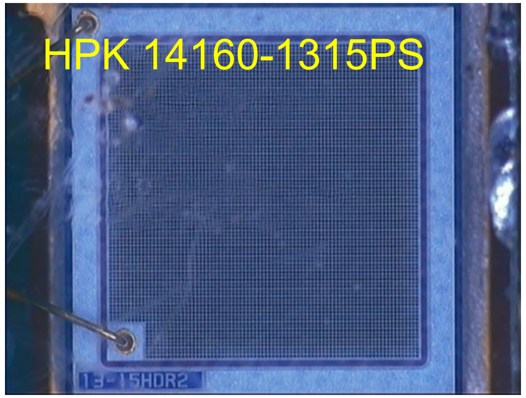
➔ ~ 4 % BMR is required for CEPC detector to well separate the S/B.

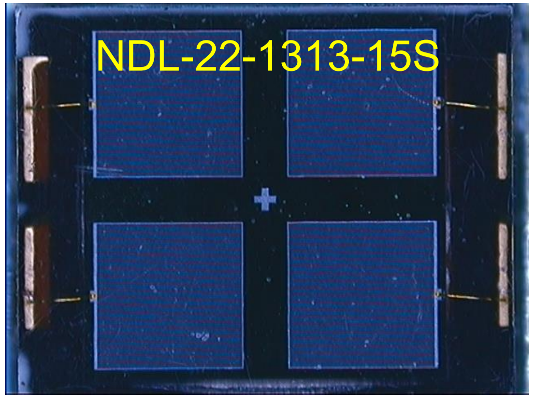
SiPM

NIMA 980 (2020) 164481

❖ HPK-SiPM
- Low PDE, dark rate and crosstalk
- High breakdown voltage
- Better quality control
- 38 layers (38 × 324 = 12312)

❖ NDL-SiPM
- High PDE, dark rate and crosstalk
- Low breakdown voltage
- Low price
- 5 layers (5 × 324 = 1620)

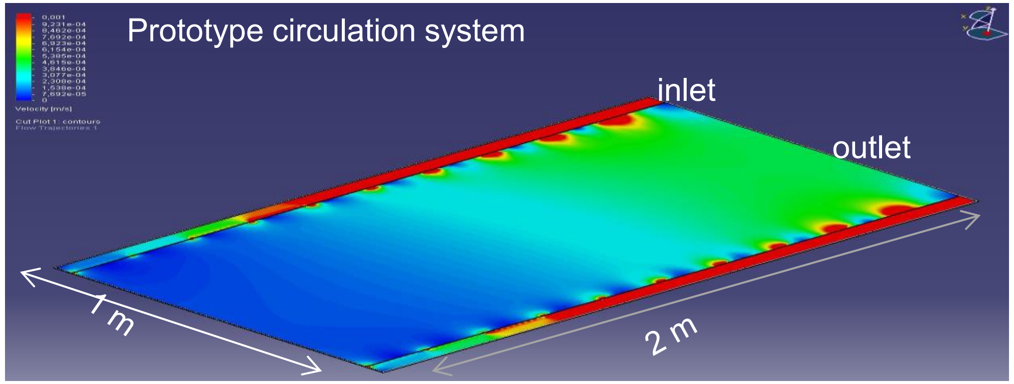


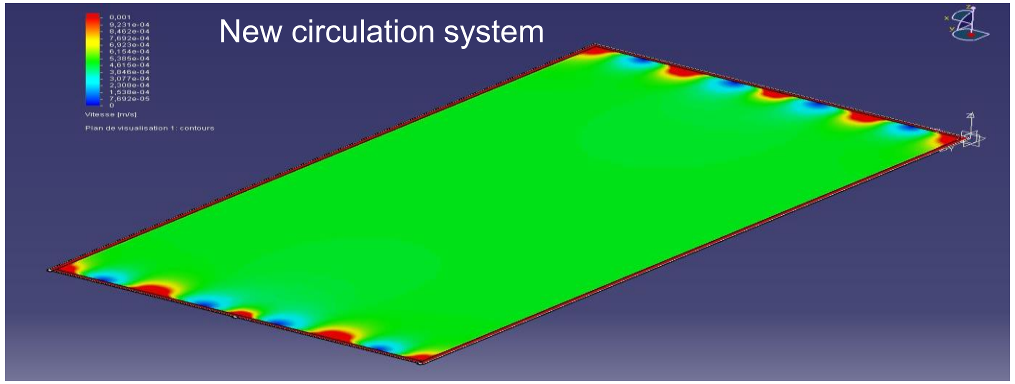


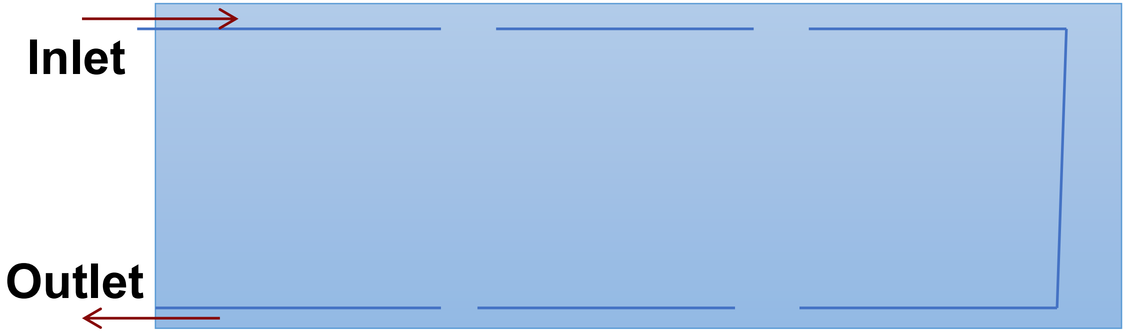
Company	HPK		NDL
Type	13360-1325PE	14160-1315PS	22-1313-15S
Light output [p.e.]	13	17	20
Crosstalk[%]	1.59	1.17	4.4
Dark Counts [kHz]	120	290	550
Breakdown[V]	53	38	27.5

SDHCAL: Improvements

- Construction and operation of large GRPC necessitate some improvements with respect to the present scenario.
- **Cassette conception** to improve contact between GRPC and electronics
- **New gas distribution** is proposed to improve uniformity of gas circulation.







T-SDHCAL: Electronics

➢ T-SDHCAL electronics (PETIROC, LIROC+PicoTDC)

Present baseline solution

- 32 channels
- on-chip TDC
- Time resolution below 50ps

Pros: embeds preamp, TDC, QDC

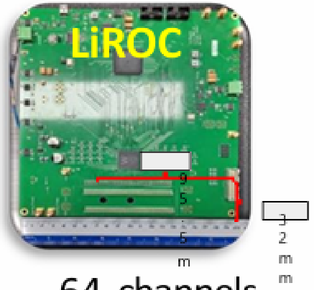
Cons: limited digital logic, difficult to chain, deadtime

Developed at CNRS-OMEGA partially thanks to AIDA2020 for CMS-muon upgrade

Medium/long term possible option

weeroc

Board is under development by the WEEROC company



- 64 channels
- FWHM < 20 ps

Developed for SiPMs readout on LIDAR (*) No internal TDC

- 64 channels
- Time resolution <12 ps

(*) LIDAR = LIght Detection And Ranging