

IAS PROGRAM

Fundamental Physics

January 12-16, 2026

Status of CEPC Hadronic Calorimeters

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



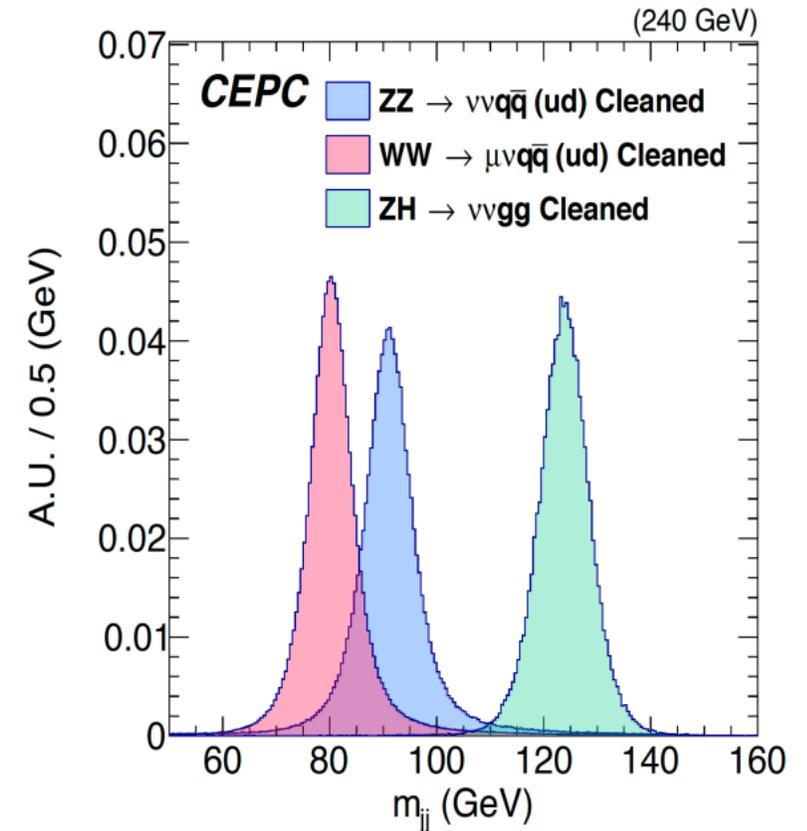
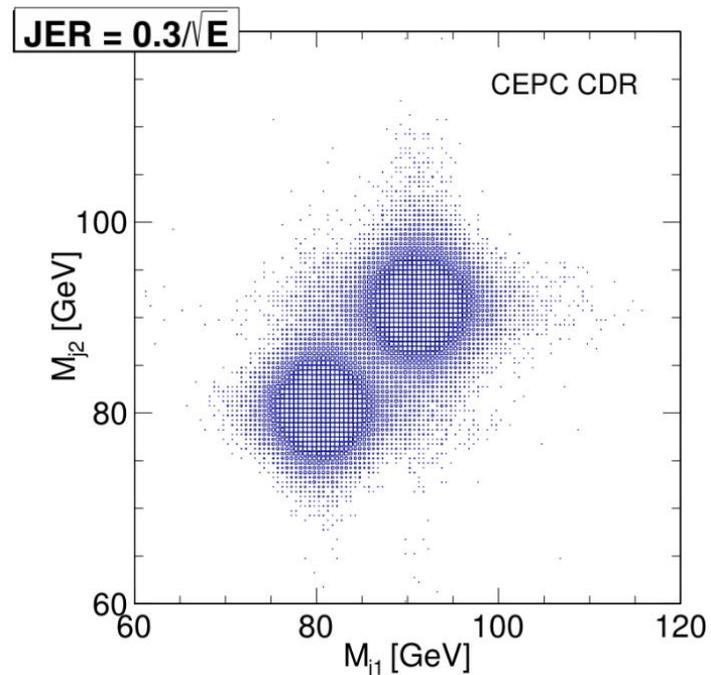
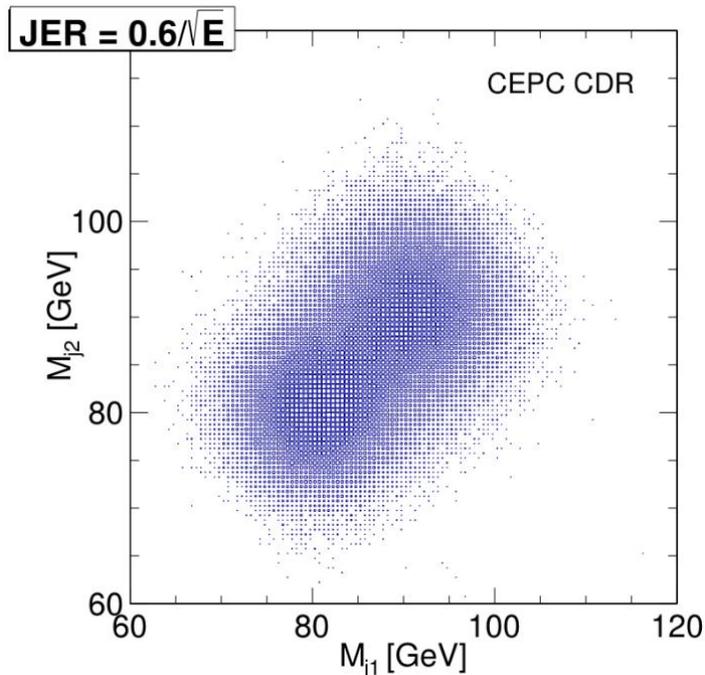
上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

李政道研究所
Tsung-Dao Lee Institute

- ❖ **Introduction: Motivation and Requirements**
- ❖ **SDHCAL Prototype based on GRPCs**
- ❖ **AHCAL Prototype based on Plastic Scintillators**
- ❖ **AHCAL based on Glass Scintillators (new material)**
- ❖ **Summary and Future Plans**

➤ CEPC as Higgs/W/Z boson factories

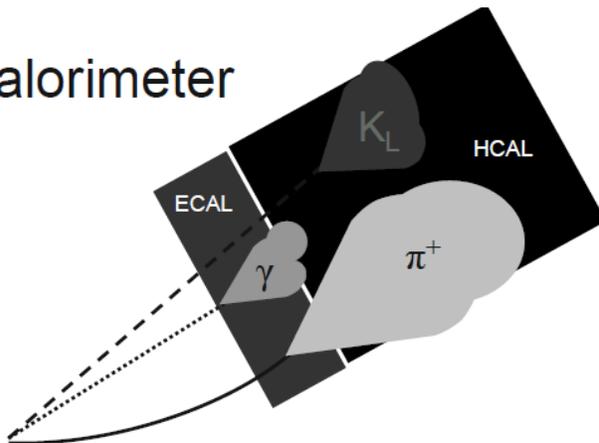
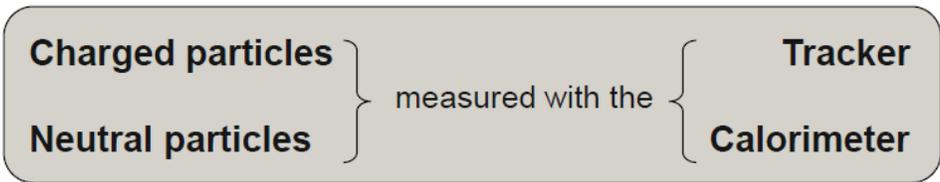
- ❖ H/W/Z hadronic decays are dominant, it is crucial to design calorimetry system to well separate them and make precision measurements
- ❖ Required Jet Energy Resolution, $\sigma/E \sim 30\%-40\%/\sqrt{E}$
- ❖ Boson Mass Resolution, **BMR $\sim 4\%$ or better**



CEPC CDR (arXiv:1811.10545)
CEPC TDR (arXiv:2510.05260)

Particle Flow Algorithms and Imaging Calorimeter

The idea...

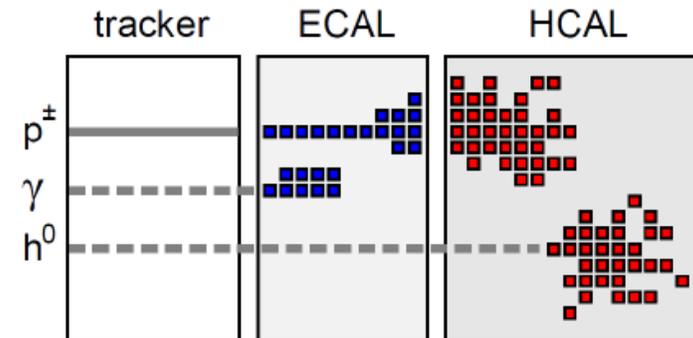


Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with $15\%/\sqrt{E}$	$0.07^2 E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with $50\%/\sqrt{E}$	$0.16^2 E_{jet}$
Confusion		Required for $30\%/\sqrt{E}$	$\leq 0.24^2 E_{jet}$

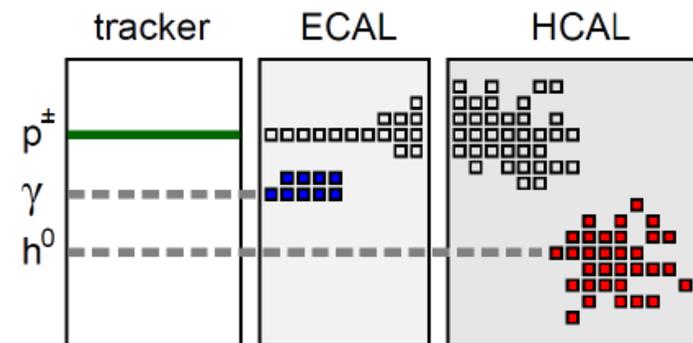
} 18%/√E

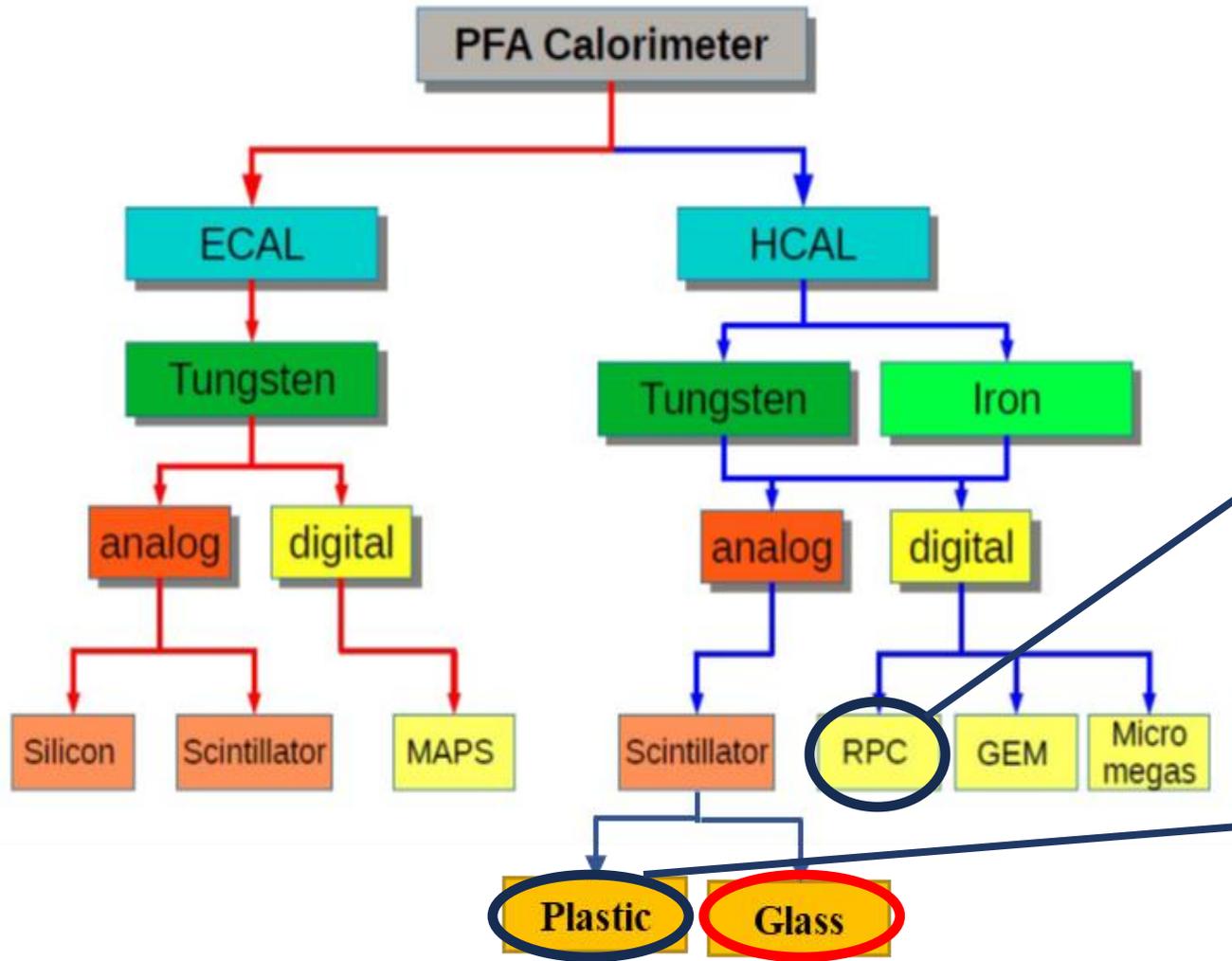
Requirements for detector system

- Need excellent tracker and high B – field
 - Large R_1 of calorimeter
 - Calorimeter inside coil
 - Calorimeter as dense as possible (short X_0, λ_1)
 - Calorimeter with **extremely fine segmentation**
- } **thin active medium**

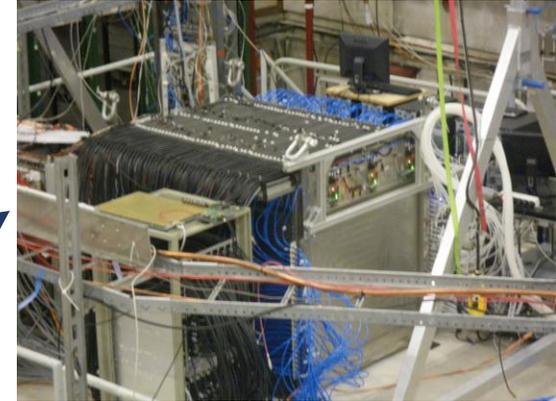


↓ **Particle Flow**





Prototypes



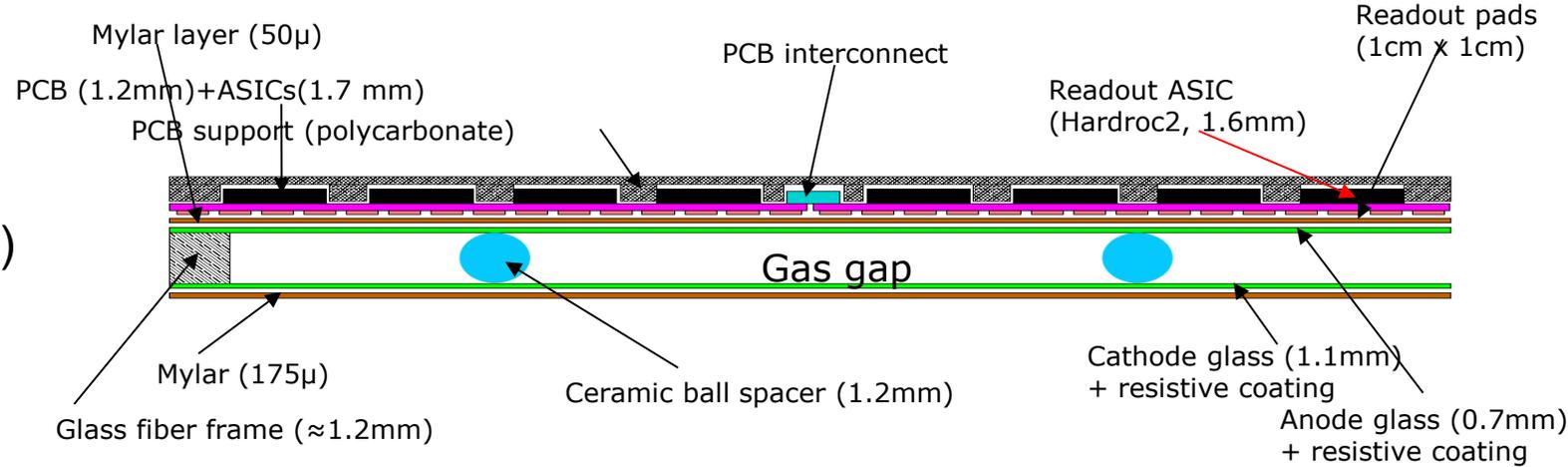
SDHCAL, 48 layers, 1x1 cm²



AHCAL, 40 layers, 4x4 cm²

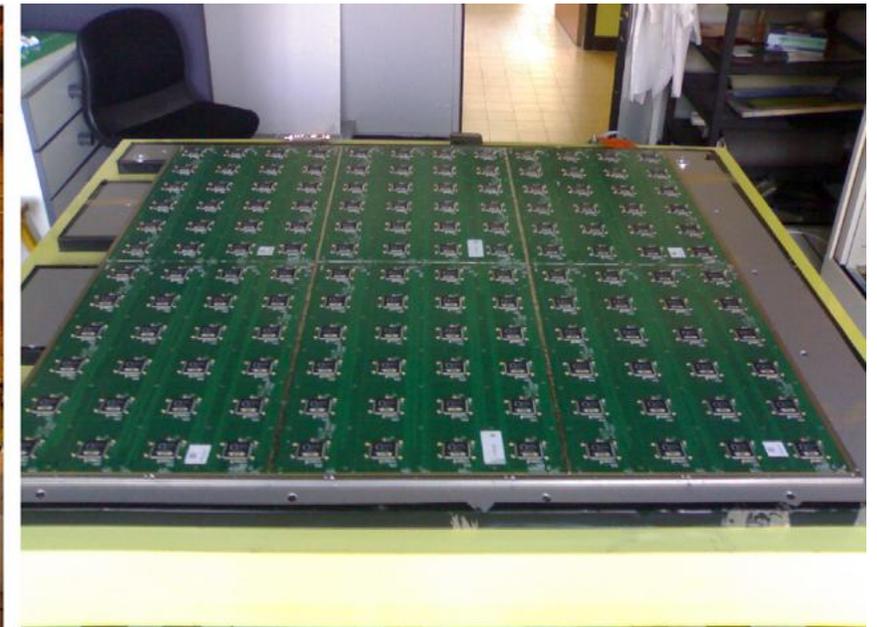
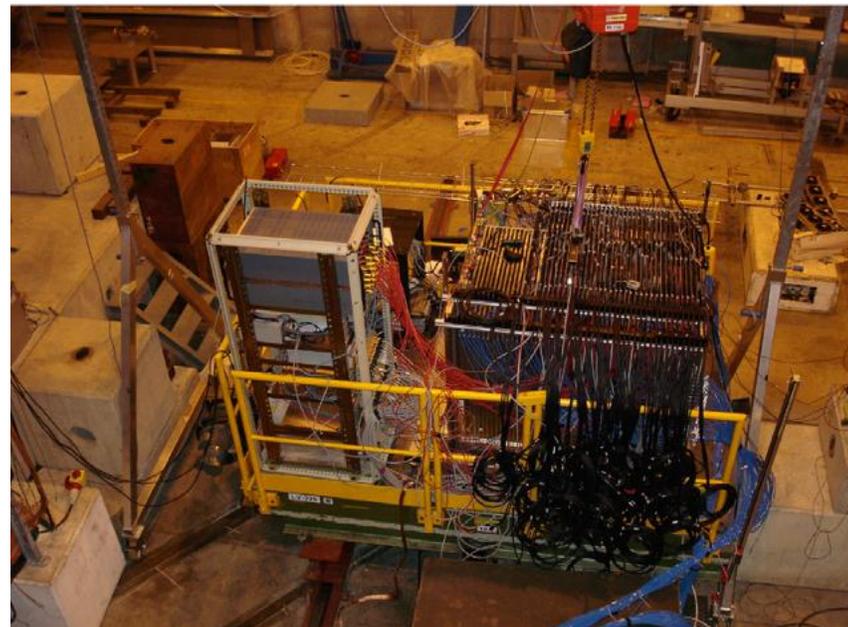
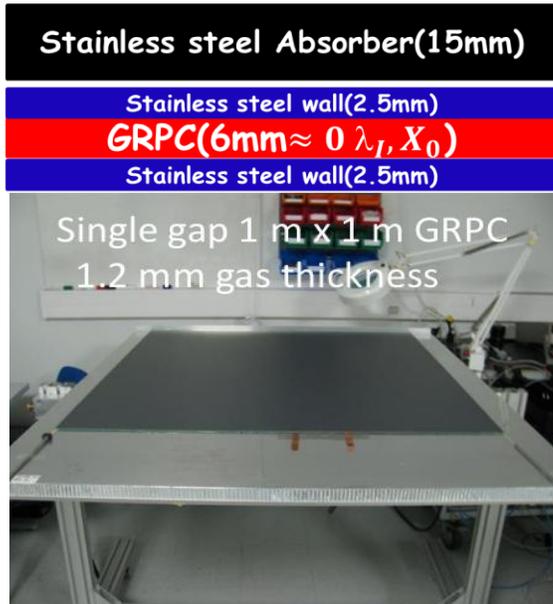
■ Semi-Digital HCAL (SDHCAL)

- 48 layers (1m x 1m GRPCs, 6mm)
- High granularity (1cm x 1cm)
- 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 λ_I , 1.14 X_0)



◆ 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

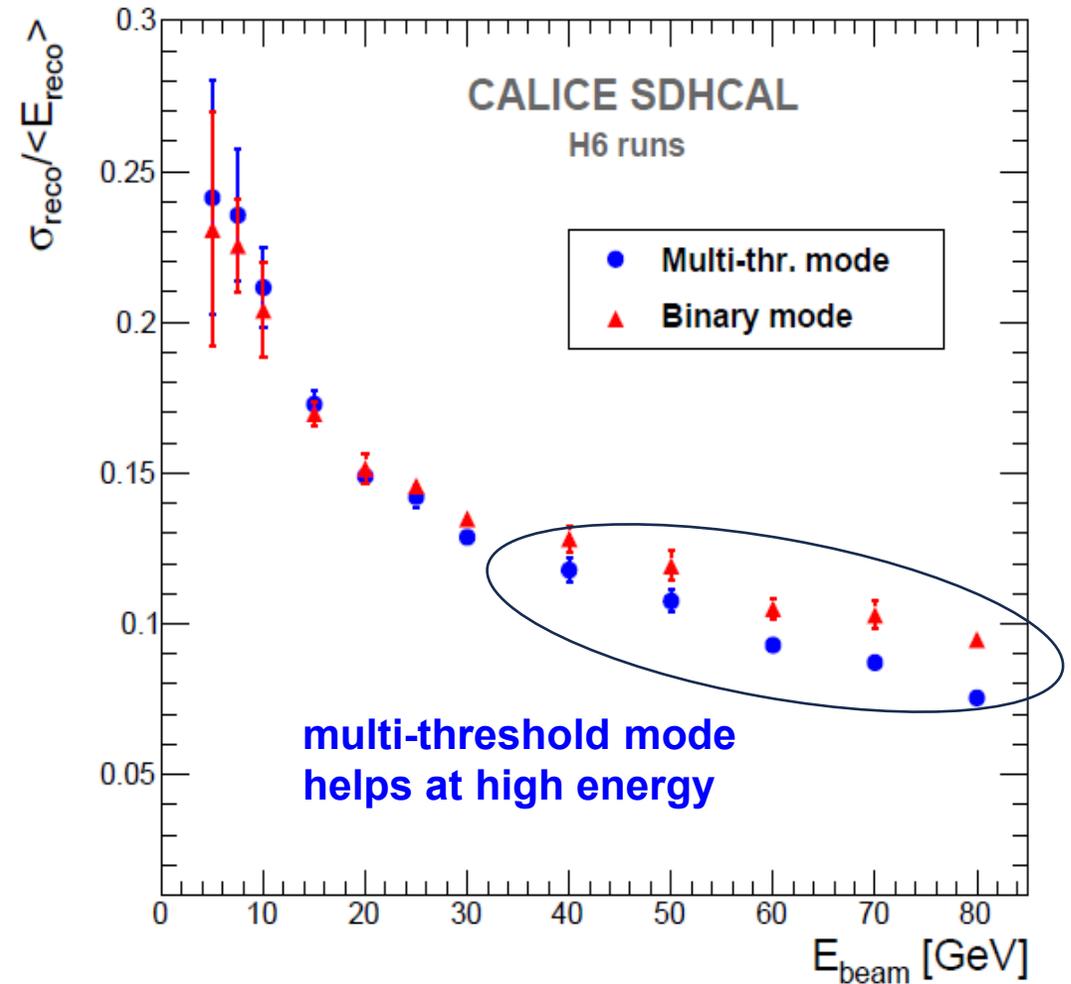
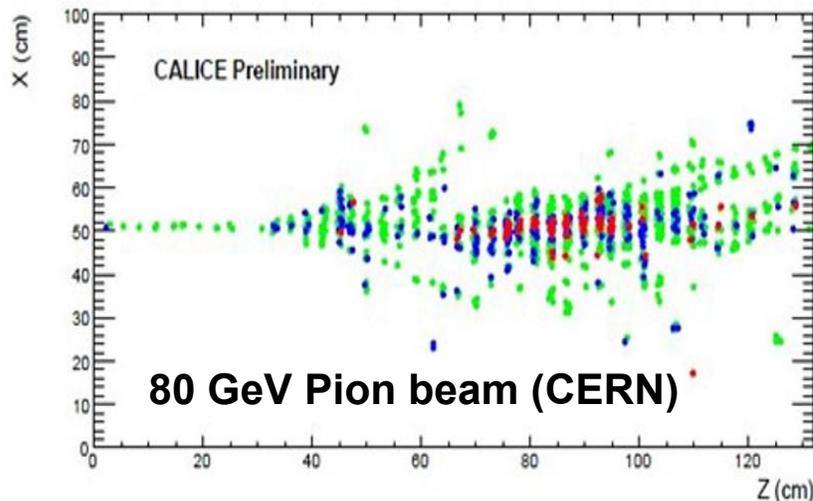
N_3 = #pads with signal > 3rd threshold

α, β, γ are parameterized as functions of total number of hits ($N_{total} = N_1 + N_2 + N_3$)

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

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

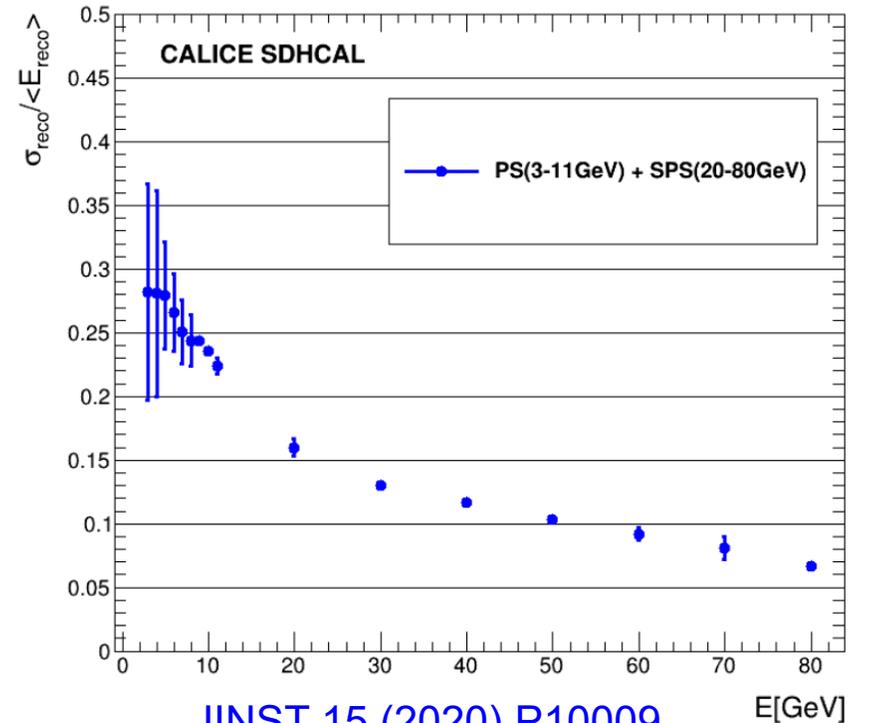
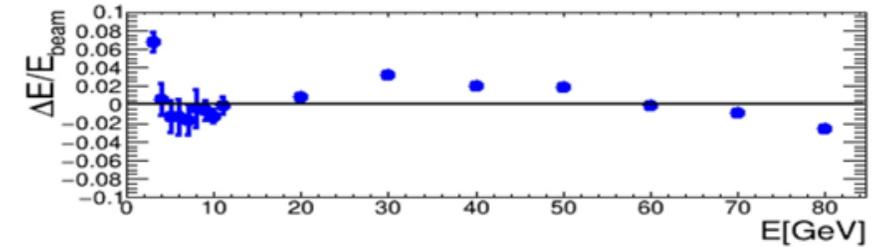
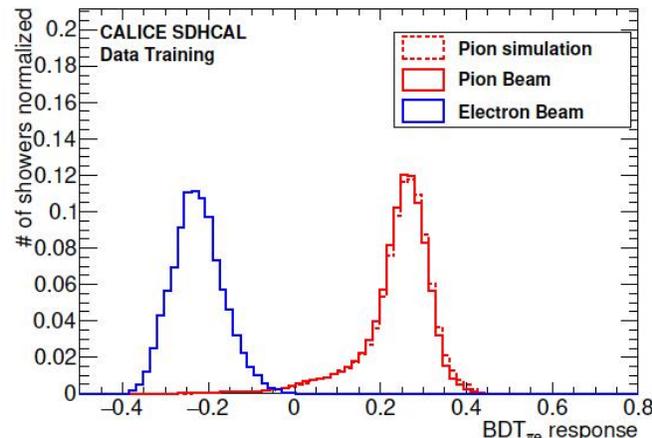
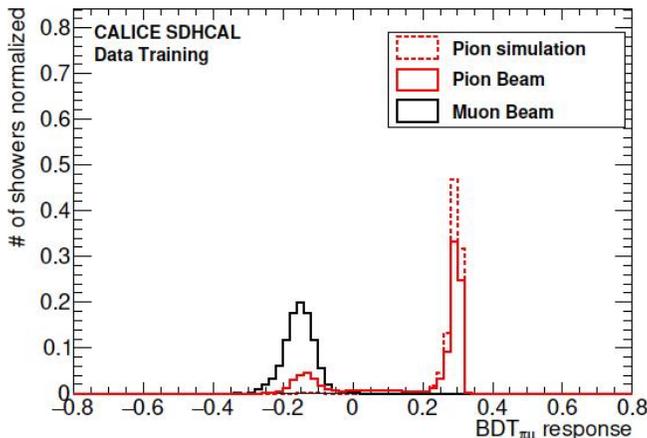
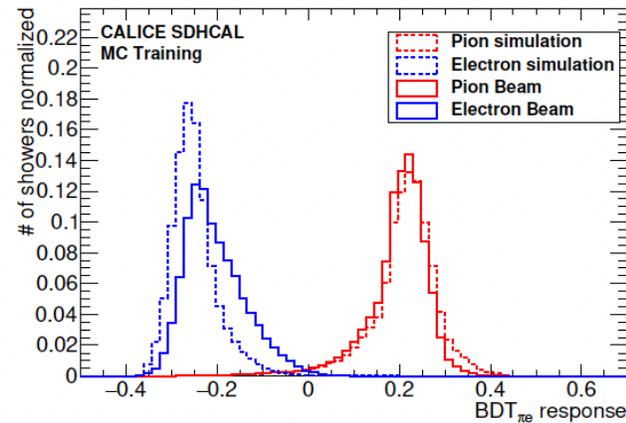
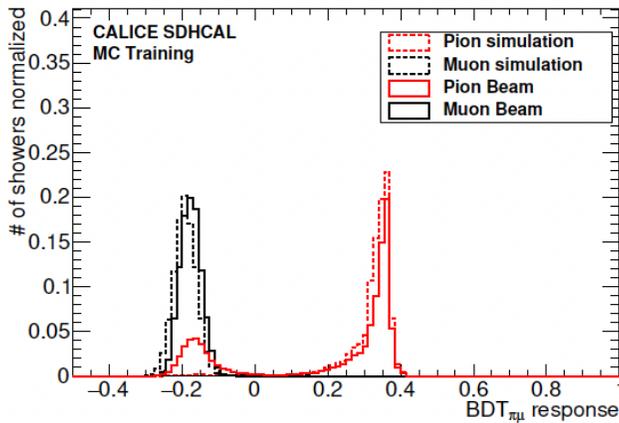
$$\gamma = \gamma_1 + \gamma_2 N_{total} + \gamma_3 N_{total}^2$$



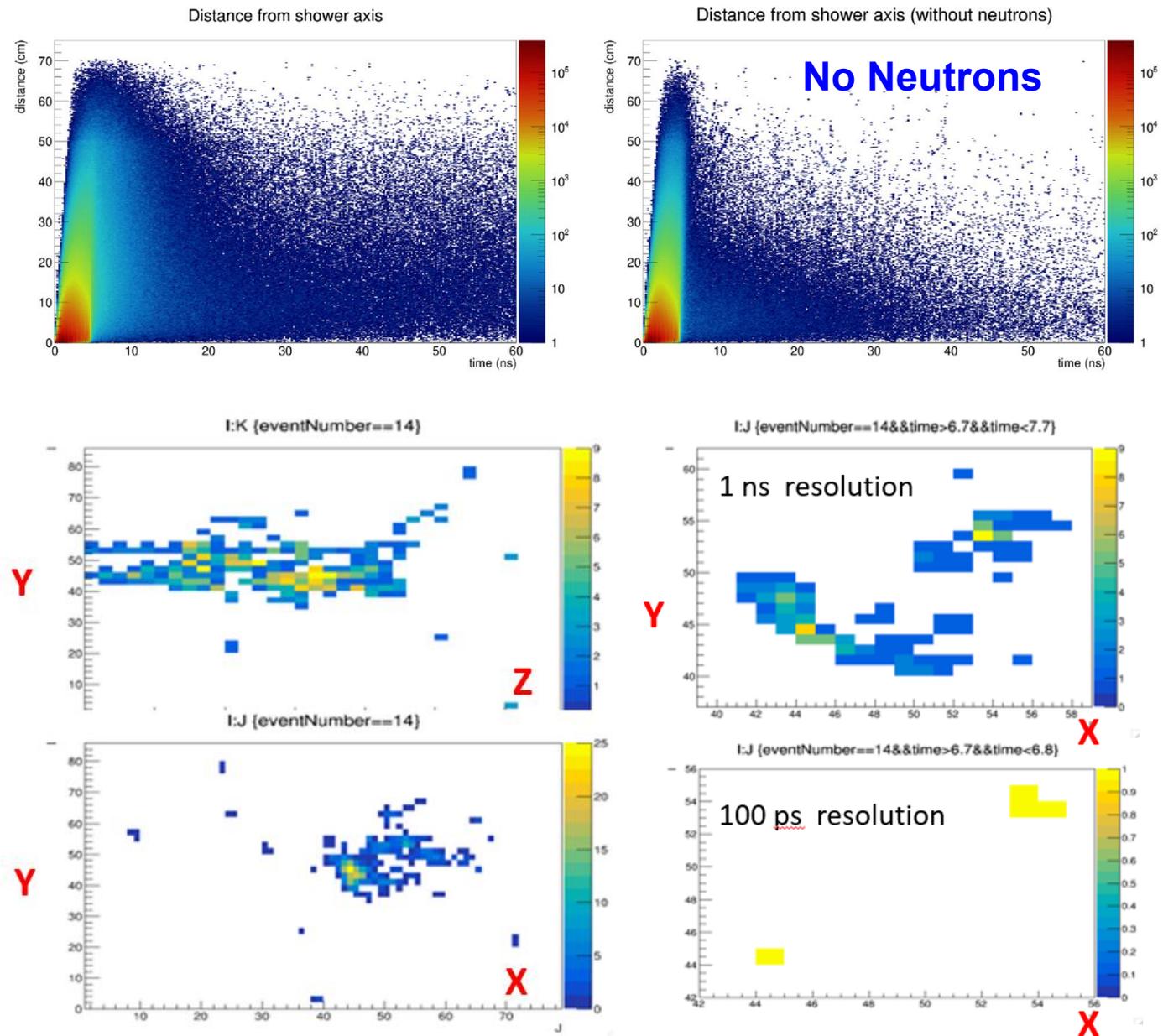
JINST 10 (2015) P10039
 JINST 11 (2016) P04001
 JINST 12 (2017) P05009

- ◆ 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

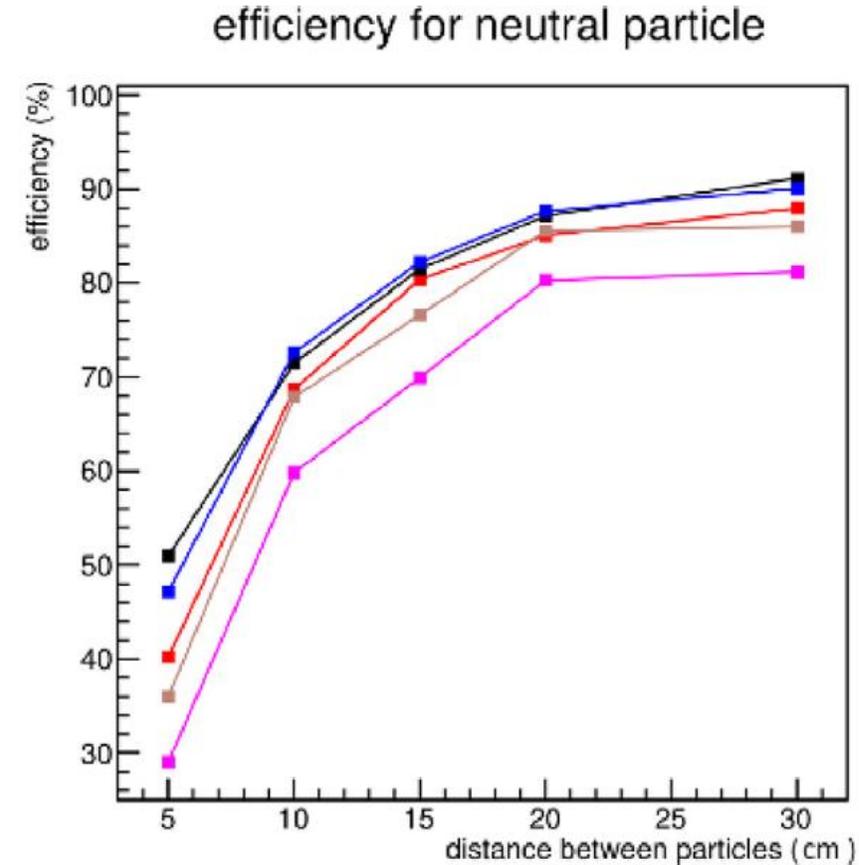
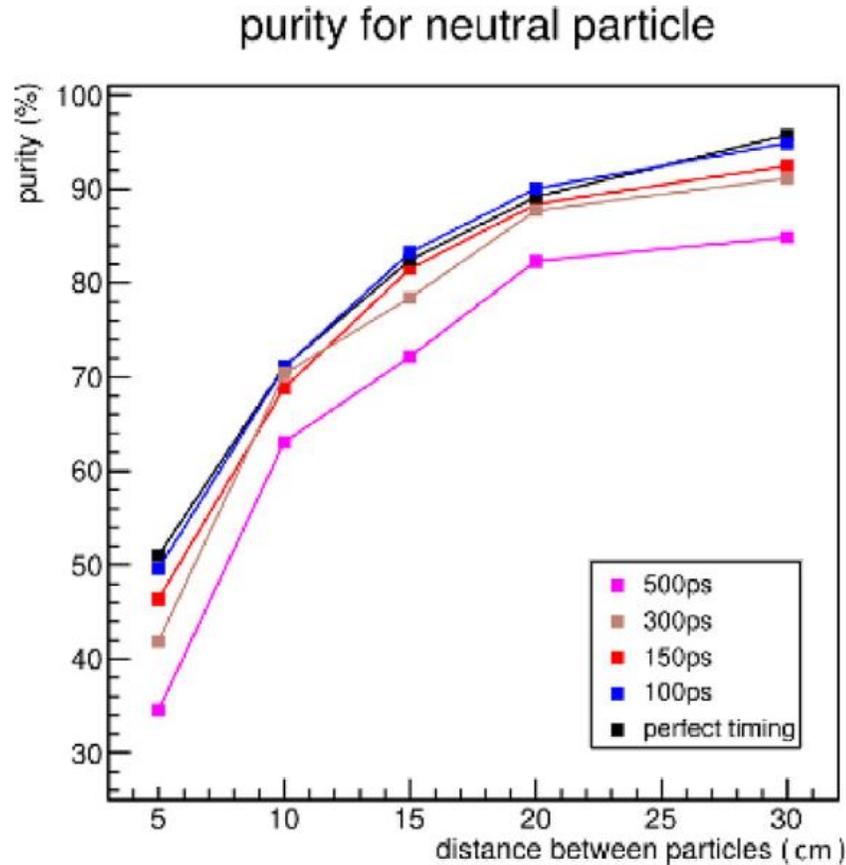
- ◆ Energy linearity: $< \sim 3\%$
- ◆ Energy resolution: $65\%/\sqrt{E} \oplus 2.5\%$



- 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 shorter 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.



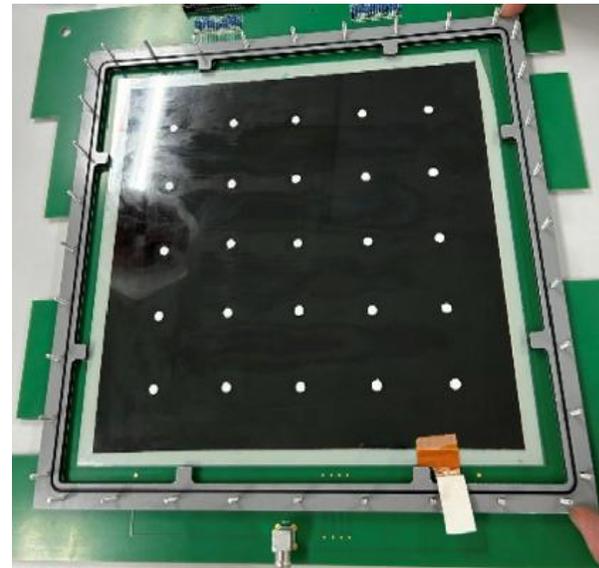
- Separation of close-by hadronic showers with variant timing resolutions (e.g. 10 GeV neutral and 30GeV charged particle, 100ps – 500ps)
- **Timing resolution ~100ps** provides descent efficiency & purity of neutral particles



- 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 ($\sim 40\text{ps}$ 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

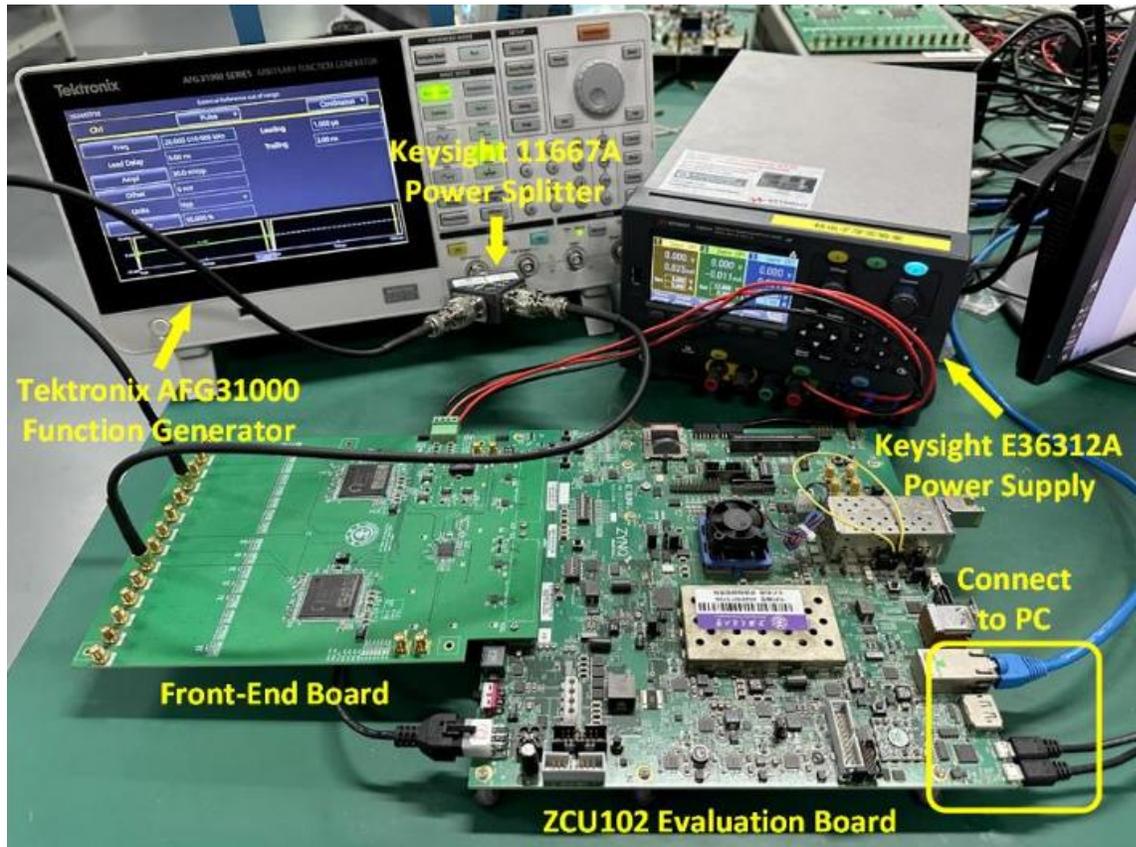


MRPC: 30 x 30 cm²

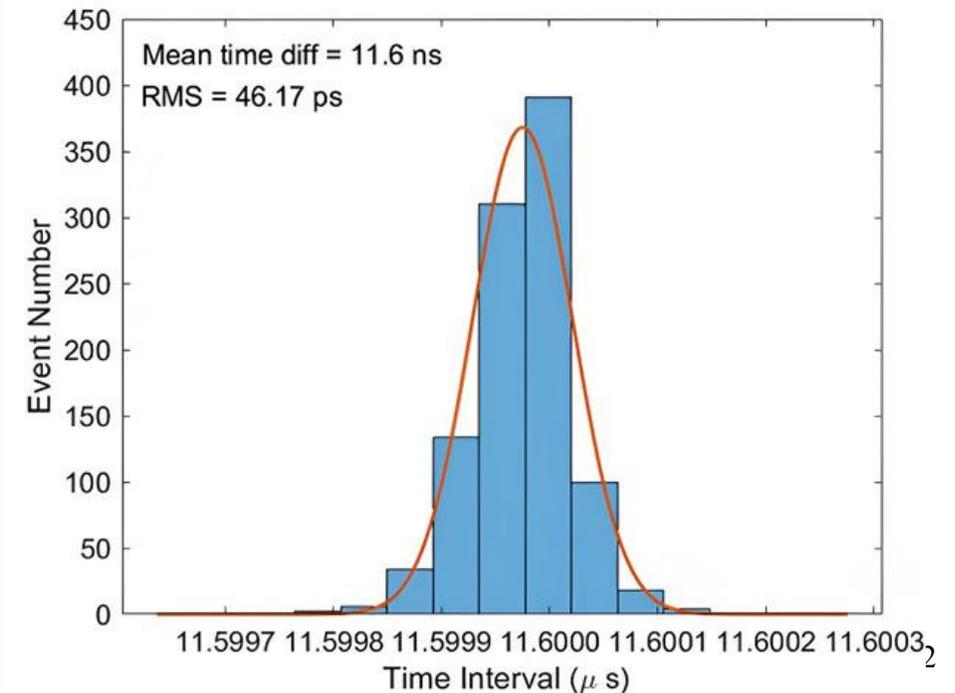
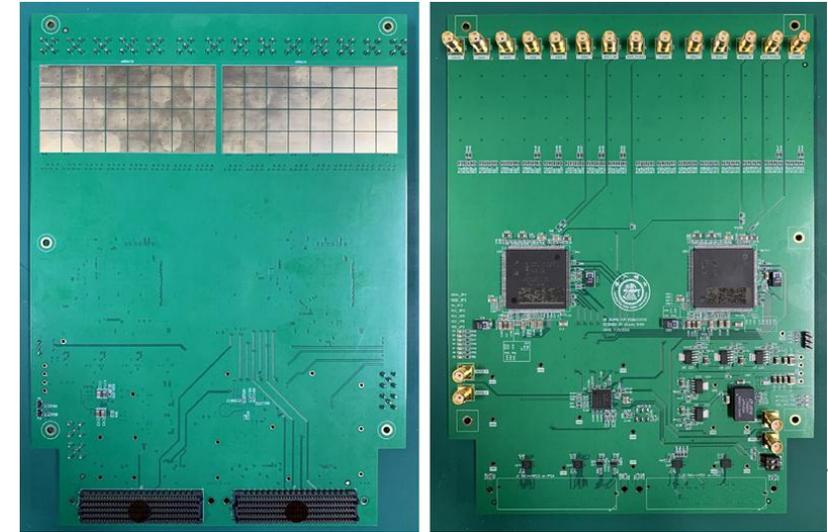


MRPC: 100 x 100 cm²

- 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
 IEEE TNS (2024) 0018-9499



❖ Sampling PS-AHCAL

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

❖ Sensitive Detector

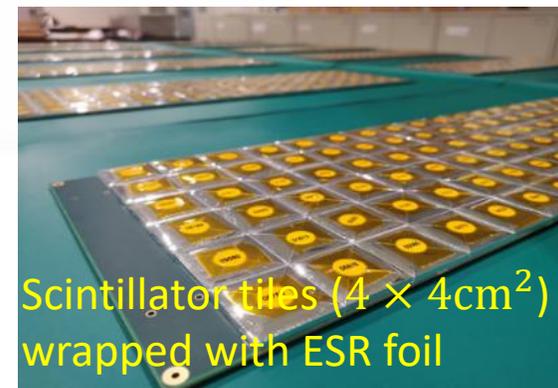
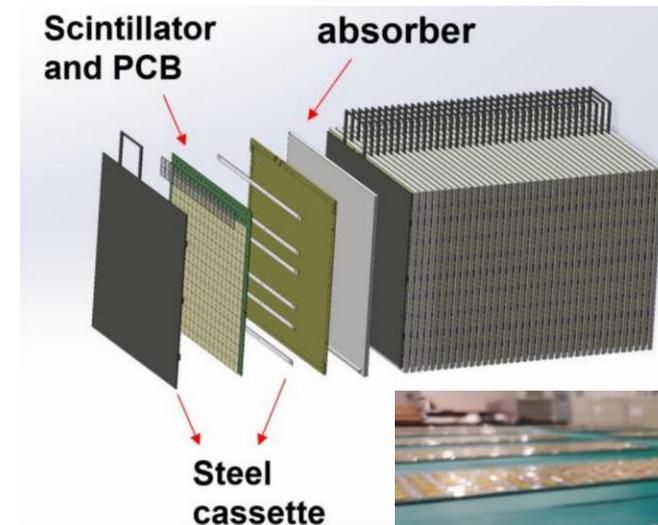
- Scintillator cell size: 40 × 40 × 3 mm³
- SiPM: HPK S14160-1315 and NDL-22-1515

❖ Absorber

- Iron, 2 cm thickness / layer

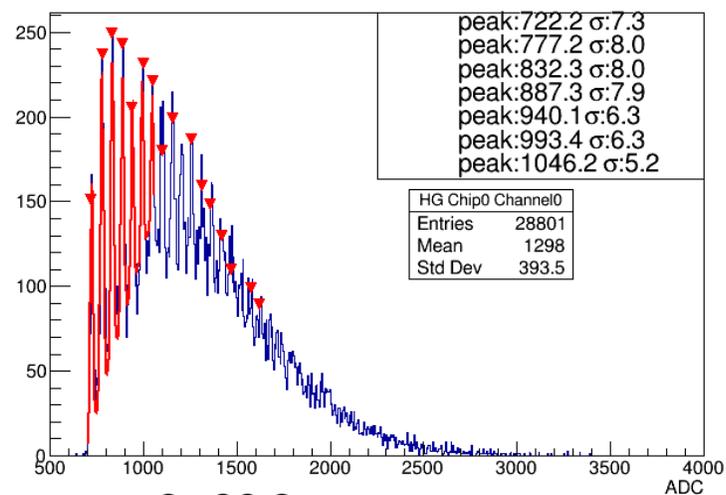
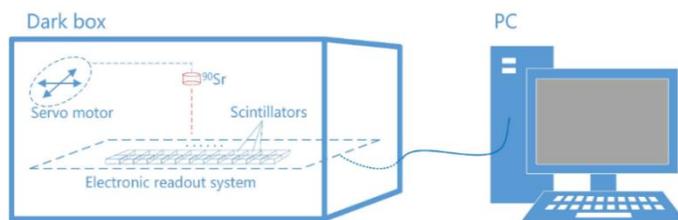
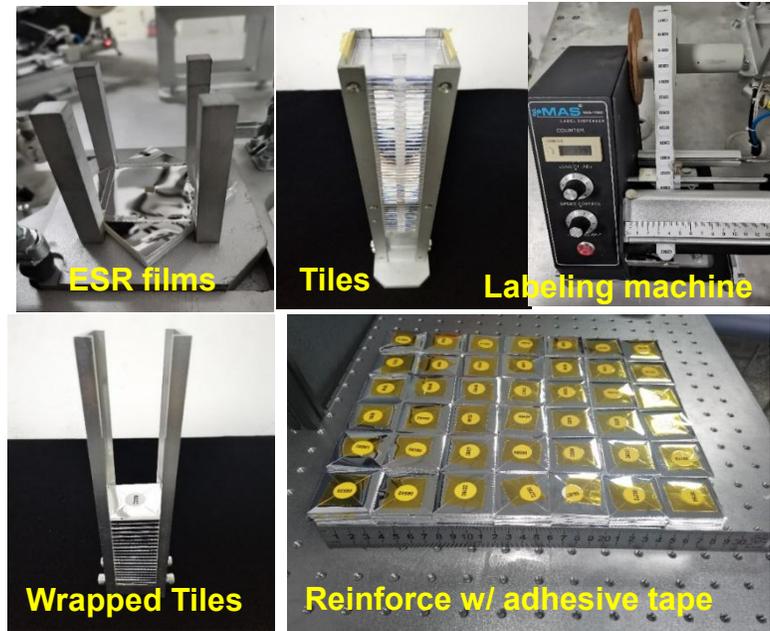
❖ Electronics with analog readout

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

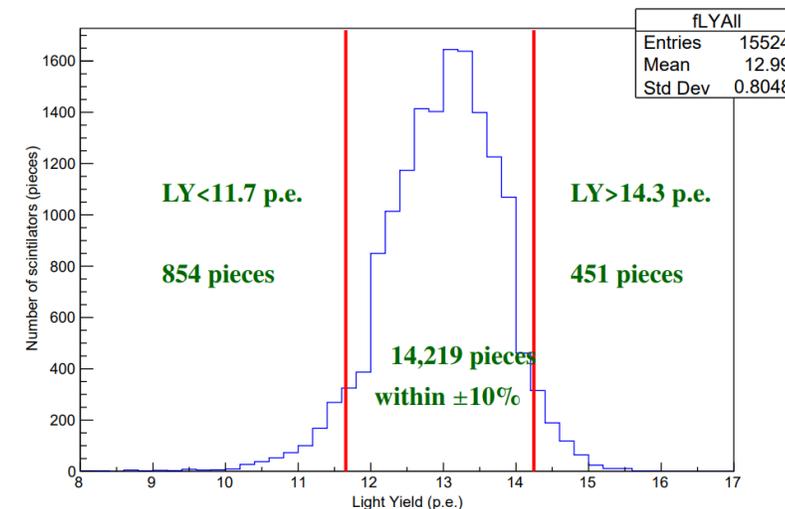


- ❖ >15K scintillators are produced with injection molding technique which are wrapped automatically with ESR films
- ❖ The batch test platform (with Sr-90)
 - HPK 13360-1325PE SiPM + SPIROC readout
 - 144 channels / batch
 - The light yield is fitted by landau-gauss function

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

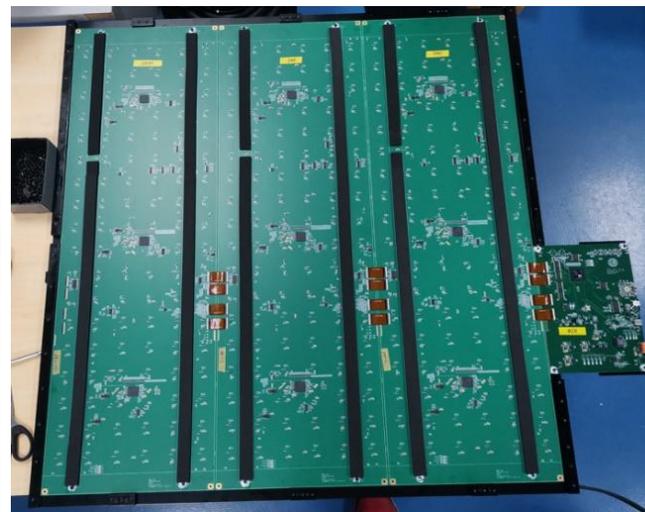
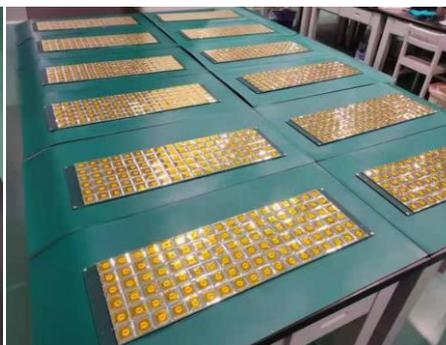
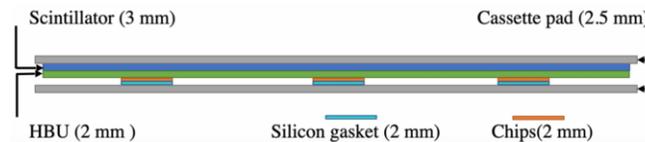


JINST 17 (2022) P05006



Light yield for all scintillators 14

- ❖ **Assemble of the AHCAL Prototype (12960-ch)**
 - 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

Oct 19 – Nov 2, 2022

Apr 26 – May 10, 2023

May 17 – 31, 2023

SPS H8 beamline

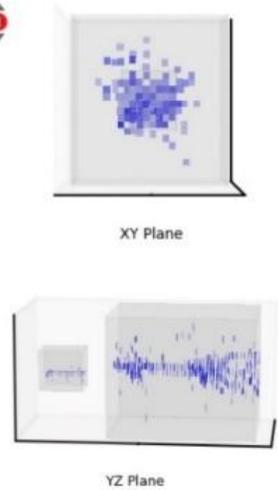
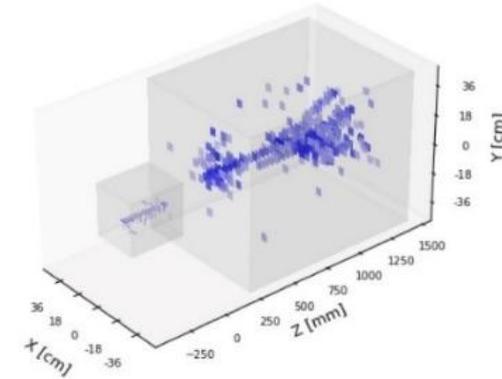
SPS H2 beamline

PS T9 beamline

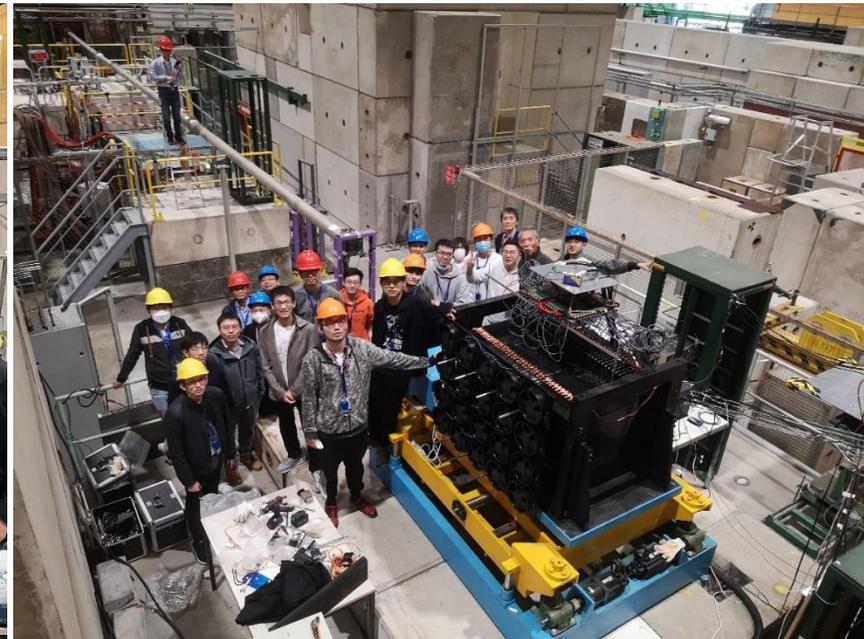
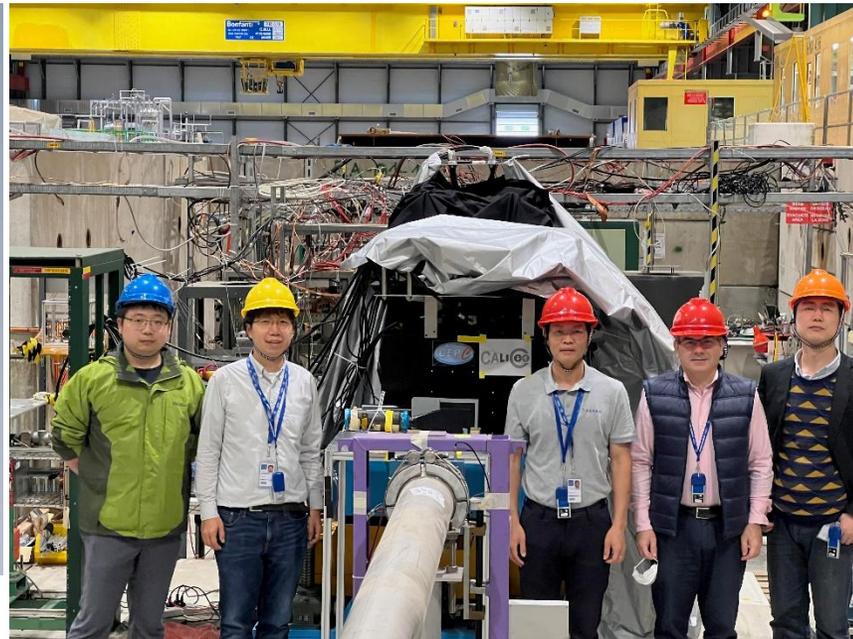
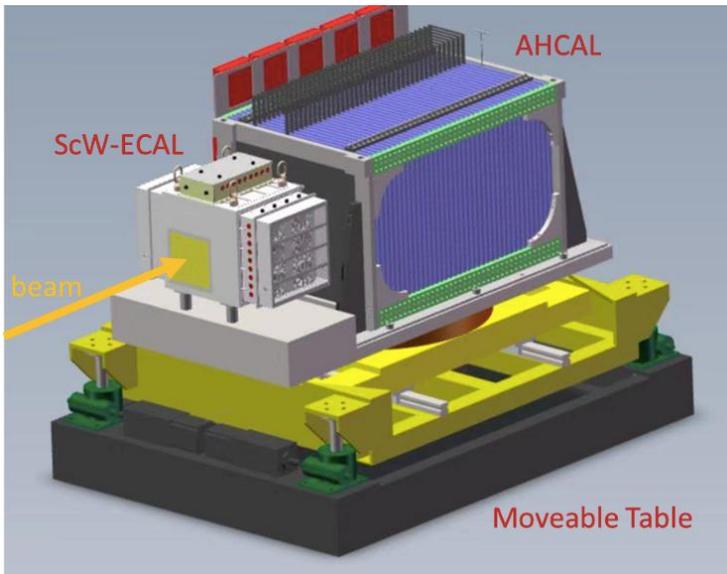
CEPC ScW-ECAL + AHCAL Prototype CALICE
CERN SPS H8 Beamline

Collected ~60M of test beam data samples

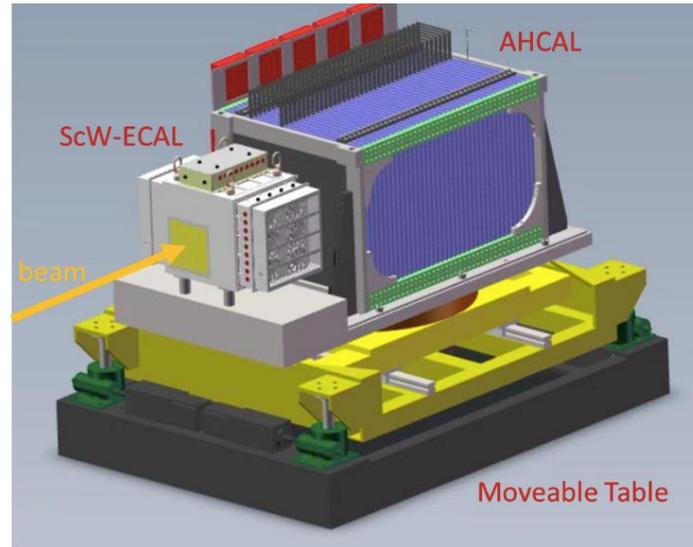
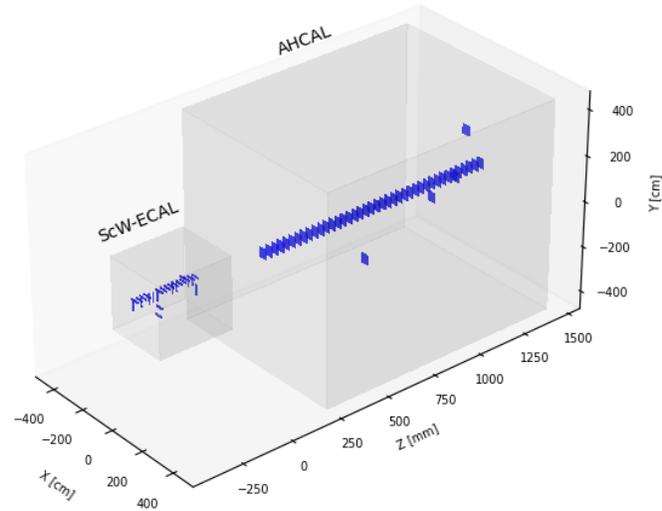
- Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
- Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 – 250 GeV at SPS
- Pions: 1 – 15 GeV at PS, 10 – 120 – 150 – 350 GeV at SPS



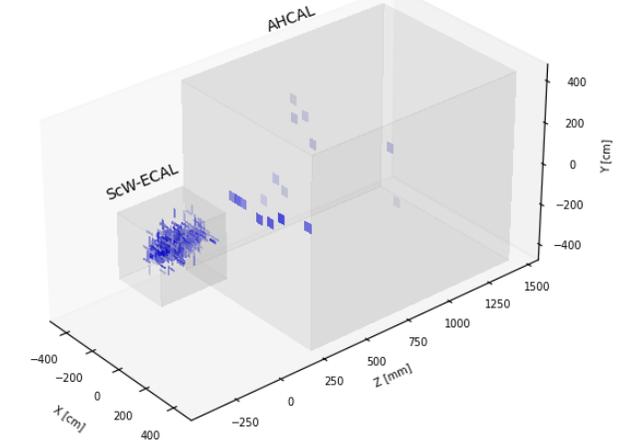
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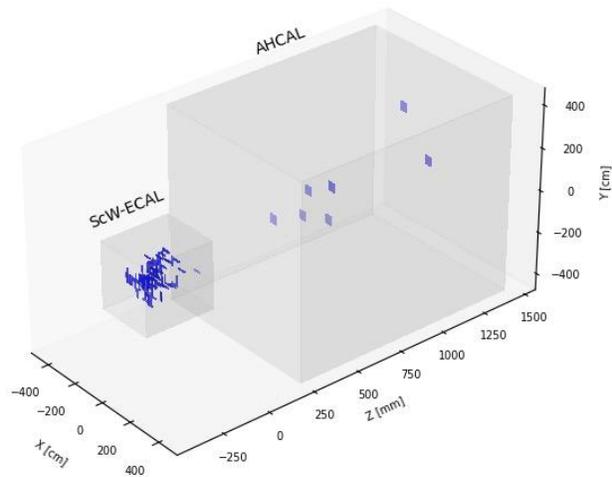
100 GeV mu-



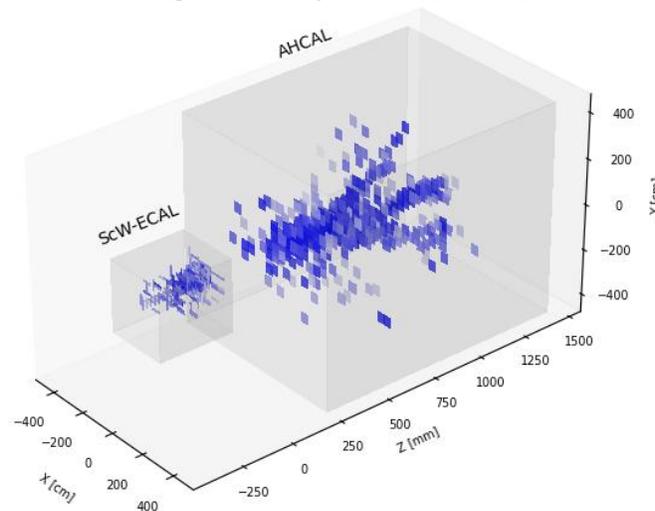
60 GeV electron



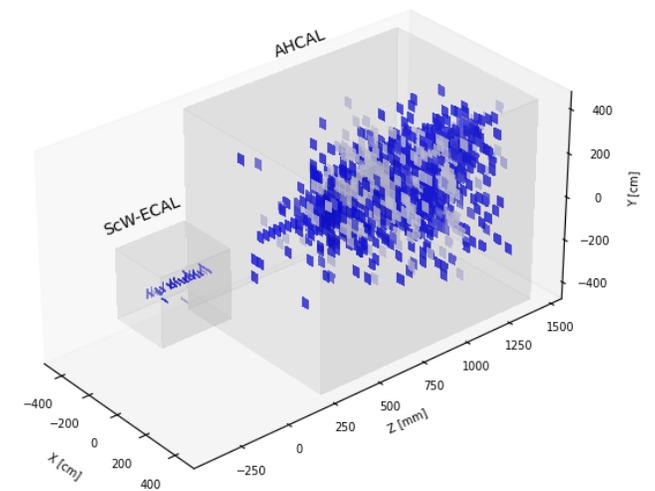
10 GeV negative pion (PS)



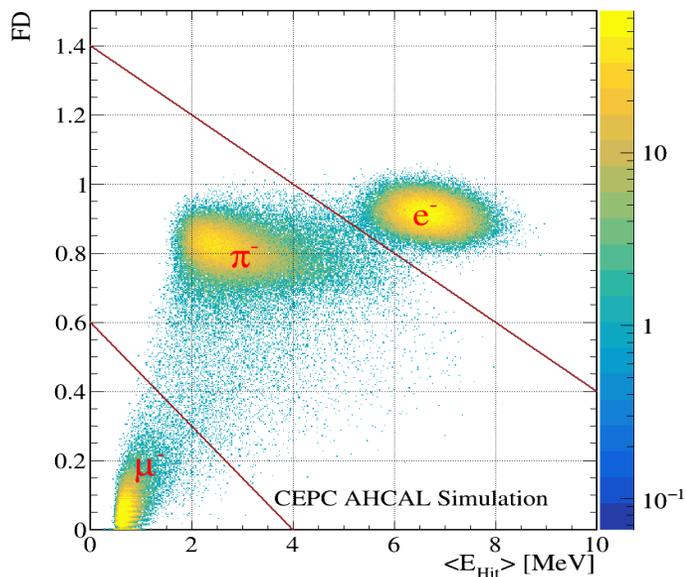
60 GeV negative pion (SPS)



350 GeV negative pion (SPS)



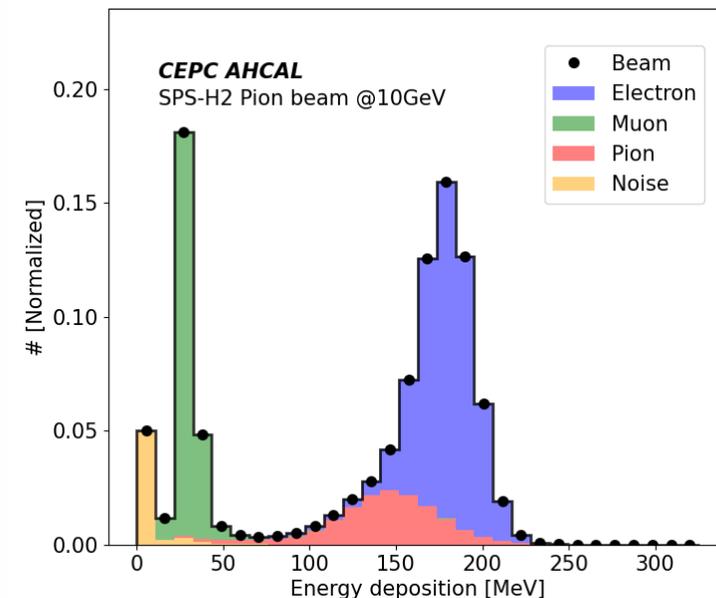
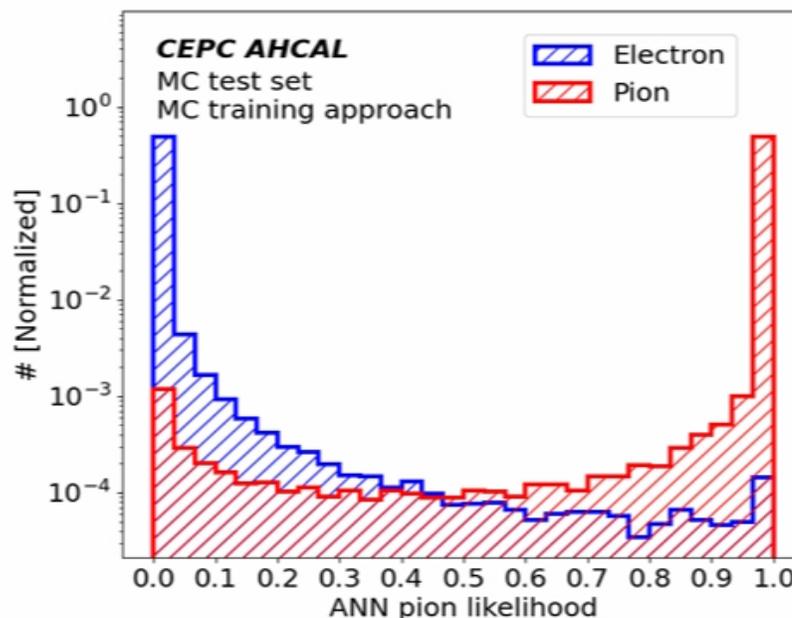
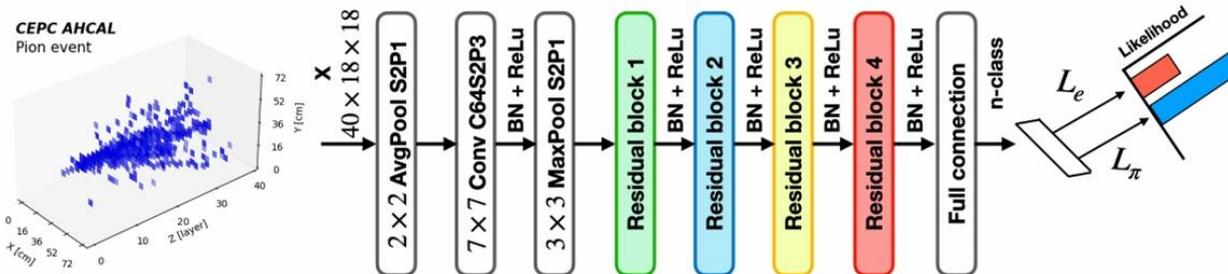
- PID based on ANN: input tensor of energy deposition per AHCAL tile
- ANN (ResNet) is consistent with FD within $\sim 1\%$ level for electron and pion



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

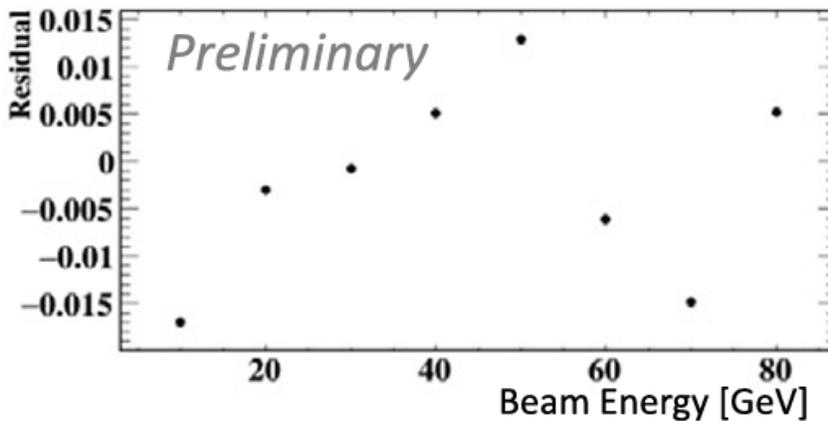
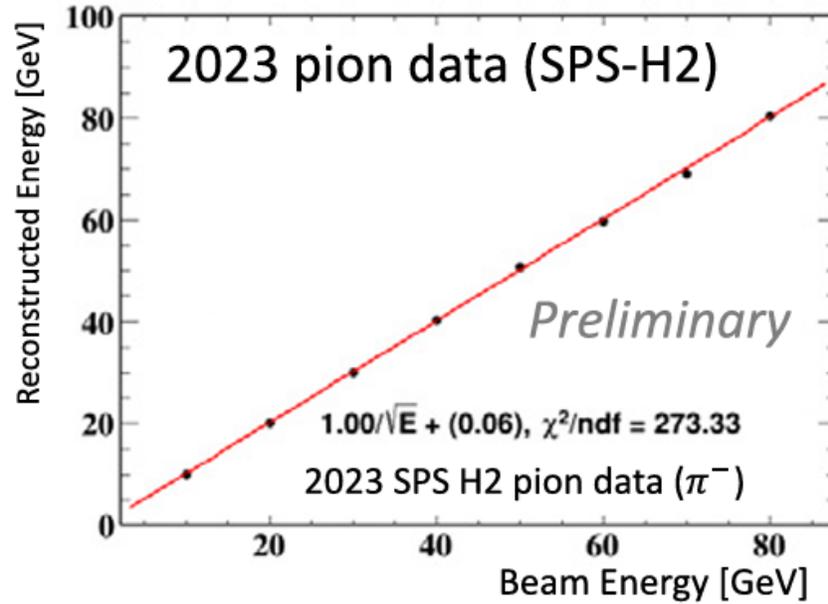
$$FD = \left\langle \frac{\log(R_{\alpha,1})}{\log(\alpha)} \right\rangle \text{ where } R_{\alpha,1} = \frac{N_1}{N_\alpha} \text{ and } N_\alpha$$

is number of hits scaled by factor α



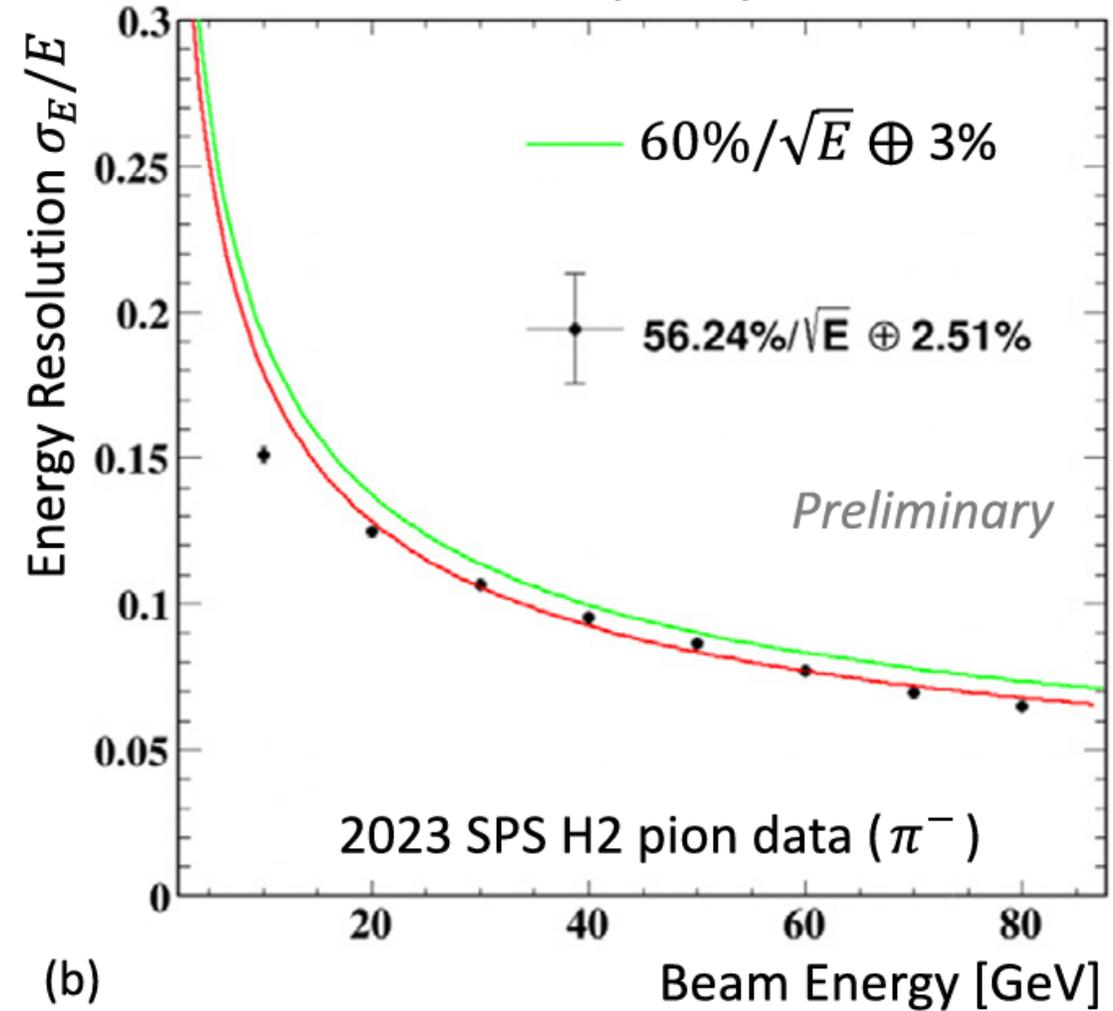
Siyuan Song's thesis work

NIMA 1072 (2025) 170191



(a)

Rec. Energy Linearity < 1.5%

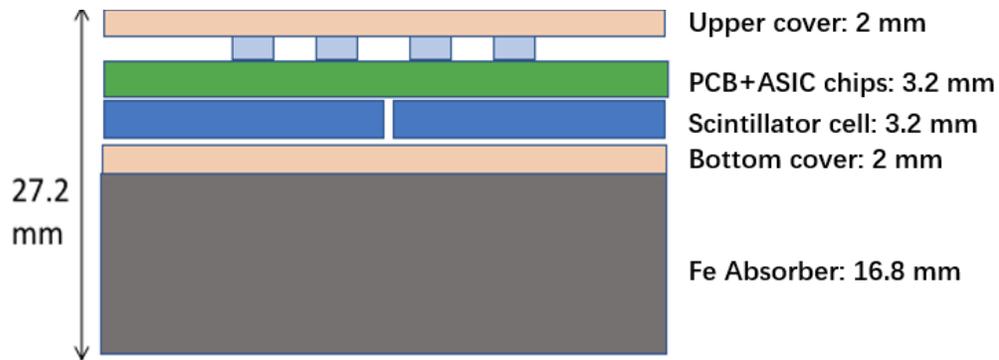


(b)

**Hadron Energy Resolution:
56.2%/√E ⊕ 2.5%**

- **Basic idea:** to increase sampling fraction for better energy resolution
- With **high density and thick GS cell design**, the sampling fraction of GS-HCAL can be increased by **a factor of ~20** compared to that of PS-HCAL

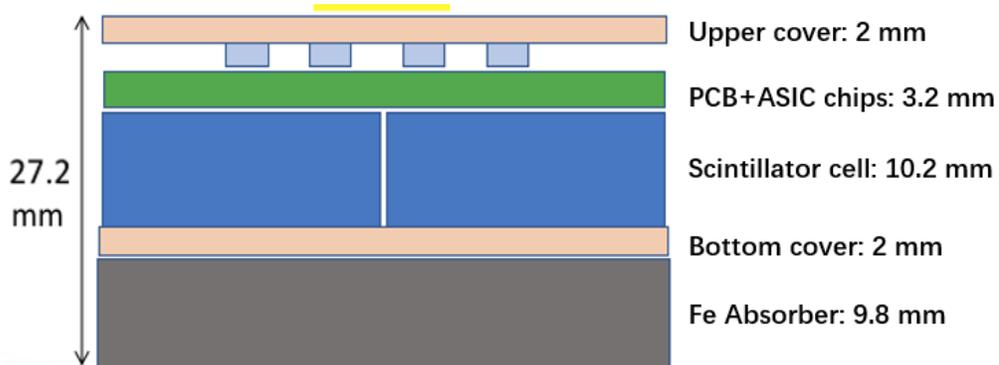
PS-HCAL



PS-HCAL

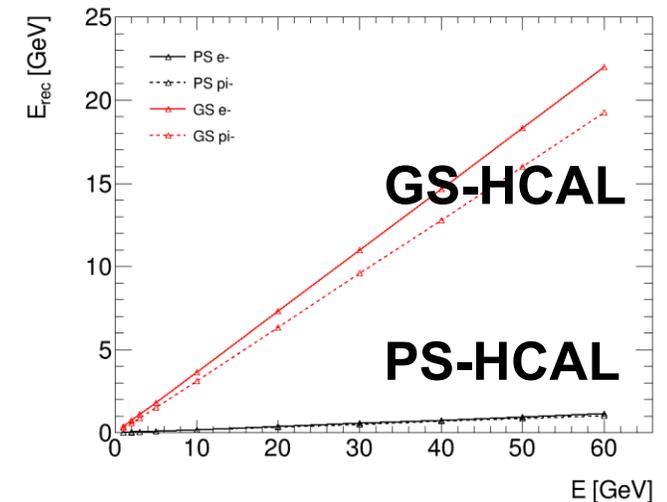
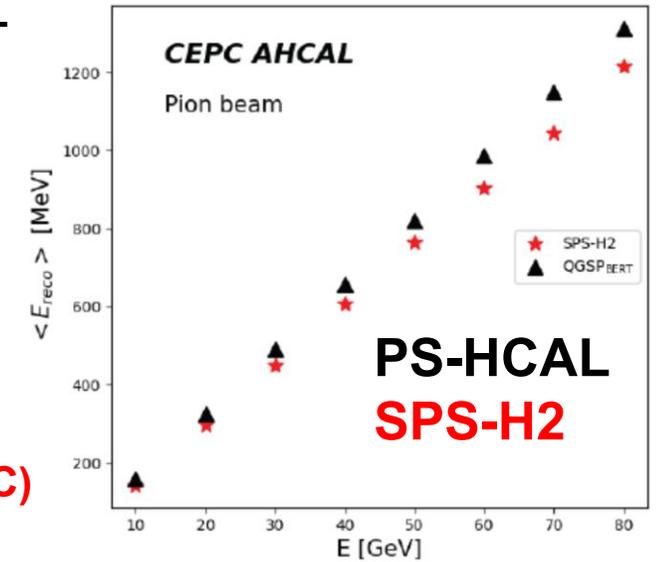
Fe: $20.8\text{mm}/171.5\text{mm}=0.1213 \lambda_1$
 PS: $3\text{mm}/688.7\text{mm}=0.0044 \lambda_1$
 PCB: $1.2\text{mm}/492.2\text{mm}=0.0024 \lambda_1$
Sampling fraction ~ 1.6% (π TB, MC)

GS-HCAL

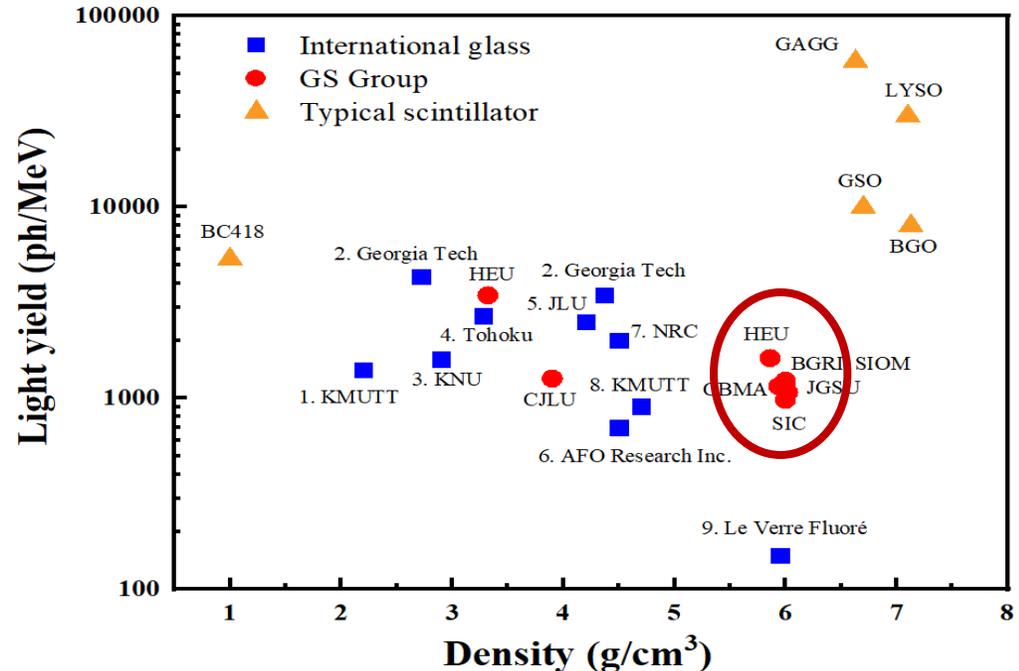
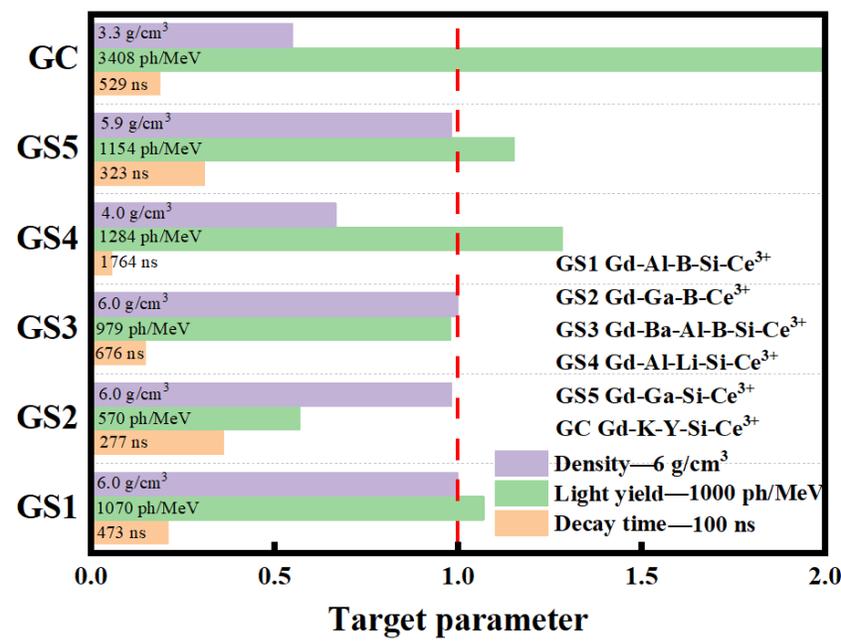


GS-HCAL

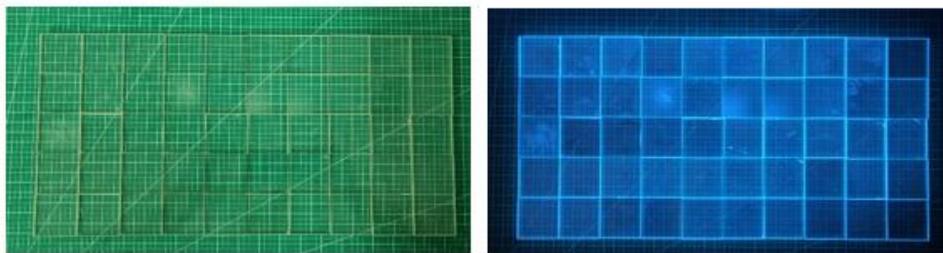
Fe: $13.8\text{mm}/171.5\text{mm}=0.0805 \lambda_1$
 GS: $10.2\text{mm}/242.8\text{mm}=0.0425 \lambda_1$
 PCB: $1.2\text{mm}/492.2\text{mm}=0.0024 \lambda_1$
Sampling fraction ~ 31% (MC)



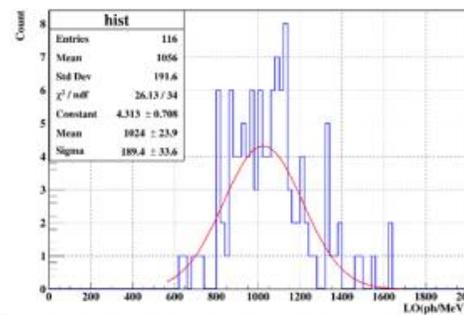
- **GS collaboration** was established in 2021 and aiming the large-area & high-performance GS for application in nuclear and high energy physics.
- The GS collaboration includes IHEP, 3 Institutes of CAS, 5 Universities, 3 Factories currently.
- The performance of glass scintillator samples look promising, i.e. **6 g/cm³ & 1000 ph/MeV & O(100) ns**



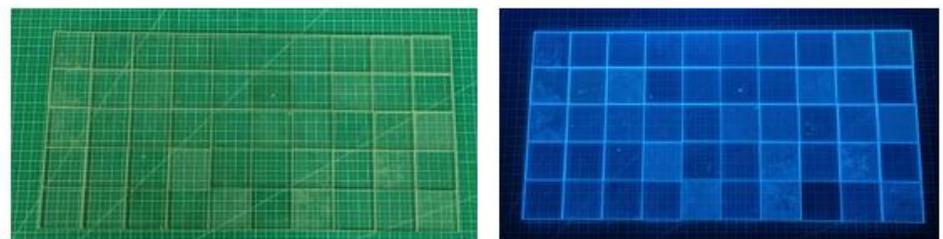
- 291 GS tiles (size: $4 \times 4 \times 1 \text{ cm}^3$) produced by three companies
- Test setup: Radiation source (^{137}Cs) with 2' PMT (xp2020)
- About 57% of GS tiles with light yield greater than 1000 ph/MeV



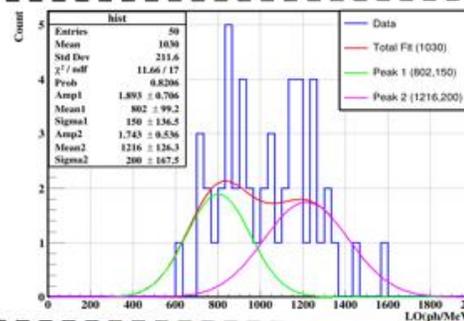
BGRI



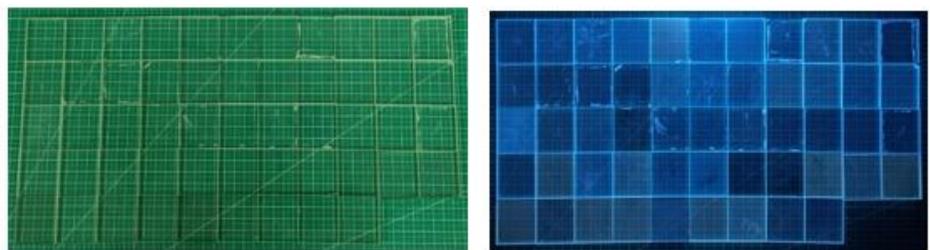
- The light yield of 60.3% of GS is ≥ 1000 ph/MeV (70/116)
- The light yield of 20.7% of GS is ≥ 1200 ph/MeV (24/116)



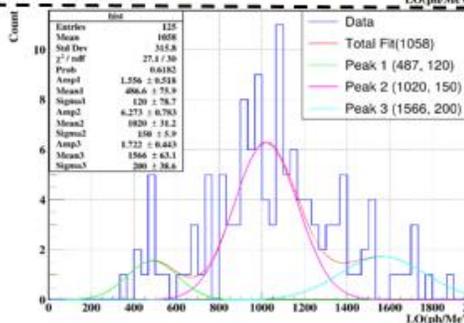
SIOM



- The light yield of 54.0% of GS is ≥ 1000 ph/MeV (27/50)
- The light yield of 24.0% of GS is ≥ 1200 ph/MeV (12/50)



CBMA



- The light yield of 55.2% of GS is ≥ 1000 ph/MeV (69/125)
- The light yield of 30.4% of GS is ≥ 1200 ph/MeV (38/125)

- GS attenuation length: 6.1 cm @ 400nm
- Feasible to use one SiPM per GS tile

- Cosmic ray test of GS-SiPM coupling
- Light output is ~ 64 pe/MIP

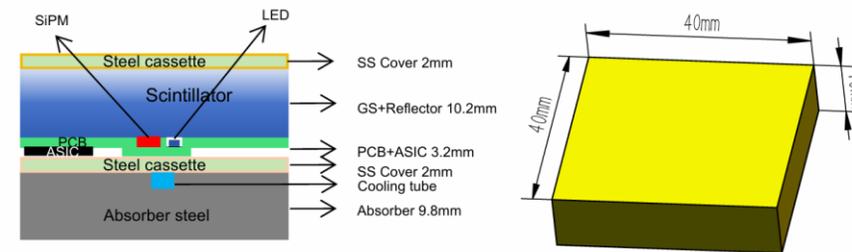
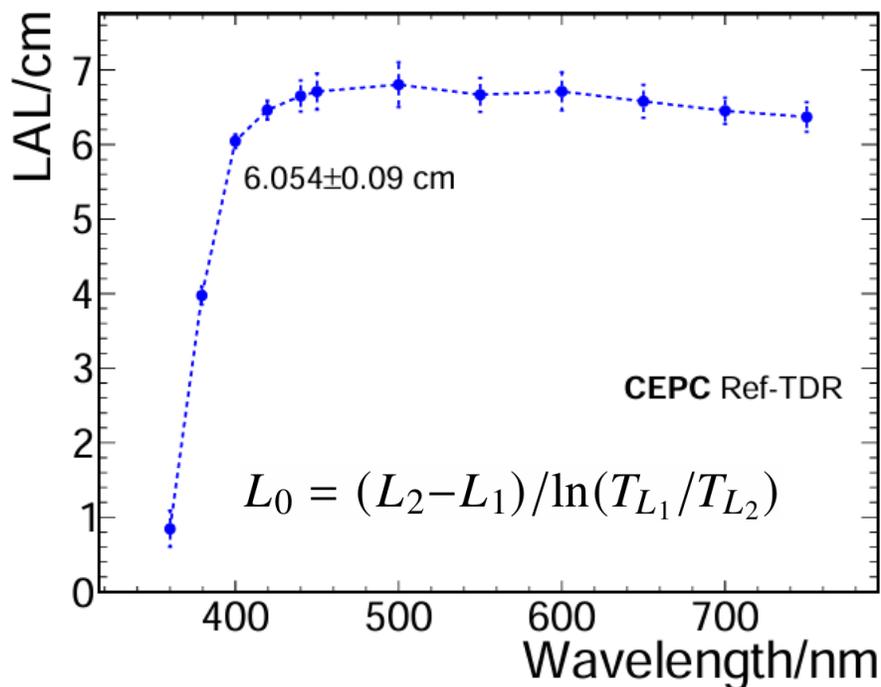
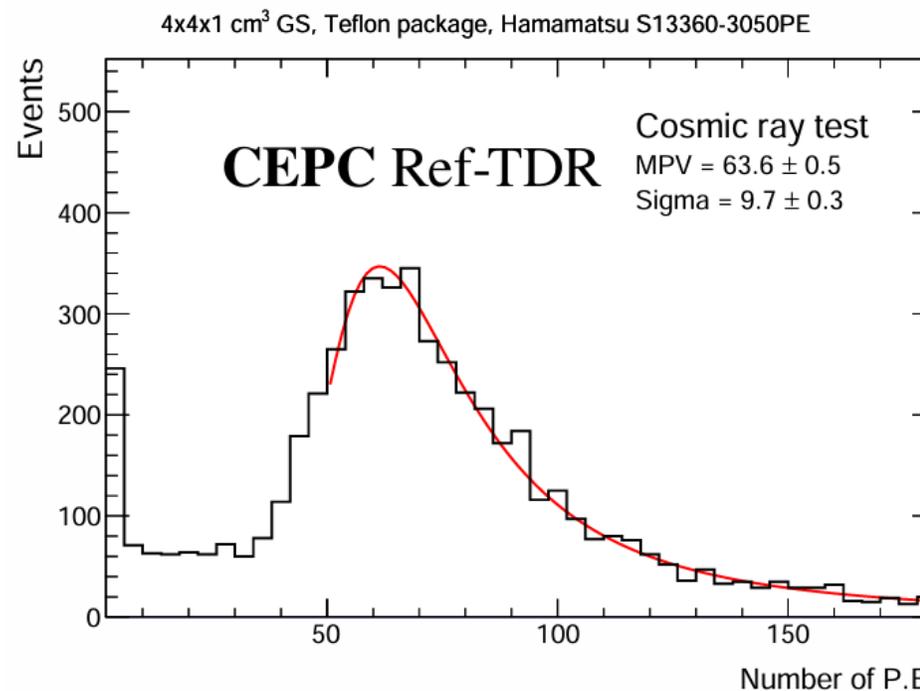
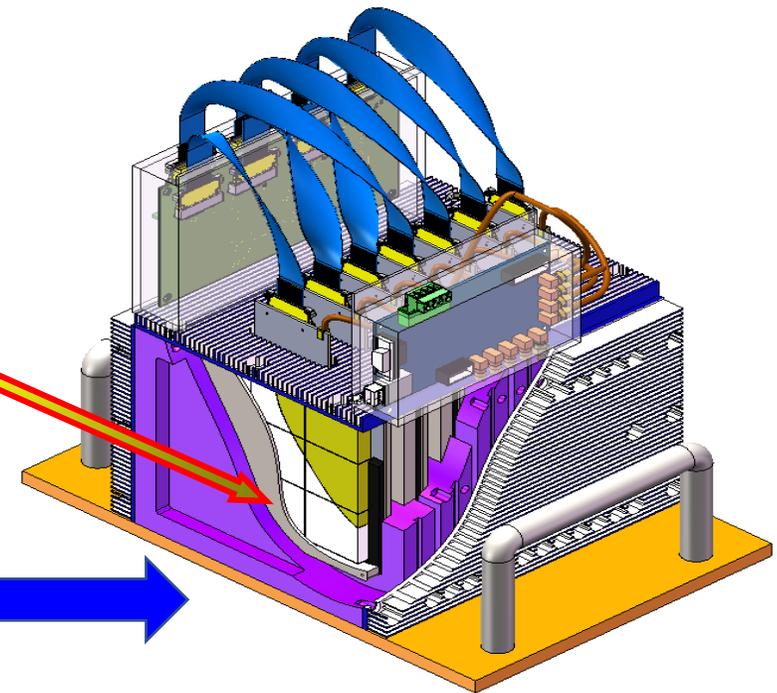
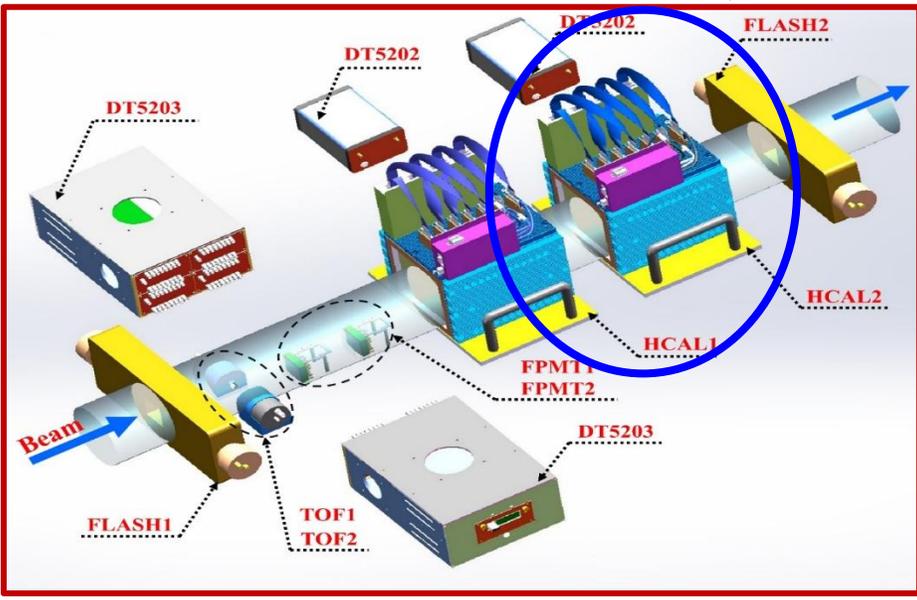
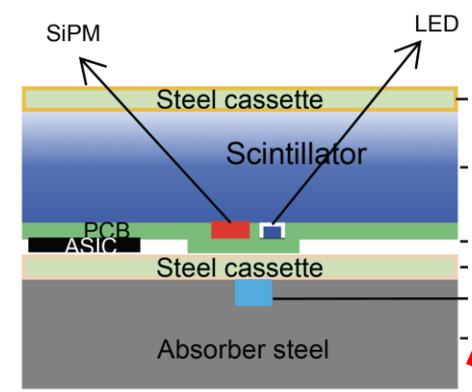
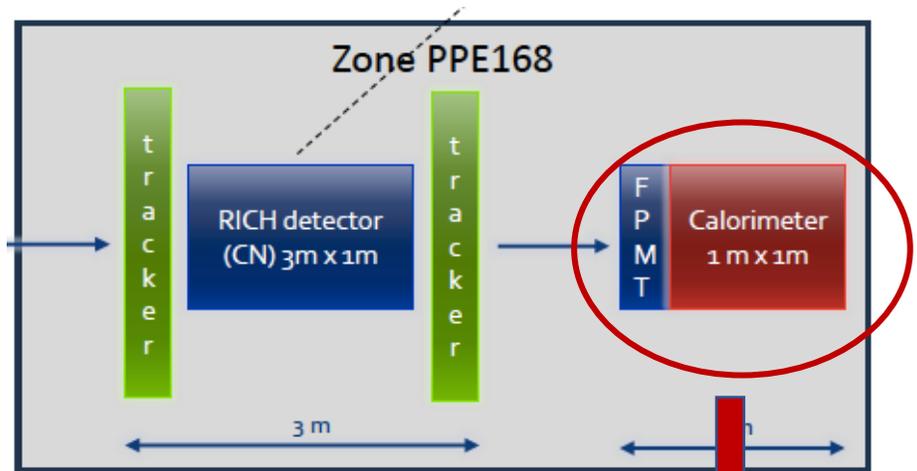


Figure 8.2: (a) Single layer structure of GS-HCAL. (b) One GS cell.



Z.H. Hua, S. Qian, et al. NIMA, 2025, 1072, 170182.

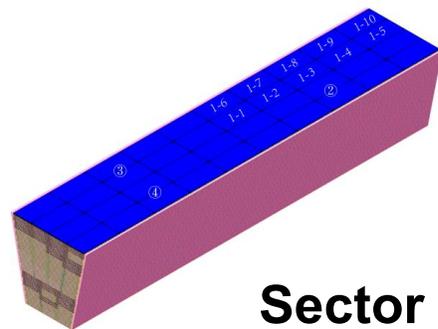




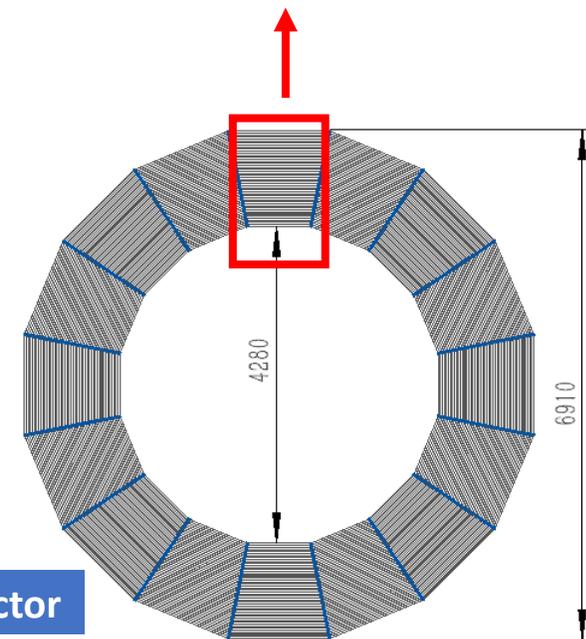
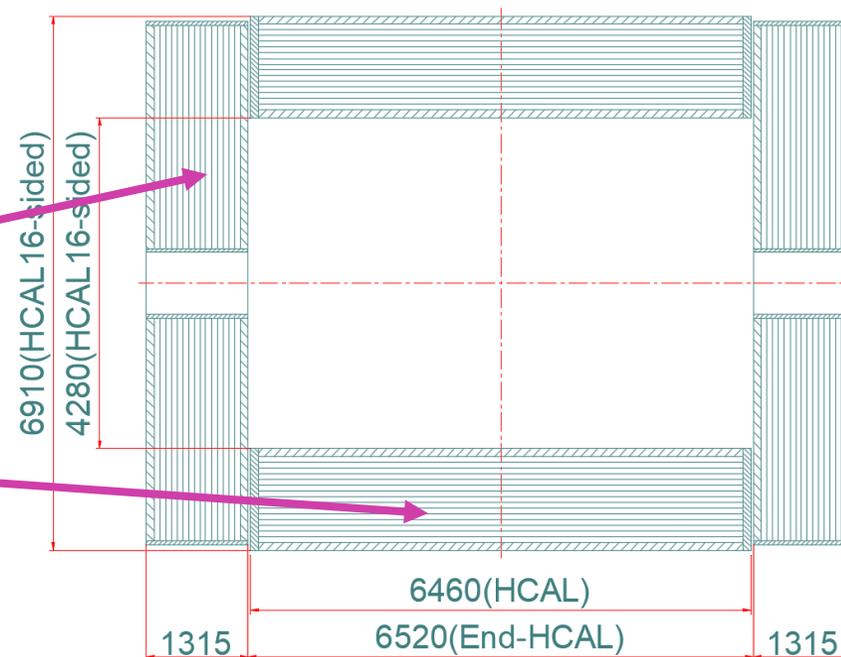
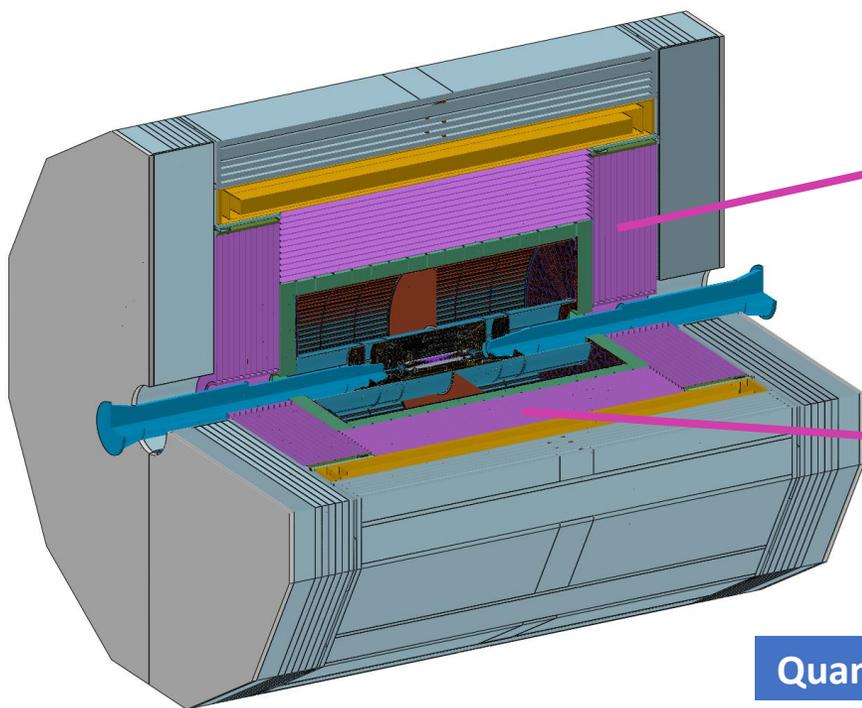
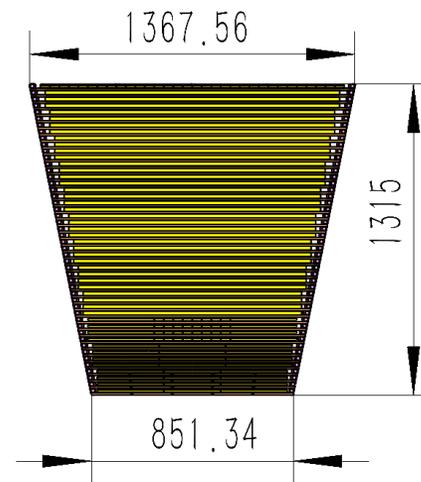
- **Mini-Prototype:** 7 layers, each layer has $3 \times 3 = 9$ GS tiles, 63 GS tiles in total, each GS size of $4 \times 4 \times 1 \text{ cm}^3$
- **Two mini-prototypes** using HPK & NDL, respectively
- **CERN beam tests (Pion / Muon) in October 2025**

➤ **GS-HCAL: One Barrel (16 sectors) and Two Endcaps**

- Thickness of the barrel : 1315 mm
- Inner radius of the barrel : 2140mm ($D_{in}=4280$ mm)
- Barrel length along beam direction : 6460 mm
- Number of layers : 48 ($6 \lambda_1$)



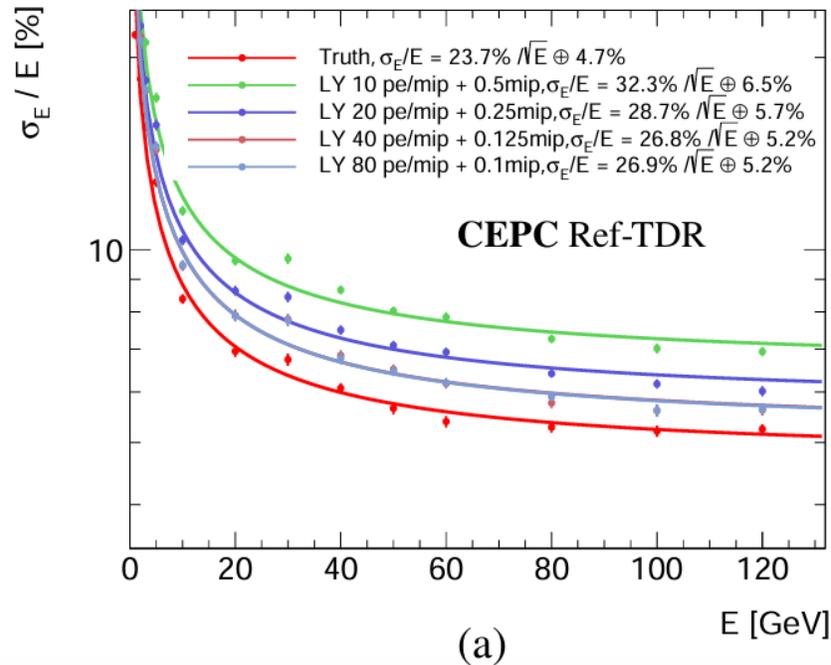
Sector



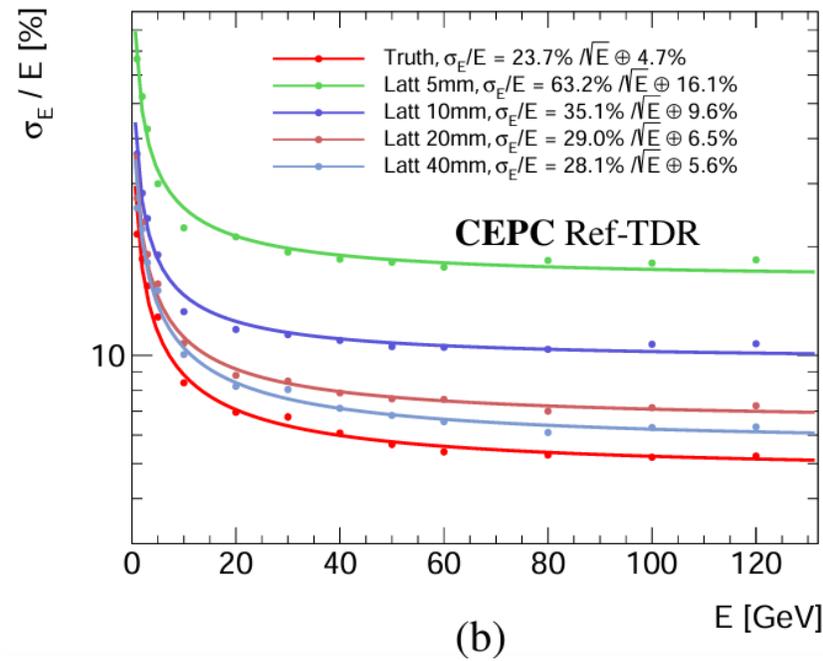
Quantities	Cell	Box	Layer	Sector
Barrel	3212800	27840	48×16=768	16
Endcap×2	1006080×2	3072×2	48×16×2	16×2

➤ A full detector geometry constructed with DD4hep in CEPCSW

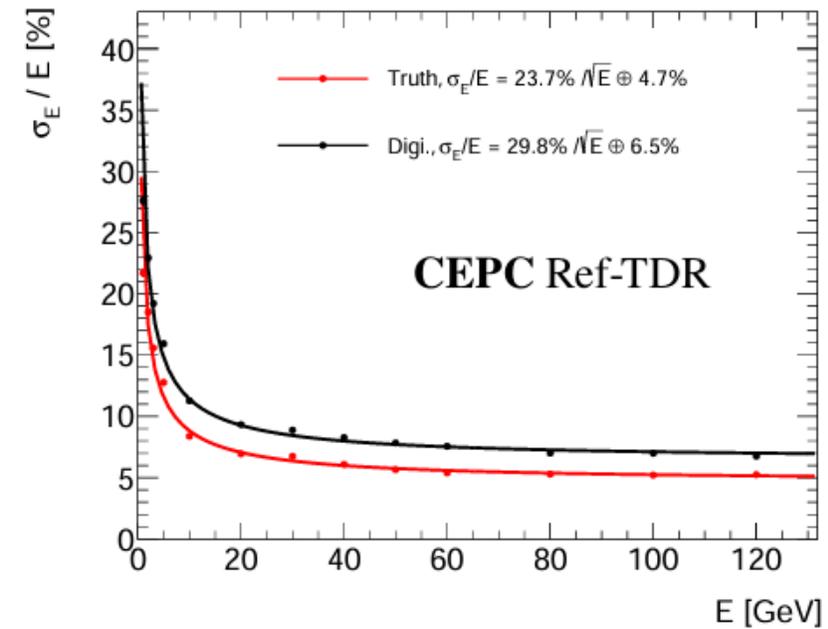
- GS density 6 g/cm^3 , $\lambda_I = 242.8 \text{ mm}$, attenuation length $\sim 60\text{mm}$
- GS cell size $4 \times 4 \times 1 \text{ cm}^3$, 48 layers, $6\lambda_I$ in total
- Geometry: follow the mechanics design with supporting structures.



(a)



(b)



$$\sigma_E/E = 29.8\% / \sqrt{E} \oplus 6.5\%$$

- GS light yield: $> 50 \text{ p.e./MIP}$
- Threshold: 0.1 MIP ($> 5 \text{ p.e.}$)

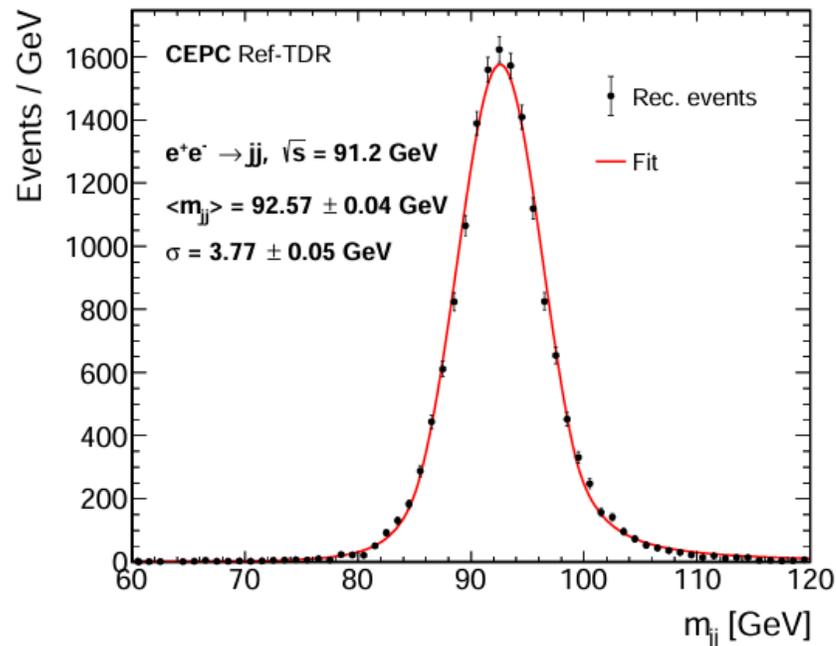
- GS attenuation length

- GS attenuation length: $\sim 60\text{mm}$

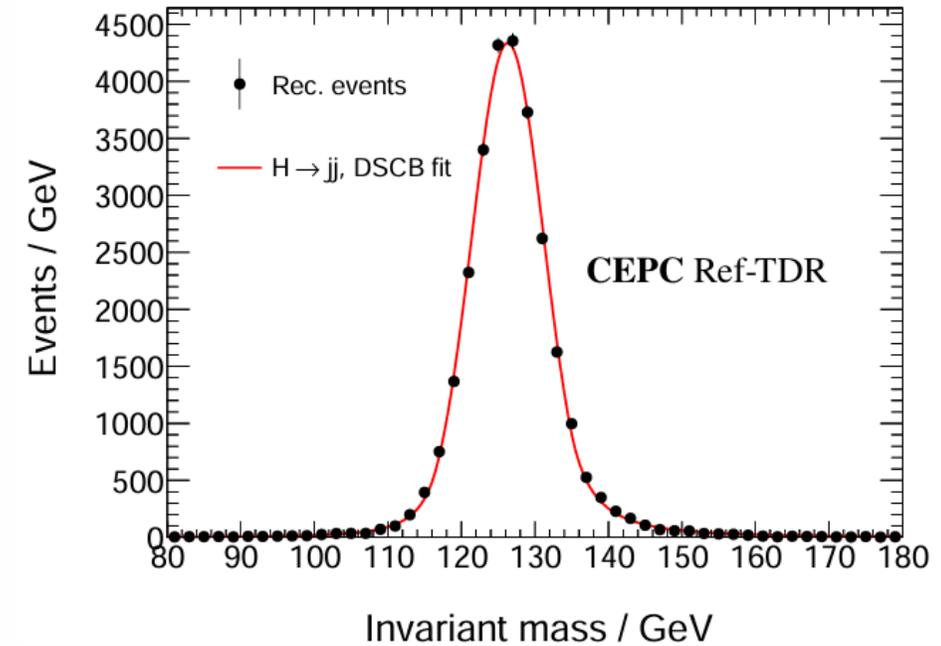
➤ **Hadron Energy Resolution (full simulation + digitization):**

- MC Samples: **$ee \rightarrow Z \rightarrow jj$ @ 91.2 GeV, $ee \rightarrow ZH \rightarrow \nu\nu gg$ @ 240 GeV**
- Tracker (Si + TPC) + Crystal ECAL + GS-HCAL, Cyber PFA Reconstruction

BMR ($Z \rightarrow jj$) = 4.0%



BMR ($H \rightarrow gg$) = 3.87%



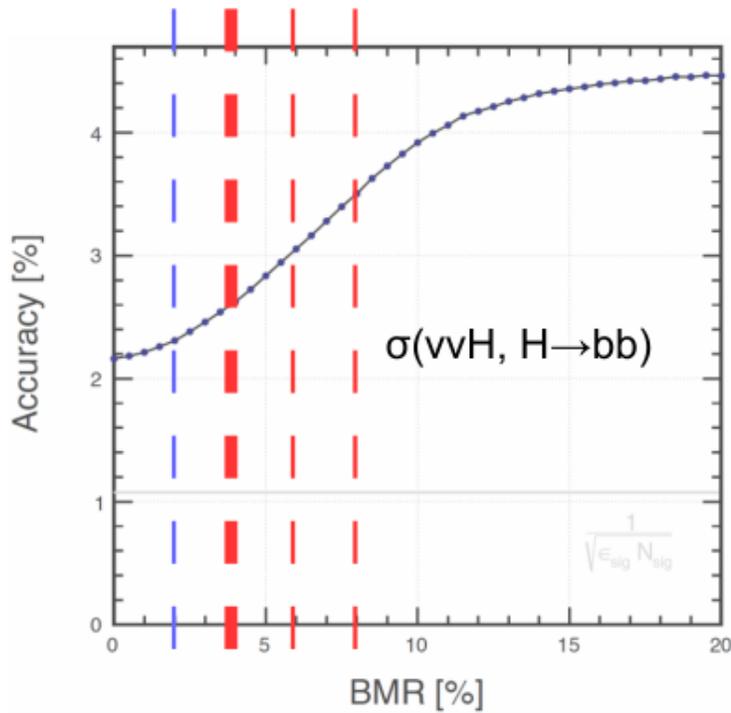
- **PFA calorimeter prototypes (Plastic Scintillators or GRPC based)**
 - Successful beam test campaigns at CERN PS/SPS
 - Invaluable for detector performance evaluation and shower studies
- **GS-HCAL is selected as baseline based on its promising performance**
 - Intensive R&D on high quality GS (e.g. light yield, decay time, attenuation length)
 - Study with CEPCSW shows promising result
- **PID and validation studies: preliminary results promising**
 - Particle Identification with machine learning: muons, electrons, pions
 - Prototype simulation + digitization: validation studies with beam data
- **Future Plan: DRD-on-Calorimetry (DRD6 and DRD1) collaboration**
 - To develop common software, DAQ and beamtest campaigns
 - To develop better GS and mature techniques for mass production with low cost
 - Towards 5D hadronic calorimeter system

Thanks for your attention !

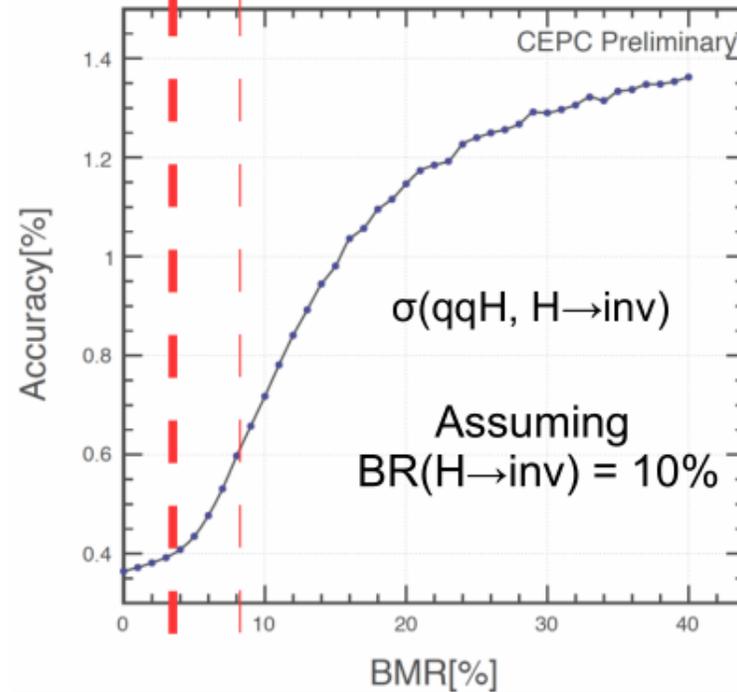
- ❖ Two prototypes are supported by the MOST and NSFC grants
- ❖ Successful beam test campaigns at CERN during 2022-2023
- ❖ We highly appreciate strong teamwork and enormous support received from CERN, CALICE and EuroLabs



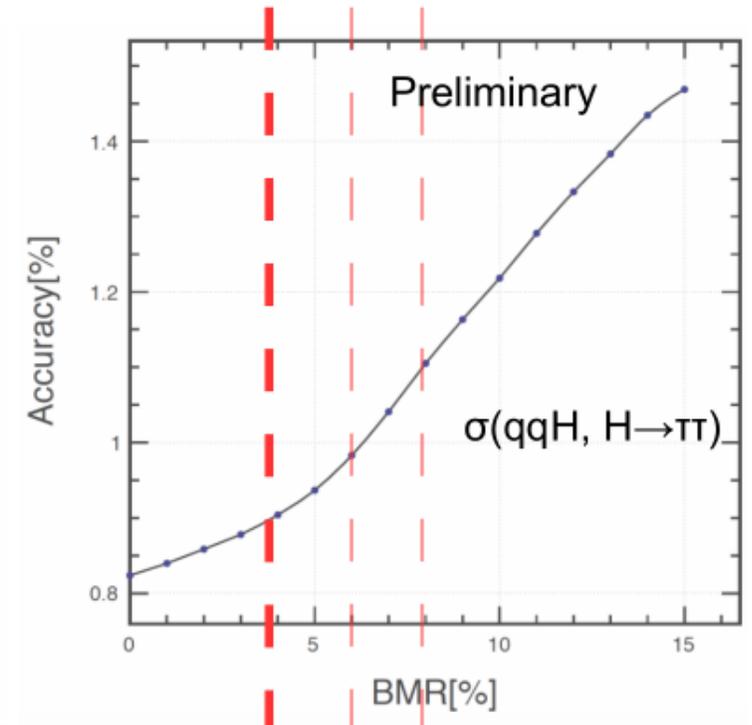
Accuracy($\sqrt{S+B}/S$) vs BMR (Boson Mass Resolution)



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



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



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

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

- The connection design of the barrel HCAL (955 tons) bypasses the magnet, it fixes directly to the barrel yoke using 60 mm thick rings.

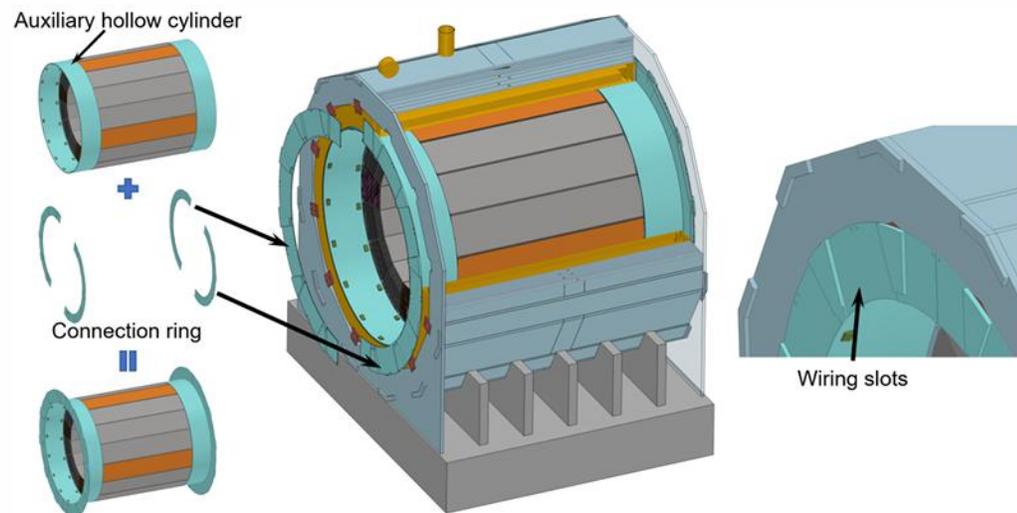
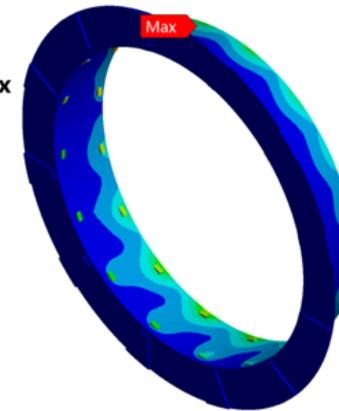
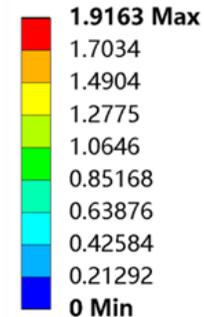
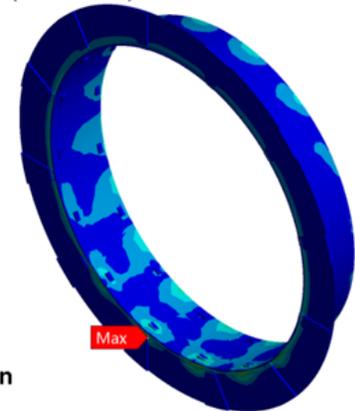
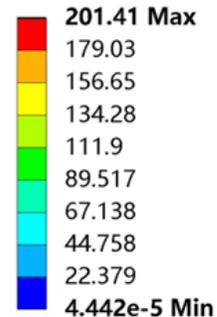


Figure 14.12: Connection structure of the barrel HCAL. There is a steel circular ring as two detachable halves at each end for connecting the auxiliary hollow cylinder of the HCAL's and the end flange of the barrel yoke's. The ring features some slots for cable routing.

A: Static Structural
 Total Deformation 4
 Type: Total Deformation
 Unit: mm
 Time: 1

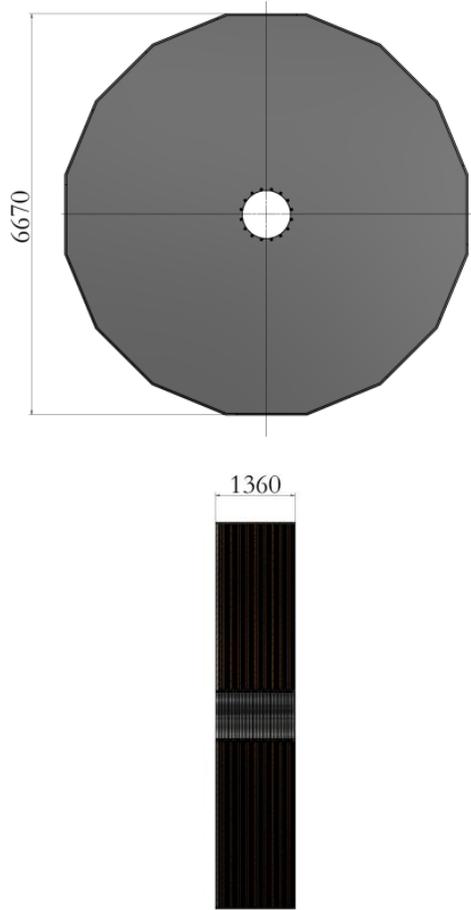


A: Static Structural
 Equivalent Stress 10
 Type: Equivalent (von-Mises) Stress
 Unit: MPa
 Time: 1



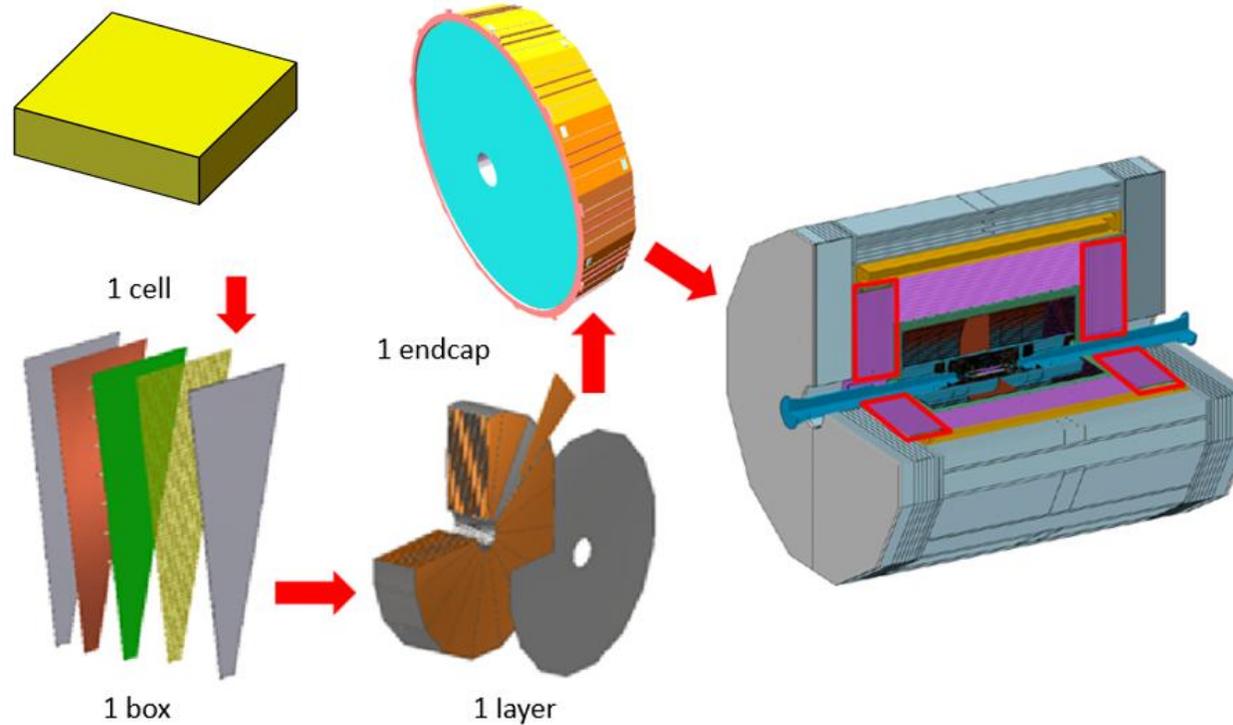
- FEA simulation result of the barrel HCAL connection structure:
 - Maximum deformation is 1.9 mm
 - Maximum stress is 201 MPa

Main Structure



Two endcap HCAL

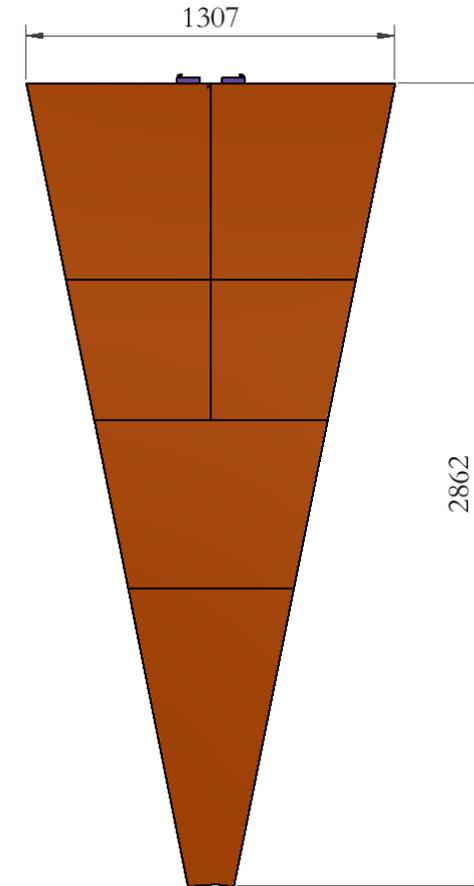
Integration of barrel HCAL structure



	Cell	Box	Layer	Sector
Quantities	1006080*2	3072*2	48*16*2	16*2

Total weight: $367 \times 2 = 734$ tons

Boxes in one layer



4 types Box

- Each endcap HCAL weighs about 367 tons and is installed in the auxiliary hollow cylinder of the barrel HCAL.

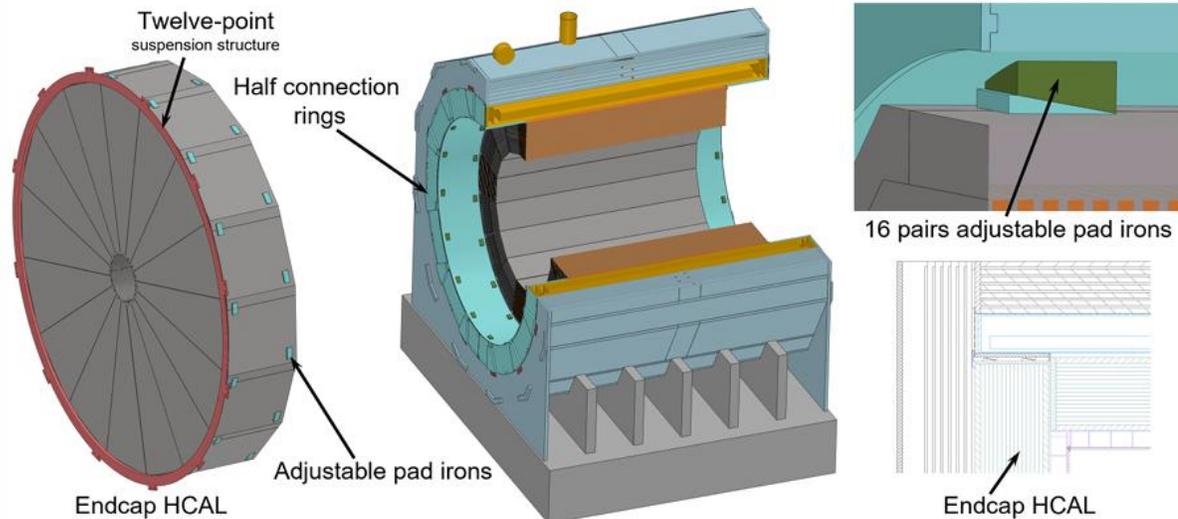
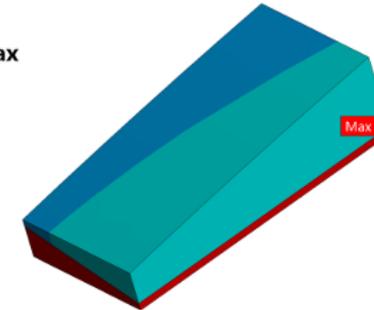


Figure 14.15: Connection structure of the endcap HCAL. The endcap HCAL is rigidly connected to the barrel yoke through 16 pairs of adjustable pad irons, two pairs of axial pads, and a twelve-tooth flange, ensuring stable support for the superconducting magnet.

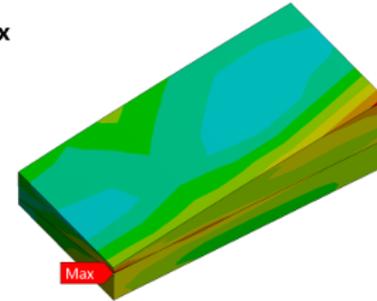
A: Static Structural
 Total Deformation 3
 Type: Total Deformation
 Unit: mm
 Time: 1

2.7779 Max
 2.476
 2.1741
 1.8723
 1.5704
 1.2685
 0.9666
 0.66471
 0.36283
 0.060943 Min



A: Static Structural
 Equivalent Stress 3
 Type: Equivalent (von-Mises) Stress
 Unit: MPa
 Time: 1

94.459 Max
 83.964
 73.468
 62.973
 52.477
 41.982
 31.486
 20.991
 10.495
 2.0402e-5 Min



- FEA simulation result of the endcap HCAL connection structure:
 - Maximum deformation is 2.8 mm
 - Maximum stress is 94 MPa

- A water cooling system is designed to manage thermal loads from ASIC chips.
- Heat load is $\sim 76.8\text{W}$ per layer ($5120 \text{ ch} \times 15\text{mW}/\text{ch}$) from FEE in barrel.
- Eight-in-one pipe line design, 4 pipes in each layer in parallel, 8 layers gather in one pipe, so each barrel sector has 6 independent cooling loops.
- Endcap has 16 sectors, each detector layer has 16 separate cooling regions.

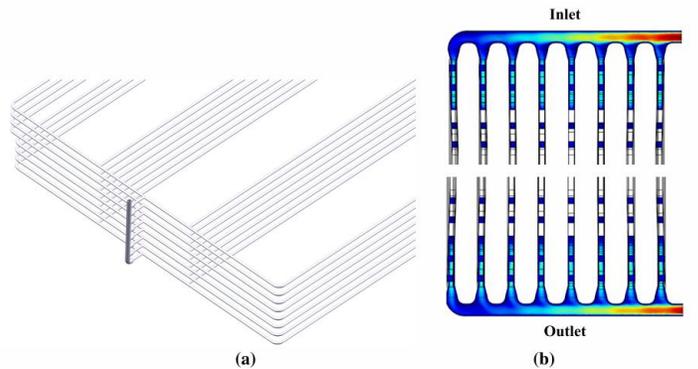
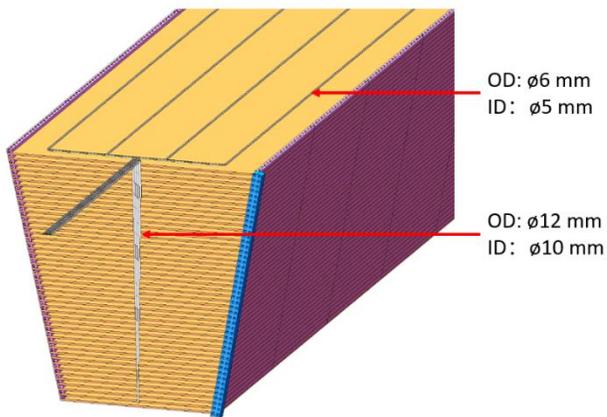
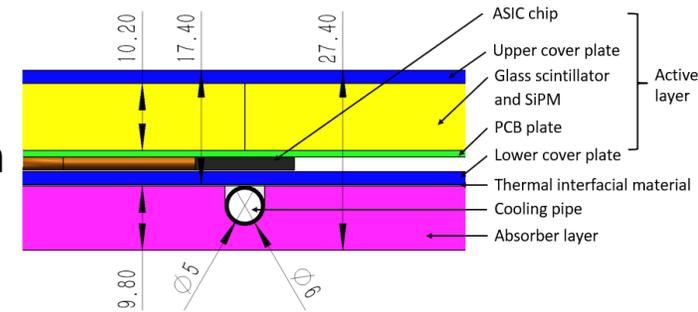


Figure 8.6: Cooling pipe routing for a barrel sector of the GS-HCAL. (a) Schematic of the eight-in-one pipeline design. (b) Simulated flow velocity (m/s) distribution of the coolant along the pipeline, with inlet and outlet positions indicated.

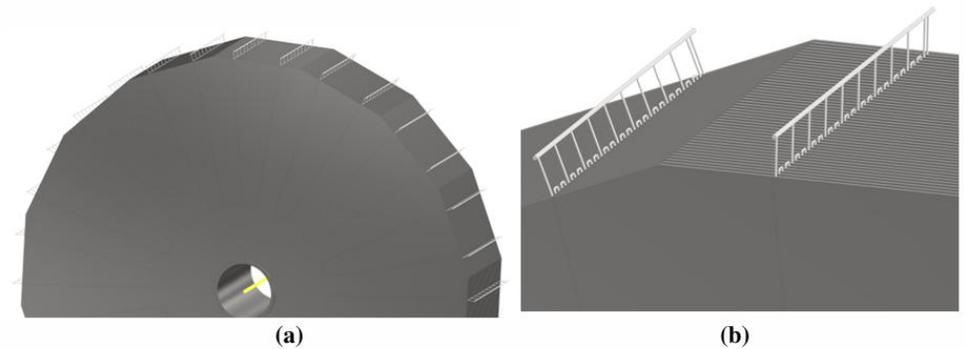


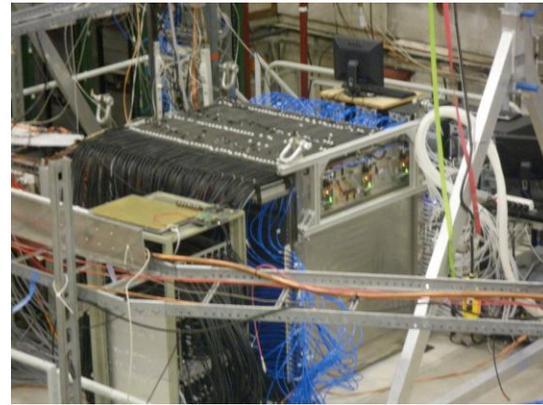
Figure 8.8: Cooling pipe structure for the endcap, where (a) is showing a half of the endcap, and (b) is showing a zoomed in corner of the endcap.



Si-W ECAL, 30 layers, 1x1 cm²



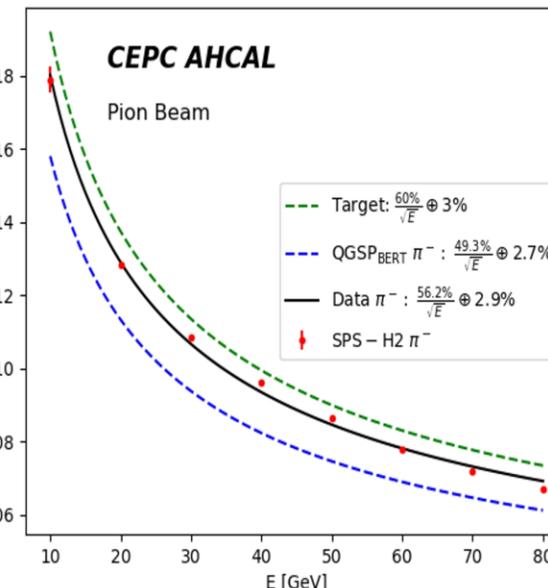
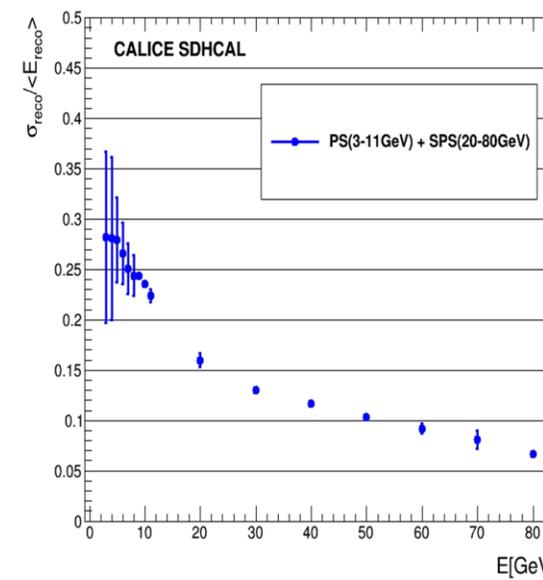
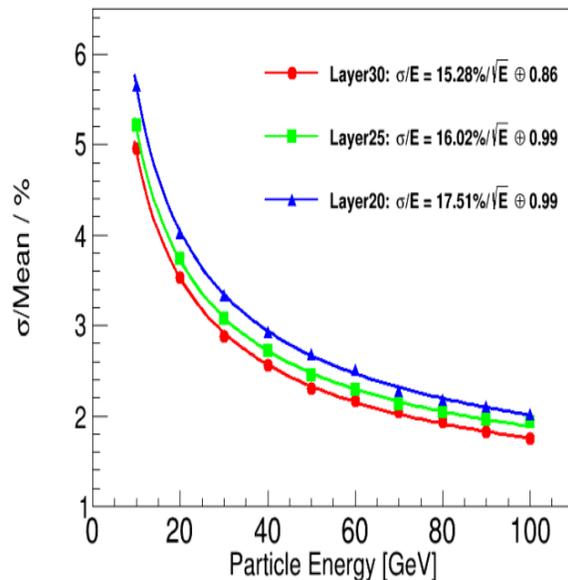
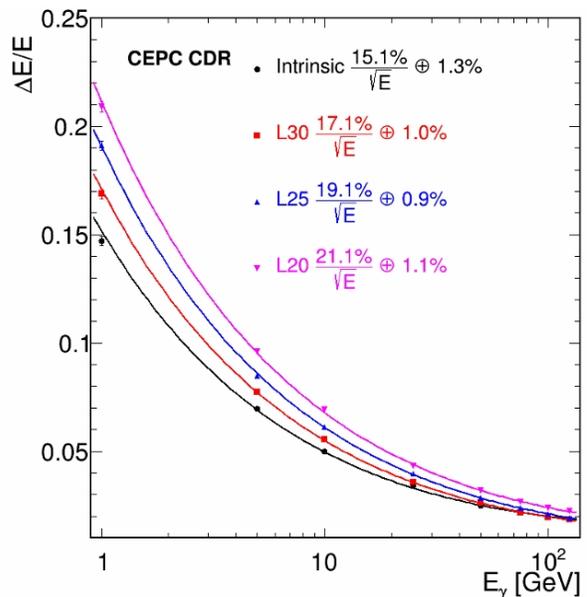
Sci-W ECAL, 32 layers, 5x5 mm²

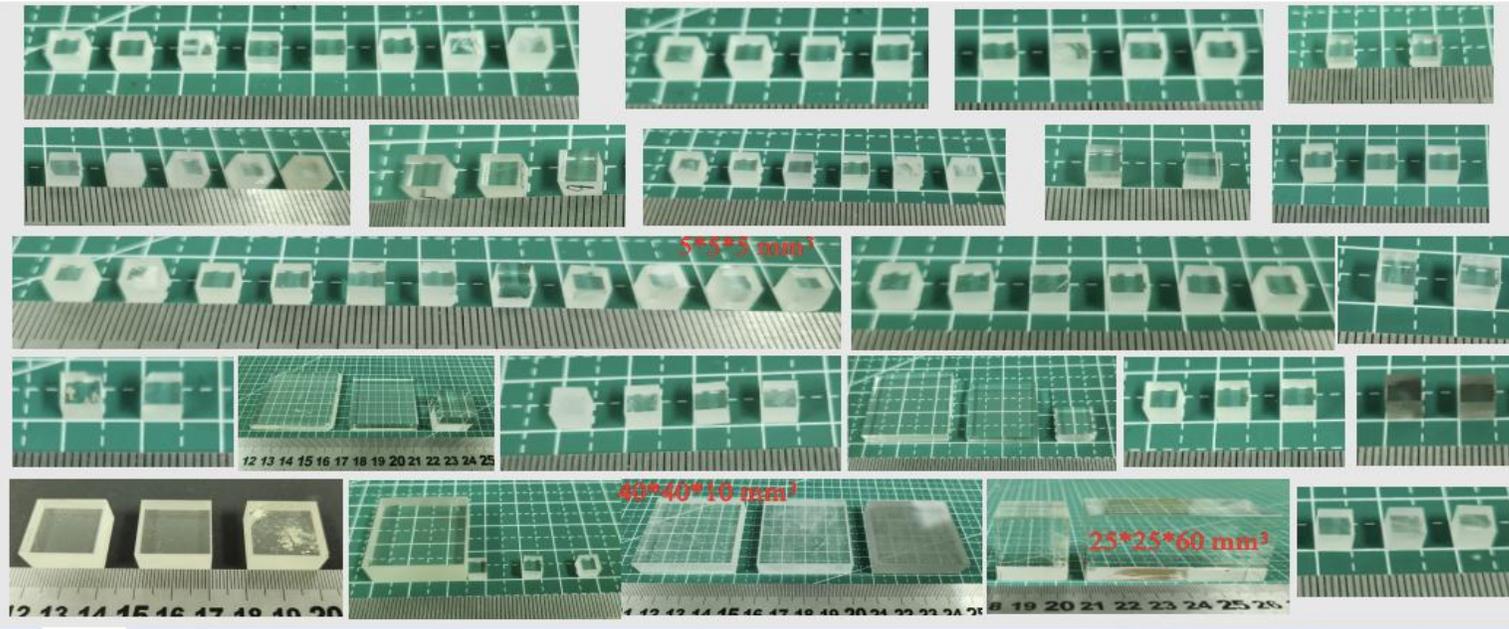


SDHCAL, 48 layers, 1x1 cm²

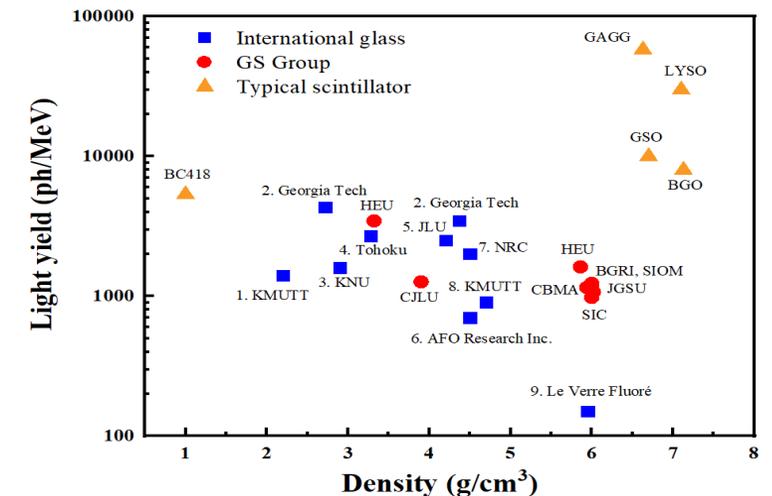
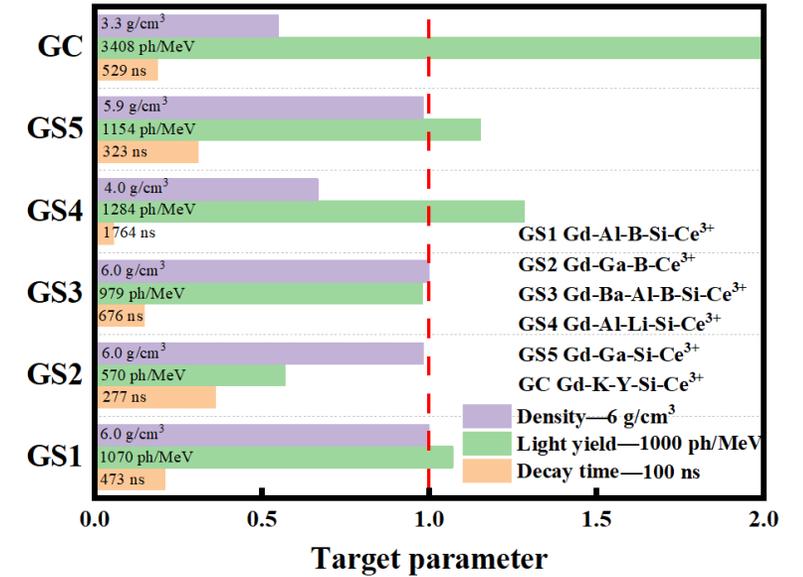


AHCAL, 40 layers, 4x4 cm²





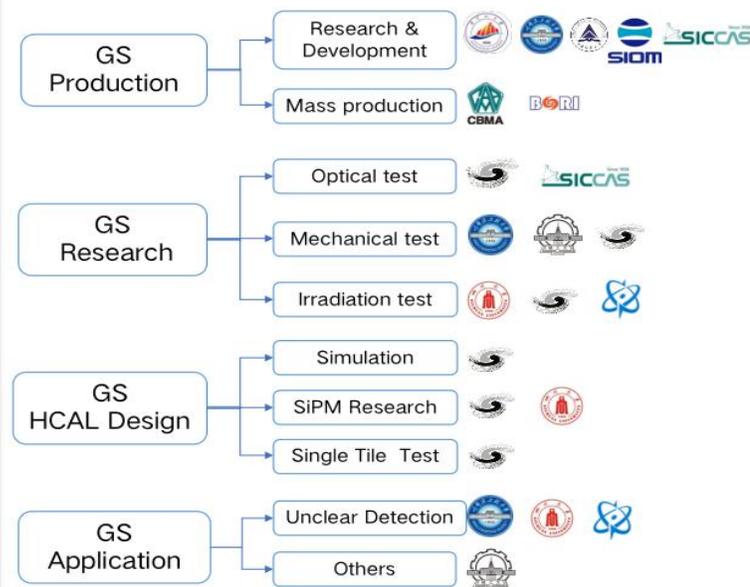
- ✓ The GS group did substantive research based on five glass system simultaneously and **impressive progress has been achieved**
- ✓ The performance of the best glass sample **approach our initial goals**, i.e. 6 g/cm³ & 1000 ph/MeV & 100 ns
- ✓ For high density glass scintillator, the light yield of GS group samples is **in the absolute lead**



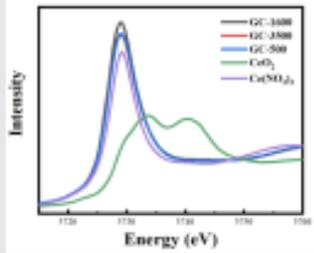
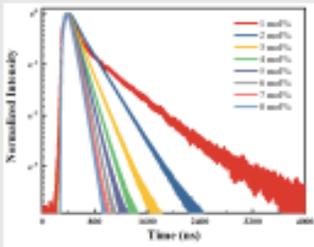
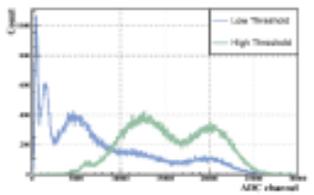
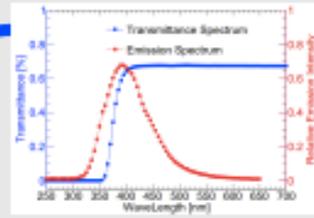
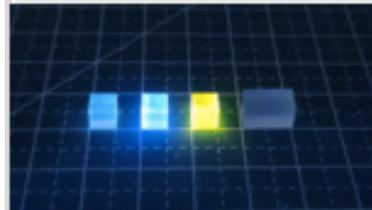
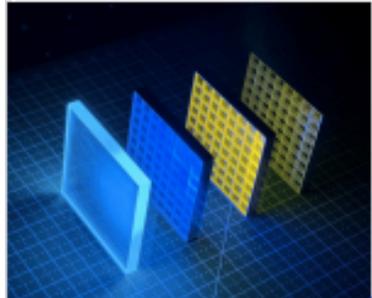
- 2021, GS collaboration was established and has been devoted to the large-area & high-performance GS meeting the requirements of nuclear and high energy physics.
- The GS collaboration was led by the IHEP and the members include 3 Institutes of CAS, 5 Universities, 3 Factories currently.



闪烁玻璃合作组
Glass Scintillator Collaboration



- Institute of High Energy Physics, CAS
中国科学院高能物理研究所
- Jinggangshan University
井冈山大学
- Beijing Glass Research Institute
北京玻璃研究院
- China Building Materials Academy
中国建筑材料研究院
- China Jiliang University
中国计量大学
- Harbin Engineering University
哈尔滨工程大学
- Harbin Institute of Technology
哈尔滨工业大学
- Sichuan University
四川大学
- Shanghai Institute of Ceramics, CAS
中国科学院上海硅酸盐研究所
- Shanghai Institute of Optics and Fine Mechanics,
中国科学院上海光学精密机械研究所
- CNNC Beijing Unclear Instrument Factory
中核（北京）核仪器有限责任公司



Others
.....

- Transmittance
- Absorbance
- Refractive index
- Emission peak
- Light yield
- Energy resolution
- MIP response
- Neutron discrimination
- Rise time
- Fall time
- Decay time
- Afterglow
- Coincidence time
- Valence state
- Coordination
- Elemental analysis
- Structural analysis
- Faraday effect
- Radiation resistance
- Homogeneity

➤ IHEP--PMT Lab for Scintillator Test



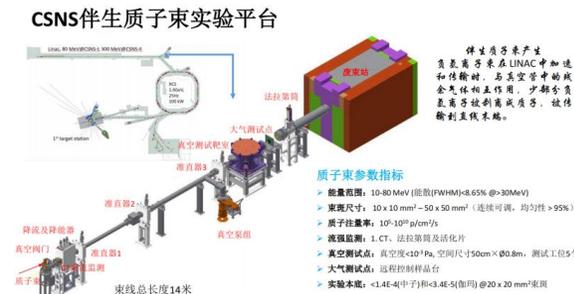
➤ IHEP--Radioactive Test



➤ IHEP--XAFS



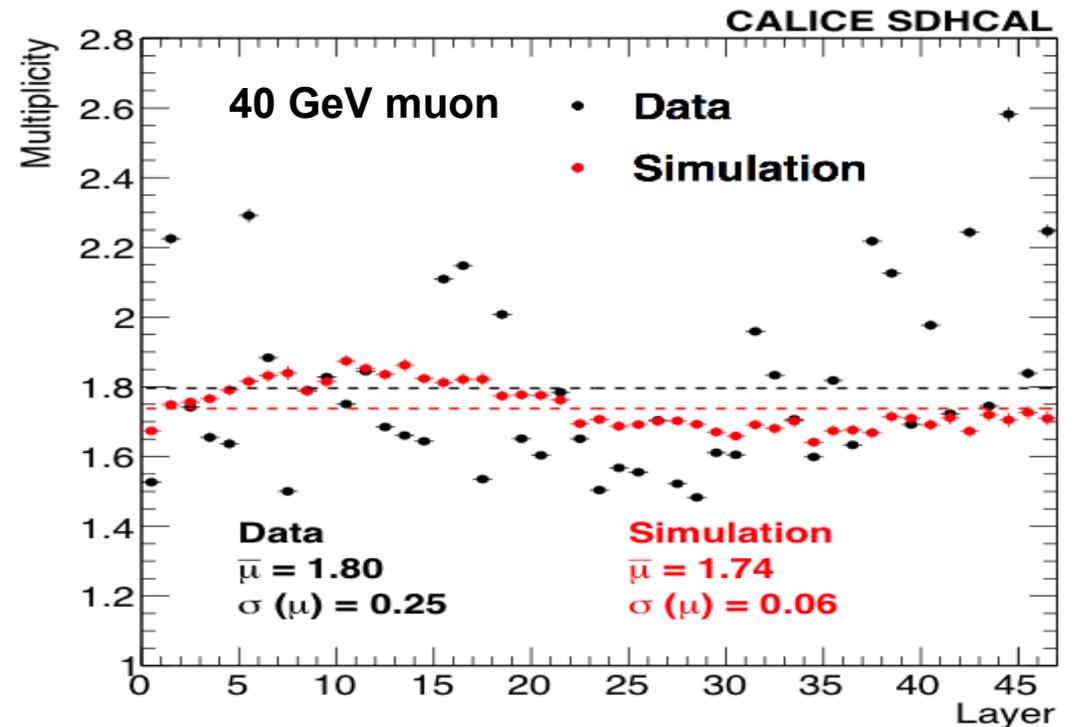
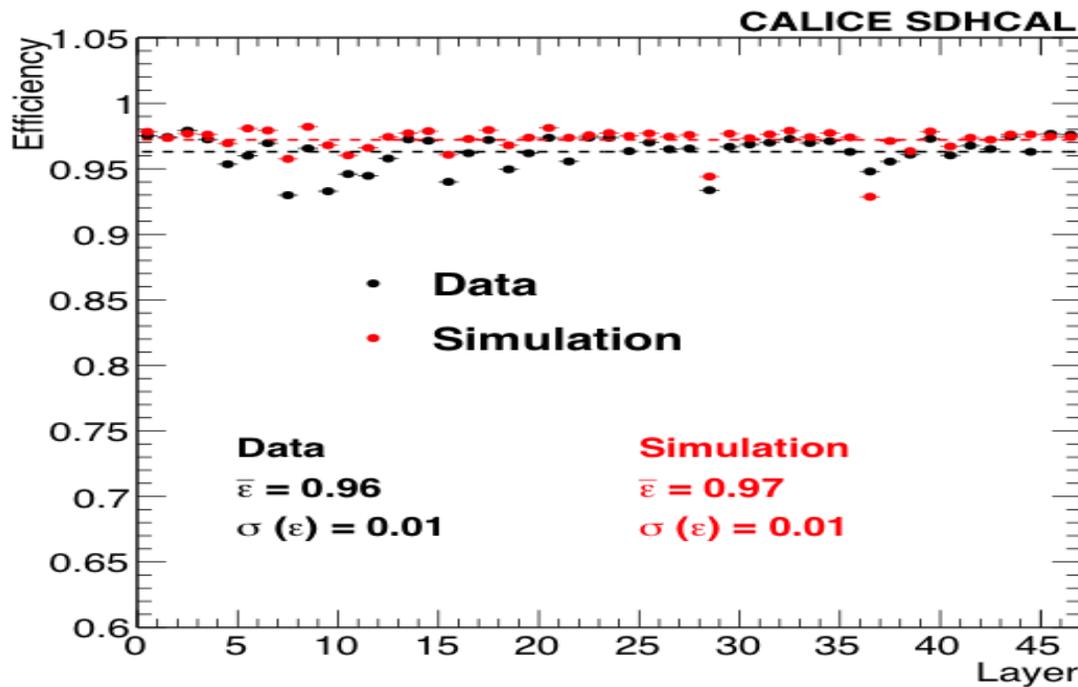
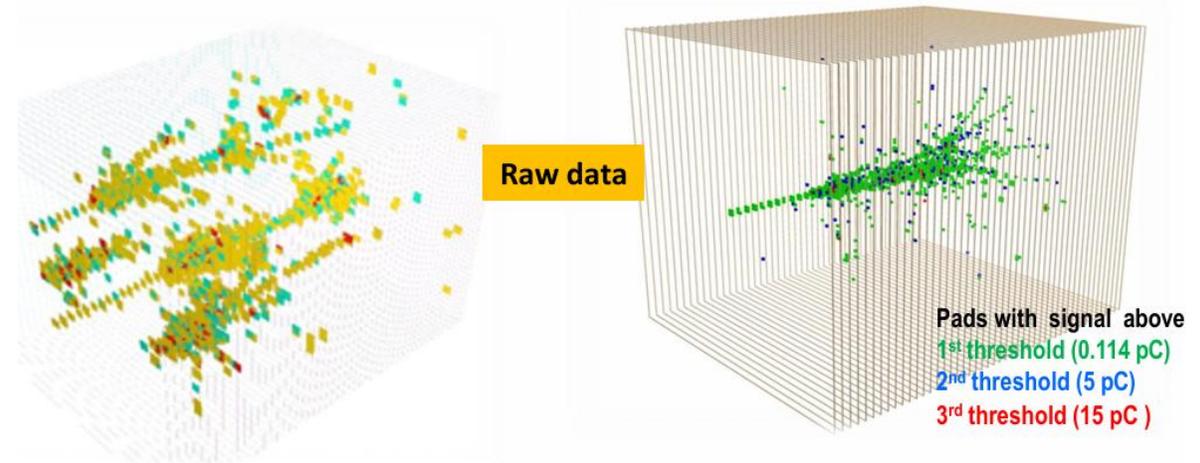
➤ IHEP-CSN-- P Beam



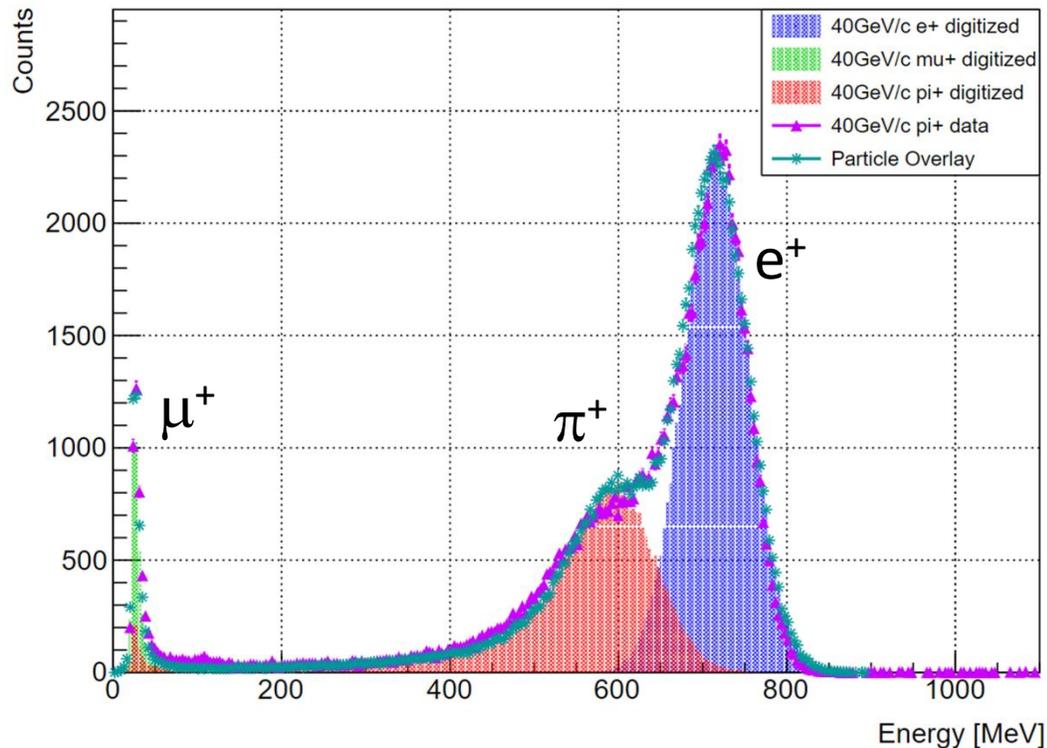
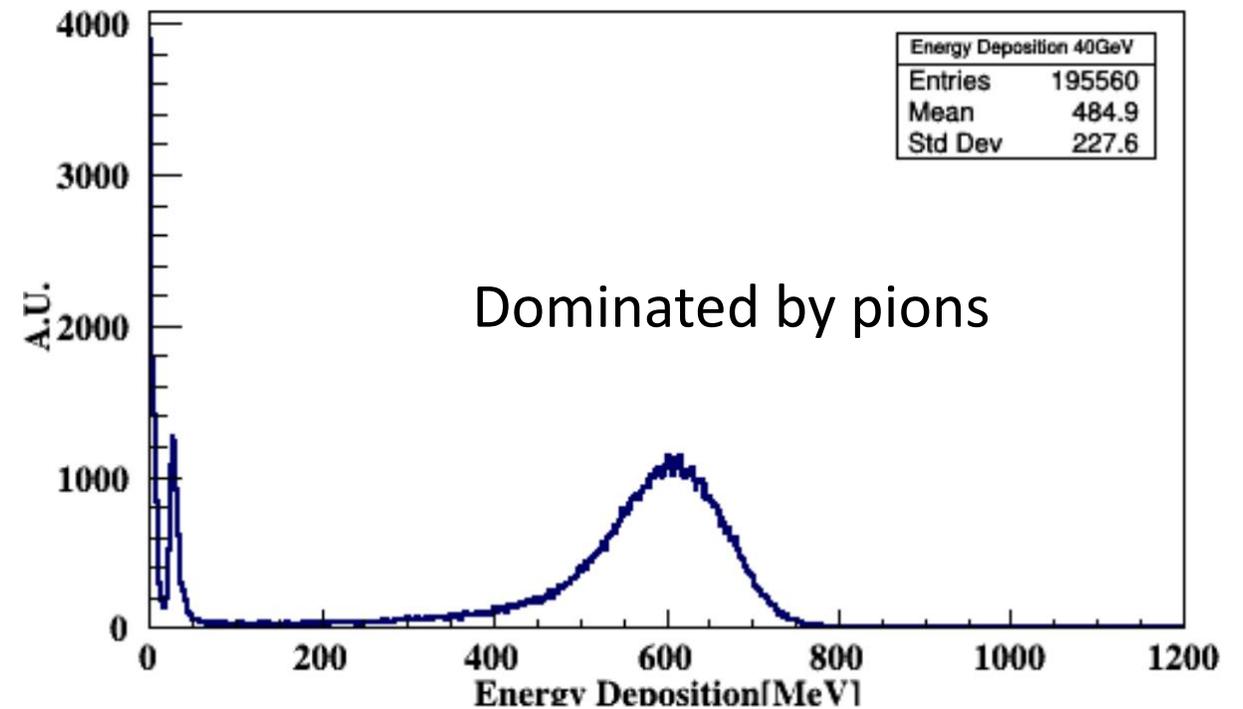
➤ CERN-MUON Beam



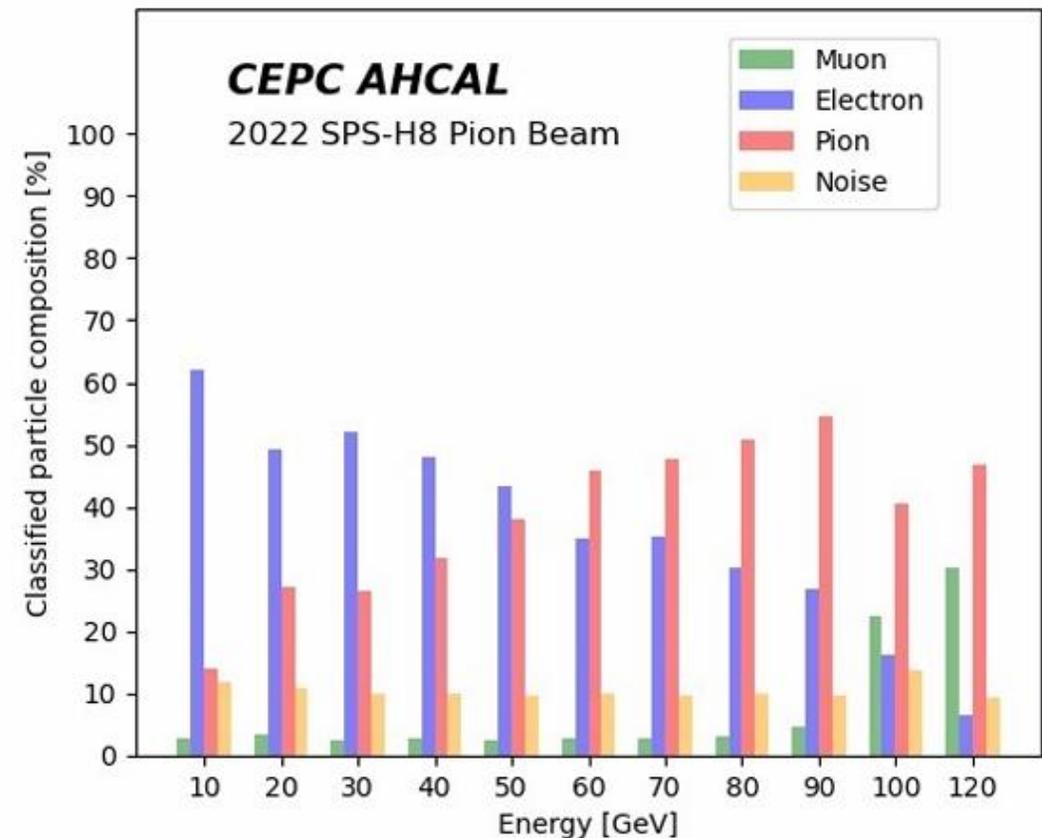
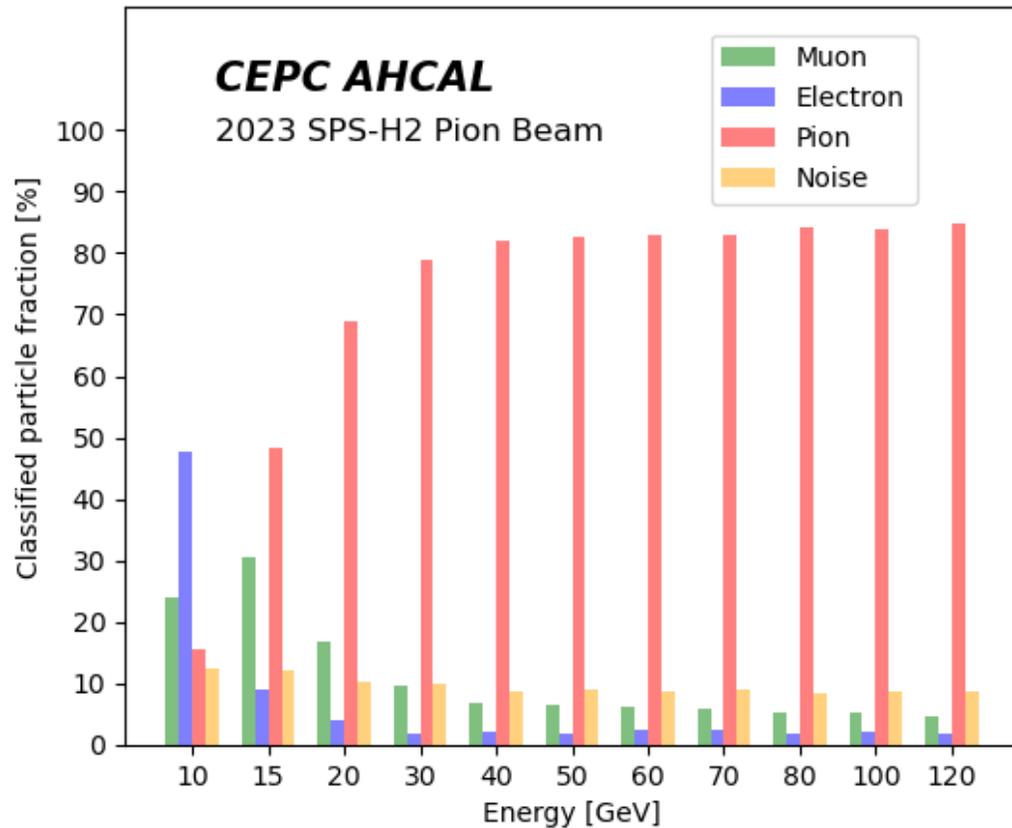
- ➔ SDHCAL Efficiency (Data/MC): 96% / 97%
- ➔ SDHCAL Multiplicity (Data/MC): 1.8 / 1.74
- ➔ Good Data and MC agreement for efficiency and multiplicity obtained with cosmic and test beam muons.



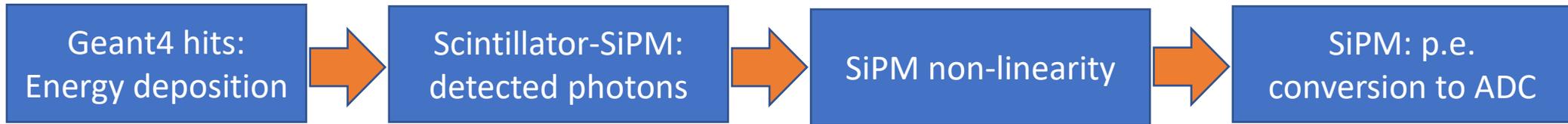
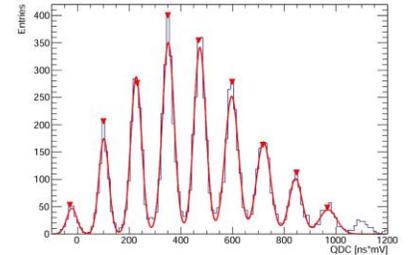
- **Significant beam contamination in SPS-H8 is observed**
 - Mixture of pions, muons, positrons in SPS-H8 beam data
 - Beam purity at SPS-H2 (2023) is significantly better than SPS-H8 (2022)
 - Particle identification techniques developed: to select high-purity data samples

40 GeV π^+ data SPS-H8 (2022)40 GeV π^- data SPS-H2 (2023)

- **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 ≥ 30 GeV
 - SPS-H8 π^+ : purity is less than 60% with significant contamination from electron



- 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



MC truth

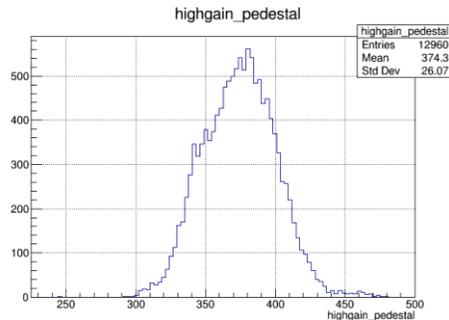
Poisson Distribution
based on muon data

SiPM saturation curve
from measurements

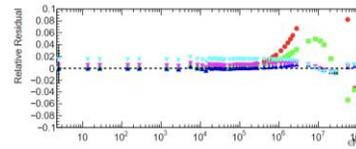
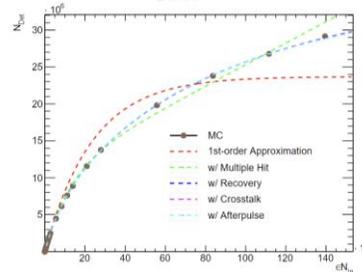
SiPM gain calibration
from LED data



Extracted from data

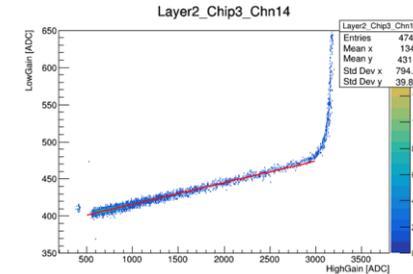


Pedestals (data)



SiPM saturation (data)

ASIC HG-LG ADC (data)



Marking in Red: based on data

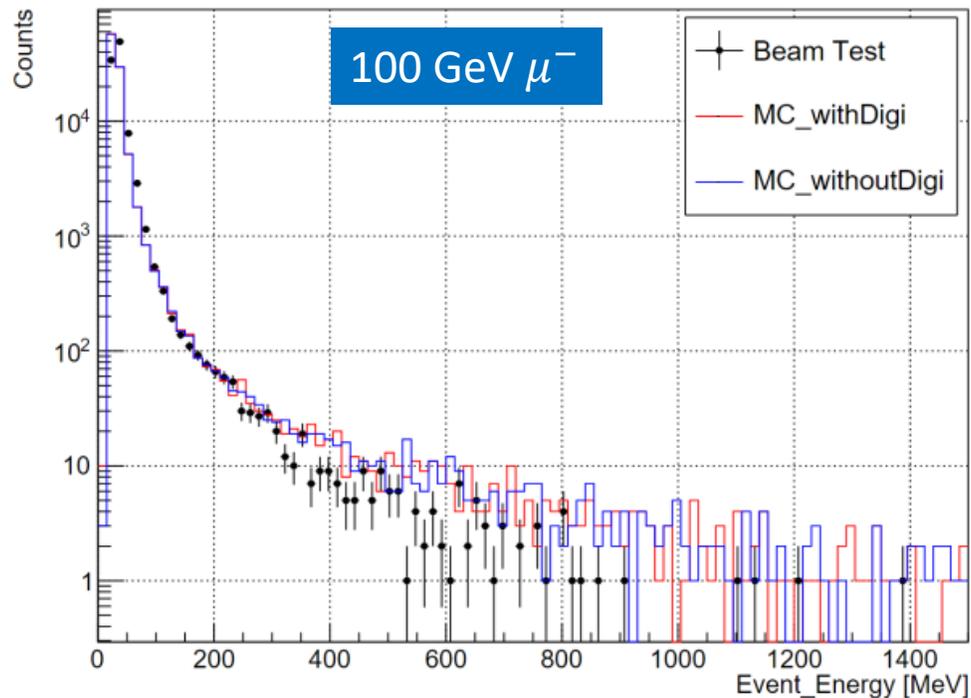


SPIROC2E HG-LG slope
extracted from beam data

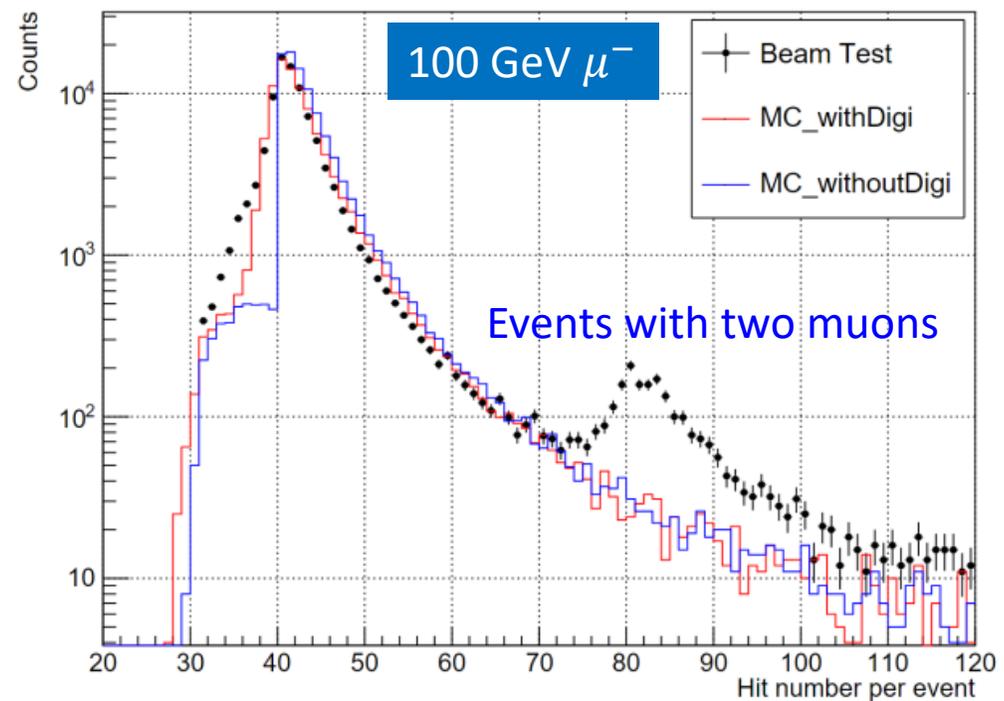
Key: digitization is fully based on calibration data

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

Energy response: Data/MC



Total Hit Number: Data/MC



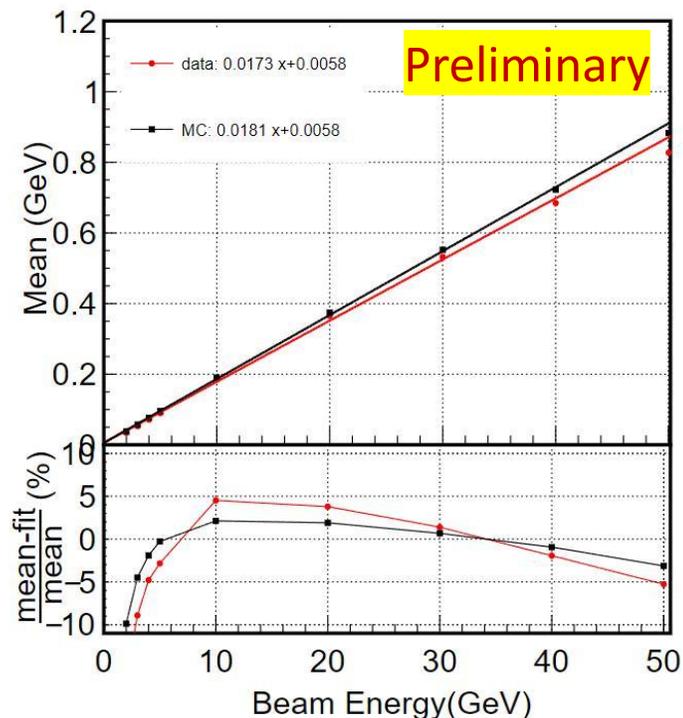
MC is consistent with muon data

- 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

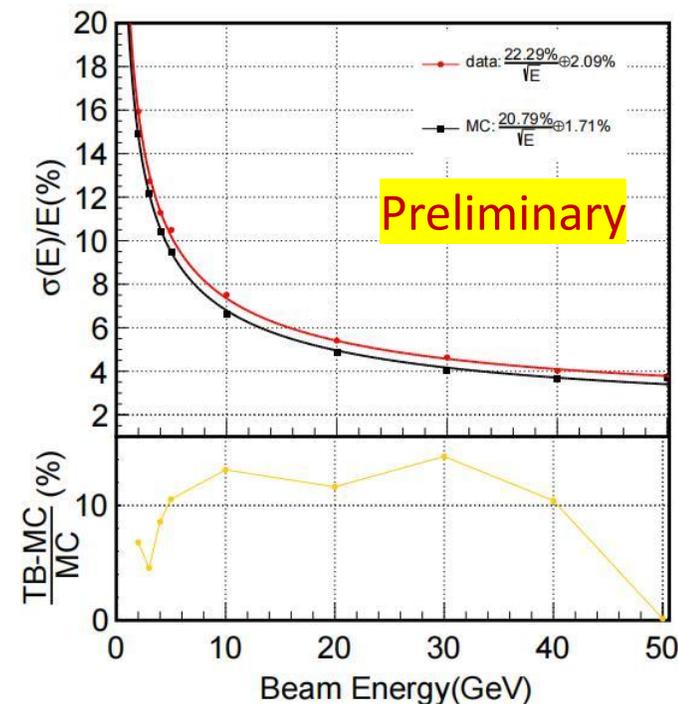
PS-T09 low-energy electron data (1-5 GeV) also included

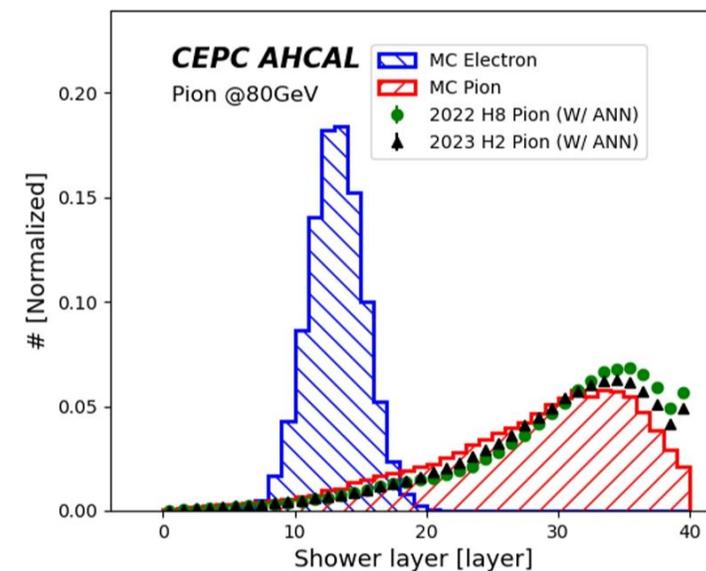
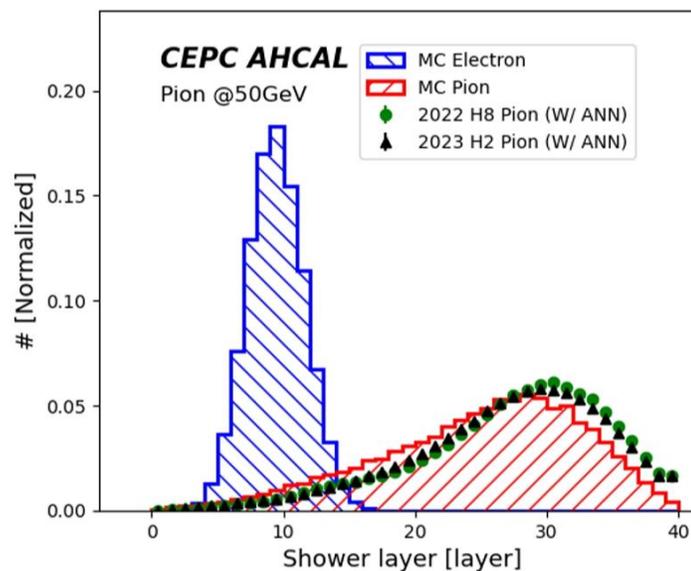
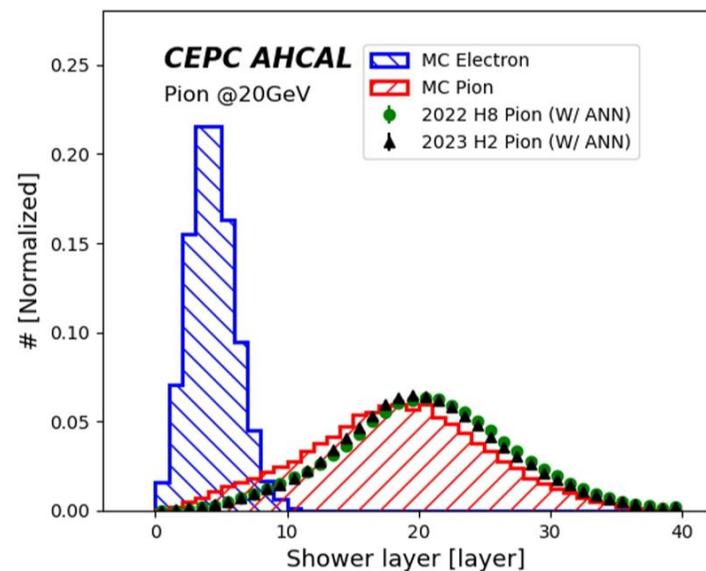
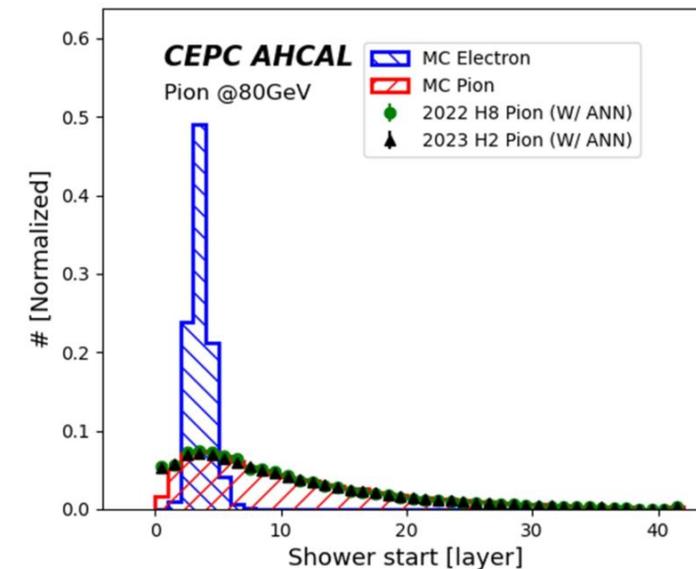
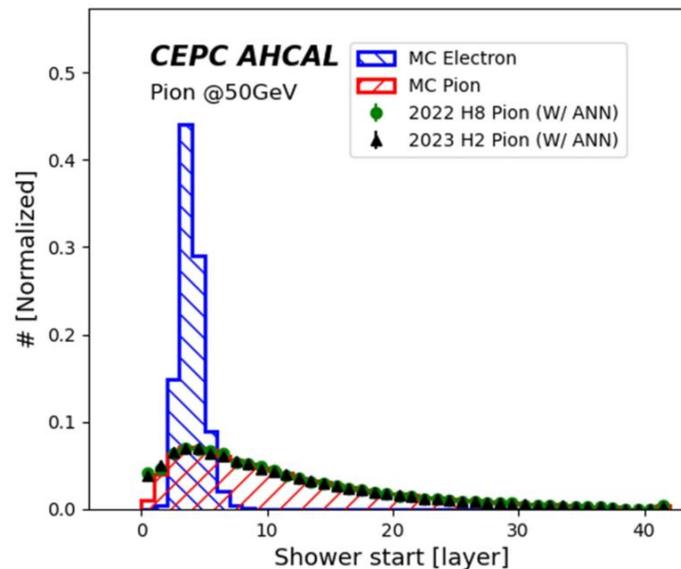
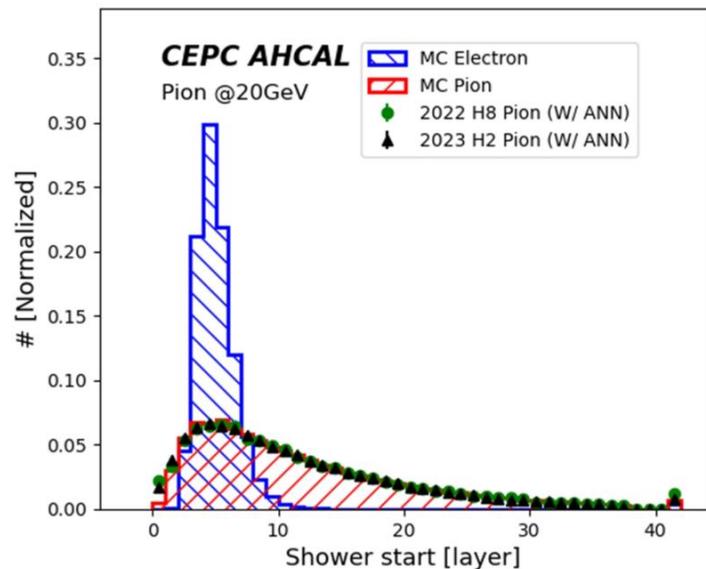
Data/MC comparisons: ~10% discrepancy in EM response linearity and energy resolution

EM response linearity



EM energy resolution

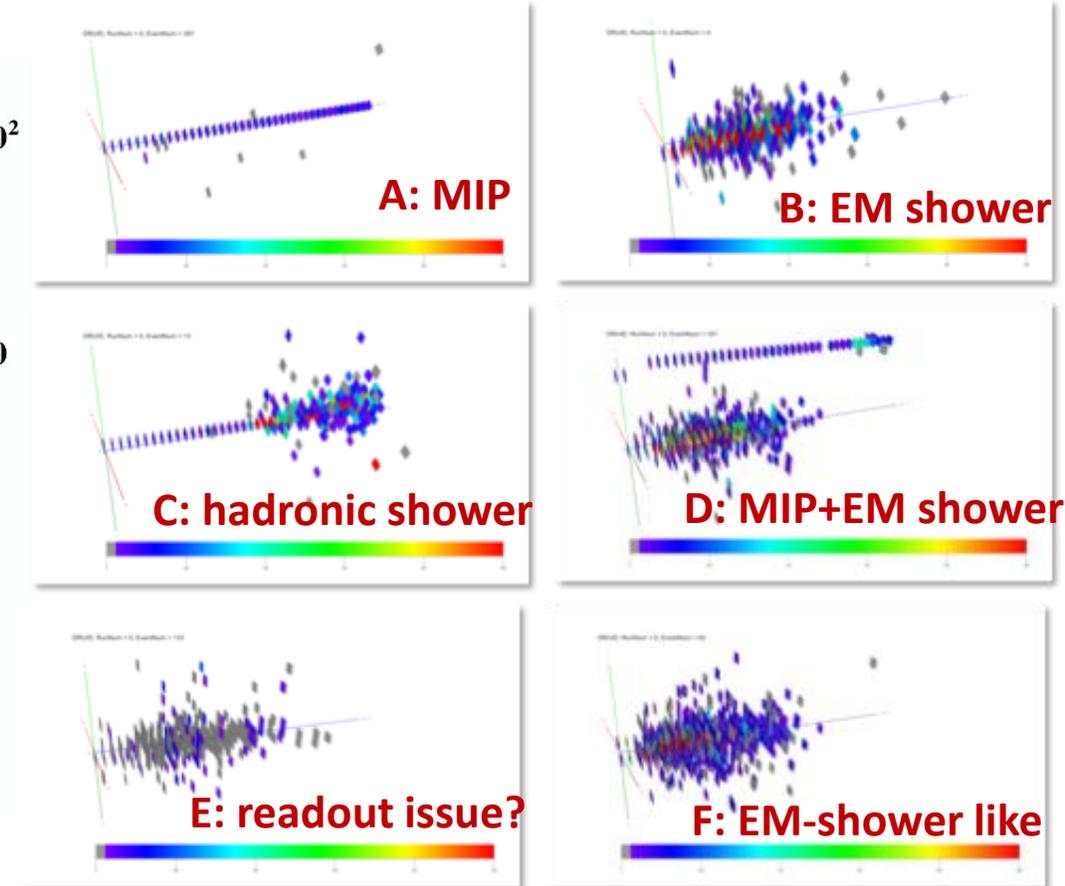
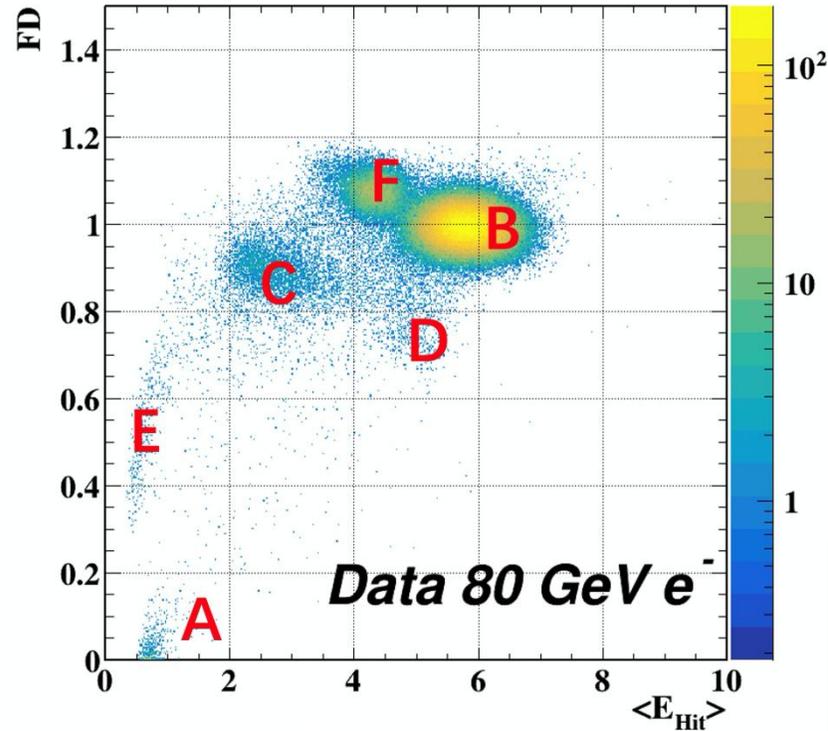
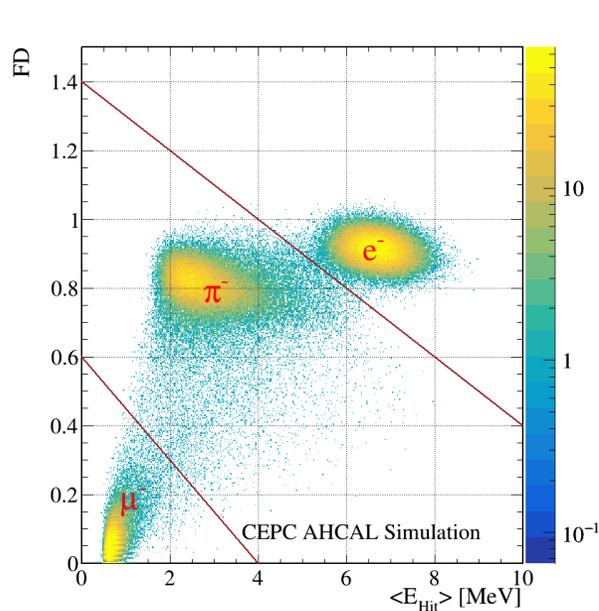




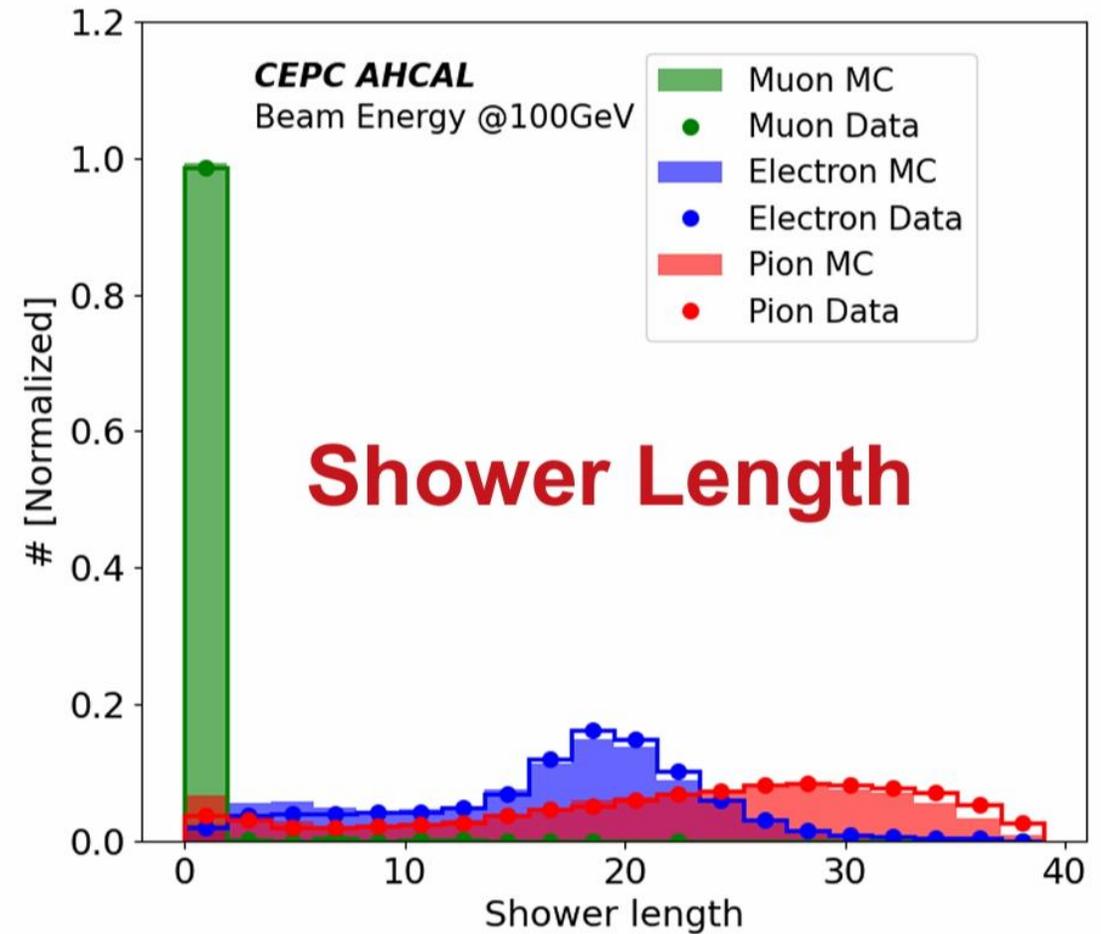
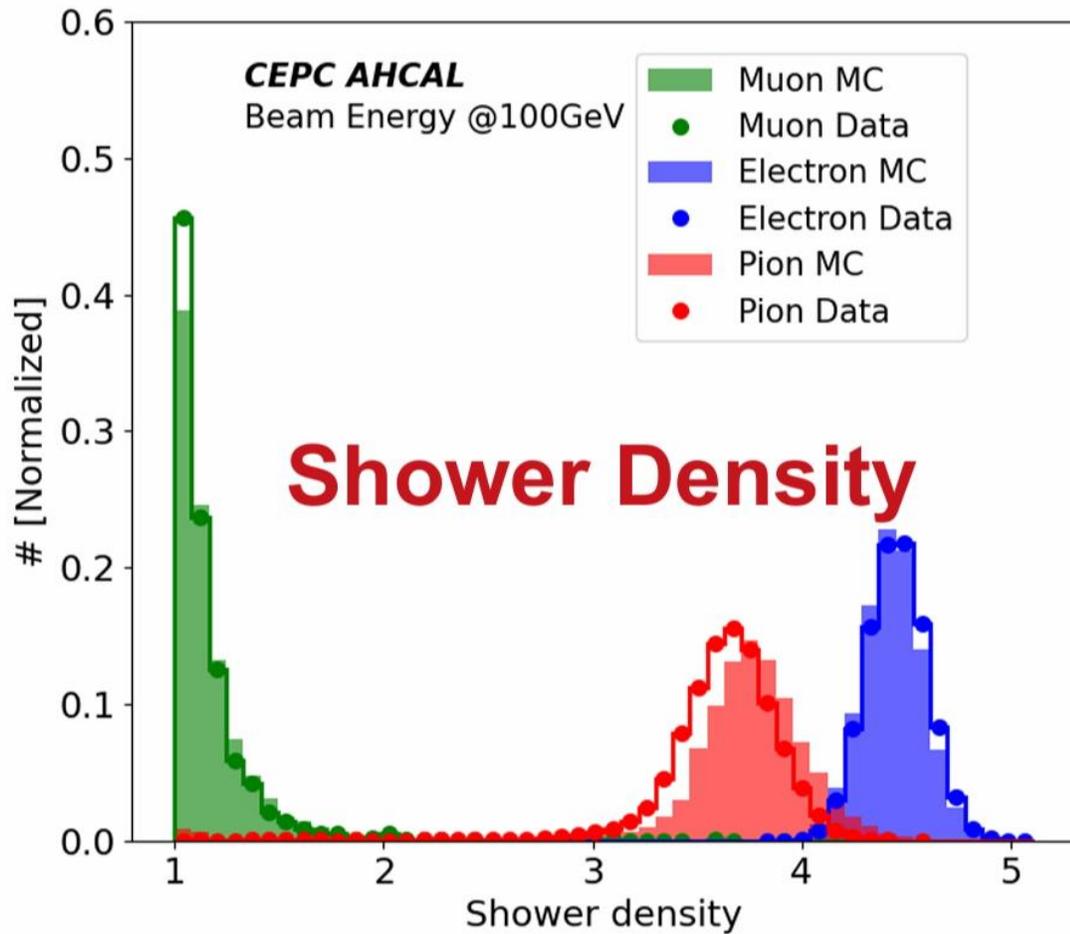
- **Fractal Dimension (FD)**

- 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

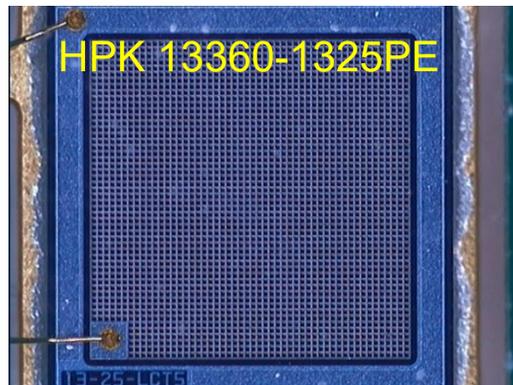


FD methodology based on
 M. Ruan et al., Phys. Rev. Lett. 112, 012001

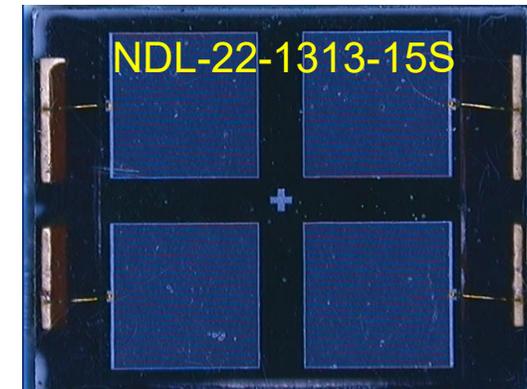


❖ **HPK-SiPM**

- Low PDE, dark rate and crosstalk
- High breakdown voltage
- Better quality control
- 38 layers ($38 \times 324 = 12312$)

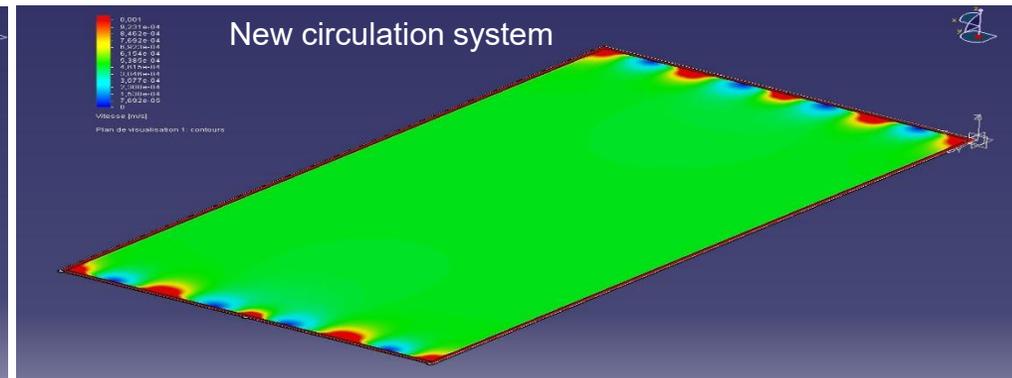
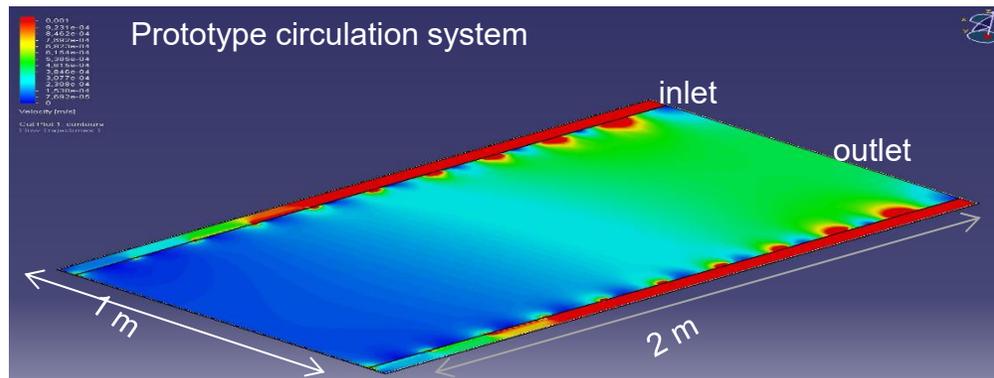
❖ **NDL-SiPM**

- High PDE, dark rate and crosstalk
- Low breakdown voltage
- Low price
- 5 layers ($5 \times 324 = 1620$)



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

- 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 (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



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