Progress of CEPC Hadronic Calorimeters

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



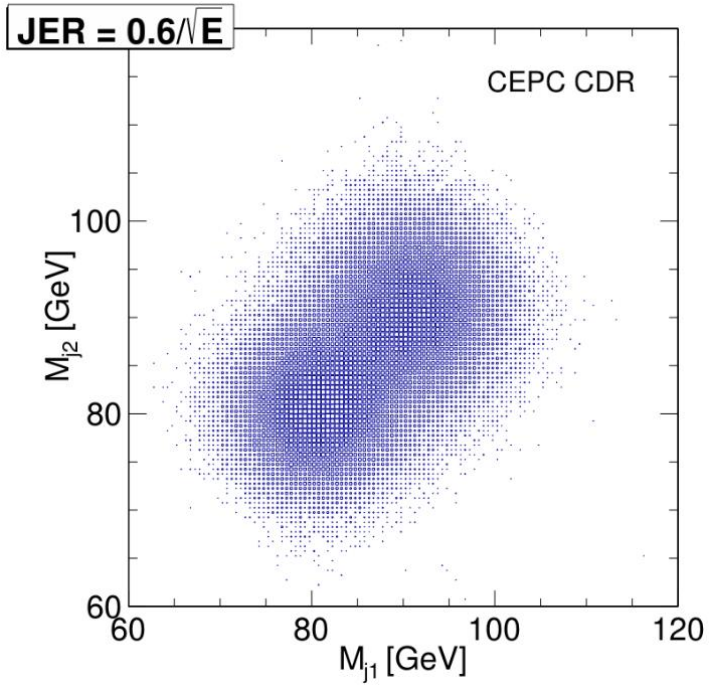
Outline

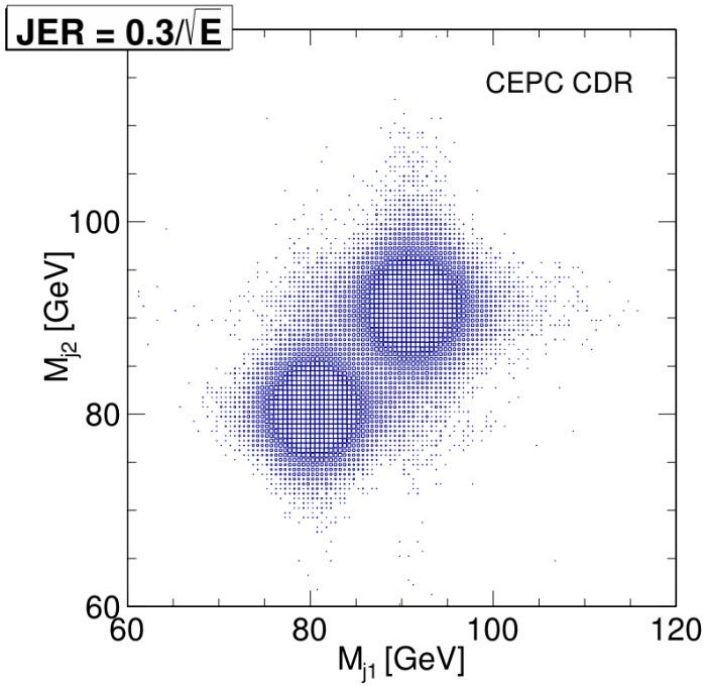
- Introduction: Motivation and Requirements
- SDHCAL Prototype based on Glass RPCs
- PS-HCAL Prototype based on Plastic Scintillators
- GS-HCAL based on Glass Scintillators
- Summary and Future Plans

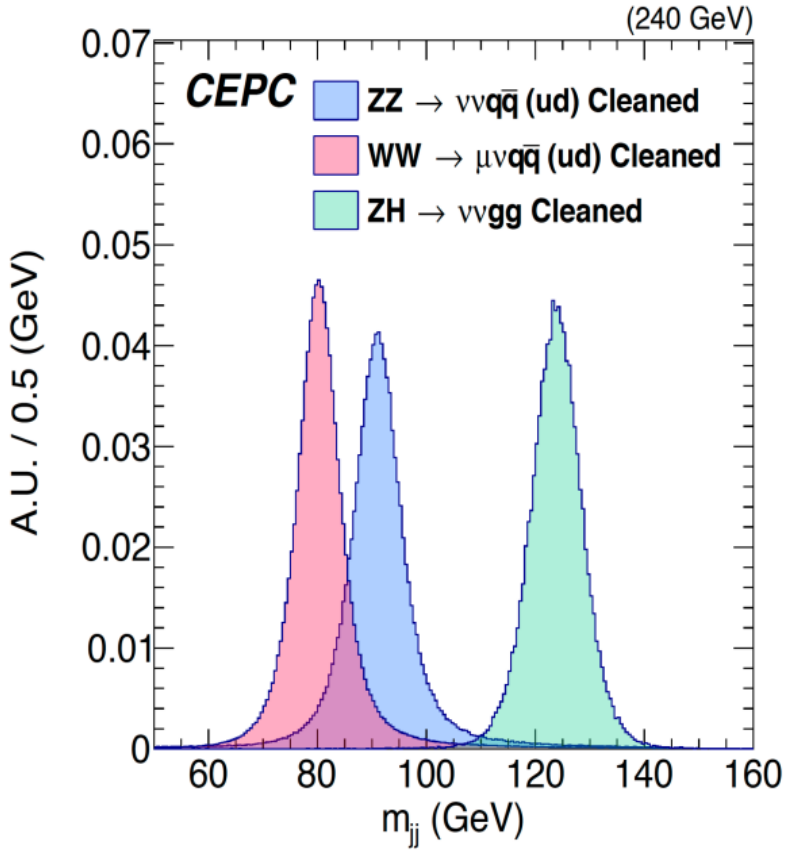
Introduction

➢ 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, $\sigma/E \sim 30\%\text{-}40\%/\sqrt{E}$
- ❖ Boson Mass Resolution, BMR ~ 4% or better







CEPC Ref-TDR (arXiv:2510.05260)

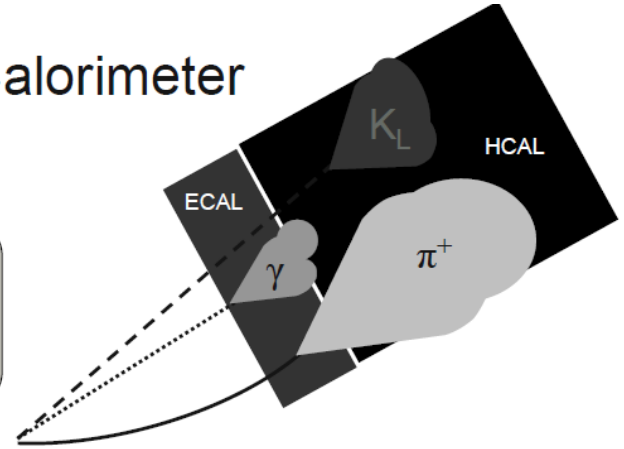
Particle Flow Algorithm (PFA)

Particle Flow Algorithms and Imaging Calorimeter

The idea…

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

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

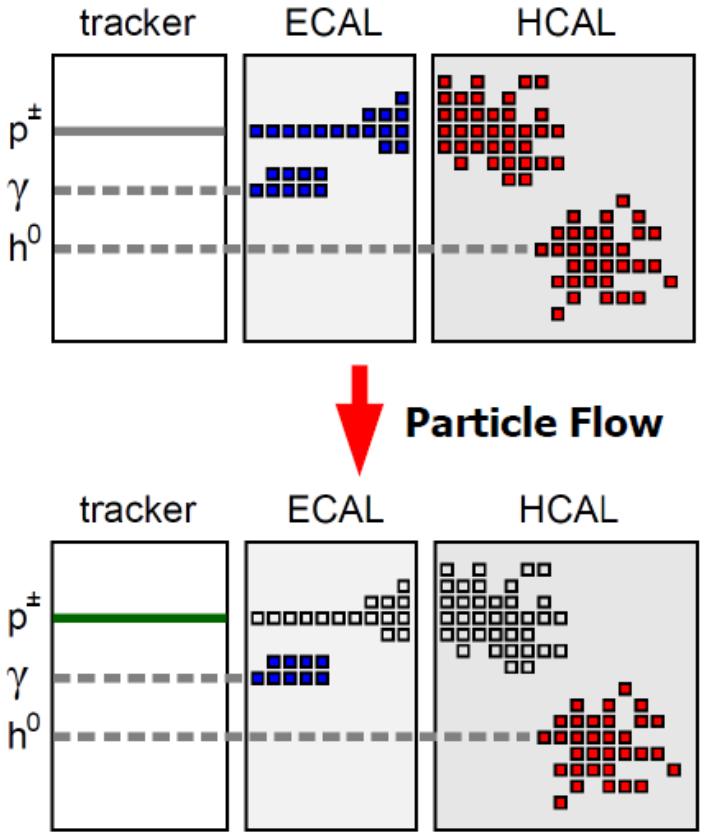


Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion	Required for 30%/√E		$\leq 0.24^2\ E_{jet}$

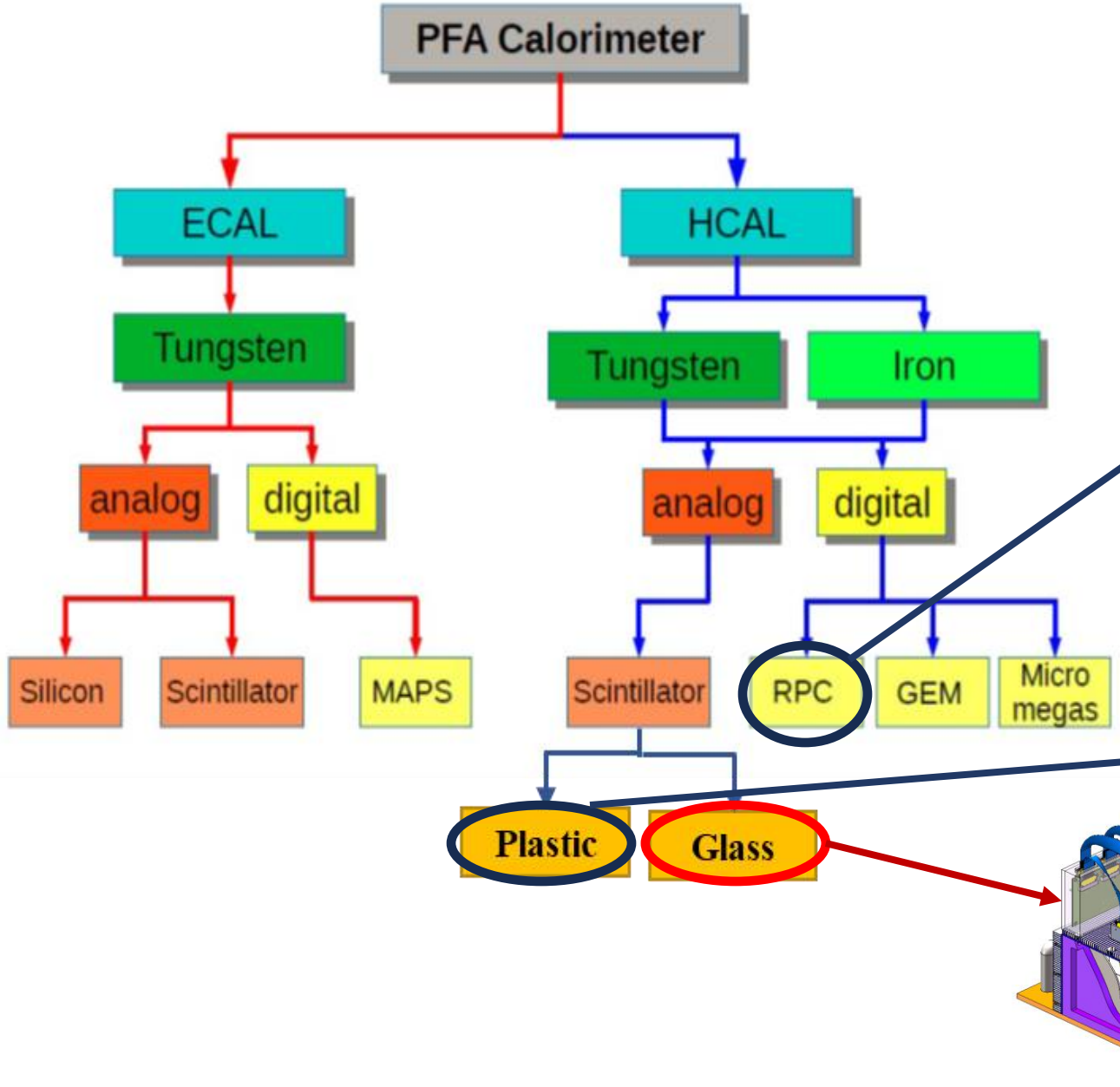
} 18%/√E

Requirements for detector system

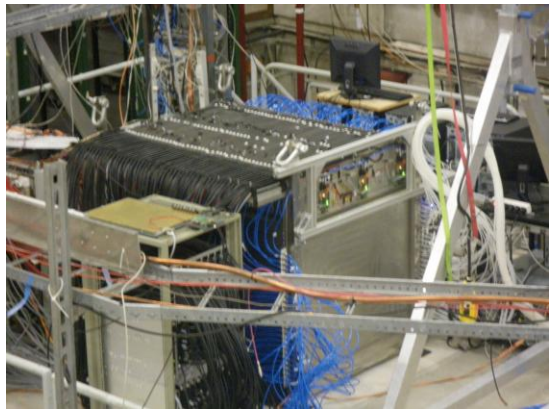
→ Need excellent tracker and high B – field
→ Large R_I of calorimeter
→ Calorimeter inside coil
→ Calorimeter as dense as possible (short X_0, λ_I) } **thin active medium**
→ Calorimeter with **extremely fine segmentation**



Introduction



Prototypes



SDHCAL, 48 layers, 1x1 cm^2

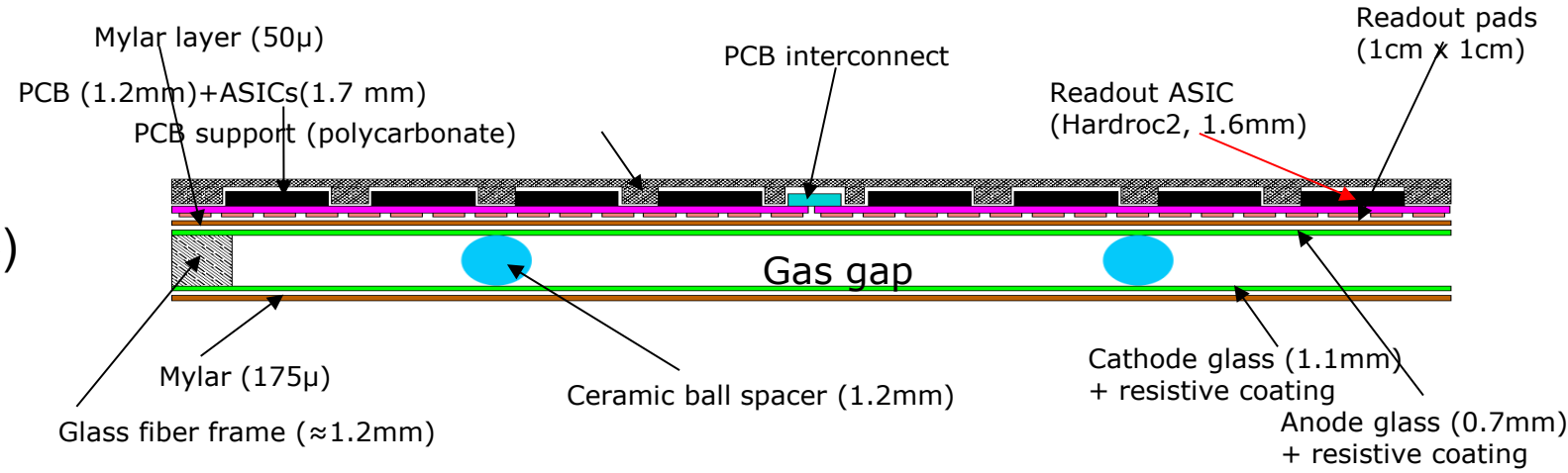


PS-HCAL, 40 layers, 4x4 cm^2

GS-HCAL, 7 layers, 4x4 cm^2

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

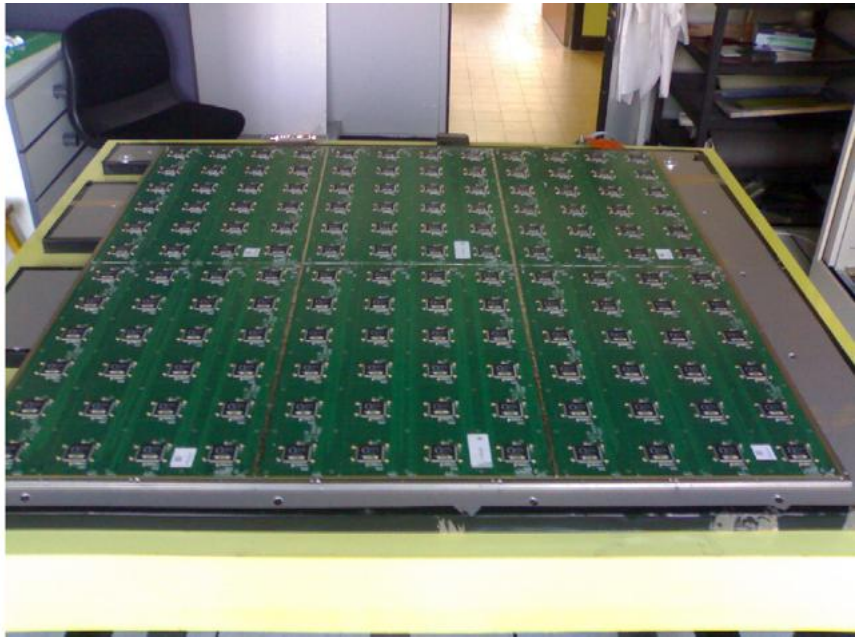


JINST10 (2015) P10039

$(0.12\lambda_I, 1.14X_0)$







SDHCAL: 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

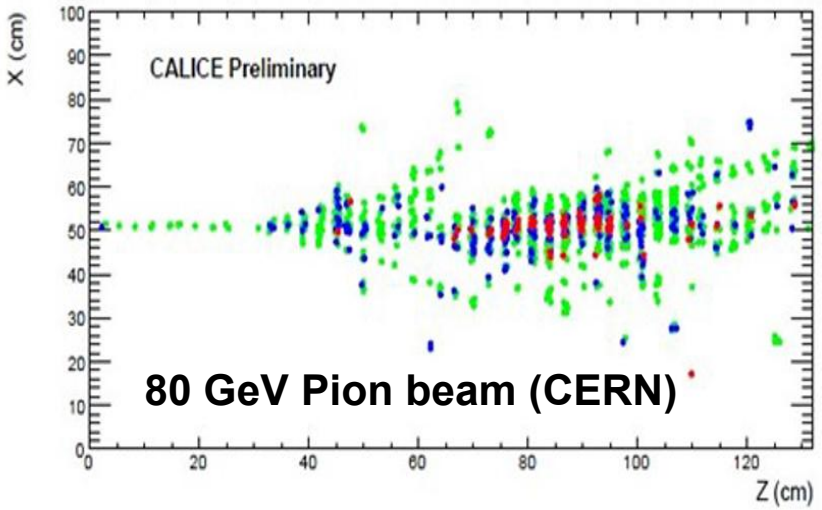
N_3 = #pads with signal> 3rd threshold

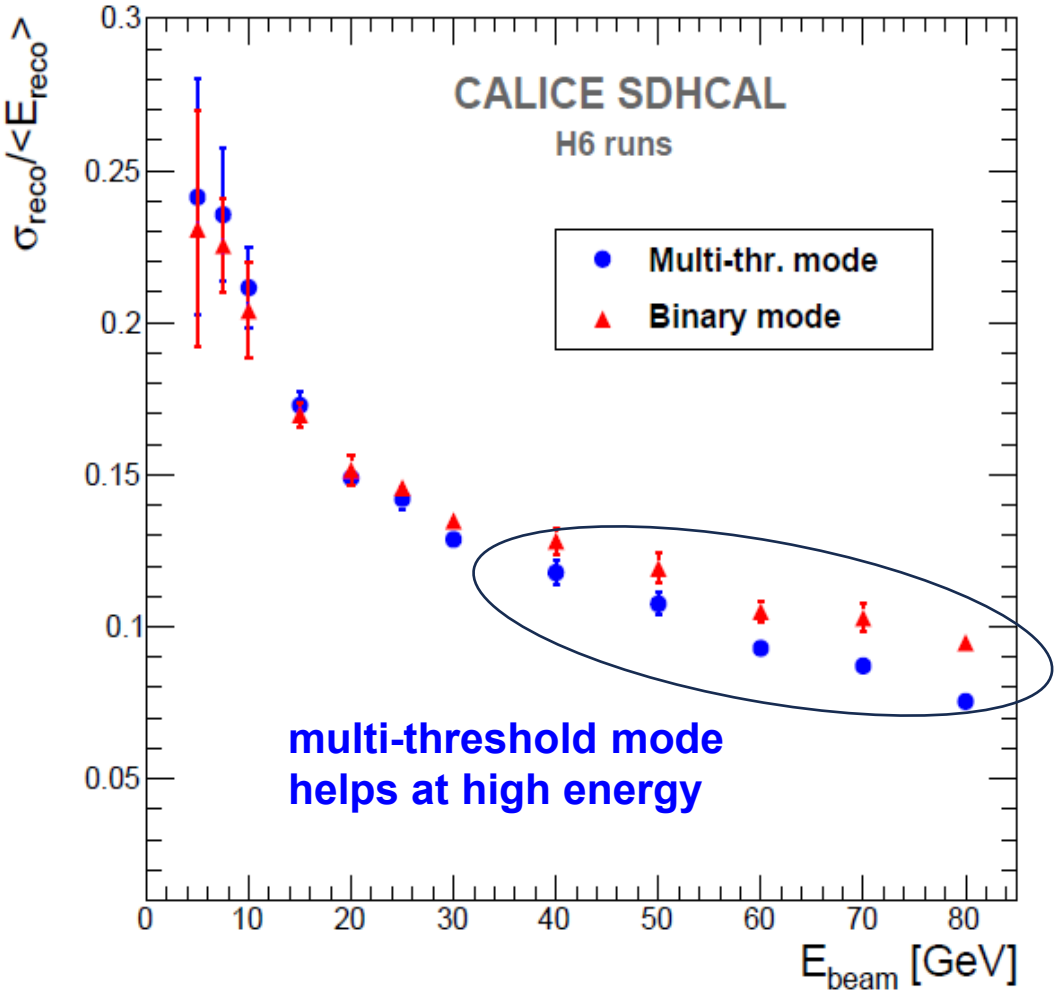
α, β, γ are parameterized as functions of total number of hits (N_{total} = N1+N2+N3)

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

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

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

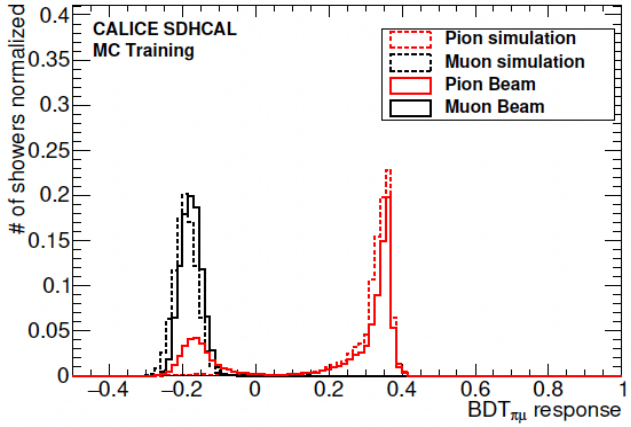


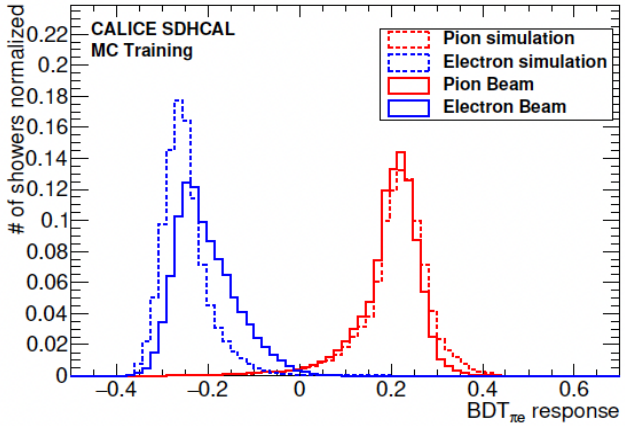


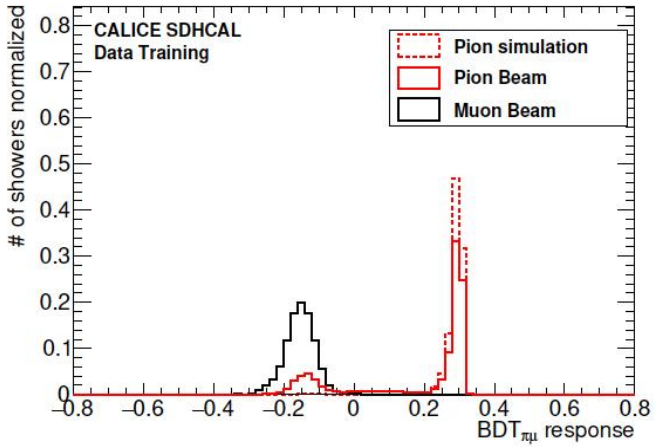
JINST 10 (2015) P10039
JINST 11 (2016) P04001
JINST 12 (2017) P05009

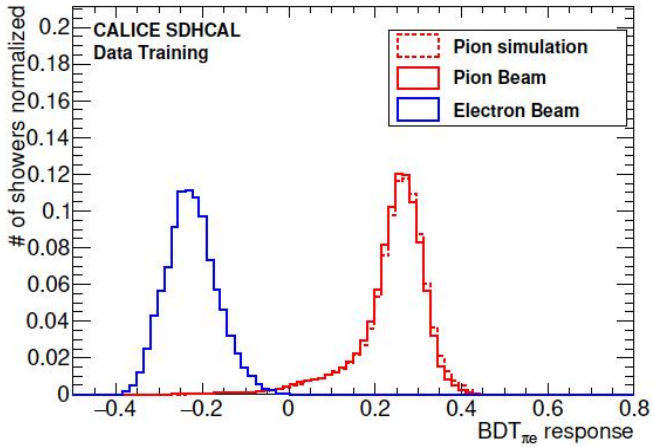
SDHCAL: PID and Energy Resolution

- 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



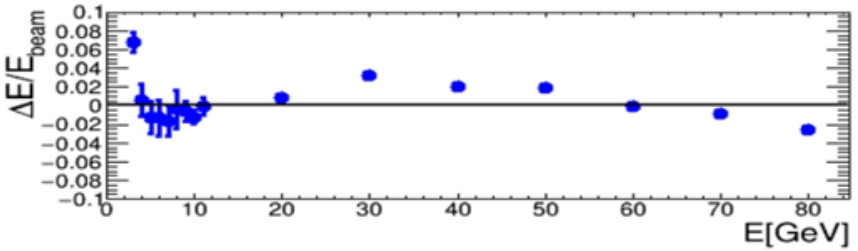


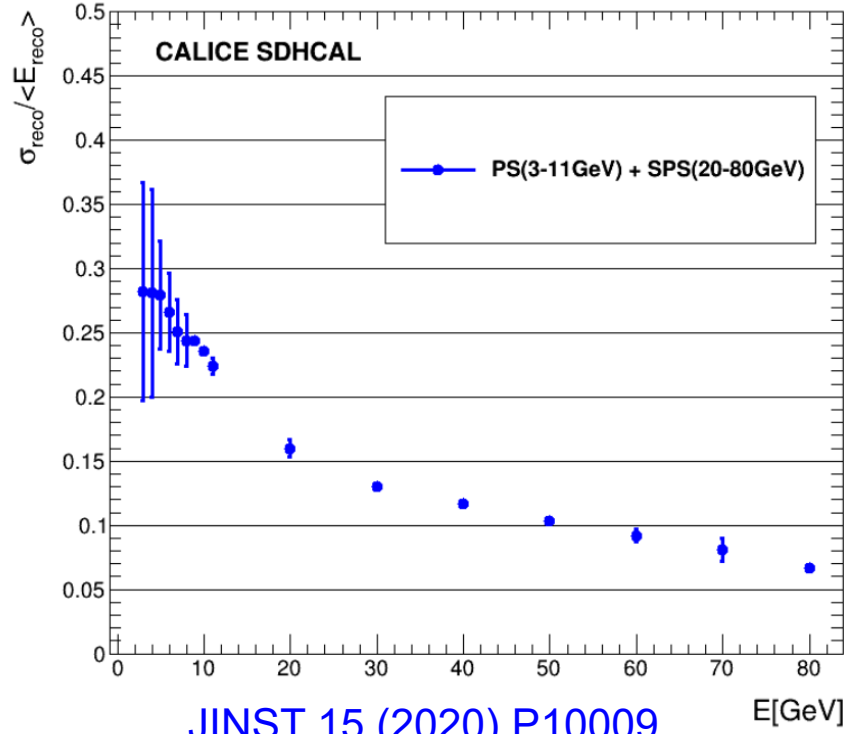




Bing Liu's thesis work

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



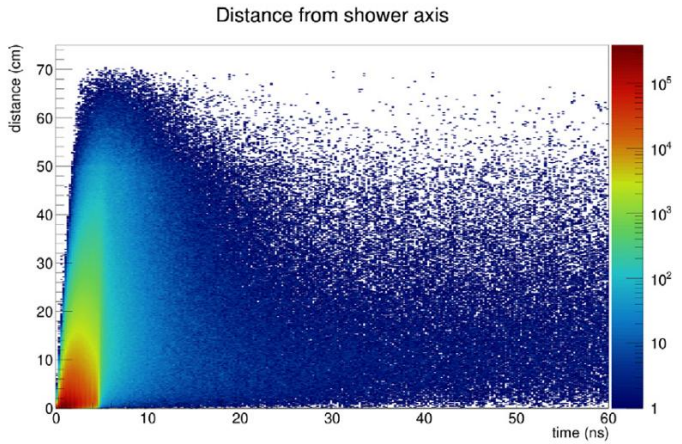


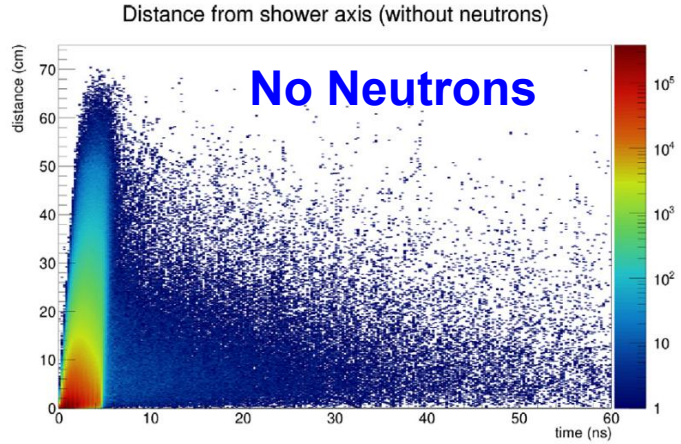
JINST 15 (2020) P10009
JINST 17 (2022) P07017

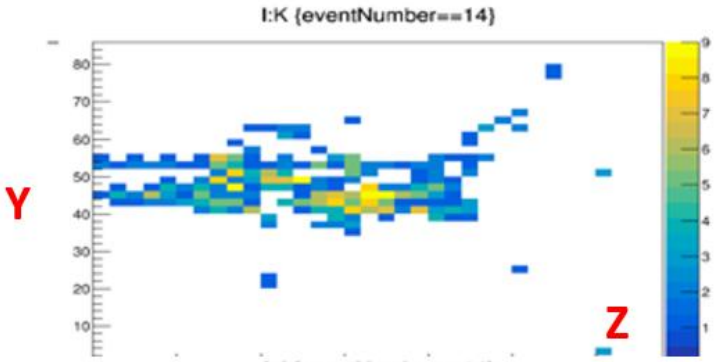
From SDHCAL to T-SDHCAL (5D)

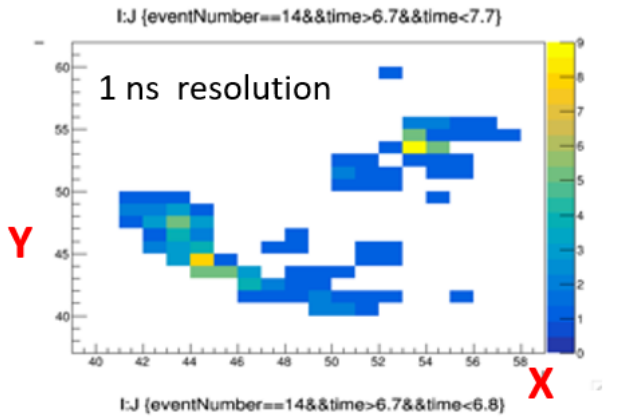
- Hadronic showers have time structure with late components connected to neutron-induced particles
- Time resolution on order of 100 ps to 1 ns results in a sharper distribution of shower core which improve significantly hadronic showers separation at shorter distances
- Fast timing info of calorimeter (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.

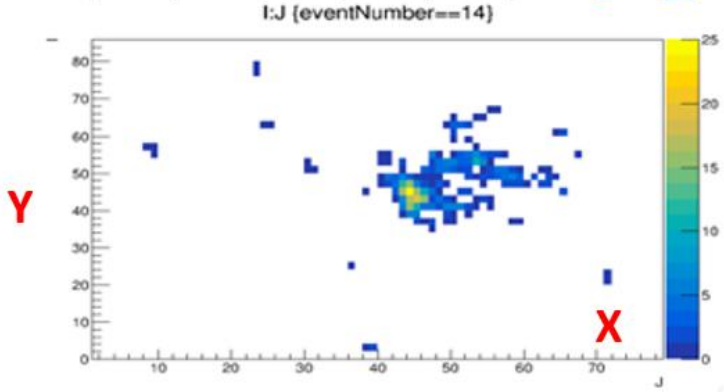
NIMA 1077 (2025) 170520

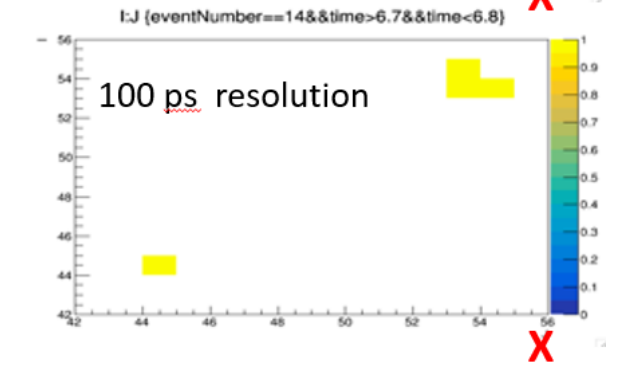






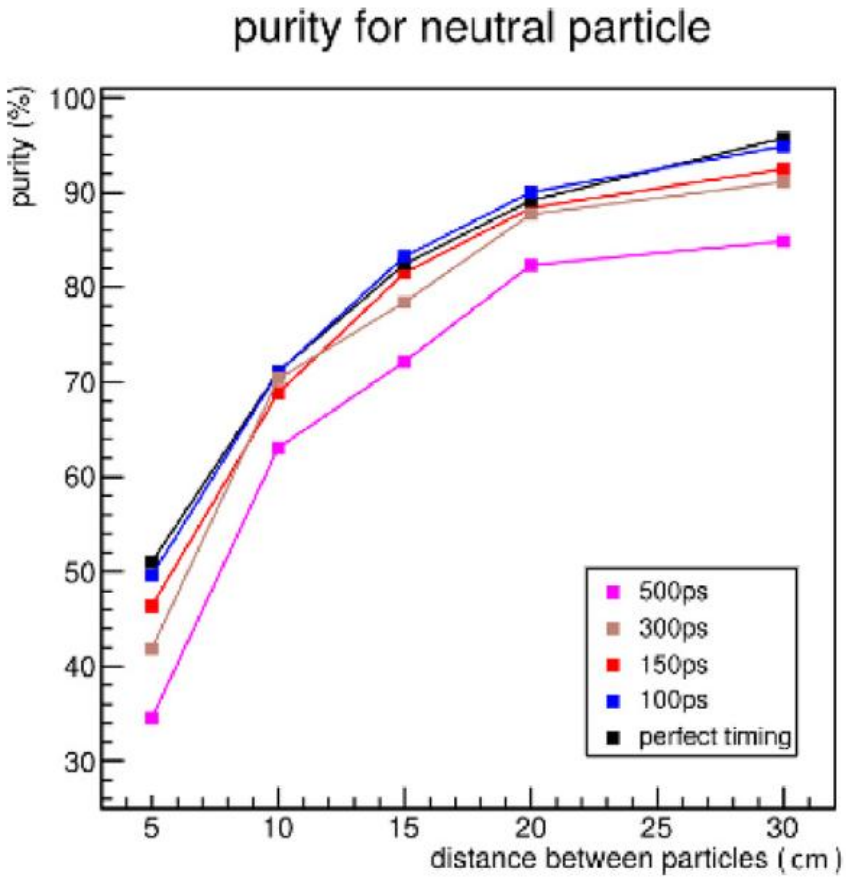


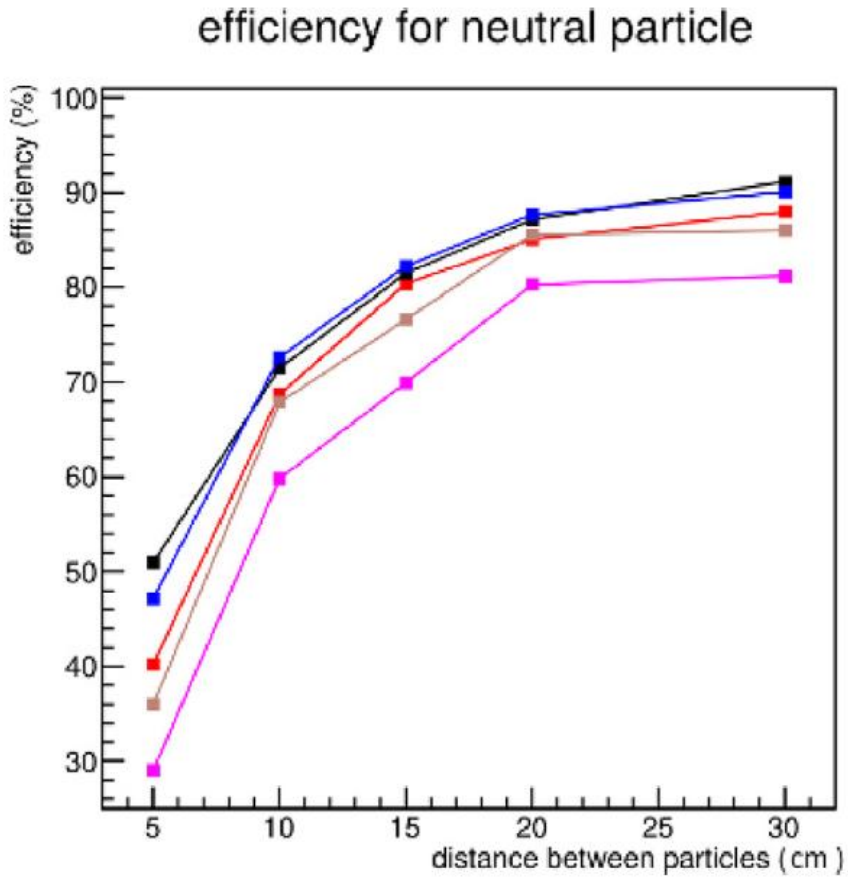




From SDHCAL to T-SDHCAL (5D)

- 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





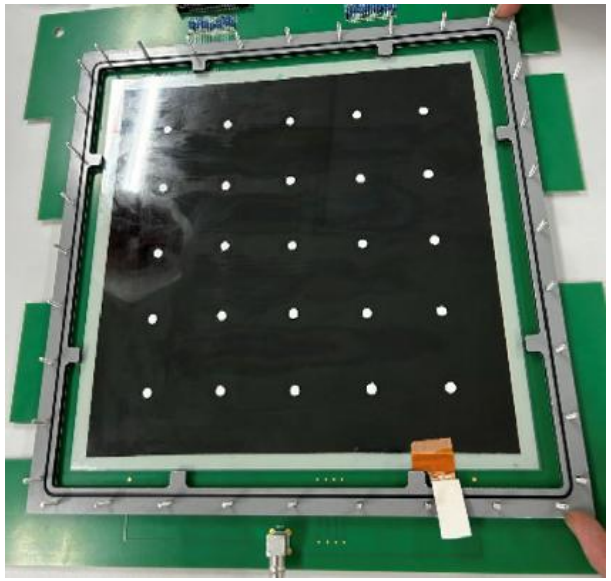
C. Devanne ‘s thesis work

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



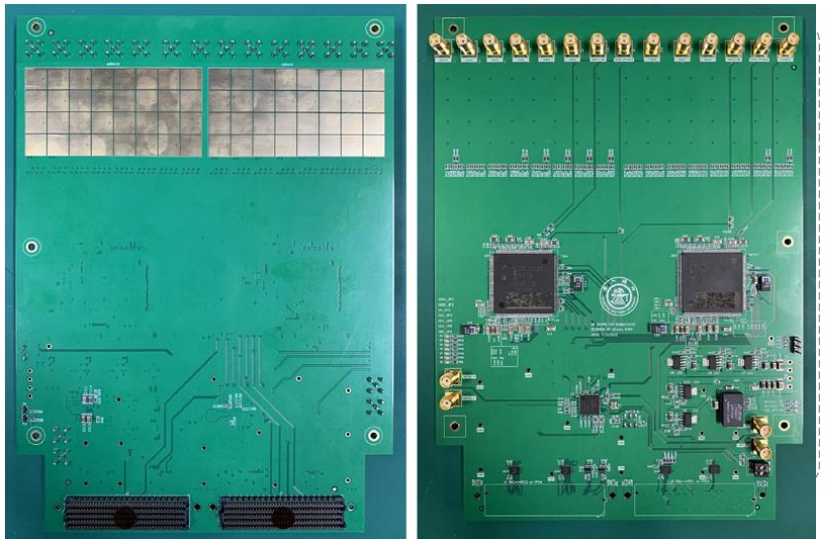
MRPC: 30 x 30 cm^2

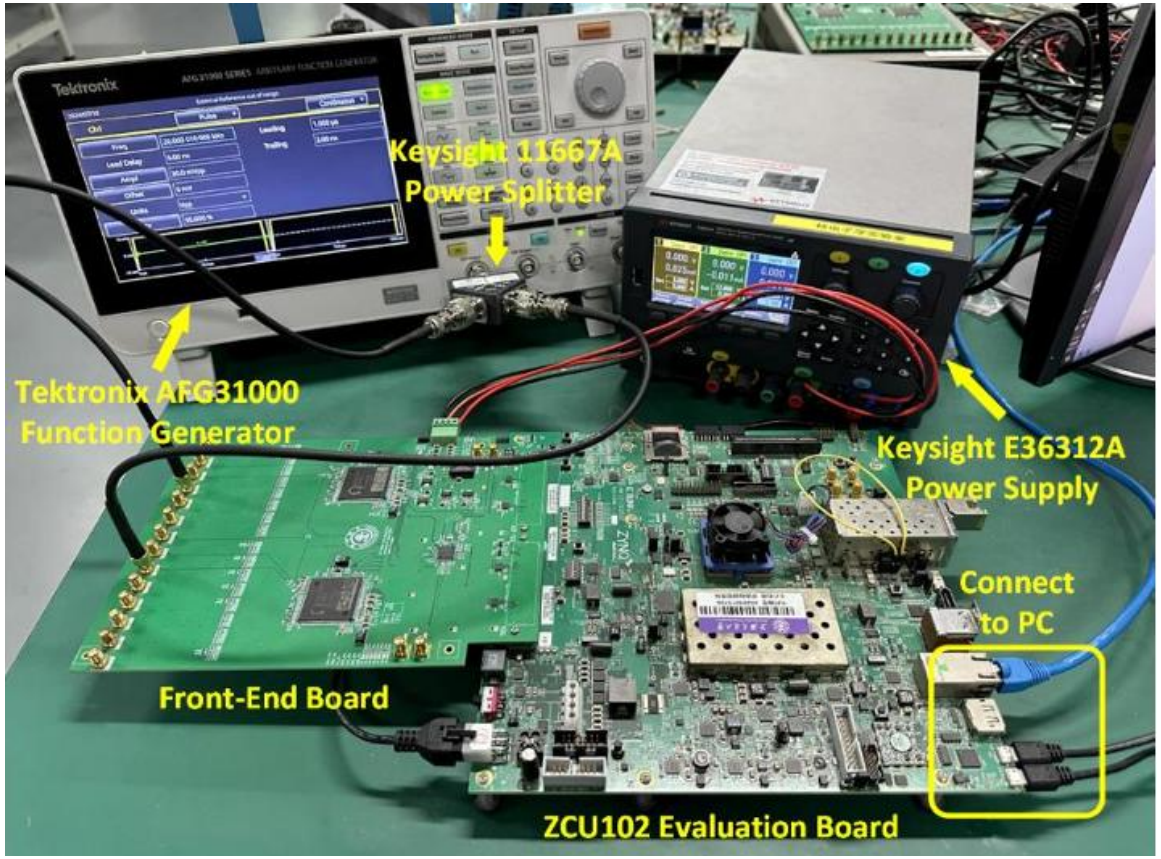


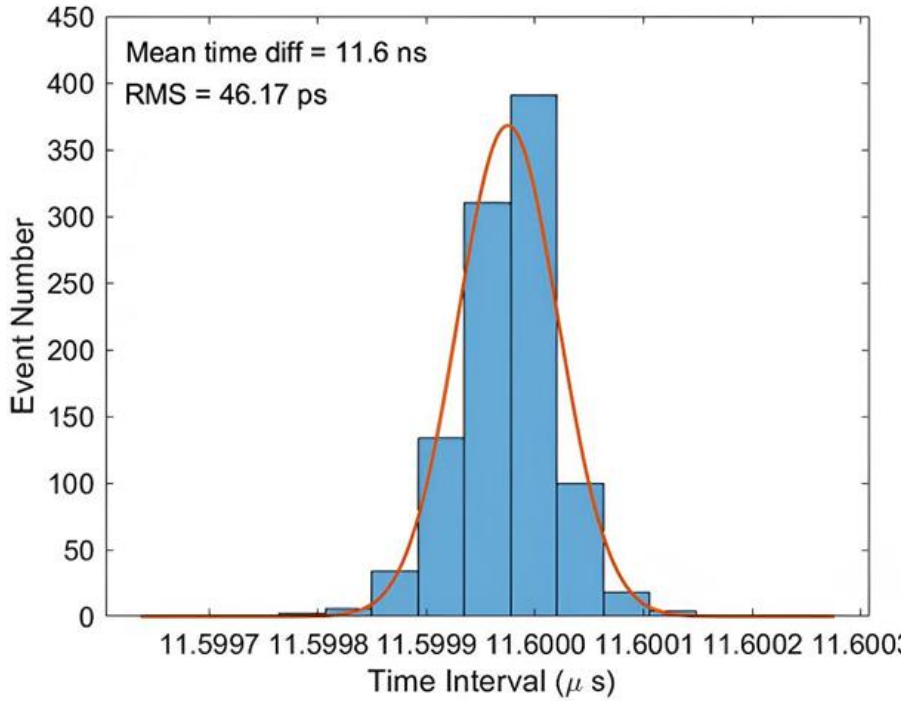
MRPC: 100 x100 cm^2

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)



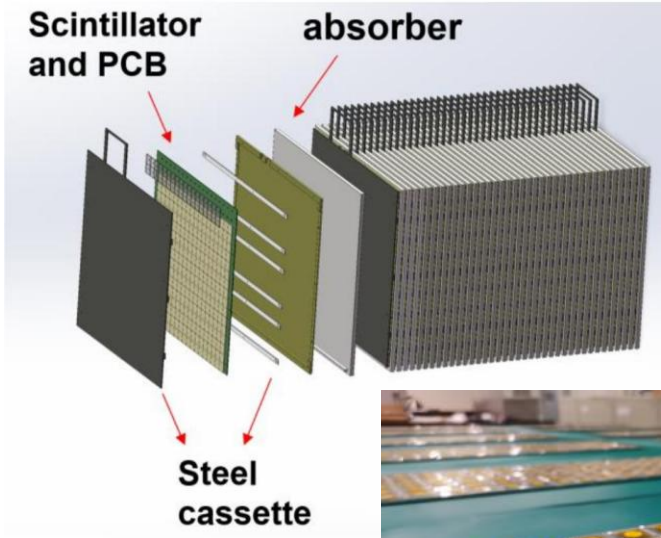


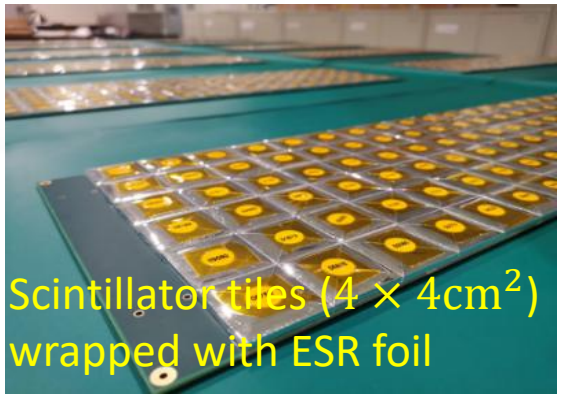


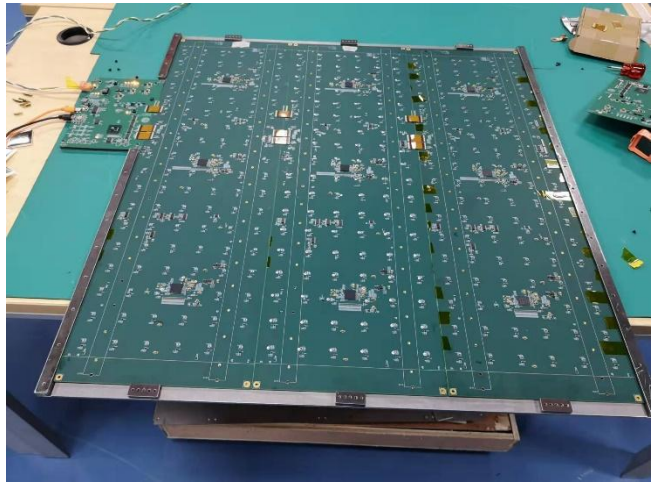
Yongqi Tan's thesis work
IEEE TNS (2024) 0018-9499

PS-HCAL Prototype based on Plastic Scintillators

- **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**





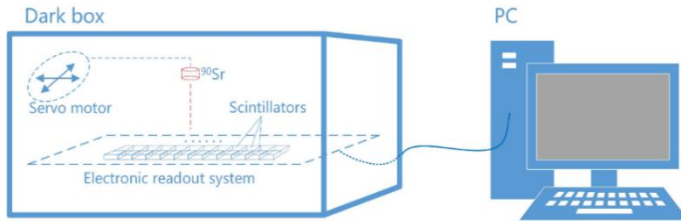


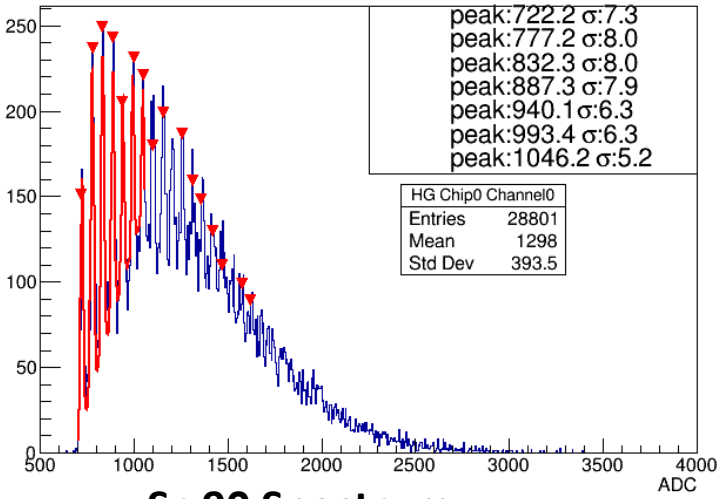
中国科学院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

Scintillators Performance Test

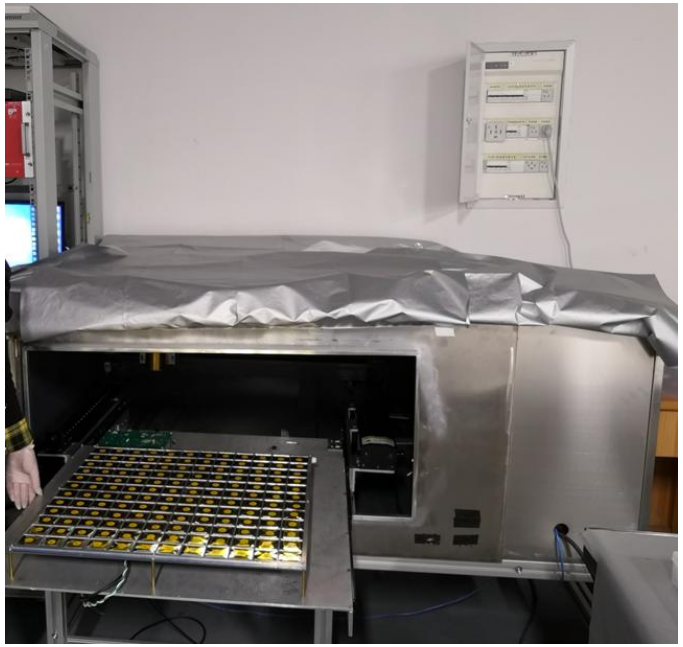
- **>15K scintillators are produced with injection molding technique which are wrapped automatically with ESR films**
- **The batch test platform (with Sr-90)**
  - HPK 13360-1325PE SiPM + SPIROC readout
  - 144 channels / batch
  - The light yield is fitted by landau-gauss function

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

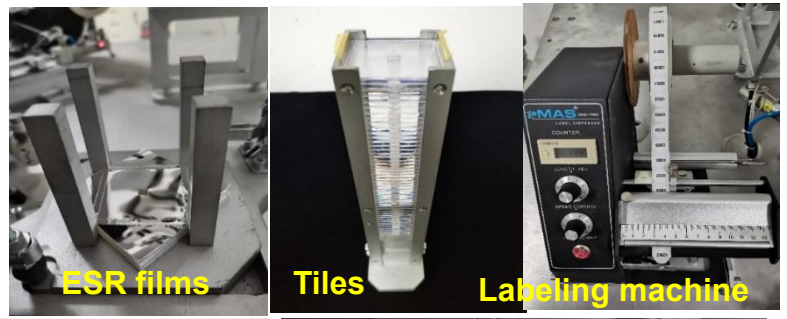


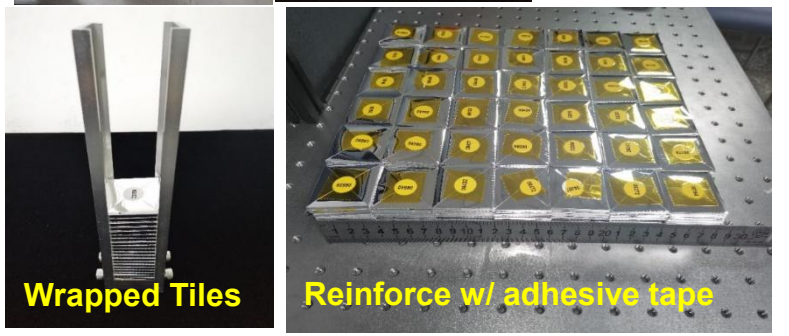


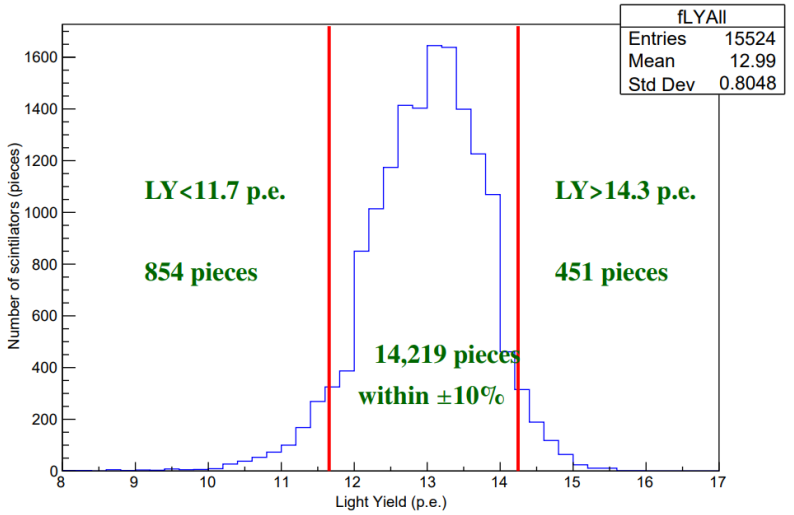
Sr-90 Spectrum



JINST 17 (2022) P05006







Light yield for all scintillators

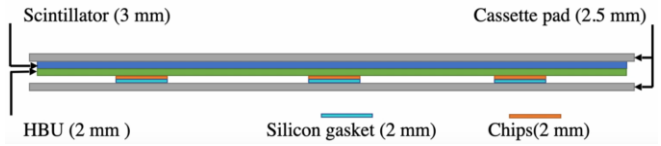
Assembly of Scintillator, SiPM and HBU

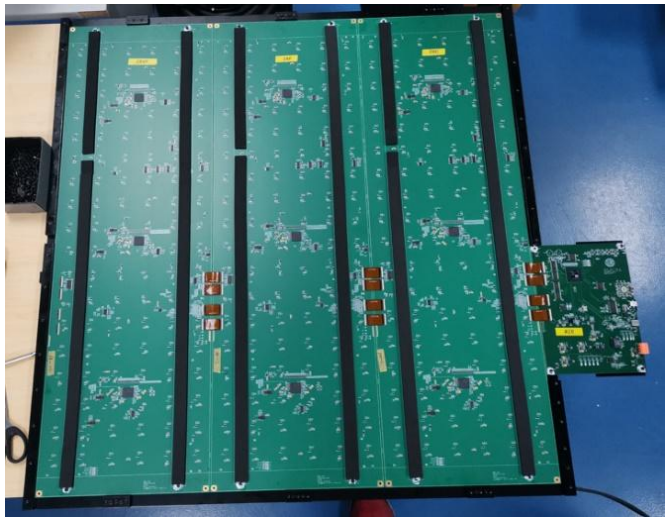
- **Assemble of the PS-HCAL Prototype (12960-ch)**
  - Assemble the scintillator on HBU with glue
  - Press them with cover plate for solidification
  - Combine 3 HBUs and install in 1 cassette (14.5mm)
  - 40 layers are assembled in the AHCAL prototype
- **38 layers with HPK and 5 layers with NDL SiPM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



Scintillators on HBU

HBU finished





3 HBUs in 1 cassette





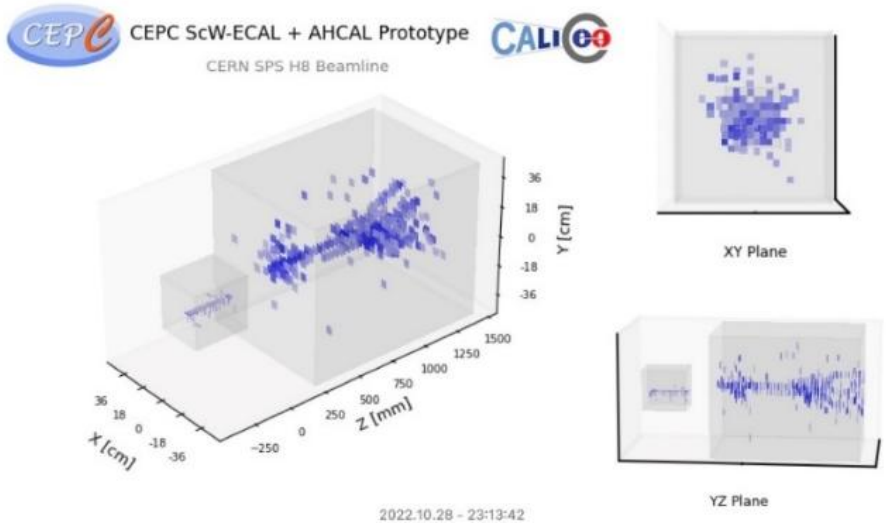
AHCAL with 40 layers

CERN Test Beam in 2022 - 2023

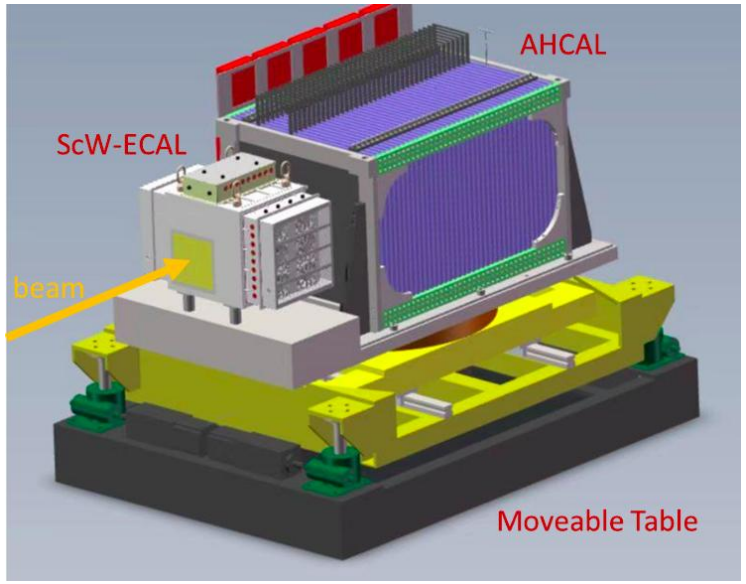
Oct 19 – Nov 2, 2022 — SPS H8 beamline

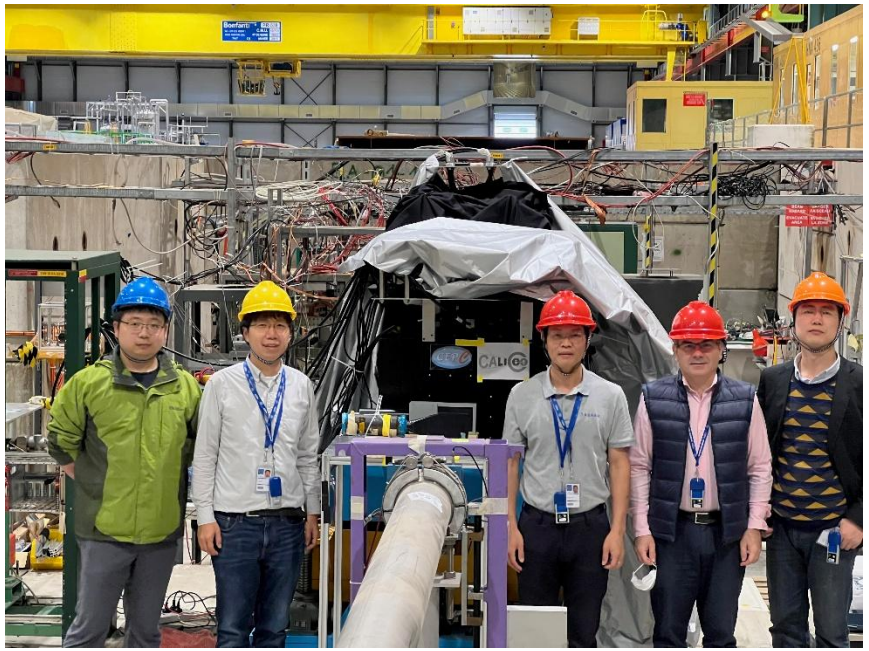
Apr 26 – May 10, 2023 — SPS H2 beamline

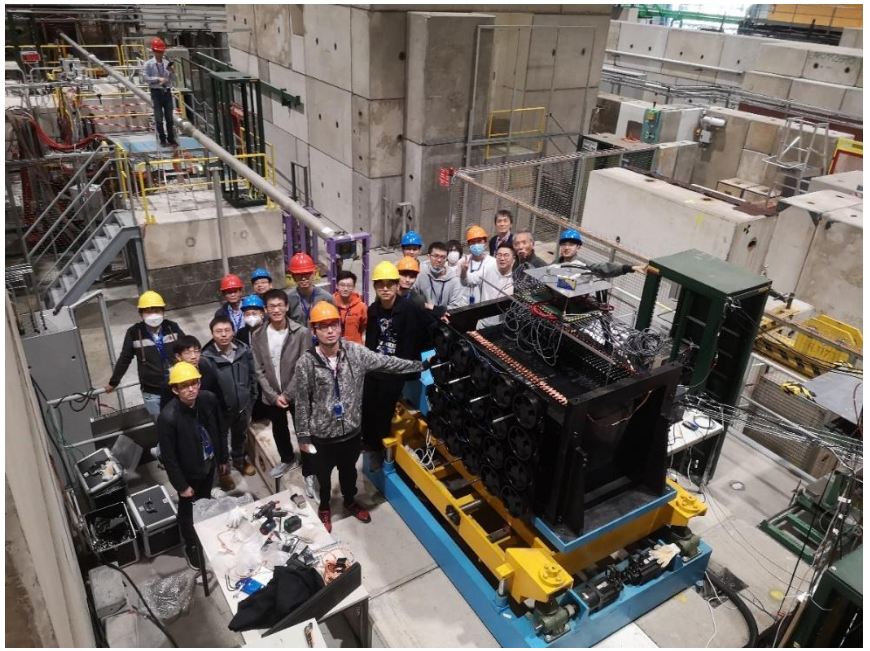
May 17 – 31, 2023 — PS T9 beamline



- **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

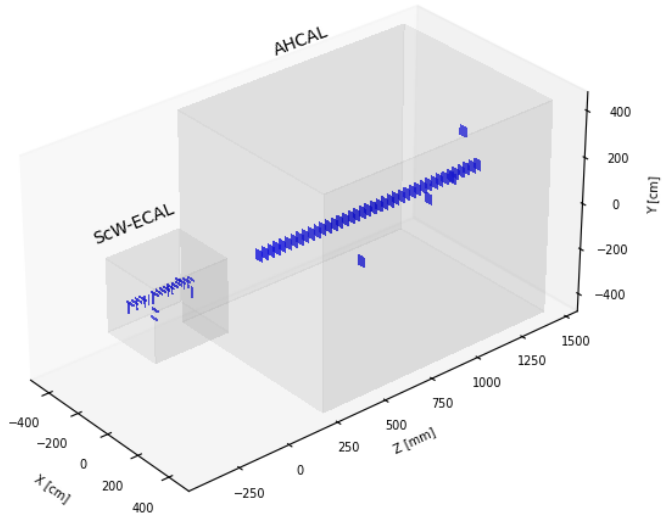


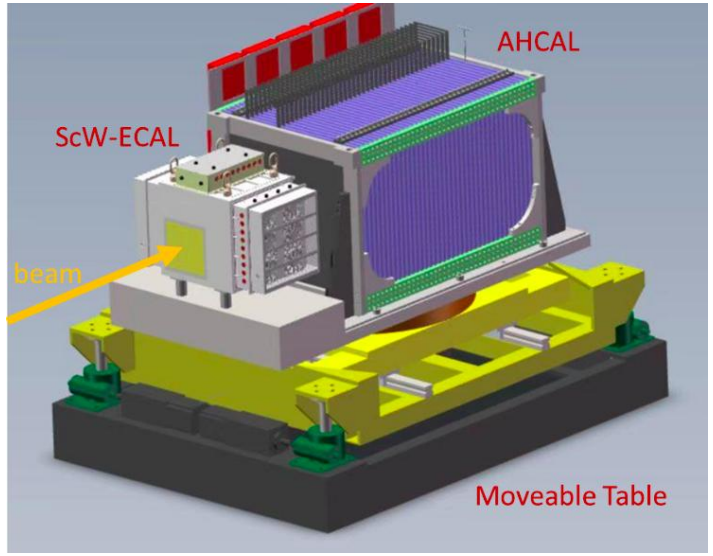




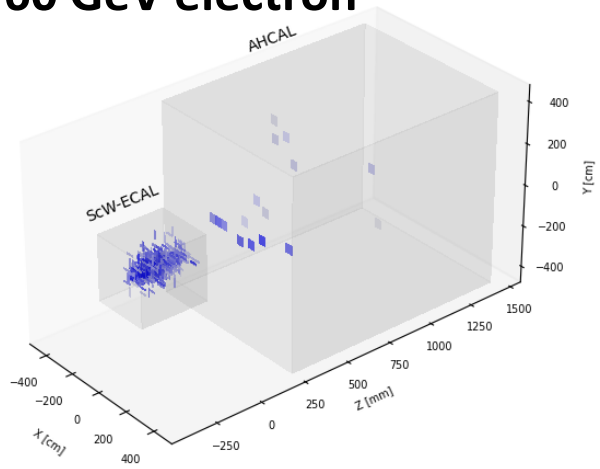
CERN Test Beam in 2022 - 2023

100 GeV mu-

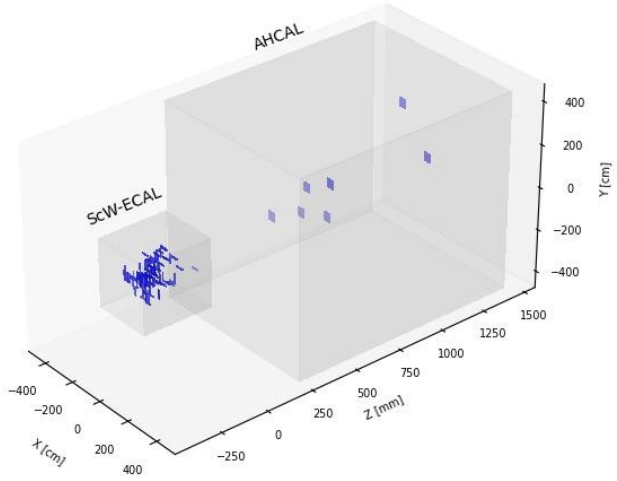




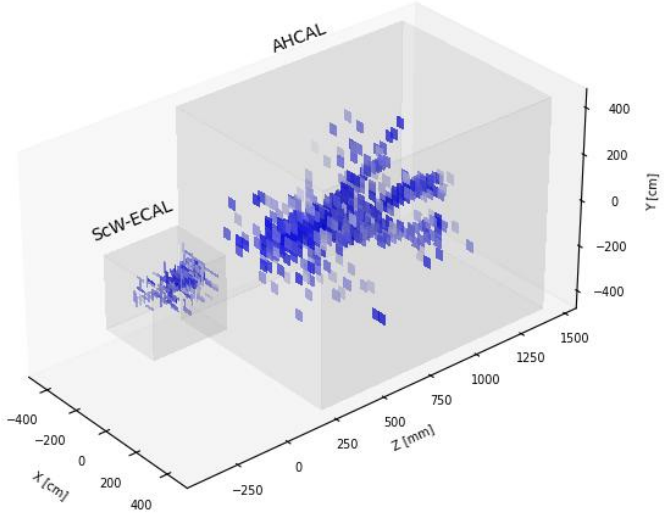
60 GeV electron



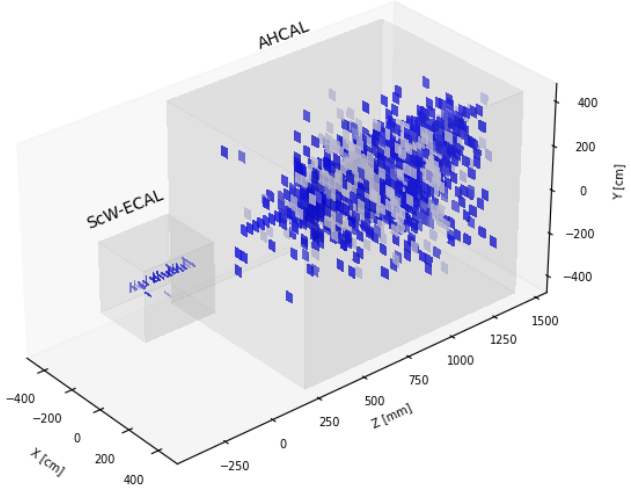
10 GeV negative pion (PS)



60 GeV negative pion (SPS)

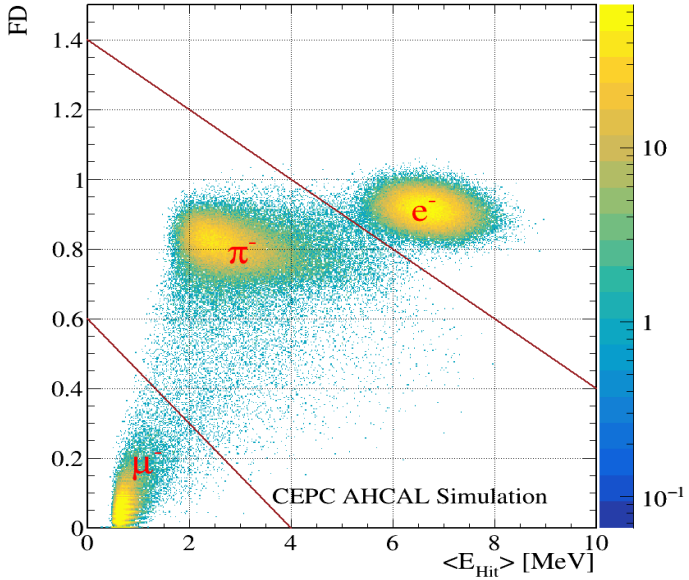


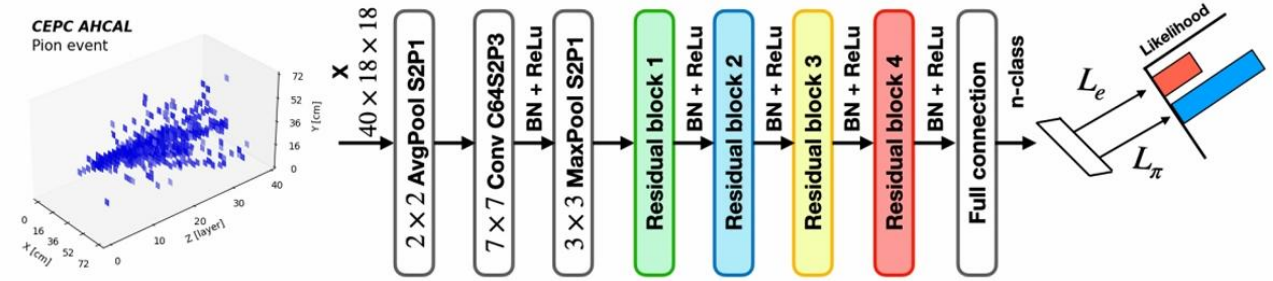
350 GeV negative pion (SPS)

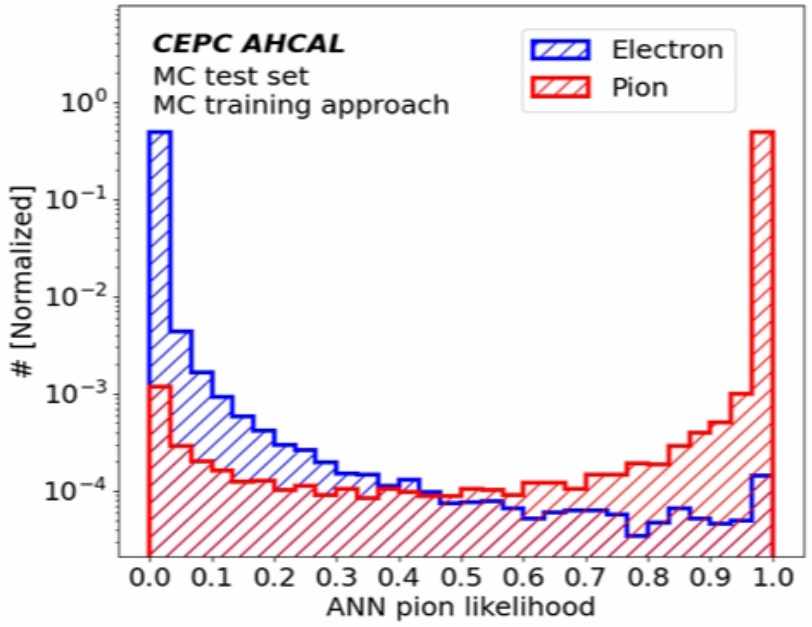


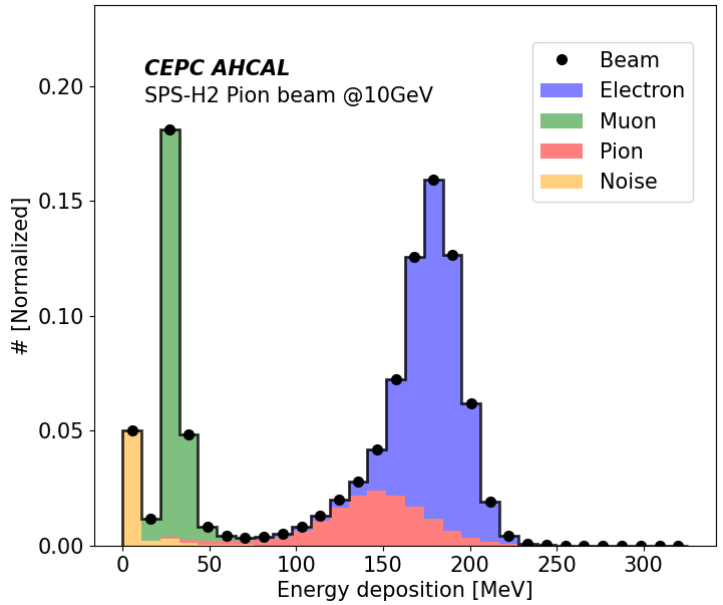
PS-HCAL: Particle Identification

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









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

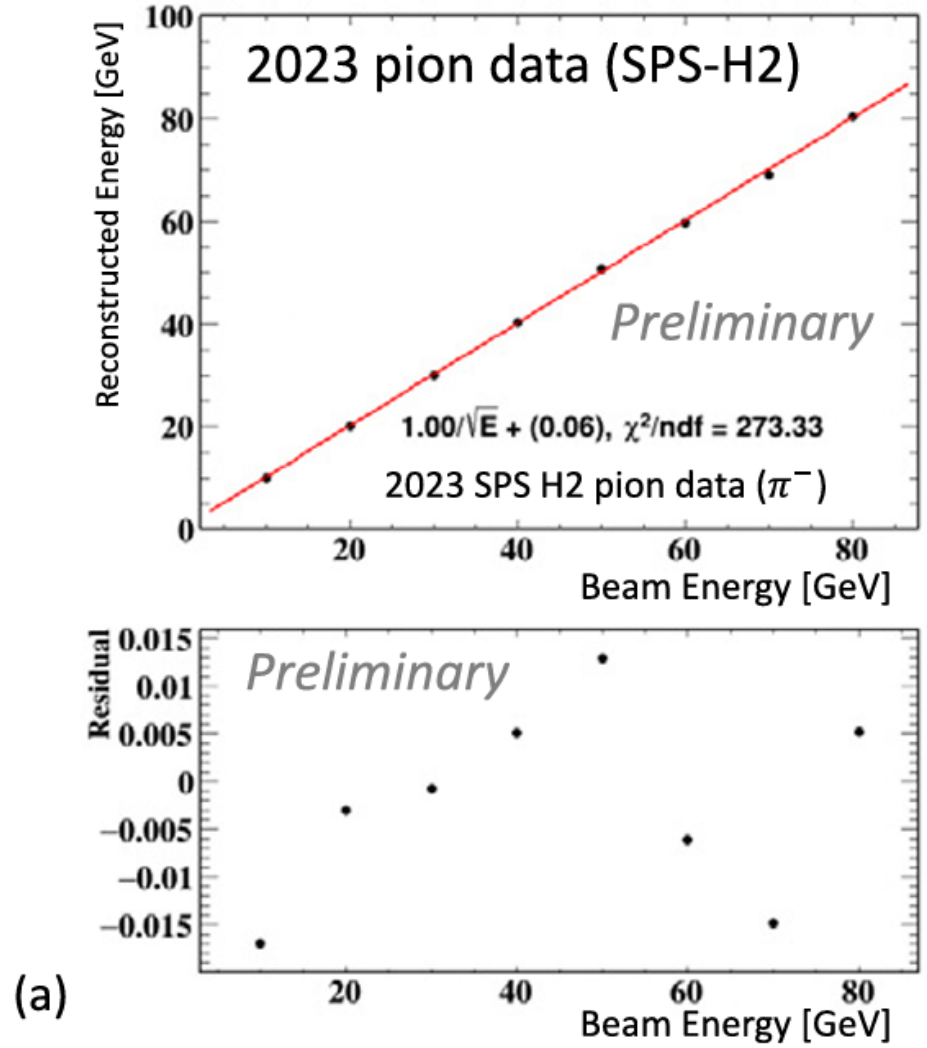
$FD = \left\langle \frac{\log(R_{\alpha,1})}{\log(\alpha)} \right\rangle$ where $R_{\alpha,1} = \frac{N_1}{N_\alpha}$ and N_α is number of hits scaled by factor α

Siyuan Song's thesis work

M. Ruan et al., PRL 112, 012001

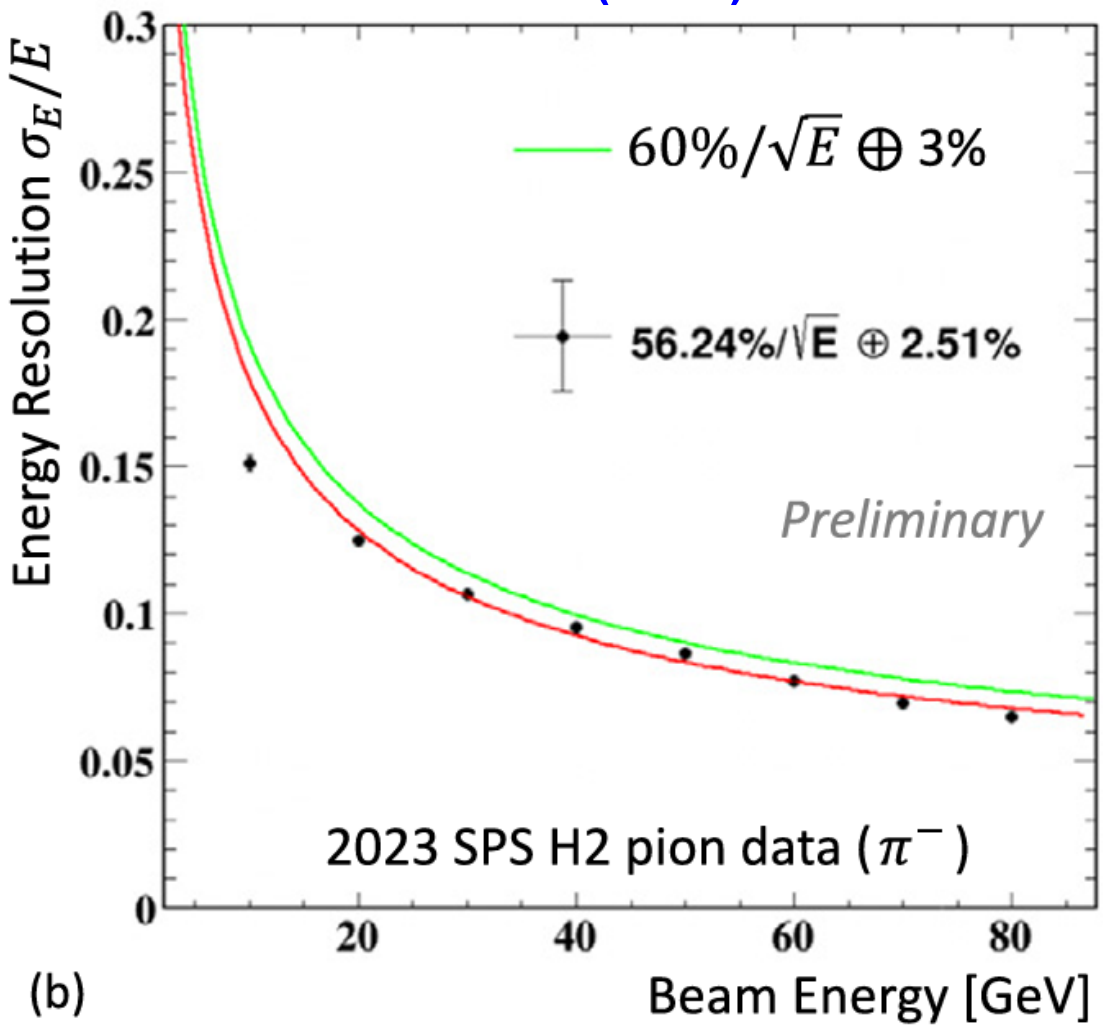
S. Song et al., JINST 09 (2024) P04033

PS-HCAL: Test Beam Performance



Reconstructed Energy Linearity < 1.5%

NIMA 1072 (2025) 170191



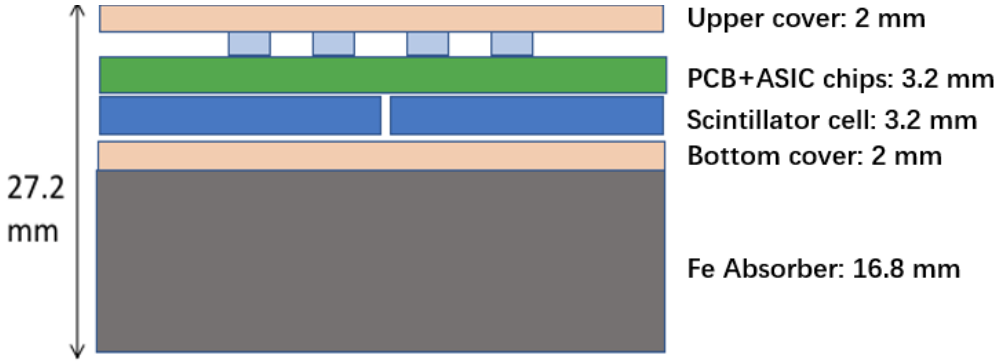
Hadron Energy Resolution：

$56.2\%/\sqrt{E} \oplus 2.5\%$

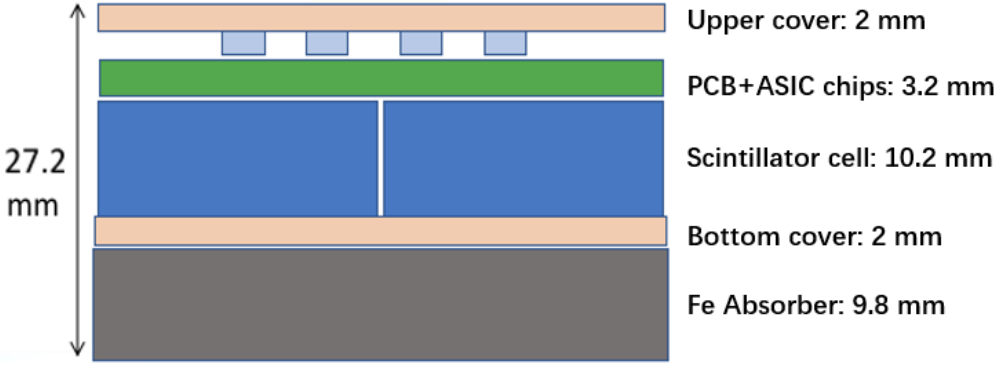
GS-HCAL: Glass Scintillator (GS)

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

PS-HCAL



GS-HCAL



PS-HCAL

Fe: 20.8mm/171.5mm=0.1213 λ_I

PS: 3mm/688.7mm=0.0044 λ_I

PCB: 1.2mm/492.2mm=0.0024 λ_I

Sampling fraction ~ 1.6% (π^- TB, MC)

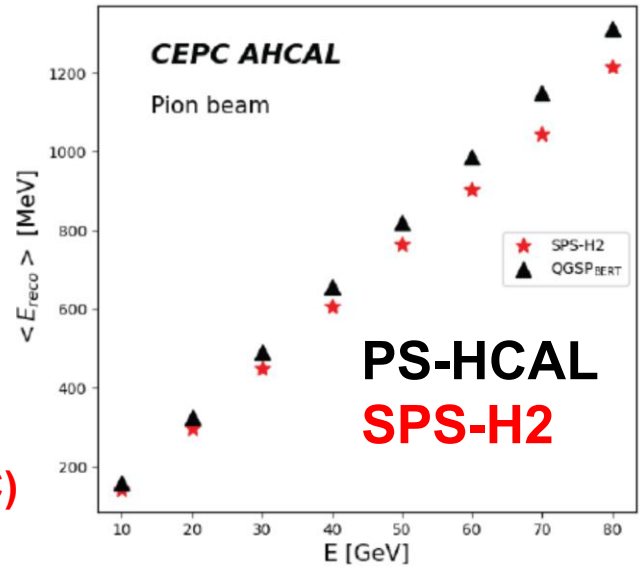
GS-HCAL

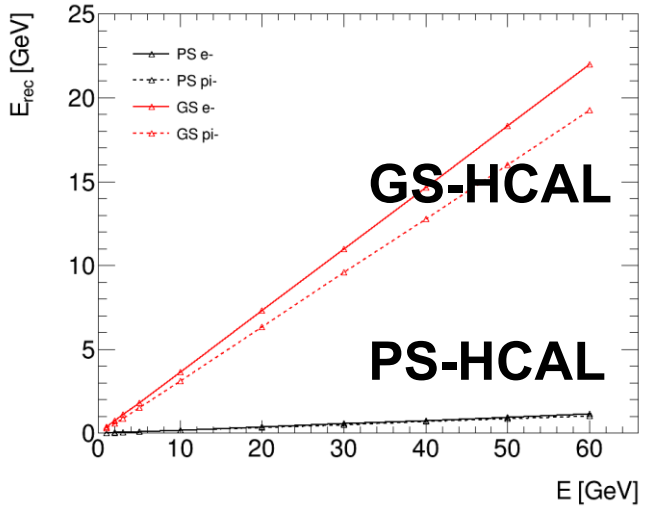
Fe: 13.8mm/171.5mm=0.0805 λ_I

GS: 10.2mm/242.8mm=0.0425 λ_I

PCB: 1.2mm/492.2mm=0.0024 λ_I

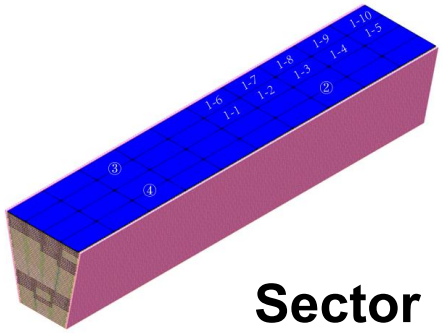
Sampling fraction ~ 31% (MC)



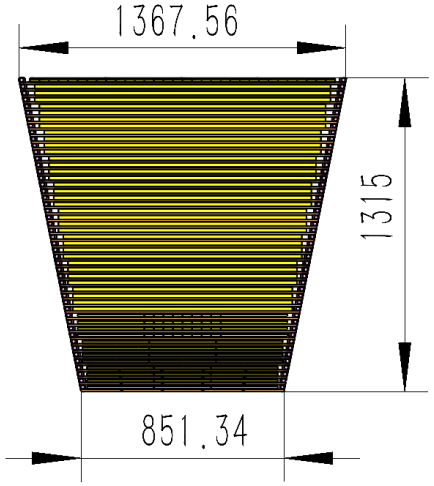


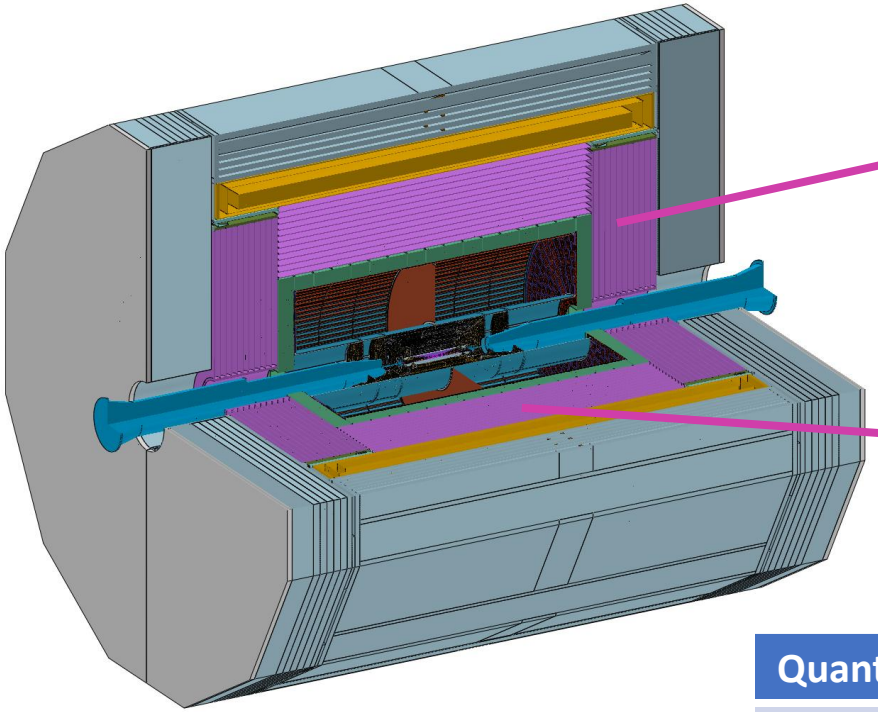
GS-HCAL: Detector Design

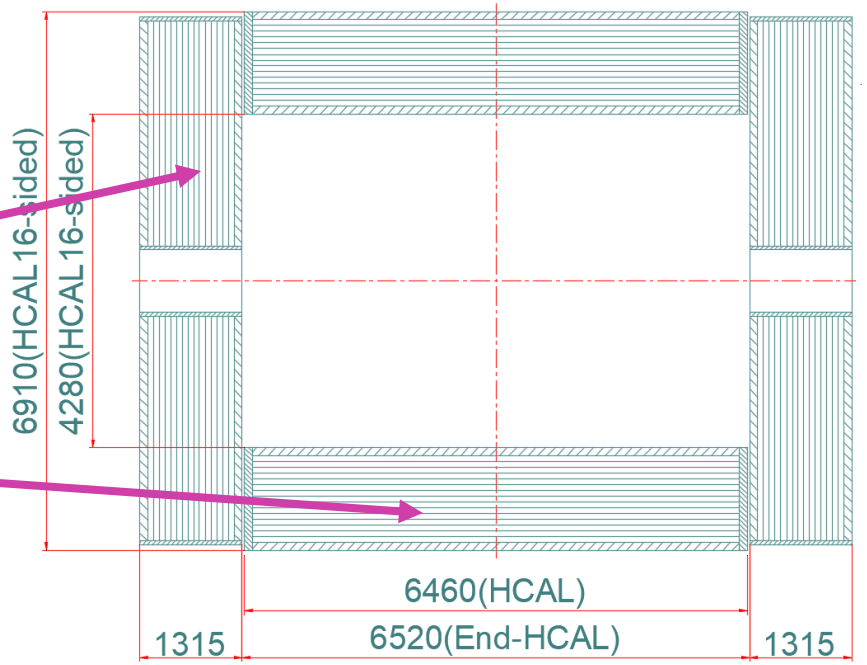
- **GS-HCAL: One Barrel (16 sectors) and Two Endcaps**
  - Thickness of the barrel : 1315 mm
  - Inner radius of the barrel : 2140mm (D_{in}=4280 mm)
  - Barrel length along beam direction : 6460 mm
  - Number of layers : 48 (6 λ_I)
  - About 5.2M readout channels

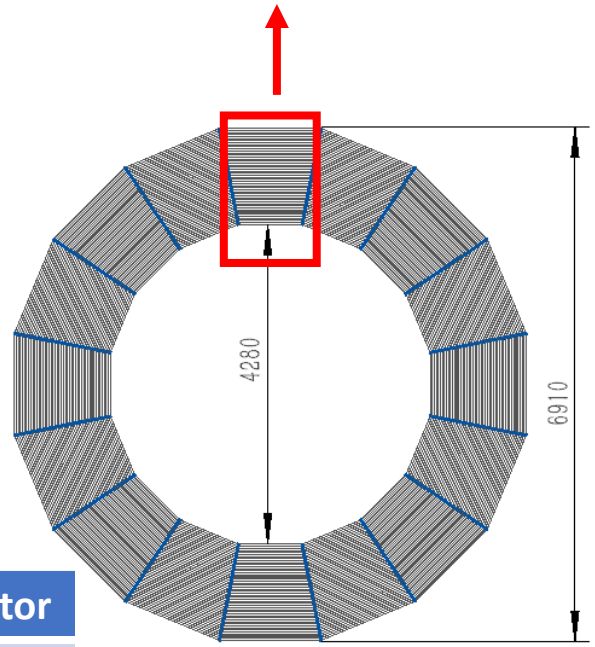


Sector







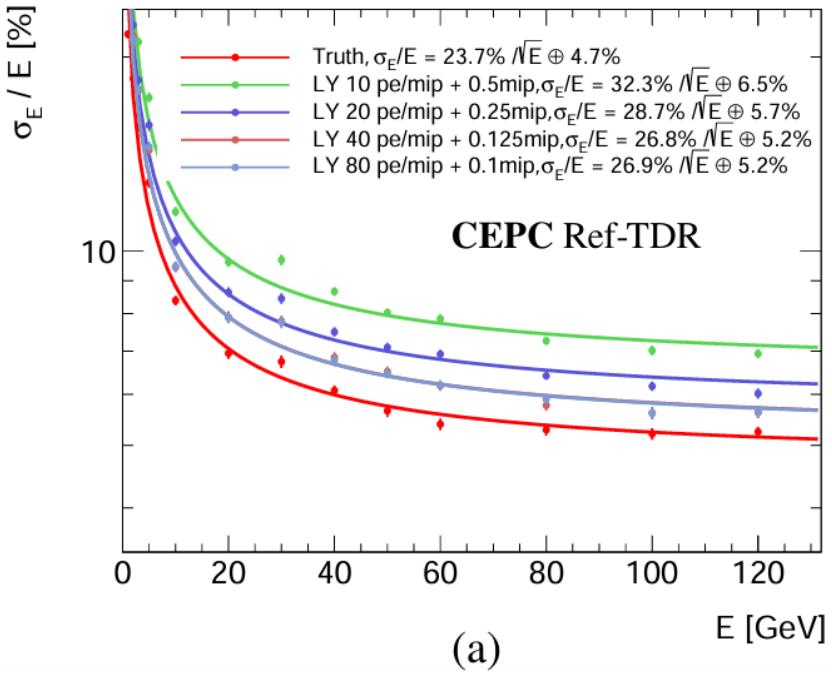


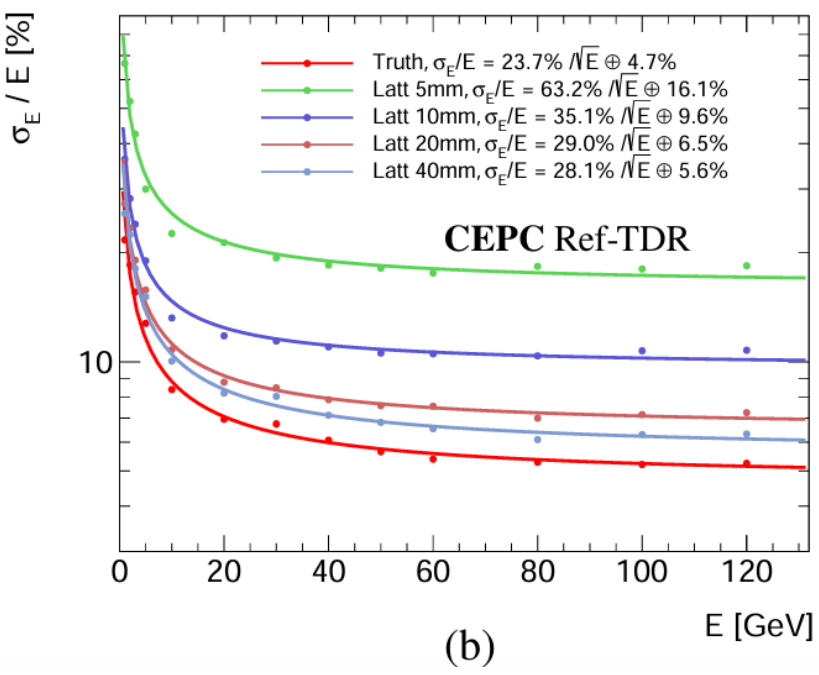
Quantities	Cell	Box	Layer	Sector
Barrel	3212800	27840	48×16=768	16
Endcap×2	1006080×2	3072×2	48×16×2	16×2

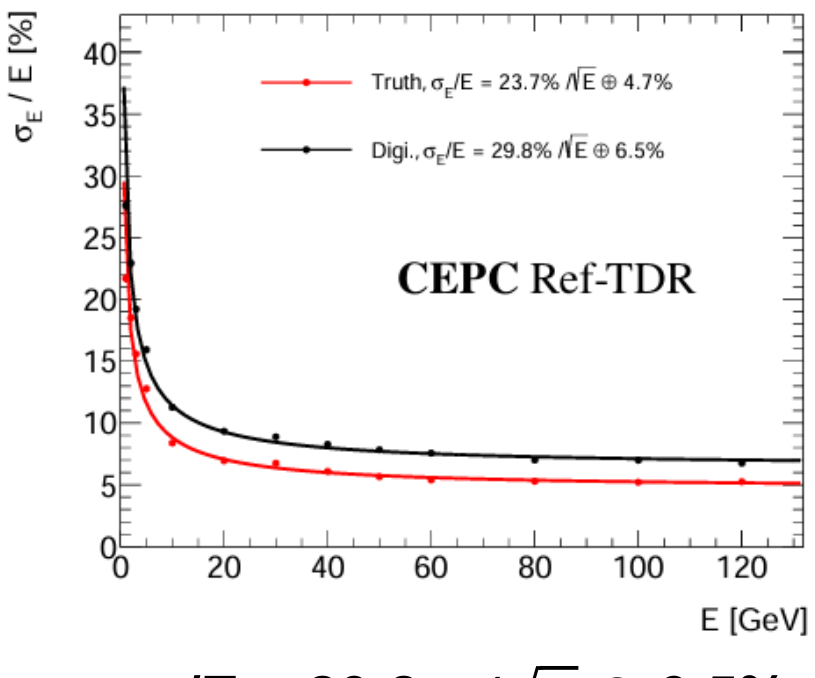
CEPC TDR (arXiv:2510.05260)

GS-HCAL: Simulation and Optimization

- **A full detector geometry constructed with DD4hep in CEPCSW**
  - GS density 6 g/cm^3, $\lambda_I = 242.8$ mm, attenuation length ~ 60mm
  - GS cell size $4 \times 4 \times 1\ \mathrm{cm}^3$, 48 layers, $6\lambda_I$ in total
  - Geometry: follow the mechanics design with supporting structures.







- GS light yield: > 50 p.e/MIP
- Threshold: 0.1 MIP (> 5 p.e)

- GS attenuation length

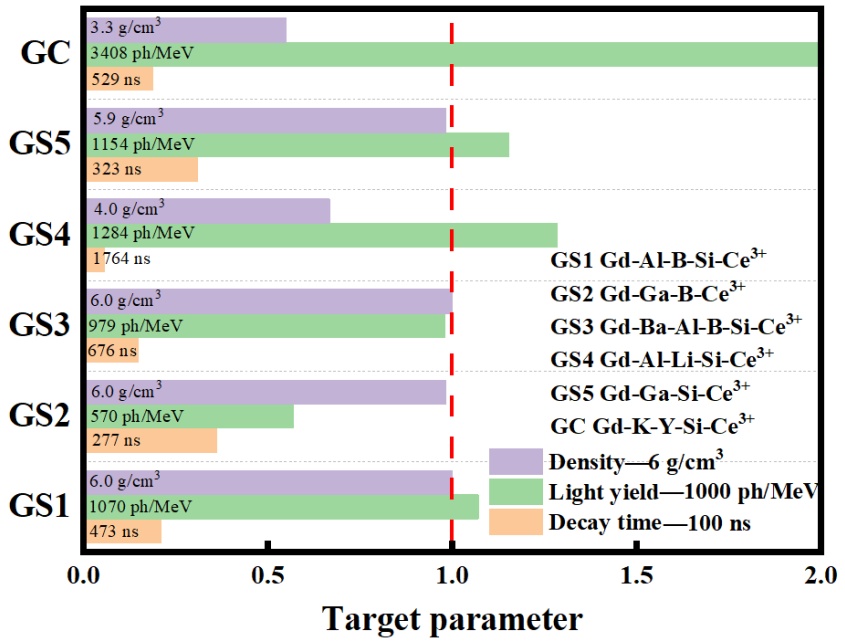
$\sigma_E/E = 29.8\%/\sqrt{E} \oplus 6.5\%$

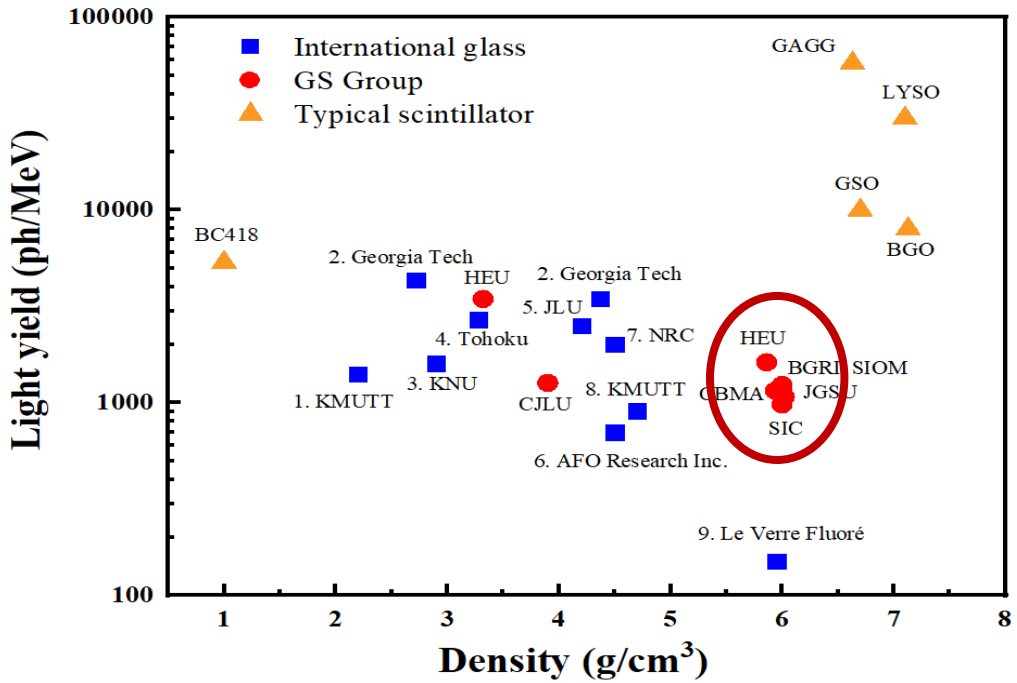
- GS attenuation length: ~60mm

Glass Scintillator Collaboration

- **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.
- The performance of glass scintillator samples look promising, i.e. **6 g/cm³ & 1000 ph/MeV & O(100) ns**

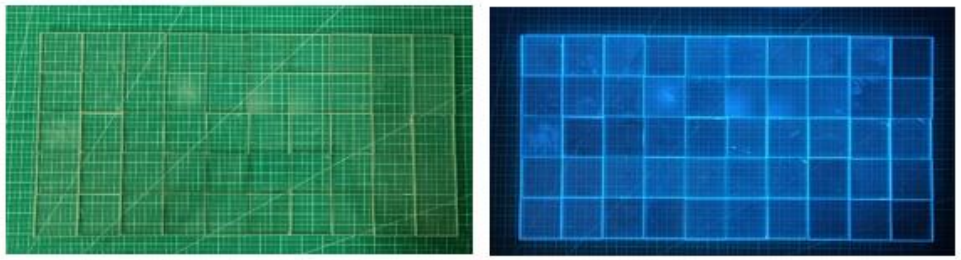




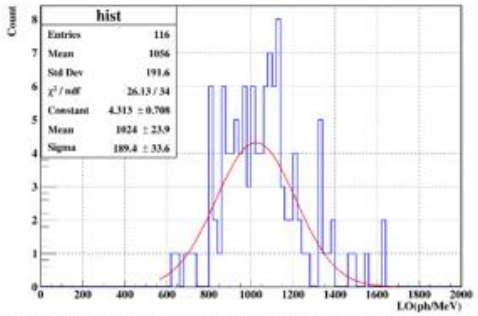


Glass Scintillators: Performance

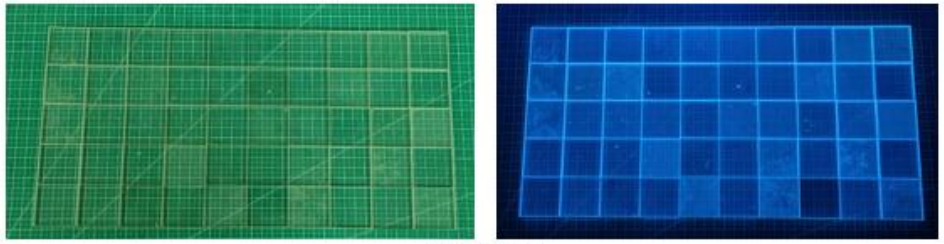
- 291 GS tiles (size: $4 \times 4 \times 1$ cm^3) produced by three companies
- Test setup: Radiation source (^{137}Cs) with 2' PMT (xp2020)
- About 57% of GS tiles with light yield greater than 1000 ph/MeV



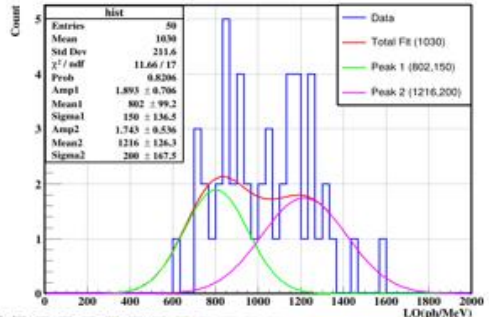
BGRI



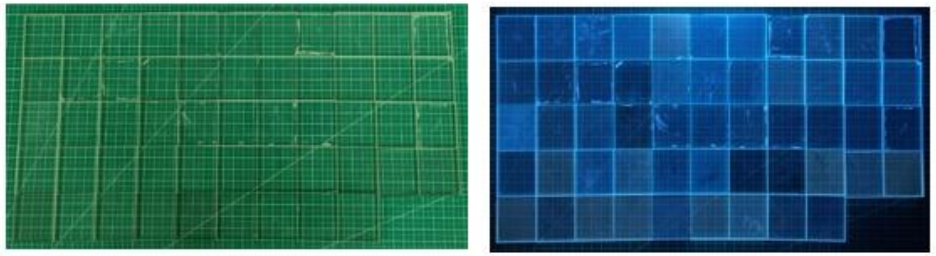
- The light yield of 60.3% of GS is ≥1000 ph/MeV (70/116)
- The light yield of 20.7% of GS is ≥1200 ph/MeV (24/116)



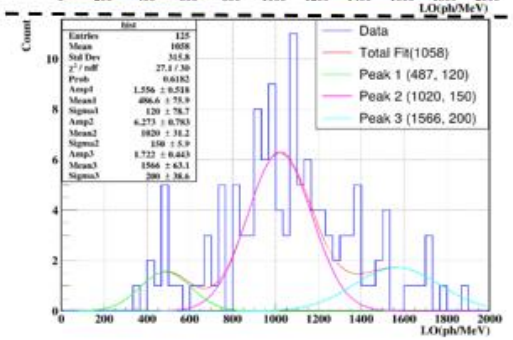
SIOM



- 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

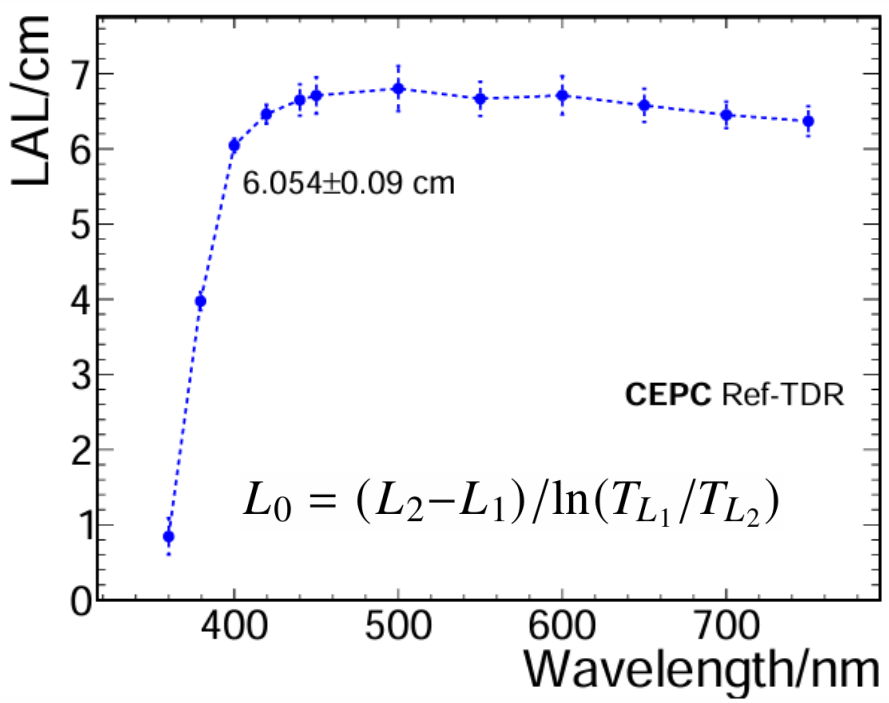


- The light yield of 55.2% of GS is ≥1000 ph/MeV (69/125)
- The light yield of 30.4% of GS is ≥1200 ph/MeV (38/125)

Glass Scintillators: Performance

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





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

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

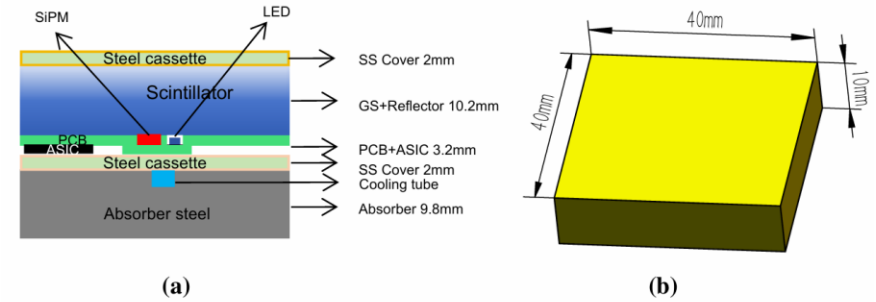
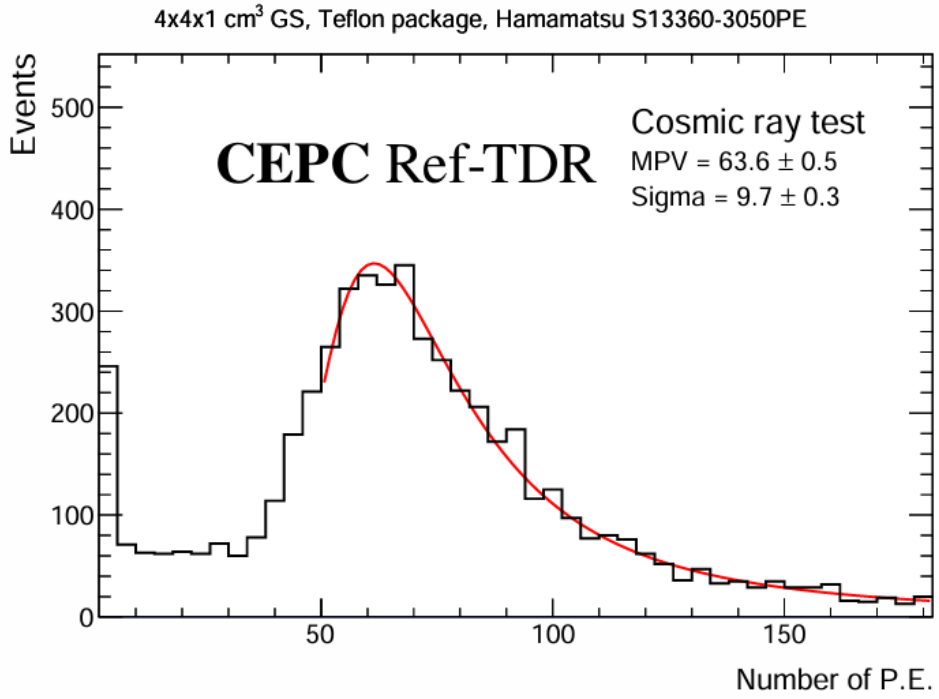
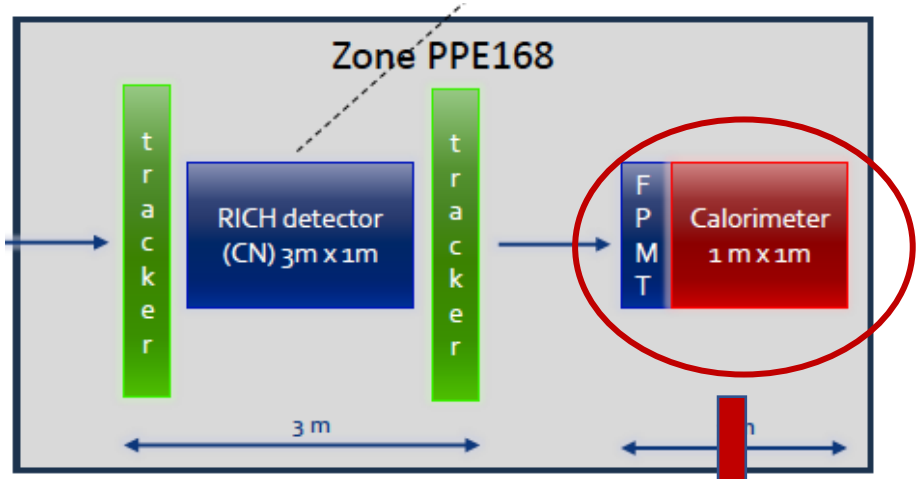
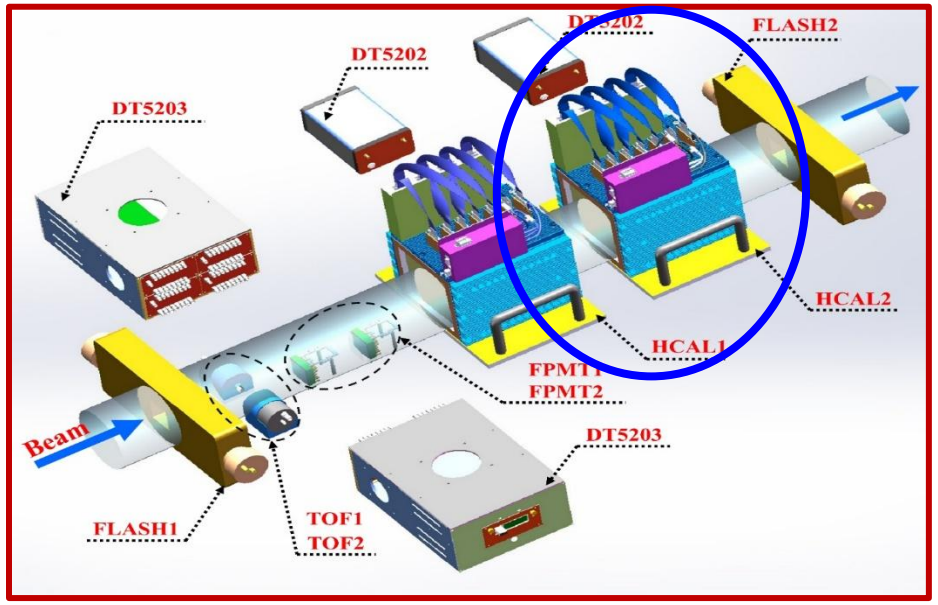


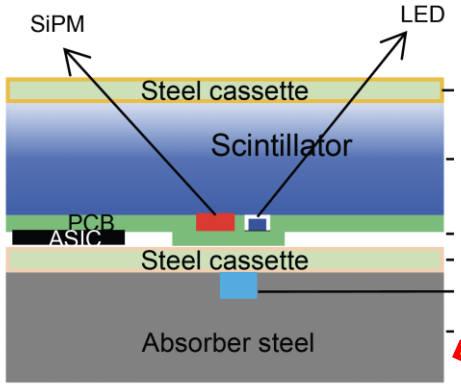
Figure 8.2: (a) Single layer structure of GS-HCAL. (b) One GS cell.

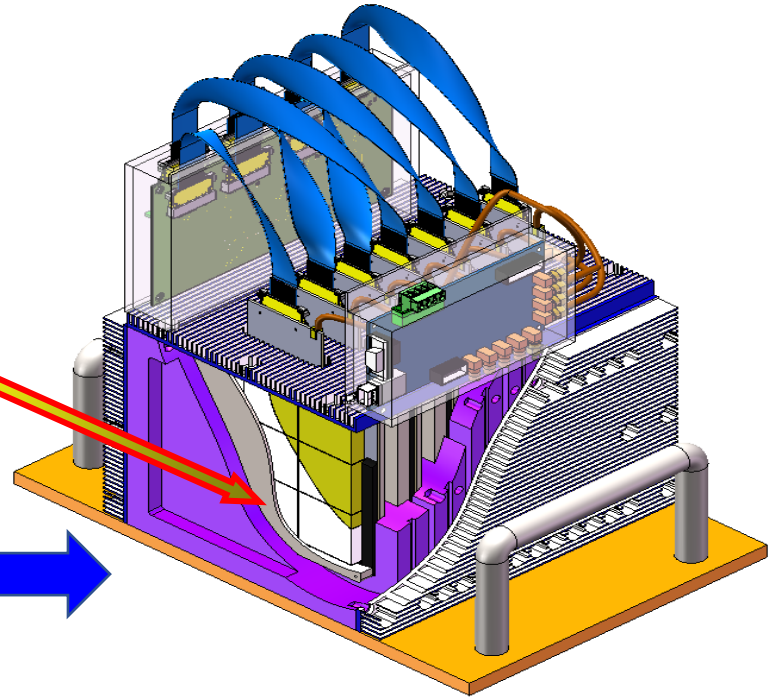


Glass Scintillators: Mini-Prototypes





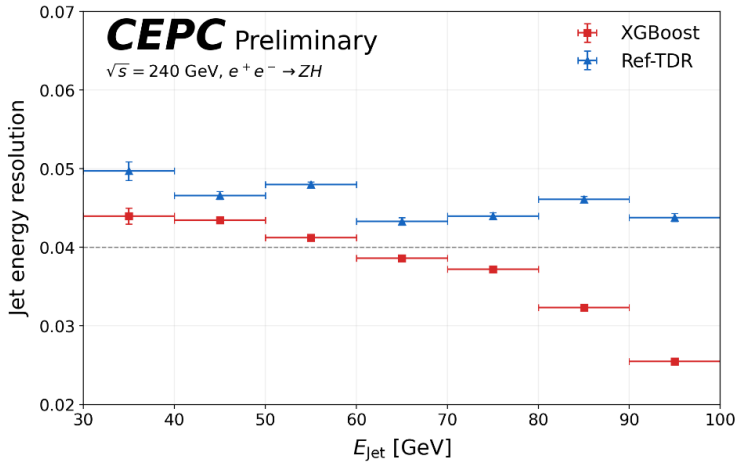


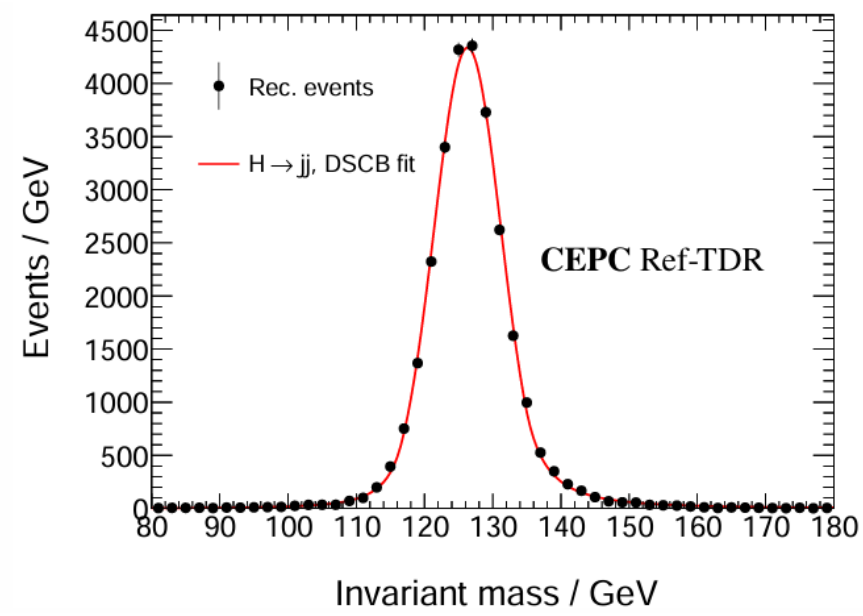


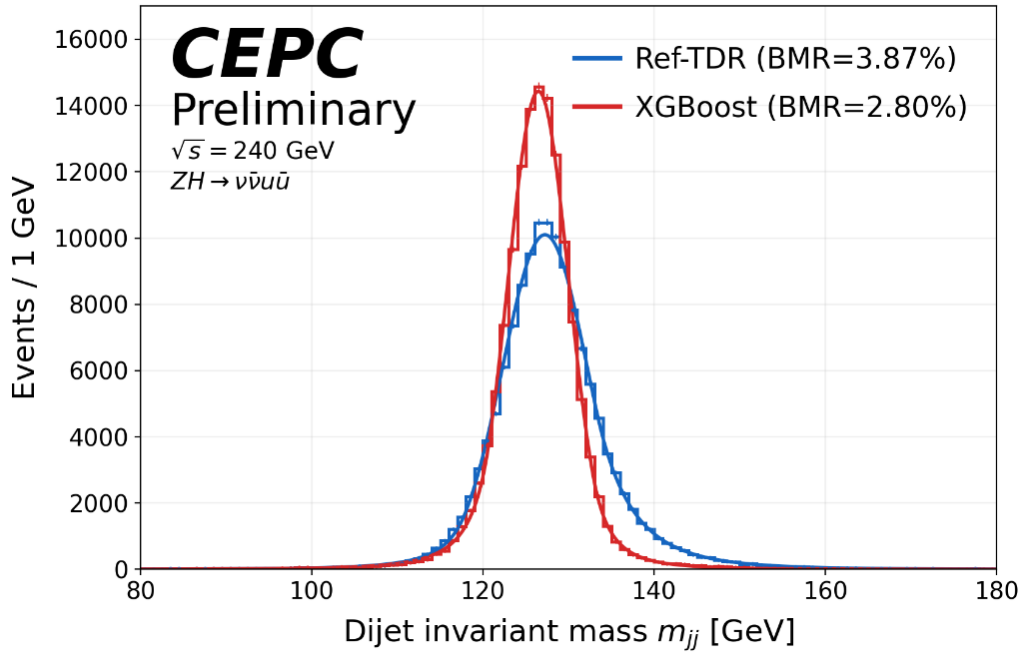
- **Mini-Prototype:** 7 layers, each layer has 3×3=9 GS tiles, 63 GS tiles in total, each GS size of 4×4×1 cm^3
- **Two mini-prototypes** using HPK & NDL, respectively
- **CERN beam tests** (Pion / Muon) **in October 2025**

Physics Performance: JER & BMR (H→qq)

- **Hadron Energy Resolution (full simulation + digitization):**
  - MC Samples: **ee → ZH → ννgg/qq @ 240 GeV**
  - **Cyber PFA** reconstruction: Tracker + Crystal ECAL + GS-HCAL
  - **XGBoost** to re-optimize jet energy using jet-level variables
    - **Jet Energy Resolution (JER): 4.3% → 2.6% at 100 GeV**
    - **Boson Mass Resolution (BMR): 3.87% → 2.8% for ZH→ννqq**



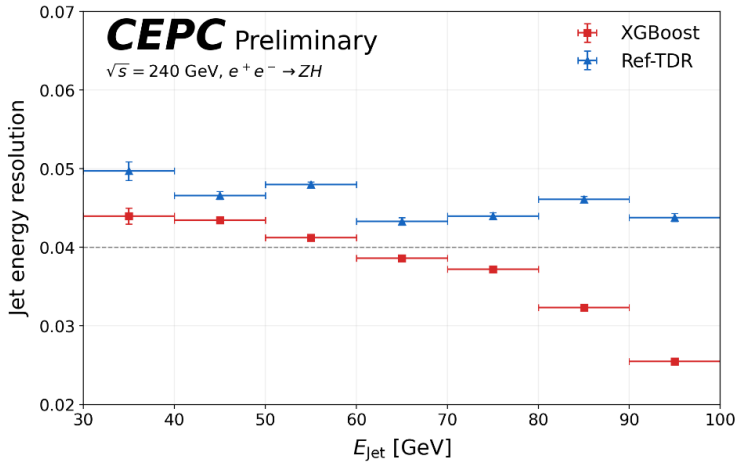


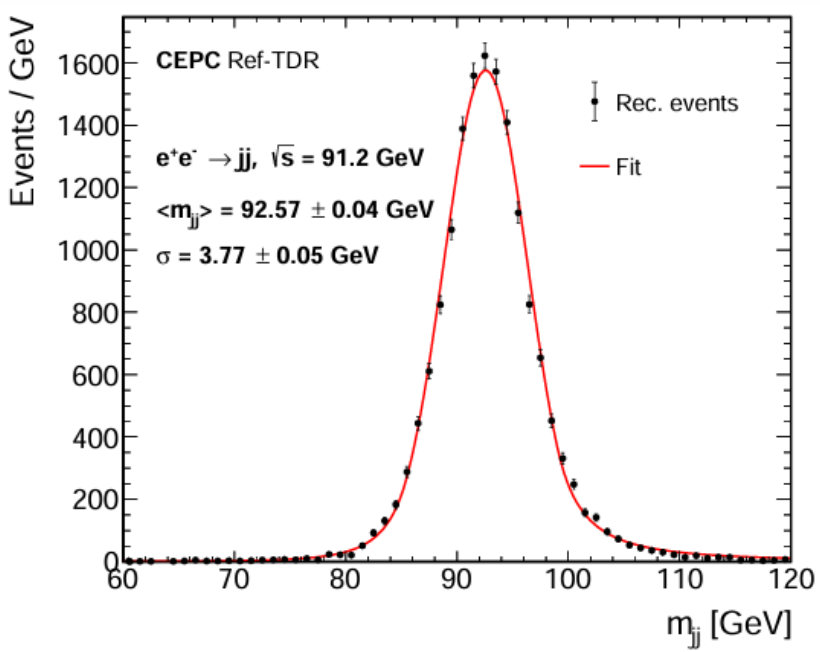


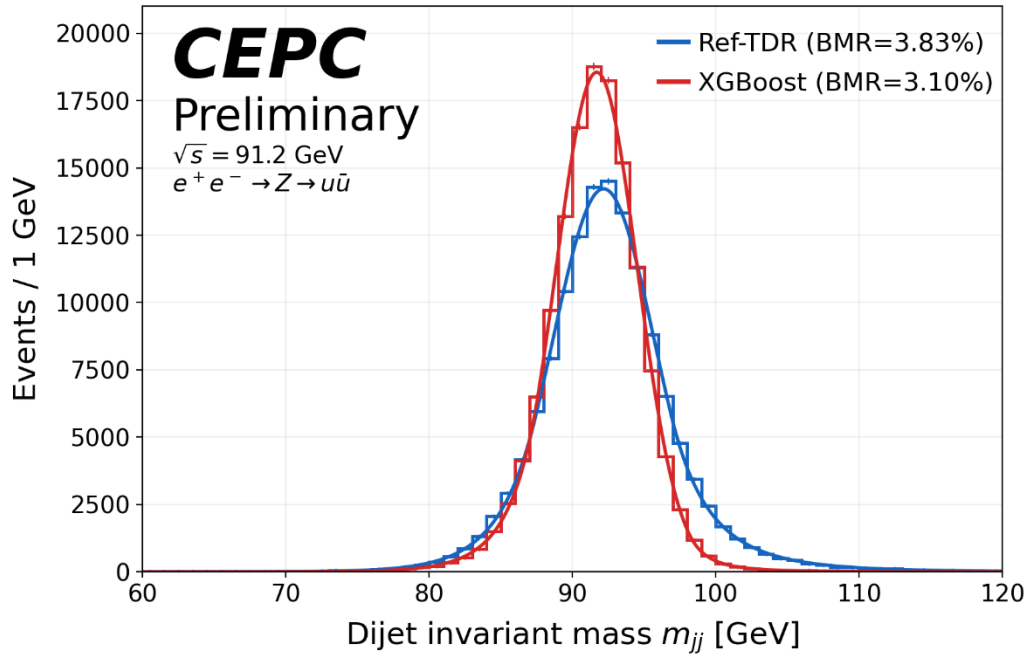
CEPC Ref-TDR (arXiv:2510.05260)

Physics Performance: JER & BMR (Z→qq)

- **Hadron Energy Resolution (full simulation + digitization):**
  - MC Samples: **ee → Z → qq @ 91.2 GeV**
  - **Cyber PFA** reconstruction: Tracker + Crystal ECAL + GS-HCAL
  - **XGBoost** to re-optimize jet energy using jet-level variables
    - **Jet Energy Resolution (JER): 4.3% ➔ 2.6% at 100 GeV**
    - **Boson Mass Resolution (BMR): 3.8% ➔ 3.1% for Z → qq**







CEPC Ref-TDR (arXiv:2510.05260)

Summary and Plan

- **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 results
- **PID, JER and BMR: preliminary results promising**
  - Particle Identification with ML: muons, electrons, pions
  - Prototype simulation + digitization: validation studies with beam data
  - Jet energy resolution and boson mass resolution improve significantly with ML
- **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 !

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

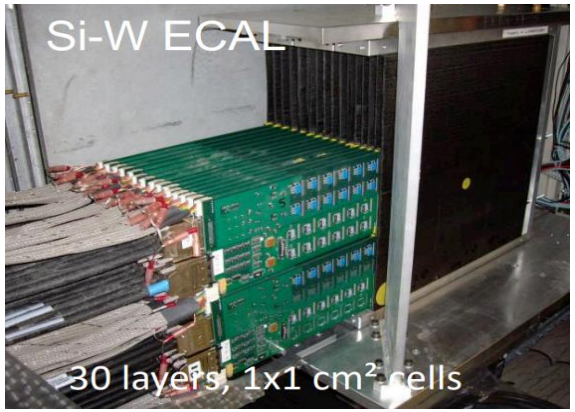


CALICE spokesperson's visit



CERN PS-T9, May 2023

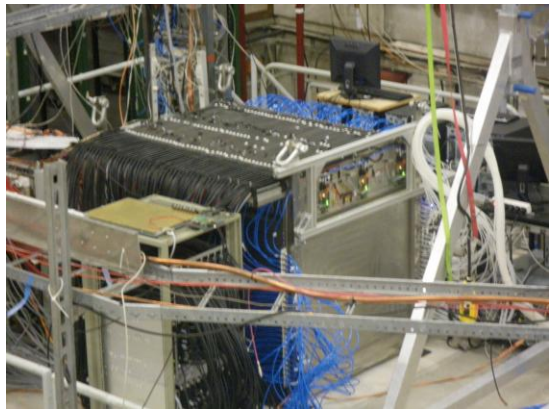
Calorimeters Prototypes for CEPC



Si-W ECAL, 30 layers, 1x1 cm²



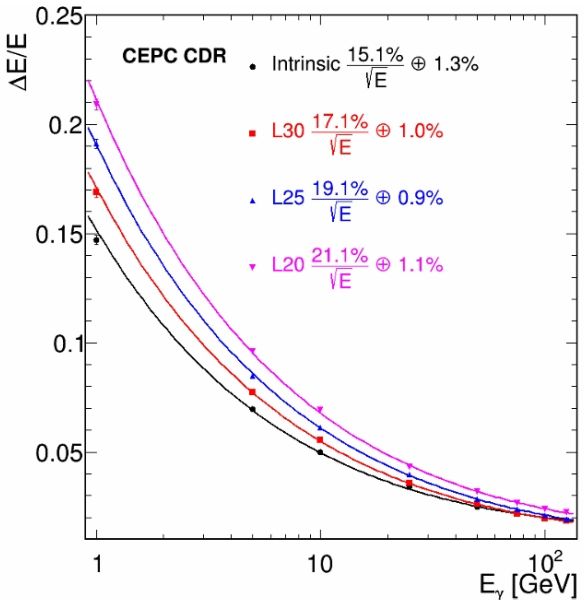
Sci-W ECAL, 32 layers, 5x5 mm²

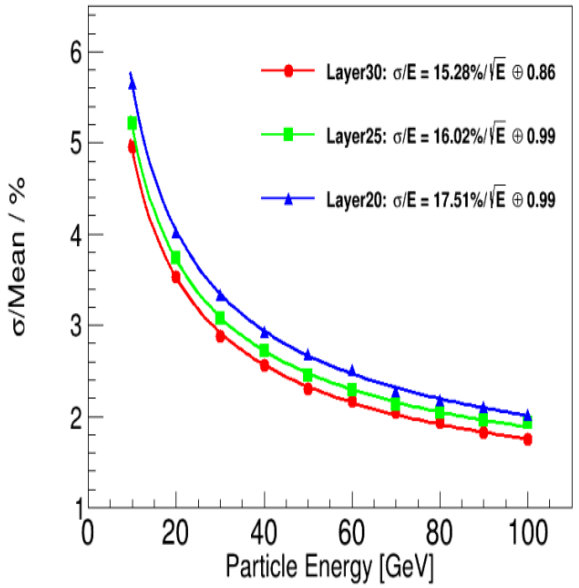


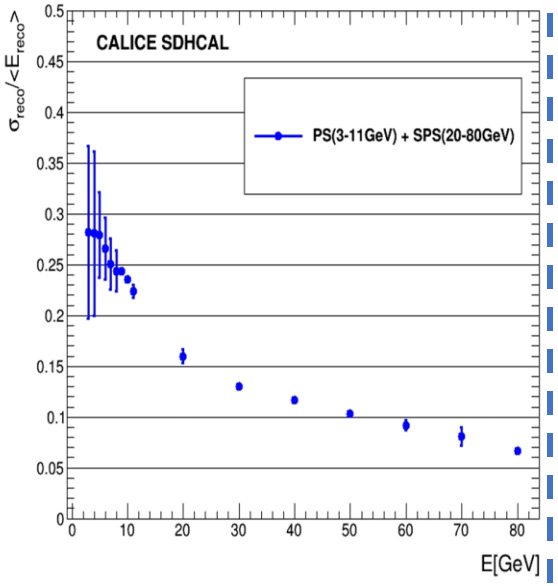
SDHCAL, 48 layers, 1x1 cm²

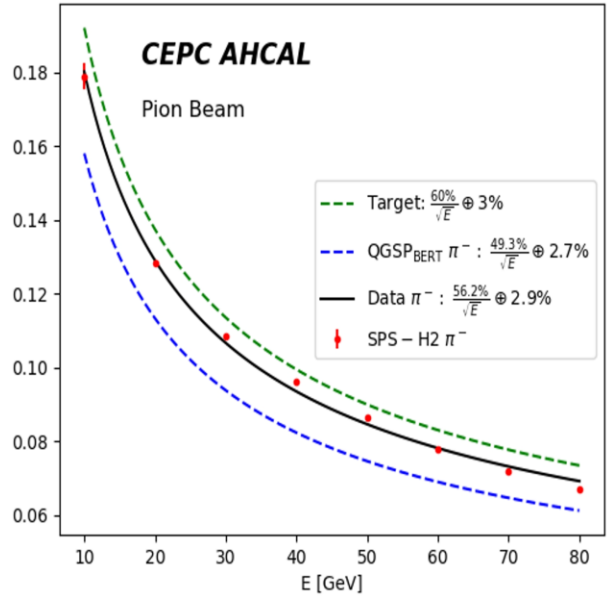


AHCAL, 40 layers, 4x4 cm²



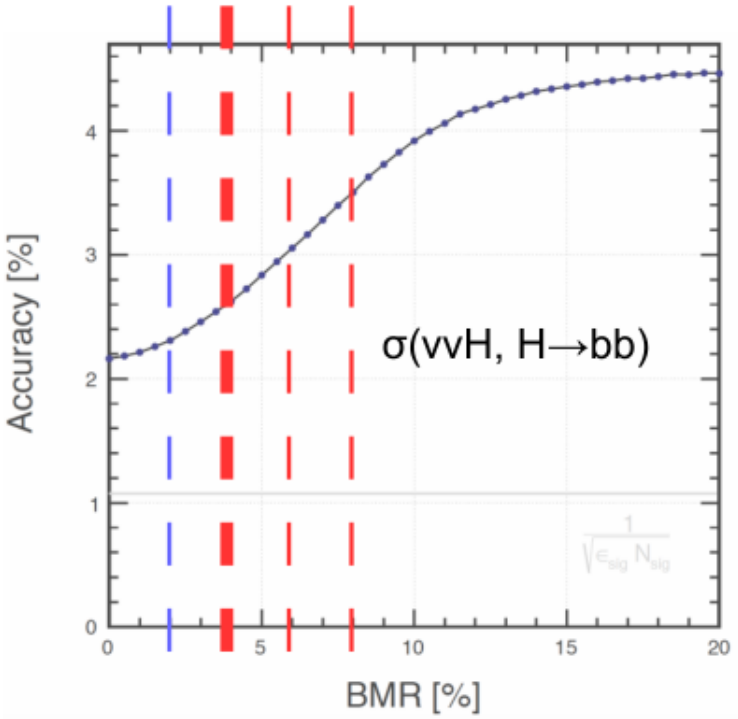




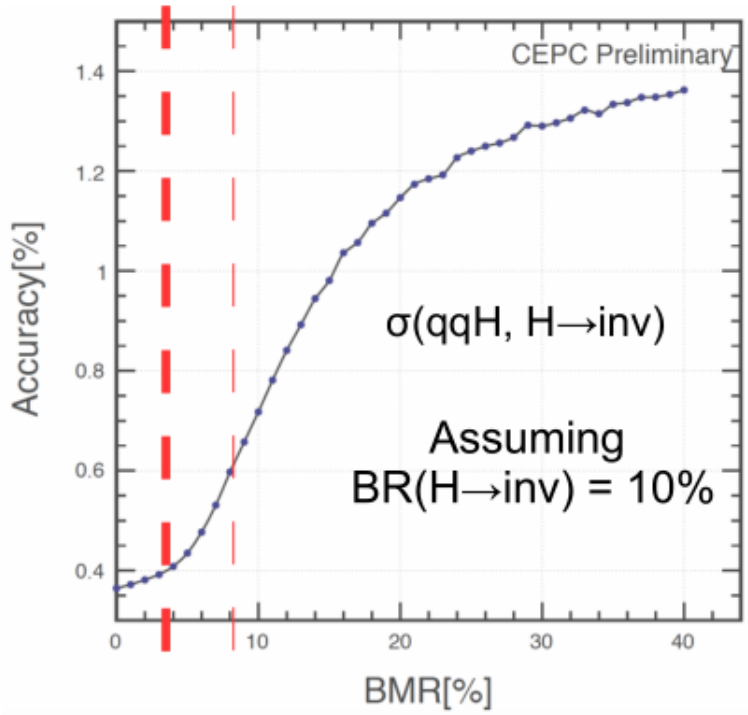


Calorimeters Design and Optimization

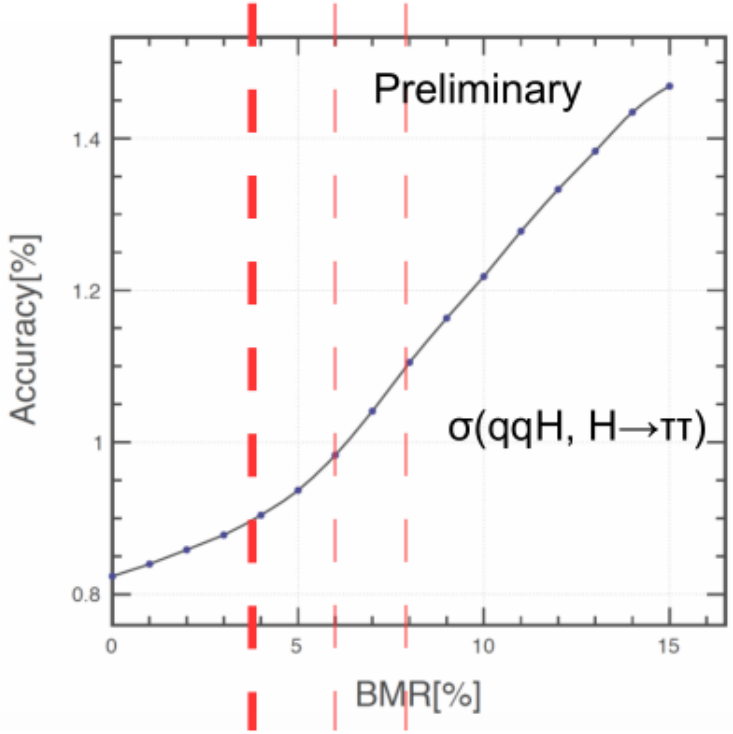
Accuracy$(\sqrt{S+B}/S)$ vs BMR (Boson Mass Resolution)



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.

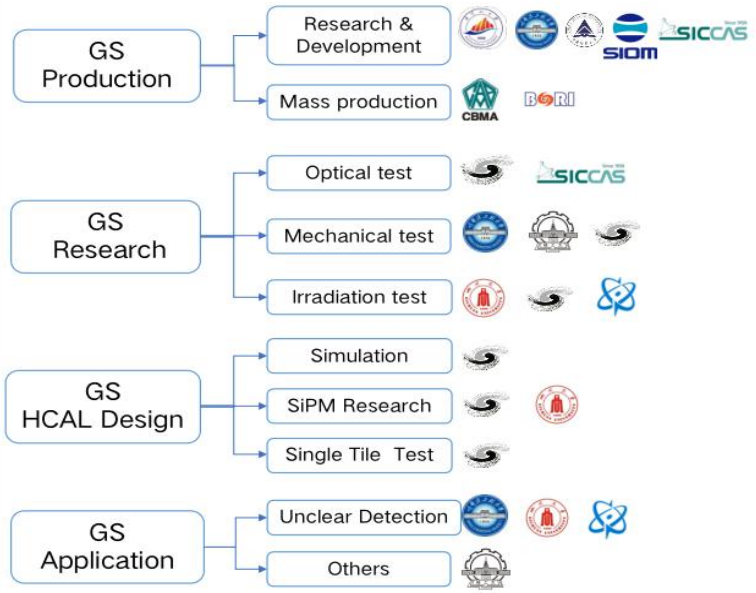
Glass Scintillator Collaboration

-- 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.

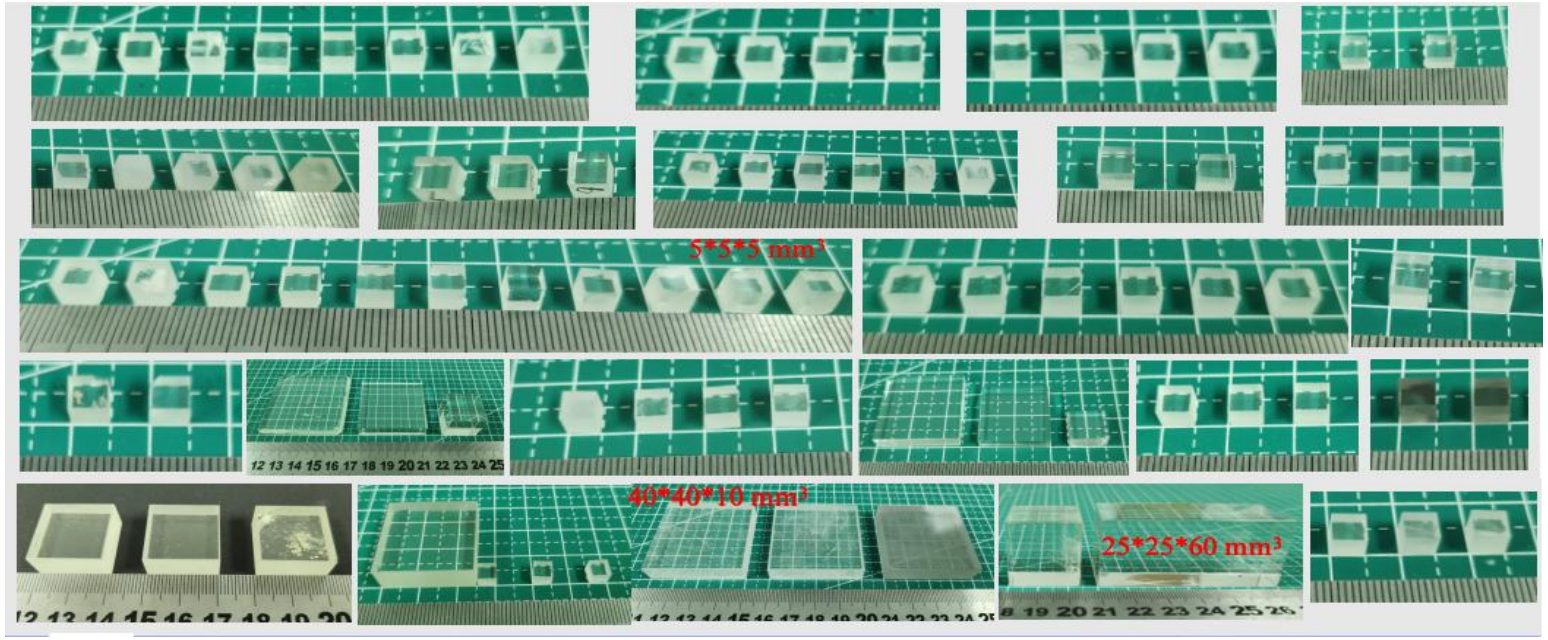
闪烁玻璃合作组
Glass Scintillator Collaboration

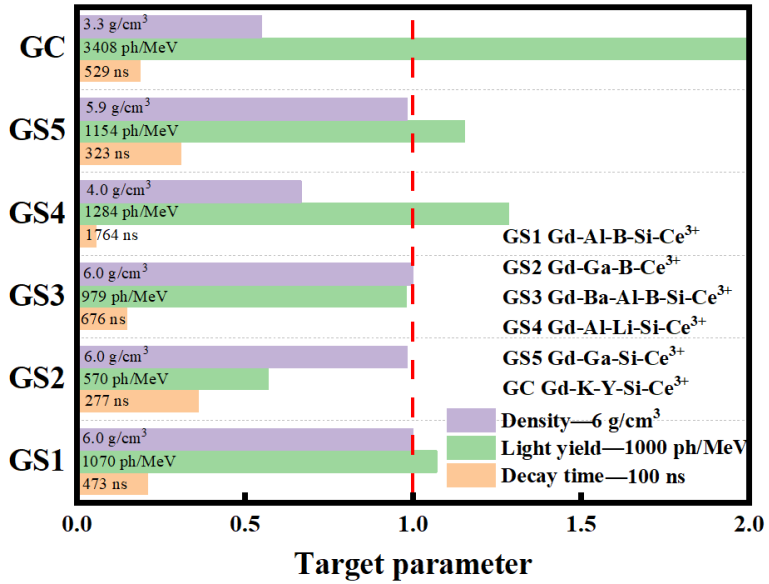


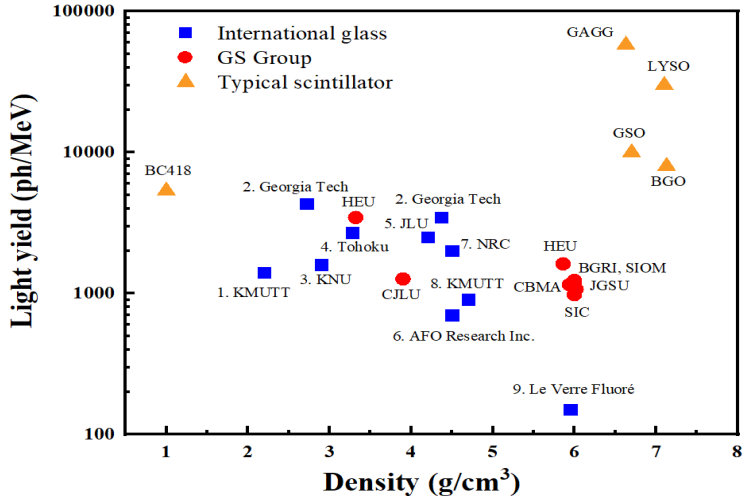


Institute of High Energy Physics, CAS 中国科学院高能物理研究所
Jinggangshan University 井冈山大学
Beijing Glass Research Institute 北京玻璃研究院
China Building Materials Academy 中国建筑材料研究院
China Jiliang University 中国计量大学
Harbin Engineering University 哈尔滨工程大学
Harbin Institute of Technology 哈尔滨工业大学
Sichuan University 四川大学
Shanghai 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

Glass Scintillator Studies

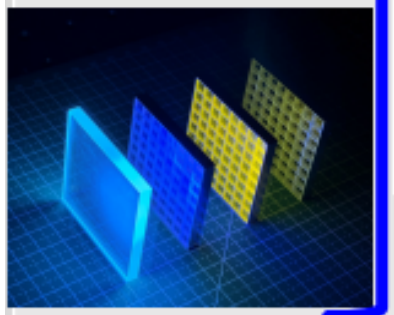


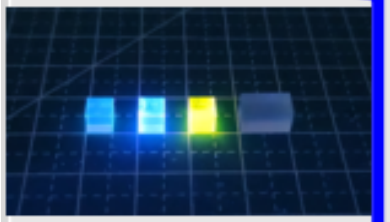


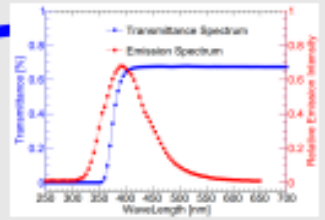


- ✓ The GS group did substantive research based on five glass system simultaneously and impressive progress has been achieved
- ✓ The performance of the best glass sample approach our initial goals, i.e. 6 g/cm3 & 1000 ph/MeV & 100 ns
- ✓ For high density glass scintillator, the light yield of GS group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

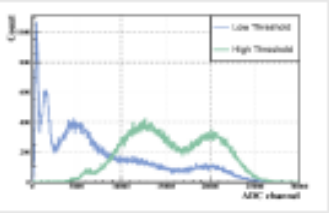
Test Facilities for GS



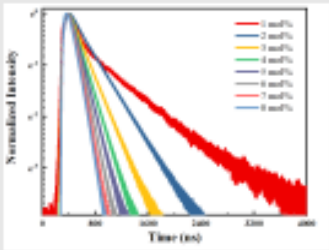




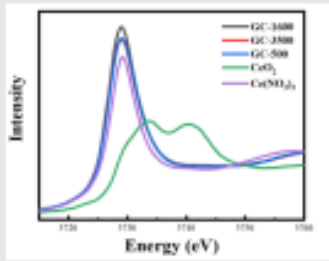
- Transmittance
- Absorbance
- Refractive index
- Emission peak



- Light yield
- Energy resolution
- MIP response
- Neutron discrimination



- Rise time
- Fall time
- Decay time
- Afterglow
- Coincidence time



- Valence state
- Coordination
- Elemental analysis
- Structural analysis

Others

.....

- Faraday effect
- Radiation resistance
- Homogeneity

- IHEP--PMT Lab for Scintillator Test



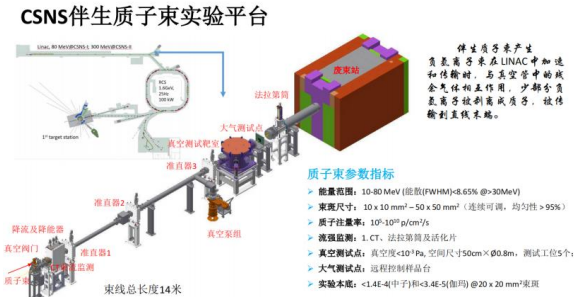
- IHEP--Radioactive Test



- IHEP--XAFS



- IHEP-CSN-- P Beam



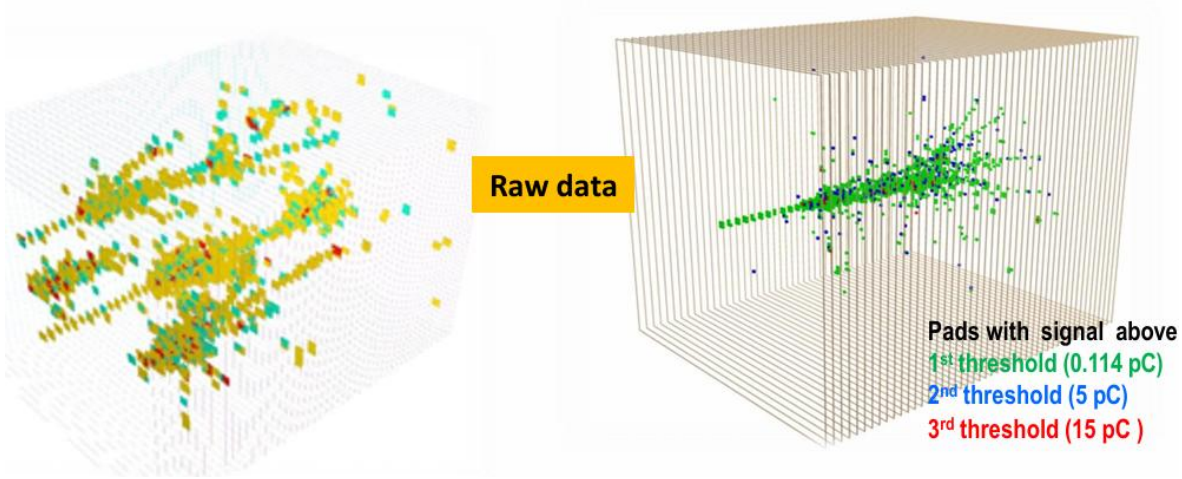
- CERN-MUON Beam

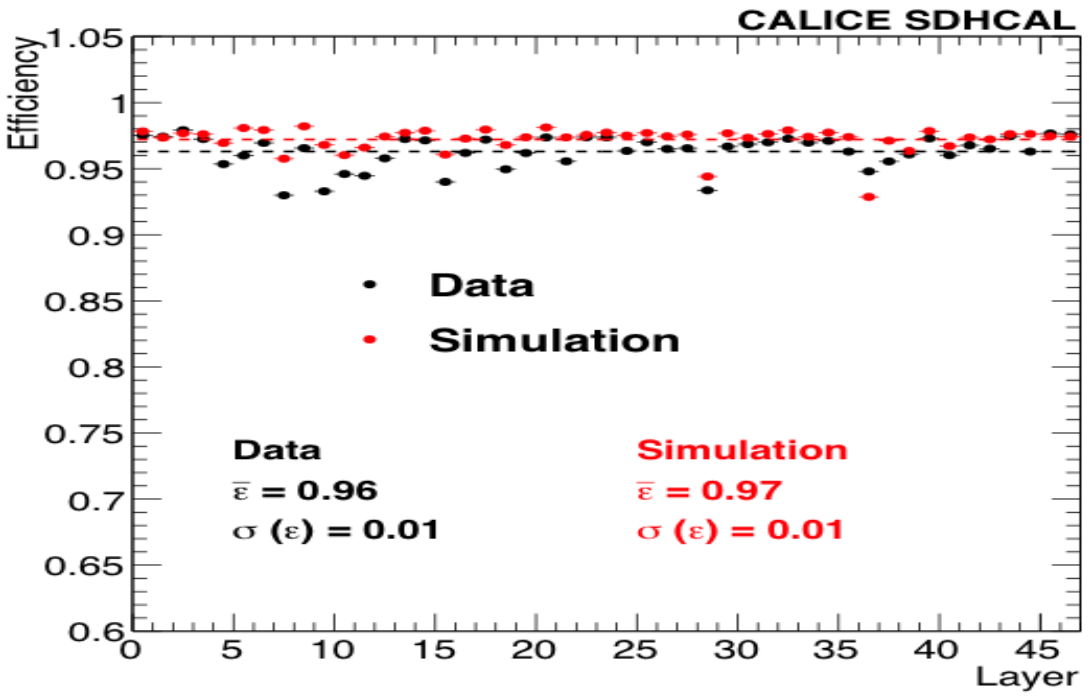


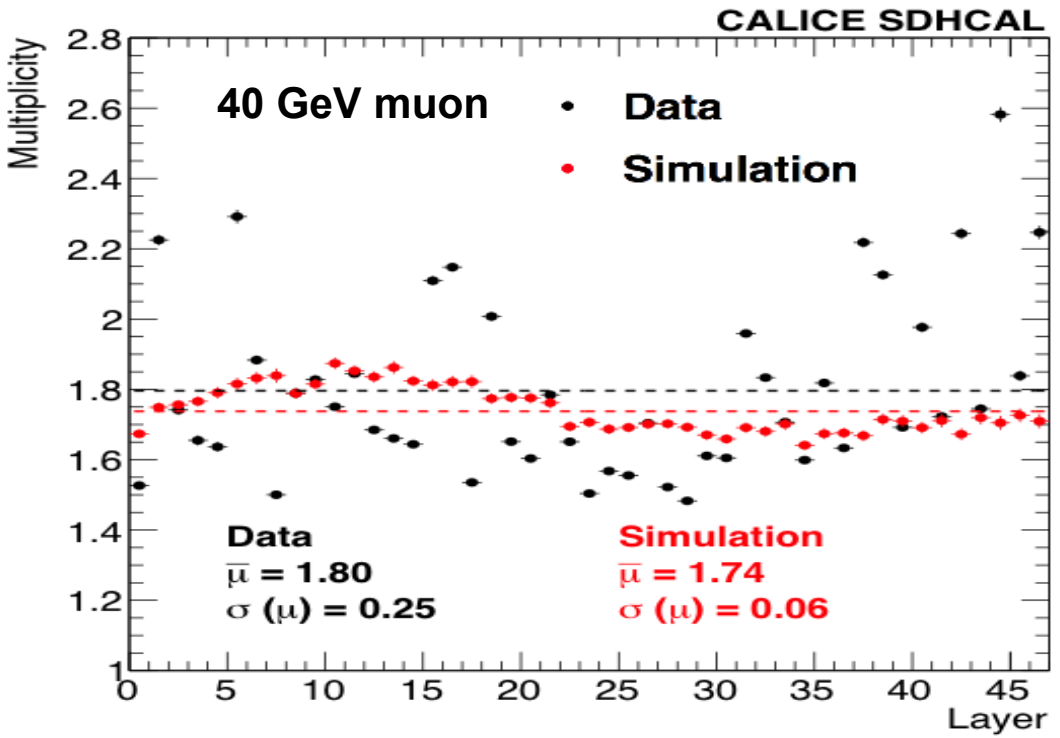
SDHCAL: Efficiency and Multiplicity

➔ 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 and test beam muons.



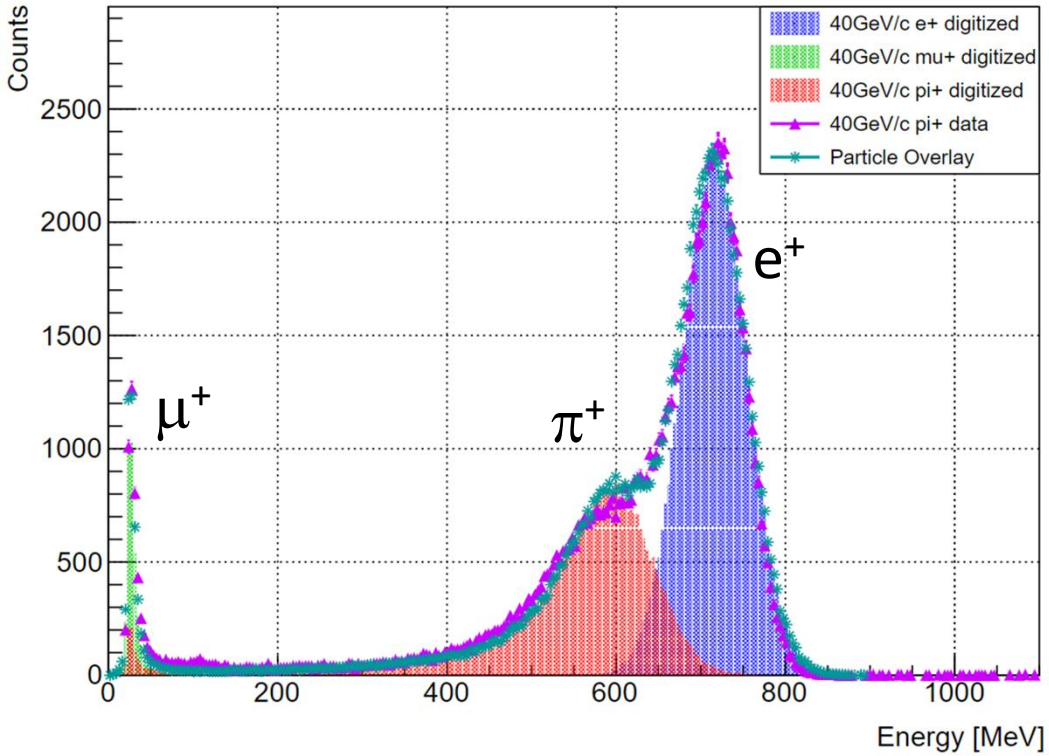




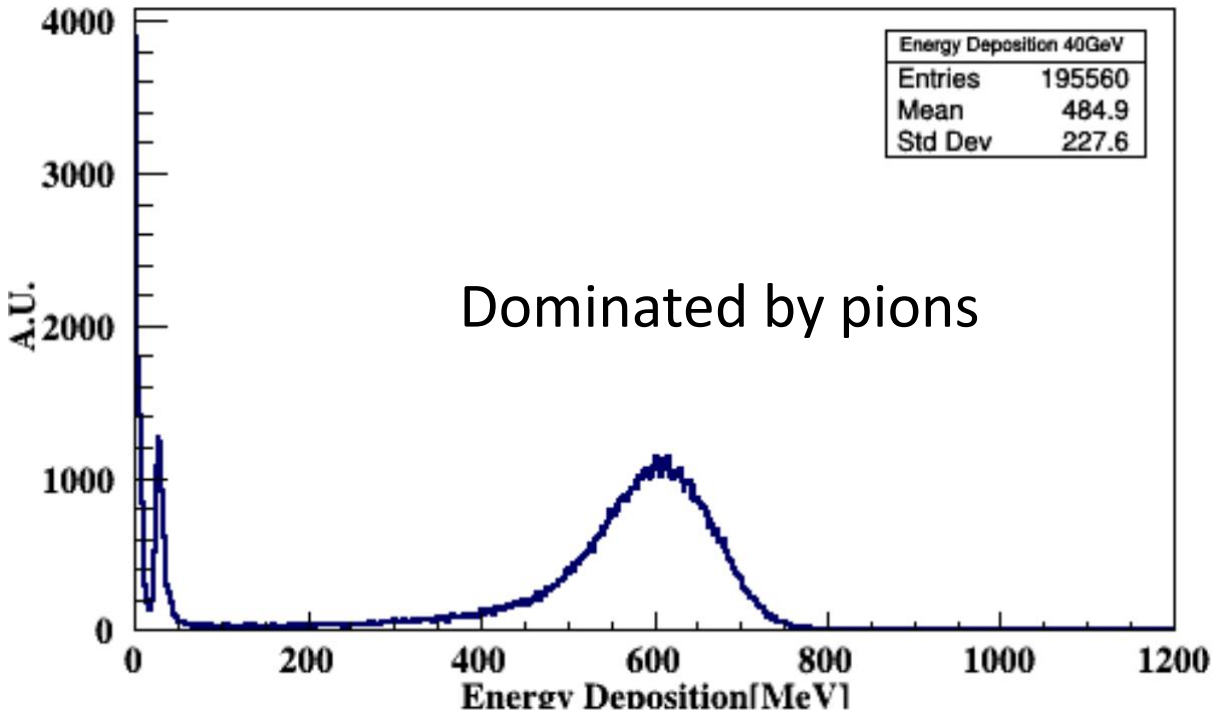
CERN Test Beam in 2022 - 2023

- **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)

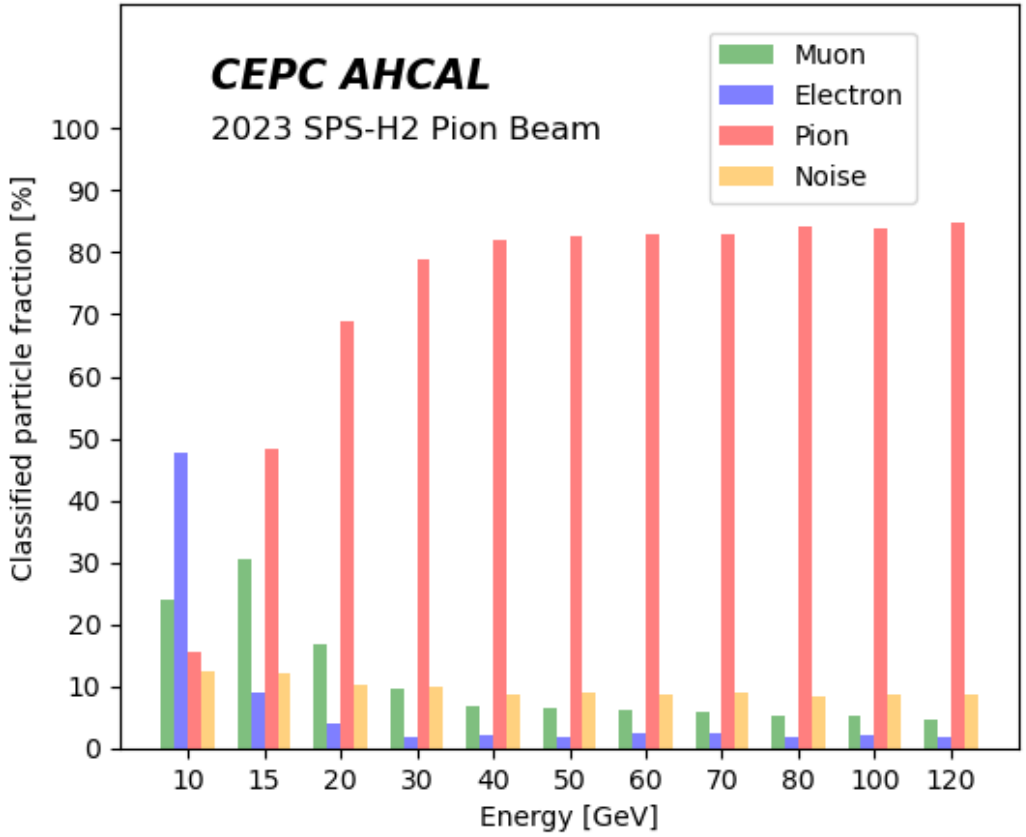


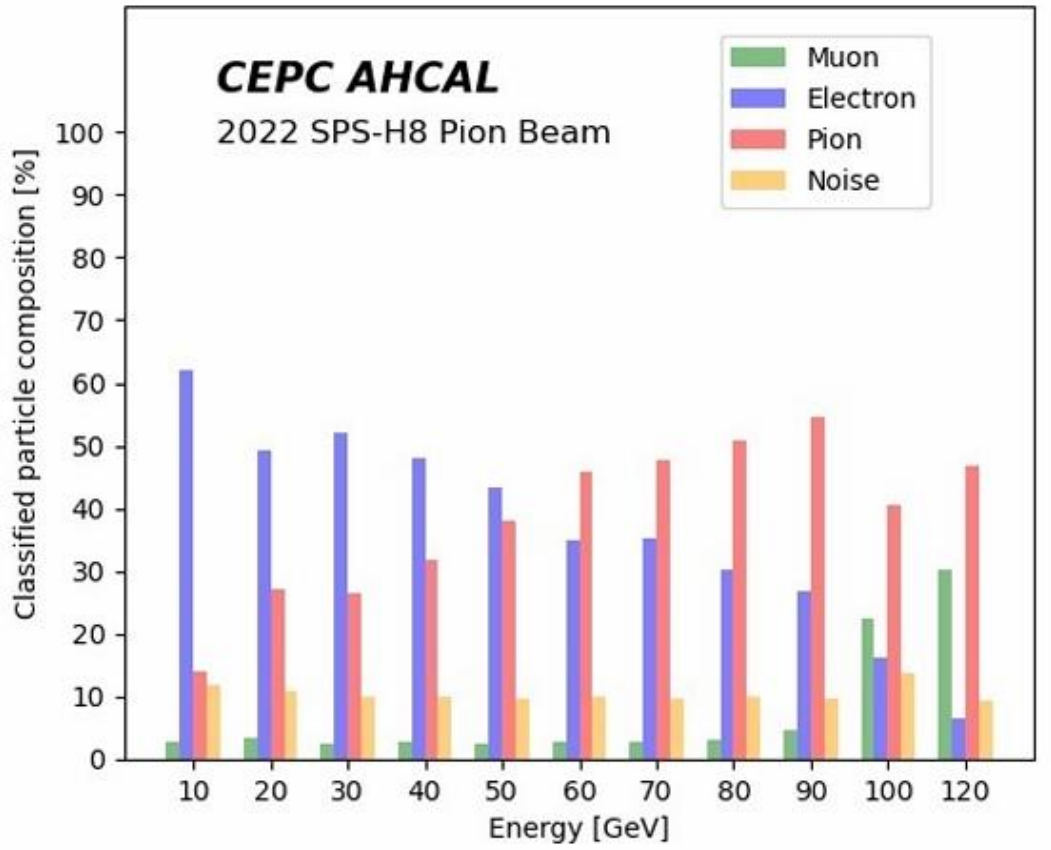
40 GeV π^- data SPS-H2 (2023)



CERN Test Beam in 2022 - 2023

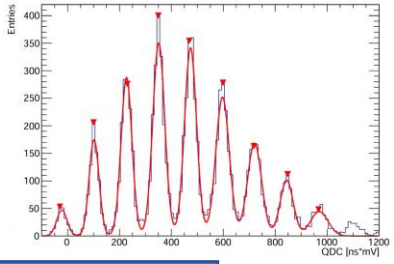
- **Beam composition from SPS-H8 and SPS-H2 beamline**
  - Particle identification techniques developed: to select high-purity data samples
  - SPS-H2 π-: purity is about 80-90% for beam energy $\geq$ 30 GeV
  - SPS-H8 π+: purity is less than 60% with significant contamination from electron





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

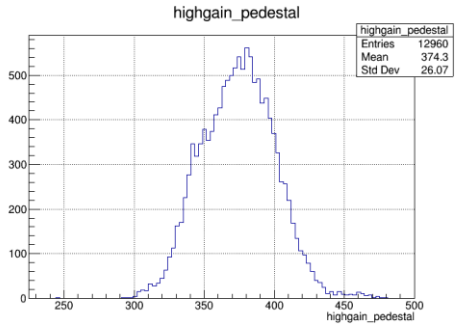
Poisson Distribution based on muon data

SiPM saturation curve from measurements

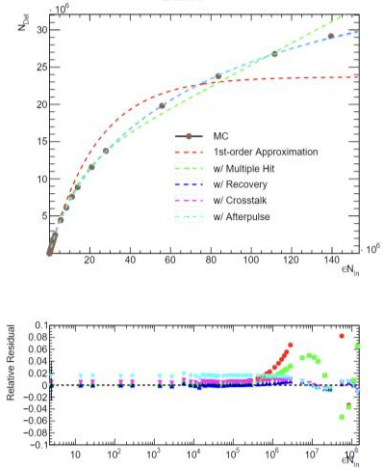
SiPM gain calibration from LED data

Pedestals (Electronics)

Extracted from data

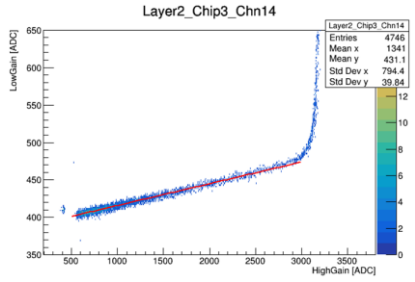


Pedestals (data)



SiPM saturation (data)

ASIC HG-LG ADC (data)



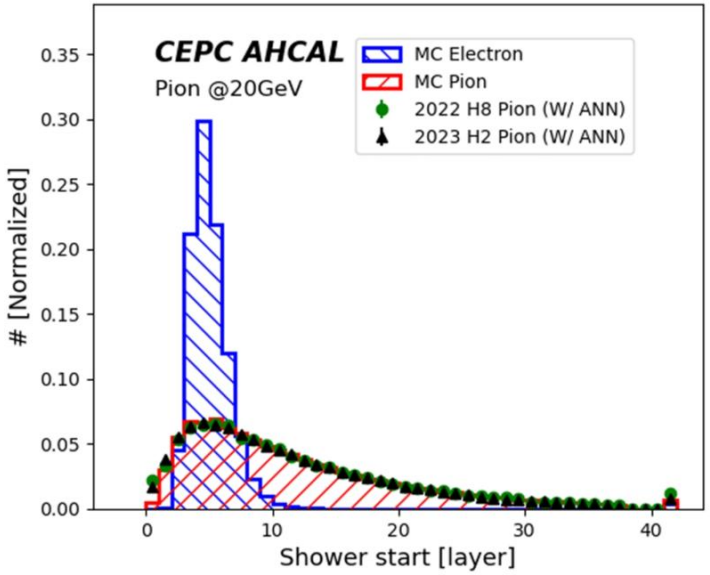
ASIC: ADC in High Gain or Low Gain

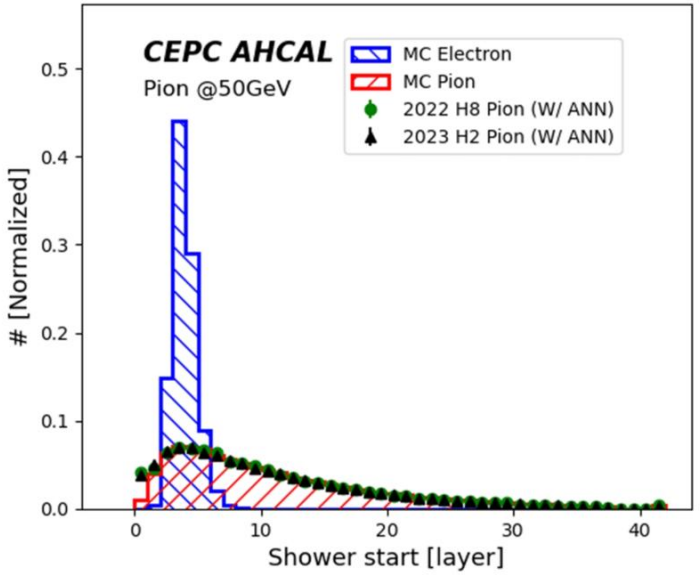
SPIROC2E HG-LG slope extracted from beam data

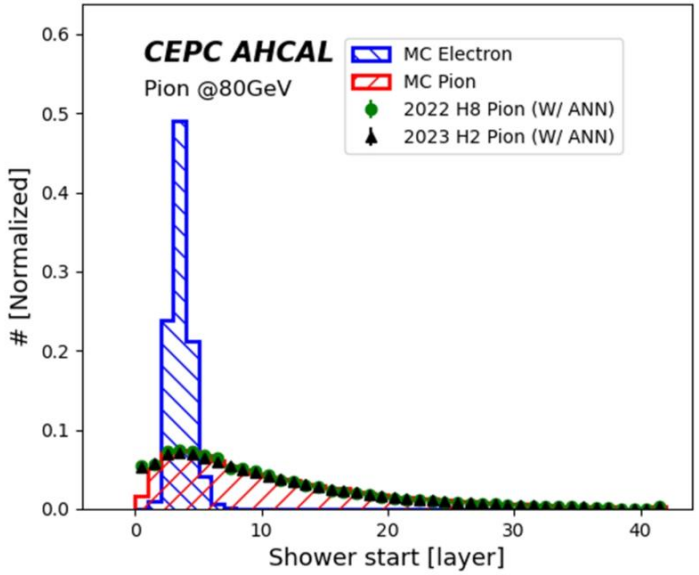
Key: digitization is fully based on calibration data

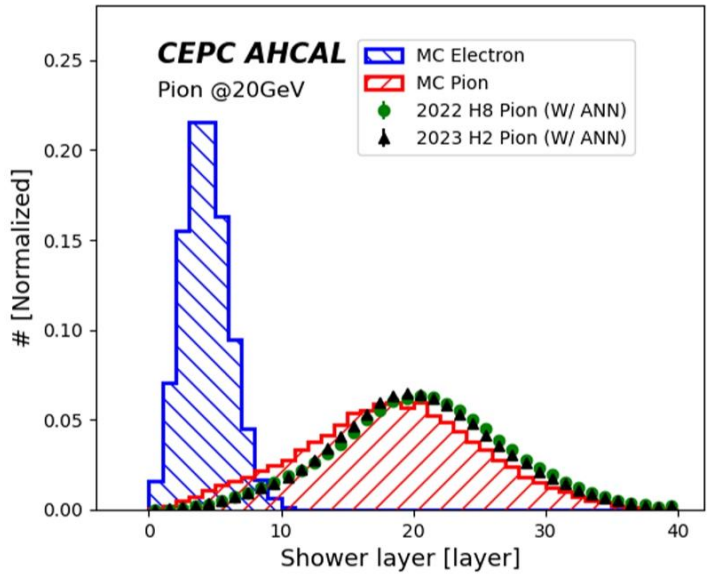
Marking in Red: based on data

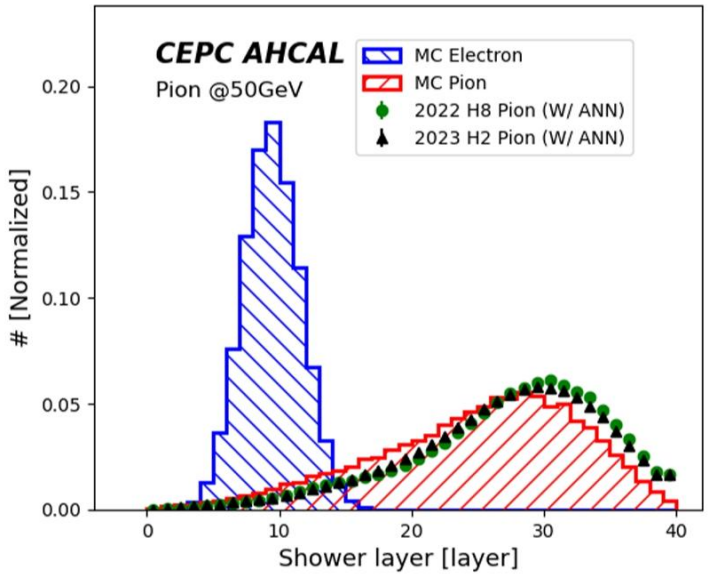
AHCAL Prototype: Pion Data vs MC

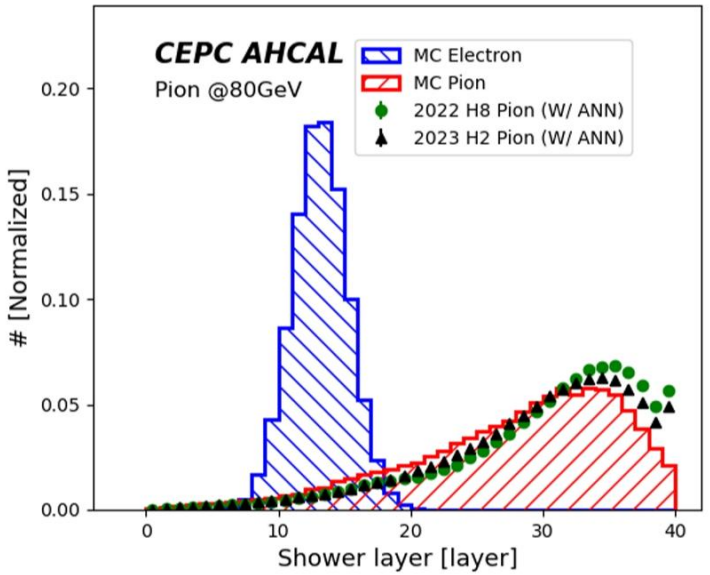






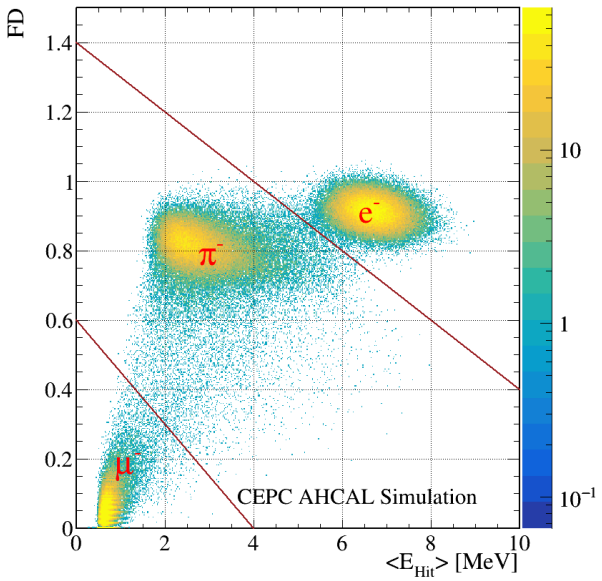


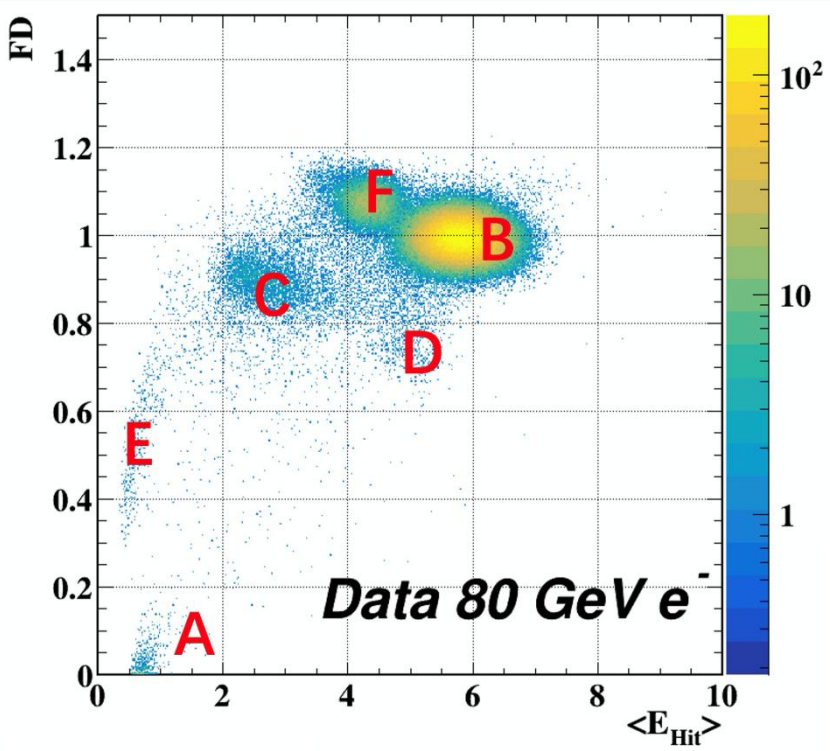


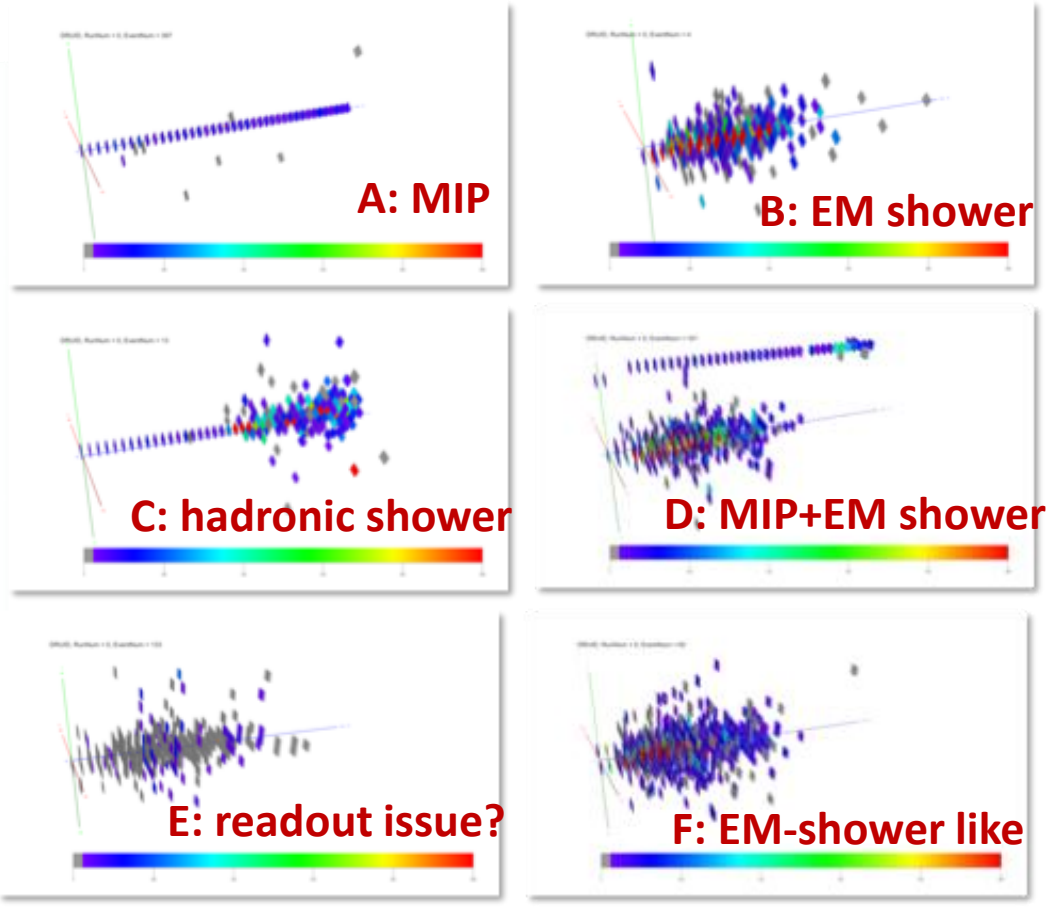


PID based on Fractal Dimension

- **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

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

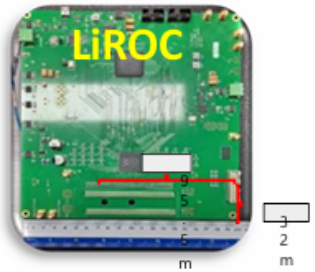
Cons: limited digital logic, difficult to chain, deadtime

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



- 64 channels
- Time resolution <12 ps

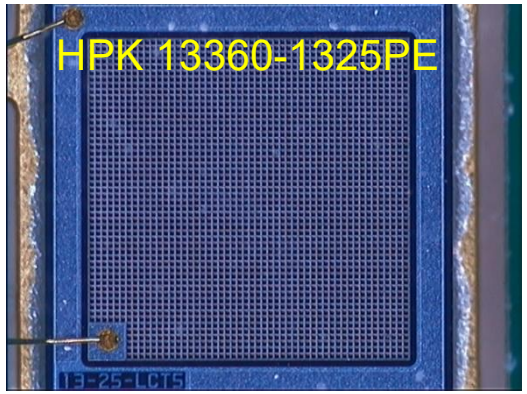
Developed for SiPMs readout on LIDAR (*) No internal TDC

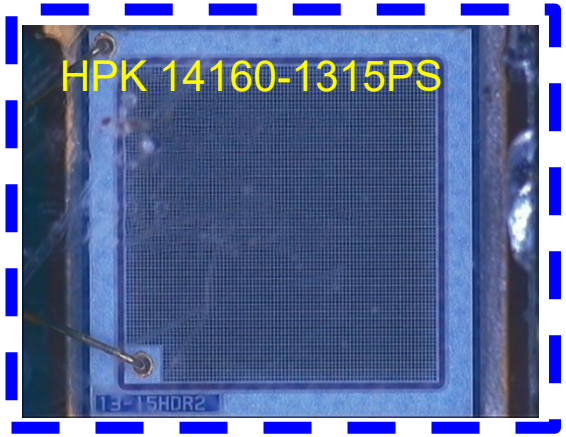
(*) LIDAR = LIght Detection And Ranging

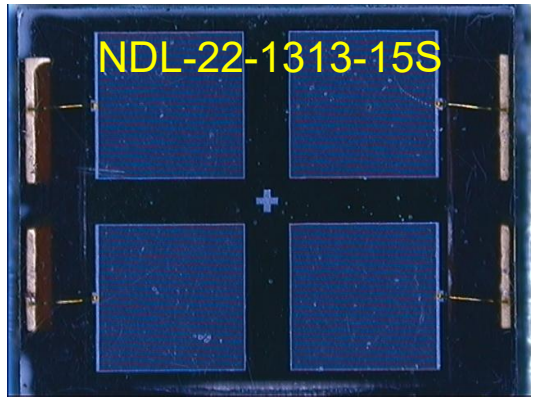
SiPM

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