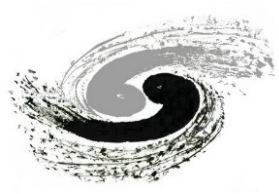
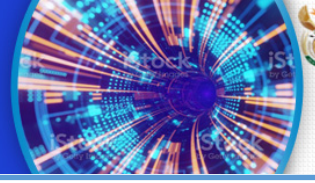


TIPP 2023
4 - 8 SEPTEMBER 2023
CTICC CAPE TOWN SOUTH AFRICA



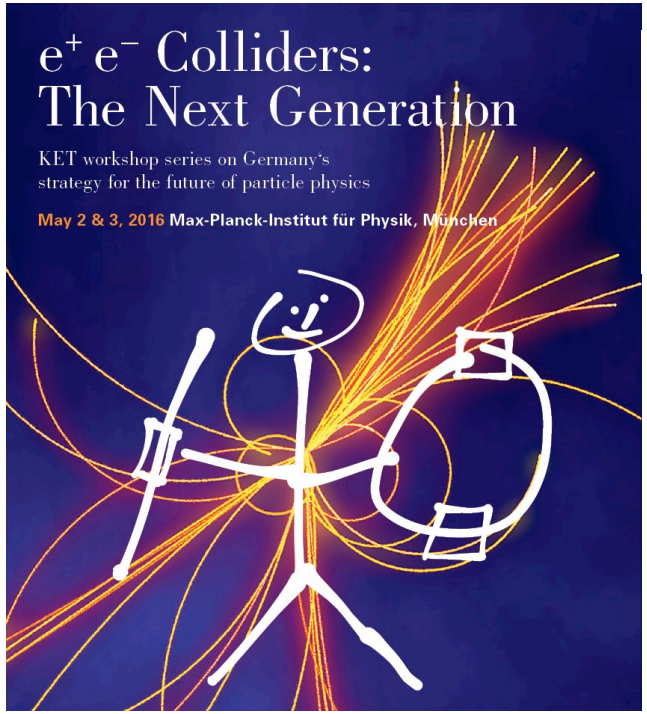
CERN beamtests of CALICE scintillator-based calorimeter prototypes

Yong Liu (IHEP),
for the CALICE and CEPC Calorimeter teams

TIPP2023 Cape Town, Sep. 6, 2023

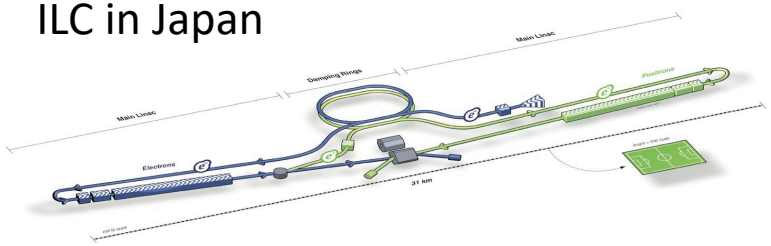
Motivation

- Higgs factories
  - Electron-positron collider: top priority for the next-generation collider exp.
  - Precision measurements of the Higgs boson as one of its main physics goals
  - Challenge: better jet energy resolution



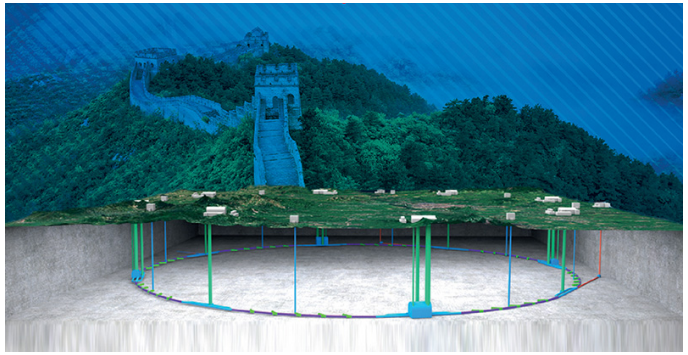
Logo of the KET Workshop on Future Lepton Colliders

ILC in Japan

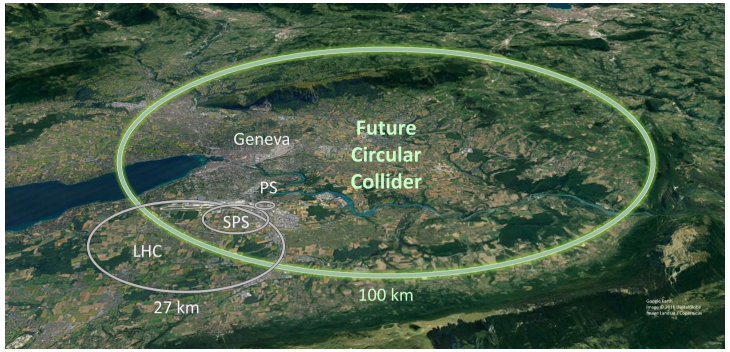


CLIC at CERN

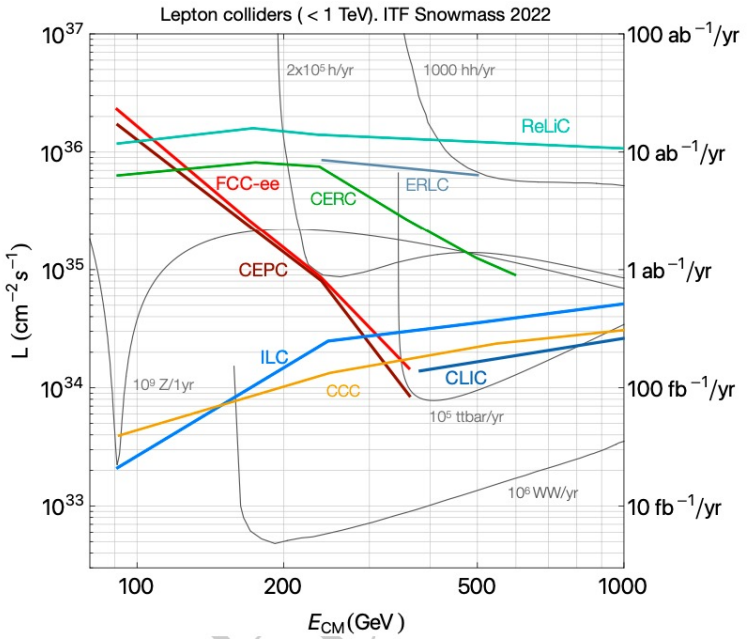
CEPC in China

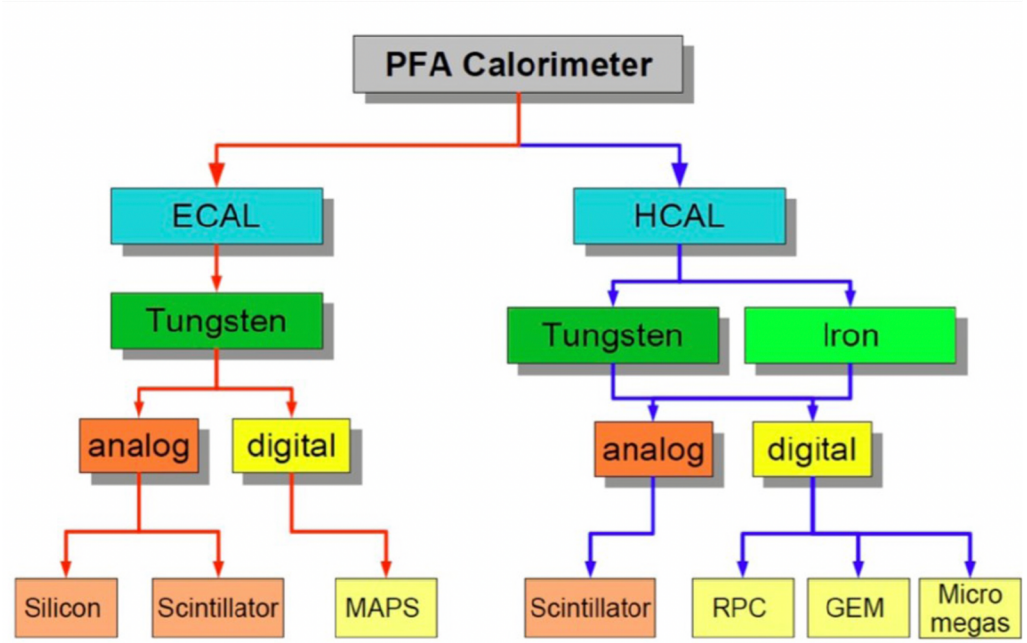


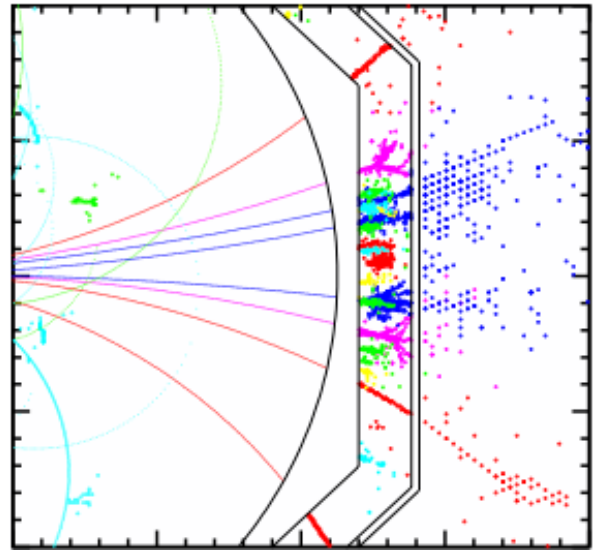
FCC at CERN



High granularity calorimetry



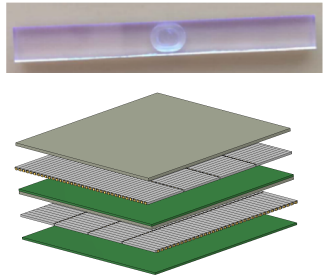


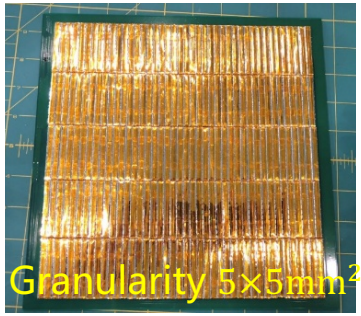


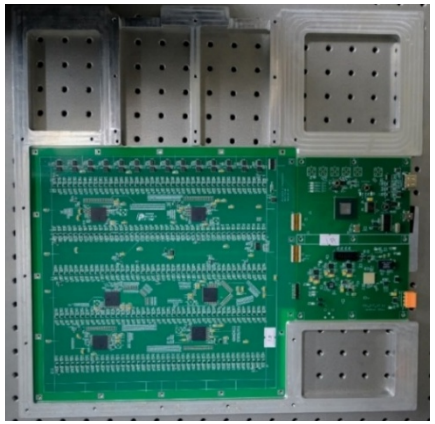
- Future Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major calorimetry option: highly granular (imaging) + particle flow algorithms (PFA)
- PFA calorimetry: various options explored in the CALICE collaboration
  - Focus in this talk: **scintillator + SiPM** technique

CALICE scintillator-calorimeter prototypes

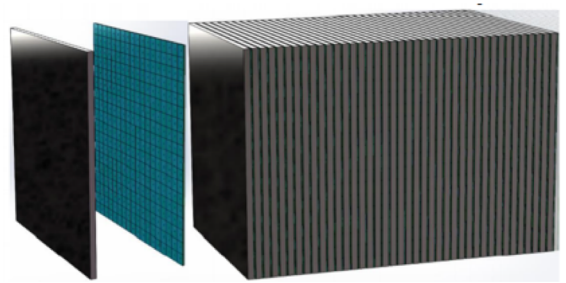
ECAL prototype：scintillator (strip)+SiPM, CuW

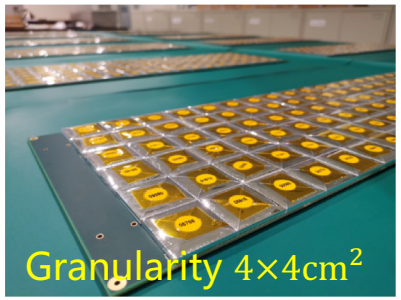


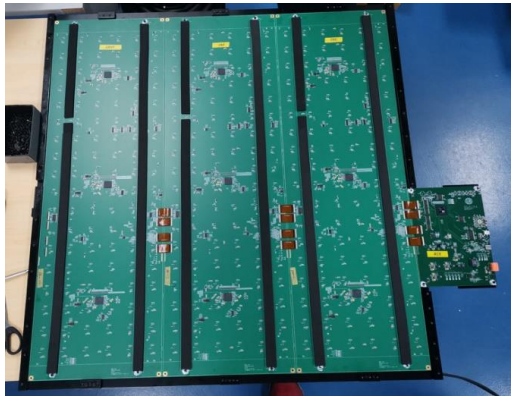




HCAL prototype： scintillator (tile)+SiPM, steel





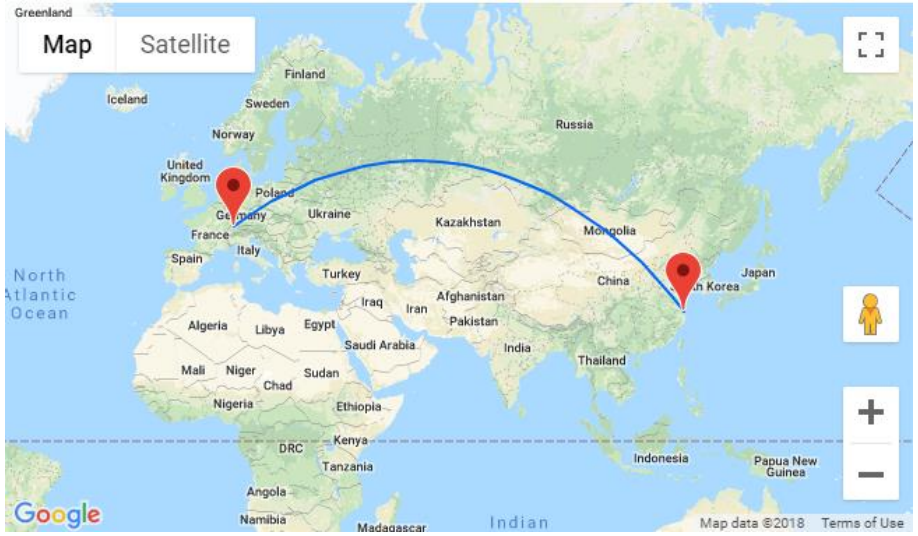


- ScW-ECAL prototype: transverse ~20x20 cm, 32 sampling layers
  - 6,720 channels, ~350 kg, SPIROC2E (192 chips), developed in 2016-2020
- AHCAL prototype: transverse 72x72 cm, 40 sampling layers
  - 12,960 channels, ~5 tons, SPIROC2E (360 chips), developed in 2018-2022

Prototypes developed within CALICE
- China：IHEP, SJTU, USTC
- Japan：U. Shinshu, U. Tokyo
- France：CNRS Omega
- Israel: Weizmann

Transport and preparations

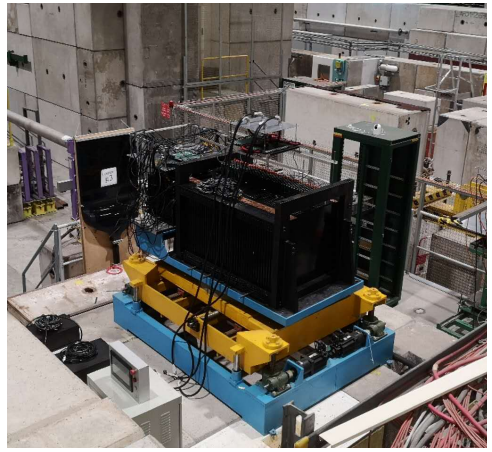
Calorimeters in flight



Flying calorimeter

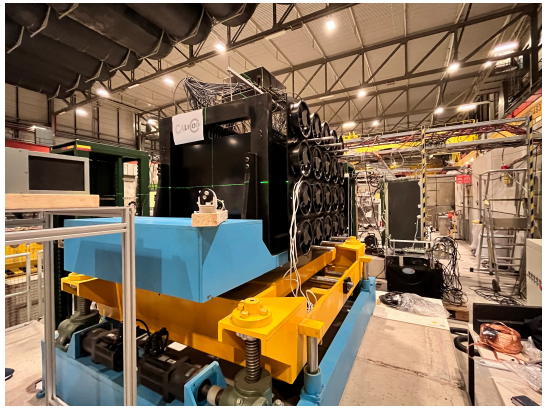
Before cabling

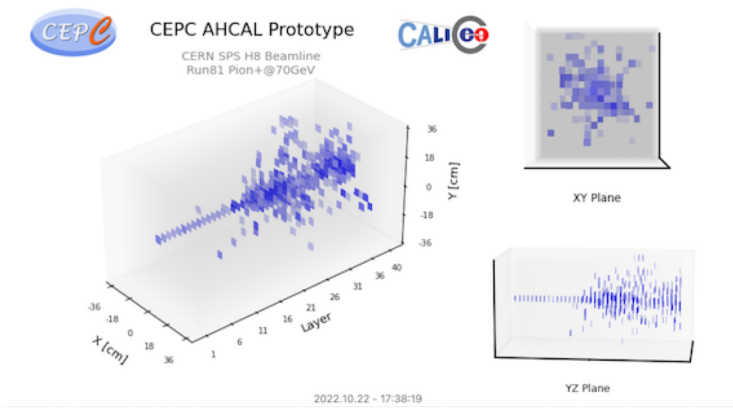
After cabling (parasitic runs)

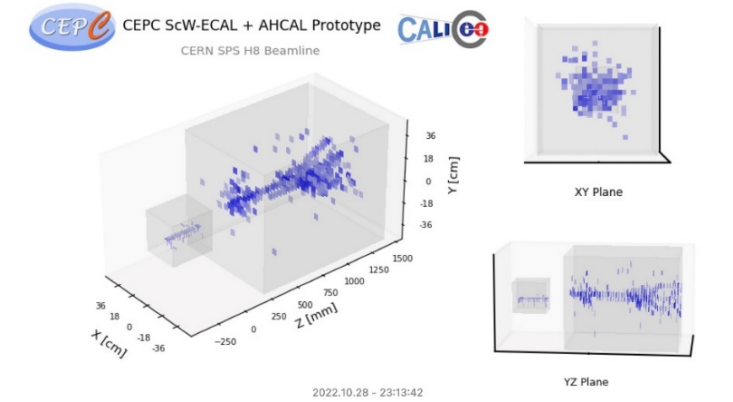


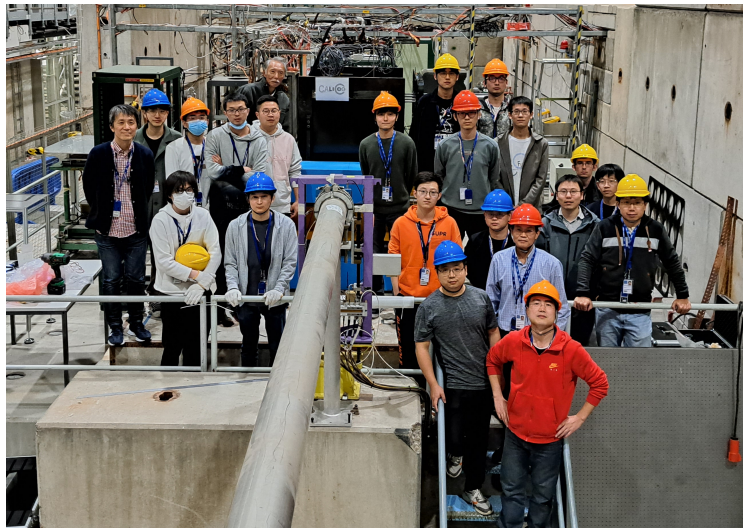
- Successful transportation from China to CERN in Sep. 2022
- First transported to SPS beam area H8C (PPE168)
  - ScW-ECAL and AHCAL prototypes + 1 supporting table
  - Impressions: cubic meters and ~10 tons
- Stayed at CERN for beamtests at SPS-H2 and PS-T09 in 2023

CERN beamtest in 2022







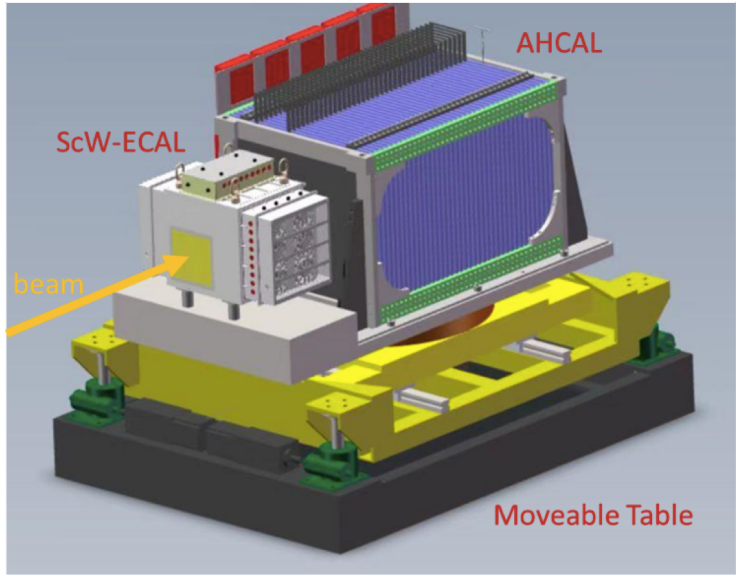


- First successful beamtest at CERN SPS H8: Oct-Nov, 2022
  - High energy particle beams: muons, positrons and hadrons (10 - 160 GeV)
  - Collected data sets for detector performance and detailed shower studies
  - Found **beam purity issue** at H8: mixture of positrons and pions/protons

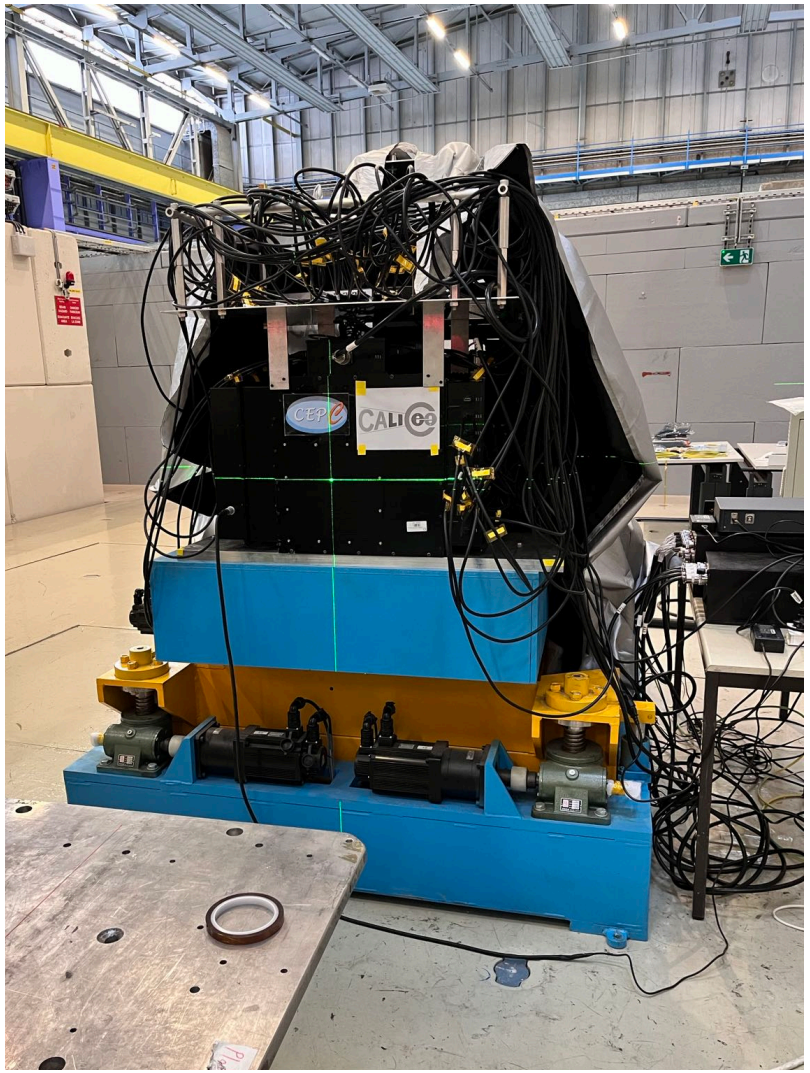
Prototypes at CERN SPS-H2 in 2023

- Muon beam: MIP calibration for each channel
  - Positioning scans with 100 GeV muons
- Electron beam: calibrations of SiPMs and ASICs, EM performance
  - Electrons: 10, 20, 30, 40, 50, 60, 70, 80, 100, 120 GeV and extra 150, 200, 250, 350 GeV
- Pions beam: hadronic performance, validation of hadronic shower simulation
  - Negative pions : 10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 120 GeV and extra 350 GeV
- Inclined beam incidence: prototypes rotated by ~5 degrees

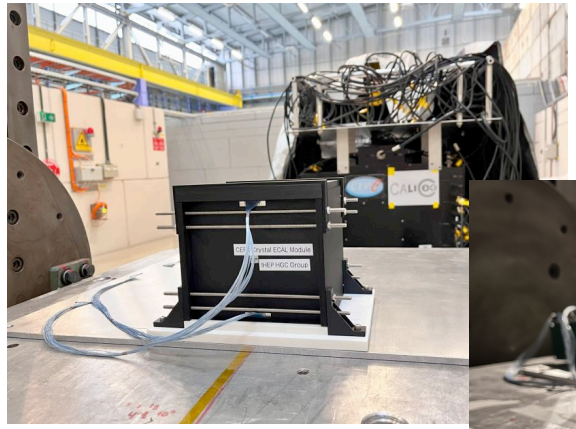
→Overlapped energy points at PS-T9

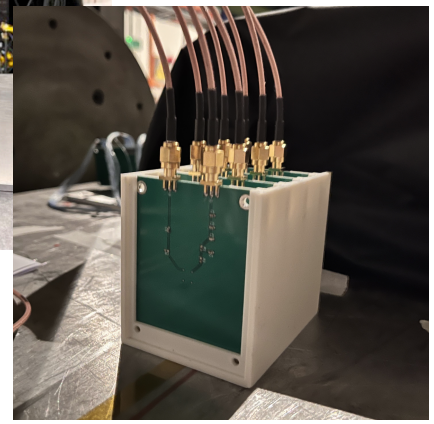


Prototypes at CERN PS-T09 in 2023



- 10 GeV μ^- beam for MIP calibration
- 1-5 GeV e^- beam: SiPM/ASIC calibrations and EM showers
- 1-15 GeV π^- beam: low energy hadronic showers
- In parallel, parasitic runs for crystal module and glass tiles
  - Talk at TIPP2023 on high granularity calorimeter R&D
  - Talk at TIPP2023 on hadronic calorimeter with glass scintillator tiles

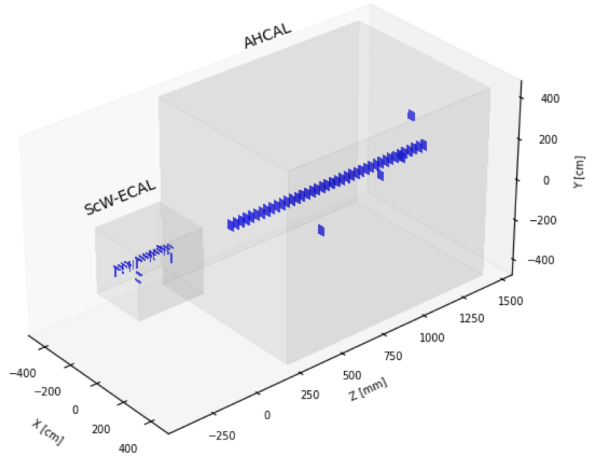


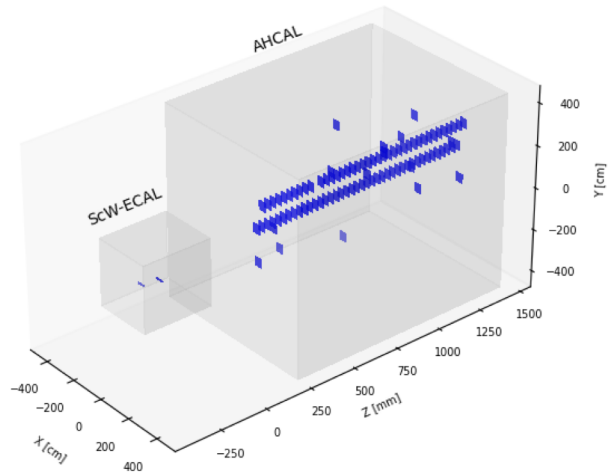


Event display with ScECAL+AHCAL

Siyuan Song (SJTU)

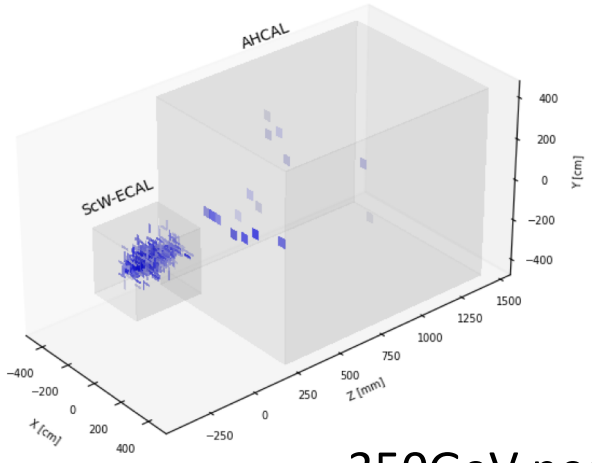
100 GeV mu-



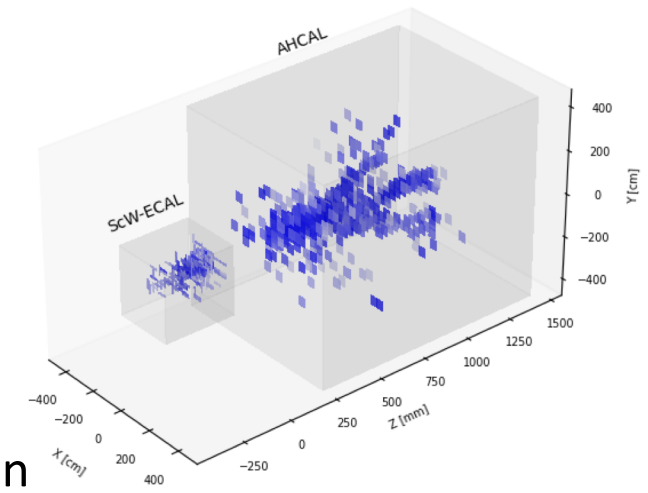


One run of different position scans: muon beam out of ScW-ECAL acceptance

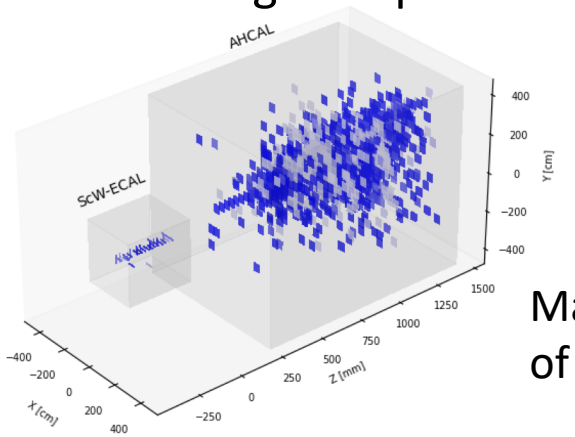
60GeV electron



60GeV negative pion



350GeV negative pion



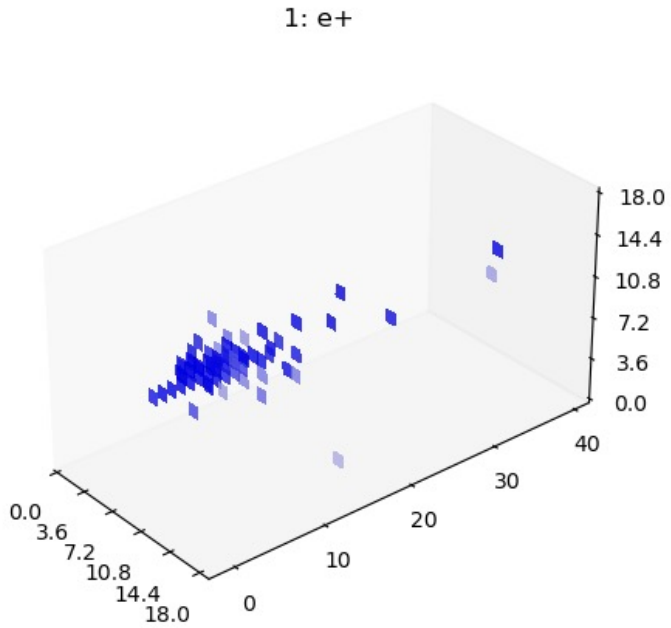
Maximum pion beam energy of existing testbeam facilities

General impressions: much better purity of electron and pion beams than data taken at H8 in 2022

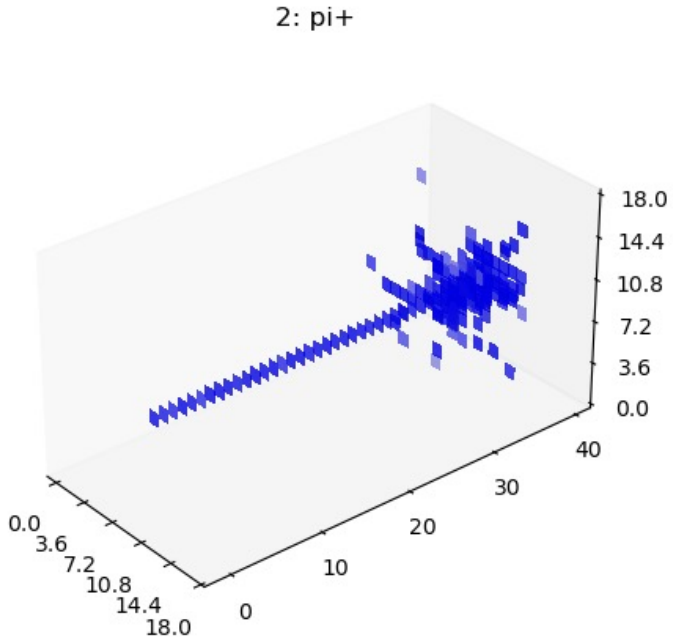
Hadronic shower events in AHCAL and PID

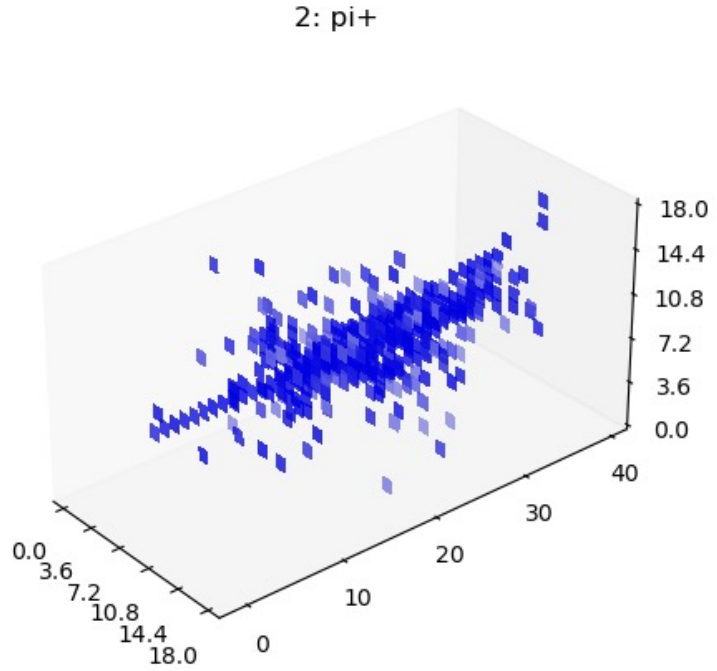
Siyuan Song (SJTU)

50 GeV electron



50 GeV pions





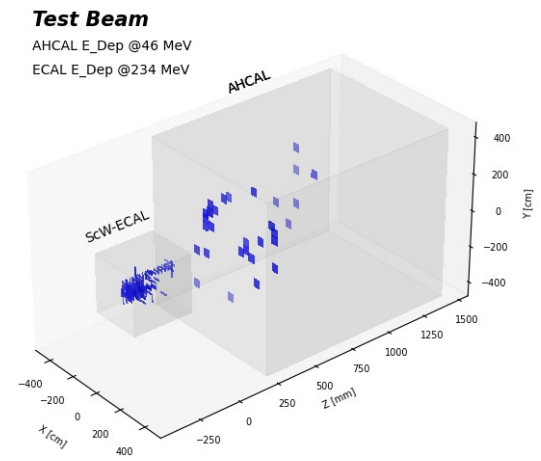
Please be noted about the typo of beam polarity, which should be negative

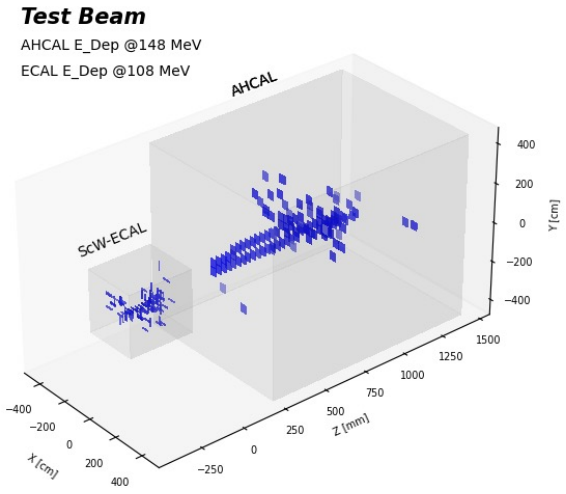
- PID studies with calorimeters only for electrons and pions

Hadronic showers in ECAL+HCAL at PS

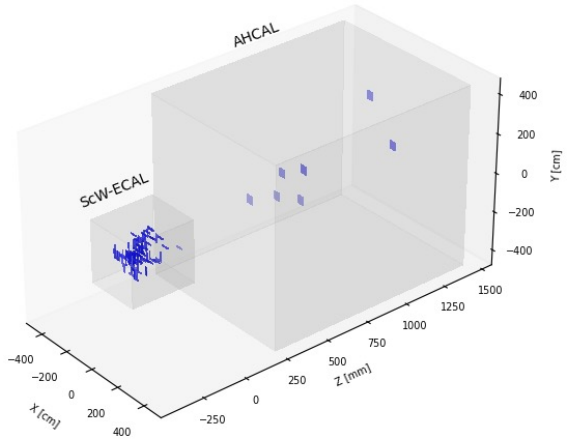
Siyuan Song (SJTU)

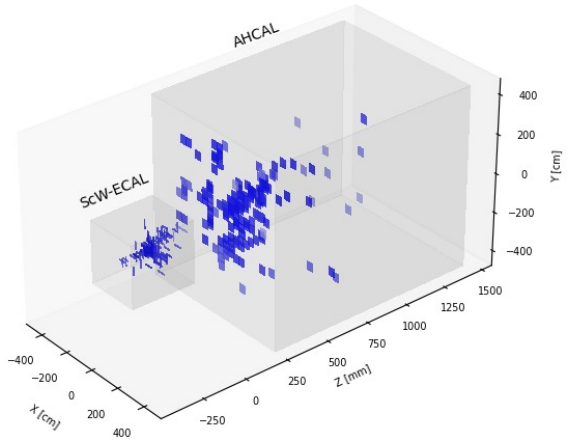
5 GeV π^-



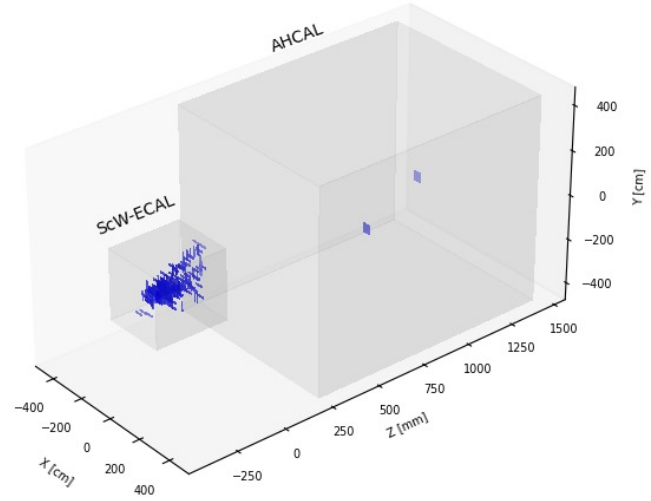


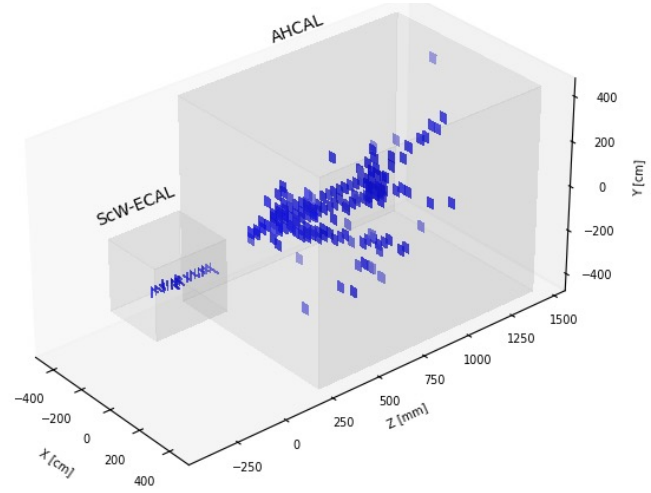
10 GeV π^-





15 GeV π^-





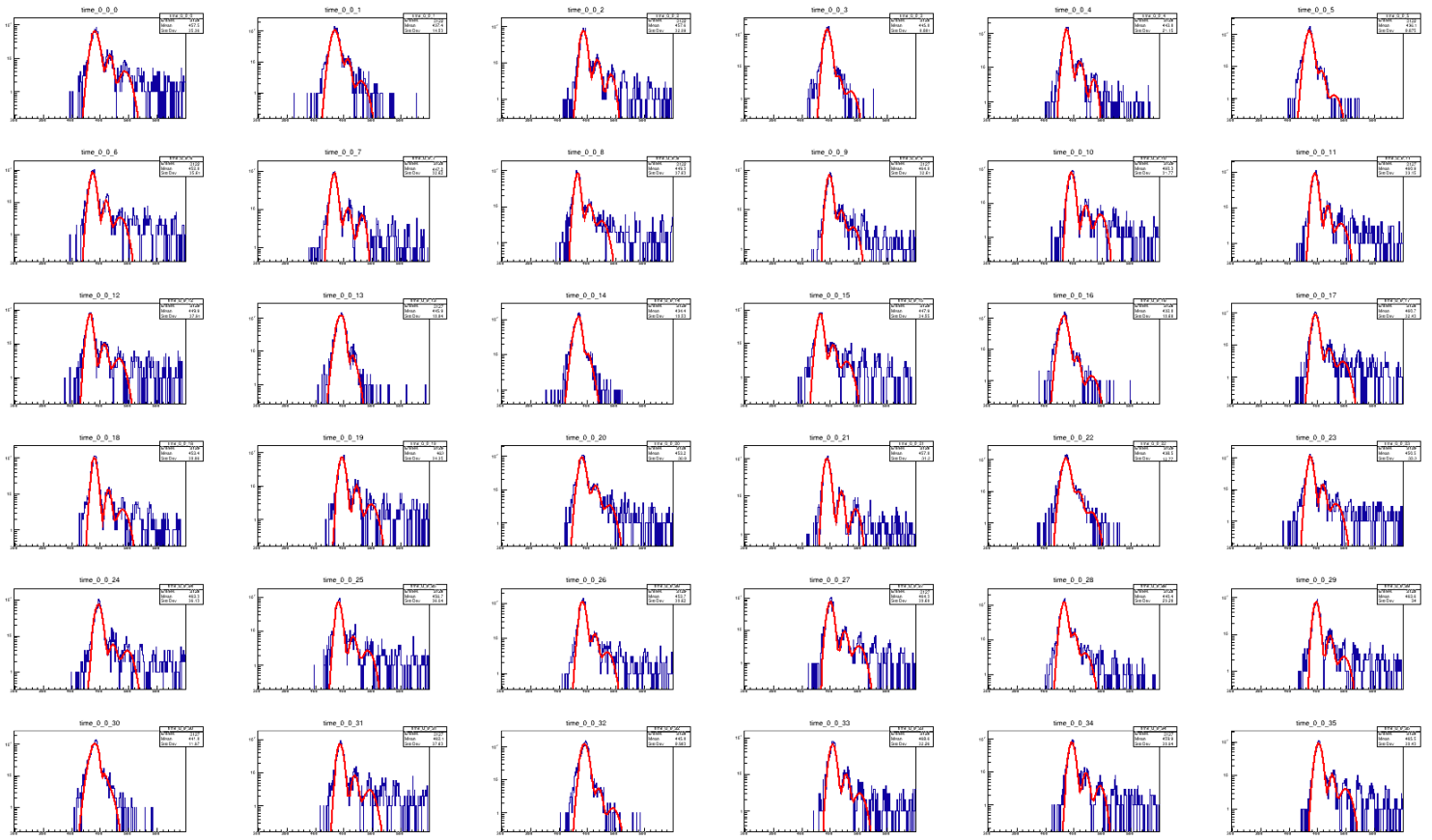
LED calibration: single photon spectra

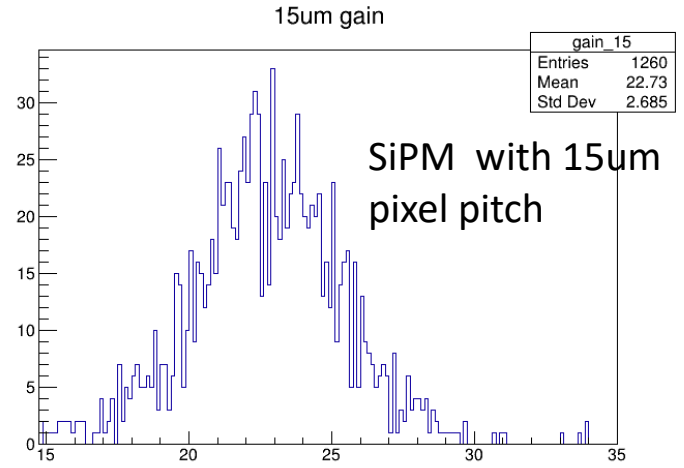
Tatsuki Murata (U. Tokyo)

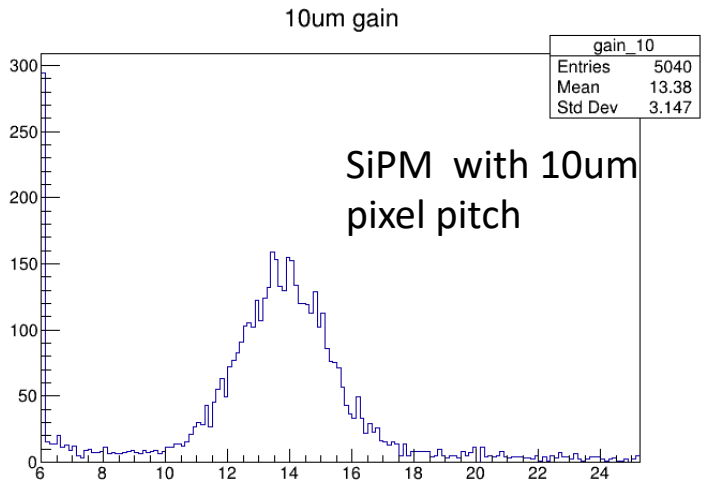
ScECAL data

- Determine SiPM gain with on-board LED per channel

Single Photon Spectra with in-situ LED calibration runs







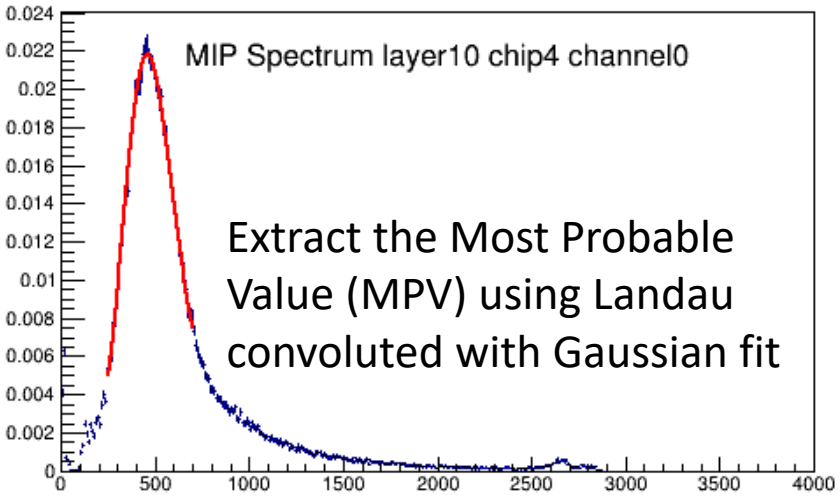
Calibration with muon beam

Yukun Shi (USTC)

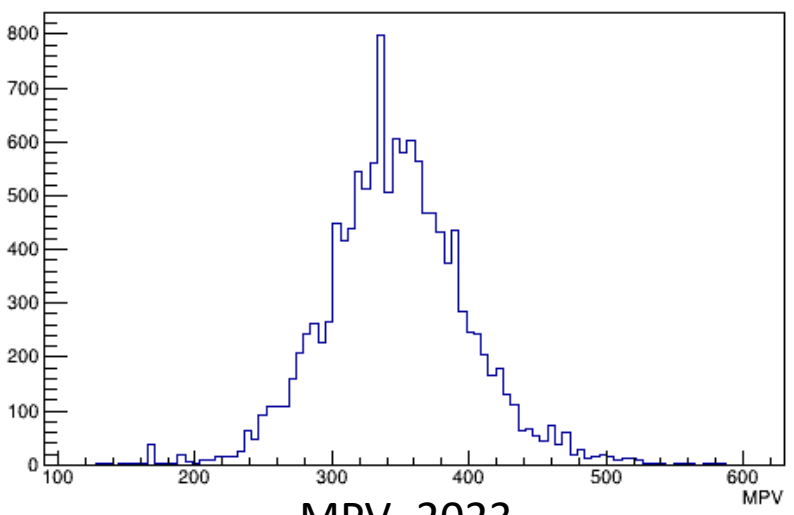
AHCAL data

- Minimum Ionisation Particle (MIP) calibration
  - Basis for energy reconstruction: energy scale
  - Channel-wise calibration
  - Crosschecks with 2022 and 2023 muon data sets: observed some difference

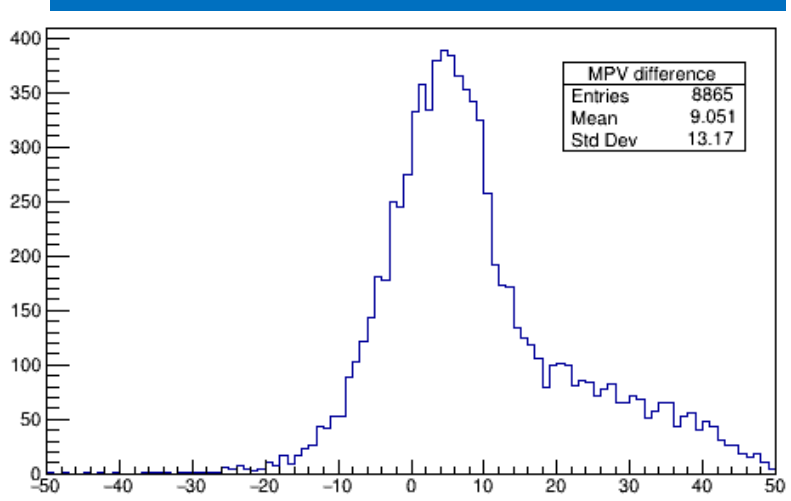
MIP response of a single channel



MIP MPVs of all channels



MIP MPV difference between 2023 and 2022



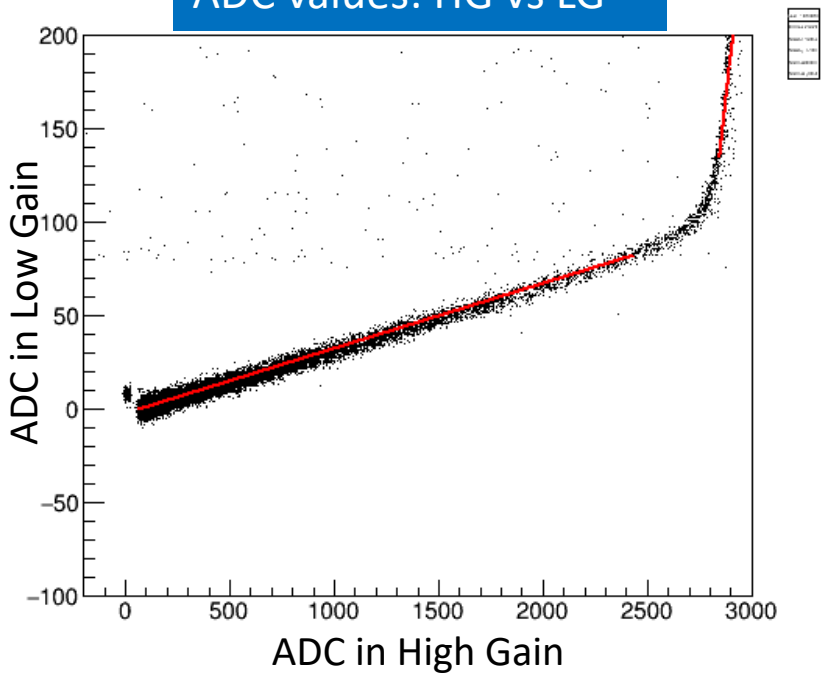
High Gain vs Low Gain: inter-calibration

Zhen Wang (SJTU)

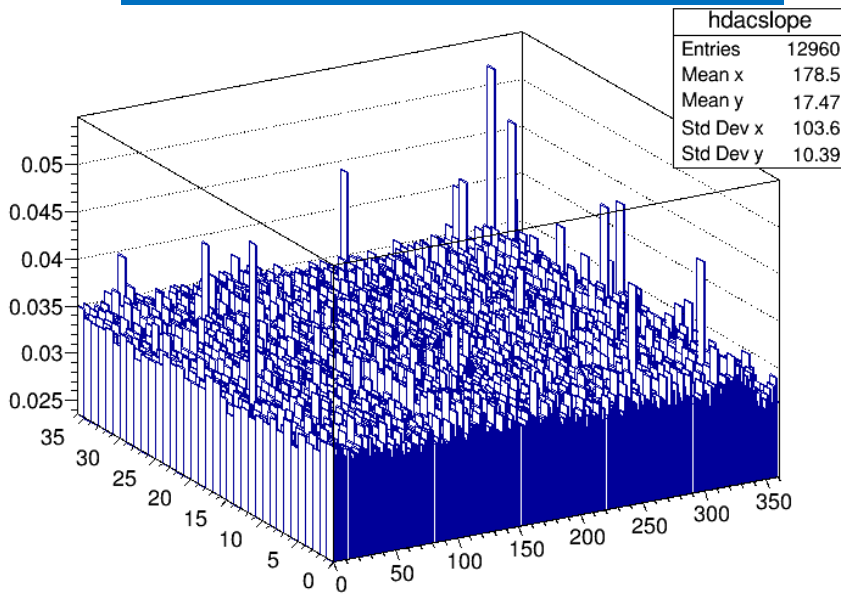
AHCAL data

- HG/LG inter-calibration ratio: essential for energy reconstruction
  - Improved fitting for the HG-LG slope and interception
  - Inter-calibration done for each channel
  - IC ratio very stable: 0.1% relative difference between 2022 and 2023 SPS data sets

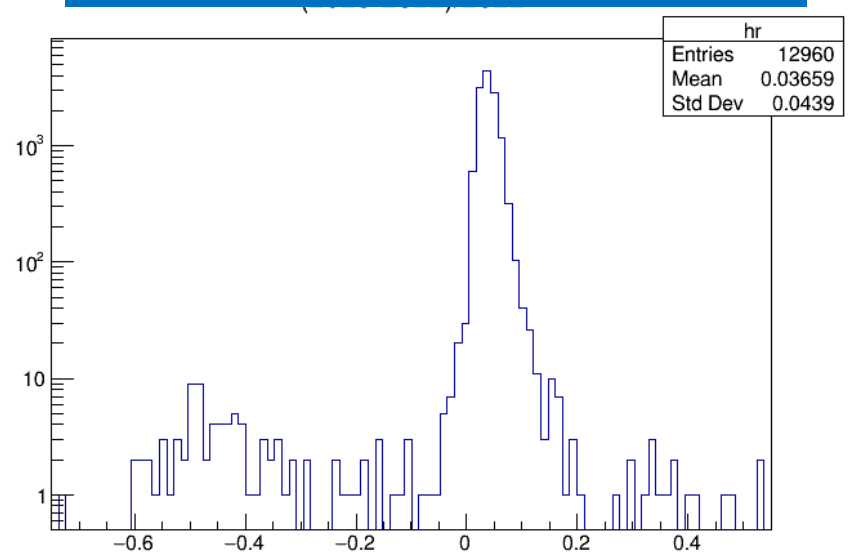
ADC values: HG vs LG



IC ratios for all AHCAL channels



IC ratio difference in 2022 and 2023



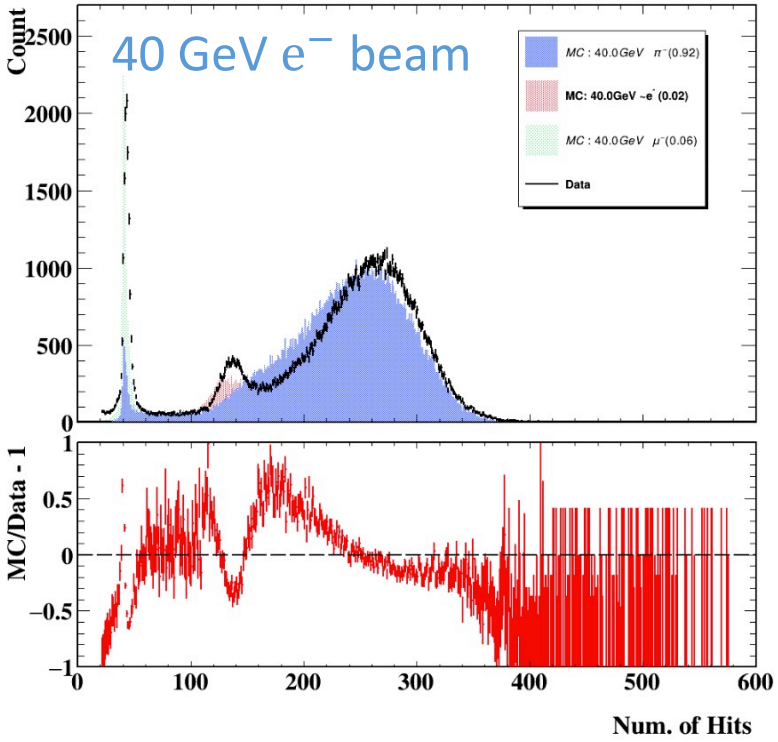
Relative difference of IC ratio per channel

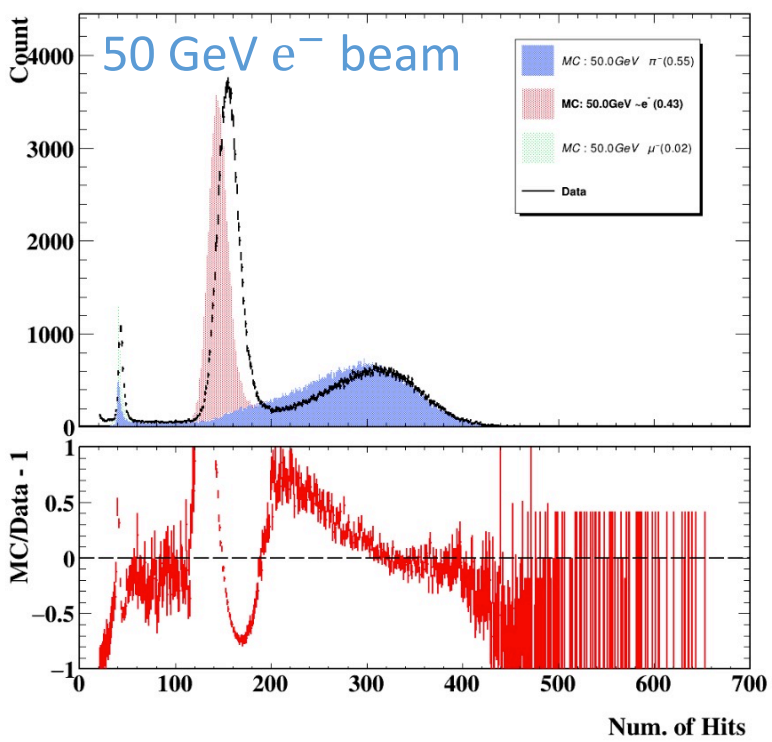
PID studies with calorimeter hit patterns

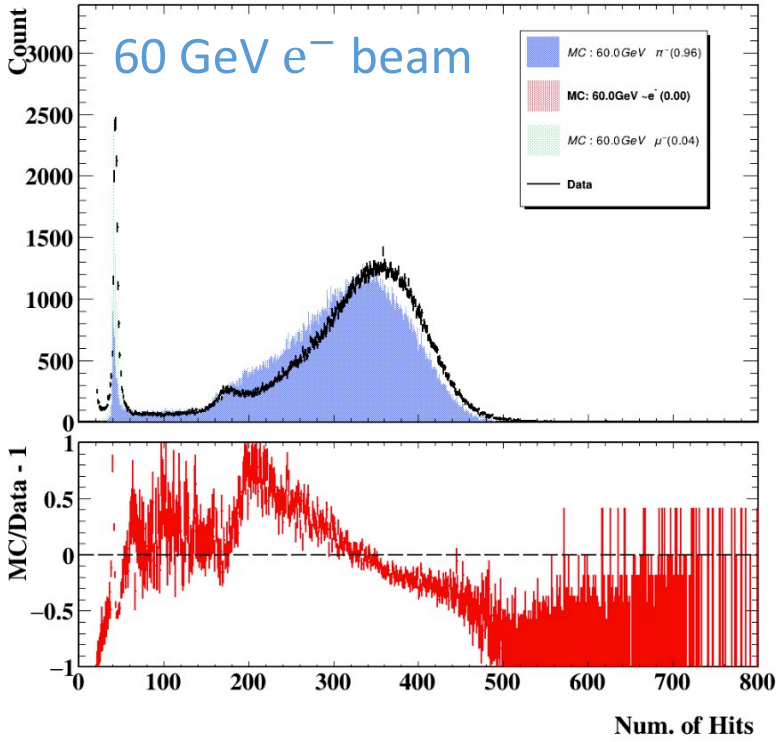
Yuzhi Che (IHEP)

2022 SPS-H8 electron data with AHCAL

- Characteristics of hit patterns with different beam particles
  - SPS-H8 beam (positive polarity): $\mu^+/e^+/\pi^+$
  - Determine compositions by varying fractions of MC for best consistency
  - MC/data consistency: ongoing studies for better digitization in simulation





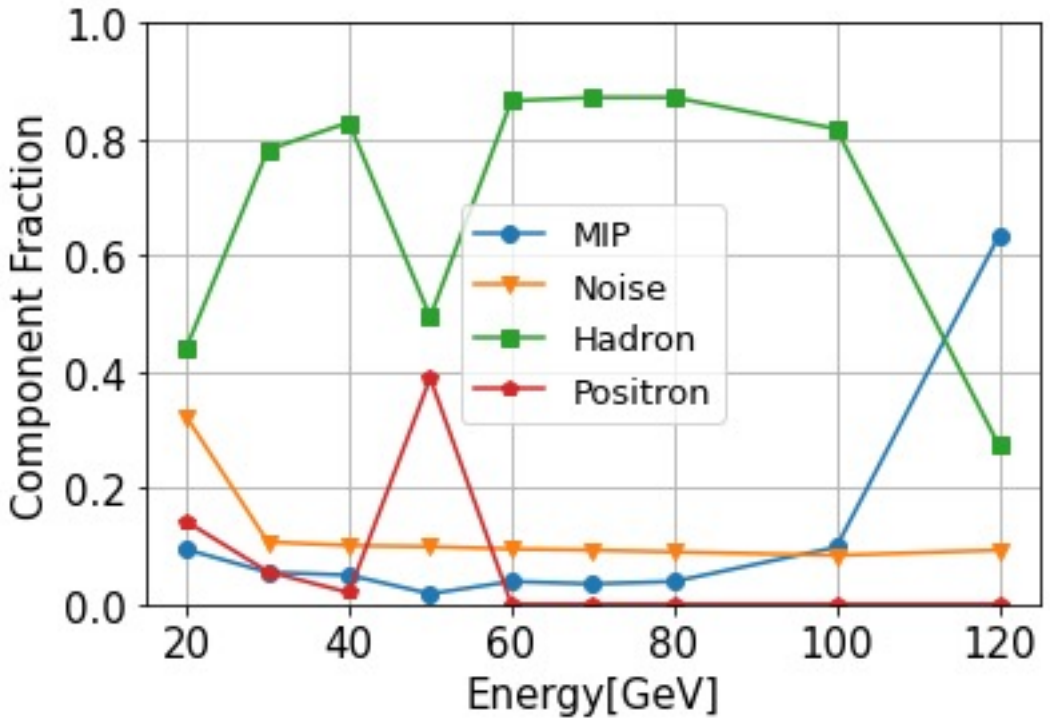


2022 SPS-H8 beam purity: preliminary results

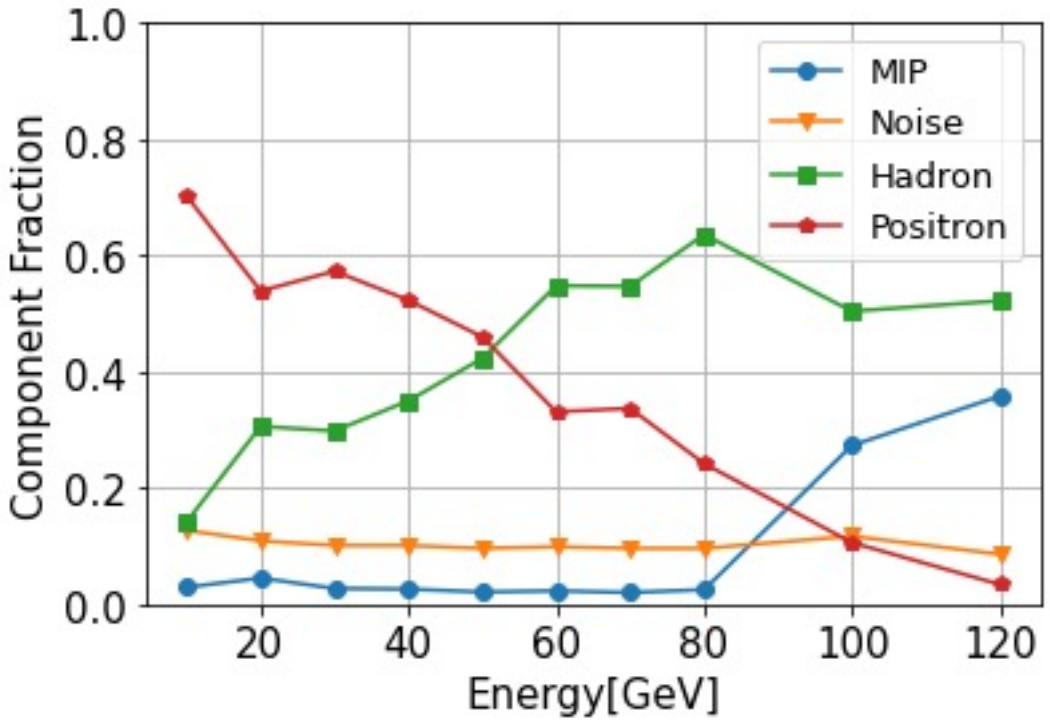
Yuzhi Che (IHEP)

- Imaging calorimeter: characteristics of hit patterns with $\mu^+/e^+/\pi^+$
- Positron beam: largely dominated by hadrons, barely no positrons >60 GeV
- Hadron beam: a considerably large fraction of positrons (esp. with lower energy)

2022 SPS-H8 positron beam data



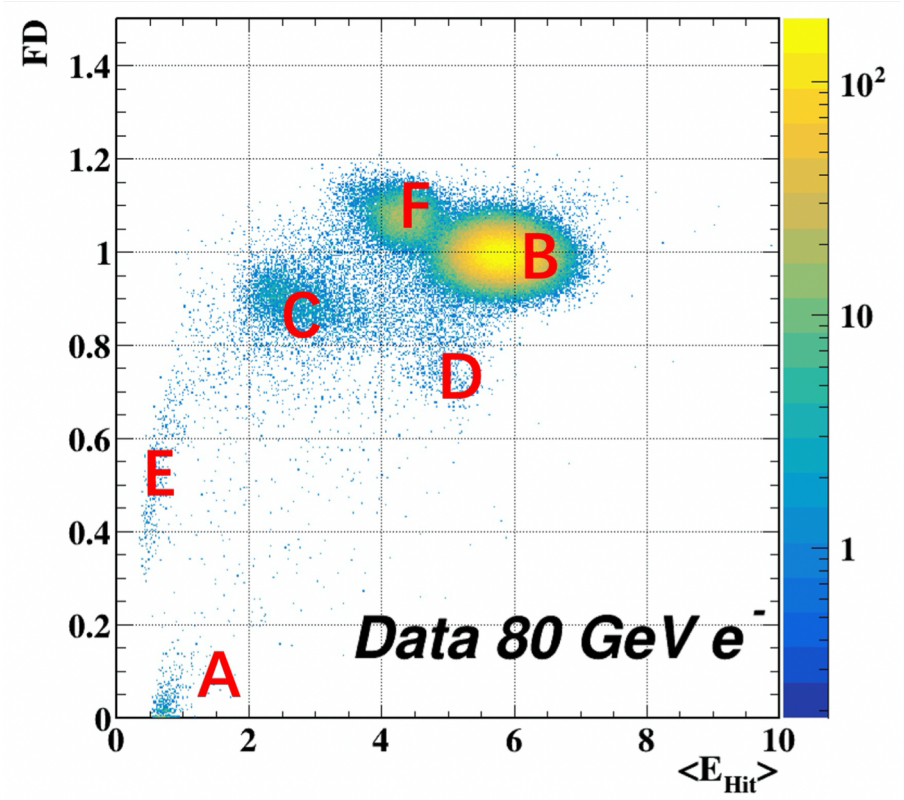
2022 SPS-H8 hadron beam data



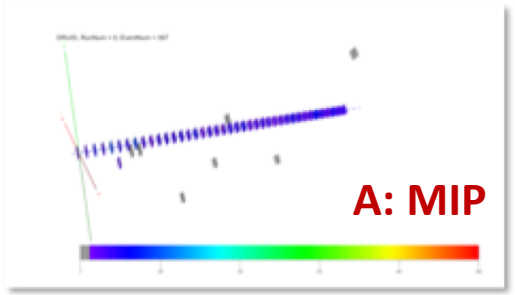
PID studies with fractal dimension

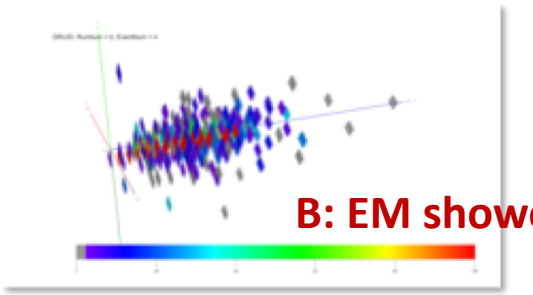
Xin Xia (IHEP)

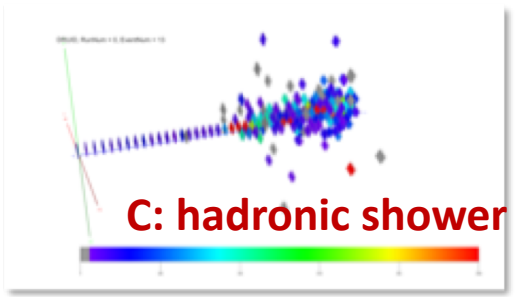
- Characteristics of fractal dimension (FD) with different beam particles
  - Only possible with imaging calorimeter (high granularity)

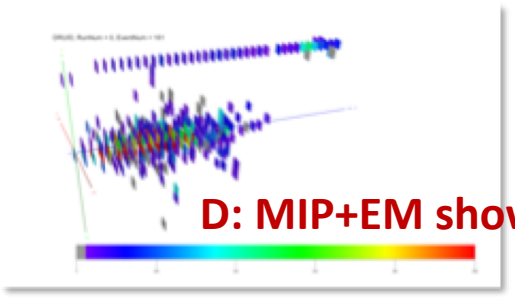


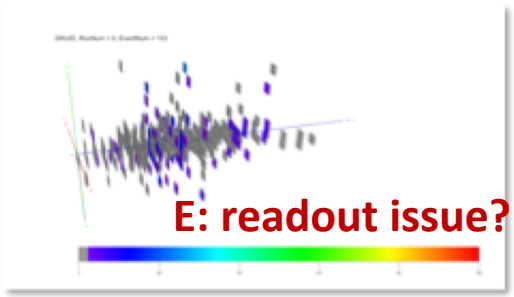
FD methodology based on
M. Ruan et al., Phys. Rev. Lett. **112**, 012001

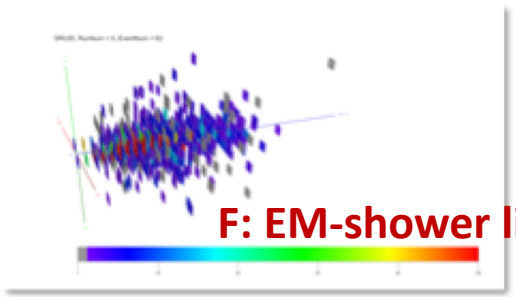








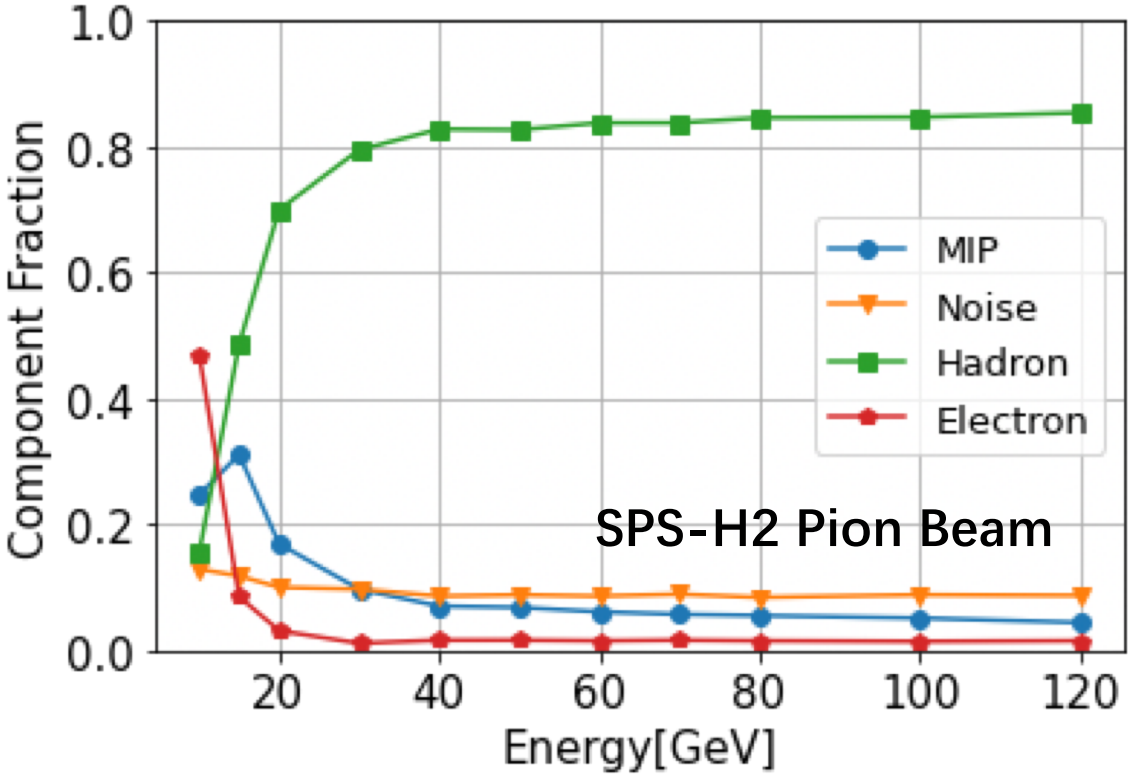


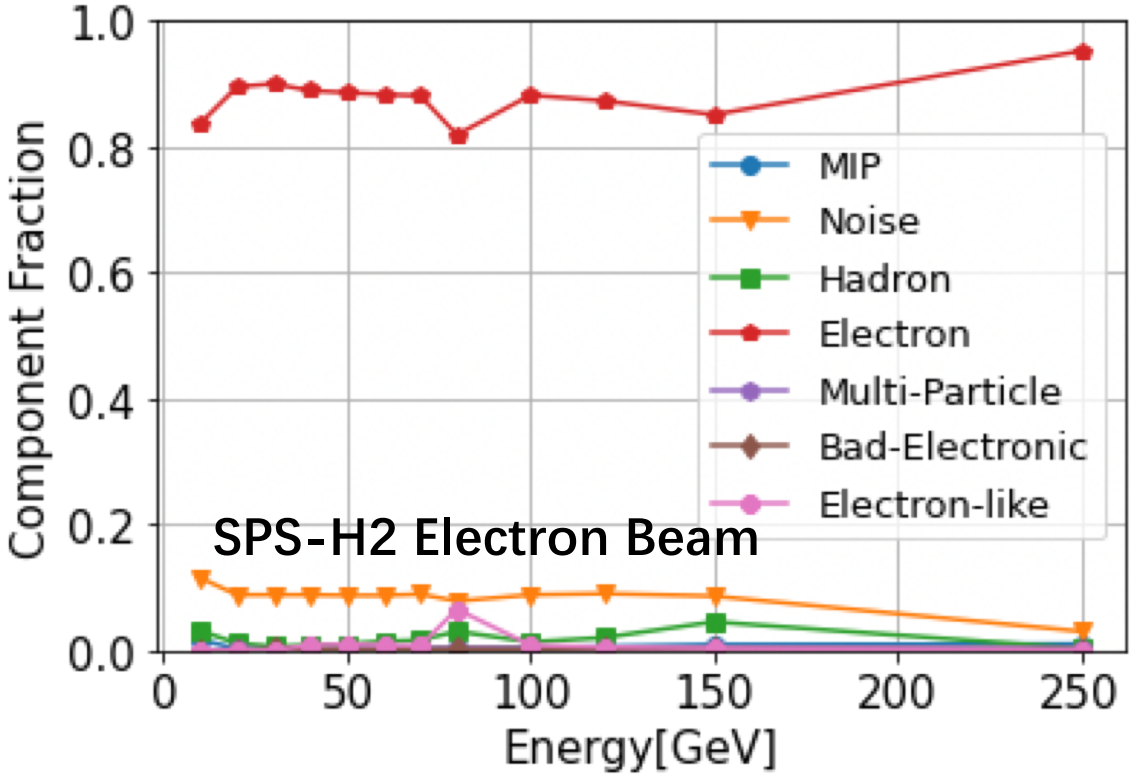


PID studies with fractal dimension

Xin Xia (IHEP)

- SPS-H2 beam purity: >80% for electron and pion beams with >30 GeV
- Significantly better purity at H2 than H8
- Noise events now become a dominating factor: ongoing studies

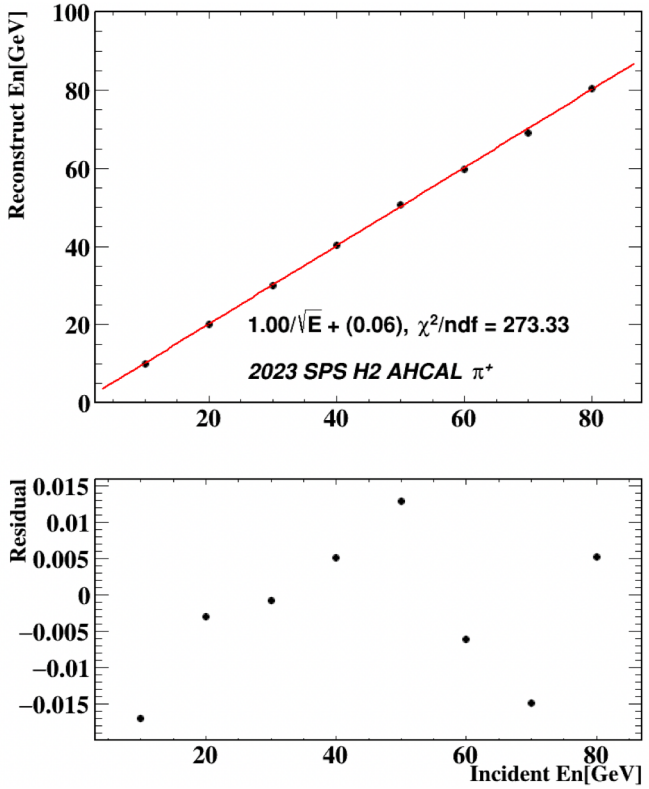


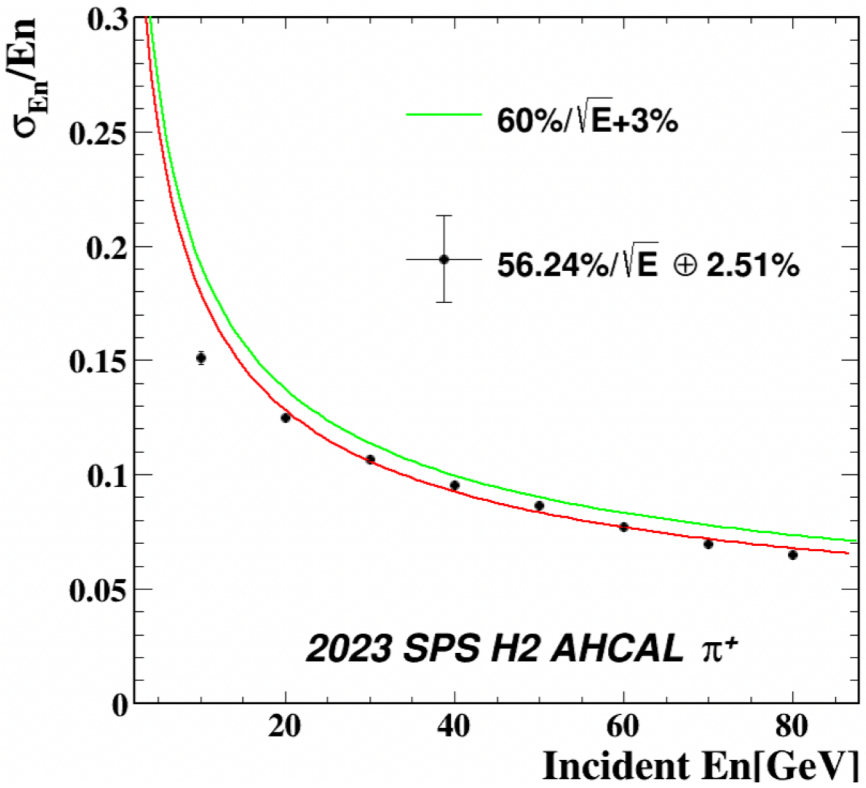


Key performance: first preliminary results

Xin Xia (IHEP)

- AHCAL prototype: data sets selected with FD for PID
  - Energy linearity within $\pm 1.5\%$
  - Energy resolution $56.2\%/\sqrt{E(GeV)} \oplus 2.5\%$ (expected $60\%/\sqrt{E(GeV)} \oplus 3\%$)





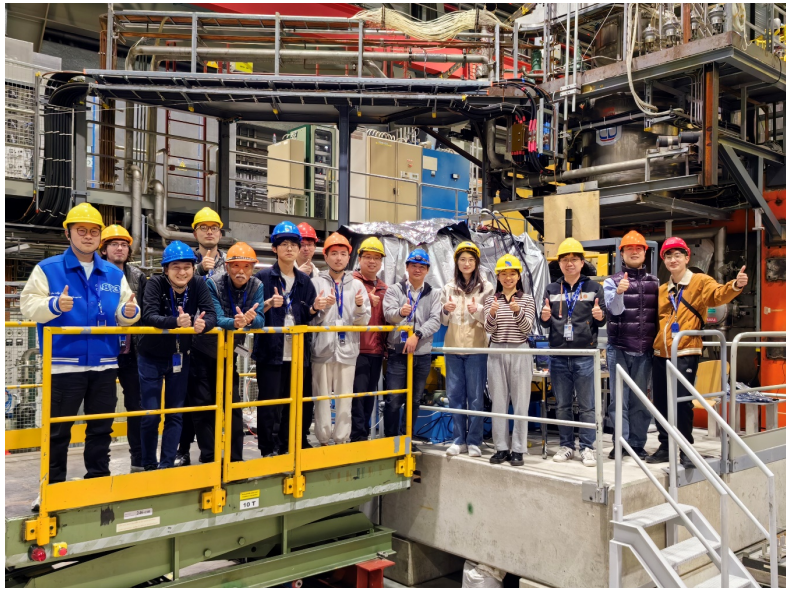
Final transportation back to China

- Loading at CERN on June 7, 2023
- Successfully transported back to China (Hefei) on June 17, 2023

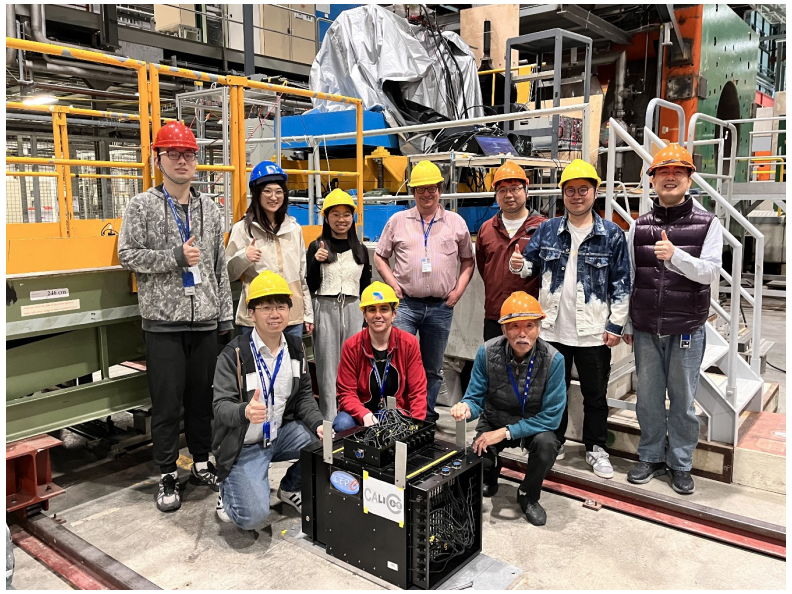
Acknowledgements

- Successful beam test campaigns with strong teamwork
- A big Thank You to CALICE and CEPC calorimeter teams
- Enormous and substantial support from CERN and CALICE
- Funding support from MOST, NSFC and CAS

Team at SPS-H2



CALICE spokesperson's visit



Team at PS-T9

Summary: beamtest campaigns at CERN

- Very successful beam test campaigns at SPS-H2, H8 and PS-T9
  - Thanks to the strong teamwork
- Collected decent statistics of data samples in the wide energy range
  - SPS-H8: 10-160 GeV; SPS-H2: 10– 120 GeV (also 150 – 350 GeV); PS-T9: 1 – 15 GeV
  - A few overlapped energy points (10-15 GeV) at both SPS and PS
  - Significantly better beam purity at SPS-H2 than SPS-H8
  - Invaluable for detector performance evaluation and shower studies
- Preliminary results look promising, detailed studies under way
  - Key performance: energy linearity and resolution
  - PID and particle-flow studies
  - Validation of Geant4 hadronic models

Thank you!

Backup

Introduction: beamtest campaigns at CERN

- Oct. – Nov. 2022: CERN SPS-H8
  - Positive beams: 10 – 160 GeV
  - First successful experiences with combined ScECAL + AHCAL prototypes
  - Beam purity issue: PID studies with imaging calorimeters
- Apr. – May 2023: CERN SPS-H2
  - Negative beams: 10 – 350 GeV
  - Significantly better beam purity
- May 2023: CERN PS-T09
  - Negative beams: 1 – 15 GeV
  - Large data sets with low energy hadrons

Data taking summary at SPS-H2

- Collected more than 30 million events at H2 during 16 days

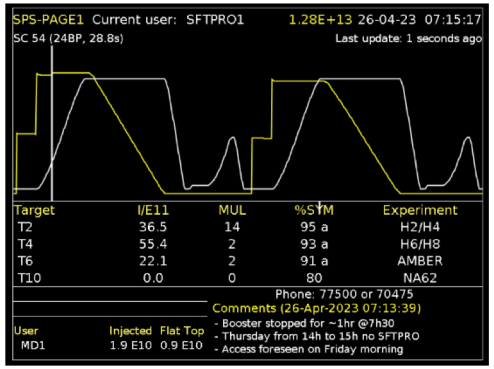
Particle	Momentum (GeV/c)															Events
	10	15	20	30	40	50	60	70	80	100	120	150	200	250	350	
Pion	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	20M
Electron	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	4.7M
Muon										✓						6M
Proton															✓	1M

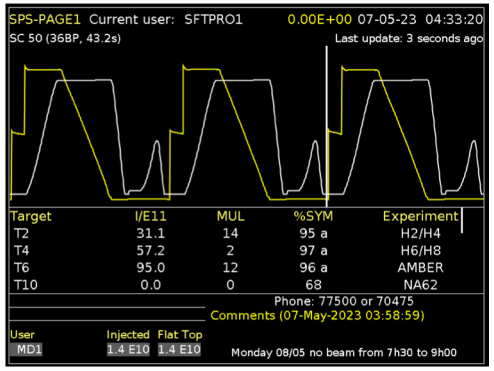
Typical SPS beam structure

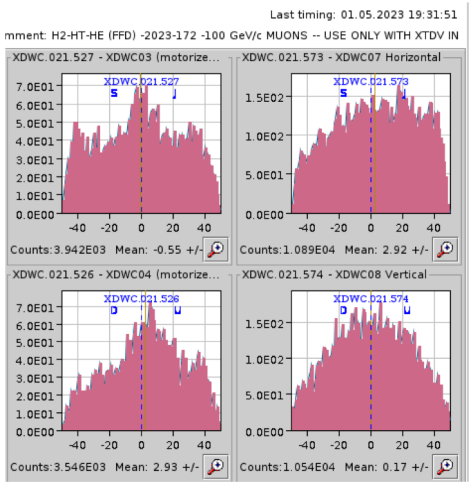
- 1 super cycle: 35s
- 1 spill: 4.8s
- 2-3k events per spill
- 1-3 spills per cycle

Typical SPS beam profiles

- ~4cm (FWHM) for electrons/hadrons
- Wider beam for muons



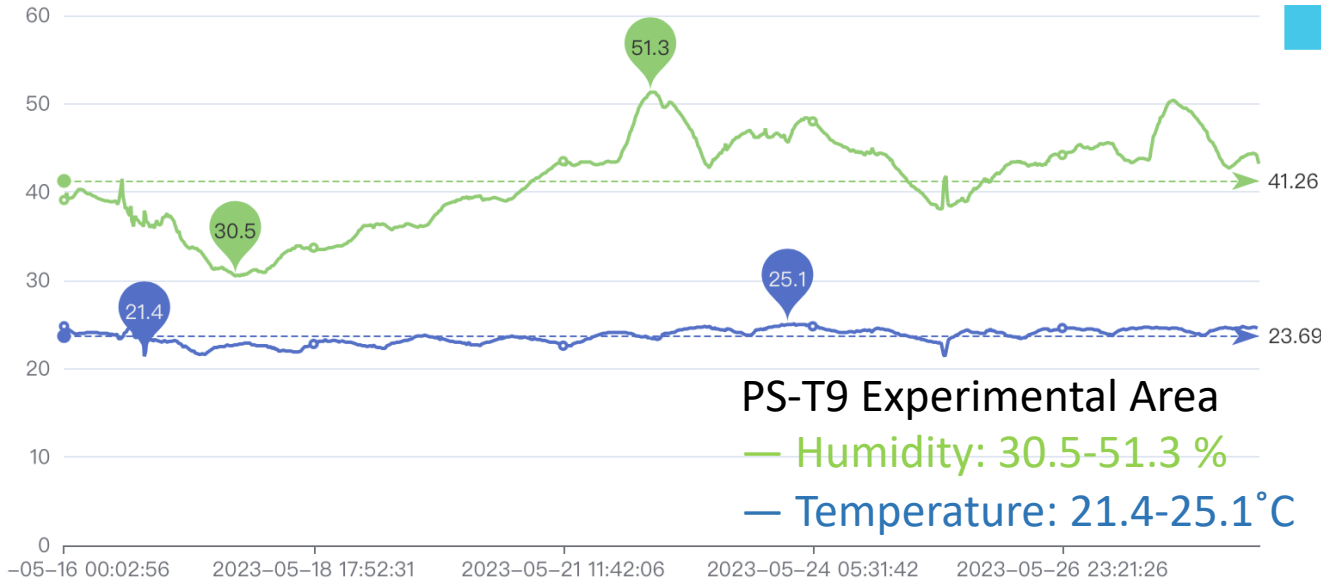




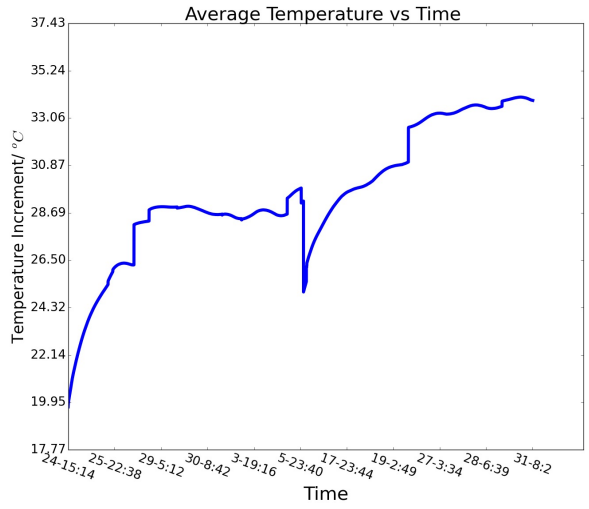
Data taking summary at PS-T9

Particle	Momentum (GeV/c)													Events
	0.5	1	2	3	4	5	6	7	8	9	10	12	15	
Pion		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	2.6M
Electron	✓	✓	✓	✓	✓	✓								8M
Muon											✓			

- Over 10M events recorded with electrons and pions



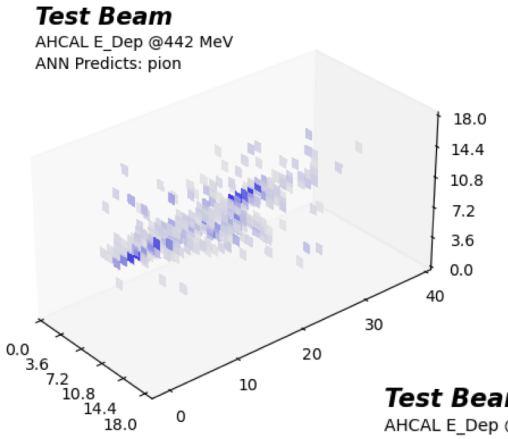
Temperature within AHCAL

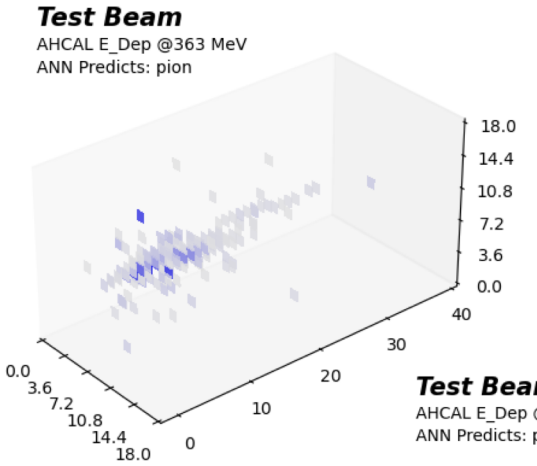


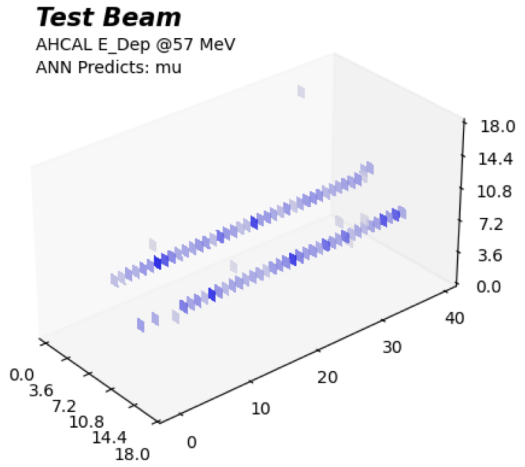
Event display with AHCAL alone at PS

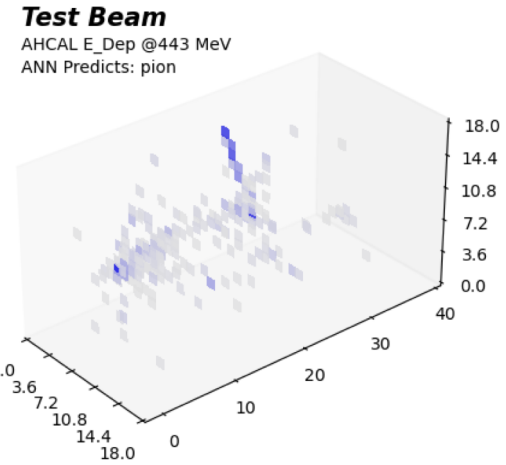
Siyuan Song (SJTU)

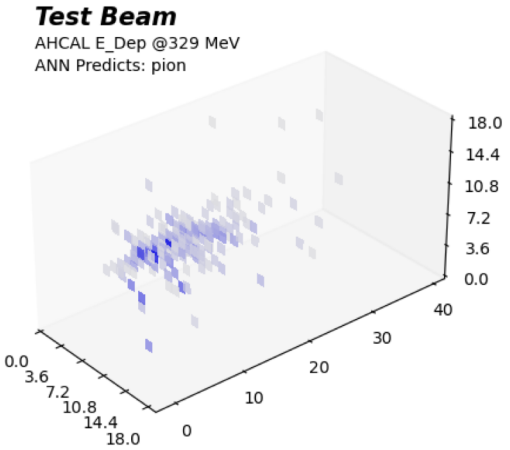
- Hadronic showers with 10 GeV pions
- Multiple MIP tracks from 10 GeV muons

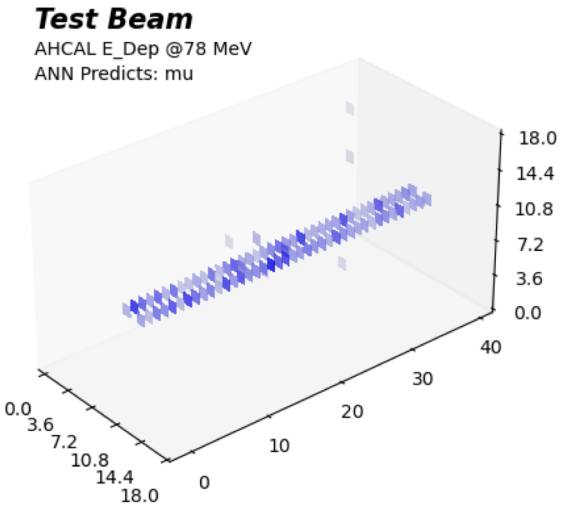








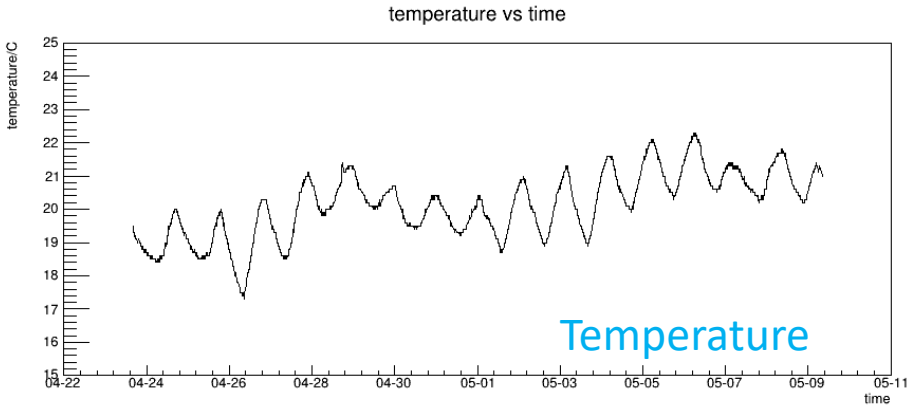


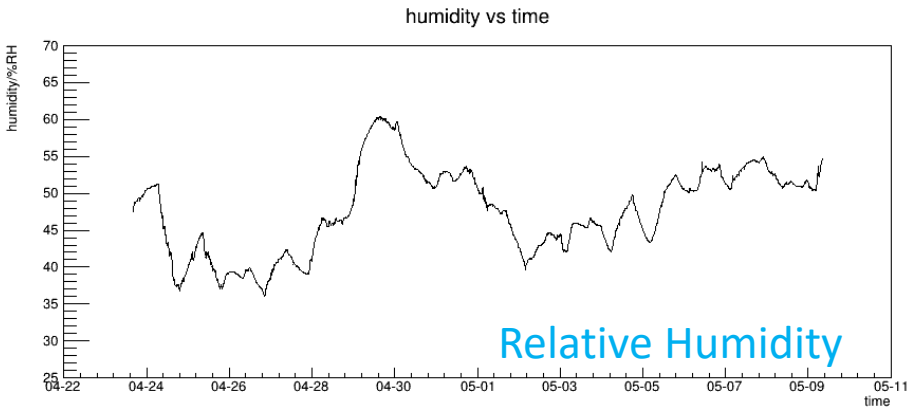


Environment monitoring

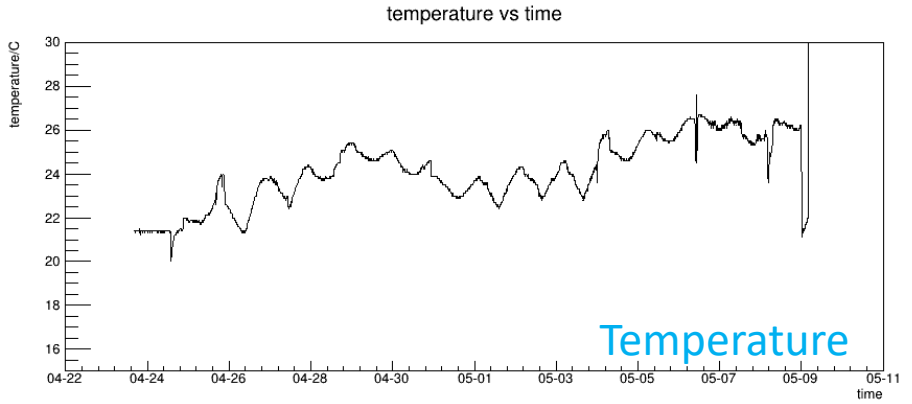
Yunlong Zhang (USTC), Siyuan Song (SJTU)

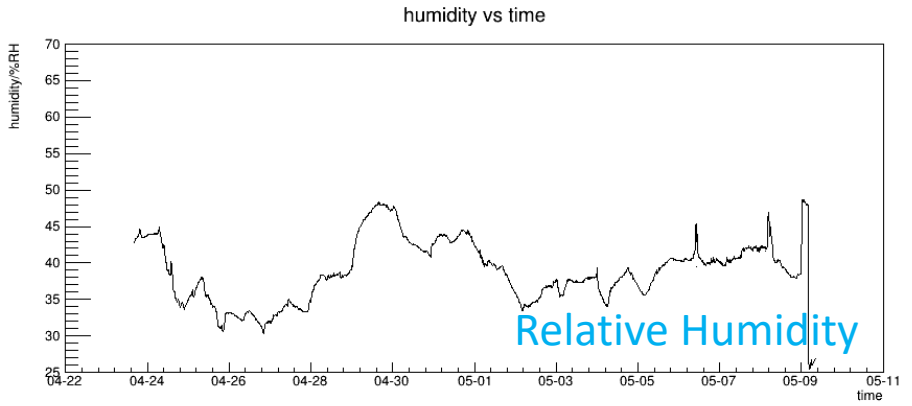
- Temperature and humidity at SPS-H2





Experimental area

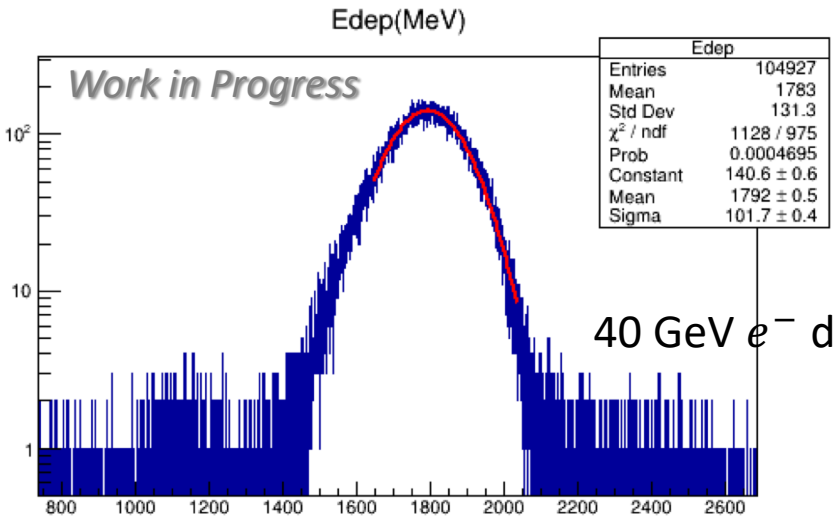




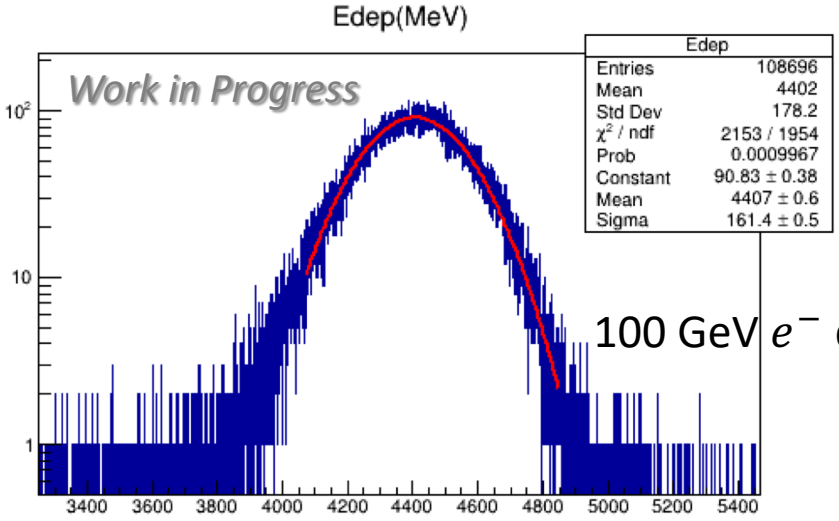
Within AHCAL sensitive layers

Preliminary results: energy reconstruction

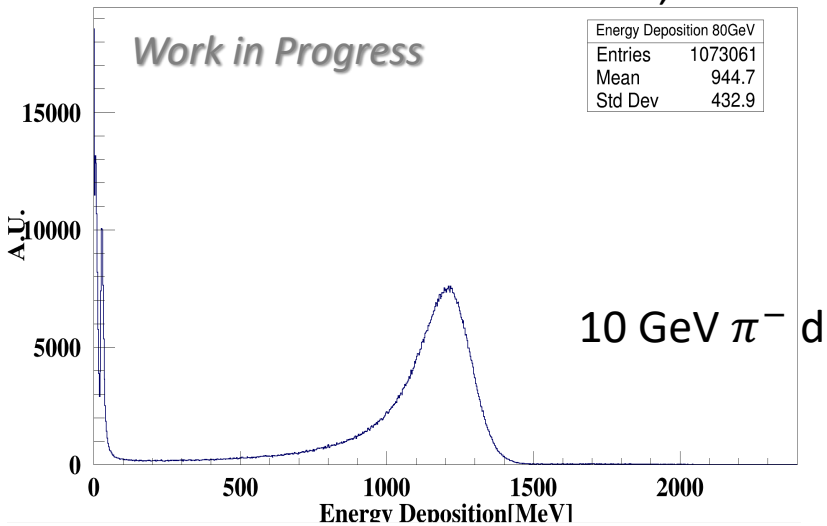
Yukun Shi, Jiaxuan Wang (USTC)



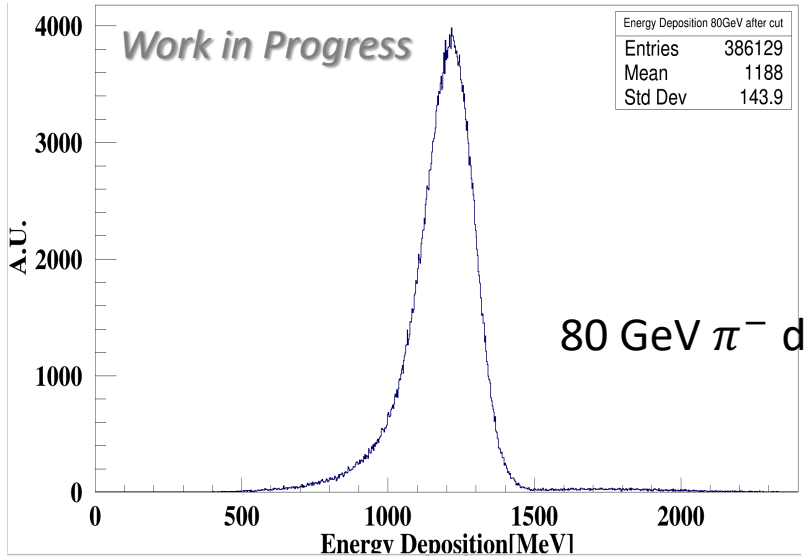
40 GeV e^- data: ScECAL



100 GeV e^- data: ScECAL



10 GeV π^- data: AHCAL



80 GeV π^- data: AHCAL