AHCAL beamtest and data analysis progress

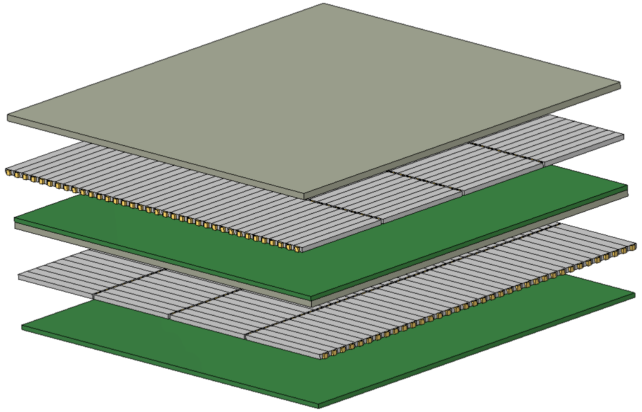
Yong Liu (IHEP), for the CERN beamtest team

Mar. 30, 2023

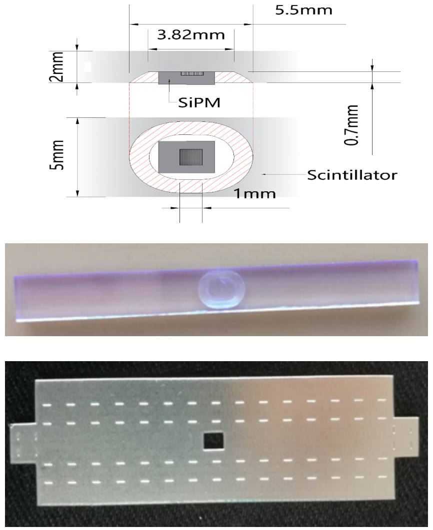
CALICE Collaboration Meeting at GAU Göttingen

Scintillator-tungsten ECAL prototype: recap

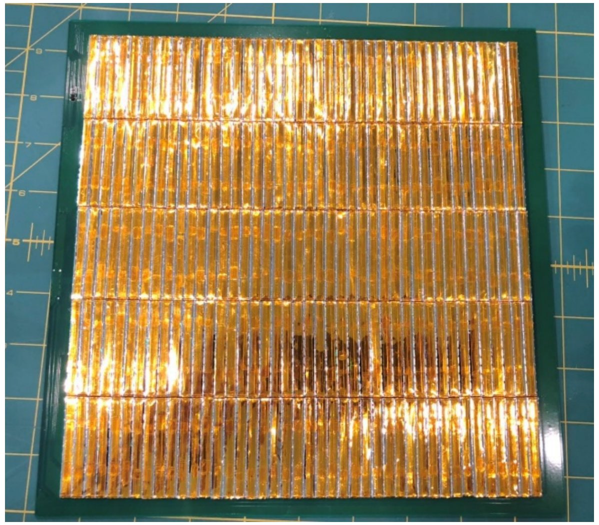
Sampling structure: scintillator strips + tungsten-copper plates



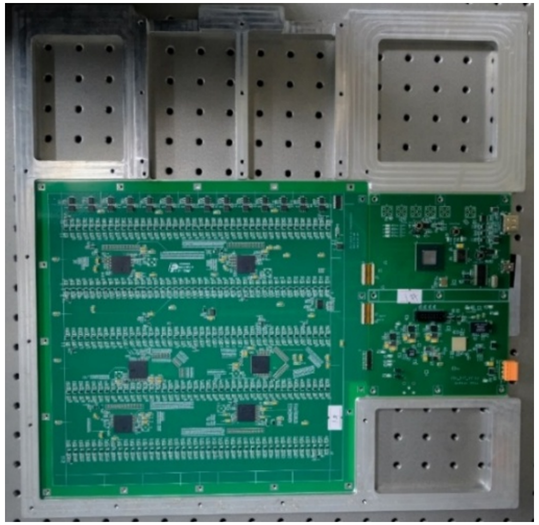
Detector unit: scintillator + SiPM



One sensitive layer (EBU): fully integrated with ASICs



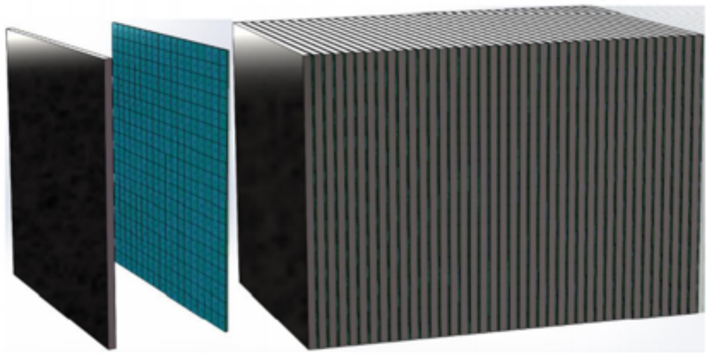
Two EBUs + absorber: integrated with mechanics

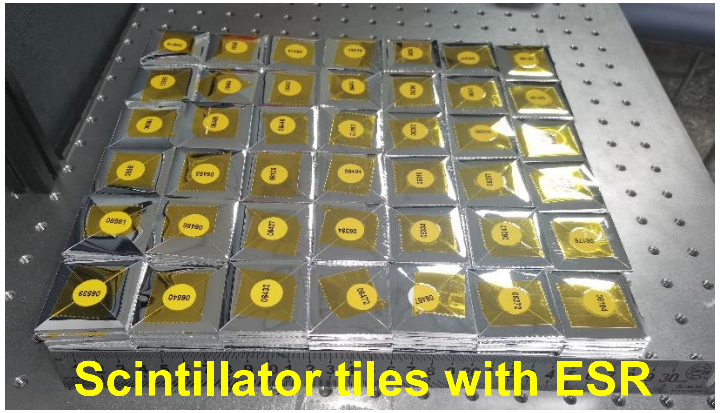


ScW-ECAL prototype

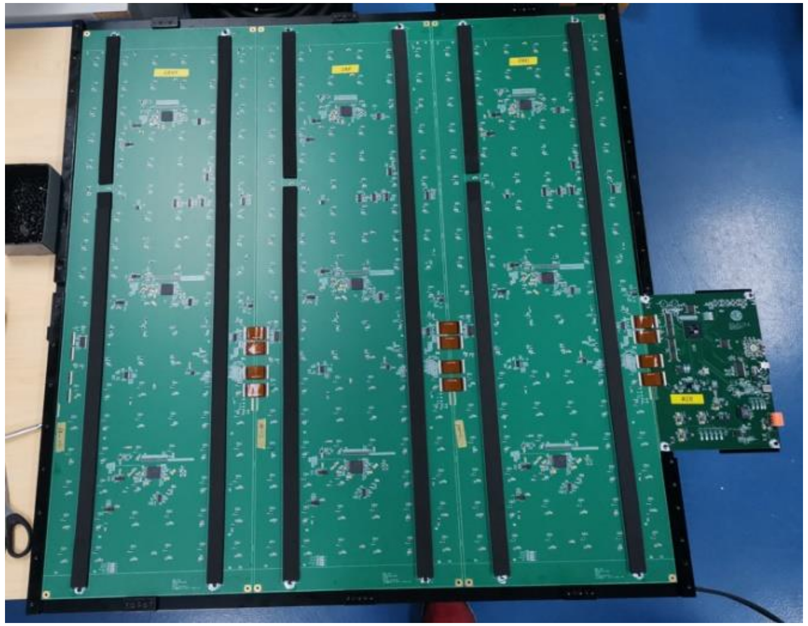
- ScW-ECAL prototype
  - Transverse size $\sim 22\times 22\ \mathrm{cm}^2$, 32 longitudinal layers ($\sim 25X_0$)
  - 6700 readout channels, ~300 kg in weight
  - Developed during 2016 – 2020
  - Tested with beams at BEPCII-TBF (IHEP) and cosmics at USTC

Scintillator-iron HCAL prototype: recap





1 full layer: 3 HBUs + cassette

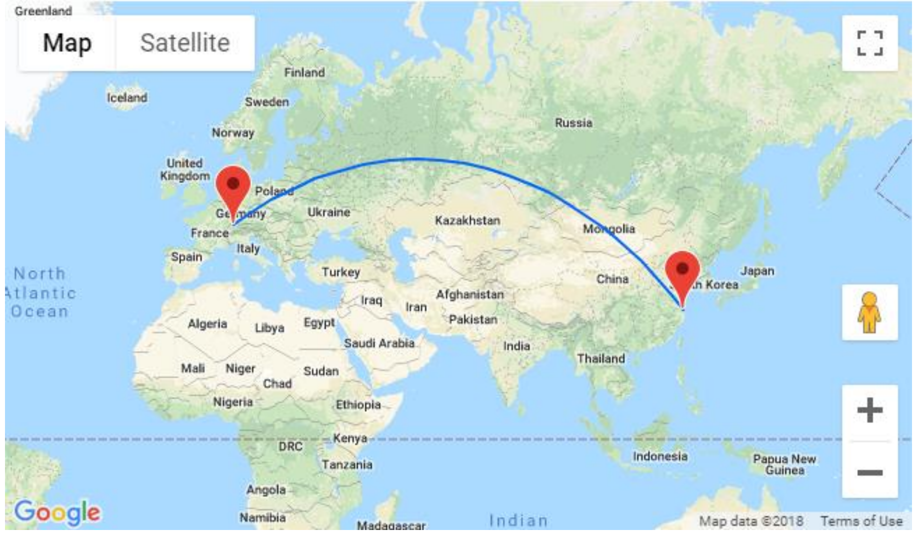


Mechanics Integration

- AHCAL prototype: “SiPM-on-Tile” design
  - Transverse size $72\times72\ \mathrm{cm}^2$, 40 longitudinal layers ($\sim4.6\lambda_I$)
  - 12960 readout channels, ~5 ton in weight
  - Developed during 2018 – 2022
  - HBU assembly and commissioning (cosmic muons) at USTC

Transport and preparations at CERN SPS

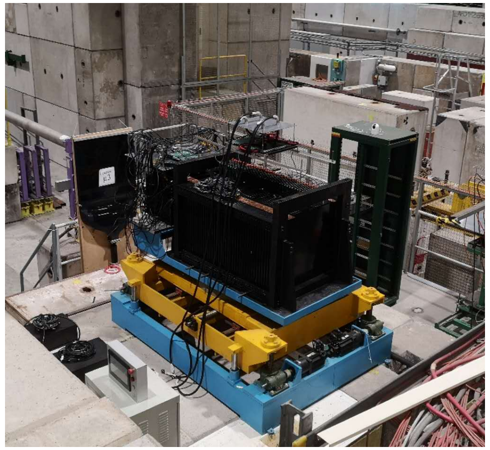
Calorimeters in flight



Flying calorimeter

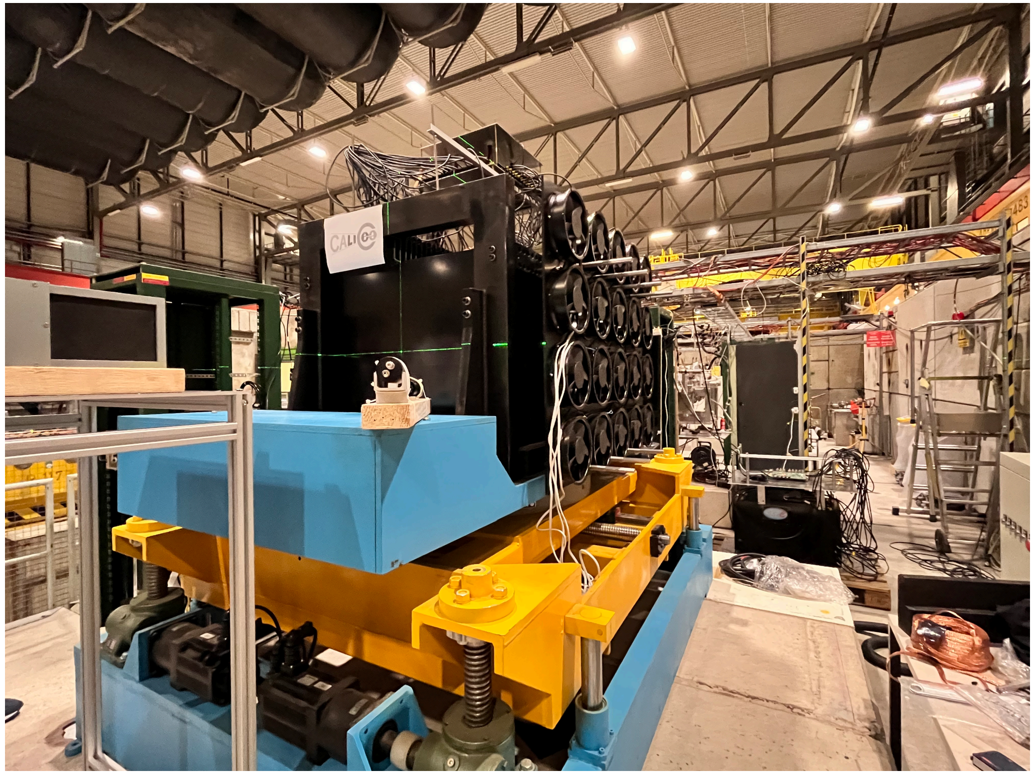
Before cabling

After cabling (parasitic runs)



- Successful transportation from China to CERN
- Transported to SPS beam area H8C (PPE168)
  - ScW-ECAL and AHCAL prototypes + 1 supporting table
  - Impressions: cubic meters and ~10 tons

Beam test: motivations and plans

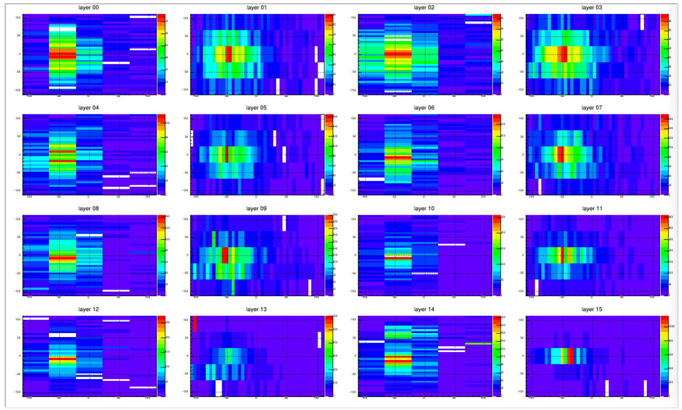


AHCAL prototype alone in H8 beam line
(the 1st week as main user in Oct. 19-26)

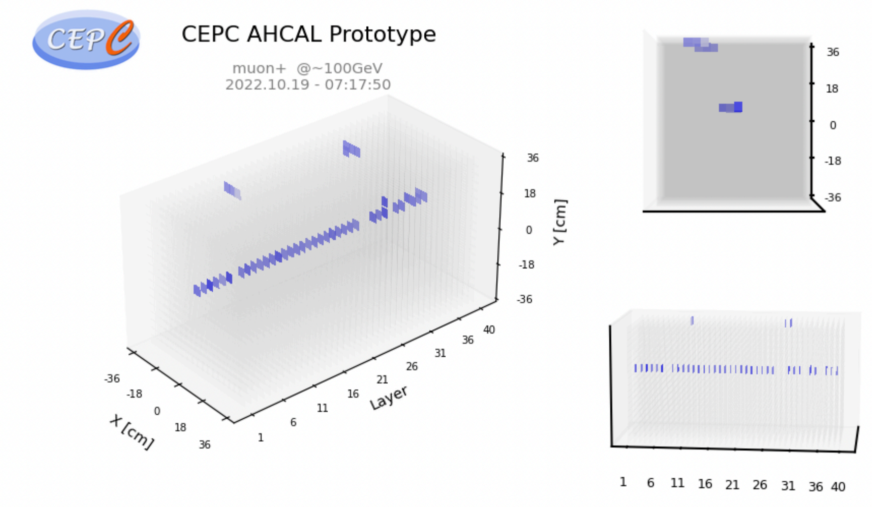
- Muon beam: 160 GeV (1st week); 108 GeV (2nd week)
  - MIP calibration → energy reconstruction
- Positron beam: 10 - 120 GeV
  - Compact EM showers → high energy density → SiPM saturation corrections (essential)
  - EM performance
  - Validation of simulation and digitisers
- Pion beam: 10 - 120 GeV
  - Major goal: hadronic performance (10-80 GeV), e.g. energy linearity and resolution
  - Shower profiles in 3D and time domain
  - Geant4 simulation validation (“Physics Lists”)
  - Particle-flow studies: e.g. ArborPFA

Parasitic beam test

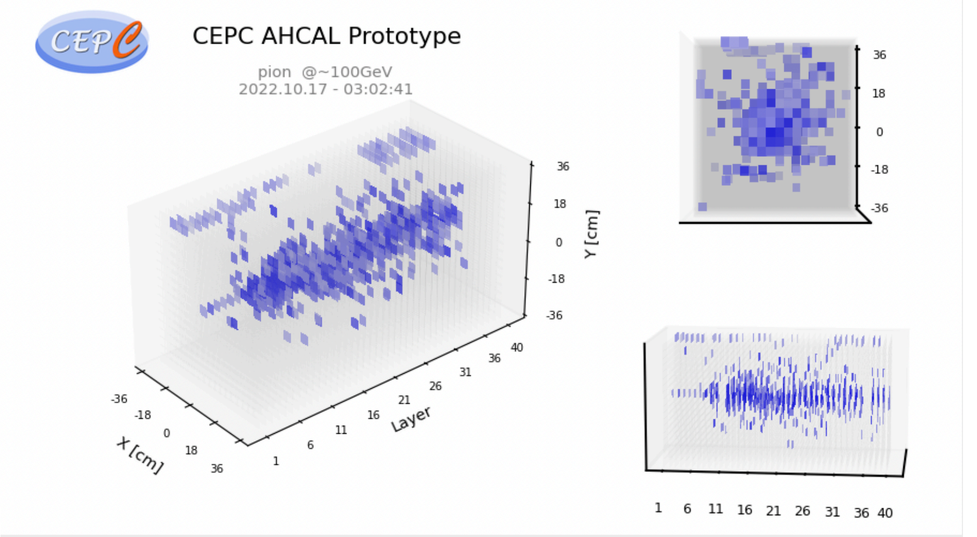
Muons in ECAL: Hit Maps



Muon MIP track in HCAL



Pion hadronic shower in HCAL

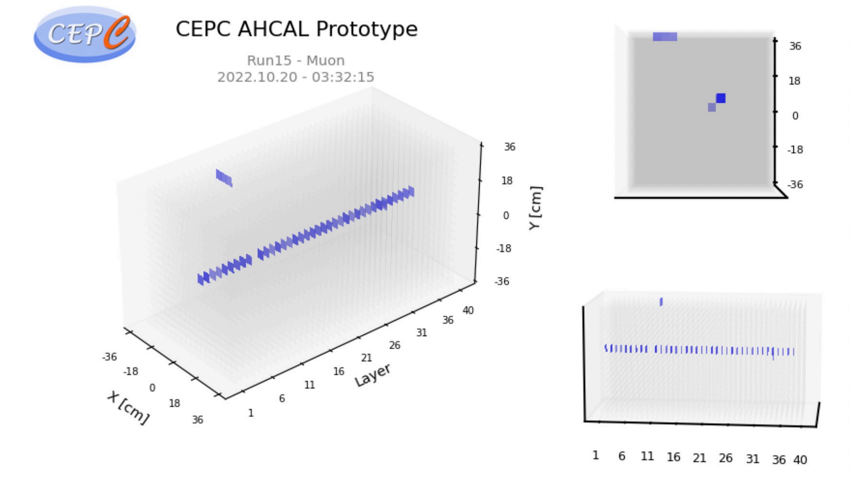


- Motivations: full system commissioning; muons for MIP calibration
- Successful data taking with parasitic beams (Oct. 14-19, 2022)
  - Setup: combined ECAL and HCAL, in downstream of LHCb detectors
  - Beams: 160-180 GeV muon+ or pion+
  - Thanks to the LHCb muon detector team

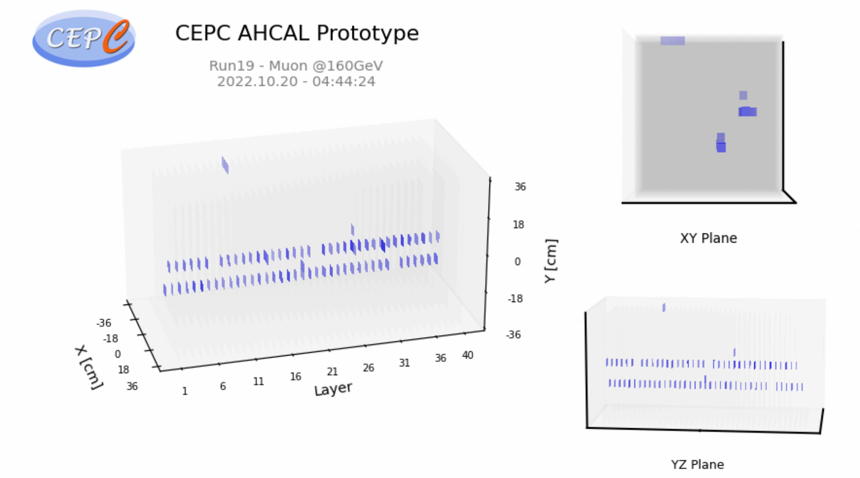
AHCAL prototype with muons

- Muon beam (~160 GeV)
  - Normal incidence to the calorimeter plane
  - Wide beam profile: covers AHCAL lateral area (72×72 cm^2)
  - Threshold scans, SiPM bias voltage tuning (all 40 layers)
  - Data sets for MIP calibration

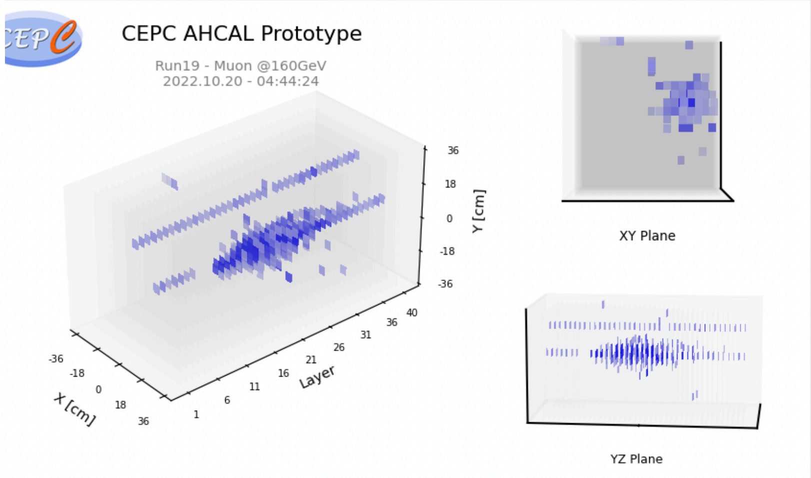
Impressions of high granularity



1 muon track



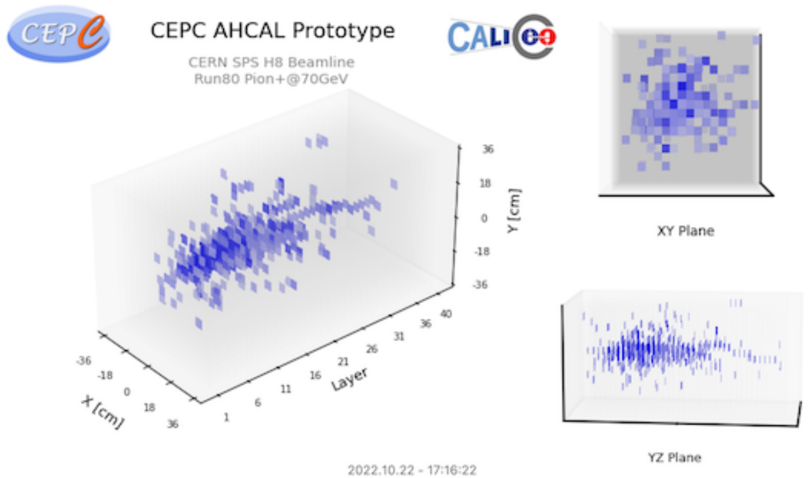
2 muon tracks



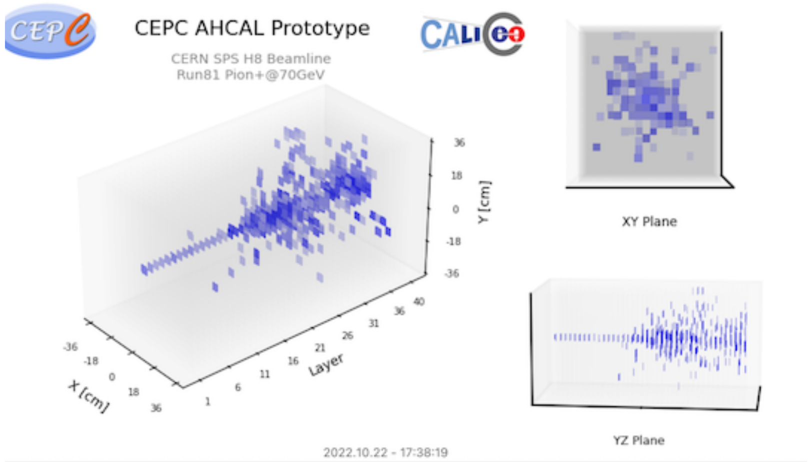
1 muon + 1 pion

AHCAL prototype with pions

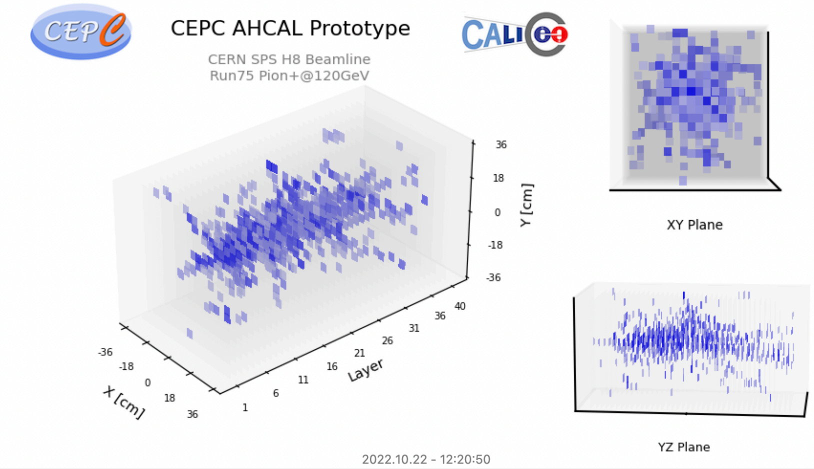
- Energy scans with pi+ beam
  - 10 – 120 GeV: ~1M events accumulated per energy point
  - SPS running very smoothly and with high beam intensity (Oct. 20 – 26, 2022)
- Beam purity issue
  - Contaminations of hadron beam with positrons (energy dependent)
  - 2 Cherenkov counters implemented in DAQ: recorded in data, not part of hardware trigger



70 GeV pion+ (early showers)



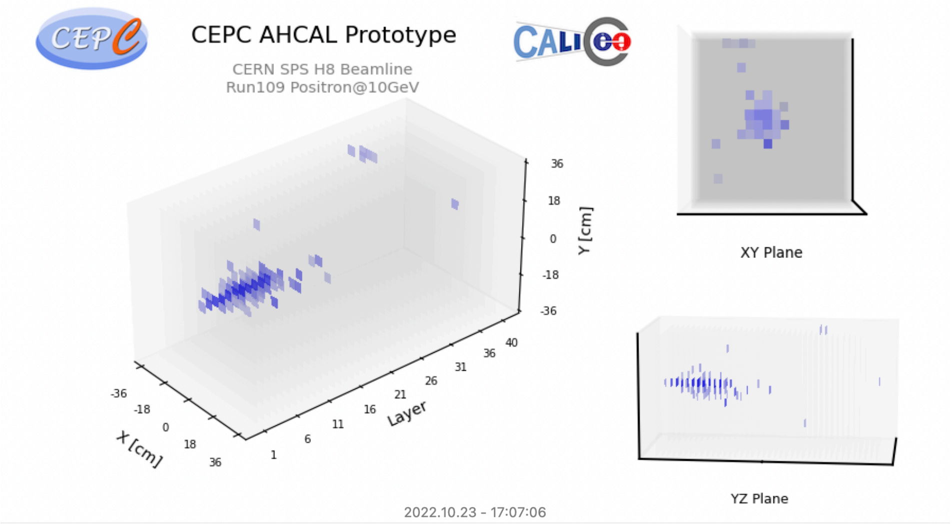
70 GeV pion+ (late showers)



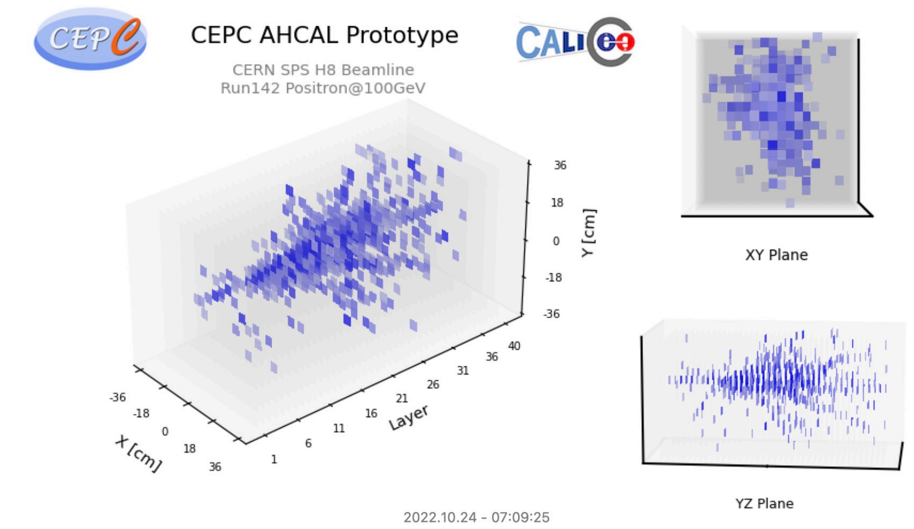
120 GeV pion+

AHCAL prototype with positrons

- Energy scans with e+ beam
  - 10 – 120 GeV: ~200k events accumulated per energy point
  - Finished data taking plan within half a day thanks to SPS smooth running
- Beam purity issue
  - Significant contaminations of positron beam with hadrons (energy dependent)
  - 2 Cherenkov counters implemented in DAQ: recorded in data, not part of hardware trigger



10 GeV positron beam: EM showers

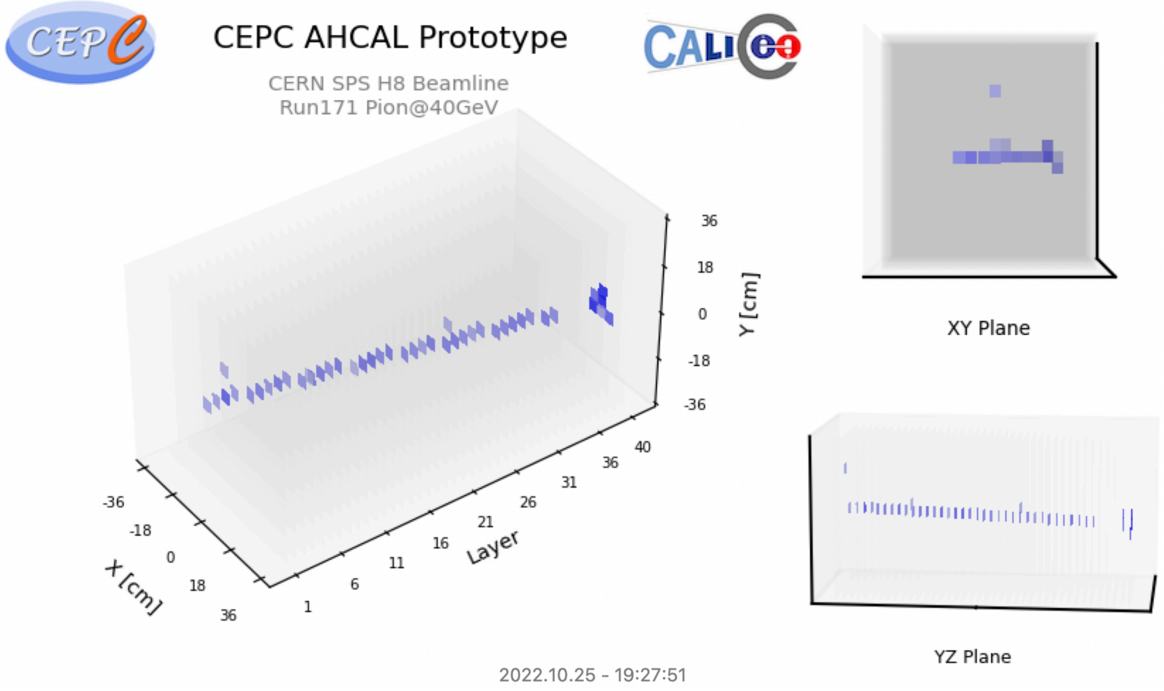


Hadronic showers in 120 GeV positron beam

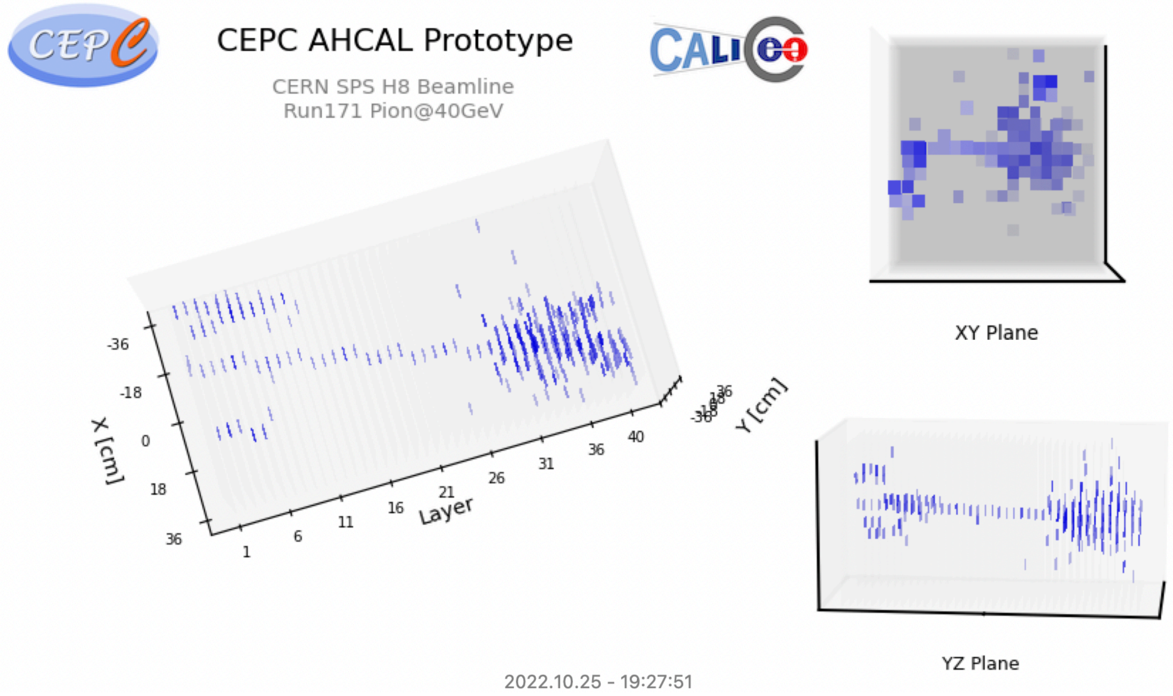
AHCAL prototype: inclined beam incidence

- AHCAL was rotated at 15° w.r.t the beam incidence
  - To study angular dependences: shower energy and profiles
  - Pi+ beams: 20GeV (273k events), 30GeV (1.11M events), 40 GeV (134k events)

40 GeV pion beam: muon track

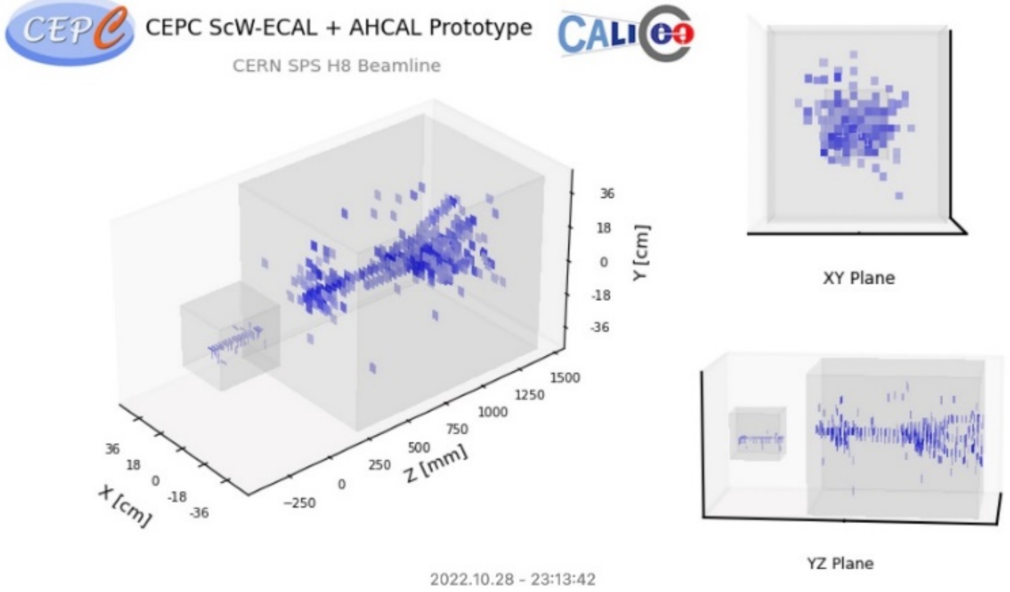


40 GeV pion beam: hadronic showers



Beam test of combined ECAL+HCAL

- Obtained all data sets as planned for the combined ECAL+HCAL
  - 2nd main user week: Oct. 27 – Nov. 2, 2022
  - Muon beam: ~108 GeV
  - Positron beam: 10 – 120 GeV
  - Pion beam: 10 – 120 GeV
- Event-level synchronisation is the key (ongoing efforts)



Outline for preliminary results

- MIP calibration
- Simulation and validation with data
- PID studies to mitigate contamination
- Arbor clustering studies

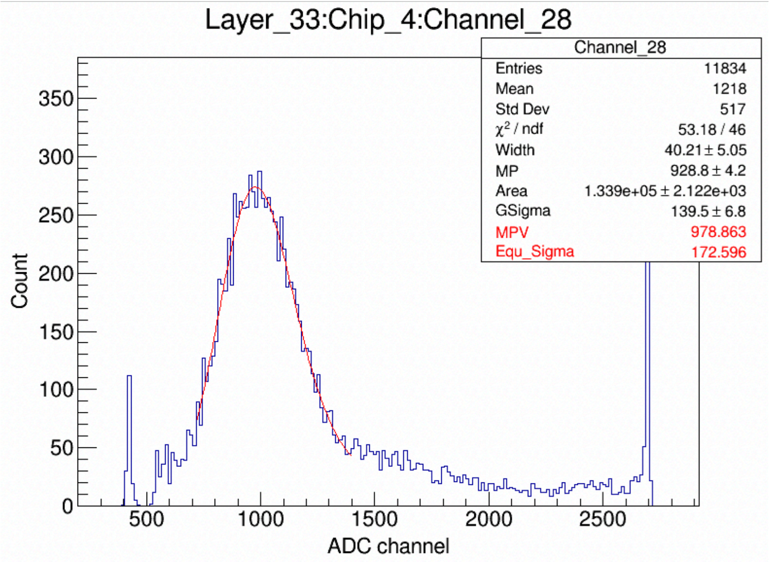
Muon data studies

Peng Hu (IHEP)

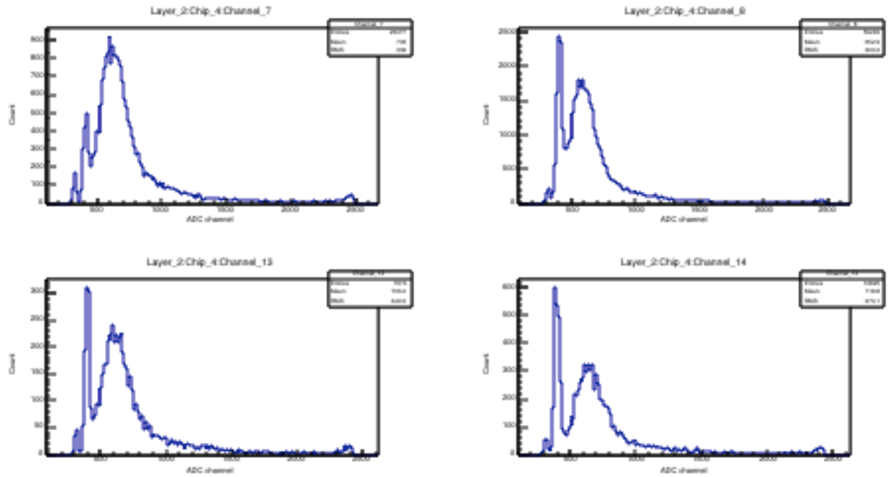
- MIP calibration done for each channel: muon data
  - Most probable value (MPV): Landau convoluted with Gaussian
  - Ongoing studies: to quantify the MPV spread and run-by-run stability
  - Also observed ADC saturation in High Gain (HG) mode

AHCAL in HG-LG mode;
No TDC output

MIP spectrum fitting: Landau+Gauss

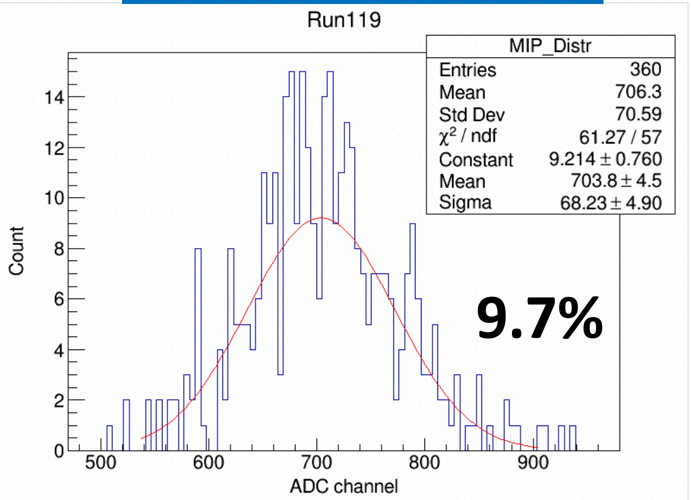


Selected MIP spectra (in ADC tics)



Noise peak and MIP peak clearly separated

MPV for 360 channels

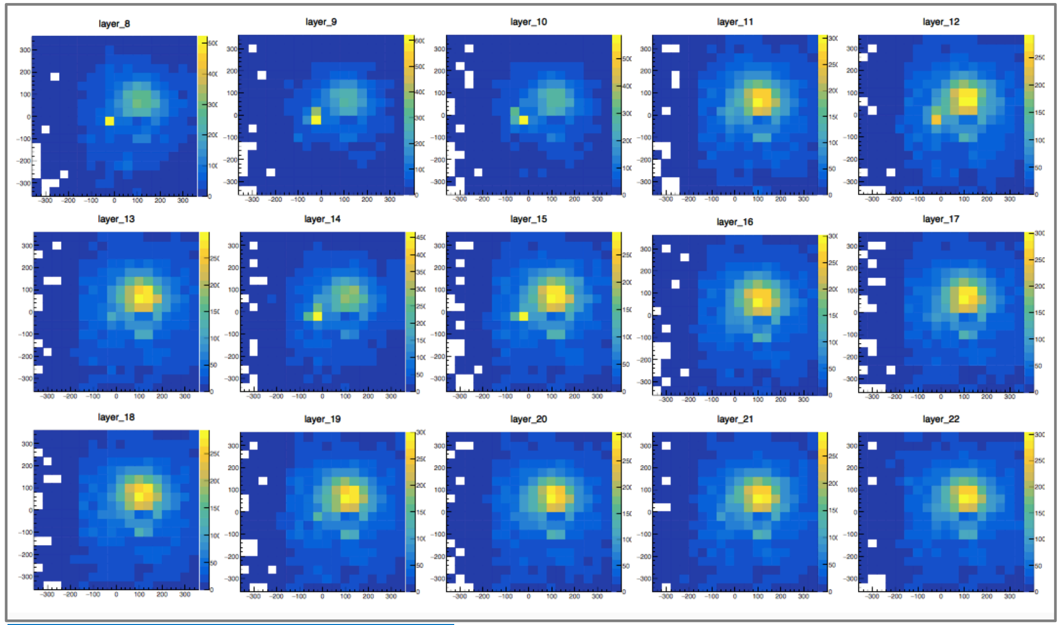


9.7% spread for 9 tiles per layer with including all 40 layers (wo pedestal subtraction)

Muon data studies

Ryunosuke Masuda (U. Tokyo)

- MIP calibration per channel: crosscheck
- AHCAL: 0.3% dead channels
- Temperature corrections: to be done



Muon Data: Run 333

AHCAL beamdata analysis

- MIP analysis : All channel scan

  ➡ Using a merged muon data file (all run files)
  ➡ 40 channels (~0.3 % of all channel) are dead
  ➡ A lot of channels of last two layers have abnormal MIP value as reported by Chinese group
  ➡ Same tendency as slope analysis

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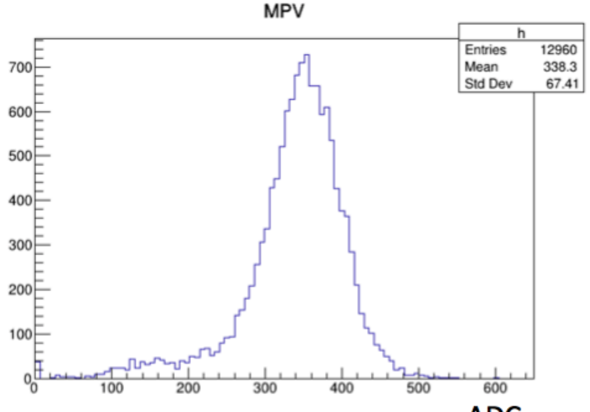
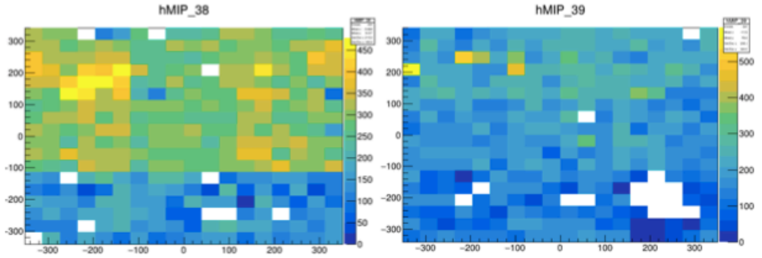
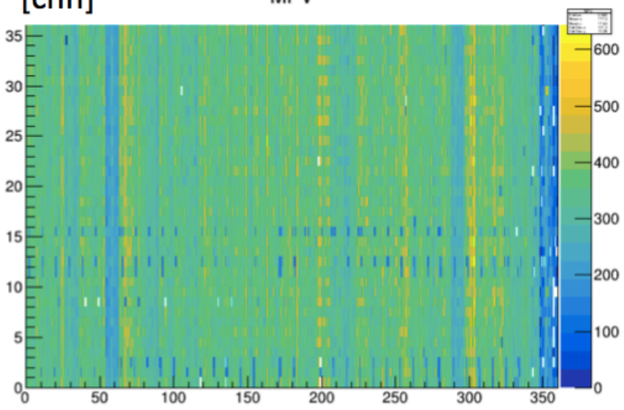


MIP value map layer 38 & 39





Combined all muon data runs

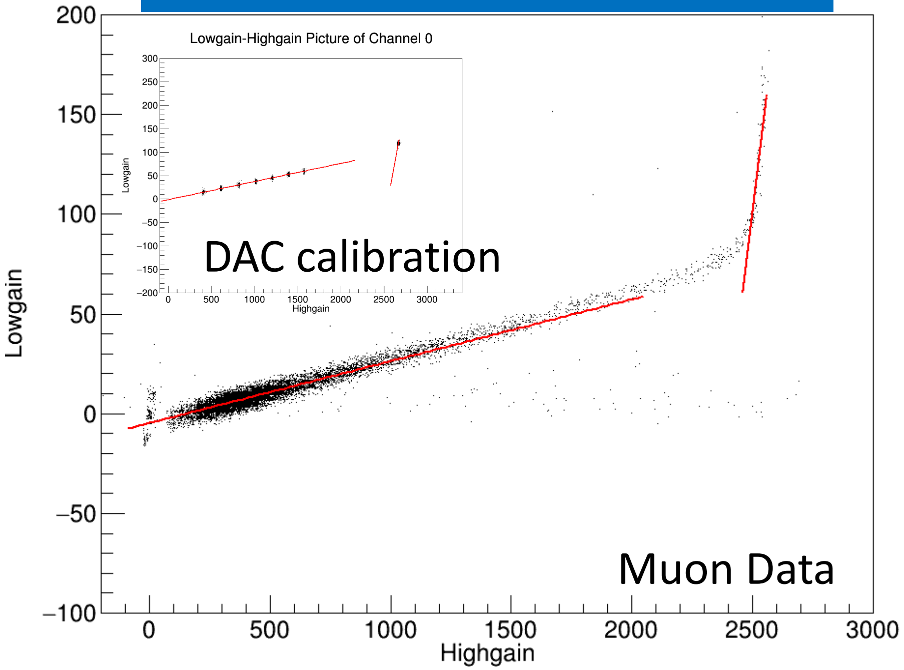
- Last two layers equipped with NDL-SiPMs: needs more time to optimise configurations

SPIROC2E: HG-LG intercalibration

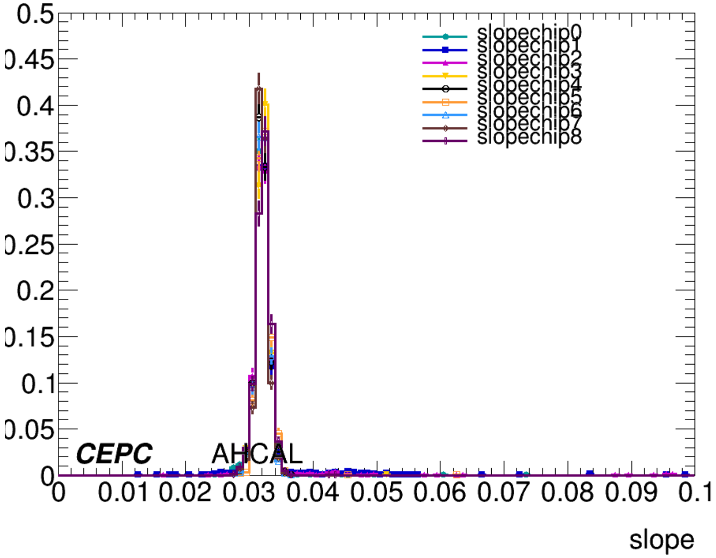
Zhen Wang, Zixun Xu (SJTU)
Yukun Shi, Hongbin Diao (USTC)

- Muon data: ADC in High Gain and Low Gain modes
  - LG/HG ratio: observed different values in muon data and DAQ calibration data (average ~10% difference)

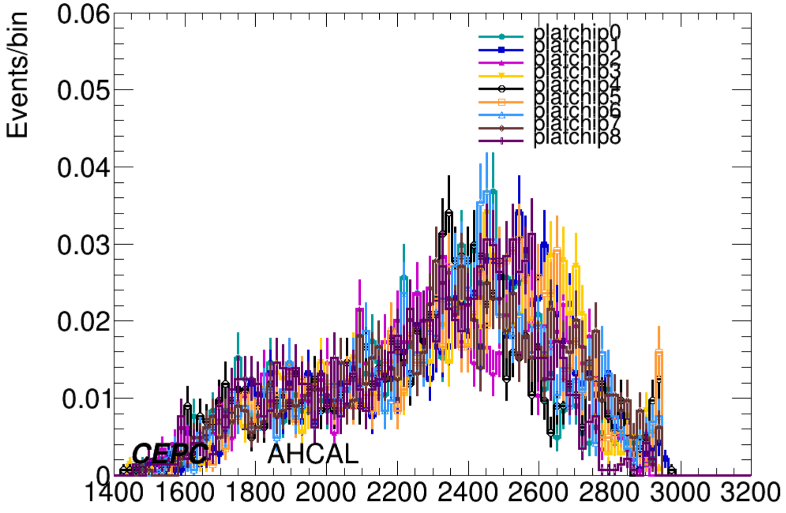
ADC: High Gain vs Low Gain

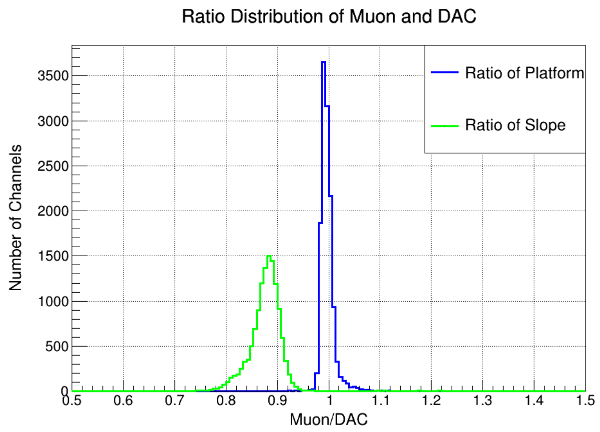


LG/HG ratio spread



HG Saturation: Plateau Position





Simulation and validation

- Geant4 full simulation established
  - Geometry: for both ScW-ECAL and AHCAL prototypes
  - Scintillation: quenching effect (Birks' law) implemented
  - Assuming perfect response uniformity for each channel
    - MIP calibration of each channel: done in data
  - Digitisation
    - Photon statistics, SiPM non-linearity, ASIC saturation

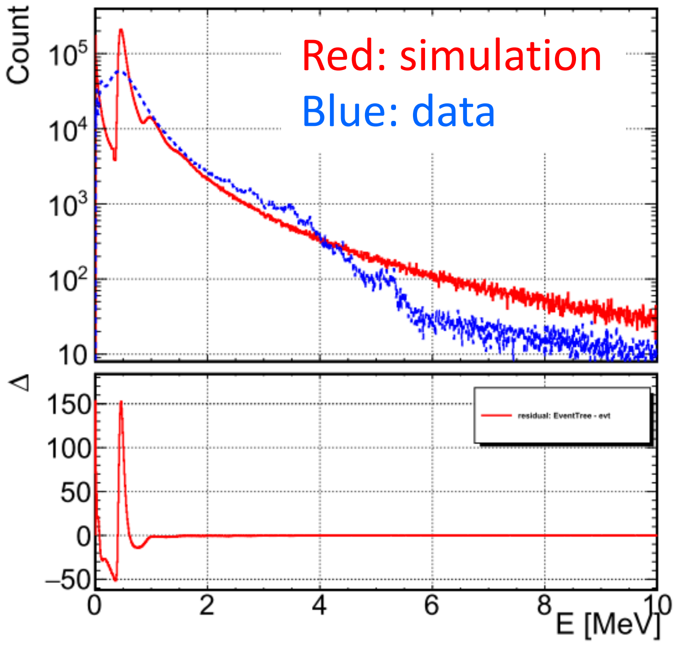
- AHCAL: comparisons of data vs MC
  - Muons: noises, channel-wise uniformity, etc.
  - Positrons and hadrons: work in progress
    - Beam contaminations, SiPM and ASIC saturation effects, etc.

Simulation and validation

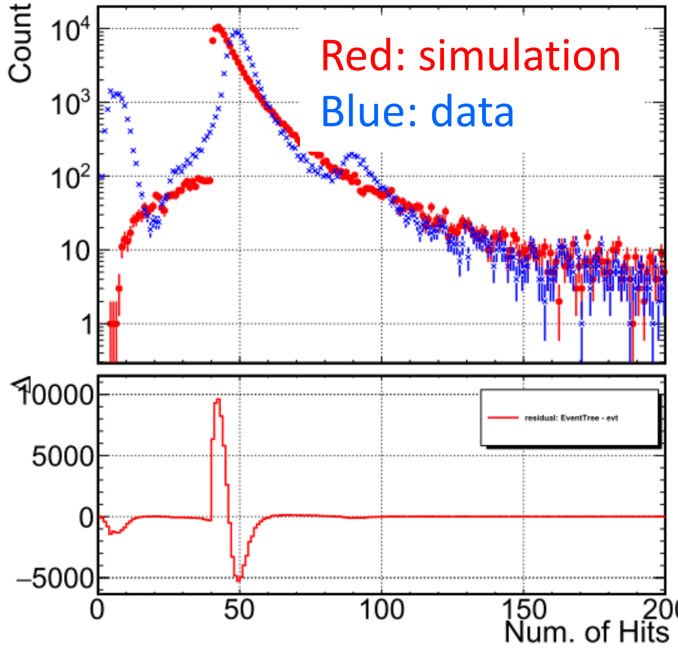
Yuzhi Che, Baohua Qi (IHEP)

- AHCAL: first data vs MC comparison
  - 160 GeV muons: data in blue (before calibrations of MIP, HG/LG), simulation in red
  - Data: MIP peak with significant spread in data (channel-wise non-uniformity)
  - More #hits in data → significant noises, and a second muon (2-MIP peak)

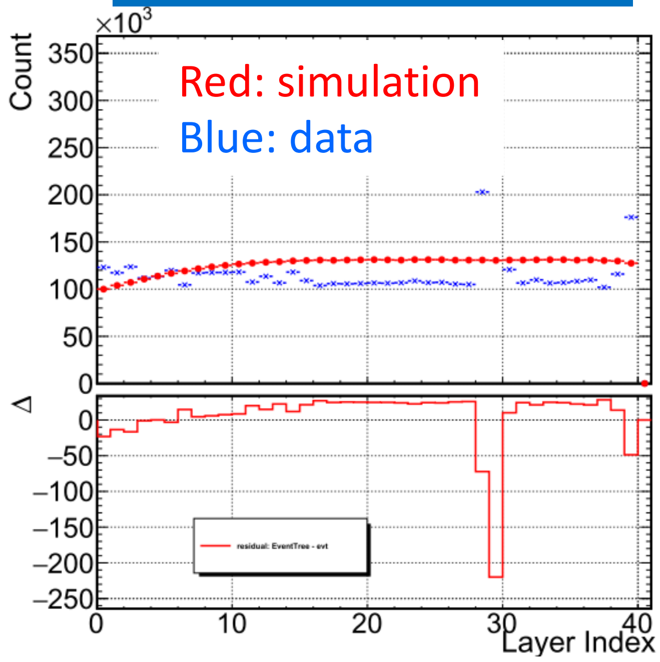
Hit-level energy



Total number of hits per event



Number of hits per layer



Simulation and validation

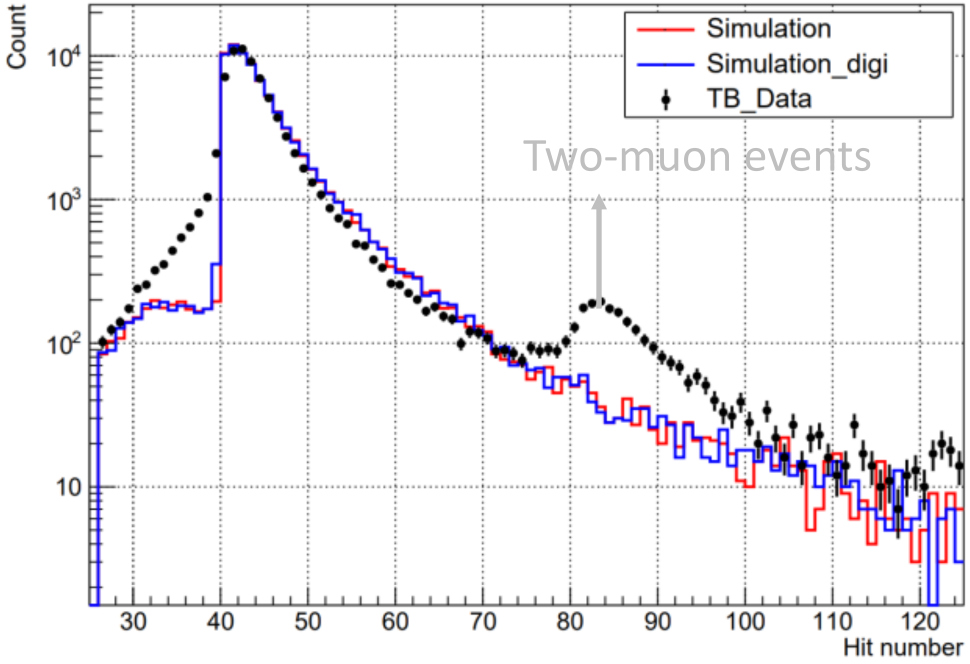
Dejing Du, Baohua Qi (IHEP)

- AHCAL: updated comparison

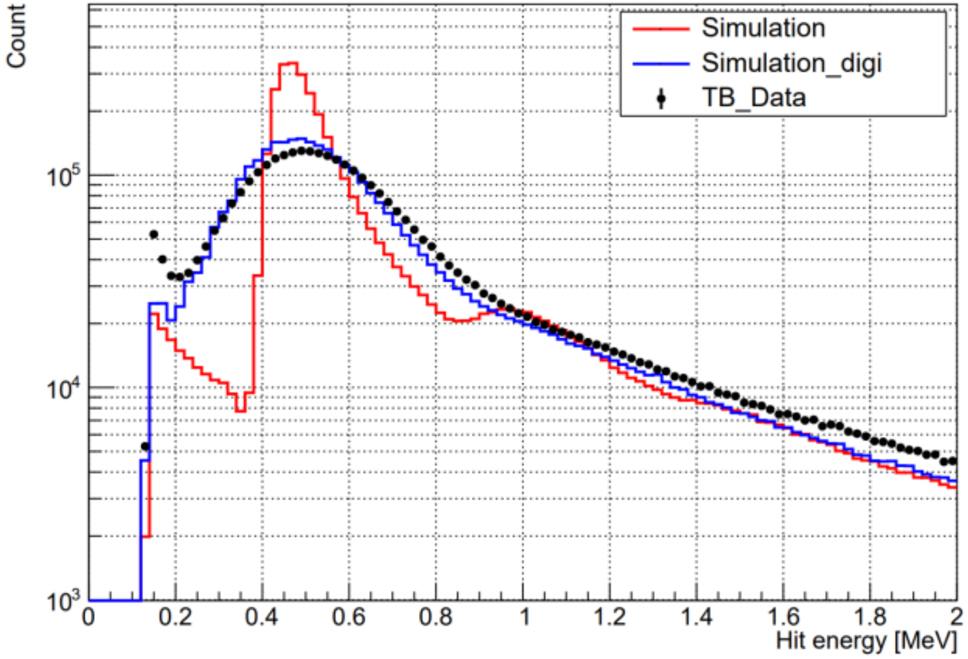
160 GeV muon data: Run 119

  - Energy threshold: 0.3 MIP; noisy channels with light leakage masked in data
  - MC can reasonably reproduce muon data; discrepancy in #hit spectrum

Number of hits per event

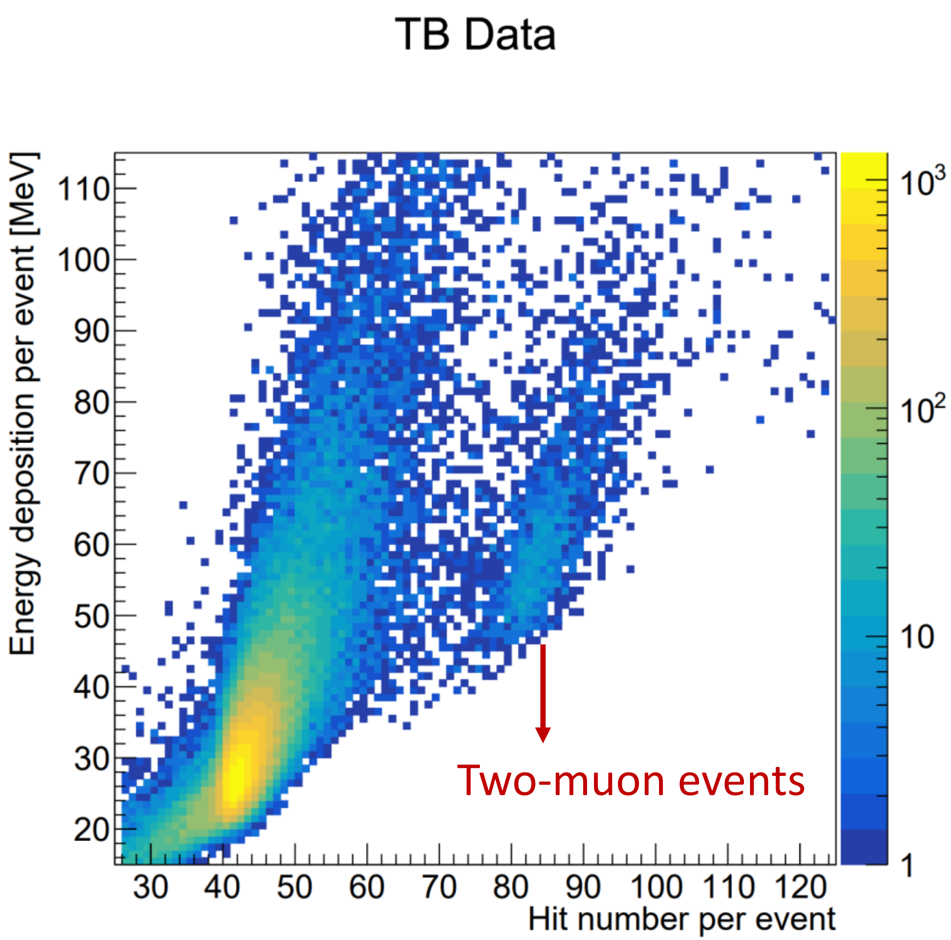


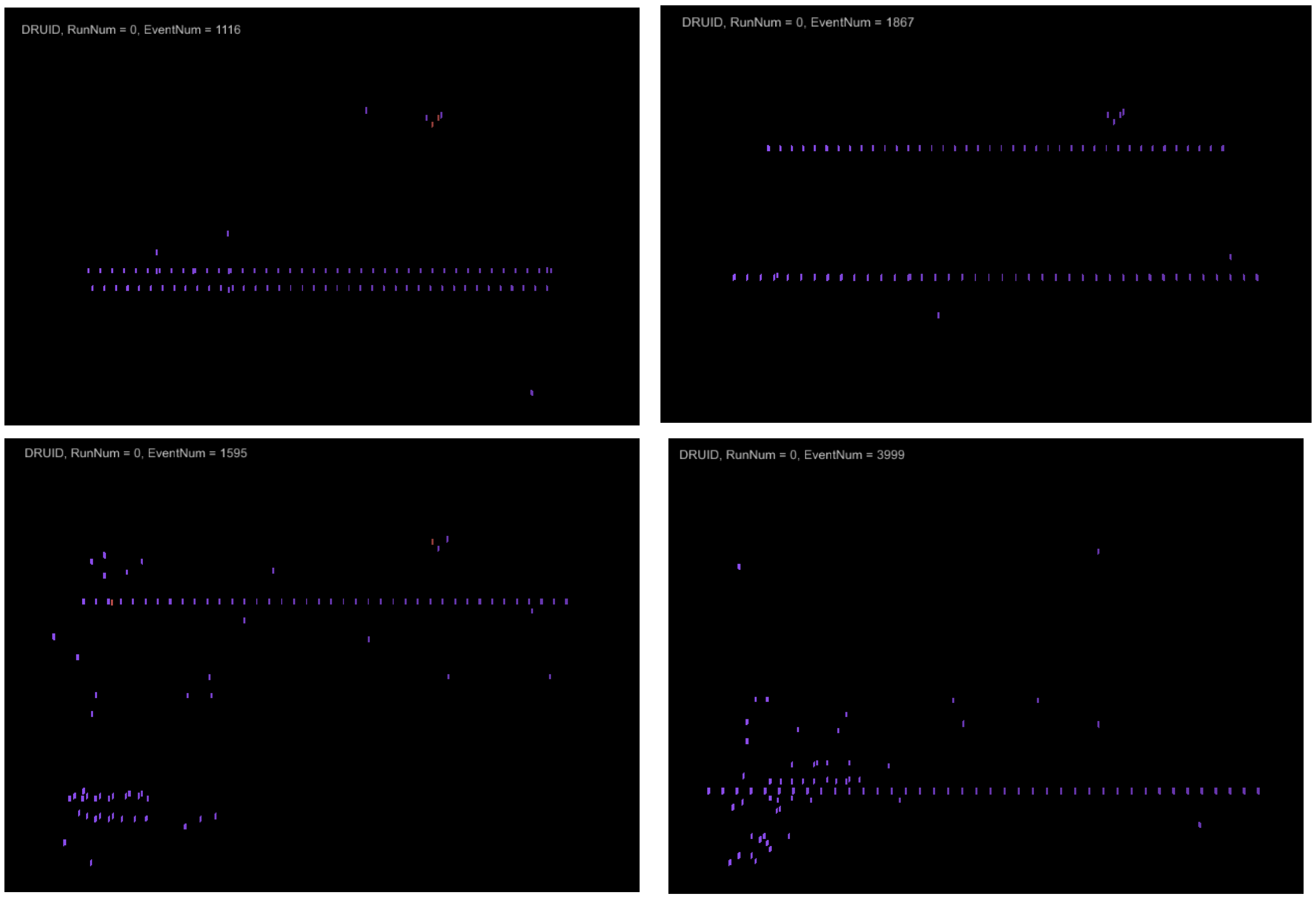
Hit-level energy



Event display: two-muon events

Dejing Du, Baohua Qi (IHEP)



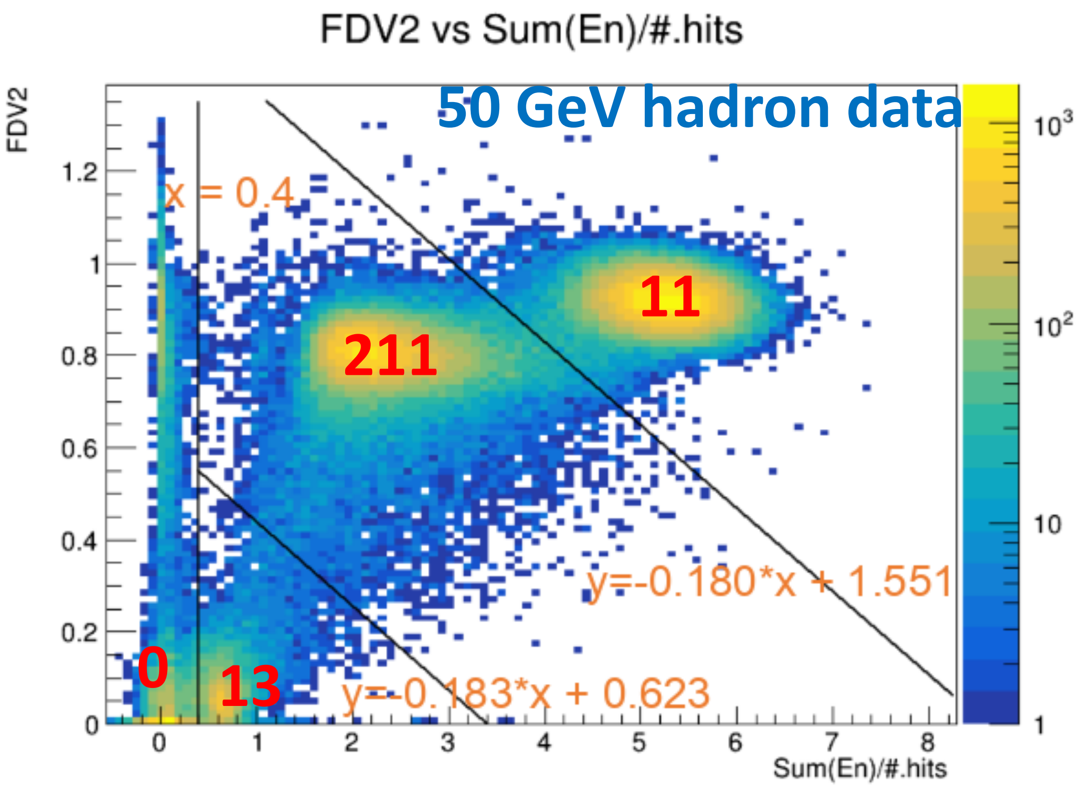


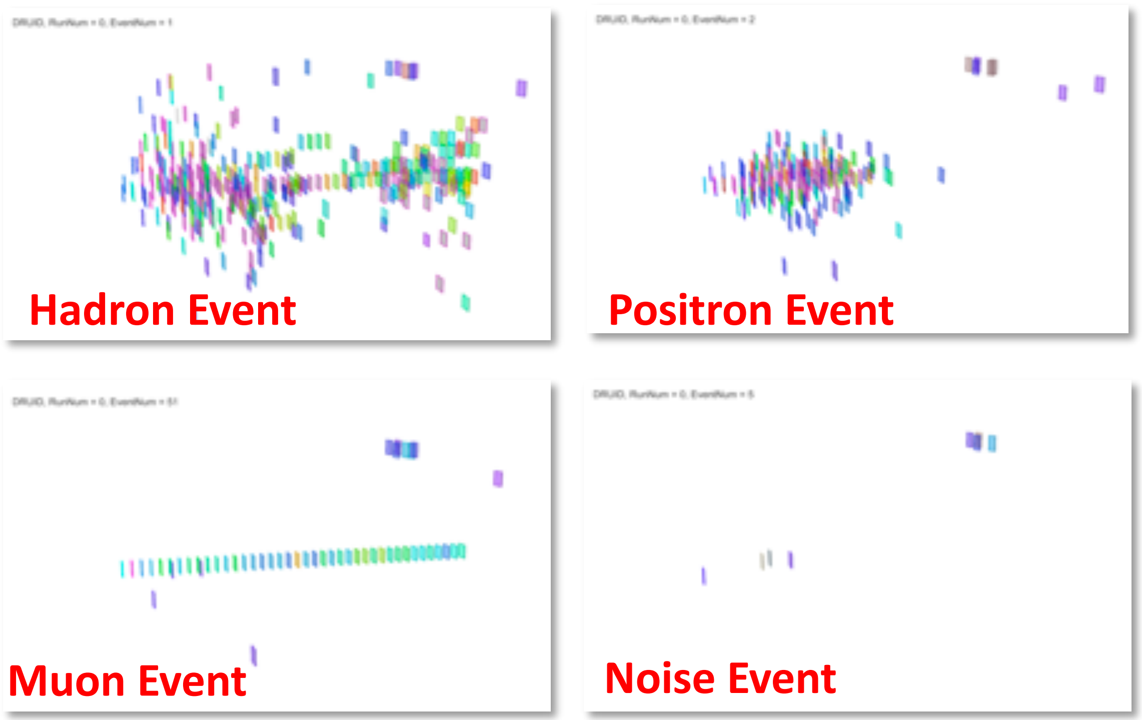
Also observed a few events with clusters of hits

PID studies: beam contamination

Xin Xia, Manqi (IHEP)

- PID to categorise events in data
  - Fractal Dimension: efficient PID of muons, positrons and pions
  - Cut-based selections → a major aim for high-purity samples at this stage





Fractal Dimension of Particle Showers Measured in a Highly Granular Calorimeter (M. Ruan et al, PRL 112, 012001)

Cherenkov detector data: a first glance

Ryunosuke Masuda (U. Tokyo)

- Threshold Cherenkov counter (XCET)
  - Two XCETs used in data taking
- Implementation in DAQ
  - Not involved in hardware trigger
  - 1 digit from each XCET
  - 2 digits read out along with AHCAL data for offline analysis
- XCET configurations
  - XCET-1 with minimum pressure (~0.02bar)
  - XCET-2 with higher pressure for protons (tuning for each momentum point)

AHCAL beamdata analysis

- Cherenkov counter efficiency

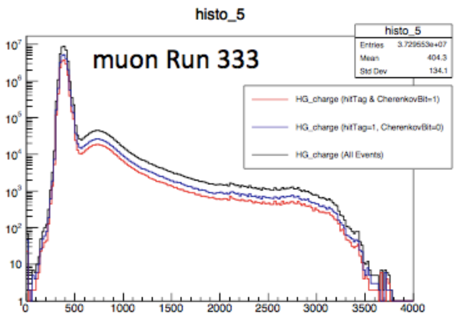
Defined as ratio (event whose Cherenkov bit is true)/(all event)

➡ Data scan has been finished

mu+ : ~ 41 [%]

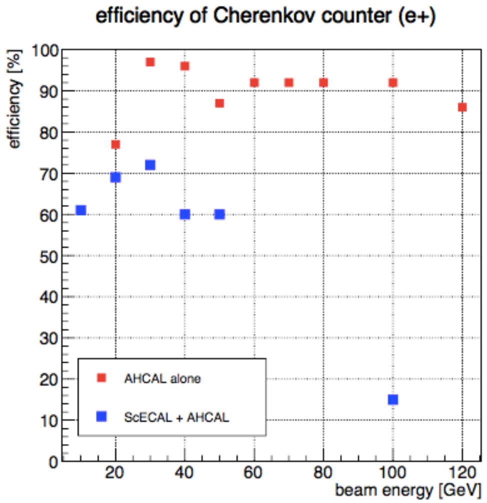
e+ : 15 ~ 97 [%]

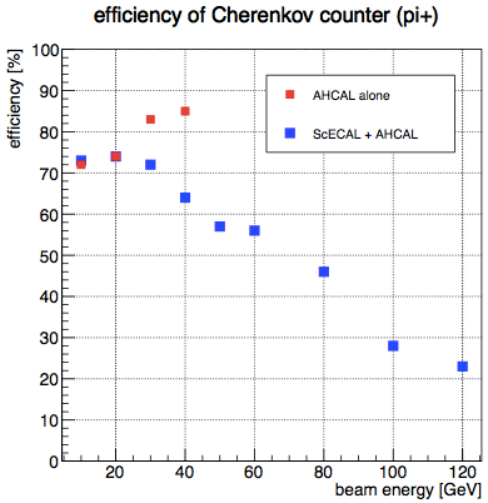
pi+ : 22 ~ 85 [%]



➡ The data of some measurement pattern don't have Cherenkov information

➡ For combined run, the efficiency tends to decrease as beam energy increases





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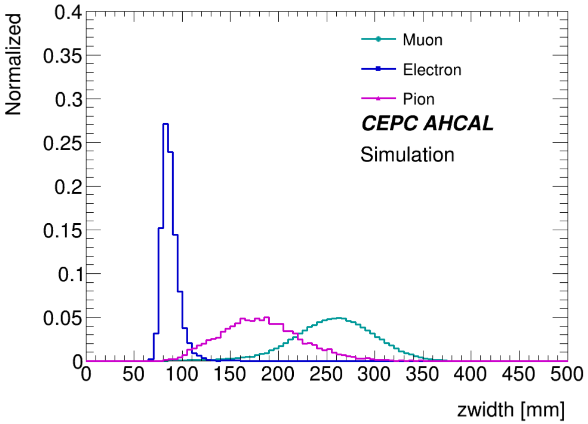
PID studies

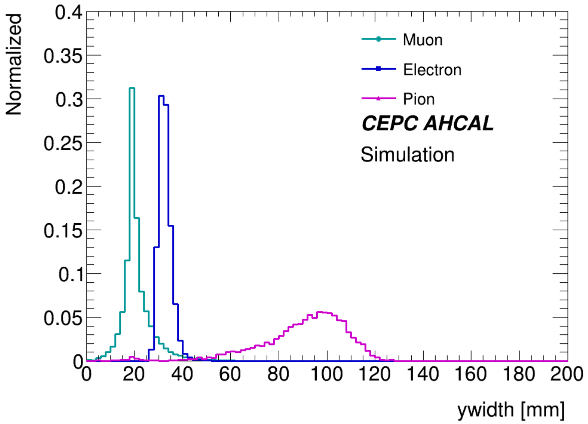
Siyuan Song, Zhen Wang (SJTU)

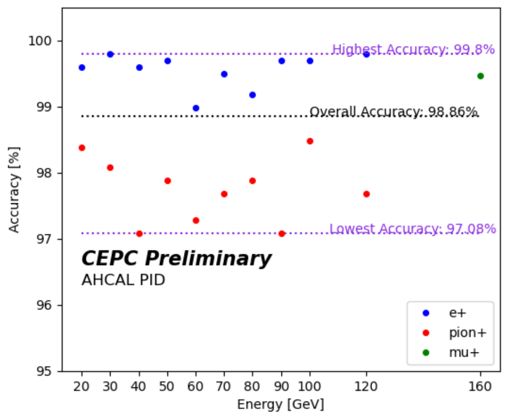
- Motivations: to study beam purity and mitigate beam contaminations
- PID techniques
  - Method 1: BDT with input variables (shower profiles, shower start layer,…)
  - Method 2: Artificial Neuron Network (ANN)
  - For MC samples: consistent with each other and both show accuracy above 98%
- Cherenkov counters (beam instrumentation): next slide

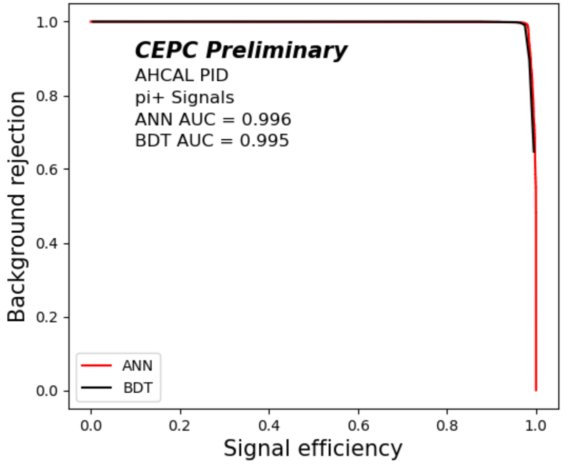
Longitudinal Center of Gravity



Transverse Center of Gravity

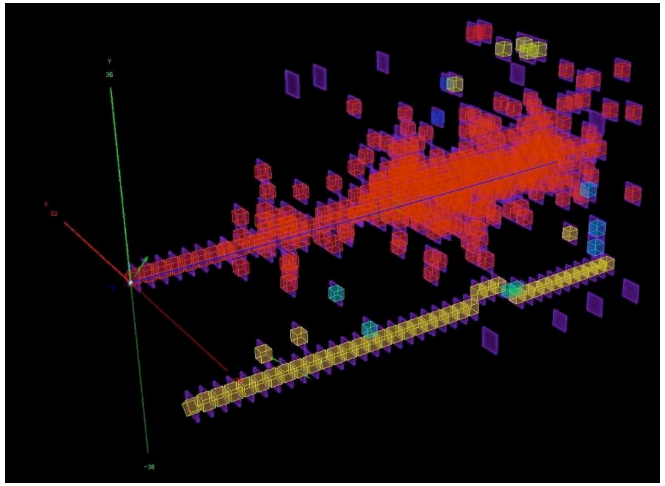
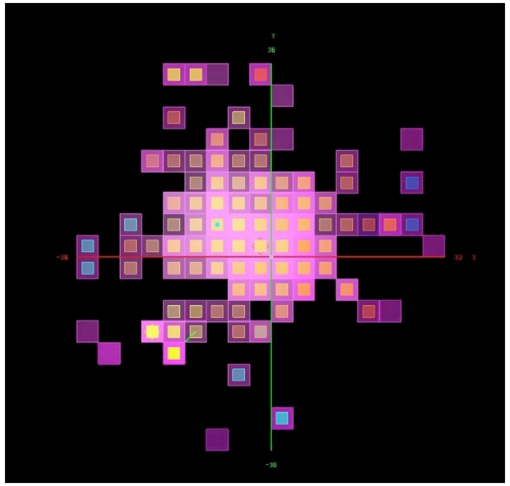
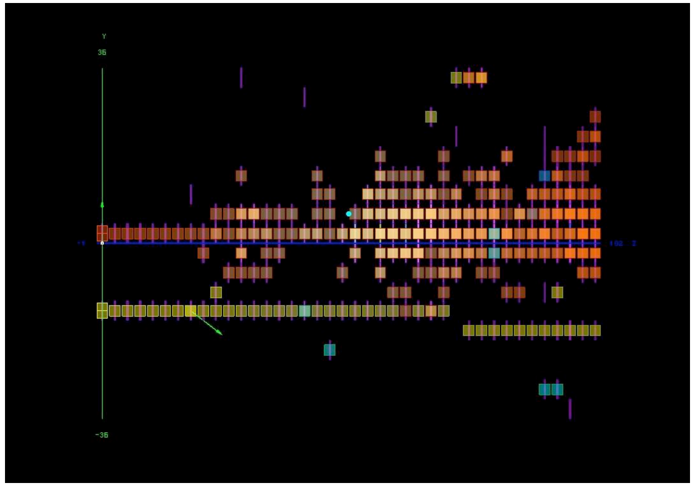






Arbor clustering studies with data

Yuzhi Che, Hengyu Wang, Xin Xia (IHEP)

Data Sample : AHCAL_Run144_20221024_073230 (120GeV e+)

- Qualitative studies with Druid event display
  - Color coding for different clusters
  - Clusters of two incident particles can be successfully reconstructed
- Quantitative studies: in progress
  - Clustering efficiencies: based on energy or #hits, for EM/hadronic showers

Brief summary of CERN beam test

- First experiences with two PFA calorimeter prototypes (~20k channels)
- Successfully completed all the plans, thanks to
  - Strong teamwork, robust detector system and stable SPS beam running
  - Great substantial support from CALICE and CERN
- Decent statistics of data sets collected (~25M events in total), enabling for
  - Highly granular calorimeter performance
  - Shower studies in 3D space and time domain
  - Validation of Geant4 simulation
  - Particle-flow algorithm studies: e.g. Arbor
- Ongoing data analysis
  - Calibrations done (pedestal, MIP, HG/LG), PID techniques to improve sample purity
  - EM/hadronic: detector performance (**linearity & resolution**) and shower properties

Acknowledgements

- CALICE calorimeter teams: strong team work
  - IHEP, SJTU, USTC; U. Shinshu, U. Tokyo; Weizmann
  - With funding support from MOST, NSFC, CAS, etc.
- CALICE collaboration
  - Management (Roman and Lucia) : coordination with CERN EP for the storage
  - Colleagues at SPS-H2 beamline for sharing experiences and information
- CERN
  - Experimental Areas group: transport, installation, beam tuning
  - HSE Unit: radiation protection support, safety training
  - PS/SPS coordinators: information exchange at weekly users meeting
  - EP department: coordination of platform certificate issue, prototype storage

Beamtest plans in 2023

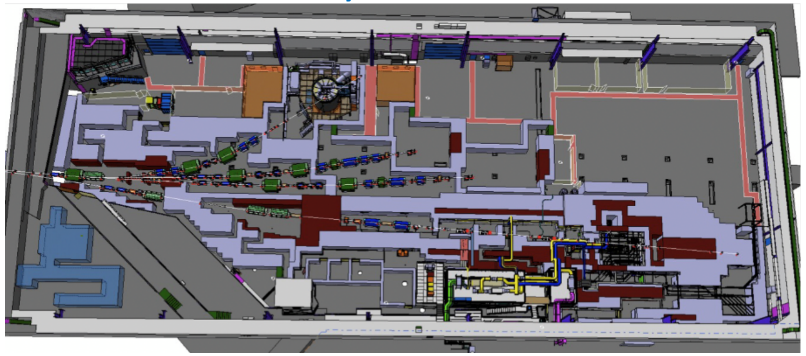
- Calorimeter prototype status: stored at CERN
- CERN beam tests: 2023 schedule
  - **Apr. 24 – May 10: 16 days at SPS H2**
  - **May 14 -31: 2 weeks at PS T9**

Storage at CERN B.190

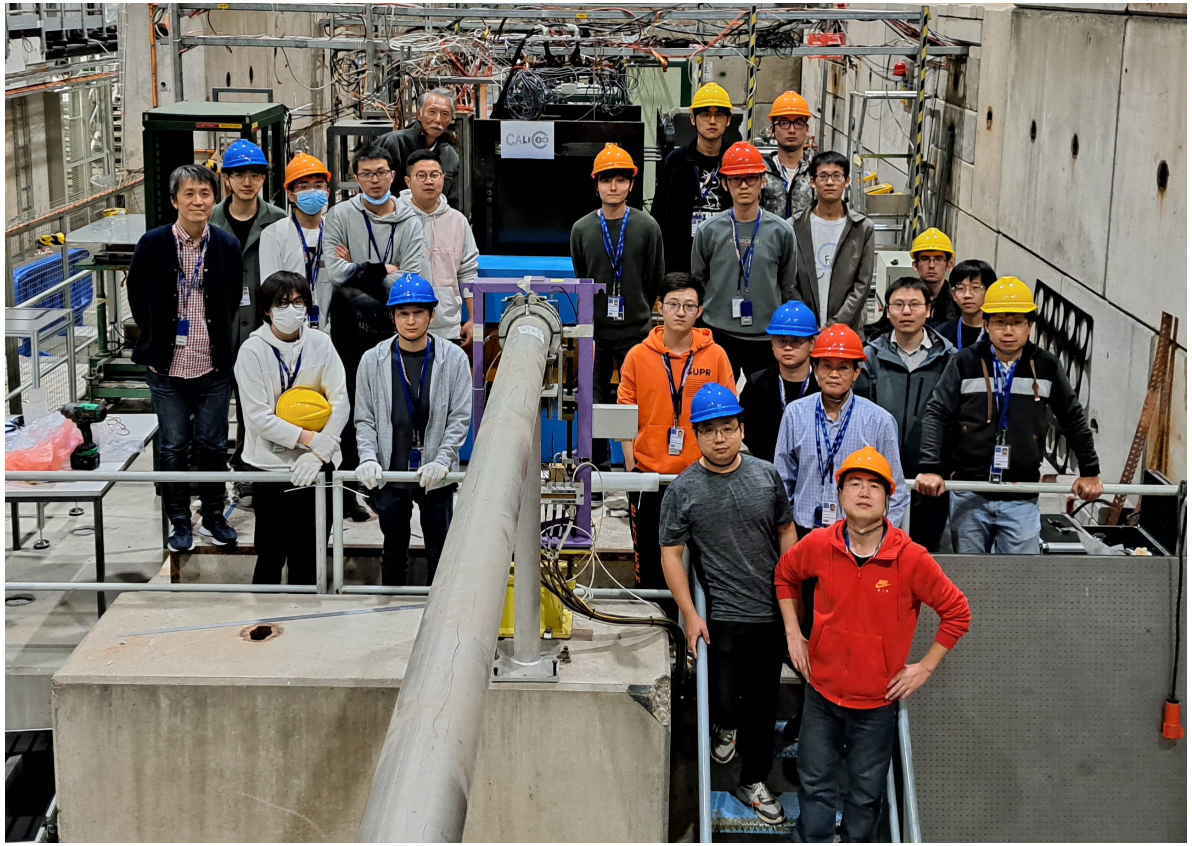

Our on-site visit to PS (Nov. 10, 2022)

- PS (T9): 1-15 GeV beam
- SPS (H2/H4): 10-120 GeV beam (high purity)

PS beamlines: layout after renovations



A big thank you



- IHEP: Yuzhi Che, Fangyi Guo, Peng Hu, Xinghua Li, Yong Liu, Baohua Qi, Qi Wu
- SJTU: Francois Lagarde, Siyuan Song, Zhen Wang, Haijun Yang
- USTC: Hao Liu, Jianbei Liu, Zhongtao Shen, Yukun Shi, Jiaxuan Wang, Yunlong Zhang
- U. Shinshu: Tohru Takeshita
- U. Tokyo: Ryunosuke Masuda, Tatsuki Murata, Wataru Ootani,, Yuki Ueda
- Weizmann: Luca Moleri, Giannis Maniatis

Spare Slides

Arbor clustering studies with data

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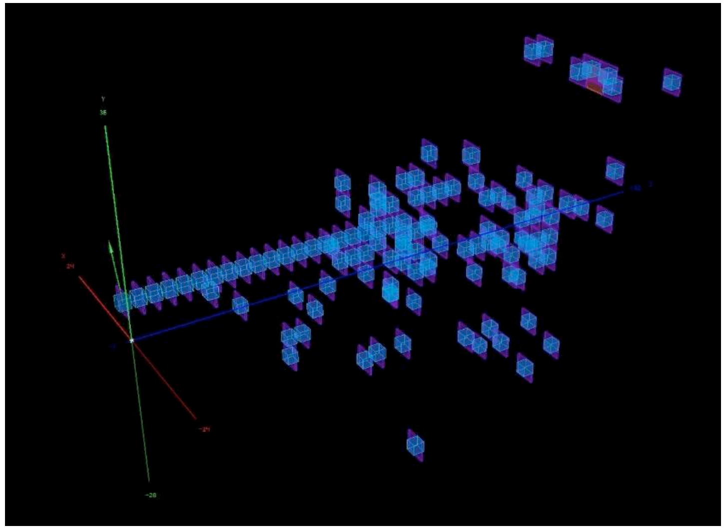
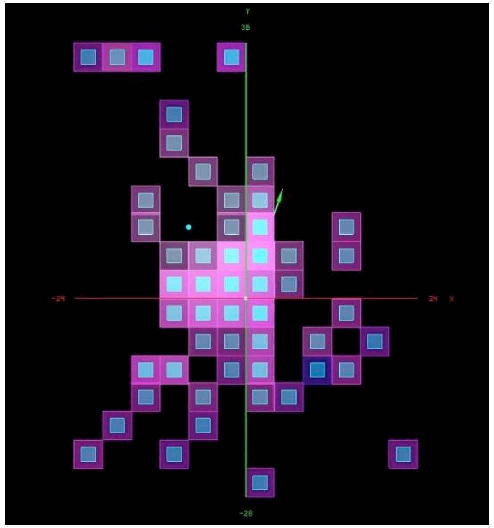
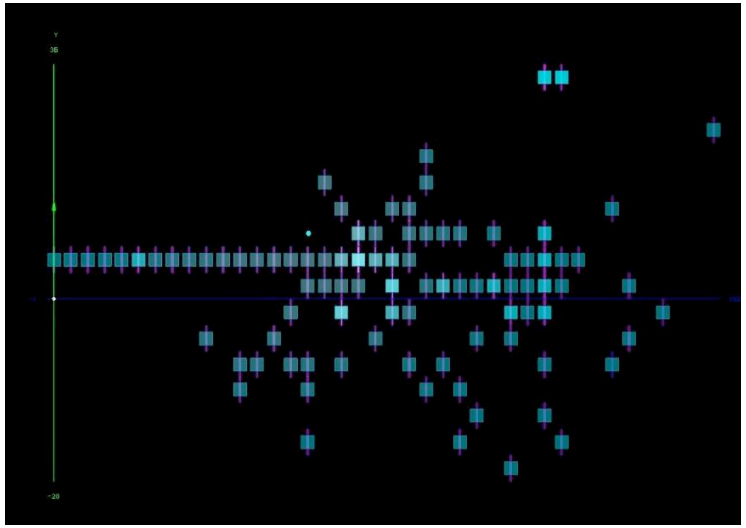
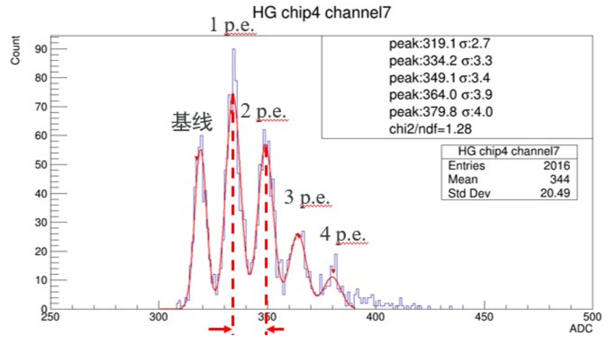
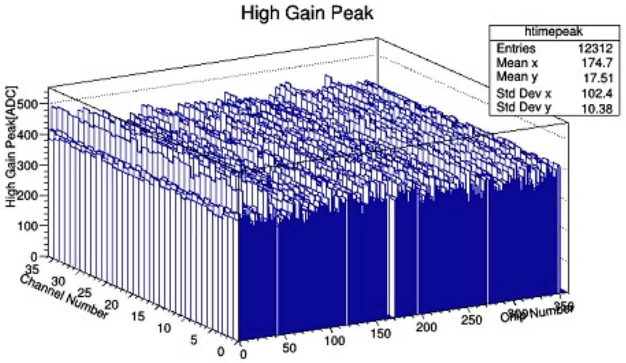
- Qualitative studies with Druid event display
  - Larger cube: raw hits in data; small cube: reconstructed hits in clusters
  - Color coding for different clusters
  - Most hits are correctly reconstructed as a single cluster (major shower part), with a few noise hits and isolated hits

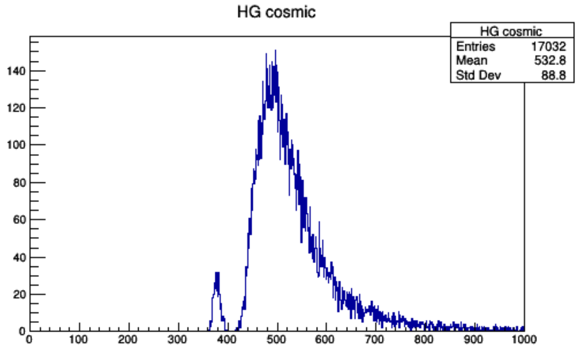




Data Sample: AHCAL_Run156_20221024_231347 (10GeV pi+)

AHCAL: assembly and commissioning (August 2022)



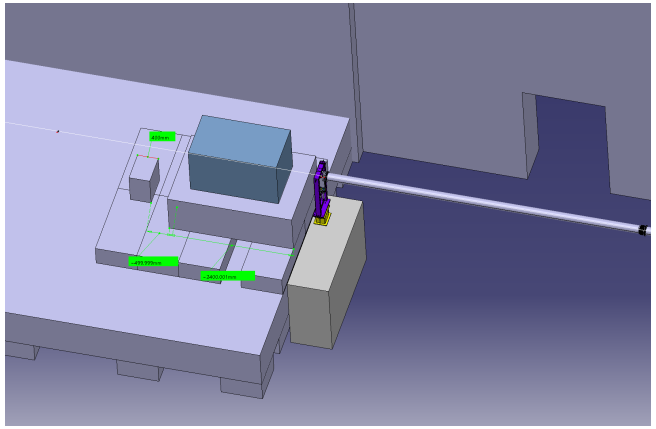


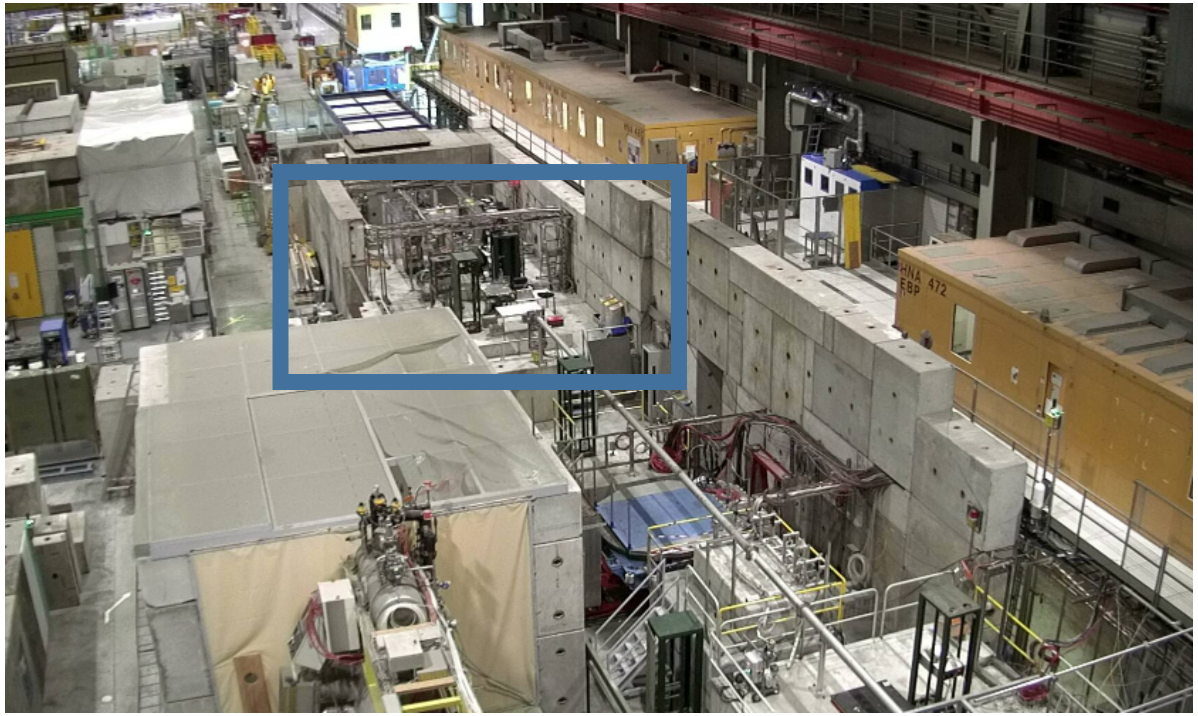


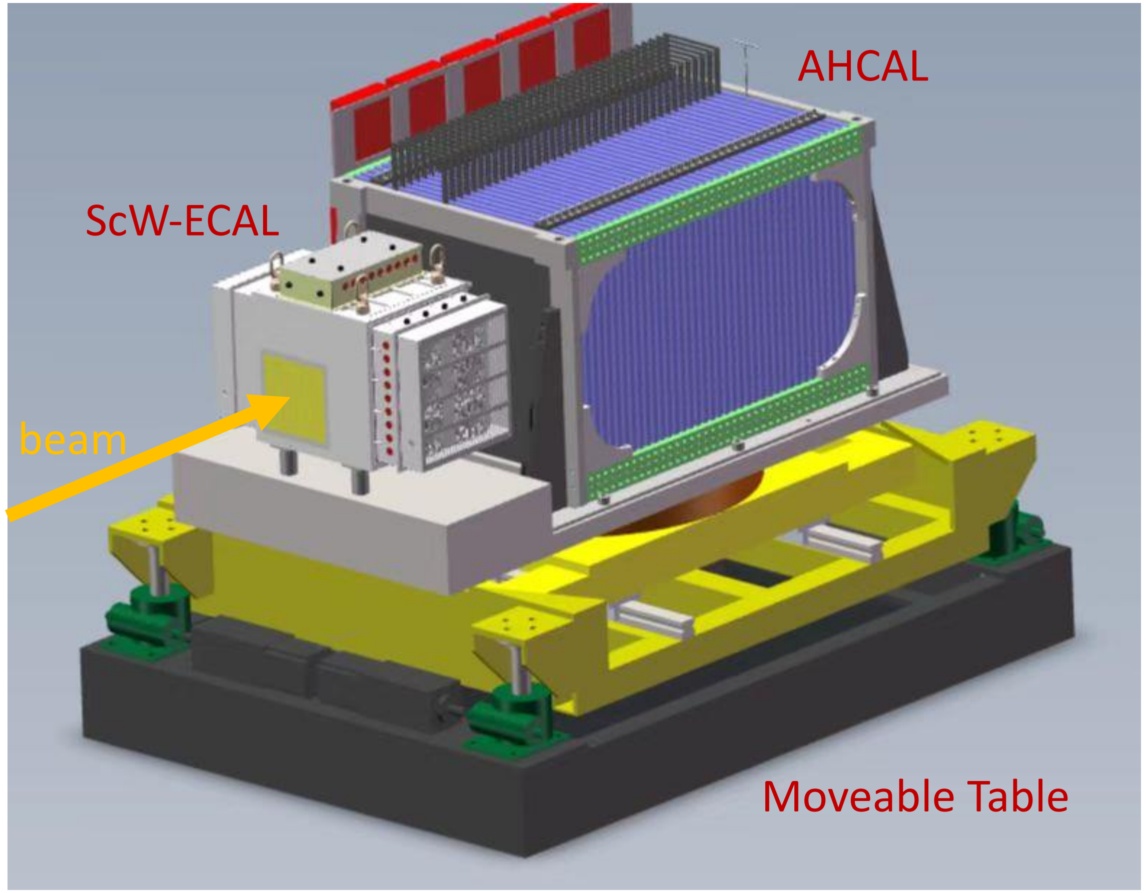
- HBU assembly and commissioning with DAQ at USTC
  - Pedestal runs and calibration
  - LED data for SiPM gain calibration
  - ASIC inter-calibration: High Gain vs. Low Gain
- Cosmic-ray tests: MIP peaks can be seen for most layers
- Joint efforts of USTC, IHEP and SJTU: “rehearsals” for the beamtest

H8 beam area arrangement

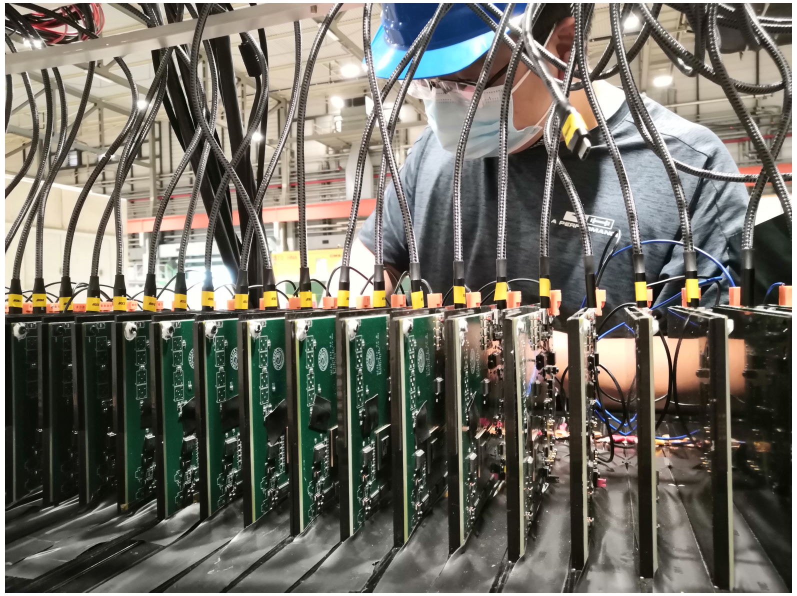
Technical discussions with Michael Lazzaroni (CERN)







Unpacking and installations



Yong Liu (liuyong@ihep.ac.cn)

AHCAL pion beam data

- Plans for AHCAL (alone) with pion+ beam
  - 1M events per energy point
  - Accumulate more statistics at one or two low energy point
- Data taking
  - Successfully completed plans
  - SPS running very smoothly and with high beam intensity during Oct. 20 – 26
- Beam purity: issue and solution
  - Contaminations of pion+ beam with protons (energy dependent)
  - 2 Cherenkov counters implemented in DAQ: recorded in data, not part of hardware trigger

AHCAL data list (pion+)

Momentum (GeV)	Number of Events	Total Runs
120	1086169	8
100	1392510	8
90	1118714	8
80	1040225	8
70	1038162	7
60	1074803	9
50	1066431	6
40	1339732	8
30	2108208	10
20	2059772	14
10	675699	5

AHCAL positron beam data

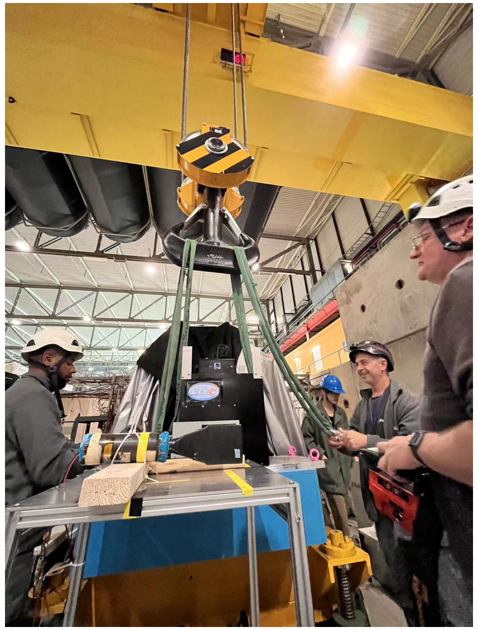
- AHCAL (alone) with e+ beam
  - Plan: ~200k events per energy point
  - Successfully completed the plan within half a day
  - Thanks to SPS smooth running
- Beam purity: issue and solutions
  - Contaminations of e+ beam with hadrons: generally lower positron purity when beam energy increases
  - 2 Cherenkov counters implemented in DAQ: recorded in data, not part of hardware trigger
  - Shower profiles: EM vs hadronic

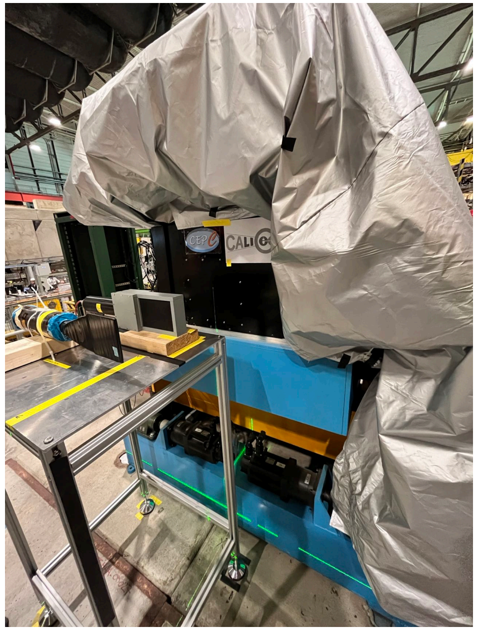
AHCAL data list (e+)

Momentum (GeV)	Number of Events	Total Runs
20	337956	2
30	193054	2
40	159087	2
50	220352	2
60	253464	2
70	189186	2
80	429414	3
100	196267	2
120	286107	2

ScW-ECAL and AHCAL: combined beam test

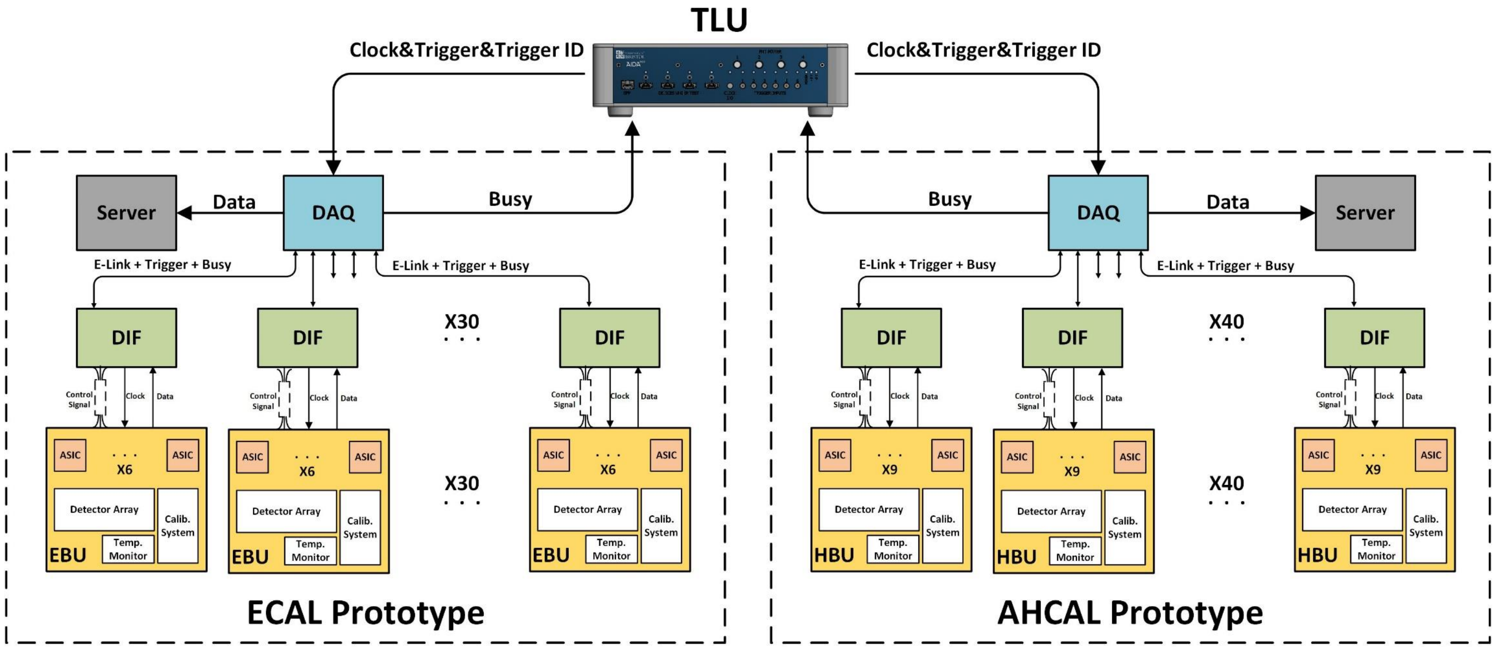
- 120 GeV secondary hadron beam used (180 GeV in the first week)
  - Trying to improve the beam intensity
- Muon beam: wide profiles for MIP calibration
- Positron and pion beams: energy scans

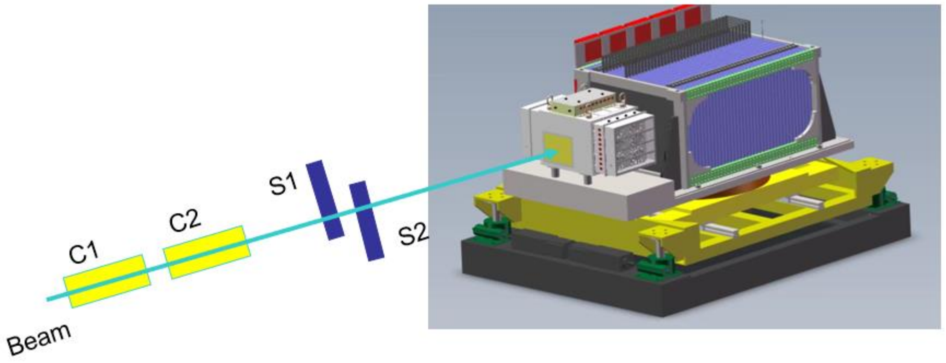




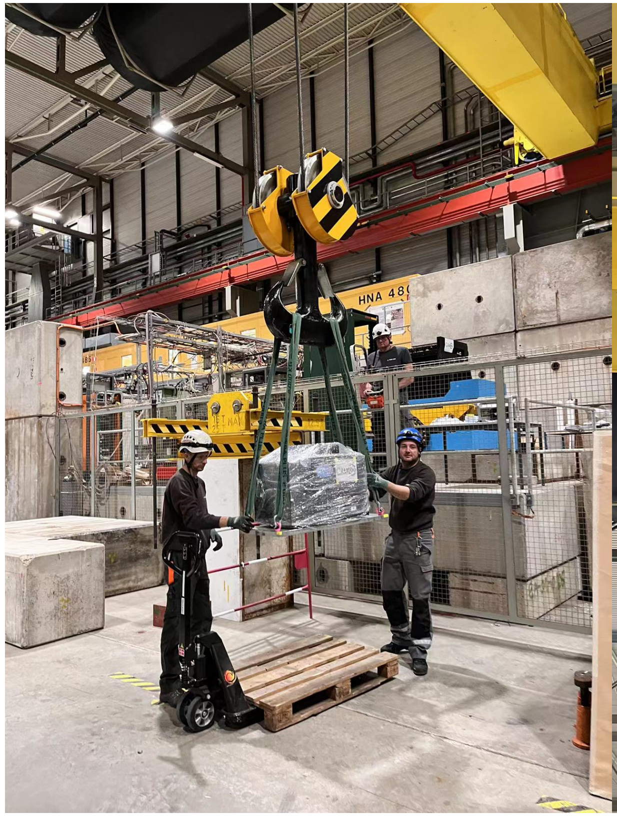
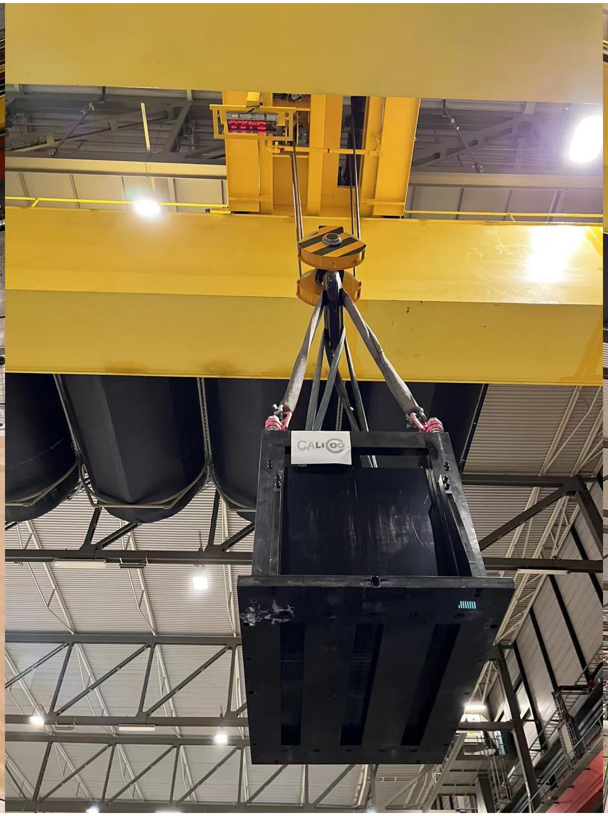
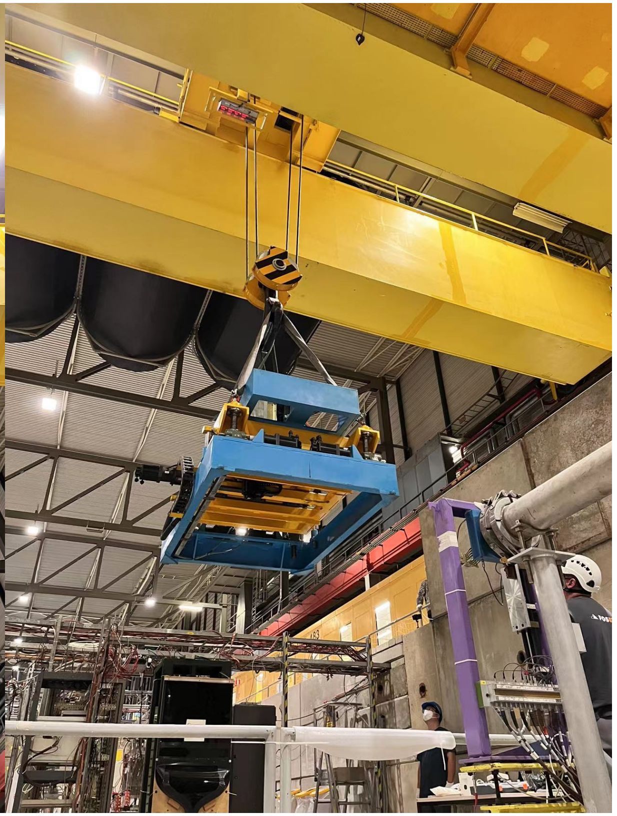
ScW-ECAL and AHCAL: integrated DAQ system

- Integration of 2 DAQ systems
  - ECAL DAQ: 30 DIFs and 1 data aggregator board
  - HCAL DAQ: 40 DIFs and 1 data aggregator board
  - Synchronise via TLU (Trigger Logic Unit) using Trigger ID





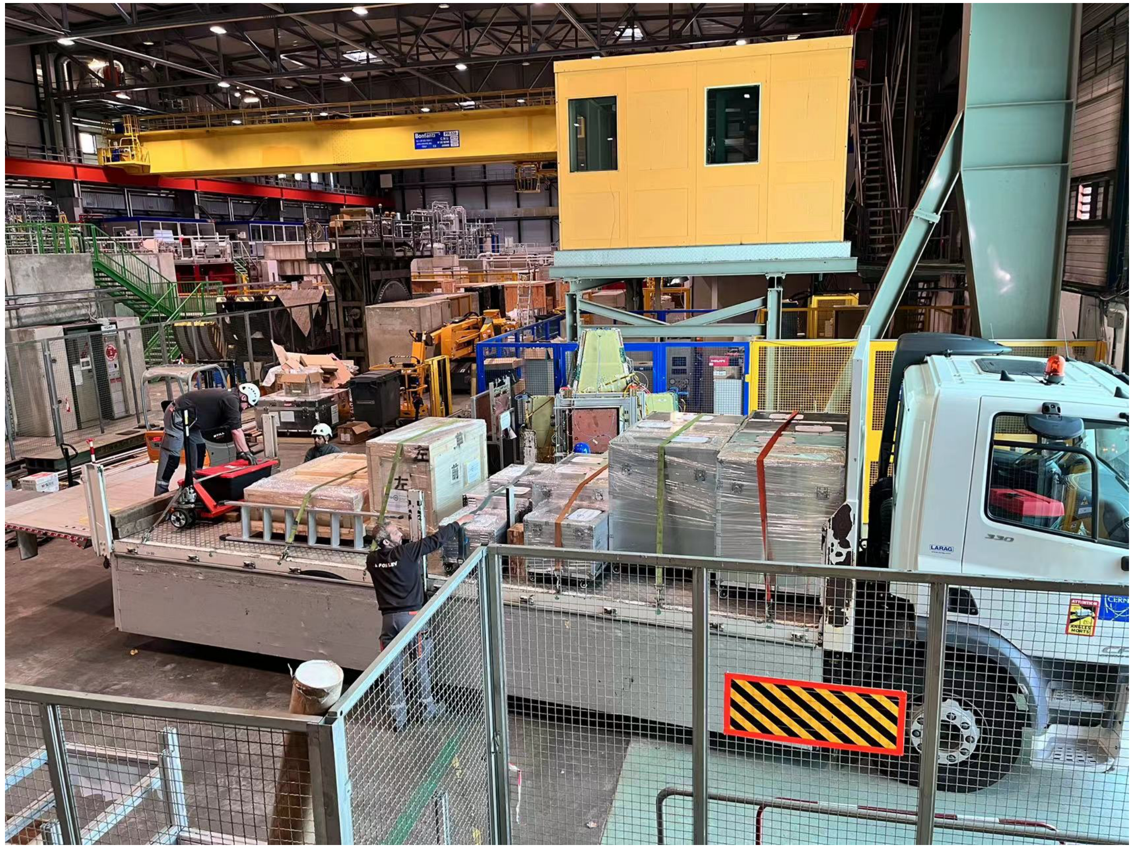
Decommissioning and transport


- Successfully moved out of the beam area (Nov. 2)
  - ECAL + HCAL prototypes, support table

Transport and storage at CERN

- Internal transportation and storage at Building 190: completed in Nov. 9
  - Thanks to the CERN EP support and coordinating efforts of CALICE management



Taskforce on CERN testbeam data

- Taskforce on data conversion and analysis (same groups that participated the CERN beamtest)
  - Data conversion and cross checks (4): Jiaxuan Wang, Yukun Shi; Yuzhi Che; Francois Lagarde
  - Event display (5): Siyuan Song, Zhen Wang; Yuzhi Che, Baohua Qi, Hengyu Wang
  - Data analysis and software tooling (5): Hongbin Diao, Jiaxuan Wang, Yukun Shi; Yuzhi Che; Francois Lagarde
  - Full simulation and validation (5): Dejing Du, Baohua Qi; Yukun Shi; Zhen Wang, Zixun Xu
  - Arbor clustering studies (3): Yuzhi Che, Hengyu Wang, Xin Xia
  - Japanese groups on ScW-ECAL performance (5): Ryunosuke Masuda, Tatsuki Murata, Wataru Ootani, Tohru Takeshita, Yuki Ueda
  - Coordination: Yong Liu
- Institutions involved in the taskforce
  - China (14): IHEP, SJTU, USTC
  - Japan (5): U. Shinshu, U. Tokyo
- Weekly meetings: updates, questions and discussions
  - https://indico.ihep.ac.cn/category/322/
- Welcome new members to join
  - A full task list (evolving) prepared for data analysis