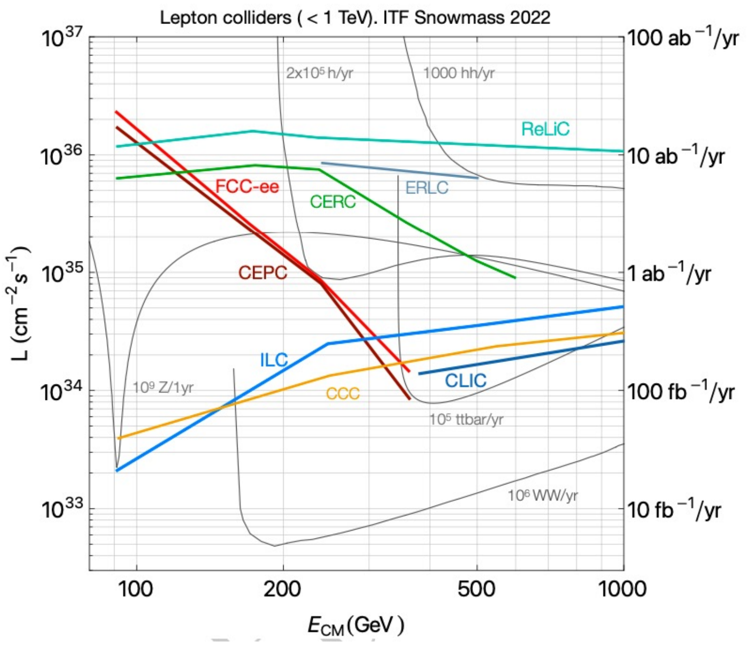
CERN Beamtest of Calorimeter Prototypes

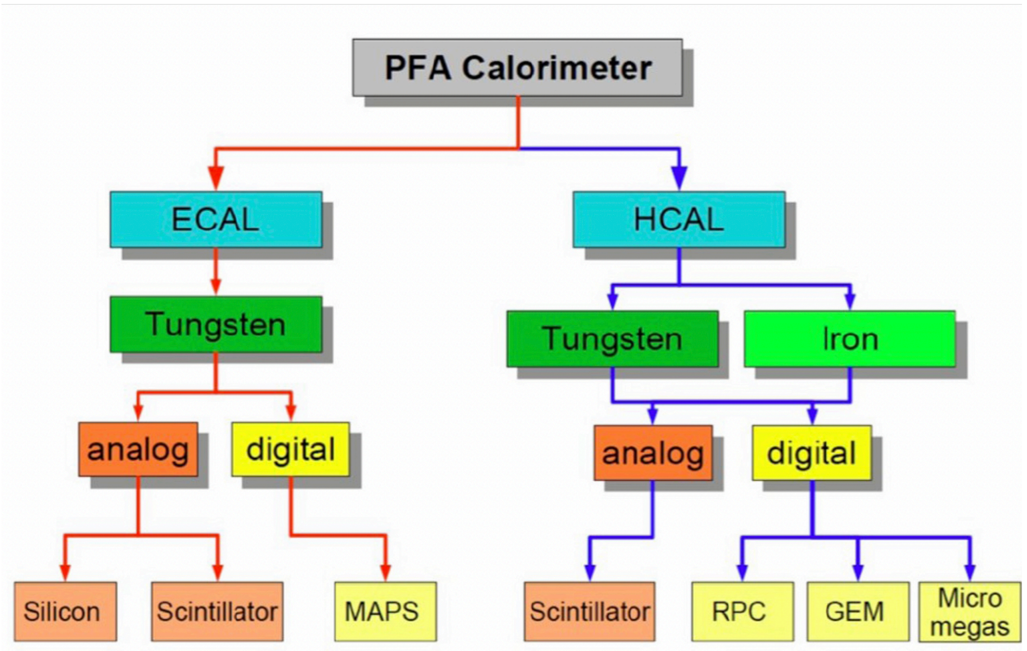
Yong Liu (IHEP),

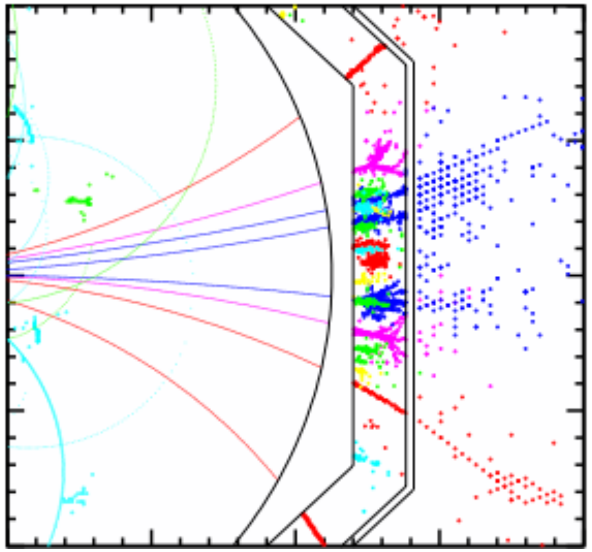
for the CALICE and CEPC Calorimeter teams

Feb. 12, 2023

High granularity calorimetry



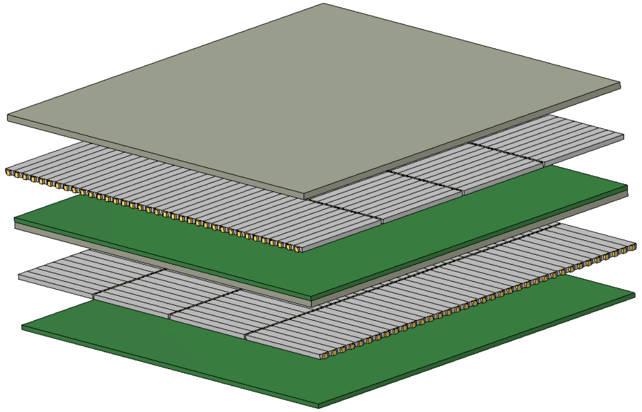




- Future Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major calorimetry option: highly granular (imaging) + particle flow algorithms (PFA)
- PFA calorimetry: various options explored in the CALICE collaboration
  - Selected technical options presented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

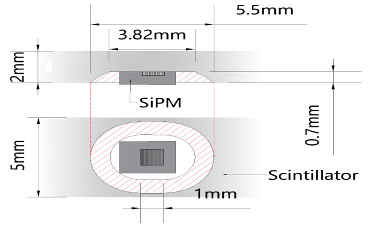
Scintillator-tungsten ECAL prototype

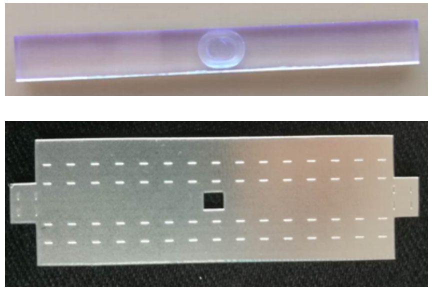
Sampling structure: scintillator strips + tungsten-copper plates



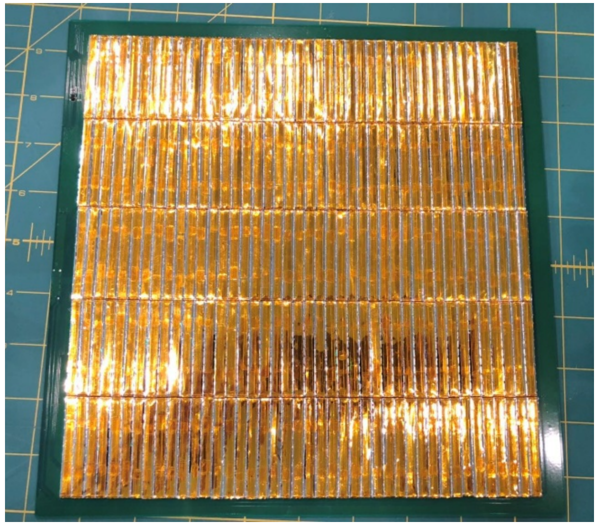
ScW-ECAL prototype

Detector unit: scintillator + SiPM

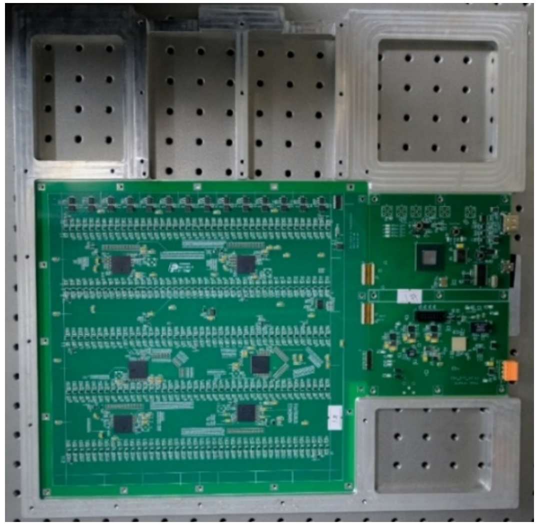




One sensitive layer (EBU): fully integrated with ASICs

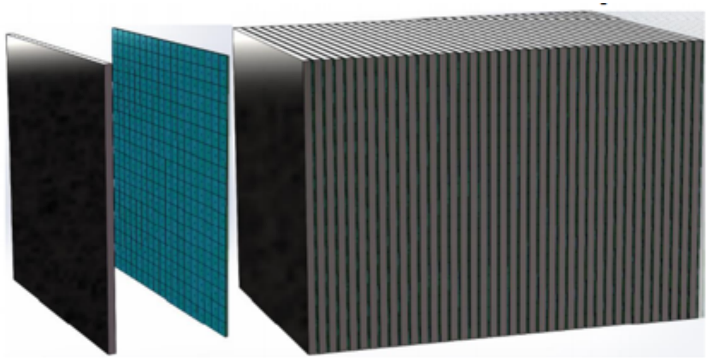


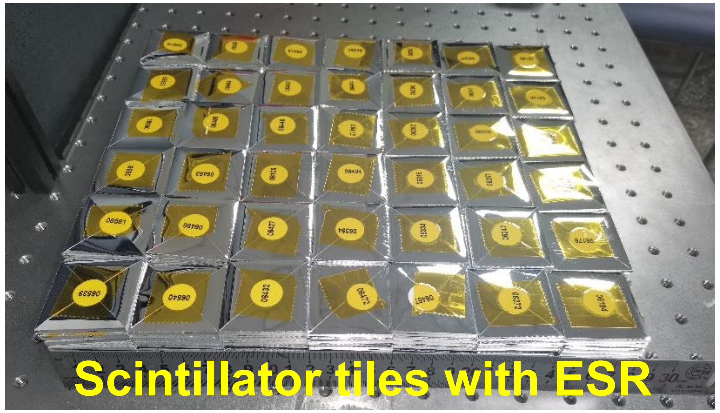
Two EBUs + absorber: integrated with mechanics



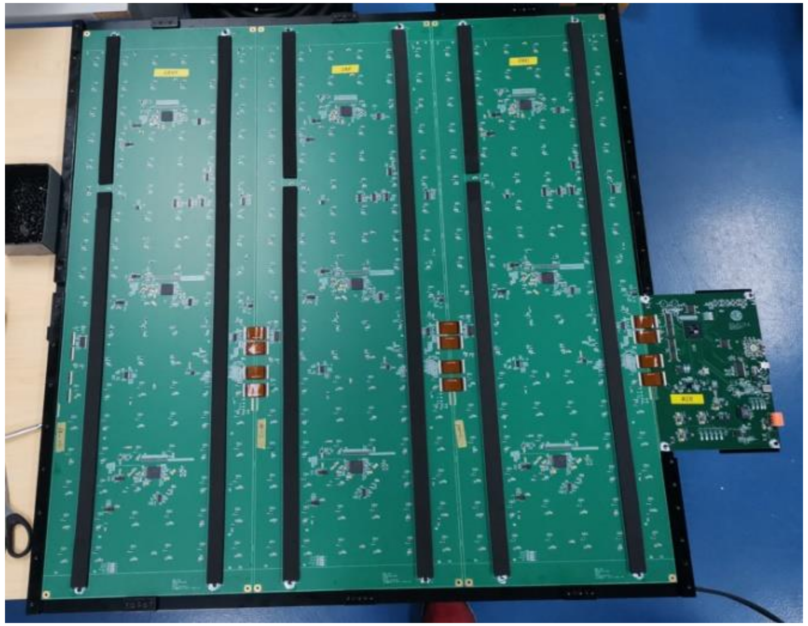
- ScW-ECAL prototype
  - Transverse size $\sim 22\times 22\ \mathrm{cm}^2$, 32 longitudinal layers ($\sim 25X_0$)
  - 6700 readout channels, ~300 kg in weight
  - Developed during 2016 – 2020
  - Tested with beams at BEPCII-TBF (IHEP) and cosmics at USTC

Scintillator-iron HCAL prototype





1 full layer: 3 HBUs + cassette

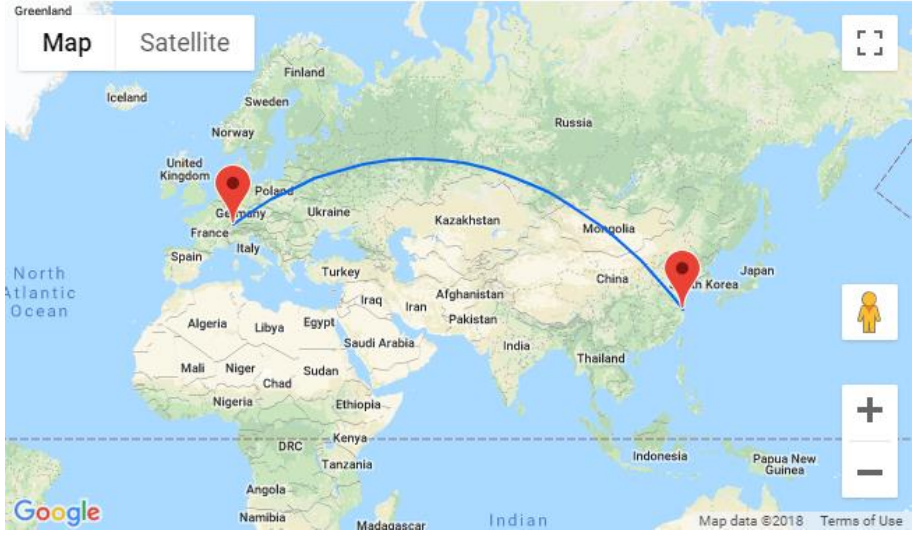


Mechanics Integration

- 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

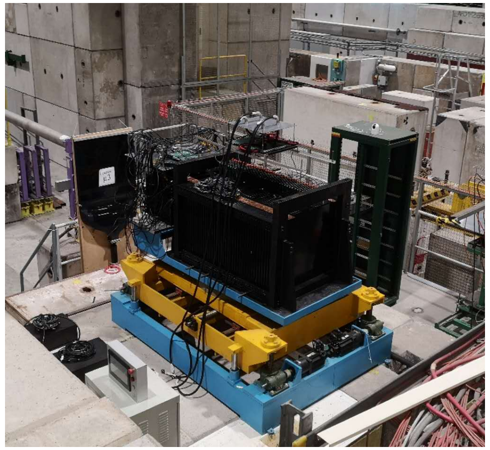
Calorimeters in flight



Flying calorimeter

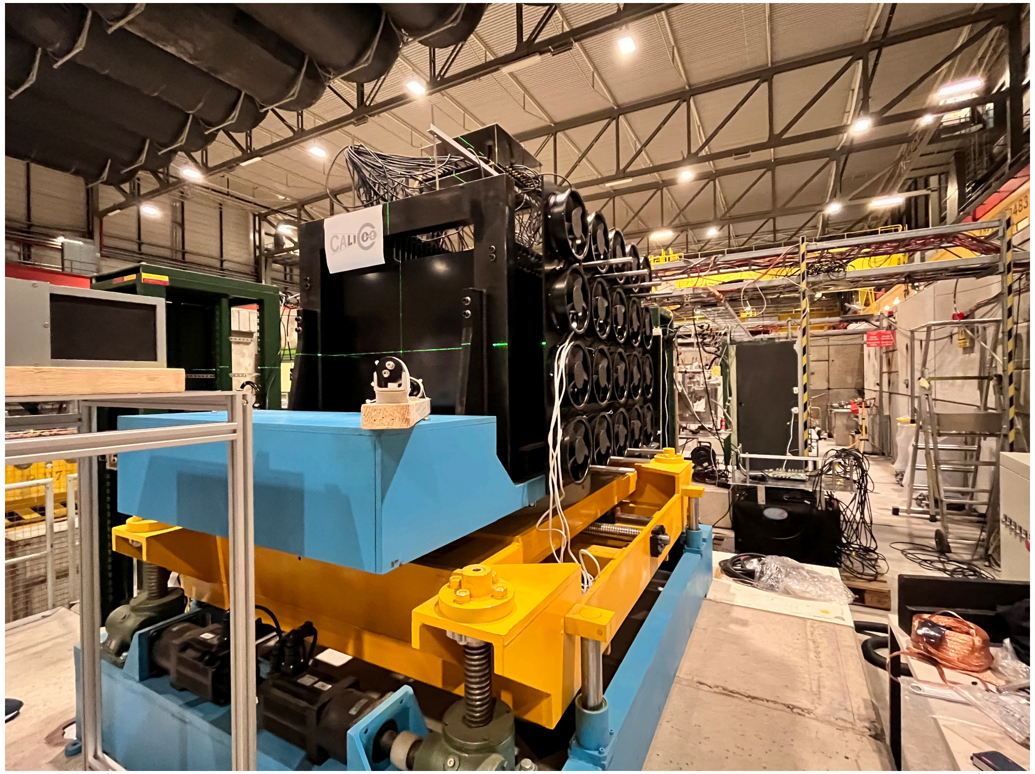
Before cabling

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

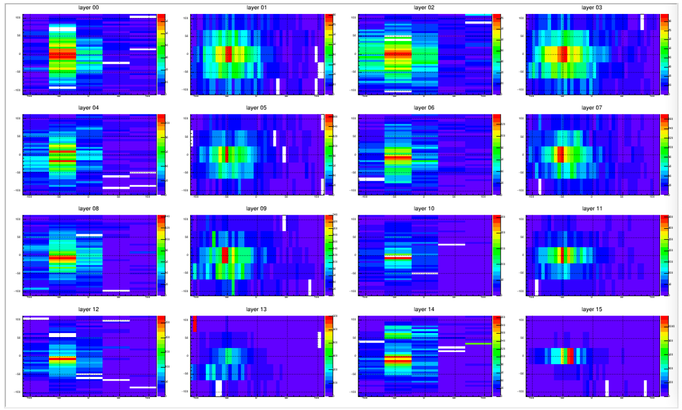


AHCAL prototype alone in H8 beam line
(the 1st week as main user in Oct. 19-26)

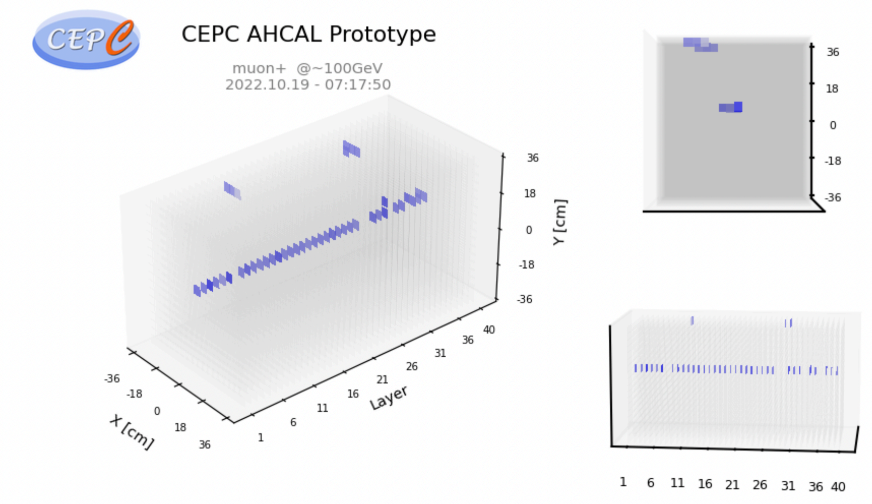
- Muon beam: 160 GeV (1st week); 108 GeV (2nd week)
  - MIP calibration → energy reconstruction
- Positron beam: 10 - 120 GeV
  - Compact EM showers → high energy density → SiPM saturation corrections (essential)
  - EM performance
  - Validation of simulation and digitisers
- Pion beam: 10 - 120 GeV
  - 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

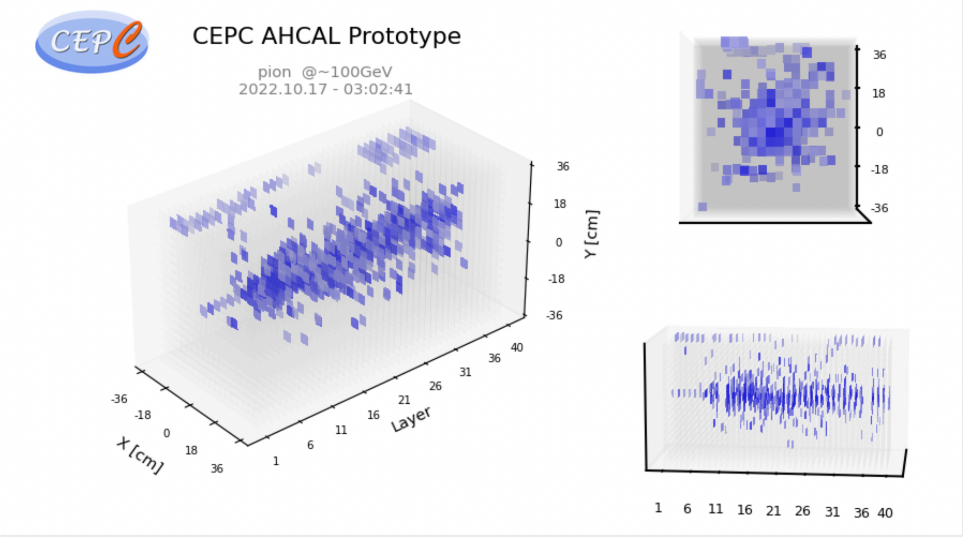
Muons in ECAL: Hit Maps



Muon MIP track in HCAL



Pion hadronic shower in HCAL

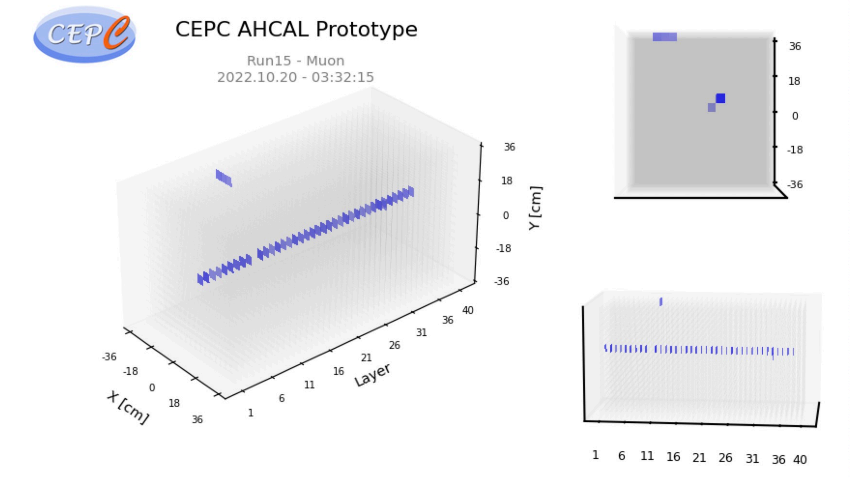


- Motivations: full system commissioning; muons for MIP calibration
- Successful data taking with parasitic beams (Oct. 14-19, 2022)
  - Setup: combined ECAL and HCAL, in downstream of LHCb detectors
  - Beams: 160-180 GeV muon+ or pion+
  - Thanks to the LHCb team (muon detector)

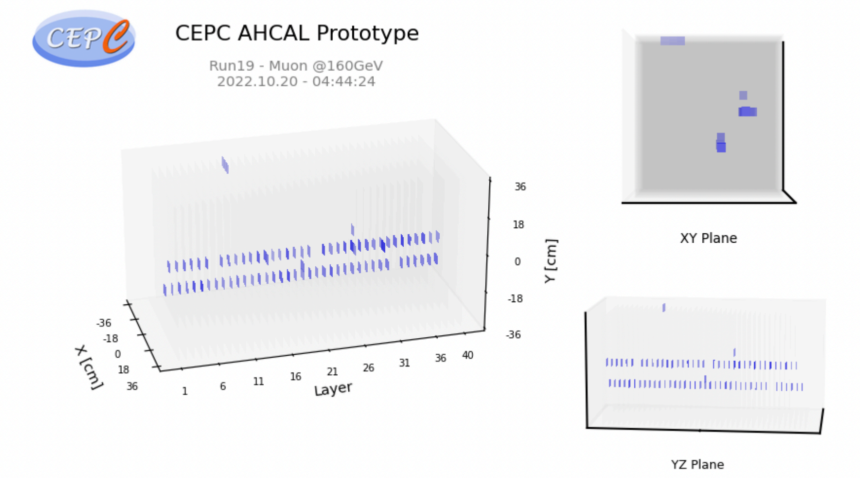
AHCAL prototype with muons

- Muon beam (~160 GeV)
  - Normal incidence to the calorimeter plane
  - Wide beam profile: covers AHCAL lateral area ($72\times72\ \mathrm{cm}^2$)
  - Threshold scans, SiPM bias voltage tuning (all 40 layers)
  - Data sets for MIP calibration

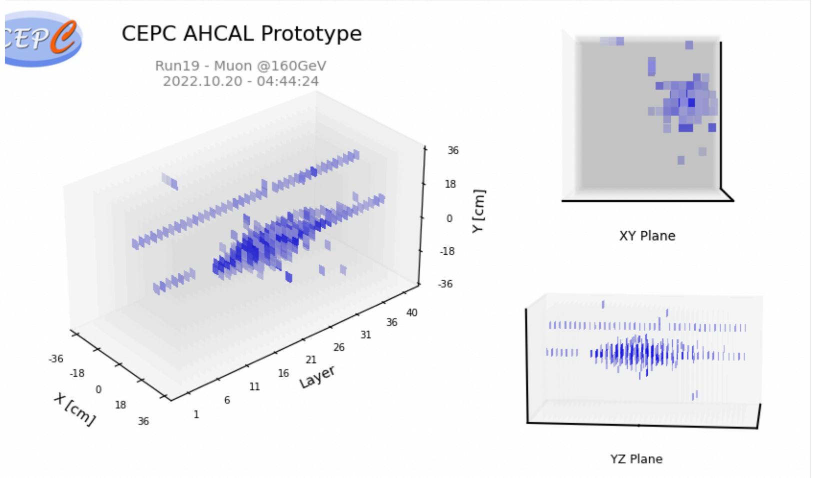
Impressions of high granularity



1 muon track



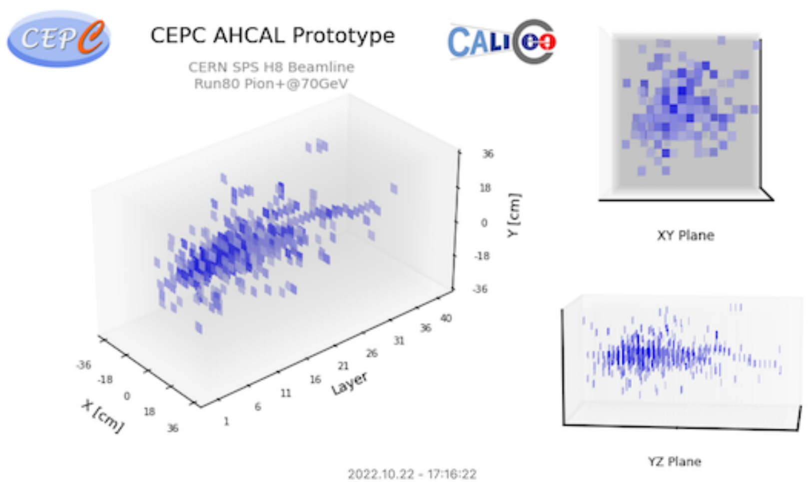
2 muon tracks



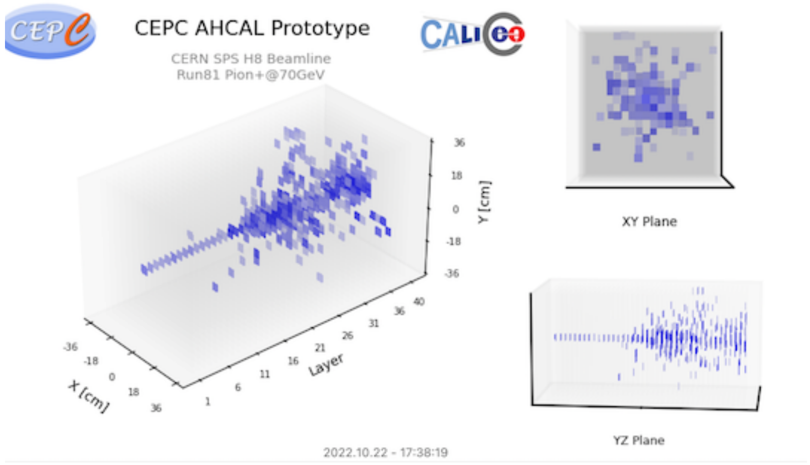
1 muon + 1 pion

AHCAL prototype with pions

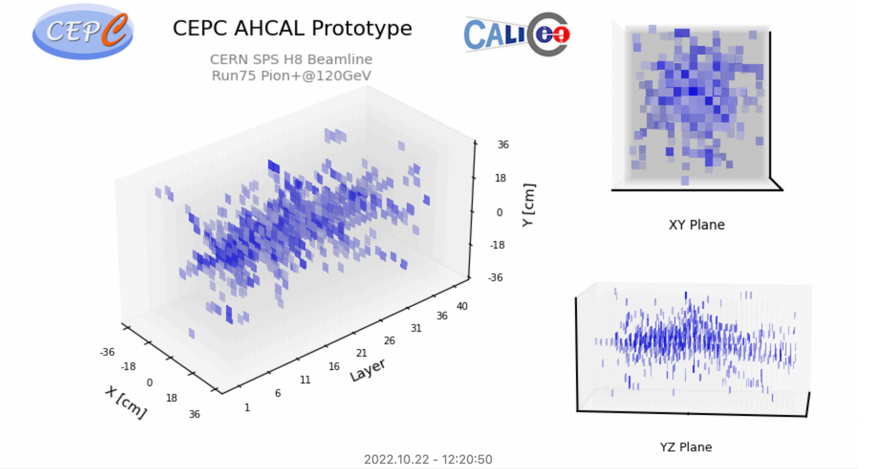
- Energy scans with pi+ beam
  - 10 – 120 GeV: ~1M events accumulated per energy point
  - SPS running very smoothly and with high beam intensity (Oct. 20 – 26, 2022)
- Beam purity: issue and solution
  - Contaminations of pion+ beam with protons (energy dependent)
  - 2 Cherenkov counters implemented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



70 GeV pion+ (early showers)



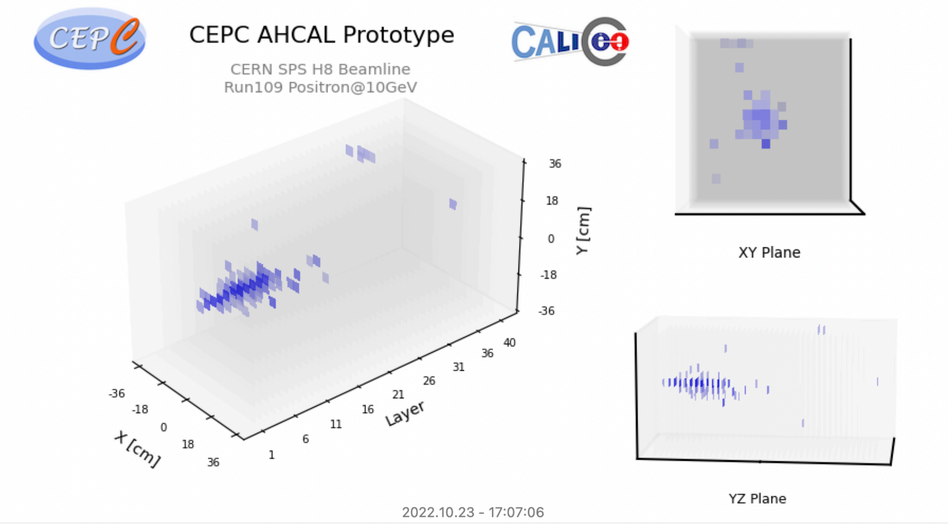
70 GeV pion+ (late showers)



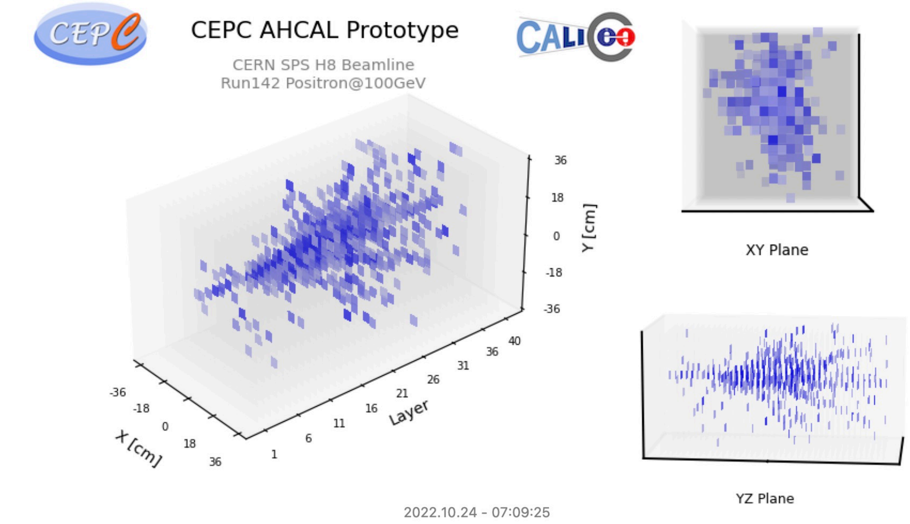
120 GeV pion+

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 and solution
  - 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

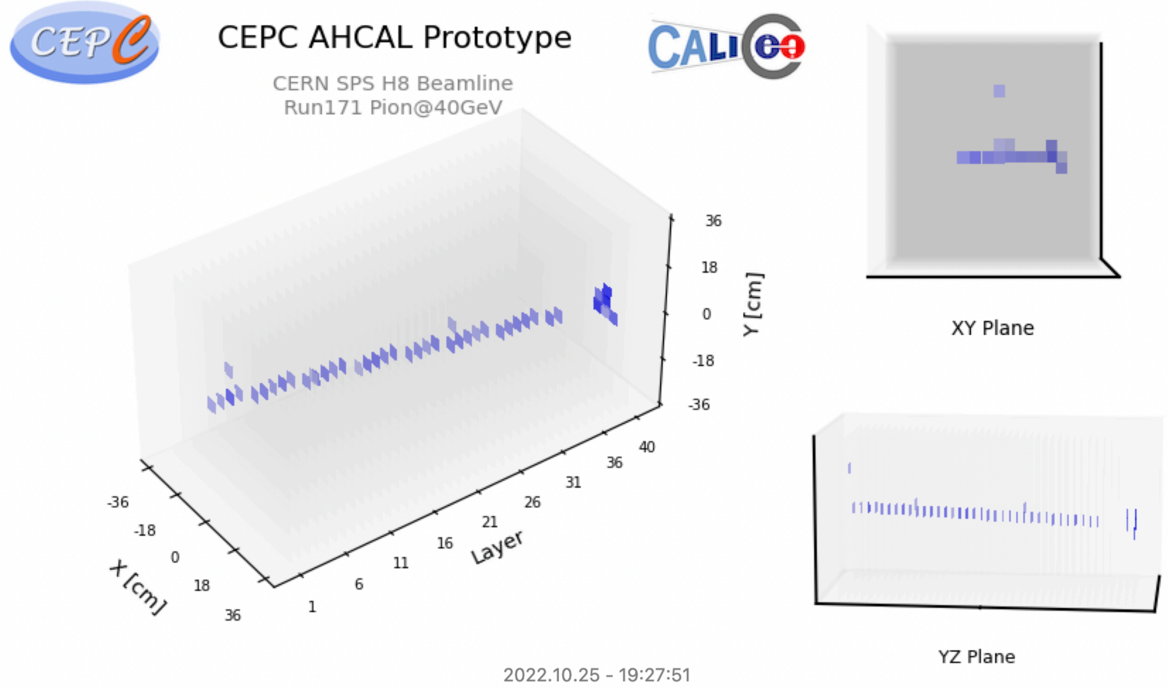


Hadronic showers in 120 GeV positron beam

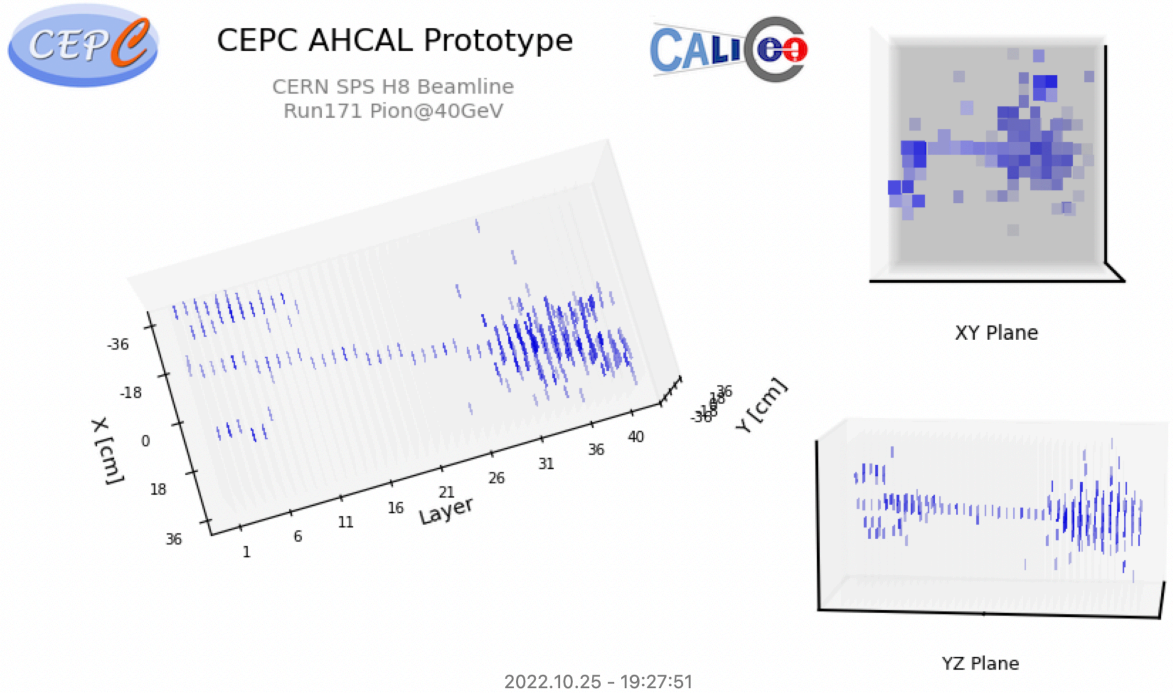
AHCAL prototype: inclined beam incidence

- 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

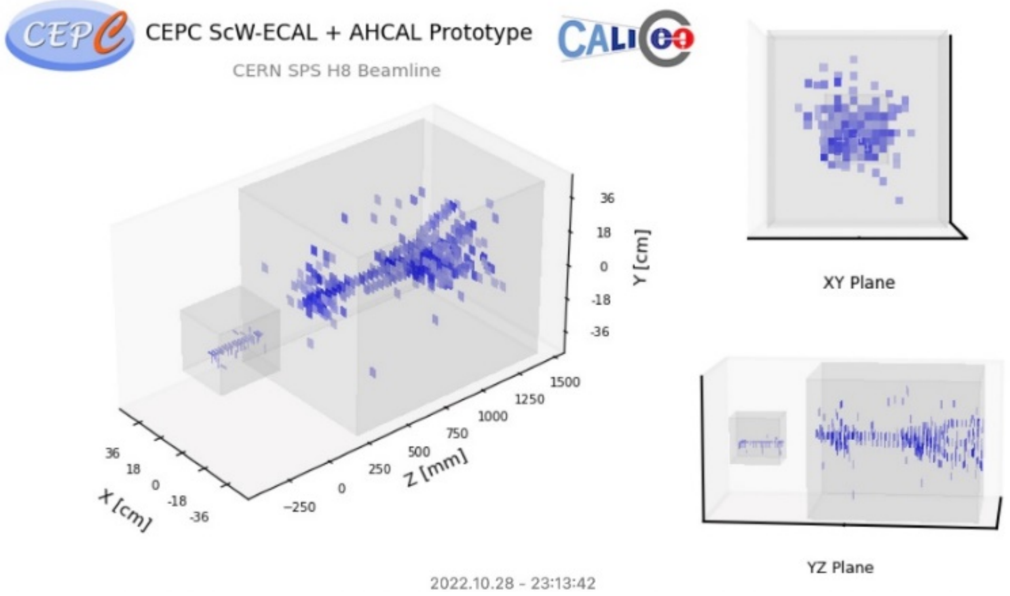


40 GeV pion beam: hadronic showers



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

- Pedestal and MIP calibrations
- Simulation and validation with data
- Event display with animations and PID studies
- Arbor clustering studies

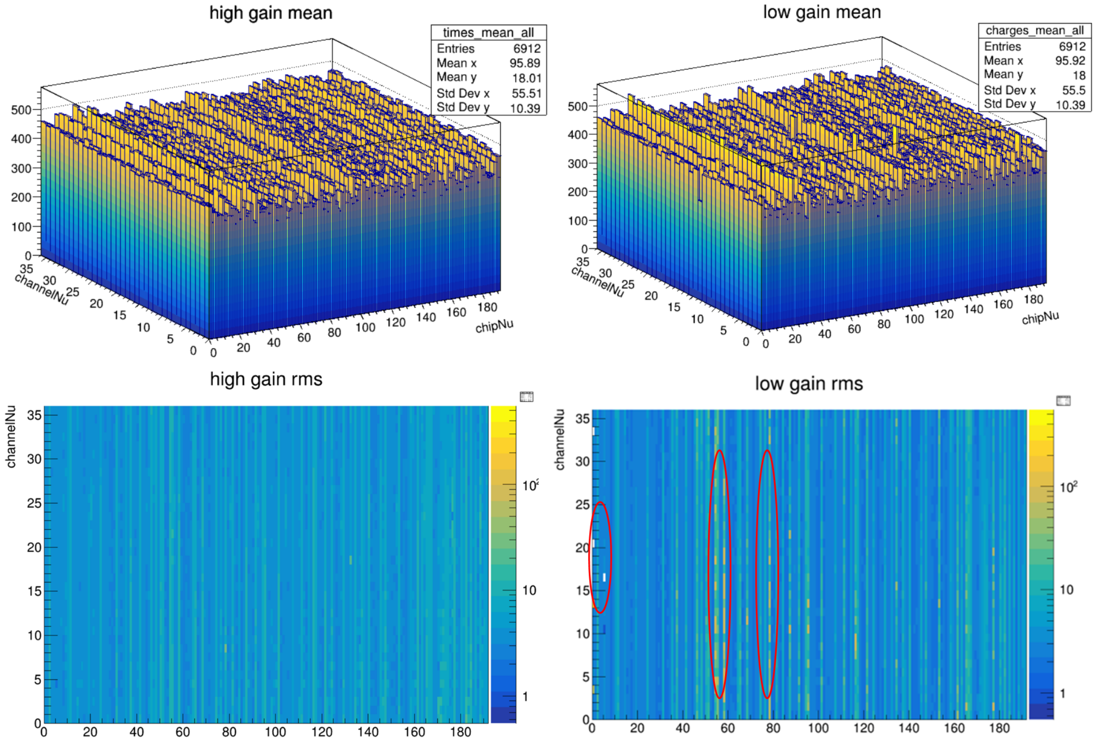
Pedestal calibration

Hongbin Diao, Jiaxuan Wang (USTC)

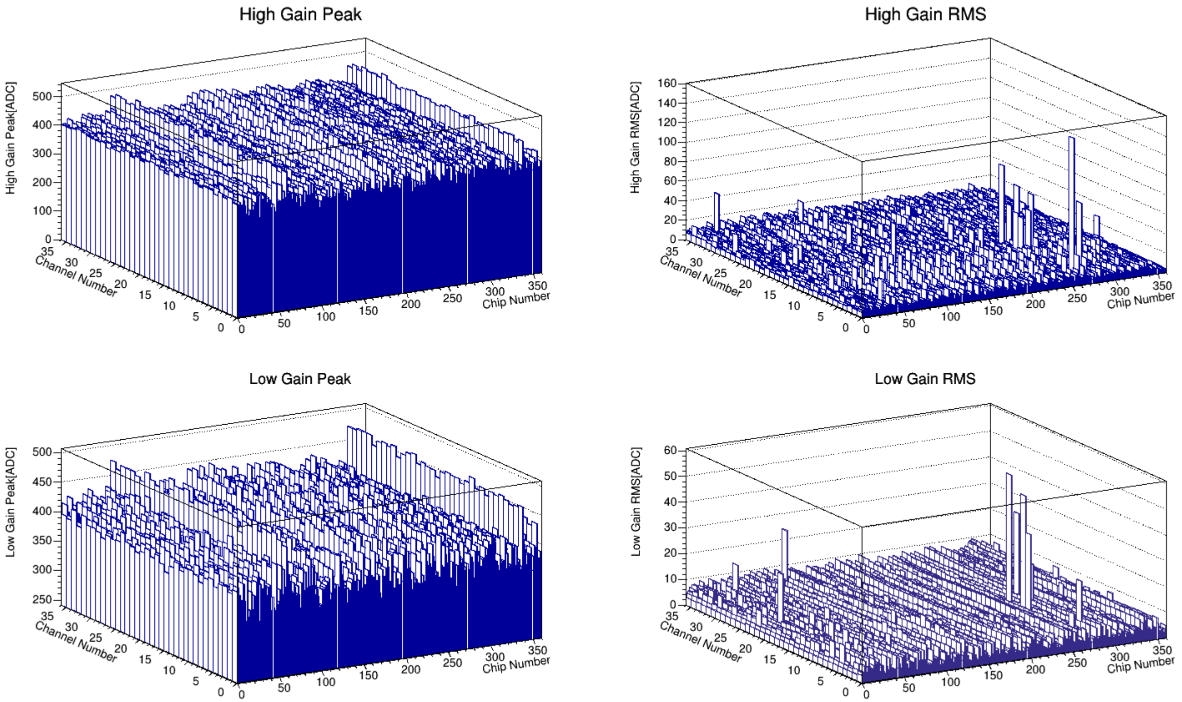
- Extracted for pedestal calibration per channel
  - Basis for MIP calibration and all other analyses

Featuring ASIC-dependent spreads

ScW-ECAL data: pedestals for all 6912 channels



AHCAL data: pedestals for all 12960 channels



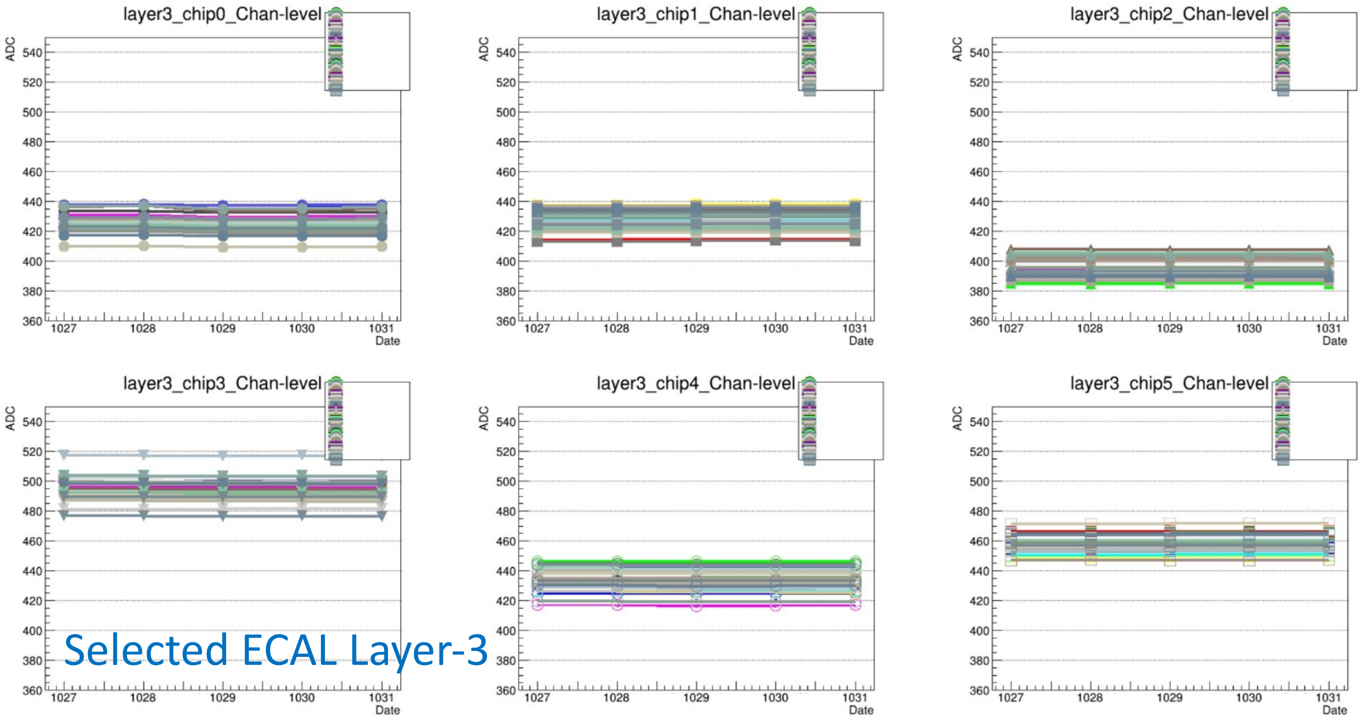
Only a few channels with large pedestal spreads: under investigation

Pedestal calibration

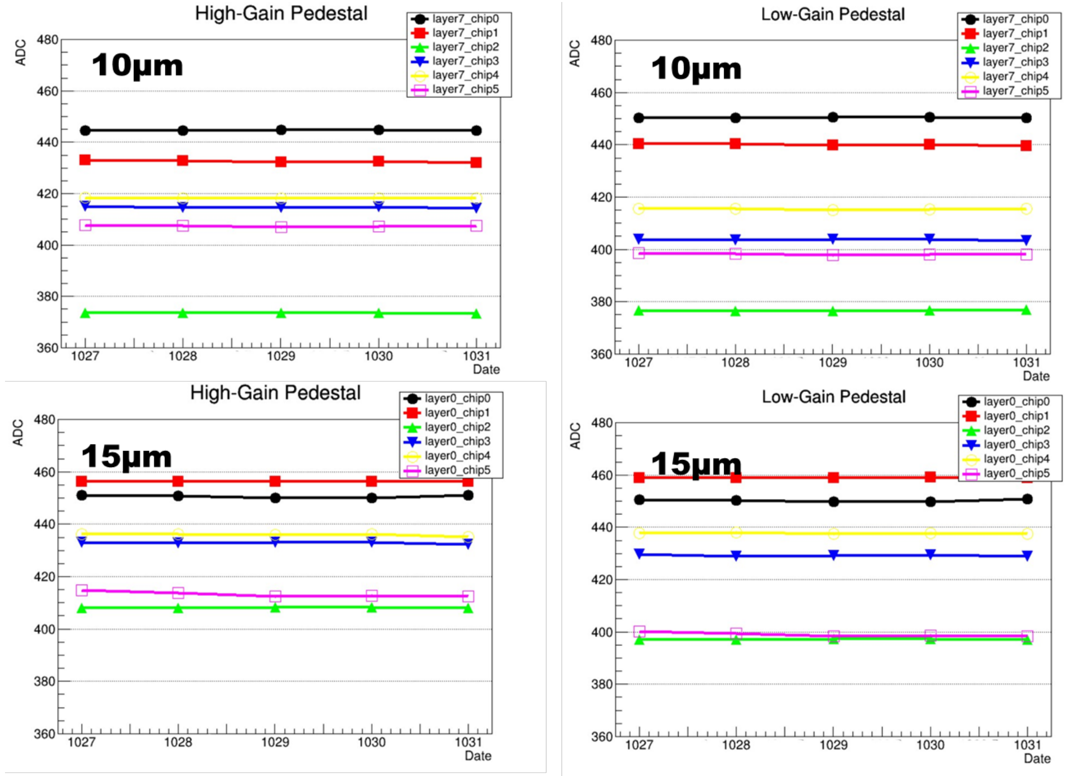
Hongbin Diao, Jiaxuan Wang (USTC)

- Generally pedestals show good stability along with time

ScW-ECAL data: pedestals in 5 days (layer-level)



ScW-ECAL data: pedestals in 5 days (chip-level)

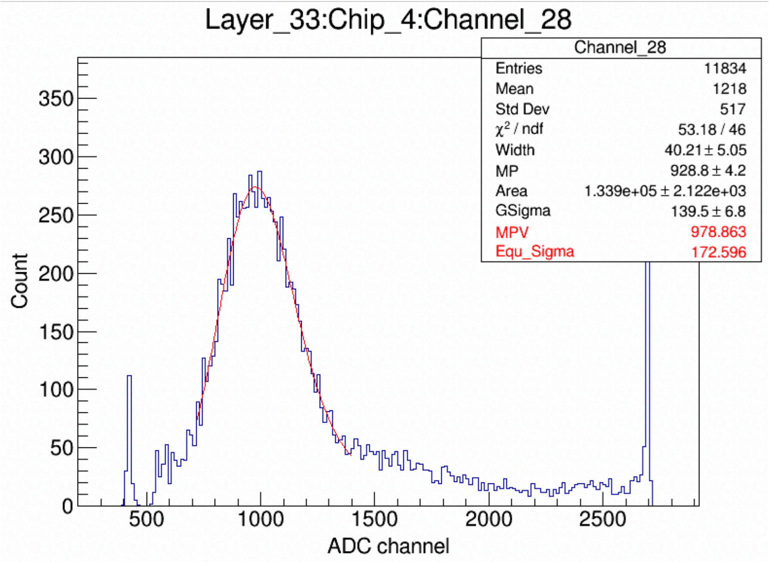


MIP calibration studies

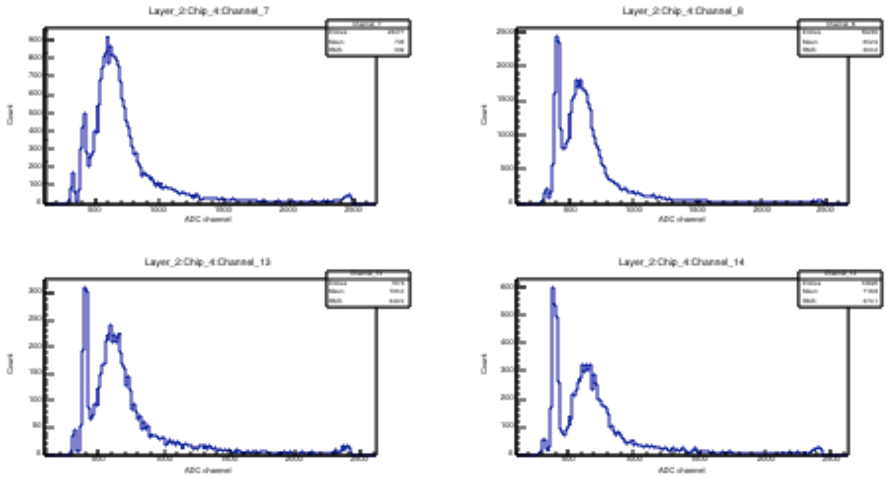
Peng Hu (IHEP)

- MIP calibration for each channel: using muon data
  - Most probable value (MPV): Landau convoluted with Gaussian
  - Ongoing studies: to quantify the MPV spread and run-by-run stability
  - Also observed saturation behavior: probably due to ASICs (under investigation)

MIP spectrum fitting: Landau+Gauss

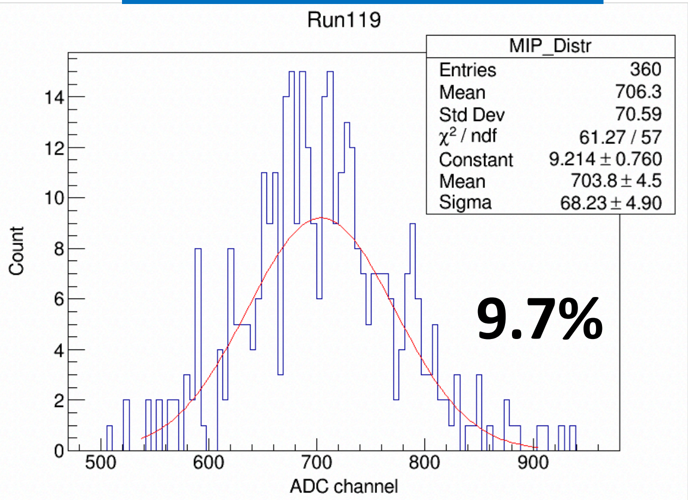


Selected MIP spectra (in ADC tics)



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)

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
    - Reasonable as MIP calibration (channel-wise) can be done in data (ongoing)
  - Digitisation tool
    - Photon statistics, SiPM non-linearity, ASIC saturation

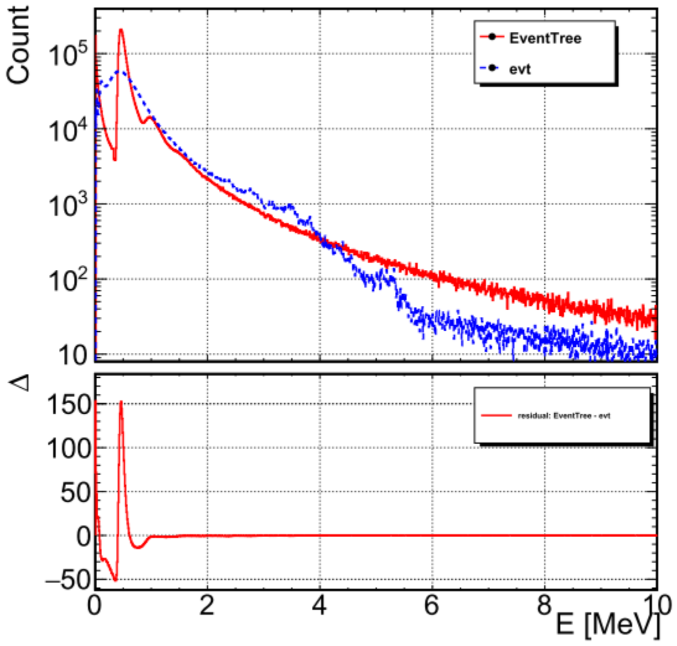
- First comparisons of data vs MC for AHCAL prototype
  - Muons: noises, channel-wise uniformity, etc.
  - Positrons and hadrons: beam contaminations, SiPM and ASIC saturation effects, etc.

Simulation and validation

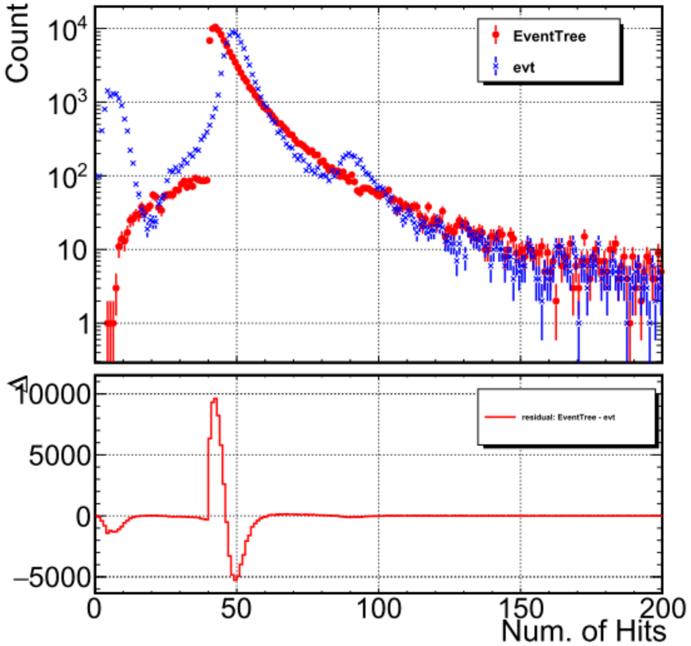
Yuzhi Che, Baohua Qi (IHEP)

- First comparisons of data vs MC for AHCAL prototype
  - 160 GeV muons: data in blue, simulation in red
  - MIP peak in data is less significant than MC → most likely due to non-uniformity per channel
  - More #hits in data → significant noises, likely with a second muon (2-MIP peak)

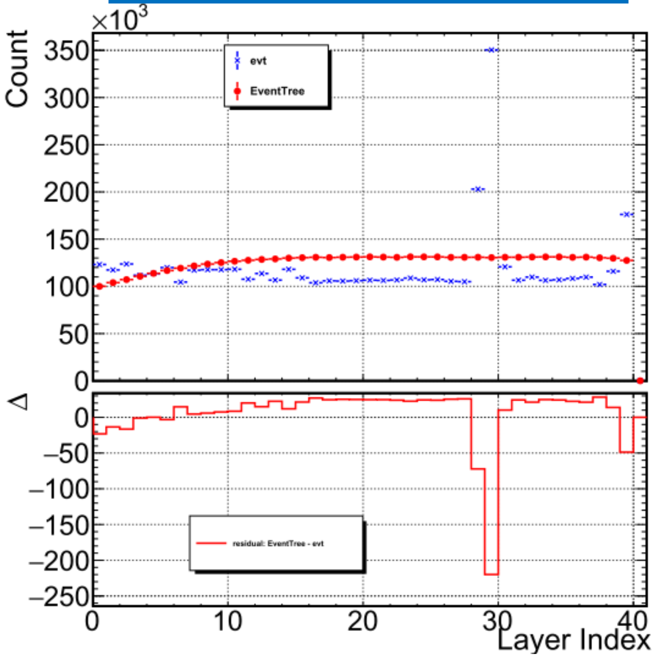
Hit-level: energy spectrum



Total number of hits per event

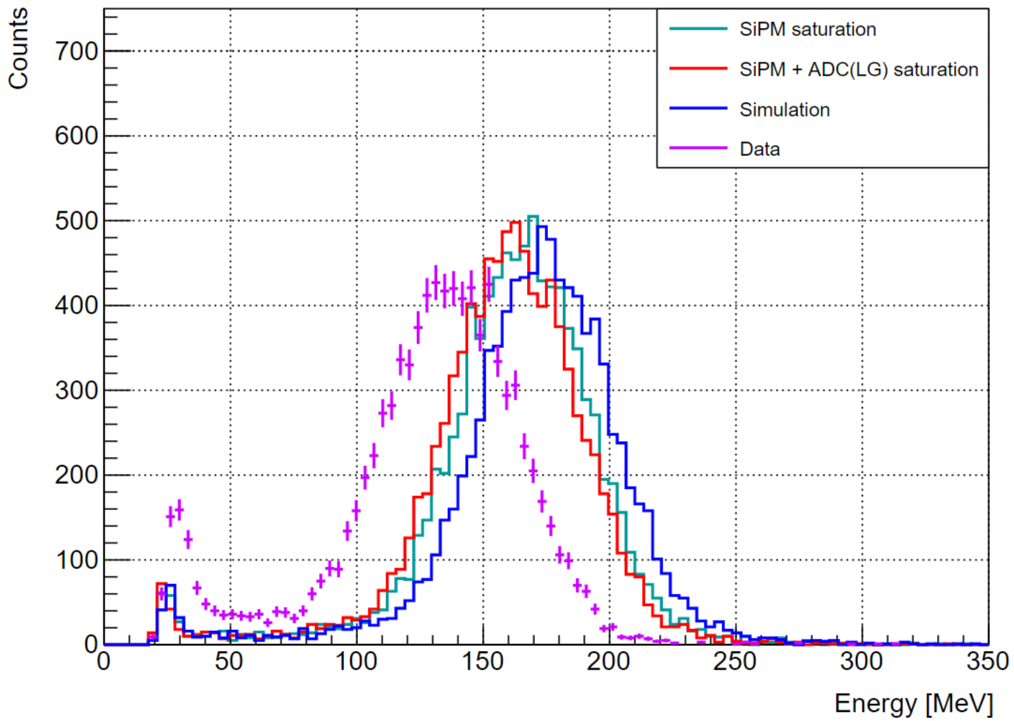


Number of hits per layer



Simulation and validation

- First comparisons of data vs MC for AHCAL prototype
  - 10 GeV pi+ beam: data in blue, simulation in red
  - Energy sum: clustering of all hits (above trigger threshold)
  - Generally MC can reproduce data at first order, except a few known effects (below)



Possible reasons for MC/data discrepancies

- Data: MIP calibration for each channel is not done yet
- Data: HG/LG inter-calibration (High Gain vs. Low Gain) not yet implemented
- Also observed muons in pion beam (e.g. via pion decays)
- MC: simple modeling of ASIC saturation

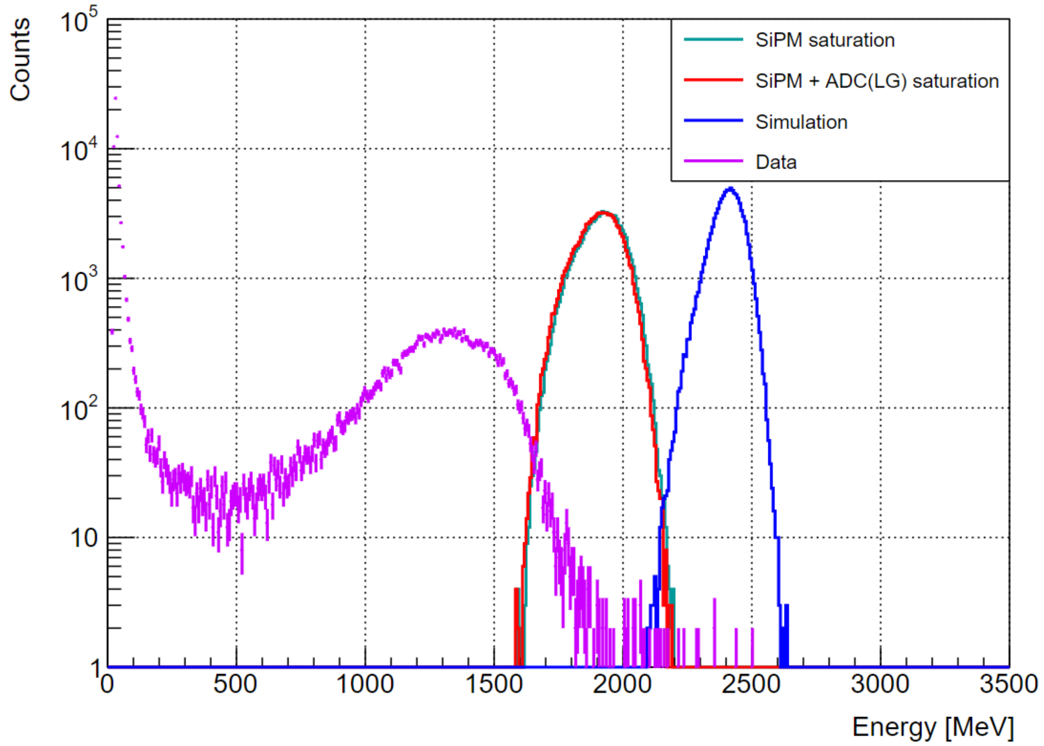
Planning

- Implementations of above points and improve MC
- Further comparisons with more energy points

Simulation and validation

Baohua Qi (IHEP)

- First comparisons of data vs MC for AHCAL prototype
  - 120 GeV e+ beam: data in blue, simulation in red
  - Energy sum: clustering of all hits (above trigger threshold)
  - Prominently large MC/data discrepancy: not a big surprise



Discussions

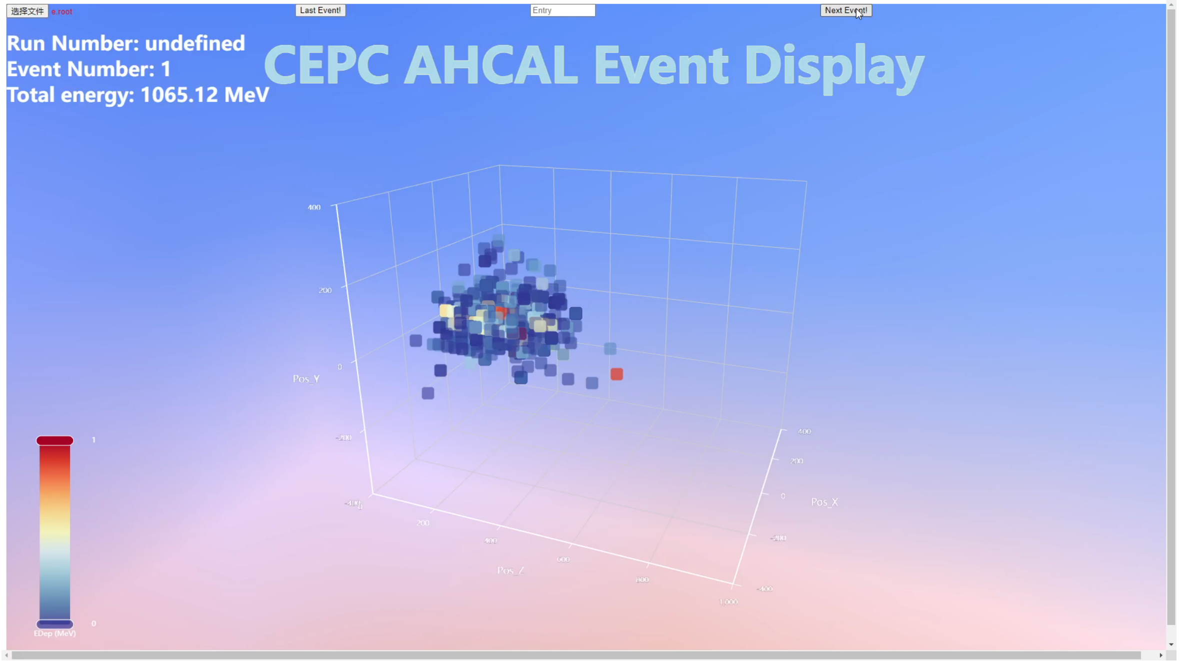
- We've known contamination issues in positron beams at H8 (beam experts + other H8 users)
- Generally positron purity goes down along with beam energy
- If the simulation is correct (appears so with hadrons), this would indicate positron purity at 120 GeV is very low
- More crosschecks to be done with PID studies (shower profiles, Cherenkov counters)

Event display developments

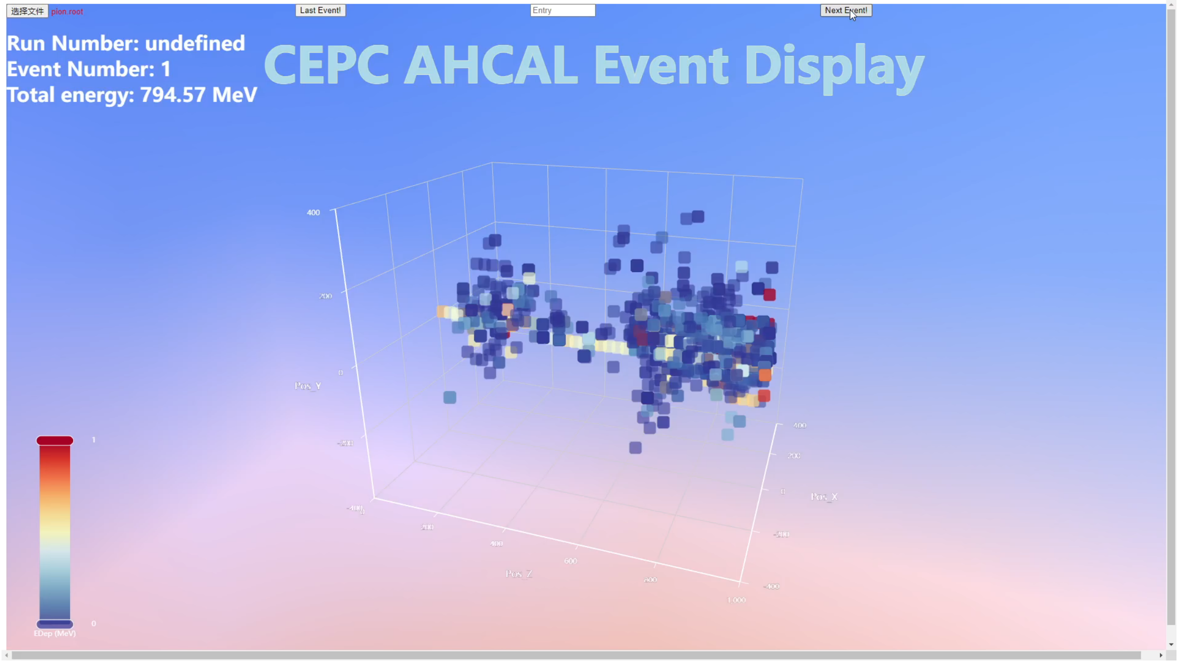
Zhen Wang (SJTU)

- Event display: animations for EM/hadronic shower evolution

50 GeV Electrons (MC sample)



50 GeV Pions (MC sample)



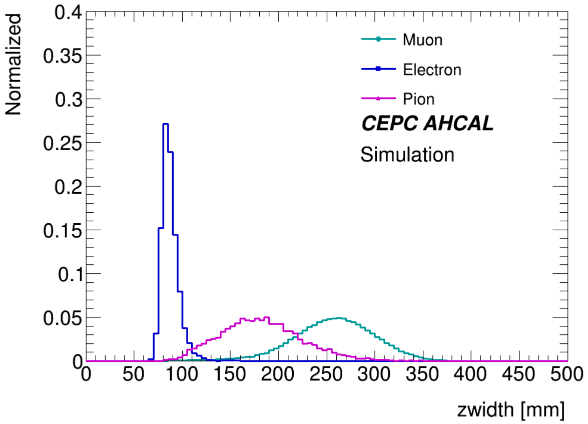
It would be interesting to apply this tool to testbeam data (requiring TDC calibration beforehand)

PID studies with simulation samples

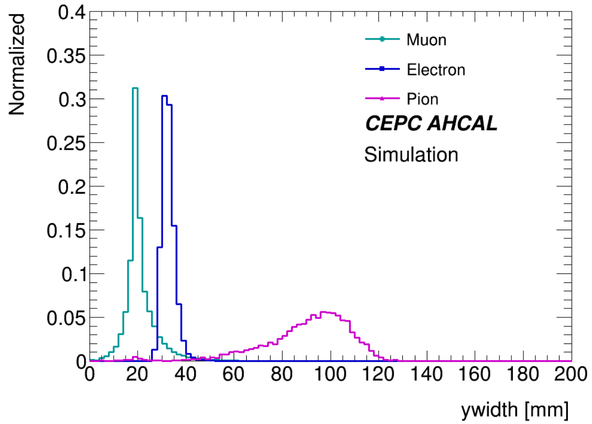
Siyuan Song, Zhen Wang (SJTU)

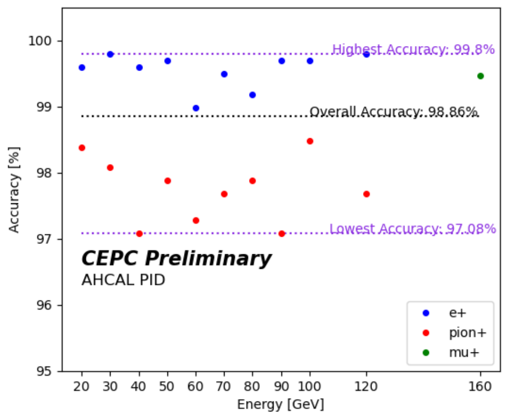
- Motivations: to study beam purity and mitigate beam contaminations
- PID techniques
  - Shower profiles to distinguish different incident particles
  - Method 1: BDT with input variables (shower profiles, shower start layer,…)
  - Method 2: Artificial Neuron Network (ANN)
  - MC samples: consistent with each other and both show accuracy above 98%
- Cherenkov counters (as part of CERN beam instrumentation): not presented here

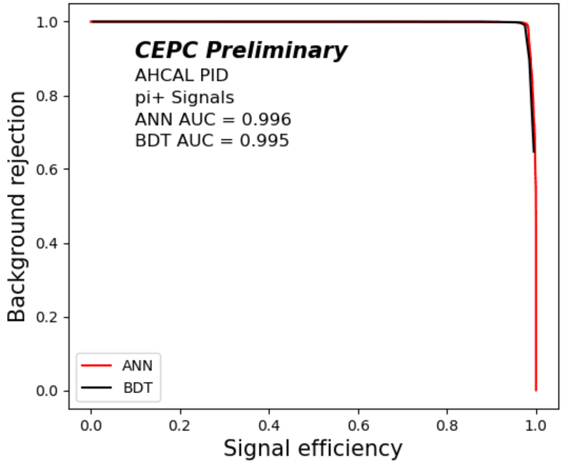
Longitudinal Center of Gravity



Transverse Center of Gravity



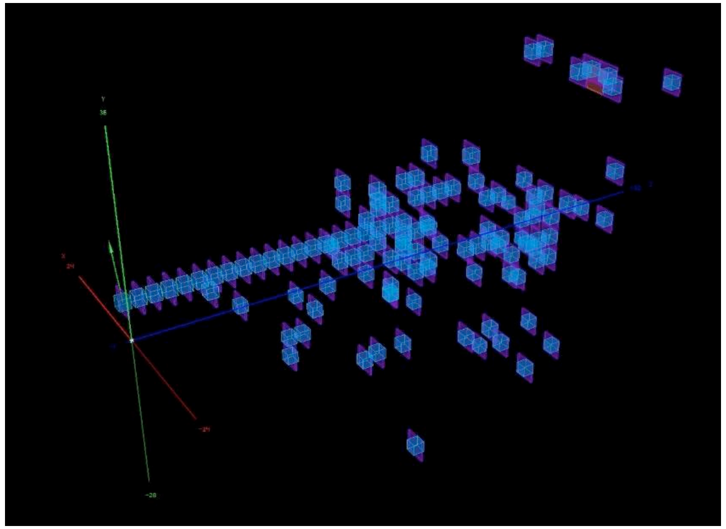
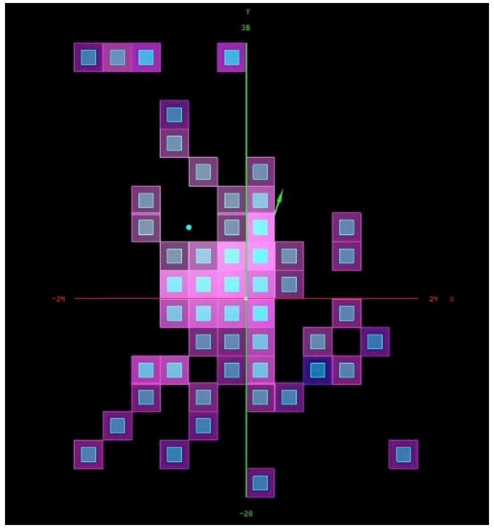
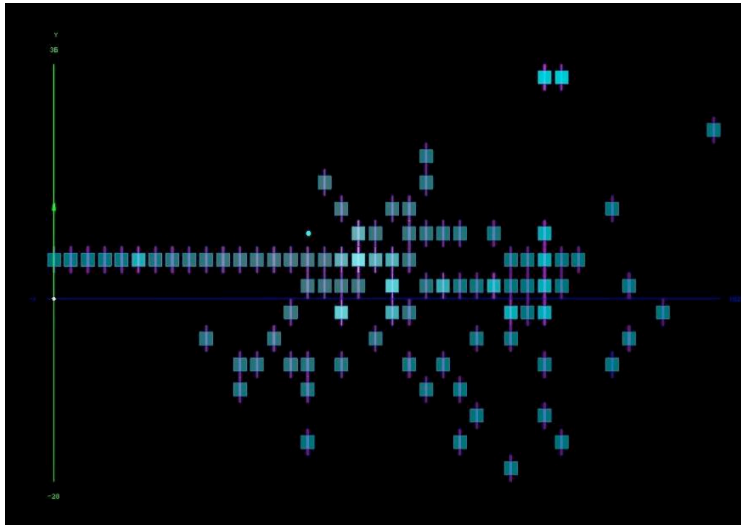




Arbor clustering studies with data

Yuzhi Che, Hengyu Wang, Xin Xia (IHEP)

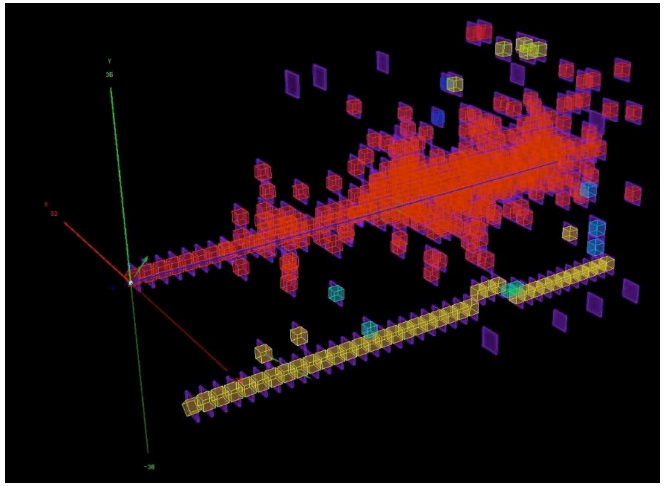
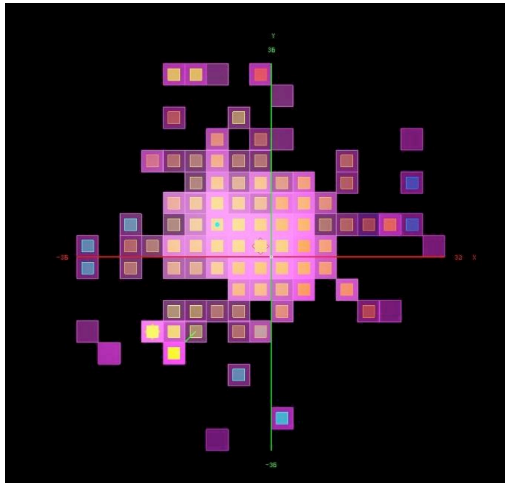
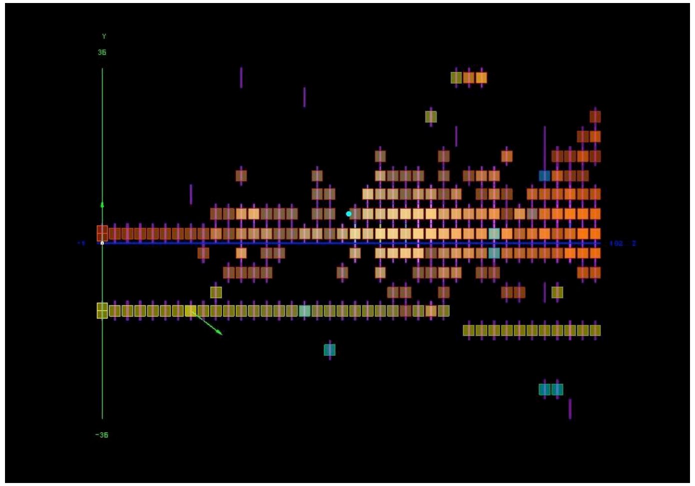
- Qualitative studies with Druid event display
  - Larger cube: raw hits in data; small cube: reconstructed hits in clusters
  - Color coding for different clusters
  - Most hits are correctly reconstructed as a single cluster (major shower part), with a few noise hits and isolated hits

Data Sample: AHCAL_Run156_20221024_231347 (10GeV pi+)

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
  - MIP calibration, PID techniques to improve sample purity
  - EM/hadronic: detector performance (**linearity & resolution**) and shower properties

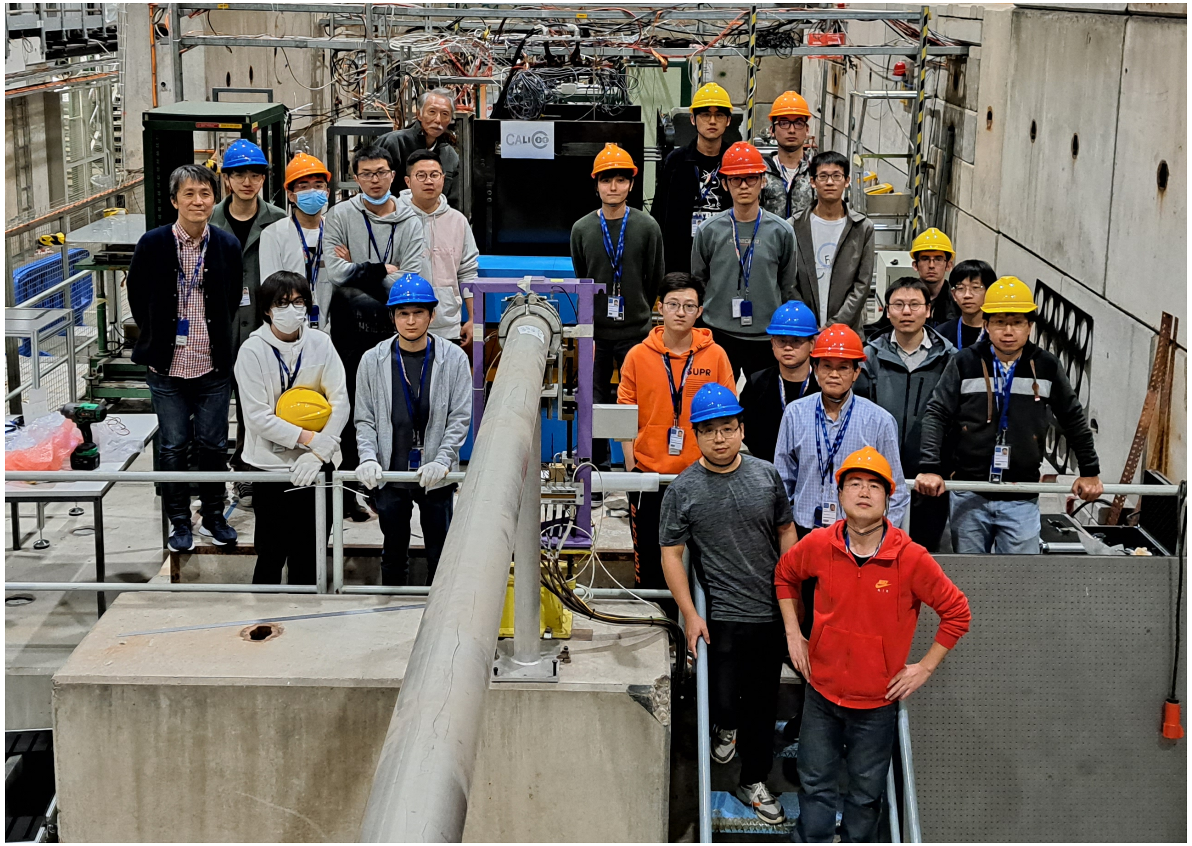
Acknowledgements

- CALICE and CEPC 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 other beamlines 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

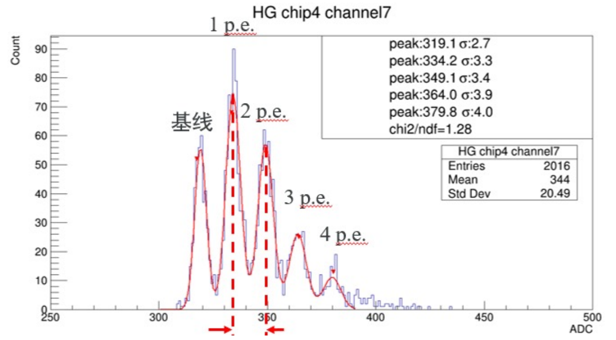
A big thank you

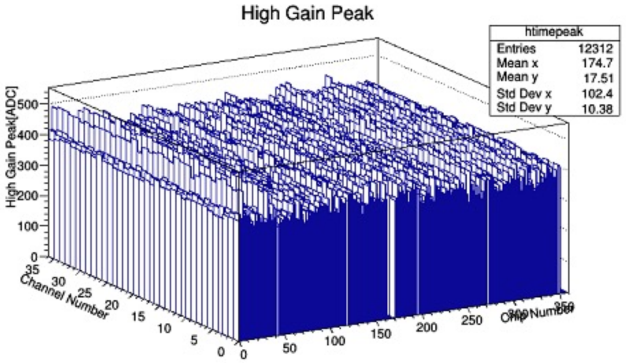


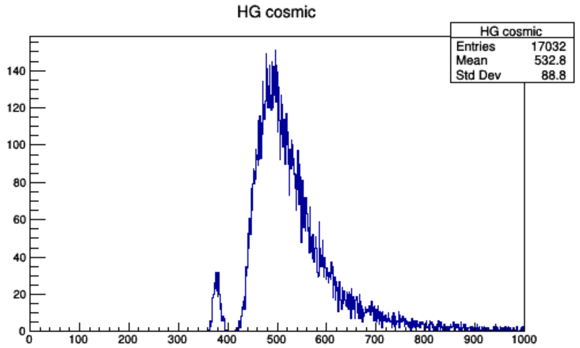
- IHEP: Yuzhi Che, Fangyi Guo, Peng Hu, Xinghua Li, Yong Liu, Baohua Qi, Qi Wu
- SJTU: Francois Lagarde, Siyuan Song, Zhen Wang, Haijun Yang
- USTC: Hao Liu, Jianbei Liu, Zhongtao Shen, Yukun Shi, Jiaxuan Wang, Yunlong Zhang
- U. Shinshu: Tohru Takeshita
- U. Tokyo: Ryunosuke Masuda, Tatsuki Murata,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

Spare Slides

AHCAL: assembly and commissioning (August 2022)



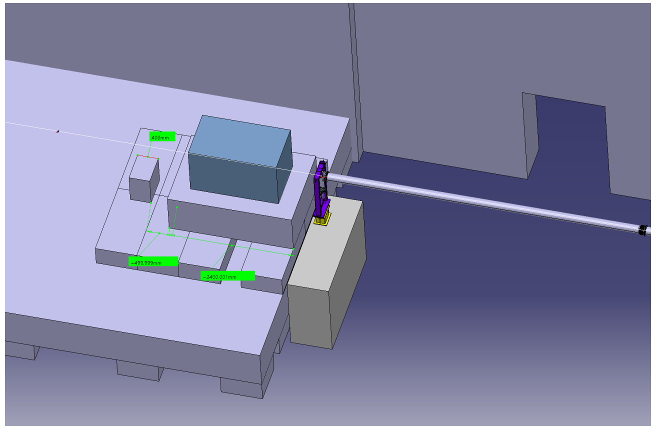


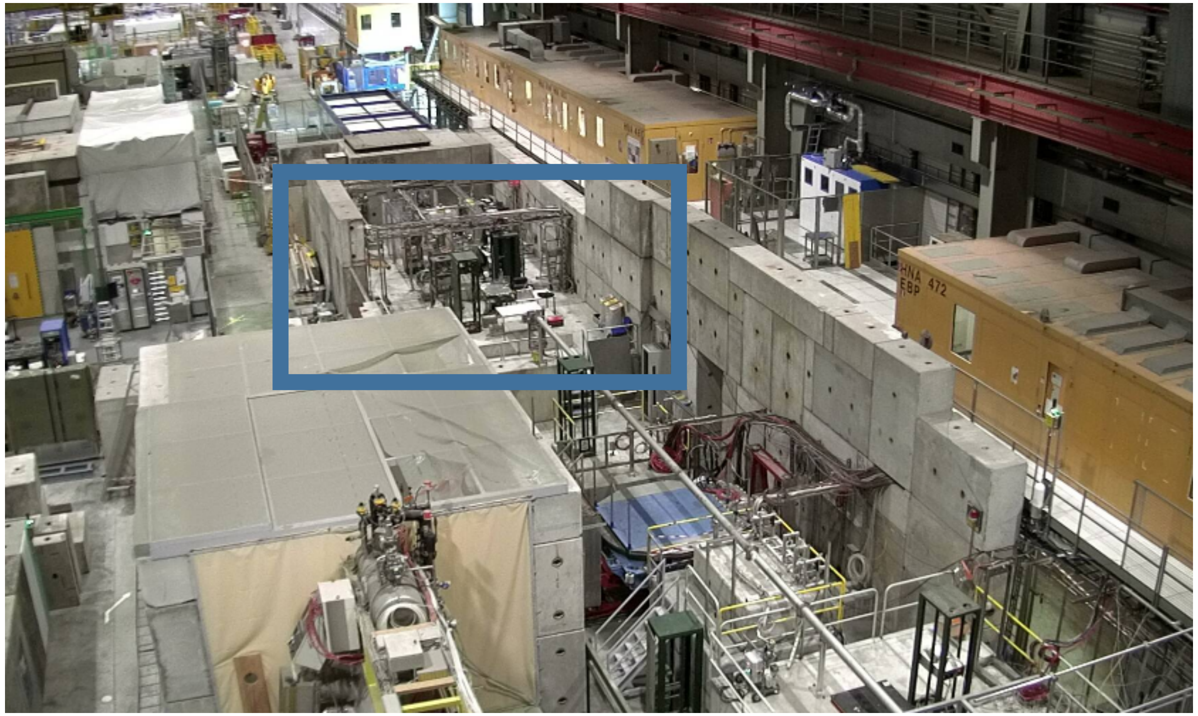


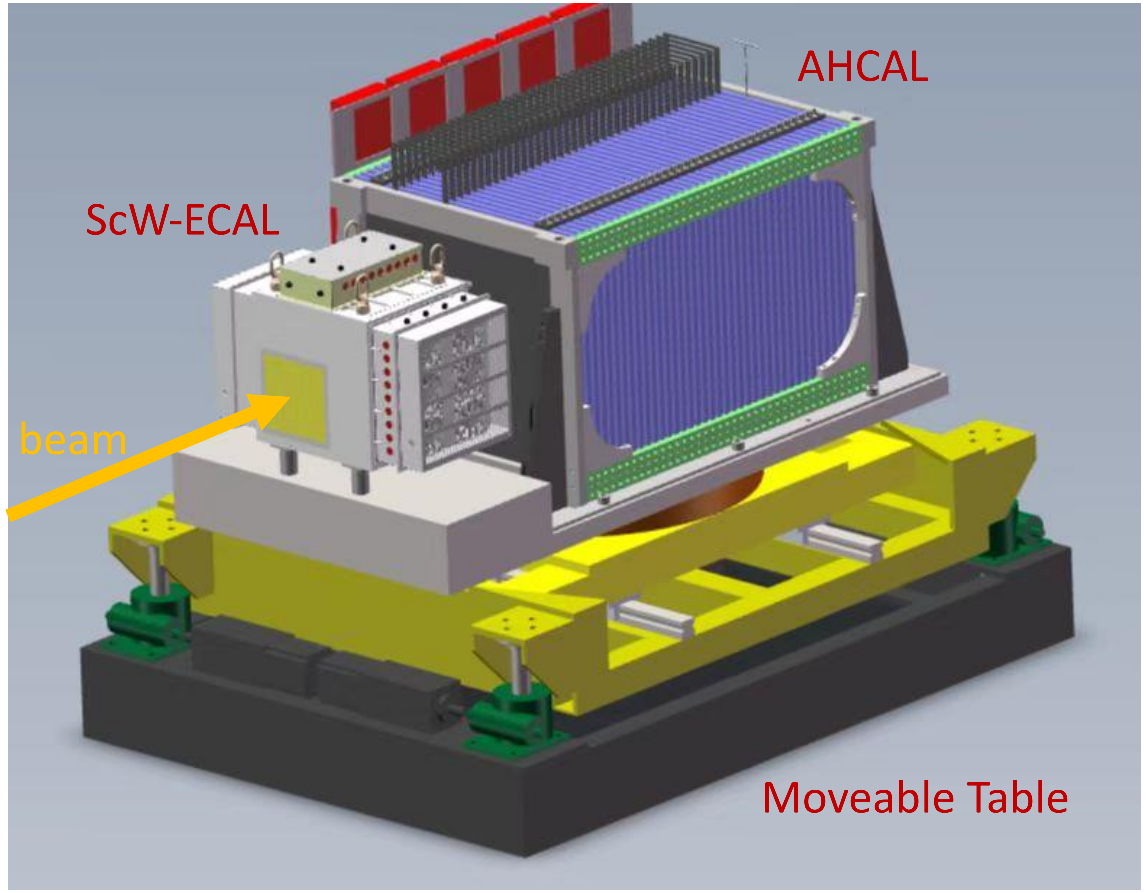
- HBU assembly and commissioning with DAQ at USTC
  - Pedestal runs and calibration
  - LED data for SiPM gain calibration
  - ASIC inter-calibration: High Gain vs. Low Gain
- Cosmic-ray tests: MIP peaks can be seen for most layers
- Joint efforts of USTC, IHEP and SJTU: "rehearsals" for the beamtest

H8 beam area arrangement

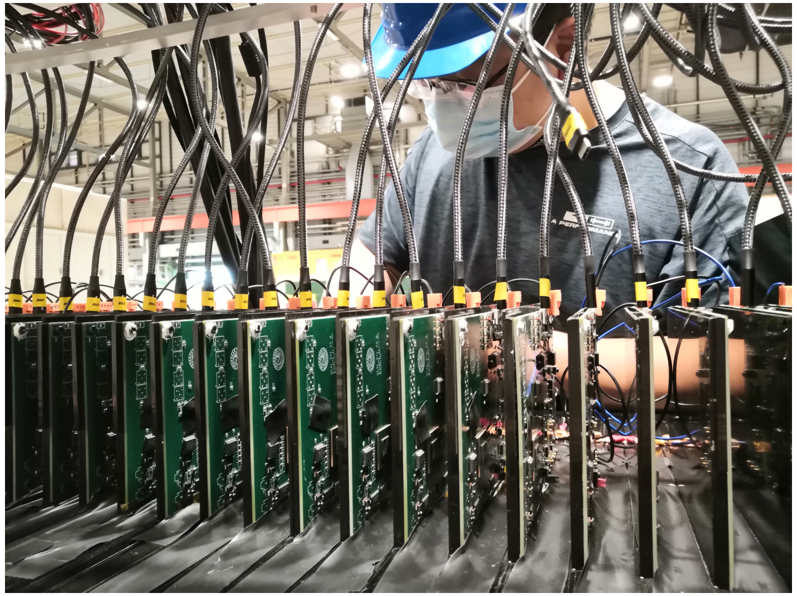
Technical discussions with Michael Lazzaroni (CERN)







Unpacking and installations



AHCAL pion beam data

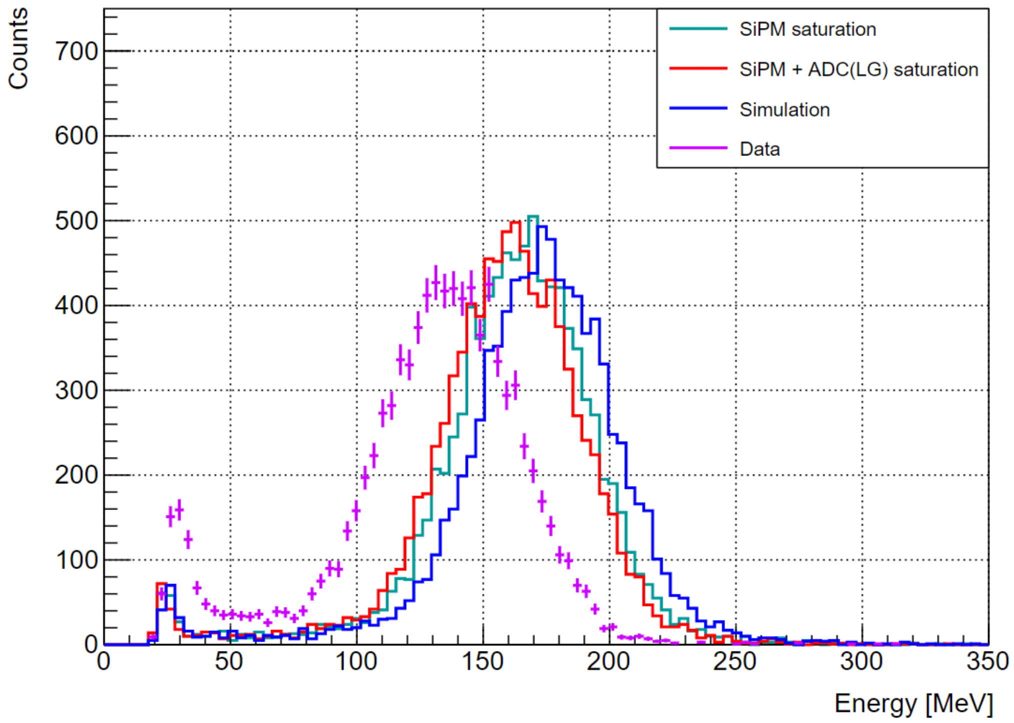
- Plans for AHCAL (alone) with pion+ beam
  - 1M events per energy point
  - Accumulate more statistics at one or two low energy point
- Data taking
  - Successfully completed plans
  - SPS running very smoothly and with high beam intensity during Oct. 20 – 26
- Beam purity: issue and solution
  - Contaminations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

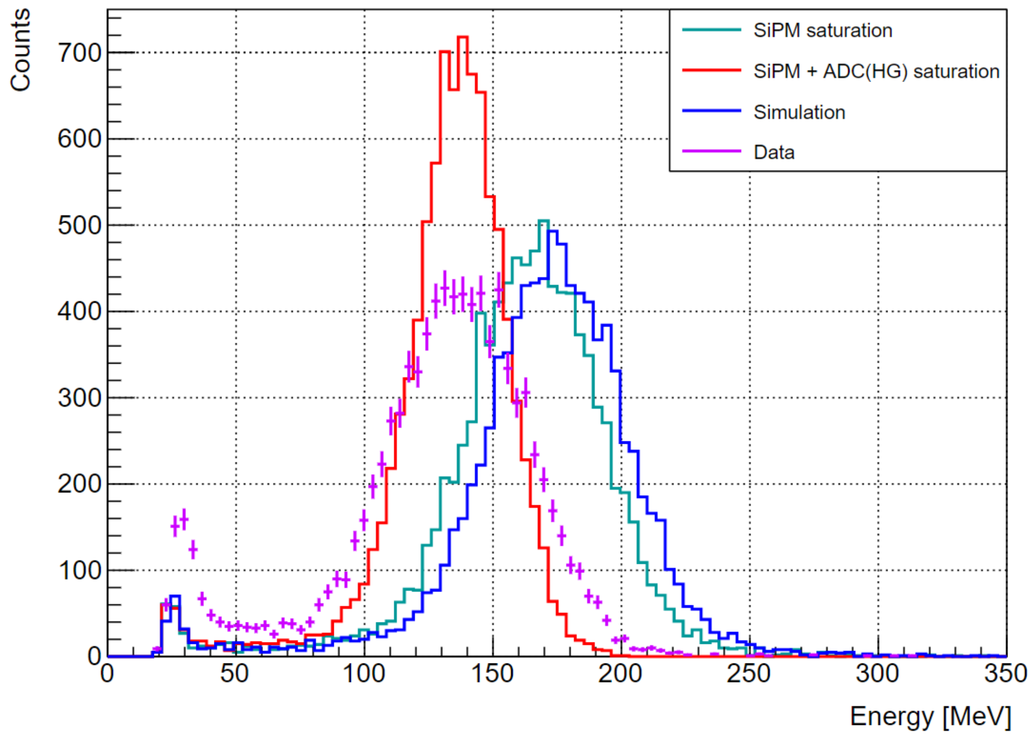
AHCAL data list (pion+)

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

Simulation and validation

- First comparisons of data vs MC for AHCAL prototype
  - 10 GeV pi+ beam: data in blue, simulation in red
  - Energy sum: clustering of all hits (above trigger threshold)
  - Generally MC can reproduce data at first order, except a few known effects (below)





AHCAL positron beam data

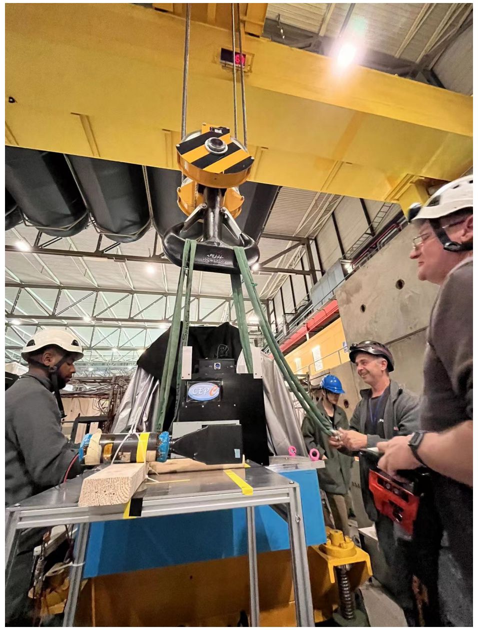
- AHCAL (alone) with e+ beam
  - Plan: ~200k events per energy point
  - Successfully completed the plan within half a day
  - Thanks to SPS smooth running
- Beam purity: issue and solutions
  - Contaminations of e+ beam with hadrons: generally lower positron purity when beam energy increases
  - 2 Cherenkov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

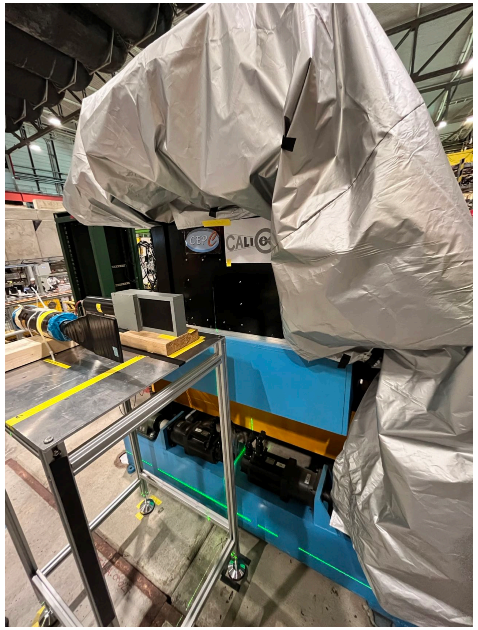
AHCAL data list (e+)

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

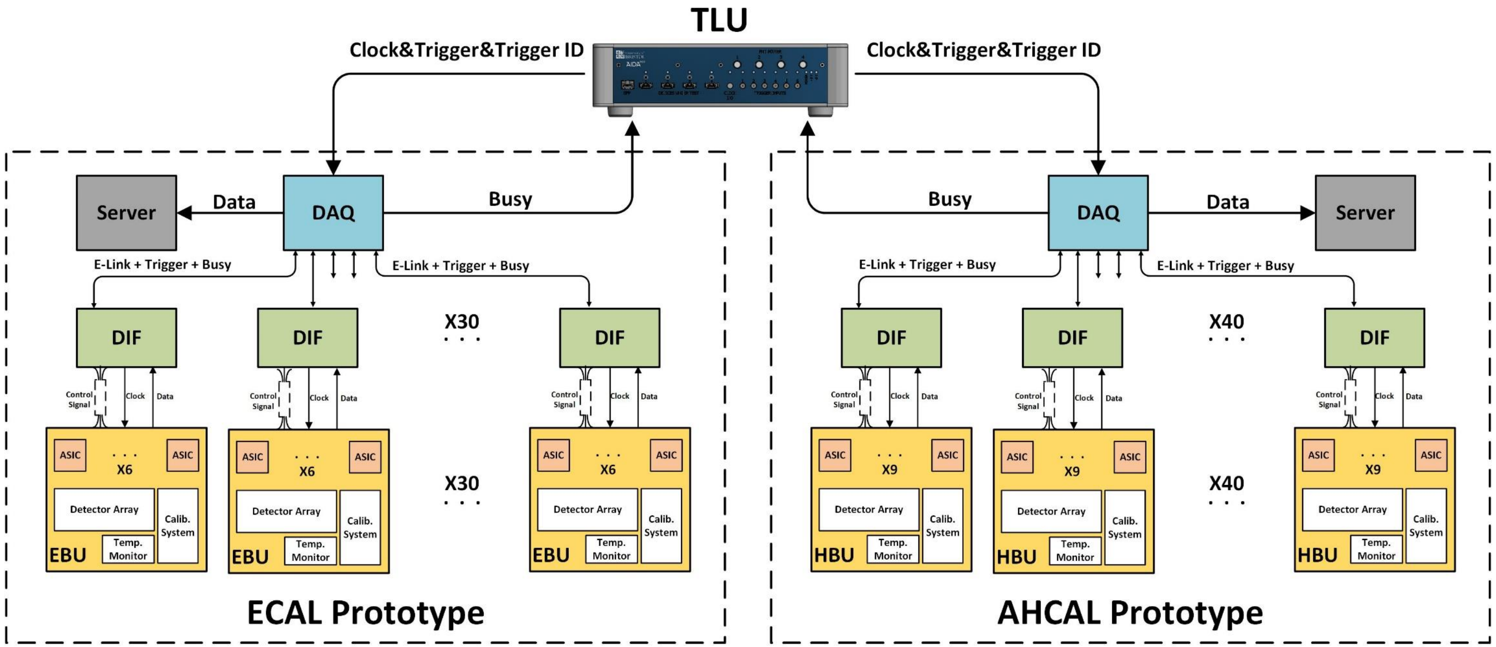
- 120 GeV secondary hadron beam used (180 GeV in the first week)
  - Trying to improve the beam intensity
- Muon beam: wide profiles for MIP calibration
- Positron and pion beams: energy scans

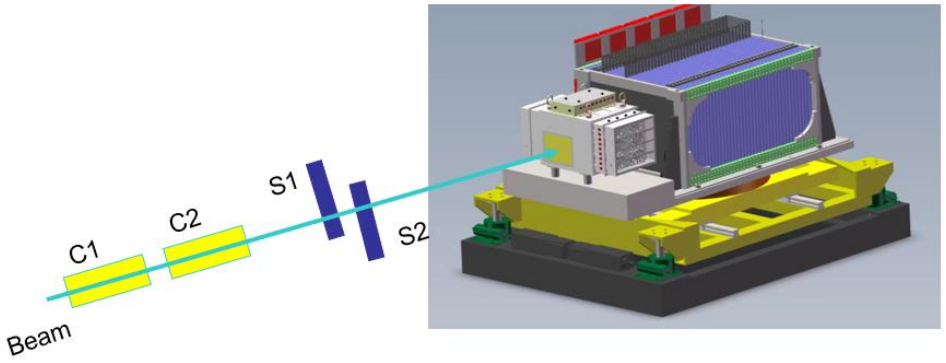




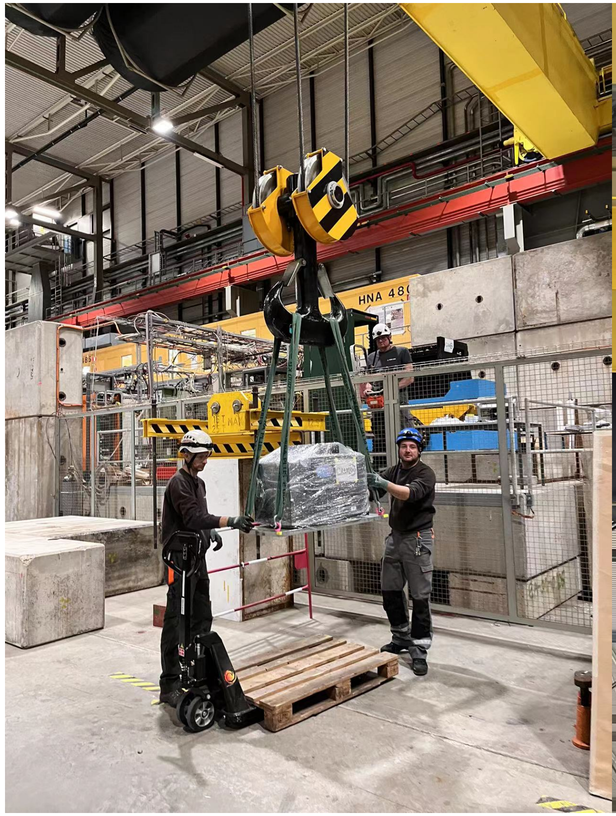
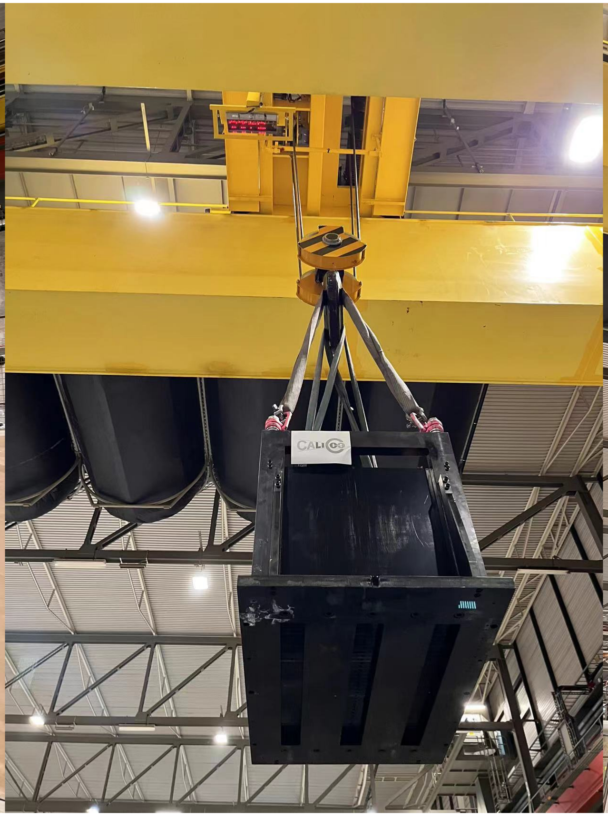
ScW-ECAL and AHCAL: integrated DAQ system

- 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

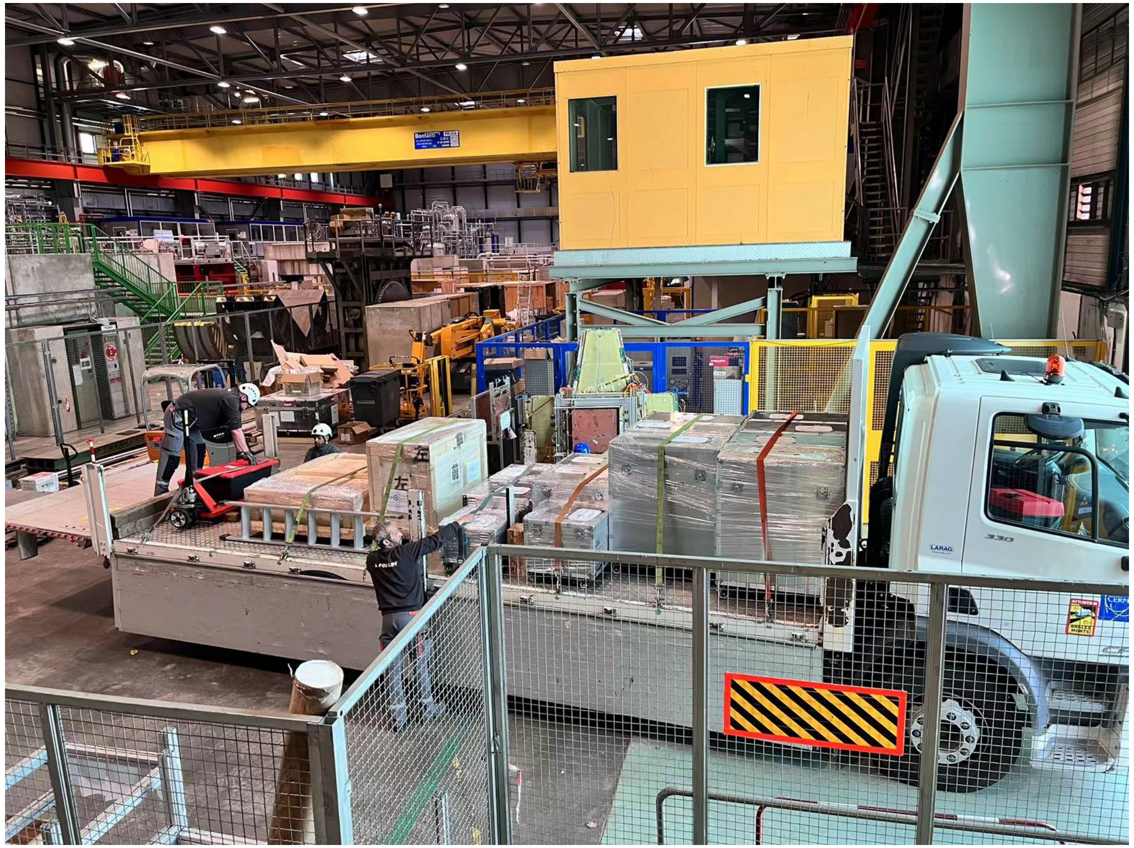





- Successfully moved out of the beam area (Nov. 2)
  - ECAL + HCAL prototypes, support table

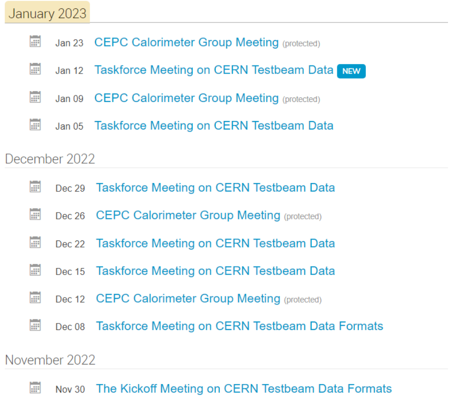
Transport and storage at CERN

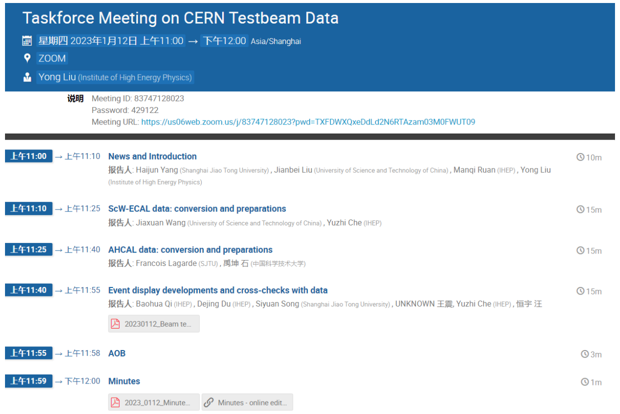
- Internal transportation and storage at Building 190: completed in Nov. 9
  - Thanks to the CERN EP support and coordinating efforts of CALICE management



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





Beamtest plans in 2023

- Calorimeter prototype status: stored at CERN
- CERN testbeam application
  - Proposal submitted (Jan. 6), coordination within CALICE Technical Board
  - Beam time: 2 weeks at PS (T9) and 2 weeks at SPS (H2/H4)
    - Target period: May 30 - Aug. 30, 2023
  - SPS-Committee reviews for proposals: scheduled in Feb. 7, 2023

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