CALICE scintillator-SiPM calorimeter prototypes: R&D highlights and beamtests

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16^{th} Pisa Meeting on Advanced Detectors, La Biodola, Isola d'Elba

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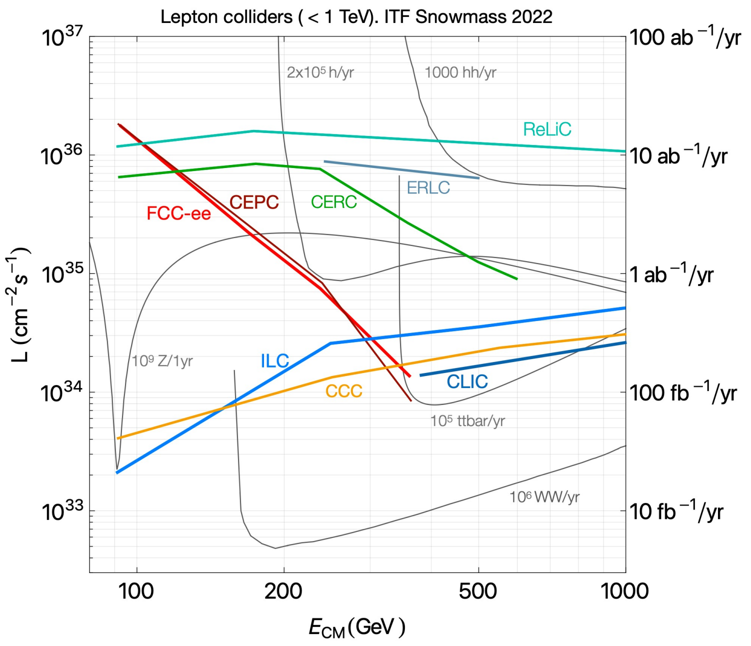
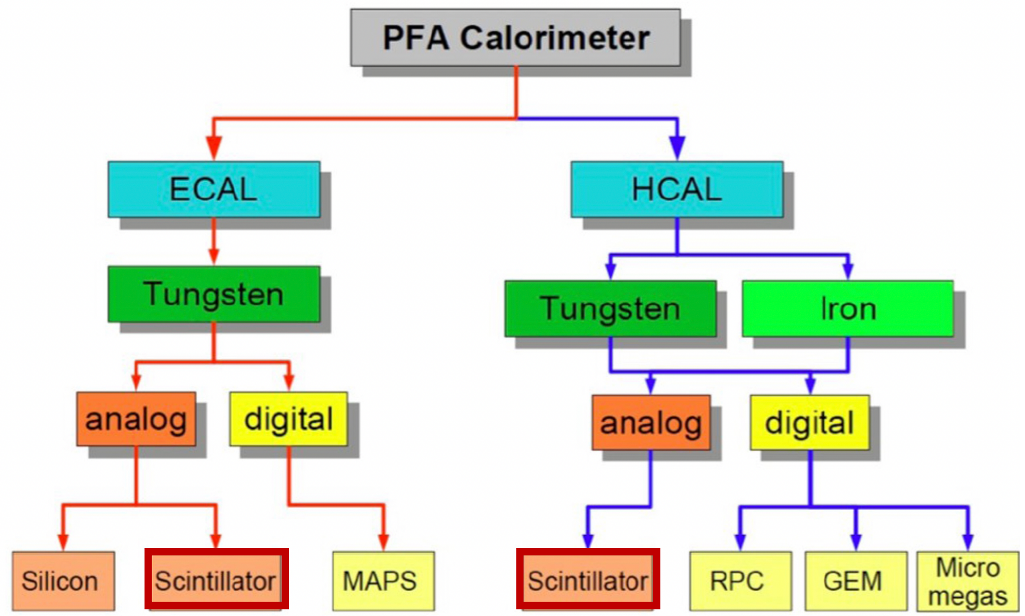
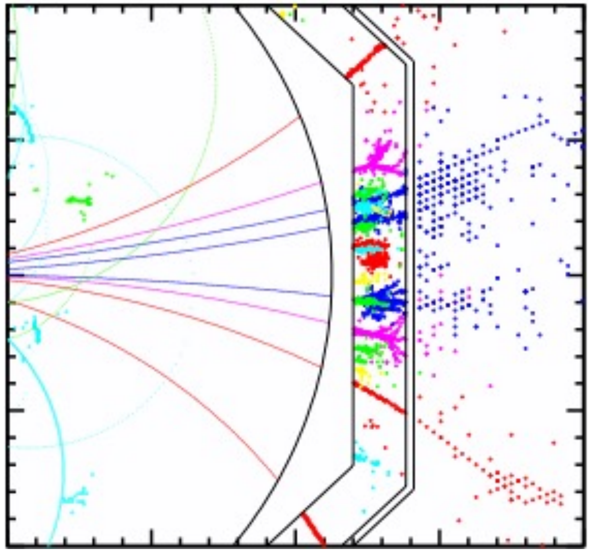
High granularity calorimetry





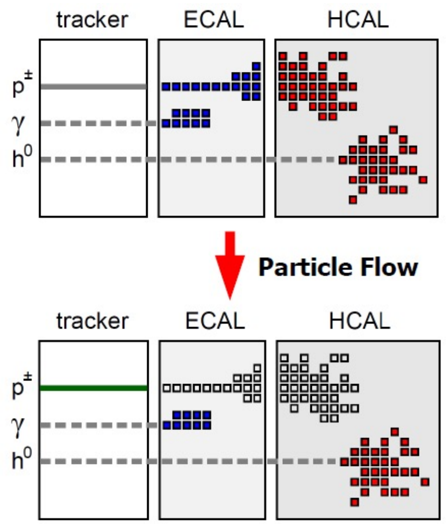


PM2024 Poster: F. Guo, High-granularity crystal calorimeter R&D (May 28, 2024)

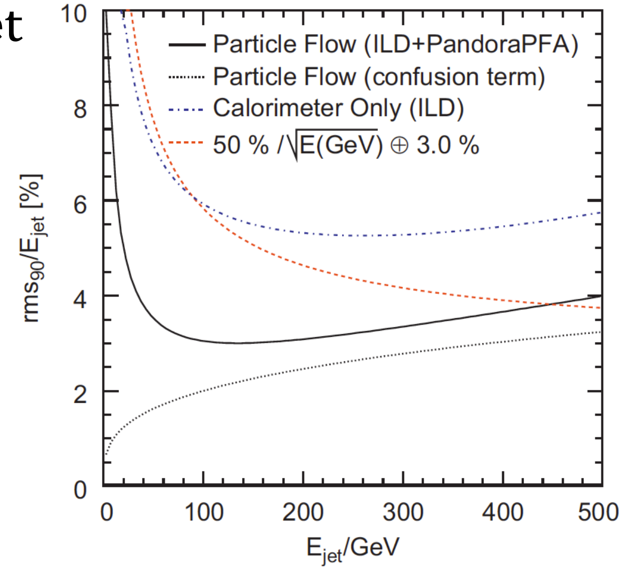
- Future Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major calorimetry option: highly granular (imaging) + particle flow algorithm (PFA)
- PFA calorimetry: various options explored in the CALICE collaboration
- Focus in this talk: **scintillator-SiPM**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

Particle-flow algorithm

Components in jets	Sub-Detectors	Energy fraction (average) within a jet	Detector Resolution
charged particles ($X^{\pm}$)	Tracker	$60\% \; E_j$	$10^{-4} E^2{}_X$
photons (γ)	ECAL	$30\% \; E_j$	$0.15 \sqrt{E_\gamma}$
neutral hadrons (h)	ECAL+HCAL	$10\% \; E_j$	$0.55 \sqrt{E_h}$



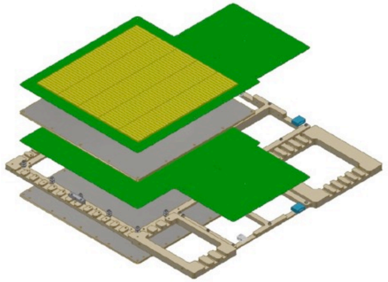
- Particle Flow Algorithm (PFA)
  - To achieve unprecedented jet energy resolution of $\sim 30\% / \sqrt{\mathrm{E_{jet}}}$
  - (Reminder: multiple particles within a jet)
  - **Choose a sub-detector best suited for each particle type**
  - Charged particles measured in tracker
  - Photons in ECAL and neutral hadrons in HCAL
- Separation of close-by particles in the calorimeters
- PFA-oriented calorimeters: high granularity (1~10 million channels)

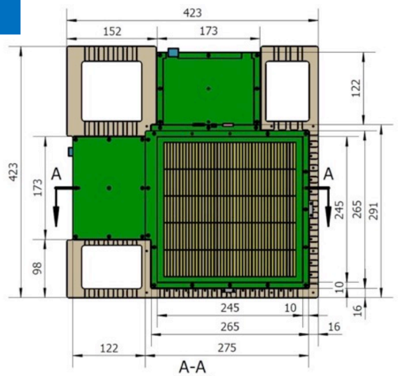


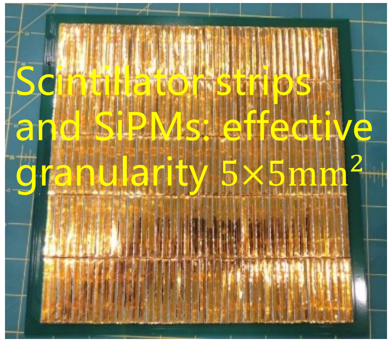
Scintillator-tungsten ECAL prototype

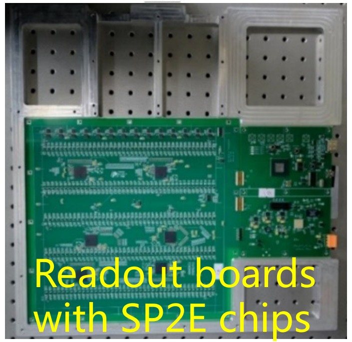
ScW-ECAL tech. prototype

"Super-layer" design

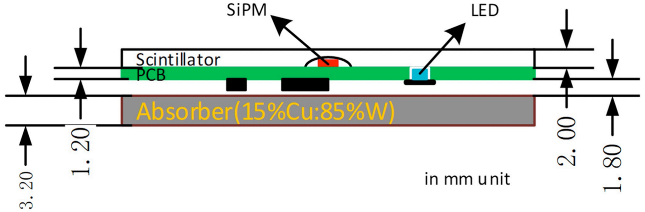




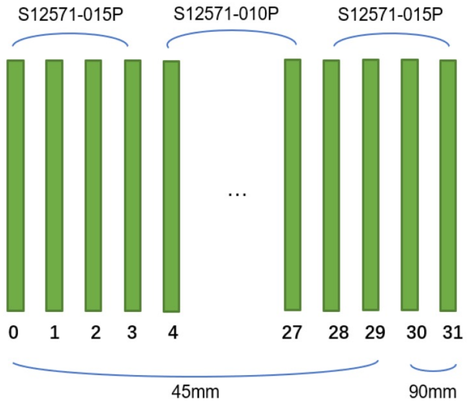


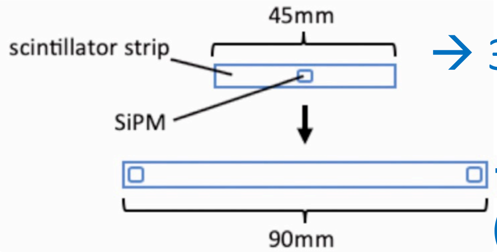


Scintillator-SiPM readout scheme



Sensitive layer arrangements



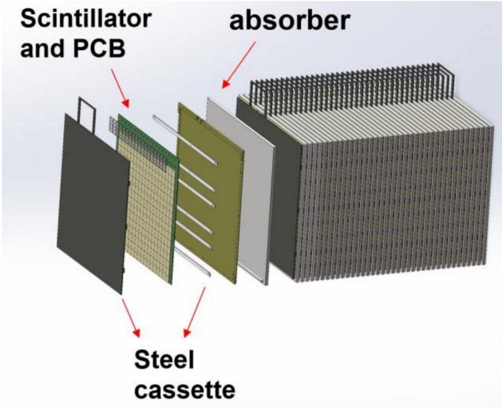


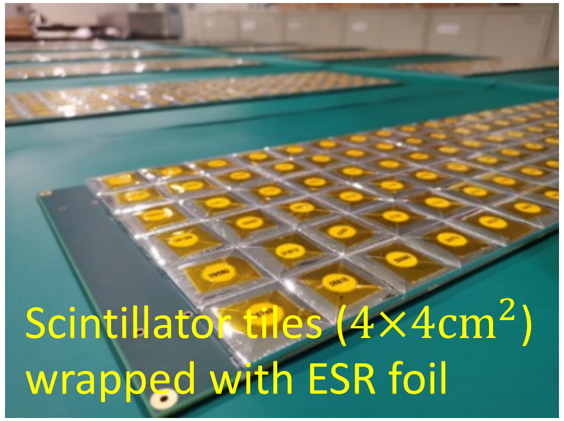
→ 30 sampling layers

→ 2 sampling layers (in the rear part)

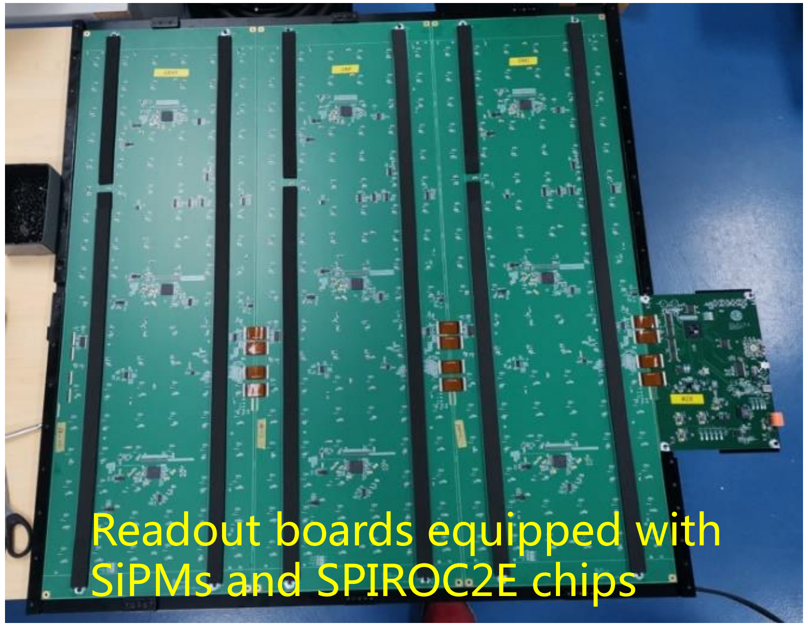
- ScW-ECAL prototype: developed in 2016-2020
  - Transverse area of ~22x22 cm, 32 longitudinal sampling layers
  - 6,720 channels, ~350 kg, SPIROC2E (192 chips)
- Beamtest campaigns at CERN in 2022-2023
  - Along with AHCAL prototype

Scintillator-Steel HCAL (AHCAL) prototype

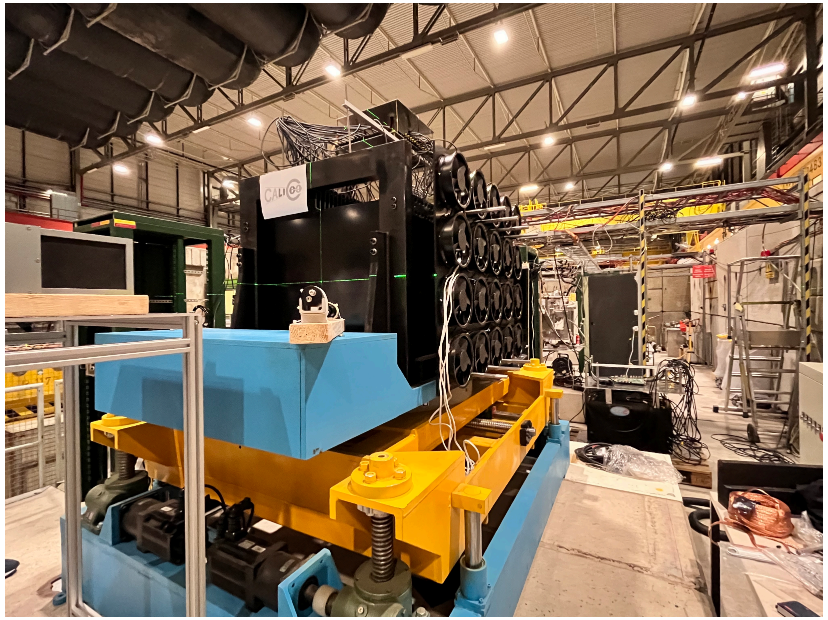




1 full layer: 3 HBUs + cassette



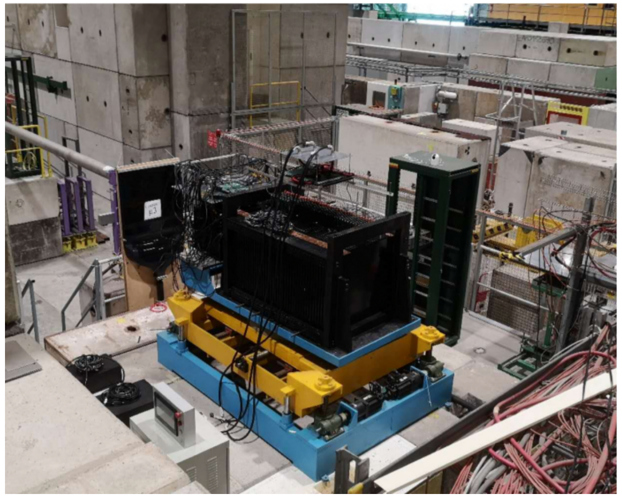
Beamtest Setup



- AHCAL prototype using "SiPM-on-Tile" design
  - Transverse size $72\times72\ \text{cm}^2$, 40 longitudinal layers ($\sim4.6\lambda_I$)
  - 12960 readout channels, SPIROC2E (360 chips), ~5 ton in weight
  - Developed during 2018 – 2022

CERN beamtests in 2022-2023

Oct 19 – Nov 2, 2022	Apr 26 – May 10, 2023	May 17 – 31, 2023
SPS H8 beamline	SPS H2 beamline	PS T9 beamline

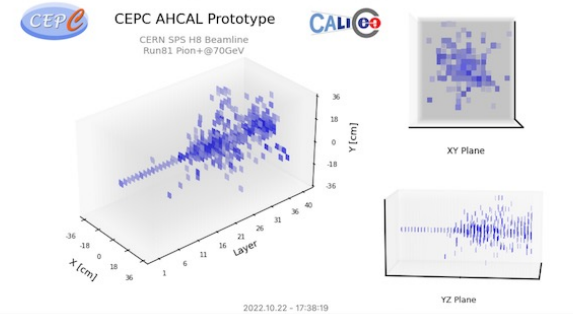


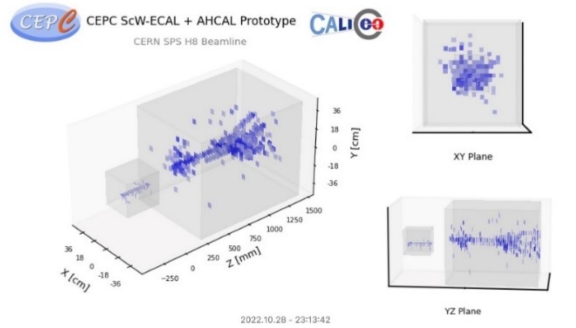
- Successful beamtest campaigns
  - Two prototypes (ScW-ECAL and AHCAL)
  - Both mounted on a motorised stage (XYZ+U)
  - Impressions: a few cubic meters and ~10 tons

CERN beamtests in 2022-2023

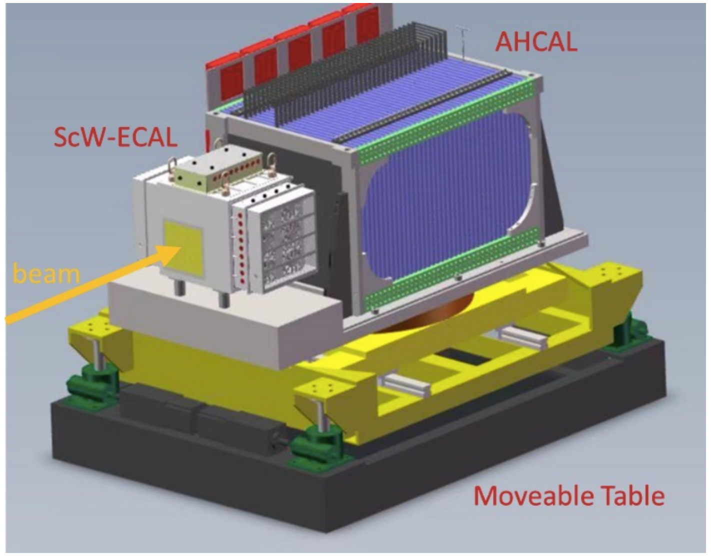
Oct 19 – Nov 2, 2022 — SPS H8 beamline
Apr 26 – May 10, 2023 — SPS H2 beamline
May 17 – 31, 2023 — PS T9 beamline

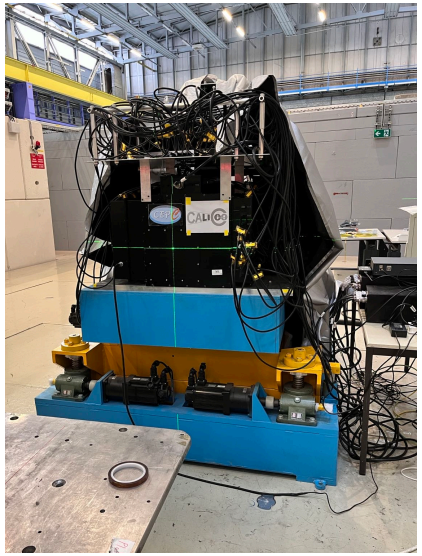
- Collected decent statistics of testbeam data samples
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 GeV at SPS (also up to 250 GeV)
  - Pions: 1 – 15 GeV at PS, 10 – 120 GeV (also 150 – 350 GeV) at SPS





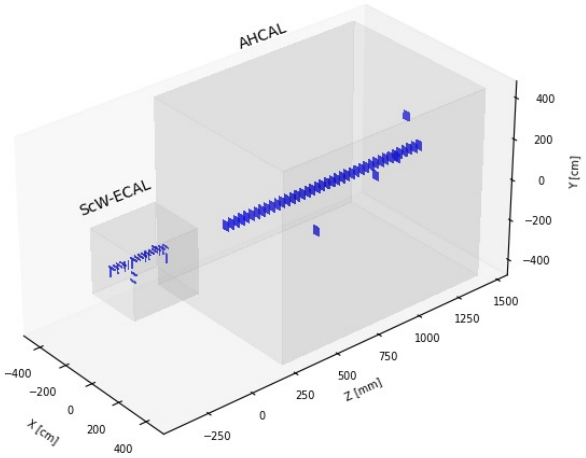
Overlapped energy points (10-15 GeV) at PS and SPS

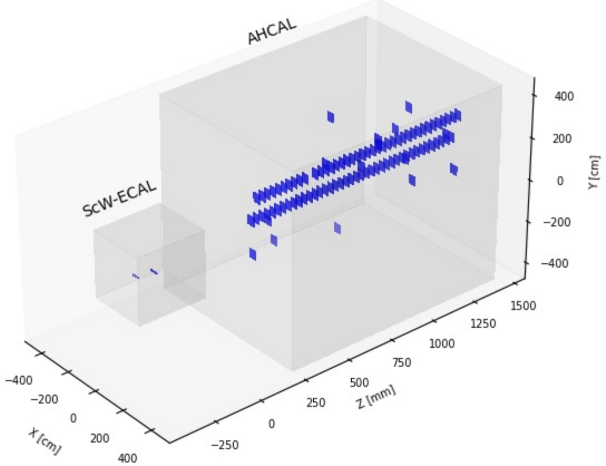




Event display with ScECAL+AHCAL

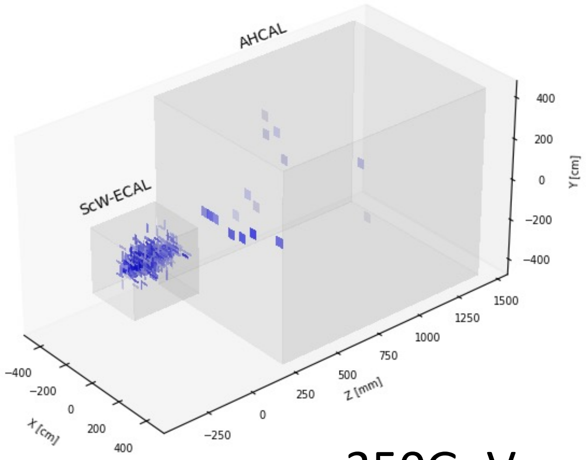
100 GeV mu-



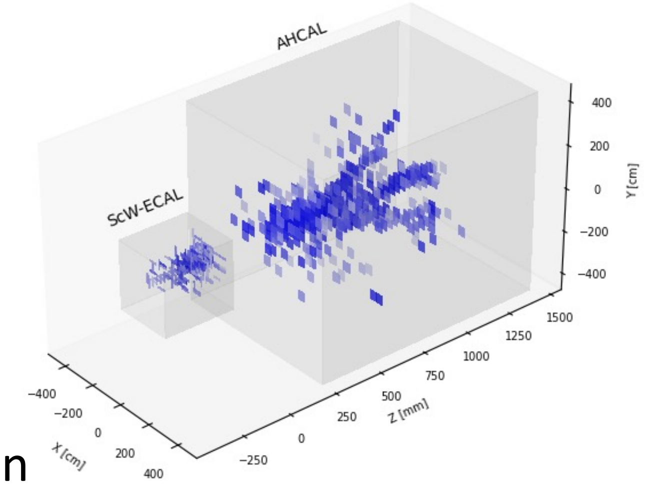


One run of different position scans: muon beam out of ScW-ECAL acceptance

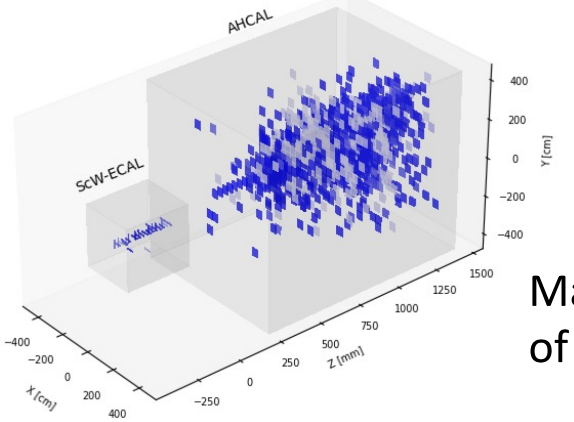
60GeV electron



60GeV negative pion



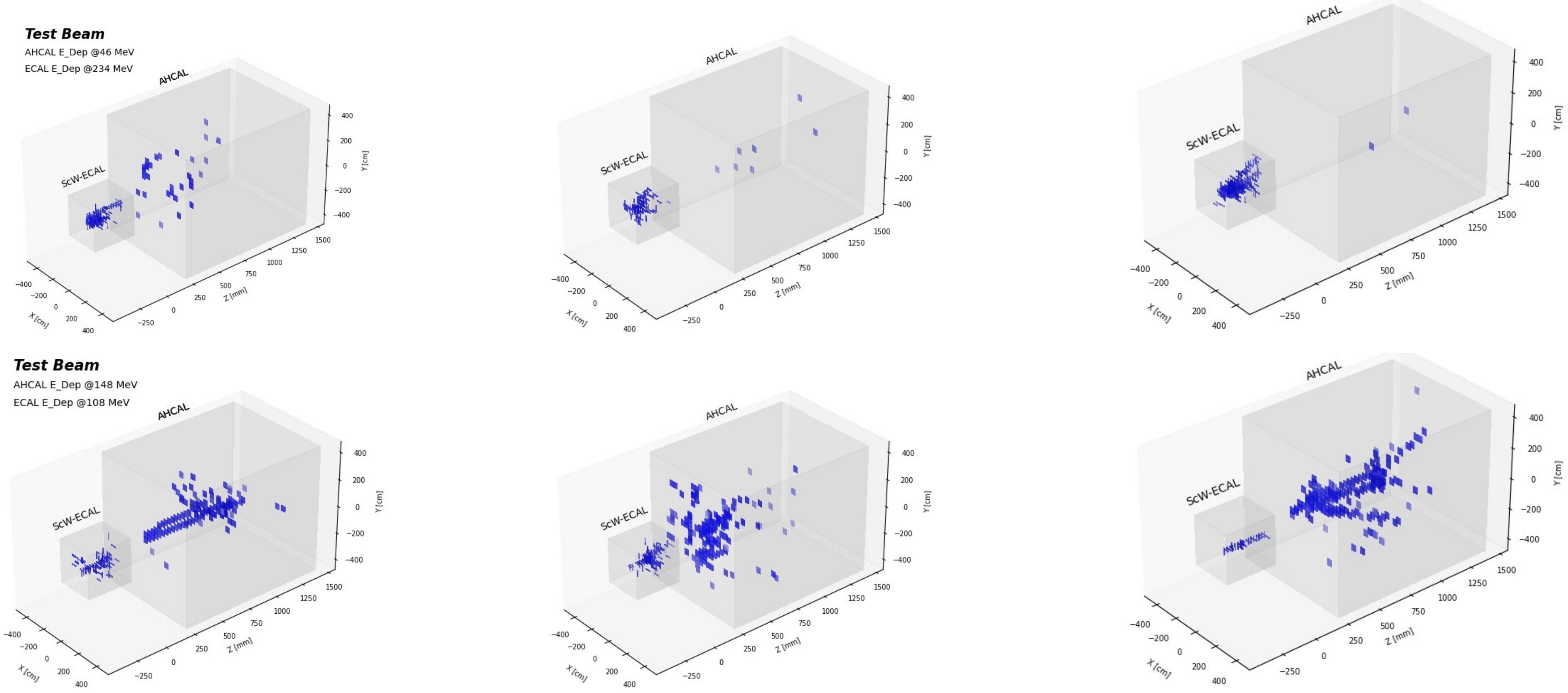
350GeV negative pion



Maximum pion beam energy of existing testbeam facilities

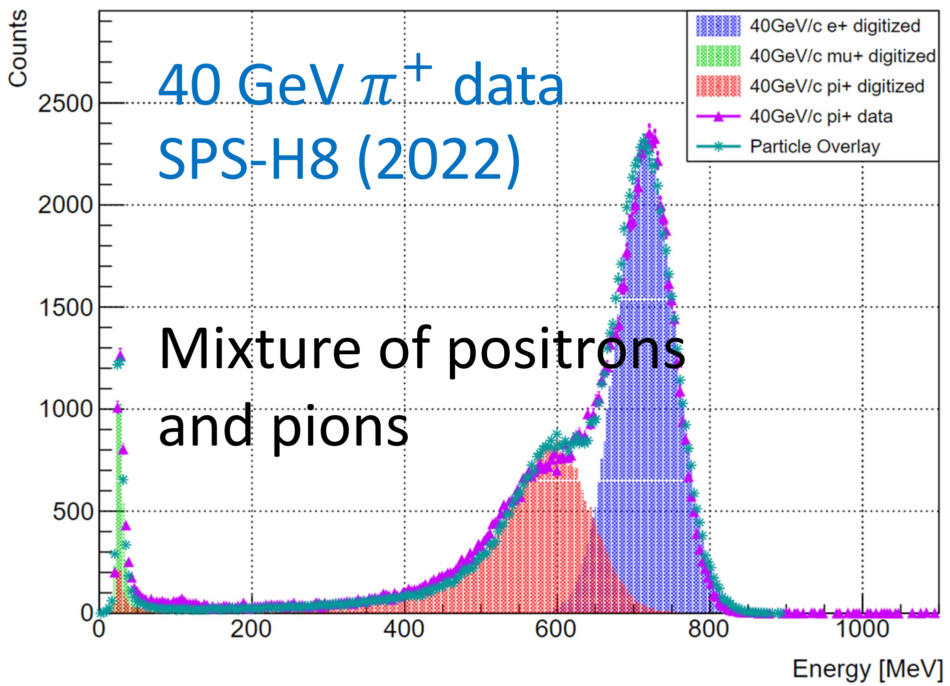
Hadronic showers in ECAL+HCAL at PS

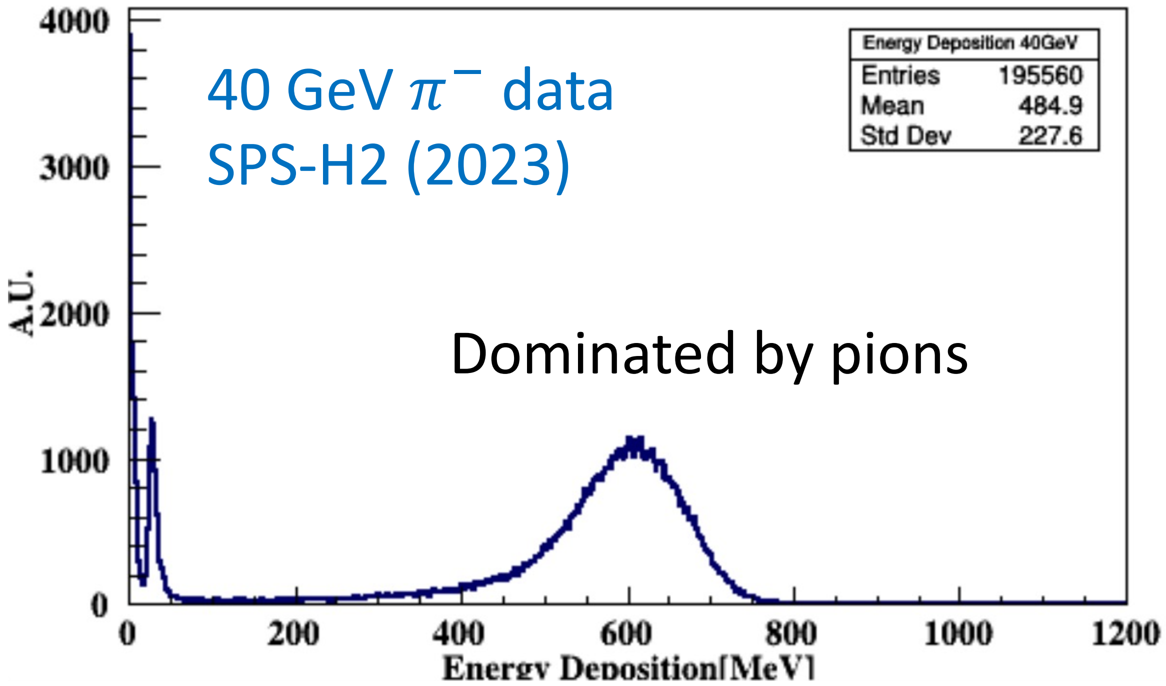
5 GeV π^- | 10 GeV π^- | 15 GeV π^-



Beam purity issue at SPS

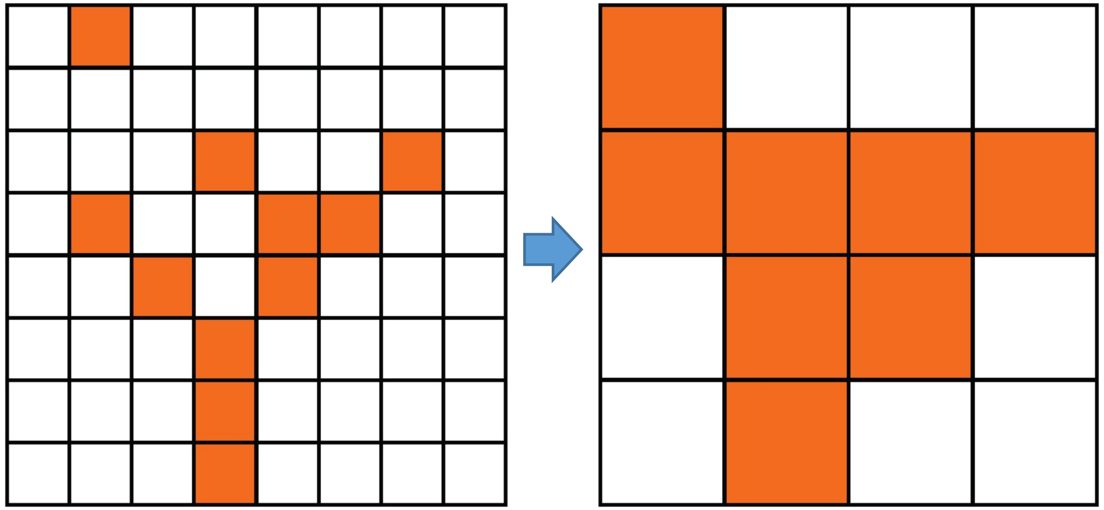
- Observed significant beam contamination SPS-H8
  - Mixture of pions, muons, positrons in H8 beam data
  - Beam purity at SPS-H2 (2023) is significantly better than SPS-H8 (2022)
  - Particle identification techniques developed: to select high-purity data samples



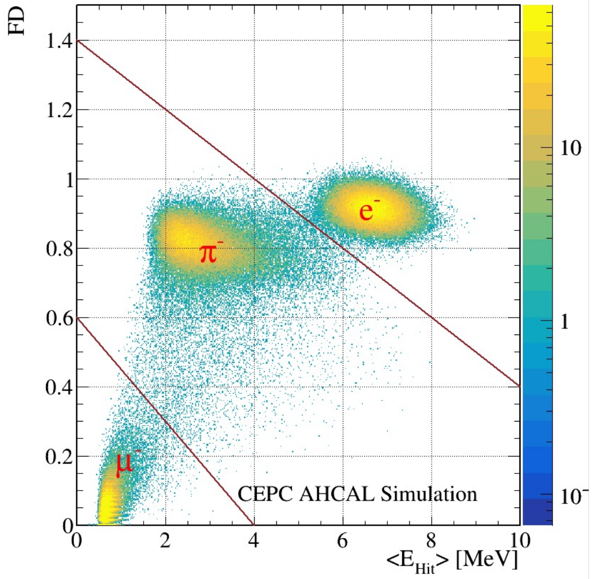


PID technique based on Fractal Dimension

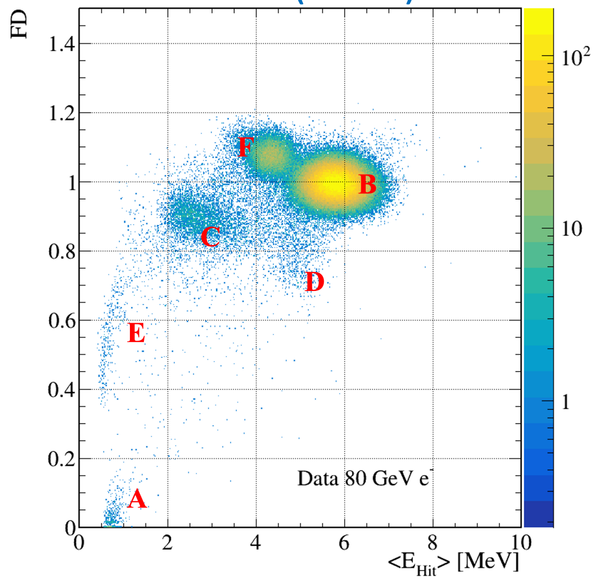
- Fraction Dimension (FD)
  - Self-similarity in patterns of particle showers in the transverse plane
  - $FD = \left\langle \frac{\log(R_{\alpha,1})}{\log(\alpha)} \right\rangle$ where $R_{\alpha,1} = \frac{N_1}{N_\alpha}$ and N_α is number of hits scaled by the factor α



Simulation



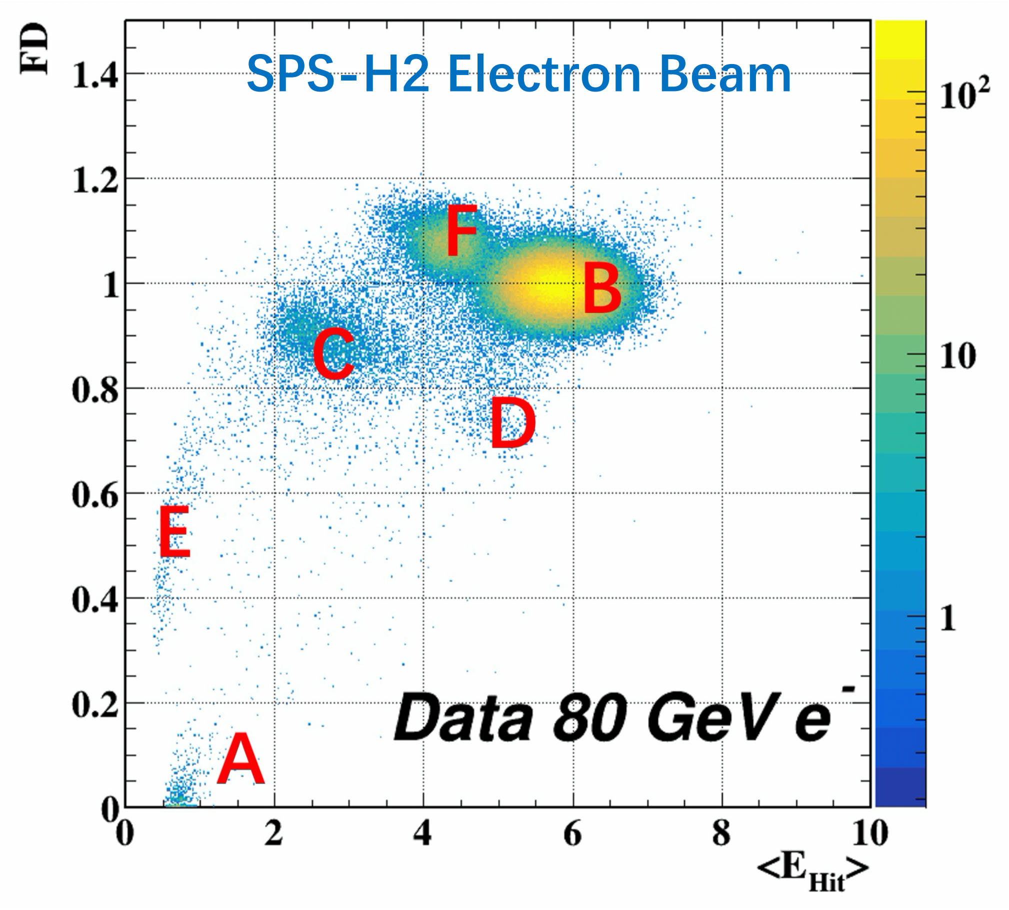
50 GeV π^- data
SPS-H2 (2023)

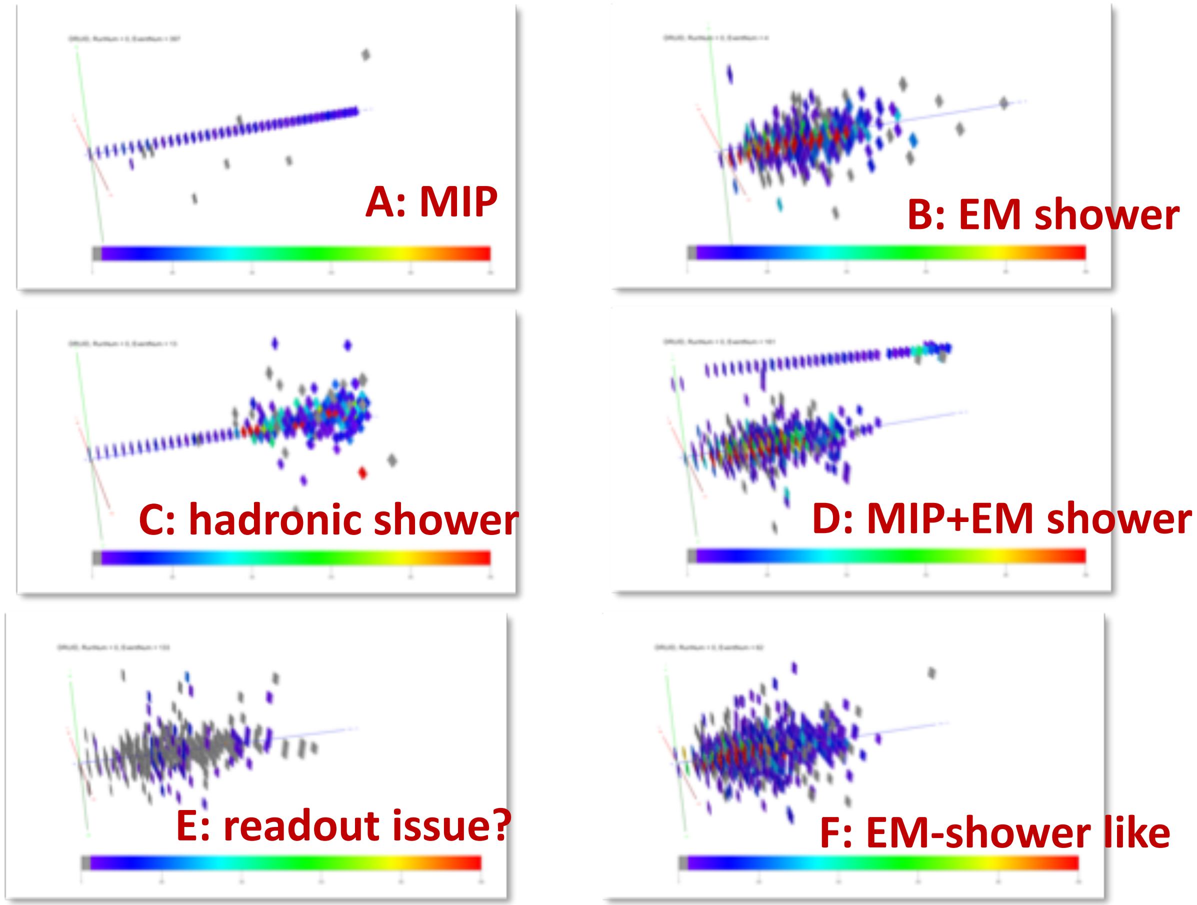


FD methodology based on
M. Ruan et al., Phys. Rev. Lett. **112**, 012001

PID studies with beamtest data

- FD characteristics of different beam particles
  - Imaging capability of high granularity calorimeter: diagnosis with event display

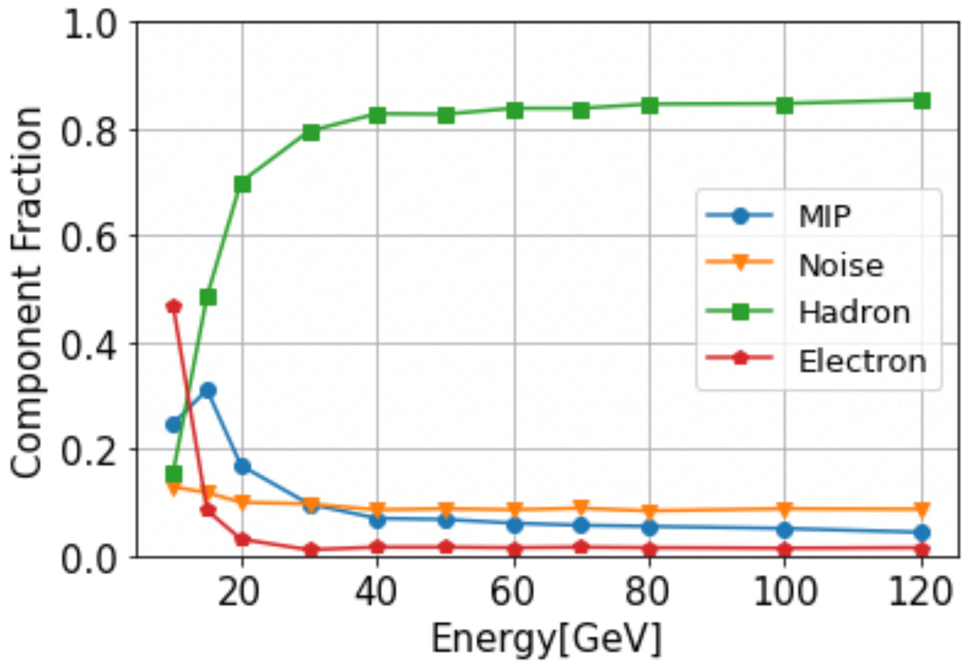




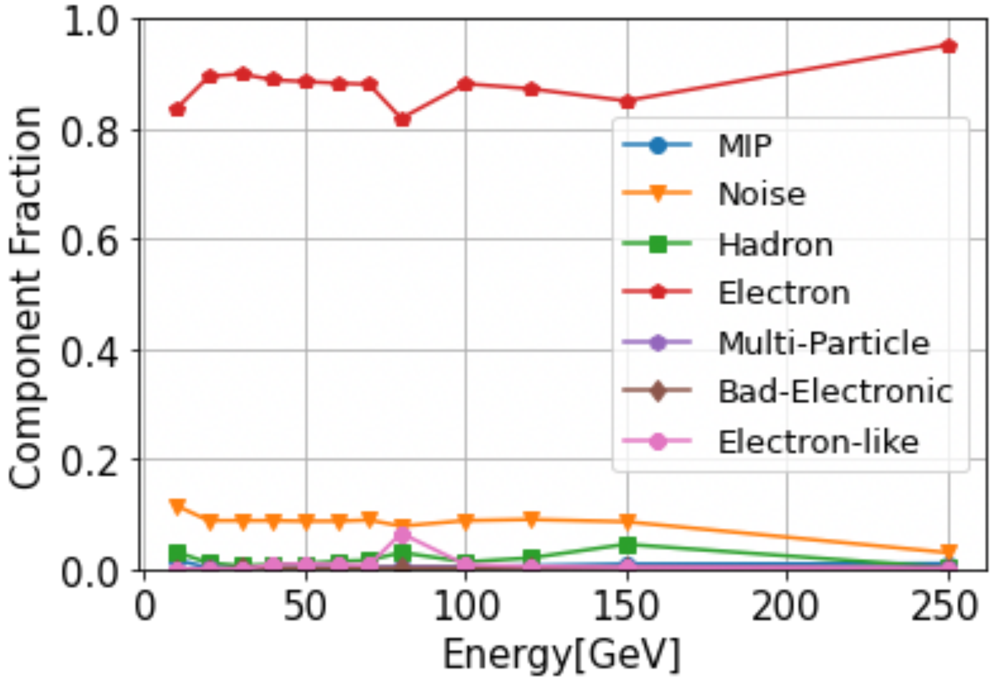
PID studies based on fractal dimension

- SPS-H2 beam purity >80% for electron and pion beams >30 GeV
- Significantly better beam purity at H2 than H8
- Noise-only events now become a dominating factor (~10%): ongoing studies

SPS-H2 Pion Beam

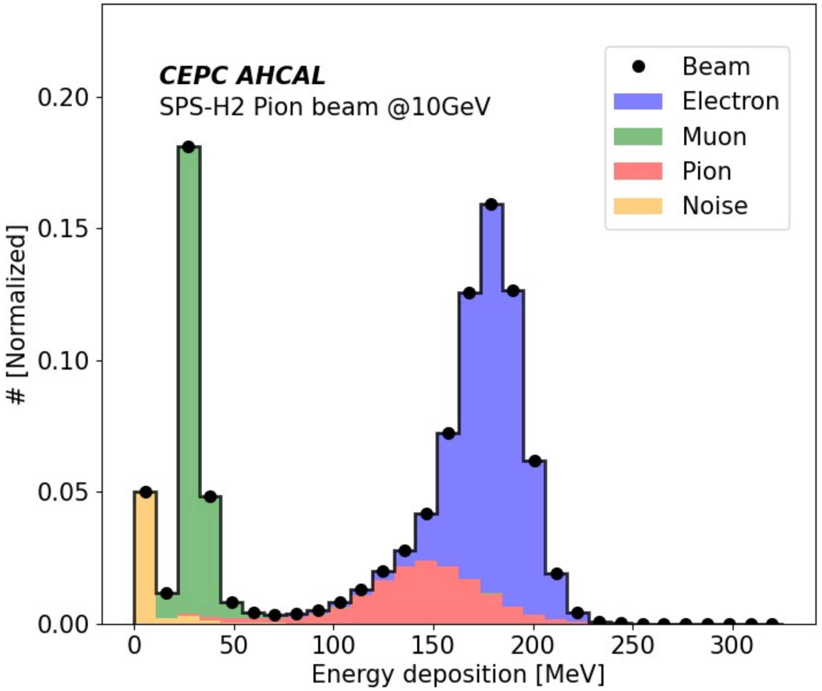


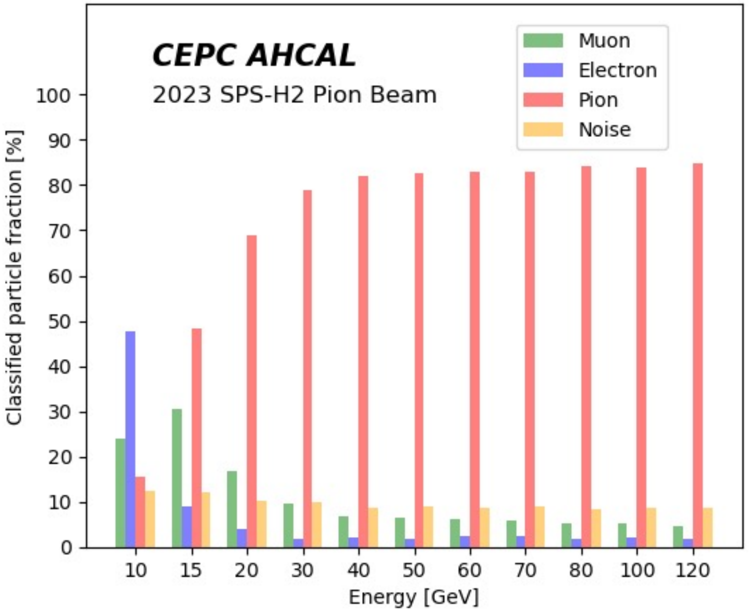
SPS-H2 Electron Beam

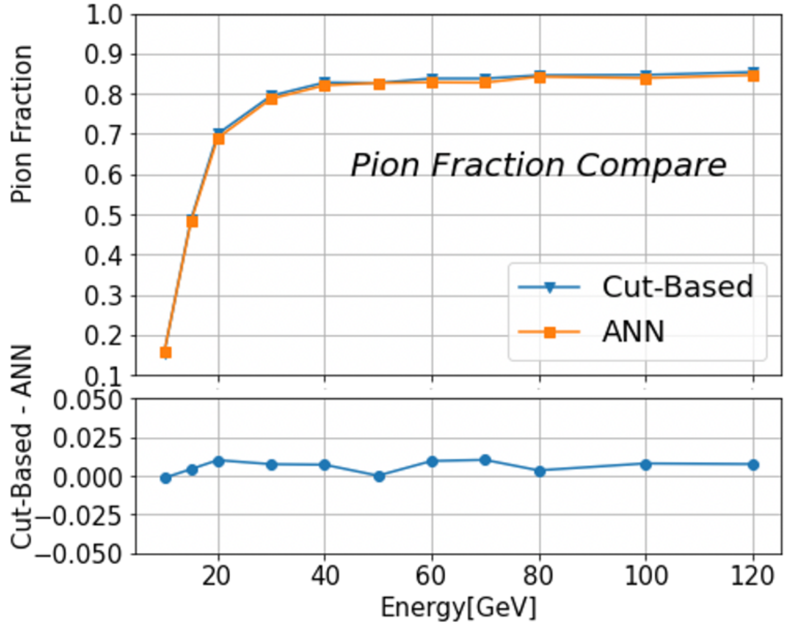


PID studies with Artificial Neural Network

- **PID based on ANN (ResNet): input tensor of energy deposition per AHCAL tile**
- ANN results mostly consistent with Fractal Dimension (FD)
  - Difference within ~1% level for both electrons and pions



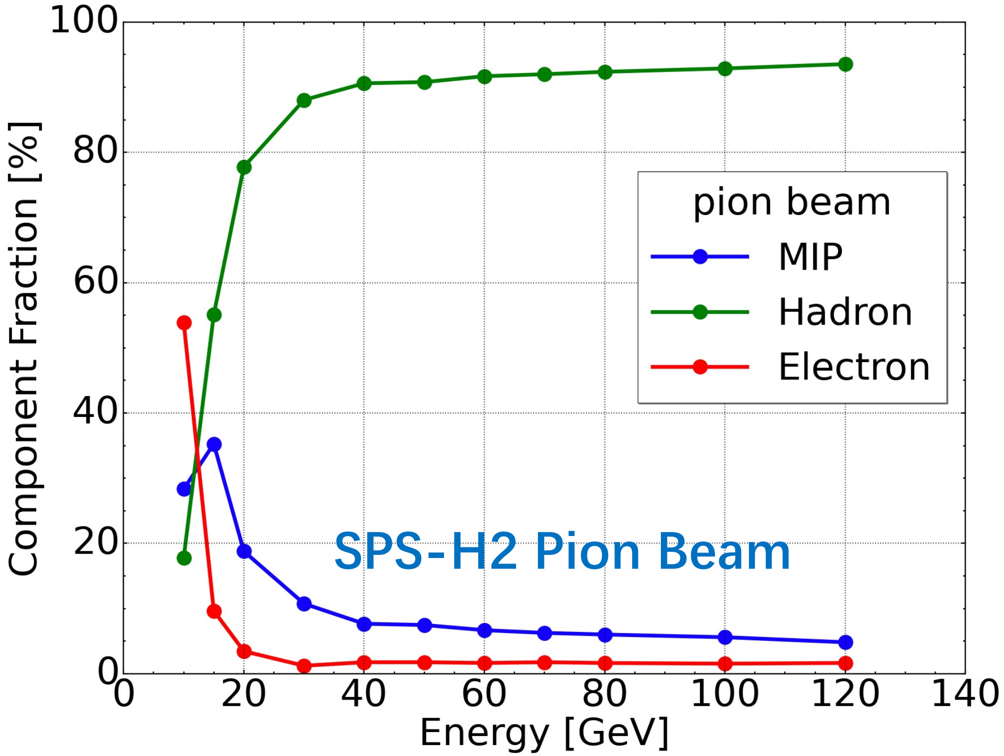


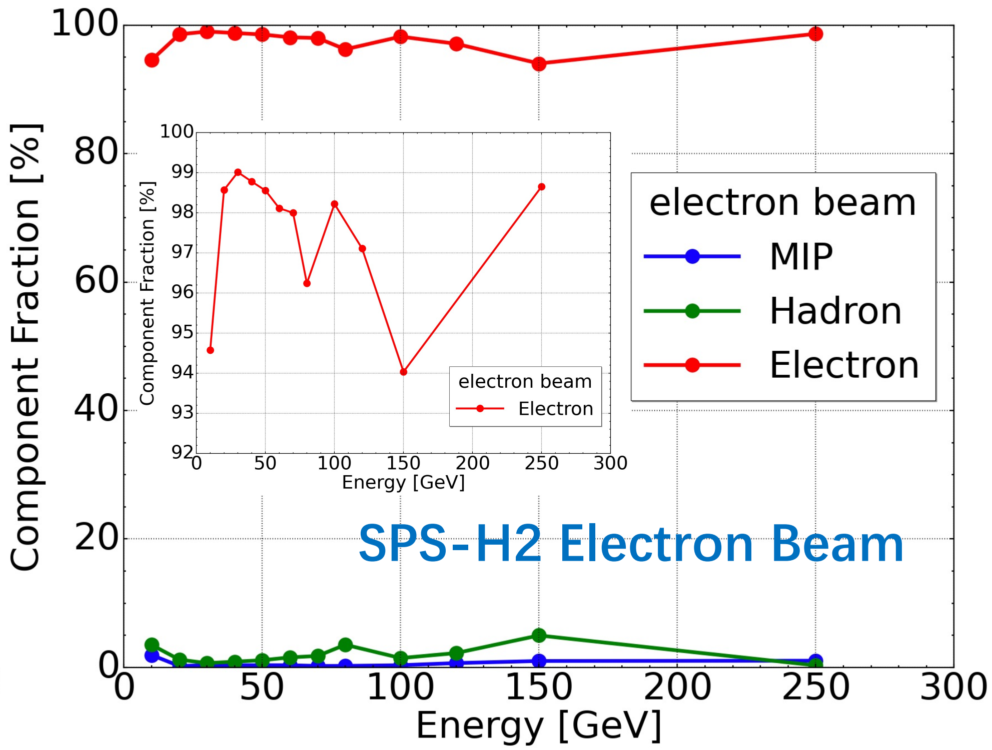


ResNet: He K, Zhang X, Ren S, et al. "Deep residual learning for image recognition" Proceedings of the IEEE conference on computer vision and pattern recognition. 2016: 770-778.

2023 SPS-H2 beam purity: preliminary results

- Updates on SPS-H2 beam purity: based on Fractal Dimension
  - Excluding noise-only events, incomplete EM/hadronic showers
    - Regarded as an instrumentation issue (but still need to understand possible reasons)
  - Electron beam purity >94%, pion purity > ~90% when p>30GeV

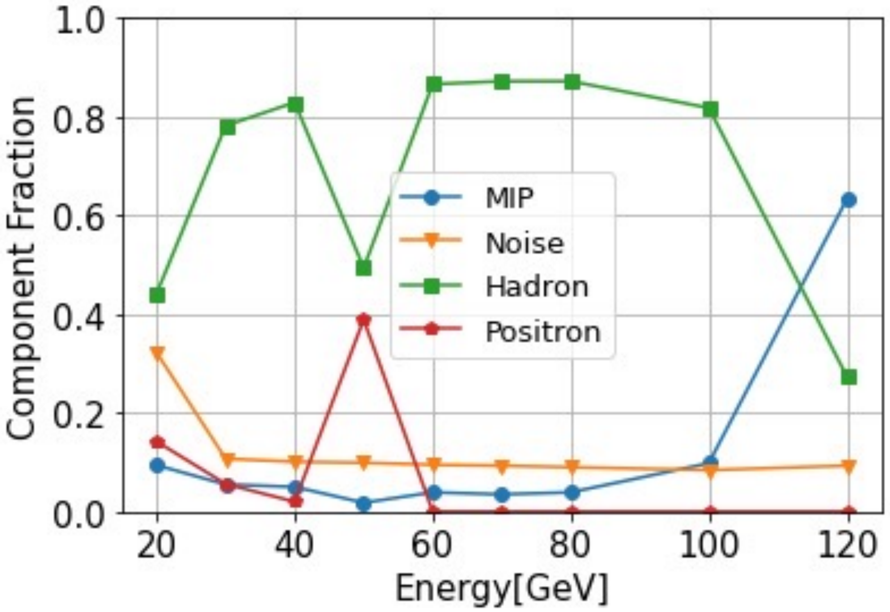




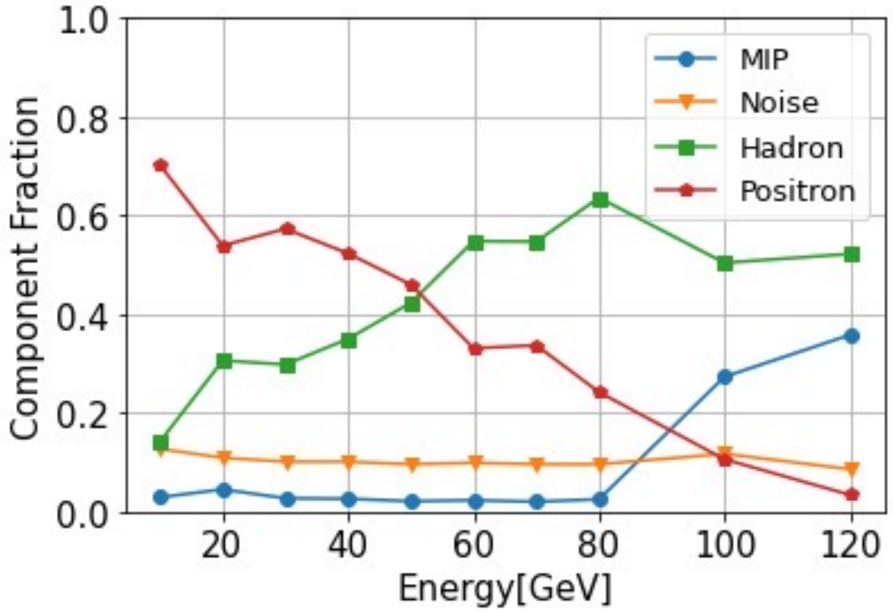
2022 SPS-H8 beam purity: preliminary results

- Revisited SPS-H8 beam purity: mixture of $\mu^+/e^+/\pi^+$ (characteristics of hit patterns)
- Positron beam: largely dominated by hadrons, barely no positrons >60 GeV
- Hadron beam: a considerably large fraction of positrons, esp. in low energy region

2022 SPS-H8 positron beam data

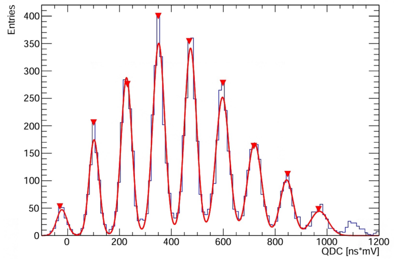


2022 SPS-H8 hadron beam data



Simulation and digitisation

- Geant4 simulation including detailed geometry of ScW-ECAL and AHCAL prototypes
- Digitisation: 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

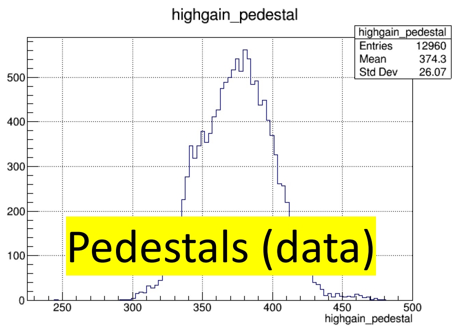
Poisson Distribution based on muon data

SiPM saturation curve from measurements

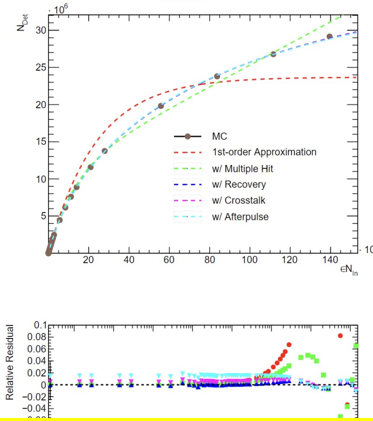
SiPM gain calibration from LED data

Pedestals (Electronics) ↑ (to Geant4 hits)

Extracted from data

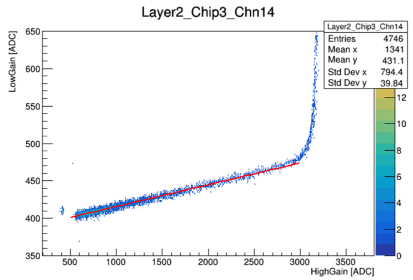


Pedestals (data)



SiPM saturation (data)

ASIC HG-LG ADC (data)



SiPM: p.e. conversion to ADC ↓ ASIC: ADC in High Gain or Low Gain

SPIROC2E HG-LG slope extracted from beam data

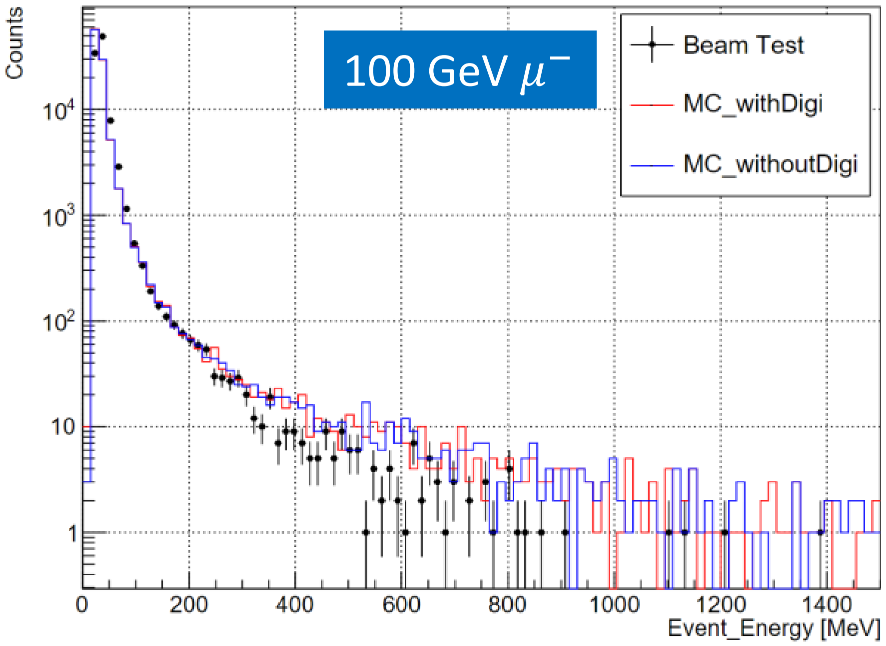
Key: digitisation is fully based on calibration data

Marking in Red: based on data

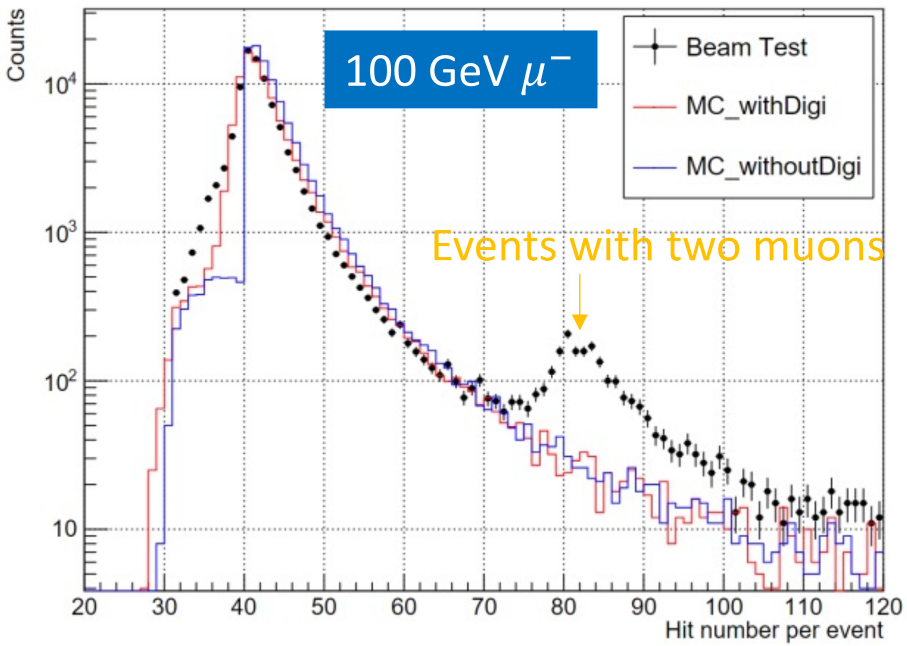
AHCAL prototype: muon data/MC

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

Energy response: Data/MC



Total Hit Number: Data/MC



MC is in general consistent with muon data

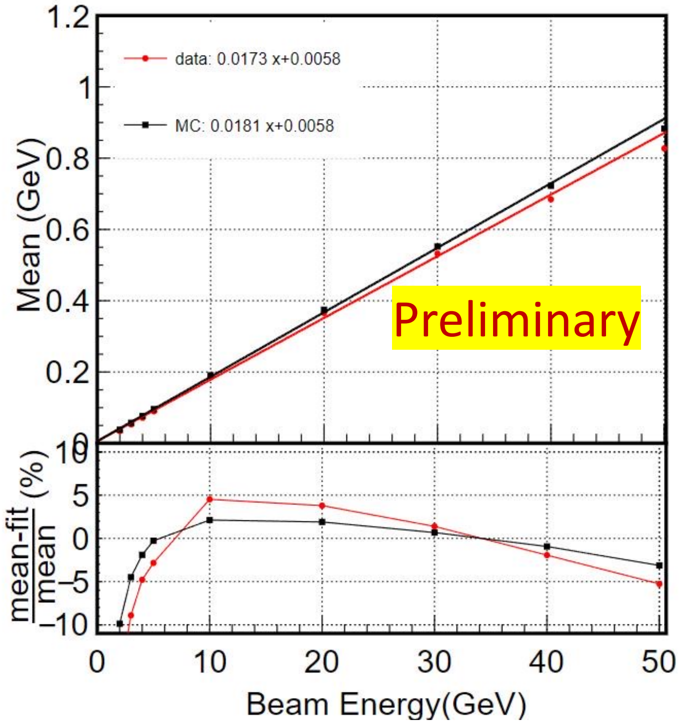
AHCAL prototype: electron data/MC

- Critical issue: non-linearity effects in SiPM and ASIC (SPIROC2E) with large signals
- Digitisation significantly improves MC/data consistency
- But still requires a better digitization model for SiPM+ASIC saturations effects

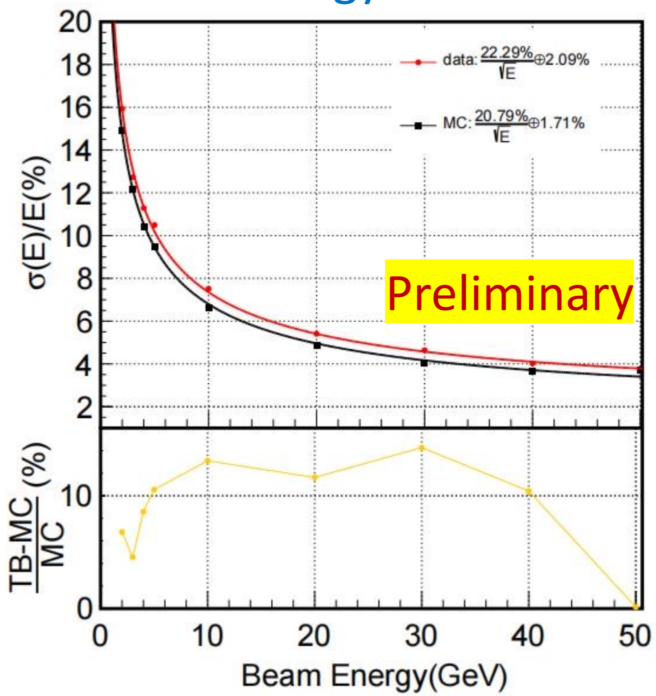
PS-T09 low-energy electron data (1-5 GeV) also included

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

EM response linearity

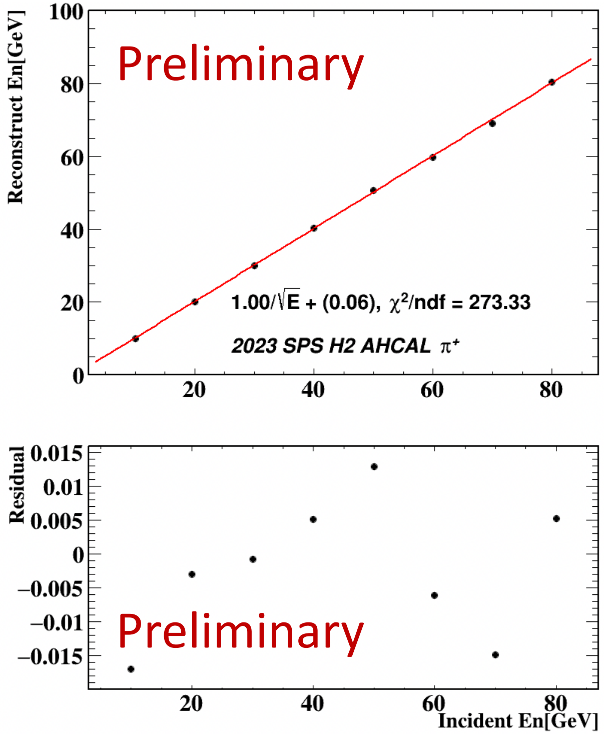


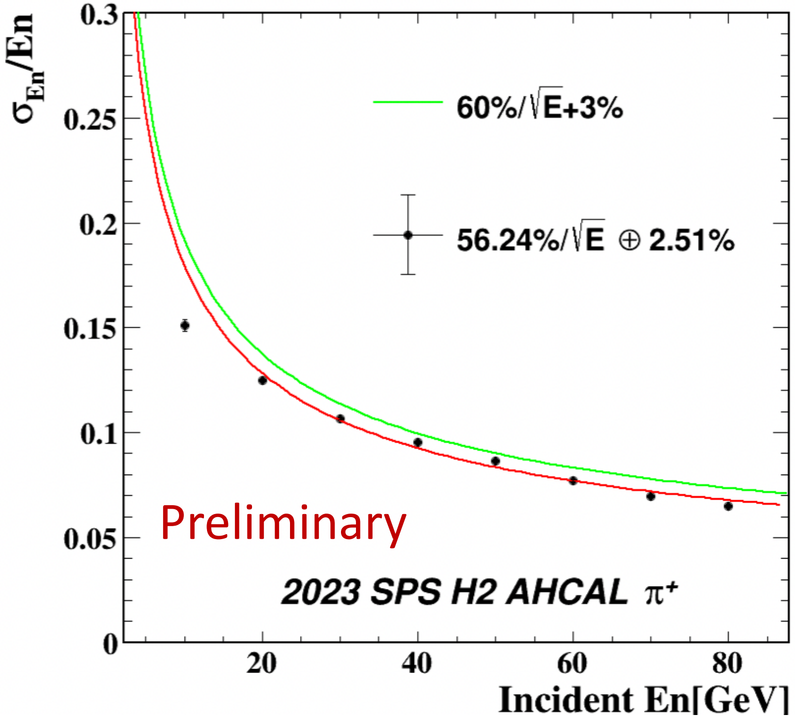
EM energy resolution



AHCAL performance: preliminary results

- AHCAL prototype using pion data sets after PID selections
  - Energy linearity within $\pm 1.5\%$
  - Energy resolution $56.2\%/\sqrt{E(GeV)} \oplus 2.5\%$ (expected $60\%/\sqrt{E(GeV)} \oplus 3\%$)





Ongoing studies to address critical issues : non-linearity effects and corrections (SiPMs, ASICs), MC validation

Summary and prospects

- CEPC scintillator-based calorimeter prototypes
  - Successful beam test campaigns at CERN PS/SPS during 2022-2023
  - Collected decent statistics of data samples in the wide energy range
  - Invaluable for detector performance evaluation and shower studies
- PID and validation studies: preliminary results promising
  - Particle Identification with imaging calorimeters: muons, electrons, pions
  - Prototype simulation + digitisation: validation studies with beam data
  - Ongoing efforts to improve data/MC consistency
- Future: ECFA DRD-on-Calorimetry (DRD6) collaboration
  - Common software, DAQ and beamtest campaigns
  - Geant4 validation and PFA performance studies with beamtest data sets

Thank you!

Acknowledgements

- Successful beam test campaigns during 2022-2023
- All these beam data taken would only be possible
  - With strong teamwork and enormous and substantial support received from CERN, CALICE and EuroLabs

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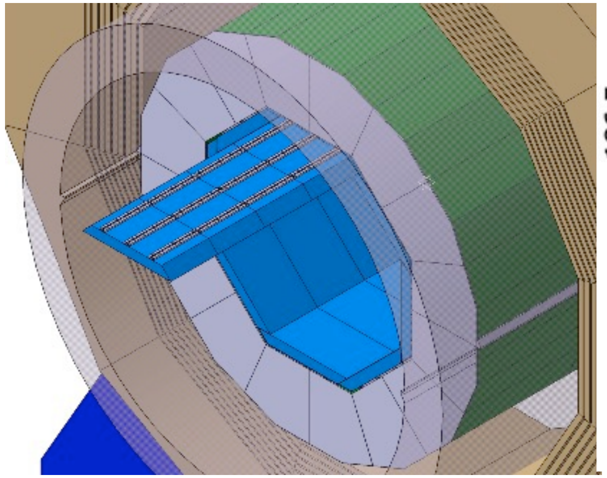
CERN SPS-H2, May 2023

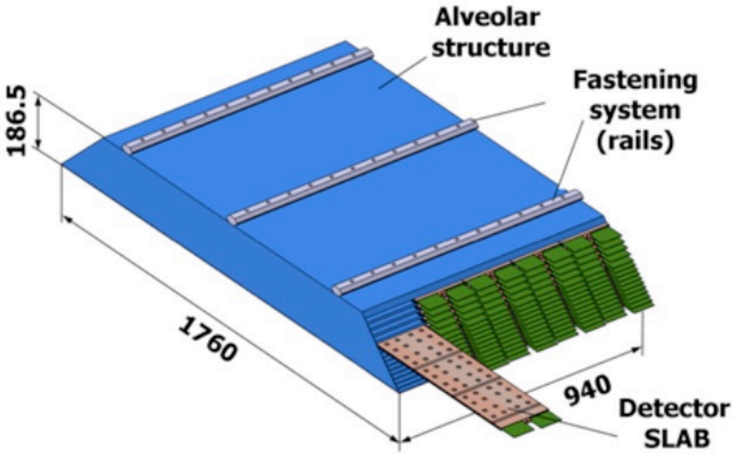
CALICE spokesperson's visit

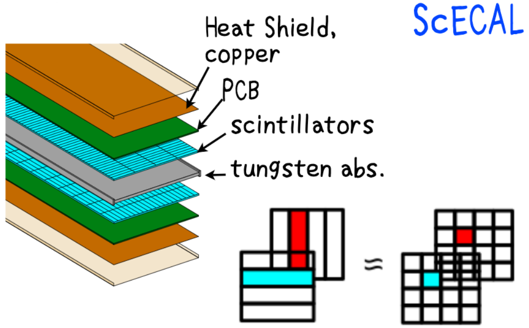
CERN PS-T9, May 2023

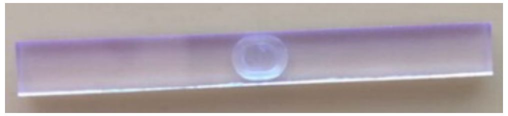
Backup

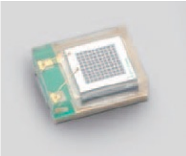
CALICE scintillator-tungsten ECAL option

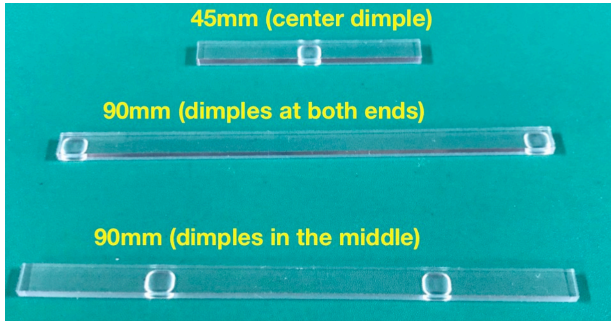


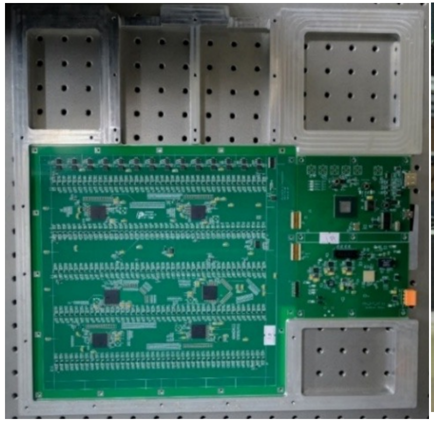






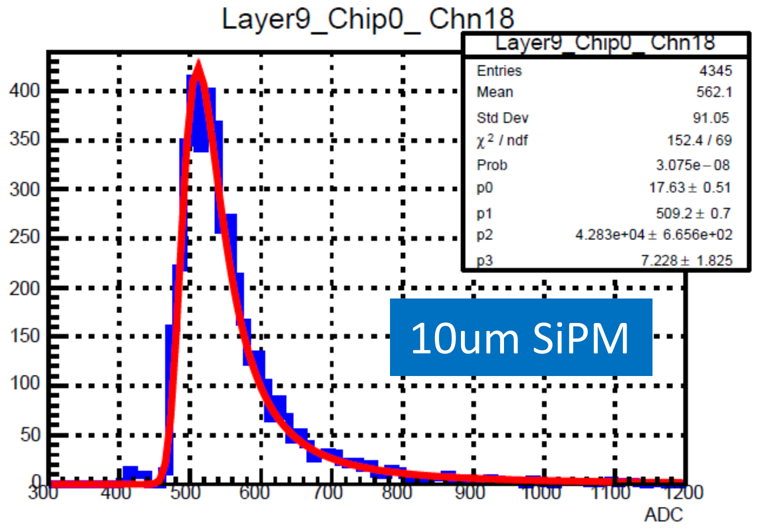


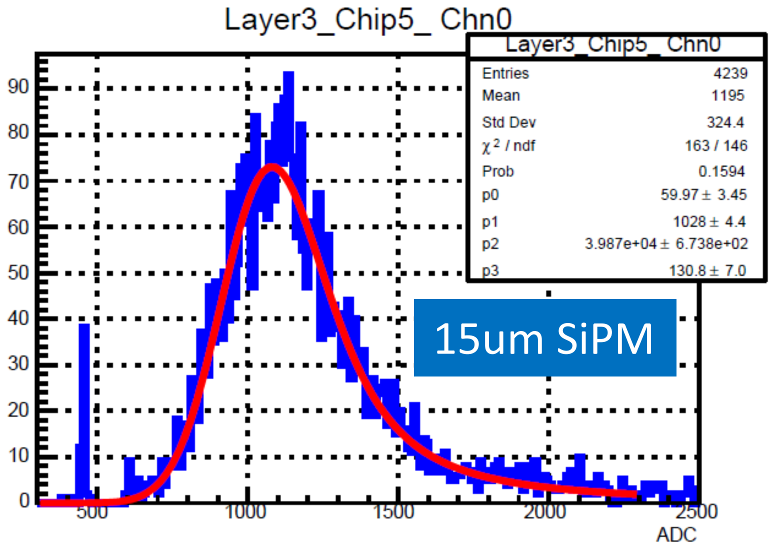




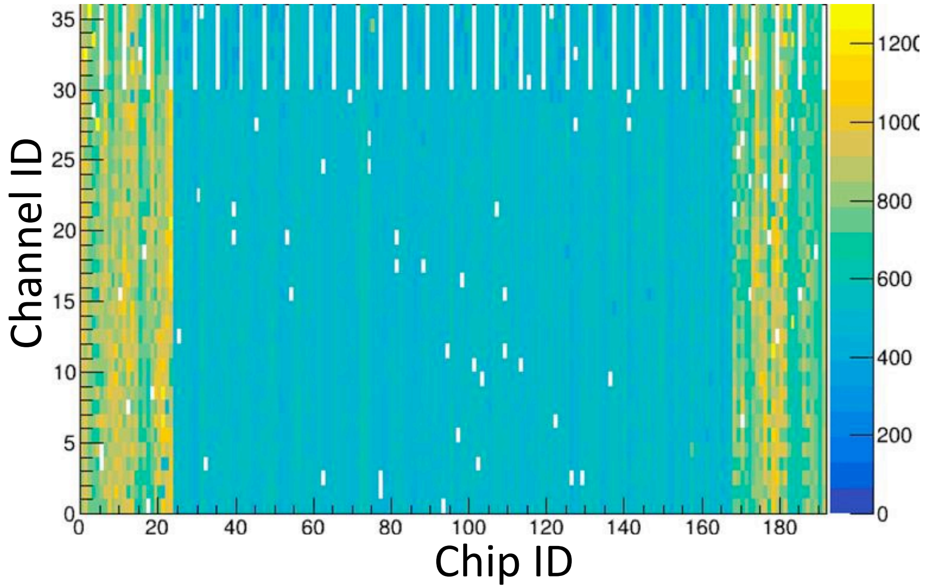
- ScW-ECAL: scintillator strips with SiPM readout + CuW absorber
  - A cost-effective option with plastic scintillator and less readout channels than SiW-ECAL
  - Effective transverse granularity of $5{\times}5\mathrm{mm}^2$
  - Pattern recognition issue (“ghost hits”): to be addressed by the “Strip-Splitting” algorithm
- ScW-ECAL technological prototype: developed in 2016-2020

ScW-ECAL data analysis: MIP calibration

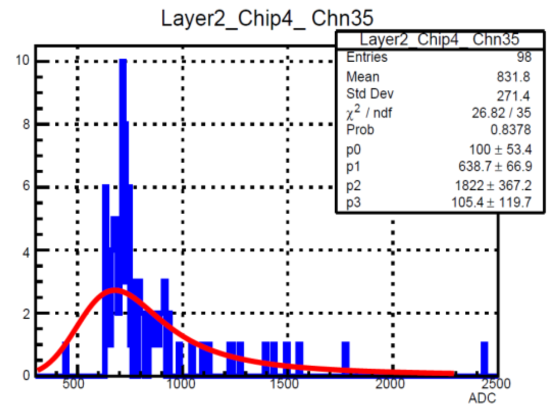




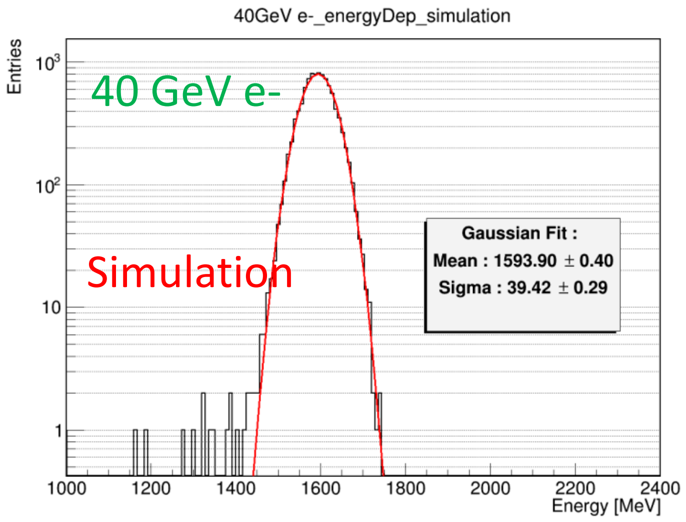
Intercalibration Ratio: ChipID vs ChnID

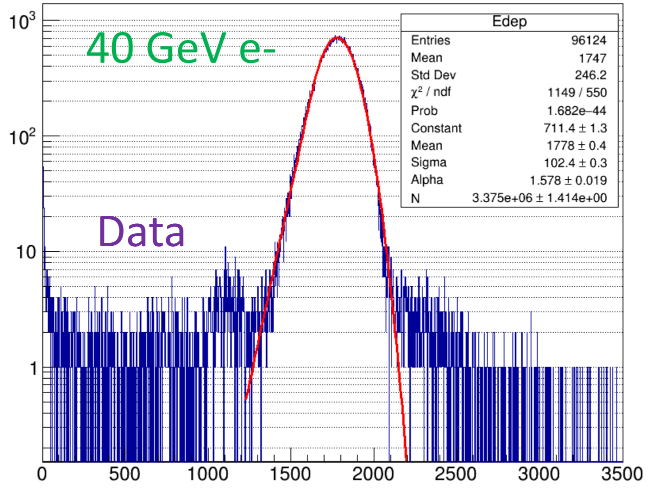


- MIP calibration with 100 GeV muon data
  - Extracted MPV value from Landau distribution convoluted with Gaussian
  - Trigger threshold and SiPM bias voltage optimized
  - Muon tracking algorithm applied to improve fitting quality
  - A small fraction of channels failed, due to insufficient statistics

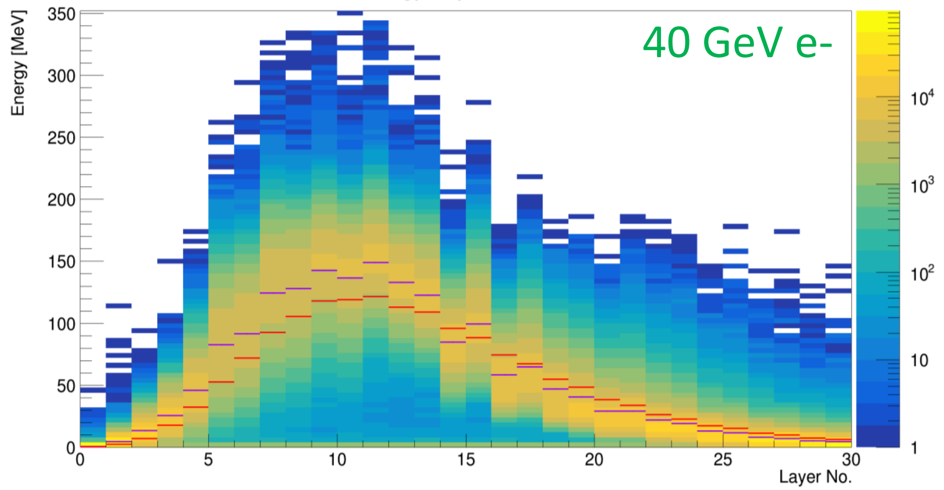


ScW-ECAL electron data: EM shower studies



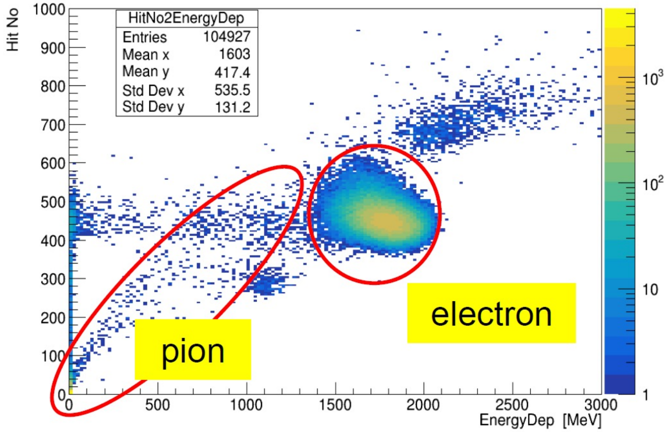


Longitudinal Shower Profile: MC vs Data



- Simulation including digitisation: photon fluctuations, trigger or energy threshold (0.5 MIP), SiPM saturation
- Still discrepancy in MC/data: energy response, shower profile
- Observed contamination from pions
- Ongoing efforts: simulation + digitisation, PID for better purity, impacts of SiPM noises

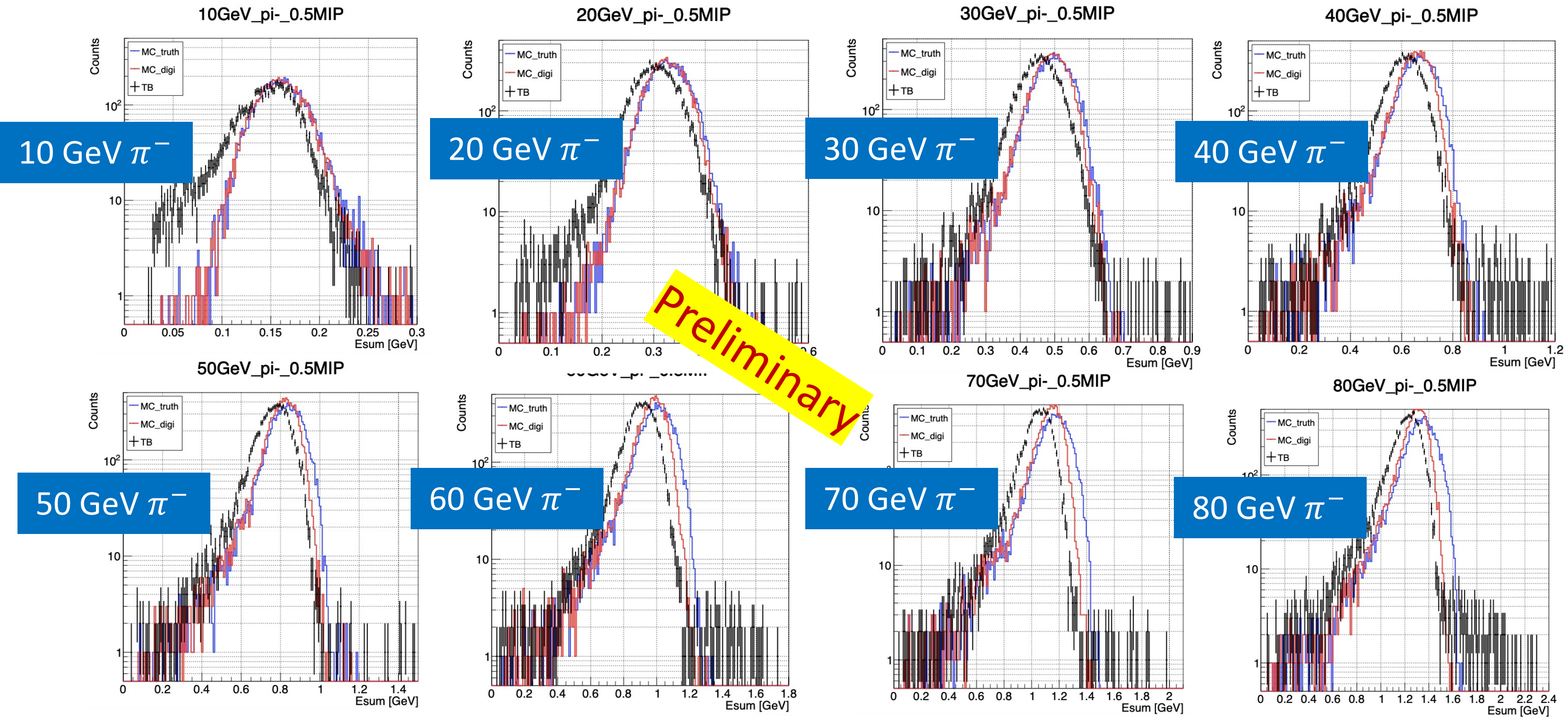
Energy vs Hit Number



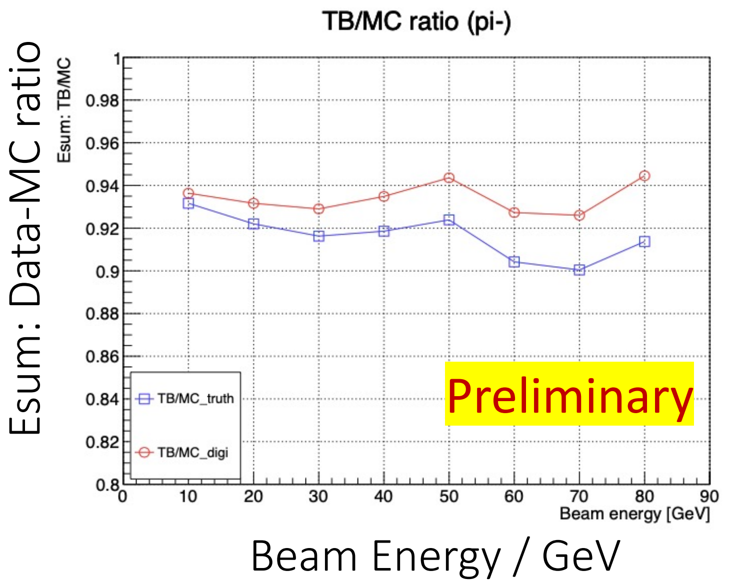
Validation of AHCAL simulation with beam data

Jiyuan Chen, Hongbin Diao, Dejing Du, Siyuan Song, Jiaxuan Wang, Xin Xia

- Pion data: ongoing studies to address critical issues
  - Digitisation significantly improves MC/data consistency: discrepancy from 10% to 8%
  - Critical issue: non-linearity effects (saturations in SiPM and ASIC with large signals)
  - Requires a better model for saturations effects in digitisation



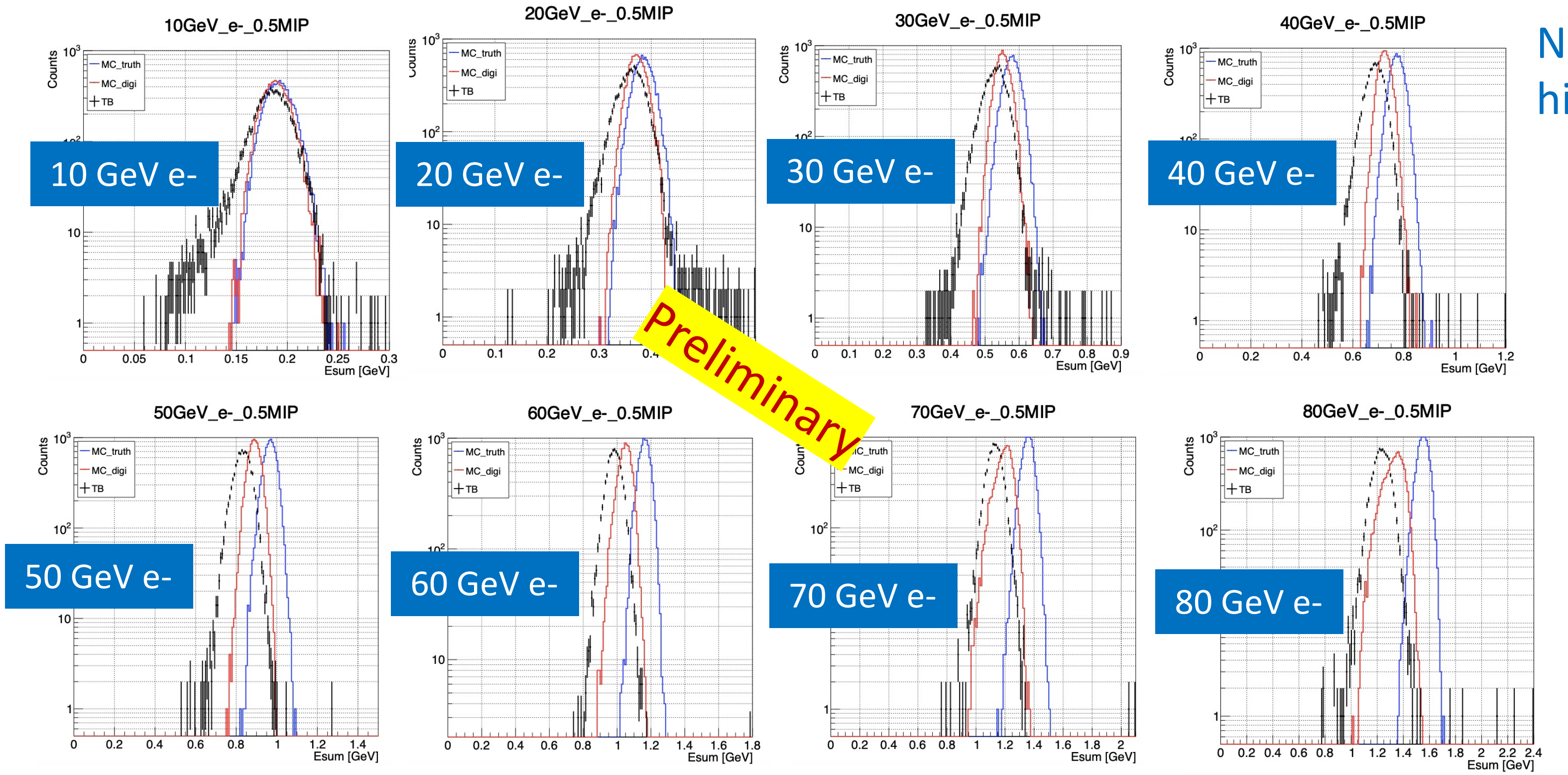
Energy response ratio: Data/MC



Validation of AHCAL simulation with beam data

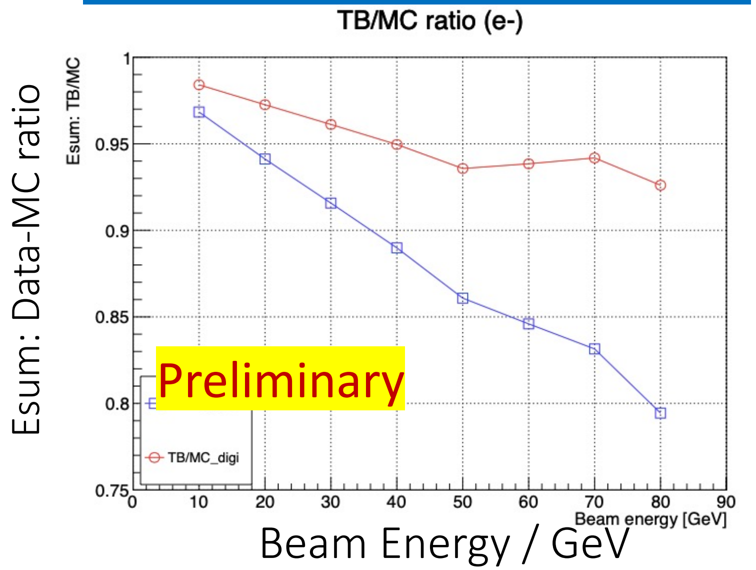
Jiyuan Chen, Hongbin Diao, Dejing Du, Siyuan Song, Jiaxuan Wang, Xin Xia

- Electron data: ongoing studies to address critical issues
  - Digitisation significantly improves MC/data consistency: discrepancy from 21% to 7%
  - Critical issue: non-linearity effects (saturations in SiPM and ASIC with large signals)
  - Requires a better model for saturations effects in digitisation



Note: EM showers with compact profiles → higher energy deposition density in core region

Energy response ratio: Data/MC



Event display with AHCAL alone at PS

Siyuan Song (SJTU)

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