AHCAL Prototype Beam Test Data Analysis

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On behalf of AHCAL working group

The 2023 International Workshop on the CEPC from Oct 23-27

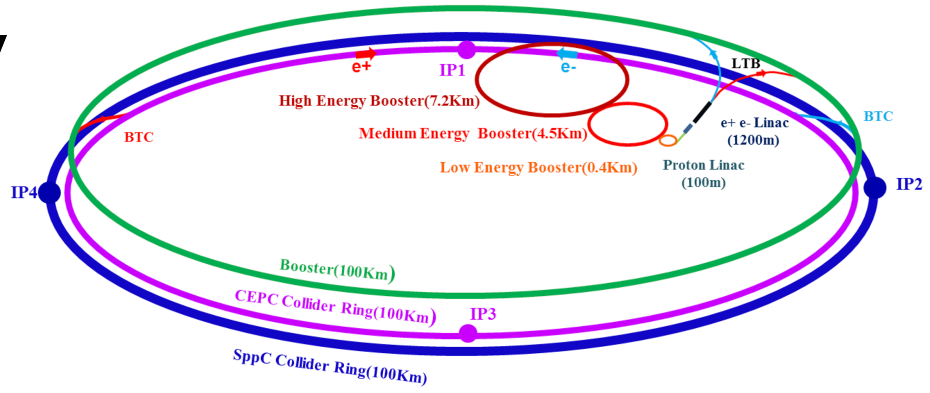
上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

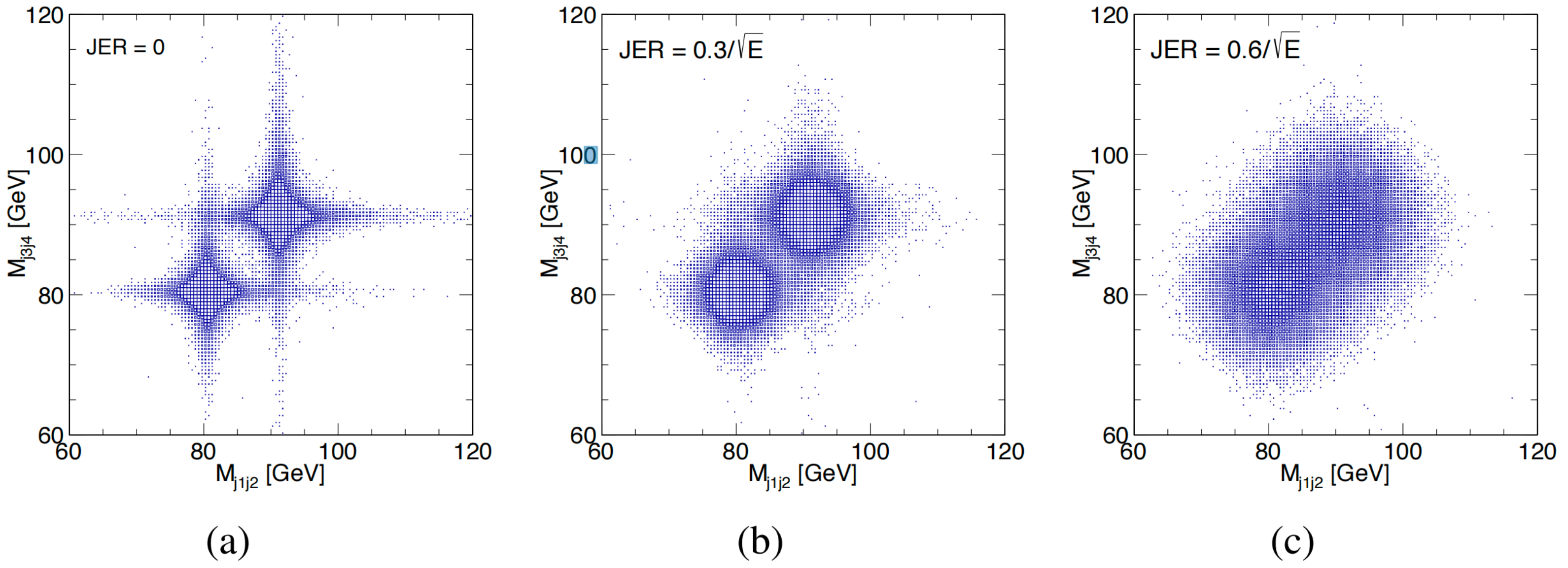
Outline

- Introduction
- Calibration
- Geant4 Simulation
- Particle Identification
- Preliminary AHCAL Prototype Performance

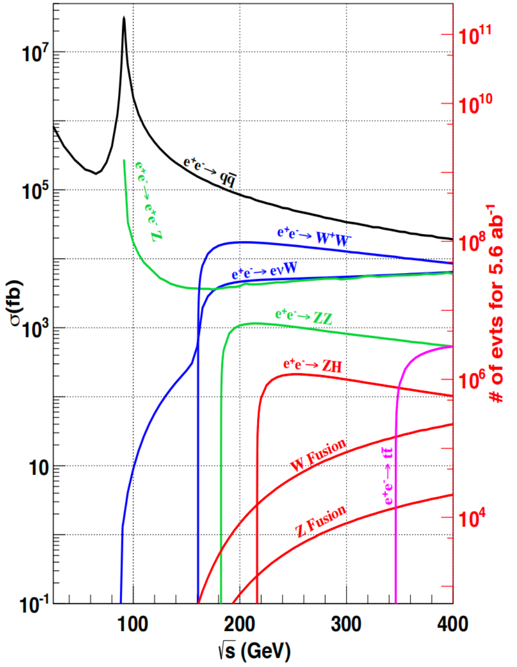
Introduction

- **CEPC: The future Higgs/W/Z factory**
  - Precise measurement of the Higgs/EW/QCD.
  - Calorimetry system requirement:
    - 4% of BMR or better,
    - Jet energy resolution: ~$30\%/\sqrt{E}$.



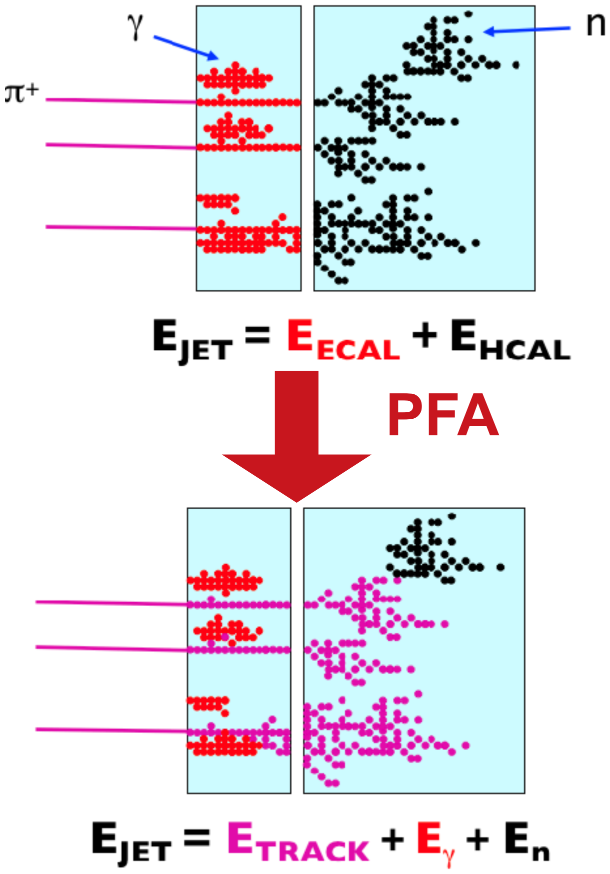


Separation of W and Z bosons in their hadronic decays with different jet resolutions.

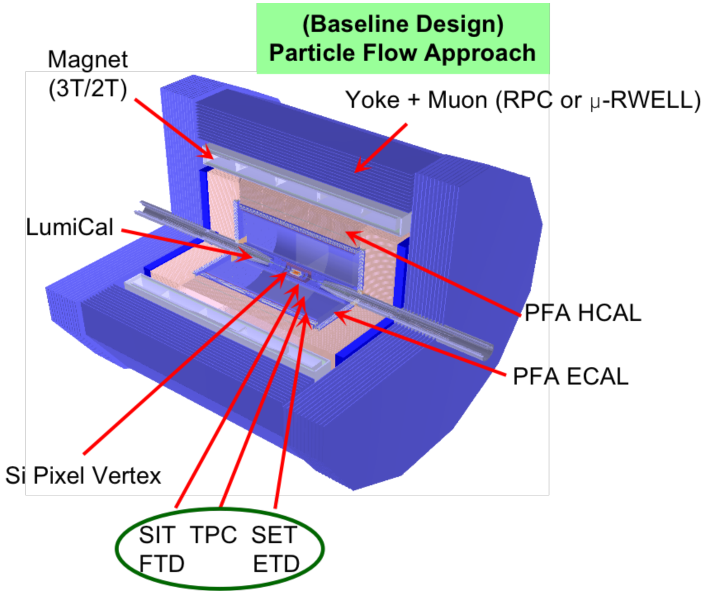


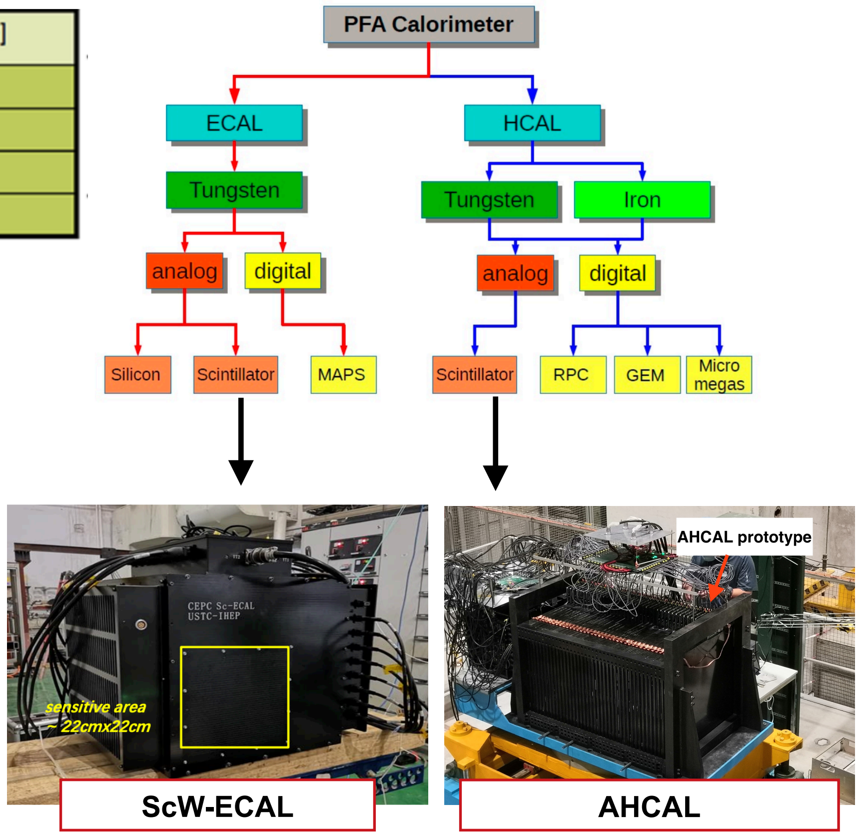
Introduction

- **Particle Flow Algorithm (PFA) : Baseline option of CEPC detector**
  - PFA-oriented calorimeter: High granularity (imaging).
  - **AHCAL** and ScW-ECAL (Tatsuki's talk) were tested at CERN in 2022, 2023.



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

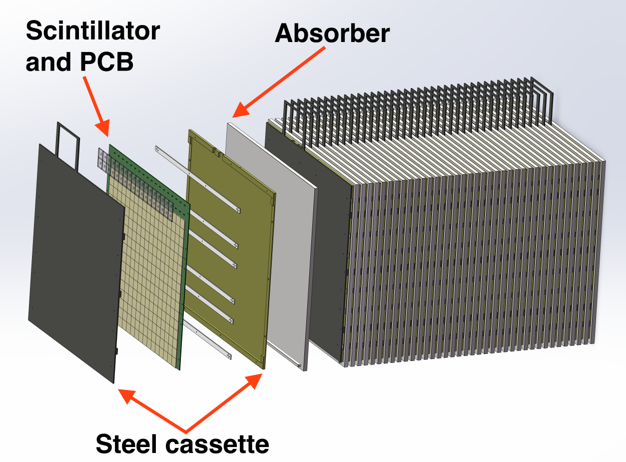


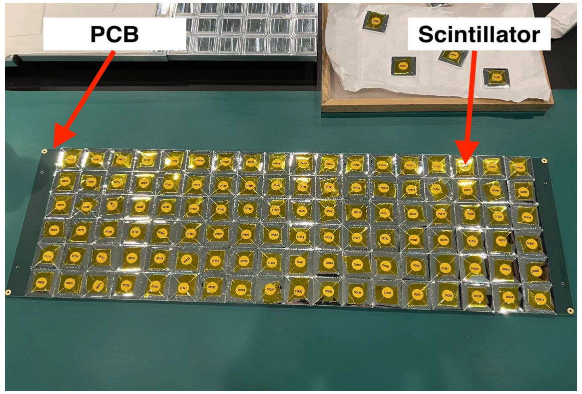


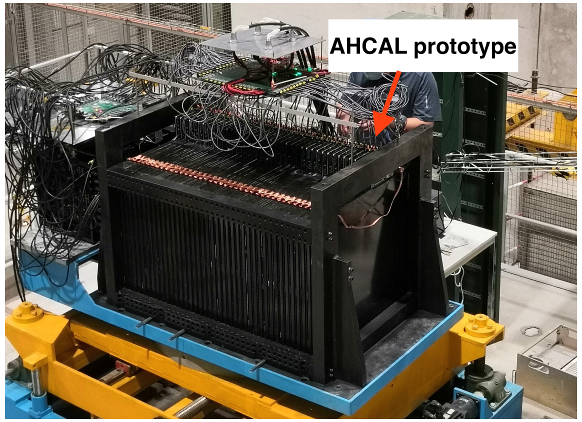
Introduction

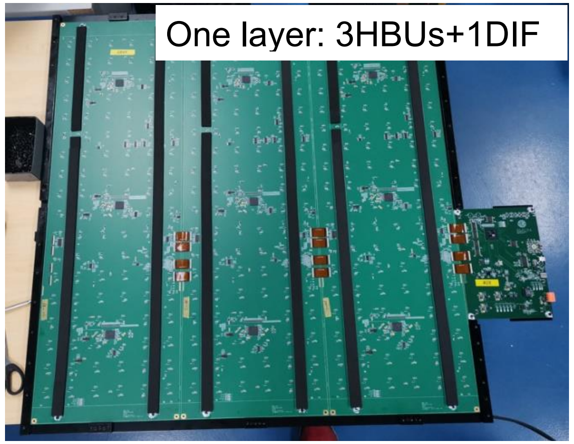
- **CEPC AHCAL prototype parameter**
  - **Hadron energy resolution target**
    - $60\%/\sqrt{E}$ [10-80 GeV].
  - **Geometry**
    - 40 sampling layers.
    - $72\text{cm} \times 72\text{cm}$ in transversal plane.
    - 120cm in longitudinal direction.
  - **Absorber**
    - 2 cm thickness/layer steel.
  - **Sensitive cells**
    - $40\text{mm} \times 40\text{mm} \times 3\text{mm}$ scintillator tile coupled with SiPM (SiPM-on-tile).
    - $18 \times 18 \times 40$ array.

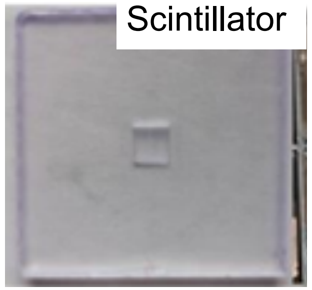
Journal of Instrumentation, 2021, 16(03): P03001.
Journal of Instrumentation, 2022, 17(11): P11034.





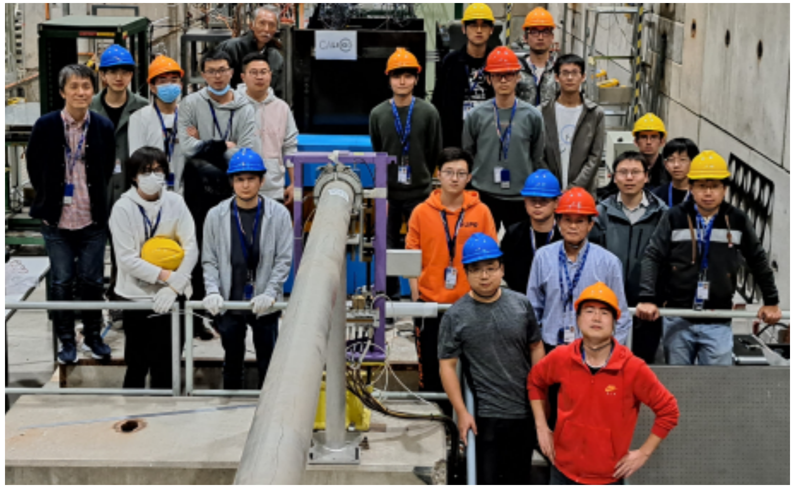




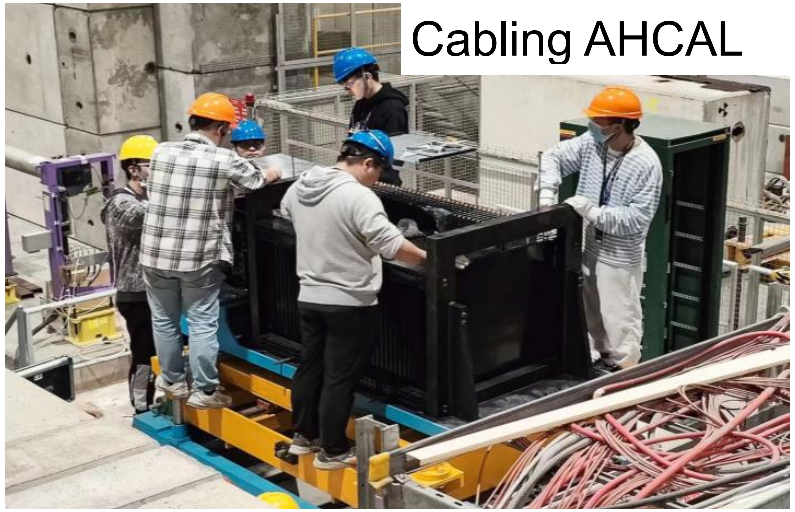


Beam Test at CERN in 2022 & 2023

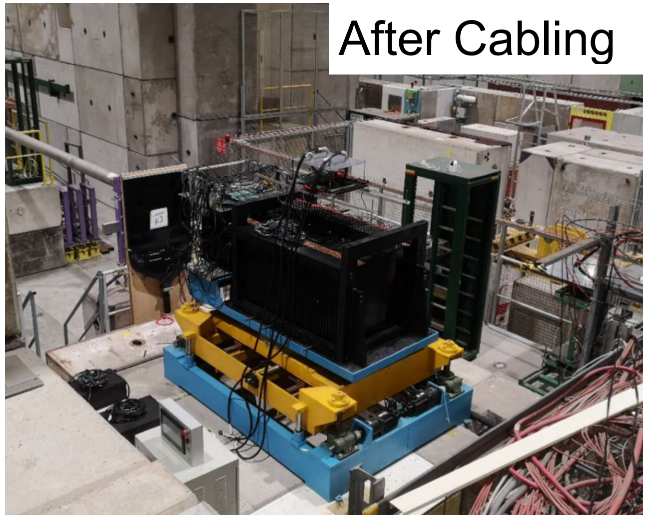
- **Successful beam test for AHCAL.**
  - Collaborators
    - China: USTC, IHEP, SJTU,
    - Japan: UTokyo, Shinshu.
  - At CERN SPS & PS in 2022, 2023.



Flying AHCAL



Cabling AHCAL



After Cabling

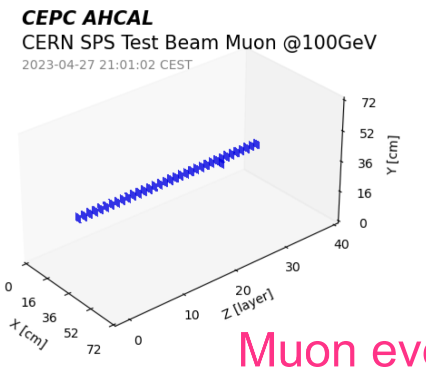
Oct 19 – Nov 2, 2022 — SPS H8 beamline

Apr 26 – May 10, 2023 — SPS H2 beamline

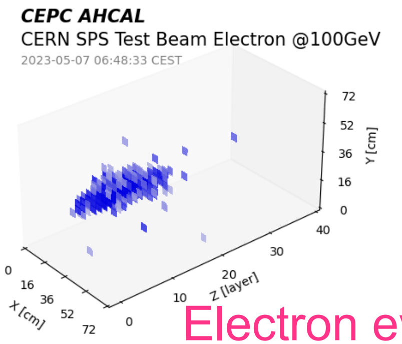
May 17 – 31, 2023 — PS T9 beamline

Beam Test at CERN in 2022 & 2023

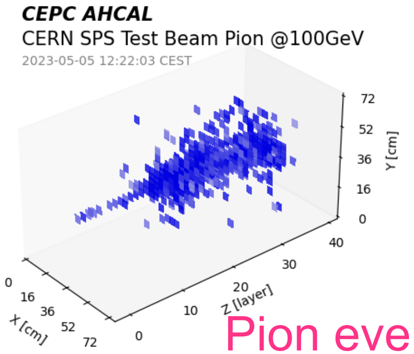
- **SPS-H8: Oct 19 - Nov 2, 2022:**
  - μ^+: 160 GeV (for calibration)
  - π^+: 10, 20, 30, 40, 50, 60, 70 , 80, 90, 100, 120 GeV (**~1M** events each point)
  - e^+: 10, 20, 30, 40, 50, 60, 70 , 80, 90, 100, 120 GeV (**~0.3M** events each point)
- **SPS-H2: Apr 26 - May 10, 2023:**
  - μ^-: 100 GeV (for calibration)
  - π^-: 10, 15, 20, 30, 40, 50, 60, 70 , 80, 100, 120, 350 GeV (**~1M** events each point)
  - e^-: 10, 20, 30, 40, 50, 60, 70 , 80, 100, 120, 150, 250 GeV (**~0.3M** events each point)
- **PS-T9: Apr 17 - May 31, 2023:**
  - μ^-: 10 GeV (for calibration)
  - π^-: 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 15 GeV (**~0.5M** events each point)
  - e^-: 1, 2, 3, 4, 5 GeV (**~50K** events each point)



Muon event

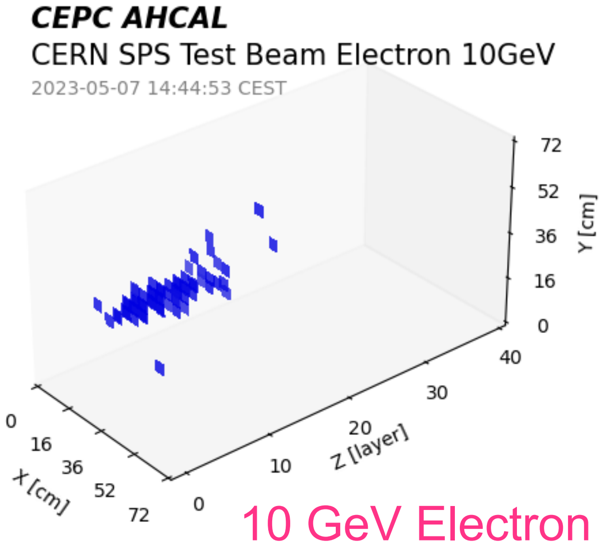


Electron event

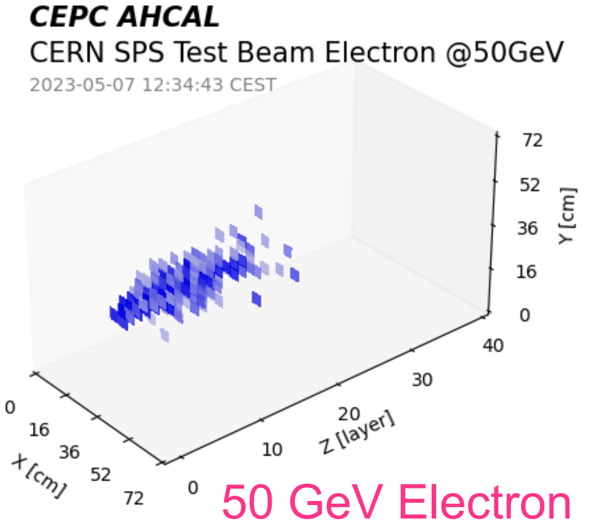


Pion event

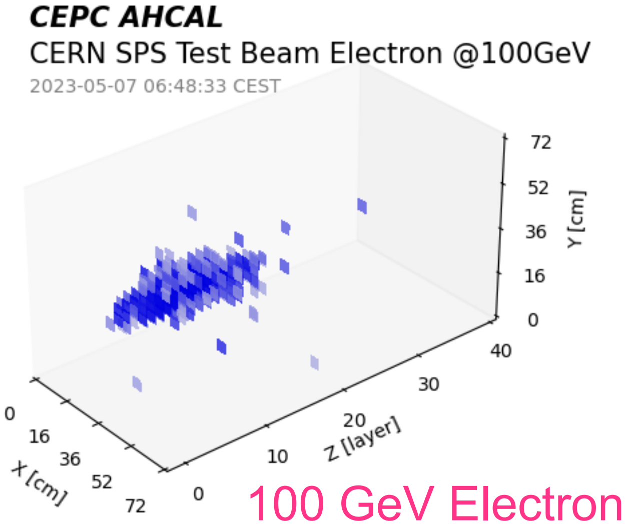
Beam Test at CERN in 2022 & 2023



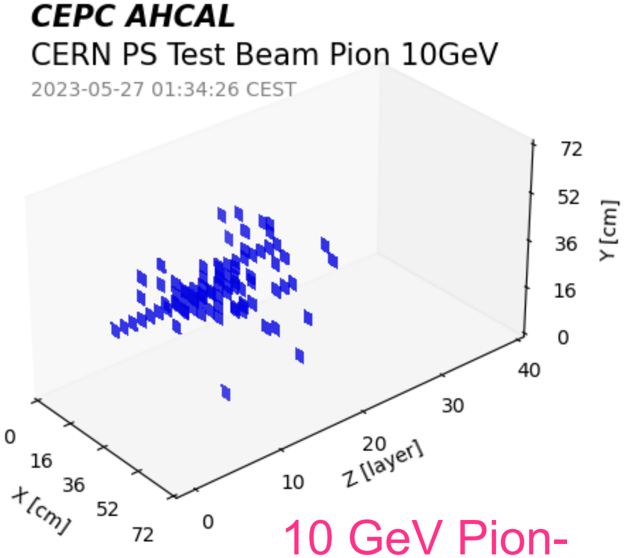
10 GeV Electron



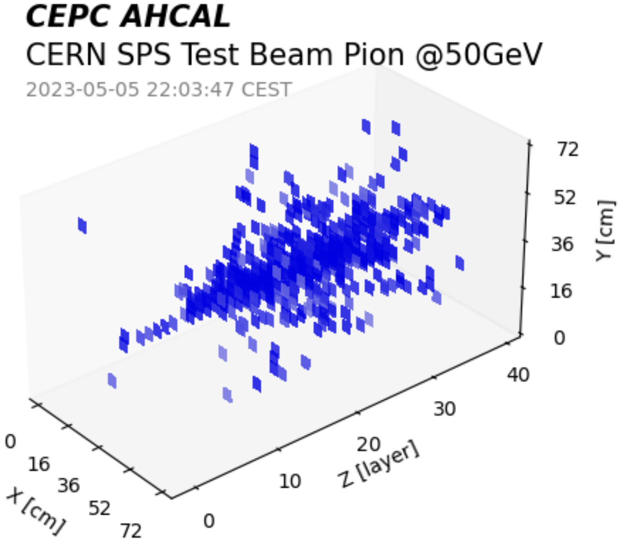
50 GeV Electron



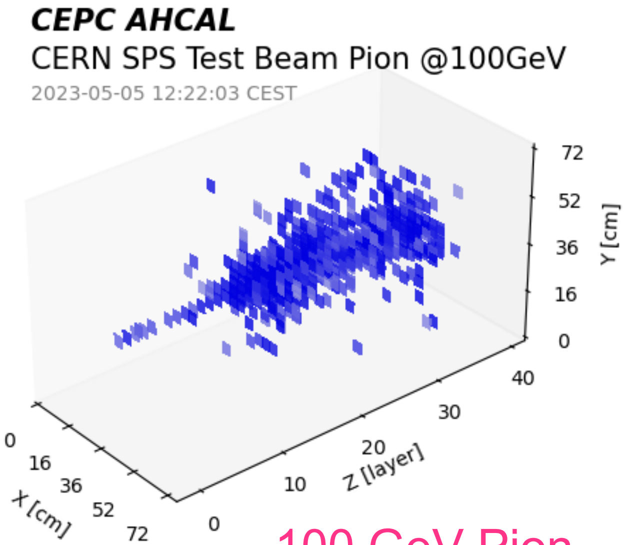
100 GeV Electron



10 GeV Pion-



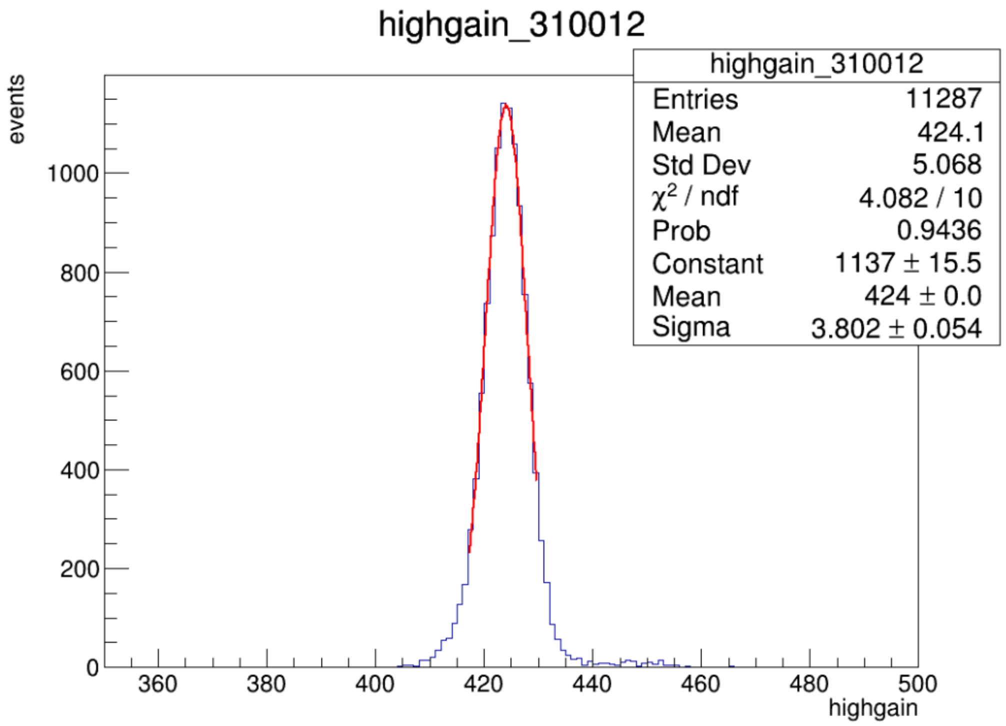
50 GeV Pion-



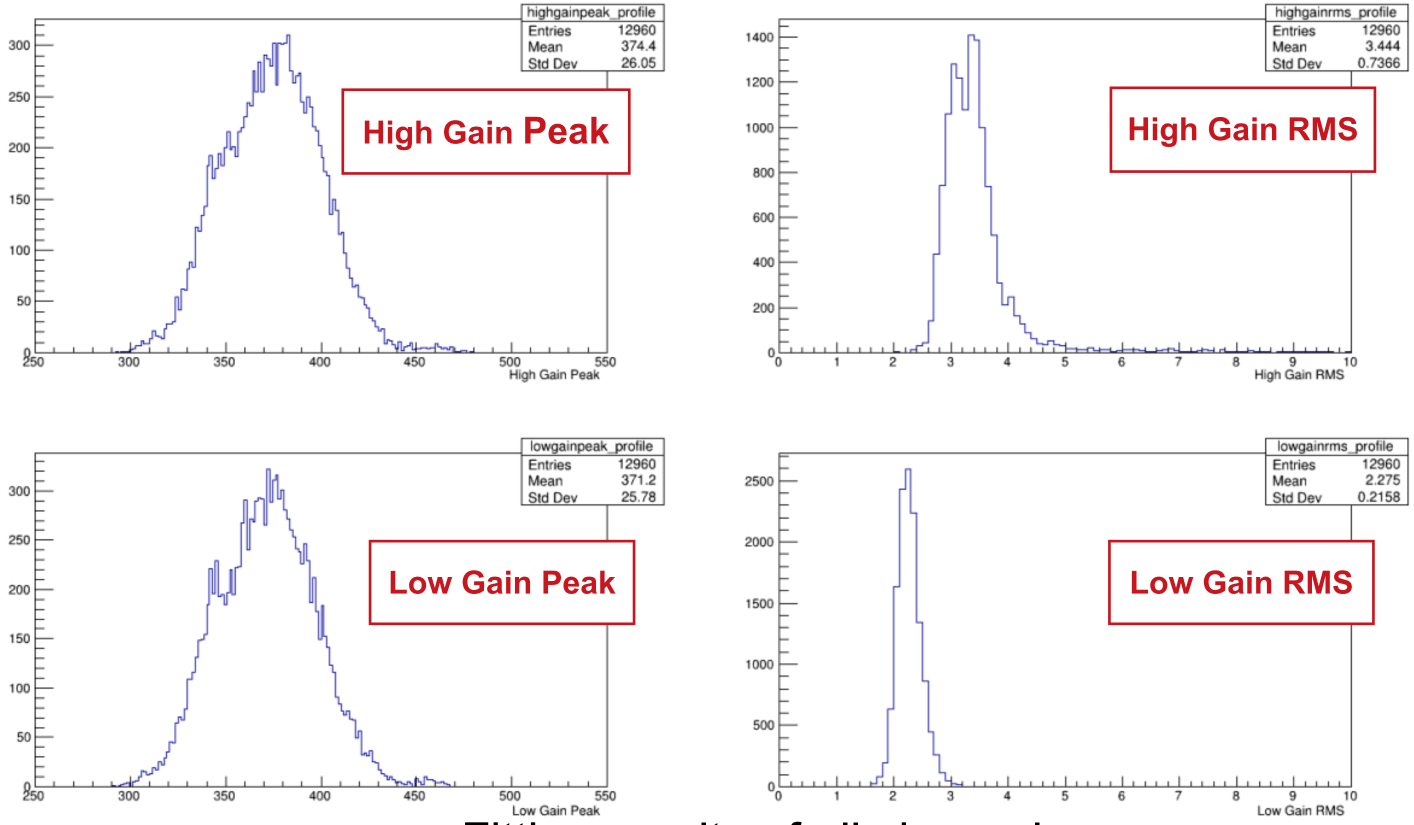
100 GeV Pion-

Calibration

- **Pedestal**
  - Pedestal calibration file: generated by a forced external trigger.
  - The pedestal of each channel is analyzed.



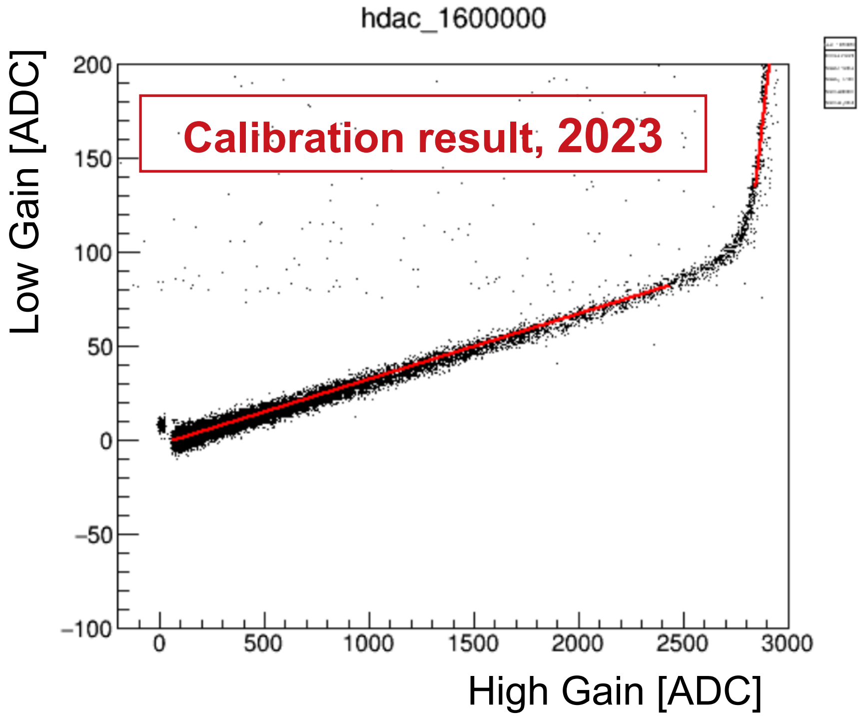
Pedestal distribution of a single channel

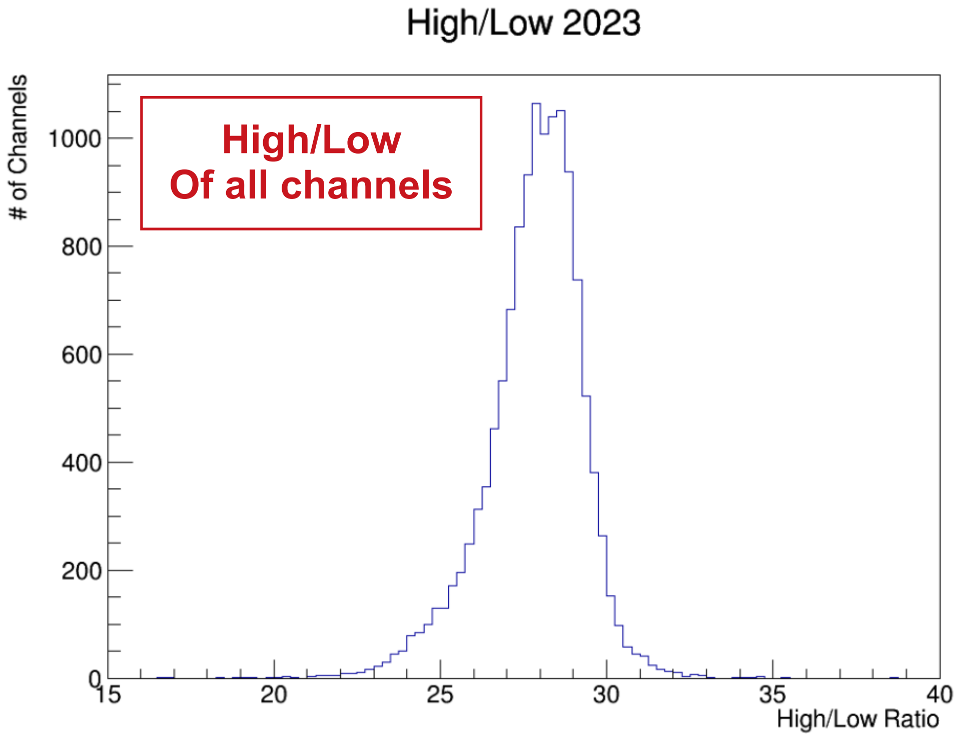


Fitting results of all channels

Gain Ratio

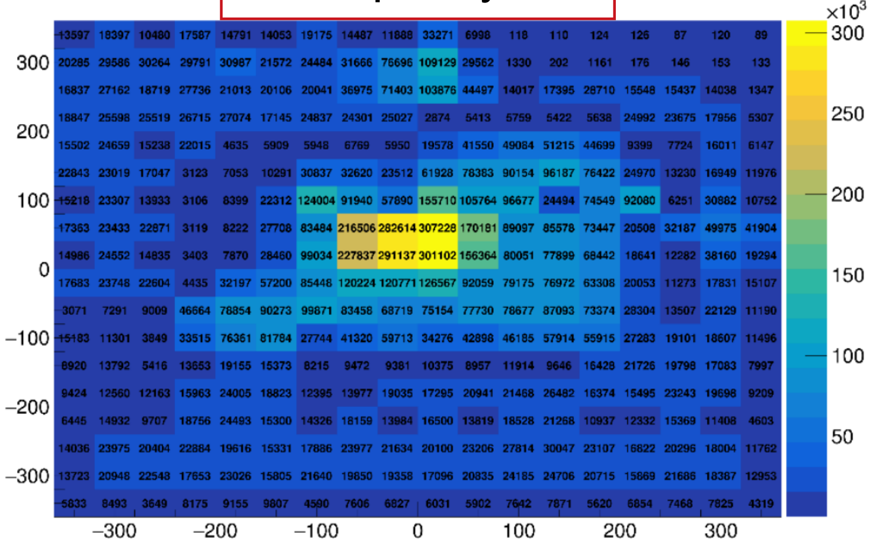
- Two gain modes in SPIROC2E Chip.
  - The saturation point of the high gain is fitted.
- The gain ratio of the high/low gain is calibrated from pion beam data.
- Each channel is fitted and the parameter is stored.

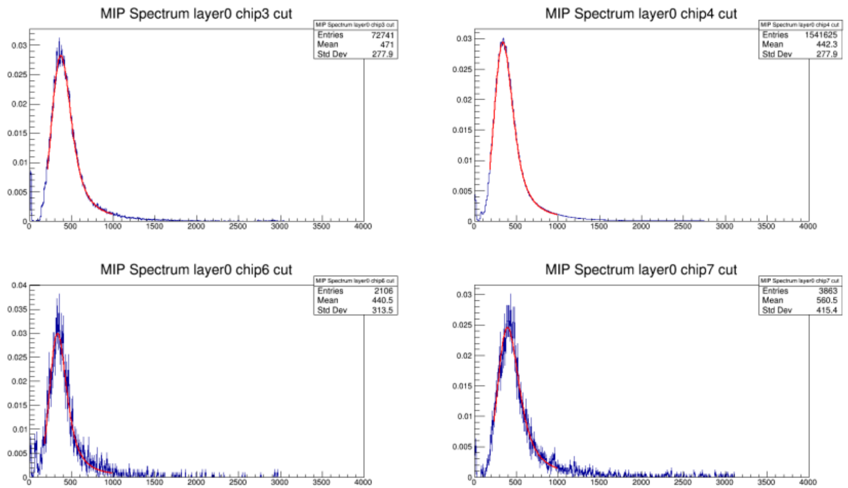




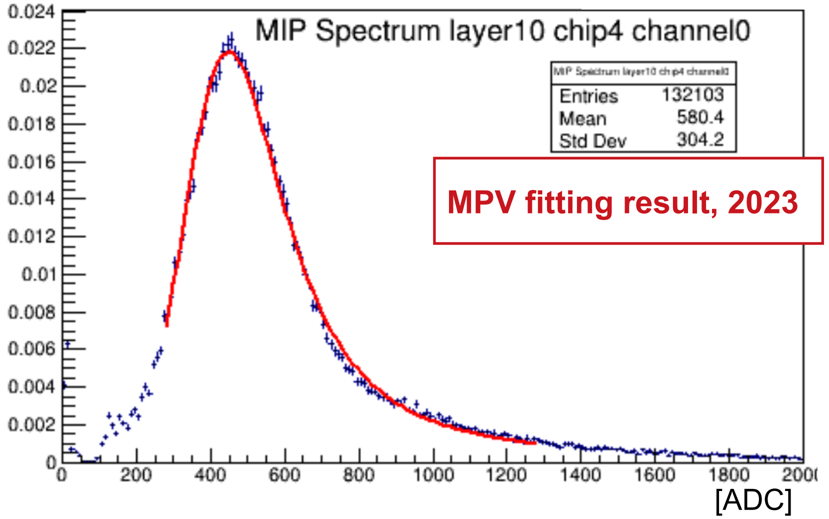
Calibration

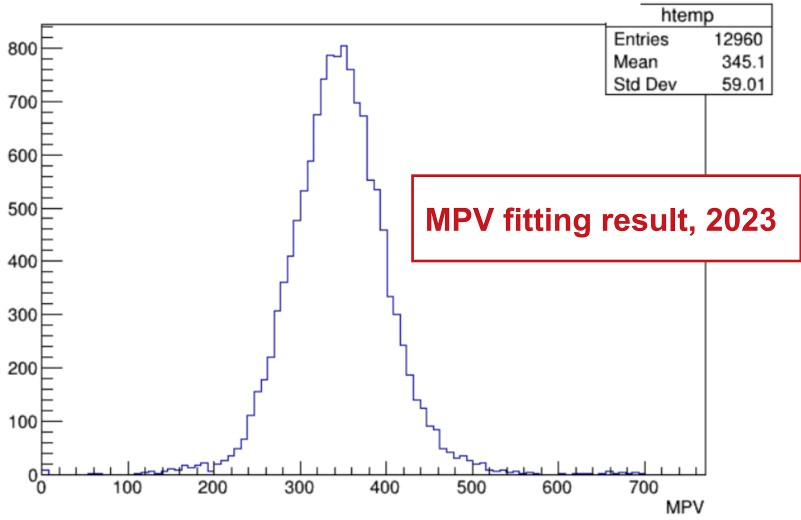
- **MIP calibration**
  - Using the landau-gauss function for fitting.
  - The fitting is first done for each chip, then each channel is fitted.
  - All chips have good fitting for 2023 data.





Fitting for each chip



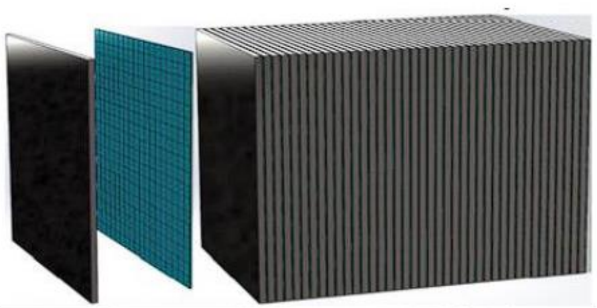


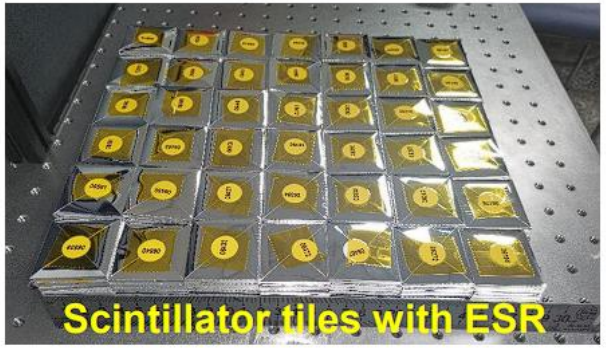
Fitting for a single channel and MPV for all channels

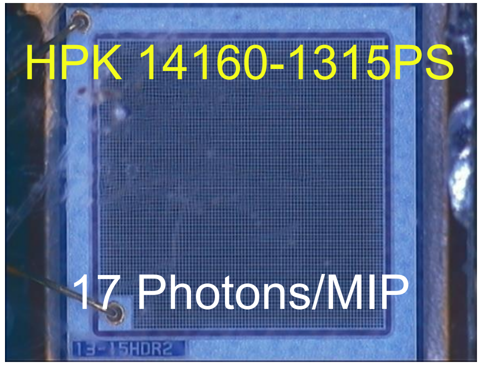
GEANT4 Simulation

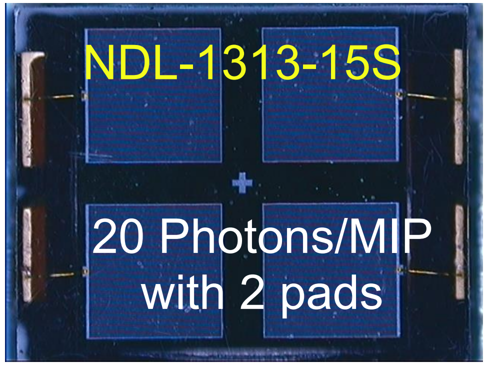
- **Simulation set up**

- $2\ mm$ plastic scintillator + $0.25\ mm \times 2$ ESR + $20\ mm$ Steel.
- Birks effect included in simulation.
- Beam: $\mu^{\pm}$, $e^{\pm}$, $\pi^{\pm}$ of 10 - 120 GeV.
- **Digitization:**
  - Photon statistics: Poisson distribution concerning #detected photons (light output).
  - SiPM saturation : $response = \#pixel \times e^{-\frac{photon}{\#pixel}}$.
  - ADC error: assume 0.02%, very low.
  - Energy cut: 0.5 MIP.
- **SiPM:**
  - S14160-1315PS for first 38 layers.
  - EQR15 22-1313D-S for last 2 layers.







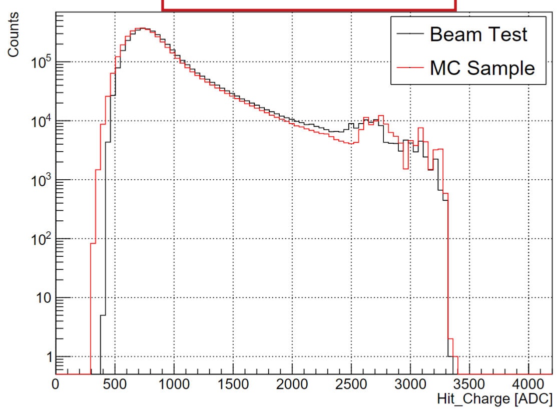


https://indico.cern.ch/event/847884/contributions/4831207/

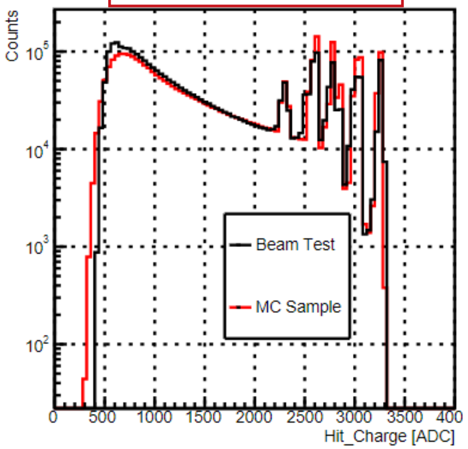
GEANT4 Simulation

- **Validation on High/Low Gain - 0.5 MIP energy threshold**
  - Generally fit in High Gain; Need optimization in Low gain saturation correction.

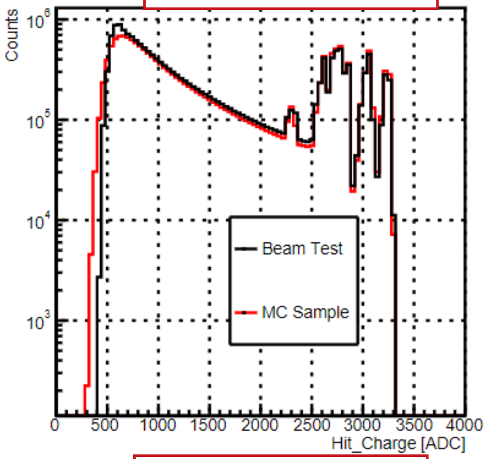
HG 100GeV μ^-



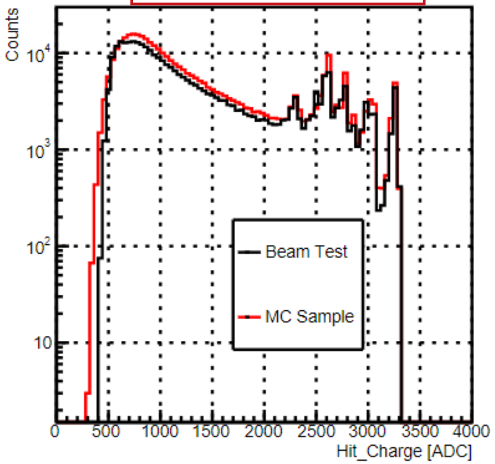
HG 10GeV e^-



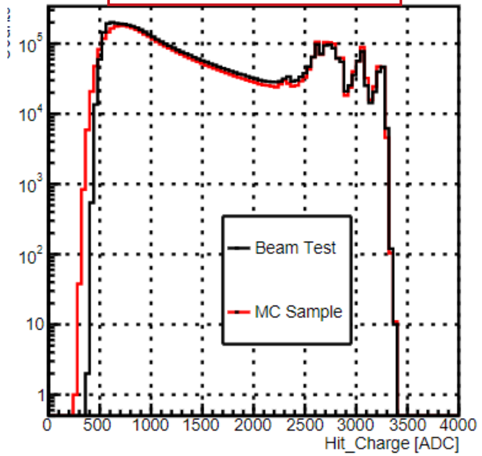
HG 80GeV e^-



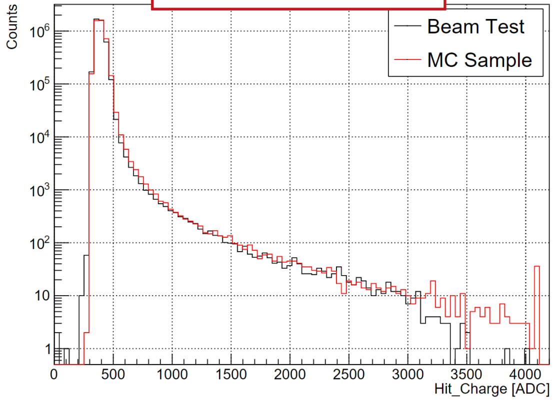
HG 10GeV π^-



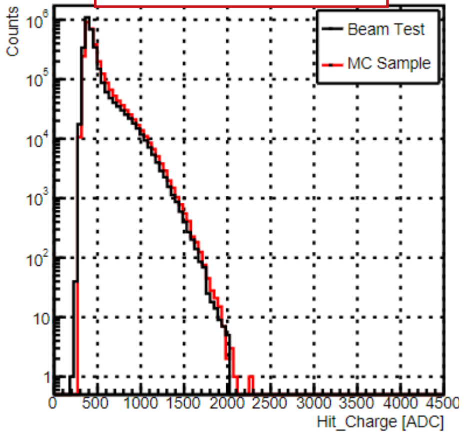
HG 80GeV π^-



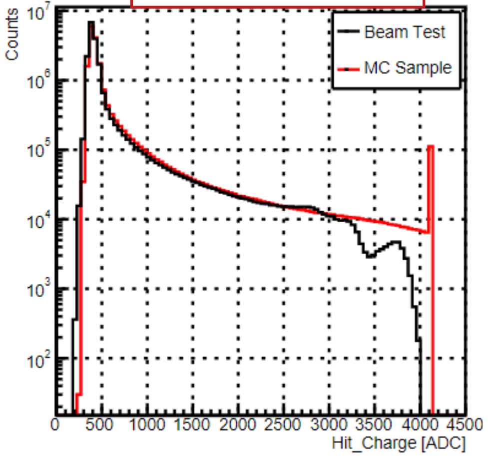
LG 100GeV μ^-



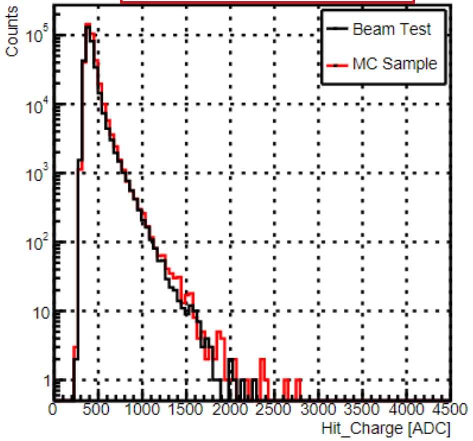
LG 10GeV e^-



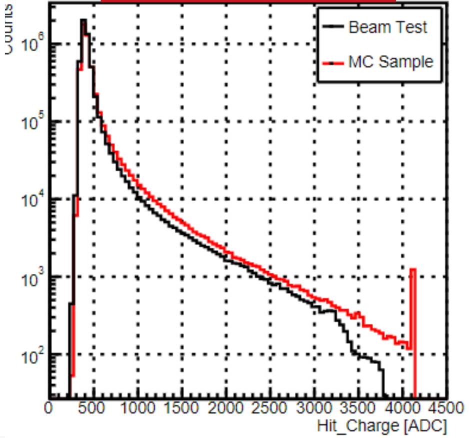
LG 80GeV e^-



LG 10GeV π^-

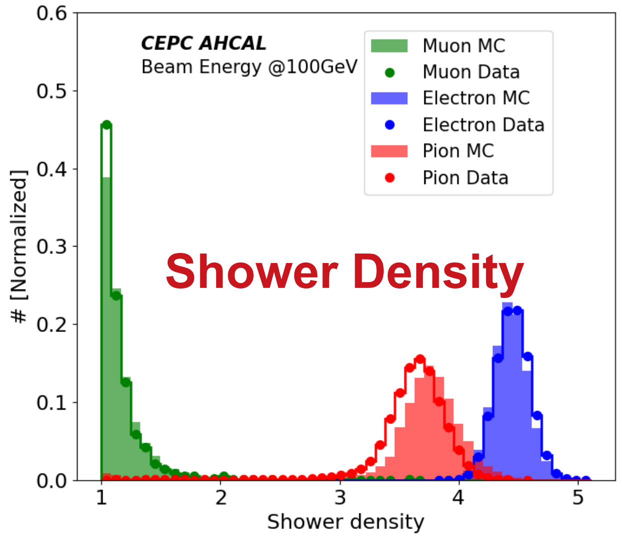


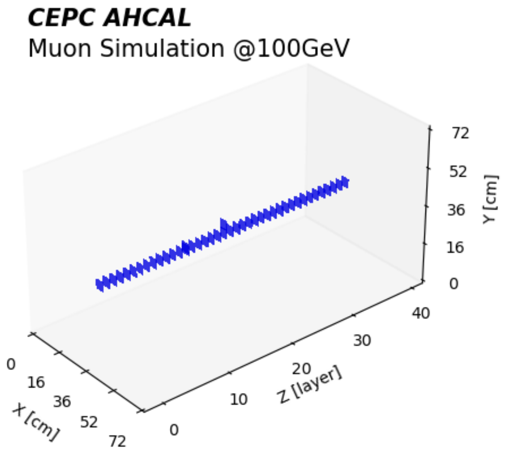
LG 80GeV π^-

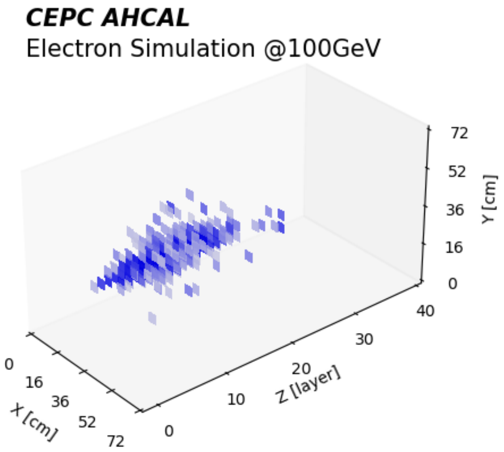


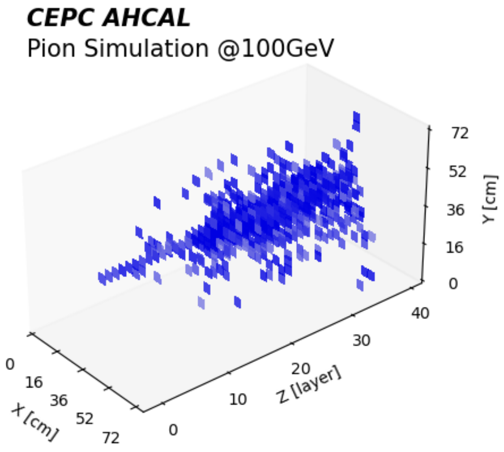
GEANT4 Simulation

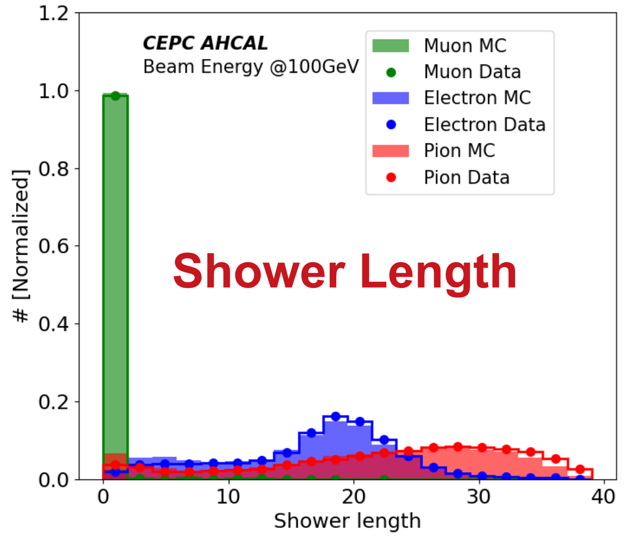
- **Validation on shower topology - 0.5 MIP energy threshold**
  - Several shower topology variables are reconstructed:
    - **Shower density**: Mean hits number in a 3×3 cell.
    - **Shower length**： Distance between the start of the shower and the layer with maximum RMS of hit transverse coordinates.
    - **Shower start, Shower Radius**, …
  - Generally, MC and Data are close in shower topology.
  - Shower topology validation is still on going.





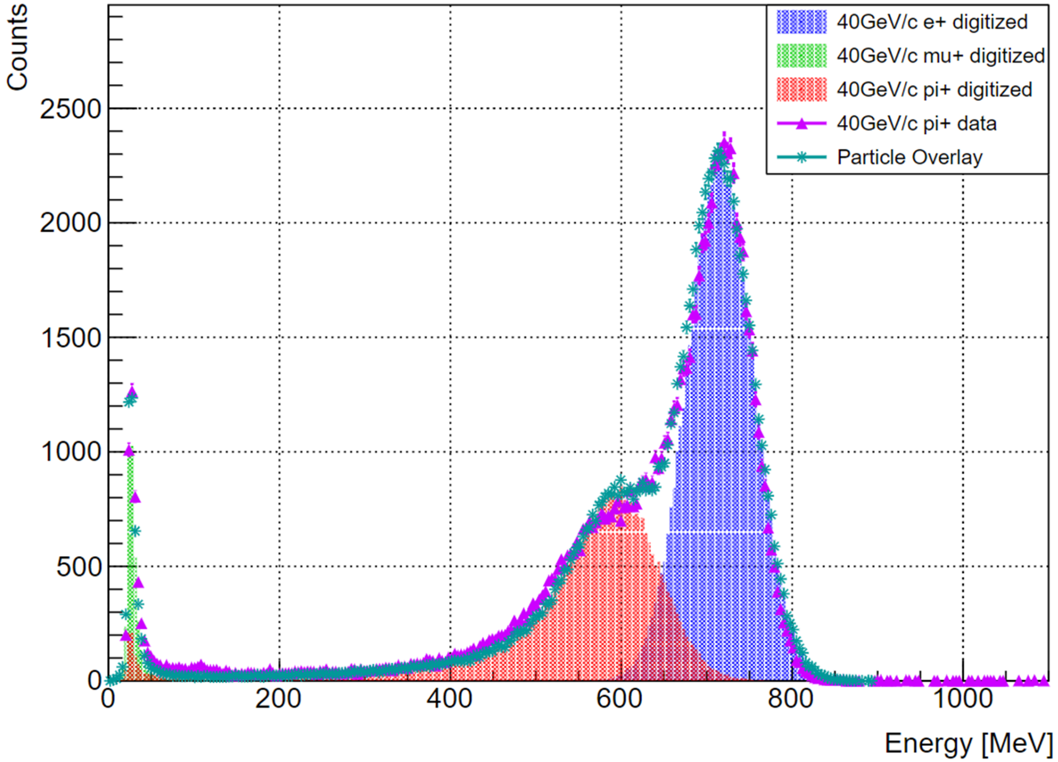


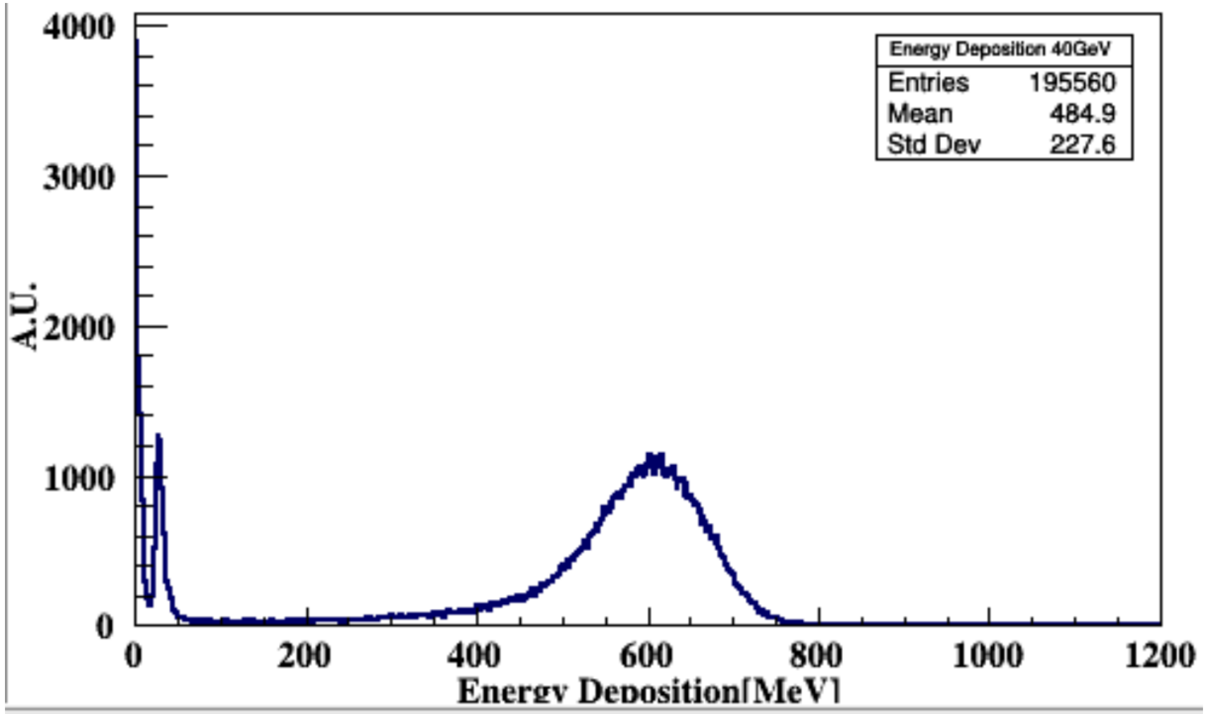




Particle Identification

- **We observed contamination in test beams from SPS&PS.**
  - Mixture of Pion, Muon and Electron events.
  - Purity of beam collected in 2023 is relatively better.
  - Multiple PID methods are developed.

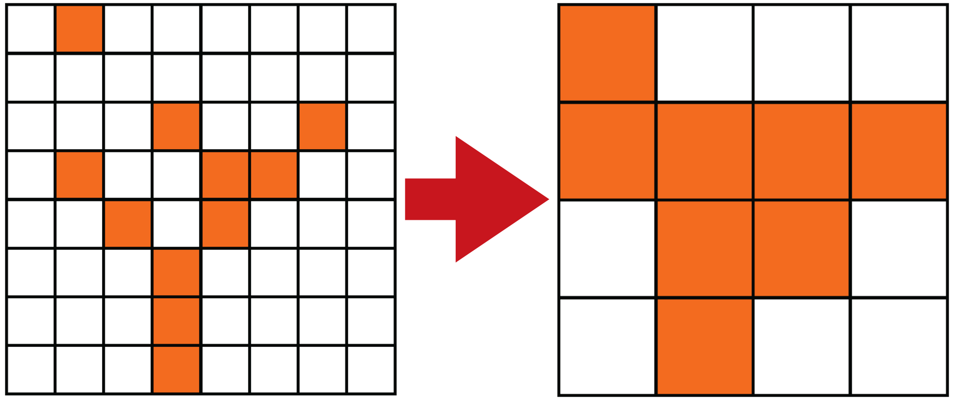




40GeV Pion beam Energy deposition spectrum from SPS-H8, 2022 and SPS-2023

Particle Identification

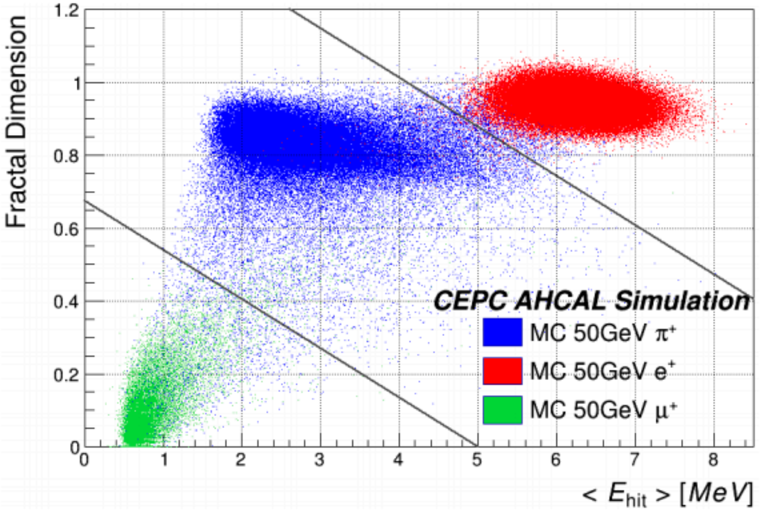
- **Cut-based PID:** FD vs $< E_{Hit} >$
  - $\text{FD} = \left\langle \frac{\log(\text{R}_{\alpha,1})}{\log(\alpha)} \right\rangle$, where $\text{R}_{\alpha,1} = \text{N}_1/\text{N}_\alpha$
  - N_α: number of hits scaled by α
  - $< E_{Hit} > = E_{dep}/N_{hit}$



Take $\alpha = 2$ as an example

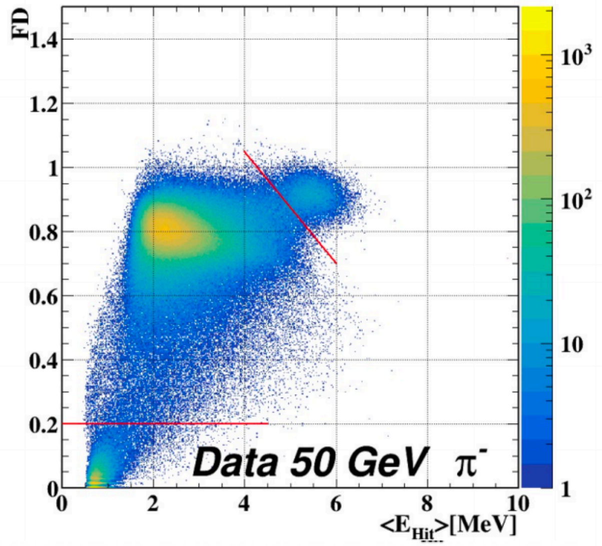
Efficiency @ 50 GeV MC

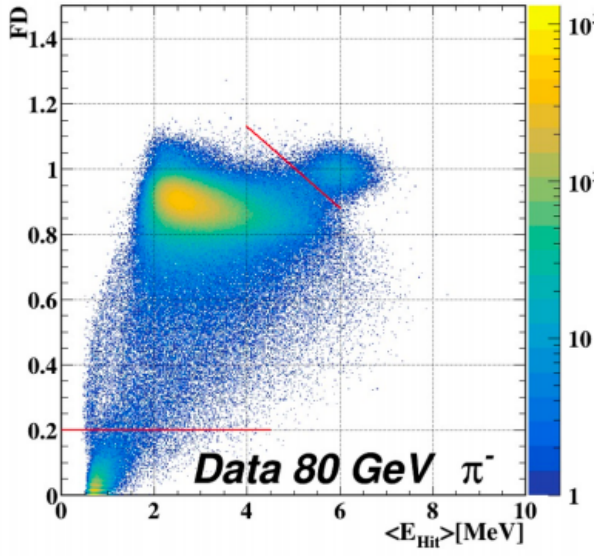
Truth \ ID	μ^+	π^+	e^+
μ^+	99.4%	0.6%	0
π^+	3.6%	94.1%	2.3%
e^+	0	0.3%	99.7%



Achieved Promising separation power on MC samples.

FD Ref: PhysRevLett.112.012001





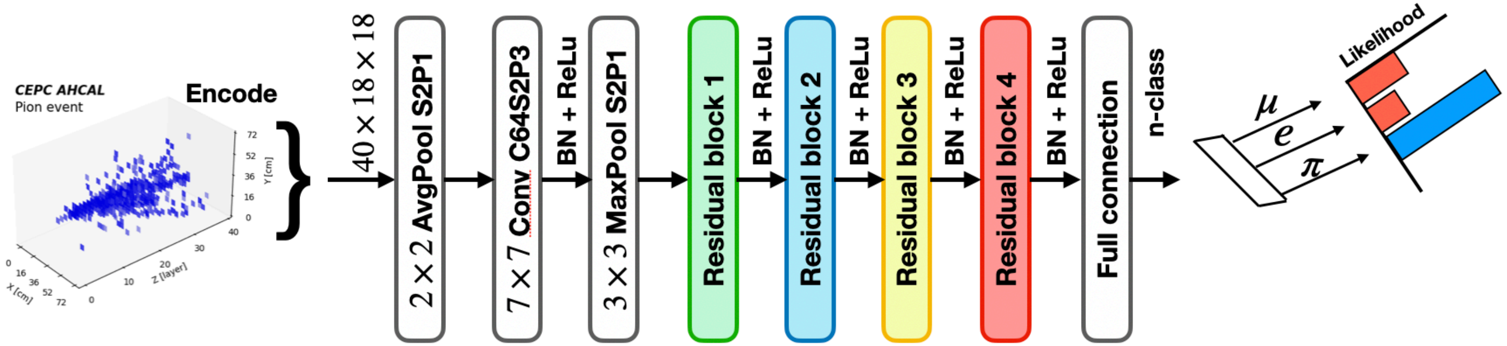
Work on Pion Beam data

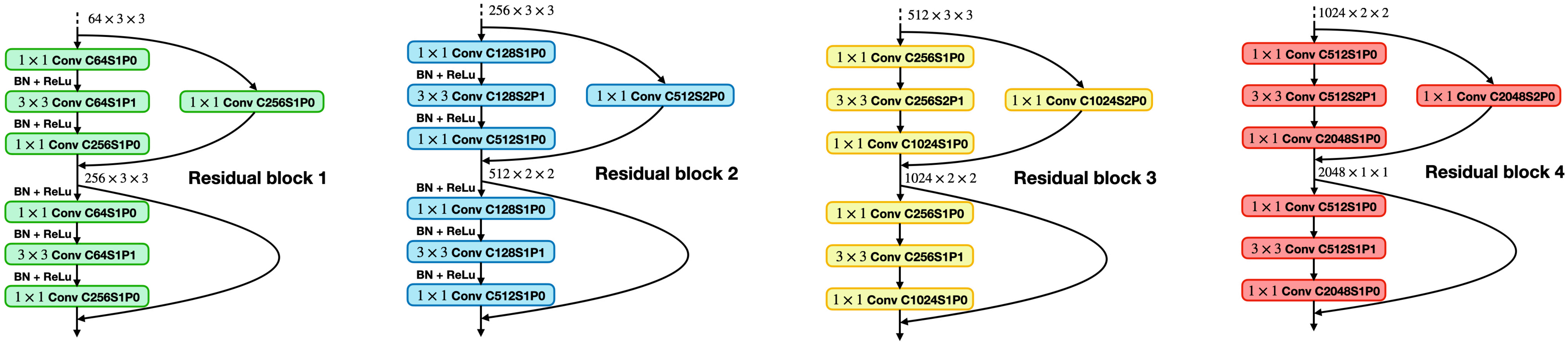
Particle Identification

• ANN-based PID: Taking the advantage of ResNet

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

- Input: energy depositions in AHCAL (Input tensor size: $40 \times 18 \times 18$) .
- Output: likelihood of each particle type candidate.

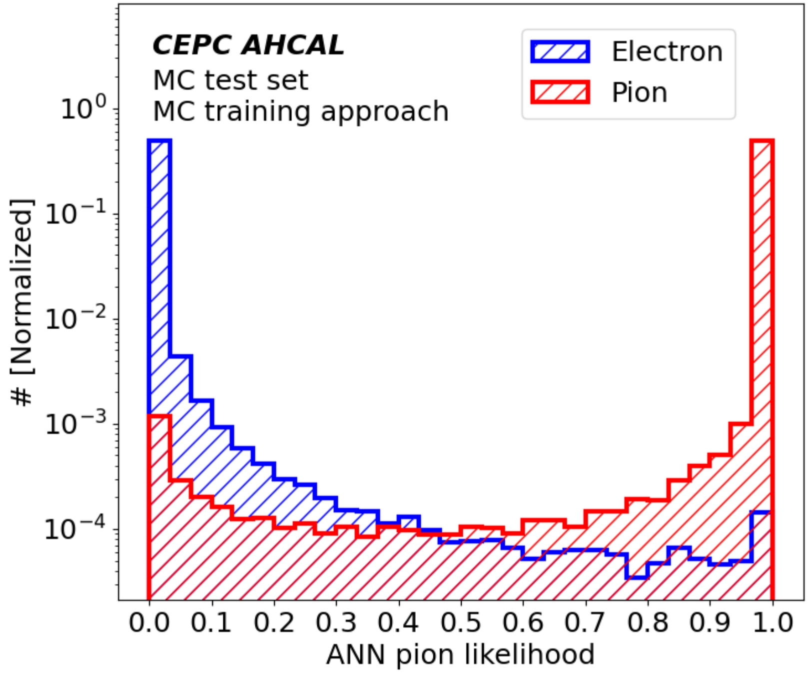


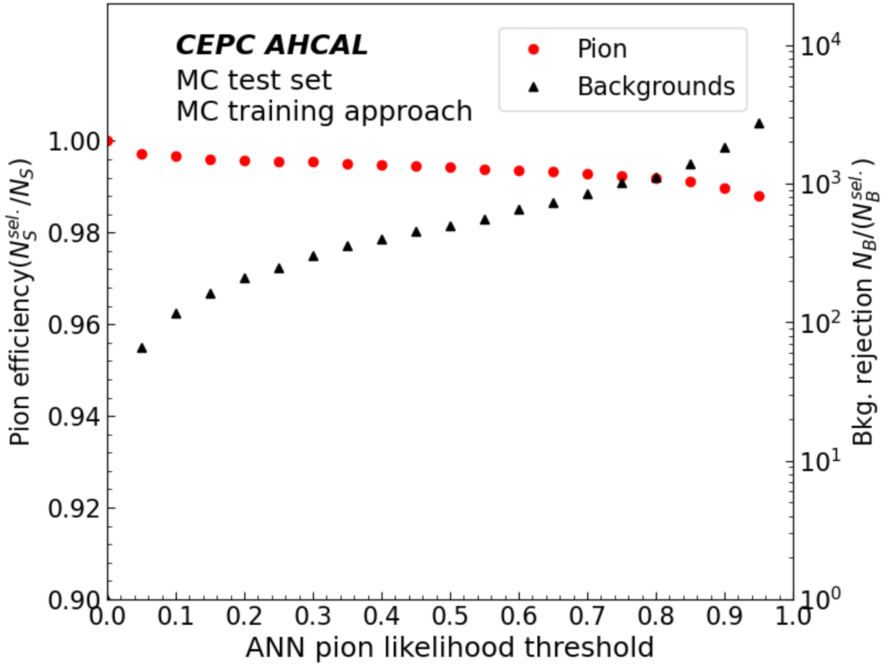


PID based on ANN

- **ANN Classifier performance in Pion identification**
  - High performance in differentiating HAD showers from EM showers.

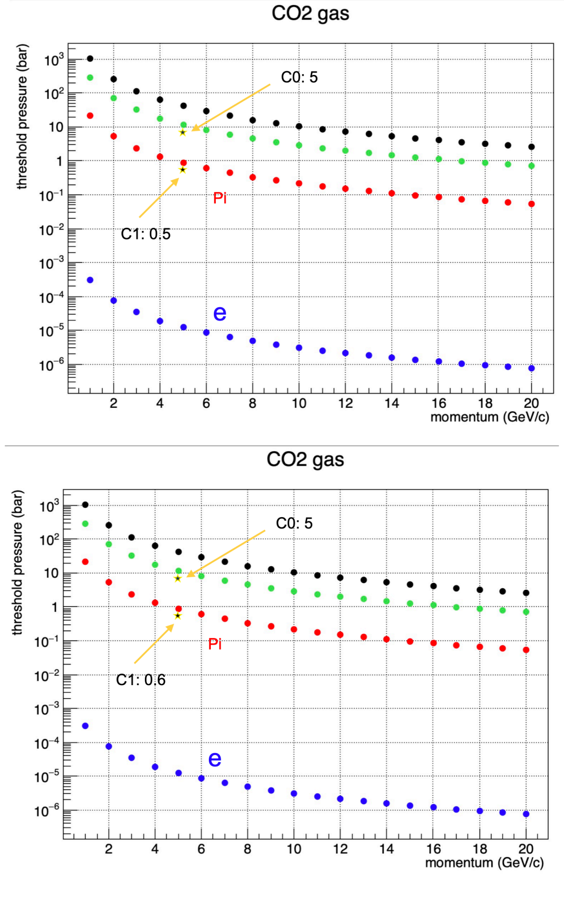
Pion efficiency	95%	96%	97%	98%	99%
Electron rejection (1/ e efficiency)	56012.7	48010.9	19769.2	9083.1	2154.3



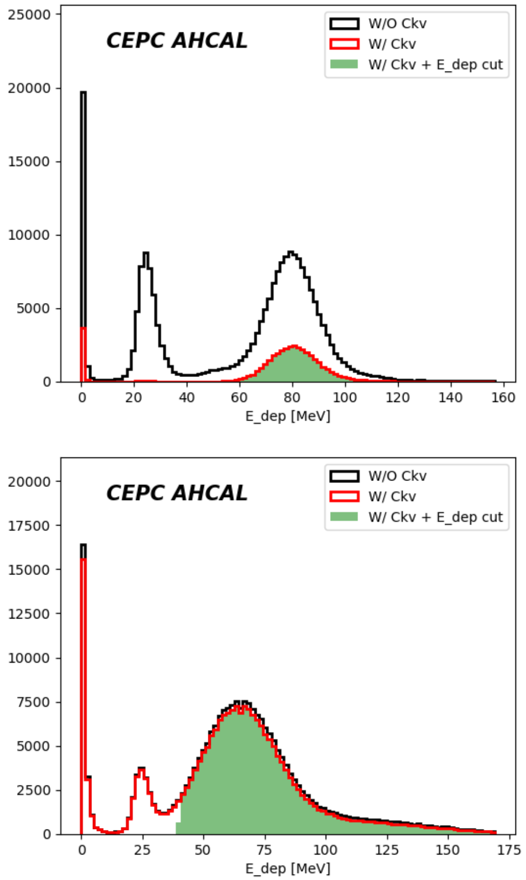


Details on ANN PID will be in my another talk on Oct27:https://indico.ihep.ac.cn/event/19316/contributions/143484/

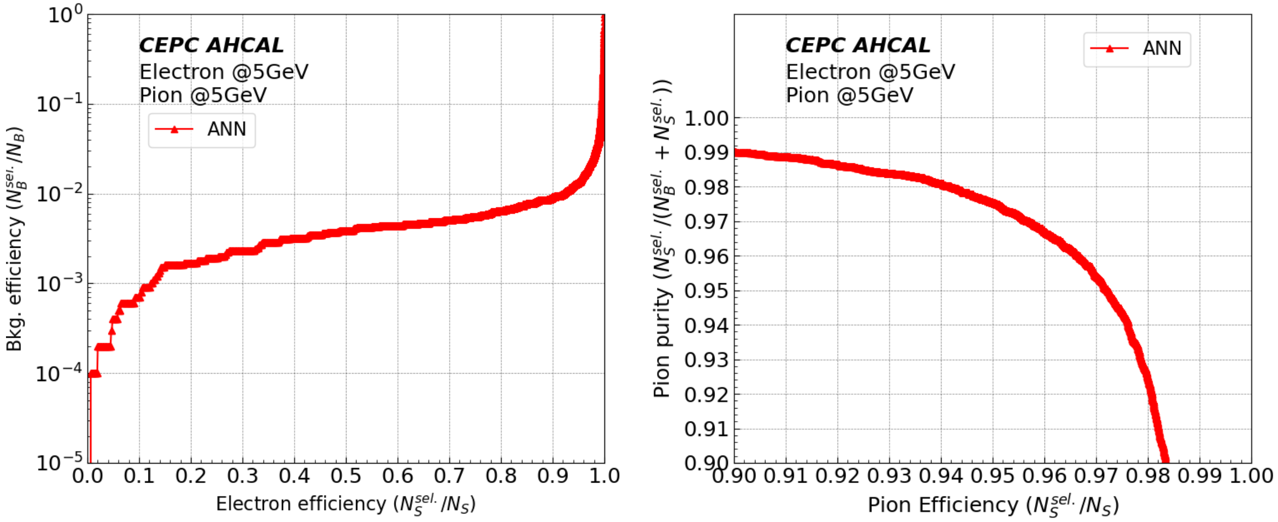
- **ANN PID cross-check using Cherenkov detectors**
  - Two CO2 Cherenkov detectors are available at PS (<15 GeV).
  - 20,000 Electron and 20, 000 Pion samples are selected as truth.



Cherenkov detector setting strategy.

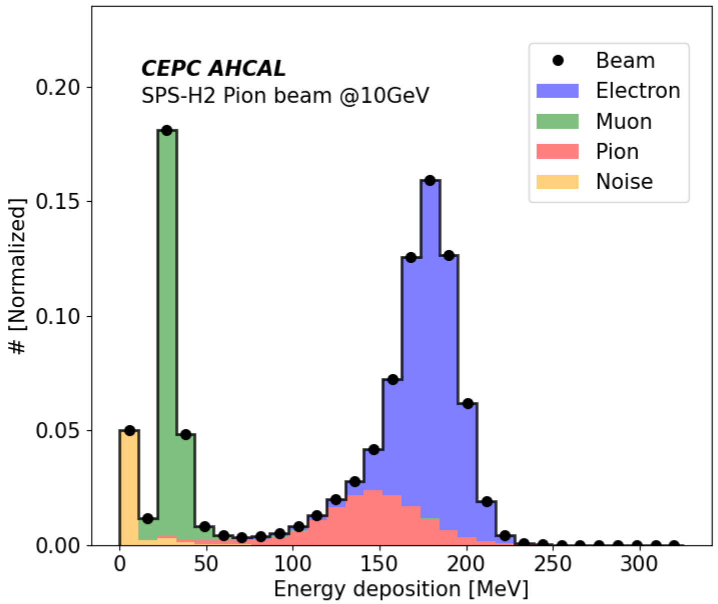


Samples after selection.

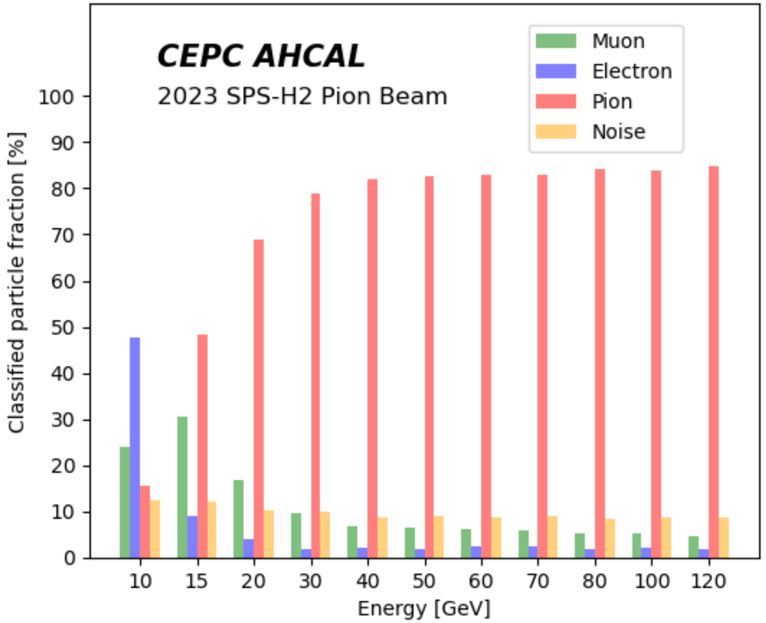


- Achieve 90% Pion efficiency and 99% Pion purity at the same time.

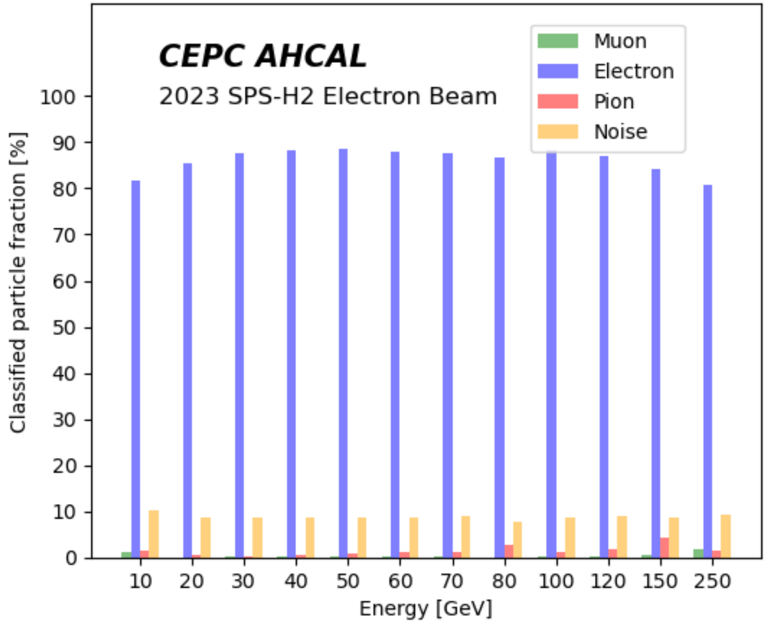
- **Beam composition is given by ANN classifier**
  - Trained on pre-selected data also tagged by Cherenkov detector.
  - Pion beam purity: around 80% when beam energy is over 30 GeV.
  - Electron beam purity: over 80% at each energy point.



Beam composition in Energy deposition spectrum (10 GeV)



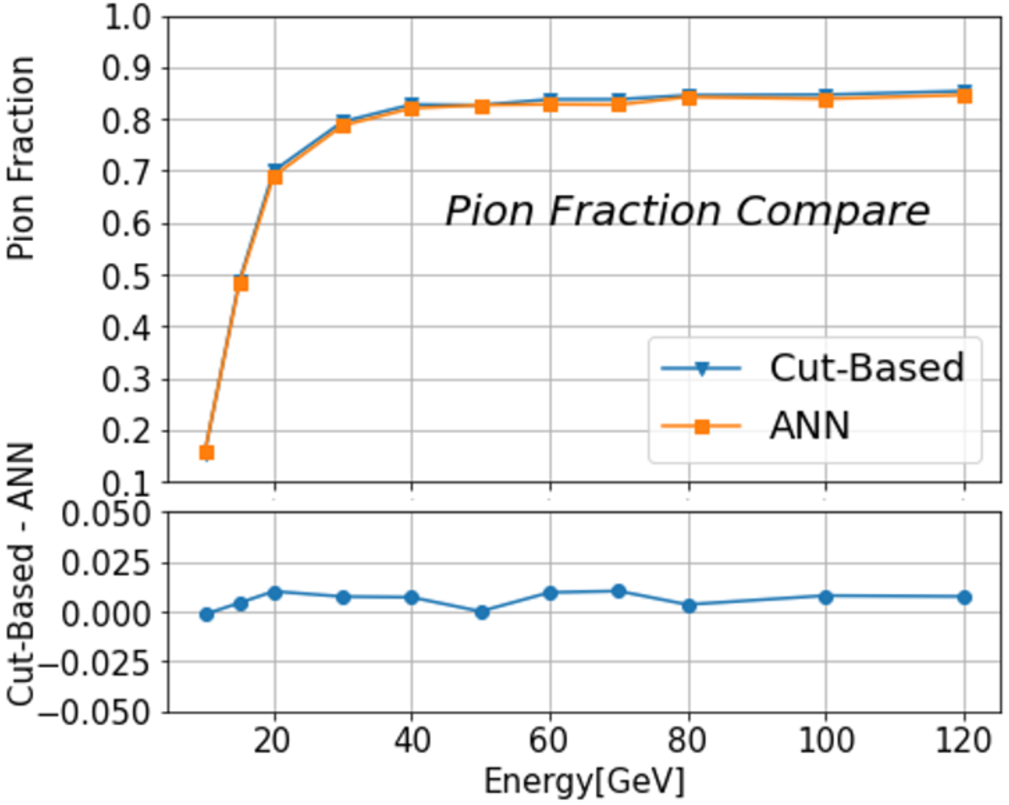
Pion Beam composition



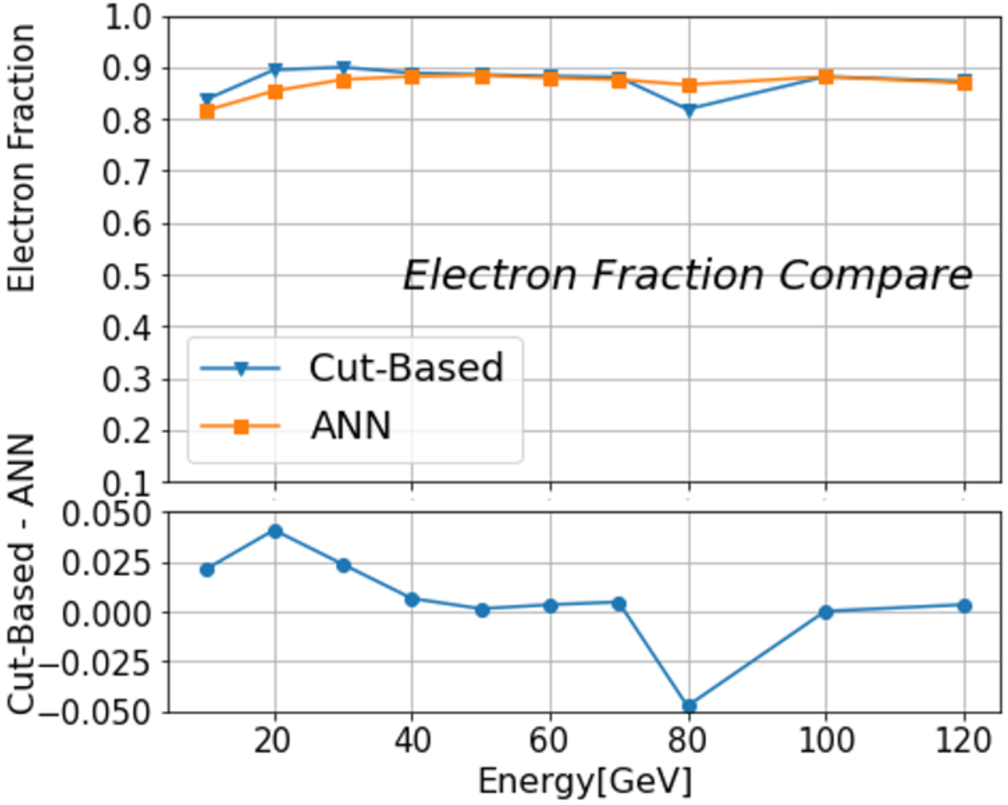
Electron Beam composition

Particle Identification

- **Comparison between two PID methods**
  - Very close in the results of particle type fraction.
  - Difference in Pion fraction: within 1%.
  - Difference in Electron fraction: within 5%.



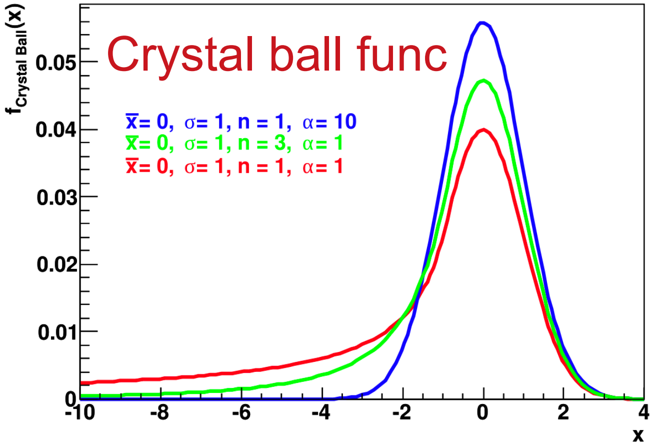
SPS-H2 Pion Beam

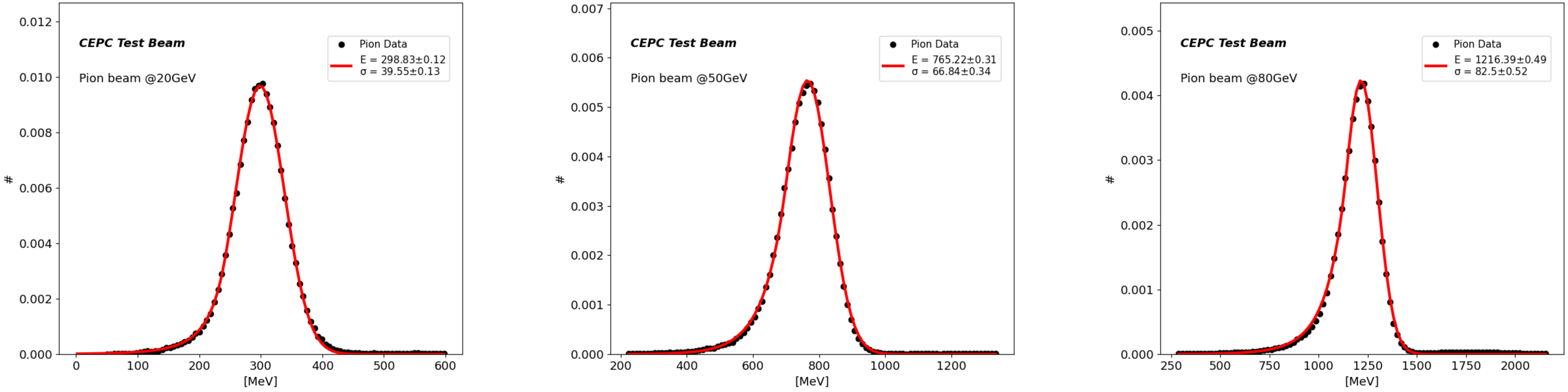


SPS-H2 Electron Beam

AHCAL Prototype Performance

- **Purified beam data fitting**
  - ANN classier is first used for purifying the Pion beam.
  - Crystal ball function is then used for fitting purified Pion Data.

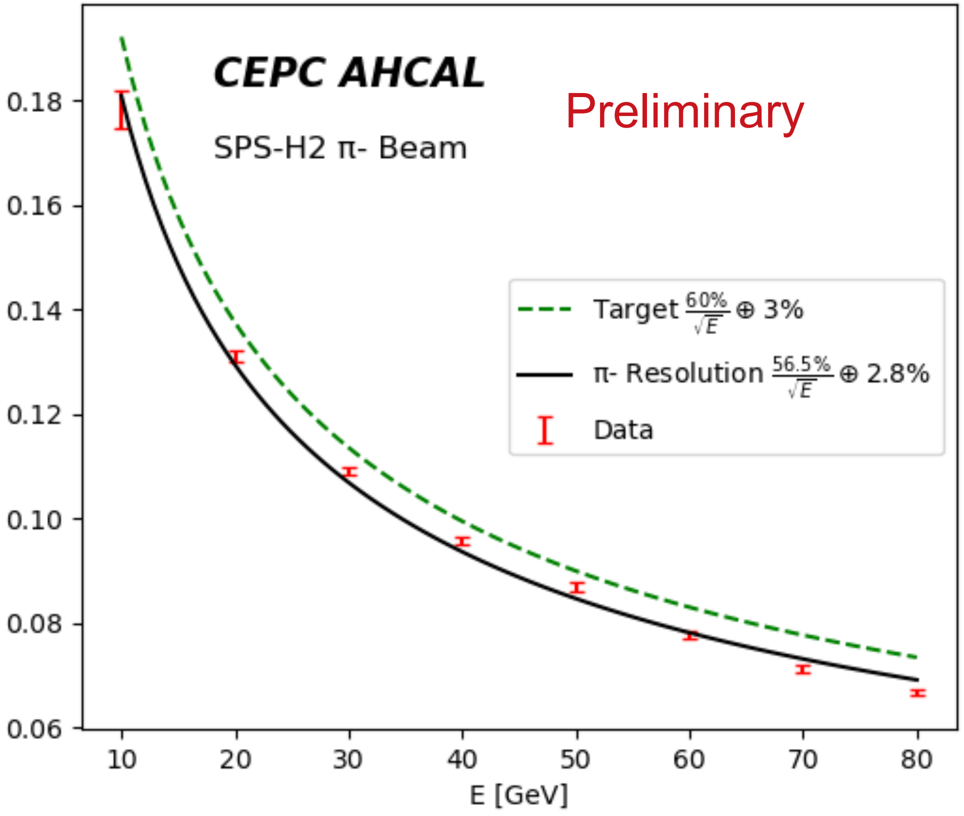


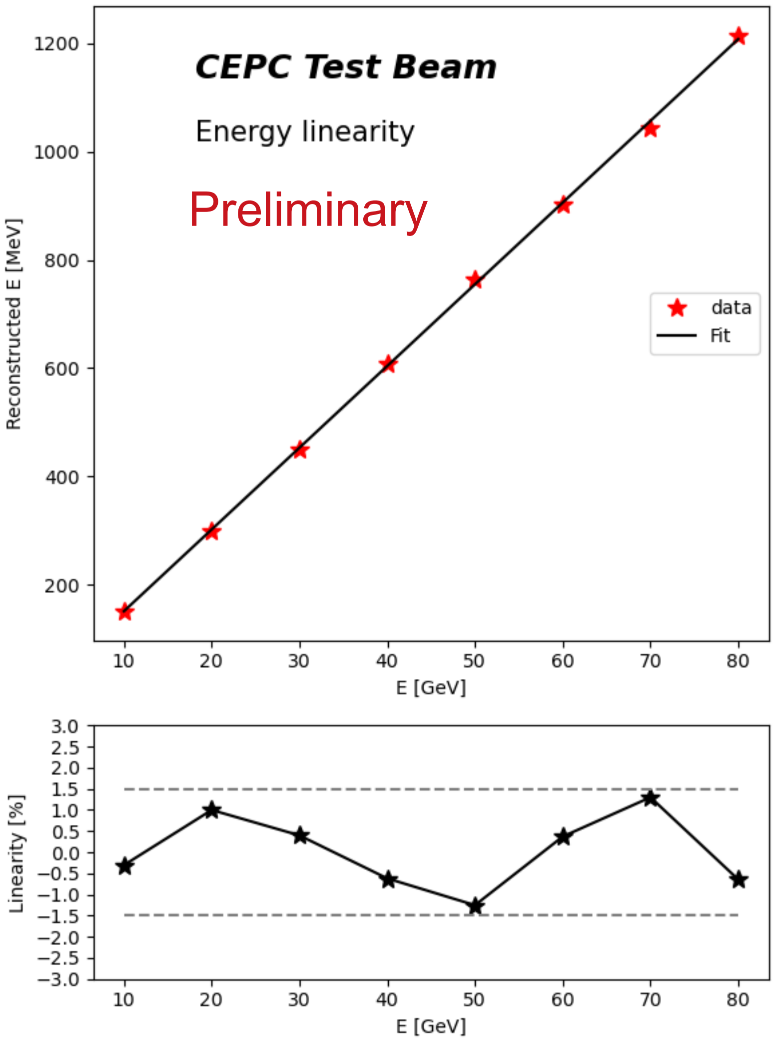


The energy of 20, 50, 80 GeV.

AHCAL Prototype Performance

- The Energy resolution is $\frac{56.5\,\%}{\sqrt{E}} \oplus 2.8\,\%$.
- The Energy linearity is $\pm 1.5\,\%$.





Summary and Outlook

- **Preliminary progress:**

☑Three AHCAL beam tests have been done @CERN.

- ⭐@SPS-H8, Oct-Nov ,2022.
- ⭐@SPS-H2, Apr-May, 2023.
- ⭐@PS-T9, May, 2023.

☑$\pi^{\pm}$ of 1-120 GeV and $e^{\pm}$ of 1-250 GeV have been collected.

☑Calibration has been done for pedestal, gain ratio and MIP response.

☑The PID on CEPC AHCAL test beam data has been done.

☑The AHCAL prototype achieves preliminary energy linearity of $\pm 1.5\,\%$ and resolution of $\frac{56.5\,\%}{\sqrt{E}} \oplus 2.8\,\%$ for hadron.

- **Plan & On going:**

- SiPM saturation correction.
- SiPM temperature compensation.
- Electronics saturation correction.
- GEANT4 MC validation.
- The synchronization of AHCAL and ScW-ECAL.

We appreciate the support from CERN staff and CALICE Collaboration!

感谢聆听

Thanks for your attention

Back up

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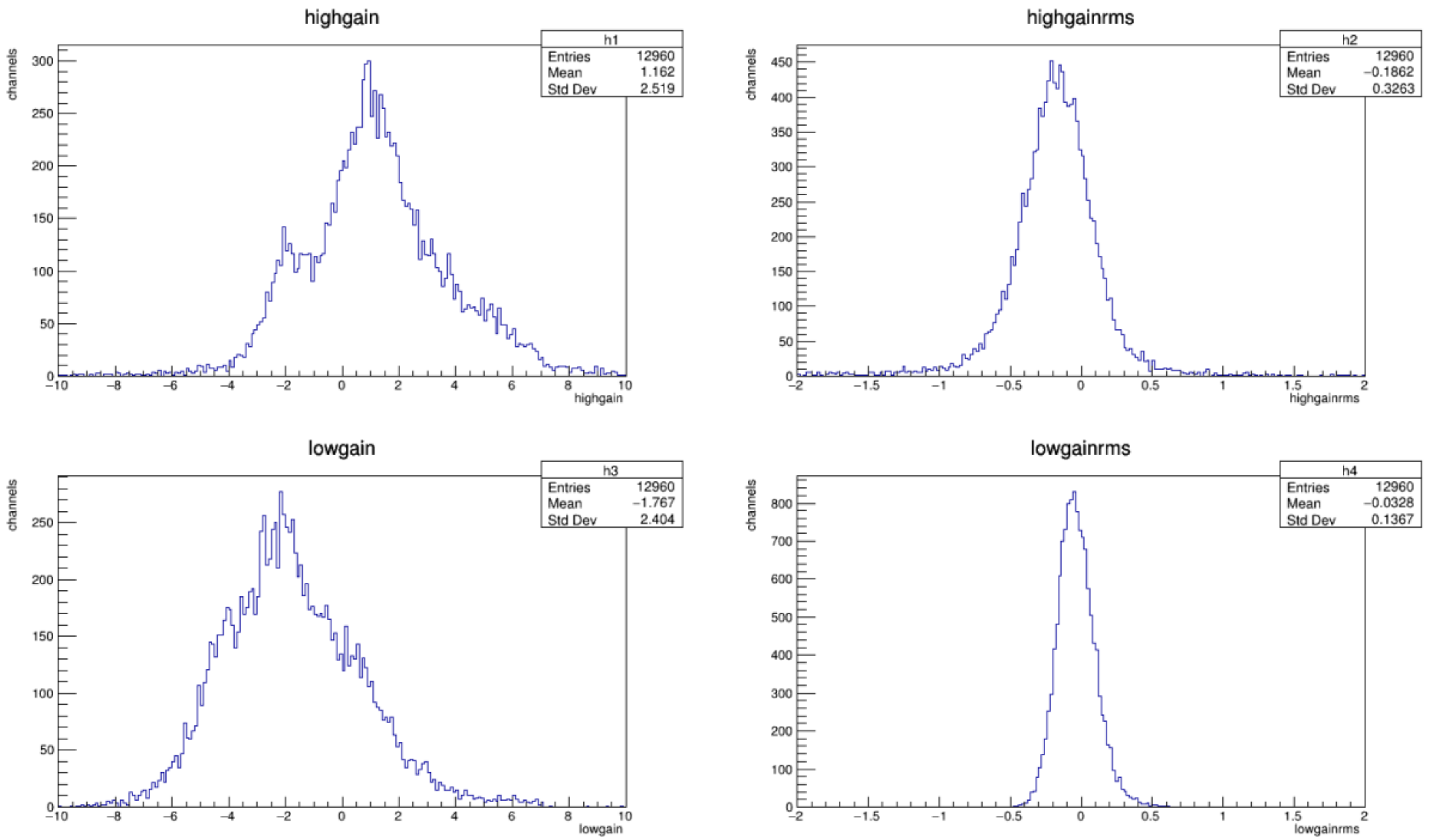
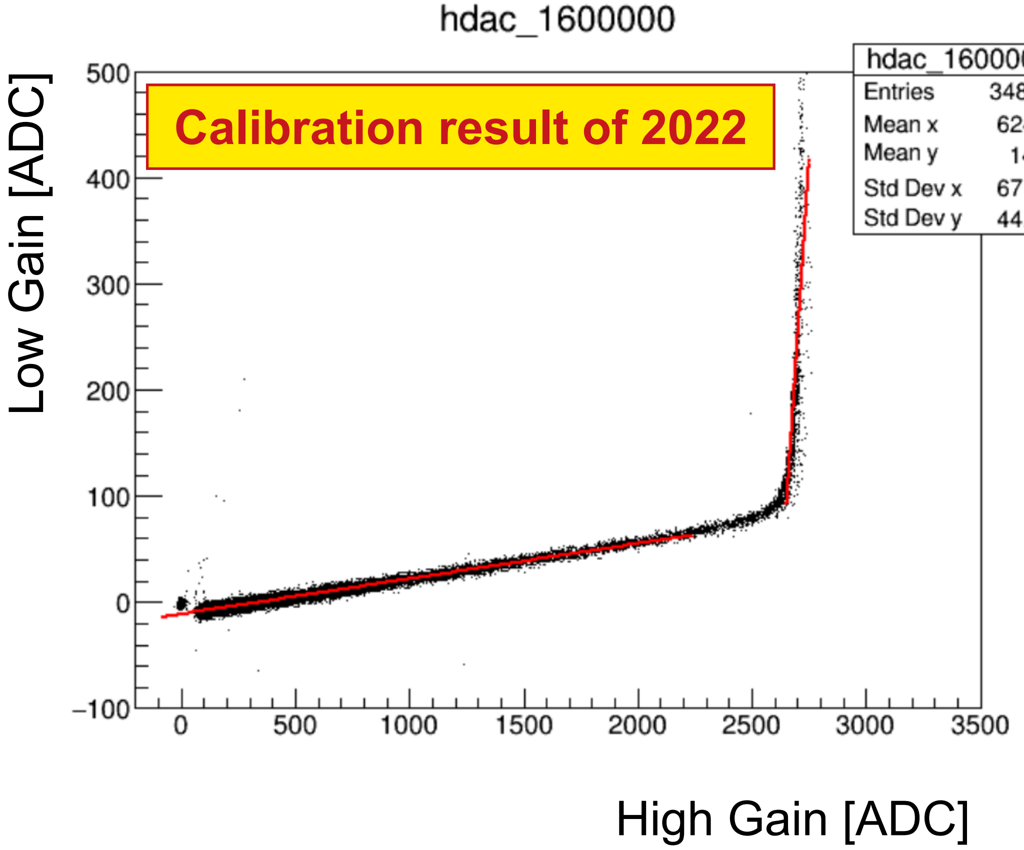
MIP Calibration

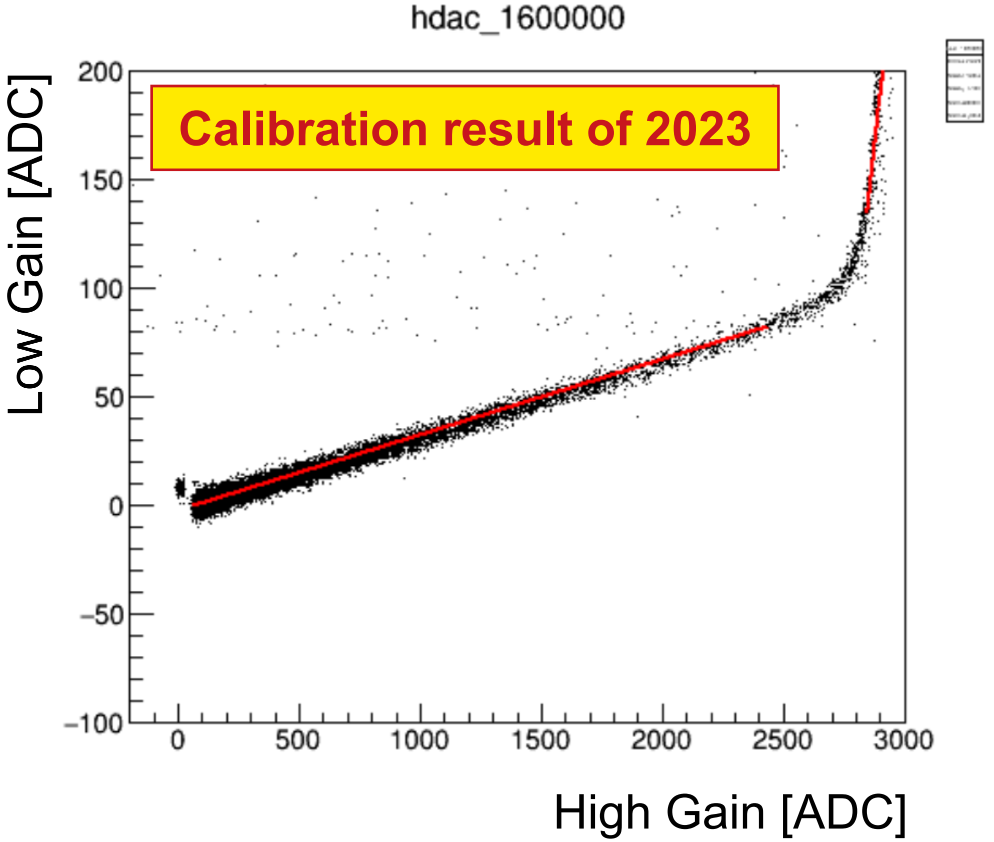
- The difference between pedestal of 2022 and 2023 is small.



- **Gain Ratio**

  - Two gain modes in SPIROCE Chip.
    - The saturation point of the high gain is fitted.
  - The gain ratio of the high/low gain is calibrated from pion beam data.



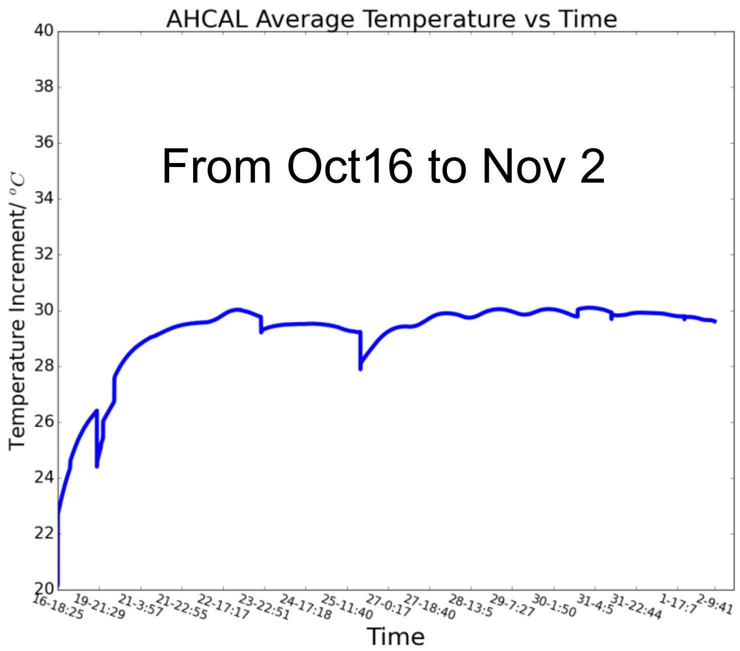


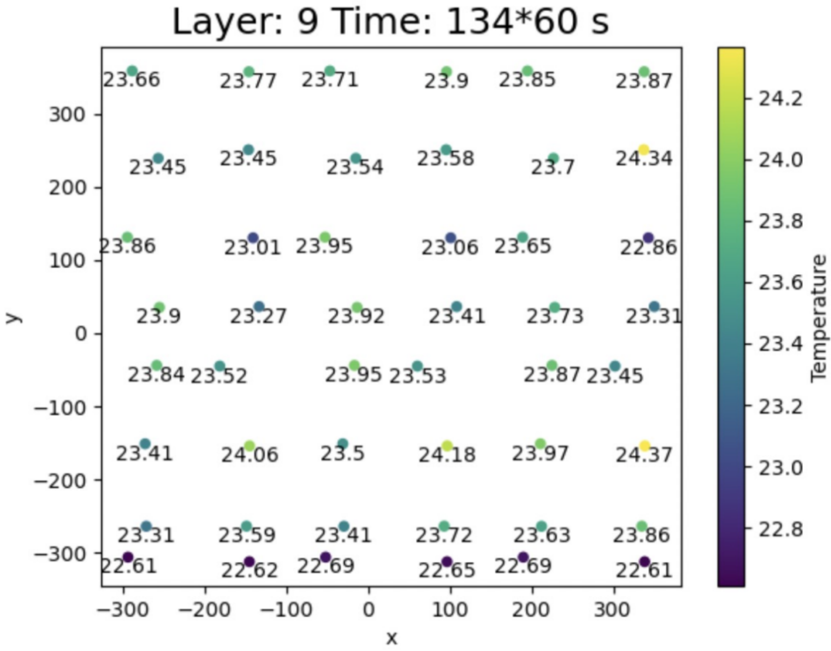
Temperature

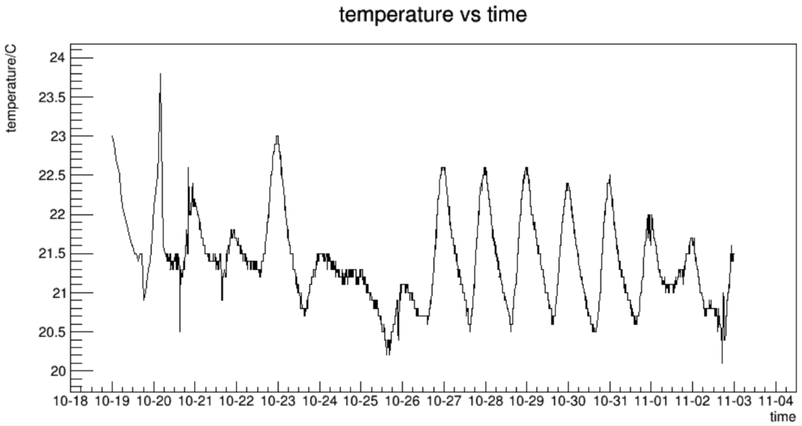
- The AHCAL's average temperature is stable after reaching plateau. (Taking 3-5 days).

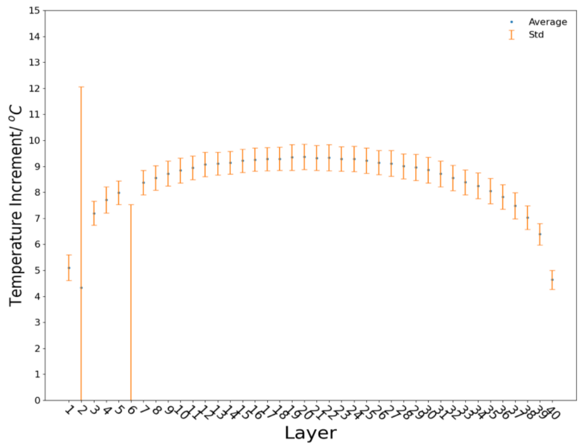
- Room temperature changes with a daily cycle (Around 3 ^{o}C).

- On temperature sensors in HBU, temperature differences on different points is with 2 ^{o}C.



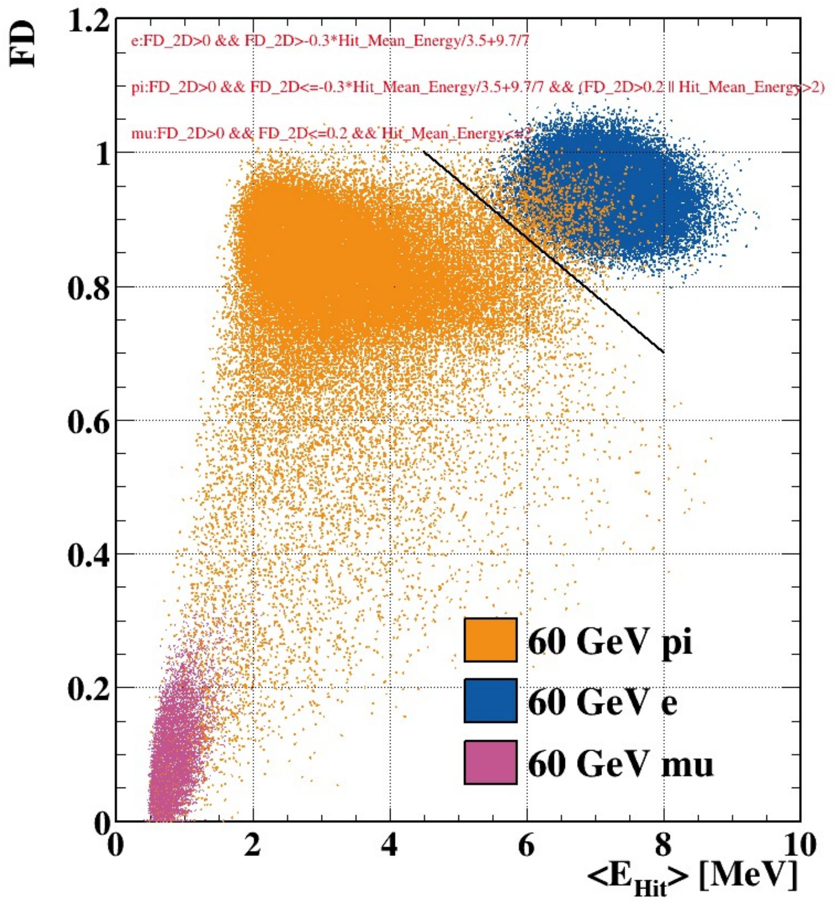






Compared with FD+E_MEAN cut

- **Energy: 5, 20, 40, 60,80 GeV**
- **MC samples**
- **20, 000 Electron + 20, 000 Pion**
- **FD: a linear boundary**
- **ANN: argmax(likelihood)**



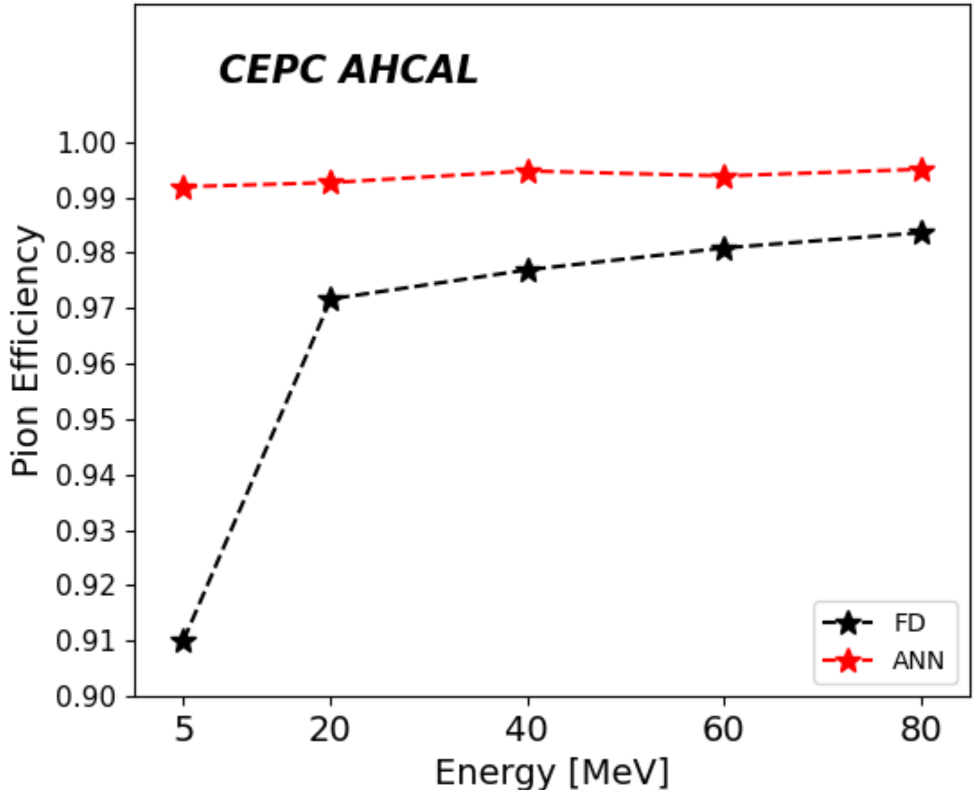
FD + E_Mean_hit cut

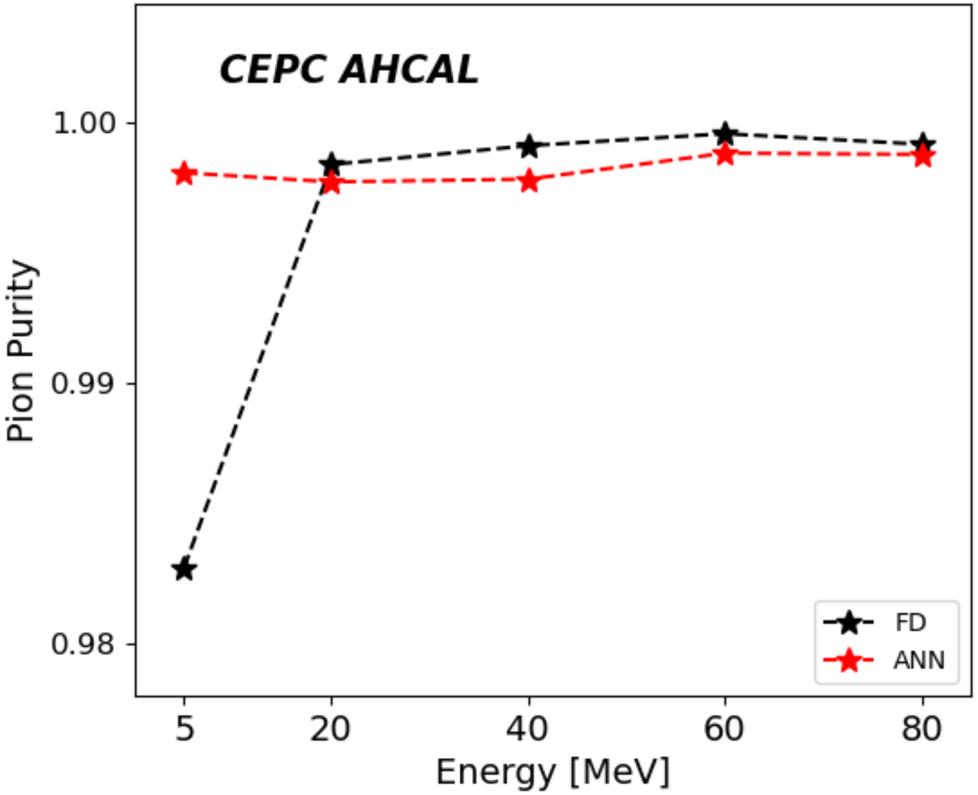
Compared with FD+E_MEAN cut

- **Improvement in Efficiency out-weighs losses in Purity**

E [GeV]	5	20	40	60	80
$\Delta(effi)$	8.19%	2.1%	1.84%	1.4%	1.08%

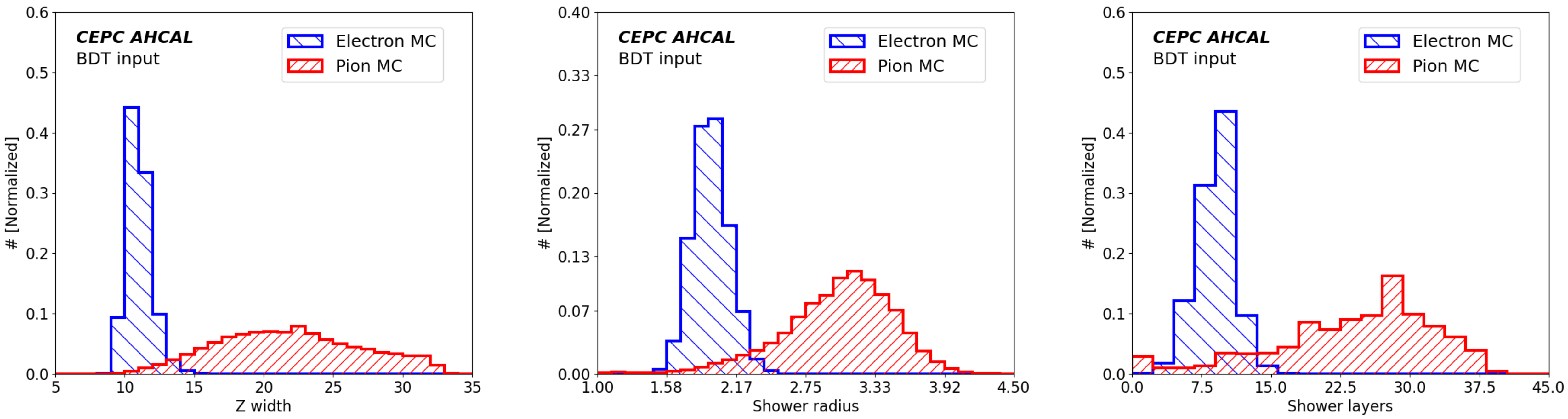
E [GeV]	5	20	40	60	80
$\Delta(puri)$	1.52	-0.07%	-0.07%	-0.09%	-0.09%





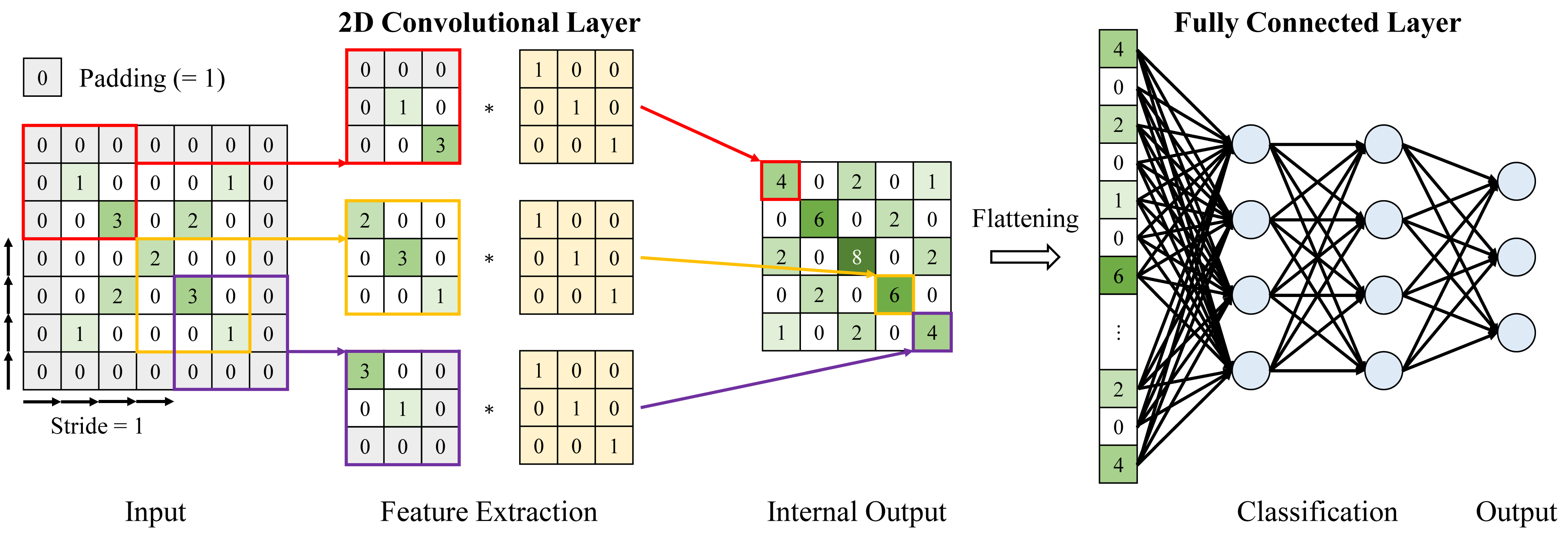
BDT input

- **Top 3 variables in separating between EM showers and HAD showers.**
  - Z width: The RMS of the z-axis coordinates.
  - Shower Radius: The RMS of the distance with respect to the z-axis.
  - Shower layers: The number of layers in which the RMS of positions in the x-y plane exceeds 4 cm.



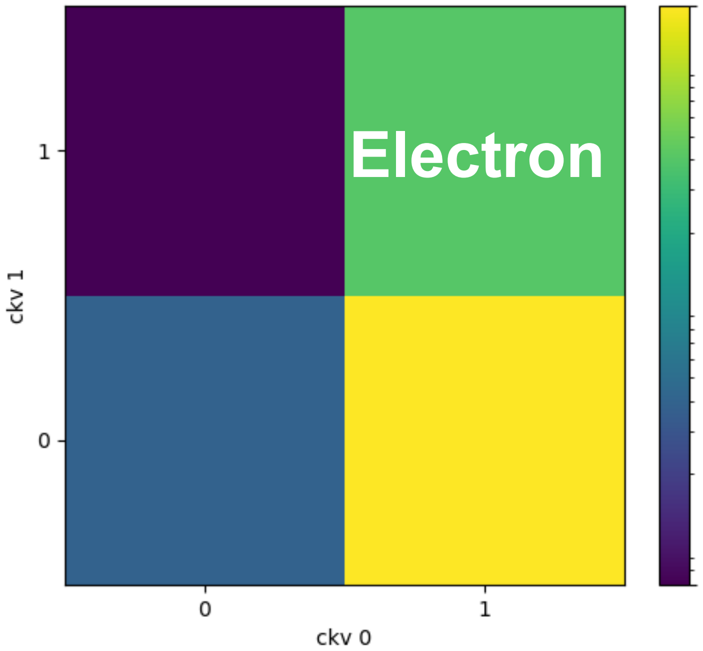
The rest is demonstrated in backup.

- **Cell-based Artificial Neural Networks (ANN) make full use of high-dimensional input ($18 \times 18 \times 40$).**
  - Compile layers to extract features.
  - Output is the probability (likelihood) of each particle type candidate.

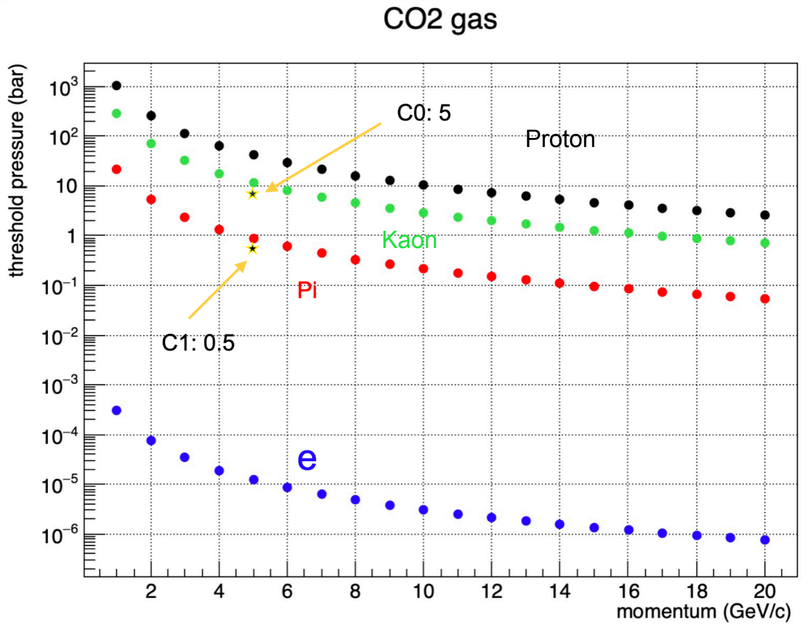


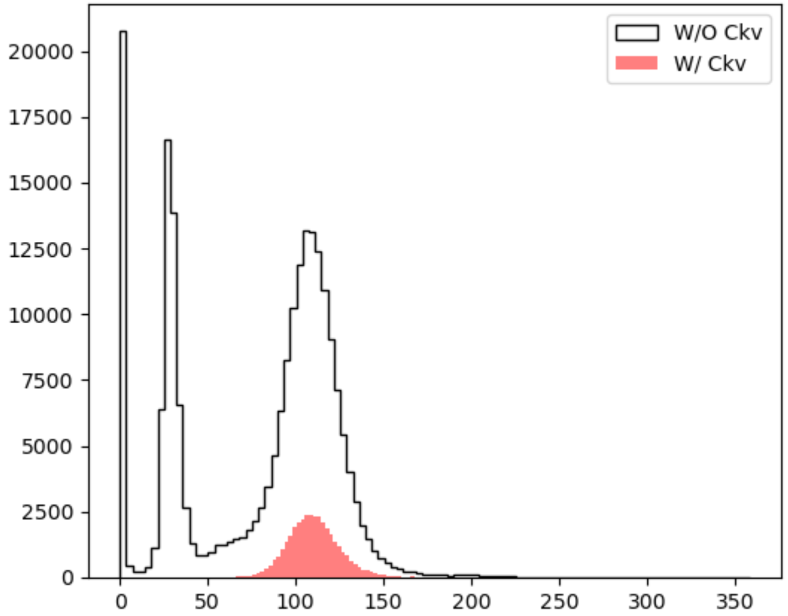
Prepared test set using Cherenkov detector

- **5GeV Electron data from PS-T9 (Run 133)**
  - **Cut: C0=1 & C1=1 & E_dep>20MeV.**



Cherenkov Threshold （by Takeshita-san）, both C0 and C1 are CO2

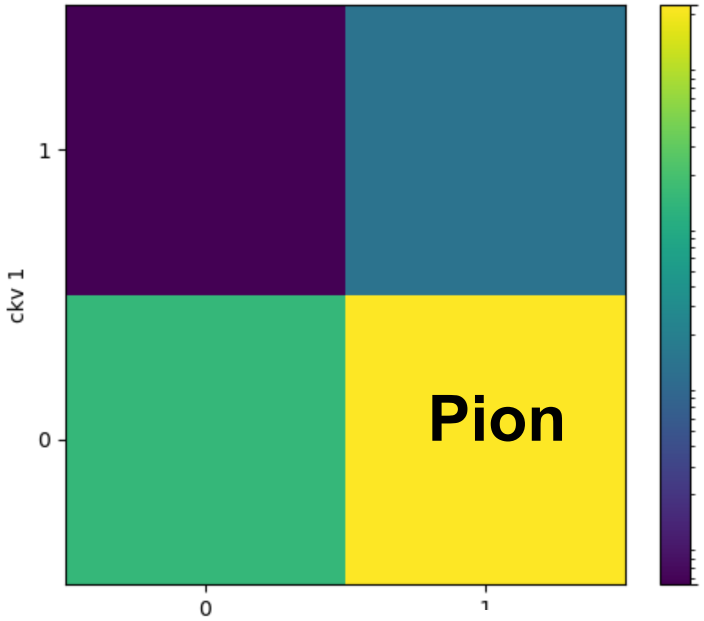




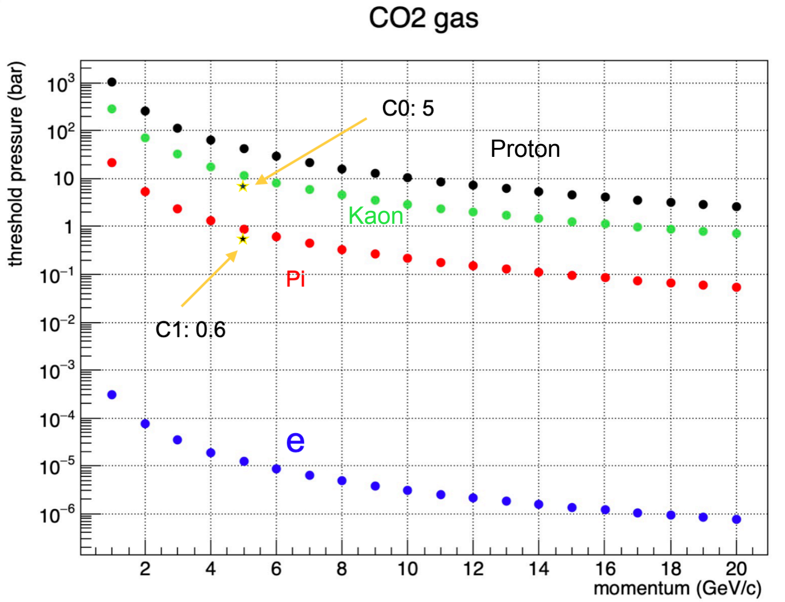
No.	Time	Name	Particle	Mom. GeV/c	Event No.	Backup
1	5.28	AHCAL_Run132_20230528_194338.dat	e-	5	217184	Trigger Counter:~2.2k/spill;
2	5.28	AHCAL_Run133_20230528_214827.dat	e-	5	218148	C0:5;C1:0.5;

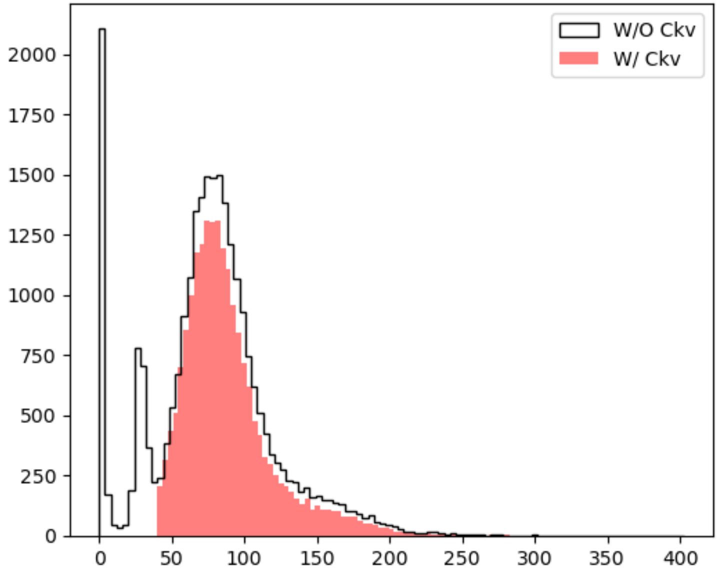
Prepared test set using Cherenkov detector

- **5GeV Pion data from PS-T9 (Run 123)**
  - **Cut: C0=1 & C1=0 & E_dep>40 MeV; Cherenkov detectors don't reject Muon.**



Cherenkov Threshold （by Takeshita-san）, both C0 and C1 are CO2



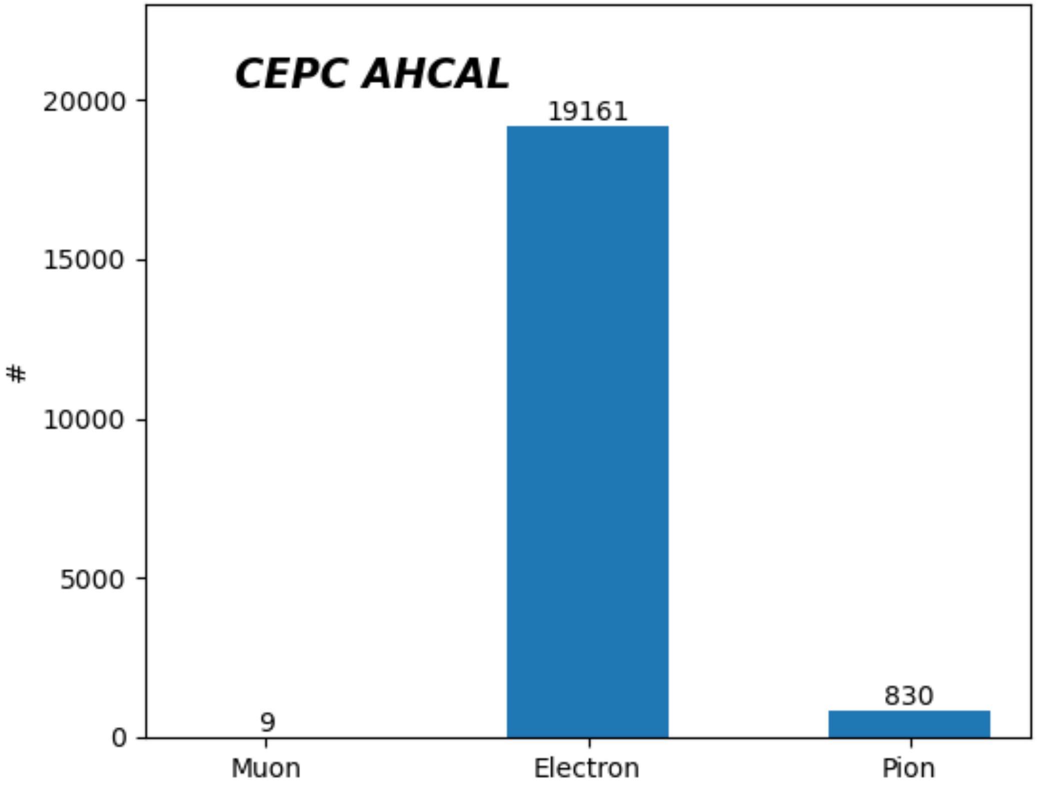


No.	Time	Name	Particle	Mom. GeV/c	Event No.	Backup
21	5.27	AHCAL_Run118_20230527_141601.dat	Pi-	10	263848	C0:1.5;C1:0.1, supplement
22	5.27	AHCAL_Run120_20230527_161750.dat	Pi-	5	227300	Trigger Counter:~17.8k/spill; C0:5;C1:0.6;
23	5.27	AHCAL_Run121_20230527_174513.dat	Pi-	5	228080	
24	5.27	AHCAL_Run122_20230527_191028.dat	Pi-	5	227427	
25	5.27	AHCAL_Run123_20230527_203428.dat	Pi-	5	244491	
26	5.27	AHCAL_Run124_20230527_220455.dat	Pi-	5	304558	

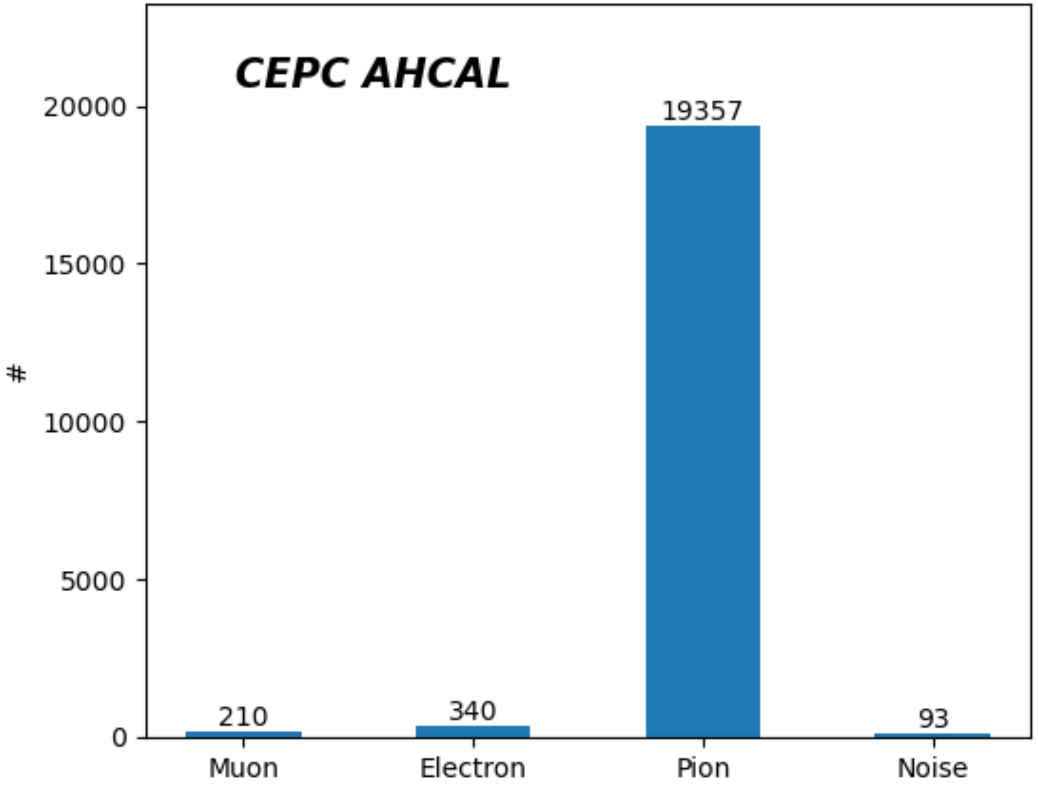
Electron and pion identification

- **Quick look on how events are classified.**
  - **Prediction is based on the highest candidate likelihood**

20, 000 5 GeV "Electrons"



20, 000 5 GeV "Pions"



Signal Purity vs. Signal Efficiency

- **20, 000 5 GeV "Electrons" + 20, 000 10GeV "Pions "**
- **99% signal purity can be achieved (ε_e=90%, ε_π=90%)**