中国科学技术大学
University of Science and Technology of China

Analysis of test beam data

Yukun Shi
USTC
CEPC calo group

Outline

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- Beam test
- Calibration
  - Pedestal
  - Gain ratio
  - MIP
- Performance
  - Selection and PID
  - Linearity and energy resolution
- Summary

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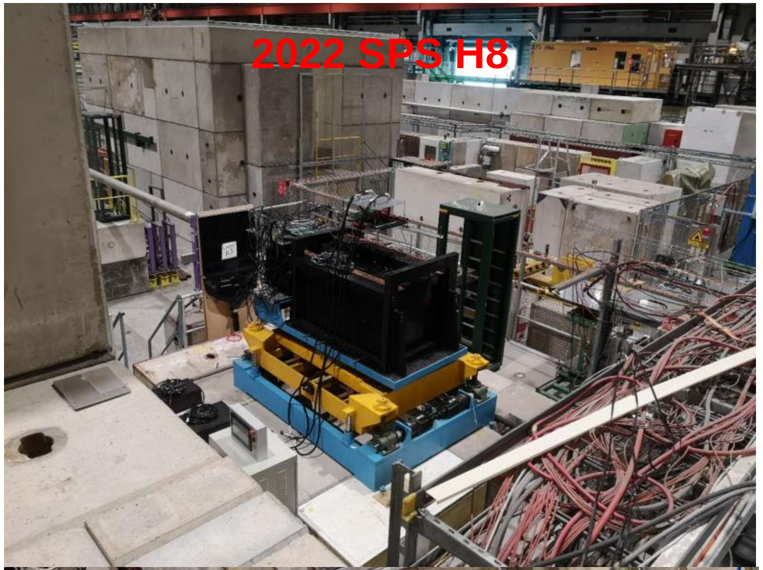
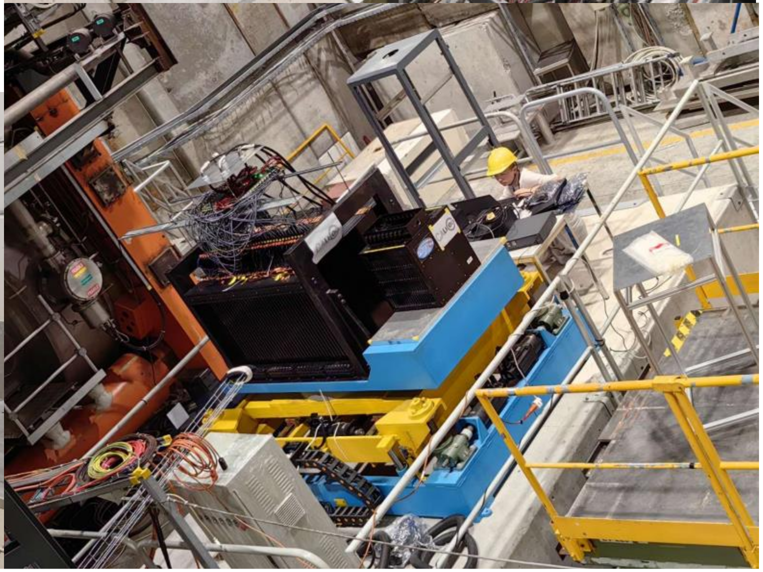
Beam test

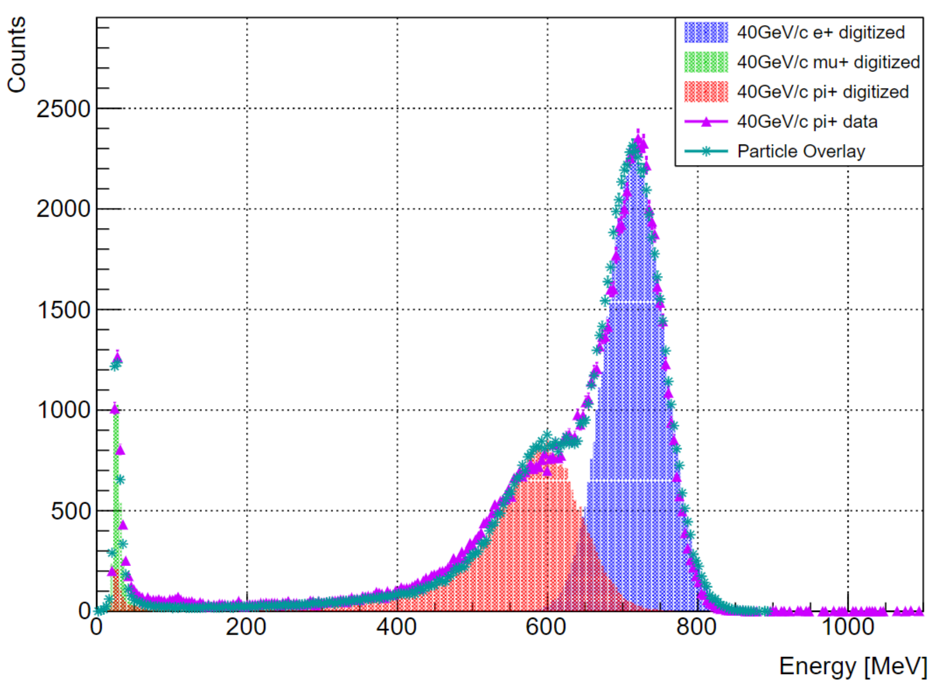
- 2022 October, 2 weeks in SPS H8,25 million events were collected
- 2023 April and May, 2 weeks in SPS H2 and PS T9 respectively, 40 million events were collected
- Electronic calibration data
- Muon scanning
- $\pi^{\pm}$:1-120GeV,$e^{\pm}: 0.5 - 250\text{GeV}$

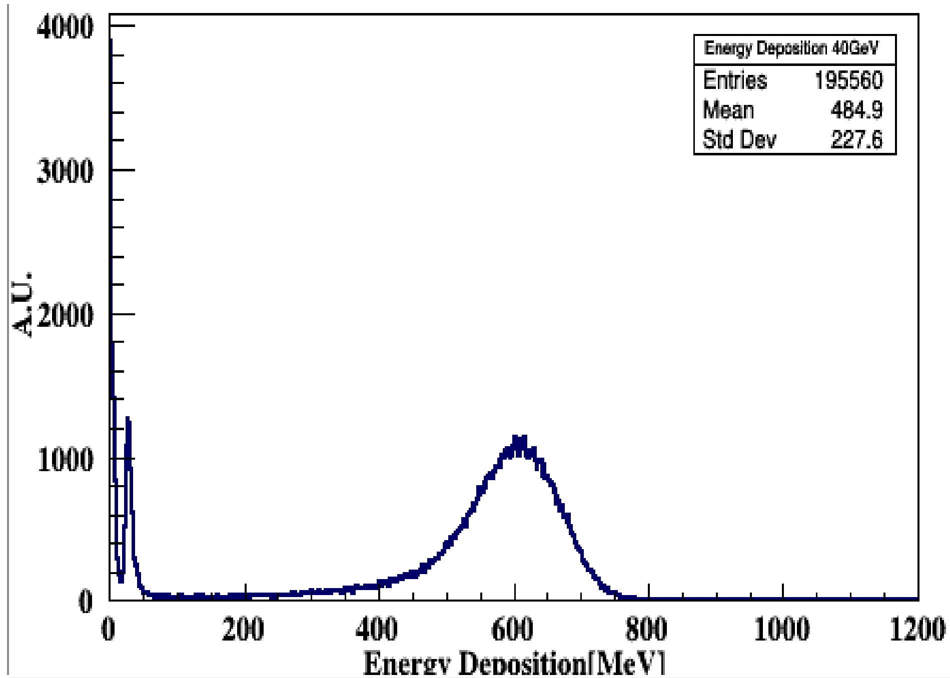

2022 SPS H8


2023 PS T9


2023 SPS H2

- The 2022 SPS H8 beam data is of bad purity
- The 2023 SPS H2 beam data is much better





Energy deposition of 40 GeV pion beam:2022 and 2023

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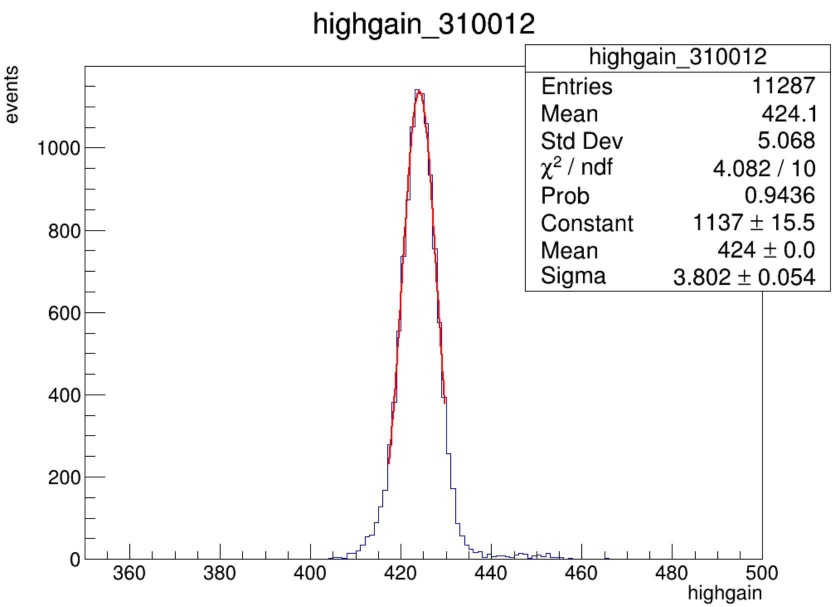
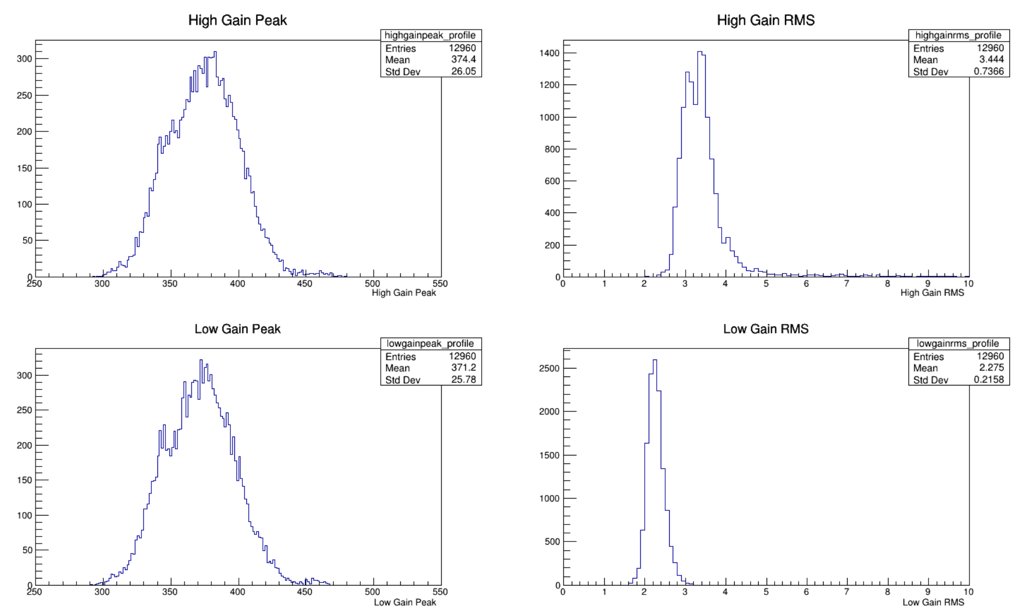
Pedestal

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



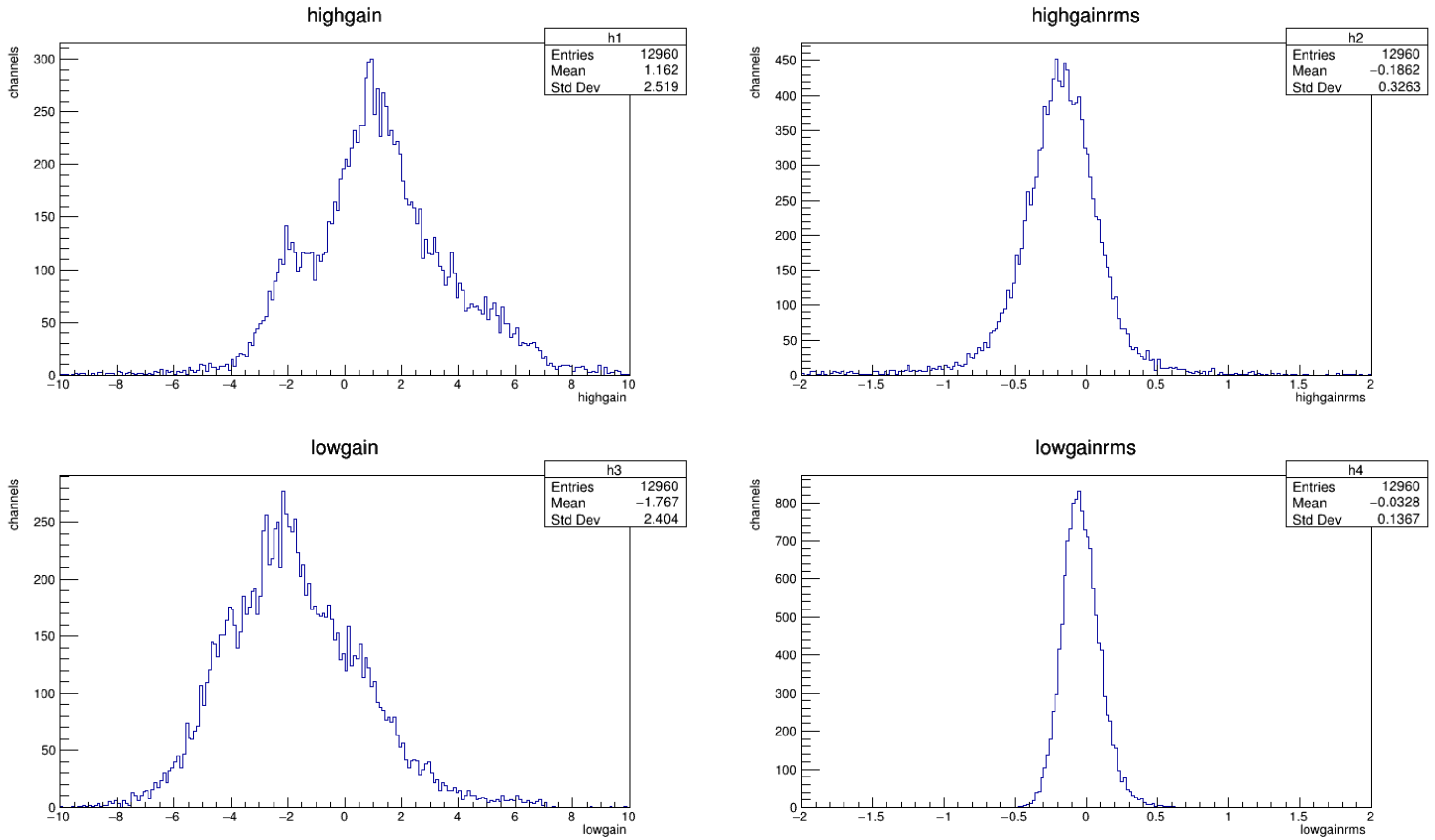
Pedestal distribution of a single channel



Fitting result of all channels

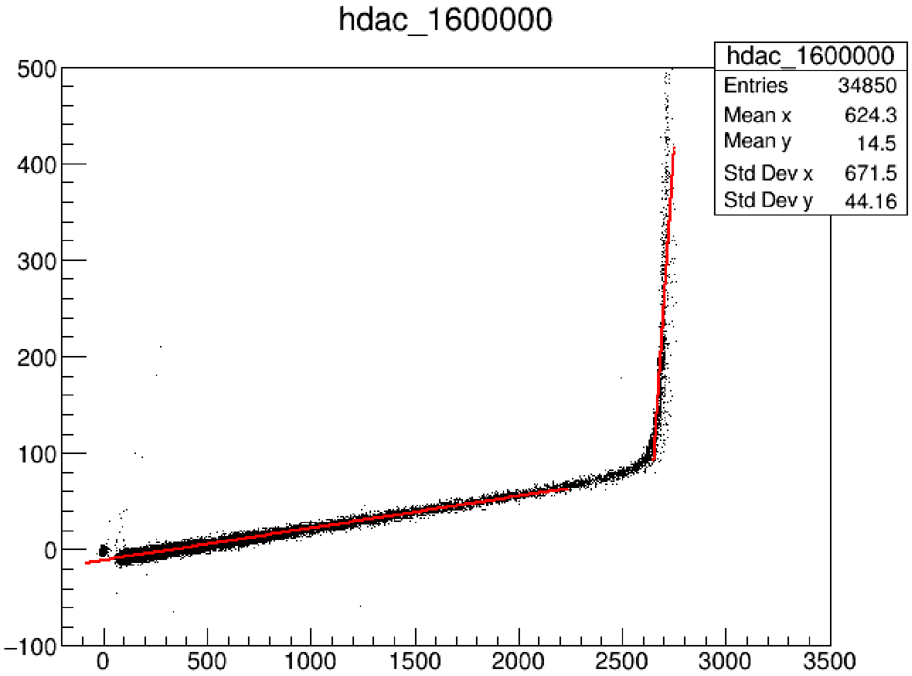
Pedestal

- The difference between pedestal of 2022 and 2023 is small

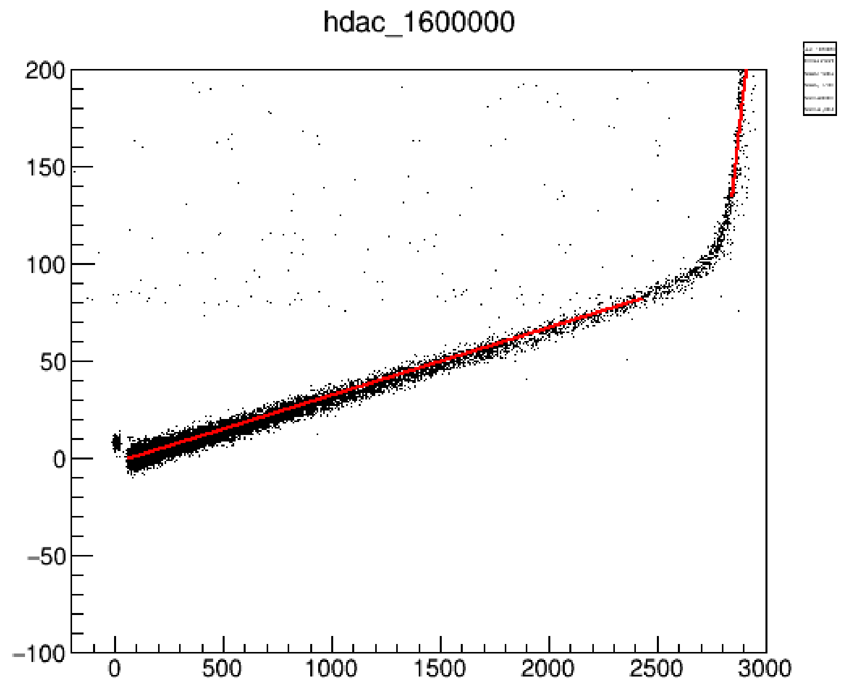


Gain ratio

- The gain ratio of the high/low gain is calibrated from pion beam data
- The saturation point of the high gain is fitted as a parameter of the fitting function



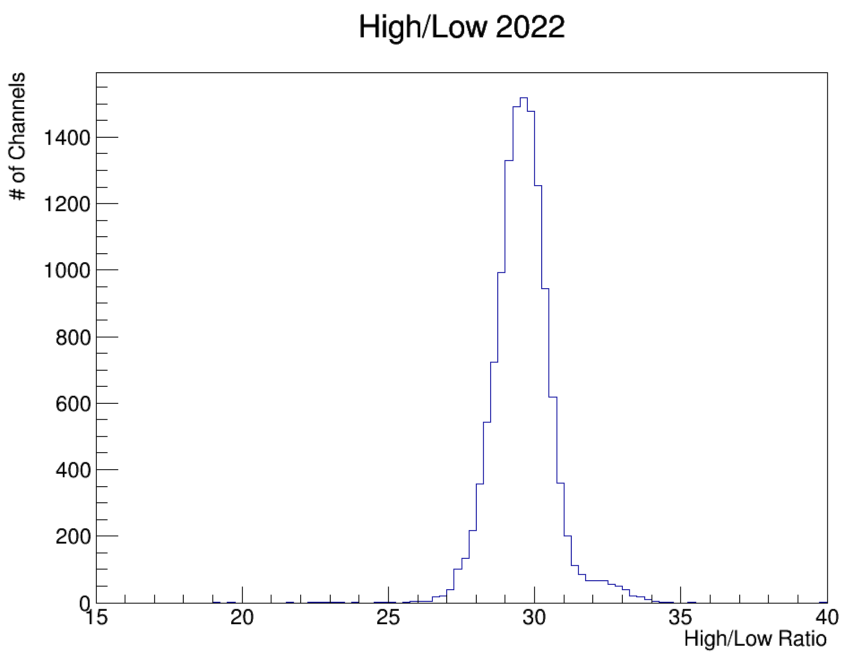
Calibration result of 2022



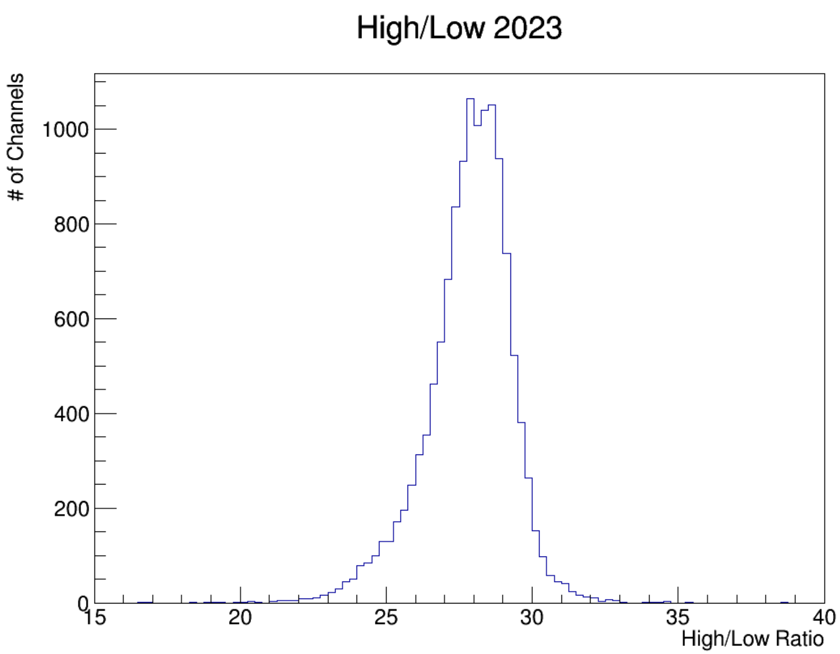
Calibration result of 2023

Gain ratio

- Each channel is fitted and the parameter is stored



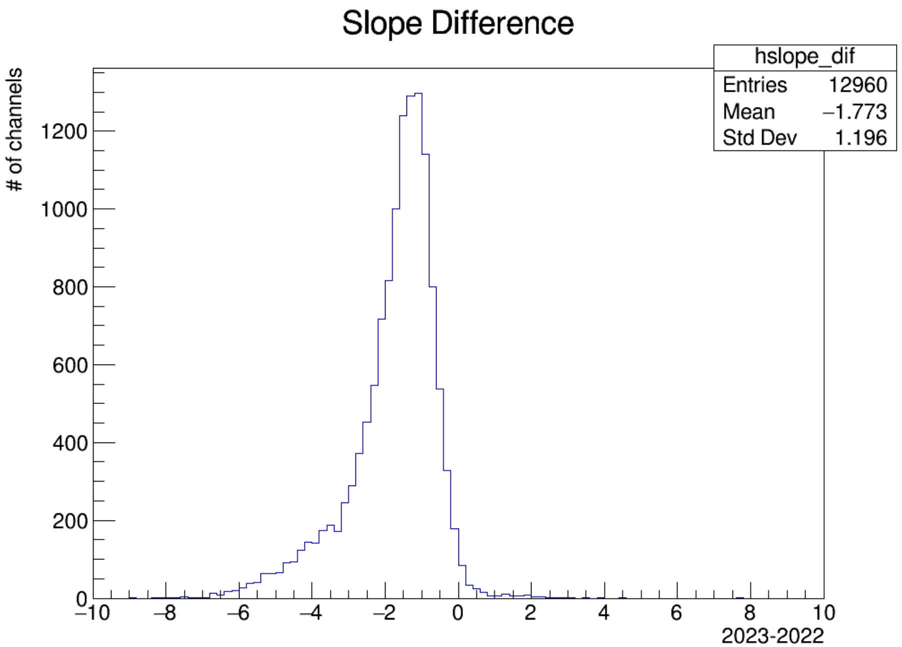
Calibration result of 2022

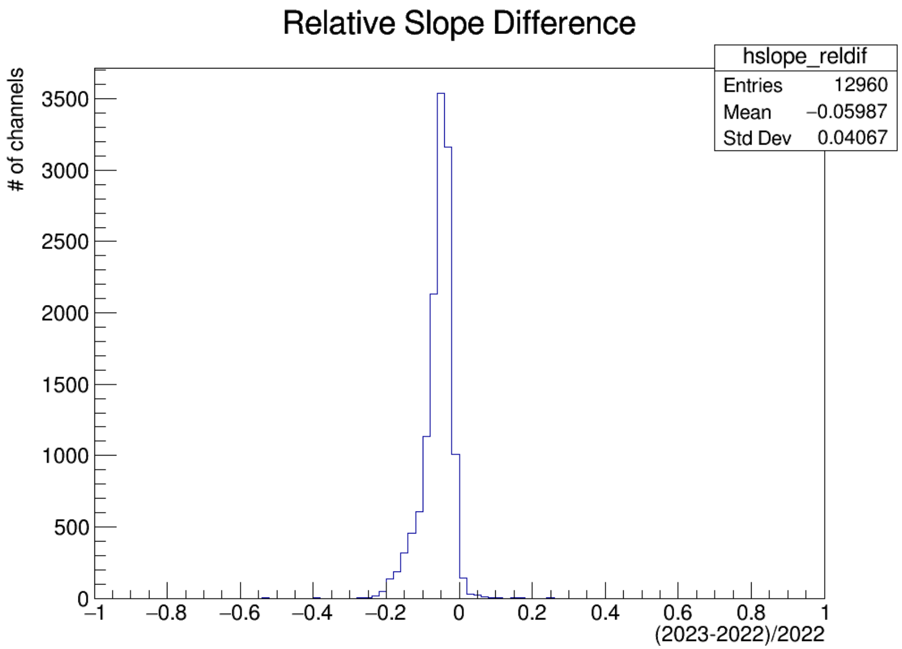


Calibration result of 2023

Gain ratio

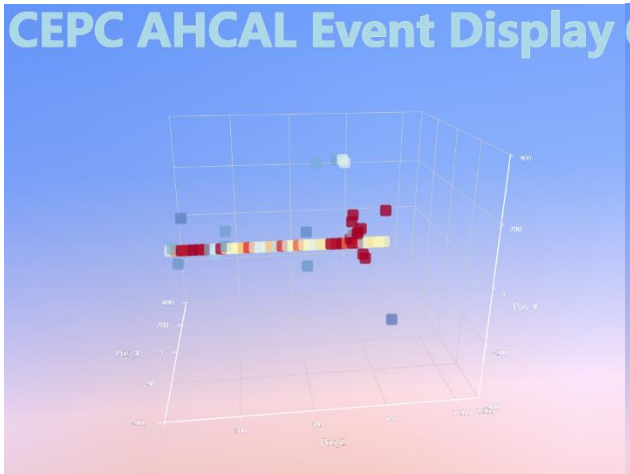
- The result of 2022 and 2023 has small differences, this parameter is stable

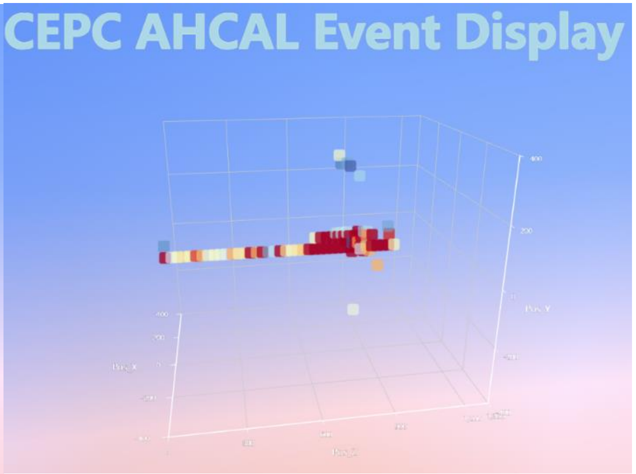




Difference on the gain ratio slope:2023-2022

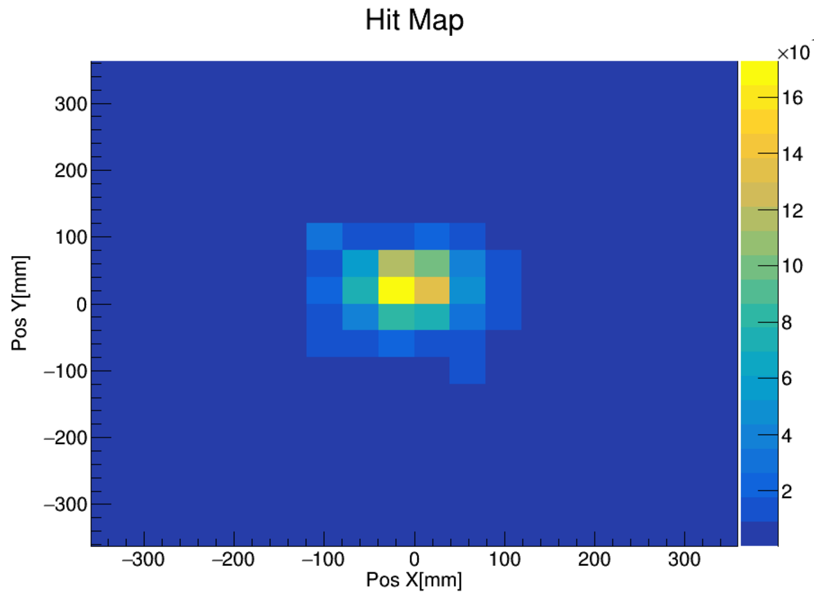
- Combined muon data
  - Different energy:100,108 and 160GeV
  - Different position
  - Different configuration
    - ECAL+HCAL and HCAL alone
    - Auto gain and normal gain

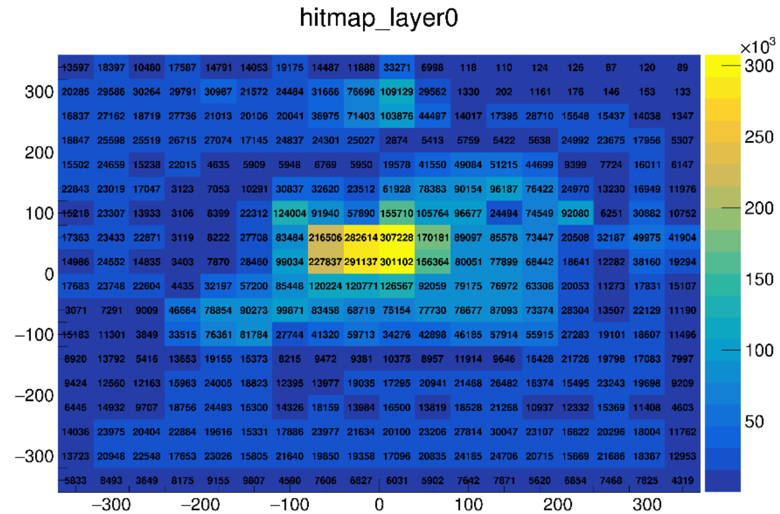




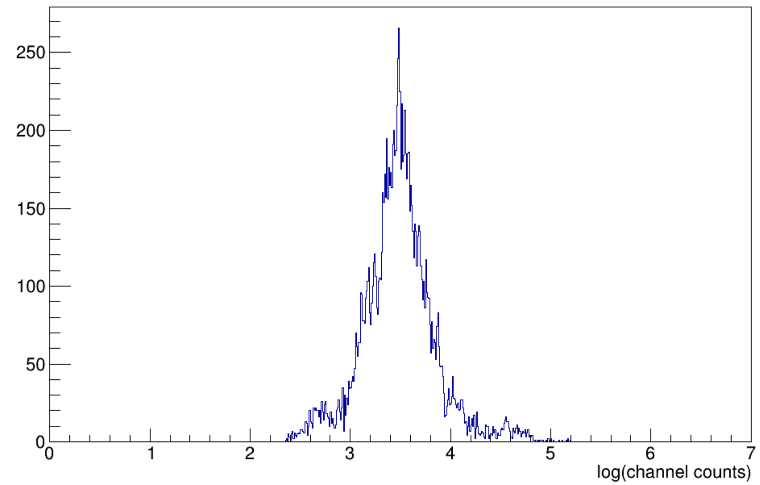
MIP Calibration

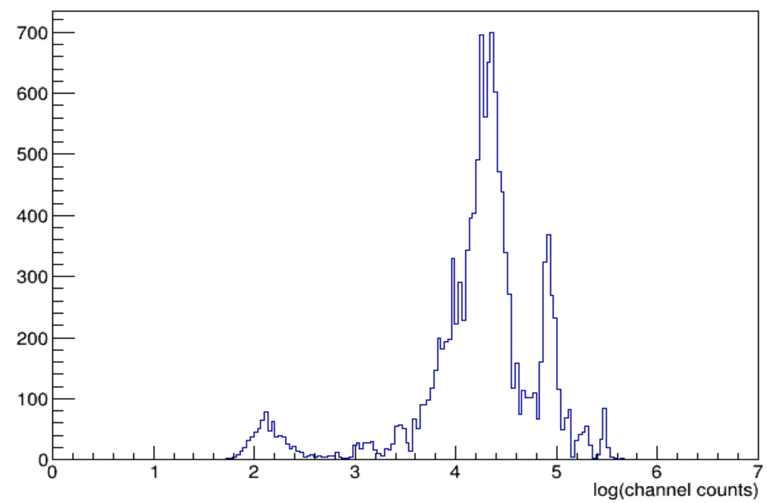
- Statistics overview





Hit map 2022 and 2023





Channel counts in log scale

MIP Calibration

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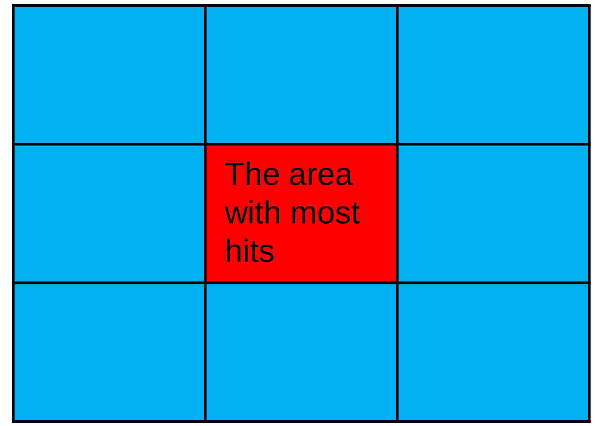
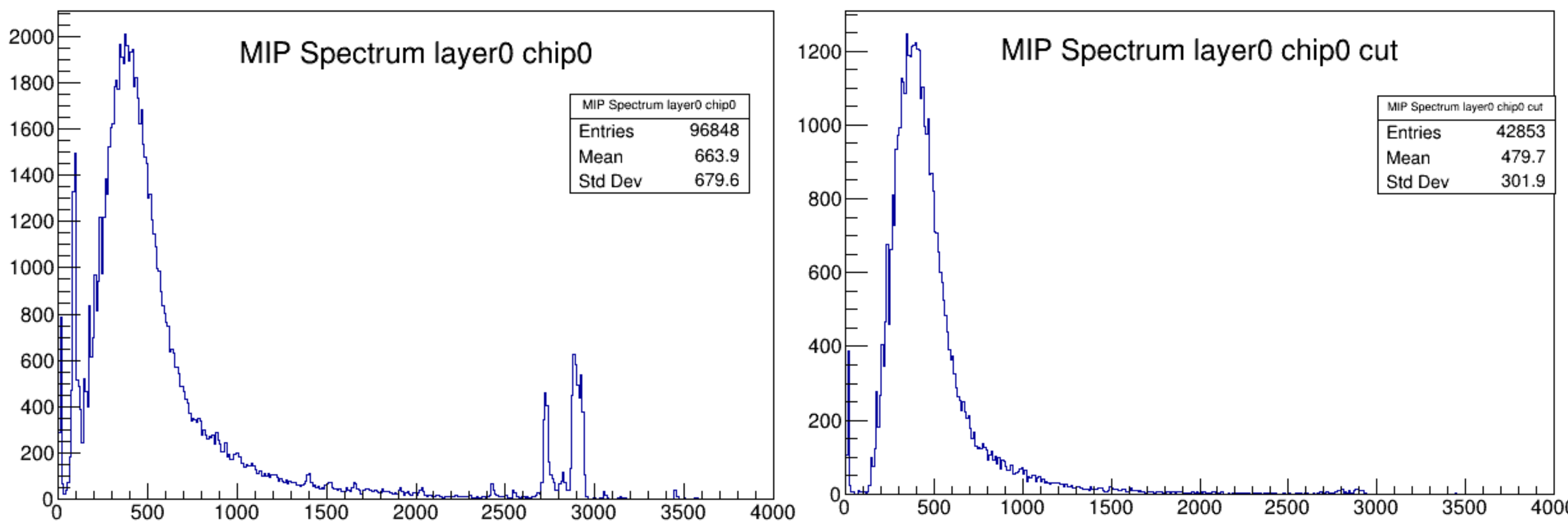
- Selection criteria
  - Shower rejection
    - Max hits in a single layer <5
  - Position Selection
    - Select hits in the area with most hits

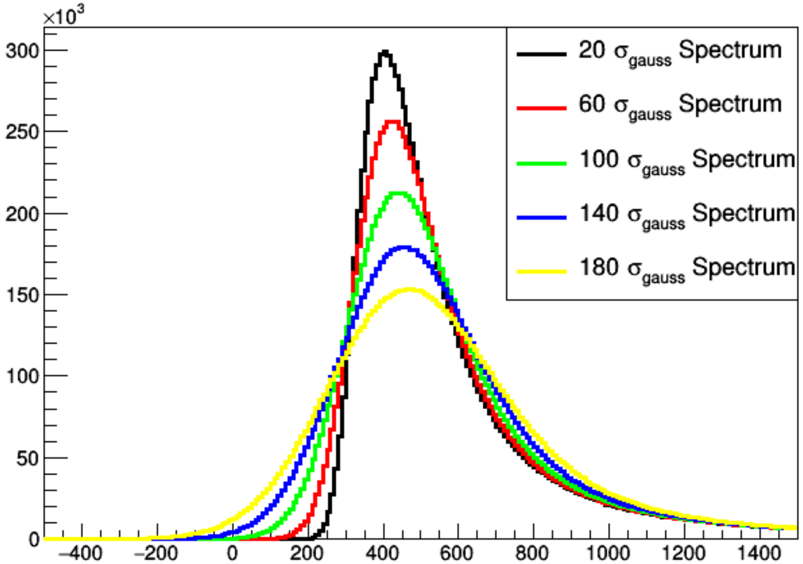


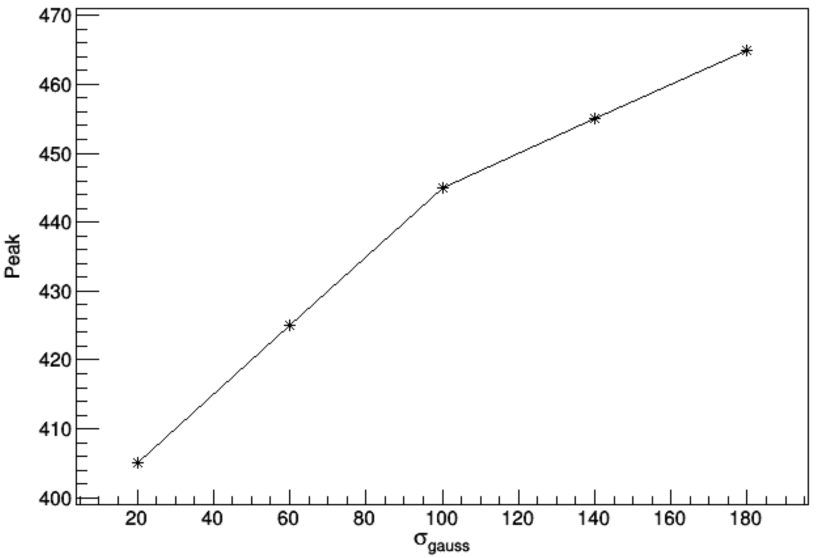


MIP Spectrum before and after Selection

MIP Calibration

- The landau-gauss function is studied
  - The peak value is not only determined by the MPV but also determined by the σ_{gauss}
  - The MPV describes the energy deposit of the MIP while the σ_{gauss} describes the detector effect

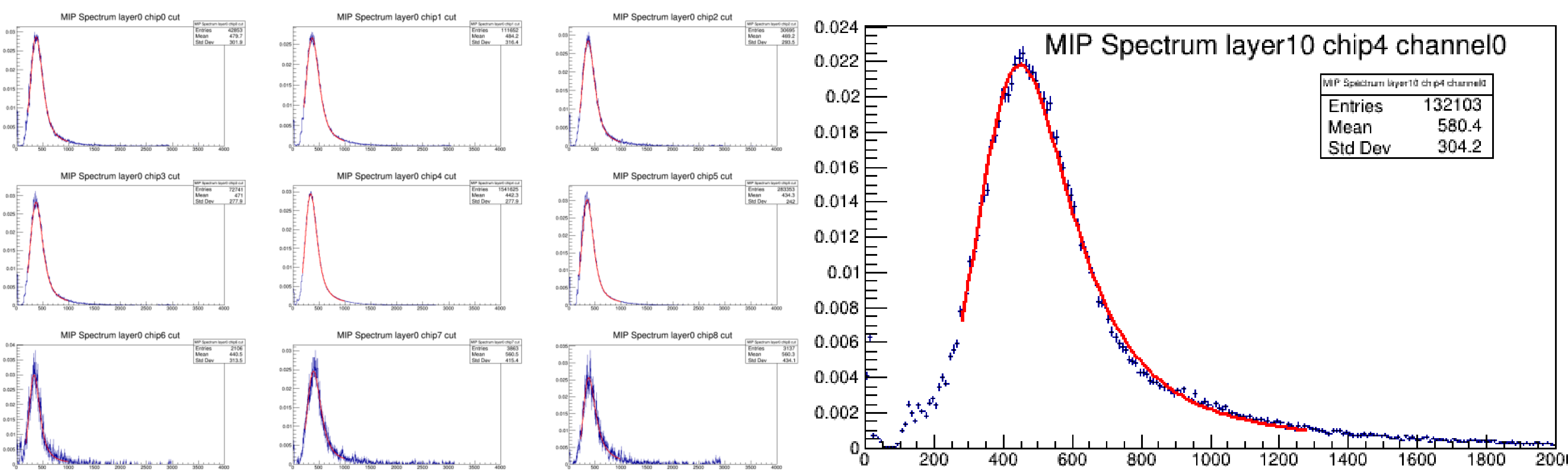




Convolution of landau and gauss at different

MIP Calibration

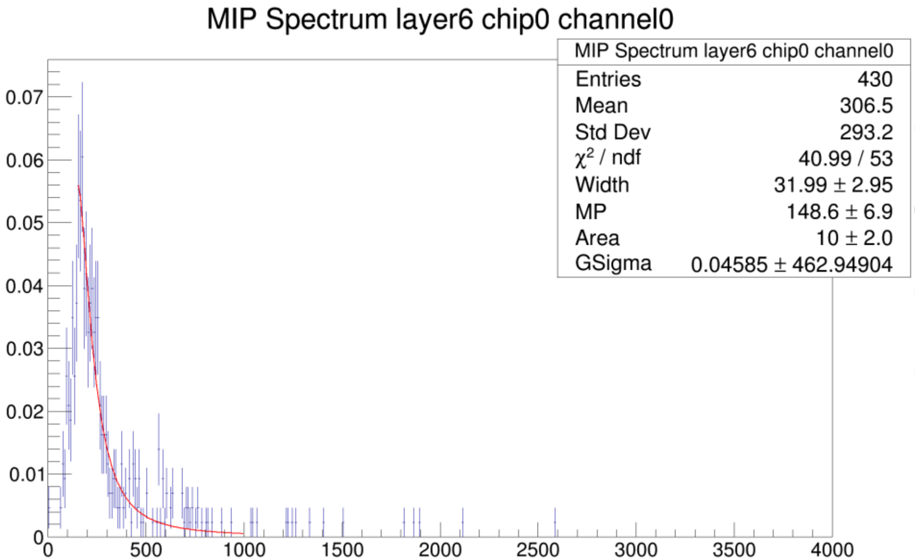
- The fitting is first done for each chip, then each channel is fitted
- All chips have good fitting for 2023 data



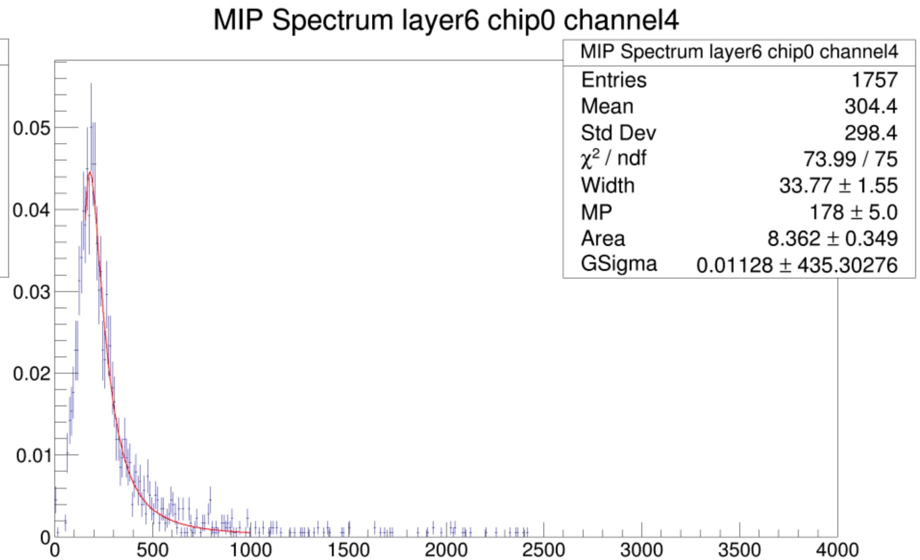
MIP Spectrum Fitting: chip and channel

MIP Calibration

- Good channels will be tagged as 1
- Some channels fail the fitting
  - Bad chip: tagged as -1
  - Inadequate statistics: tagged as -2
  - Bad fitting: tagged as -3

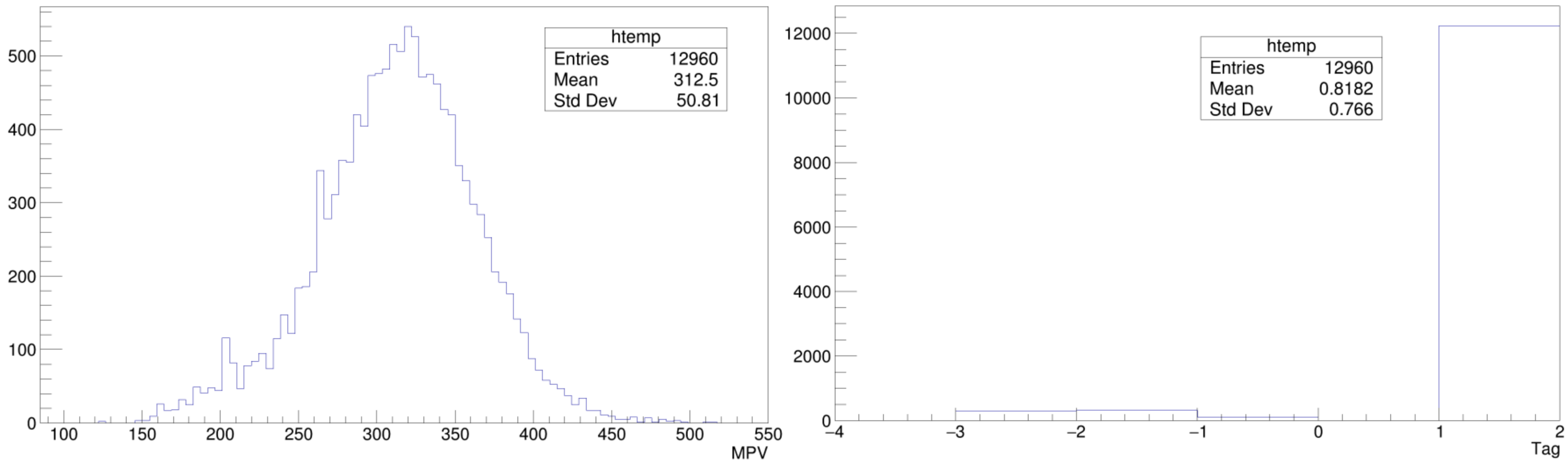


Inadequate statistics

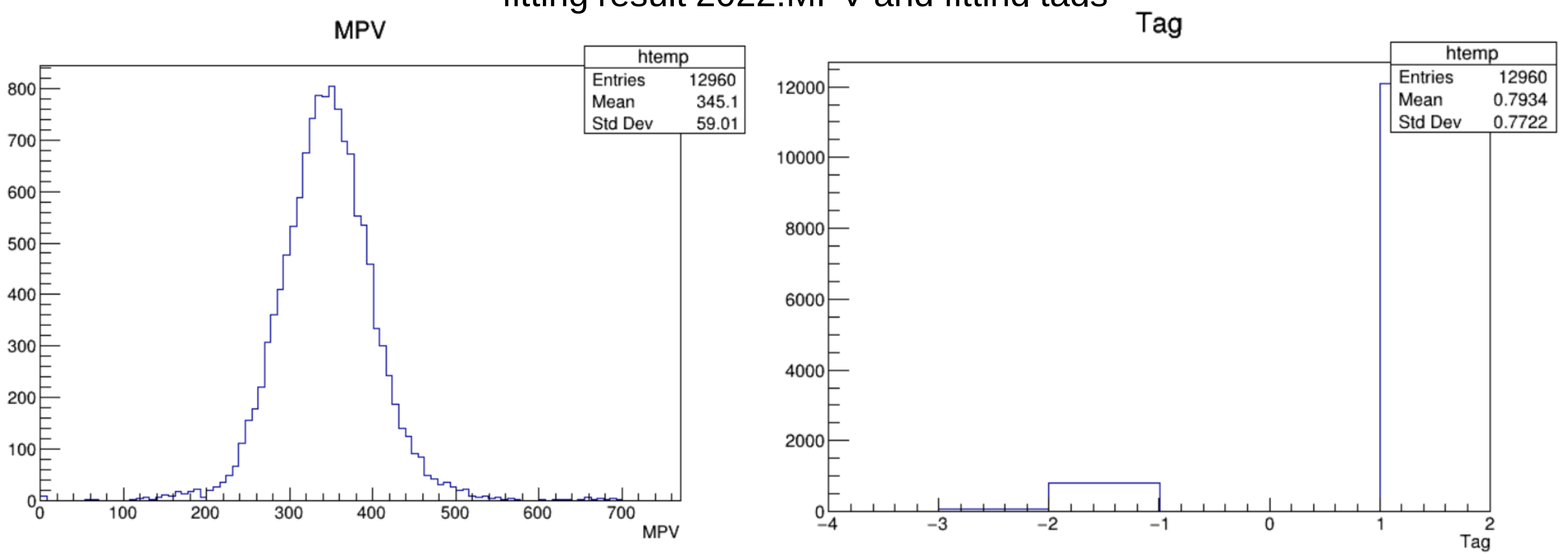


bad fitting: small MPV

MIP Calibration



fitting result 2022:MPV and fitting tags



fitting result 2023:MPV and fitting tags

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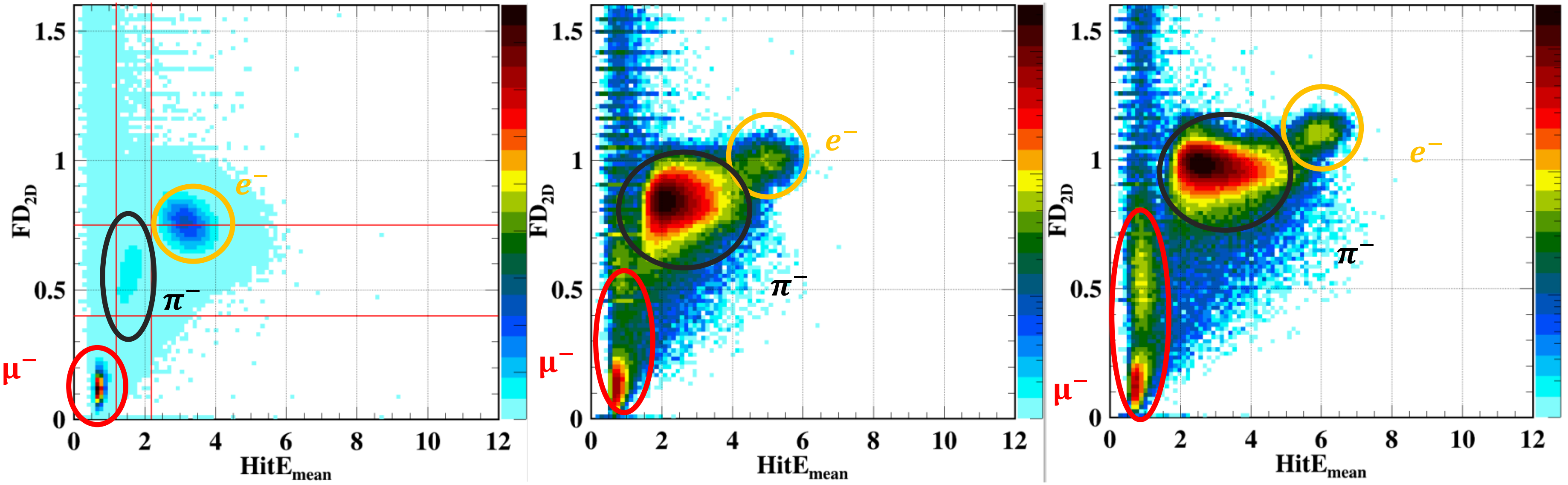
Selection and PID

- The 2023 SPS H2 data
  - The beam is contaminated by μ^- and e^-, especially for the beam of which the energy less than 30GeV
  - PID cut on the data is necessary to get a pure pion sample



FD vs Hit Emean: 10,40 and 80GeV

Selection and PID

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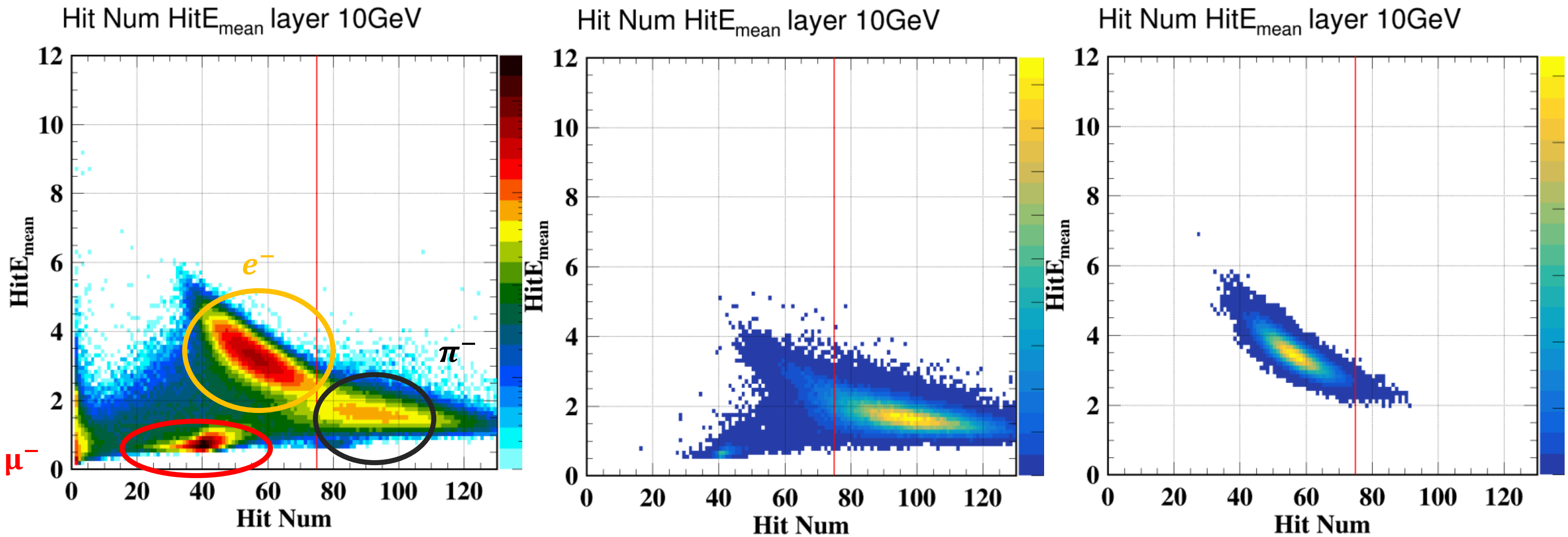
- Total hit number cut
  - This cut is determined to the π^- and e^- MC
  - This cut can reject the μ^- or non-shower events
  - e^- events are also cut by the selection

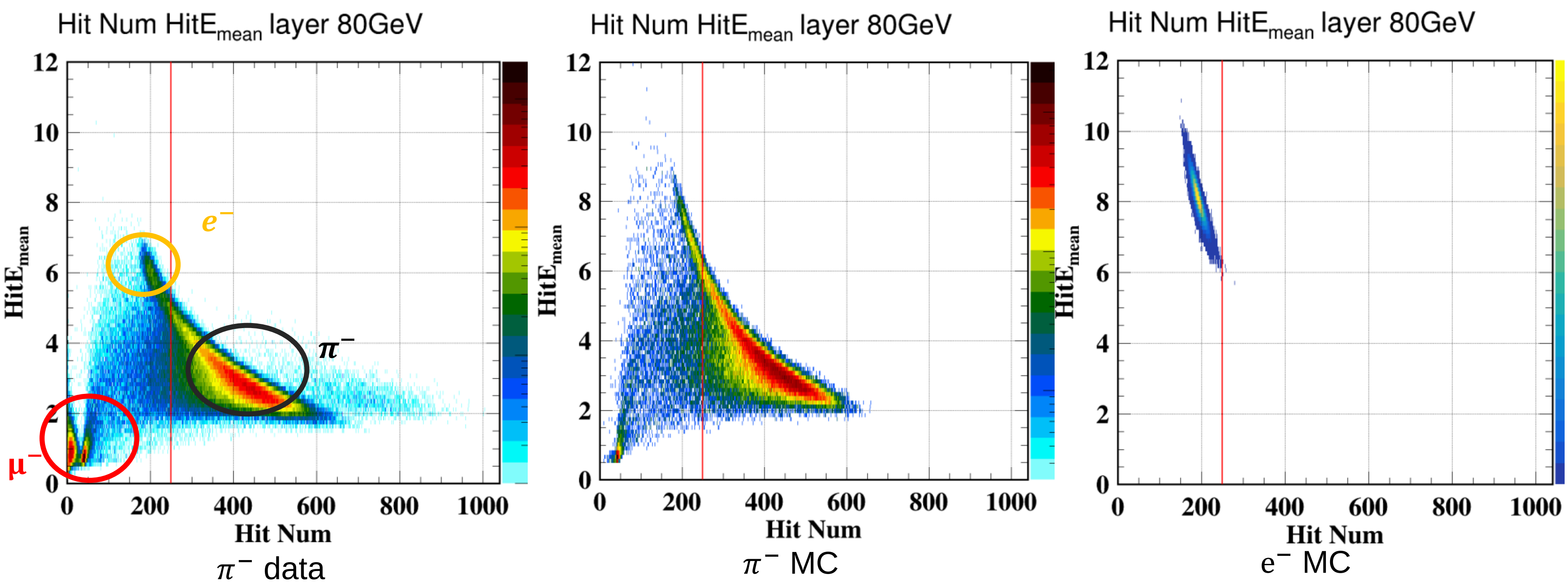


π^- data | π^- MC | e^- MC

Hit No vs Hit E mean at 10GeV

Selection and PID

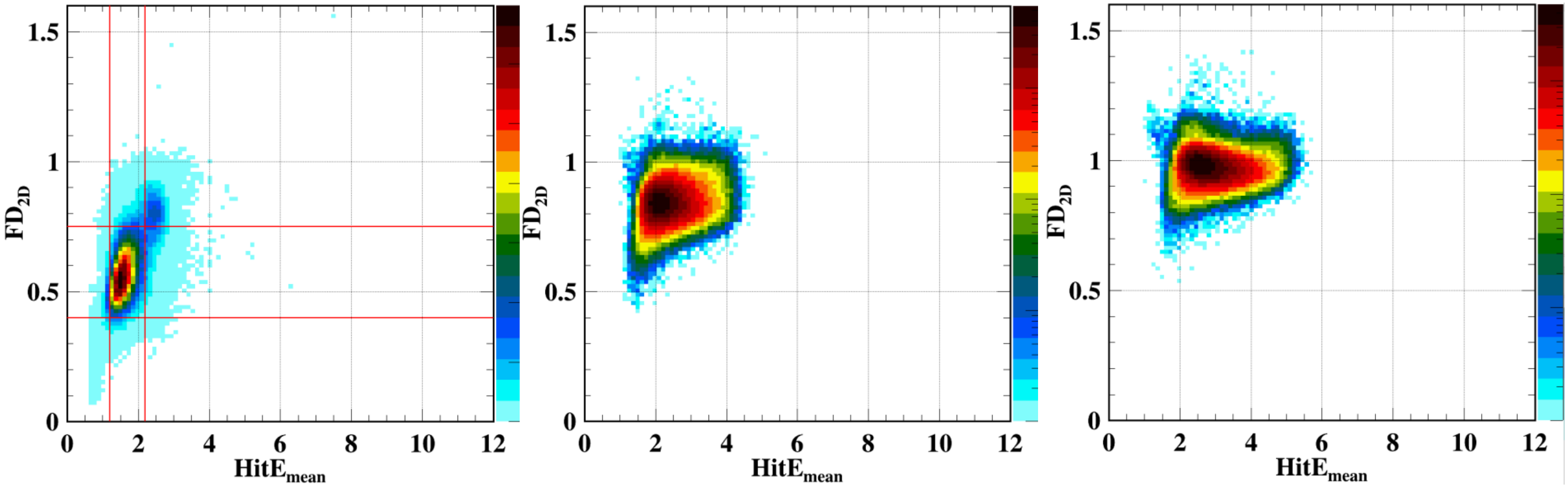
- Total hit number cut
  - The distribution of the hit number and hit E mean is highly correlated to the particle energy
  - The hit number cut varies with the particle energy respectively



Hit No vs Hit E mean at 80GeV

Selection and PID

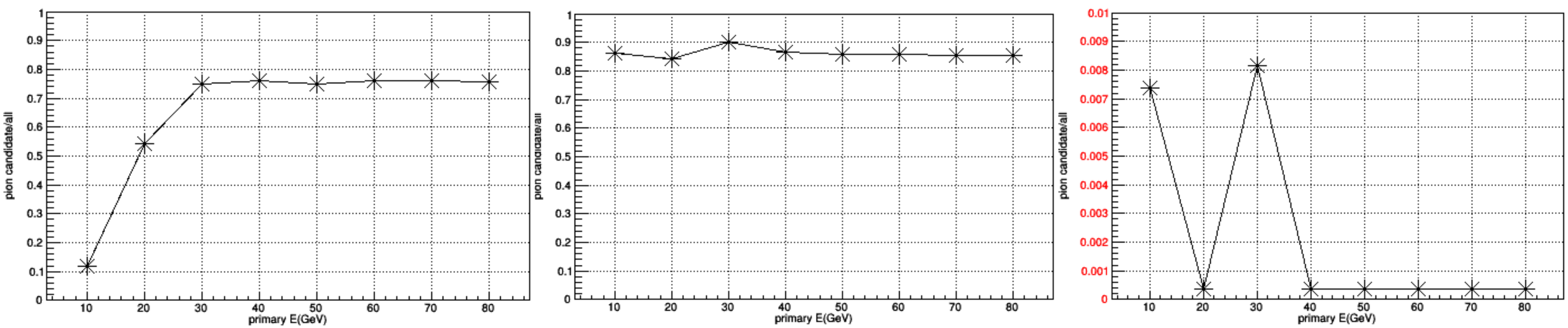
- The purity after the hit number cut
  - Purity for data <30 GeV is still poor after the hit number cut
  - FD and Hit E mean cut is applied to data with energy < 30GeV
  - FD and Hit E mean cut isn't apply to the MC because of the disagreement between MC and Data on the FD



FD vs Hit E mean data : 10,40 and 80GeV

Selection and PID

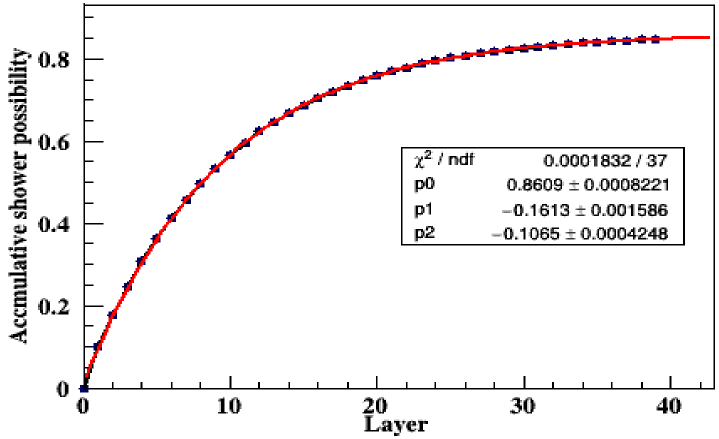
- Selection efficiency for PID cut
  - About 90% of π^- MC events could pass the PID
  - Less than 1% of e^- MC events could pass the PID
  - The PID cut could efficiently select π^- candidate from beam data while rejecting the μ⁻ ,non-shower and e^- events

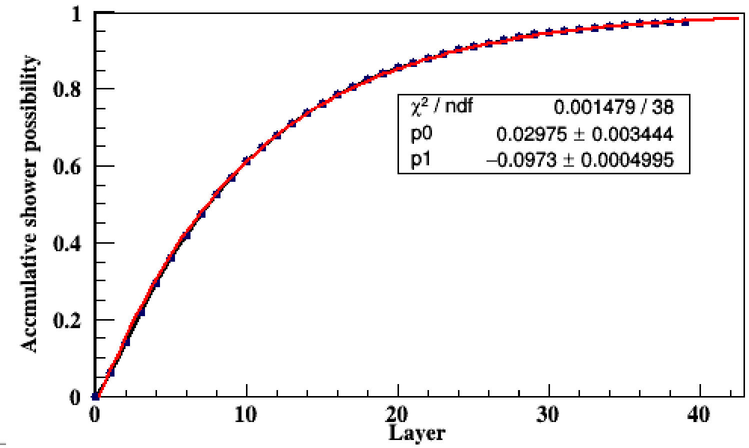


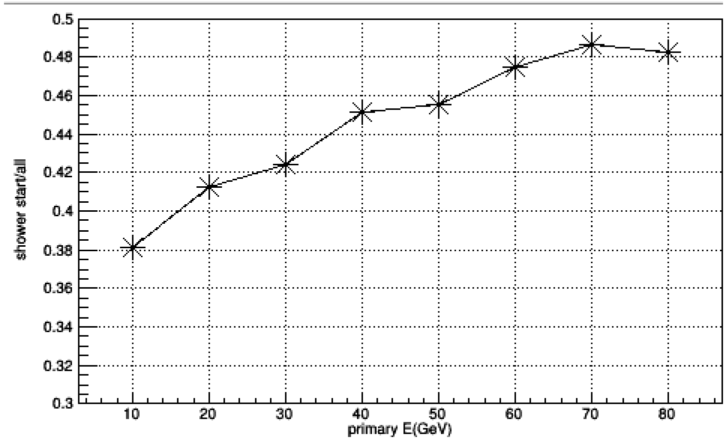
Pion candidate/all events: $\pi^-\ data, \pi^-\ MC\ and\ e^-\ MC$

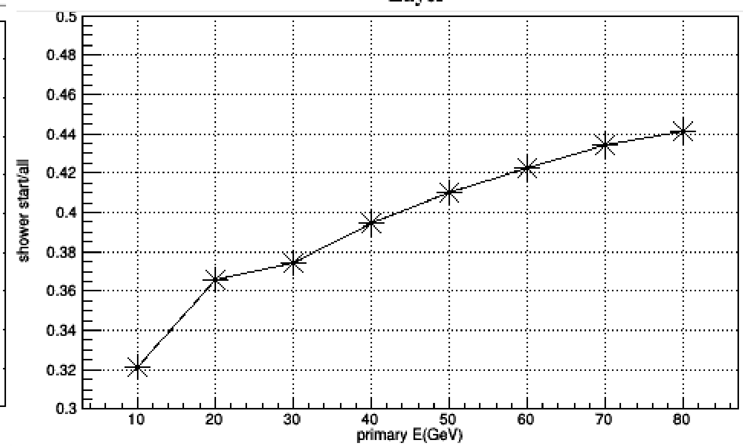
Selection and PID

- The shower start layer is defined as the first layer with more than 4 hits
- Accumulative shower possibility is calculated according to the shower start layer
- About 10 layers equals an nuclear interaction length
- Start Layer cut: start layer < 5(~0.5λ)





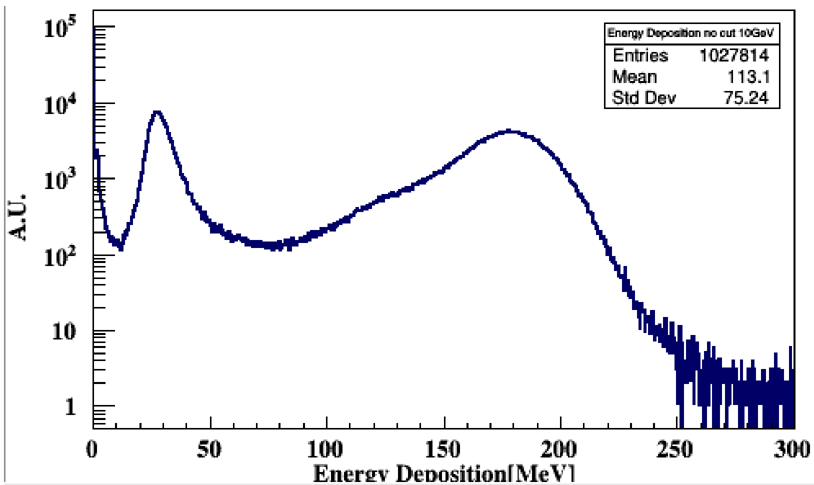


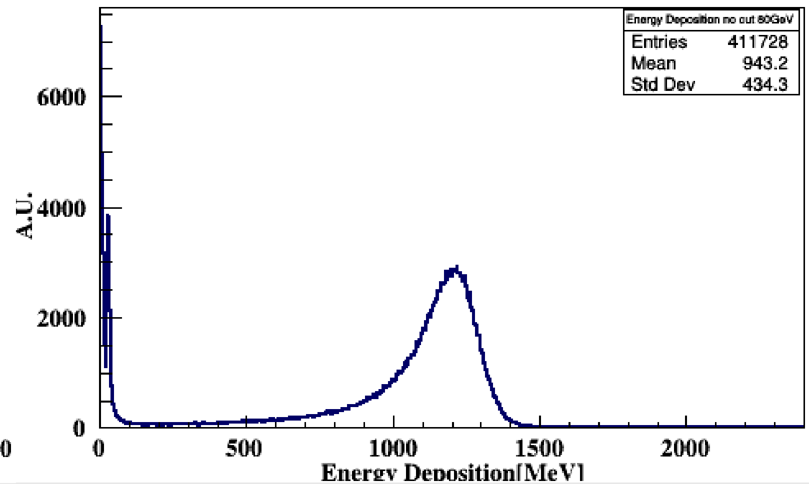


Start layer selection efficiency: π^- $data$ and π^- MC

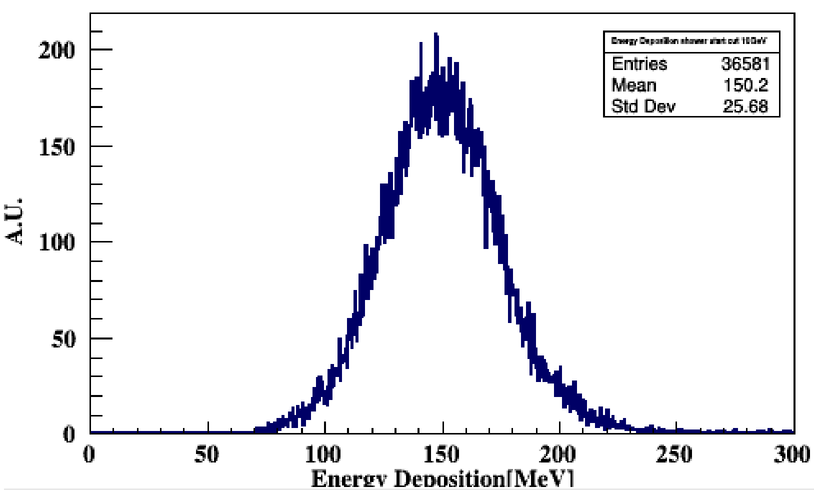
Selection and PID

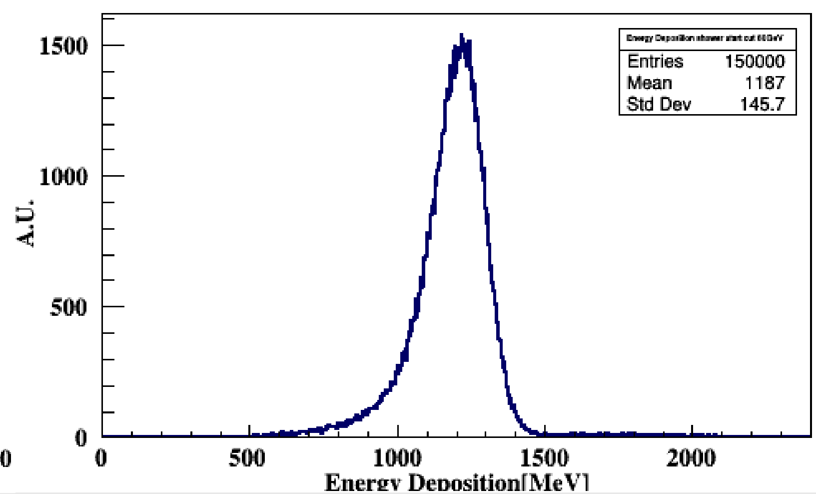
- The data performance of selection





Data before selection:10 and 80 GeV





Data after selection:10 and 80 GeV

Selection and PID

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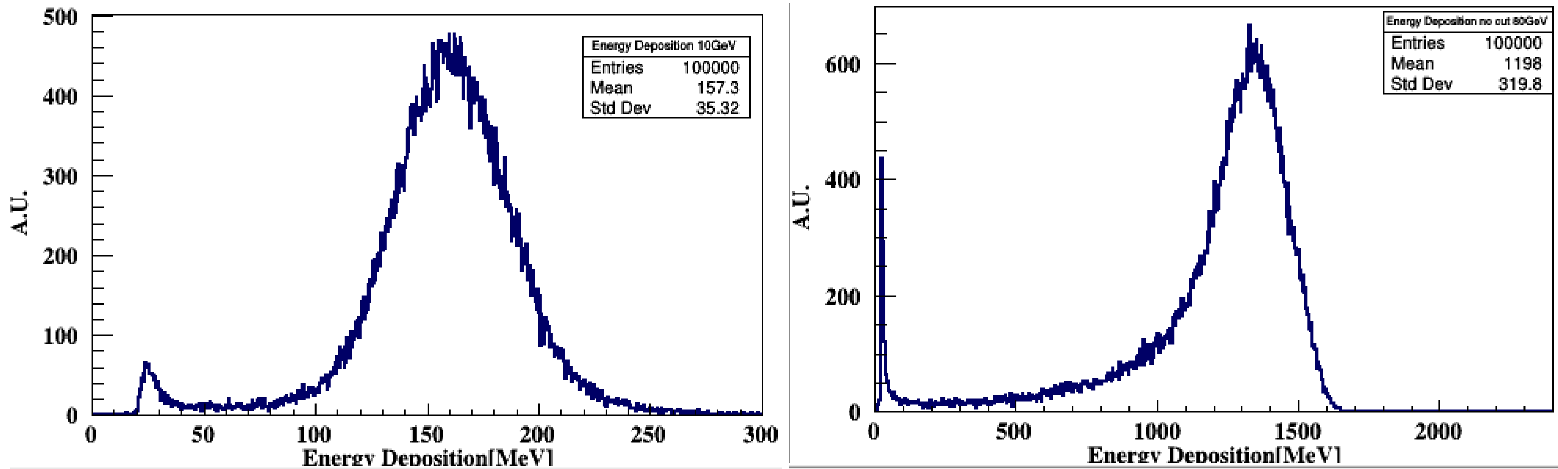
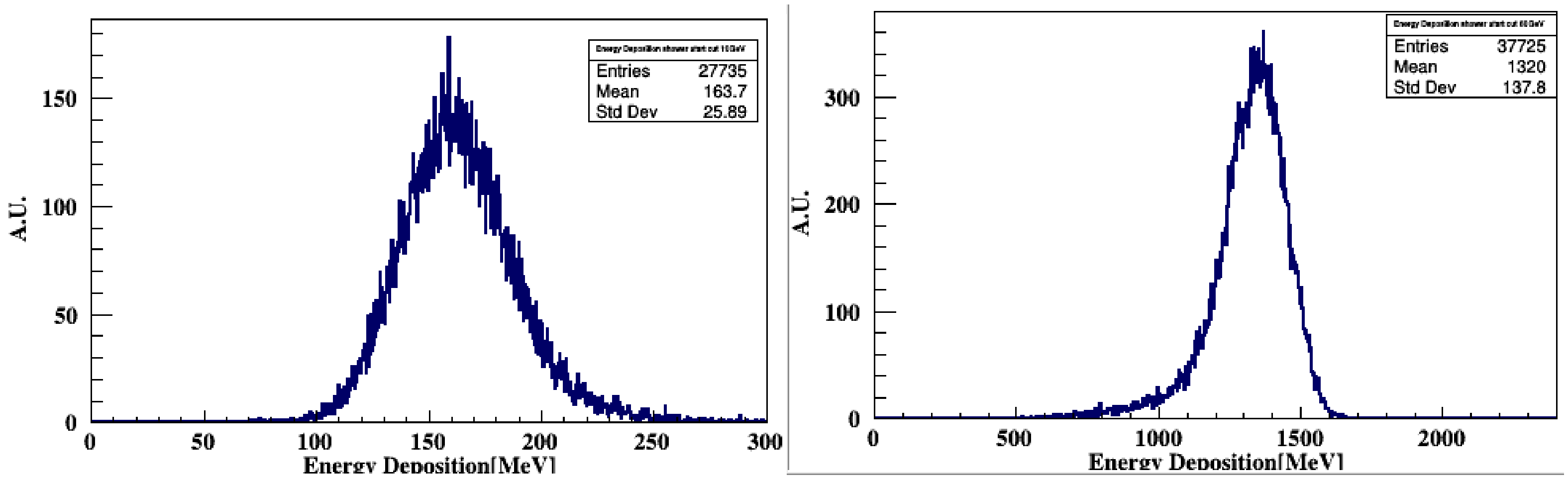
- The MC performance of selection

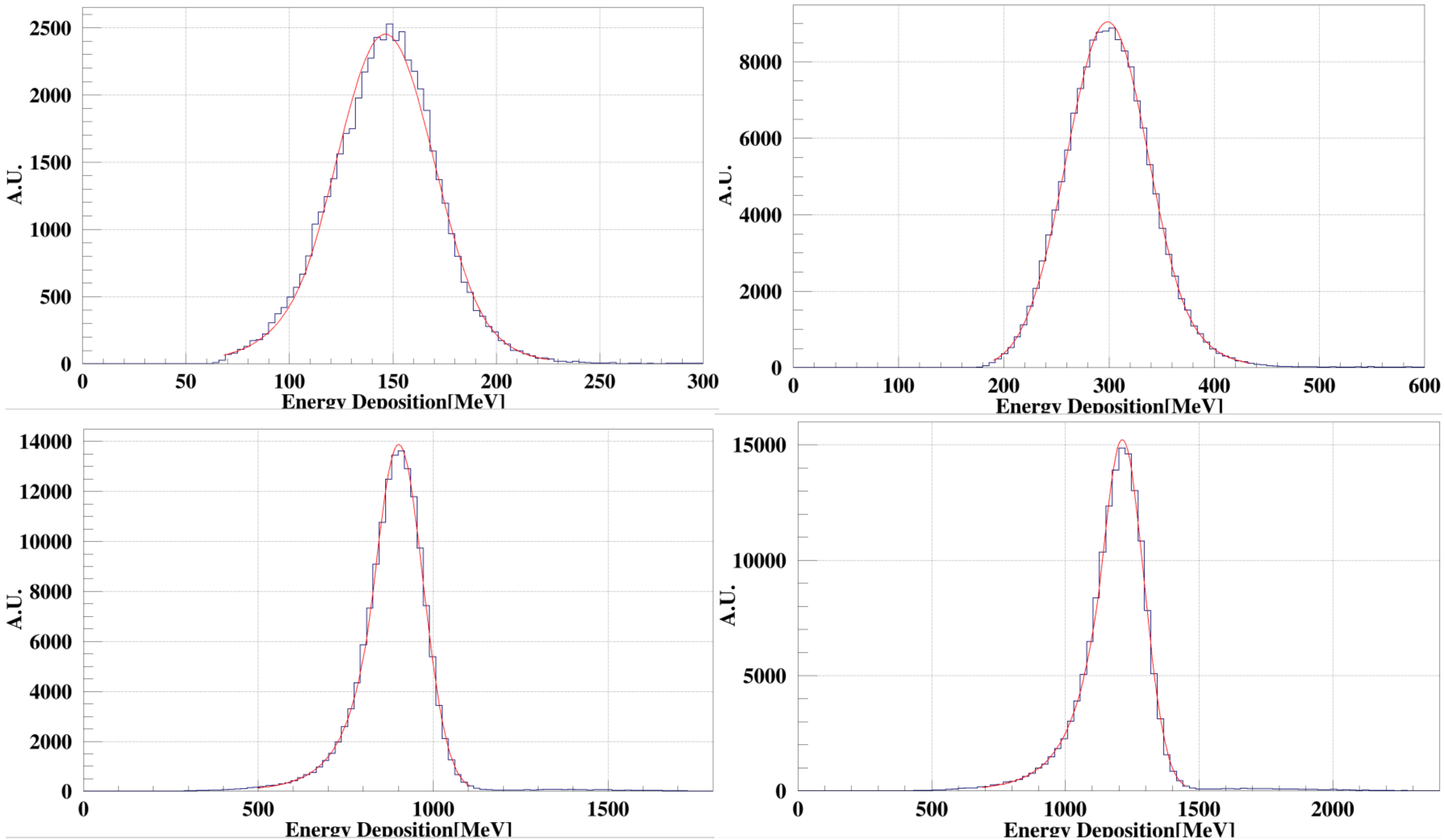


MC before selection:10 and 80 GeV



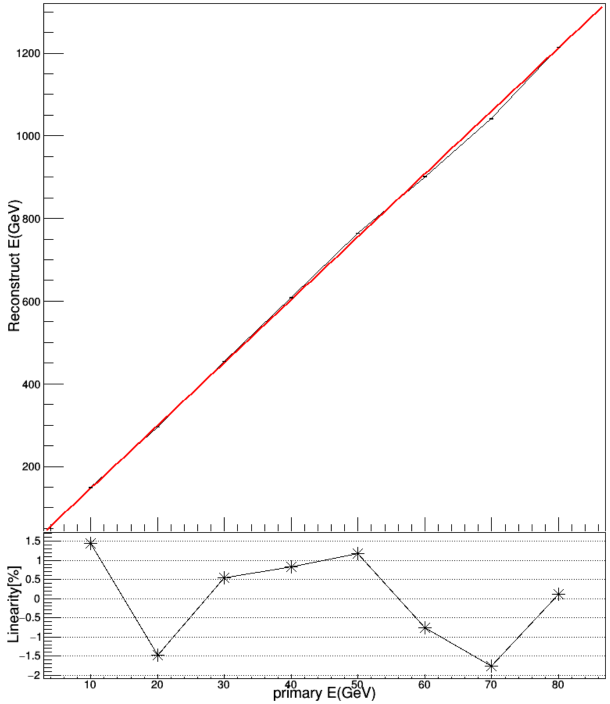
MC after selection:10 and 80 GeV

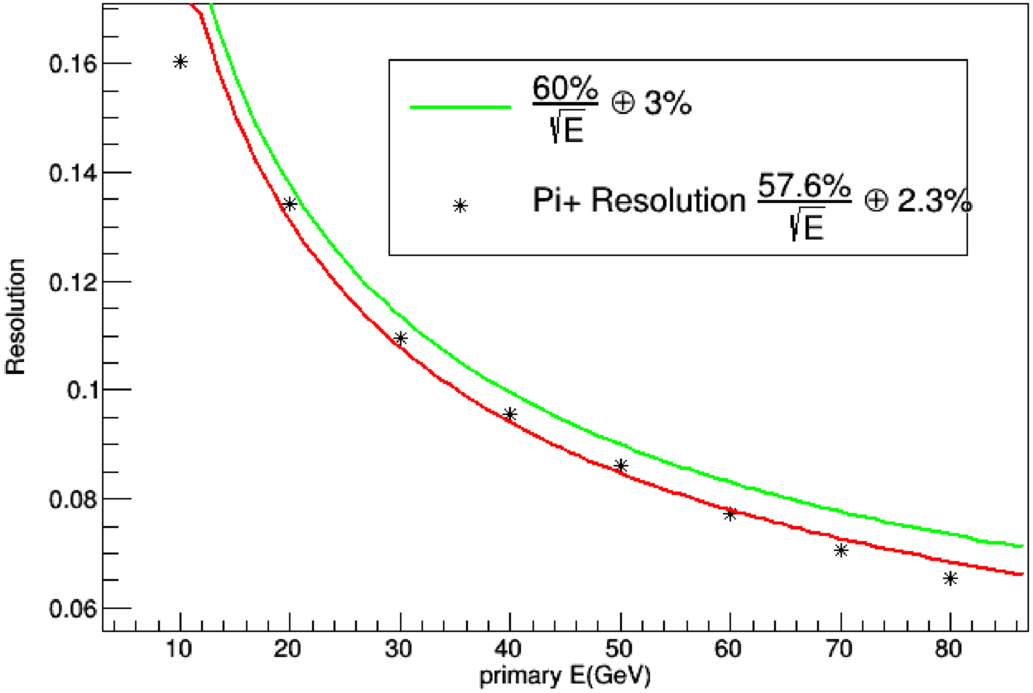
- Crystal ball function is used for fitting



Energy deposition: 10,20,60,80GeV

- The energy linearity is about $\pm 1.5\%$
- The energy resolution is $\frac{57.6\%}{\sqrt{E}} \oplus 2.3\%$





Energy linearity and resolution

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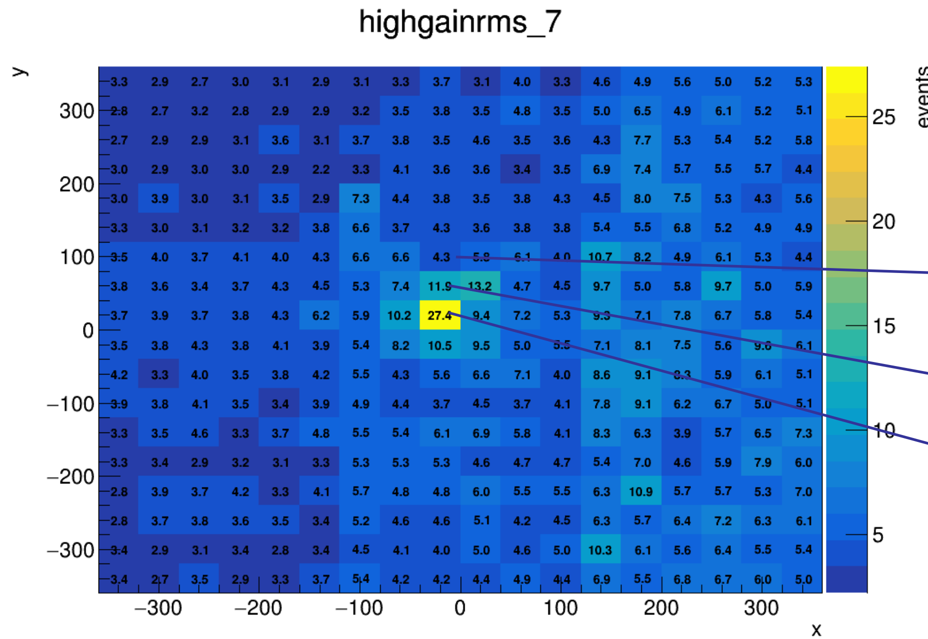
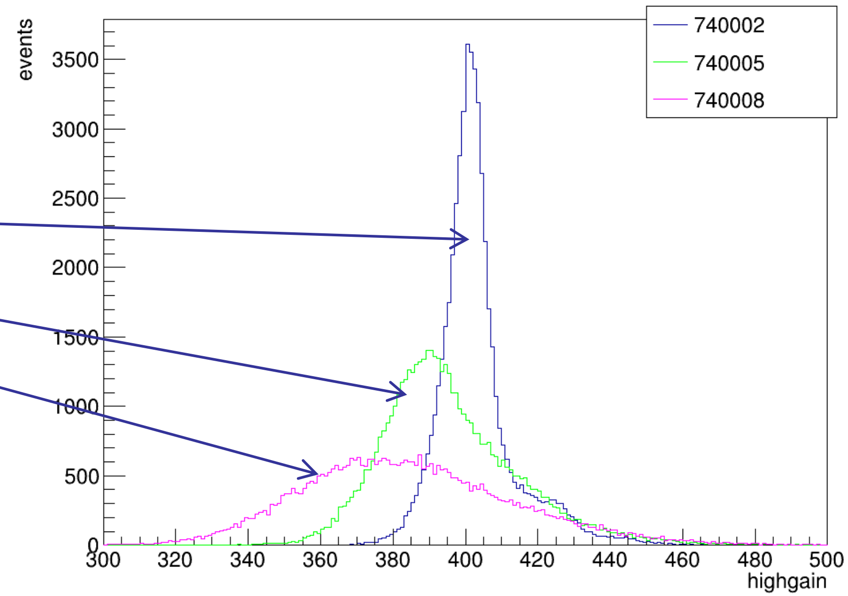
  - 3 beam tests have been done, $\pi^{\pm}$ of 1-120GeV and $e^{\pm}$ of 0.5-250GeV have been collected, muon scanning and electronic calibration was also done during the test
  - Calibration has been done for pedestal, gain ratio and MIP response
  - The HCAL prototype reaches a energy linearity about $\pm$ 1.5% and a energy resolution of $\frac{57.6\%}{\sqrt{E}} \oplus 2.3\%$ for hadron

Back up

High rms channels: observed in both beam and electronic calibration files

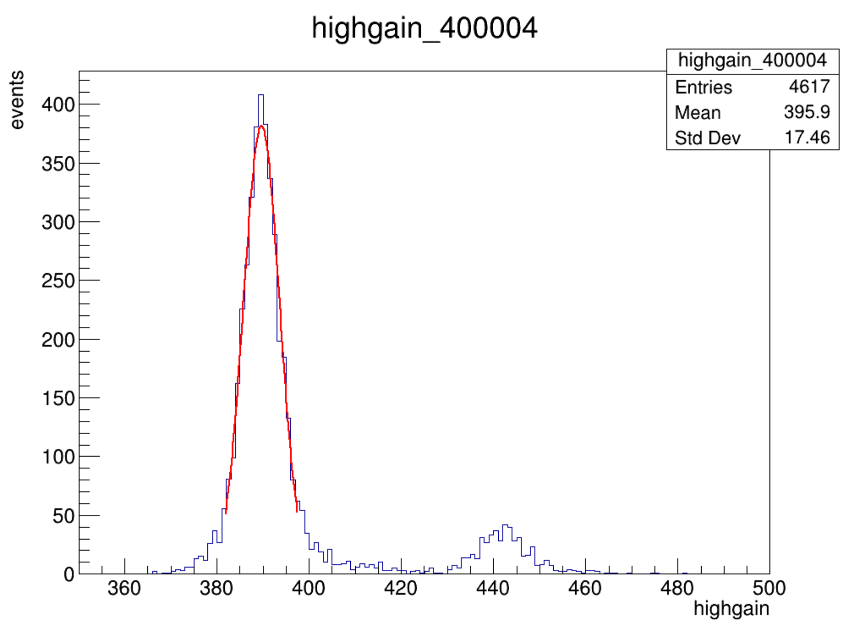


rms of each channel in layer 7

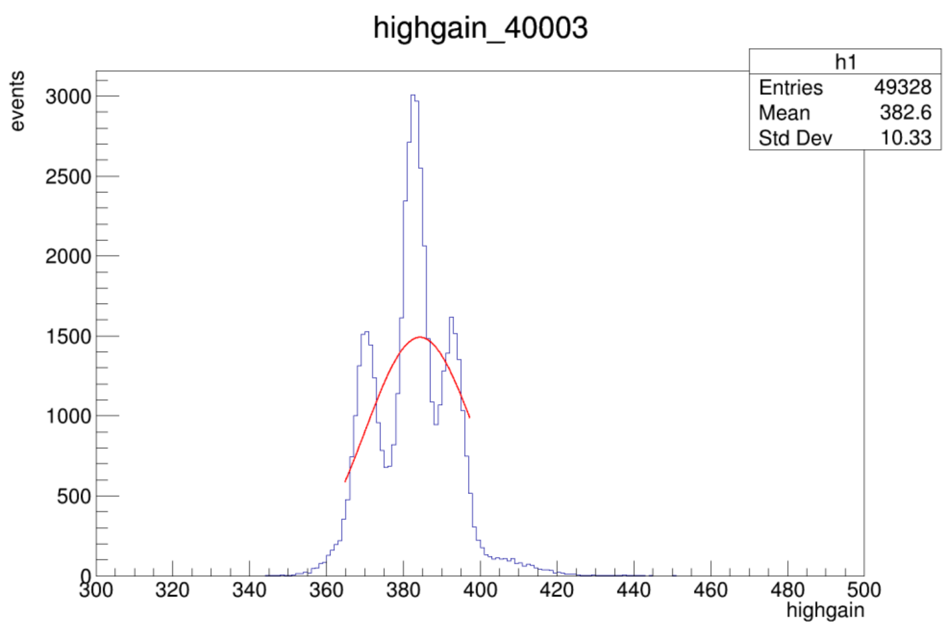


abnormal large rms

- Multi peaks
  - Extra small peak at 440 ADC
  - multiple peaks



extra small peak

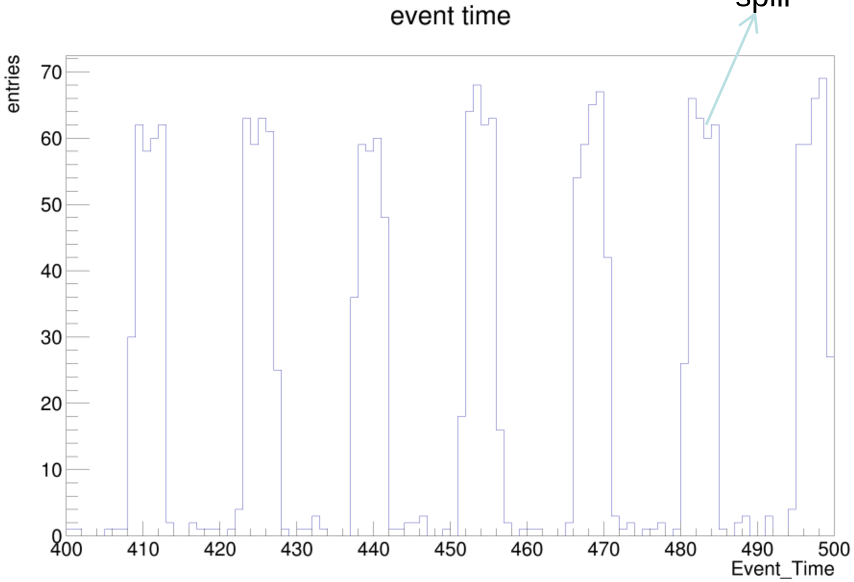


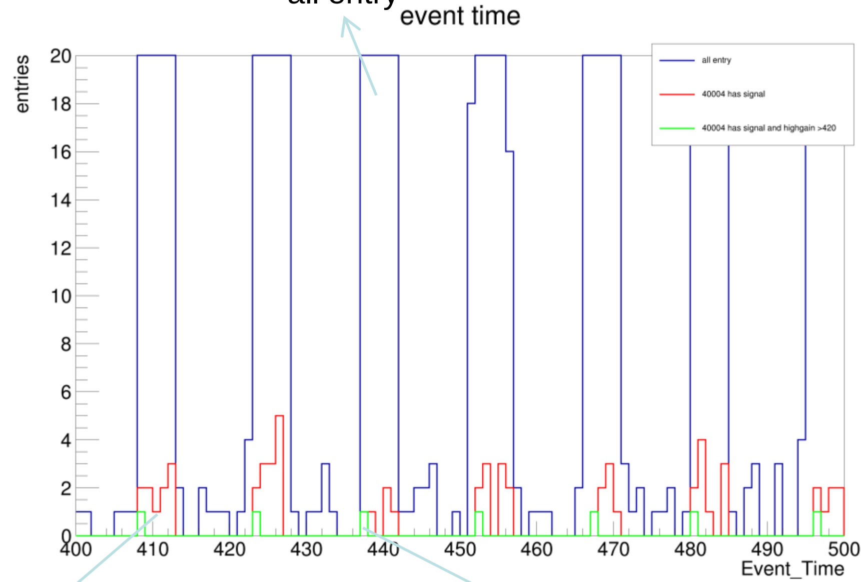
multiple peaks

- Event time dependence
  - The extra small peaks are mainly in the beginning of each spill

spill

all entry



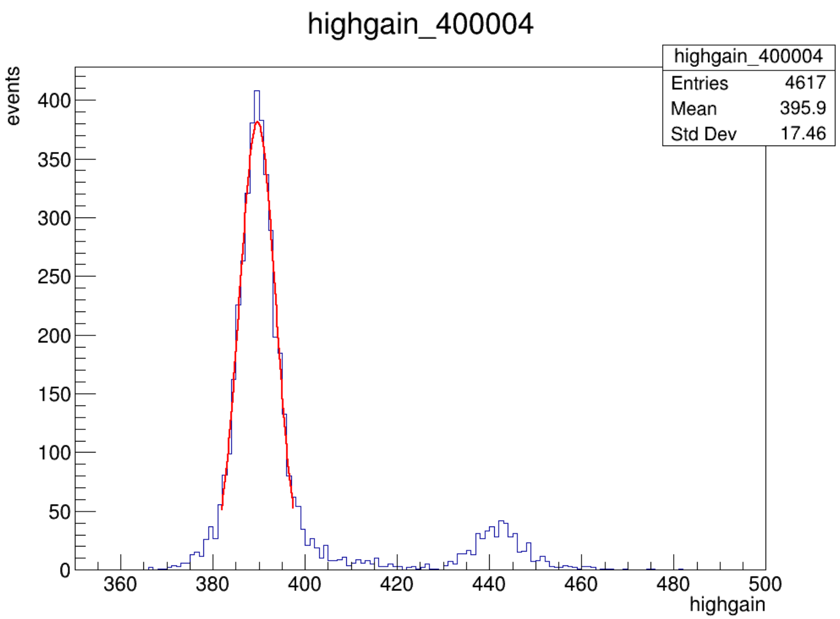


all entry

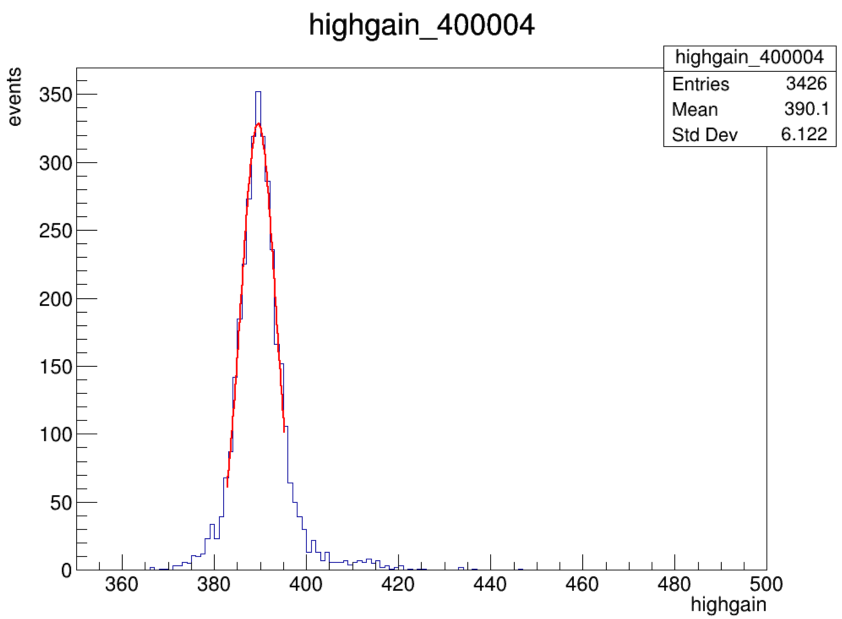
entry that 40004 has signal

entry that 40004 has signal and signal > 420

Extra small peak --good correction

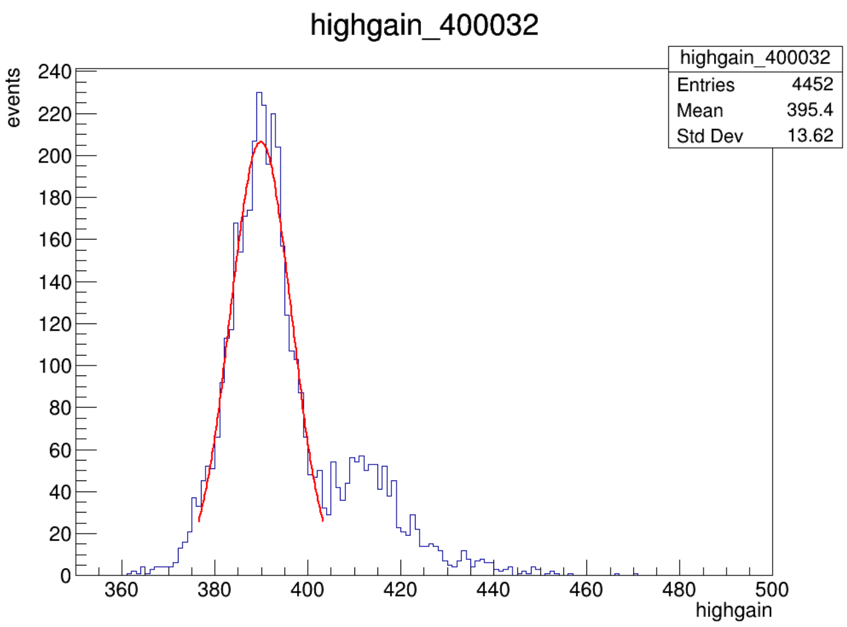


all entry

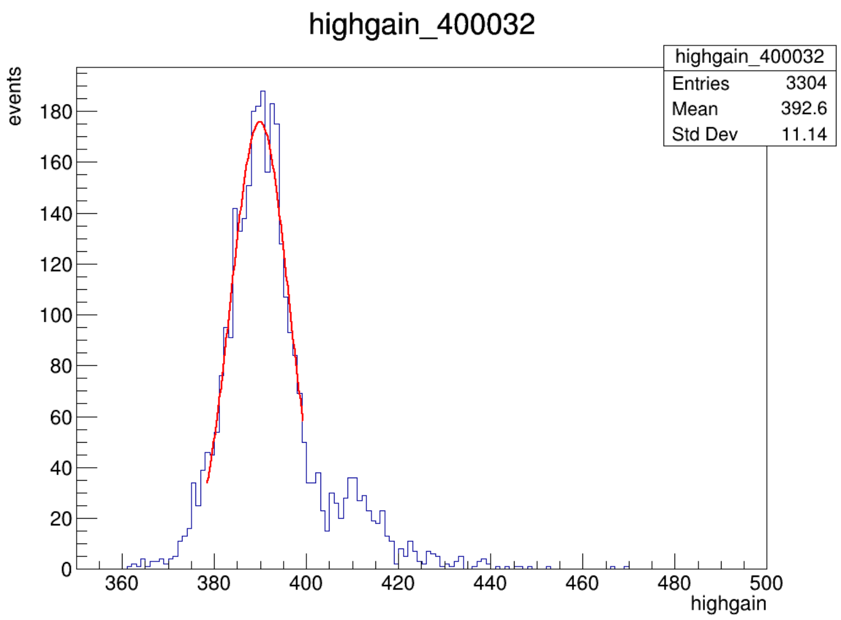


remove the first entry of every chip of every spill

Extra small peak --bad correction



all entry



remove the first entry of every chip of every spill

This correction doesn't work for the multi peaks situation

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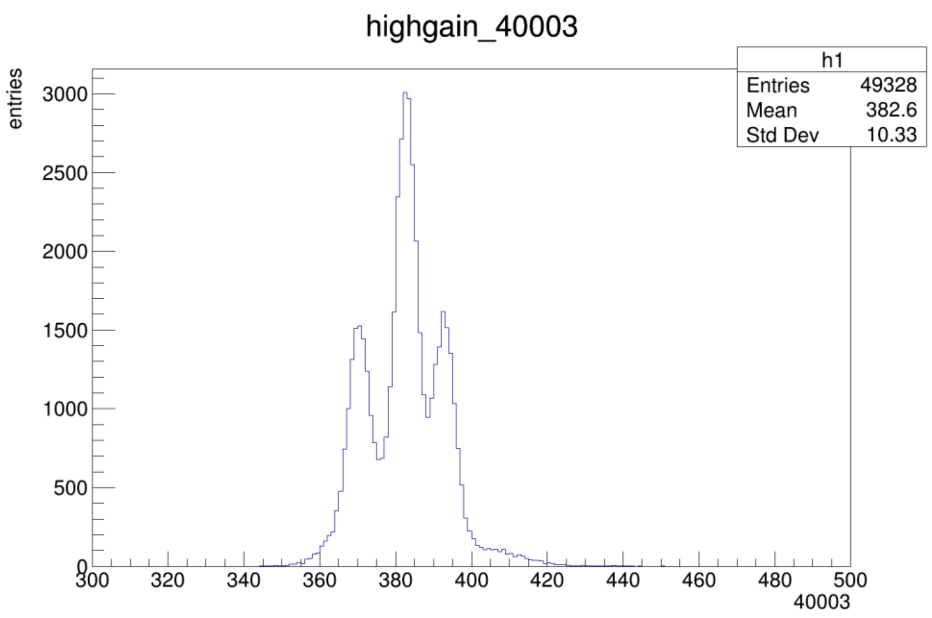
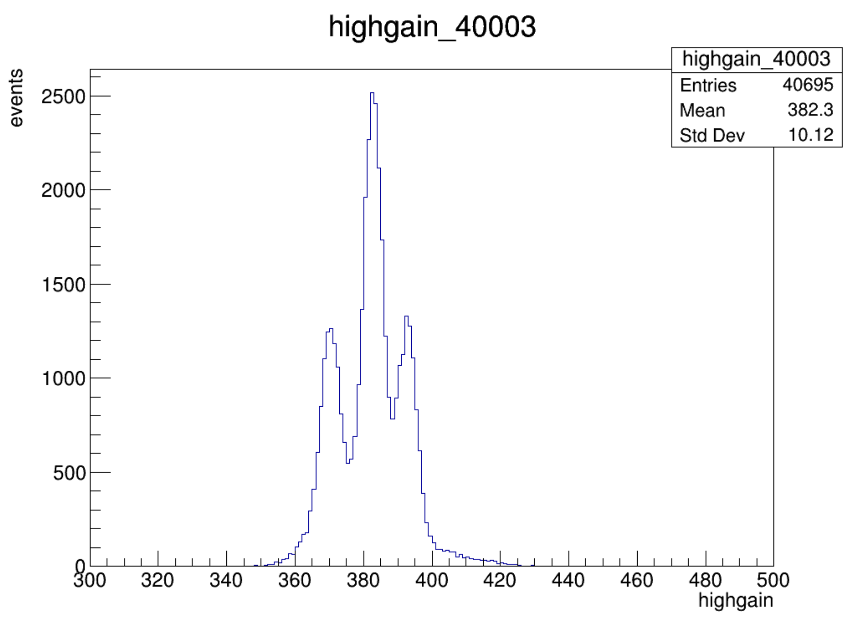
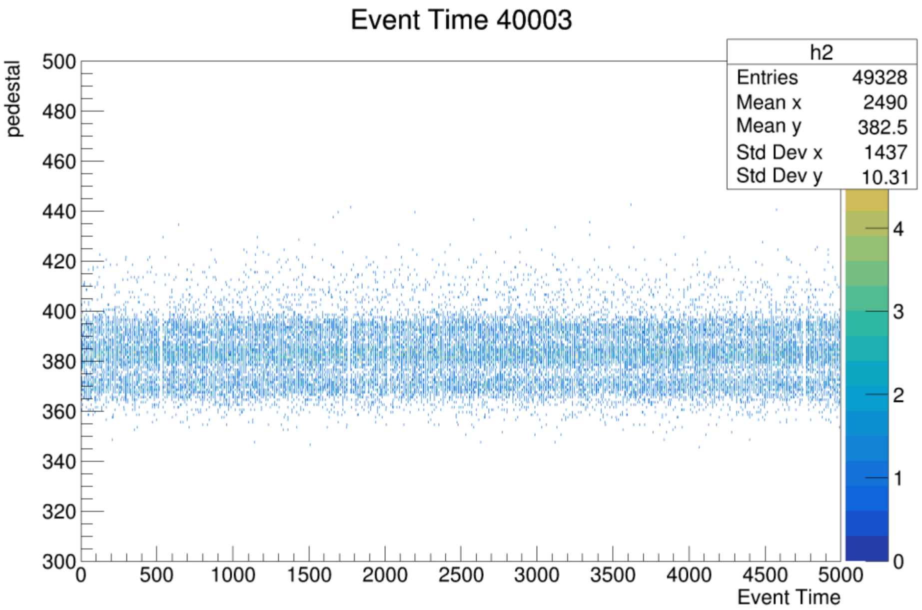
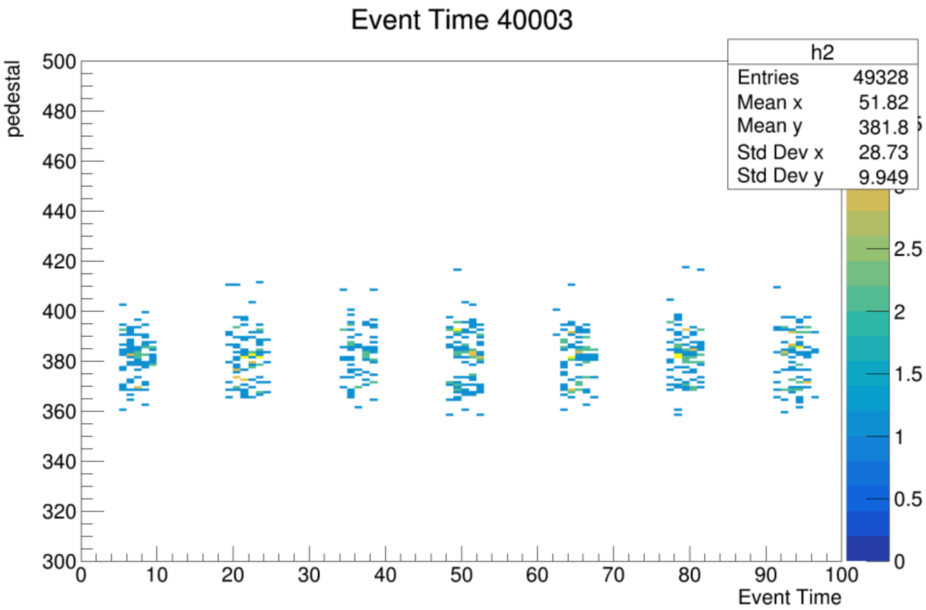
- Multi peak is introduced by the cross talk between channels





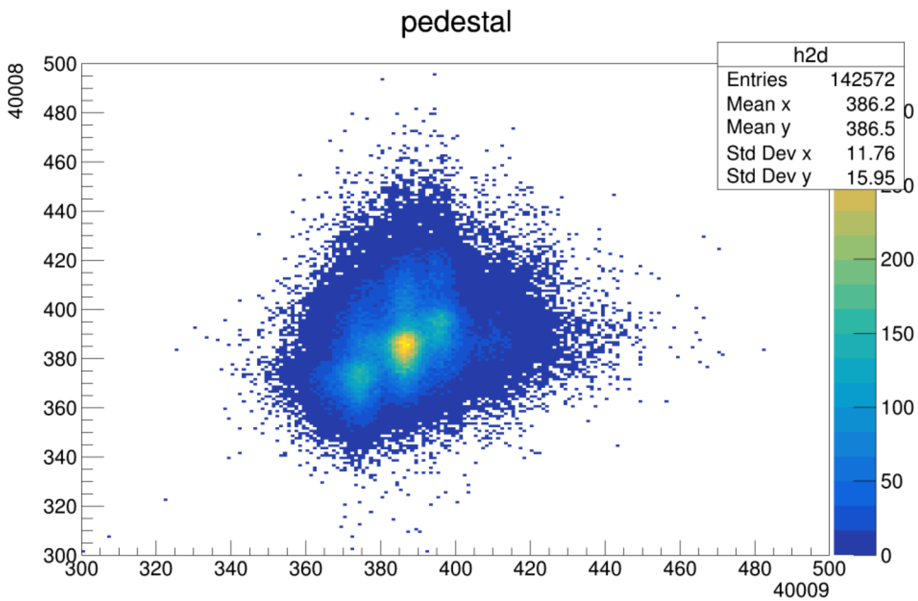
Event time dependence



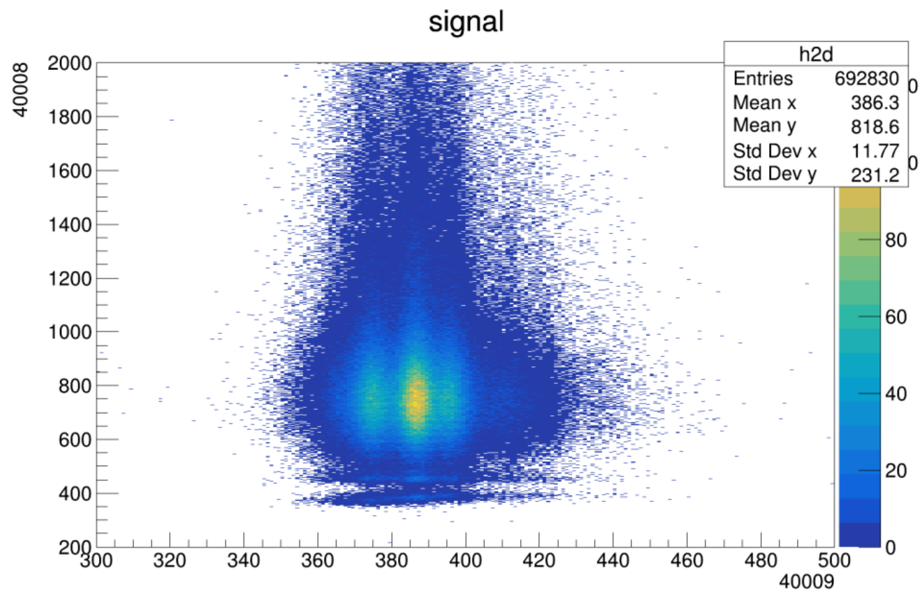


multiple peaks is independent of time

- Channel correlation
  - Pion data
  - The multi peak phenomena has channel correlation



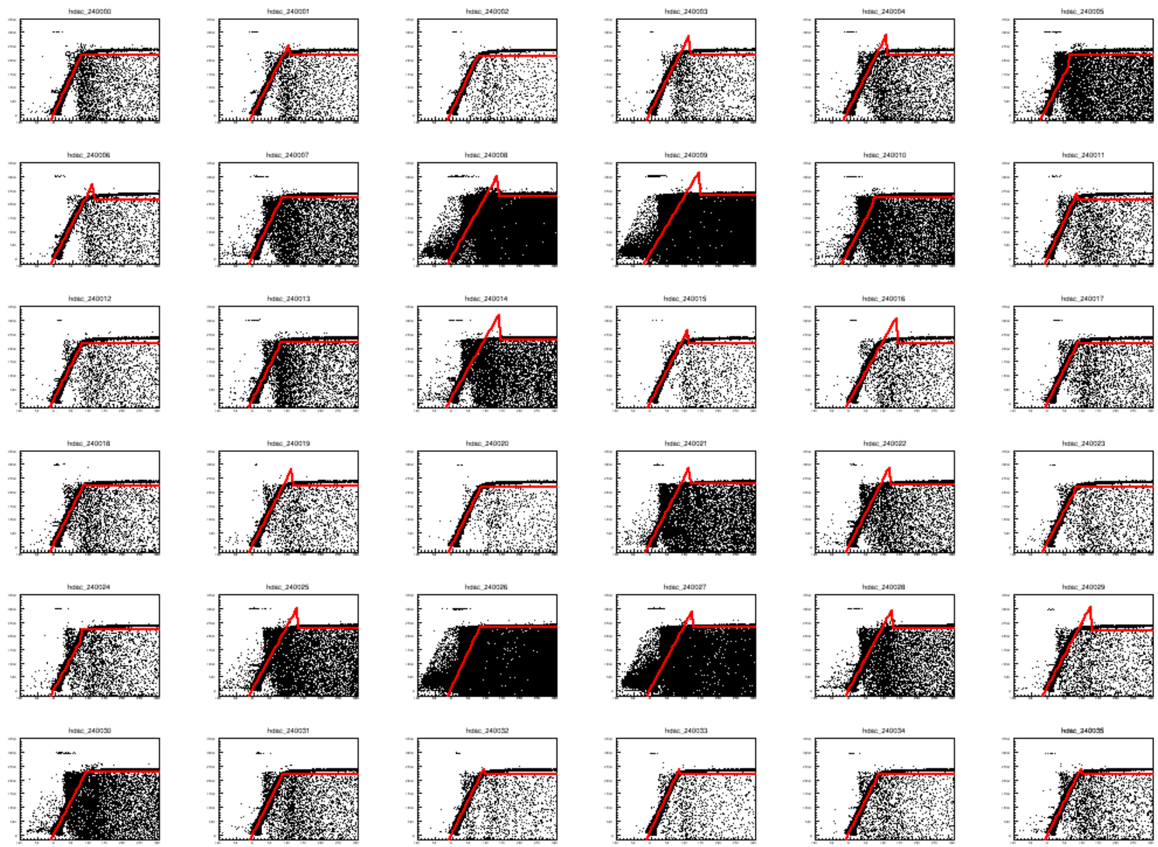
hitTag=0



hitTag=1 vs. hitTag=0

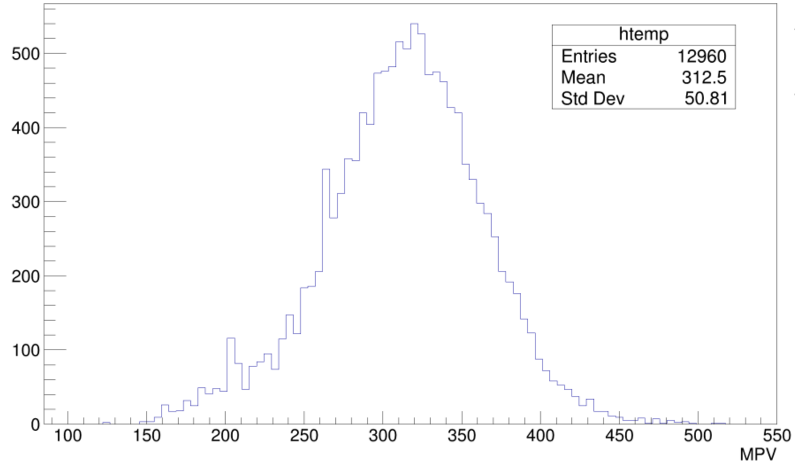
Gain ratio

- Some channels have abnormal performance
- Abnormal channel is recorded and a typical value of gain ratio and platform is set as the parameter of this channel

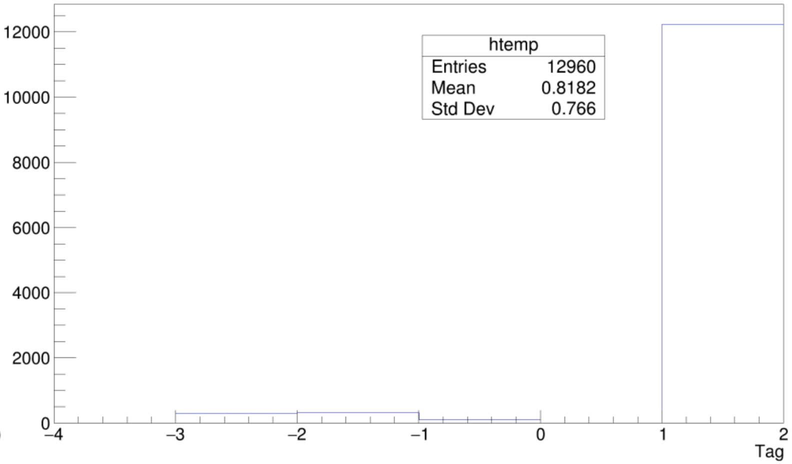


Channel selection

- Selection Criteria
  - Entries>700
  - χ^2/NDF < 20
  - 200<MPV<400 || $|MPV_{channel} - MPV_{chip}|$<80
  - 20<Landau Width<100
  - 10<Gauss Sigma<150
- Channels fail the selection will use chip MPV
- Tag: 1 for normal; -1 for abnormal chips; -2 for inadequate statistics; -3 for abnormal fitting



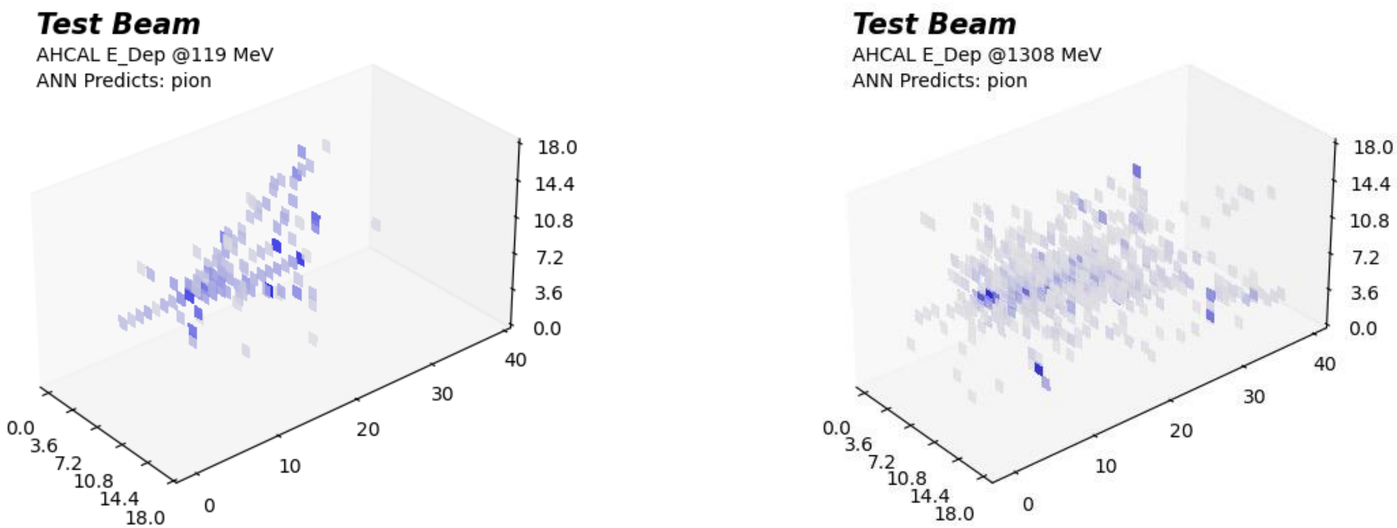
MPV



Tag

Selection and PID

- HCAL alone pi- data taken in 2023 SPS is used to see the basic performance of HCAL
- Pi- energy from 10 to 80 GeV is analyzed
- Pi- MC is also generated for analysis



event display: 10GeV and 80 GeV pi-

PRL 112, 012001 (2014) PHYSICAL REVIEW LETTERS week ending 10 JANUARY 2014

Fractal Dimension of Particle Showers Measured in a Highly Granular Calorimeter

Manqi Ruan,[1,2,*] Daniel Jeans,[1,3] Vincent Boudry,[1] Jean-Claude Brient,[1] and Henri Videau[1]
[1]Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, Palaiseau, France
[2]Institute of High Energy Physics, Beijing 100049, China
[3]Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
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We explore the fractal nature of particle showers using Monte Carlo simulation. We define the fractal dimension of showers measured in a high granularity calorimeter designed for a future lepton collider. The shower fractal dimension reveals detailed information of the spatial configuration of the shower. It is found to be characteristic of the type of interaction and highly sensitive to the nature of the incident particle. Using the shower fractal dimension, we demonstrate a particle identification algorithm that can efficiently separate electromagnetic showers, hadronic showers, and nonshowering tracks. We also find a logarithmic dependence of the shower fractal dimension on the particle energy.

DOI: 10.1103/PhysRevLett.112.012001 PACS numbers: 13.85.-t, 07.20.Fw, 13.40.-f

Introduction.—When an energetic particle impinges on matter, it may interact and produce daughter particles, which may themselves interact. This process iterates while daughter particles have sufficient energy. The resulting particle cascade is called a shower [1,2]. A profound understanding of particle showers, a fundamental phenomenon of particle-matter interactions, is crucial for experimental high energy physics, astrophysics, radiation protection, and radiotherapy.

Showers can be classified into electromagnetic and hadronic types. The development of electromagnetic showers is governed by e^+e^- pair-production and bremsstrahlung interactions. Hadronic showers are composed of long hadron tracks and localized clusters produced in π^0 decay ($\pi^0 \to \gamma\gamma$) or nuclear breakup [3]. The strong interactions between nuclei and hadrons, particularly pion generation, determine the development of hadronic showers. The typical spatial configurations of these two shower types are illustrated in Fig. 1.

These cascade mechanisms give rise to the fractal nature of particle showers. The fractal structure of high energy cosmic showers in the atmosphere has been previously studied [4–6]. In this Letter, we explore for the first time the fractal nature of particle showers produced and measured in a calorimeter. This calorimeter is designed for high energy physics experiments with ultrahigh granularity. We observe a strong dependence of the number of hits obtained when the effective granularity of the calorimeter readout is varied, from which we define the shower fractal dimension. We investigate the dependence of the shower fractal dimension on the type and energy of the incident particle, and demonstrate a particle identification algorithm based only on measurements made with the calorimeter.

Method and measurement.—The detector used in this study is a hadron calorimeter designed for a future e^+e^- linear collider [7,8]. The calorimeter structure follows the geometry of the barrel hadron calorimeter (HCAL) of the International Large Detector [9]. Prototypes of such as HCAL have been developed by the CALICE collaboration [10,11]. The calorimeter consists of 48 layers of 20 mm thick iron absorbers, interleaved with 6.5 mm thick resistive plate chambers (RPCs). In the CALICE prototypes, the RPCs are read out in binary mode with a granularity of 10×10 mm^2. Such high granularity is required by particle flow algorithms, which can achieve excellent jet energy resolution by separating the individual particles in a jet and measuring them in the most suited subdetectors. It also

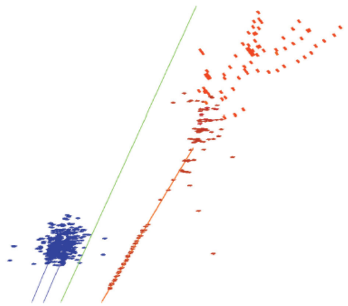
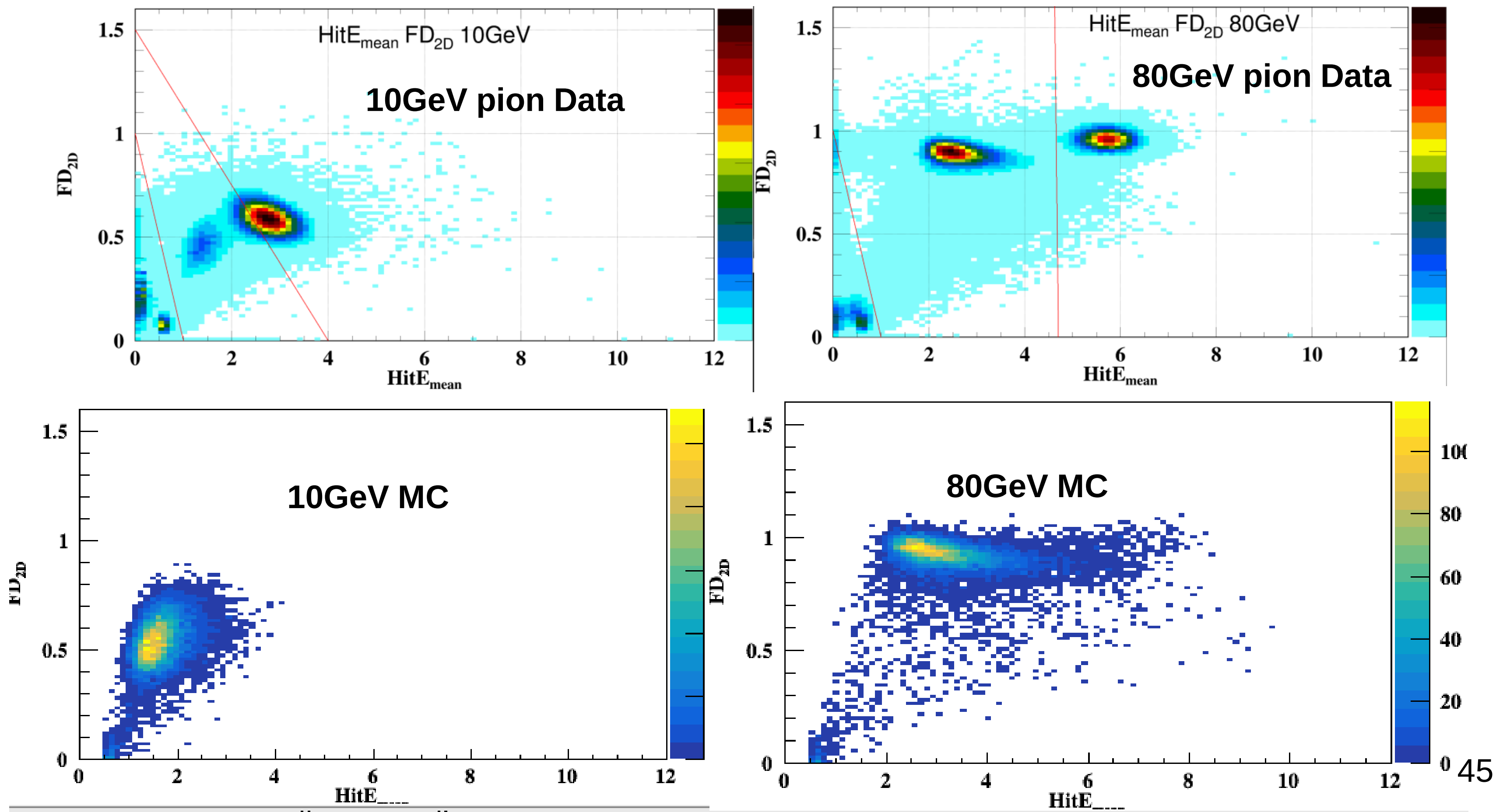


FIG. 1. A simulated $\tau^+ \to 2\gamma(\pi^0) + \pi^+ + \bar{\nu}_\tau$ event in a linear collider calorimeter. Photons and their showers (electromagnetic) are colored blue, π^+ and its shower (hadronic) are colored red. The green line indicates the neutrino trajectory, which roughly corresponds to the direction of τ^+. The detector hits are displayed according to their size (10×10 mm^2) and orientation.

Selection and PID

- A potential bias will be introduced to the data with the PID selection



Selection and PID

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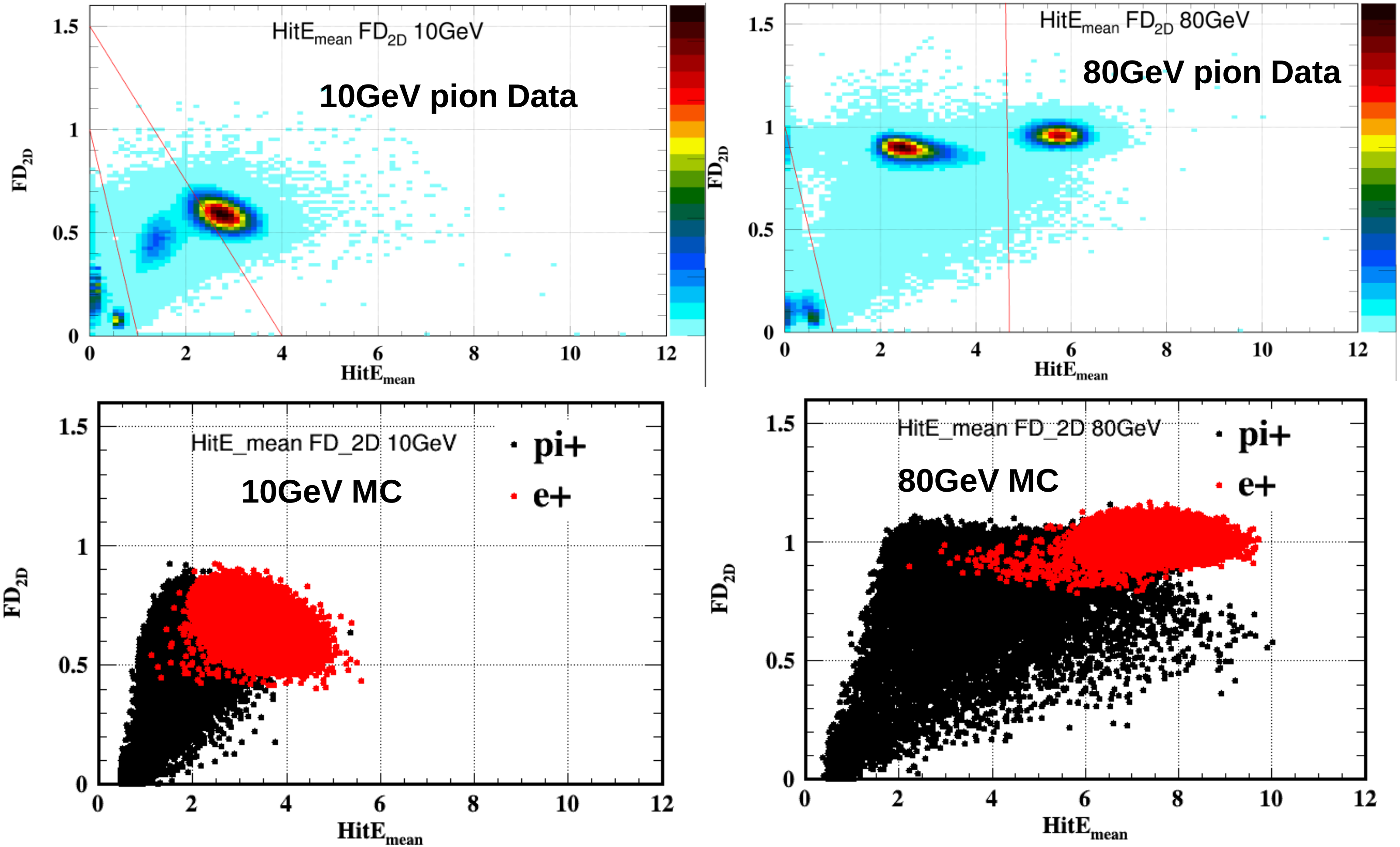
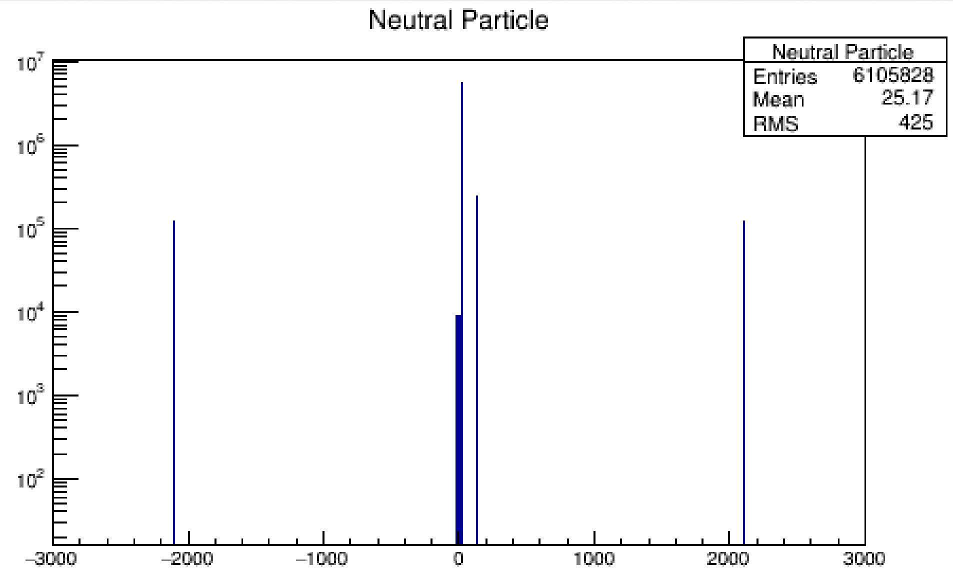
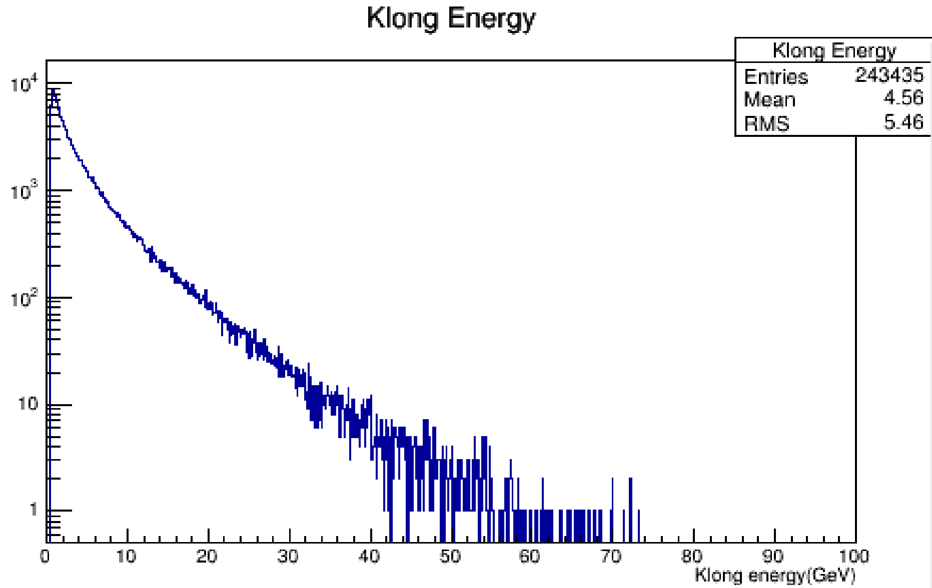
- A potential bias will be introduced to the data with the PID selection

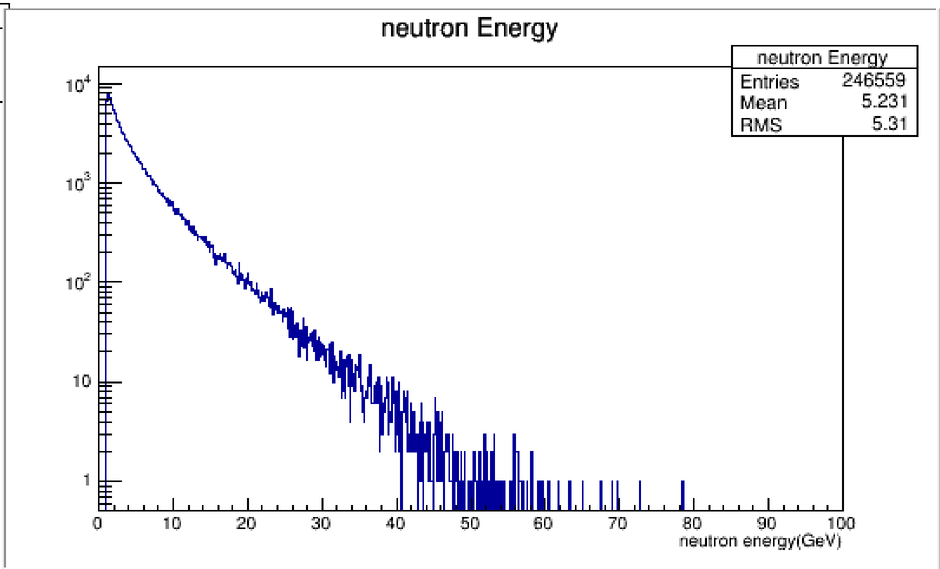


H->gg events

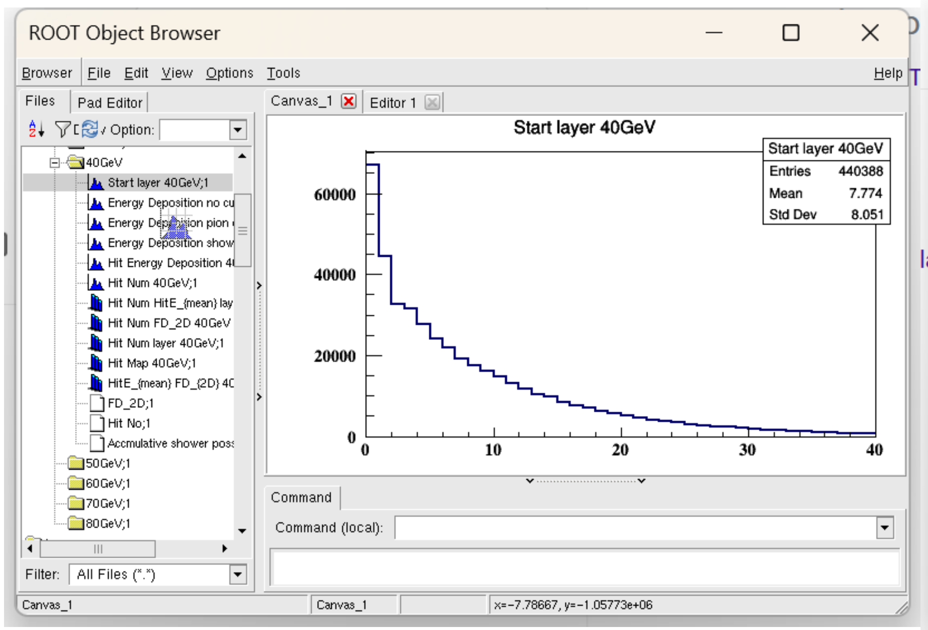
- Neutral Hadron mainly consists of Klong,neutron
- The single neutral Hadron energy < 100GeV
- HCAL should have good response to 0.5MIP-60GeV Hadron







Start layer


ROOT Object Browser
Start layer 40GeV
Start layer 40GeV
Entries 440388
Mean 7.774
Std Dev 8.051
60000
40000
20000
0
0
10
20
30
40

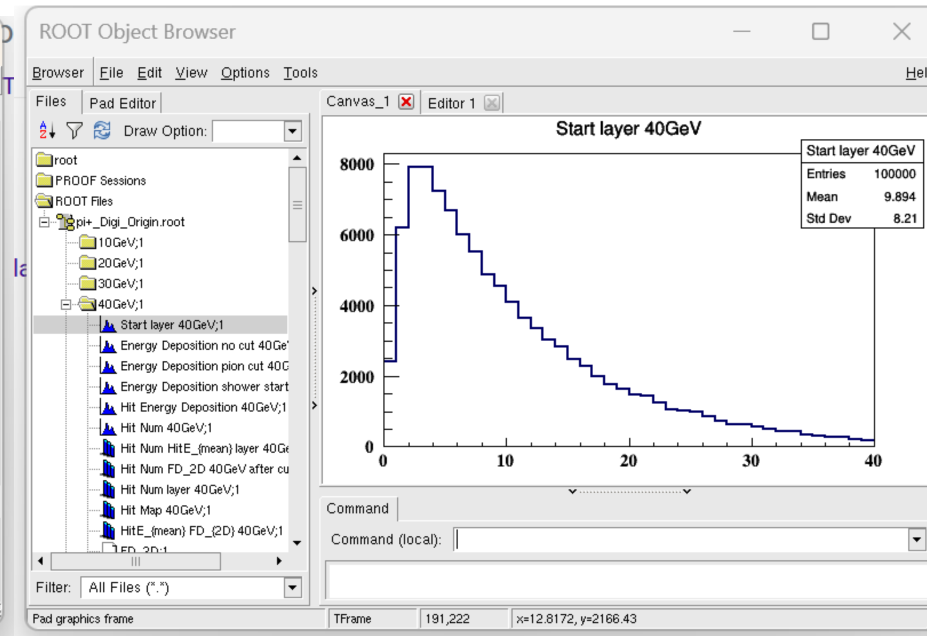
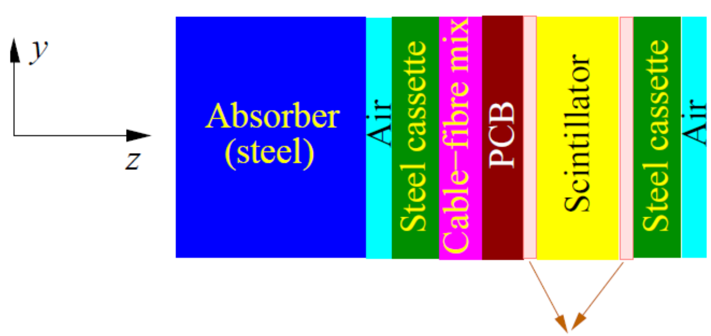

ROOT Object Browser
Start layer 40GeV
Start layer 40GeV
Entries 100000
Mean 9.894
Std Dev 8.21
8000
6000
4000
2000
0
0
10
20
30
40

Table 1. Composition and properties of the absorber (cassette) plates and materials used in a cassette of one AHCAL layer [14], where ρ, R_M and f respectively denote the density, Molière radius and fraction of components in composite materials (steel, PCB boards and cables) while other quantities are defined in the text.

material	ρ [g/cm^3]	λ_π [cm]	λ_π/ρ [g/cm^2]	λ_n [cm]	λ_n/ρ [g/cm^2]	X_0 [cm]	X_0/ρ [g/cm^2]	R_M [cm]	f [%]
Fe	7.87	20.4	160.8	16.8	132.1	1.76	13.8	1.72	98.34
Mn	7.44	21.5	160.2	17.7	131.4	1.97	14.6	1.85	1.4
C	2.27	52.0	117.8	37.9	85.8	18.9	42.7	4.89	0.17
S	2.0	70.9	141.7	56.2	112.4	9.75	19.5	5.77	0.045
P	2.2	64.0	140.7	50.6	111.4	9.64	21.2	5.39	0.045
steel	7.86	20.5	160.8	16.8	132.1	1.76	13.9	1.72	100
tile	1.06	107.2	113.7	77.1	81.7	41.3	43.8	9.41	100
Si	2.33	59.1	137.7	46.5	108.4	9.37	40.2	4.94	18.1
O		106.8	121.9	79.0	90.2	30.01	34.2	9.52	40.6
C	2.27	52.0	117.8	37.9	85.8	18.9	42.7	4.89	27.8
H		1134	80.3	734.6	52.0	890.4	63.0	67.92	6.8
Br	3.1	56.6	175.5	47.5	147.2	3.68	11.4	4.52	6.7
FR4	1.7	71.4	121.4	52.6	89.45	17.5	29.8	6.06	100
3M foil	1.06	107.2	113.7	77.1	81.7	41.3	43.8	9.41	100
PVC	1.3	98.9	128.5	74.6	97.0	19.6	25.5	8.34	87.2
polystyr.	1.06	107.2	113.7	77.1	81.7	41.3	43.8	9.41	11.9
Cable	1.35	93.7	126.5	70.2	94.8	19.9	26.9	7.95	100
air		101k	122	74.8k	90.1	30.4k	36.6	7.3k	0.9



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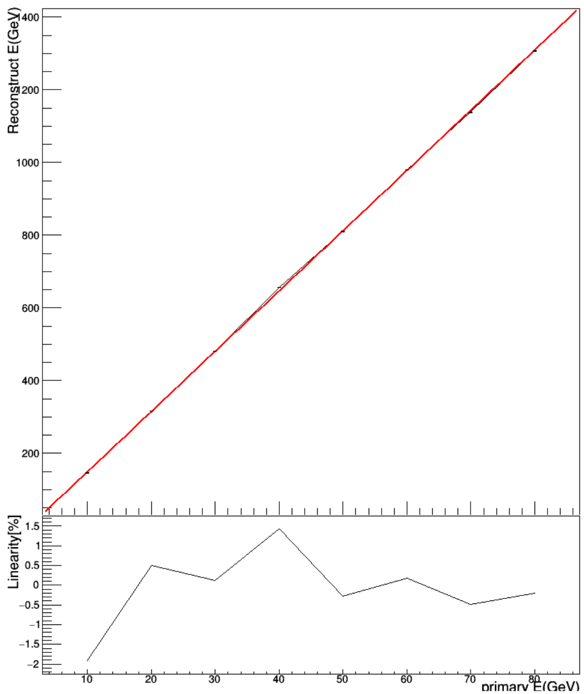
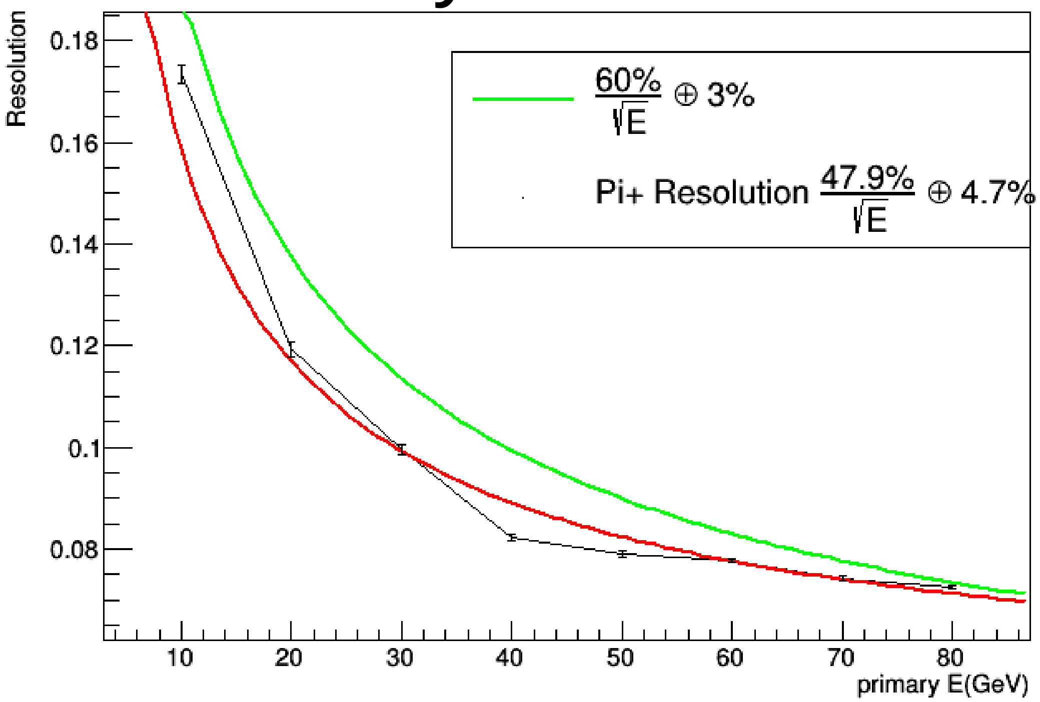
Calibration V2

- Tight cut is applied to calibrated pion V2 data
- The resolution is obviously better





Selection and PID

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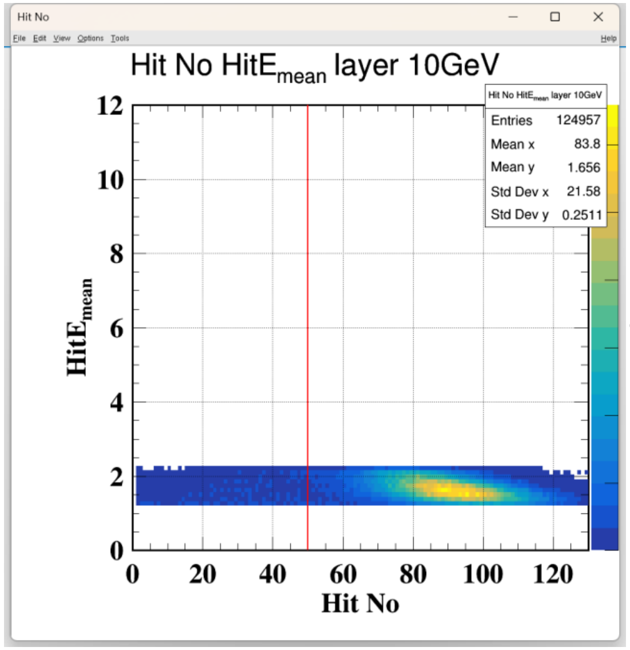
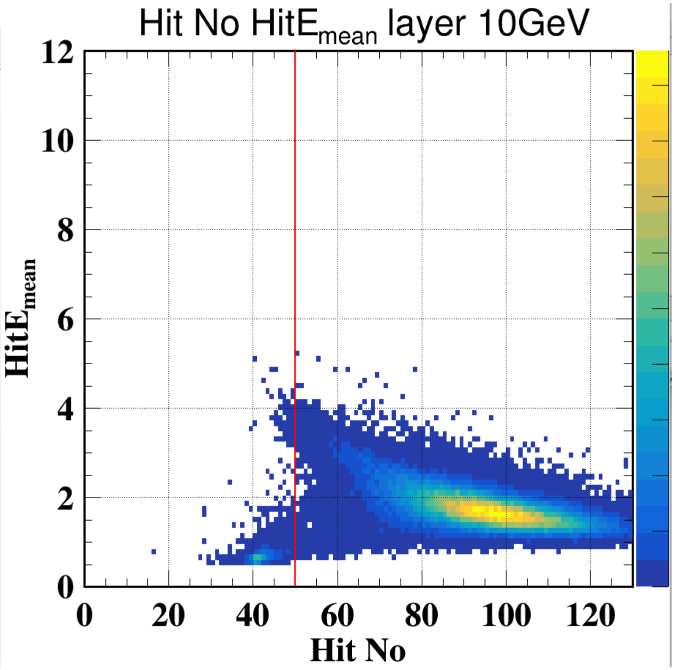
- Leakage cut is applied to pion data and MC
  - Start layer
    - The first layer with more than 4hits is defined as the shower start layer
    - The start layer<5
  - Hit no
    - Different hit no cut is applied for different energy point





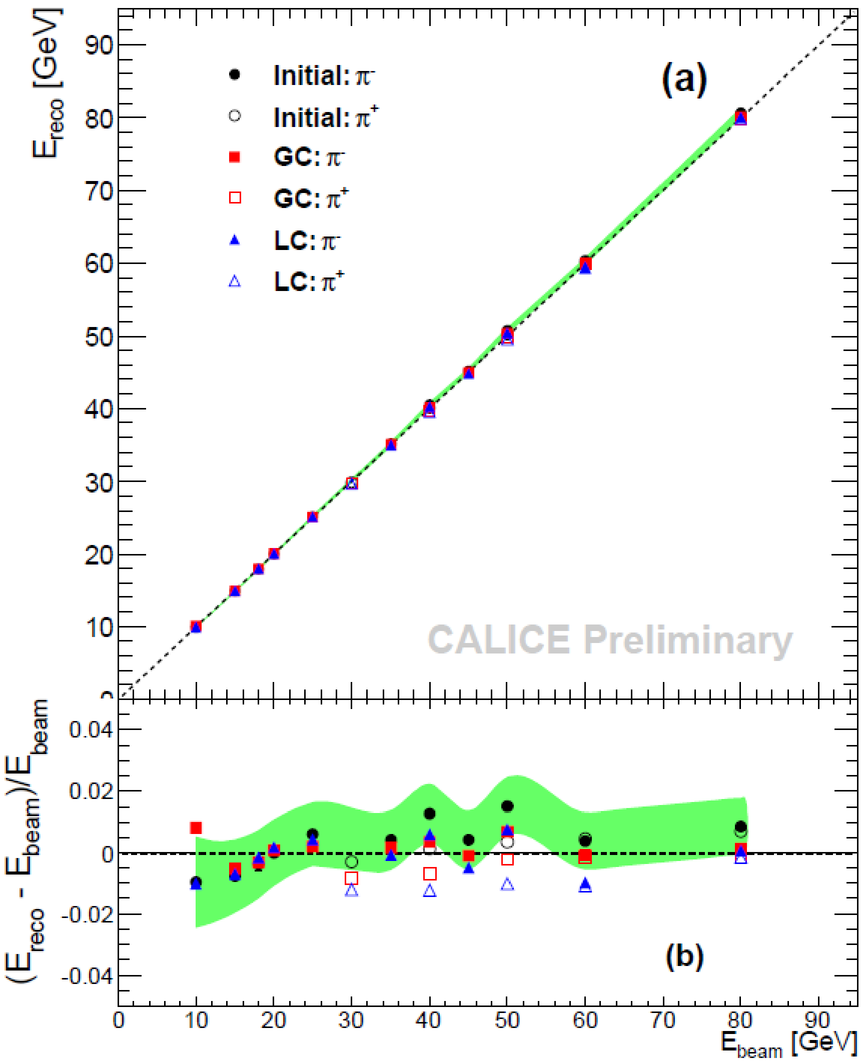
Hit No vs Hit E mean: 10GeV data and MC

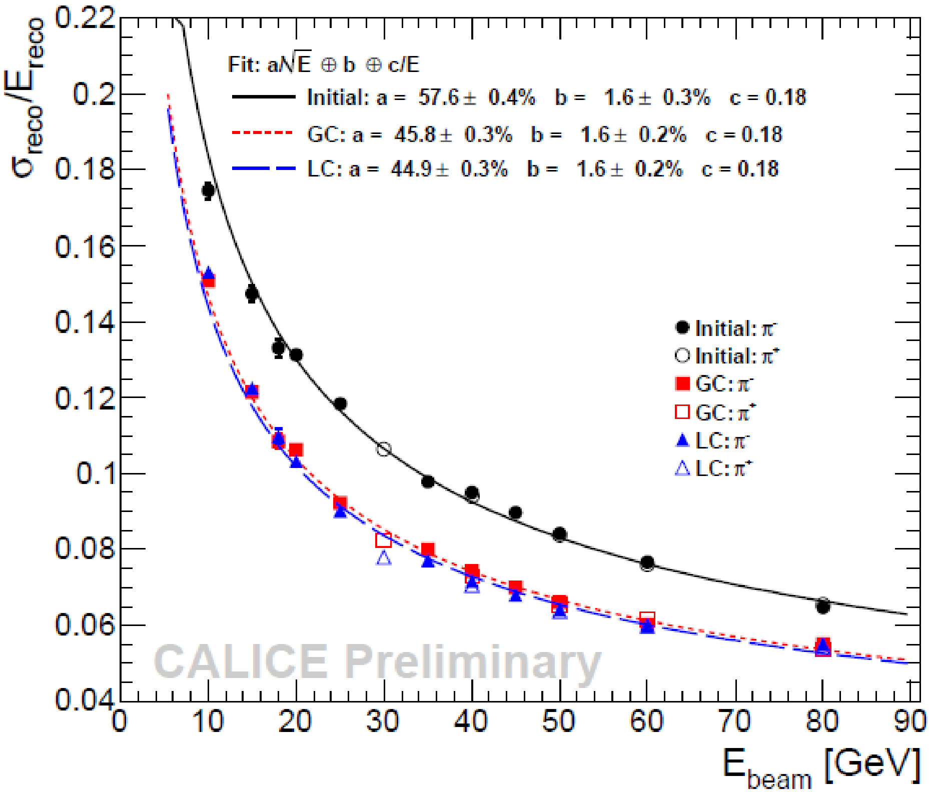
CALICE efficiency

particle type	beam energy [GeV]	all pions	selected pions
π^-	10	440208	84706
π^-	15	127554	24997
π^-	18	52880	10492
π^-	20	342798	67093
π^-	25	201243	39631
π^-	35	272987	54126
π^-	40	472345	93301
π^-	45	325092	63547
π^-	50	304023	59076
π^-	60	647090	121588
π^-	80	741440	139248
π^+	30	155210	30884
π^+	40	307177	60595
π^+	50	159414	30843
π^+	60	449273	86947
π^+	80	272441	52442

Table 1. Summary of the data samples. The total number of pions is the number of events classified as pions, after rejection of empty, noisy and double particle events, and the application of muon rejection and particle identification cuts. The number of selected pions are the events with an identified shower start in the first five layers of the AHCAL, which are used in the present analysis. For most energies, several run periods at different temperatures are combined to maximise statistics.

CALICE AHCAL





Linearity and energy resolution

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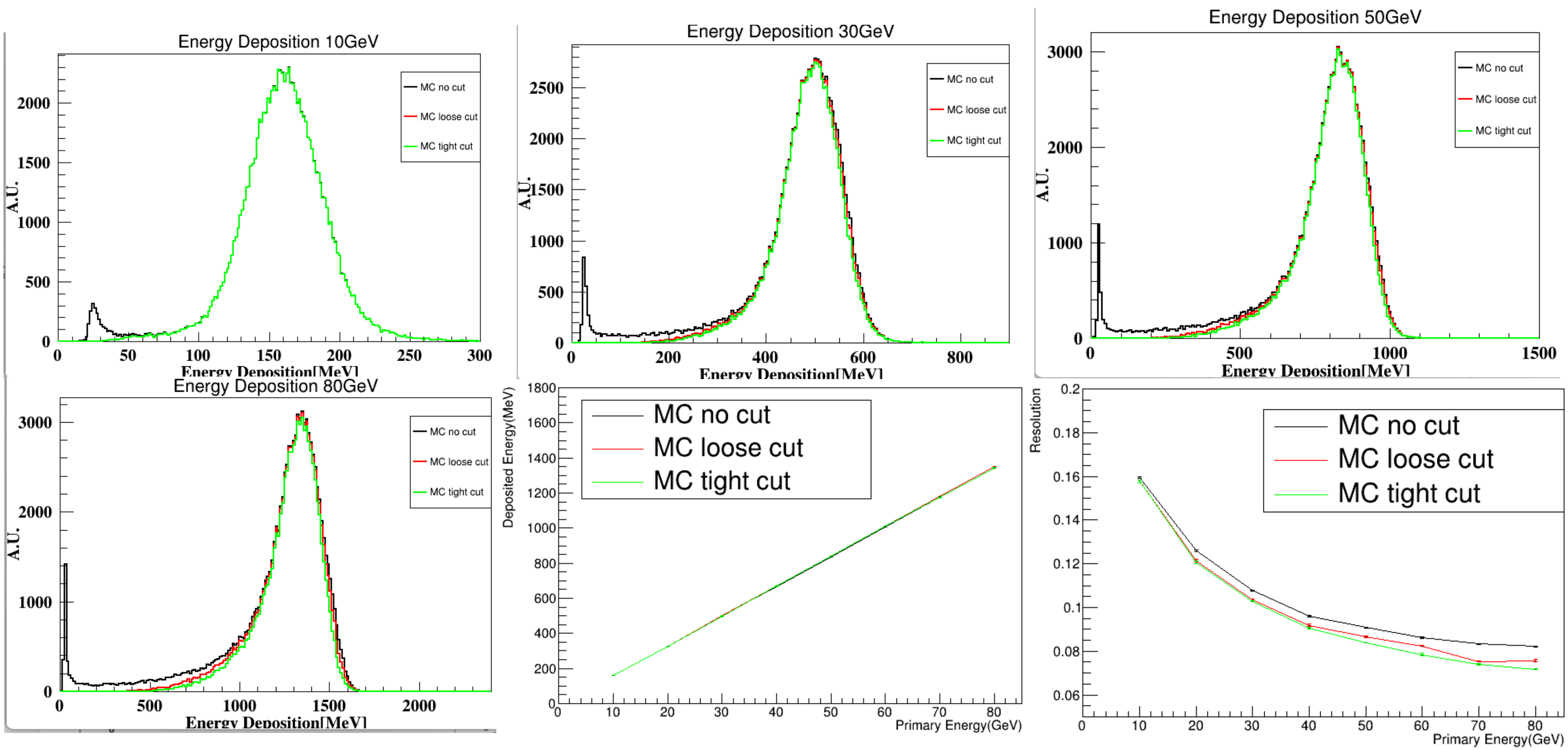
- Leakage cut has no visible influence on the linearity



Linearity and energy resolution

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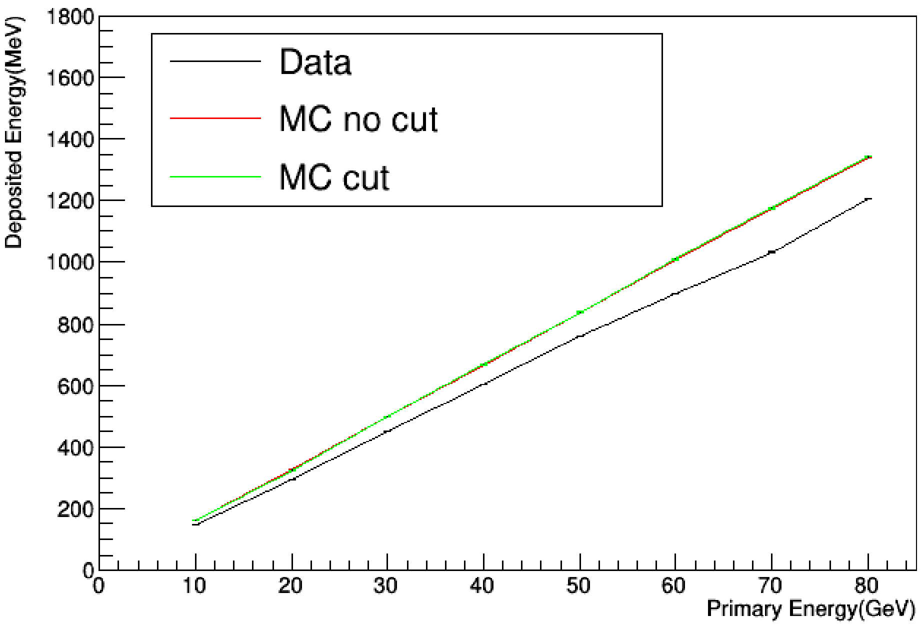
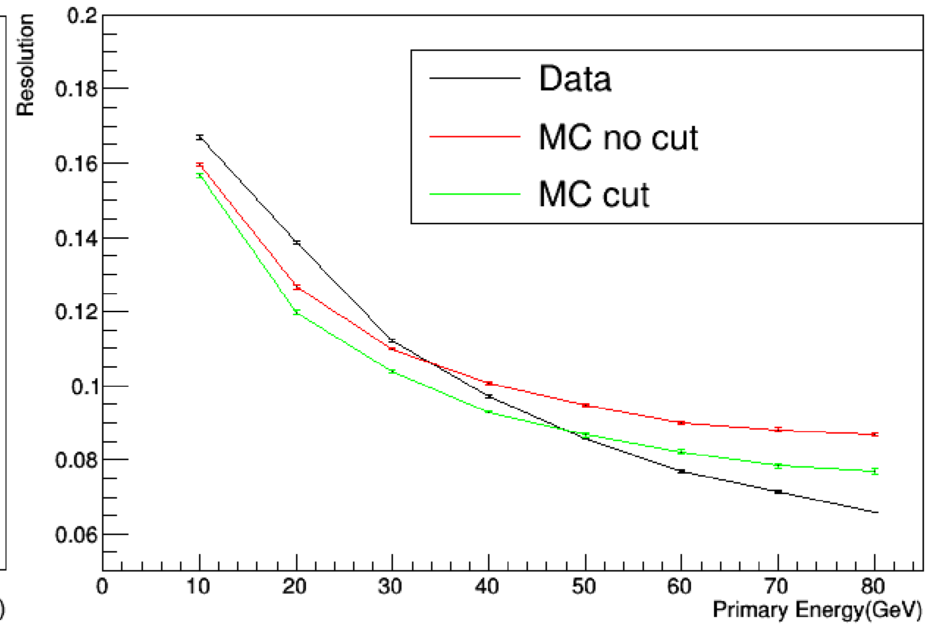
- The cut still introduces bias to the MC and makes the resolution better, but it doesn't have obvious impact on the linearity
- There is still obvious difference between Data and MC

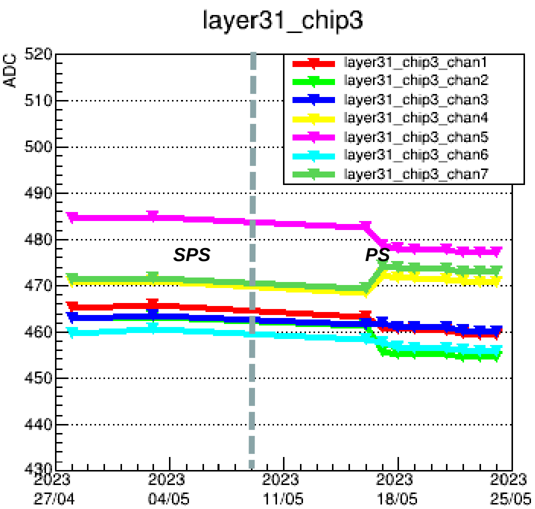




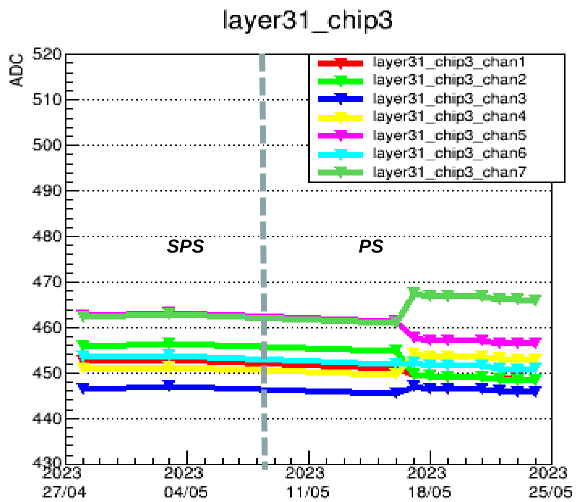
Energy linearity and resolution

Pedestal

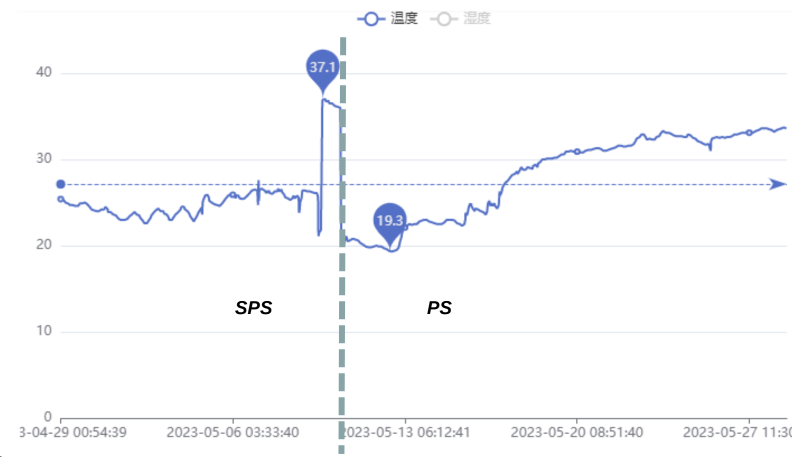
- Not so many force-trigger mode pedestal files from SPS



high-gain pedestal



low-gain pedestal

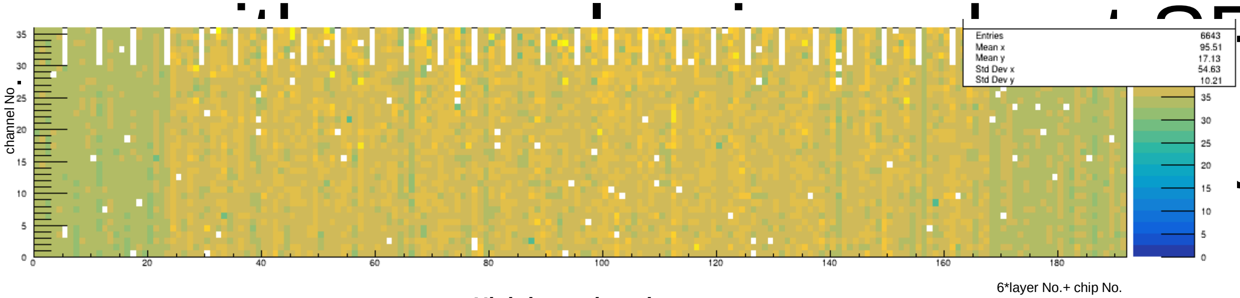


temperatue

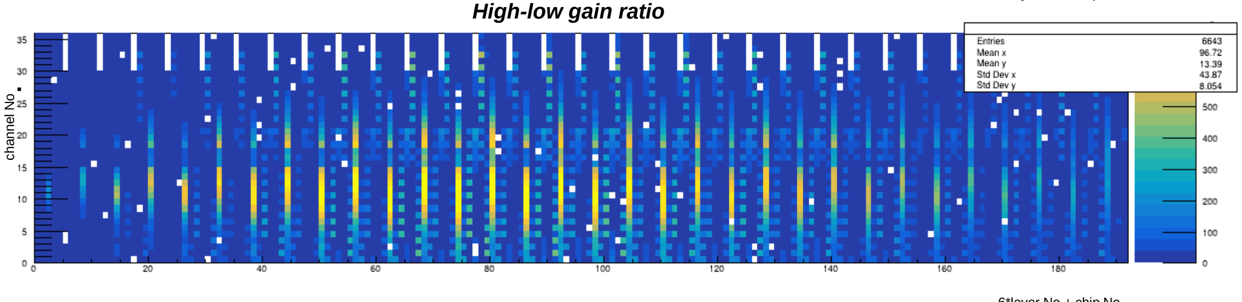
As for SPS and PS data, it shows pedestal stable respectively within 2 ADC fluctuation.
However, when combined together, large fluctuation from 0 to 8 ADC.

High-low gain ratio

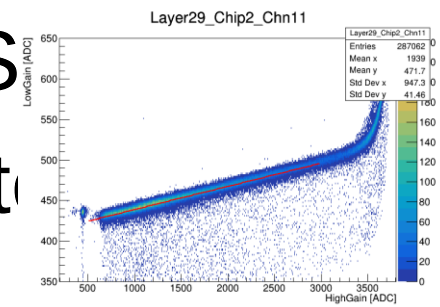
- 20GeV - 100GeV electron test beam files

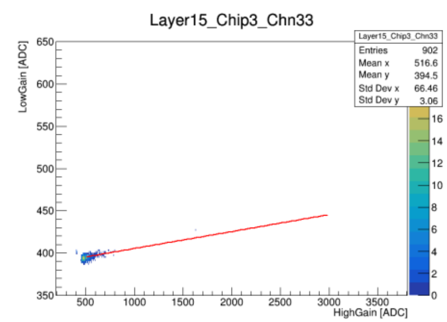


High-low gain ratio



Statistics of each channel

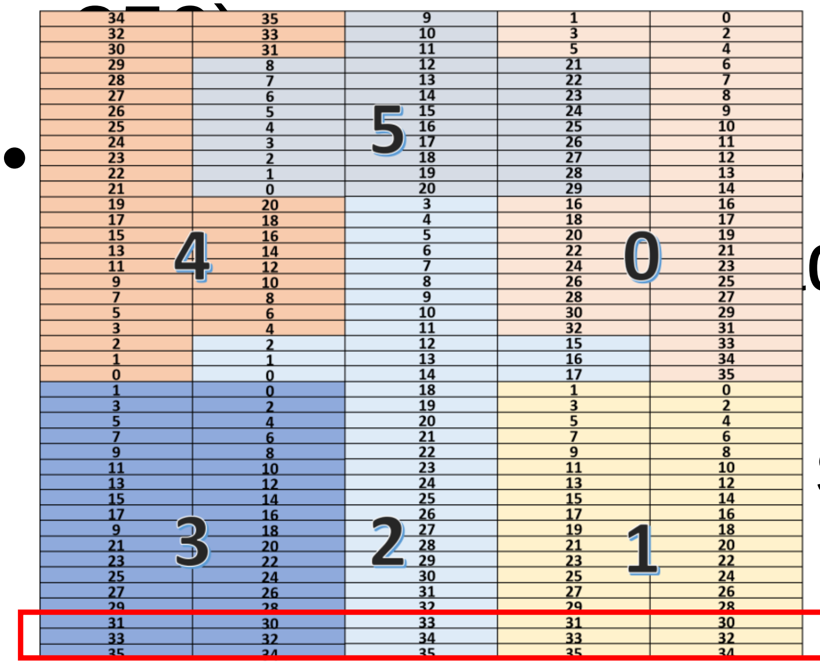




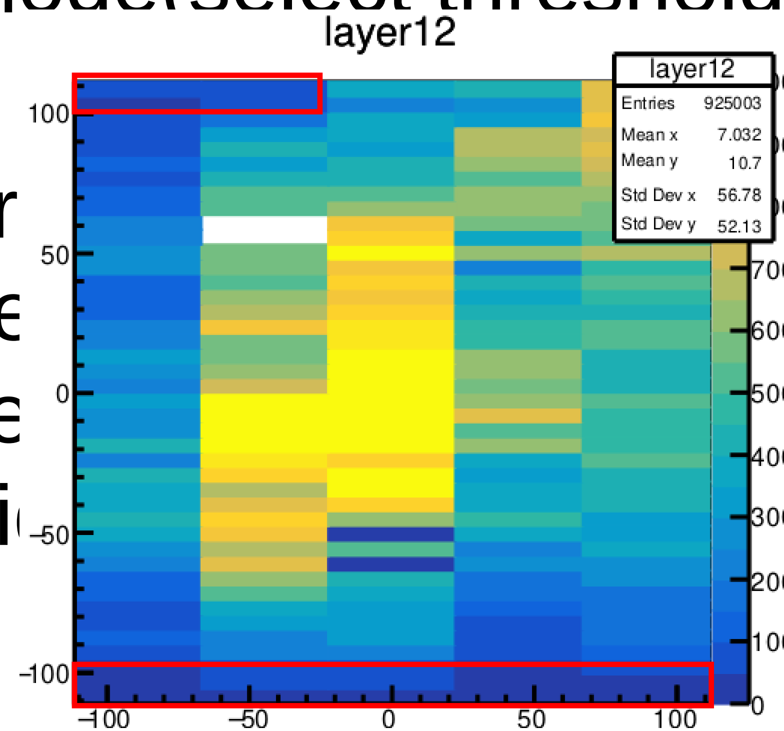
(Dead channels + inadequent statistics channels) ~ 4 channels per layer

MIP

- Use SPS 100GeV/C muon- position scan data with auto gain mode(select threshold: 250)



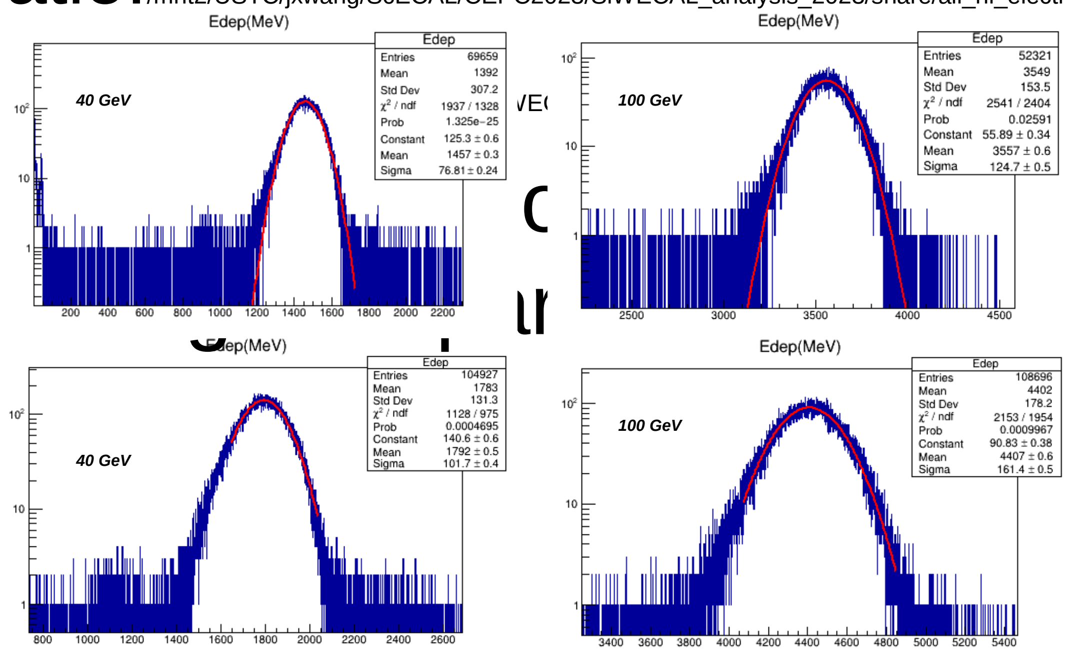
- fr … de … le … si



Energy Reconstruction

- New parameters
  - Pedestal: /mnt2/USTC/jxwang/ScECAL/CEPC2023/SiWECAL_analysis_2023/share/pedestal_2023_v1.root
  - HLratio: /mnt2/USTC/jxwang/ScECAL/CEPC2023/SiWECAL_analysis_2023/share/all_hl_electron2023_v1.root
  - MIP ... WE ... 23.root
- Little ... c ... olution when ... ar

former parameters



new parameters

Energy reconstruciton with different switch threshold

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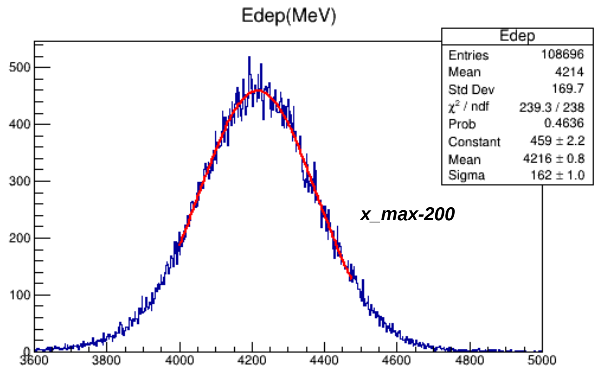
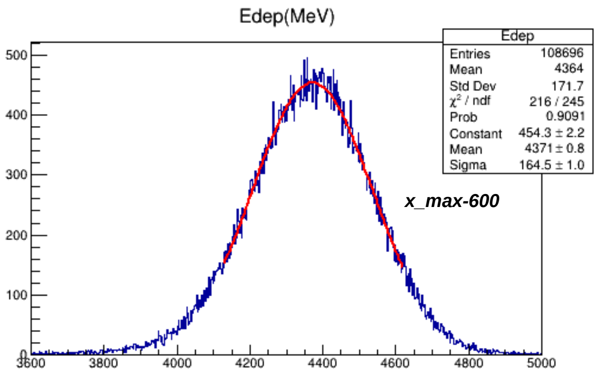
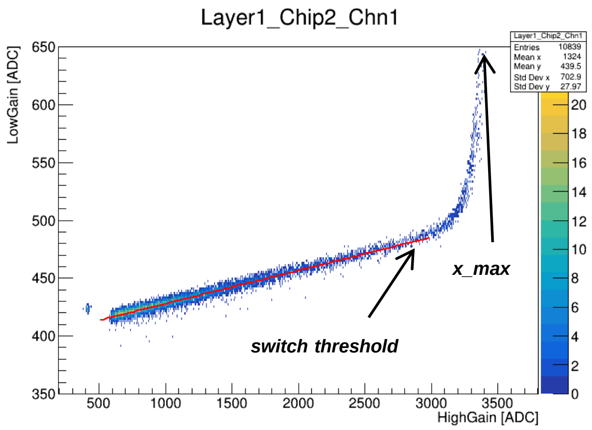
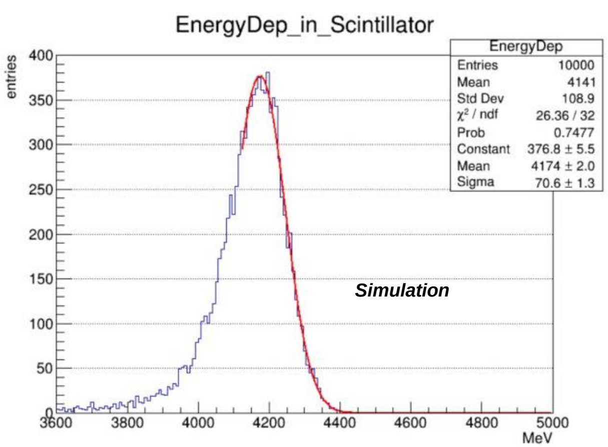
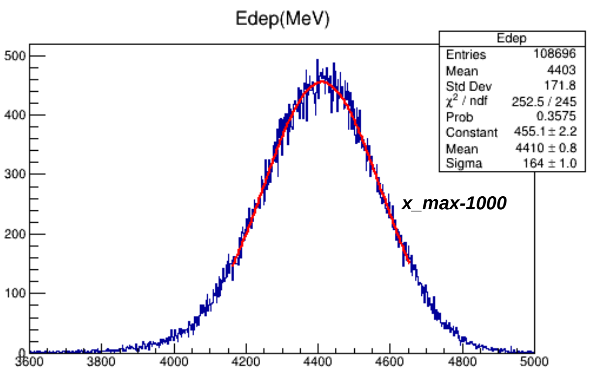




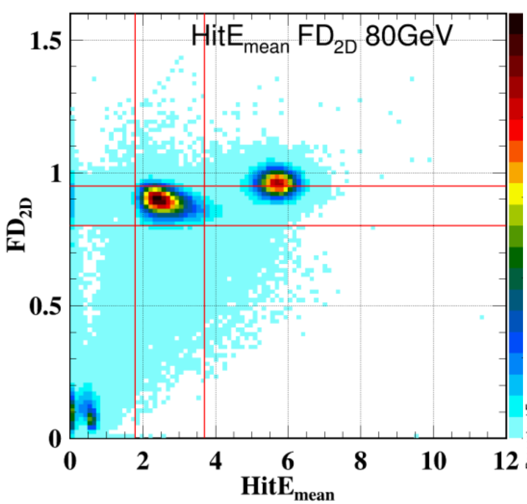


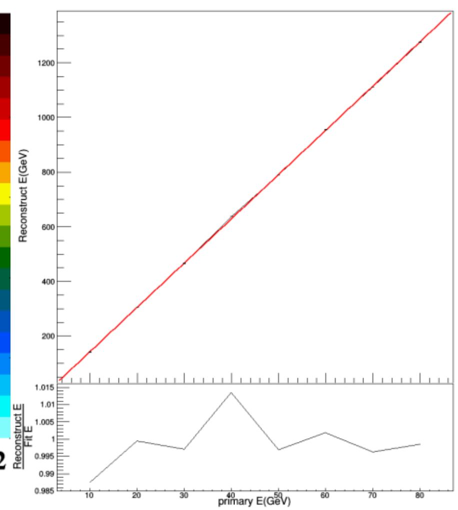


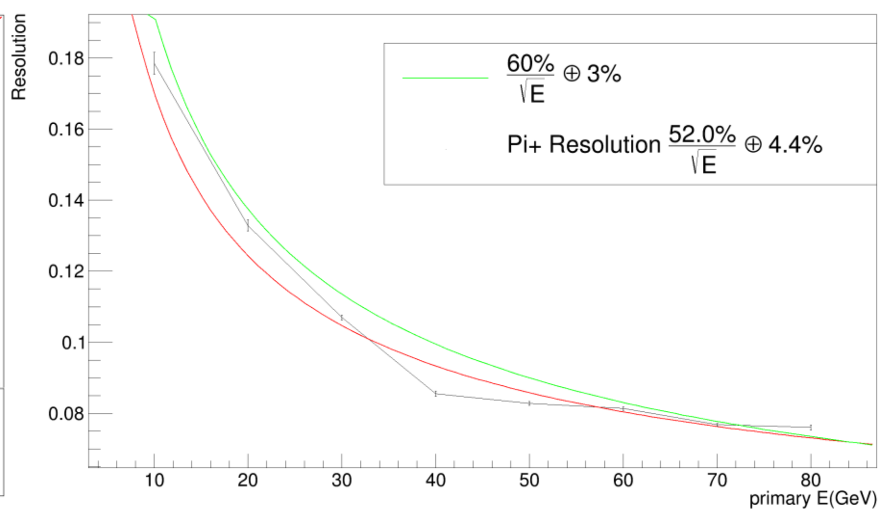


Tight cut

- Different cuts will have an obvious influence on the performance
- The selection is not only PID, but also select the hadronic dominant showers in the pion beam







Calibration V2

- Pedestal
  - Calibrated from DAC data
  - The multi-peaks disappear
  - Only high gain have some channels with high rms
- Gain
  - Calibrated from pion data instead of muon
  - V2.1: high gain is forbidden to test the reliability of high low gain switch point

Calibration V2

中国科学技术大学
University of Science and Technology of China

- Tight cut is applied to calibrated pion V2 data
- The resolution is obviously better