Energy Calibration of the CALICE AHCAL 2018 Prototype based on SPS Test Beam Data

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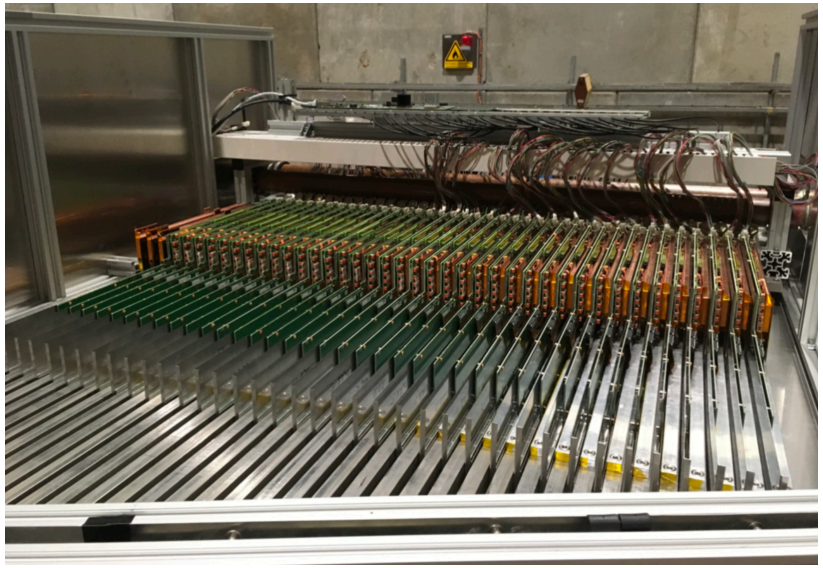
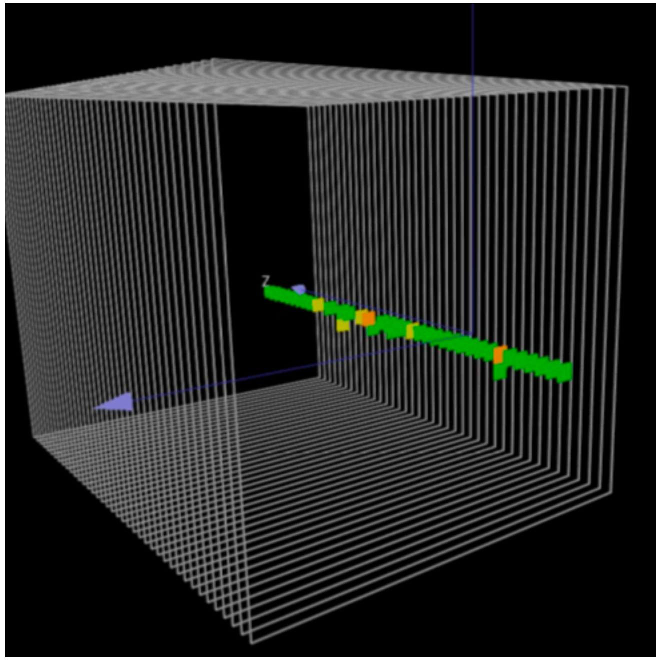
Aachen, 25. March, 2019





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Outline

For this Talk

- Energy Calibration: Motivation and Definitions
- Calibration Procedure and Results
- Closing the Loop: Quality Check of Calibration Constants

Energy Calibration
Motivation and Definitions

ADC to MIP

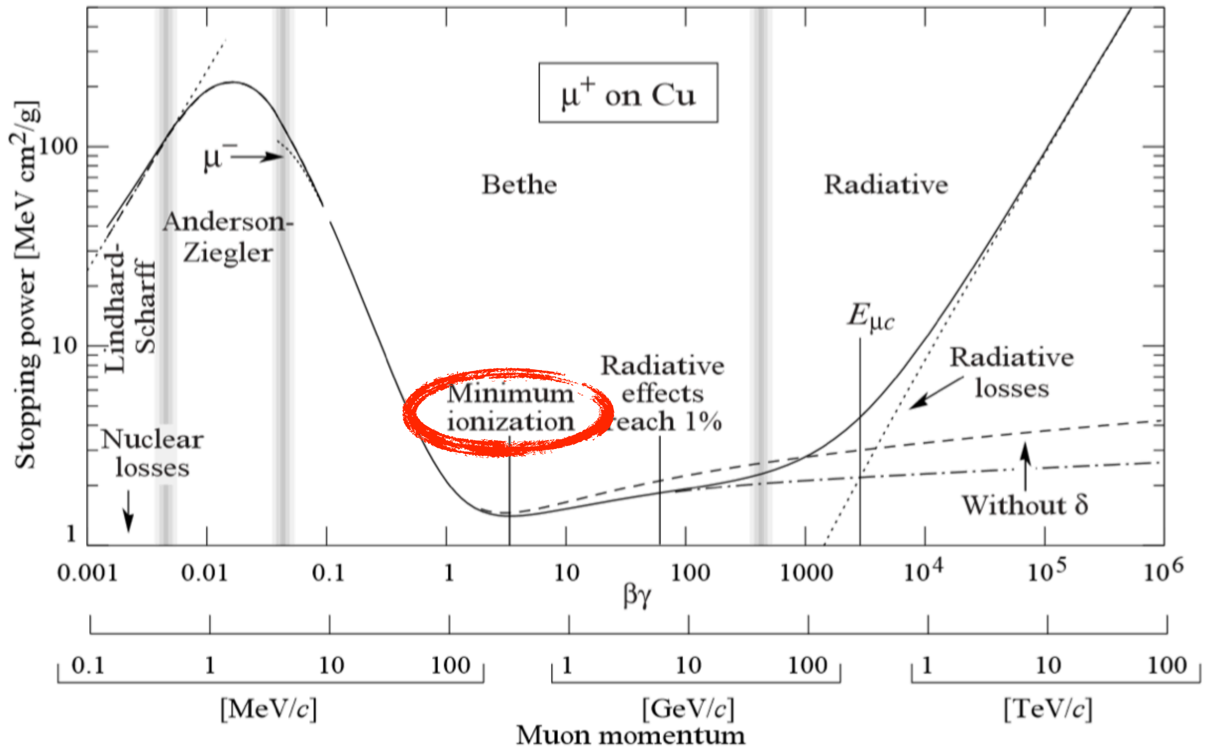
Motivation

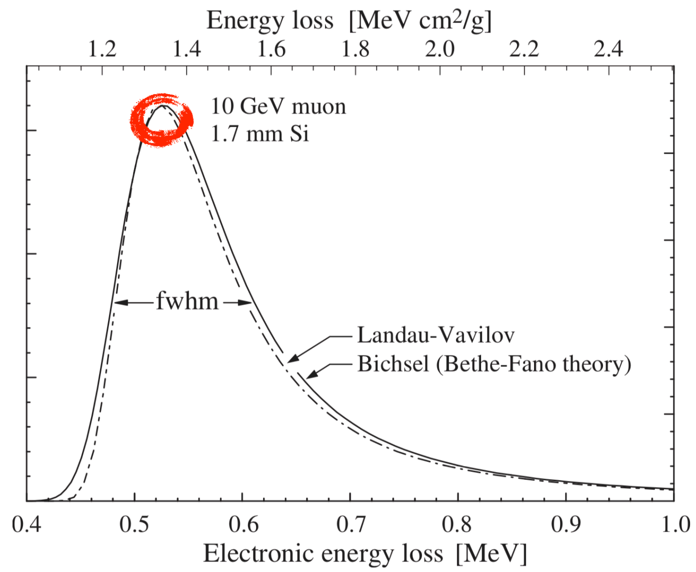
- Raw hit amplitudes of the AHCAL channels are measured in ADC units

➡ Need of physical energy scale: Energy deposition in Minimum Ionizing Particle (MIP) equivalents

  - Well defined energy deposition spectrum of MIP's (muons) in matter by ionization processes
  - Spectrum follows Landau-convoluted-Gaussian function with maximum as **Most Probable Value (MPV)** defining the deposition scale for each channel

    ➡ Standard candle: No shower assumptions required





From ADC to the MIP Energy Scale

Definition of Calibration Constants

- Several calibration constants are required to perform the ADC to MIP conversion within the reconstruction process:

$$E_{calibrated}\,[MIP] = f_{desat}(pixel) \cdot \frac{(ADC - Pedestal)/IC}{MIP} \qquad pixel = \frac{(ADC - Pedestal)/IC}{Gain}$$

With $f_{desat}(pixel) = 1 \; for \; pixel \ll N_{max,pixel}$ for negligible SiPM pixel saturation

Pedestals	MIP Constants	Gain Constants	IC Factors
Electronic base-line level in ADC units	Most probable energy deposition of a MIP in ADC units	ADC units corresponding to one fired SiPM pixel	HG/LG amplification ratio

- For each of the 21888 channels (350208 memory cells) individual constants to be determined!

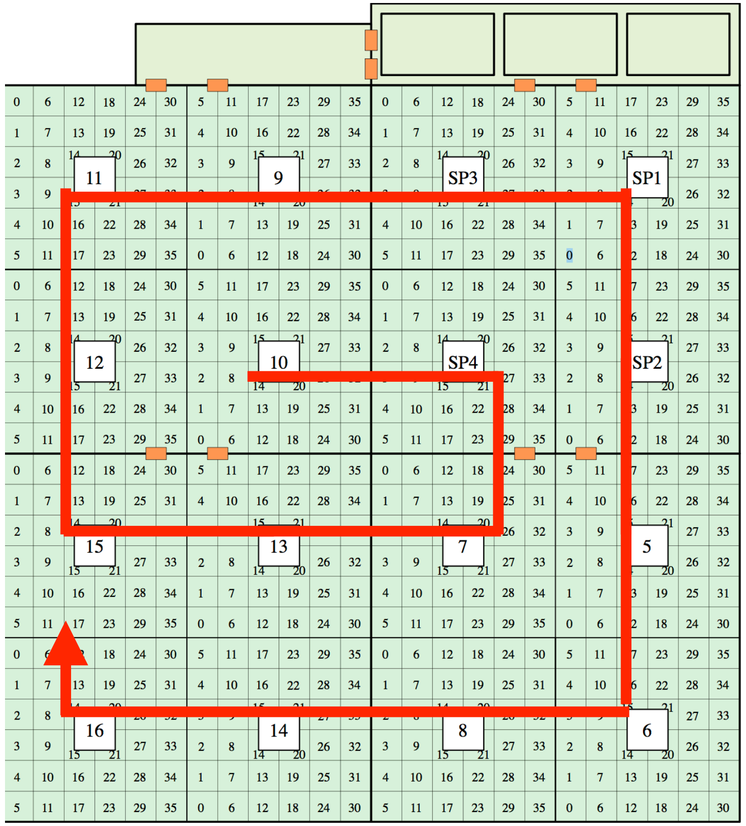
Calibration Procedure and Results:

Pedestal and MIP Constants

Calibration Test Beam Muon Runs

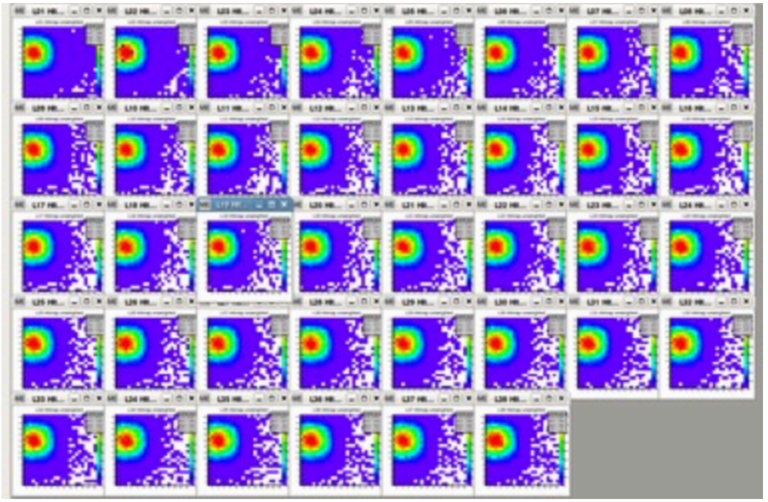
@ SPS May and June 2018

- During SPS May and June beam time a **muon beam** position scan was performed illuminating all channels:
  - ➡ 40 GeV muons
  - ➡ **May: no Power Pulsing, June: Power Pulsing**
  - ➡ For both periods: ~18 positions, ~500000 events/position
  - ➡ Scan pattern to cover all channels



➡ Combined data set of all positions provides reasonable statistics for:

- ➡ **Pedestal extraction** (HitBit = 0, no physics hit)
- ➡ **MIP calibration** (HitBit = 1, physics hit)



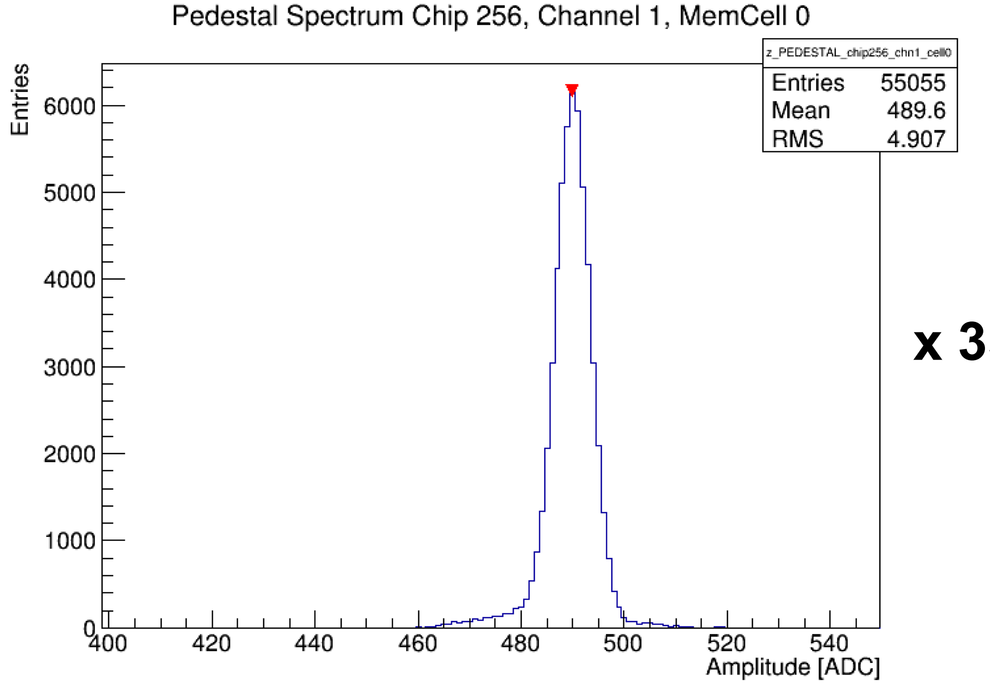
Pedestal Extraction

Method and Basic Properties

1. Fill histogram for each memory cell of a channel with HitBit = 0 ADC amplitudes (= 16 histograms per channel)
2. Two times range-iteration (range = mean ± 3 · sigma)
3. Extract mean as pedestal

Pedestal = Mean of pedestal spectrum
Intrinsic Width = RMS of pedestal spectrum

Chip, Channel, Memory Cell



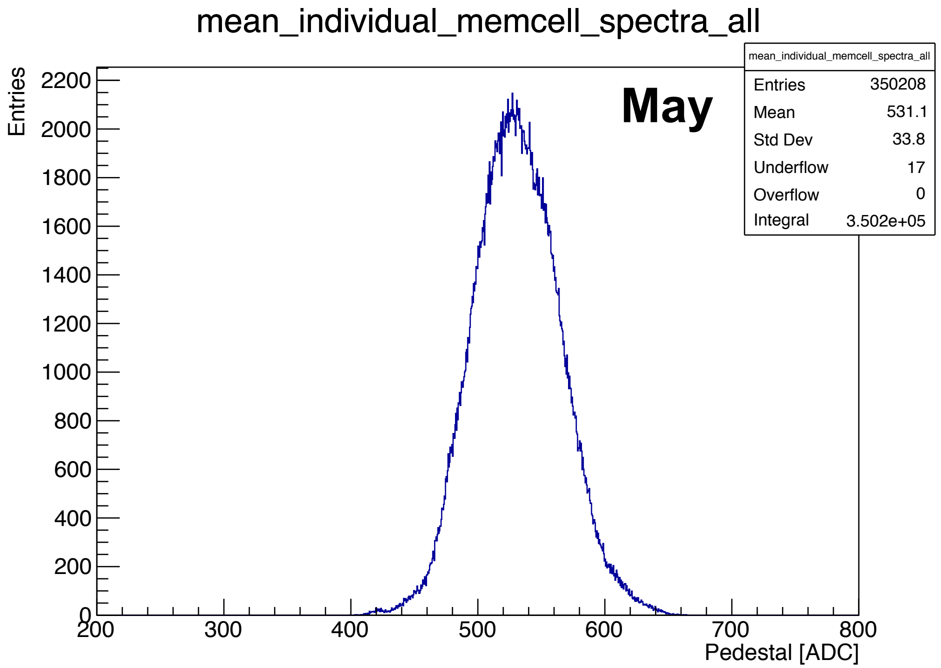
x 350208

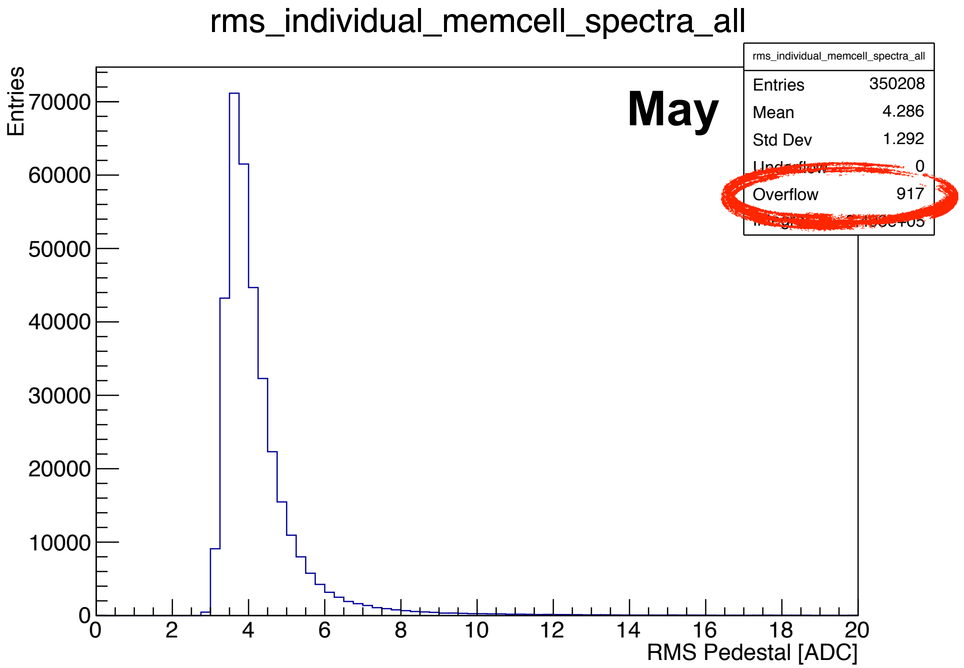
Pedestal Extraction Results

For SPS May Test Beam Data

Memory Cell Level

- Total of 350208 memory cell pedestals and corresponding intrinsic widths (RMS) of pedestal spectra





- **Mean pedestal**: 531.1 ADC
- Spread: 33.8 ADC

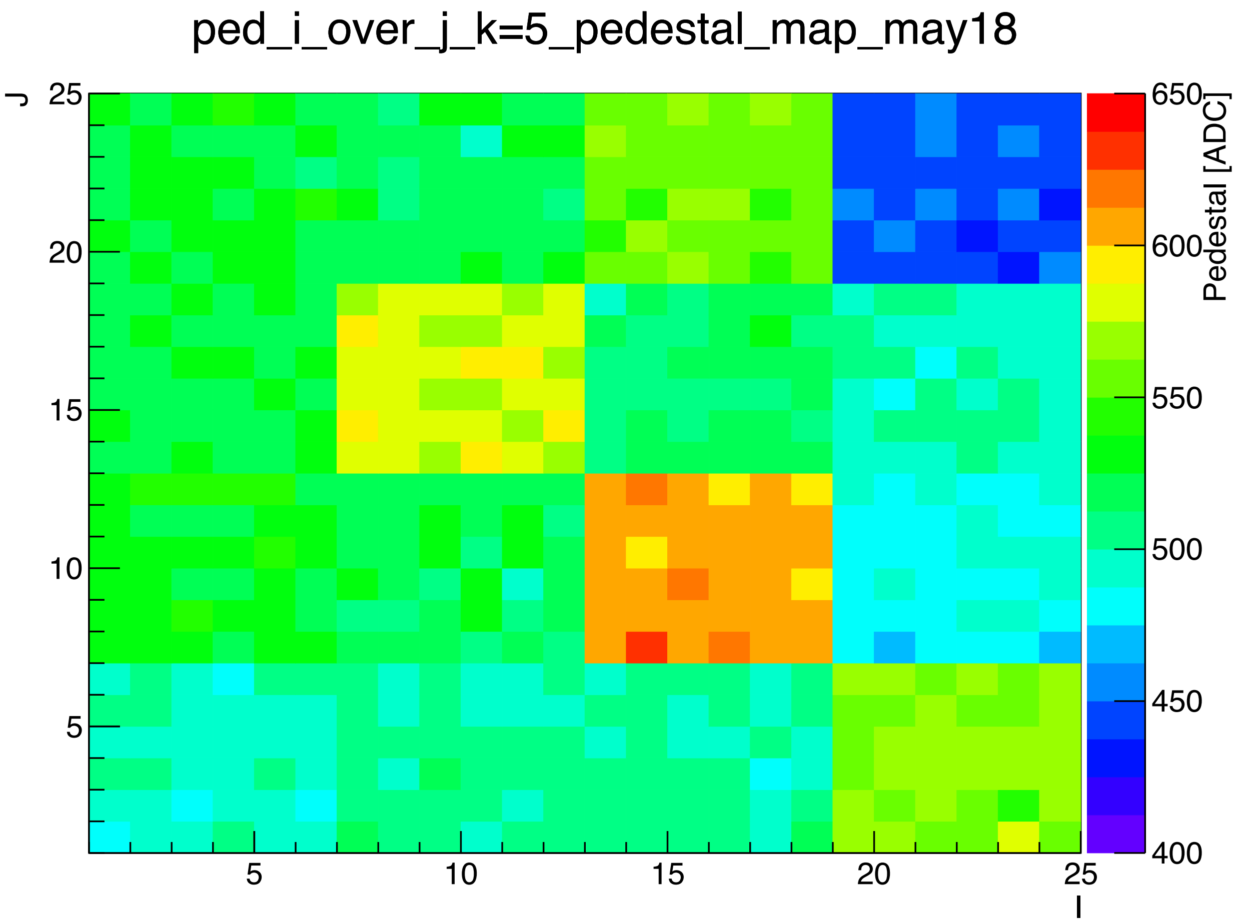
- **Mean RMS** of pedestal spectra: 4.3 ADC
- Tail to higher RMS from memory cells > 8 (excluded)

Variation of Pedestal

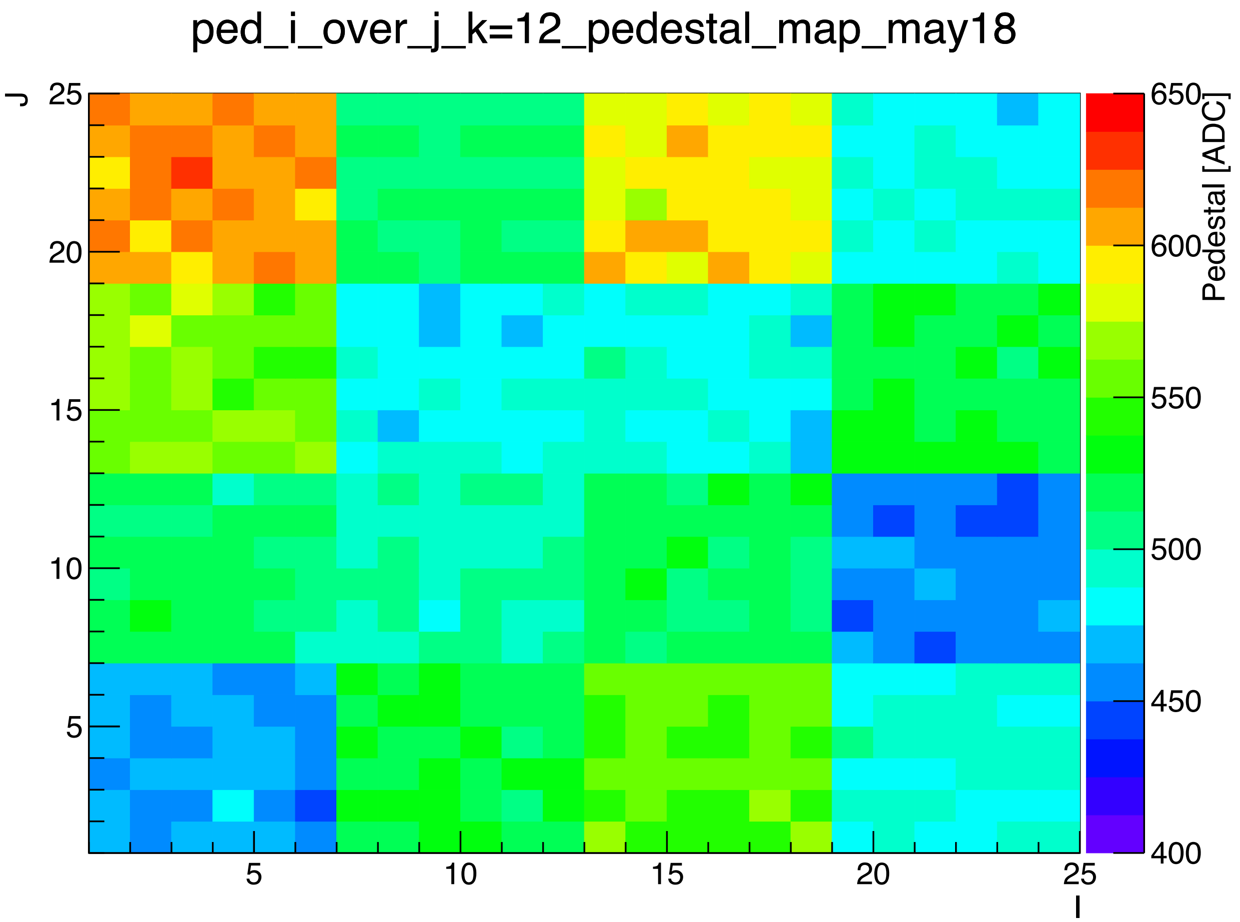
Layer Pedestal Maps for SPS May Test Beam Data

Channel Level

Pedestal Map Layer 5



Pedestal Map Layer 12



- **Chip-to-chip variation of pedestal is dominant (not cell-to-cell or channel-to-channel variation)**

MIP Constant Extraction

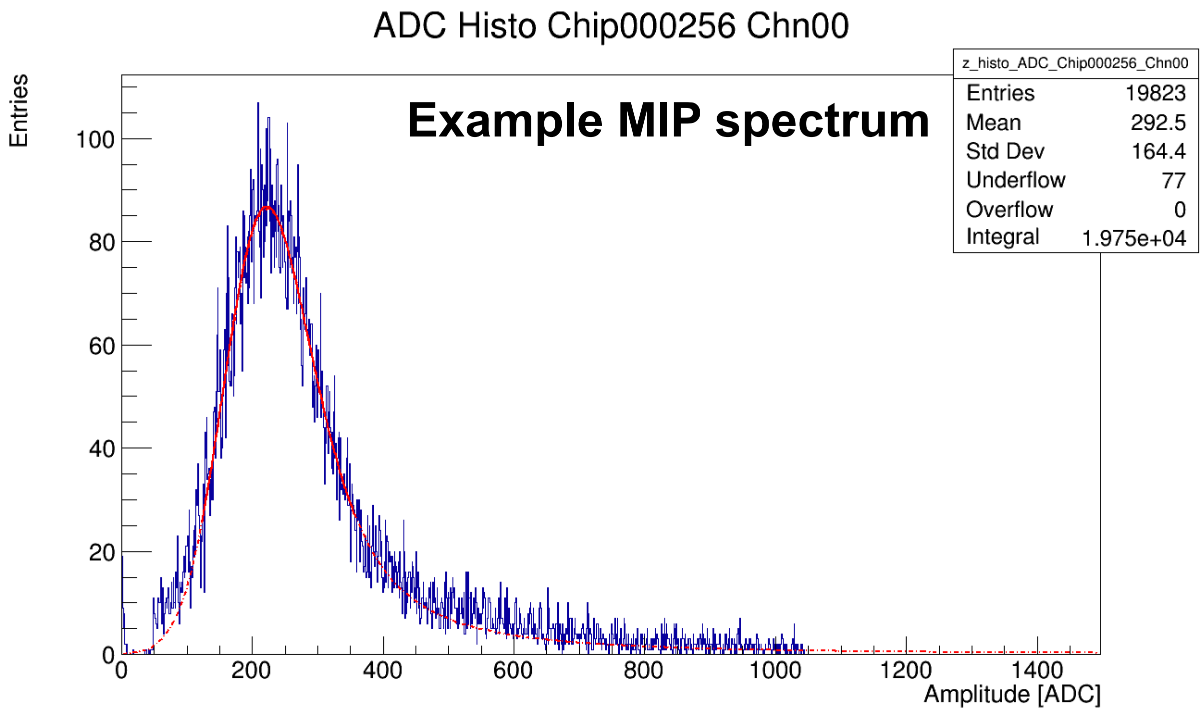
Method and Basic Properties

1. Fill histogram for each channel (memory cells 0-8 combined) with HitBit = 1 ADC amplitudes

   ➡ Memory cell specific pedestal subtraction

2. Apply 3-step Landau convoluted Gaussian fit

3. Extract maximum of fit function as the MIP constant for each channel



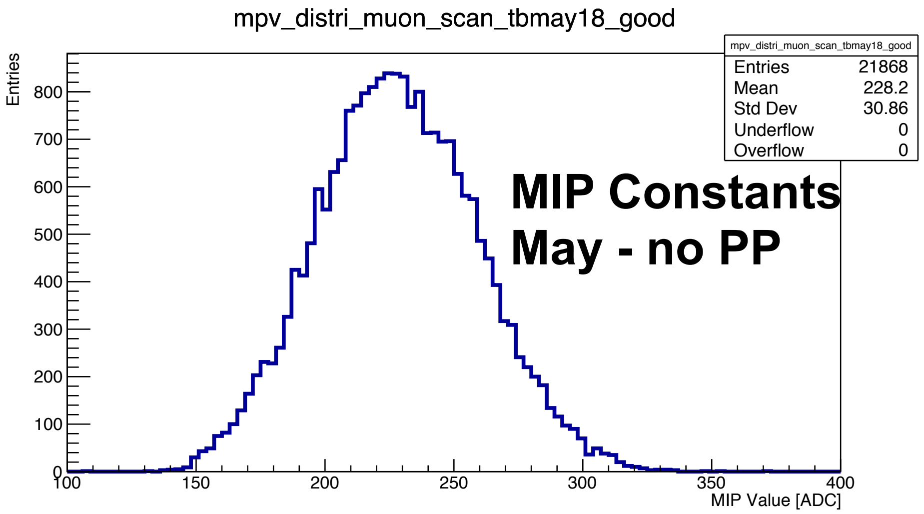
MIP Constant = Most Probable Value (Maximum) of Landau convoluted Gaussian fit

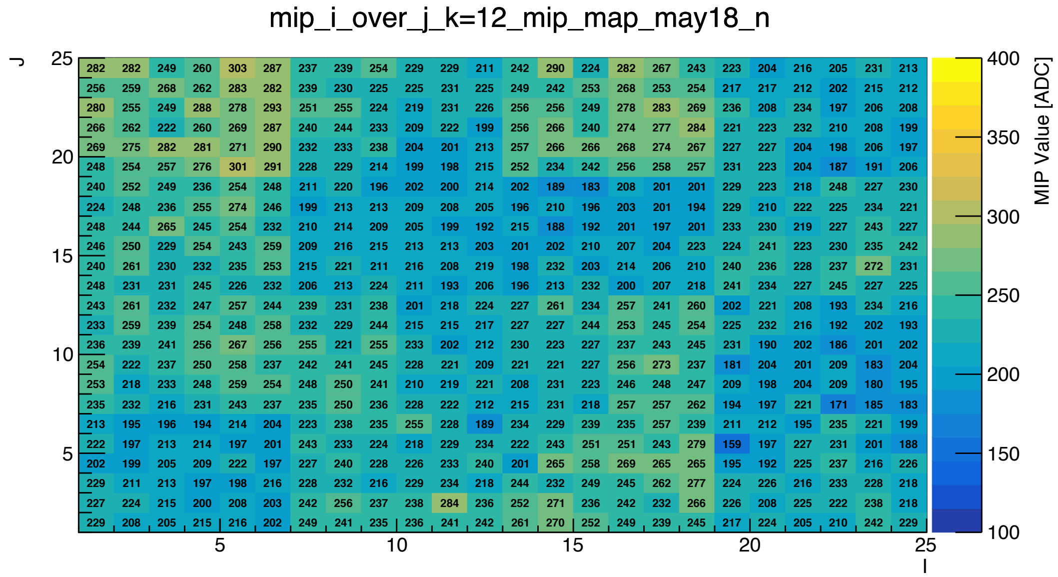
MIP Calibration Results

For SPS May Test Beam Data

Channel Level

- **21868/21888 MIP constants considered as „good“ = ~99,92 %**
  - ➡ 6 dead, 14 empty or non-Landau shaped spectra causing fit fail
  - ➡ Mean MIP value = 228.2 ADC
  - ➡ RMS MIP value = 30.86 ADC





➡ Uniformity of uncalibrated detector: RMS MIP value/Mean MIP Value = ~14 %

Pedestal and MIP Constants Comparative Studies

Comparative Studies of Pedestal and MIP Constants

Idea and Method

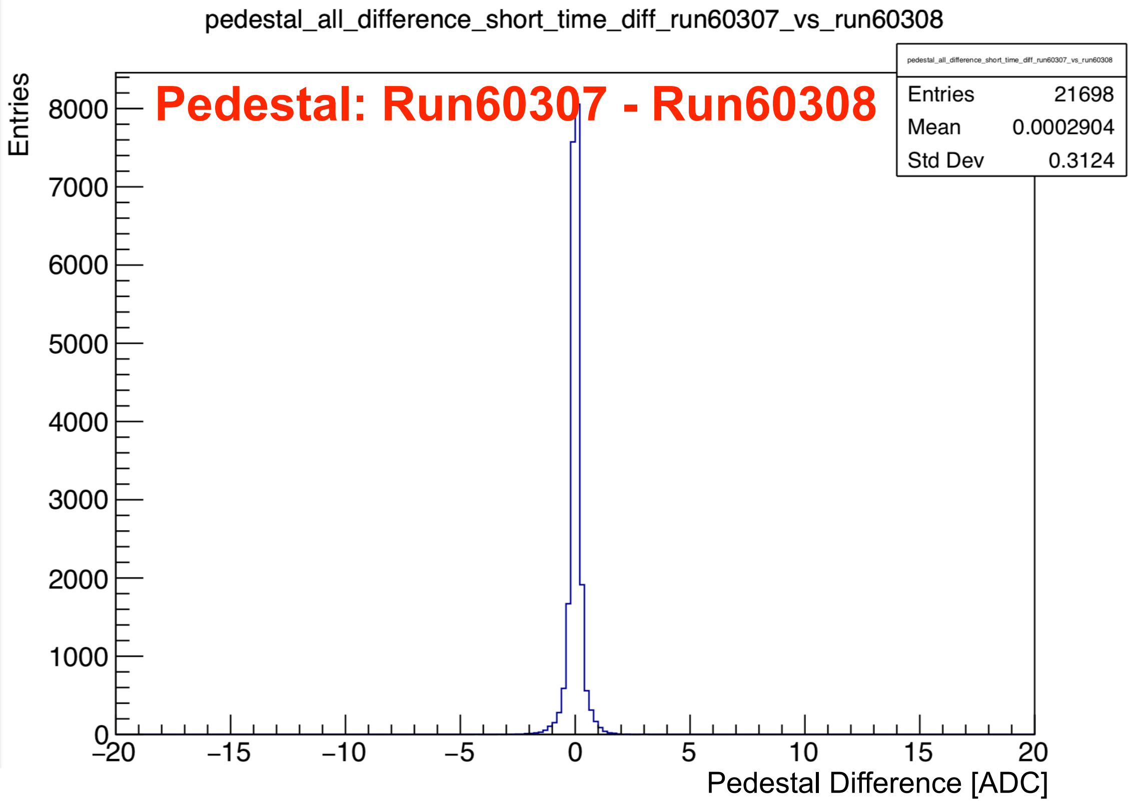
- Idea: Perform pedestal extraction and MIP calibration individually for different muon runs for overlapping beam positions
  - ➡ Compare acquired constants for same channels
    - ➡ Check stability in time
    - ➡ Check stability in different detector modes

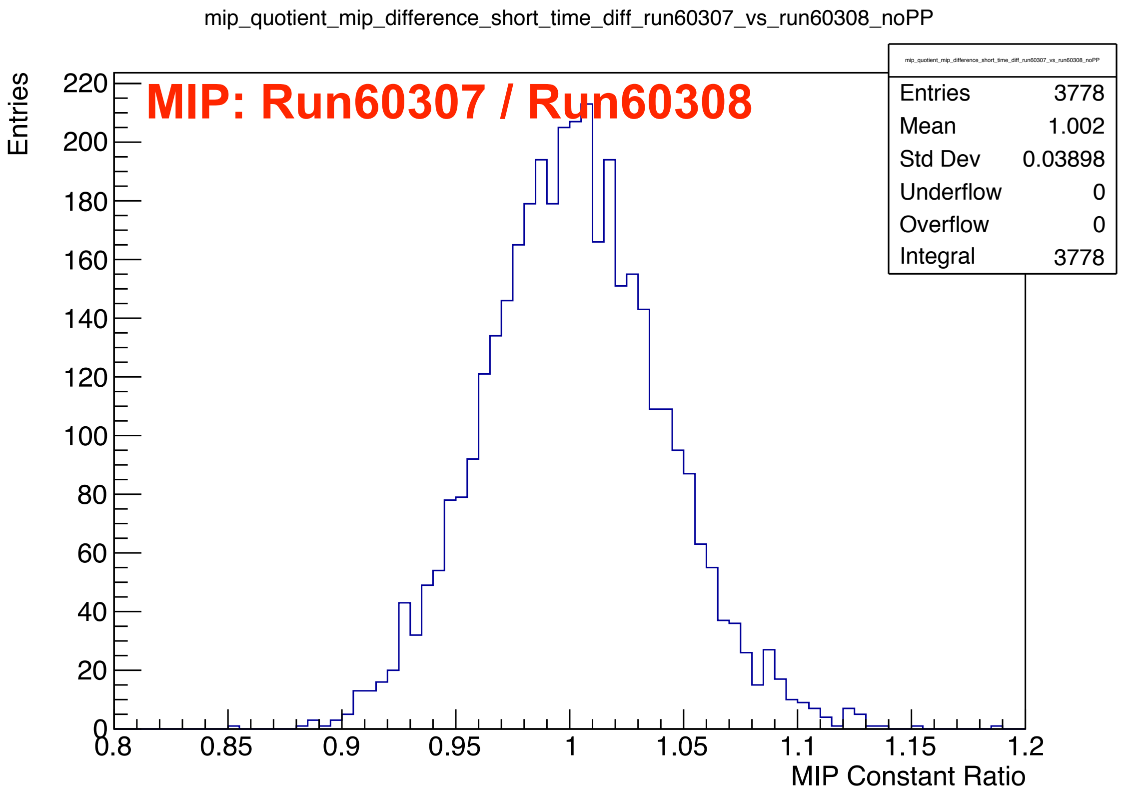
How often do we have to recalibrate?

- Sets to compare:
  1. Two consecutive runs
  2. Two runs at beginning and end of a test beam period
  3. May vs. June muon runs, no PP
  4. June muon runs in no PP mode vs. June muons runs in PP mode

Two Consecutive Runs

Comparison





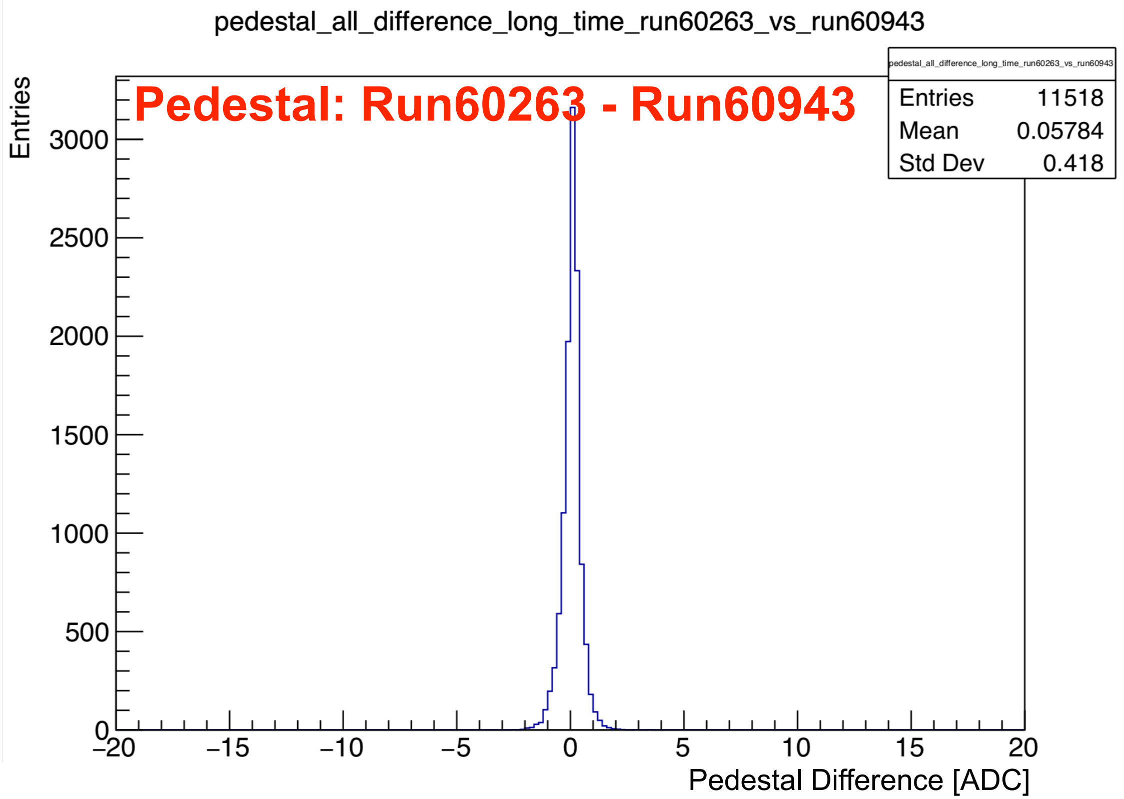
- Difference within 1 ADC and centered at 0 ADC

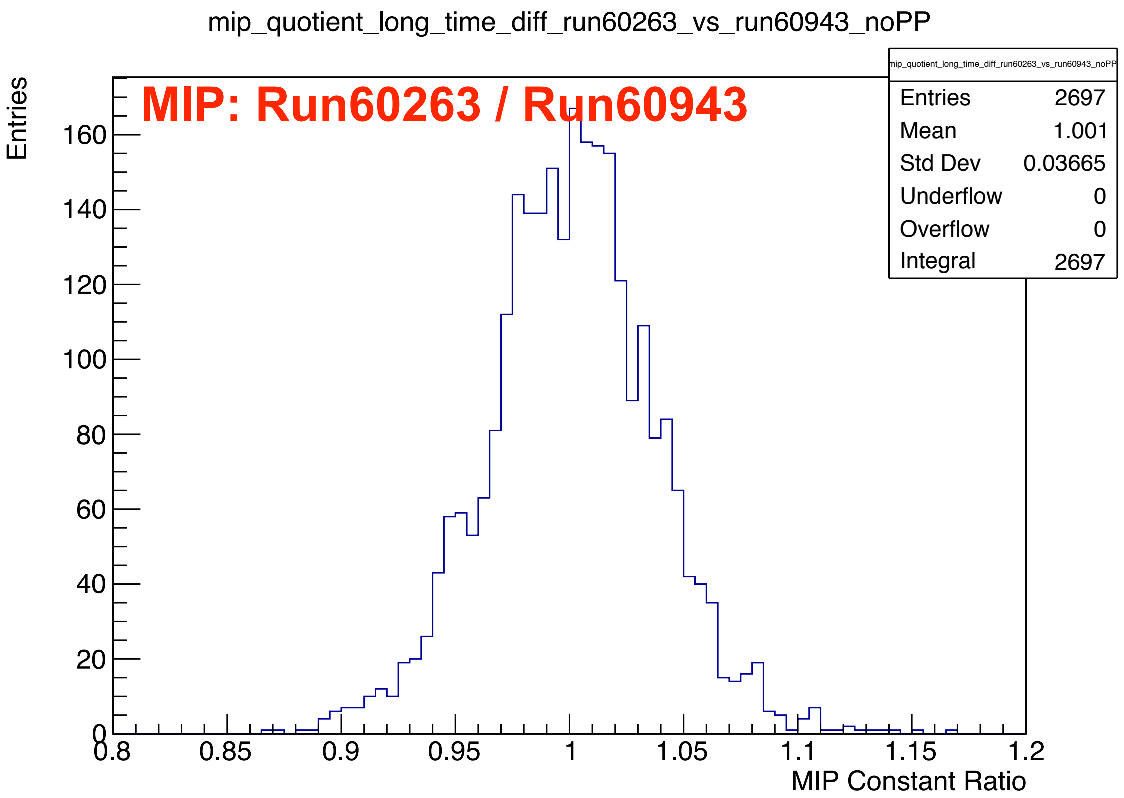
- Ratio centered at 1 and RMS ~4%
- Relatively good agreement between runs even though single runs feature low statistics

➡ **Pedestal and MIP constants stable on short time scale**

Run Beginning and End of Test Beam Period

Comparison





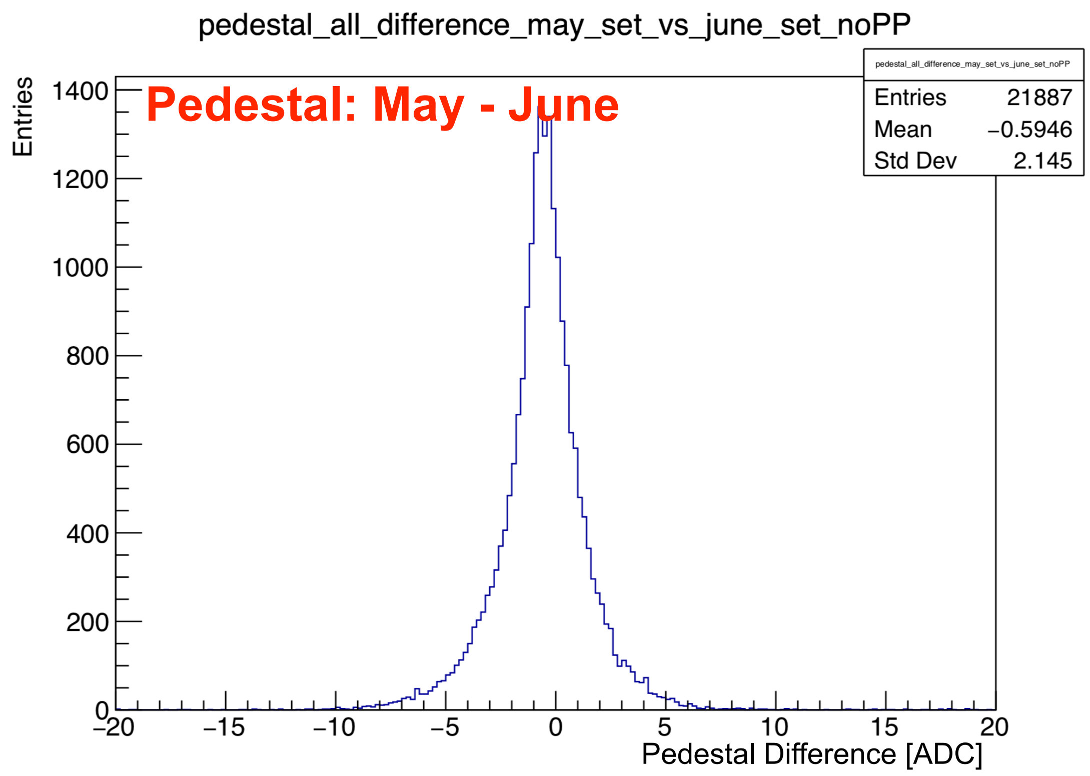
- Difference within 1 ADC and centered at 0 ADC

- Ratio centered at 1 and RMS ~3.7%
- Relatively good agreement between runs even though single runs feature low statistics

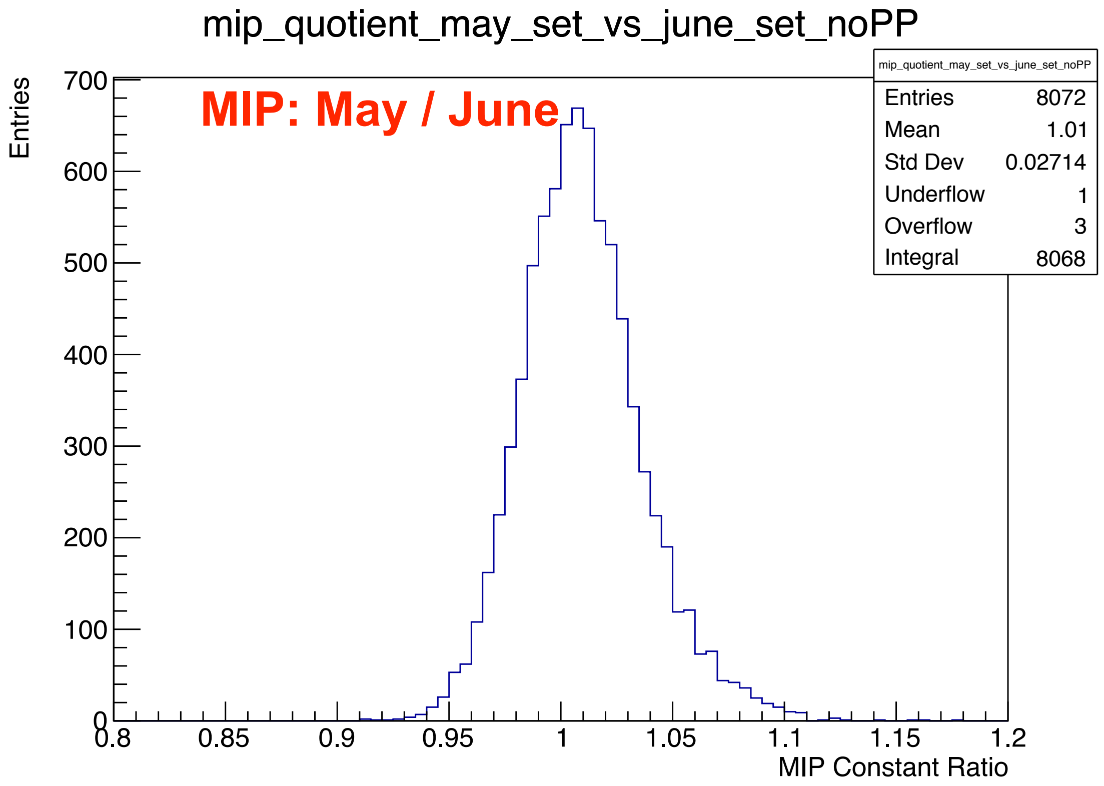
➡ **Pedestal and MIP constants stable on long time scale within same beam test period**

Muon Runs May vs. Muon Runs June, no PP

Comparison



- RMS > 2 ADC and shift of mean to ~ -0.6 ADC



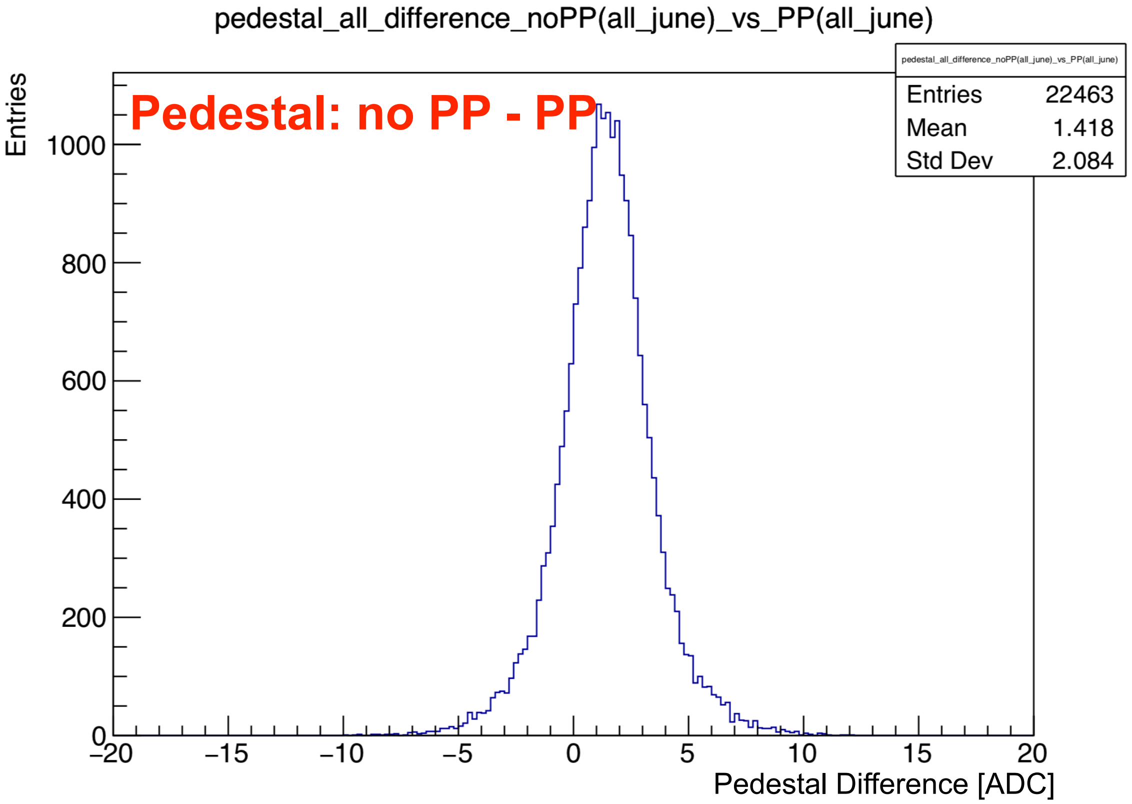
- MIP ratio off by ~1% and RMS ~2.7%

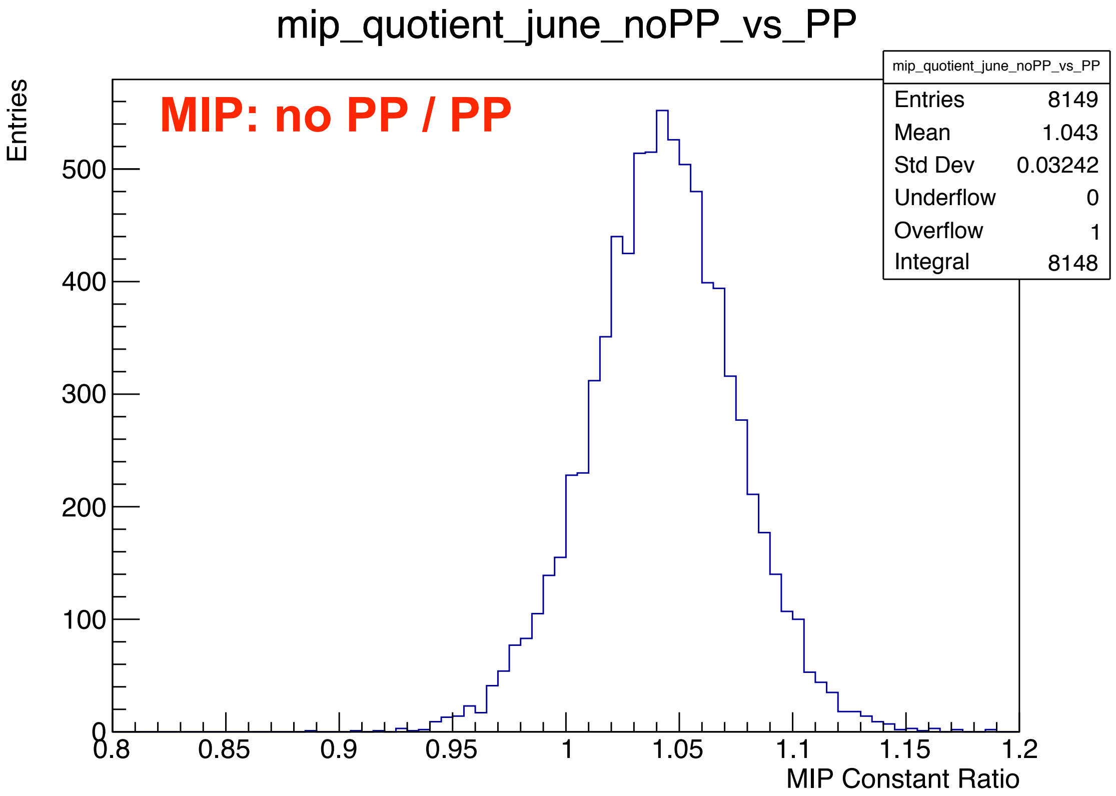
➡ Relatively good agreement between May and June

➡ **New test beam period (same detector mode): New pedestal determination recommended, but MIP constant stable**

Muon Runs June No PP vs. PP

Comparison





- RMS > 2 ADC and shift of mean to ~1.4 ADC

- **MIP ratio off by ~4.3%** and RMS ~3.2%
  - ➡ Well understood electronic effect in PP mode (shifted ground)

➡ **Different detector modes: Individual pedestals recommended, MIP constants required**

Closing the Loop: Quality Check of Calibration Constants with Test Beam Muon Runs

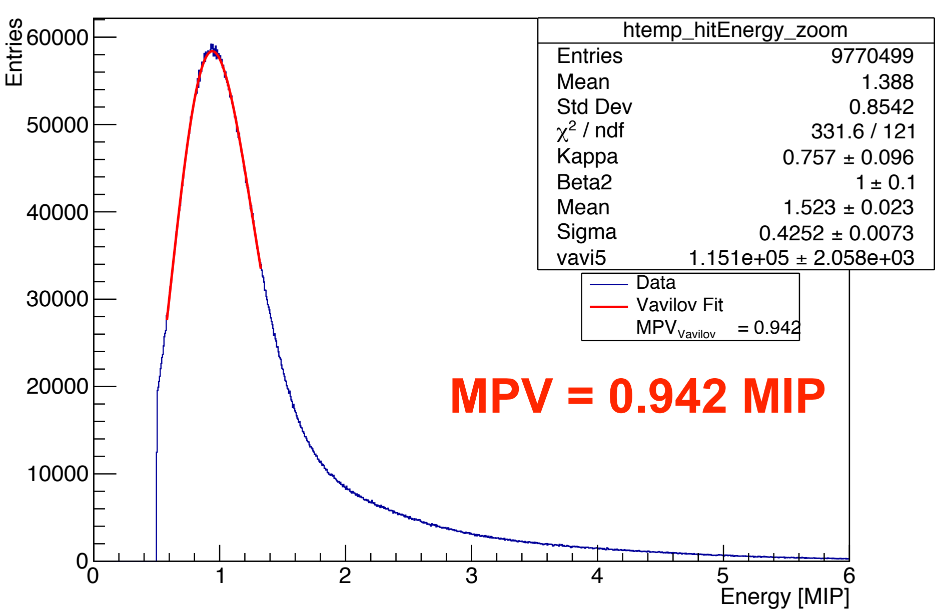
MIP Peak Position Check

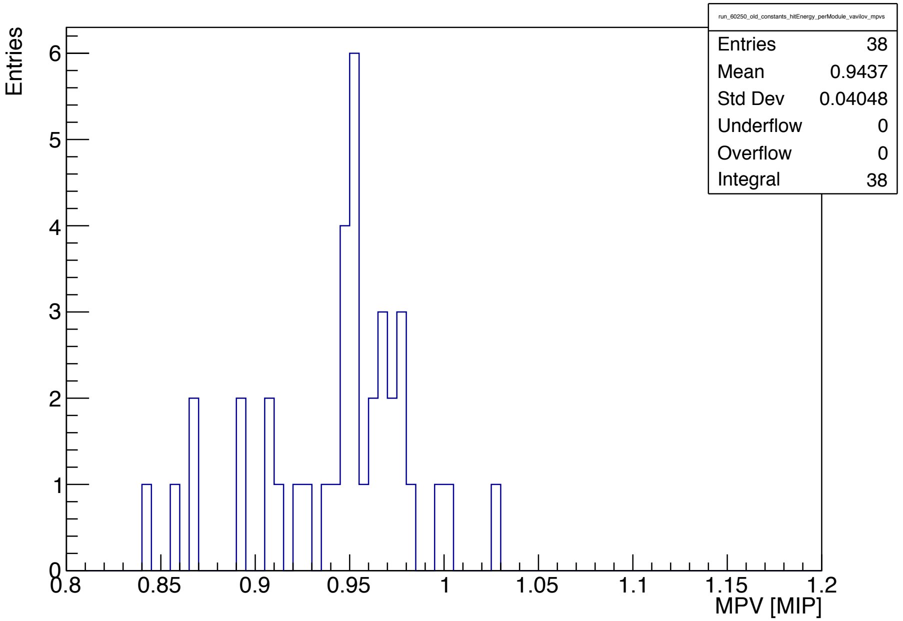
For Muon Test Beam Runs

- Idea: Reconstruct the deposited hit energy in muon runs with the determined calibration constants
  - ➡ Does the hit energy spectrum peak at 1 MIP?
  - ➡ Check for May and June test beams on global, layer and channel level

Quality check of Pedestals and MIP constants

Previous DESY electron calibration constants for May muon runs

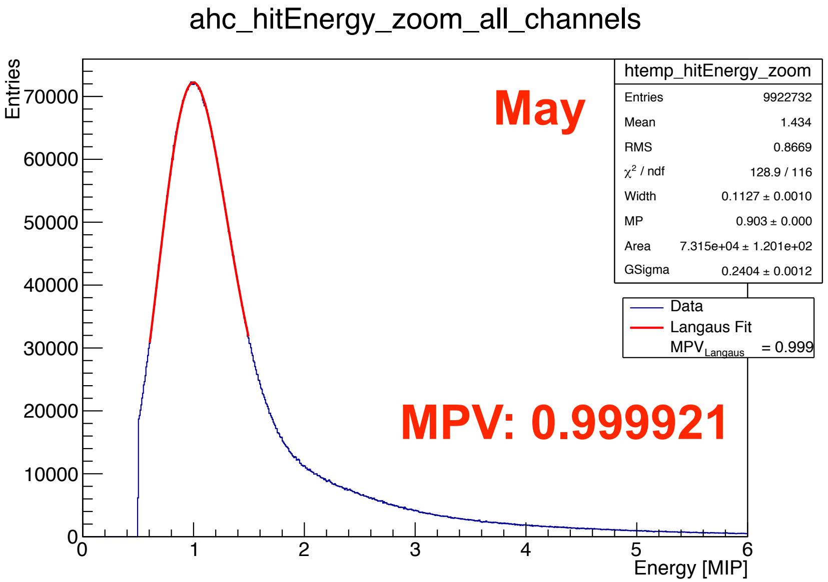


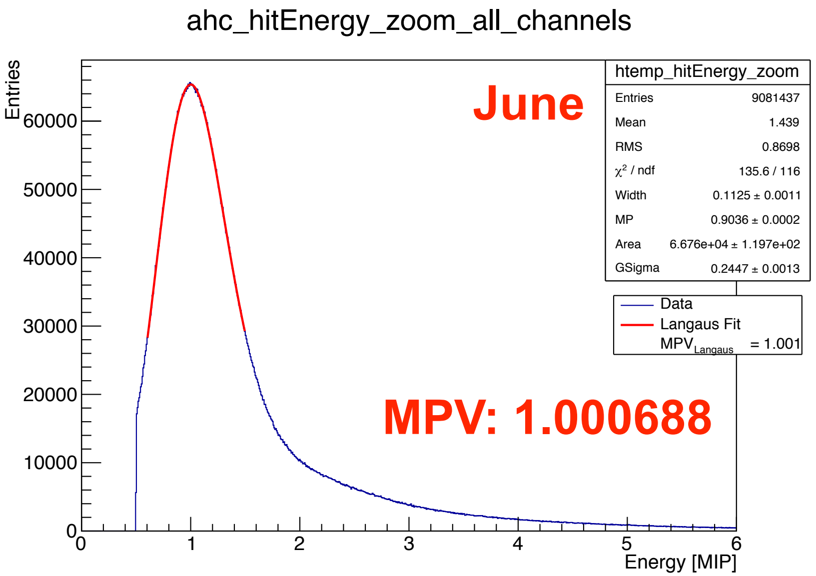


MIP Peak Position Check - Global and Layer

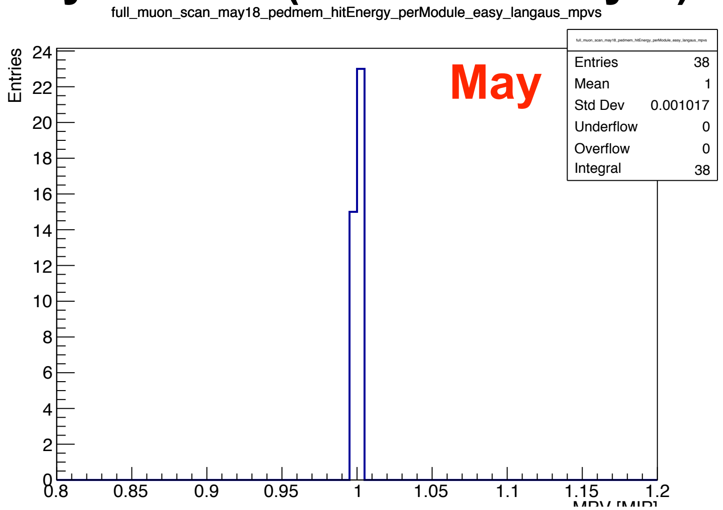
For SPS Test Beam May and June Muon Runs

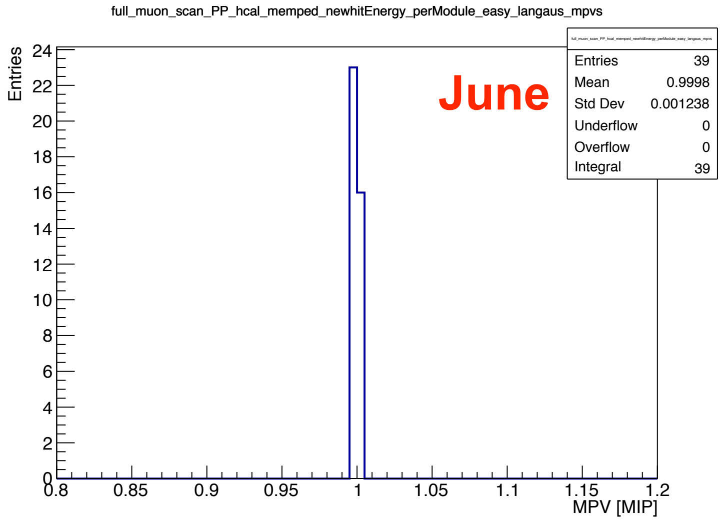
Global Level (all hits of all channels)





Layer Level (all hits of a layer)

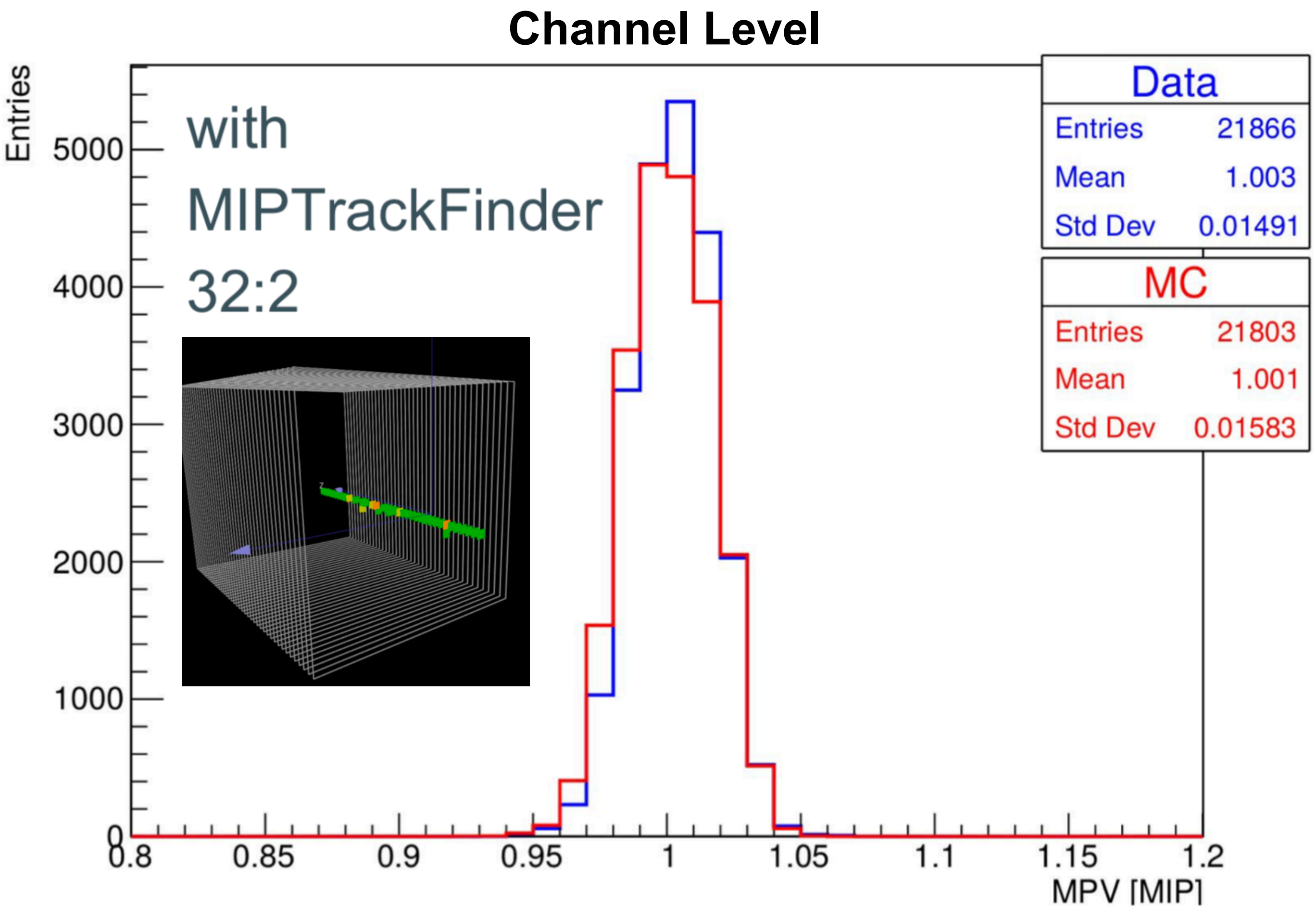




- **Calibration constants extracted for SPS May and June test beam provide excellent muon energy reconstruction on the per-mille level**

MIP Peak Position Check - Channel

For SPS Test Beam May Muon Runs



- Hit energy extraction procedure done for all individual channels
  - ➡ MPV of Landau-Gaussian fit extracted and put into histogram

➡ **Most channel spectra peak around 1 MIP (mean = 1.003 MIP)**

➡ **Excellent agreement with MC simulation concerning mean and width**

Summary and Outlook

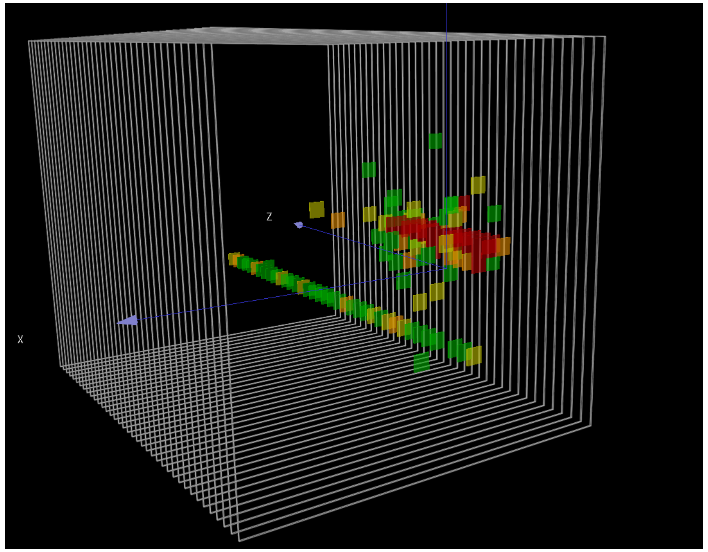
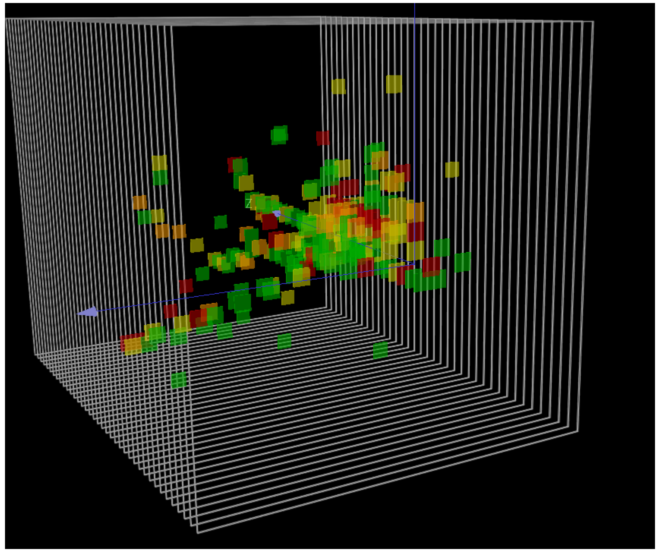
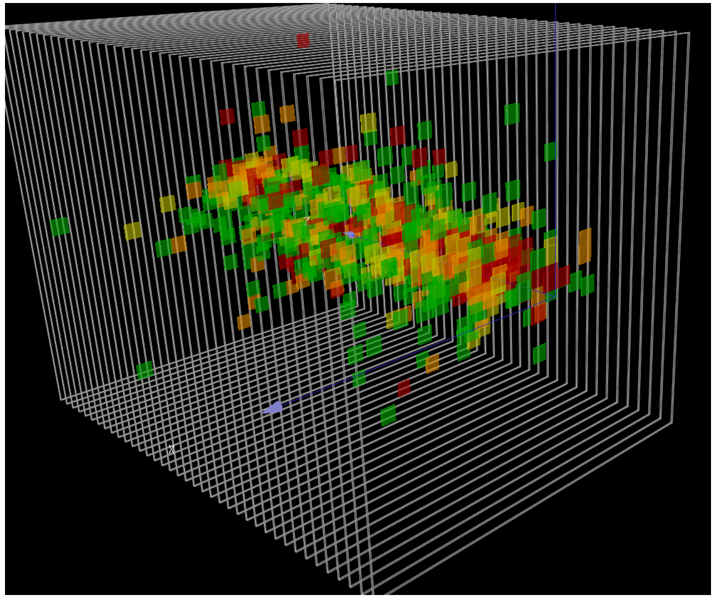
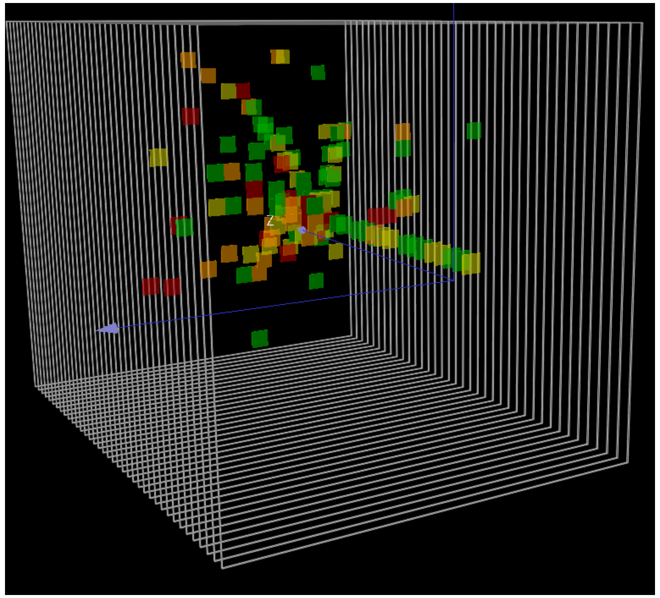
- A fully scalable AHCAL for a future e+e- collider will be a highly granular SiPM-on-tile calorimeter optimised for the Particle Flow Approach (PFA)

- In 2018: 3 successful test beam campaigns at the SPS with a 38 layer (~22000 channel) AHCAL prototype

- All calibration constants required for the energy reconstruction of ADC to MIP were determined
  - ➡ Stability in time and detector mode, uniformity and variations investigated, effects understood
  - ➡ Quality of extracted constants verified in reconstructed test beam runs

- Dedicated calibration allows to start electron and pion shower studies
  - ➡ Energy linearity/resolution, shower shapes, PFA shower separation and confusion, etc…

Thank you!

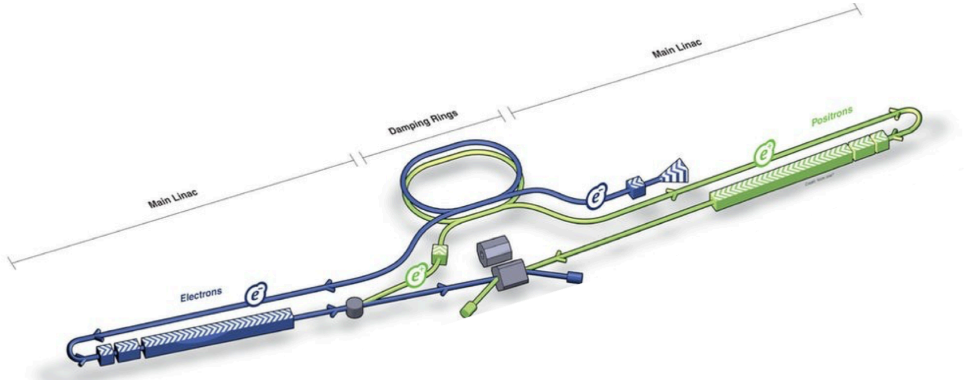
Backup

ILC, ILD and Particle Flow Approach

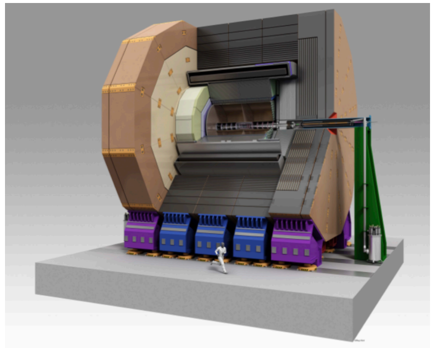
The International Linear Collider and Large Detector

The Precision Frontier

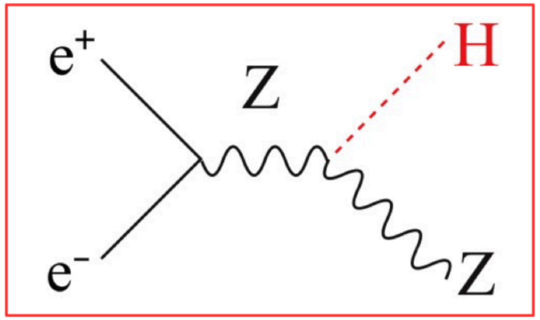
- International Linear Collider (ILC)
  - ➡ Most mature concept for an e^+e^- linear collider
  - ➡ $\sqrt{s}$ = 250 GeV (upgradeable to 1 TeV)
  - ➡ Polarised beams



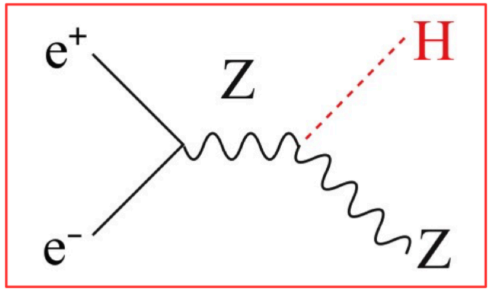
- International Large Detector (ILD)
  - ➡ Large time projection chamber (TPC) and silicon tracker
  - ➡ Highly granular calorimeters within the solenoid magnet

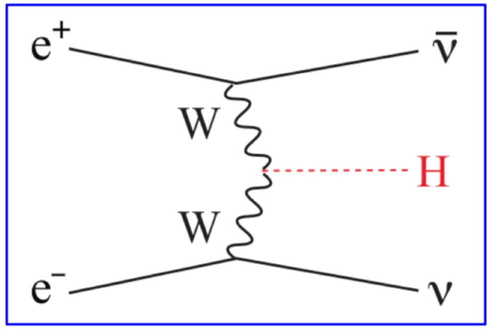


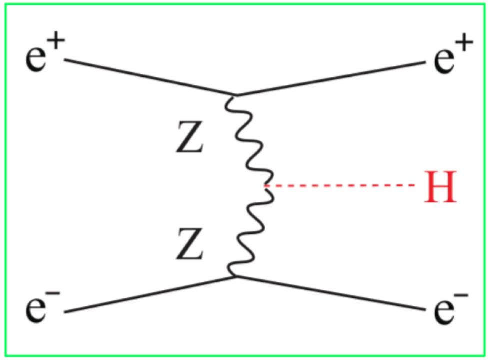
- Precision measurements of Higgs boson quantities at the ILC
  - ➡ e. g. model independent measurement of coupling and full width from Higgsstrahlung process with recoil mass technique

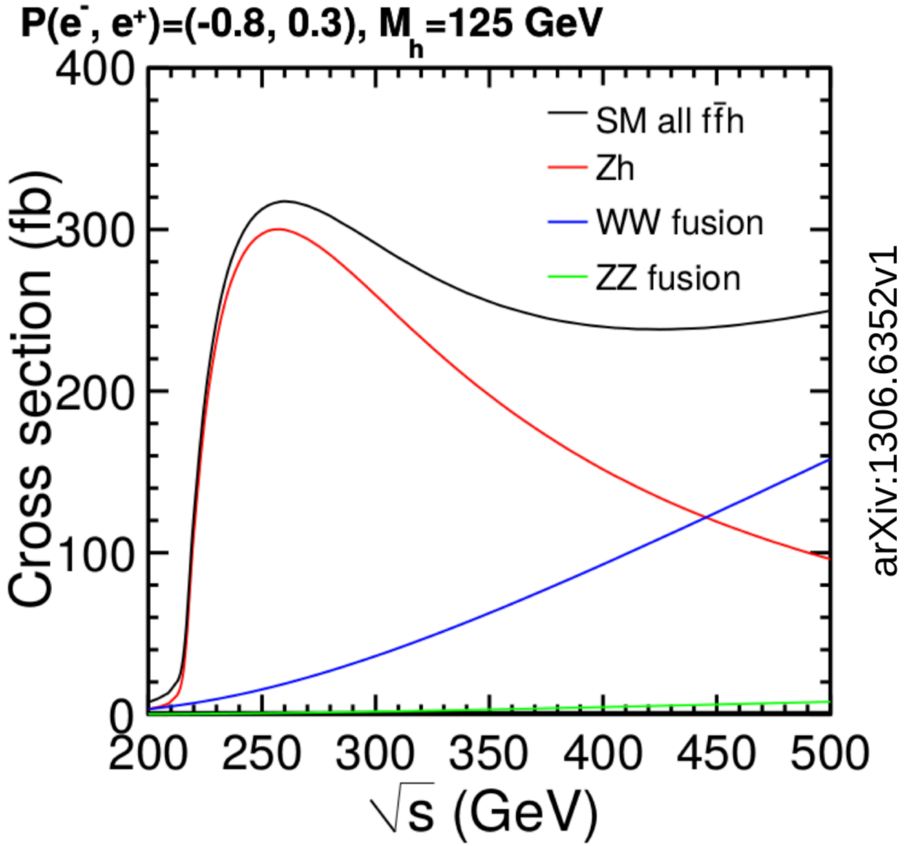


Higgs Boson Production Modes at the ILC









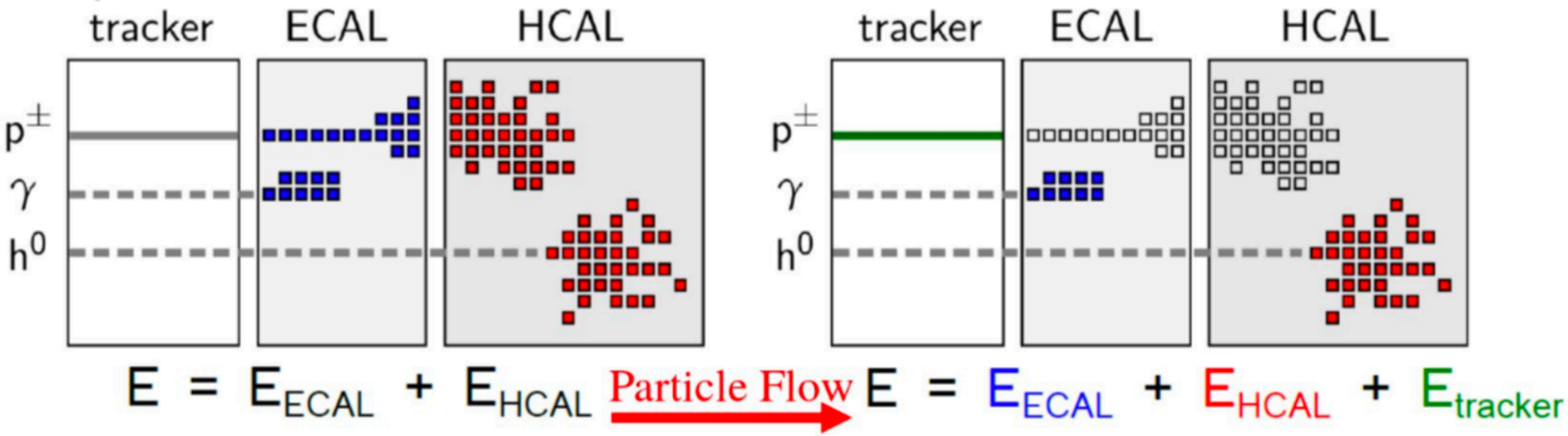
Particle Flow Approach (PFA)

Optimization with High Granularity

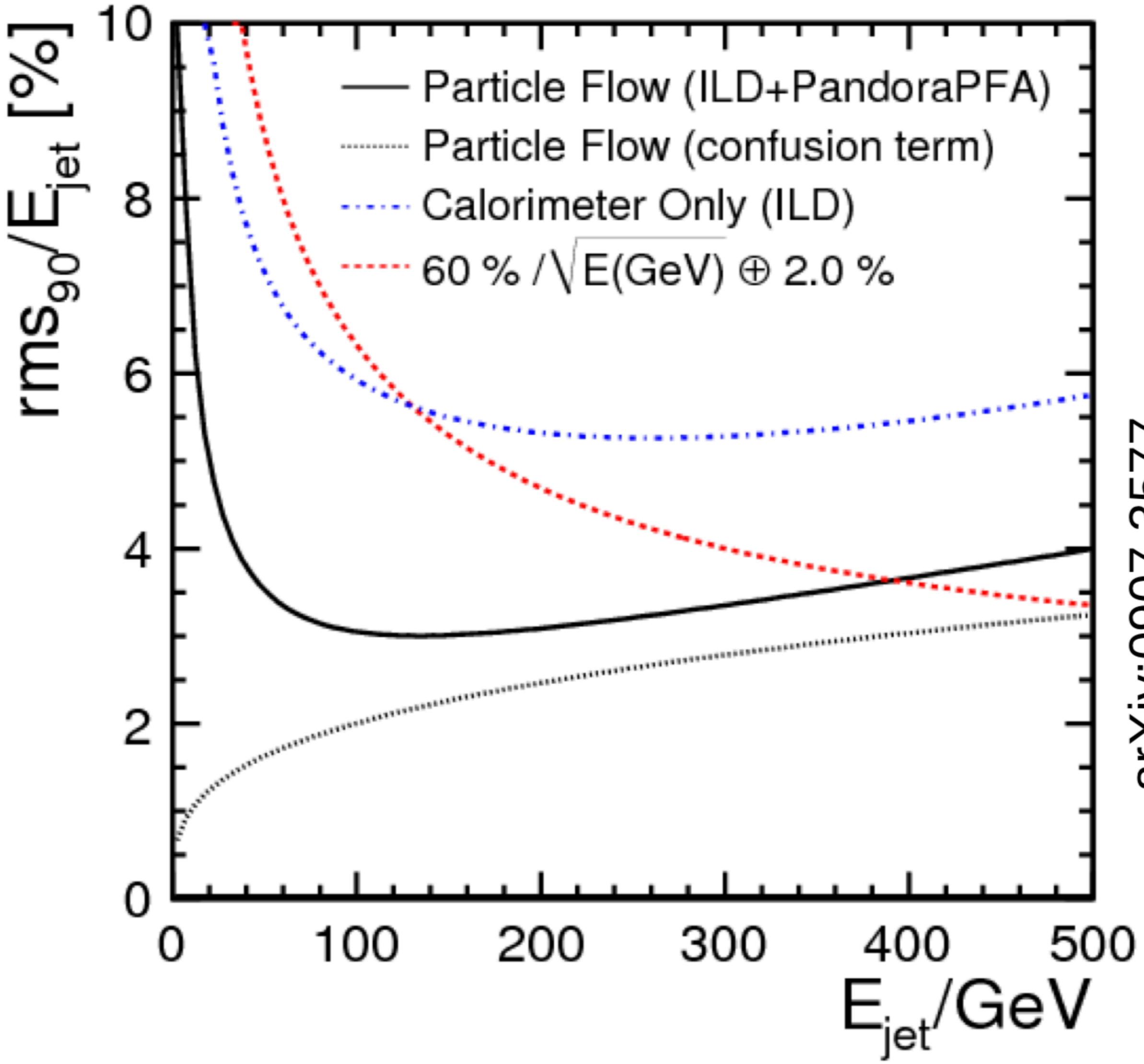
- Requirement at the ILC: Jet energy resolution of 3-4 % for jet energies between 40-500 GeV
- Typical jet composition of 70 % hadrons measured with limited hadronic energy resolution ~60%/√E

➡ PFA: Measure energy/momentum of each particle with detector providing best resolution

- ➡ 62% charged particles ➙ tracker, 27% photons ➙ ECAL, 10% neutral hadrons ➙ ECAL + HCAL
  - ➡ Highly granular calorimeters required: Energy deposition to track assignment, identifying neutral hadrons to avoid confusion



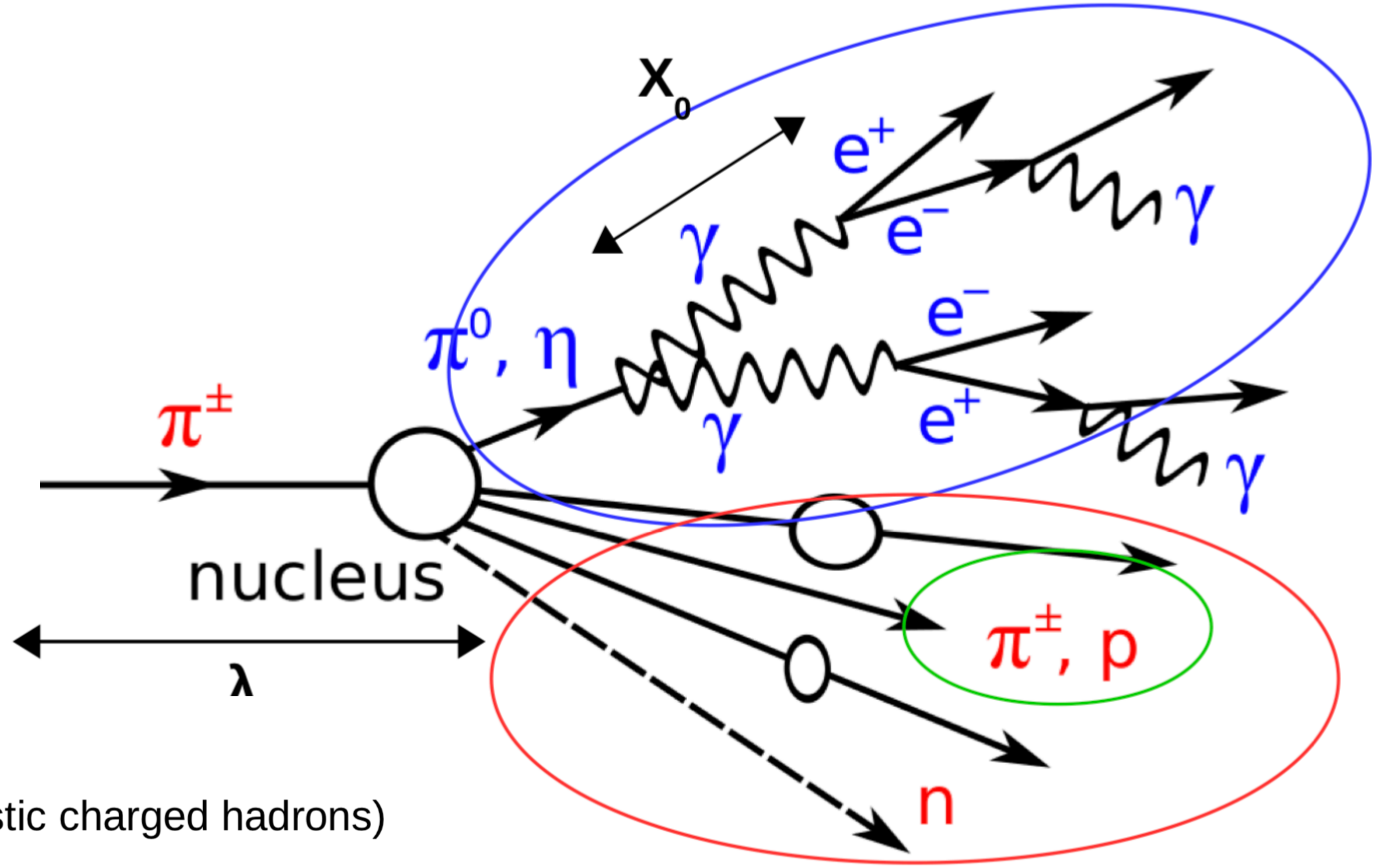
Pandora Particle Flow Algorithms



arXiv:0907.3577

Structure of Hadronic Showers

- Electromagnetic component from π^0, η scales with X_0 (X_0= 1.757 cm in Fe)
- Hadronic component scales with λ_n (λ_n = 16.77 cm in Fe)
- Invisible energy
  - Nuclear binding energy, target recoil
  - Neutrons

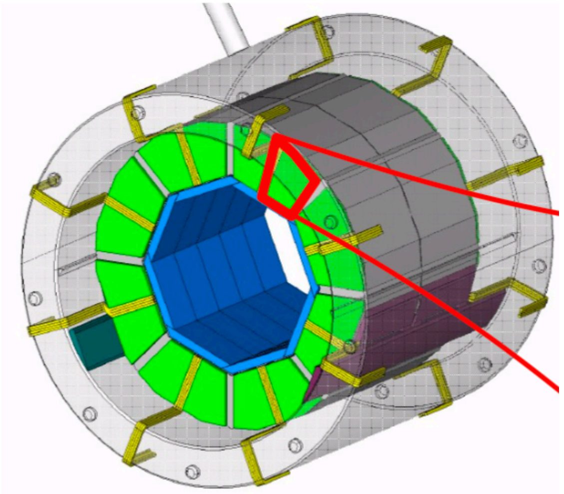


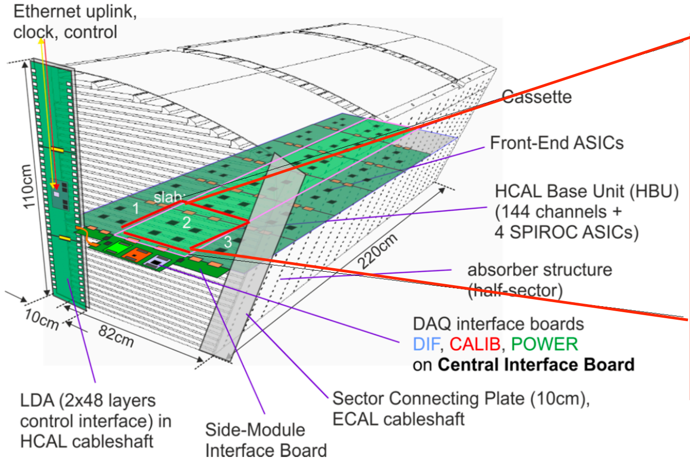
- Complex time structure
  - Instantaneous component (em, relativistic charged hadrons)
  - Delayed component (few ns up to µs)

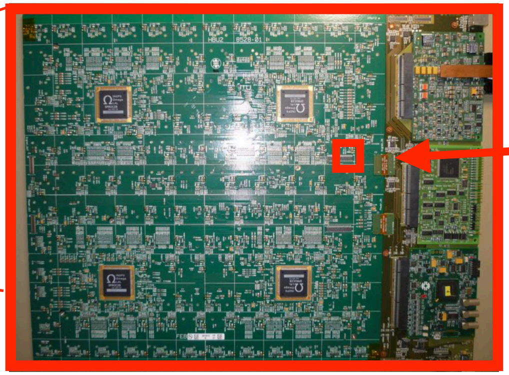
The Analog Hadron Calorimeter (AHCAL) @ ILD

Detector Concept

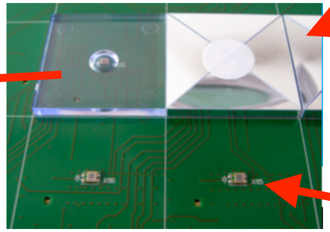
- Highly granular sampling calorimeter for the International Large Detector
  ➡ Total of ~8 million single channels: Wrapped scintillator tile coupled to SiPM readout
- **H**CAL **B**ase **U**nit: 36 · 36 cm^2 featuring 4 ASIC's reading out 144 channels
  ➡ Slabs of 6 HBU's with up to 3 slabs per layer, total of ~55000 HBU's
- Fully integrated detector design to octagonal cylinder
  ➡ Front-end readout electronics, internal LED calibration system, no cooling within active layers

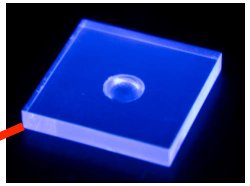


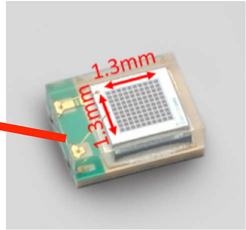




HBU







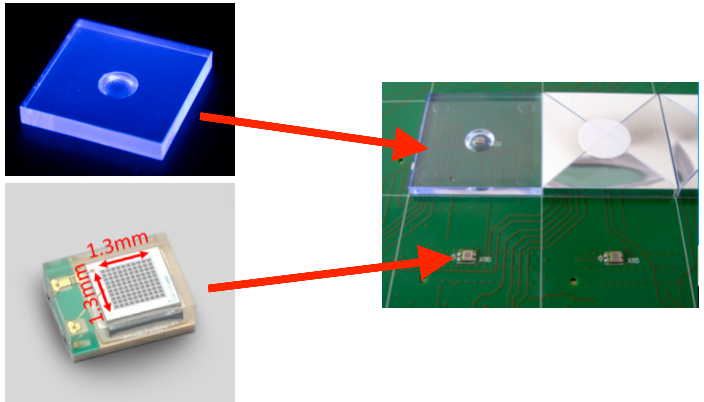
The AHCAL Technological Prototype 2018

Hardware and Goals

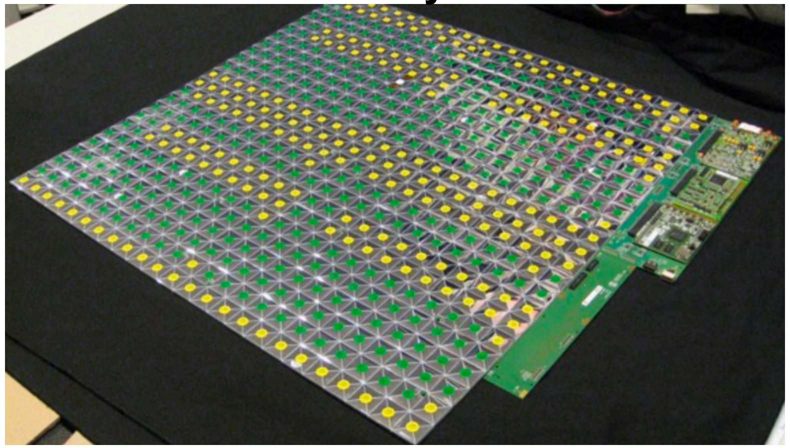
- 38 active layers of 72 · 72 cm^2 alternating with ~1.72 cm thick passive steel absorbers (~4 λ_n)
- 1 layer = 4 HCAL Base Units (HBU's) = 16 ASICS (SPIROC2E) = 576 SiPM-on-tile channels

➡ **Total of 608 ASICS, 21888 channels**

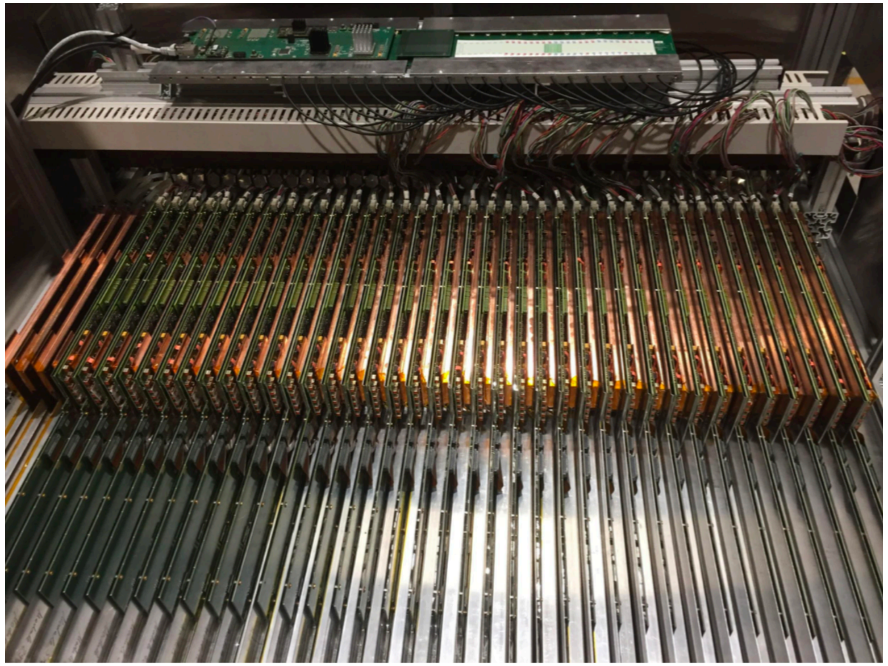
- **Goals:** Scalability of SiPM-on-tile calorimetry, reliable detector operation and studies on energy linearity, resolution and shower shapes/separation (PFA)



One layer



38 layers within steel absorber stack

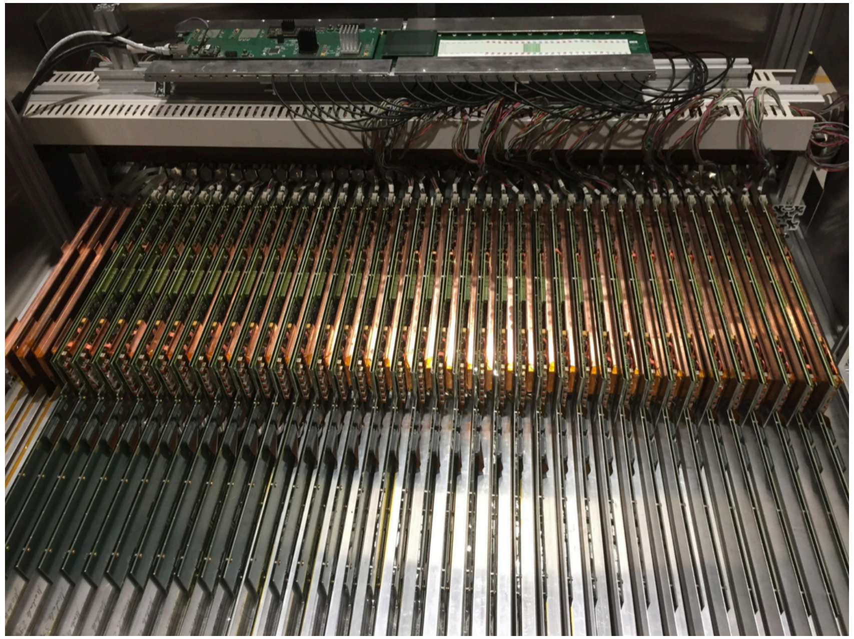


Introduction

The Current AHCAL Prototype

- Technological prototype with integrated readout electronics
- 2016/2017: Building and Testing
- In 2018: CERN SPS test beam in May and June

- 38 active layers with 72*72 cm²



- Per module: 4 HBUs

➡ 16 ASICS, 576 channels

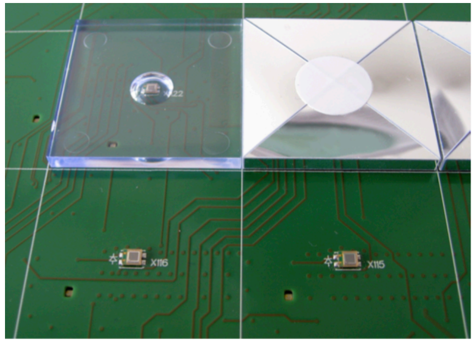
Calibration!

Total: 21888 channels

- Surface-mount SiPMs

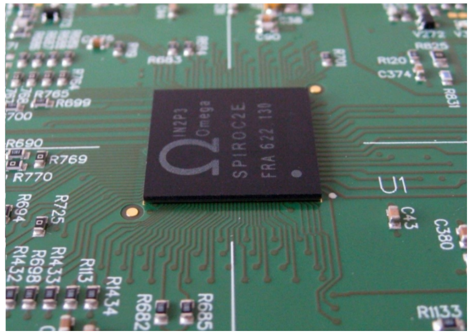
➡ 2668 pixels

➡ Operation: 5V U_{over}

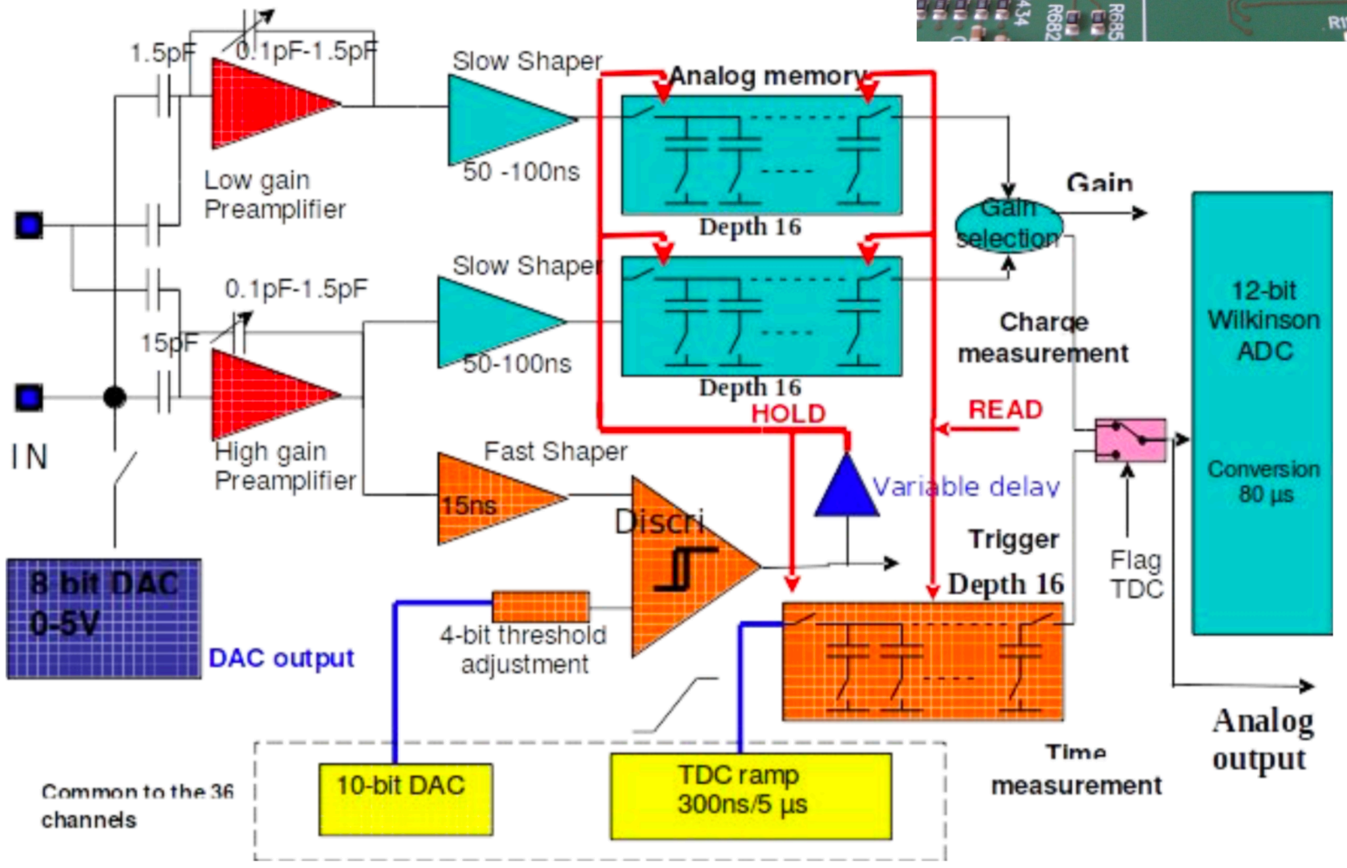


The AHCAL Readout Chip SPIROC2E

Signal Processing



- One chip reads out 36 channels
- If signal amplitude of one channel exceeds threshold, amplitude of all 36 channels is stored (auto-trigger)
- **Each channel features 16 analog buffers (memory cells)**
- High gain and low gain signal path for increased dynamic range
- TDC ramp to store timing information of each hit
- **Power Pulsing mode possible for reduction of power consumption**



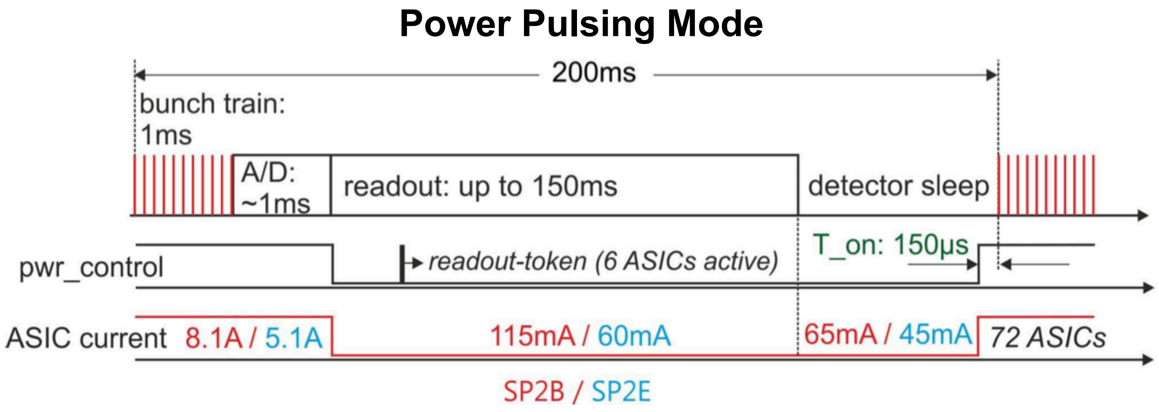
Readout schematic for one channel

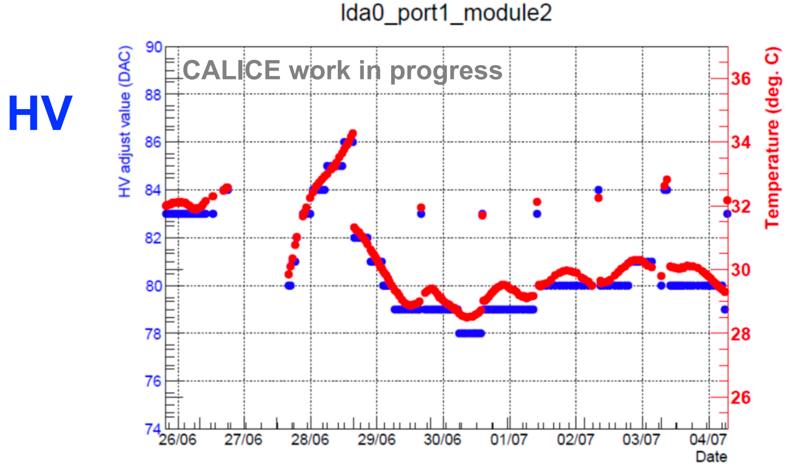
Definition of Operation Modes

AHCAL Technological Prototype 2018

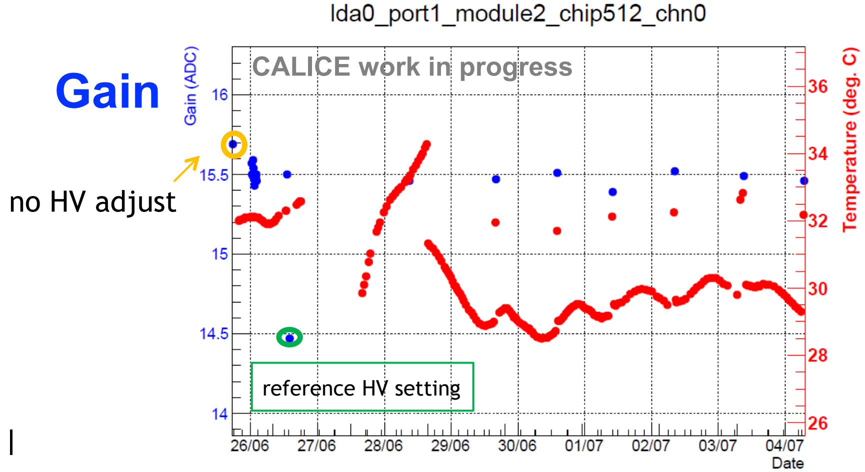
- In **physics mode** the detector is running in **ATAG** (Auto-Trigger, Auto-Gain Selection)
- In **LED calibration mode** detector is running in **ETHG** (External-trigger, High-Gain)
- **Power Pulsing mode (PP)** is used to reduce power consumption between bunch trains of ILC
  - ➡ **ALWAYS ON mode** for testing purposes
- **Temperature compensation** is frequently adjusting bias voltage of SiPM's according to temperature in layers to stabilise gain and photon detection efficiency

$$V_{over} = V_{bias} - V_{breakdown}(T)$$





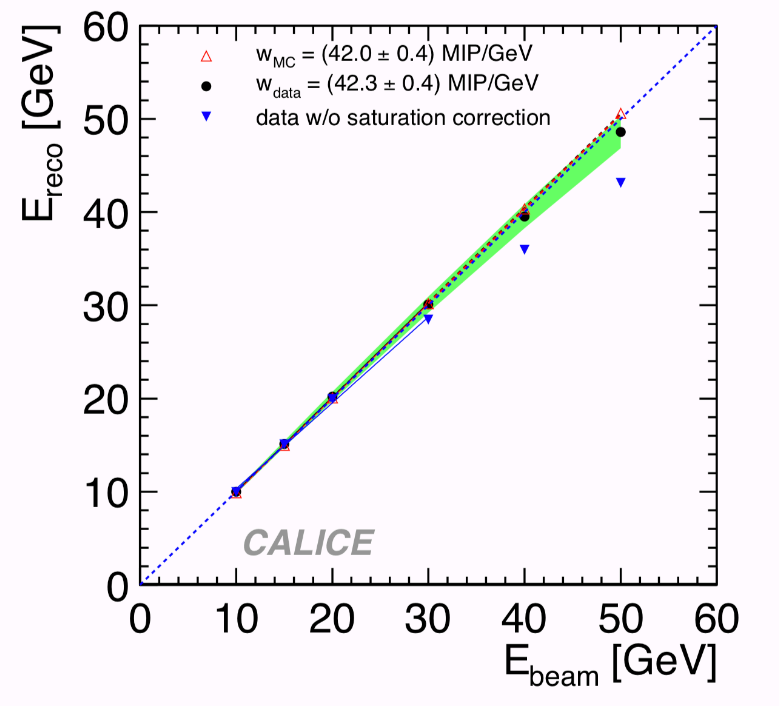
By Yuji Sudo



MIP to GEV and Software Compensation

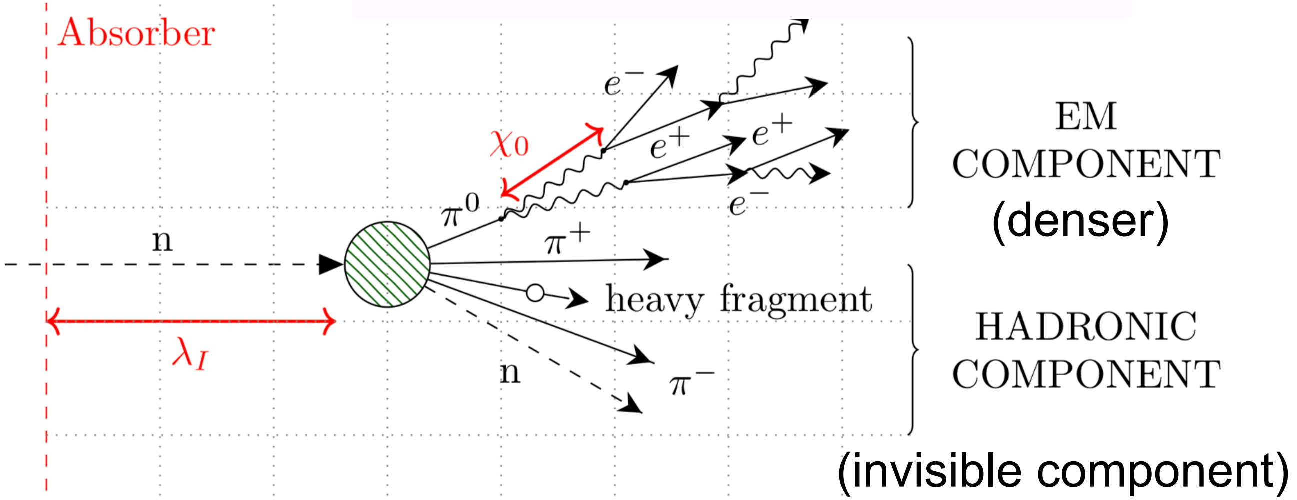
Motivation

- MIP to GeV factor extracted from MC simulation for electron/positron beam
  - ➡ Extract slope: Reconstructed energy [MIP] / beam energy [GeV]
  - ➡ Example: 1 GeV = ~ 42 MIP



Last step: Software compensation

- AHCAL is a non compensating calorimeter:
  - ➡ Higher detector response for electromagnetic compared to hadronic showers $\frac{e}{h} > 1$
    - ➡ Software compensation: Apply specific energy weights to compensate for EM/hadronic detector response

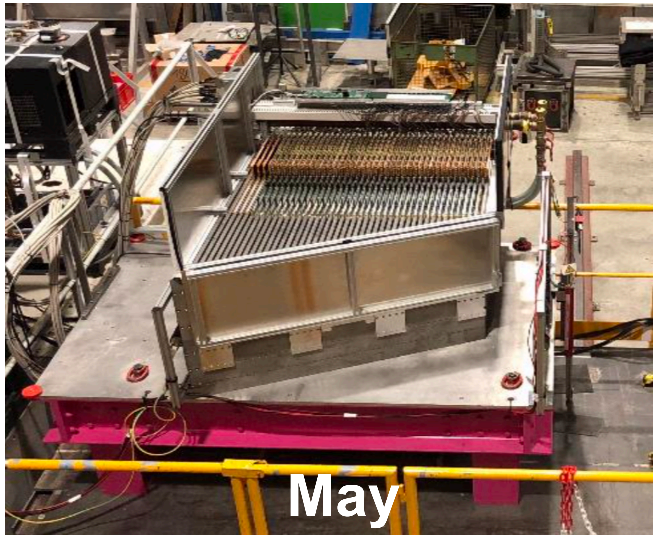


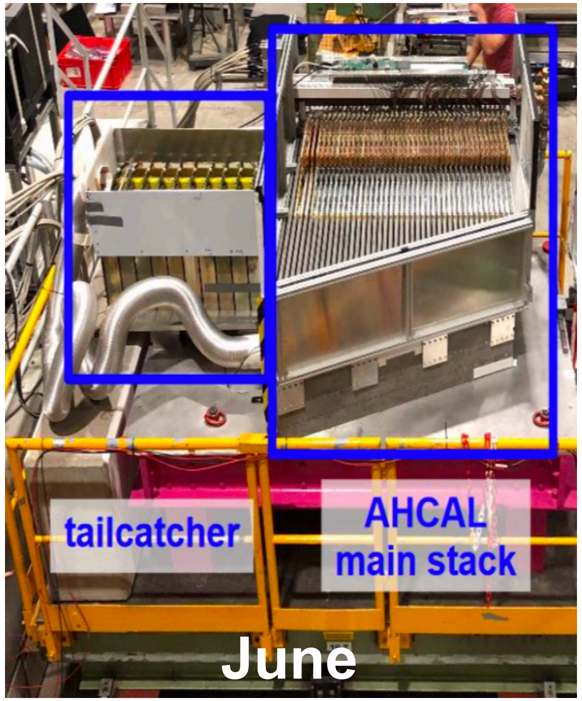
The CALICE AHCAL Test Beam Campaigns 2018

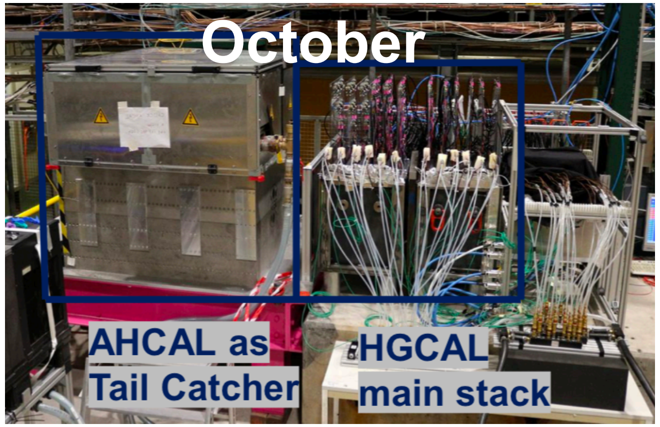
The AHCAL Test Beam Campaigns 2018

May, June and October @ SPS Cern

- May: 38 AHCAL main layers
- June: 39 AHCAL main layers + 12 single HBU’s as tail catcher
- October: 39 AHCAL main layers as CMS HGCAL tail catcher





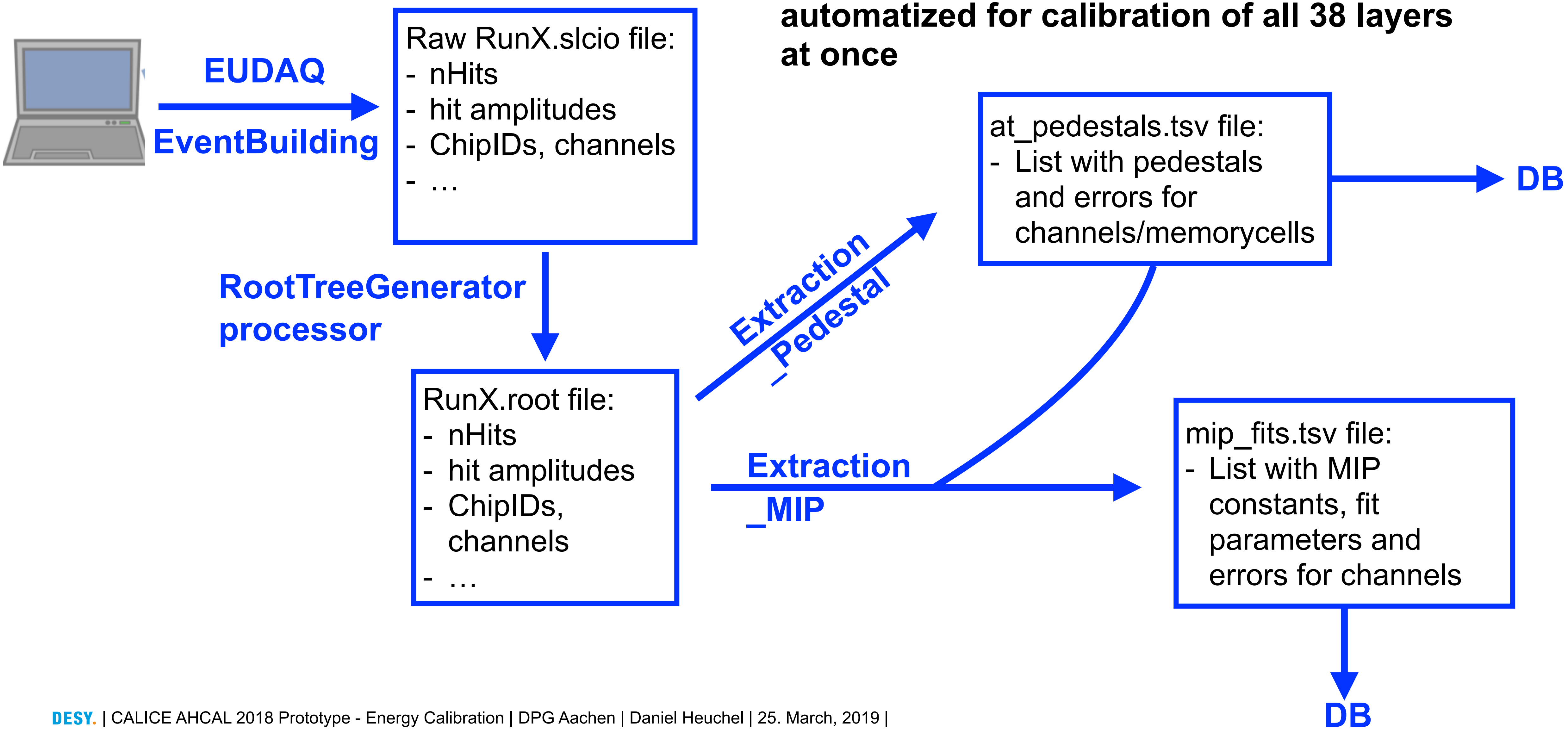


- Data sets:
  - ➡ Muons for calibration purposes
  - ➡ Electron and pion energy scans
  - ➡ LED gain calibration runs

Overview Calibration Procedure

Schematic of Procedure

- **New calibration procedure simplified and automatized for calibration of all 38 layers at once**

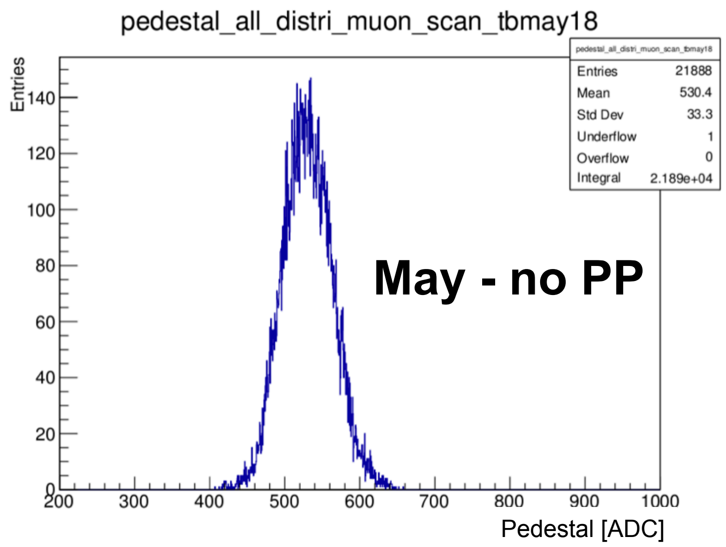


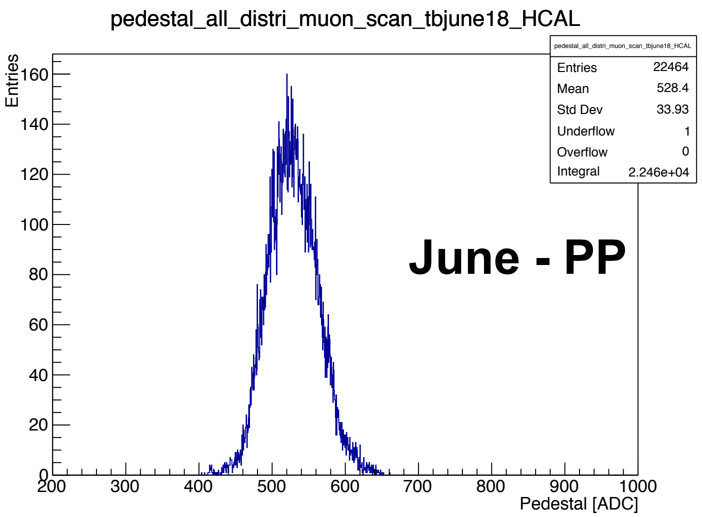
Pedestal Extraction Results

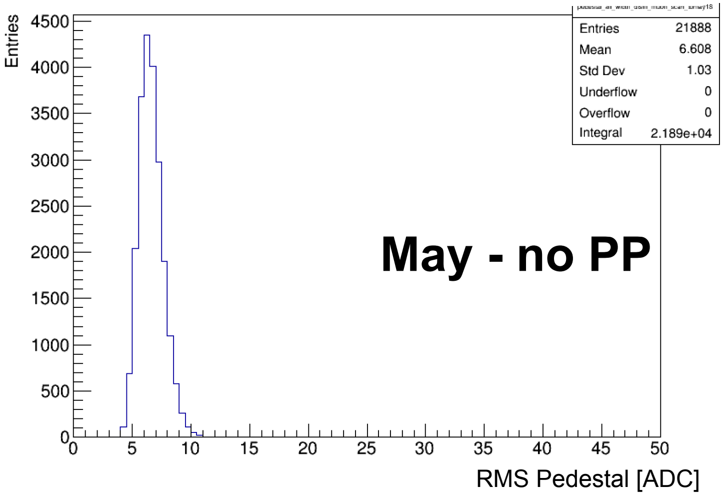
For SPS May and June Test Beam Data

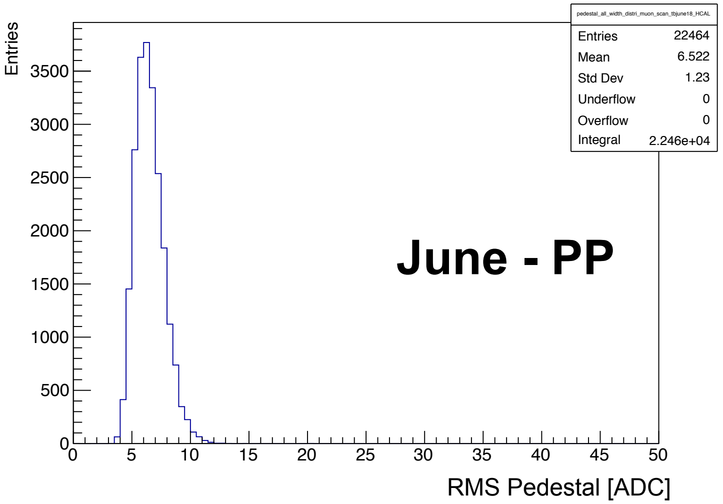
Channel Level

- Total of 21888/22464 channel pedestals (from memory cell 0-8) and corresponding RMS of pedestal spectra









- Mean pedestal: 530.4 ADC (May), 528.4 ADC (June)
- Spread: 33.3 ADC (May), 33.9 ADC (June)
- Total min-max variation within ~1 MIP

- Mean RMS of pedestal spectra: 6.6 ADC (May), 6.5 ADC (June)

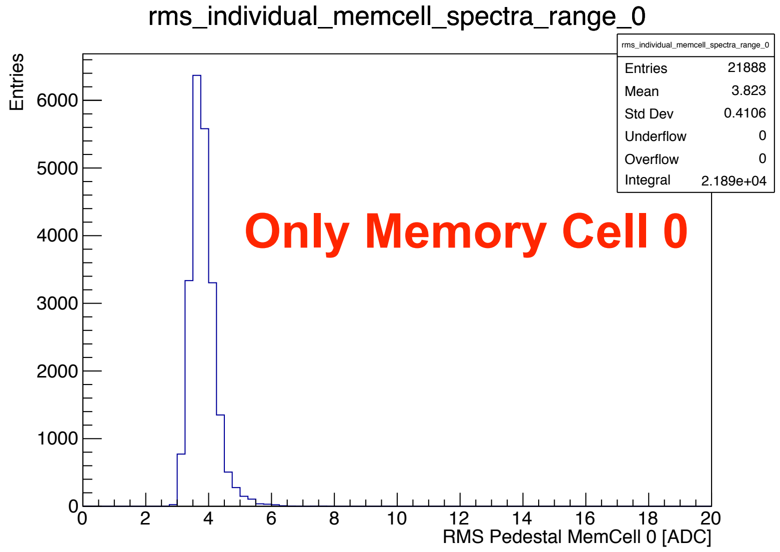
➡ Includes intrinsic width of pedestal and cell-to-cell variation of mean

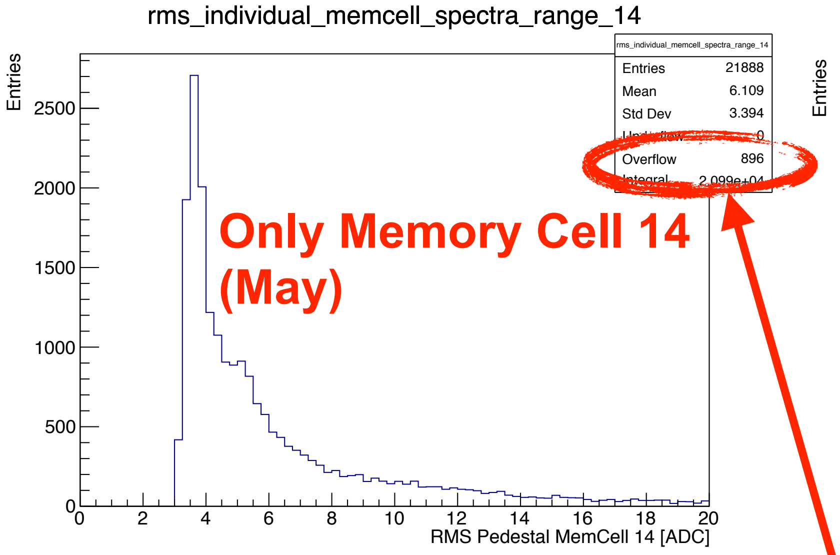
➡ No tail, no outliers

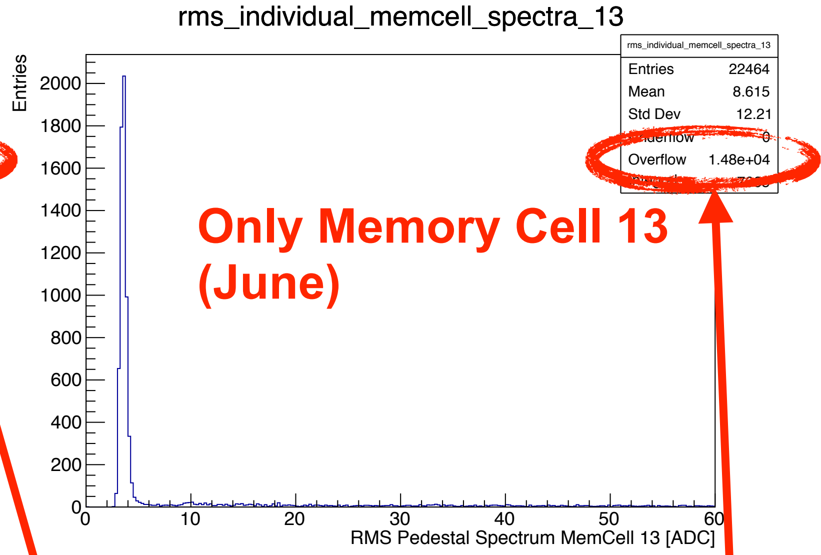
Pedestal Anomalies

For SPS May and June TB Data

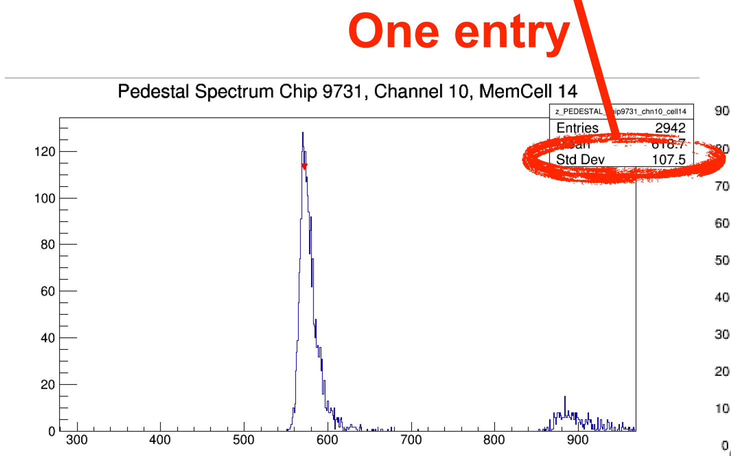
Memory Cell Level

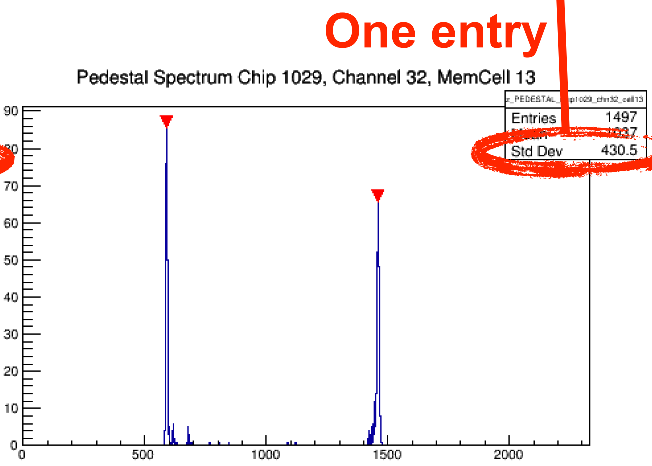






- Memory cell 0-8 fine, 9-15 larger intrinsic width
  - ➡ Origin: Second peak at higher ADC value
    - ➡ Not seen in physics/MIP signals
  - ➡ Effect more dominant in PP mode (June)
  - ➡ Use individual pedestals of memory cell 0-8
  - ➡ For memory cell 9-15 use average of 0-8





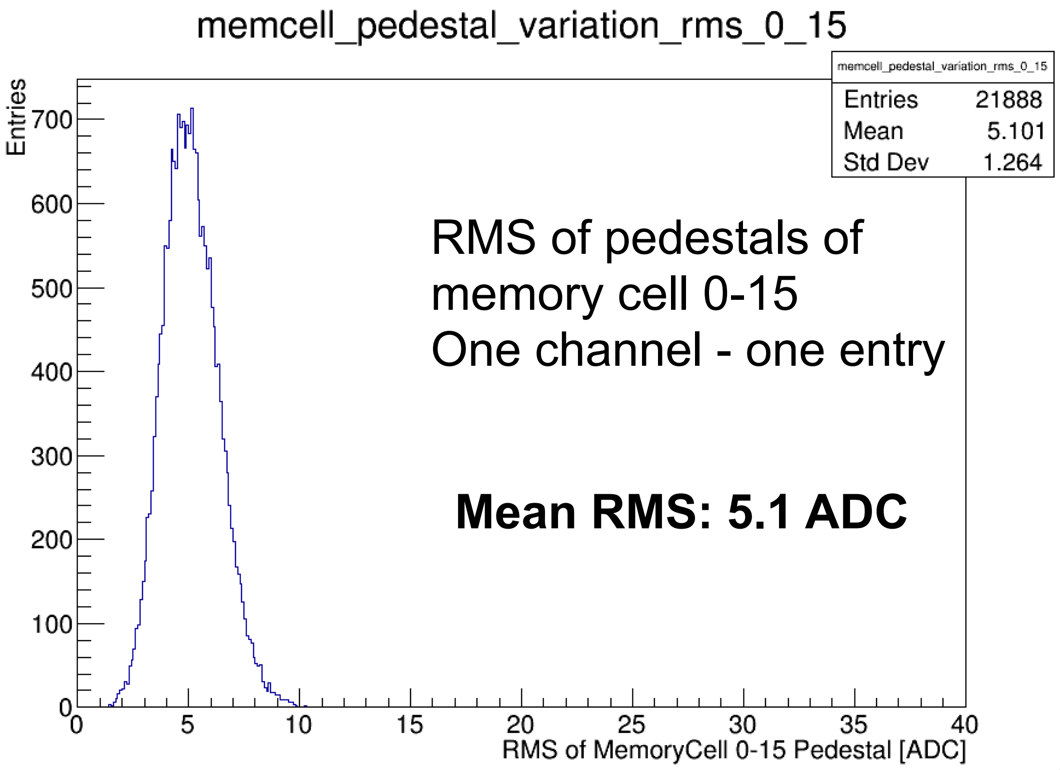
Pedestal Variations

Cell-to-Cell and Channel-to-Channel

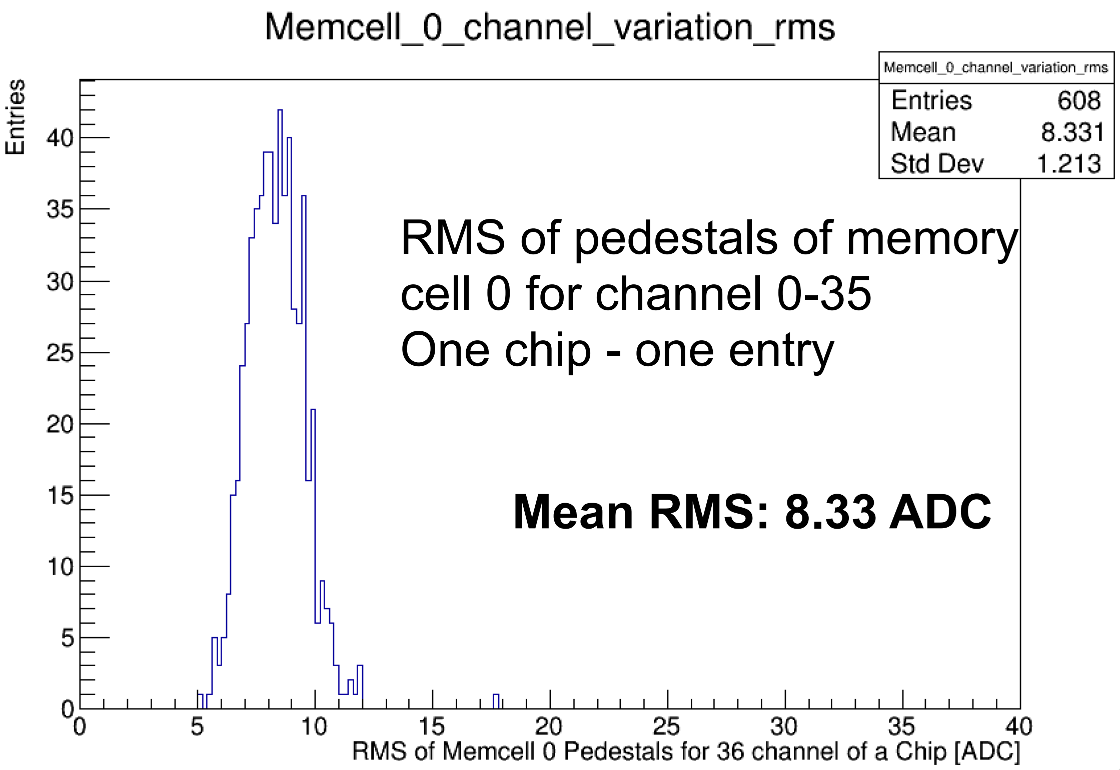
Memory Cell Level

- How is the cell-to-cell and channel-to-channel variation of the memory cell pedestals?

Cell-to-cell variation



Channel-to-channel variation (for cell 0)

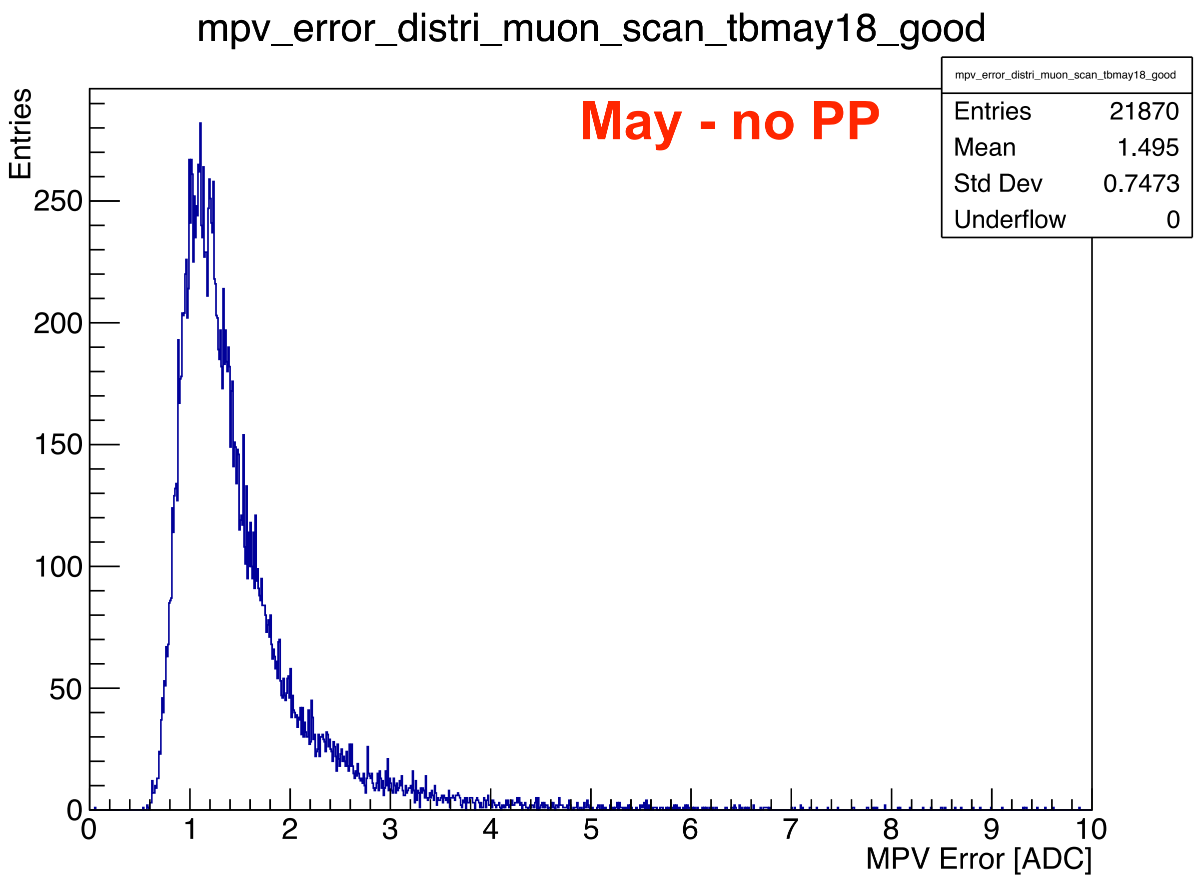


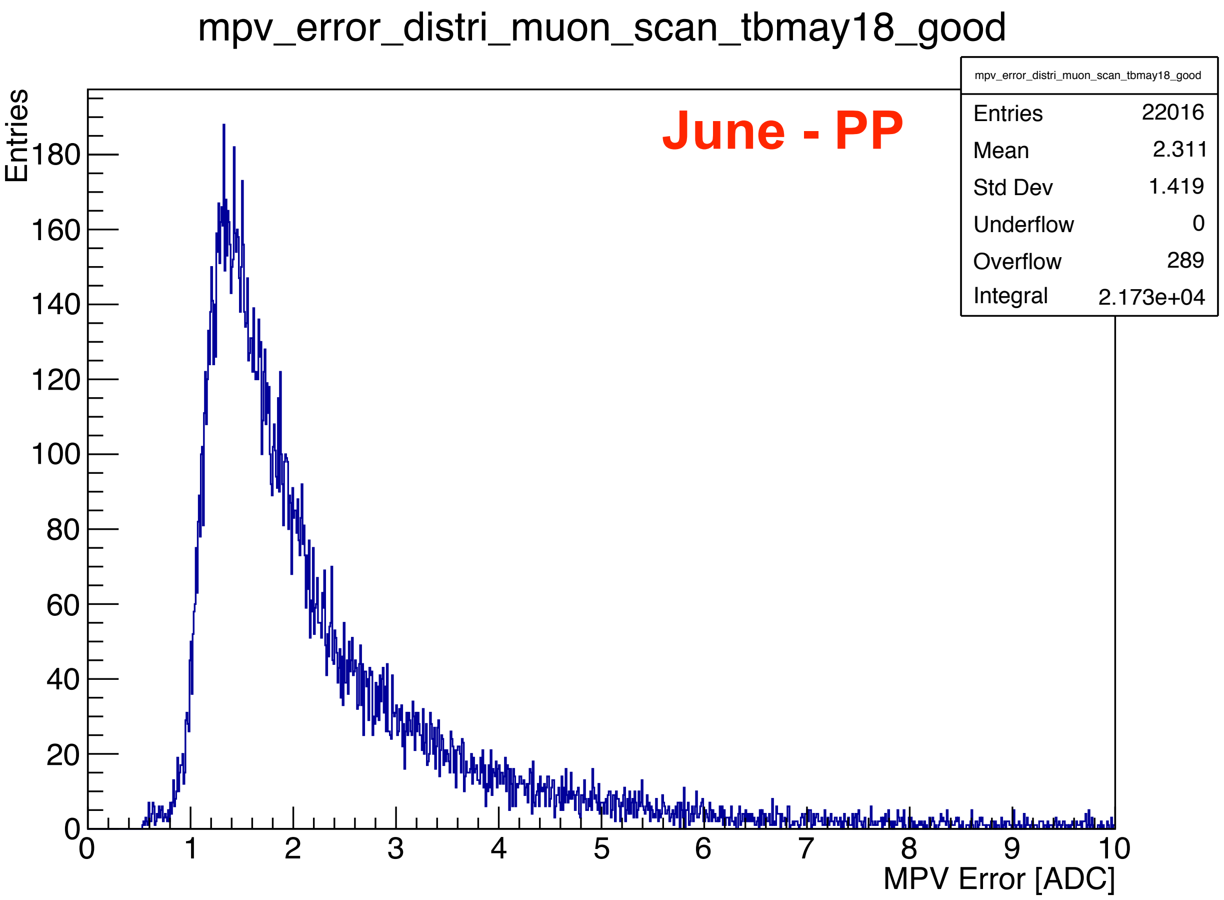
➡ Both in same order, close to mean intrinsic width of the pedestal spectra of **~ 4.3 ADC**

➡ Dominant: Chip-to-chip variation of **~ 34 ADC**

MIP Constants

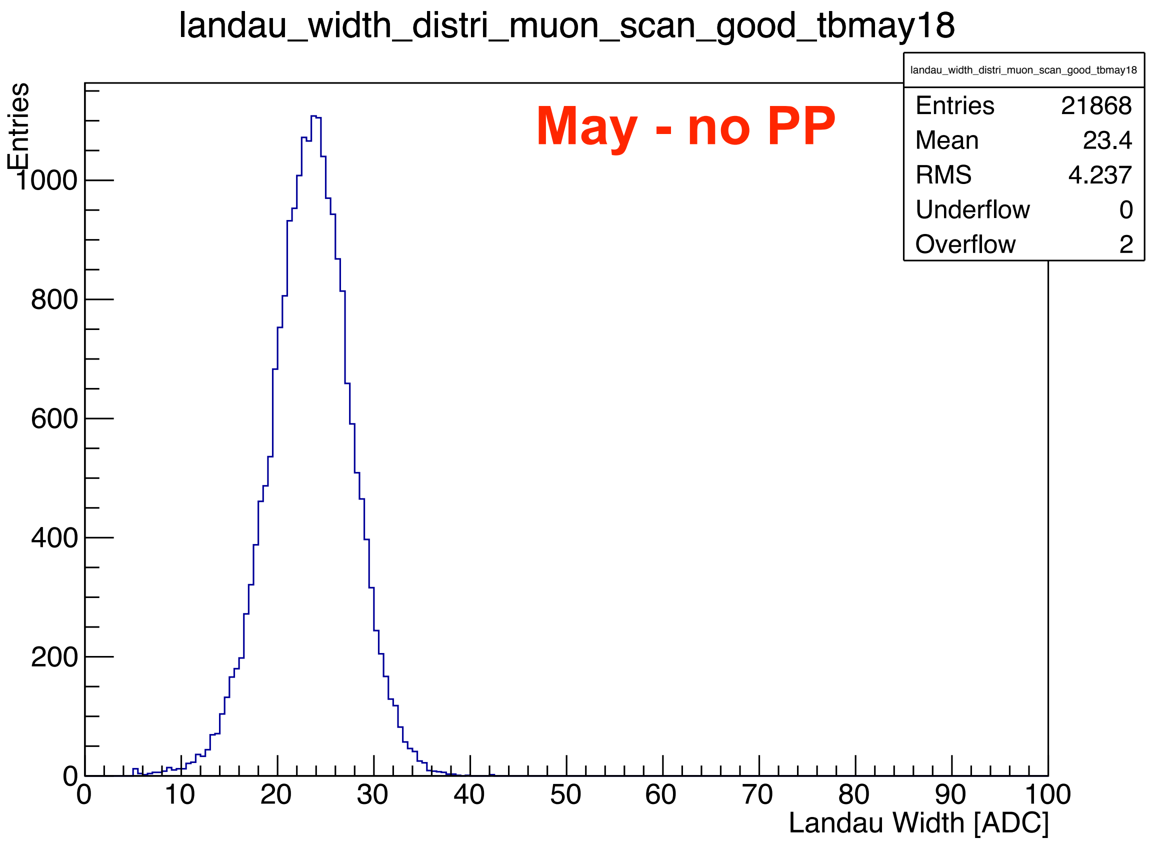
MPV Errors

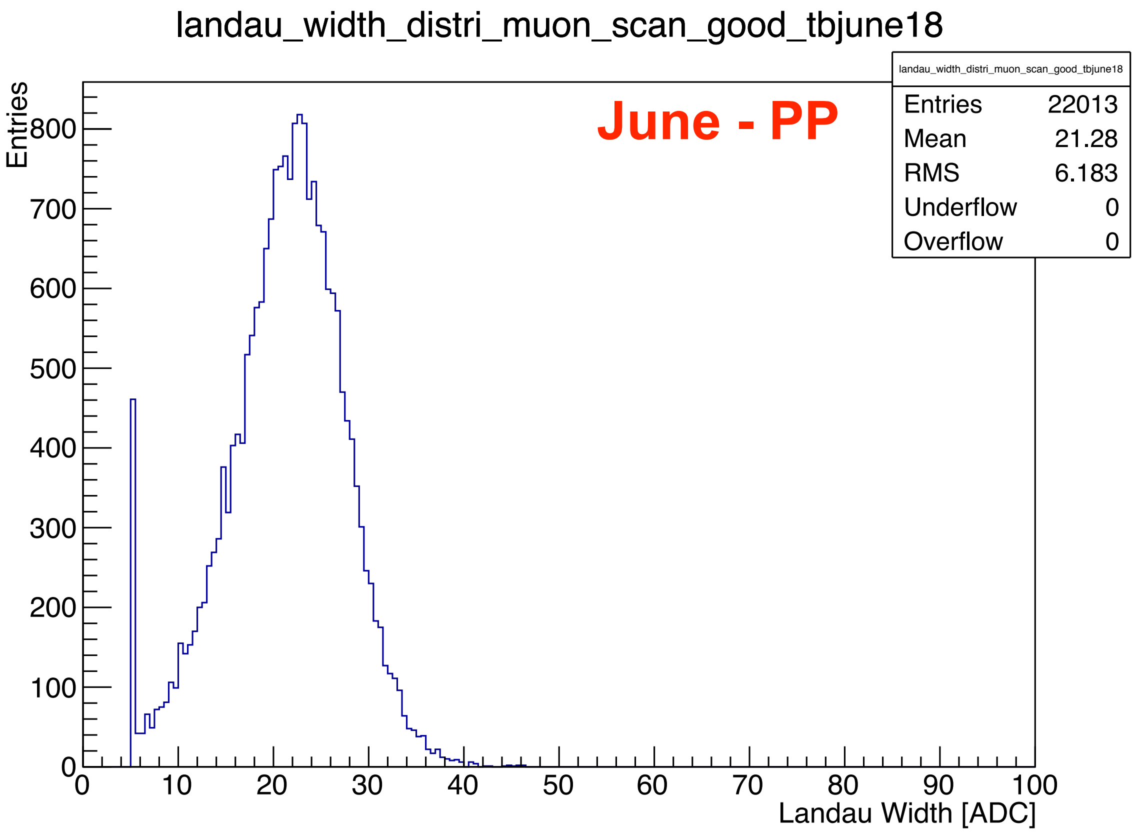




MIP Constants

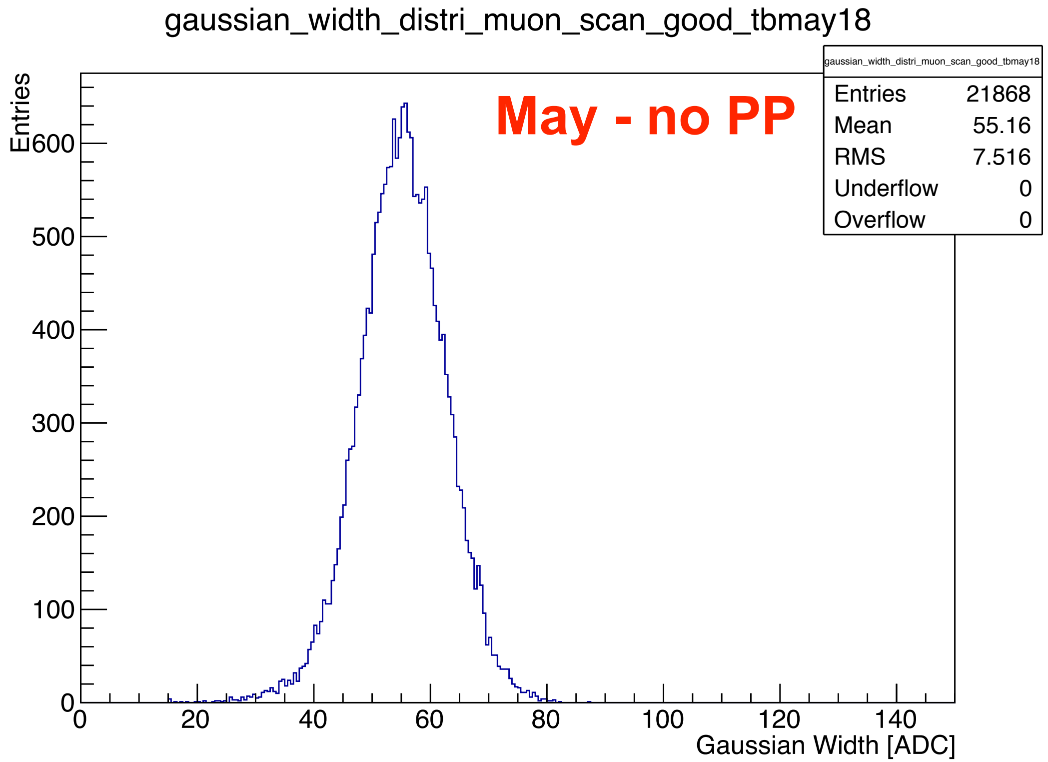
Landau Width

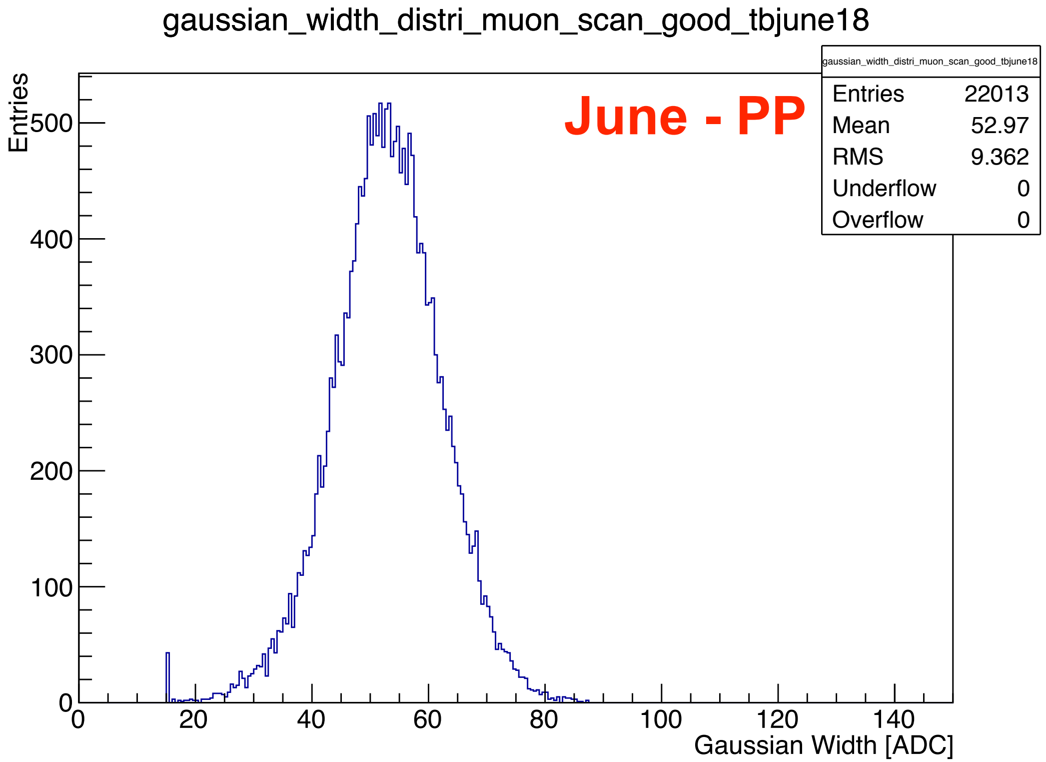




MIP Constants

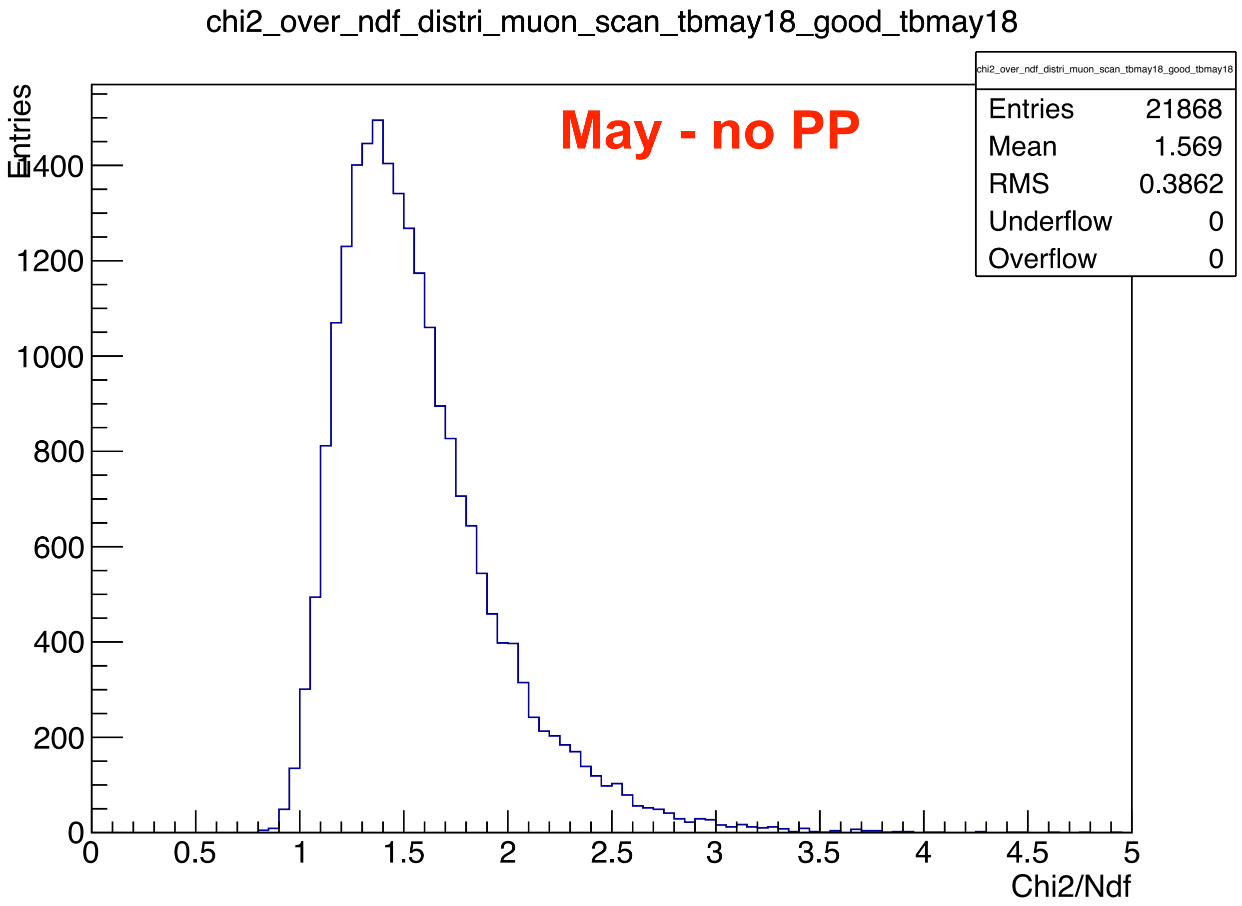
Gaussian Width

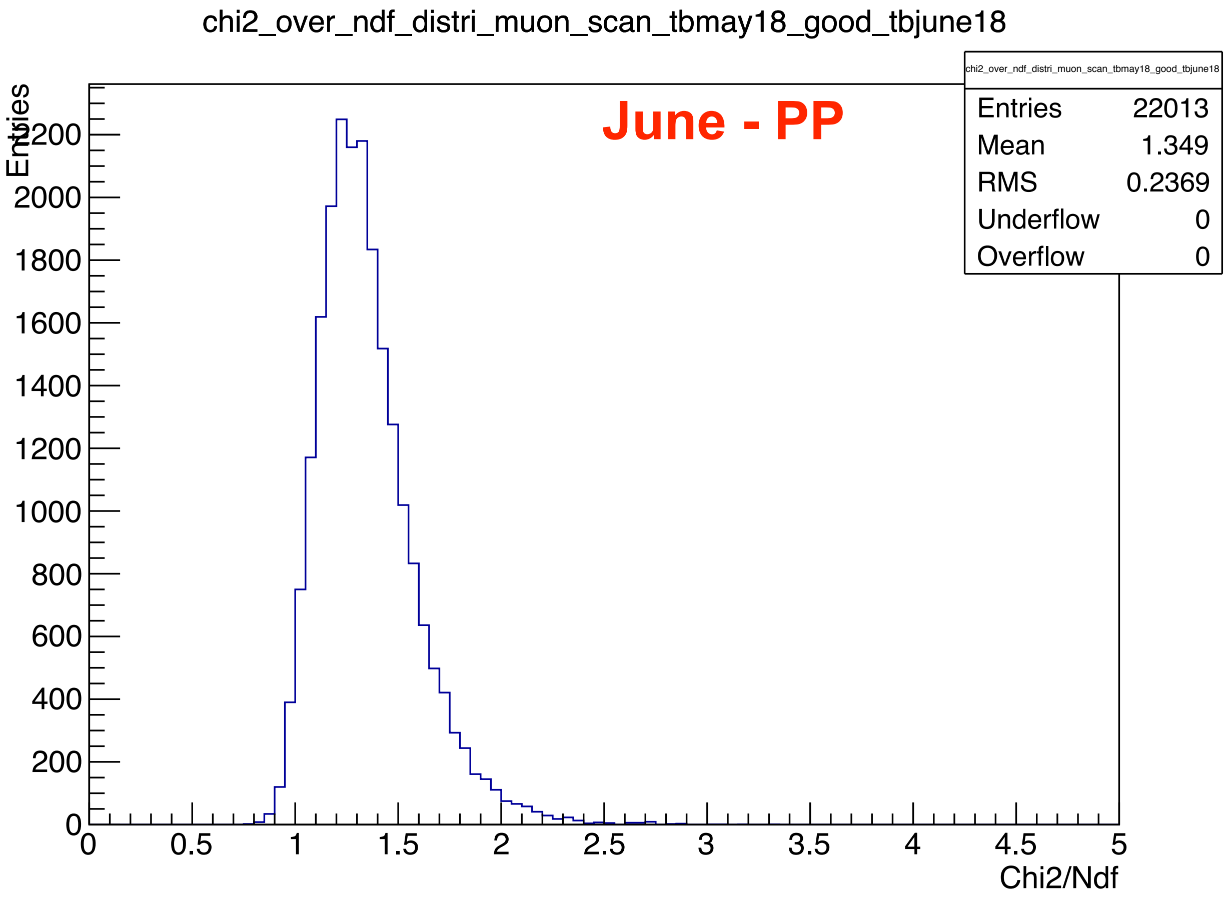




MIP Constants

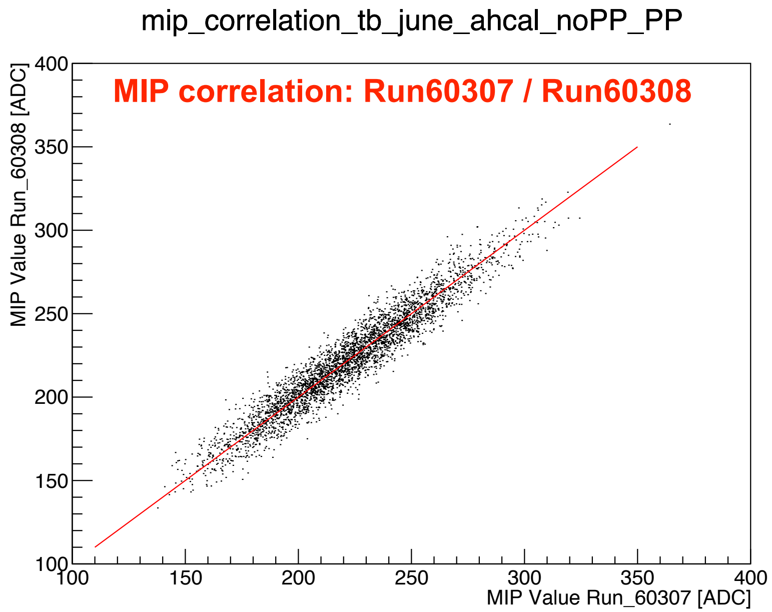
Fit Qualities

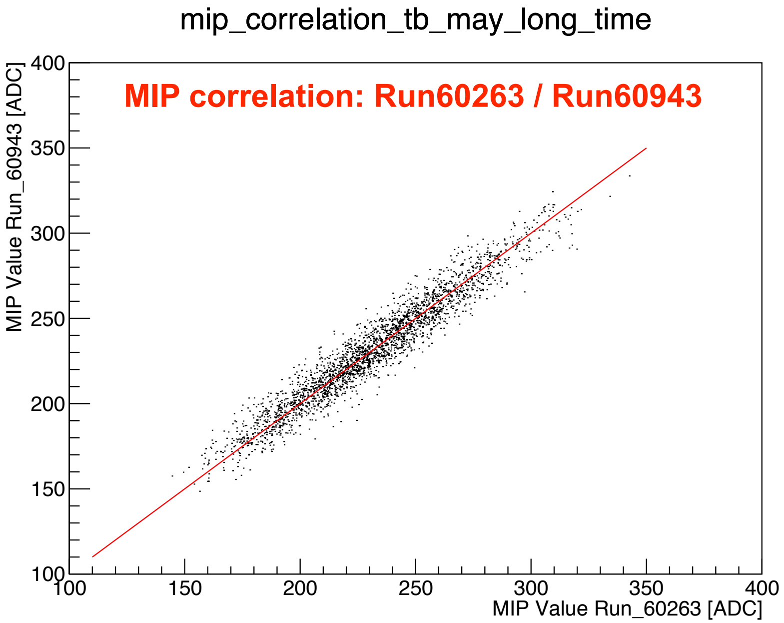


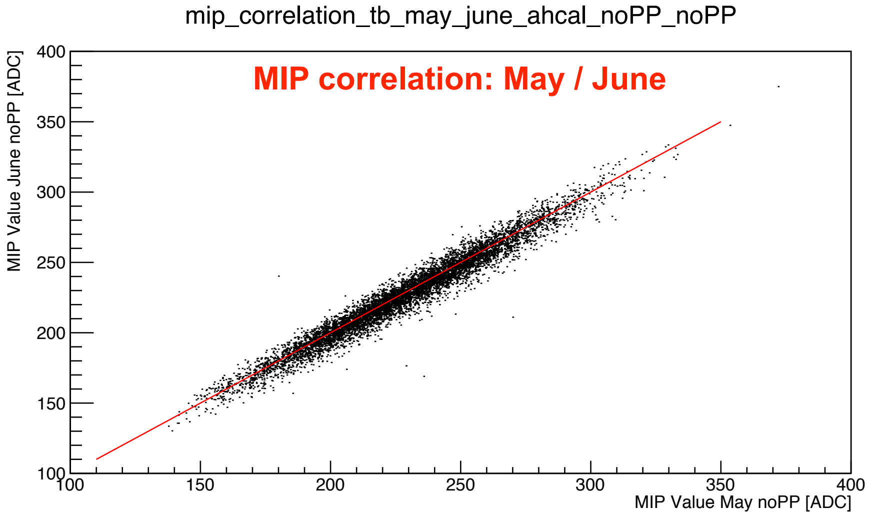


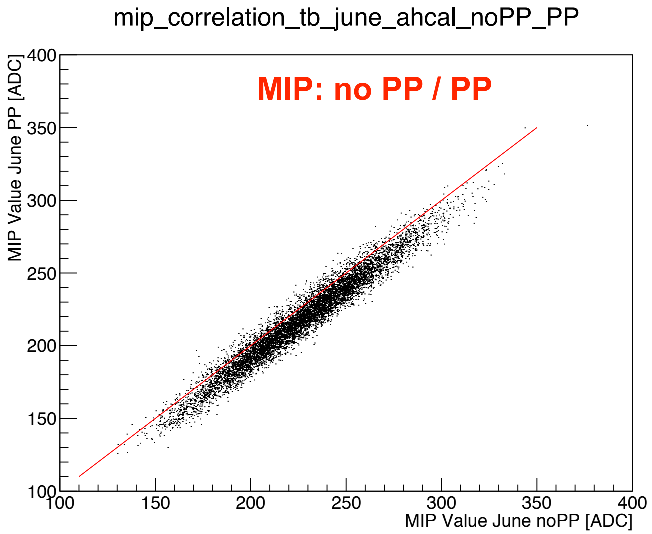
MIP Correlations

Comparative Studies



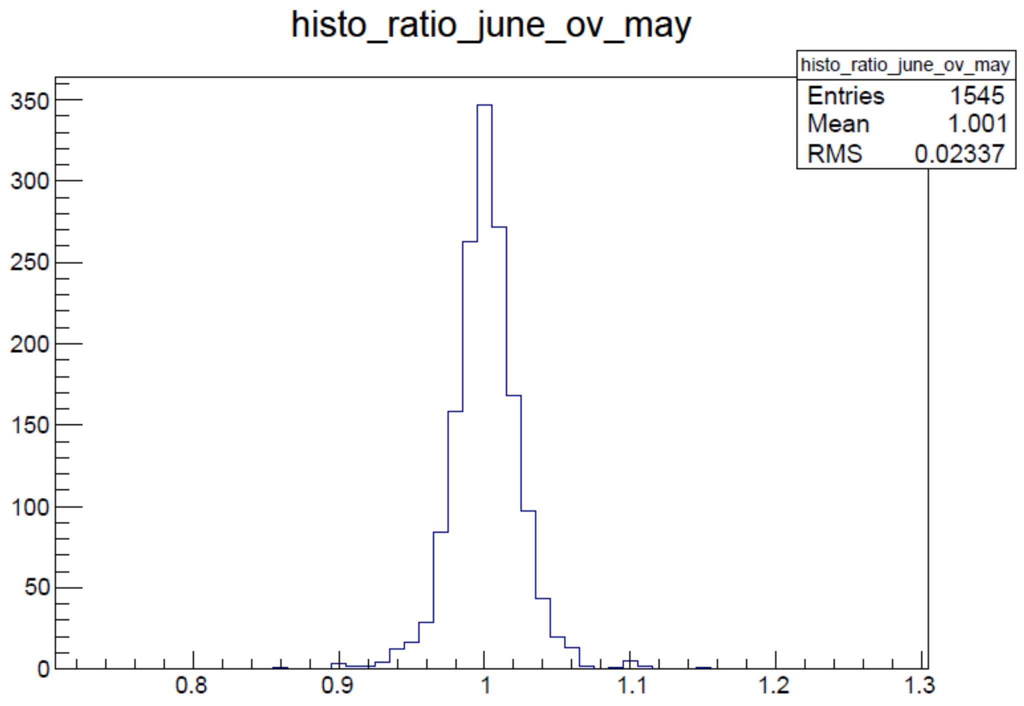




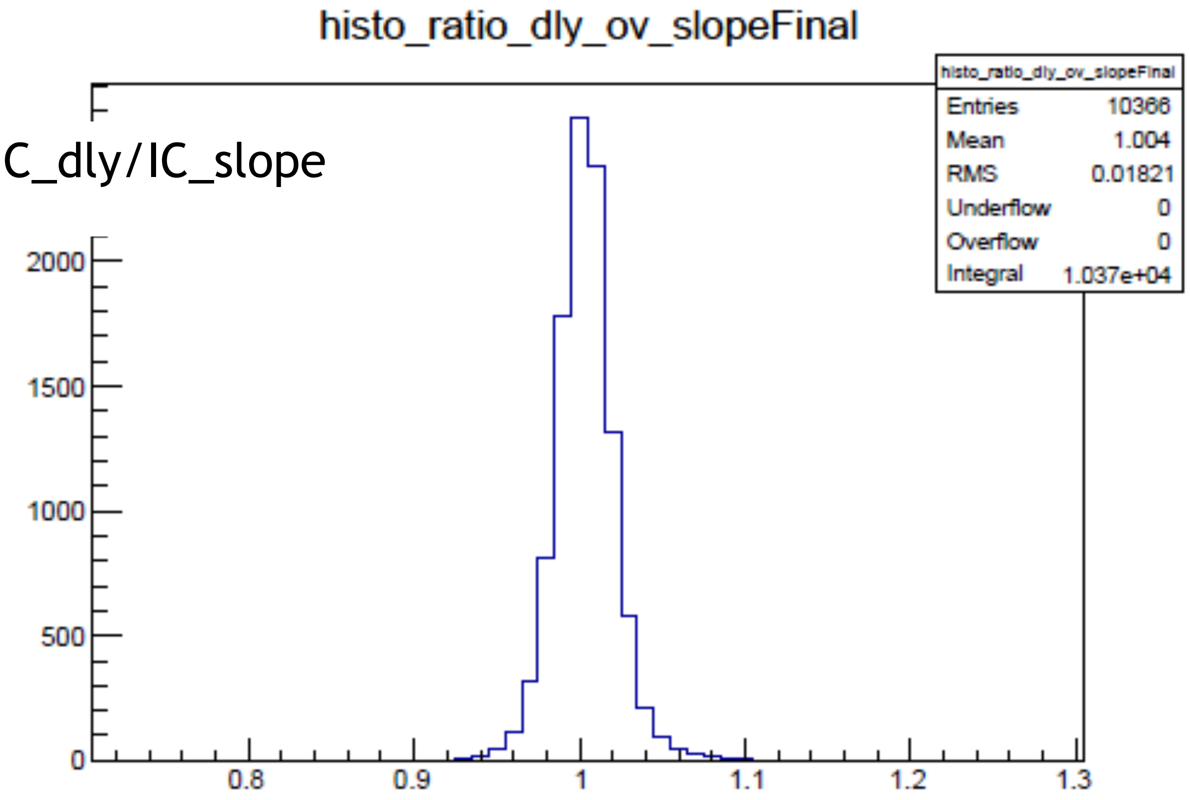


IC Constants

Comparison



IC_dly/IC_slope

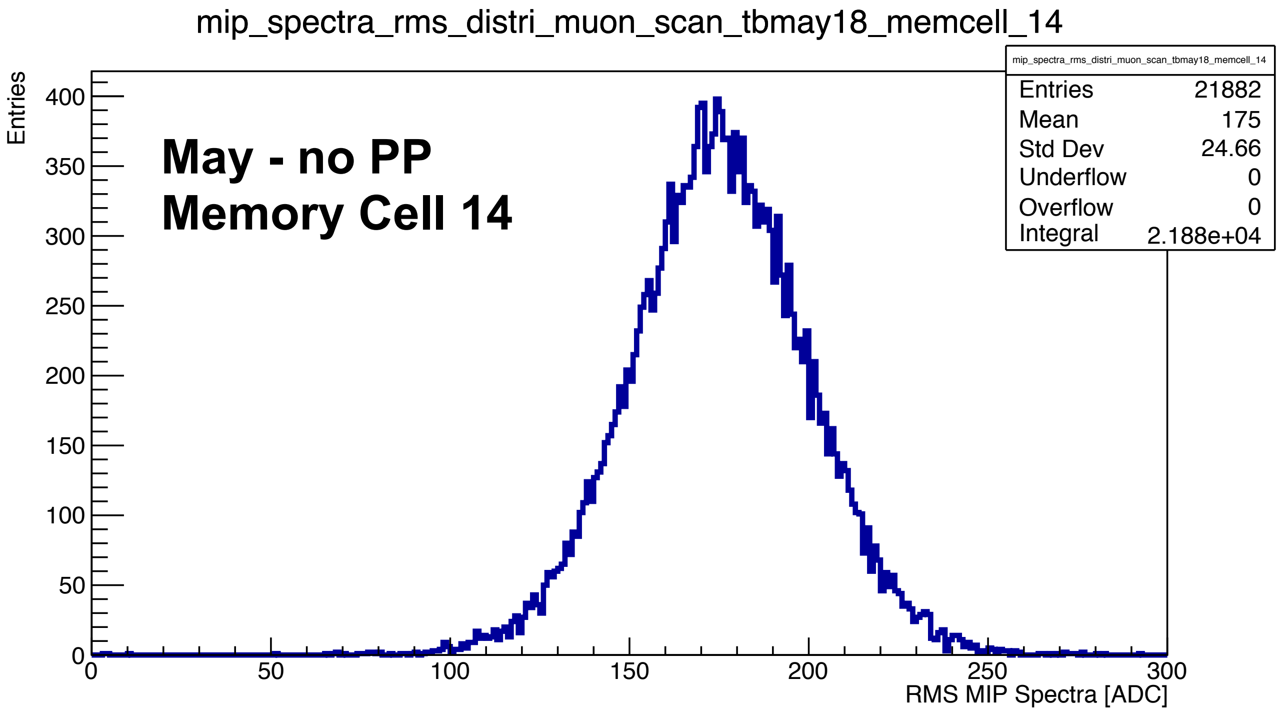


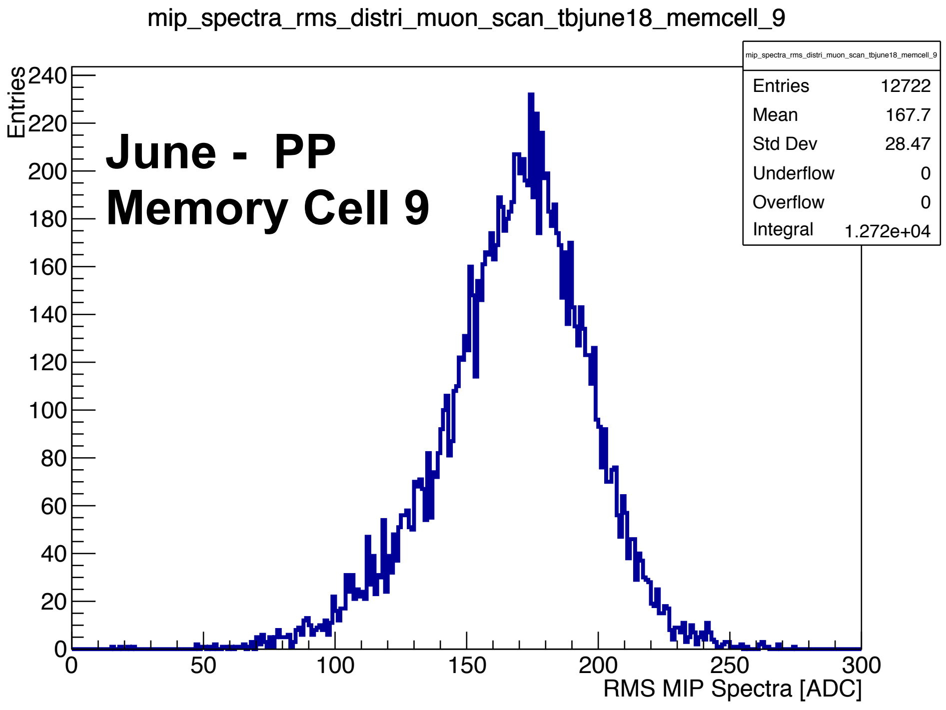
ADC Jump Studies for MIP Spectra

SPS May and June Test Beam Data

Memory Cell Level

- Extract the RMS of all MIP spectra for problematic memory cells 14 (May) and 9 (June)
  - ➡ Check for outliers, which would indicate bumps in Landau-Gaussian spectrum:





- **No ADC jumps observed in MIP physics spectra as for pedestals!**

Calibration Procedure and Results:

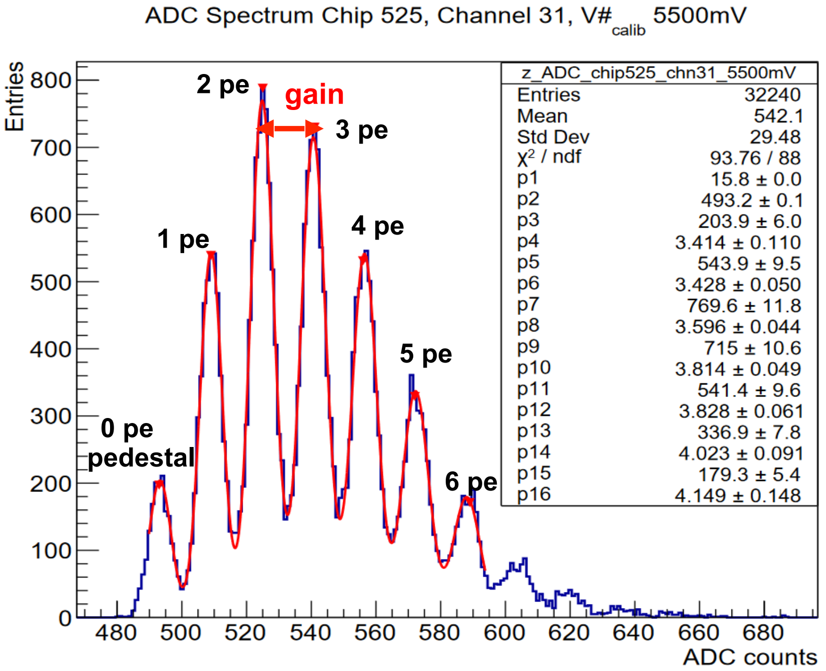
Gain and Light Yield

Gain Calibration

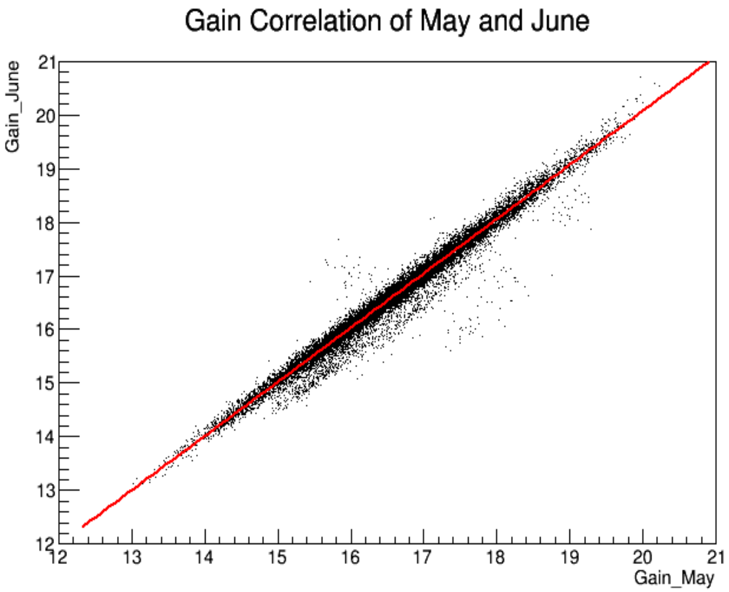
Procedure and Results

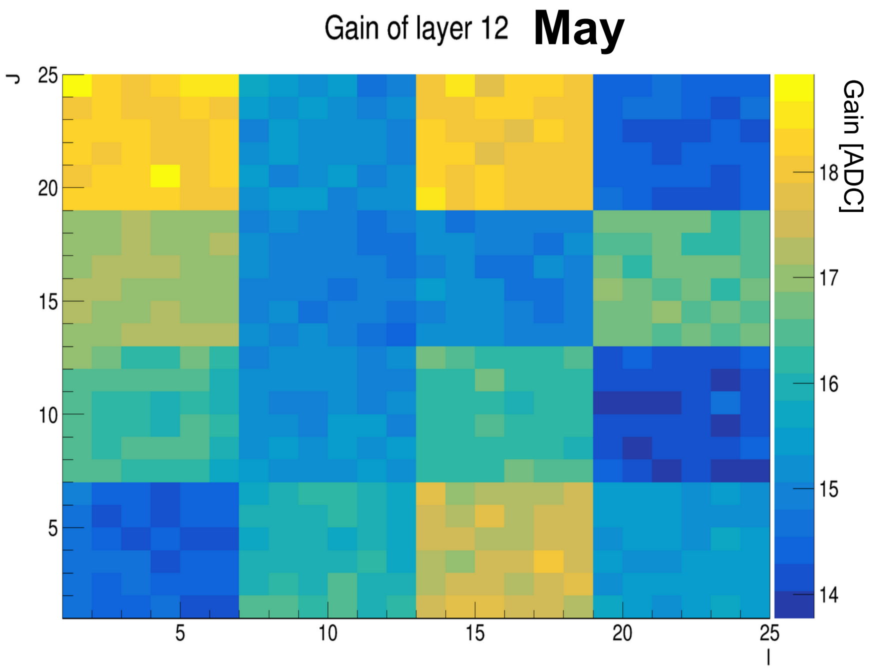
By Olin Pinto

- Integrated LED system: Illuminate the SiPMs with short-length light pulses for measurement of single photon spectrum (ETHG)
  - ➡ Memory cell specific pedestal offset correction
  - ➡ Apply multi-gaussian fit to extract the distance between the photon peaks as the **gain** in ADC (ADC ticks corresponding to one fired pixel)



- Extracted gain for 94% (May) and 98% (June) of all channels
  - ➡ Mean gain: 16.6 ADC for both periods
  - ➡ Very stable within and across test beam periods due to reliable temperature compensation





- Chip-to-chip variation (~1.05 ADC) is the dominant spread

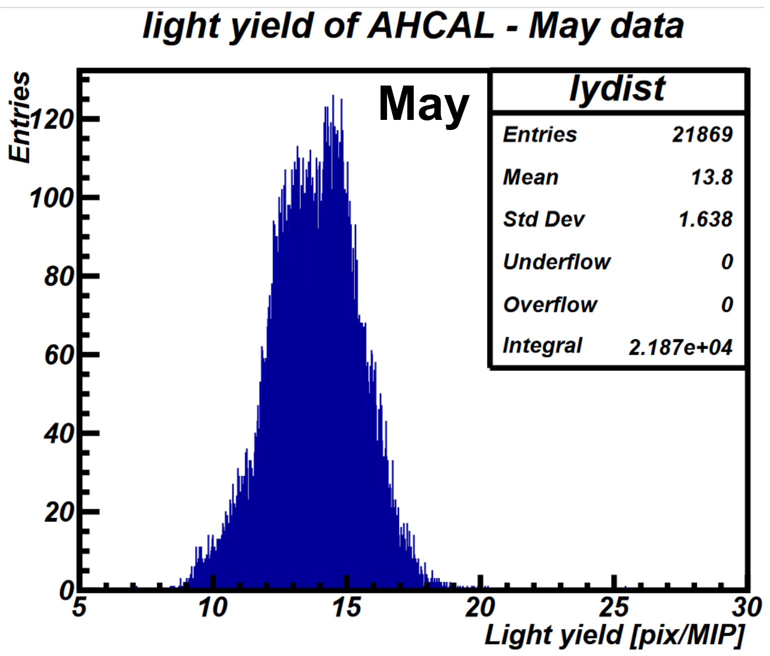
Light Yield

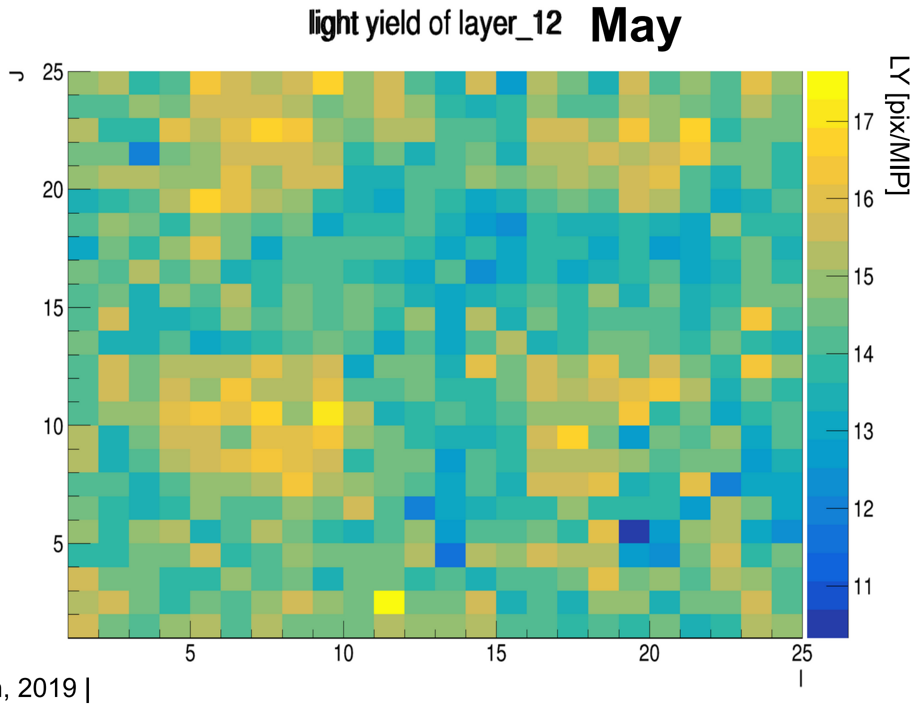
Results

By Olin Pinto and Daniel Heuchel

$$LY_i = MIP_i / Gain_i$$

- Definition: Most probable amount of fired SiPM pixels per incident MIP
  - ➡ Independent of SiPM or ASIC amplification, purely „optical"
- Mean light yield of main AHCAL channels: ~13.8 pix/MIP, RMS: ~ 1.6 pix/MIP
  - ➡ RMS LY/Mean LY = 11.6%
  - ➡ Light yield map of the detector channels shows slight inhomogeneities (different types of tile wrapping)





Calibration Procedure and Results:

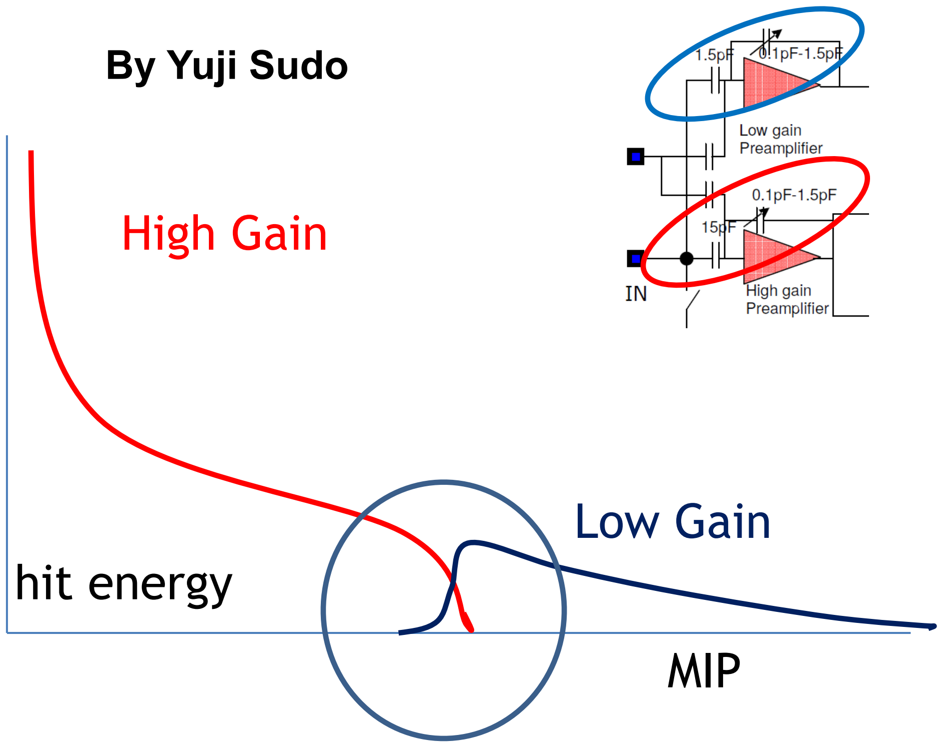
HG/LG Inter-Calibration and LG Pedestals

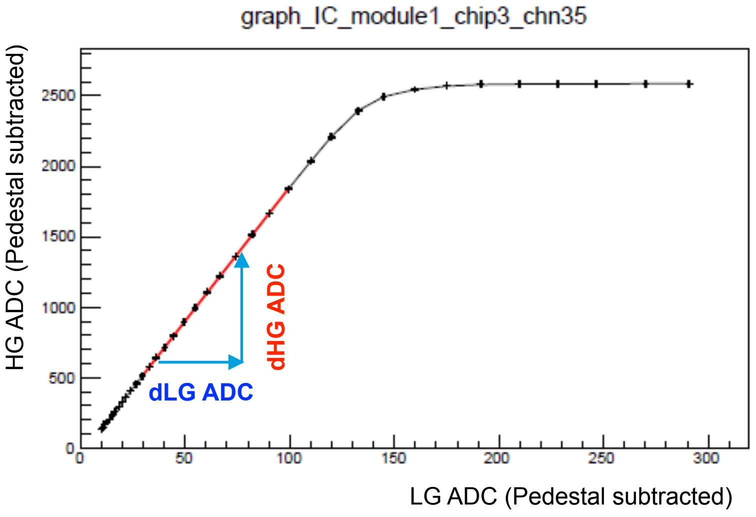
High-Gain/Low-Gain Inter-Calibration

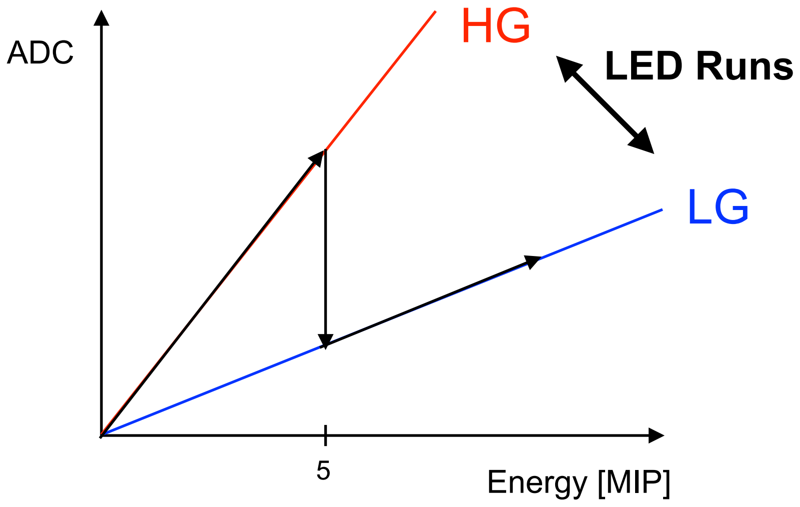
Procedure and Results

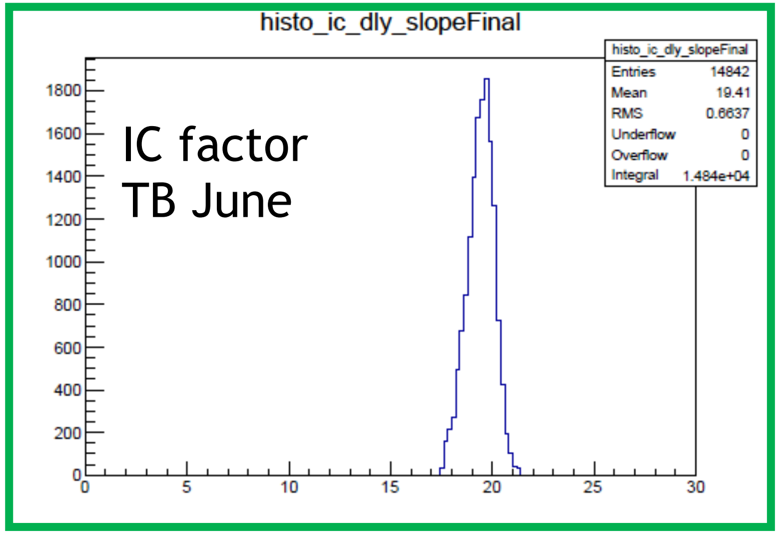
- SPIROC2E: High gain and low gain signal output
  - ➡ Inter-calibration (IC) factors required for smooth transition between HG and LG hit energies
- Consecutive LED runs with different LED voltages for HG or LG mode in all channels
  - ➡ Measure resulting slope: IC = dHG ADC / dLG ADC
  - ➡ **Mean IC = 19.4** (RMS = 0.66) -> **1 MIP (LG) = ~12 ADC**

By Yuji Sudo









Low-Gain Pedestals

Extraction Procedure and Results

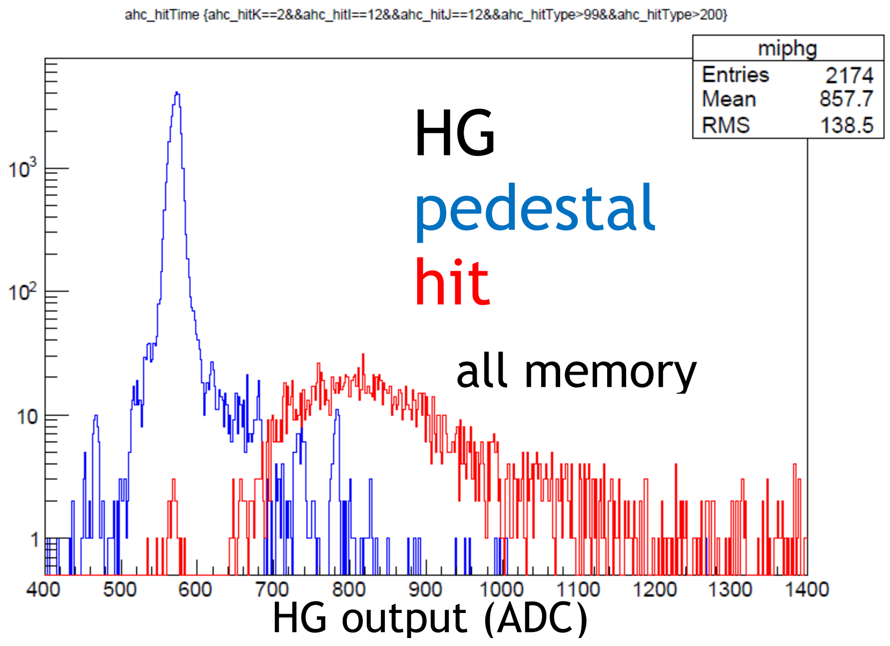
By Yuji Sudo

hit bit = 0	ATAG	ATIC	ETIC
HG Pedestal	x	x	x
LG Pedestal	First Try	x	x

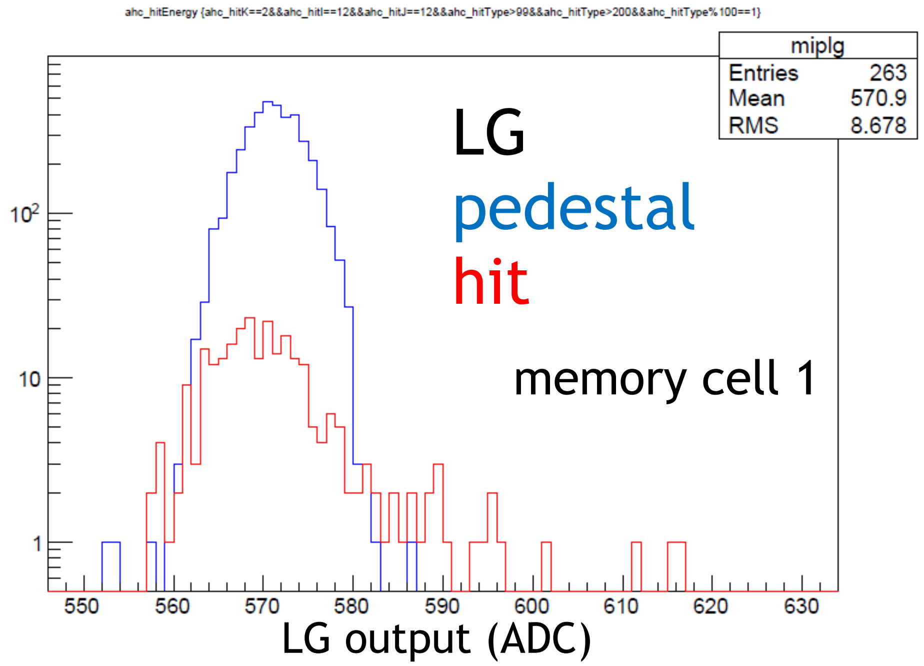
LG_offset_hitbit01

hit bit = 1	ATAG	ATIC	ETIC
HG Pedestal			
LG Pedestal	Required		

- After inter-calibration hit energy spectrum still not smooth
  - ➡ LG pedestal differs from HG pedestal
  - ➡ LG pedestal (hit bit = 0) differs from LG pedestal (hit bit = 1)
- LG_Ped1(ATAG) = LG_Ped0(ATAG) + LG_offset_hitbit01
- LG_offset_hitbit01 = [LG_MIP1(ATIC)-HG_MIP1(ATIC)]/IC - LG_Ped0(ATIC)



ATIC Muon
TB May 2018



Closing the Loop: Quality Check of Calibration Constants with Test Beam Electron Runs

High Gain/Low Gain Transition Check

For Electron Test Beam Runs

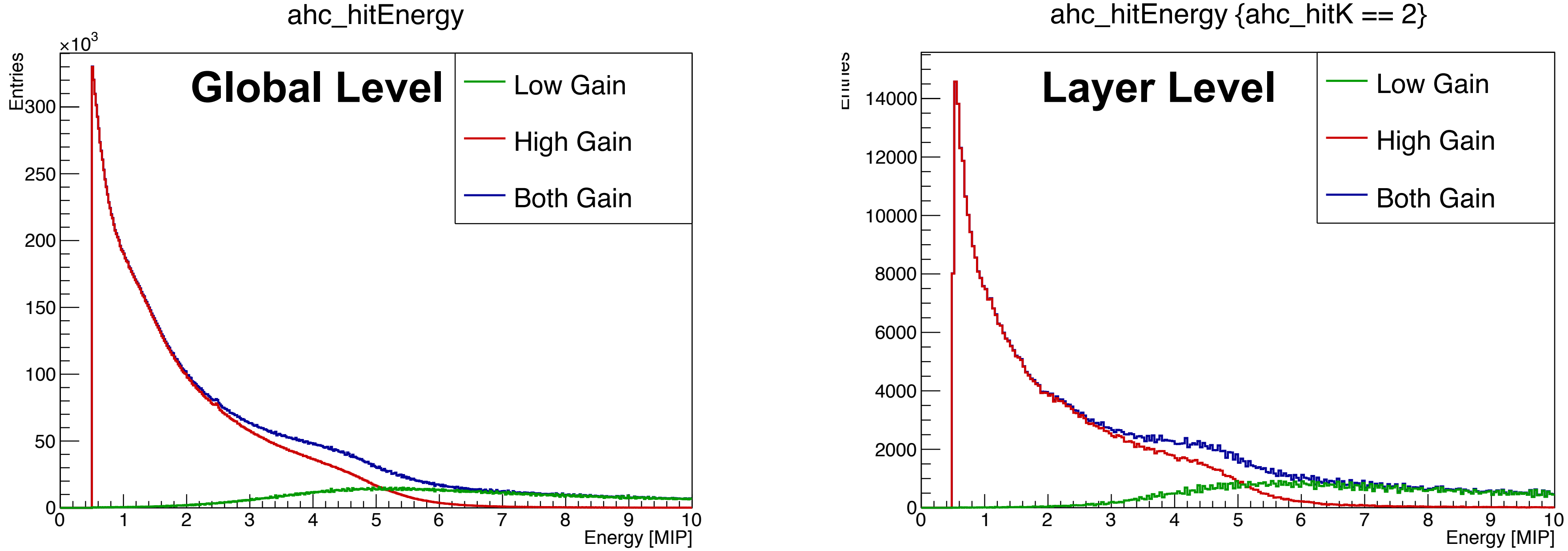
- Idea: Reconstruct the deposited hit energy in 100 GeV electron runs (May) with the determined calibration constants

  ➡ Smooth transition for HG and LG part of spectrum?

  ➡ Check on global and layer level

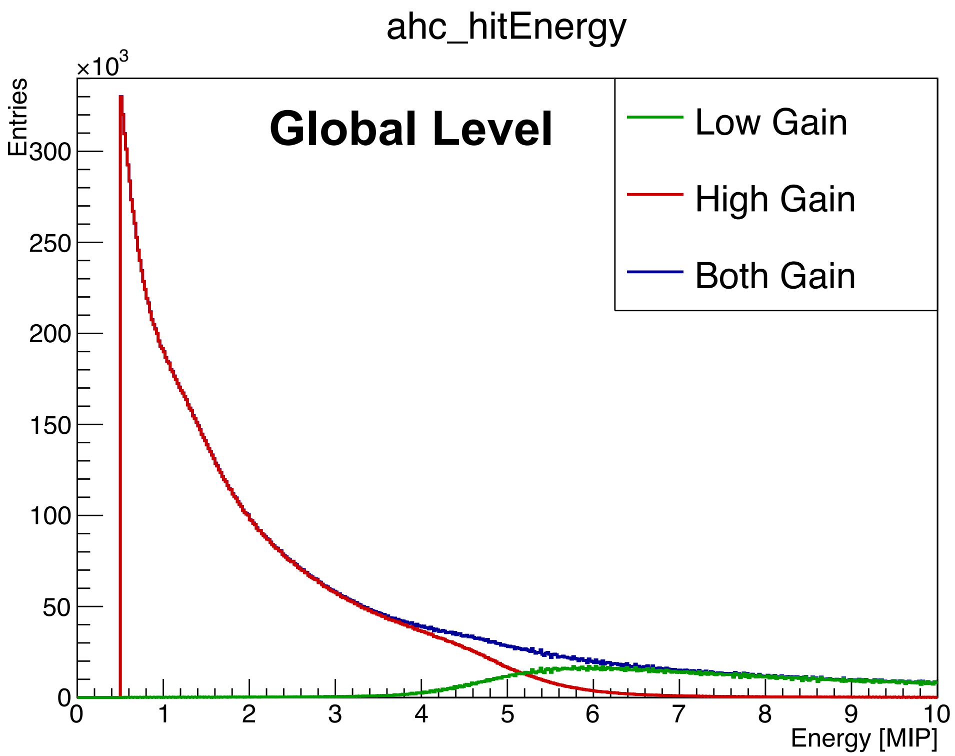
Quality check of LG Pedestals and HG/LG IC factor

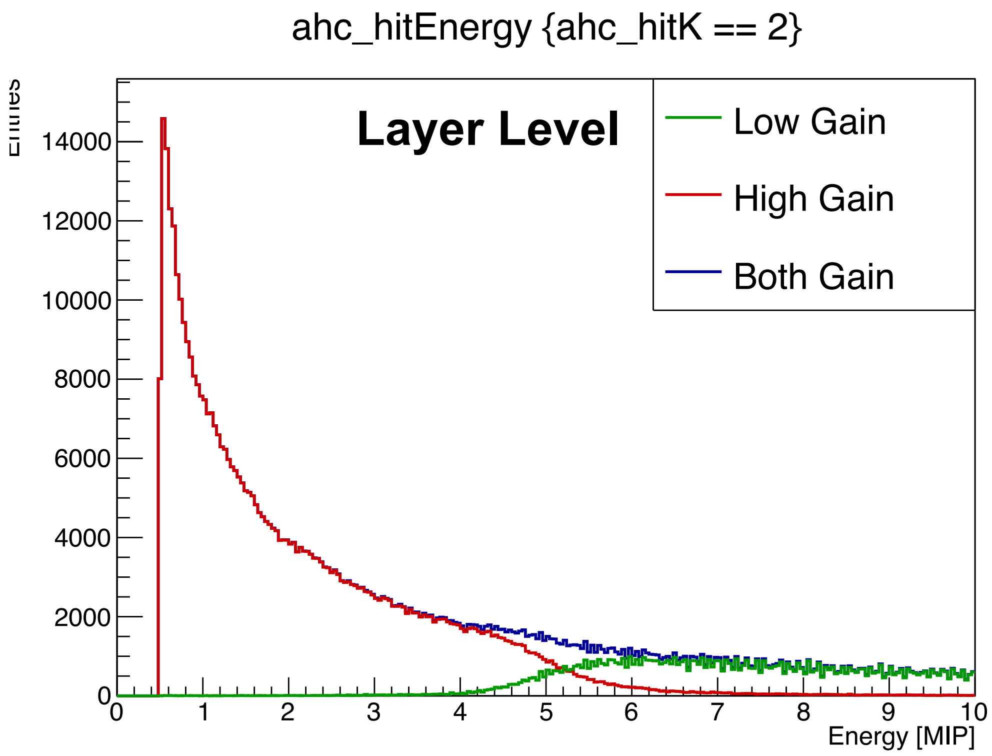
Older calibration constants and LG = HG pedestals for May electron runs



High Gain/Low Gain Transition Check

For Electron Test Beam Runs





- **HG/LG transition smooth with extracted LG pedestals and IC factors**

Calibration Procedure and Results:

SIPM Saturation and Dynamic Range

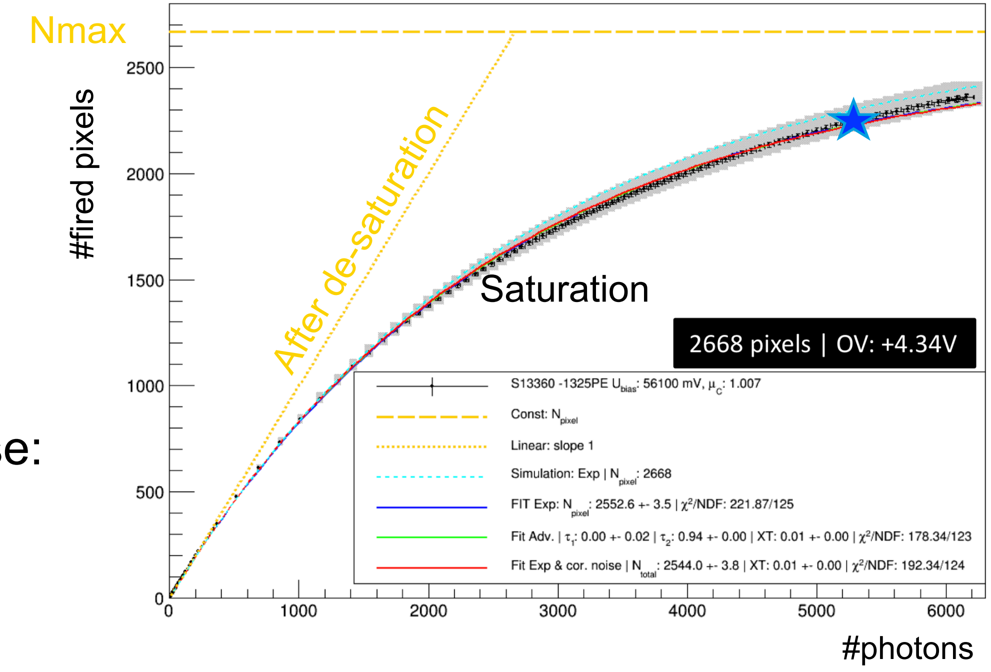
SiPM Saturation

By Olin Pinto, Sascha Krause

Correction and Dynamic Range

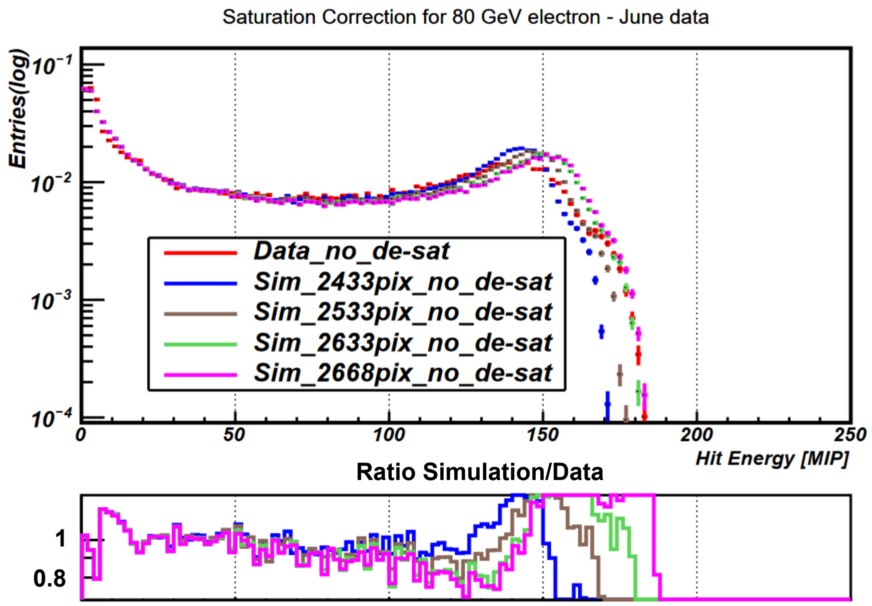
- SiPM S13360-1325PE has finite amount of pixels: 2668
  - ➡ Very high energy depositions (high number of photons) will lead to SiPM saturation since fired pixels have not recovered
  - ➡ Apply a de-saturation function to enable linear SiPM response:

$$pixel_{desat} = f_{desat}\left(pixel_{sat}\right) = -N_{eff,pix} \cdot ln\left(1 - \frac{pixel_{sat}}{N_{eff,pix}}\right)$$



- Saturation studies on LED test-bench (Mainz) have shown best agreement data/simulation for:

$$N_{eff,pix} = 2533\ pixel$$



- **Dynamic range** of the AHCAL 2018 prototype:
  - ➡ Range up to 2x SiPM pixels = 5300 pixels, fdesat < 2.39
    - ➡ With LY of ~14 pix/MIP: **~380 MIPs, ~9 GeV**

Reconstruction Check

Memory Cell Muon Spectra