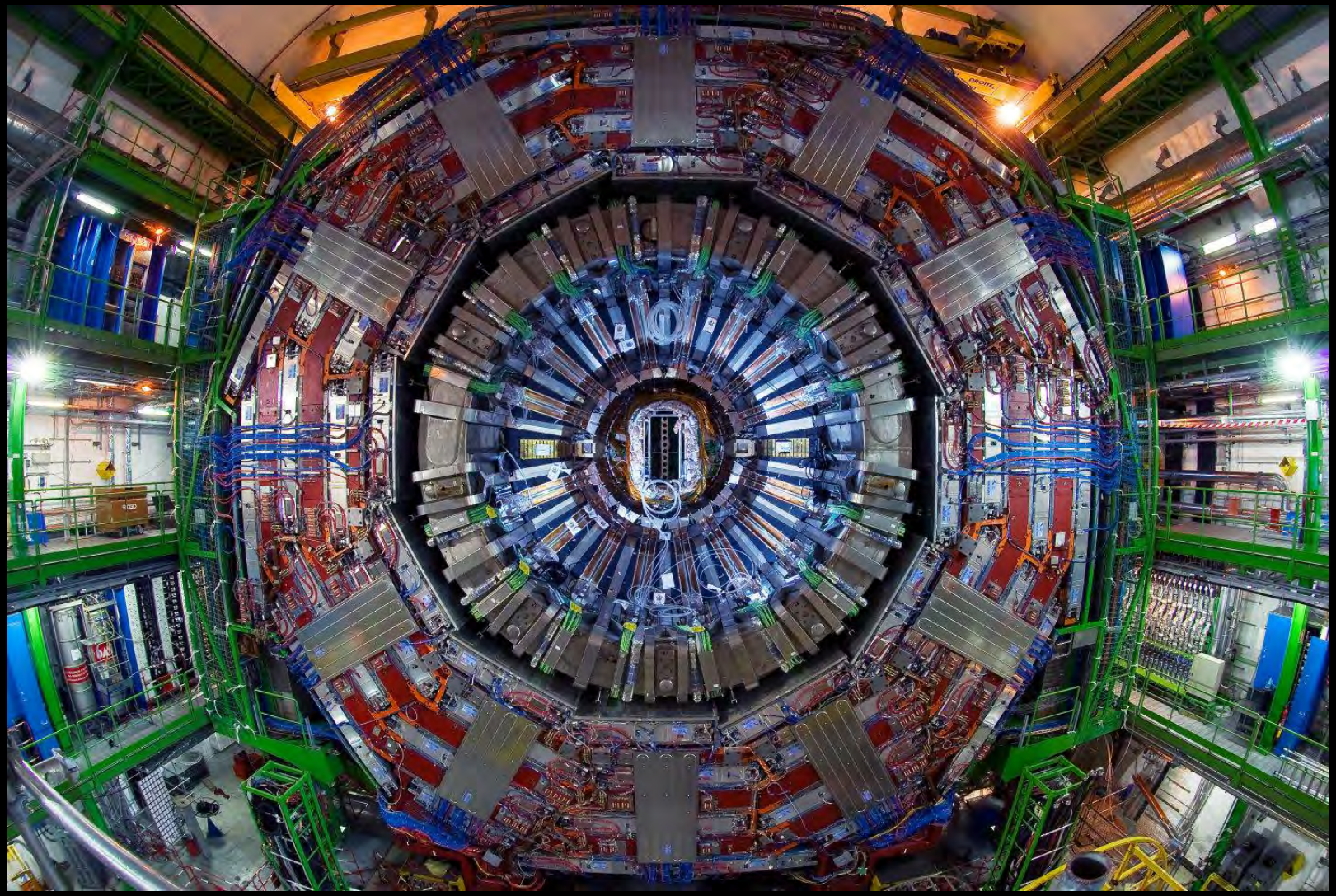


CMS HCAL Upgrade at Fermilab

Diana Patricia Méndez Méndez , Internship for Physics Majors

August 7, 2013

Overview

The Compact Muon Solenoid (CMS) is one of the detectors at the Large Hadron Collider (LHC). With the LHC, scientists are able to analize **proton-proton** collisions with a center of mass energy of **8 TeV**, searching for:

- Signatures of the Higgs boson
- Super-symmetric particles
- Dark matter

By 2019, the LHC is expected to reach higher energies, up to **14 TeV**, which means better measurements techniques will be needed to satisfy the increase in events.

CMS Design

•**Superconducting Magnet, *Solenoid***
4T magnetic field to bend the particles' paths

•**Inner Tracking System, *Tracker***
Measures the trajectories and momentum of charged particles and reconstructs secondary vertexes

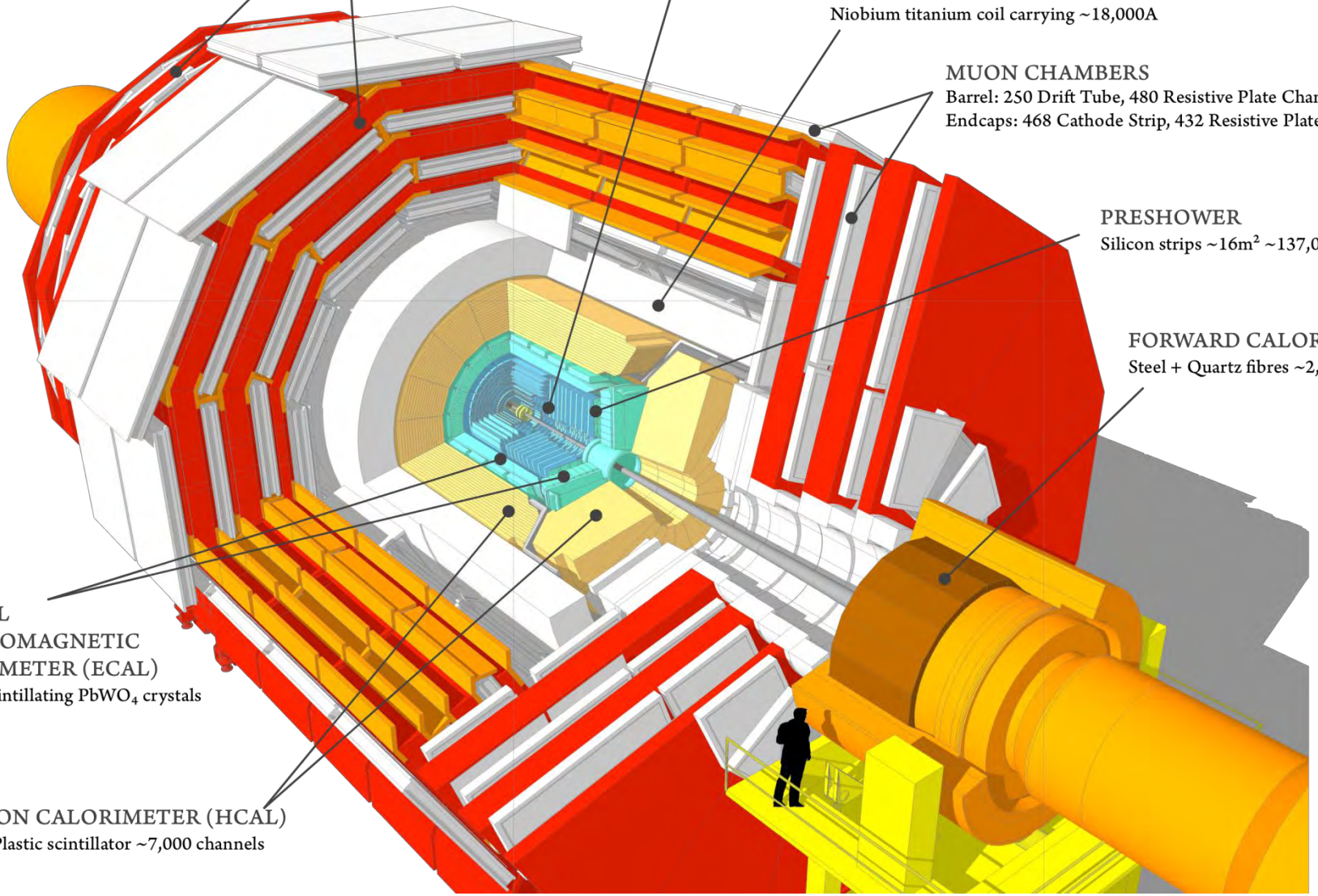
•**Electromagnetic Calorimeter , *ECAL***
Measures the energy of both electrons and charged hadrons

•**Hadron Calorimeter, *HCAL***
Measures the energy of hadron jets, and neutrinos or exotic particles resulting in apparent missing transverse energy

•**Muon Detector, *Muon Chambers***
Tracks muon trajectories outside of the solenoid

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

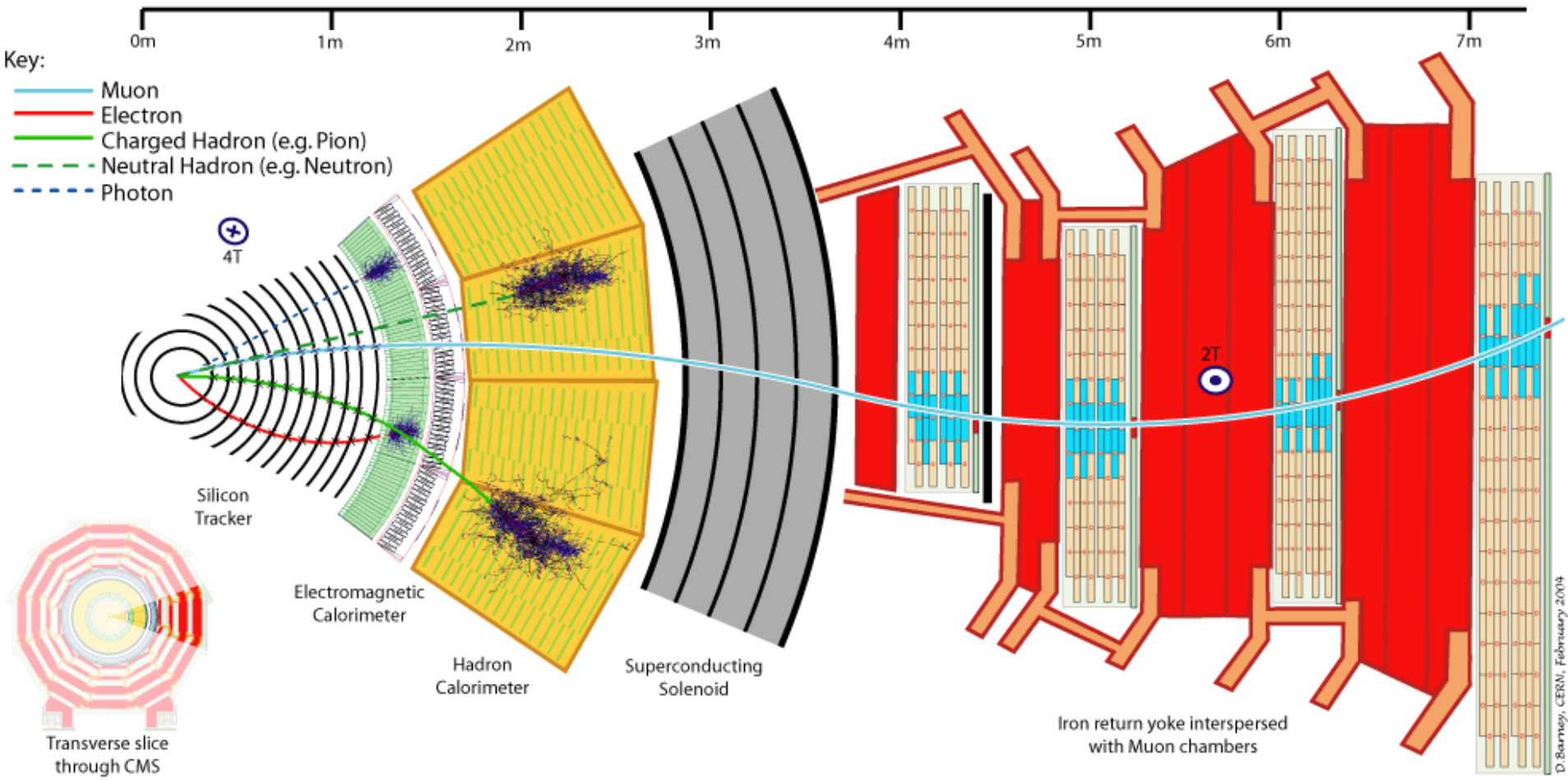
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

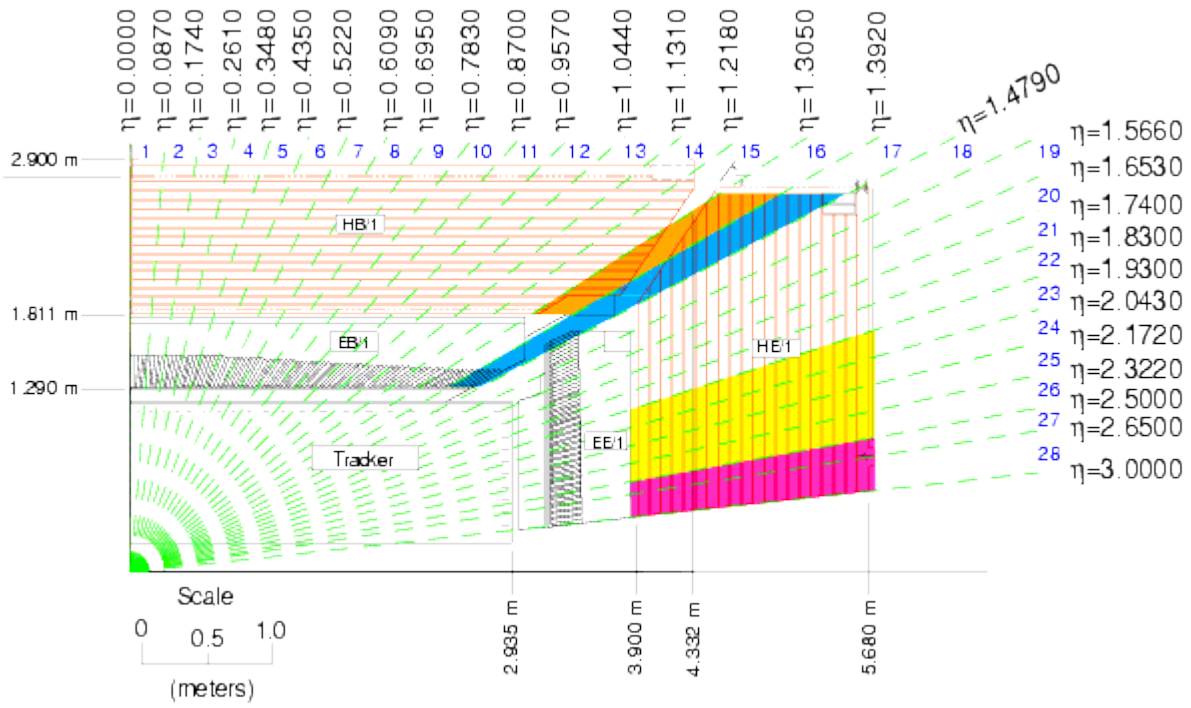

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

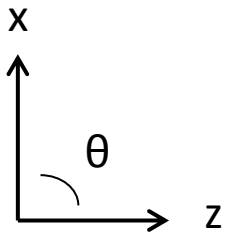
HCAL Design

- **Barrel *(HB)* and Endcap *(HE)*** Measures the trajectories and momentum of charged particles and reconstructs secondary vertexes

- **Outer *(HO)*** Tail catcher for hadronic showers

- **Forward *(HF)*** Cherenkov calorimeter

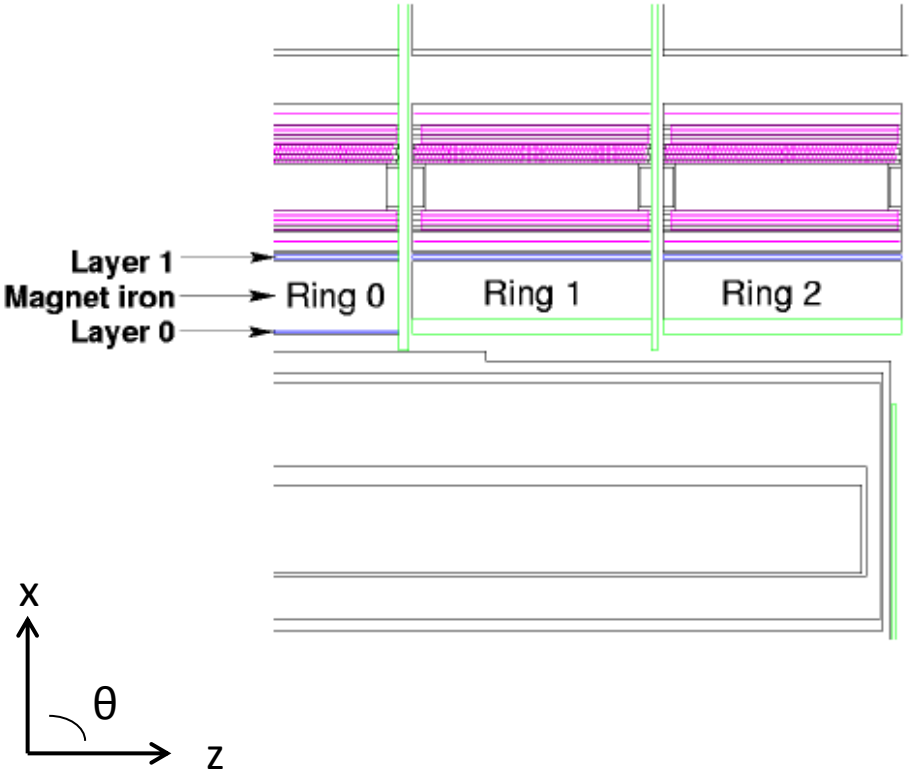


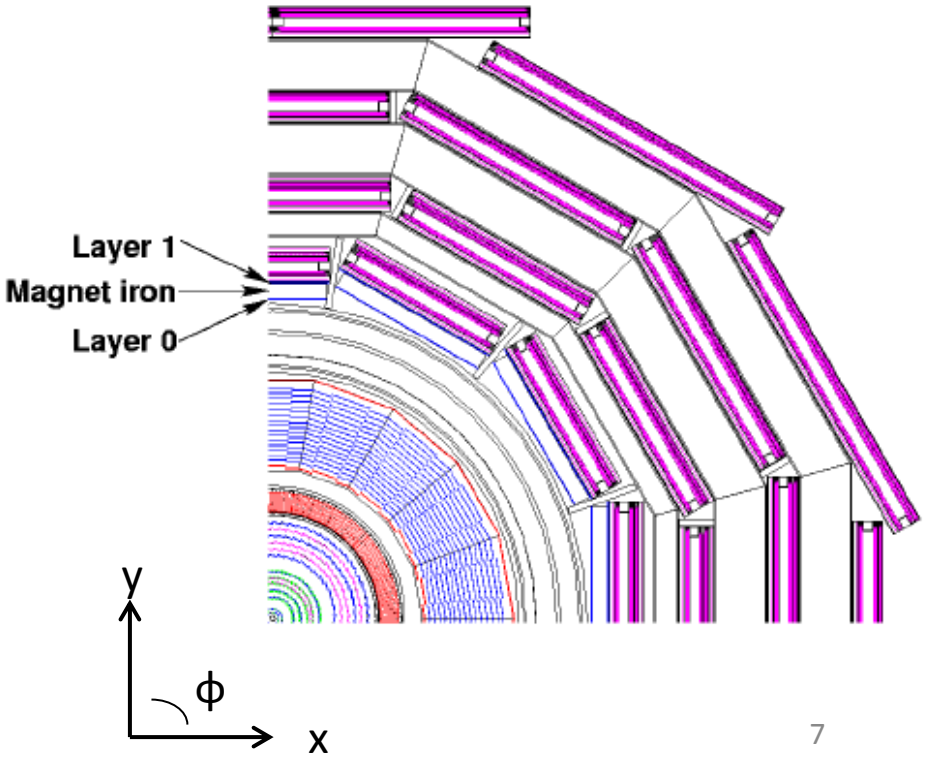


Pseudirapidity $\eta \equiv -\ln(\tan(\theta/2))$

HO

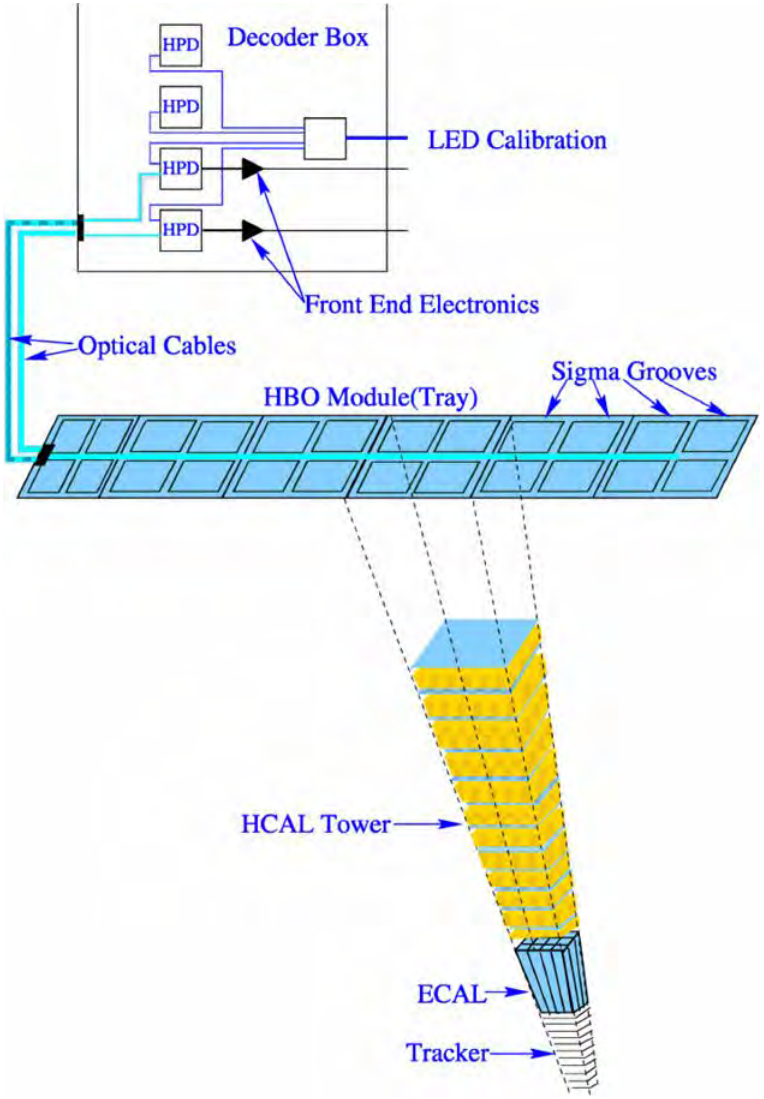
- Identifies showers that don't fit entirely in the HB
- Measures the shower energy deposited after the HB and the solenoid
- Utilizes the solenoid coil as an absorber
- Divided into five rings (0,±1,±2)





HCAL Design

HB and **HE** are composed of scintillating tiles interleaved with brass. Together with the **HO**, the tiles are read out using hybrid photodiodes *(HPDs).* The signal is digitalized via optical fiber by an **Analog to Digital Convertor/Charge Integrator Encoder** (***ADC/QIE***).

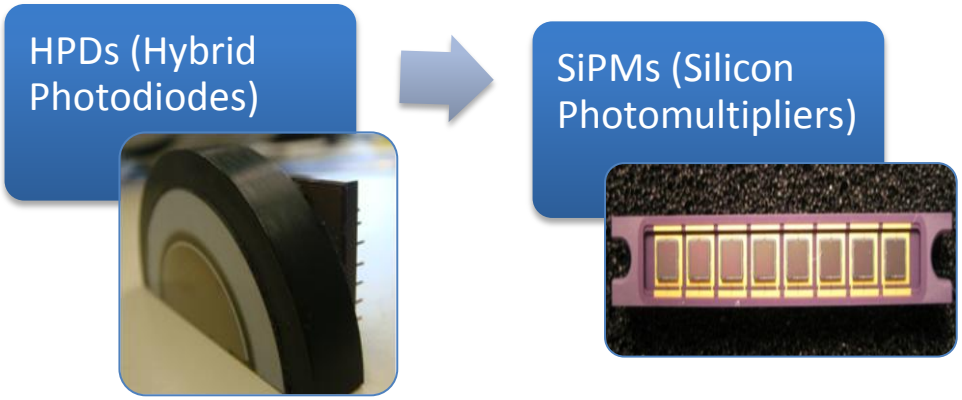


Mapping of a HB tower to a HO tile inside a tray.

HCAL Upgrade

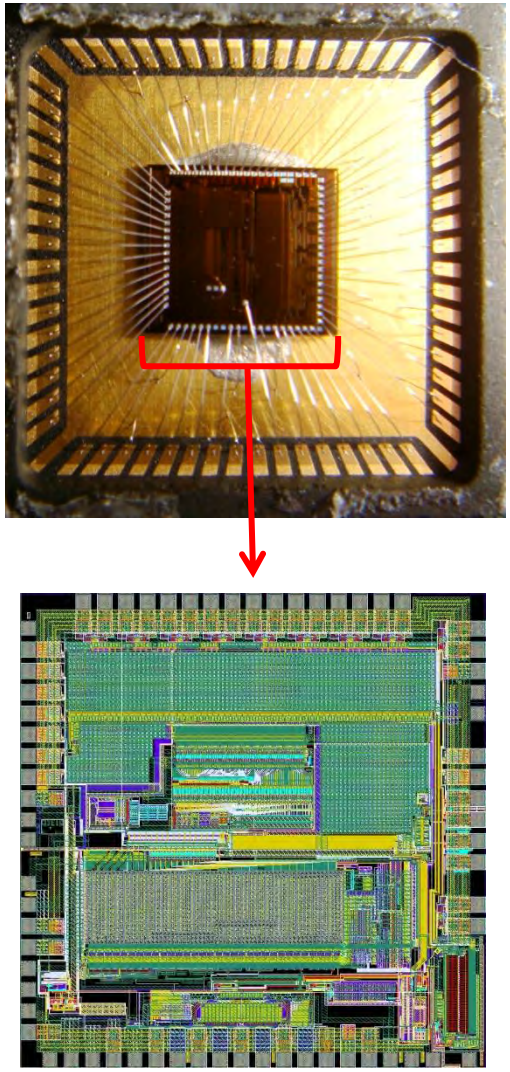
Due to the higher luminosities (~5E34 cm2/s) that the LHC will be facing after the first long shutdown, better measurement techniques will be needed in order to satisfy the increase of events.

- Sensors



- ADC ASIC

QIE10 Dynamic Range



The charge integrator and encoder (QIE) recognizes charge values in the range [3fc, 330fC].

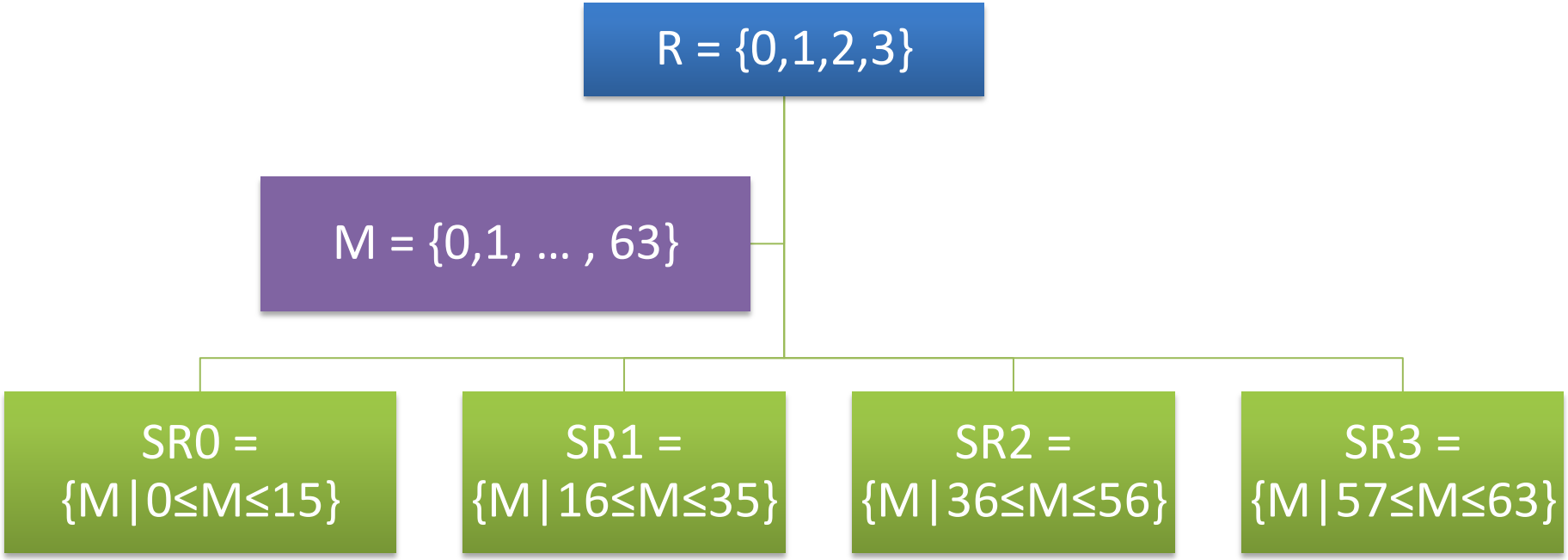
It would require 17 bits to record the entire range.

→ Charge is organized into 256 bins

∴ Only 8 bits are needed

QIE10 ADC Code

Those 256 bins are labeled by a *Range* (R) and by a *Mantissa* (M). There are 4 R, each one with 64 M values.
The *M* are grouped into 4 sets named *Subranges* (*SR*) which specify a different bin width, or sensitivity, for the chip.



Internship Goals

Adquire experience in both hardware and software for a better understanding of experimental particle physics.

Hardware

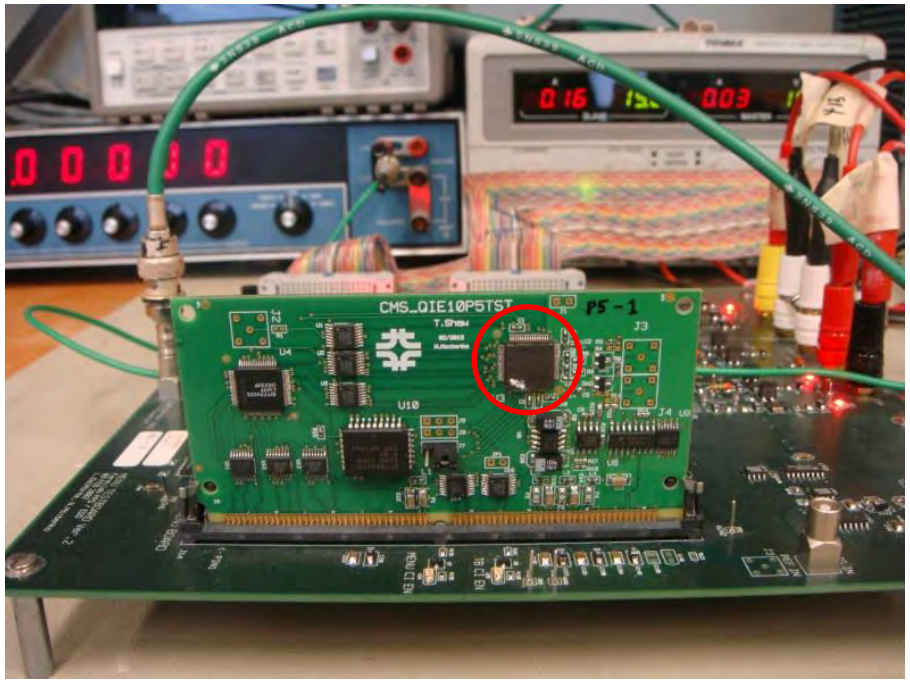
QIE10 Chip testing for the CMS hardware upgrade in the HCAL.

Software

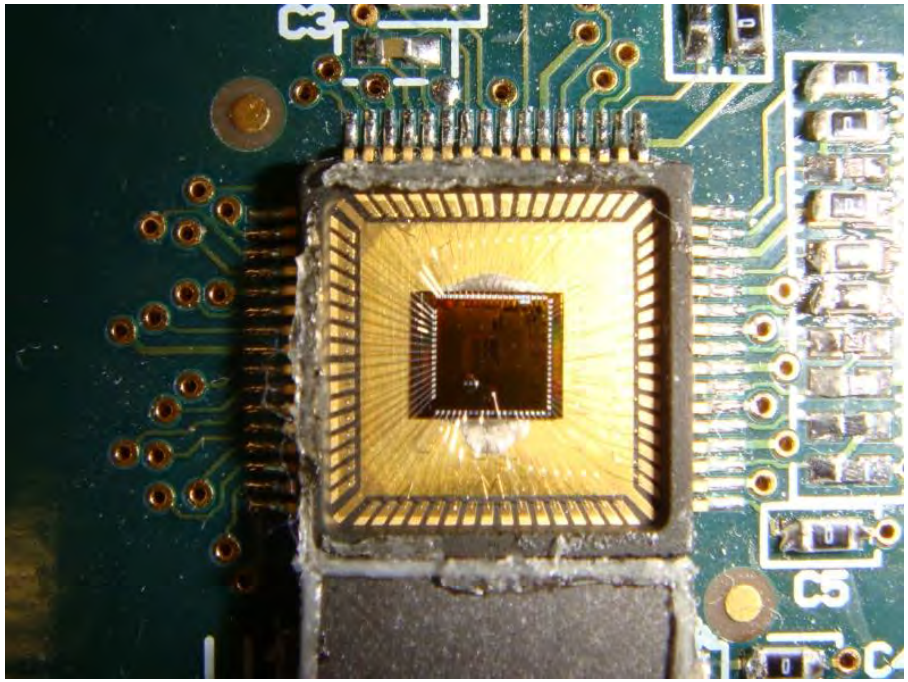
SiPM simulation and analysis focusing on the HO subdetector.

Experimental Setup

QIE10 Prototype 5 testing



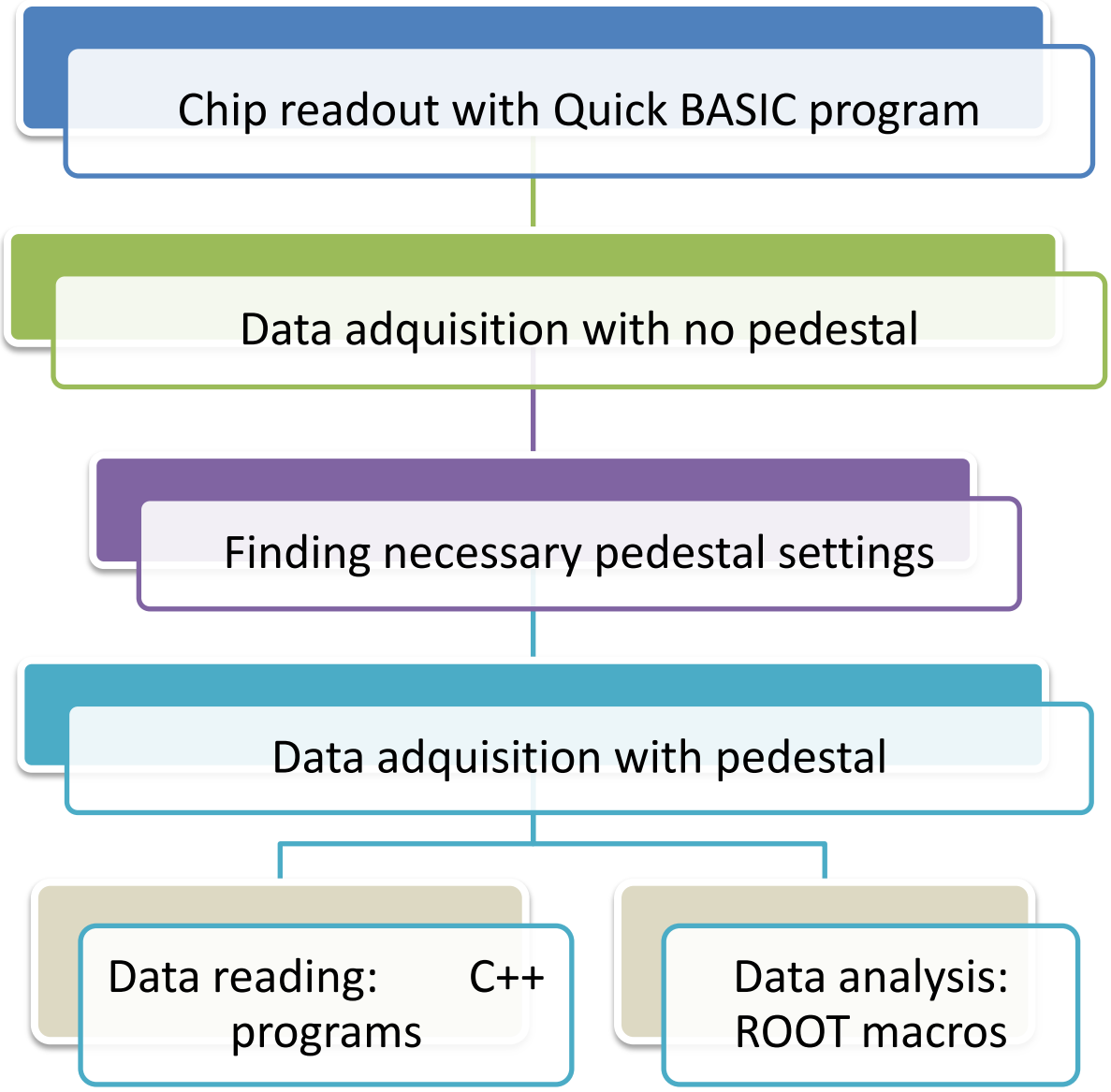
Testboard and daughter boards; the daughter board is basically an electric circuit containing the QIE10 chip (red circle).



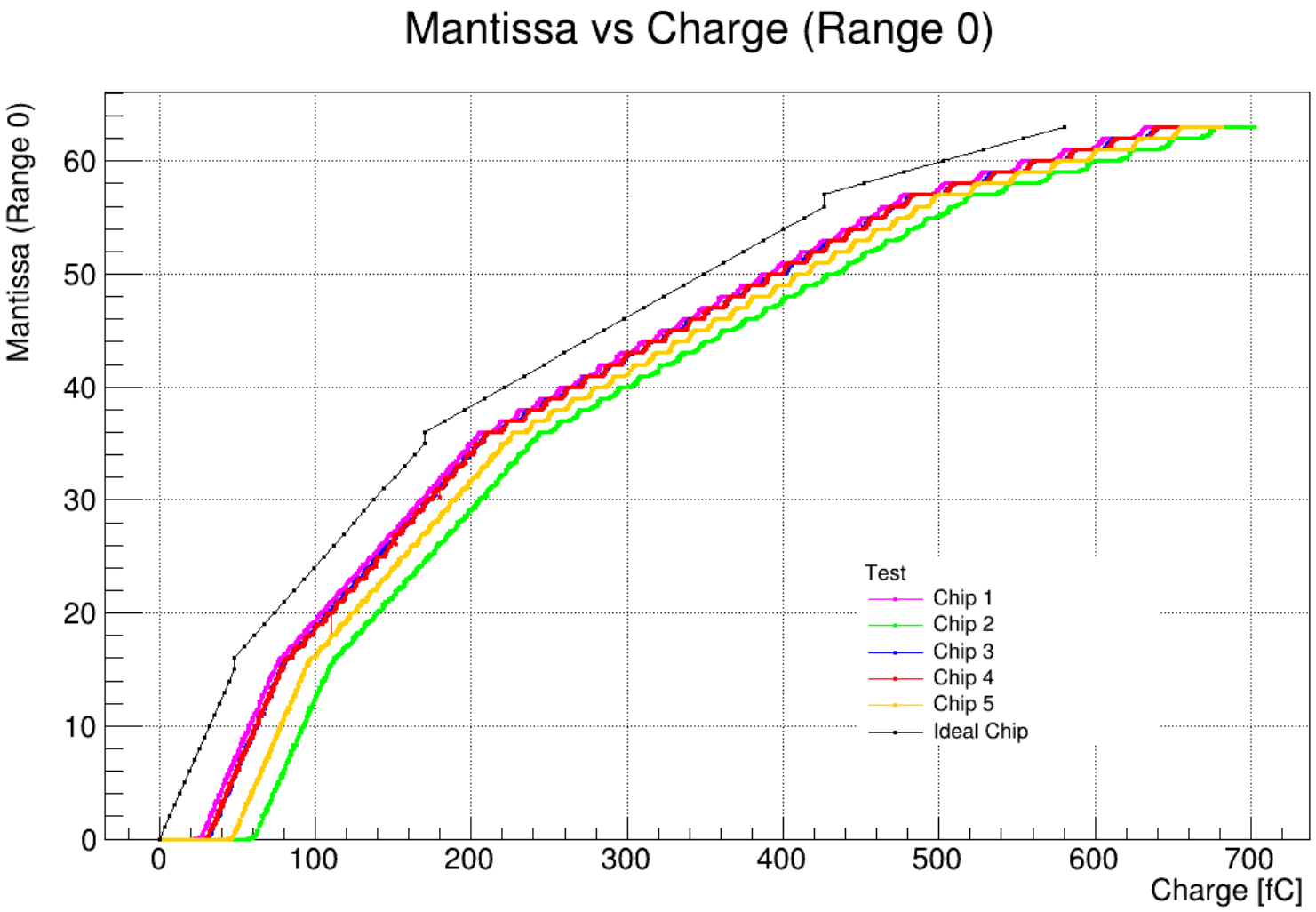
QIE10 chip

Experimental Setup

QIE10 Prototype 5 testing



Results
QIE10 Performance

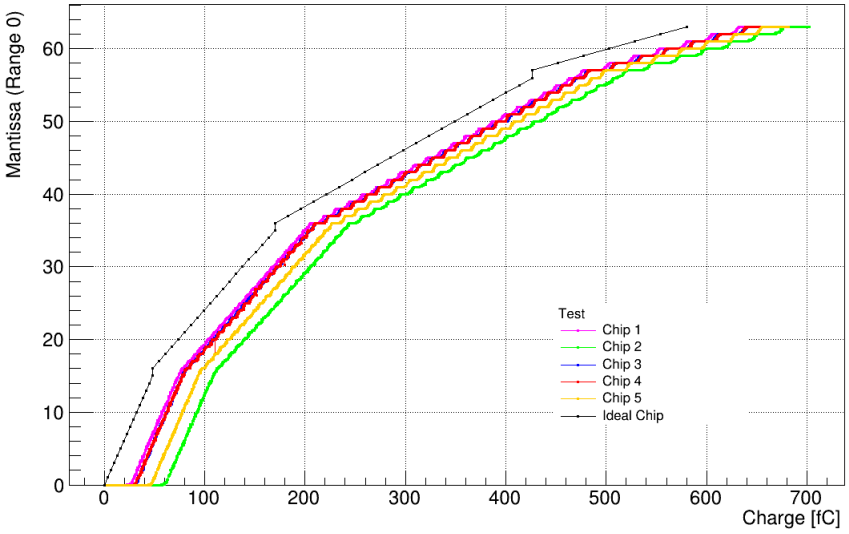


Mantissa as a function of injected charge for range 0, no pedestal, for each of the 5 chips.
*The error bars don't show because of the scale, they are <1% of the injected charge.

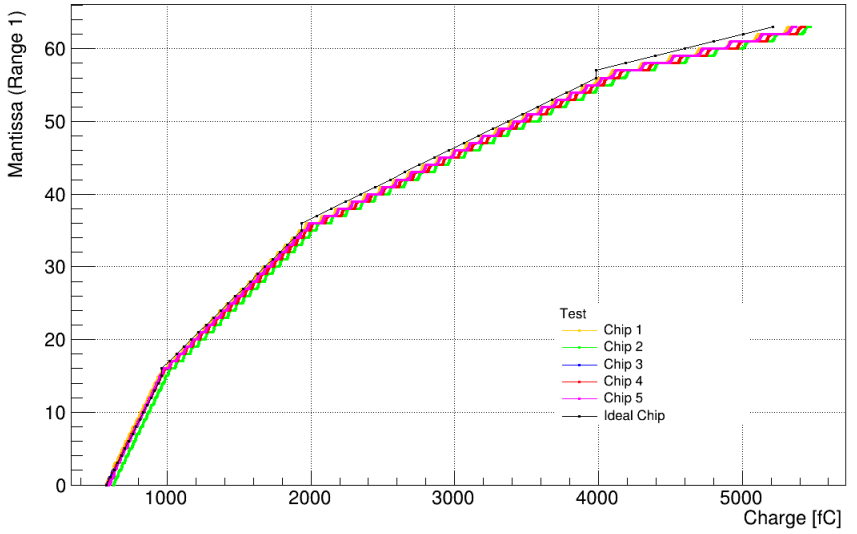
Results

QIE10 Performance

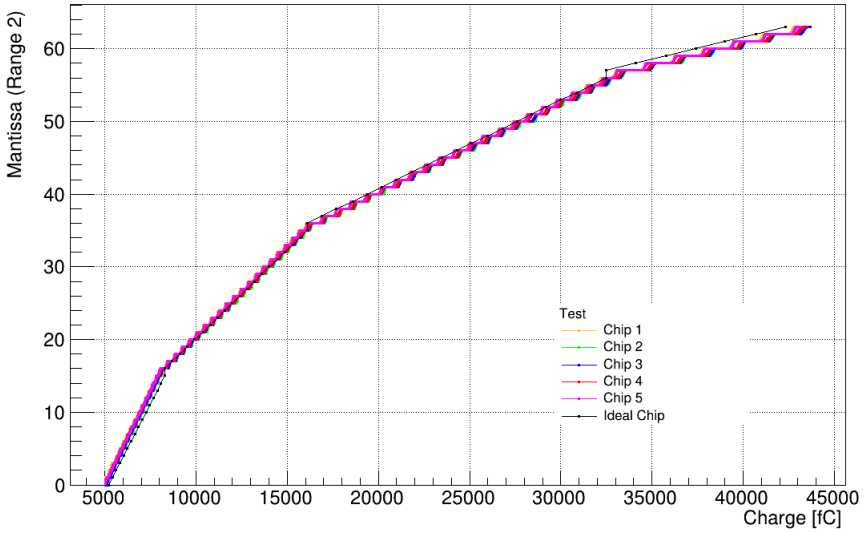
Mantissa vs Charge (Range 0)



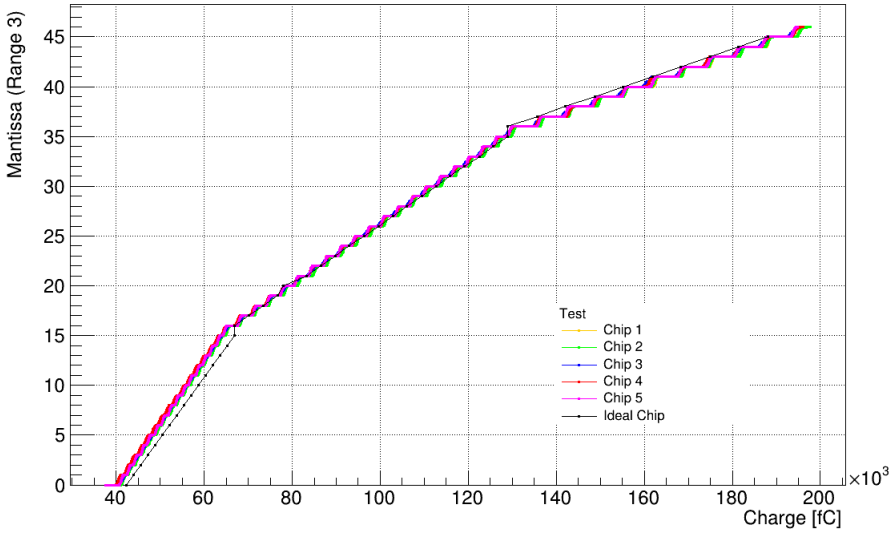
Mantissa vs Charge (Range 1)



Mantissa vs Charge (Range 2)

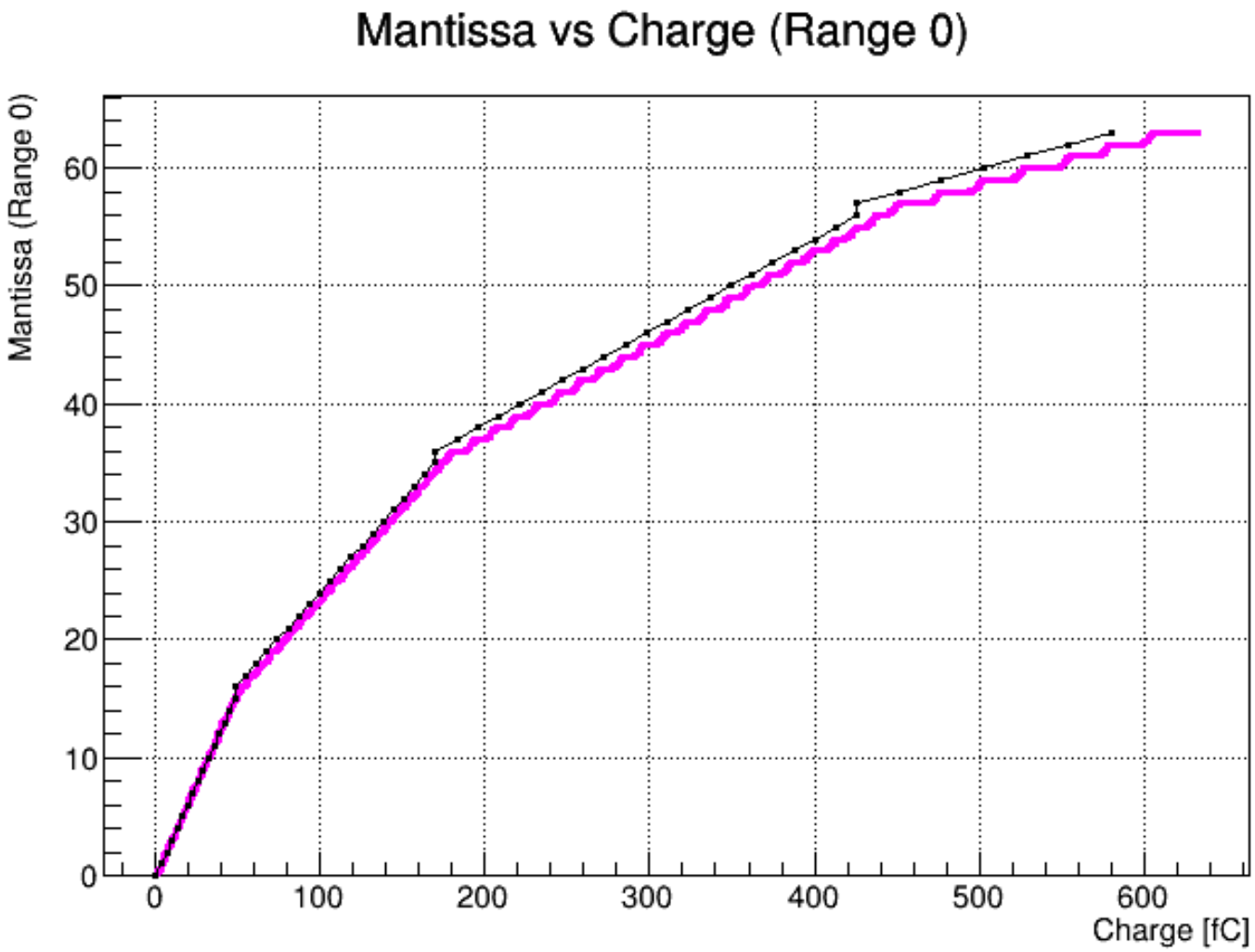


Mantissa vs Charge (Range 3)



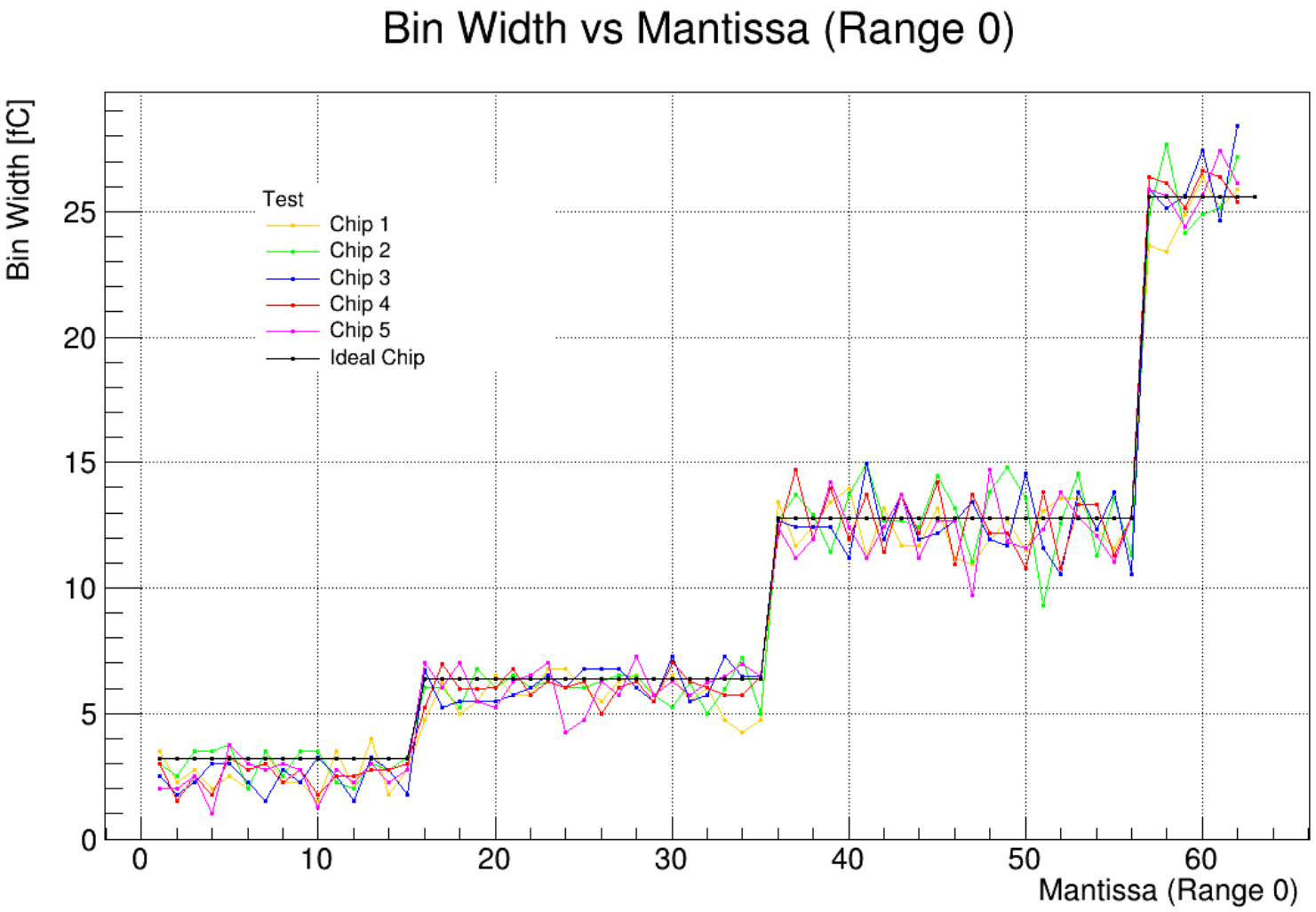
Mantissa as a function of injected charge for range 0, no pedestal, for each of the 5 chips.
*The error bars don't show because of the scale, they are <1% of the injected charge.

Results
QIE10 Performance



Charge as a function of mantissa range 0, with pedestal 12 = 21fC, for chip 1.
*The error bars don't show because of the scale, they are <1% of the injected charge.

Results
QIE10 Performance

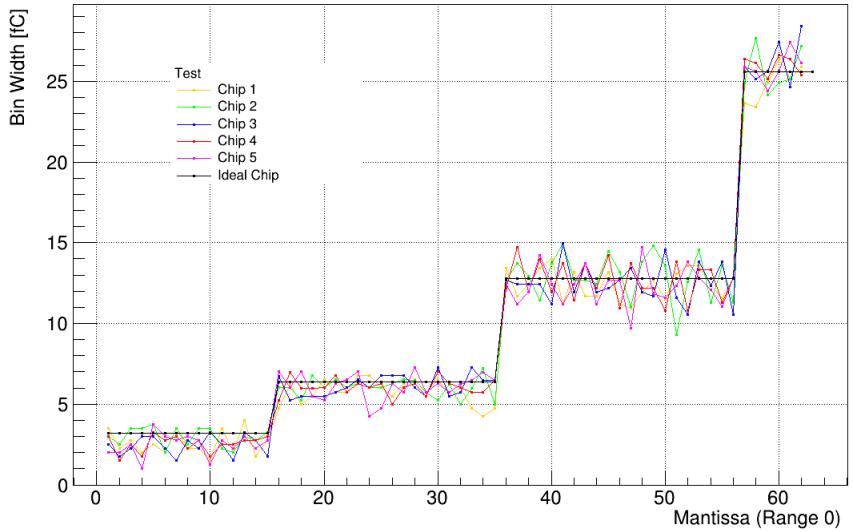


Relation between binwidth and mantissa for range 0.
*The error bars corresponding to the standard deviation, computed for each subrange dont show for better appreciation, though the values fall inside the range of confidence.

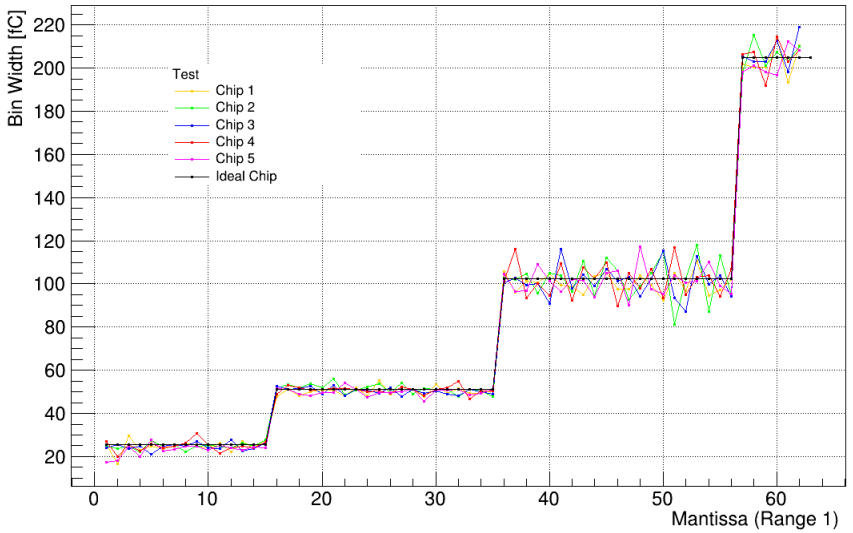
Results

QIE10 Performance

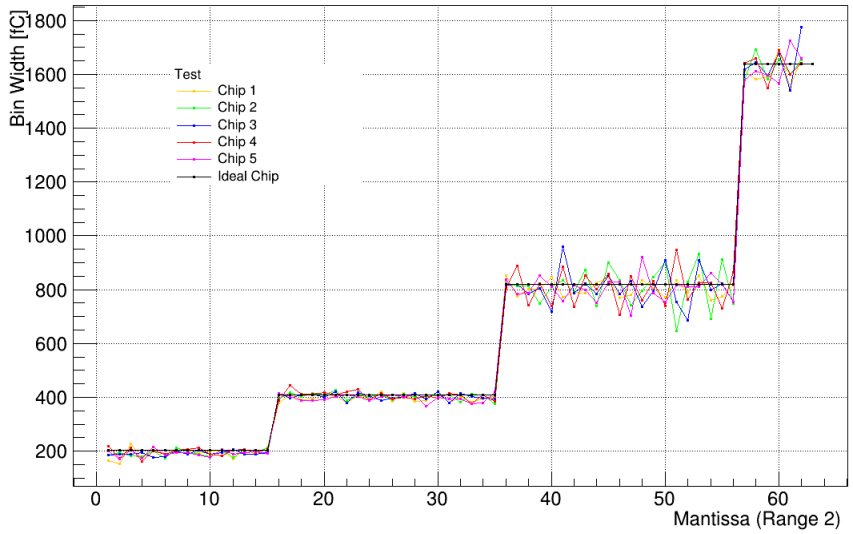
Bin Width vs Mantissa (Range 0)



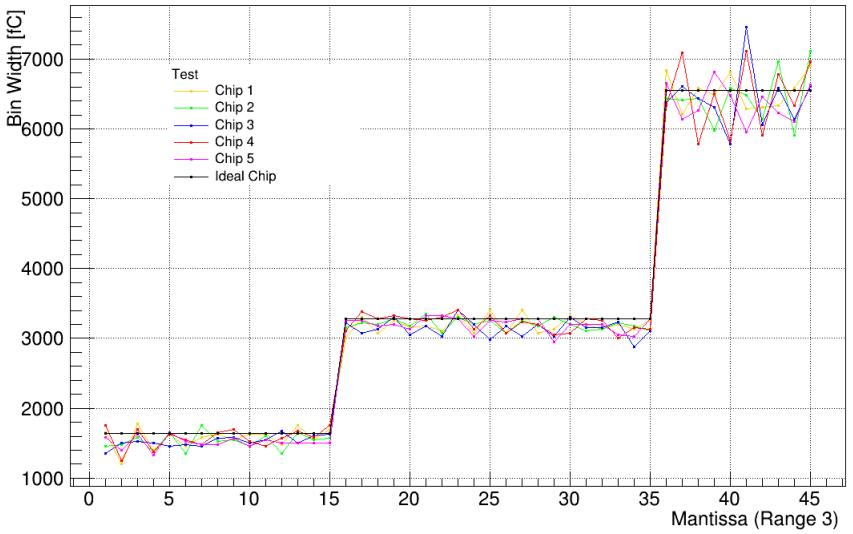
Bin Width vs Mantissa (Range 1)



Bin Width vs Mantissa (Range 2)



Bin Width vs Mantissa (Range 3)



*The error bars corresponding to the standard deviation, computed for each subrange dont show for better appreciation, though the values fall inside the range of confidence.

Results

QIE10 Performance

Range	Mantissa	Expected Sensitivity (fC/bin)	Mean Sensitivity (fC/bin)	Standard Deviation (fC/bin)
0	0-15	3.2	2.59	0.65
	16-35	6.4	6.03	0.66
	36-56	12.8	12.57	1.18
	57-63	25.6	25.72	1.18
1	0-15	25.6	24.43	2.39
	16-35	51.2	50.58	1.90
	36-56	102.4	101.33	7.07
	57-63	204.8	204.73	6.79
2	0-15	204.8	193.10	14.18
	16-35	409.6	401.36	14.02
	36-56	819.2	806.97	56.60
	57-63	1638	1627.52	55.34
3	0-15	1638	1542.76	117.48
	16-35	3276	3189.33	109.67
	36-45	6552	6450.25	375.12

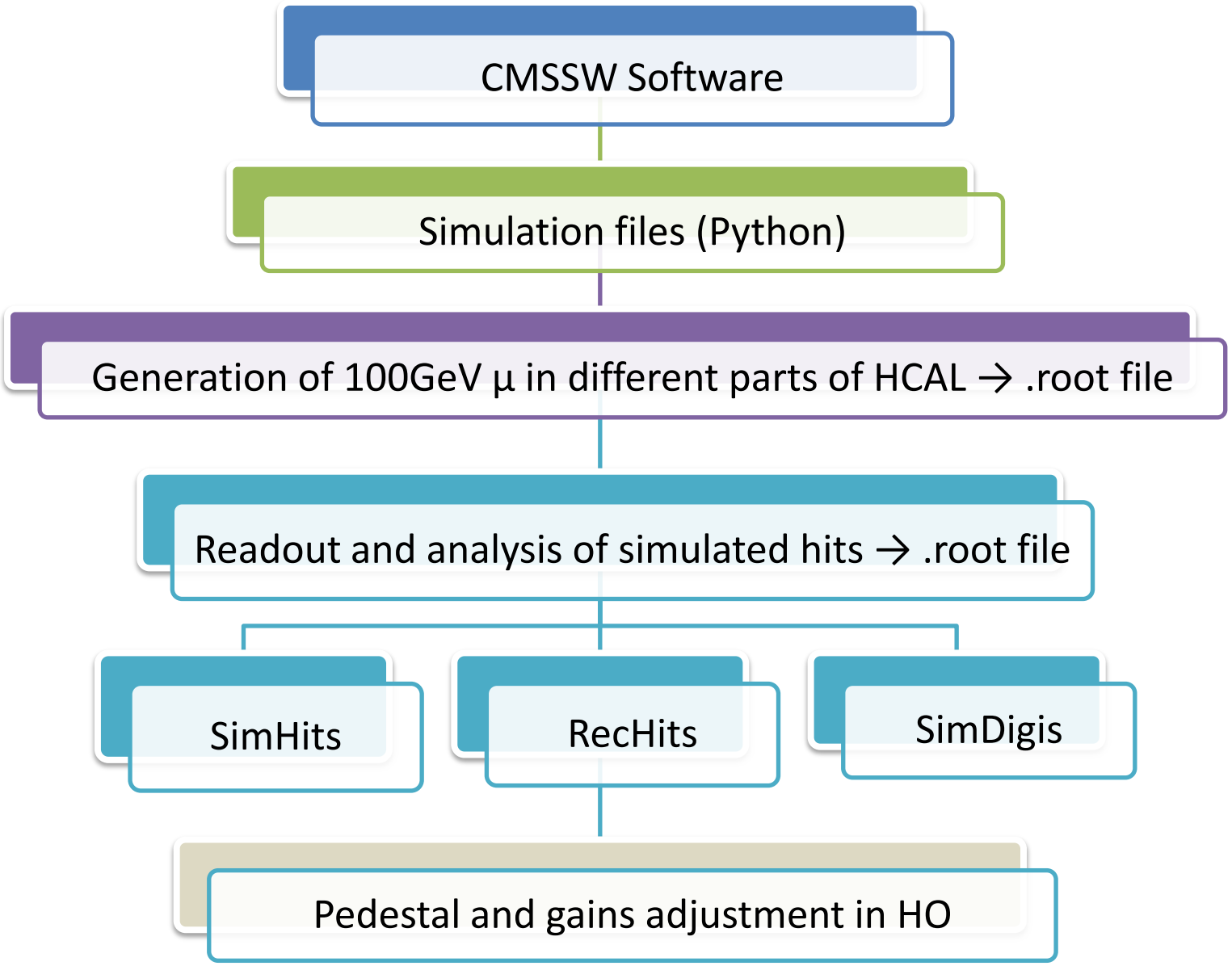
Conclusions

QIE10 Performance

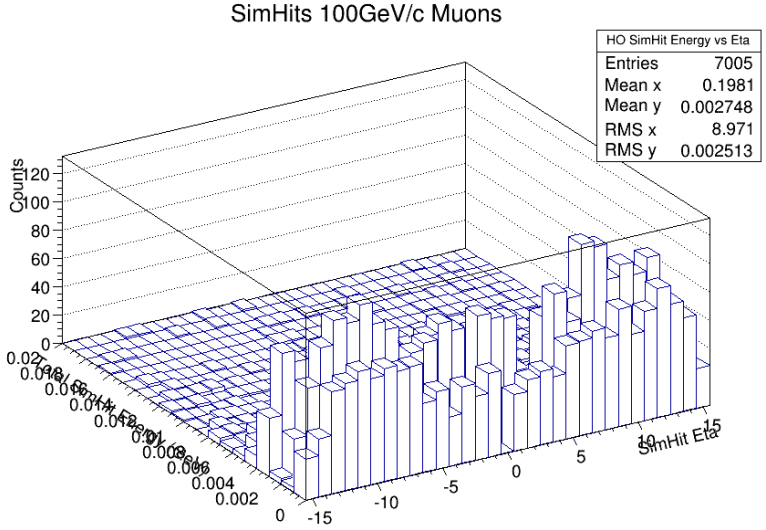
- Mantissa-charge relation is qualitatively the same as the ideal conversion.
- For subranges other than SR0, the chips behave as expected even with zero pedestal.
- Pedestals are chip dependent though none of them are greater than the maximum permited (31*2 fC).
- Setting the pedestal fits the mantissa-charge experimental curve to the ideal one.
- Charge discrepancy $< 1\%$
- Bin widths are pedestal independent but are chip dependent.
- Expectated bin widths are slightly greater than those computed.

QIE10 performance meets expectations

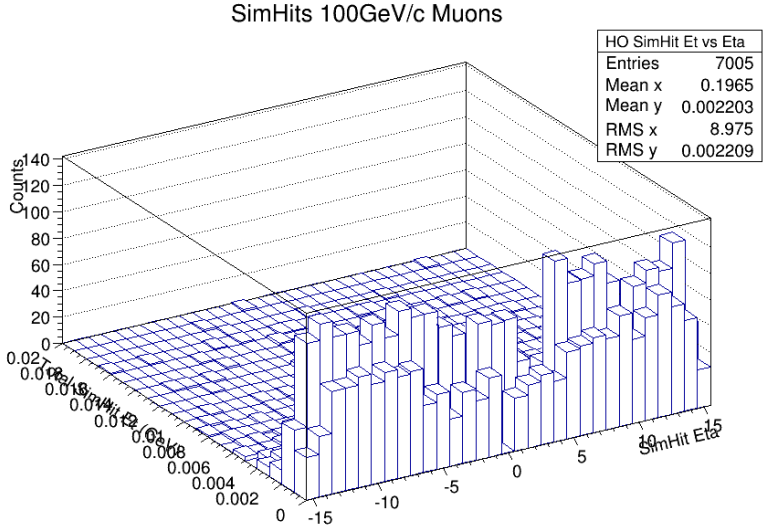
Muon Simulation



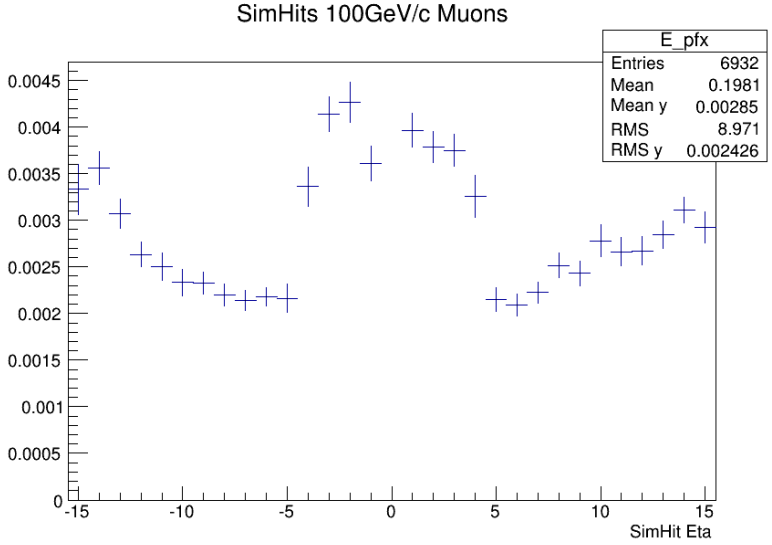
Results
Muon Simulation



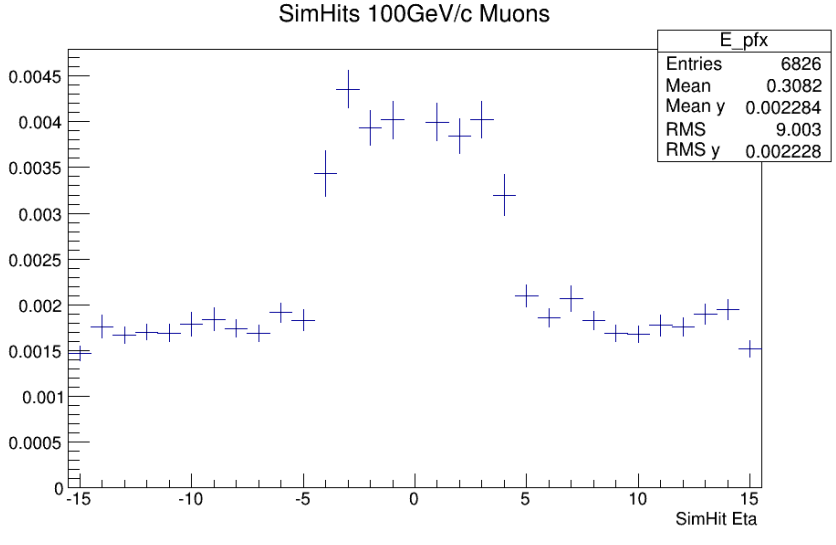
2DHistogram Energy vs Eta, 5k Muons Towers Eta∈[-15 – 15], Phi=1



2DHistogram Transverse Energy vs Eta, 5k Muons Towers Eta∈[-15 – 15], Phi=1

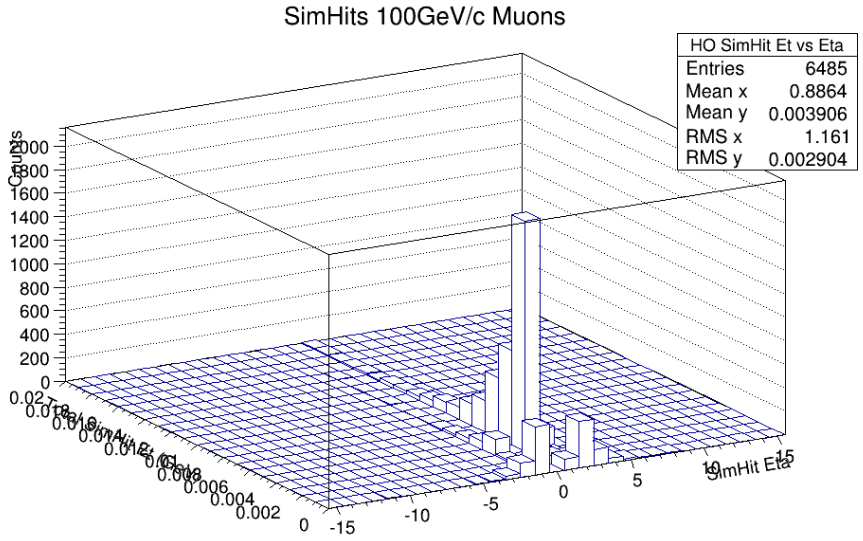


Profile Energy vs Eta, 5k Muons Towers Eta∈[-15 – 15], Phi=1

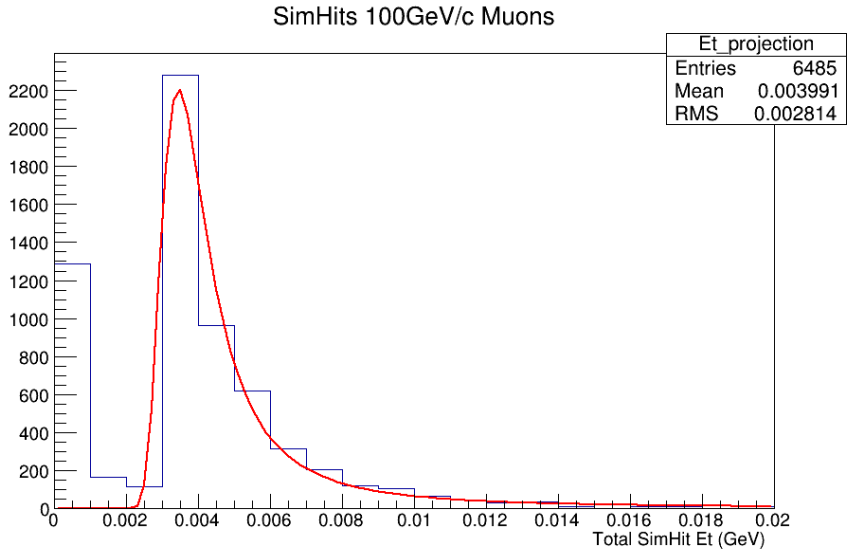


Profile Transverse Energy vs Eta, 5k Muons Towers Eta∈[-15 – 15], Phi=1

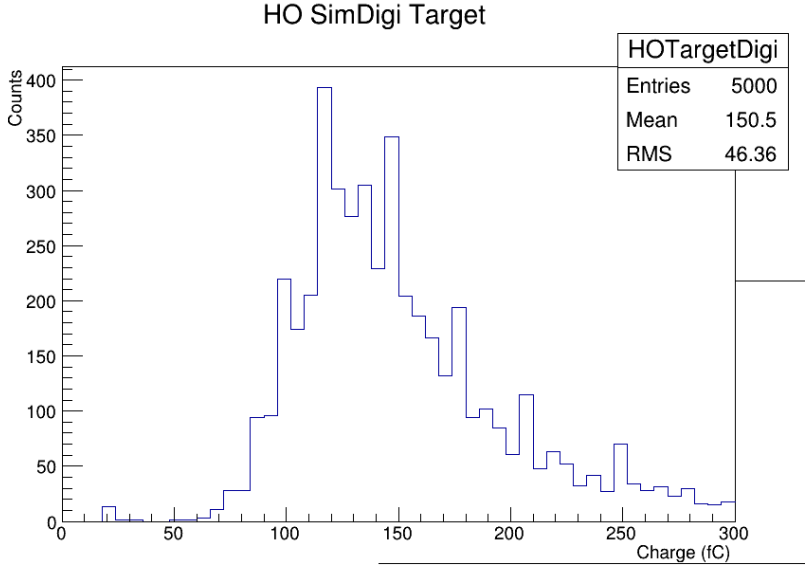
Results
Muon Simulation



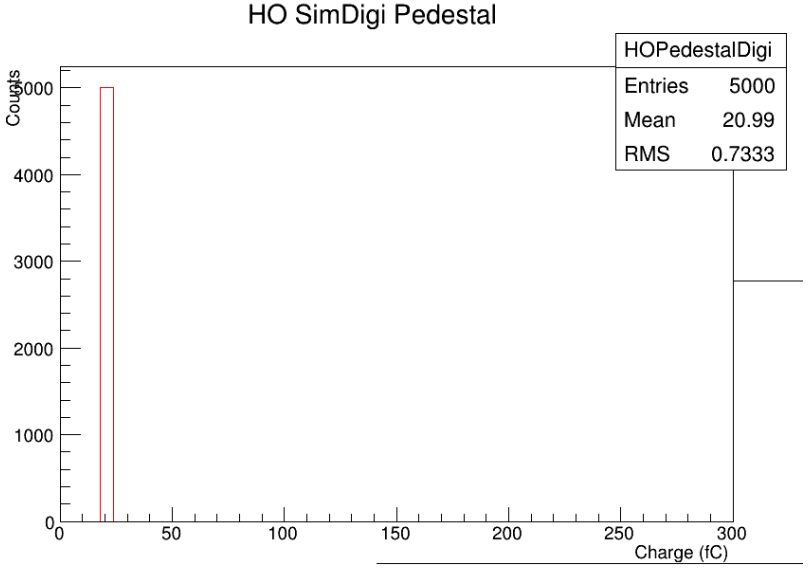
2DHistogram Traverse Energy vs Eta, 5k Muons Tower Eta=Phi=1



Projection Traverse Energy vs Eta, 5k Muons Tower Eta=Phi=1



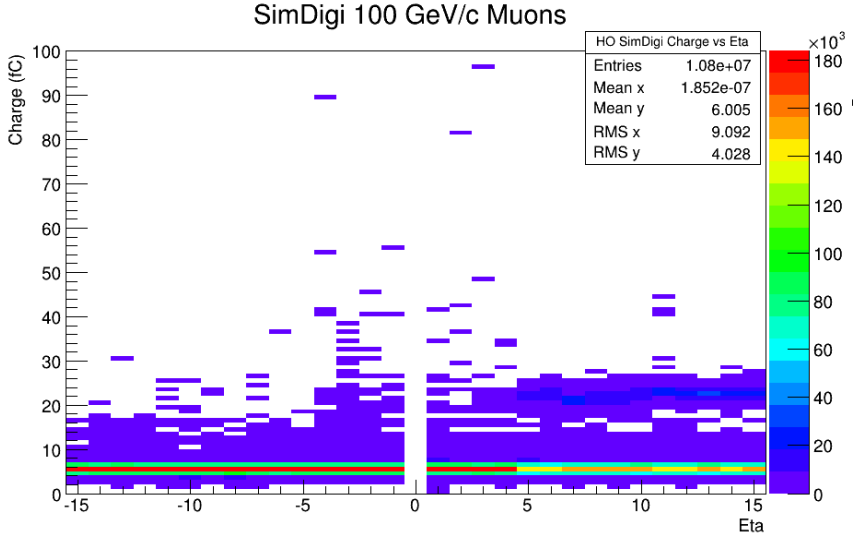
5k Muons Tower Eta=Phi=1



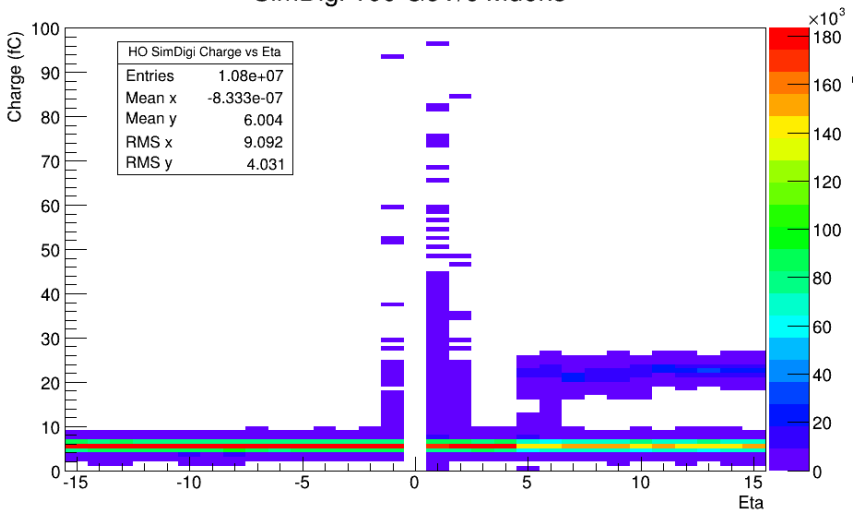
5k Muons Tower Eta=Phi=1

Results

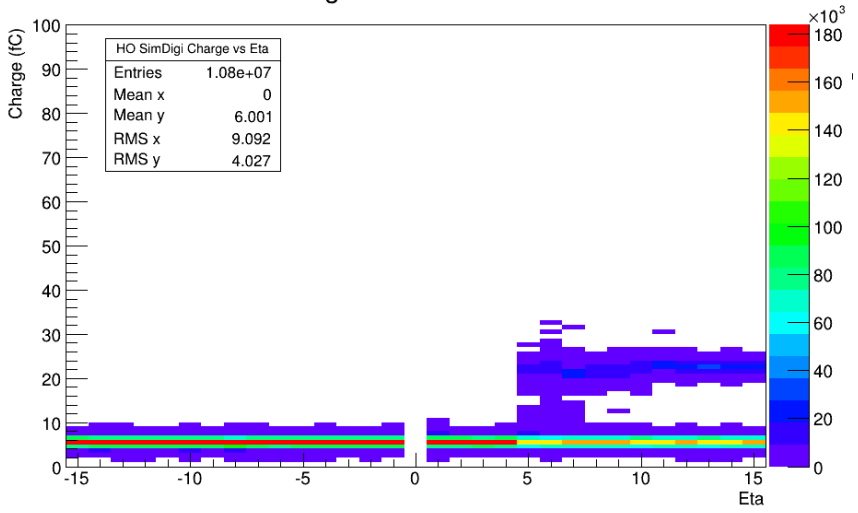
Muon Simulation



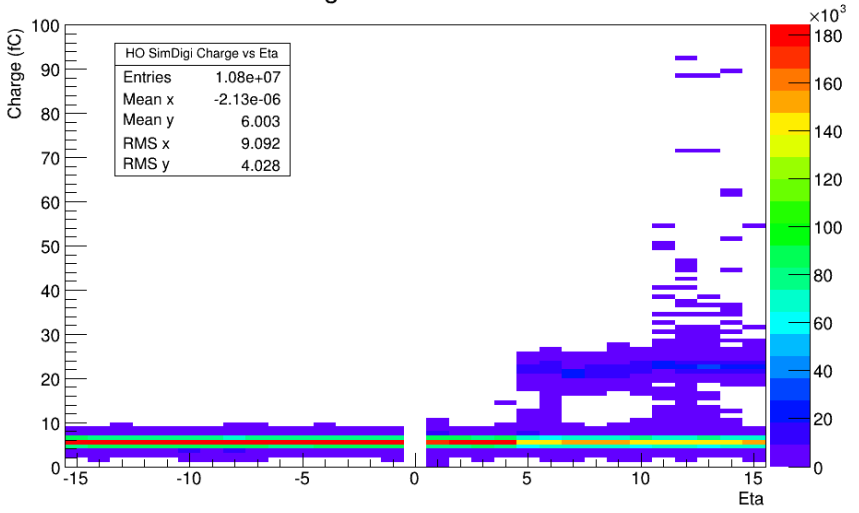
5k Muons Towers Eta∈[-15 – 15], Phi=1



5k Muons Tower Eta=Phi=1

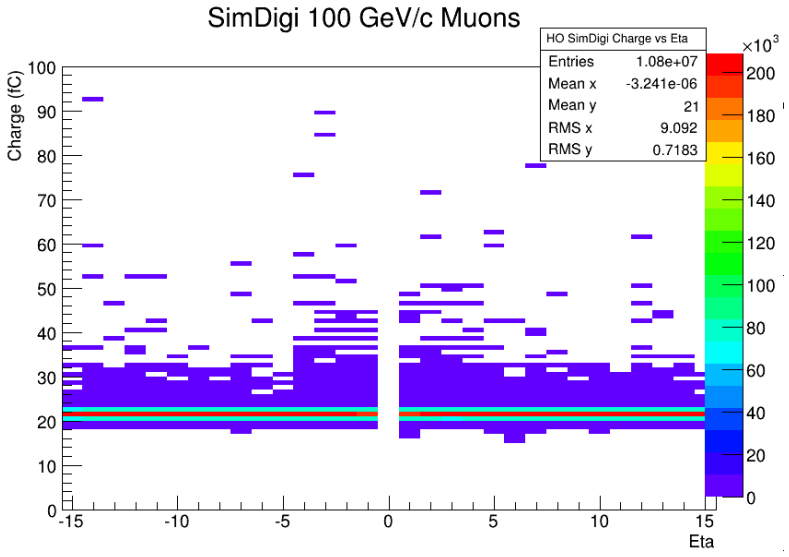


5k Muons Tower Eta=6,Phi=1

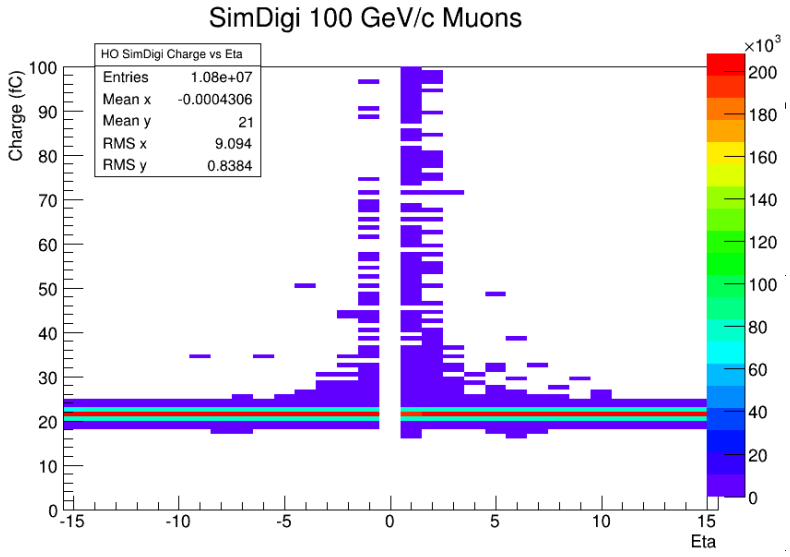


5k Muons Tower Eta=12,Phi=1

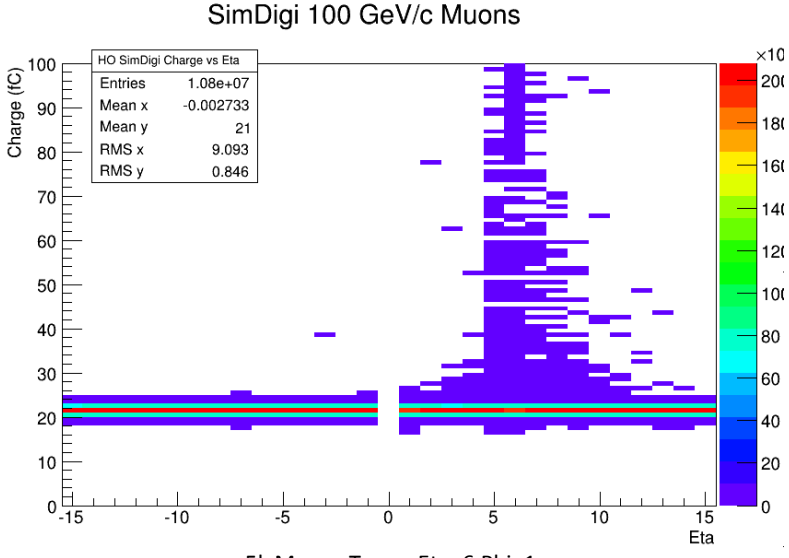
Results
Muon Simulation



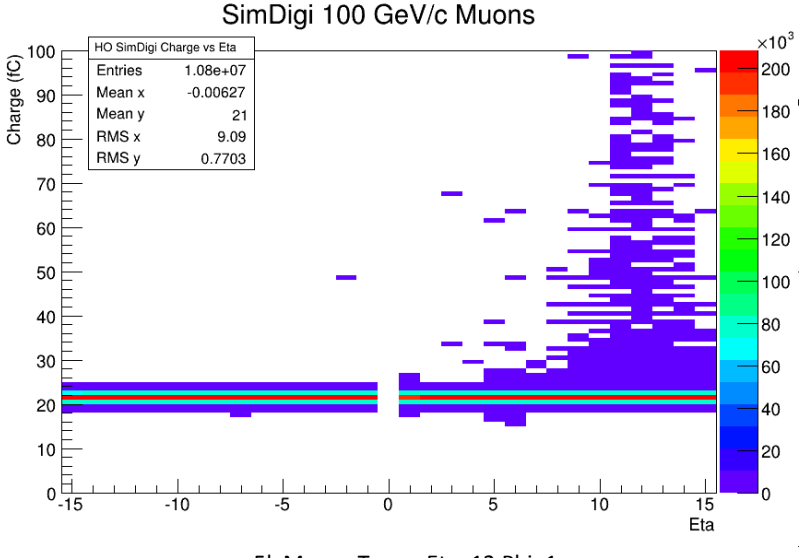
5k Muons Towers Eta∈[-15 – 15], Phi=1



5k Muons Tower Eta=Phi=1

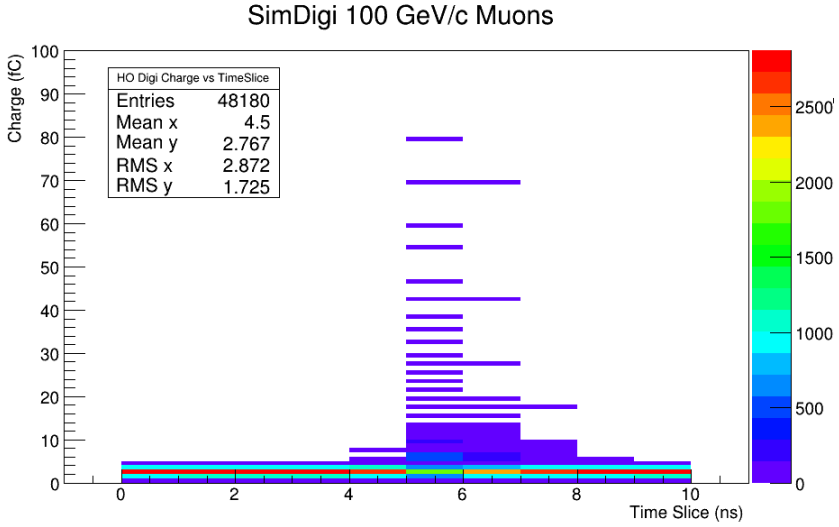


5k Muons Tower Eta=6,Phi=1

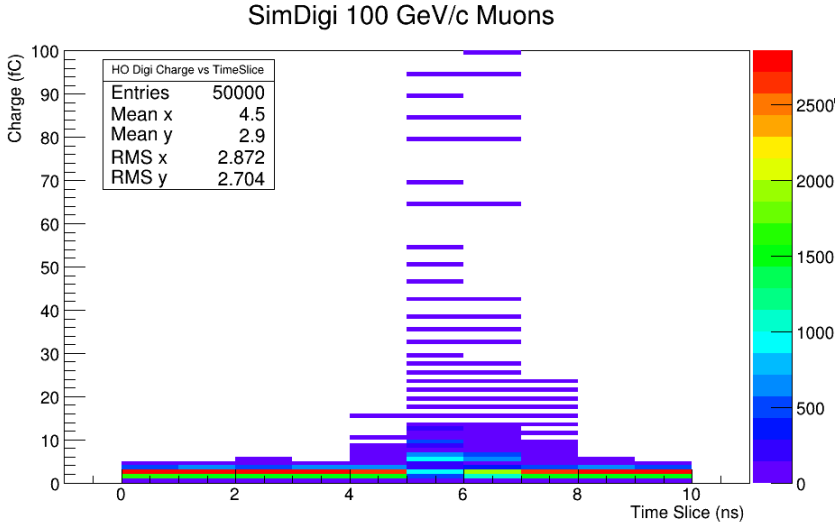


5k Muons Tower Eta=12,Phi=1

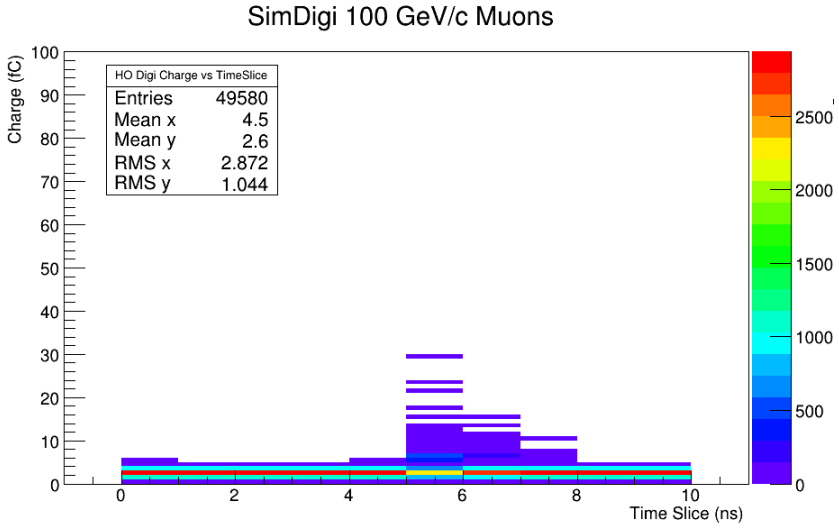
Results
Muon Simulation



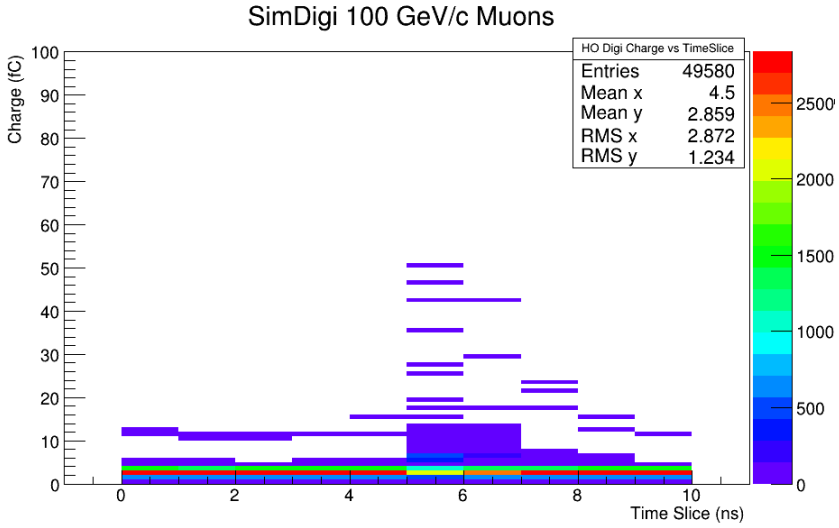
5k Muons Towers Eta∈[-15 – 15], Phi=1



5k Muons Tower Eta=Phi=1



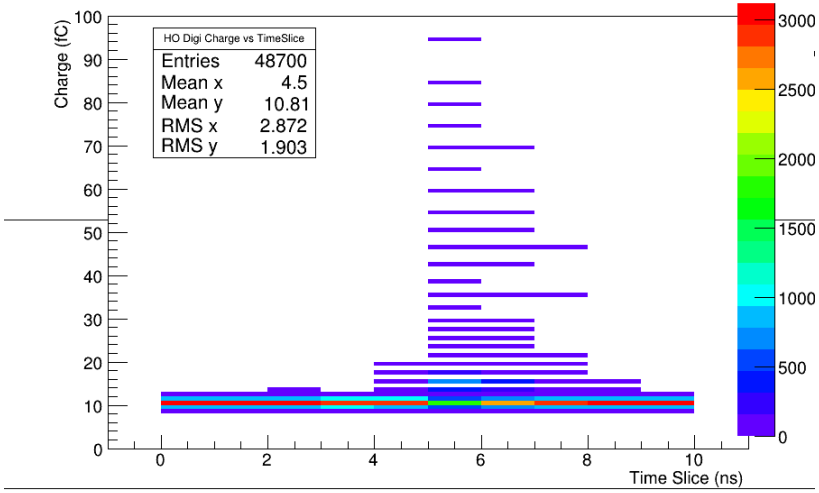
5k Muons Tower Eta=6,Phi=1



5k Muons Tower Eta=12,Phi=1

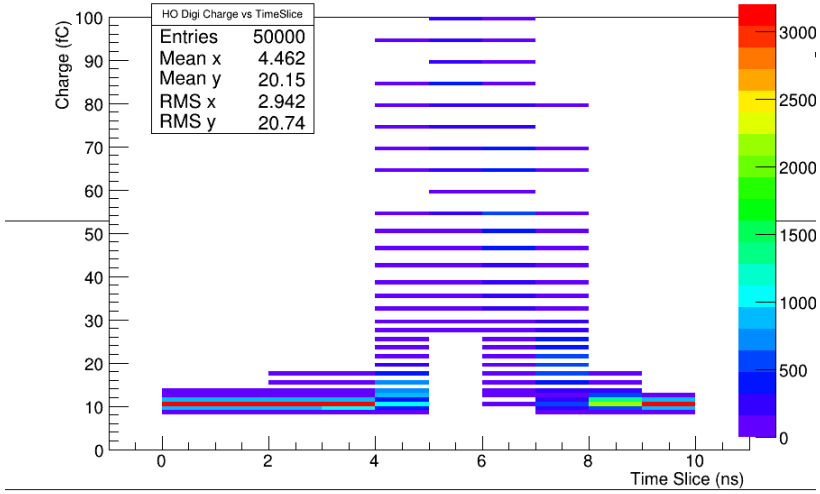
Results
Muon Simulation

SimDigi 100 GeV/c Muons



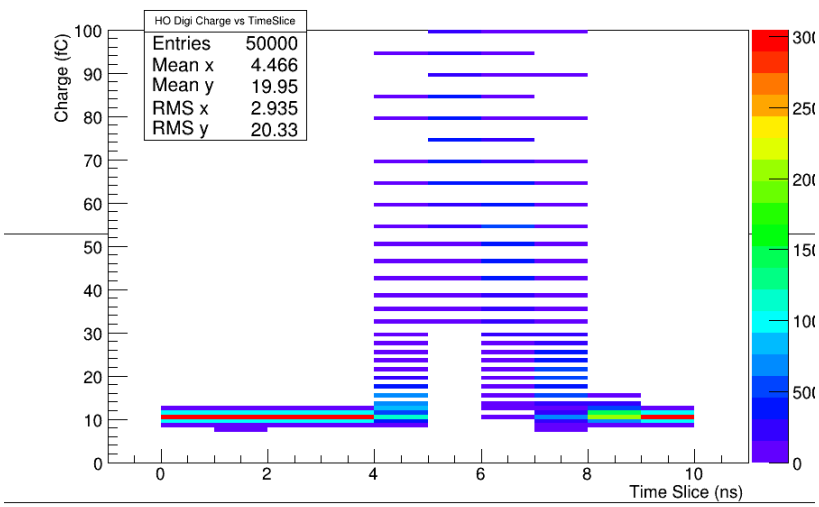
5k Muons Towers Eta∈[-15 – 15], Phi=1

SimDigi 100 GeV/c Muons



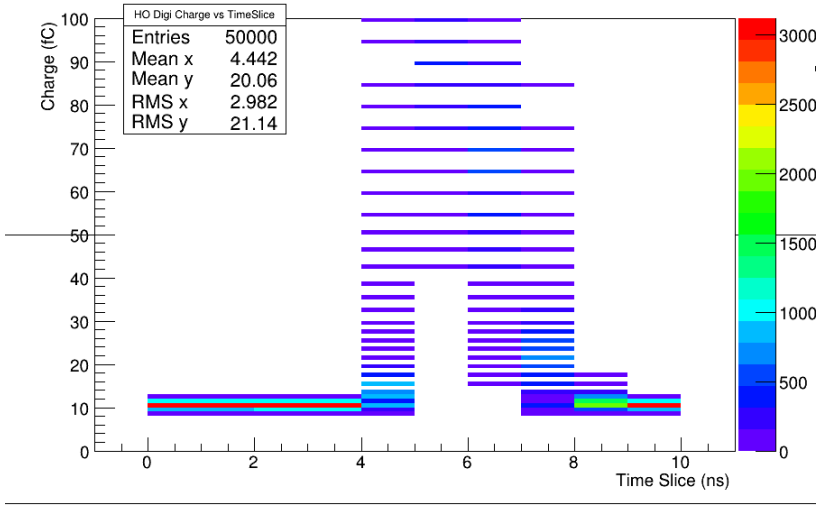
5k Muons Tower Eta=Phi=1

SimDigi 100 GeV/c Muons



5k Muons Tower Eta=6,Phi=1

SimDigi 100 GeV/c Muons

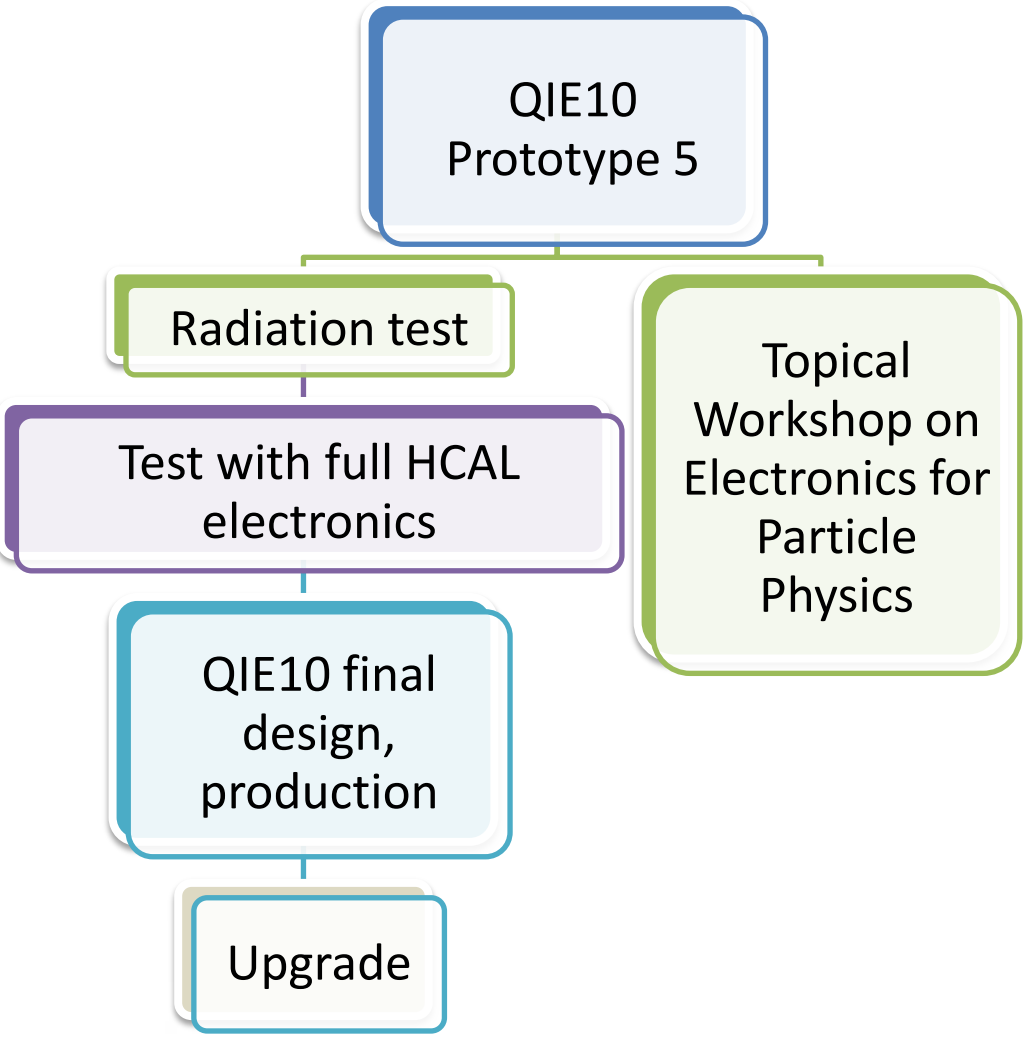


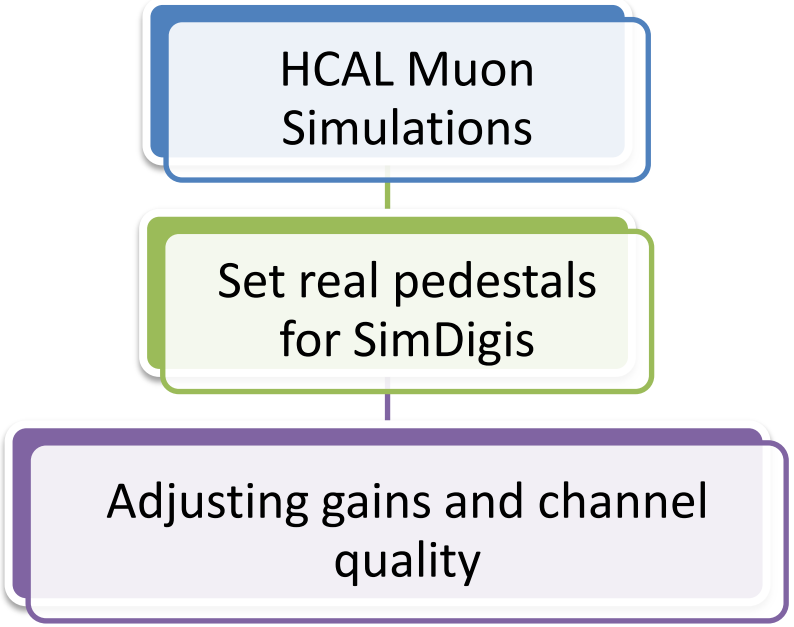
5k Muons Tower Eta=12,Phi=1

Conclusions
Muon Simulation

- Energy and transverse energy dependence on η is as expected for SimHits.
- Missing RecHits when ASCII conditions are not set to be read directly from files.
- Better signal recognition of SimDigis for rings 1 and 2 due to SiPMs.
- 11 fC pedestal for subdetector upgraded with SiPMs works well to get rid of noise.
- Gains are not, in general, η-dependent for towers in the same ring.

Further work





Acknowledgements

- Juliana Whitmore
- Jacob Anderson
- Elliot Hughes
- Hector Hernandez
- Roger Dixon and Erick Ramberg
- Carol Angarola, Amanda Thompson and Samantha Poeppelman

References

[1] The CERN Large Hadron Collider: Accelerator and Experiments, Volume 2: CMS, LHCb, LHCf, and TOTEM

[2] Upgrade of the CMS hadron calorimeter for and upgraded LHC, Jacob Anderson, for the CMS Hcal Collaboration, Journal of Physics: Conference Series 404 (2012) 012019, DOI: 10.1088/1742-6596/404/1/012019

[3] Design, performance, and calibration of the CMS hadron-outer calorimeter, The European Physical Journal C, Eur. Phys. J. C. (2008) 57: 653-663, DOI: 10.1140/epjc/s10052-008-0756-6

[4] CMS Internal Note, Study of Occupancy in the Outer Hadron Calorimeter Towers, S. Banerjee, A. Bhatti, S. Kunori, S. Sharma, 15 December 2007

[5] QIE10 Knowledge Specifically Relating To Version P5, Elliot Hughes, May 2013

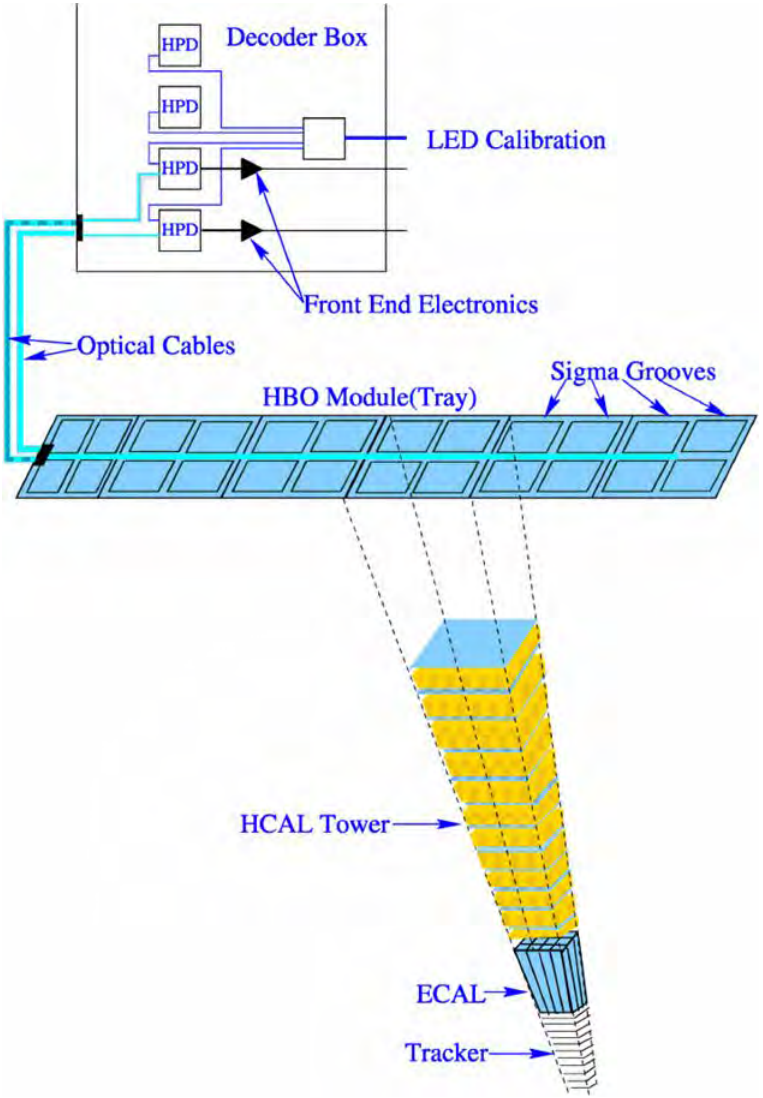
* Sugestions

- Software: QB → C++, Python *
- Hardware: Floppy disk → USB *
- Samples: 5 → >50?

* Already in process

Backup Slices

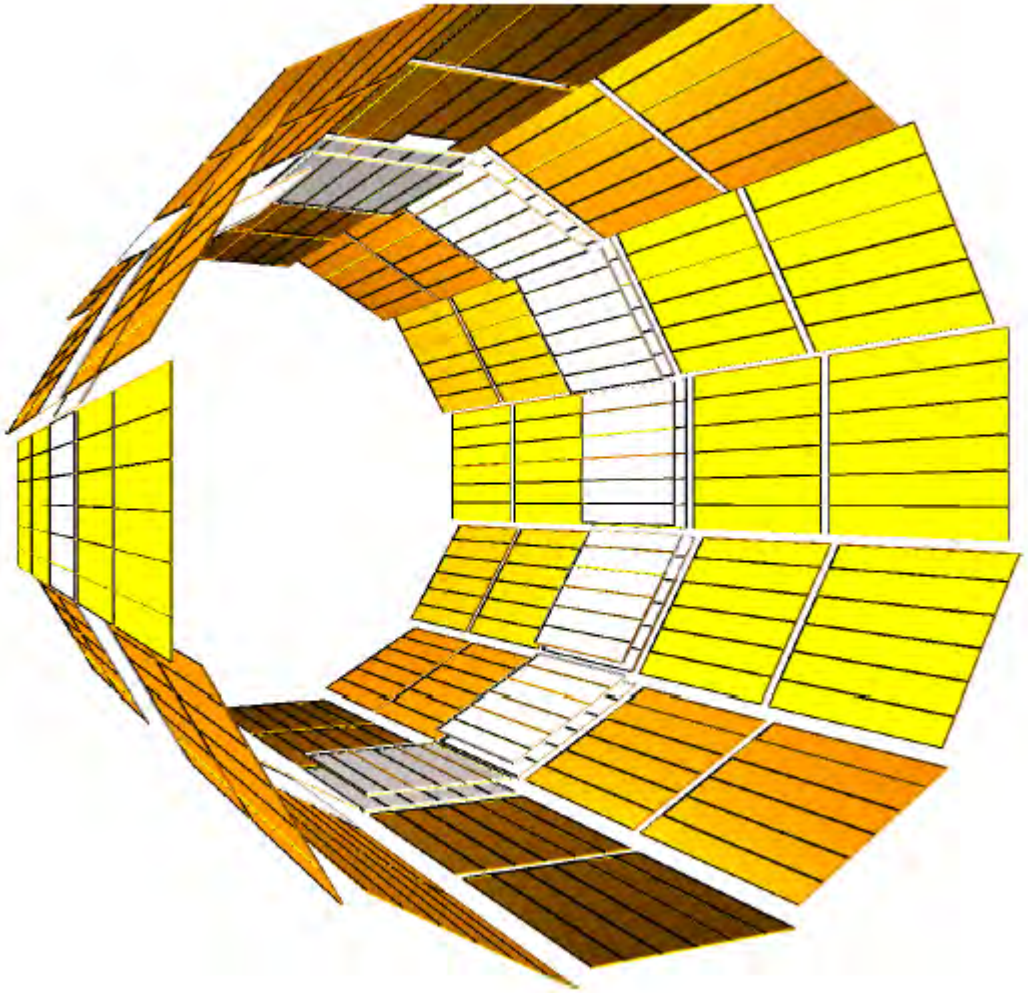
Mapping of the HB tower to a HO tile inside a tray



HO tyle with WLS fibers

Backup Slices

Layout of the HO trays



Chip 1 mean charge with pedestal 12

Mantissa	Expected charge (fC)	Mean Charge (fC) ± 1%
1	3.2	3,87
2	6.4	6,58
3	9.6	10,00
4	12.8	13,39
5	16.0	16,22
6	19.2	19,23
7	22.4	22,28
8	25.6	25,62
9	28.8	28,66
10	32.0	31,87
11	35.2	35,08
12	38.4	38,25
13	41.6	41,64
14	44.8	44,98
15	48.0	48,37
16	48.0	53,12
17	54.4	59,24
18	60.8	65,48
19	67.3	71,88
20	73.7	78,18
21	80.1	84,49
22	86.5	90,80
23	93.0	97,59
24	99.4	103,95
25	105.8	110,57
26	112.2	117,21
27	118.6	123,21
28	125.1	129,74
29	131.5	136,26
30	137.9	142,47
31	144.3	148,87

Mantissa	Expected charge (fC)	Mean Charge (fC) ± 1%
32	150.7	155,38
33	157.2	161,77
34	163.6	168,27
35	170.0	174,70
36	170.0	184,40
37	182.8	197,42
38	195.6	209,88
39	208.4	222,59
40	221.2	236,03
41	234.0	249,37
42	246.8	261,82
43	259.6	274,40
44	272.4	287,61
45	285.2	300,81
46	298.0	313,41
47	310.8	326,10
48	323.6	339,29
49	336.4	352,00
50	349.2	364,34
51	362.0	377,05
52	374.8	389,77
53	387.6	403,44
54	400.4	416,90
55	413.2	428,99
56	426.0	441,78
57	426.0	461,54
58	451.7	486,93
59	477.3	511,95
60	503.0	538,35
61	528.7	564,37
62	554.3	589,78

The ideal conversión between mantissa and input charge (ADC Code)

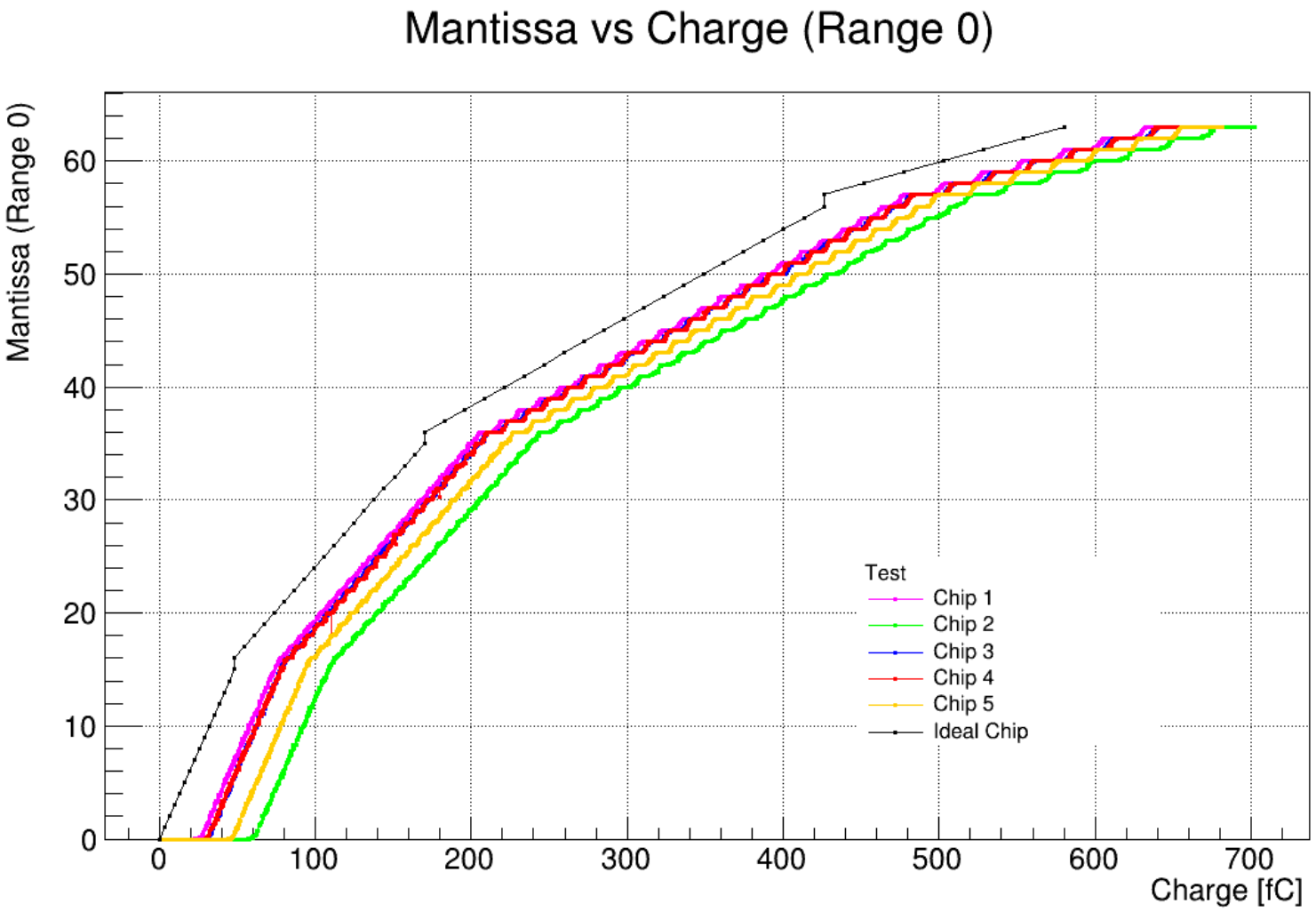
Mantissa	Input Charge (fC)			
	Range 0	Range 1	Range 2	Range 3
0	0.0	580.0	5214.0	42300
1	3.2	605.6	5418.8	43900
2	6.4	631.2	5623.6	45600
3	9.6	656.8	5828.4	47200
4	12.8	682.4	6033.2	48900
5	16.0	708.0	6238.0	50500
6	19.2	733.6	6442.8	52100
7	22.4	759.2	6647.6	53800
8	25.6	784.8	6852.4	55400
9	28.8	810.4	7057.2	57100
10	32.0	836.0	7262.0	58700
11	35.2	861.6	7466.8	60300
12	38.4	887.2	7671.6	62000
13	41.6	912.8	7876.4	63600
14	44.8	938.4	8081.2	65300
15	48.0	964.0	8286.0	66900
16	48.0	964.0	8286.0	66900
17	54.4	1015.2	8697.3	70200
18	60.8	1066.4	9108.5	73400
19	67.3	1117.6	9519.8	76700
20	73.7	1168.8	9931.1	78000
21	80.1	1220.1	10400	83200
22	86.5	1271.3	10800	86500
23	93.0	1322.5	11200	89800
24	99.4	1373.7	11600	93000
25	105.8	1424.9	12000	96300
26	112.2	1476.1	12400	99600
27	118.6	1527.3	12800	102900
28	125.1	1578.5	13200	106100
29	131.5	1629.7	13600	109400
30	137.9	1680.9	14000	112700
31	144.3	1732.2	14500	115900
32	150.7	1783.4	14900	119200
33	157.2	1834.6	15300	122500

The ideal conversión between mantissa and input charge (ADC Code)

Mantissa	Input Charge (fC)			
	Range 0	Range 1	Range 2	Range 3
34	163.6	1885.8	15700	125700
35	170.0	1937.0	16100	129000
36	170.0	1937.0	16100	129000
37	182.8	2039.4	16900	135600
38	195.6	2141.8	17700	142100
39	208.4	2244.2	18600	148700
40	221.2	2346.6	19400	155200
41	234.0	2449.0	20200	161800
42	246.8	2551.4	21000	168300
43	259.6	2653.8	21800	174900
44	272.4	2756.2	22700	181400
45	285.2	2858.6	23500	188000
46	298.0	2961.0	24300	194500
47	310.8	3063.4	25100	201200
48	323.6	3165.8	26000	207600
49	336.4	3268.2	26800	214200
50	349.2	3370.6	27600	220700
51	362.0	3473.0	28400	227300
52	374.8	3575.4	29200	233800
53	387.6	3677.8	30000	240300
54	400.4	3780.2	30900	246900
55	413.2	3882.6	31700	253500
56	426.0	3985.0	32500	260000
57	426.0	3985.0	32500	260000
58	451.7	4189.8	34100	273200
59	477.3	4394.7	35800	286300
60	503.0	4599.5	37400	299500
61	528.7	4804.3	39000	312700
62	554.3	5009.2	40700	325800
63	580.0	5214.0	42300	339000

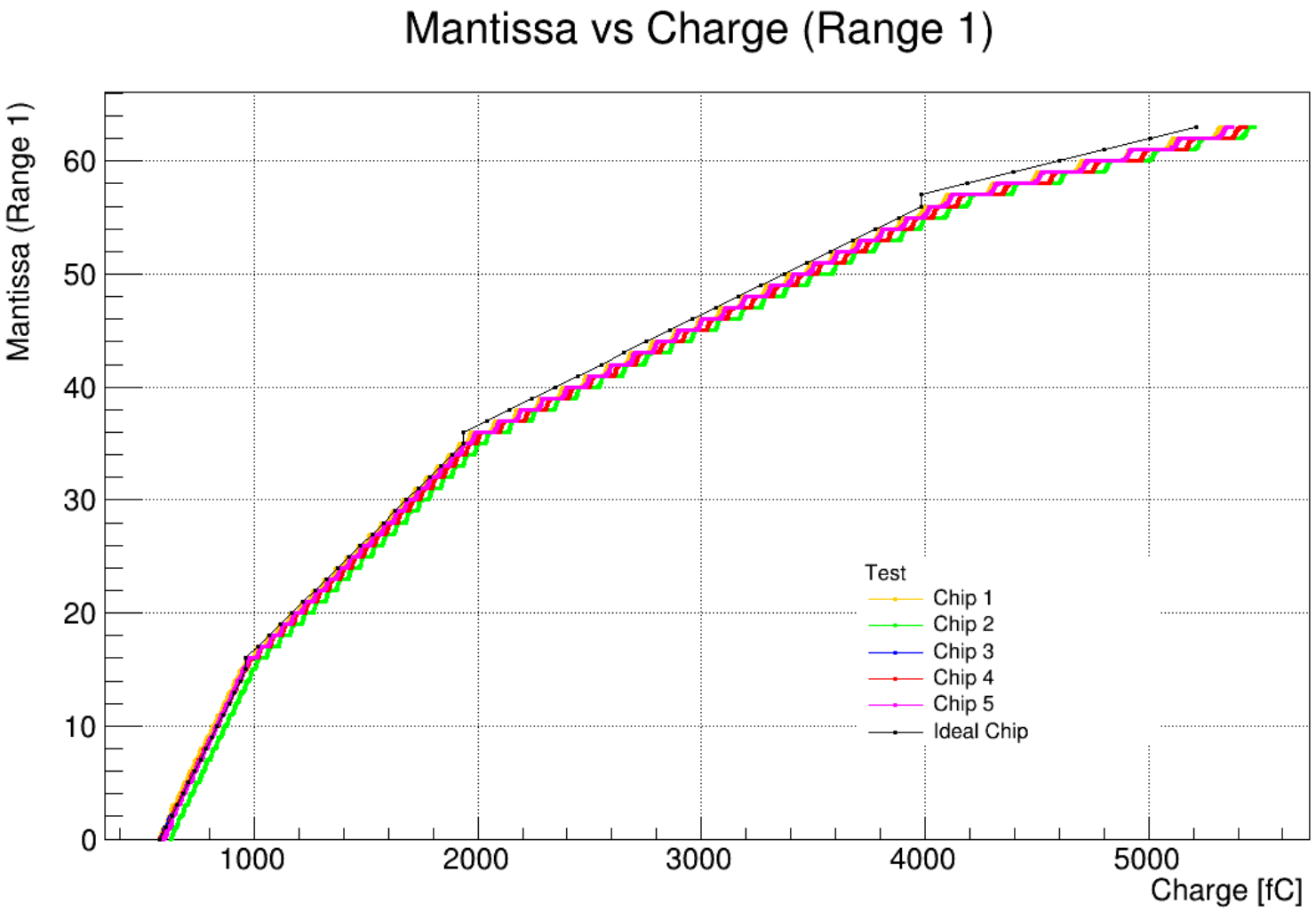
Results

QIE10 Performance



Mantissa as a function of injected charge for range 0, no pedestal, for each of the 5 chips.
*The error bars don't show because of the scale, they are <1% of the injected charge.

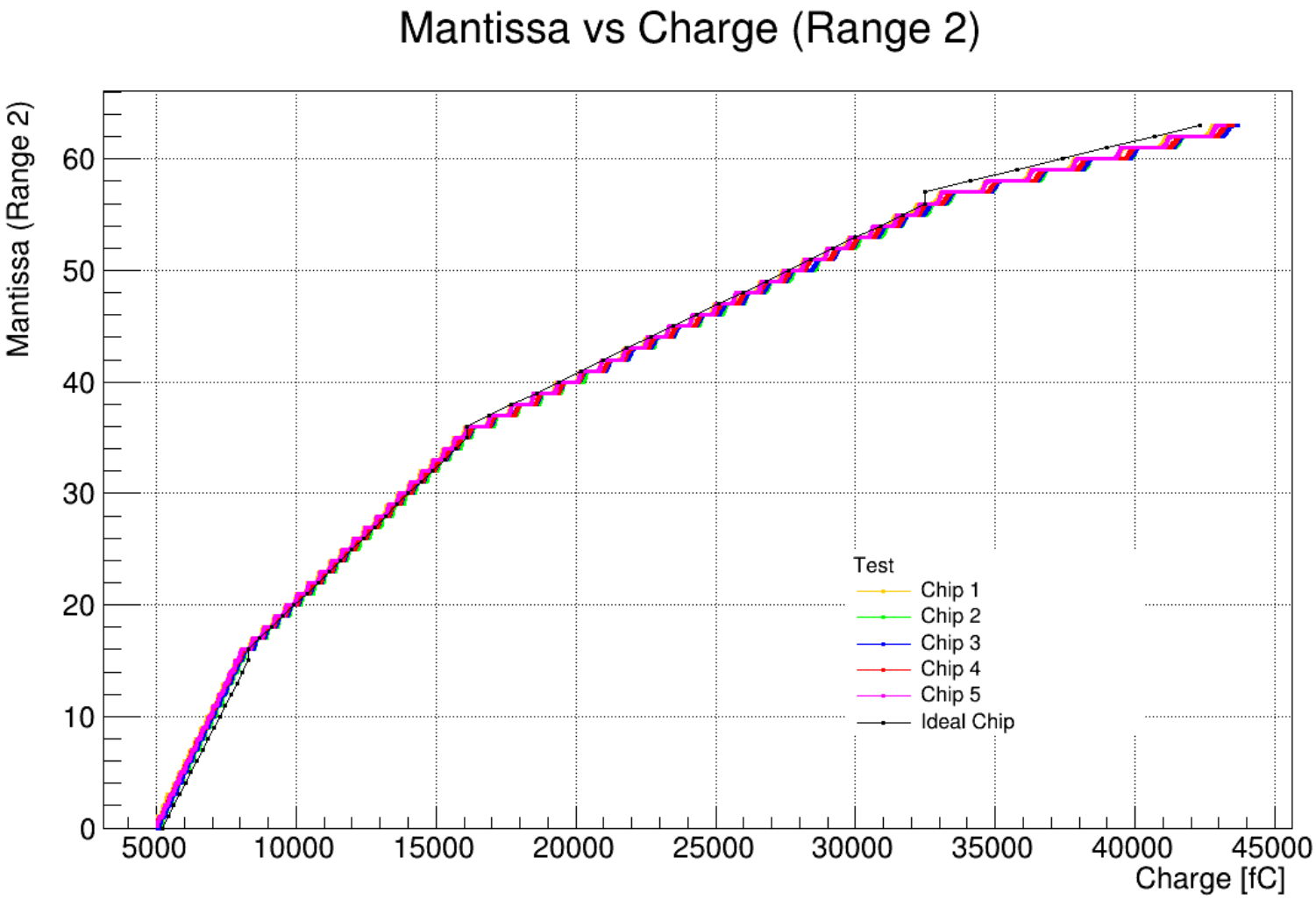
Results
QIE10 Performance



Mantissa as a function of injected charge for range 1, no pedestal, for each of the 5 chips.
*The error bars don't show because of the scale, they are <1% of the injected charge.

Results

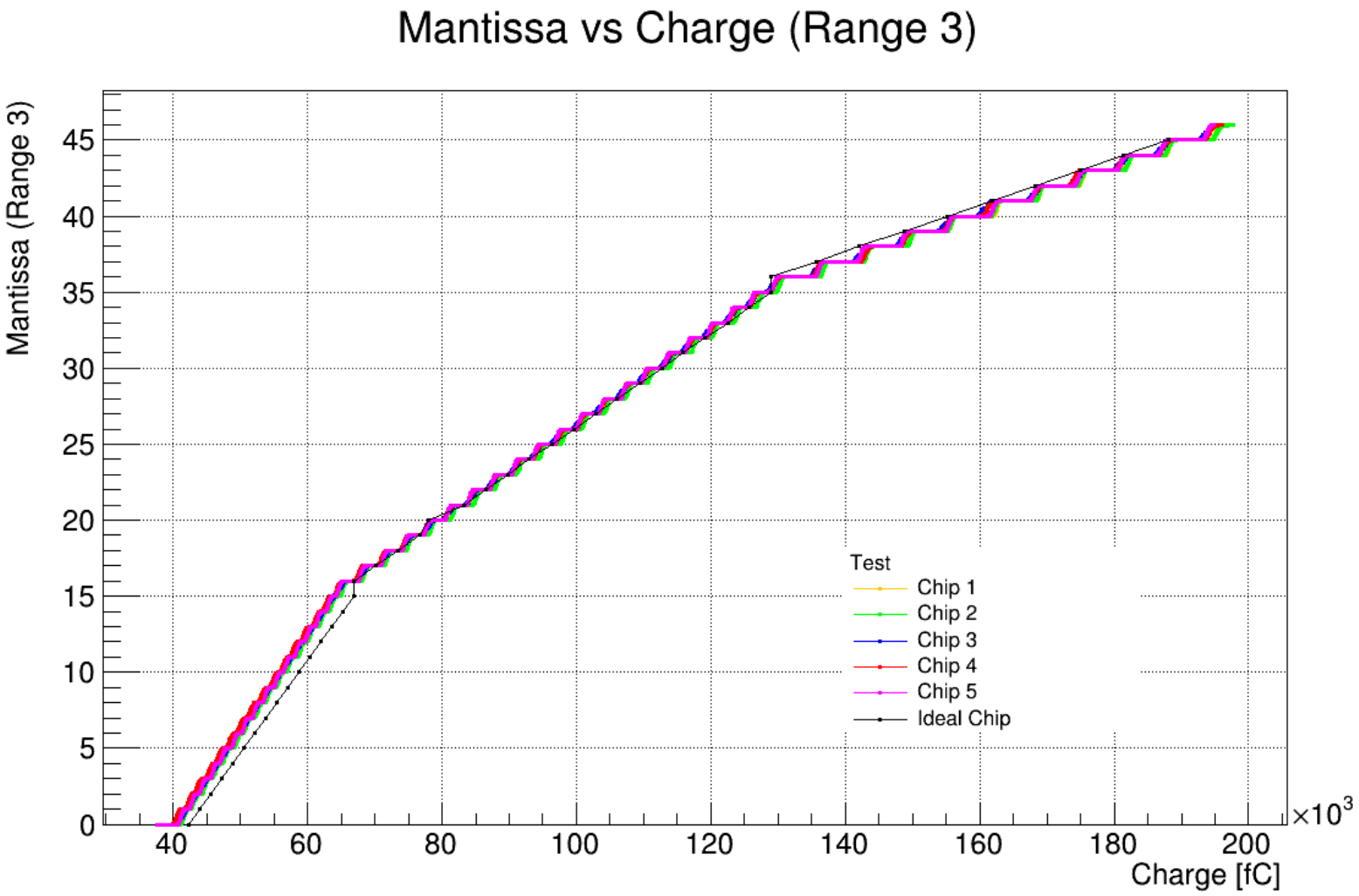
QIE10 Performance



Mantissa as a function of injected charge for range 2, no pedestal, for each of the 5 chips.
*The error bars don't show because of the scale, they are <1% of the injected charge.

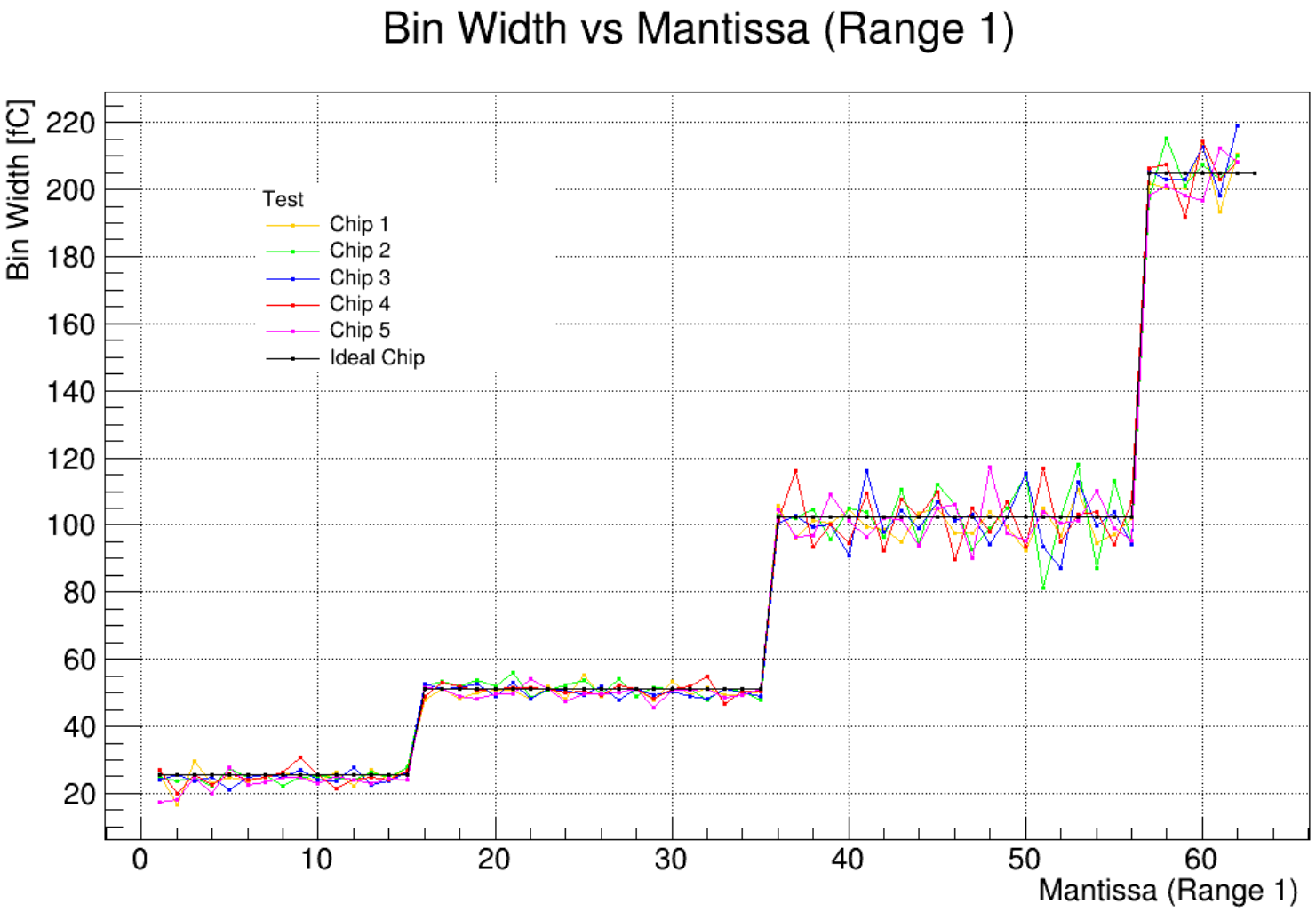
Results

QIE10 Performance



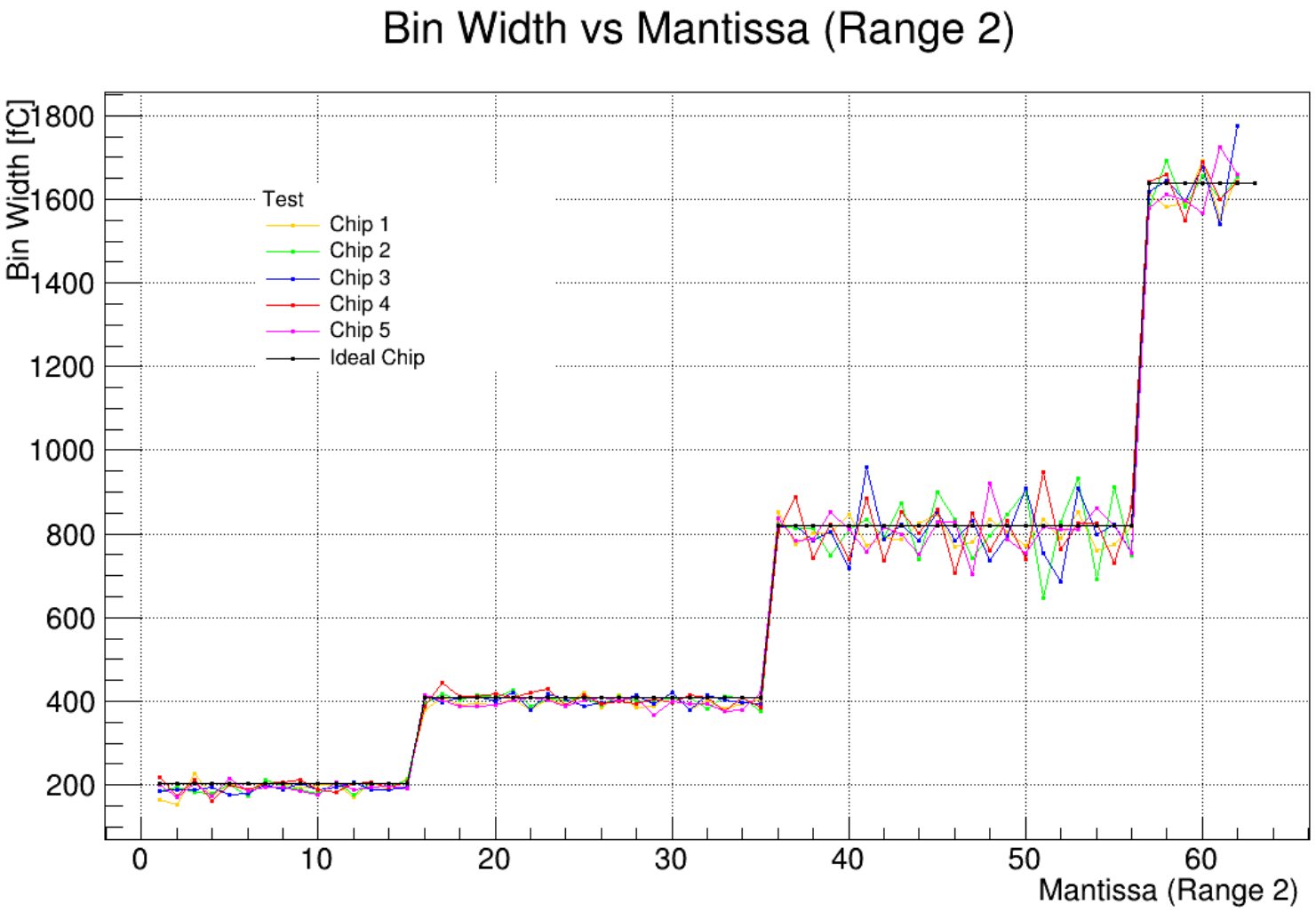
Mantissa as a function of injected charge for range 3, no pedestal, for each of the 5 chips.
*The error bars don't show because of the scale, they are <1% of the injected charge.

Results
QIE10 Performance



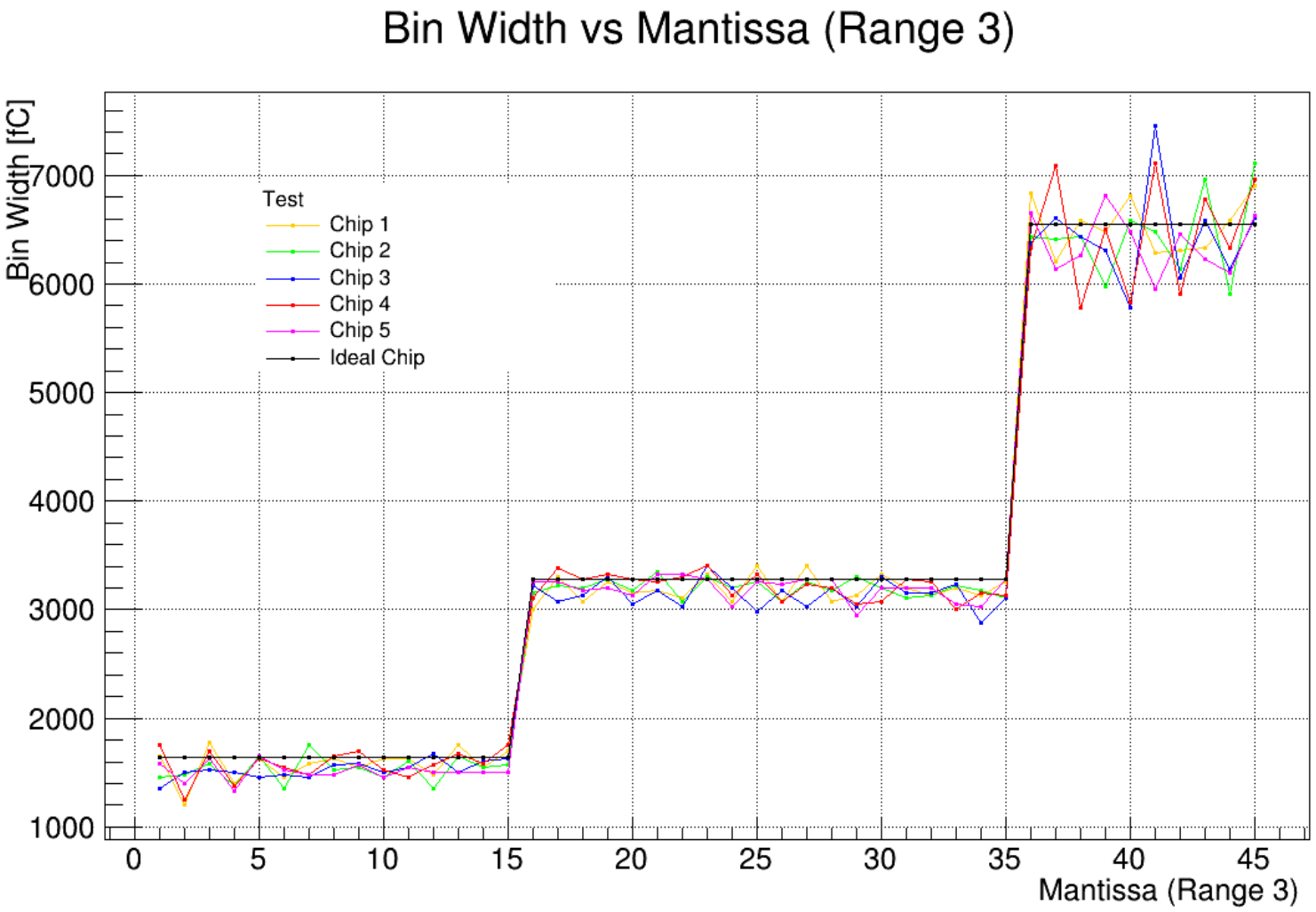
Relation between binwidth and mantissa for range 1.
*The error bars corresponding to the standard deviation, computed for each subrange dont show for better appreciation, though the values fall inside the range of confidence.

Results
QIE10 Performance



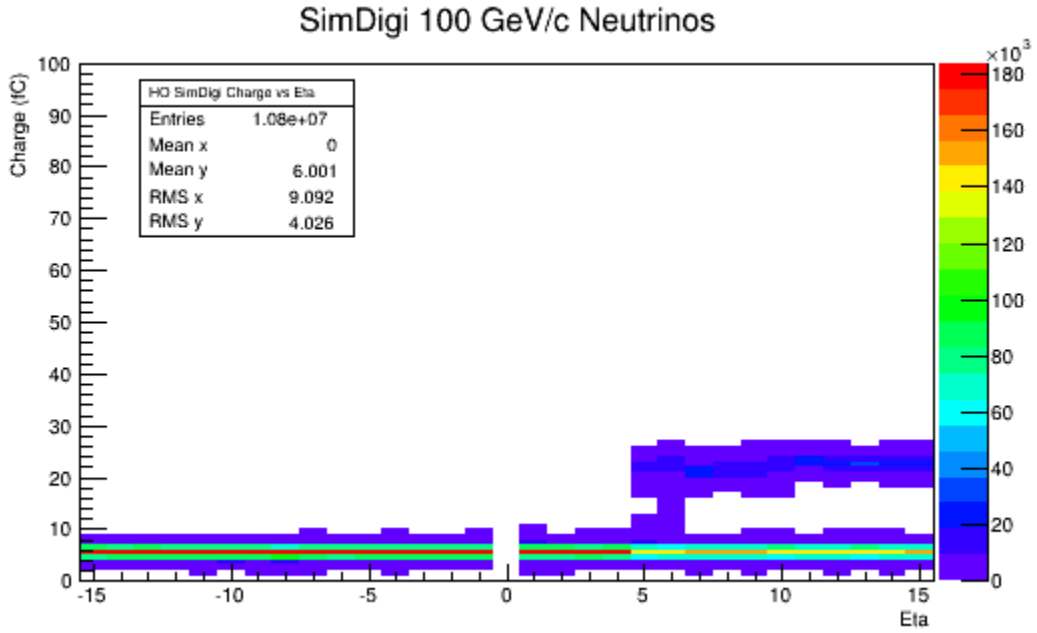
Relation between binwidth and mantissa for range 2.
*The error bars corresponding to the standard deviation, computed for each subrange doesnt show for better appreciation, though the values fall inside the range of confidence.

Results
QIE10 Performance



Relation between binwidth and mantissa for range 3.
*The error bars corresponding to the standard deviation, computed for each subrange dont show for better appreciation, though the values fall inside the range of confidence.

Backup Slices



*** 5k Muons generated in all the eta range [-1.262,1.262] for phi=1**