Characterization of the readout electronics of Arm2 silicon sensors
and
reconstruction of the incident energy with Arm2 silicon sensors

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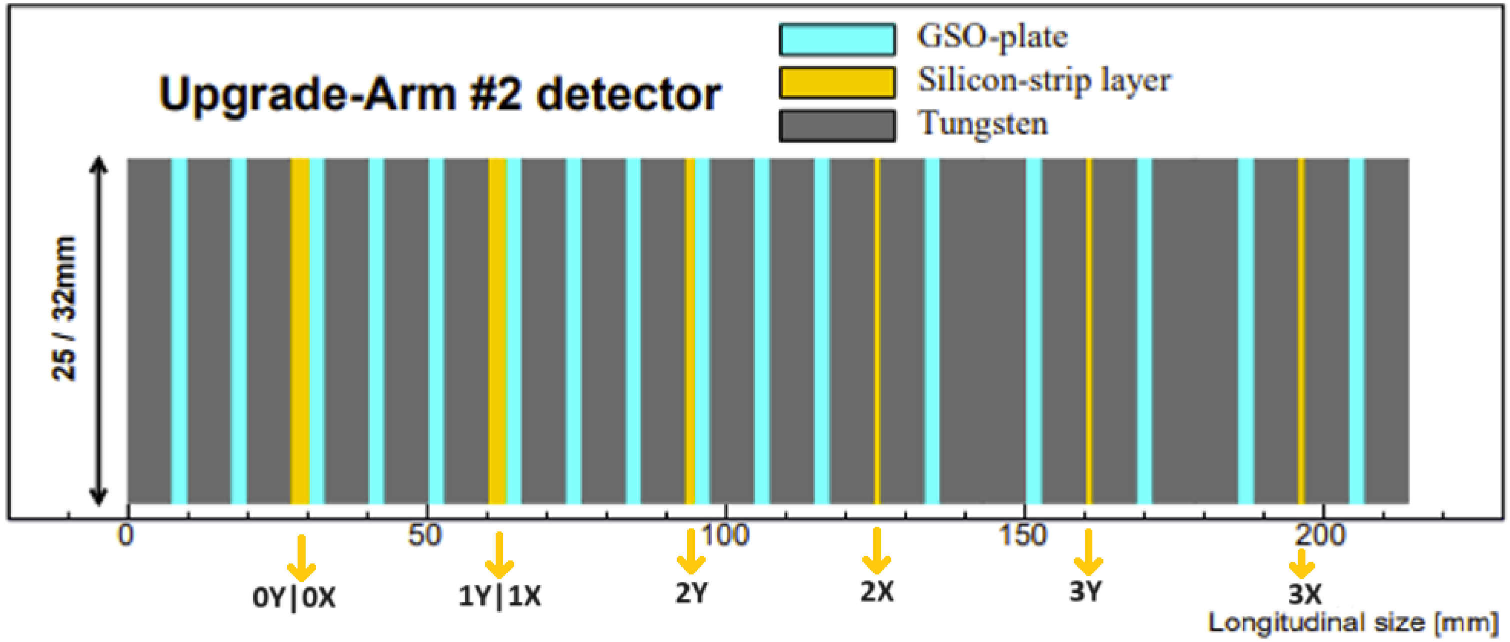
Arm2 silicon microstrips sensors

8 silicon sensors:

4 X-view and 4 Y-view

POSITION RECONSTRUCTION

Transverse profile of the shower at different depths of the calorimeter



NEW: ENERGY RECONSTRUCTION

Incident energy reconstruction using Arm2 silicon detector

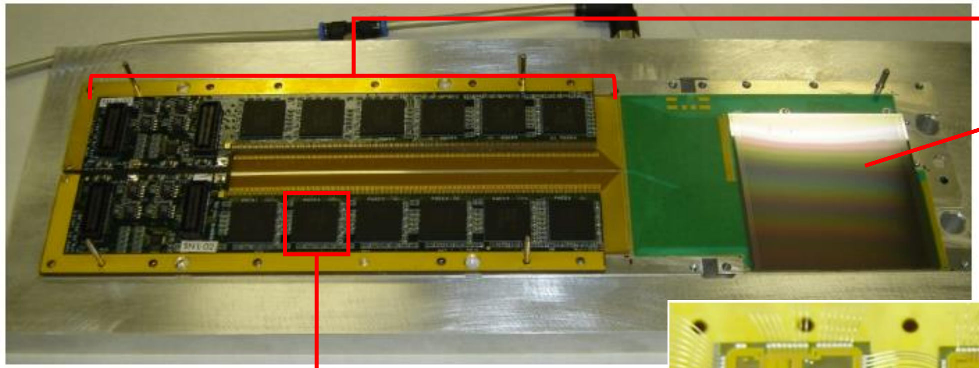
- Additional tool to recalibrate the absolute energy scale

- Characterization of the silicon readout electronics → chip PACE3
- Implementation of the energy reconstruction algorithm using the energy deposit in silicon sensors

Characterization of the readout electronics of Arm2 silicon sensors

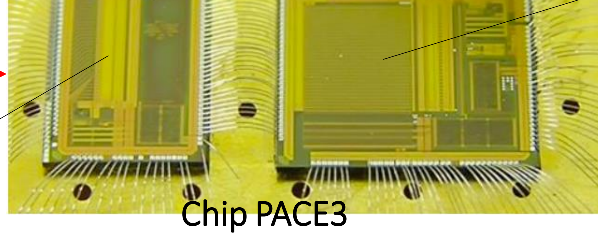
Silicon readout electronics: chip PACE3

Each silicon sensor has **384 microstrips** read by **12 chip PACE3**



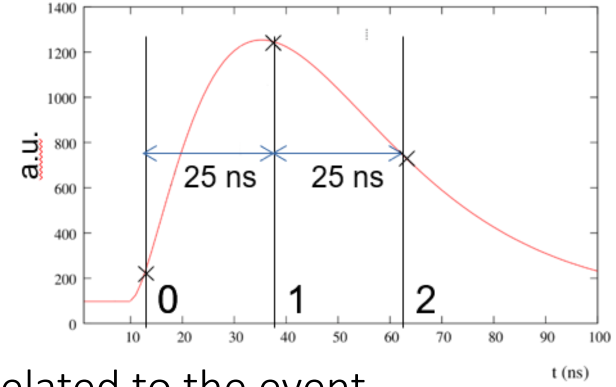
Each chip PACE3 has 32 channels and is composed by

- Delta3: preamplifiers and shapers
- PACEAM3: analog memory (capacitor array)



- ➢ Analog signals sampled at LHC clock frequency (40.08 MHz → one sample every 25 ns)
- ➢ When there is a L1 trigger, **3 consecutive samples** are saved

The delay between the actual event and the L1 trigger is called **latency**.



The latency parameter must be

- set to match the real latency of the experiment in order to read the 3 samples related to the event
- adjusted to have an average ratio sample 0 / sample 1 ~ 0.1 - 0.15

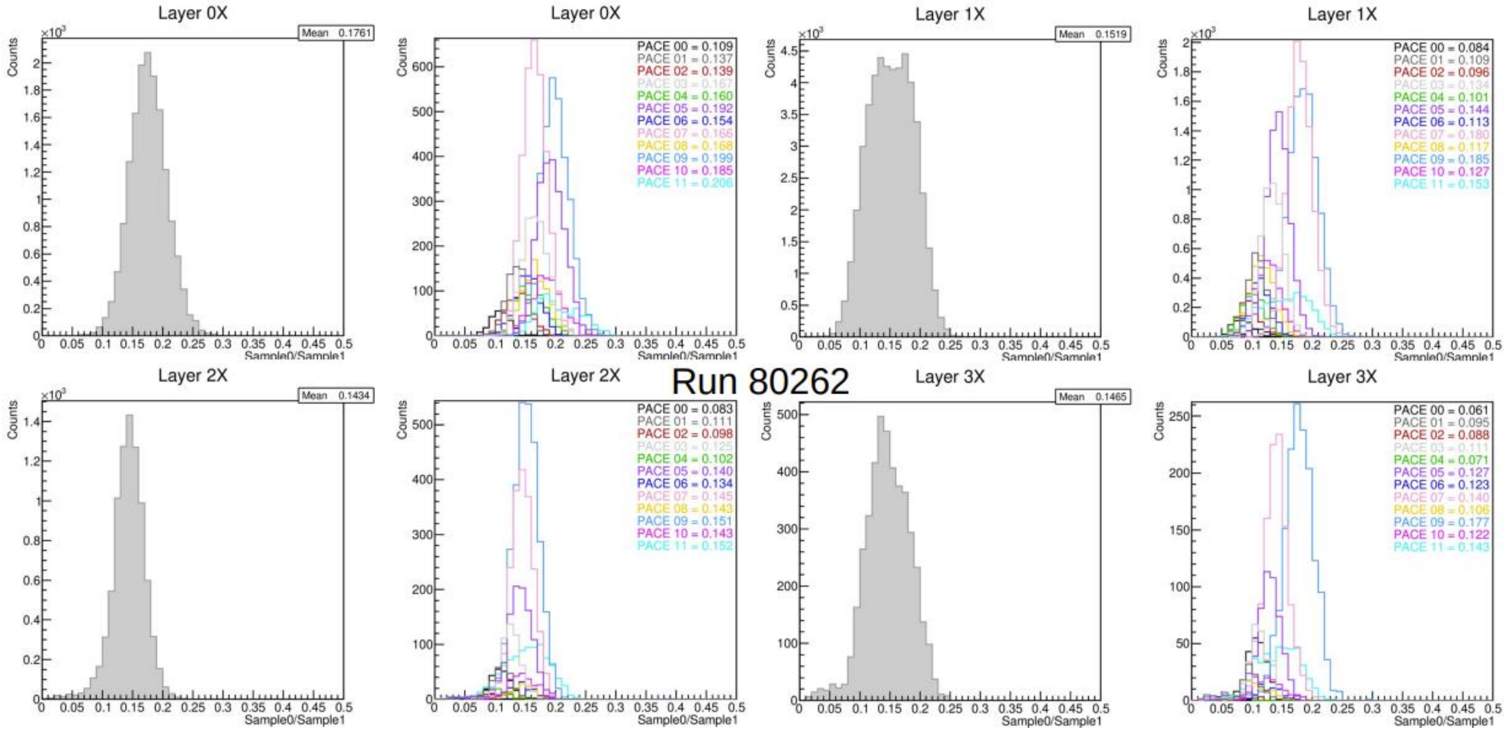
Silicon characterization: Motivation

Main motivations to perform the characterization of the electronics:

1. Dependance of the ratio sample 0 / sample 1 (S0/S1) on the chip

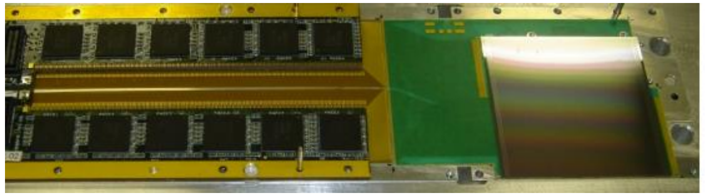
   (Eugenio’s presentation 22/02/2024)

S0/S1 ratio: Chip Dependence [Layer X] by selecting signals in [3000, 3500] ADC



Study the time shape of the signals in different chip in order to understand the origin of the chip dependance of S0/S1

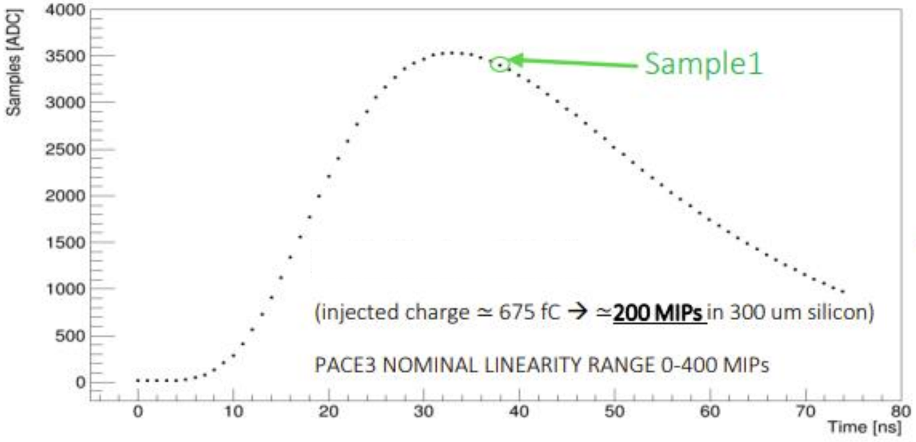
- Chip dependance due to the different electrical path lengths (different lengths of the pitch adapter from the microstrip to input channel of the chip)



Silicon characterization: Motivation

Main motivations to perform the characterization of the electronics:

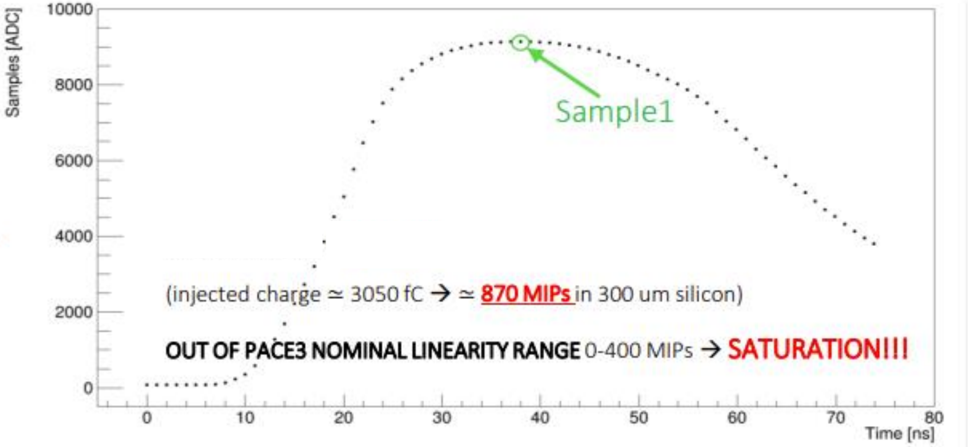
2. Saturation of the electronics



(injected charge ≃ 675 fC → ≃**200 MIPs** in 300 um silicon)

PACE3 NOMINAL LINEARITY RANGE 0-400 MIPs

Signal with a larger amplitude



(injected charge ≃ 3050 fC → ≃ **870 MIPs** in 300 um silicon)

OUT OF PACE3 NOMINAL LINEARITY RANGE 0-400 MIPs → **SATURATION!!!**

Study of the PACE3 response curve in the linear and non-linear region in order to correct Sample 1 for the non-linearity effect

Silicon calibration procedures

1. Study of the signal time shape → calibration pulses of fixed amplitude, sampled at different latencies (latency scan)
   Samples 0, Samples 1 and Samples 2 vs Time to reconstruct the time shape of the calibration pulse
2. Study of the response curve → amplitude scan of calibration pulses, sampled at a fixed latency
   Sample 1 vs Amplitude of the calibration pulse (vs injected charge) to get the response curve

Two different calibration procedures:

External calibration

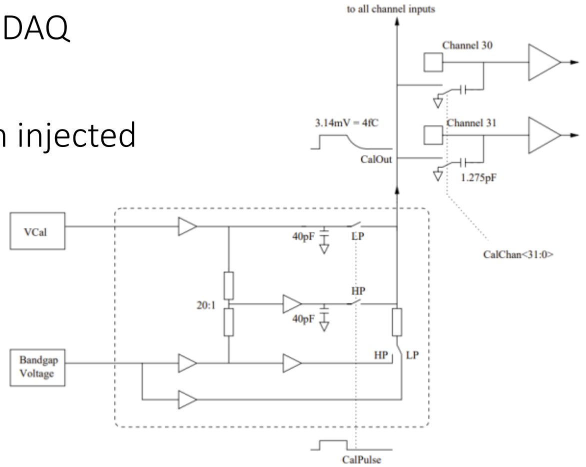
Calibration pulse injected on a capacitor on the silicon microstrip

- ✓ Study of the dependance of the time shape (and S0/S1 ratio) on the pitch adapter’s lenght
- ✓ Possible to inject high amplitude calibration signal (>850 MIPs) to better study the non-linear response region
- ✗ Impossible to calibrate every channels

Internal calibration

Calibration pulse injected on the channel of the PACE3 chip through the PACE3 internal calibration circuit

- ✓ Simultaneous calibration of all channels of all chip of all MDAQ boards
- ✗ Limitation on the maximum injected charge (<570 MIPs)



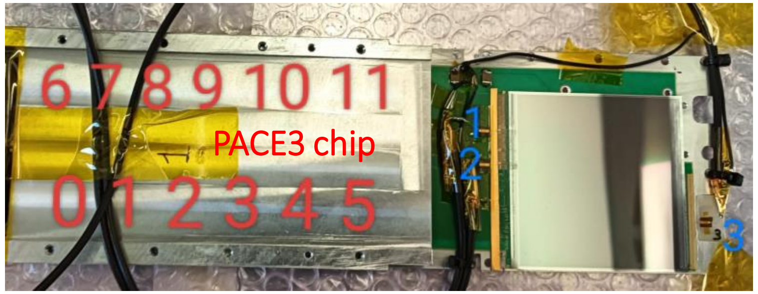
Signal time shape (external calibration)

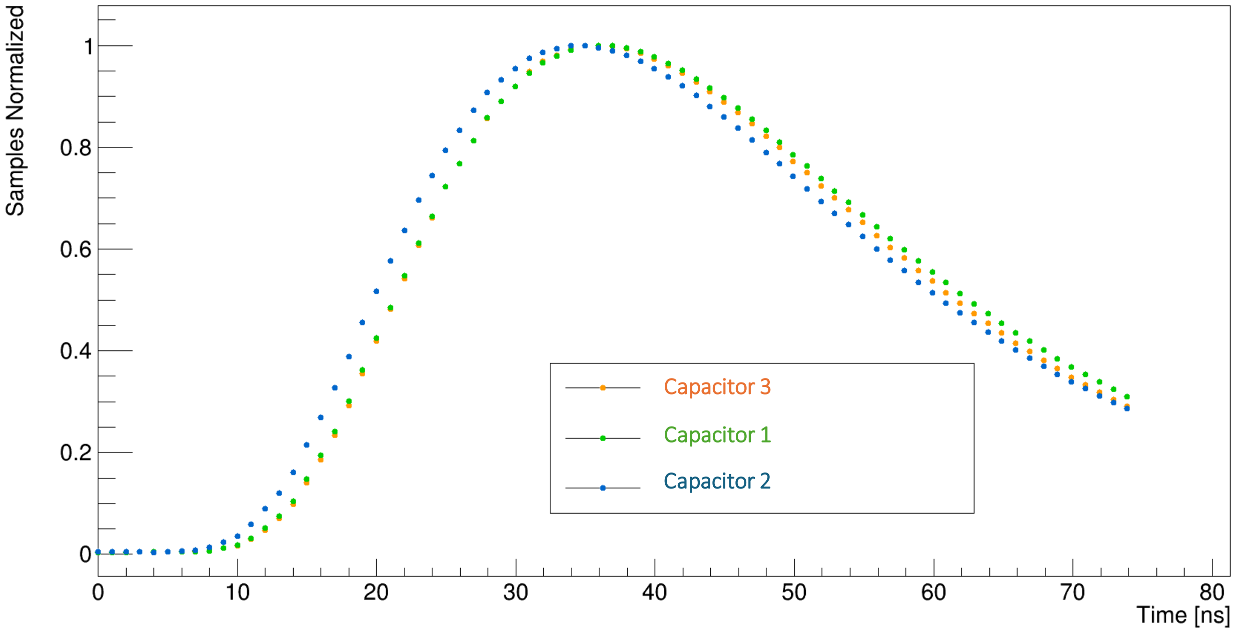
3 external capacitors on 3 silicon microstrips (Module X spare) → pitch adapter length dependance

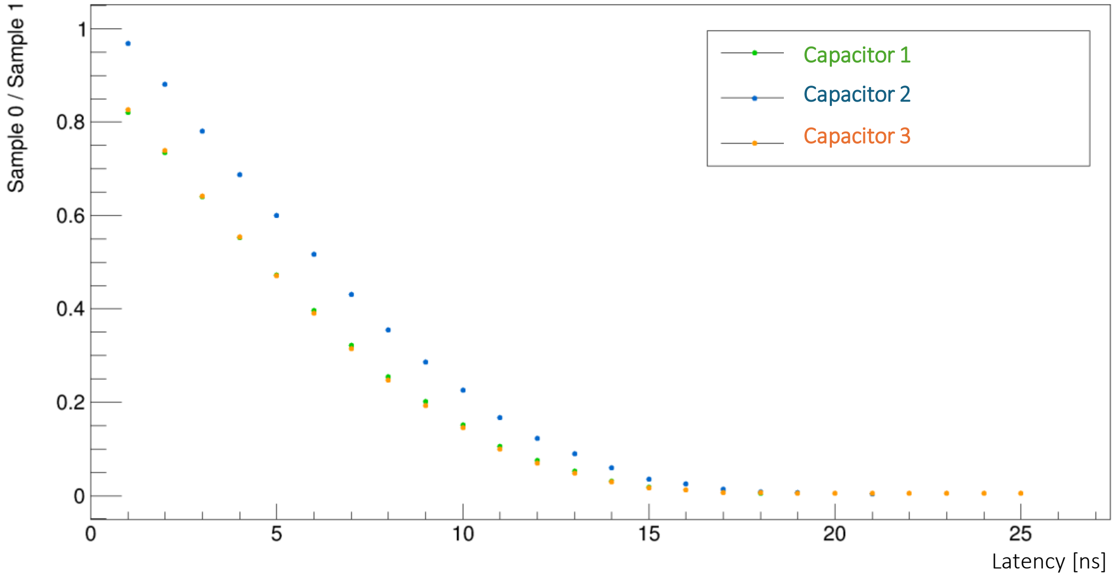
Capacitor 1: channel 20 of chip 8 (pitch adapter length: 202.99 mm)

Capacitor 2: channel 1 of chip 11 (pitch adapter length : 100.89 mm)

Capacitor 3: channel 21 of chip 3 (pitch adapter length : 238.82 mm)



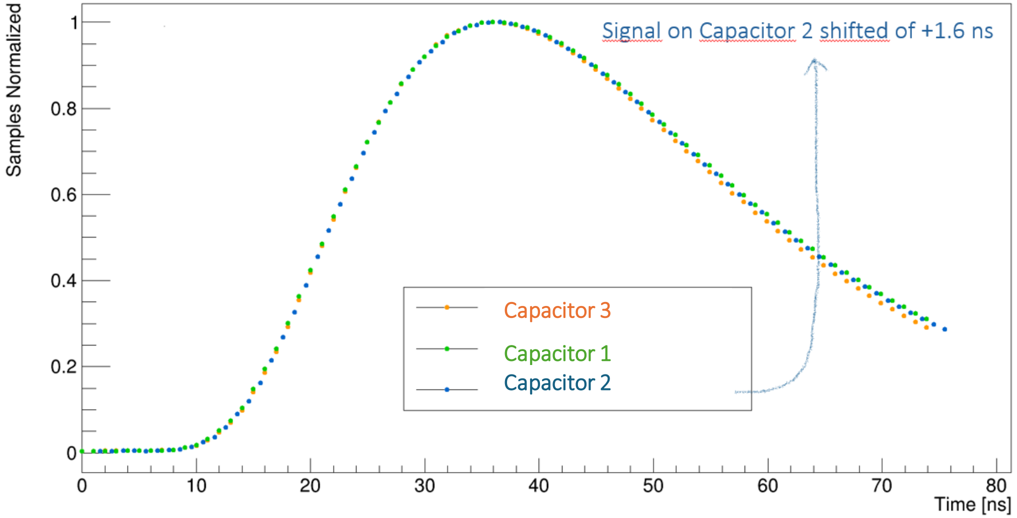


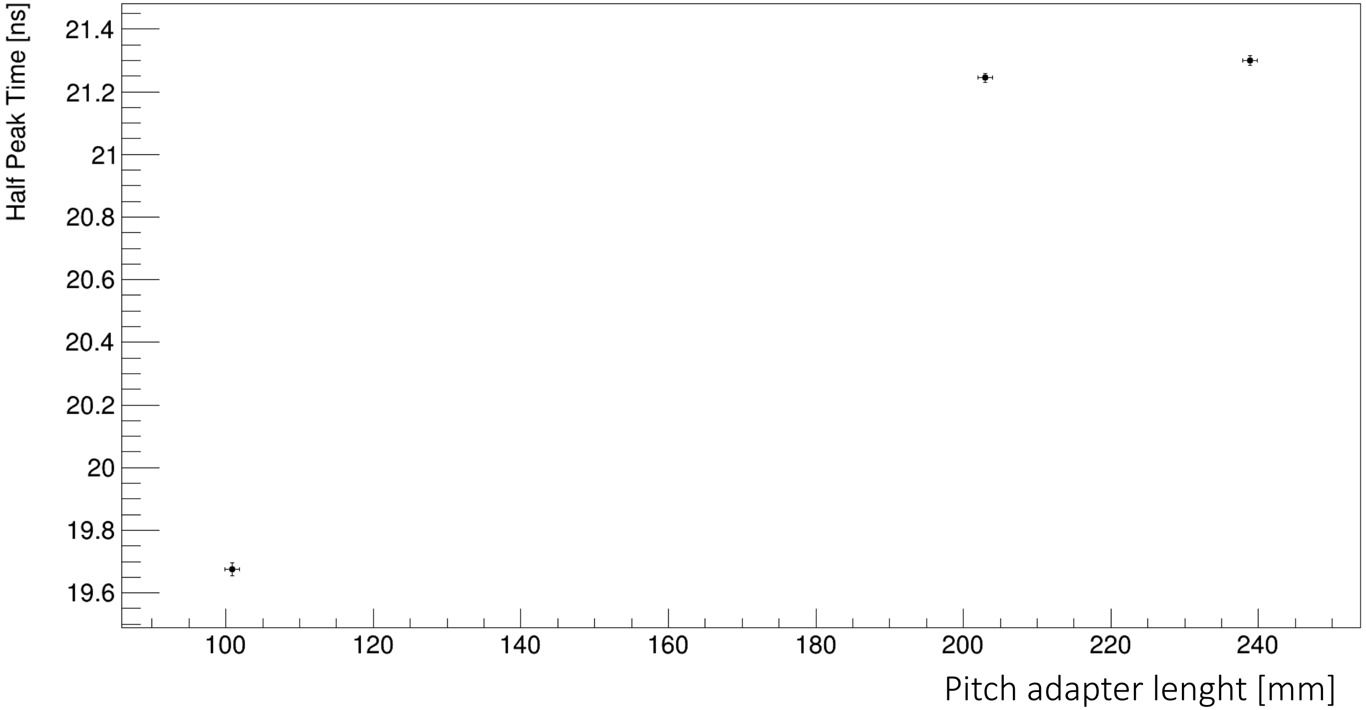


Signal time shape (external calibration)

- Different length of the pitch adapter → time shift, but no difference in the signal shape
- The time shift is not directly proportional to the pitch adapter length

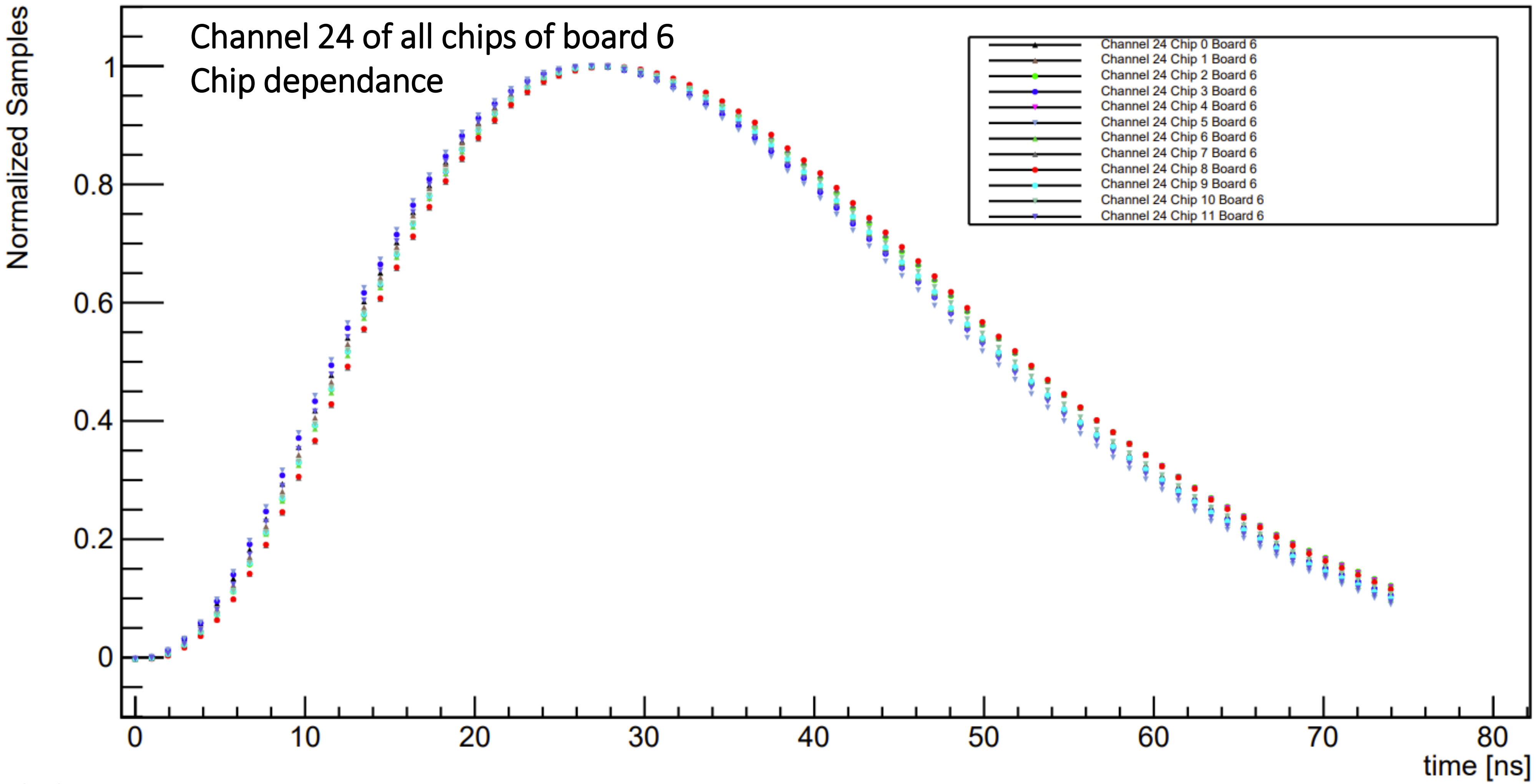
➢ Ratio S0/S1 chip dependance still not clear and understood (capacitive effects?)





Signal time shape (internal calibration)

On Arm2 silicon detector → dependance of the signal time shape on different channels/chip/MDAQ boards

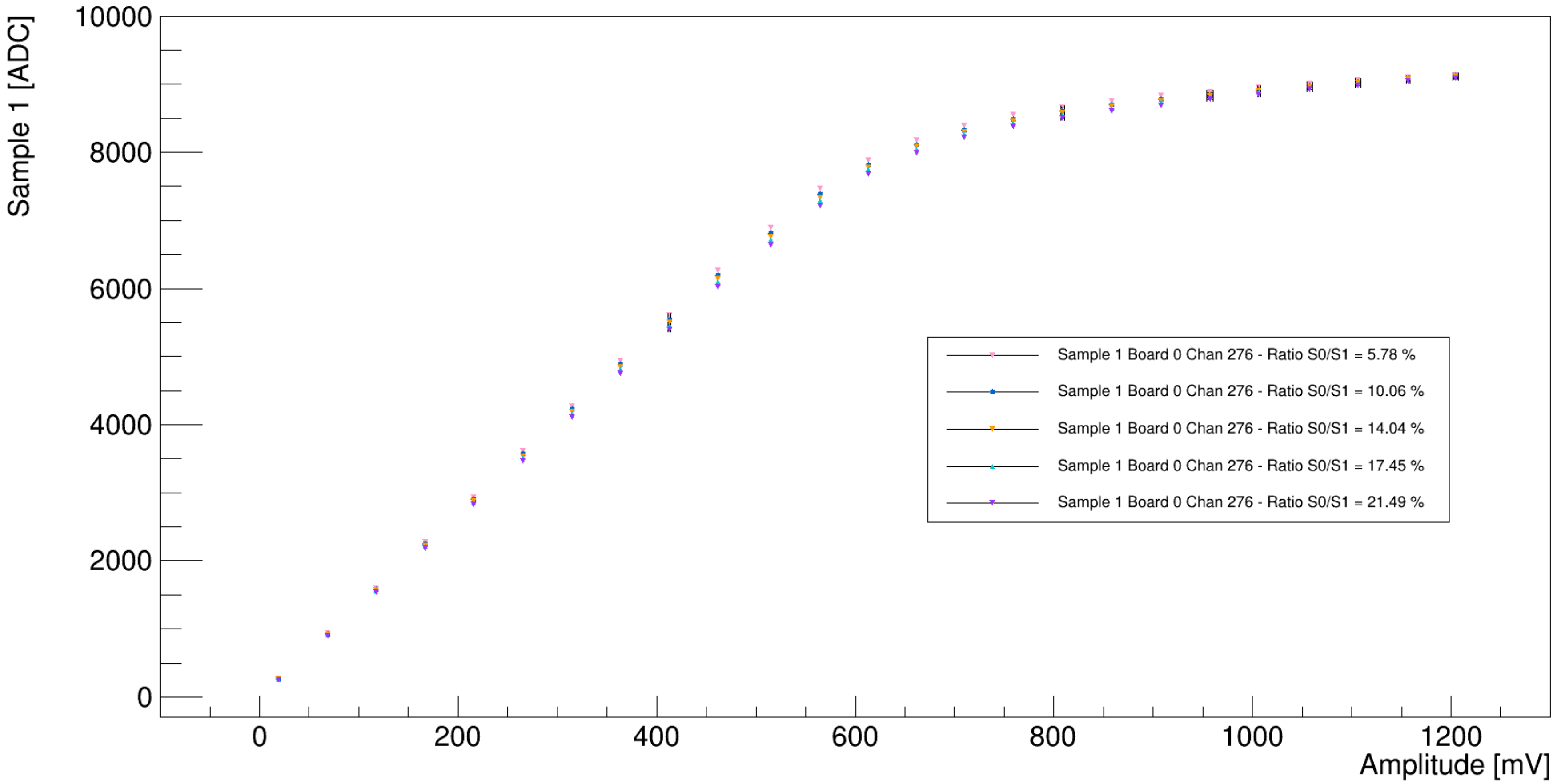


Channel 24 of all chips of board 6
Chip dependance

Response curve (external calibration)

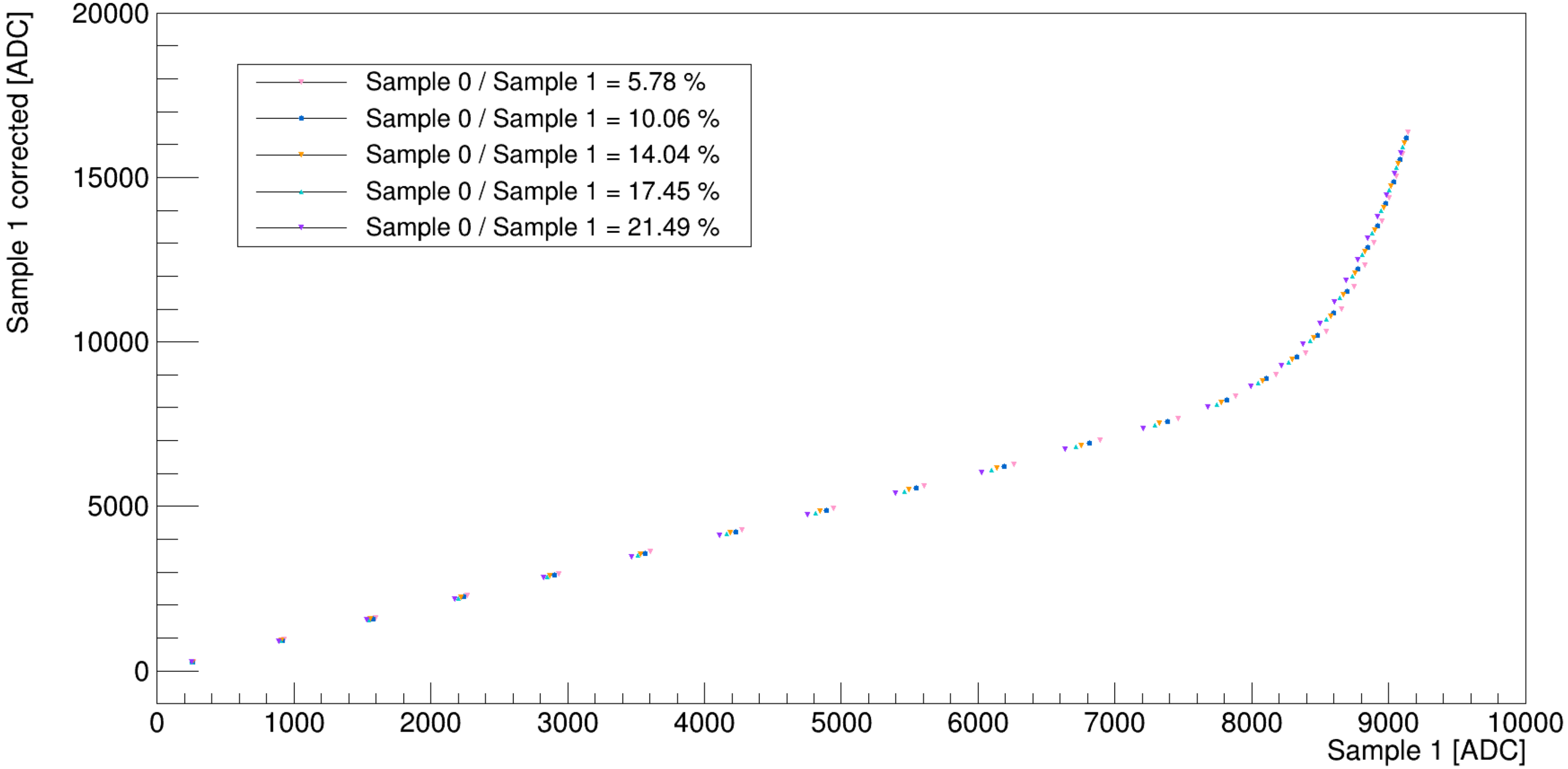
1 external capacitors on 1 silicon microstrip - channel 20 of chip 8 of a Module X spare

→ response curve and its dependance on the latency parameter (ratio S0/S1 = 6% ÷ 22%)



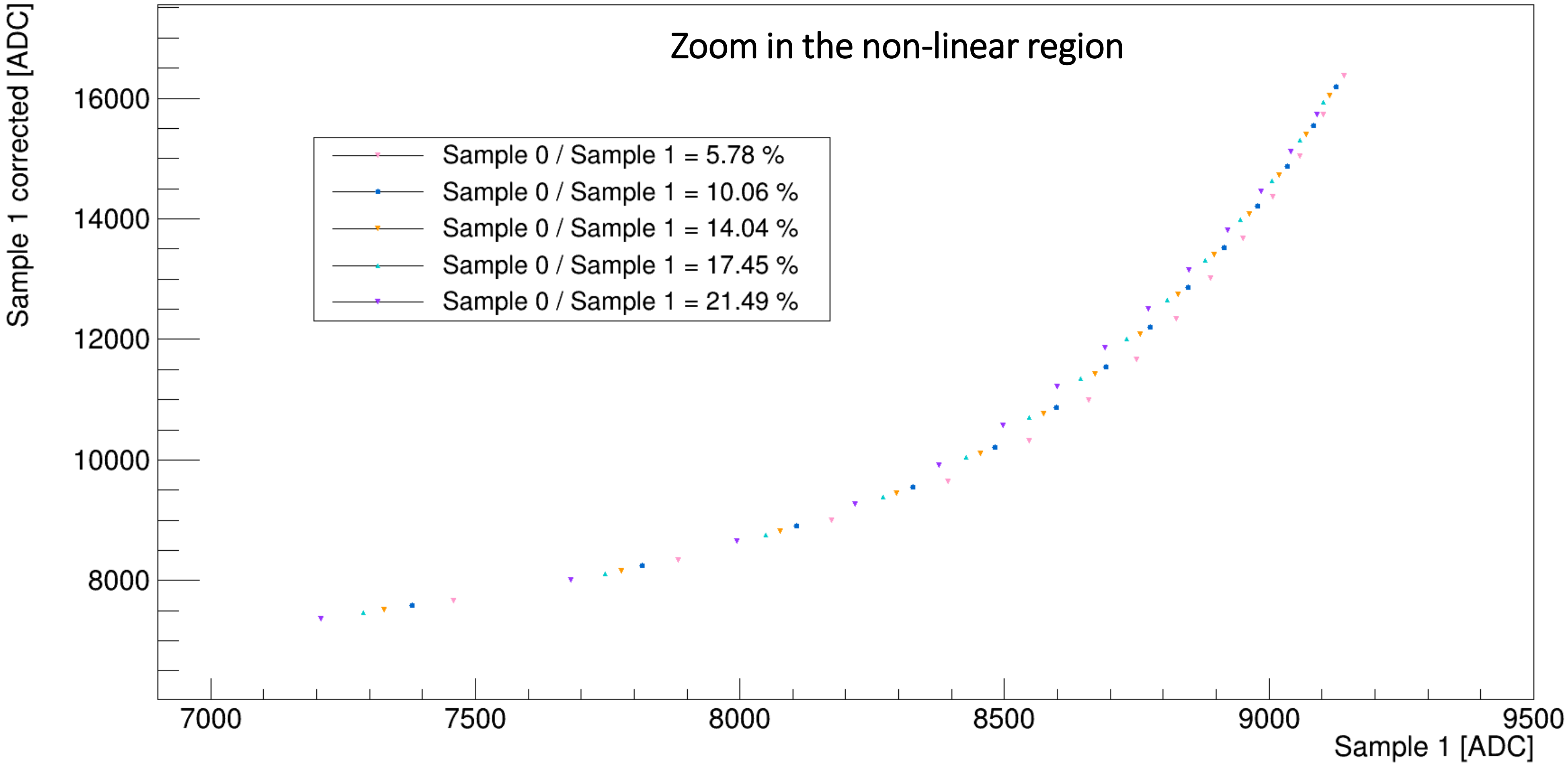
Response curve (external calibration)

Linear fit in the linear region → Sample 1 correction using the fit parameters



Correction function (external calibration)

Linear fit in the linear region → Sample 1 correction using the fit parameters

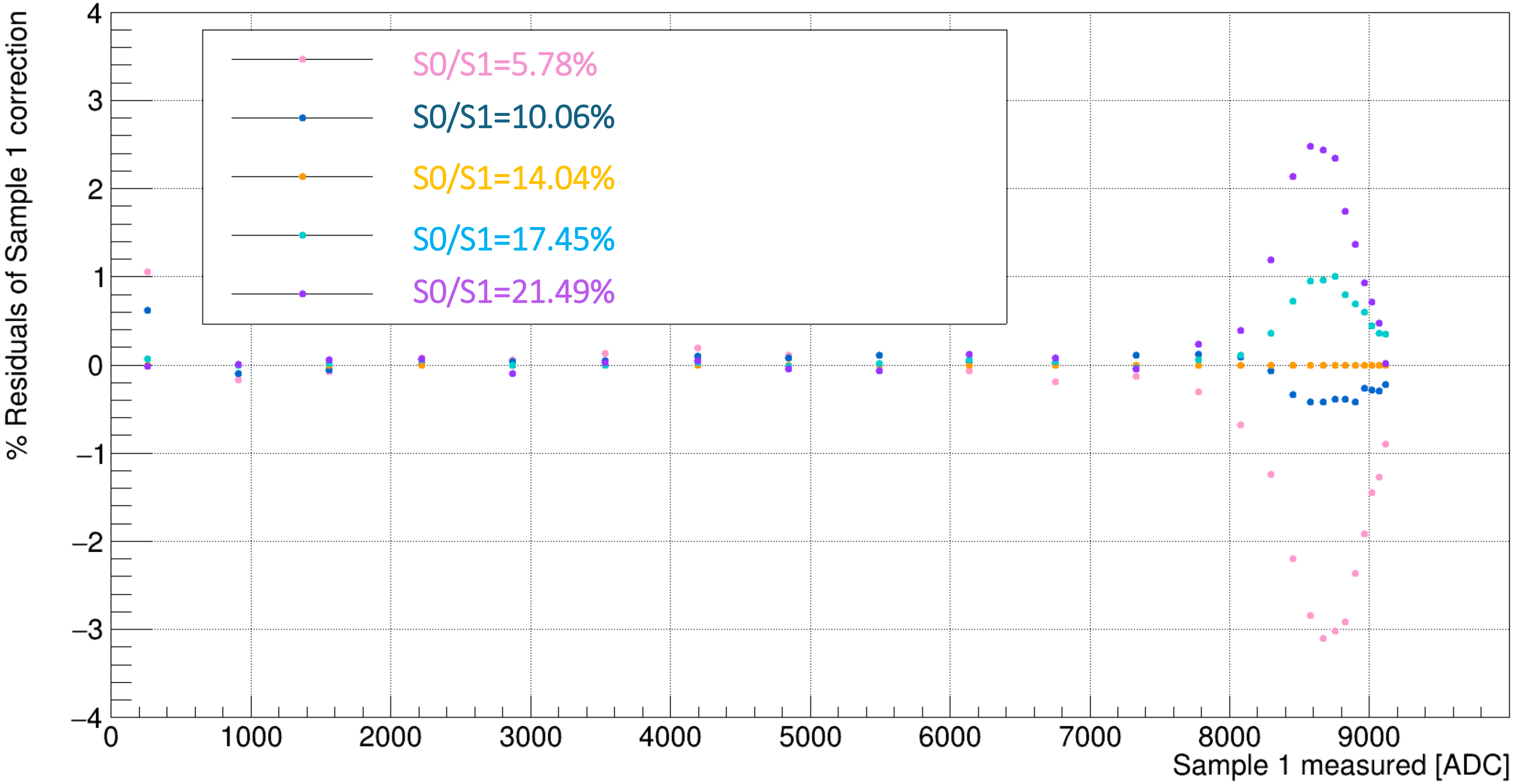


Correction function (external calibration)

In order to quantify the dependance of this correction on the latency:

% residuals between the correction at a certain latency and the correction at a reference latency

Reference latency → corresponding to S0/S1=14%



Check on the 2022 LHC data:

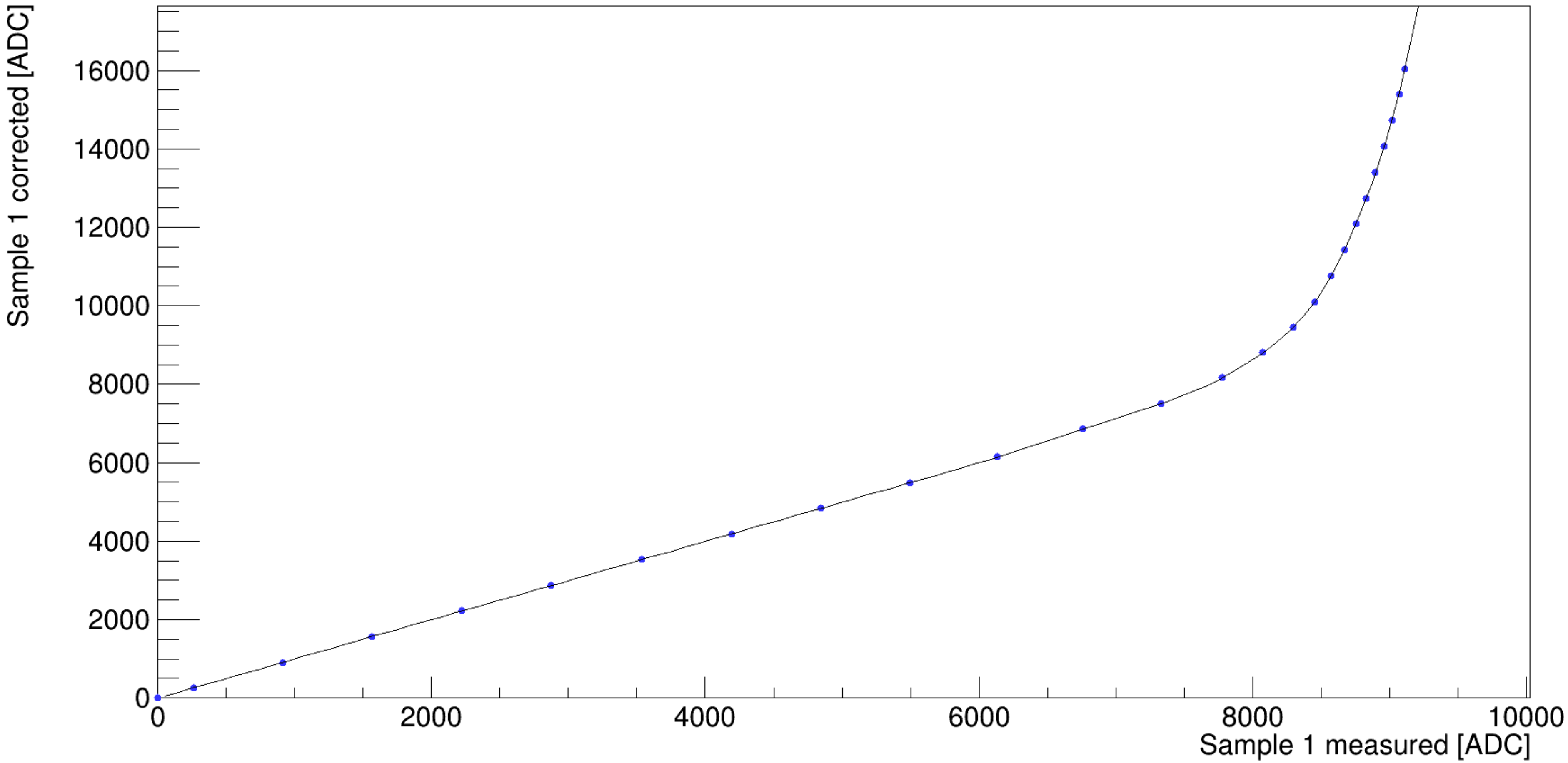
Less than 0.15% of the events has a maximum signal on a single strip higher than 7500 ADC.

The error introduced neglecting the latency dependance is below 1% for signals below 8200 ADC.

- ➢ We decided to implement the correction function for ratio S0/S1=14% in the analysis software

Correction function

Correction function for Sample 1 at the reference latency that corresponds to a ratio S0/S1=14%



Conclusion

Signal time shape

- External calibration: there is an evidence of the dependance of S0/S1 on the pitch adapter length, but it is still not very clear
- Internal calibration: the simultaneous calibration of all channels and chip shows a dispersion between different chip and MDAQ boards

Response curve

- External calibration:
    - study of the response curve and its region of non-linearity
    - study of the response curve for different latency values
    - → Implementation of the correction curve in the analysis software

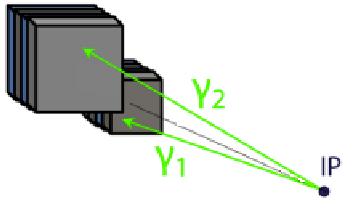
Reconstruction of the incident energy with Arm2 silicon sensors

Incident energy reconstruction with Arm2 silicon detector

Silicon sensors used to reconstruct the transversal profile of the shower in the calorimeter

NEW: **Silicon sensors** used to reconstruct the **incident energy**, independently of the scintillators

- It provides an additional check on the calibration of the absolute energy scale



Final goal of this study → Invariant mass distribution for Type I π^0

STEPS:

1. Definition of the total energy deposit on a single silicon layer
2. Definition of the algorithm that combines the deposit on the single silicon layers to get the total energy deposit <sumdE>
3. Plot of <sumdE> vs true incident energy, to get the parameters to convert the energy deposit to the incident energy
4. Study of the Leakage In and Leakage Out Maps for photon events, necessary to correct the <sumdE> for Type I π^0 events

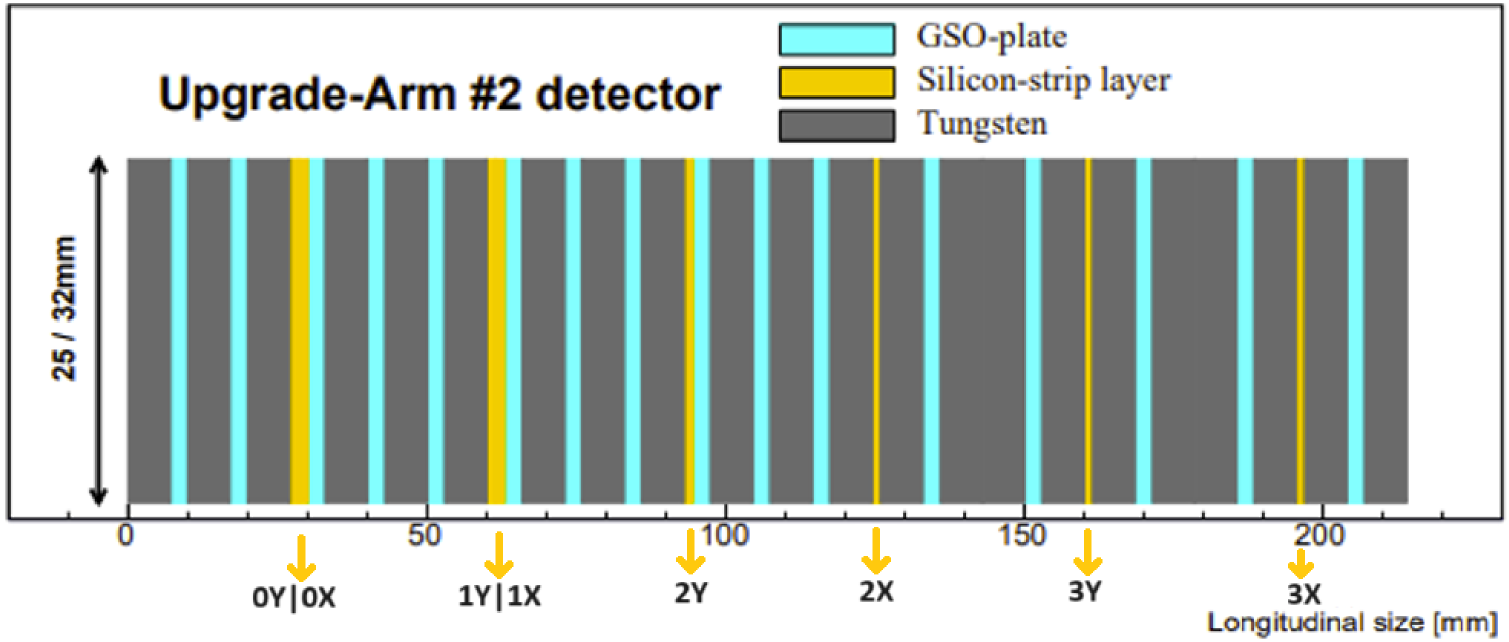
Energy deposit definition

1. Energy deposit on a single silicon layer i: sum of the energy deposit on all the microstrips (dE_n)

$$< \text{sumdE} >_i = \sum_{n=0}^{383} dE_n$$

2. Total energy deposit:

$$< \text{sumdE} > = < \text{sumdE} >_{0Y} + < \text{sumdE} >_{0X} + < \text{sumdE} >_{1Y} + < \text{sumdE} >_{1X} + 2(< \text{sumdE} >_{2Y} + < \text{sumdE} >_{2X})$$



Energy deposit

2. Total energy deposit:

$$< \mathrm{sumdE} > = < \mathrm{sumdE} >_{0Y} + < \mathrm{sumdE} >_{0X} + < \mathrm{sumdE} >_{1Y} + < \mathrm{sumdE} >_{1X} + 2(< \mathrm{sumdE} >_{2Y} + < \mathrm{sumdE} >_{2X})$$

Test of the total energy deposit algorithm:

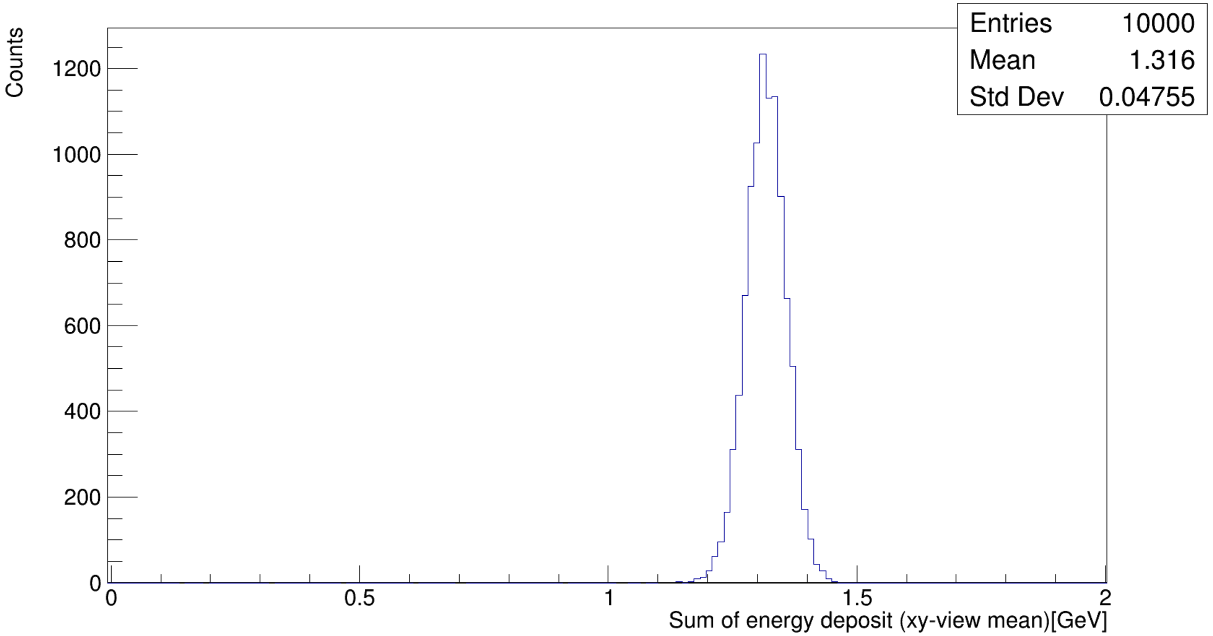
Simulation of photons of different discrete energies (from 100 GeV to 6 TeV)

- at the center of the Large Tower
- at the center of the Small Tower

Check the

- ➢ Energy resolution
- ➢ Residuals between the reconstructed energy and the true energy

500 GeV photons at the center of Large Tower



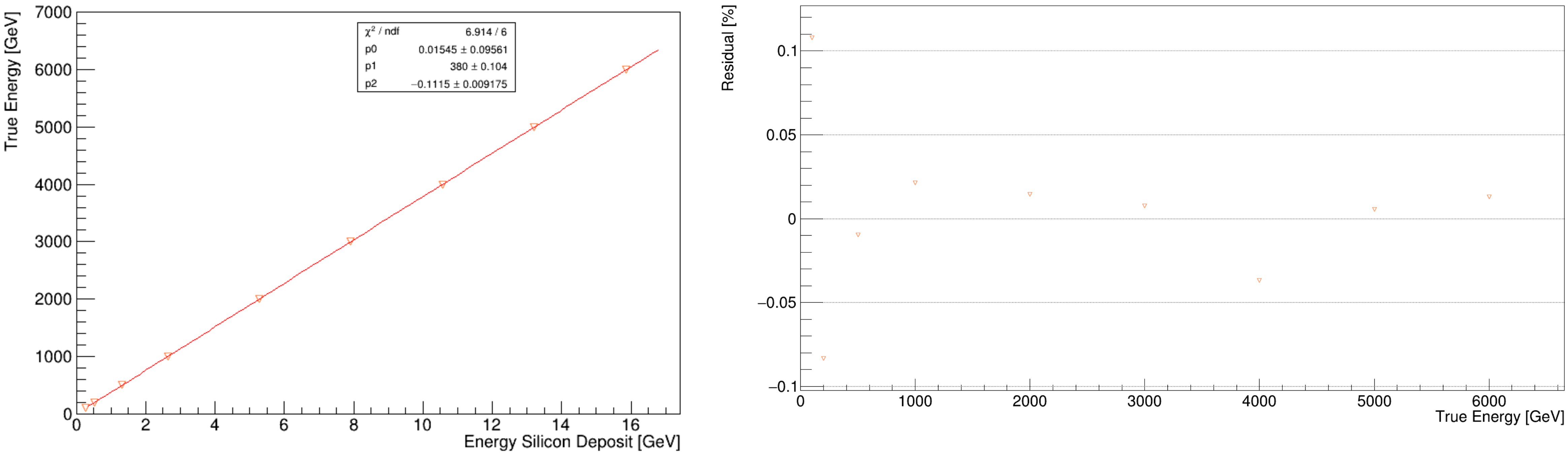
Energy deposit

$$< \mathrm{sumdE} > = < \mathrm{sumdE} >_{0Y} + < \mathrm{sumdE} >_{0X} + < \mathrm{sumdE} >_{1Y} + < \mathrm{sumdE} >_{1X} + 2(< \mathrm{sumdE} >_{2Y} + < \mathrm{sumdE} >_{2X})$$

3a. Plot of true incident energy vs energy deposit

to get the parameters to convert the energy deposit to the incident energy

Photons at the center of Large Tower

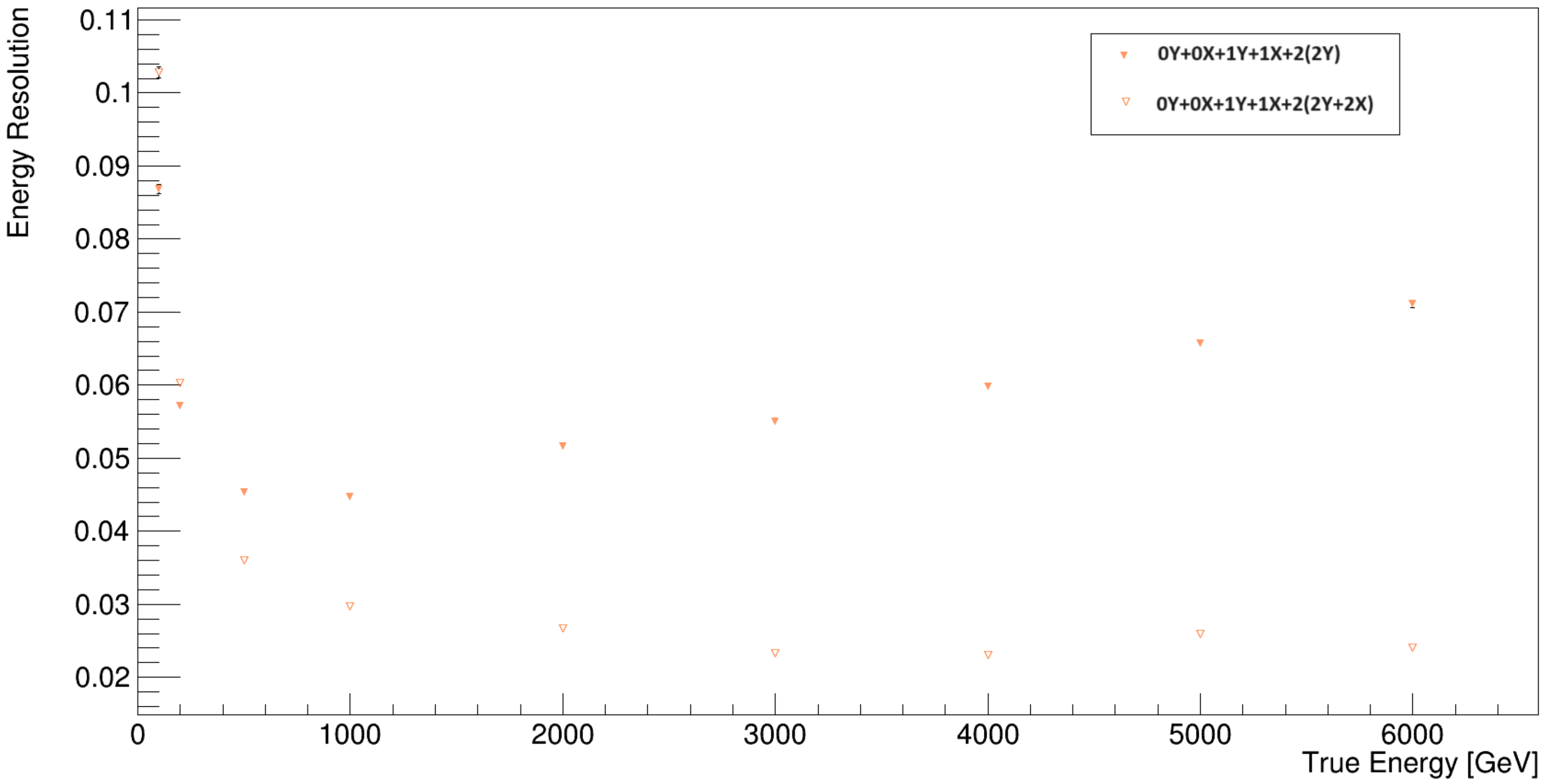


Energy deposit

$$< \mathrm{sumdE} > = < \mathrm{sumdE} >_{0Y} + < \mathrm{sumdE} >_{0X} + < \mathrm{sumdE} >_{1Y} + < \mathrm{sumdE} >_{1X} + 2(< \mathrm{sumdE} >_{2Y} + < \mathrm{sumdE} >_{2X})$$

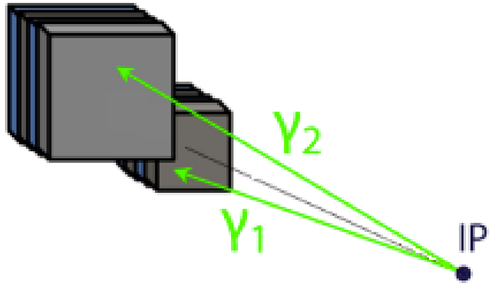
3b. Plot of the energy resolution

Photons at the center of Large Tower



Leakage in and leakage out correction

4. Correction for the effect of the lateral leakage of the shower.



- Leakage out

A photon hits the tower i , with coordinates (x_i, y_i)

→ a fraction $\mathrm{L}^i_{out}(x_i, y_i)$ of the energy leaks out of tower i

$$\mathrm{L}^i_{out}(x_i, y_i) = \frac{< \mathrm{sumdE}(x_i, y_i) >_i}{< \mathrm{sumdE}(x_{center,i}, y_{center,i}) >_i}$$

- Leakage in

Simultaneously, another photon hits the other tower, $1-i$, with coordinates (x_{1-i}, y_{1-i})

→ a fraction $\mathrm{L}^{1-i}_{in}(x_{1-i}, y_{1-i})$ of the energy from tower $1-i$ leaks in tower i

$$\mathrm{L}^{1-i}_{in}(x_{1-i}, y_{1-i}) = \frac{< \mathrm{sumdE}(x_{1-i}, y_{1-i}) >_i}{< \mathrm{sumdE}(x_{center,1-i}, y_{center,1-i}) >_{1-i}}$$

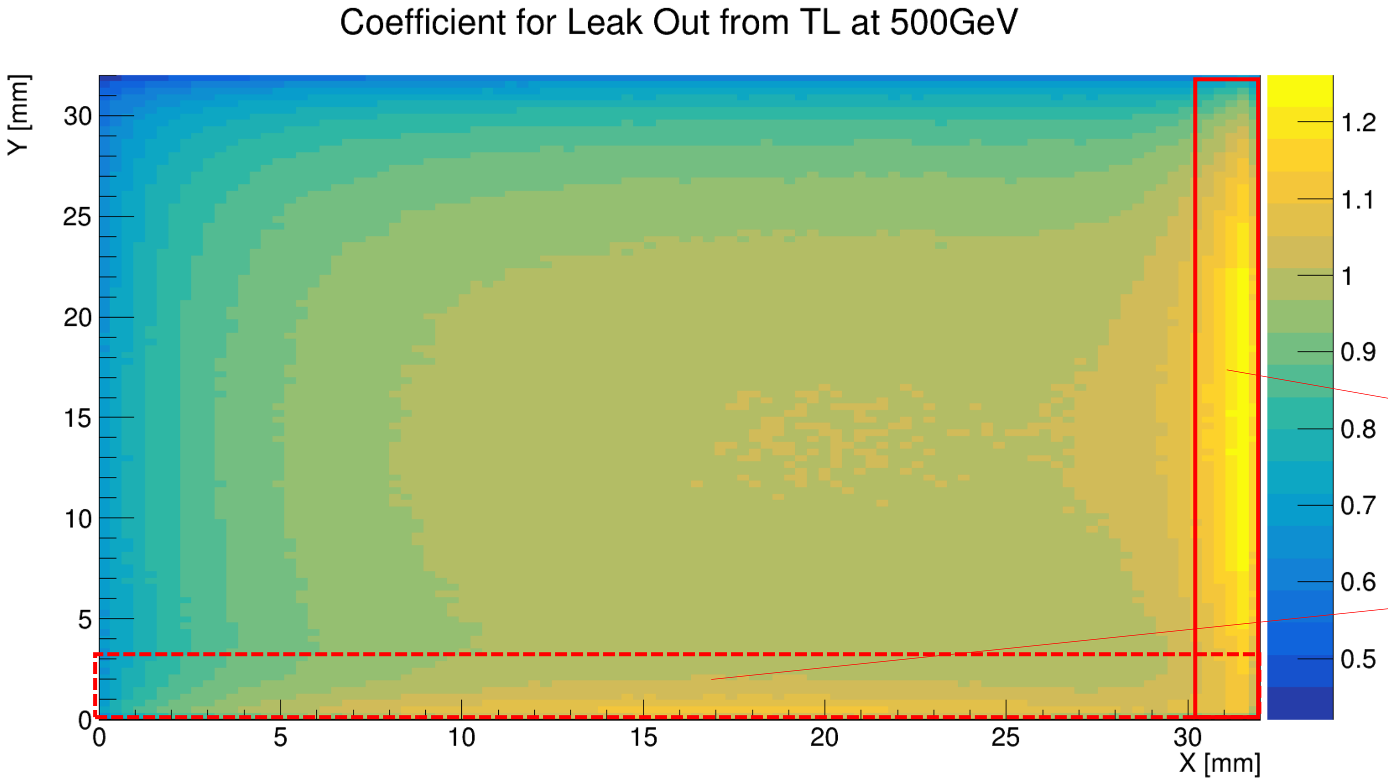
Energy deposit in tower i, corrected for the leakage in and out:

$$< \mathrm{sumdE}(x_i, y_i, x_{1-i}, y_{1-i}) >_i = \mathrm{L}^i_{out}(x_i, y_i) < \mathrm{sumdE}(x_{center,i}, y_{center,i}) >_i + \\ + \mathrm{L}^{1-i}_{in}(x_{1-i}, y_{1-i}) < \mathrm{sumdE}(x_{center,1-i}, y_{center,1-i}) >_{1-i}$$

Leakage in and leakage out correction

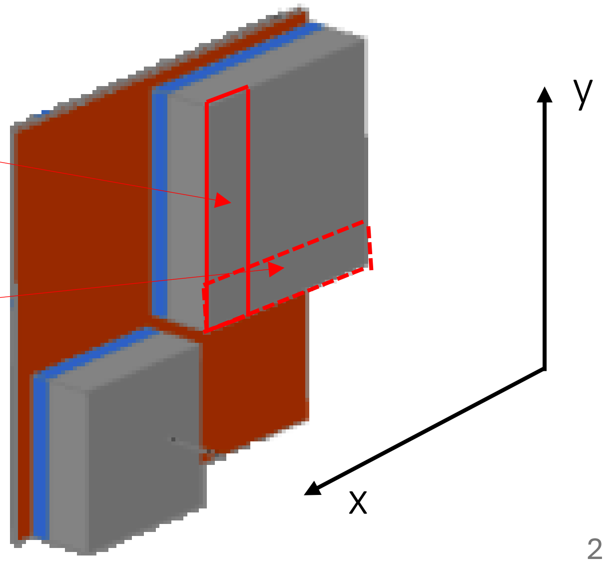
4. Correction for the effect of the lateral leakage of the shower.

$$< \mathrm{sumdE}(x_i, y_i, x_{1-i}, y_{1-i}) >_i = \mathrm{L}^{i}_{out}(x_i, y_i) < \mathrm{sumdE}(x_{center,i}, y_{center,i}) >_i + \\ + \mathrm{L}^{1-i}_{in}(x_{1-i}, y_{1-i}) < \mathrm{sumdE}(x_{center,1-i}, y_{center,1-i}) >_{1-i}$$



Asymmetry of the map:

The area covered by the silicon microstrip sensor is larger than the one covered by the large and small tower



Leakage in and leakage out correction

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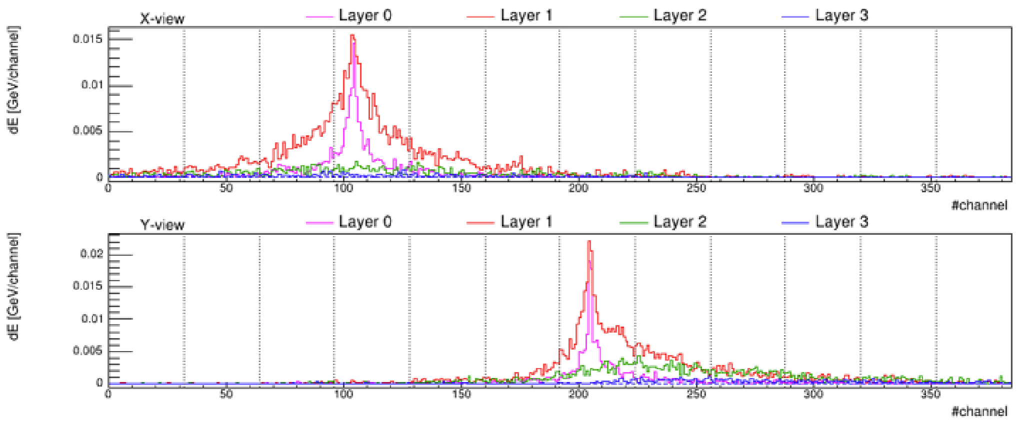
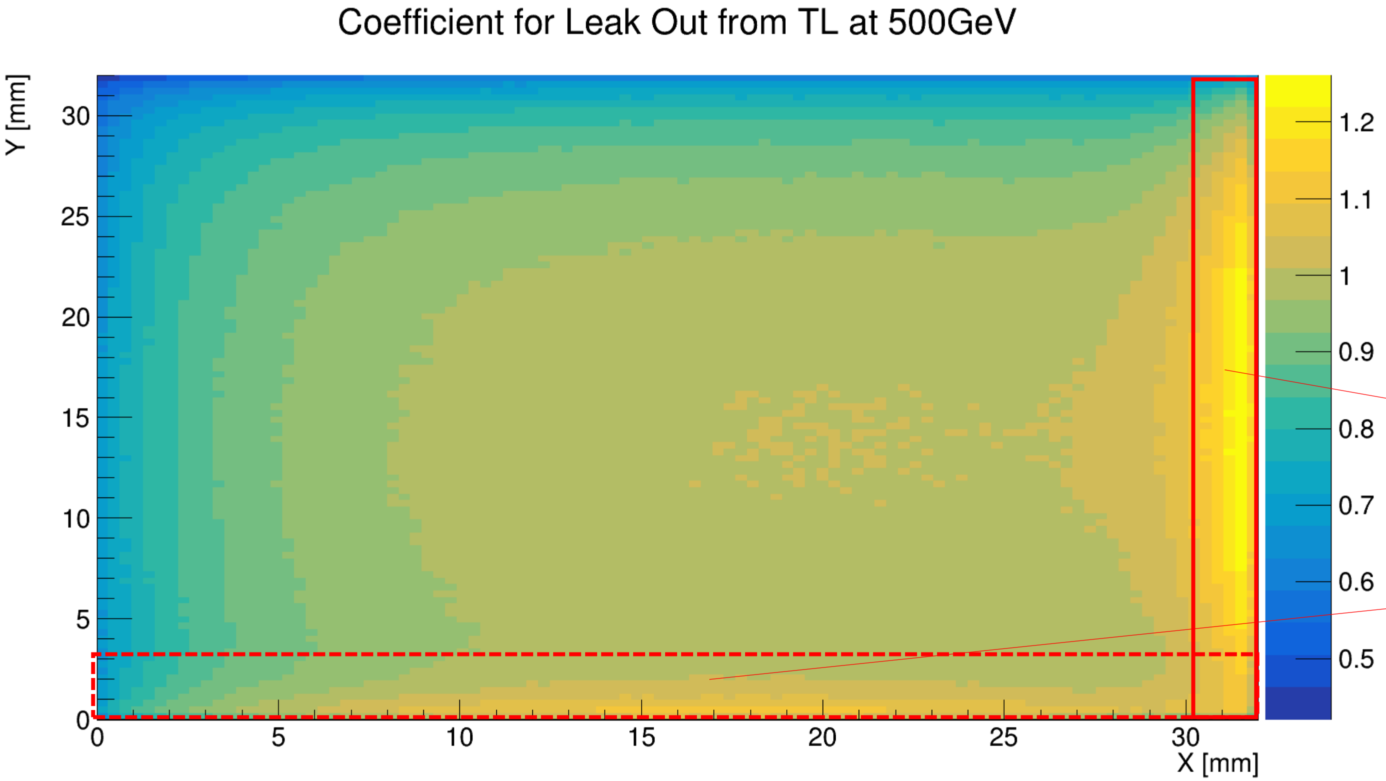
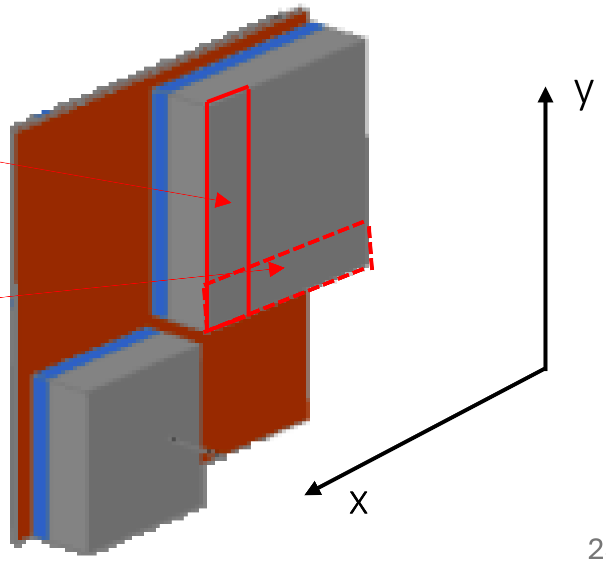


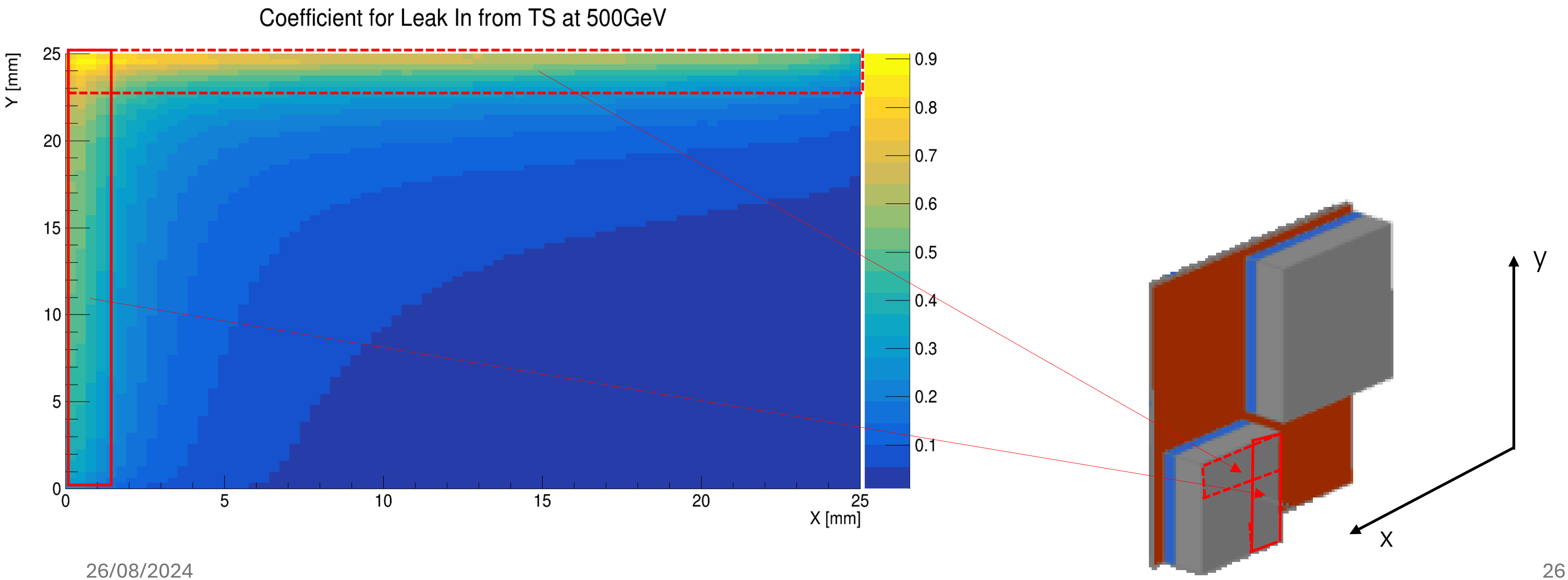




Leakage in and leakage out correction

4. Correction for the effect of the lateral leakage of the shower.

$$< \mathrm{sumdE}(x_i, y_i, x_{1-i}, y_{1-i}) >_i = \mathrm{L}^i_{out}(x_i, y_i) < \mathrm{sumdE}(x_{center,i}, y_{center,i}) >_i +$$
$$+\mathrm{L}^{1-i}_{in}(x_{1-i}, y_{1-i}) < \mathrm{sumdE}(x_{center,1-i}, y_{center,1-i}) >_{1-i}$$



Conclusion

✓ Algorithm for the energy reconstrution using the energy deposit in the silicon detector
  - Good energy resolution
  - Small residuals (<0.1%)

✓ Maps of leakage in and leakage out correction factors

Next steps

The energy reconstruction algorithm has to be implemeted in the analysis software:

- Parameters to convert the energy deposit into the incident energy
- Correction of the energy deposit for the leagake out and leakage in

Final goal of the study → Invariant mass distribution for Type I π^0

Calibration signal on the external capacitance

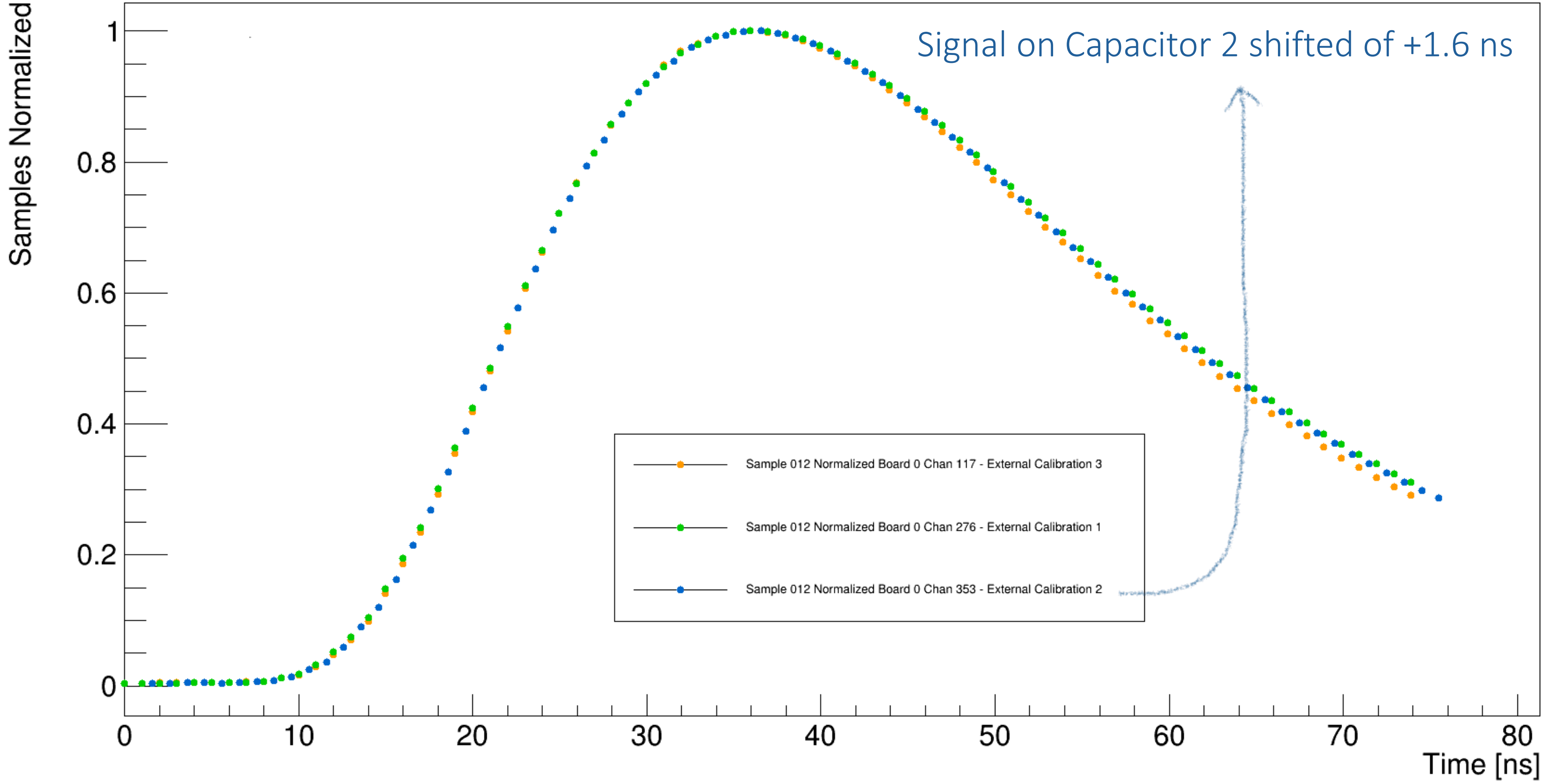
WAVEFORM GENERATOR SETTINGS

Trigger L1:	Calibration pulse:
Frequency: 2 kHz	Frequency: 2 kHz
High level 3 V – Low level 0 V	High level 270 mV – Low level 0 V
Delay: 0 ns	(Delay: 0 ns)
Pulse width 8.4 ns	Pulse width 8.4 ns
Load 50 ohm	Load 50 ohm
Source and clock EXT	Source and clock EXT

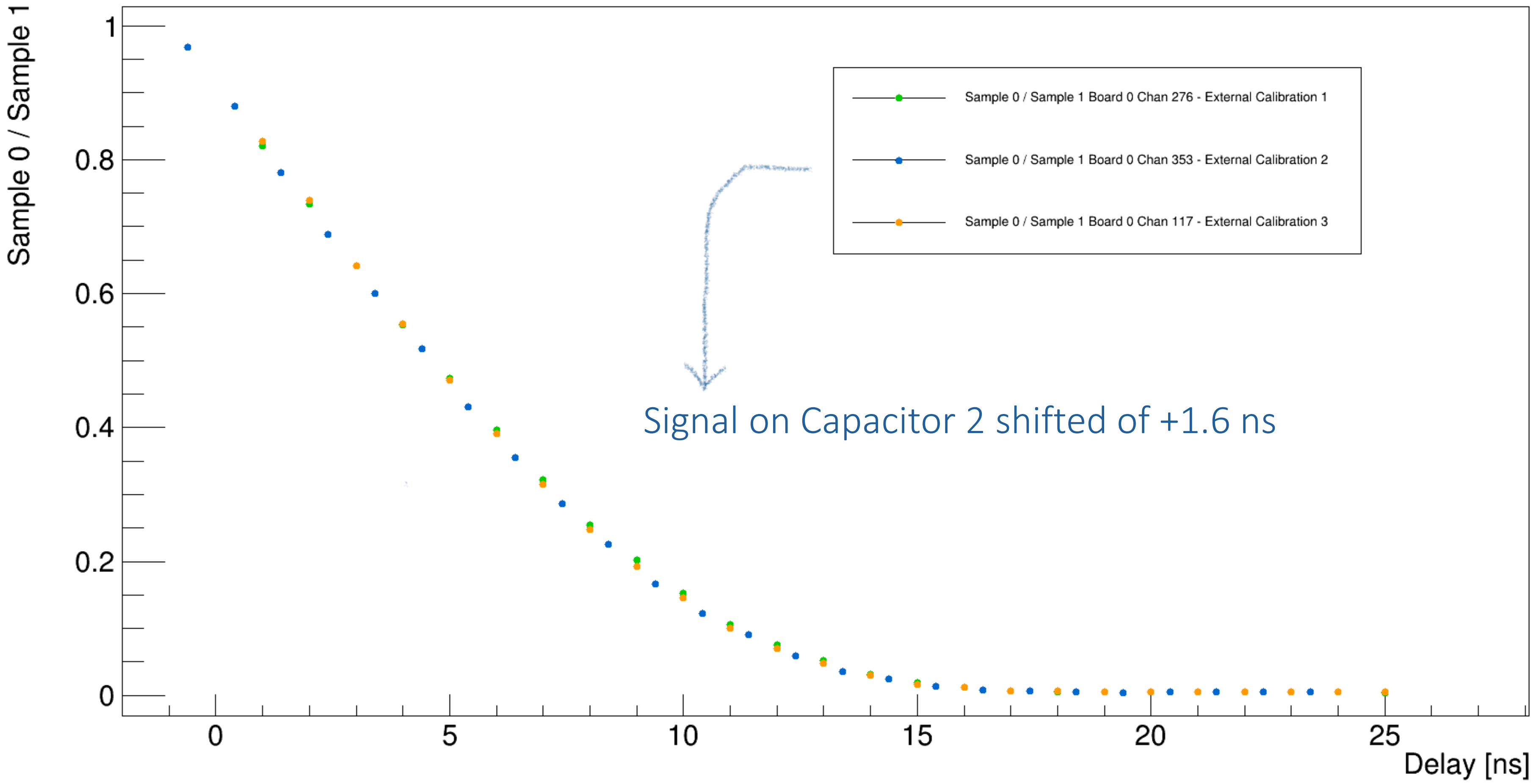
Source and Clock EXT.
Clock 10 MHz, Source Aux In 1 kHz

SILICON HV ON: 150 V

Calibration signal on the external capacitor

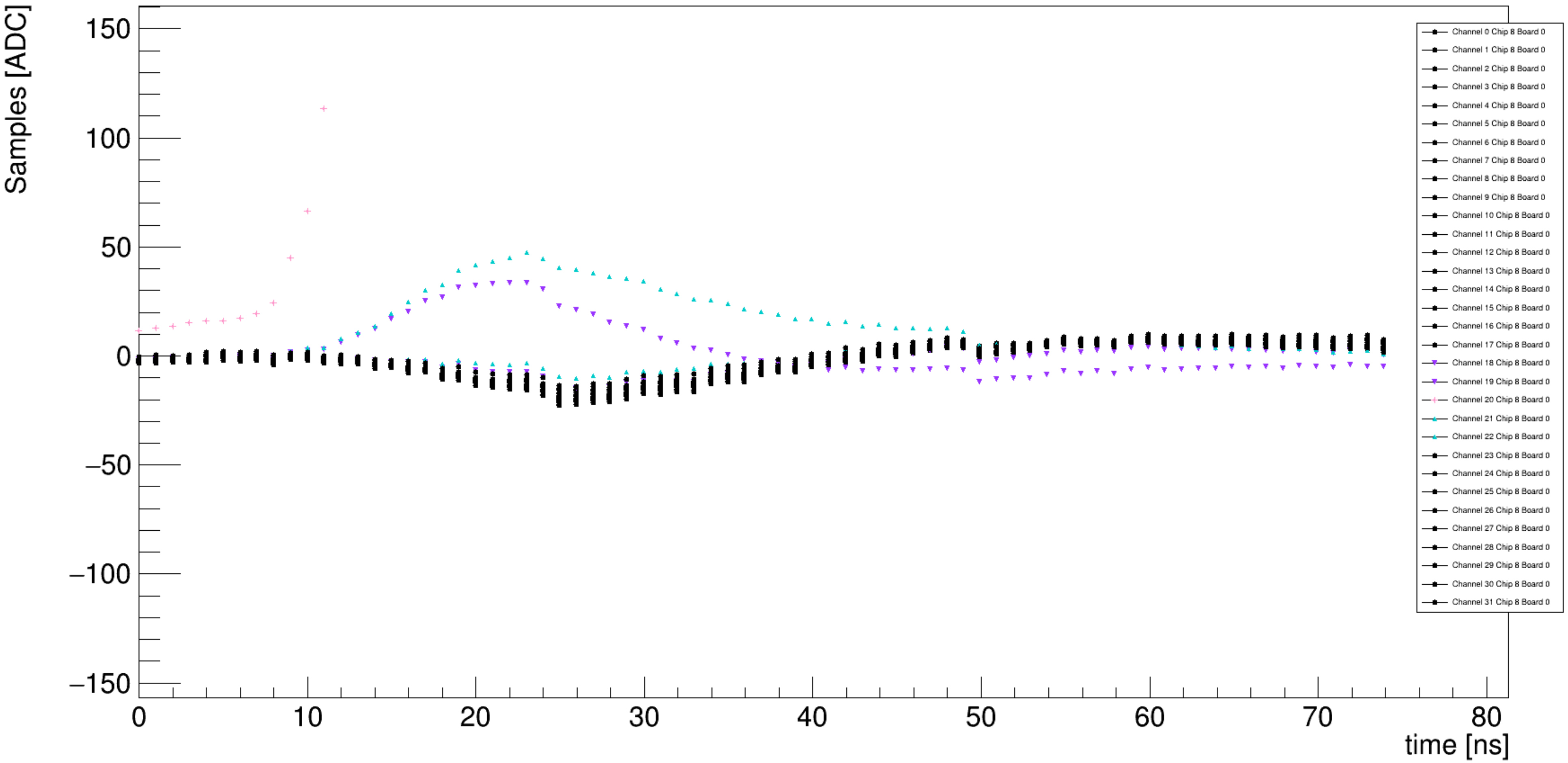


Calibration signal on the external capacitor

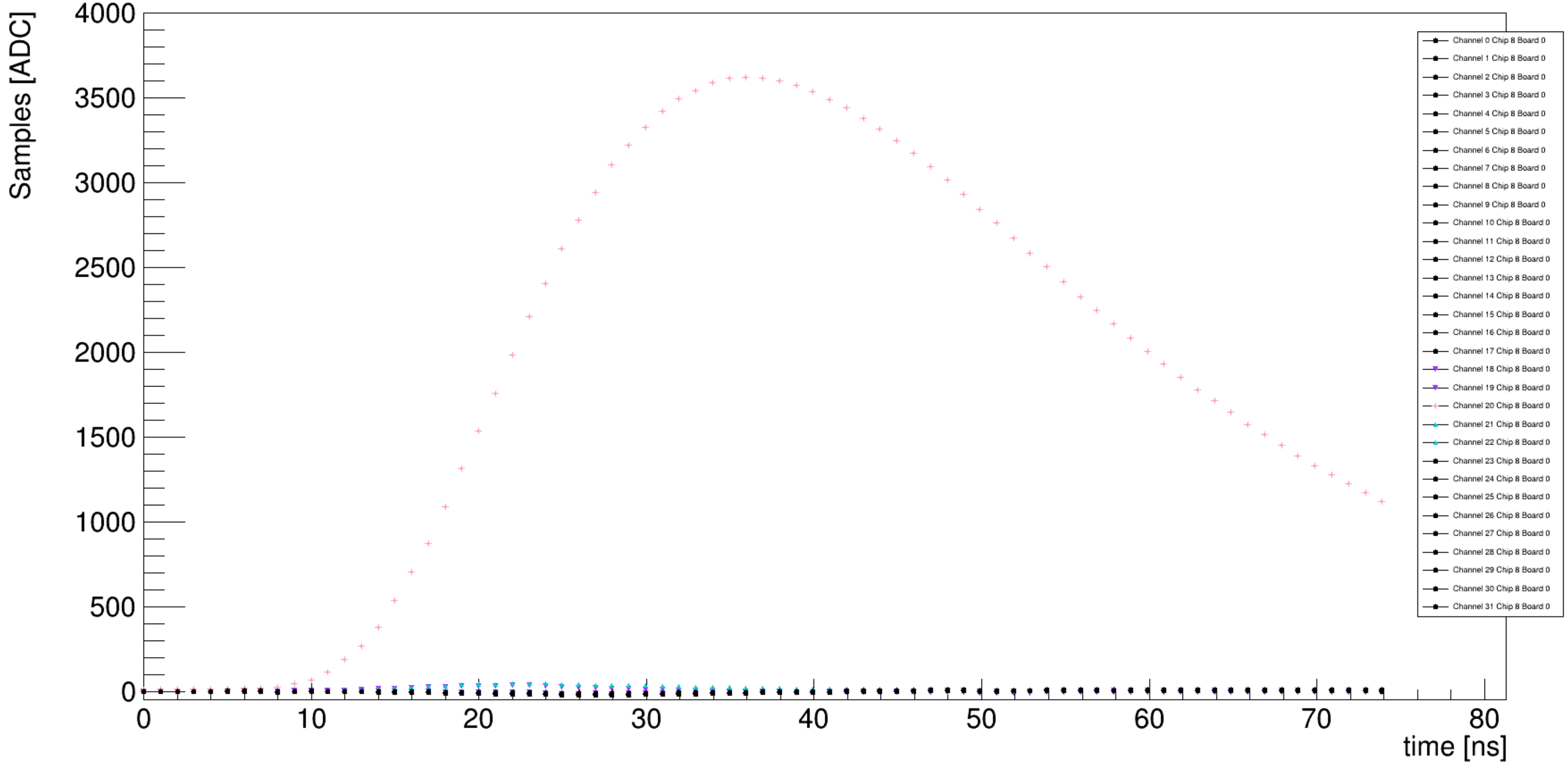


Signal on Capacitor 2 shifted of +1.6 ns

Calibration signal on the external capacitor



Calibration signal on the external capacitor



Calibration signal on the external capacitor

Software parameters setting:

- Latency: 10

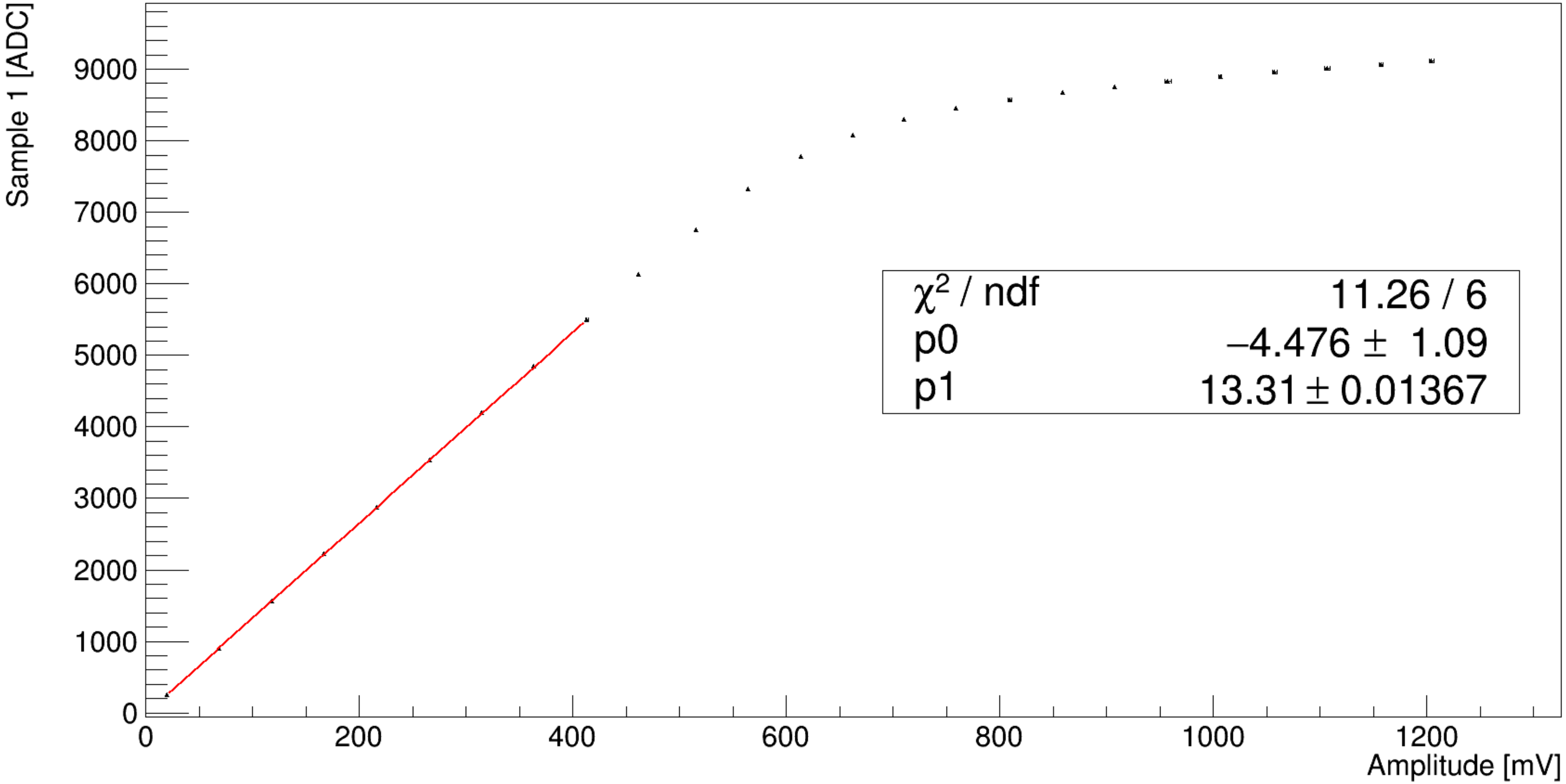
Pulse generator setting:

- Delay of calibration pulse fixed at some value, in order to have a fixed ratio S0/S1 (5.78%, 10.06%, 14.04%, 17.45%, 21.49% at 265.6 mV)

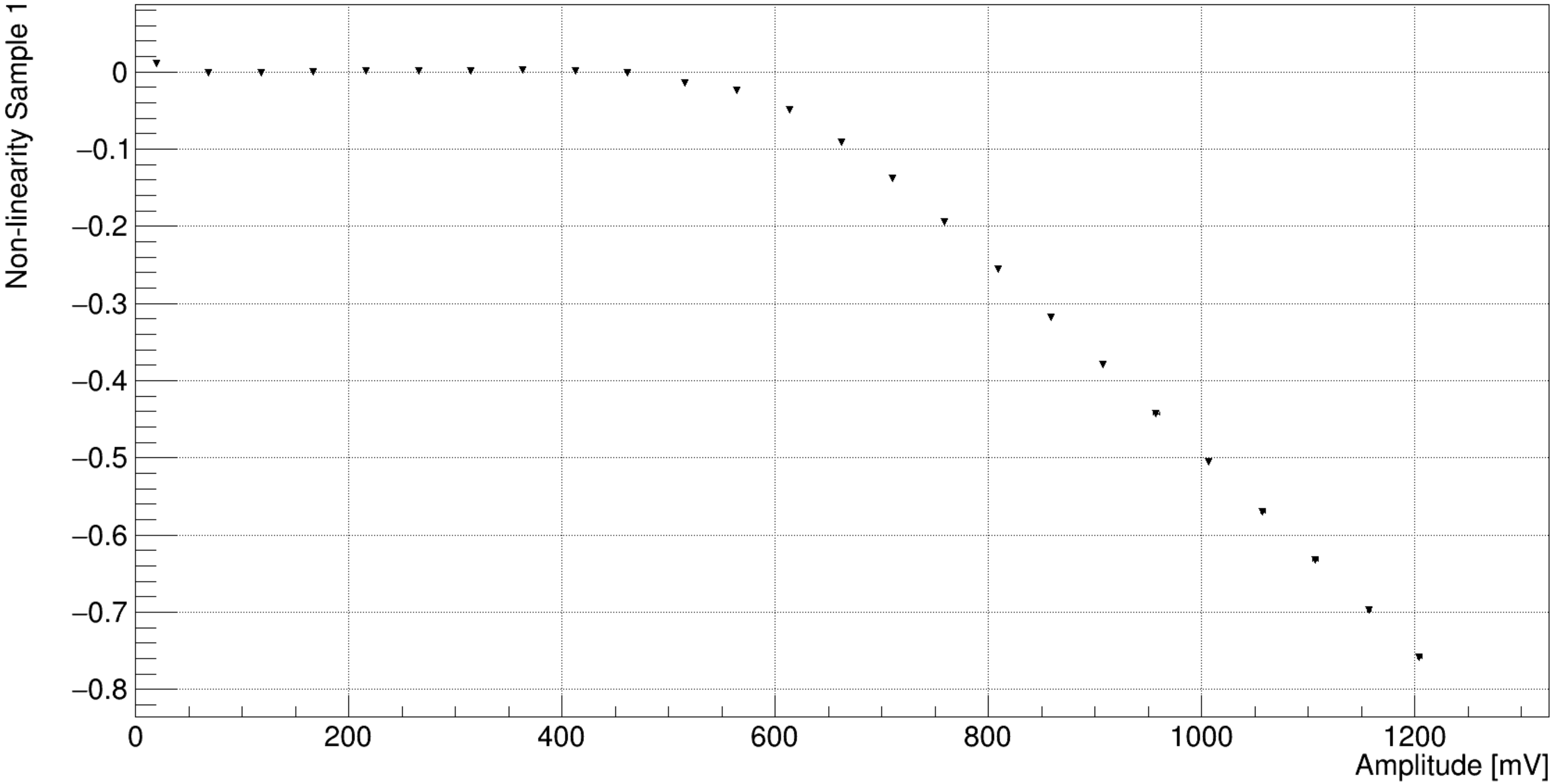
- High Level of calibration pulse from 20 mV to 1220 mV (nominal) at step of 50 mV (25 measurements)

Calibration on Capacitor 1

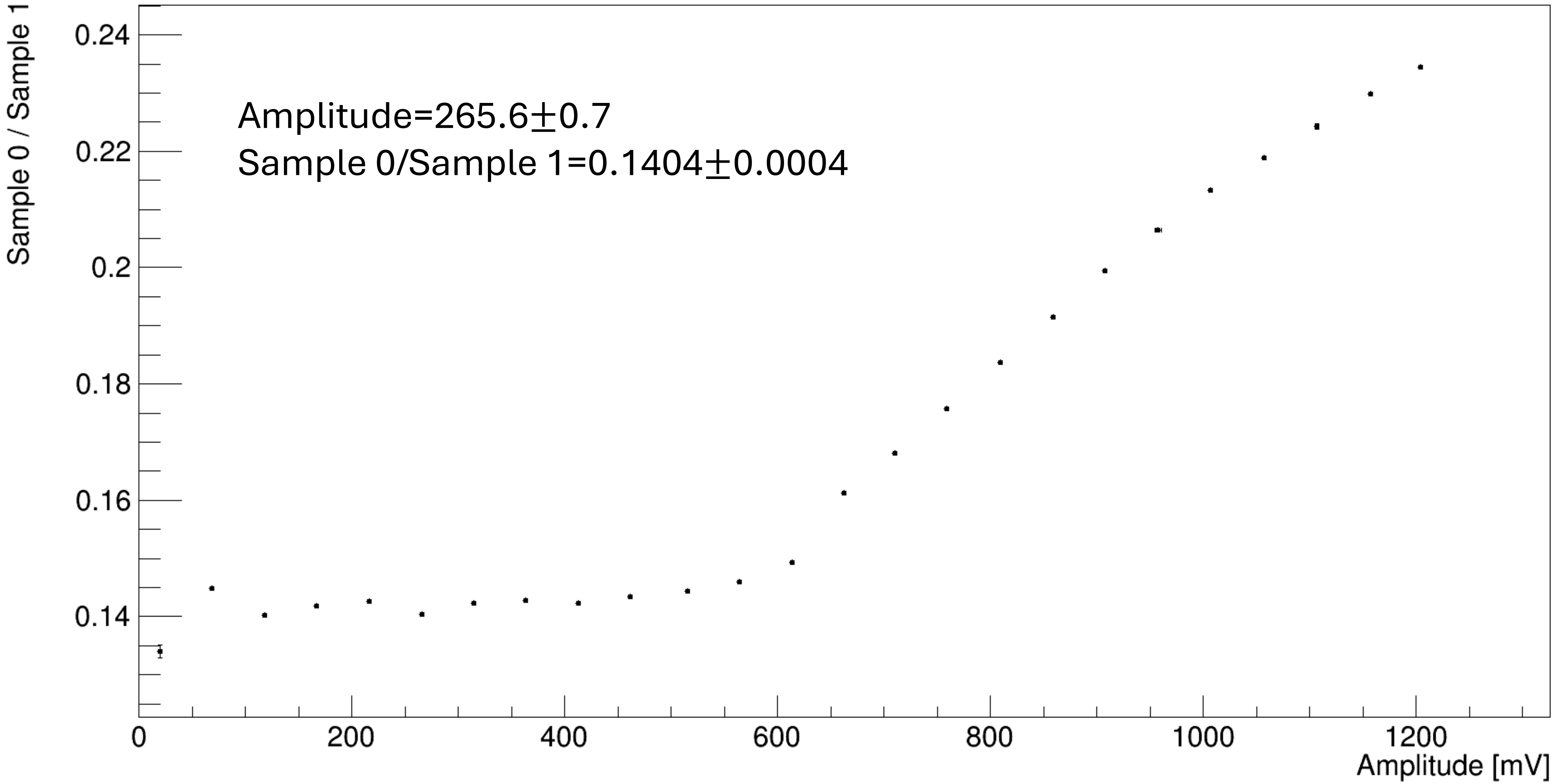
Amplitude scan at fixed latency: S0/S1=0.14



Amplitude scan at fixed latency: S0/S1=0.14



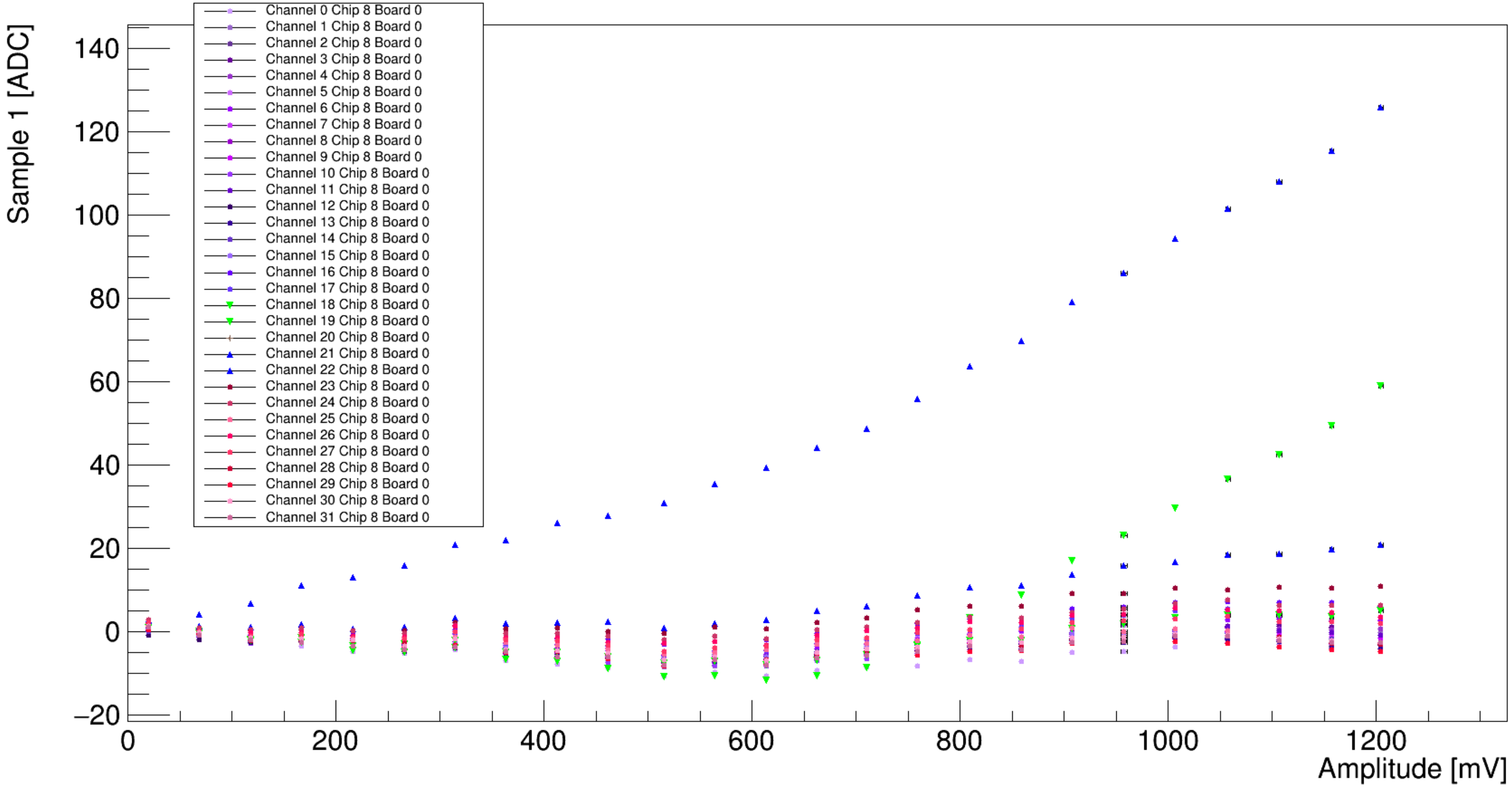
Amplitude scan at fixed latency: S0/S1=0.14



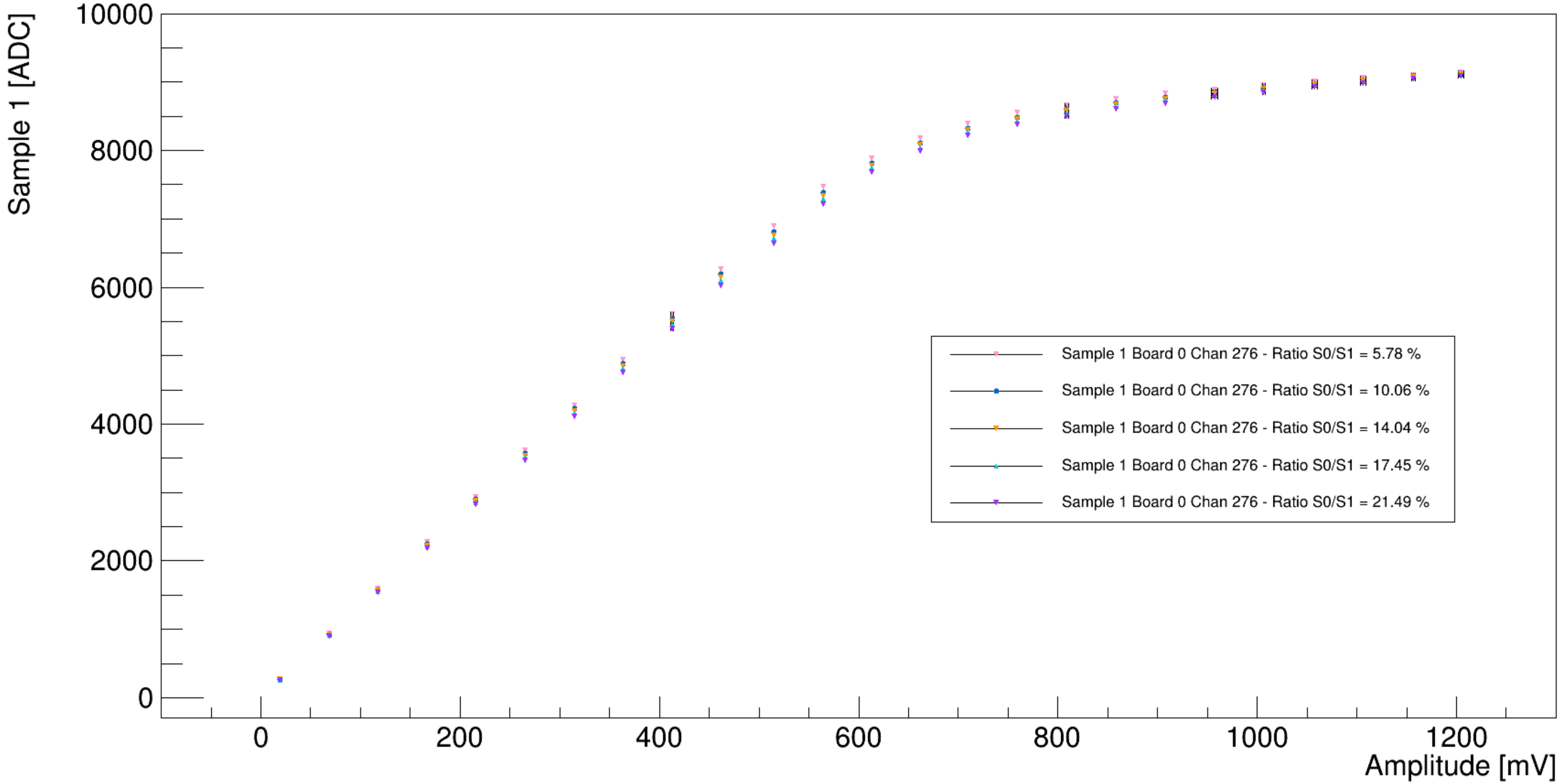
Amplitude=265.6±0.7

Sample 0/Sample 1=0.1404±0.0004

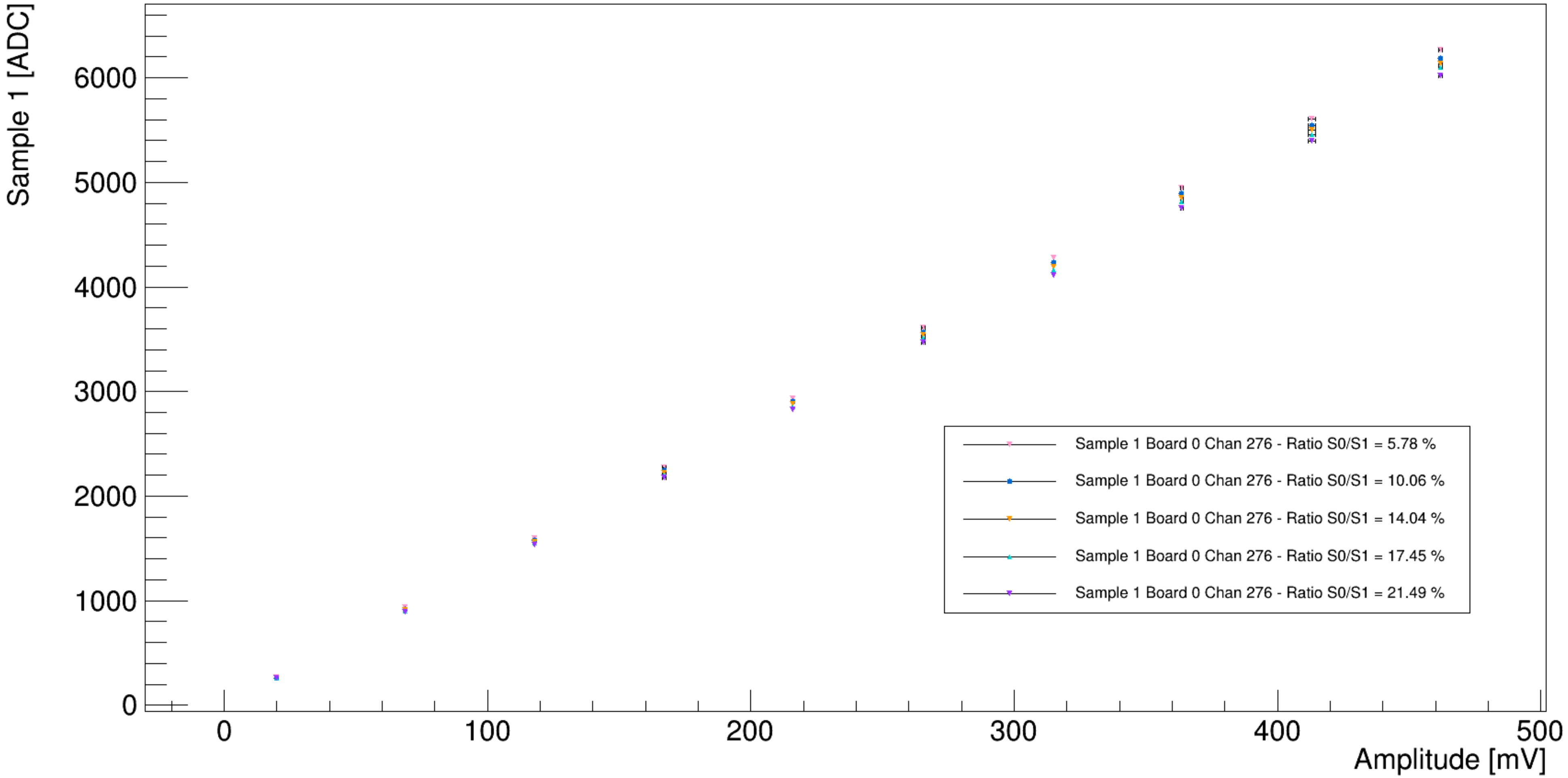
Amplitude scan at fixed latency: S0/S1=0.14 Other channels



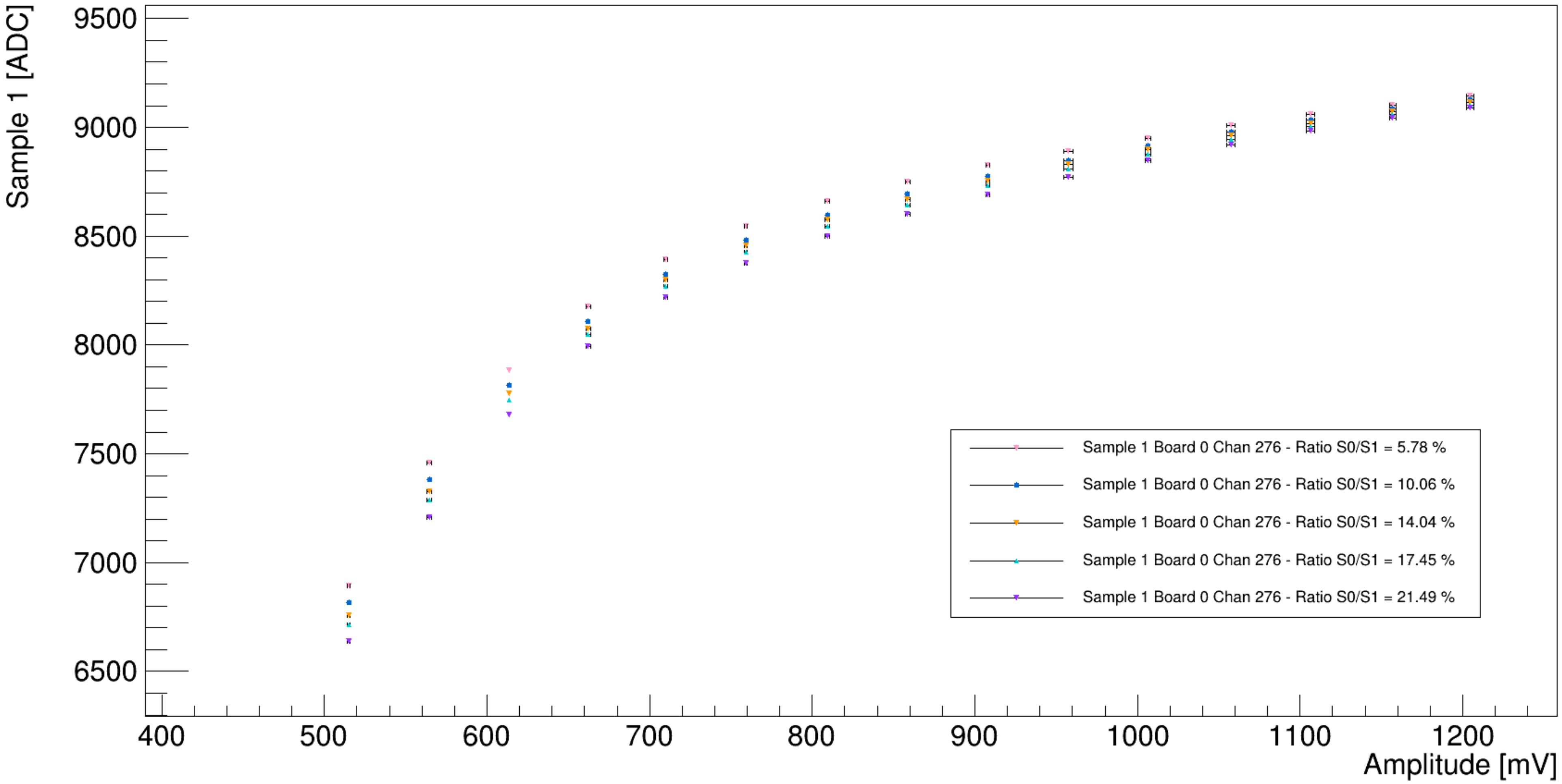
Amplitude scan at different latencies



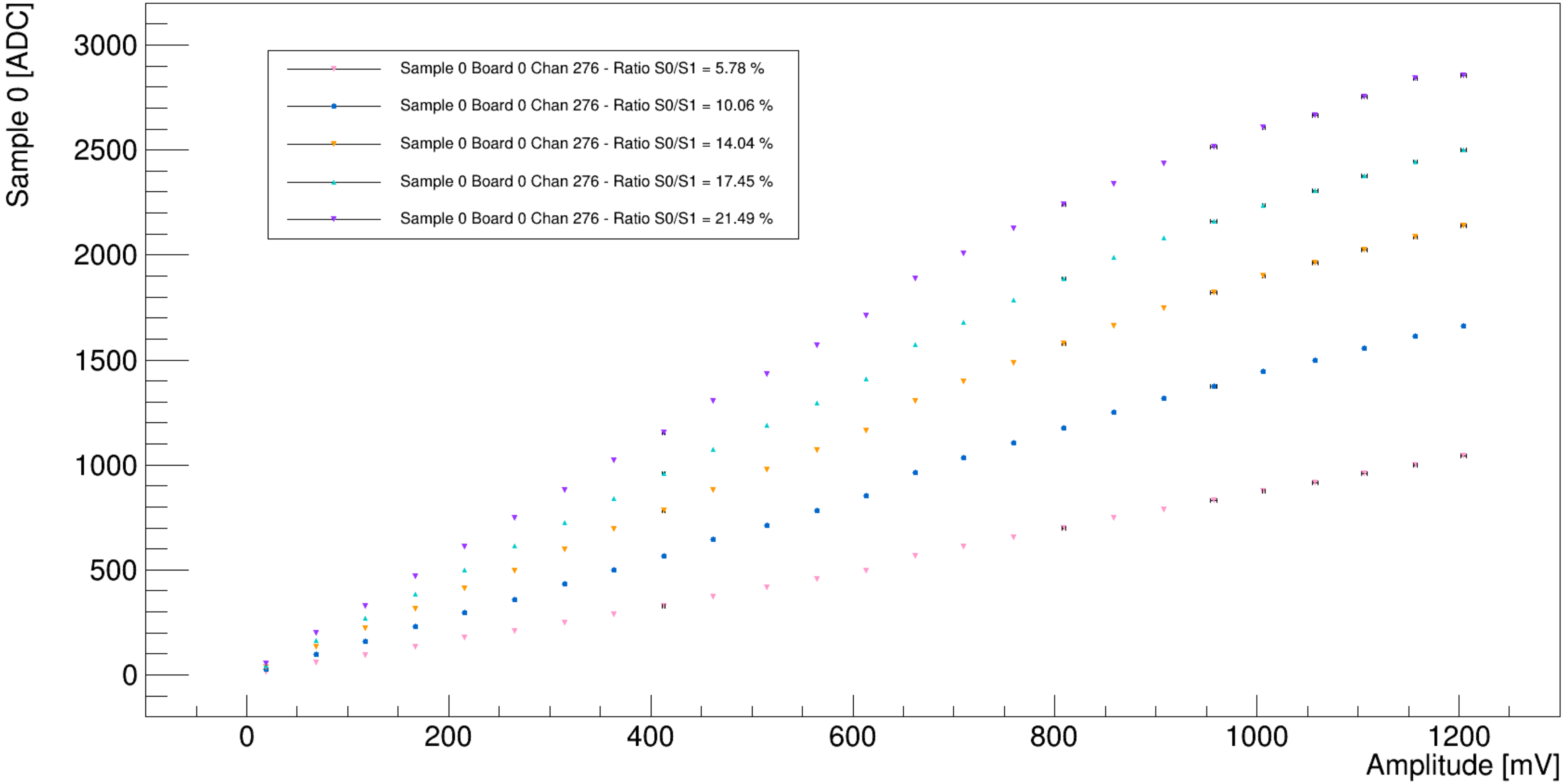
Amplitude scan at different latencies: linear region



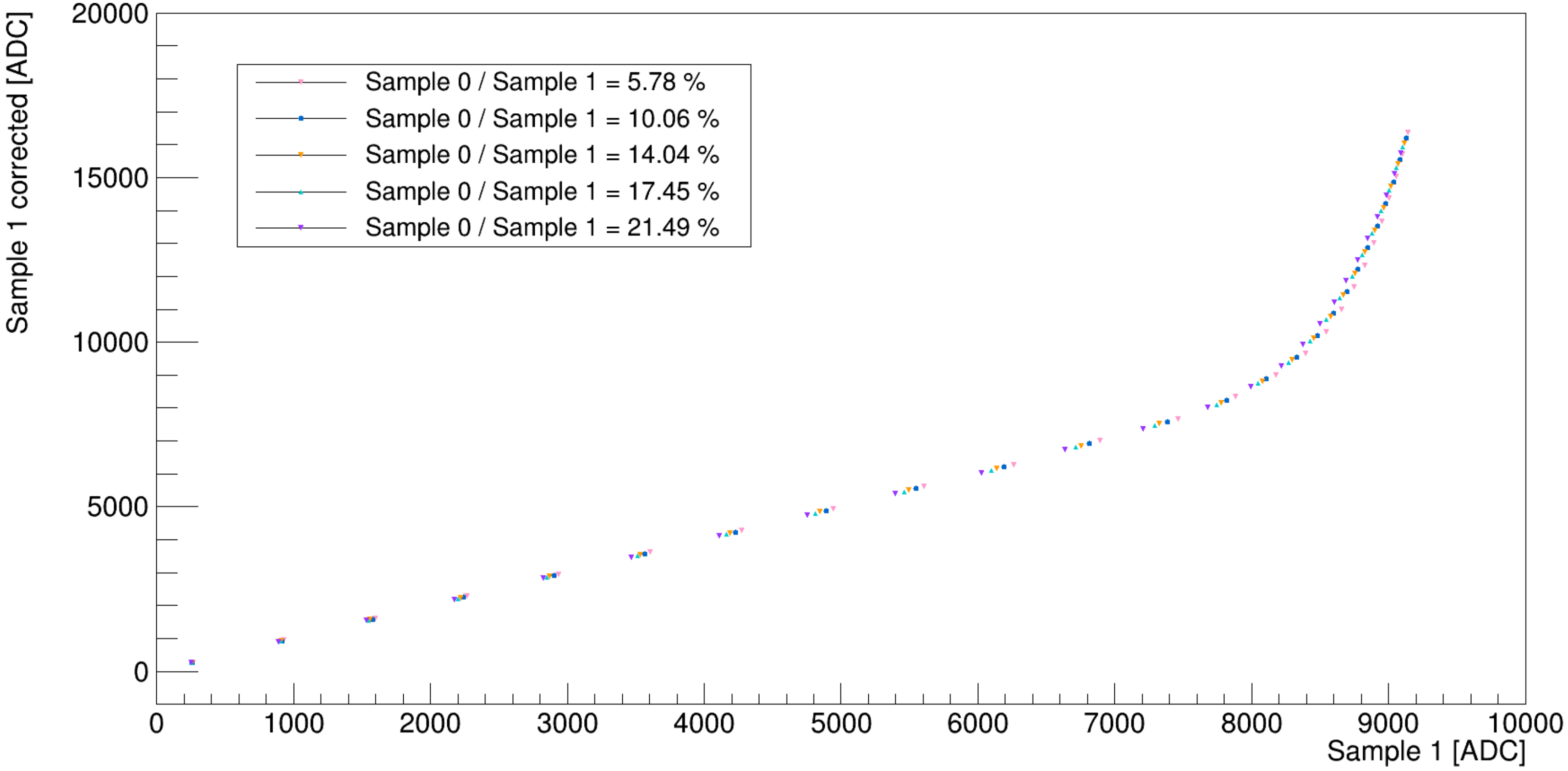
Amplitude scan at different latencies: non-linear region



Amplitude scan at different latencies



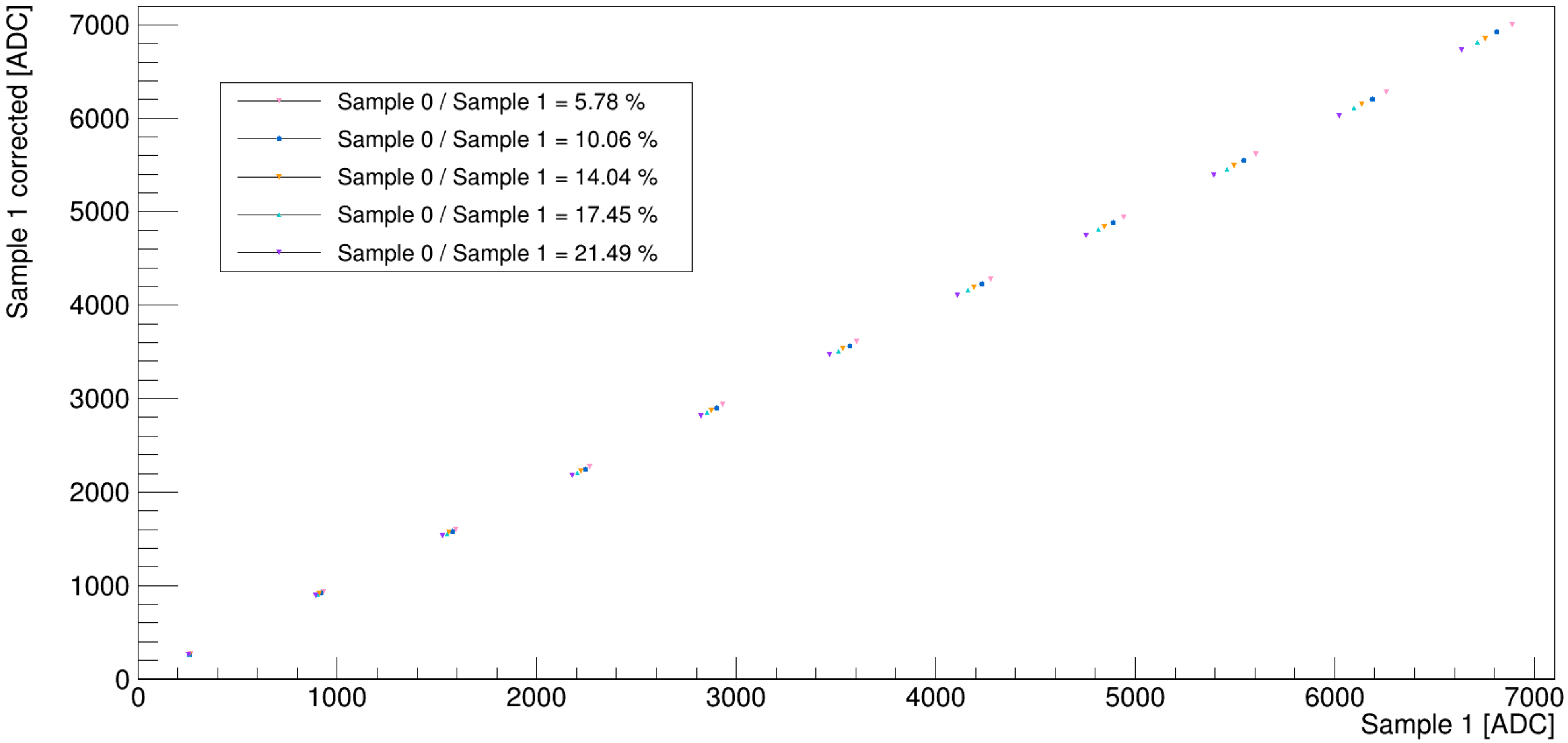
Correction curve at different latencies



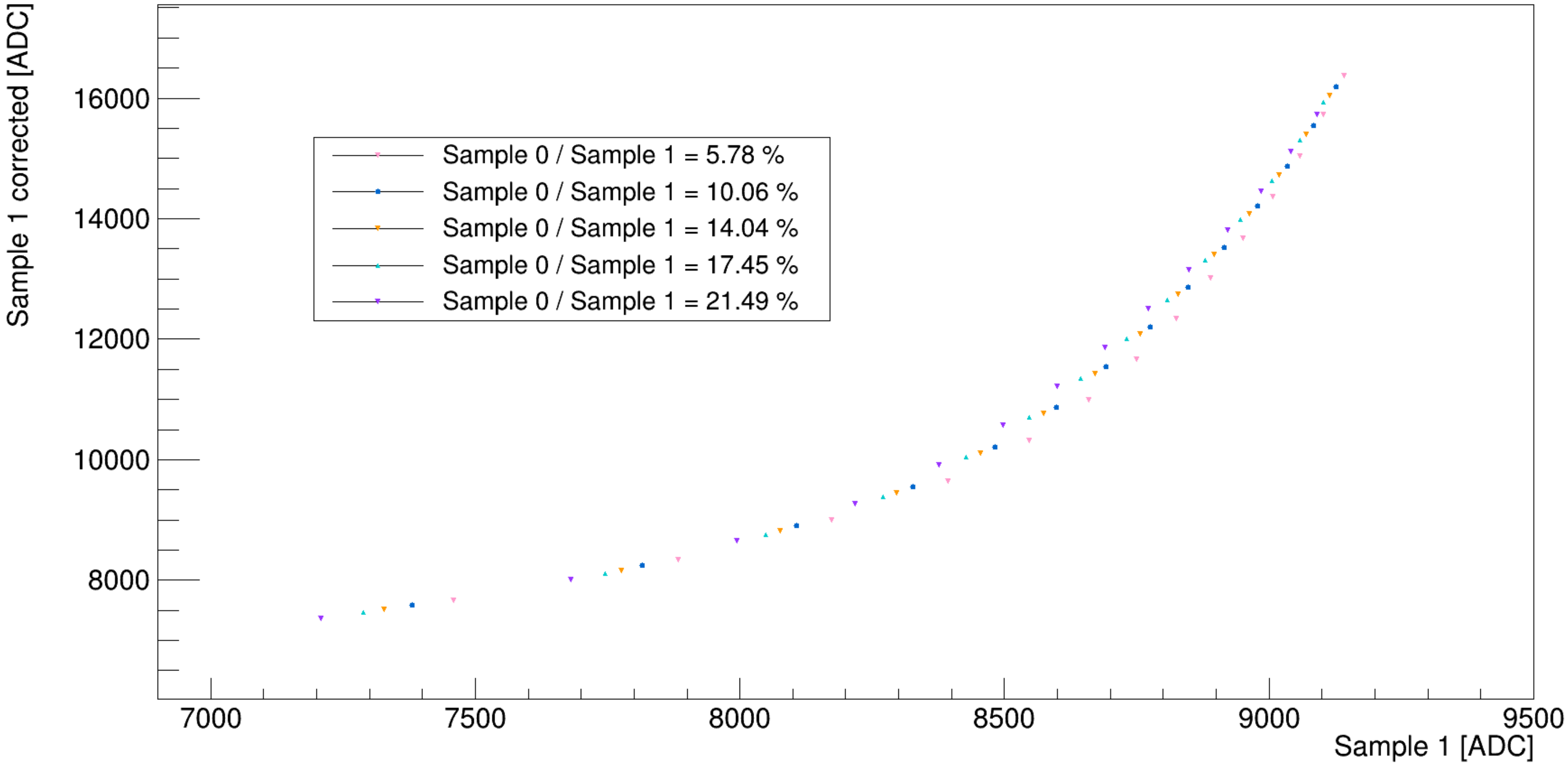
On x-axis: Sample 1 at different latencies.

On the y-axis: Sample 1 from the linear fit of Sample1 vs Amplitude of the calibration signal at difference latencies.

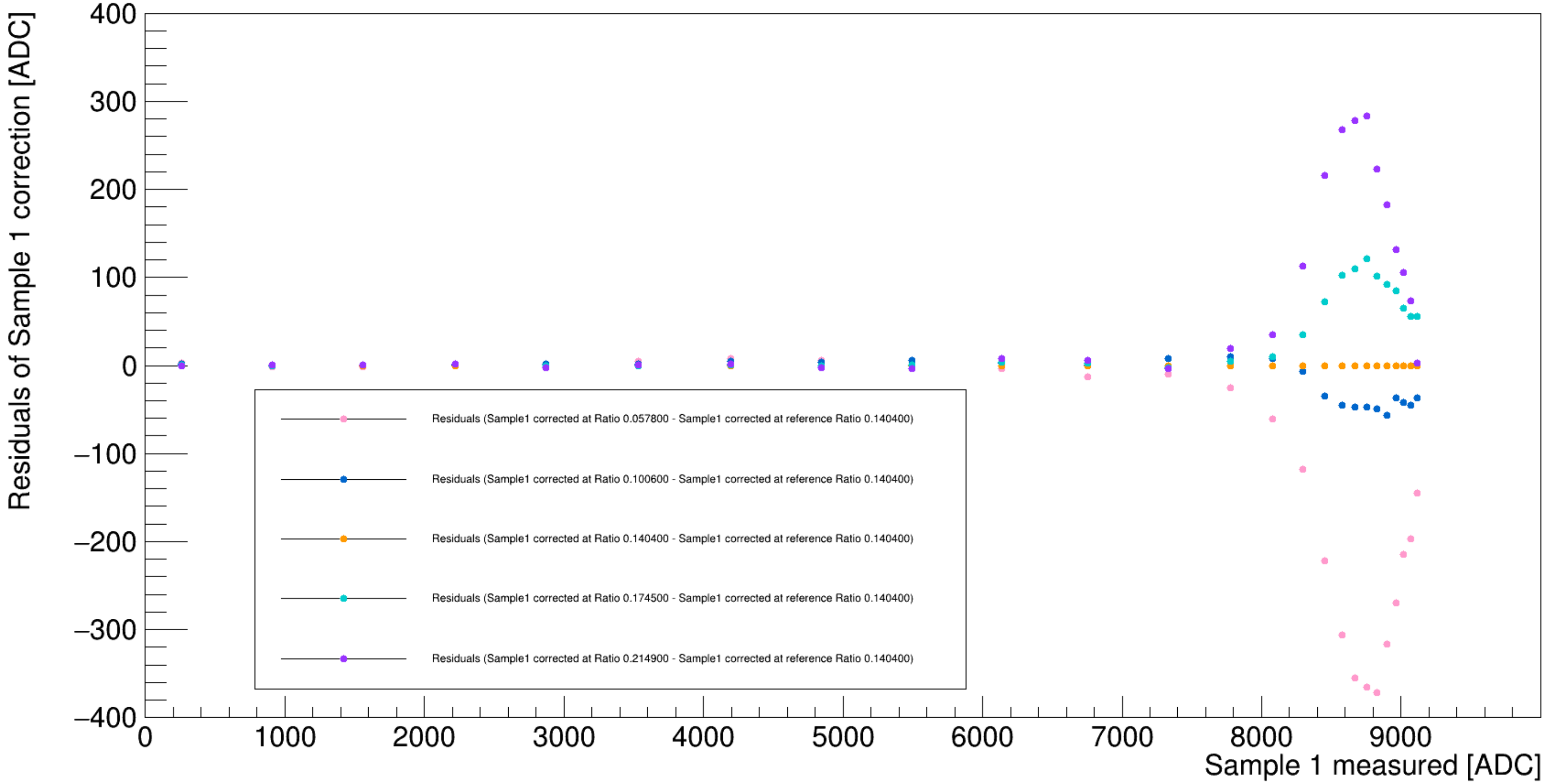
Correction curve at different latencies: linear region



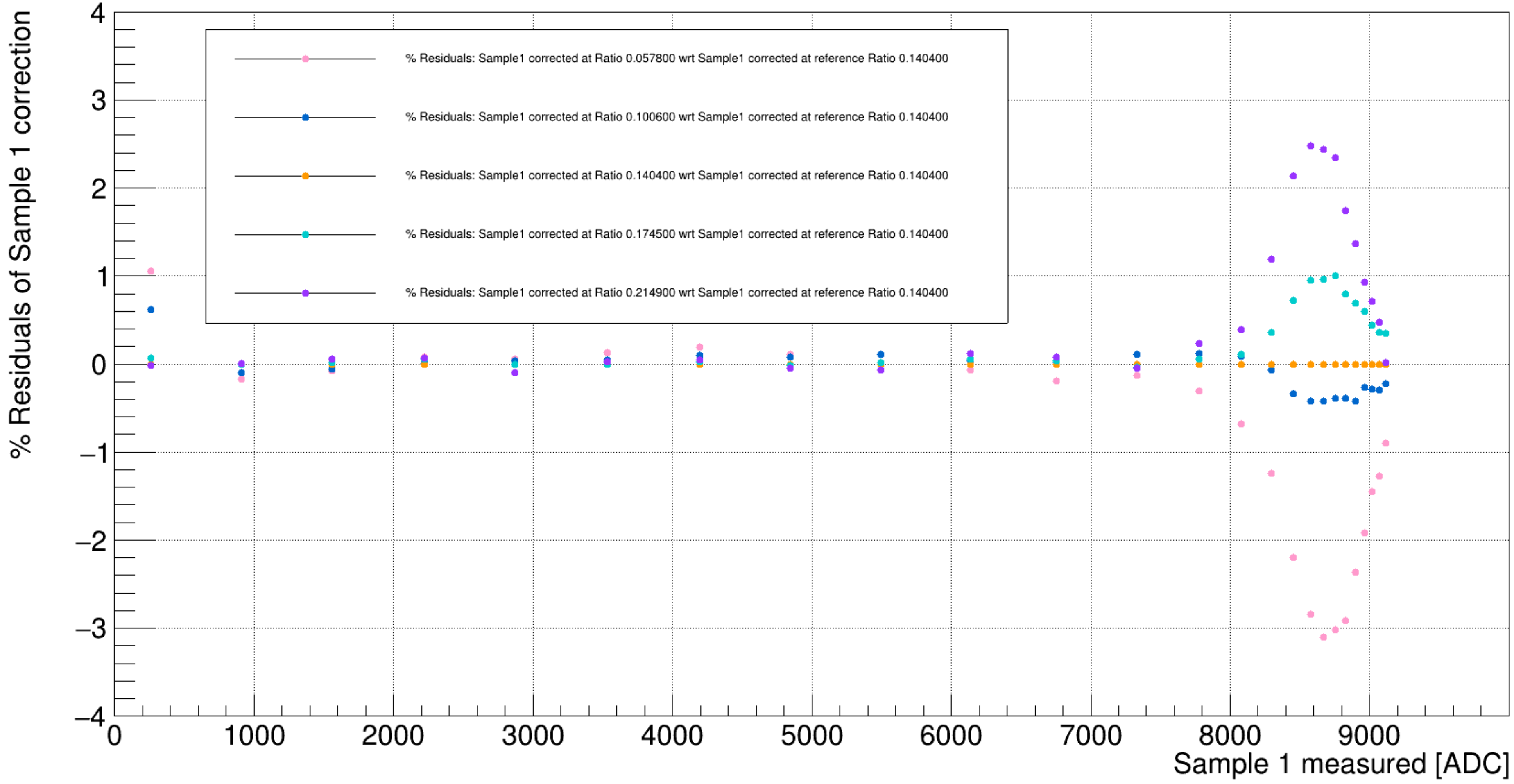
Correction curve at different latencies: non-linear region



Dependance of the correction on S0/S1



Dependance of the correction on S0/S1



Dependance of the correction on S0/S1

At Sample 1 measured = 8000 ADC, the deviation due to the dependence on the different latency is well below the 1%. This means that, if we correct the Sample 1 with the correction curve relative to the reference latency (S0/S1=14.04%), we are introducing an error well below the 1%.

I have to check how many LHC events (in the 2022 run) have a maximum signal on a single strip above 8000 ADC.

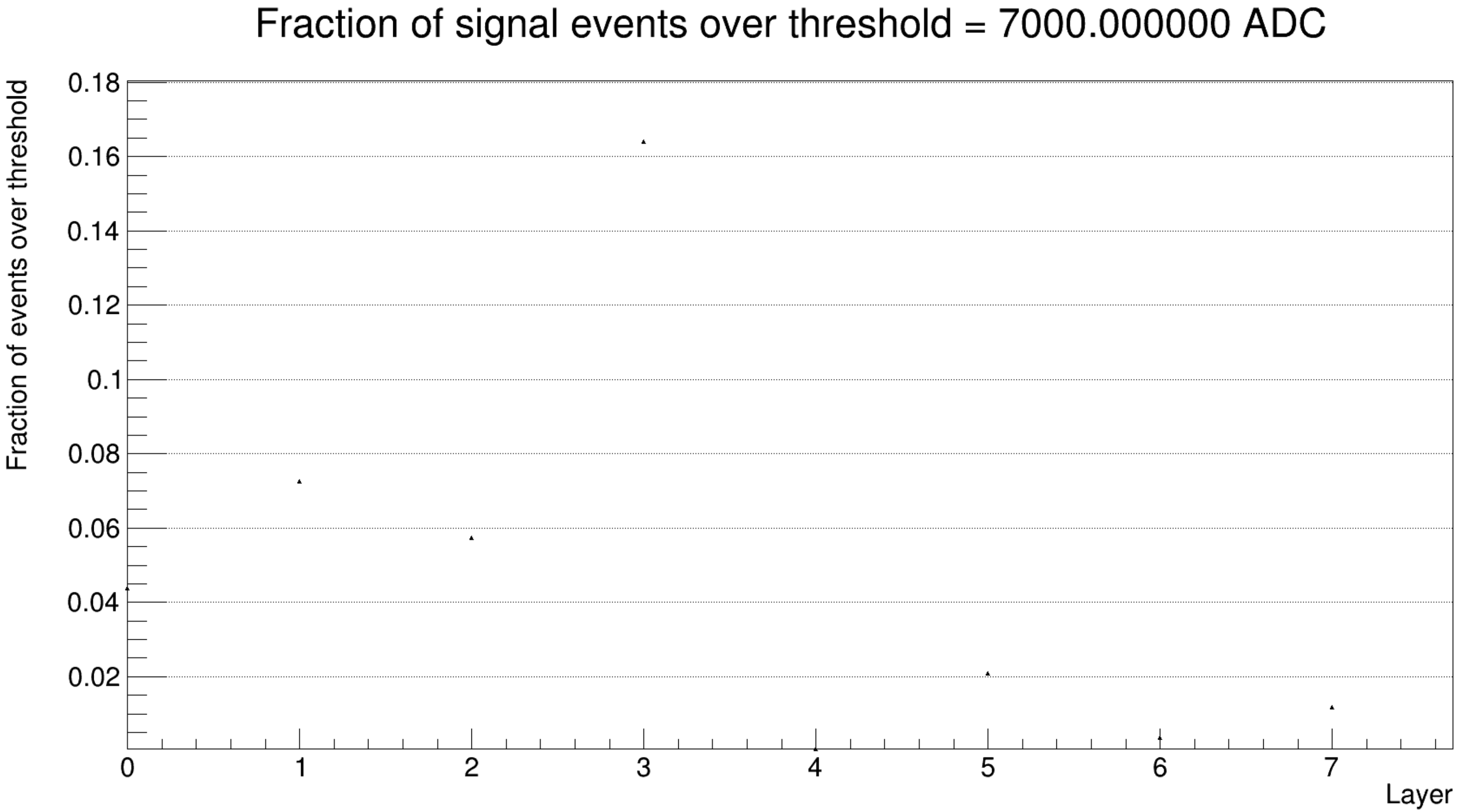
In order to calculate the fraction of events with a maximum signal above 8000 ADC, I have to cut the «noise».

How to choose the cut at low energy?

What is the probability that at least one of the 384 strips has a signal related to the noise that is higher than 3-4 times the standard deviation of the noise distribution (assuming the noise distribution as a gaussian and uncorrelated between strips)?

I would like this probability to be few %.

Fraction of events with a large energy deposit



(Total number of events=41209262)

Noise cut→3,69x(7 ADC)=25.83 ADC

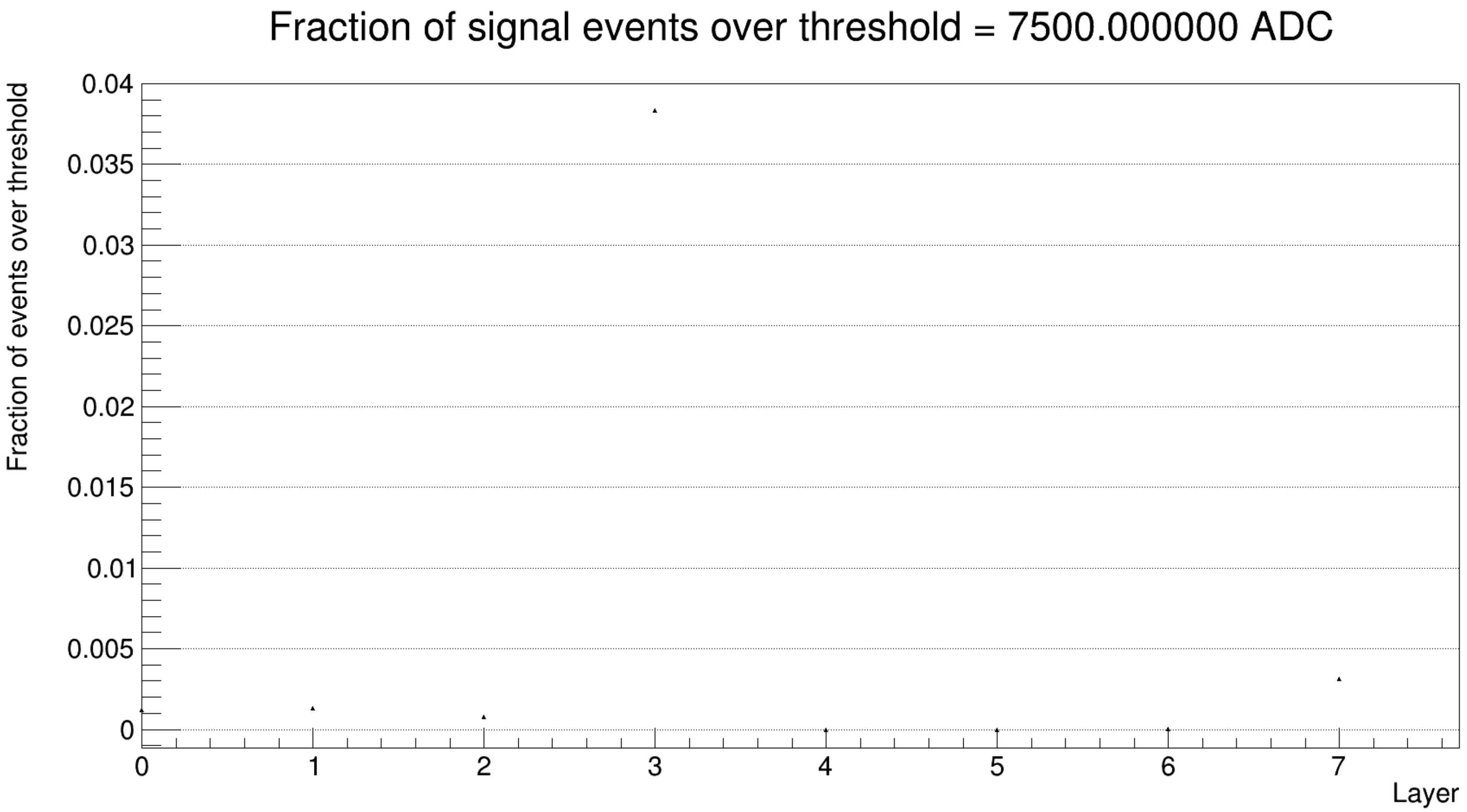
3.77% is the probability of having at least one of the 384 strips with noise above 3,69 times the RMS value of the noise (assuming the noise being gaussian distributed and uncorrelated between the strips)

7.39% the same probability but with noise above 3.5 times the RMS value (24,5 ADC).

39.3% the same, but above 3 times the RMS value (21 ADC).

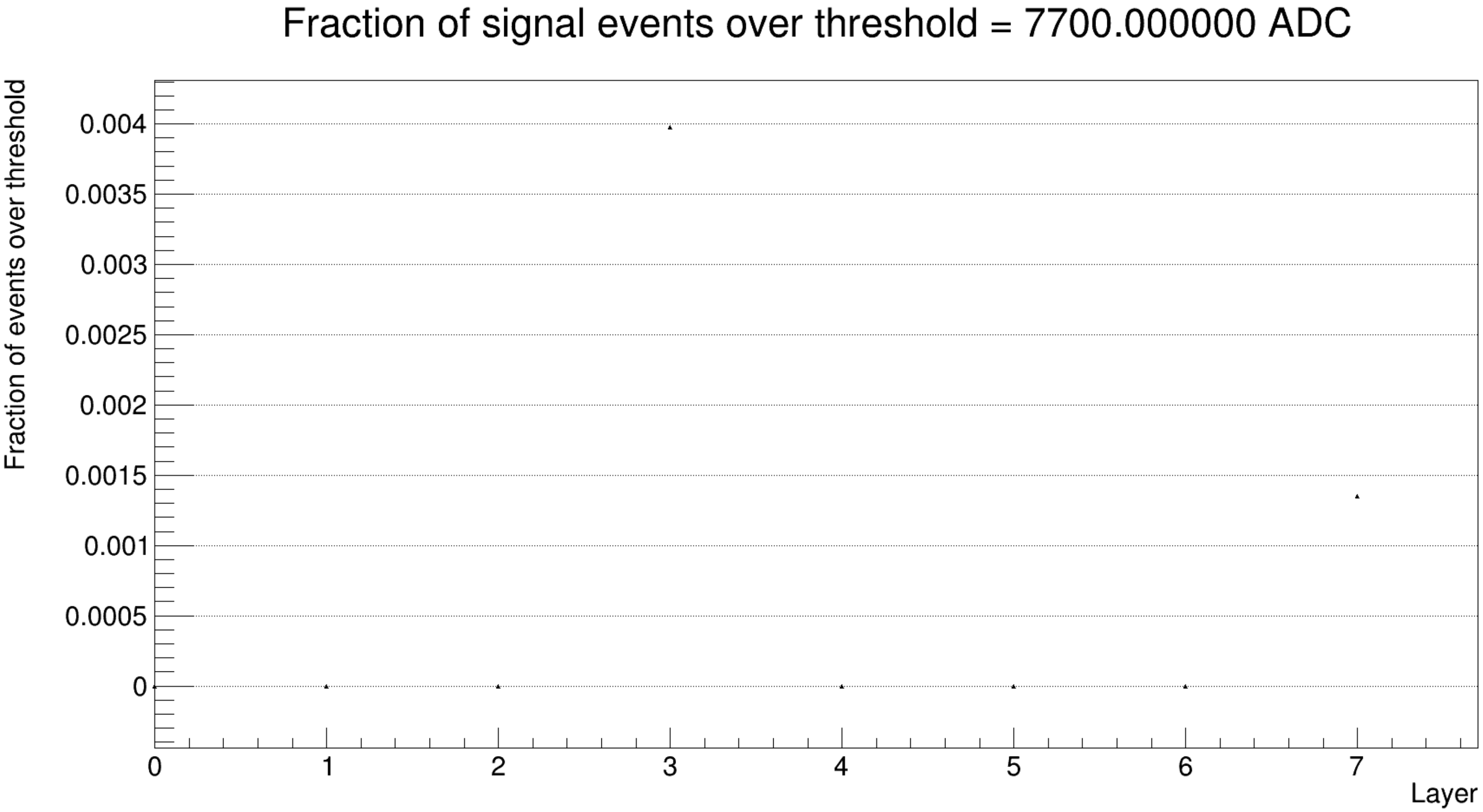
Fraction of events with a large energy deposit

(Total number of events=41209262)



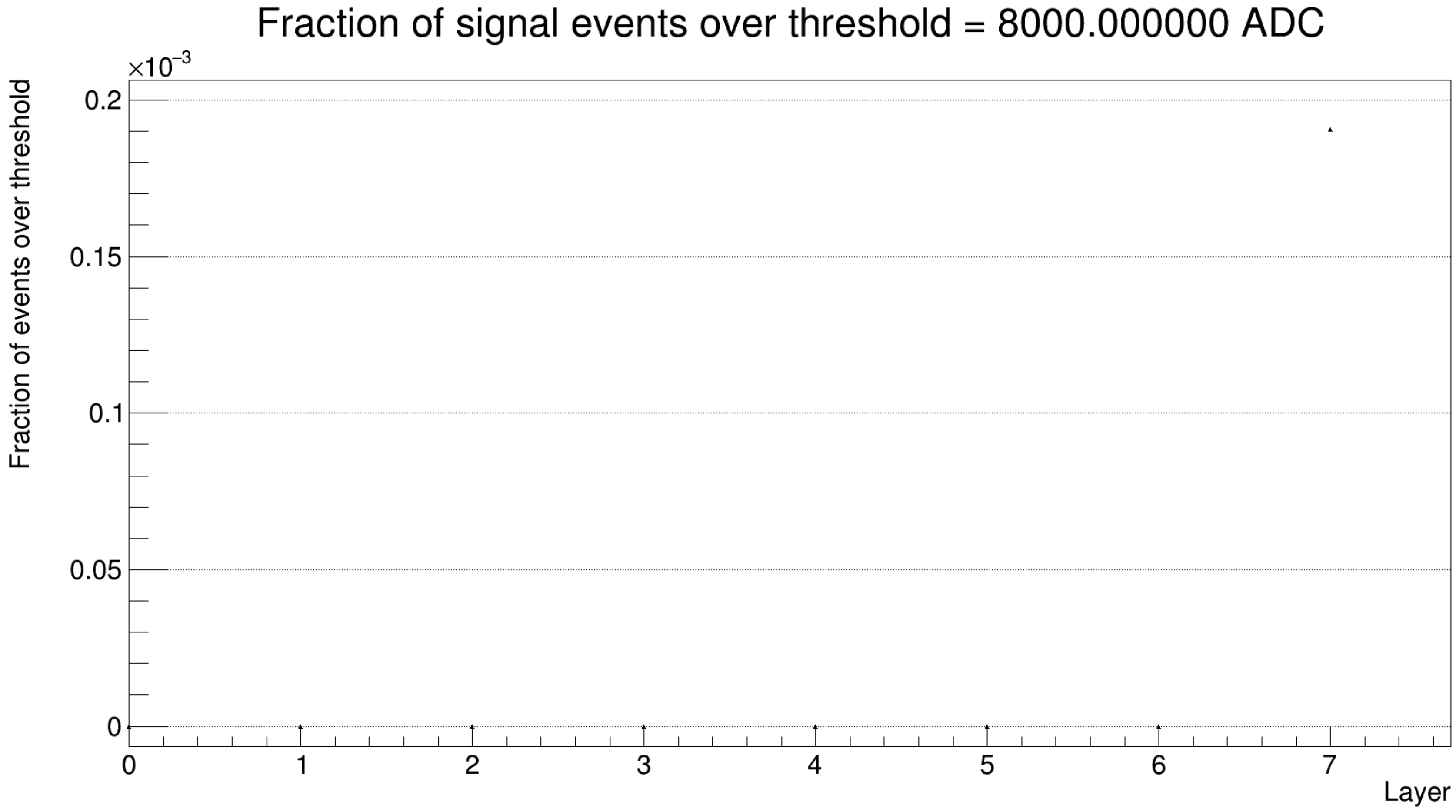
Fraction of events with a large energy deposit

(Total number of events=41209262)

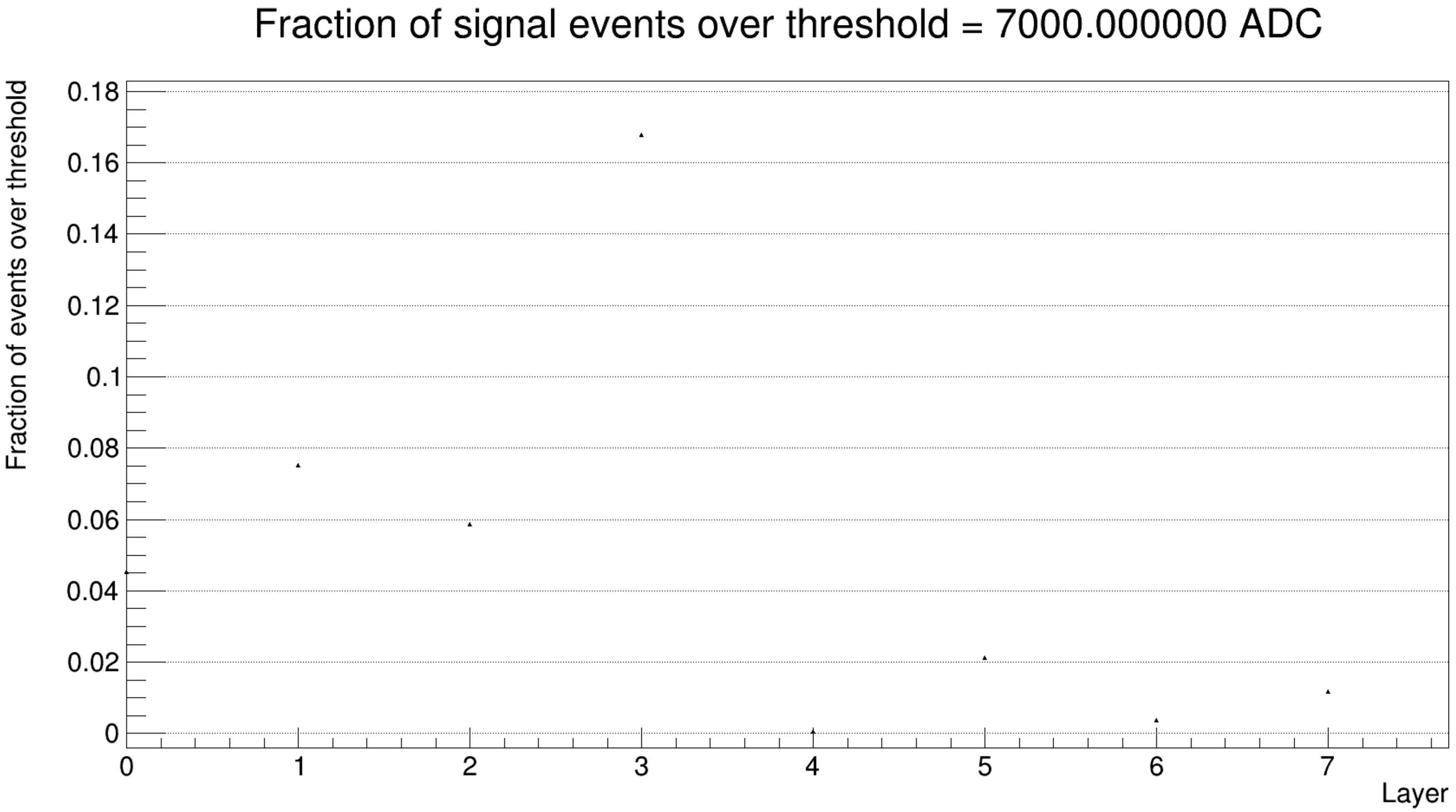


Fraction of events with a large energy deposit

(Total number of events=41209262)



Fraction of events with a large energy deposit



(Total number of events=41209262)

Noise cut→3,69x(8 ADC)=29.52 ADC

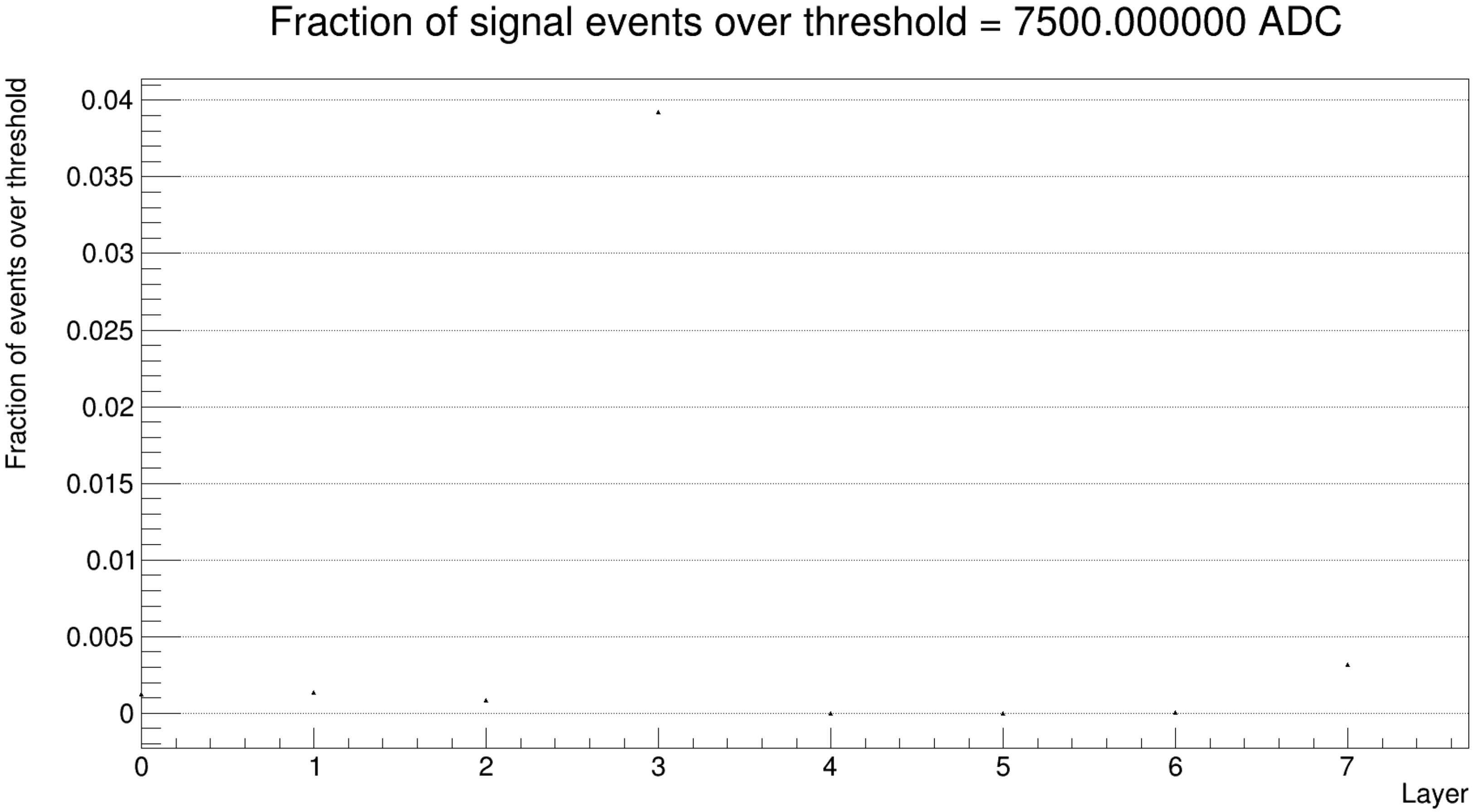
3.77% is the probability of having at least one of the 384 strips with noise above 3,69 times the RMS value of the noise (assuming the noise being gaussian distributed and uncorrelated between the strips)

7.39% the same probability but with noise above 3.5 times the RMS value (=28 ADC).

39.3% the same, but above 3 times the RMS value (24 ADC).

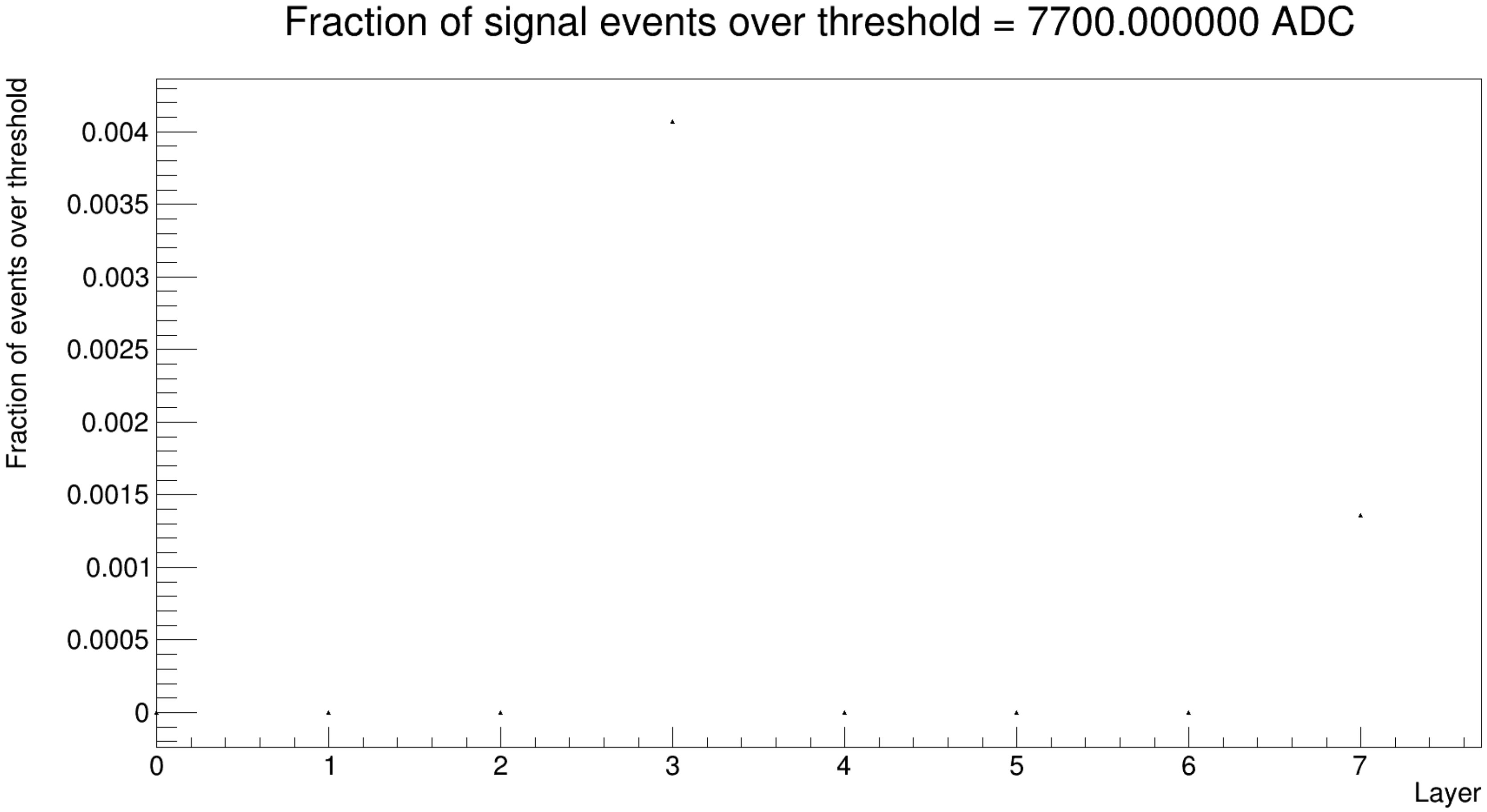
Fraction of events with a large energy deposit

(Total number of events=41209262)



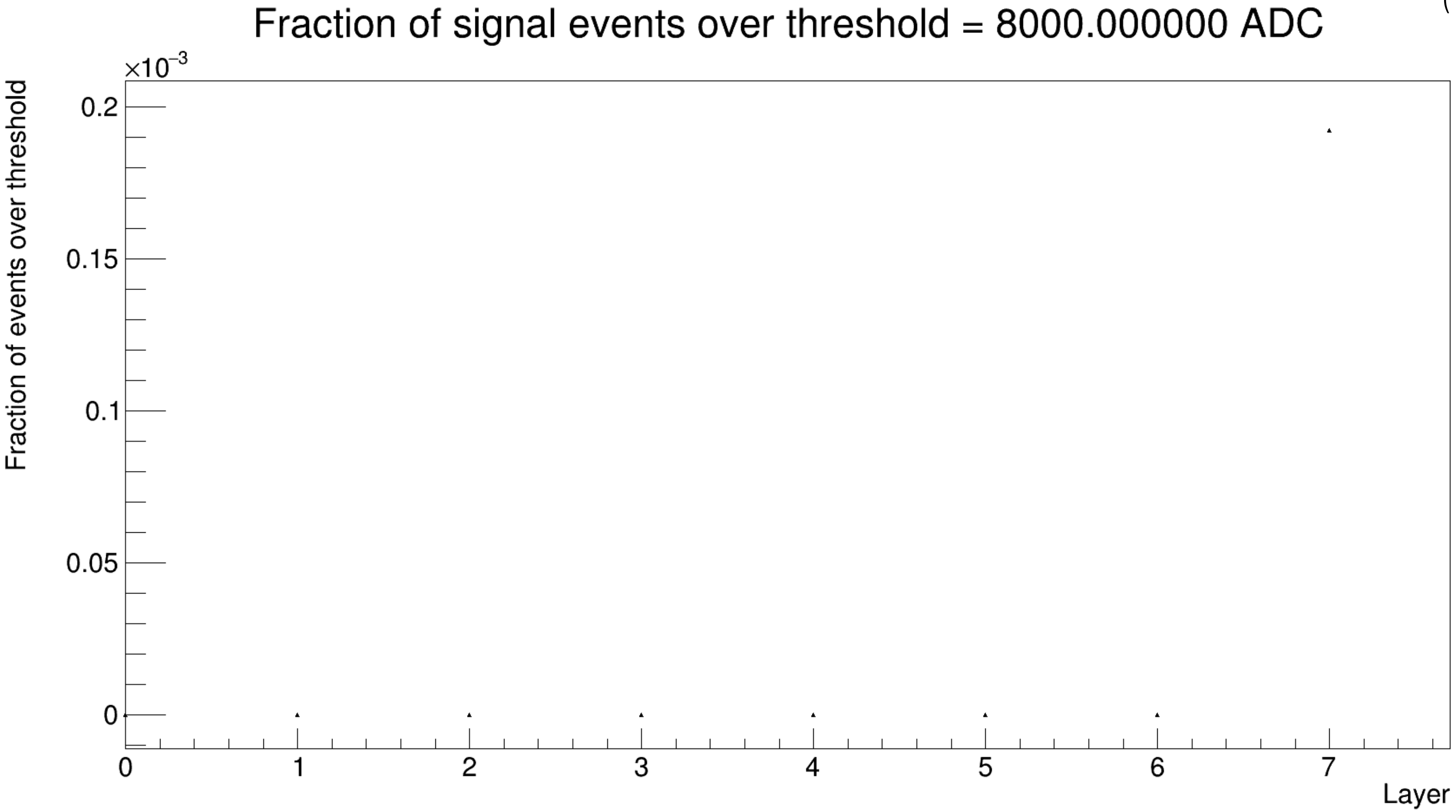
Fraction of events with a large energy deposit

(Total number of events=41209262)

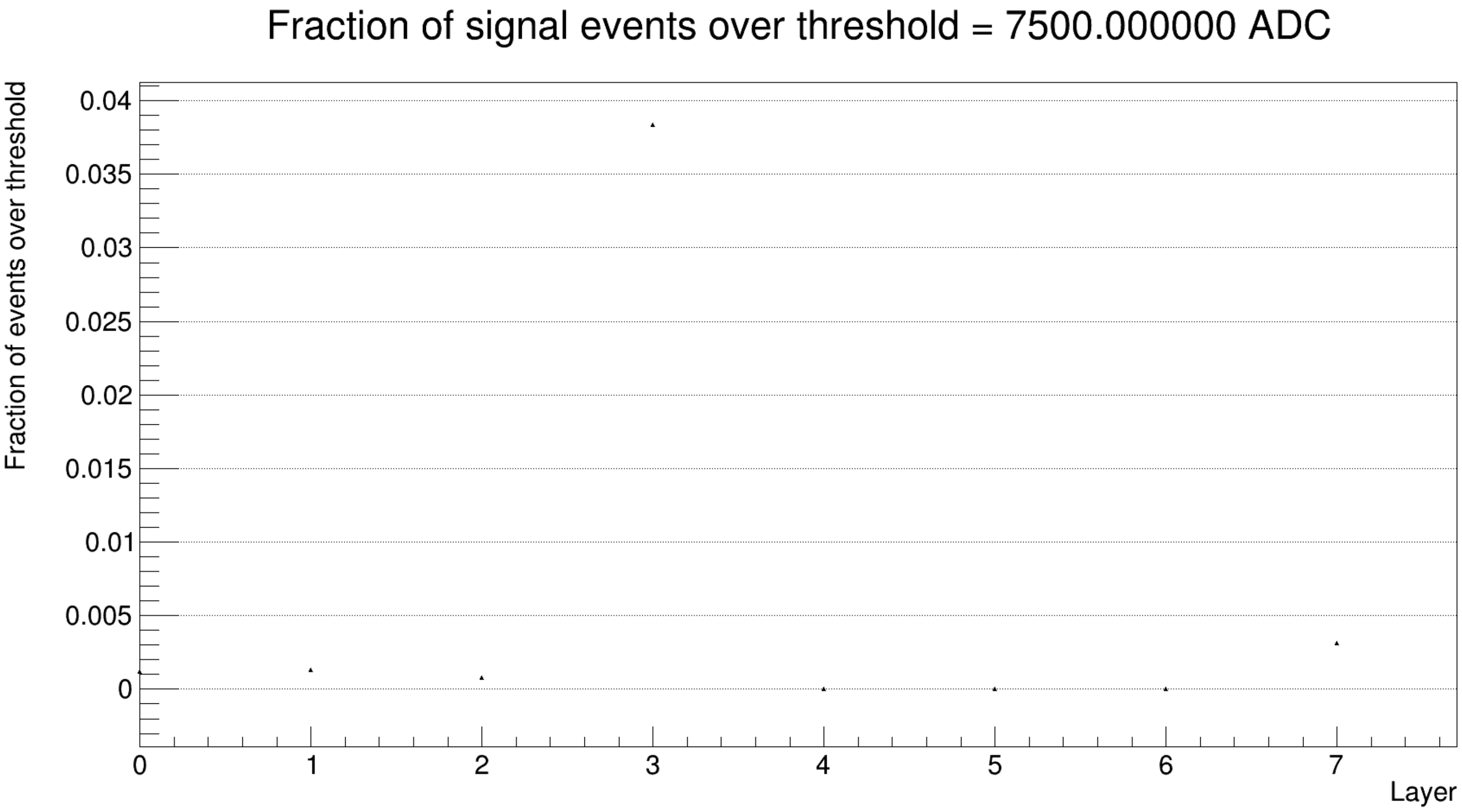


Fraction of events with a large energy deposit

(Total number of events=41209262)



Fraction of events with a large energy deposit



(Total number of events=41209262)

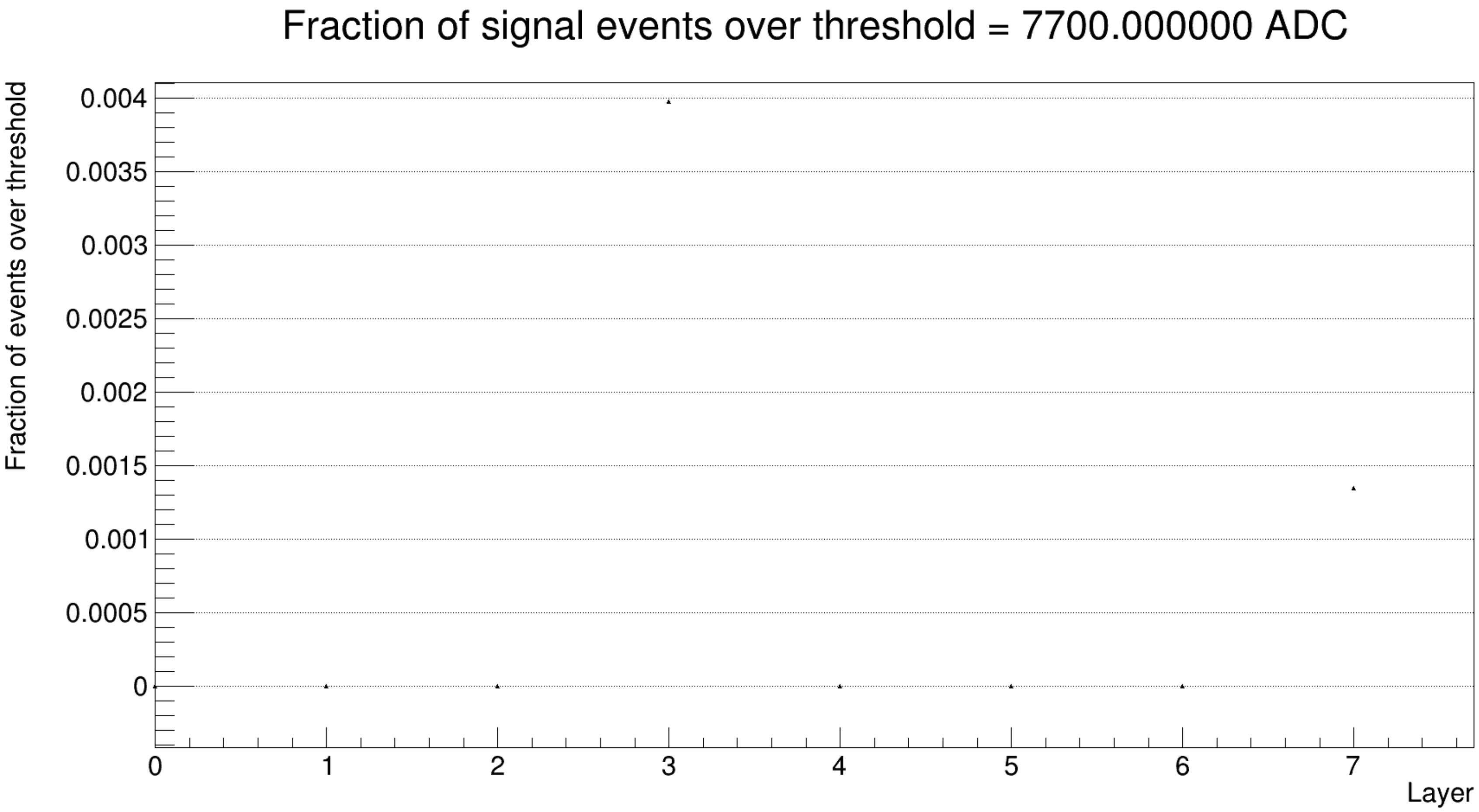
Noise cut→3.5x(7.5 ADC)=26.25 ADC

7.39% is the probability of having at least one of the 384 strips with noise above 3,5 times the RMS value of the noise (assuming the noise being gaussian distributed and uncorrelated between the strips)

The fraction of events with maximum signal above 7500 ADC is below 4% in Layer 1Y and below 0.5% in the other layers.
There are no events above 8150 ADC.

REMEMBER: Below 8200 ADC, the dependance of Sample1 correction on the value of latency is below 1% (for latencies corresponding to Sample0/Sample1 values between 5.8% and 21.5%)

Fraction of events with a large energy deposit



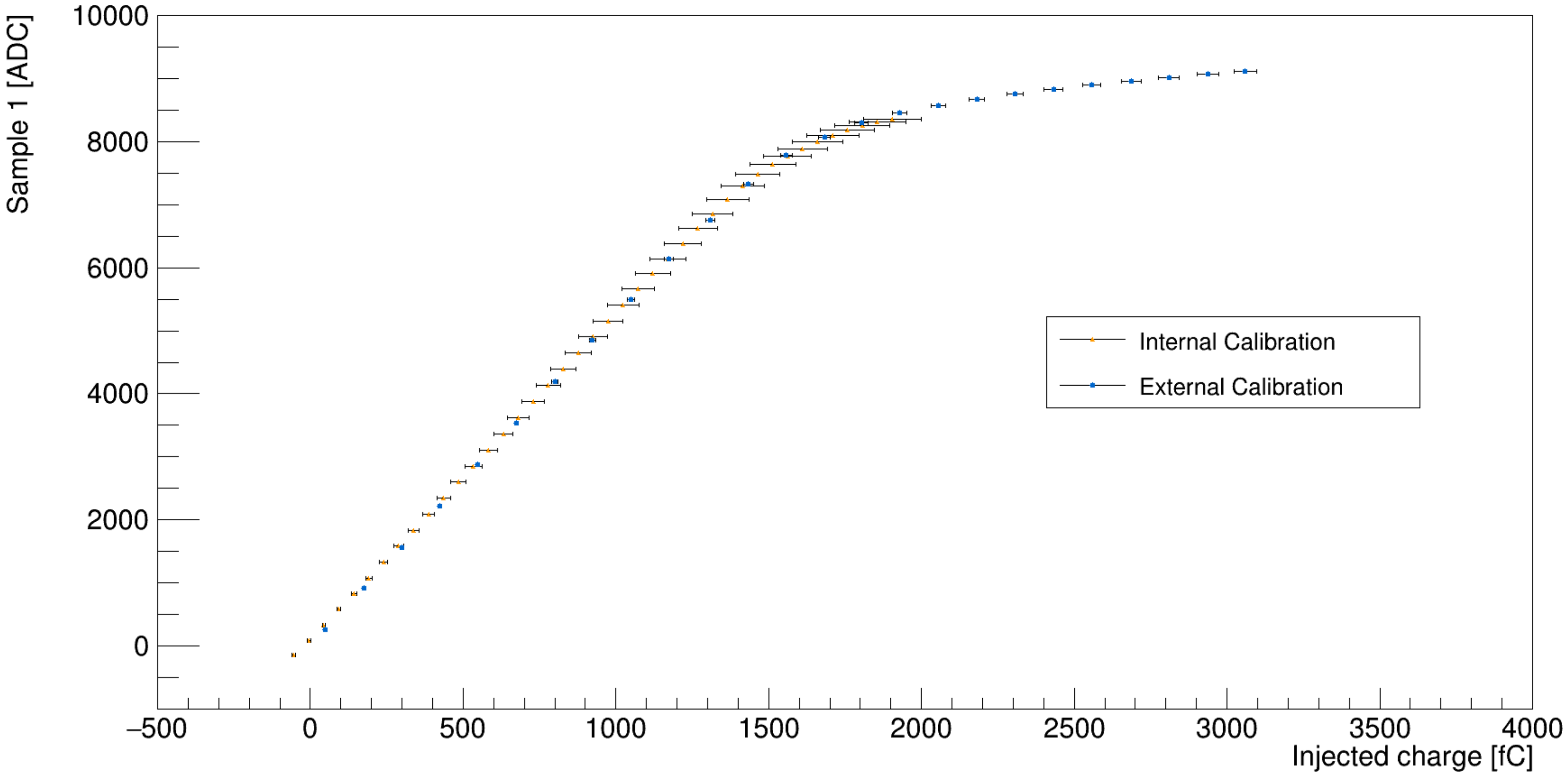
(Total number of events=41209262)

Noise cut→3.5x(7.5 ADC)=26.25 ADC

The fraction of events with maximum signal above 7700 ADC is below 0.4% in Layer 1Y and below 0.15% in the other layers.

External and Internal Calibration at S0/S1=0.14

S0/S1=0.1404±0.0004 External calibration @265.6 mV→Injected charge 674.6 fC
S0/S1=0.14260±0.00012 Internal calibration @Vcal=125 (533,9 mV)→Injected charge 680.7 fC

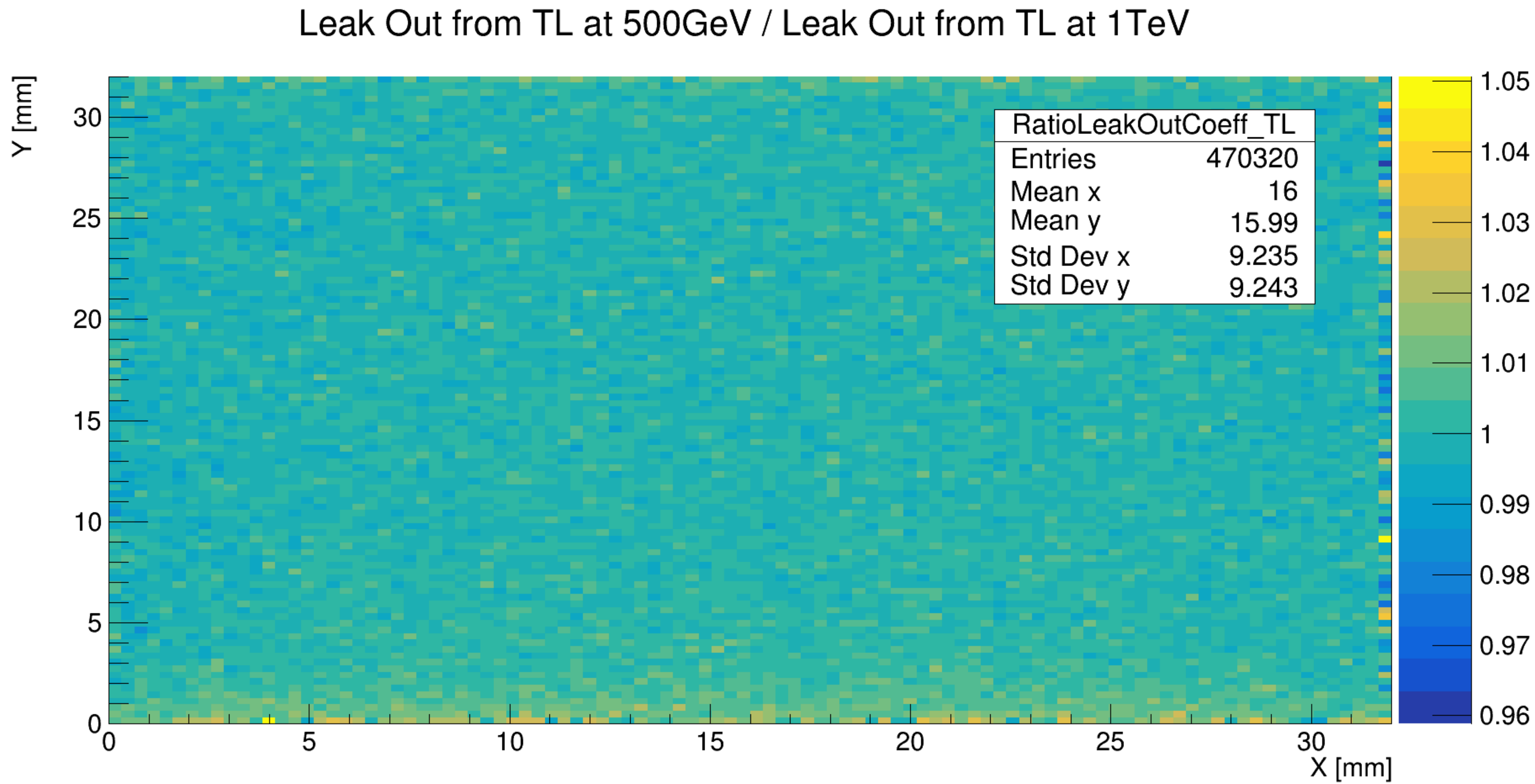


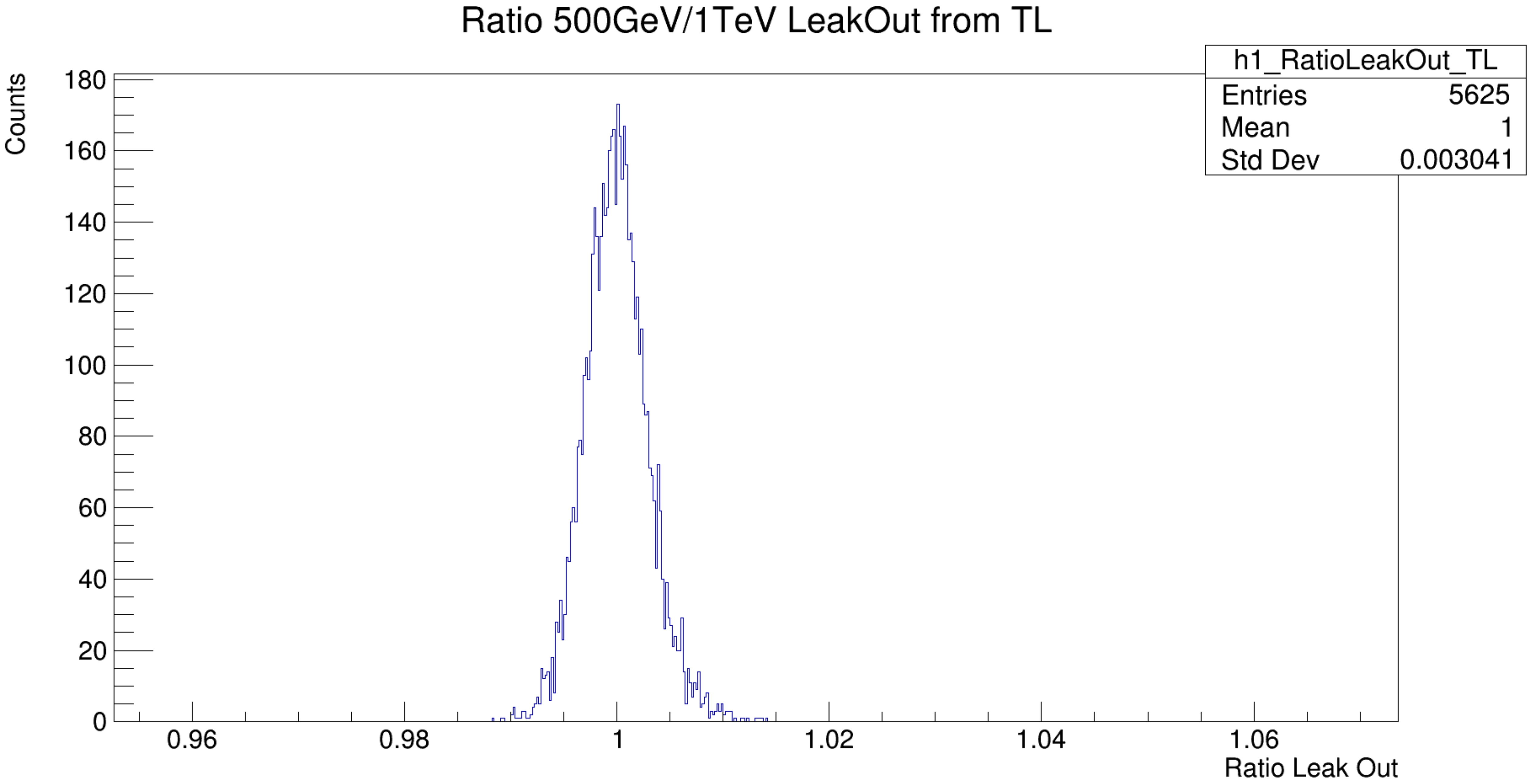
- External capacitor=(2.54±0.03) pF (Measured at 100 kHz)
- Internal capacitor=1.275 pF , relative uncertainty 5%

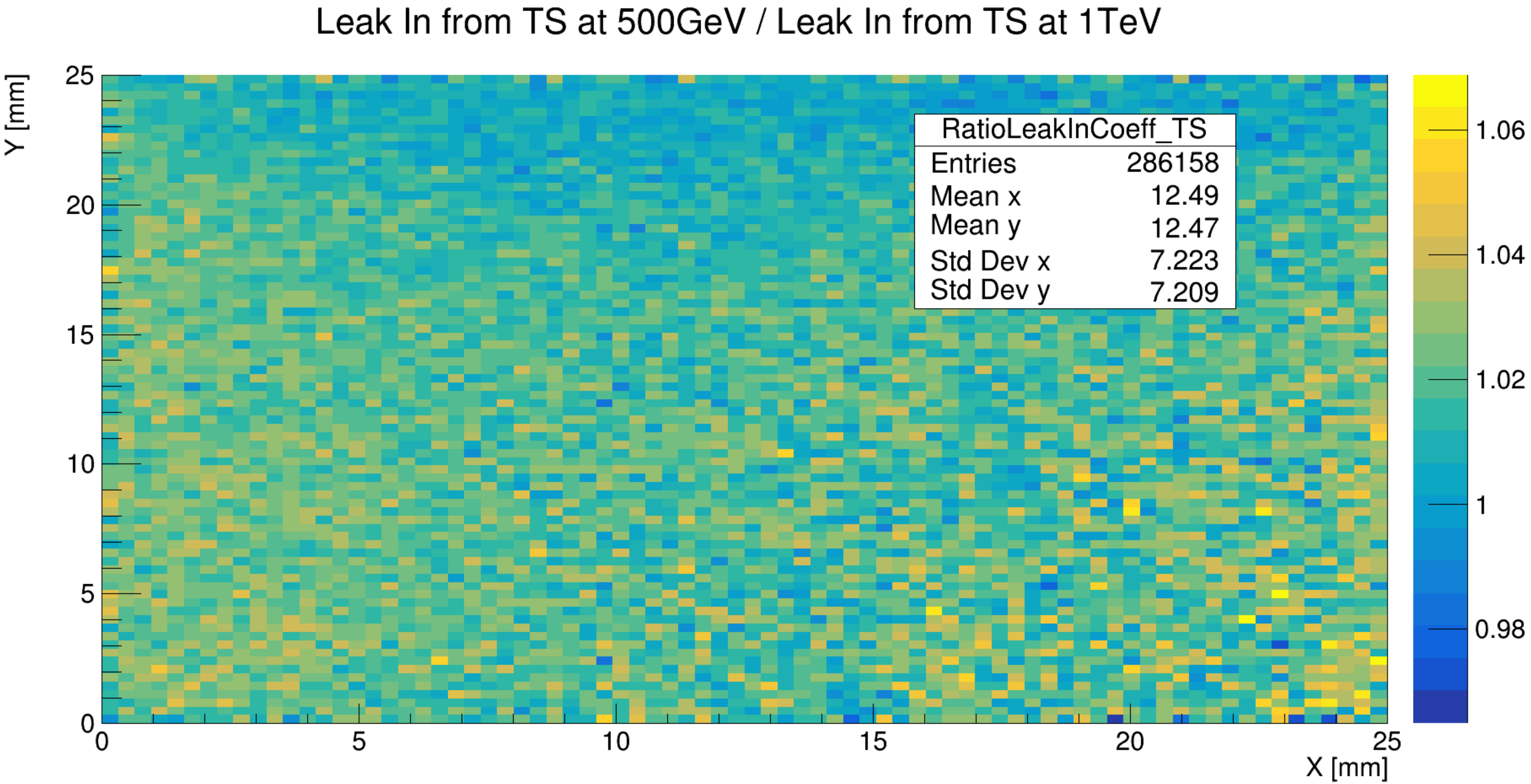
Systematic uncertainty related to the value of the capacitors.
The two calibration procedures seem to be consistent.

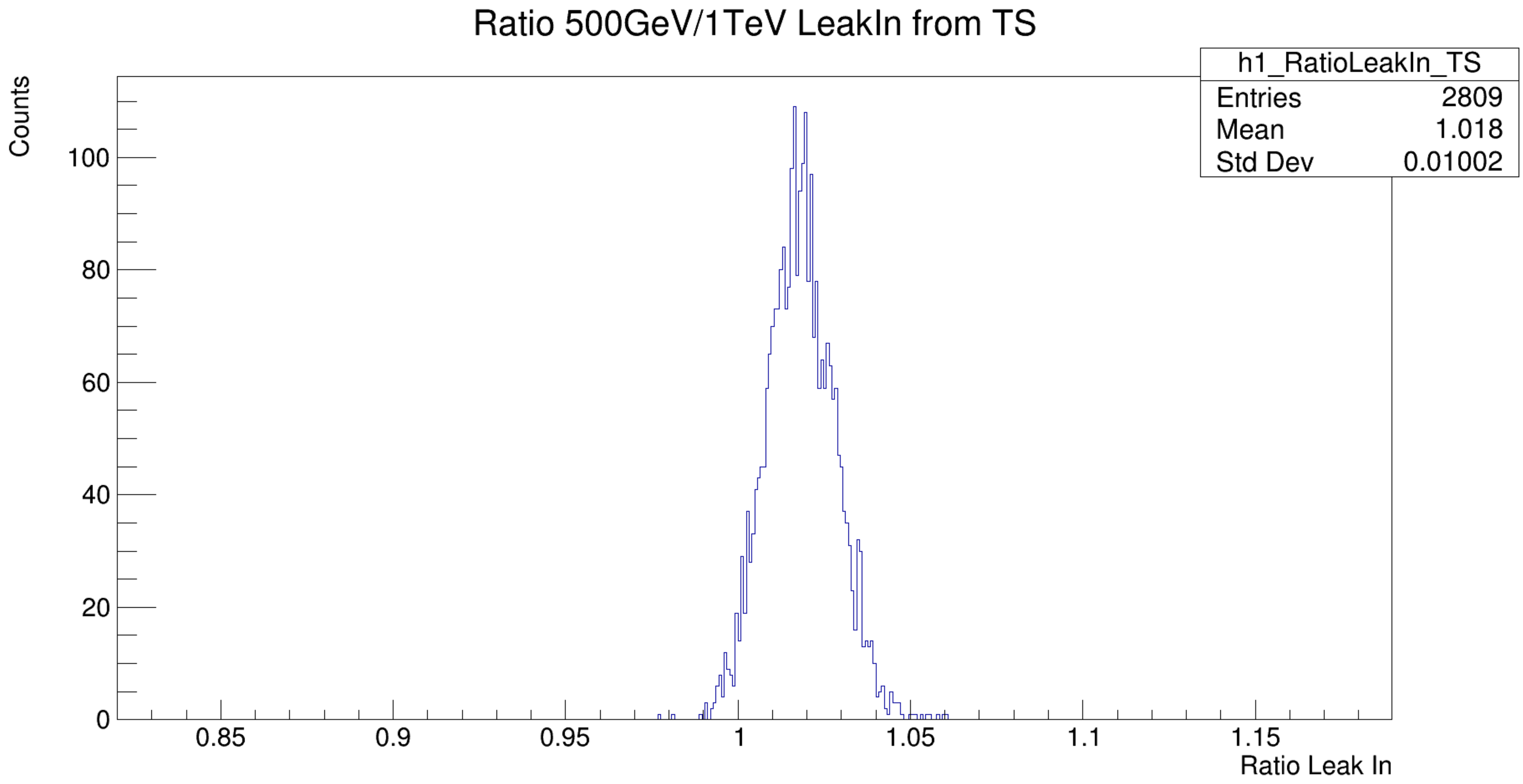
Amplitude [mV]=Vcal*7.68[mV/Vcal unit]-426.1 [mV]

See Aspell's presentation: Delta (cern.ch)
(In principle there are also uncertainties related to these conversion factors. But they are very small: σ variation from mean (LSB) = 5.81 µV ~ 1/500th MIP)


Leak Out from TL at 500GeV / Leak Out from TL at 1TeV
RatioLeakOutCoeff_TL
Entries 470320
Mean x 16
Mean y 15.99
Std Dev x 9.235
Std Dev y 9.243
Y [mm]
X [mm]
0
5
10
15
20
25
30
0.96
0.97
0.98
0.99
1
1.01
1.02
1.03
1.04
1.05


Ratio 500GeV/1TeV LeakOut from TL
h1_RatioLeakOut_TL
Entries 5625
Mean 1
Std Dev 0.003041
Counts
0
20
40
60
80
100
120
140
160
180
0.96
0.98
1
1.02
1.04
1.06
Ratio Leak Out


Leak In from TS at 500GeV / Leak In from TS at 1TeV
RatioLeakInCoeff_TS
Entries 286158
Mean x 12.49
Mean y 12.47
Std Dev x 7.223
Std Dev y 7.209
Y [mm]
X [mm]
0
5
10
15
20
25
0.98
1
1.02
1.04
1.06


Ratio 500GeV/1TeV LeakIn from TS
h1_RatioLeakIn_TS
Entries 2809
Mean 1.018
Std Dev 0.01002
Counts
0
20
40
60
80
100
0.85
0.9
0.95
1
1.05
1.1
1.15
Ratio Leak In