NPS Calorimeter Elastic Analysis

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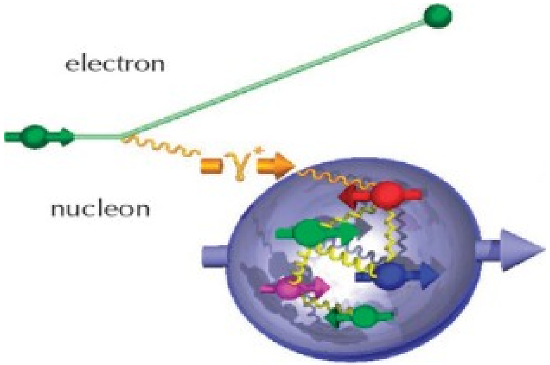
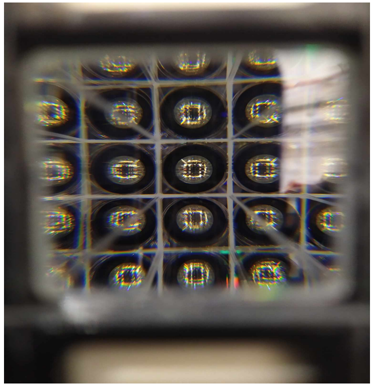
Tunisia**





NPS Collaboration Meeting

5th of May 2025

Outlines

- **Waveform Analysis**
- **Temperature Interpolation**
- **Energy Resolution**
- **Time Resolution**

Elastic Runs Analyzed (Entire Experiment!)

1st run/last run	Total of runs	HMS Central Momentum	Ee (GeV)	D.Calo (m)	Pass
6171/6183	13	3.1615	5.681	9.5	4
6151/6168	18	2.639	4.598	9.5	3
5217/5236	20	2.639	4.598	9.5	3
5183/5208	26	4.31	7.072	9.5	5
3883/3898	16	4.078	7.072	9.5	5
2900/2920	21	4.12	5.681	8	4
2875/2885	11	4.0872	7.072	9.5	5
2855/2871	17	4.0782	7.072	9.5	5
1969/1982	14	4.087	7.072	9.5	5
1423/1511	23	4.087	7.072	9.5	5

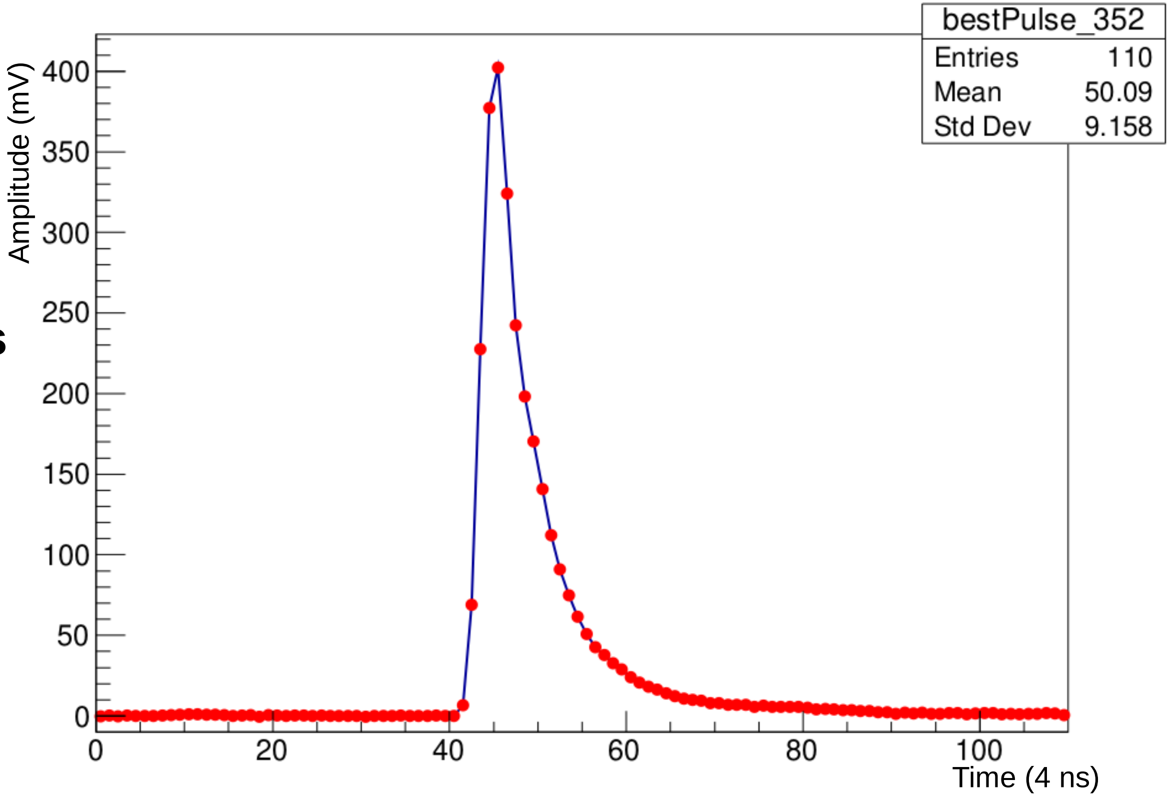
Overview Of The WF Method

1) Select the reference shape using some selective criteria:

+Highest pulse
+In coincidence (+/- 5 samples)
+No secondary pulses in the bkg regions

2) Fit the ref shape and get a rough time and amplitude to help the fit

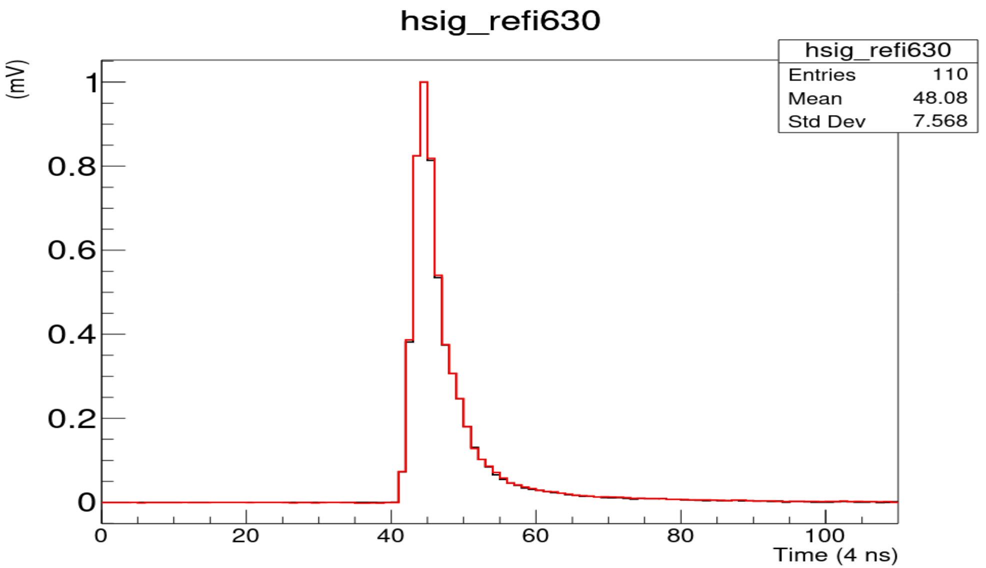
3) Apply the fit function produced for each block to production data

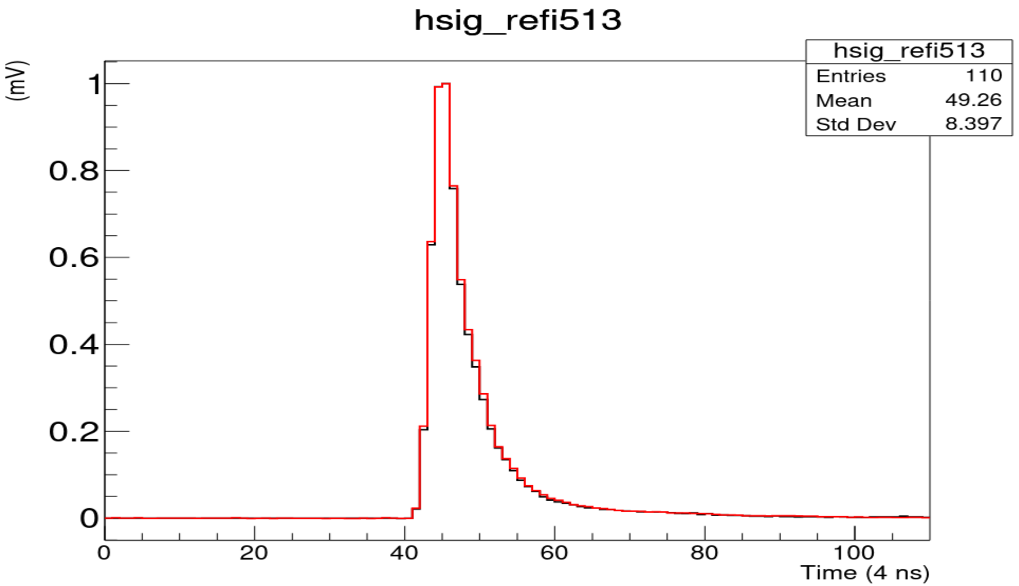


Reference Shape Check

- Tried a new method (mean of all waveforms) to determine the reference shapes instead of using the samples search logic:
  - One pulse waveforms
  - Minimum of 10 mV
  - +/- 5 samples from the coincidence time

  + Black plot => Method of samples search logic
  + Red plot => Mean of all waveforms for each block





- The reference shapes of both methods are almost compatible for the 1080 blocks (Normalized to 1 mV). They gave almost the same energy resolution.

Fit of the waveforms

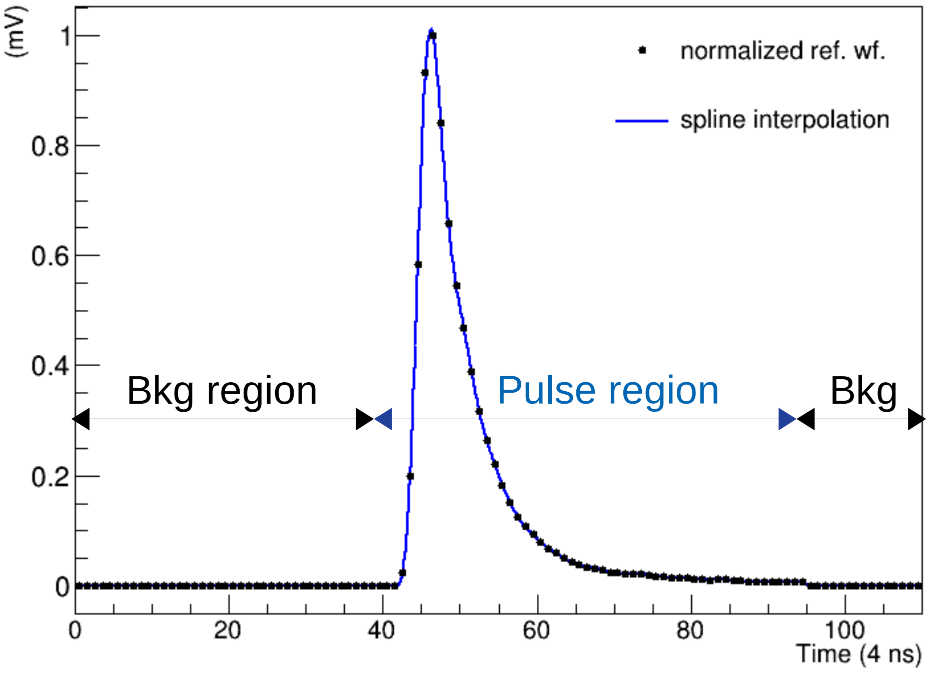
Produce a Fit function for each block

- **Interpolate the 110 samples of the ref. wf. with Spline to create a function *f(t)***

- **The fit function:**

$$F(t) = B + \sum_{i=1}^{Npulses} A_i \; f(t - t_i)$$

Baseline — **Amplitude** — **Time of pulse #i (4*ns) relatively to the ref wf time**



Elastic Calibration

- The recoiled proton was detected by the HMS and the scattered electron by the NPS

- Using the conservation of energy for a j event we get:

$$E_j = E_b + m - E_j^p$$

With E_b: the beam energy

E_j^p : the proton energy

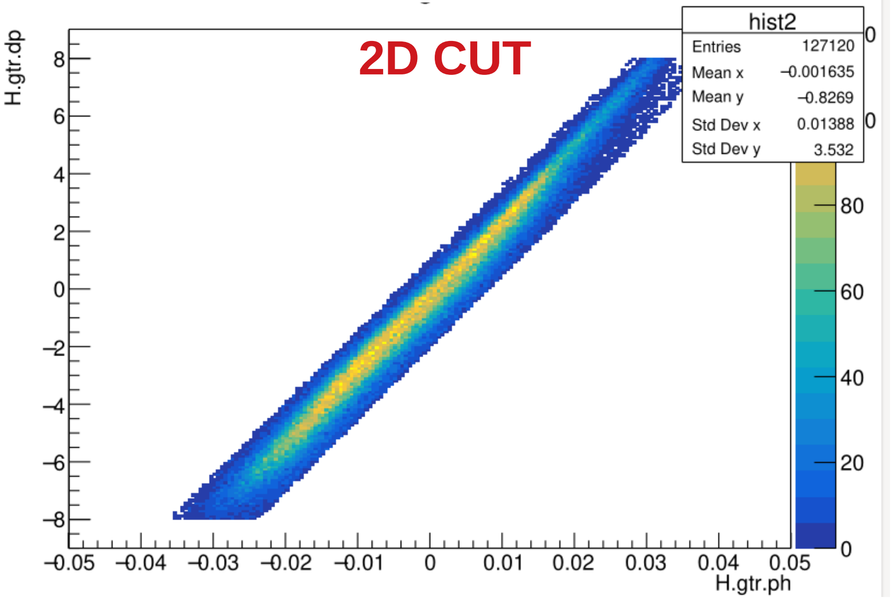
- We define the following minimization procedure:

$$\chi^2 = \sum_{j=1}^{N}\left(E_j - \sum_i C_i \cdot A_j^i\right)^2 \rightarrow \frac{\partial\chi^2}{\partial C_k} = -2C_k \sum_{j=1}^{N}(E_j - \sum_n C_i \cdot A_j^i)A_j^k = 0$$

$$\rightarrow \sum_i \left[\sum_{j=1}^{N} A_j^k A_j^i\right] C_i = \sum_{j=1}^{N} E_j A_j^k \rightarrow$$ **1080 linear** set of equations obtained

- We finally invert the matrix and get the calibration coefficients

$(e\,p \rightarrow e'\,p')$



Cuts Performed

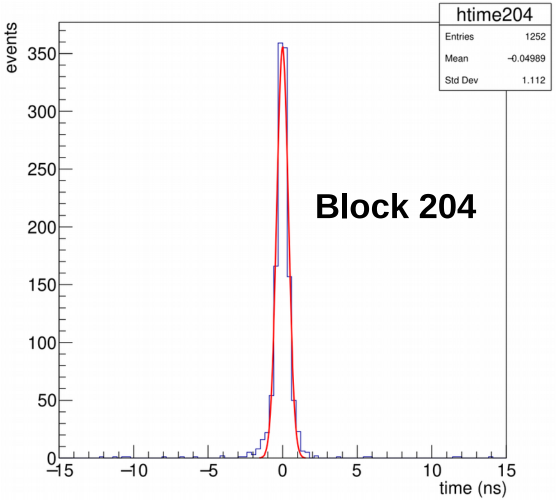
- **Timing cut for each block:**

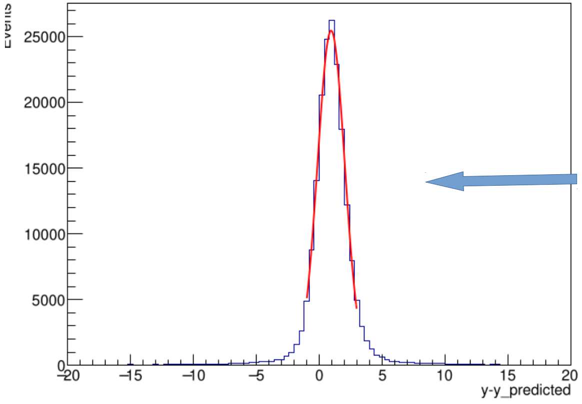
  - We fit the time distribution of each block

  - For each block:

$$|\mathrm{time}[i] + \mathrm{reftime}| < 5 \cdot \mathrm{rmstime}[i]$$

$$|\mathrm{time}[i] - \mathrm{reftime}| < 5 \cdot \mathrm{rmstime}[i]$$





- **X and y positions cut:**

  - We fit the distribution of the stored position minus the predicted position and apply a cut

$$|x_{\mathrm{predicted}} - x + \mathrm{mean}_x| < 4 \cdot \sigma_x$$

$$|y_{\mathrm{predicted}} - y + \mathrm{mean}_y| < 4 \cdot \sigma_y$$

- **Geometrical cuts:**
  - We remove columns/rows and blocks that are off along with their first neighboring columns/rows/blocks

- **Energy cut:**

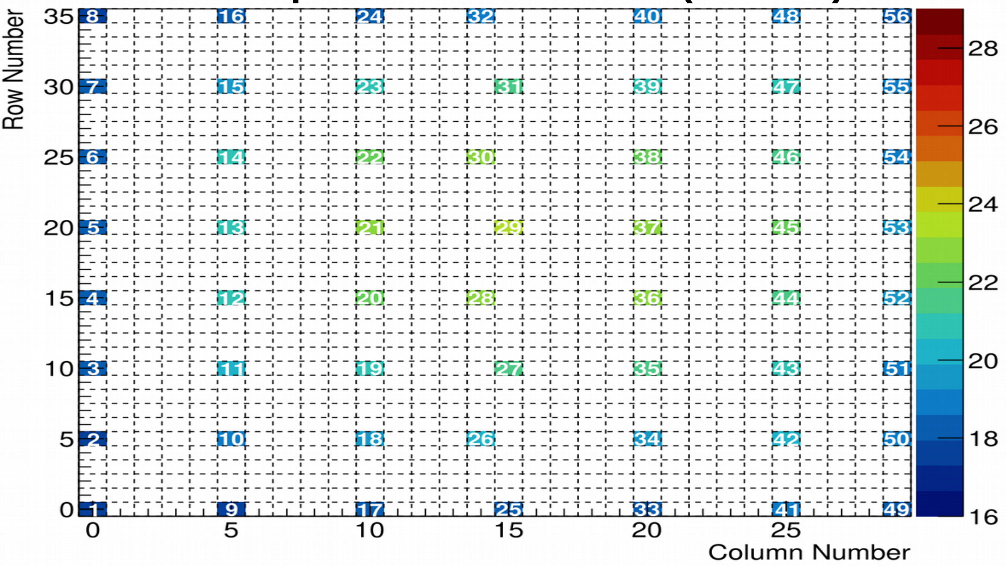
$$(\mathrm{clusener} - E_{\mathrm{th}}) > \mathrm{mean}_{\mathrm{nc}} - 2 \cdot \sigma_{\mathrm{nc}}$$

- **5 iterations were performed until a stability in the resolution was found**

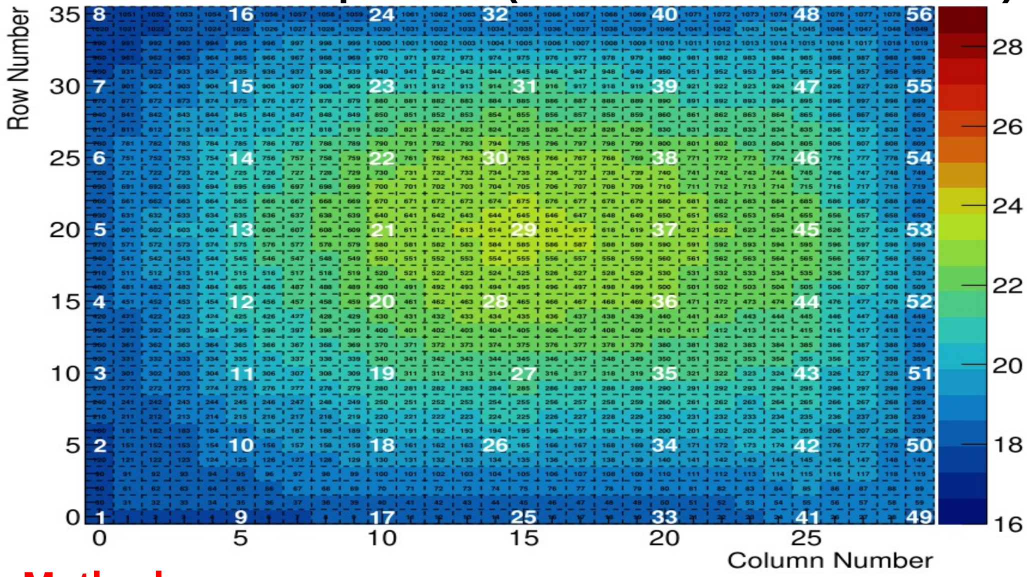
Temperature Interpolation Results

Front Sensors

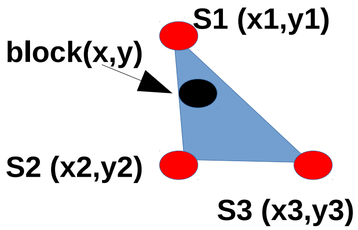
Temperature of Sensors (1 event)



After 2D Interpolation (Back view of the detector)



- **Linear 2D interpolation => Delaunay Triangulation Method**



$$x = \lambda_1 x_1 + \lambda_2 x_2 + \lambda_3 x_3$$

$$y = \lambda_1 y_1 + \lambda_2 y_2 + \lambda_3 y_3$$

$$\lambda_1 = \frac{\text{Area of Triangle}(x, y, x_2, y_2, x_3, y_3)}{\text{Area of Triangle}(x_1, y_1, x_2, y_2, x_3, y_3)}$$

$$\text{Area} = \frac{1}{2}\left|x_1(y_2 - y_3) + x_2(y_3 - y_1) + x_3(y_1 - y_2)\right|$$

$$T(x, y) = \lambda_1 \cdot T_1(x_1, y_1) + \lambda_2 \cdot T_2(x_2, y_2) + \lambda_3 \cdot T_3(x_3, y_3)$$

Interpolated Temperature

Temperature Interpolation Results

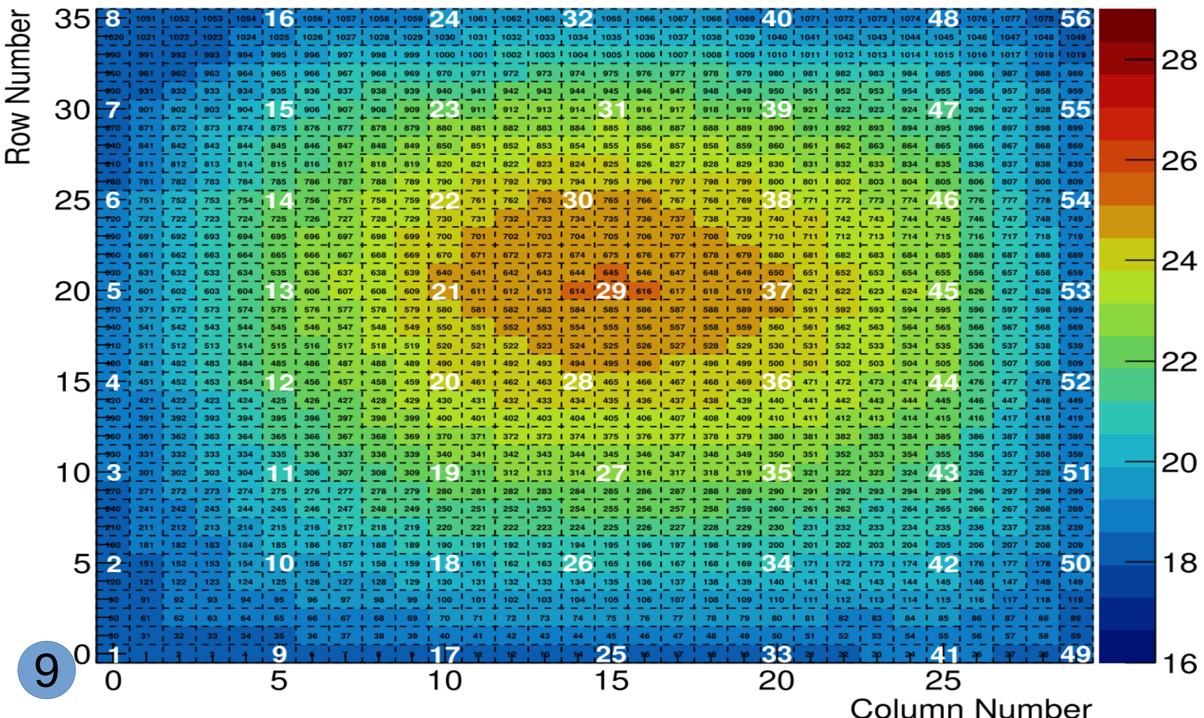
3D Interpolation

- **Added a linear interpolation along the depth of the crystals:**

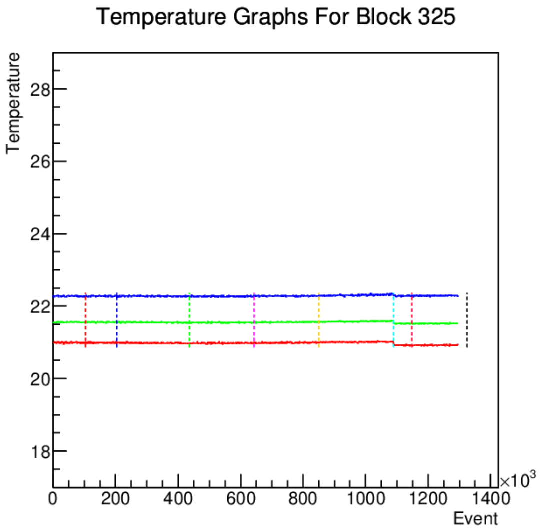
$$T_{\mathrm{middle}}[i] = \frac{(T_{\mathrm{back}}[i] - T_{\mathrm{front}}[i]) \cdot a}{\mathrm{dist\_front\_back}} + T_{\mathrm{front}}[i]$$

- **a = 10 cm (shower depth used in this example)**
- **dist_front_back = 20 cm (depth of the crystal)**

After 3D Interpolation (Back view of the detector)

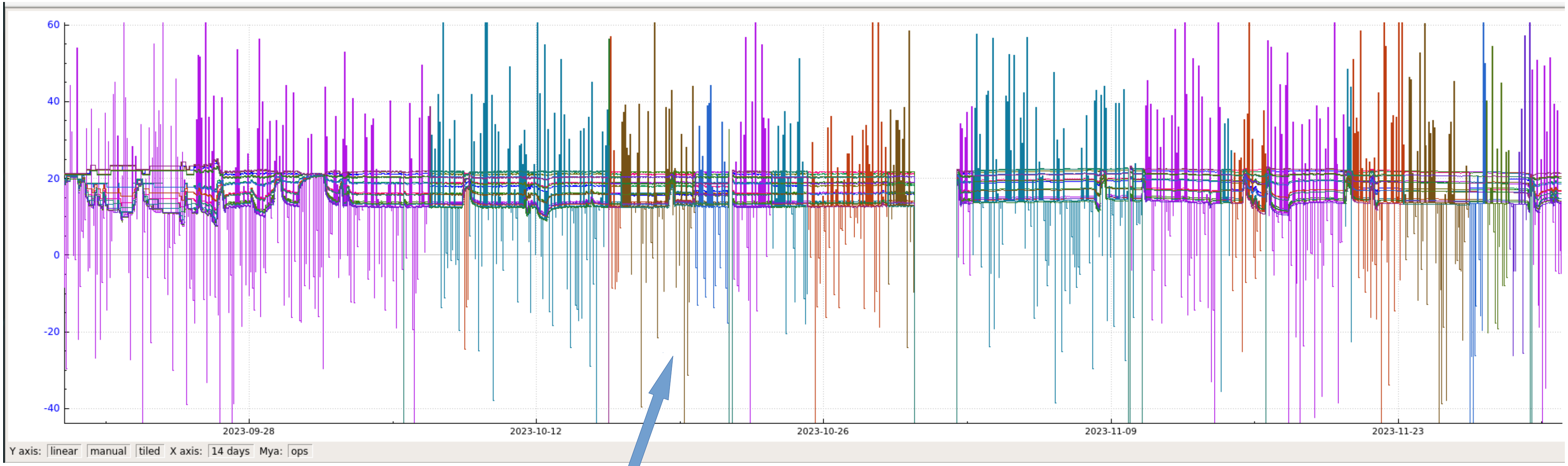


- **Temperature correction for each event was performed and tested**
- **The temperature for most of the elastic settings (9/10) were stable**



Temperature fluctuation problem

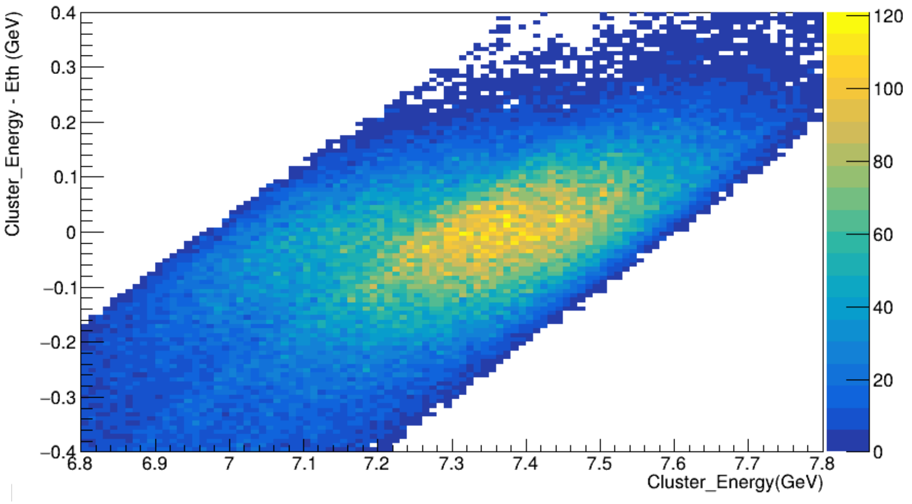
From September to December



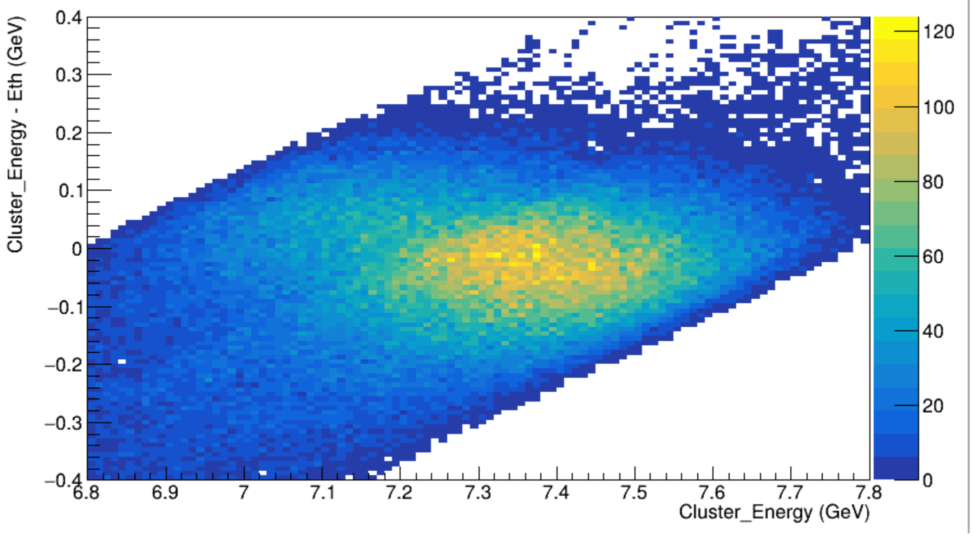
- A lot of fluctuations and jumps in the readout of the temperature sensors

Cluster Energy Threshold Correction

Non corrected



Corrected



- **The fraction of the energy loss in the cluster energy increases with the increase of the pulse threshold used**

- **This is the optimized empirical cut we used to correct for the threshold effect:**

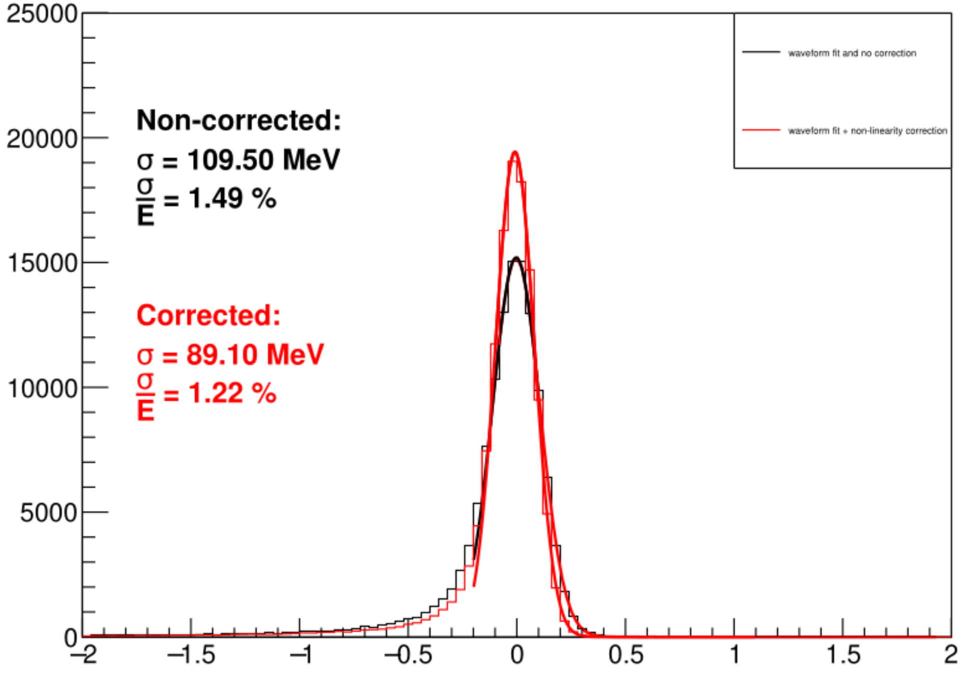
$$\left(\frac{\text{clusener}}{1+0.05\cdot(\text{clusener}-\text{mean}_{\text{energy}})}-E_{\text{th}}\right)>\text{mean}_c-2\cdot\sigma_c$$

With Eth= Ee calculated from the HMS information of the proton

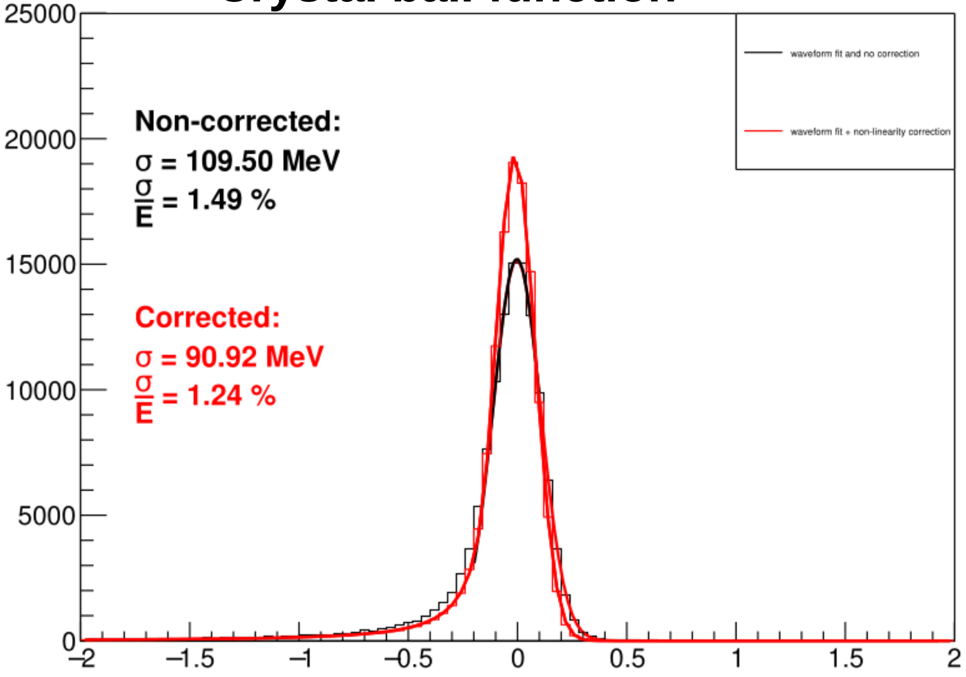
Energy Resolution

- These are the results for the setting 2855-2871 (one of the best in terms of resolution)
- The temperature for this setting was stable
- 5 iterations during the minimization was performed

Gaussian fit



Crystal ball function



Energy Resolution

Individual settings results (optimal cuts per setting)

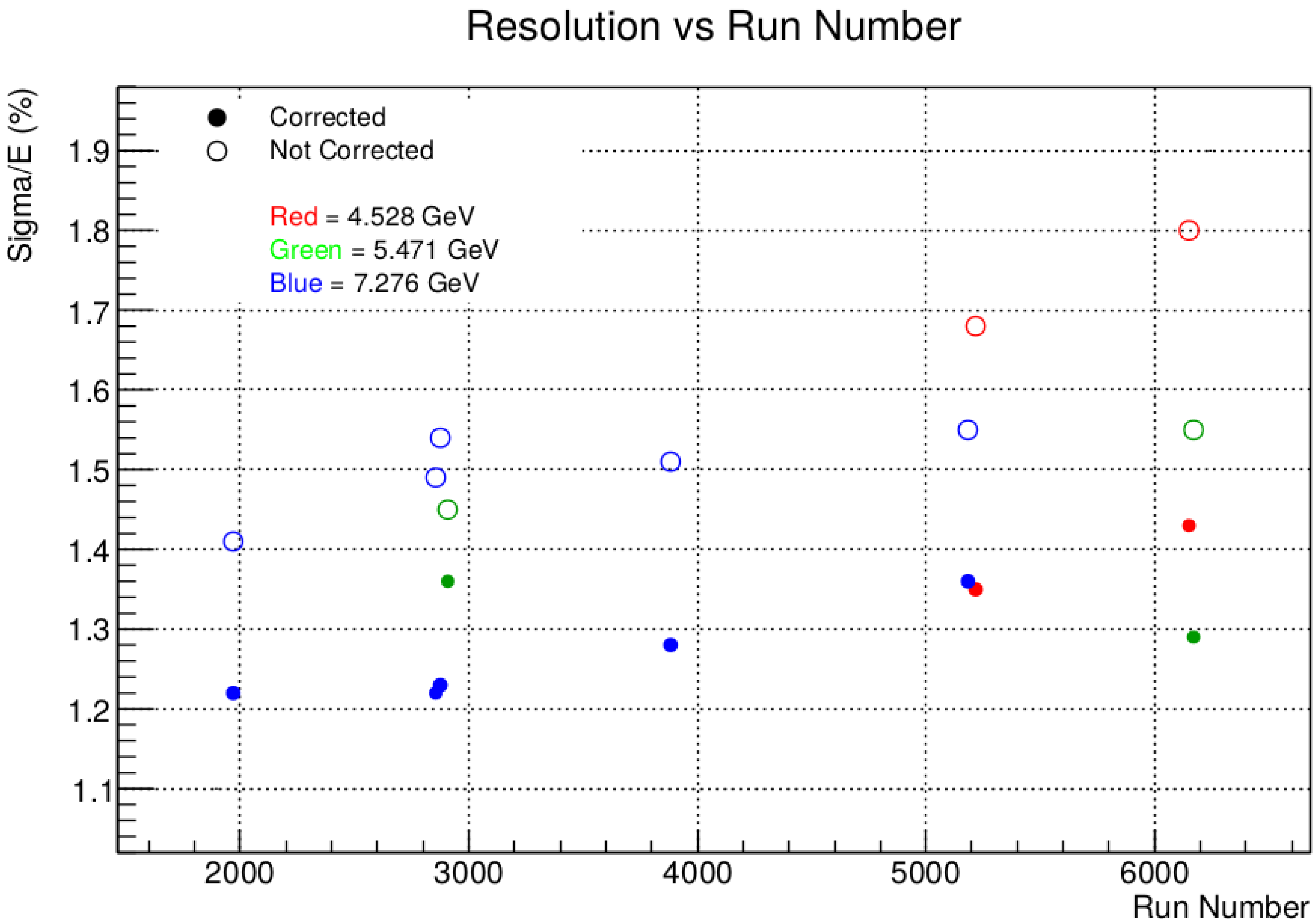
Setting	C.Factor	HMS Momentum	Theoretical Ee (GeV)	σ_{NC} (Step5)	$(\sigma/E)_{NC}$ (Step5)	σ_C (Step5)	$(\sigma/E)_C$ (Step5)
6151/6168	0.11	2.622	4.507	$81.06\pm1.92\times10^{-4}$	1.79	$57.670 \pm 1.11 \times10^{-4}$	1.27
5217/5236	0.11	2.620	4.507	$76.90\pm2.31\times10^{-4}$	1.70	$56.30\pm1.31\times10^{-4}$	1.24
6171/6183	0.05	3.578	5.660	$86.22\pm5.65\times10^{-4}$	1.51	$71.59 \pm 5.22 \times10^{-4}$	1.25
2907/2920	0.045	4.072	5.170	$80.88\pm2.02\times10^{-3}$	1.53	$68.42\pm1.52\times10^{-4}$	1.29
1969/1982	0.05	4.059	7.284	$104.17\pm5.20\times10^{-4}$	1.42	$89.15\pm4.91\times10^{-4}$	1.22
2855/2871	0.05	4.048	7.292	$110.85\pm4.67\times10^{-4}$	1.50	$88.85\pm3.07\times10^{-4}$	1.21
2875/2885	0.05	4.050	7.284	$113.38\pm7.01\times10^{-4}$	1.54	$88.22\pm5.90\times10^{-4}$	1.20
3883/3898	0.05	4.054	7.293	$110.25\pm6.23\times10^{-4}$	1.51	$92.93\pm4.54\times10^{-4}$	1.27
5183/5208	0.045	4.310	7.066	$109\pm7.59\times10^{-4}$	1.54	$94.96\pm5.66\times10^{-4}$	1.33

1.20% resolution!!

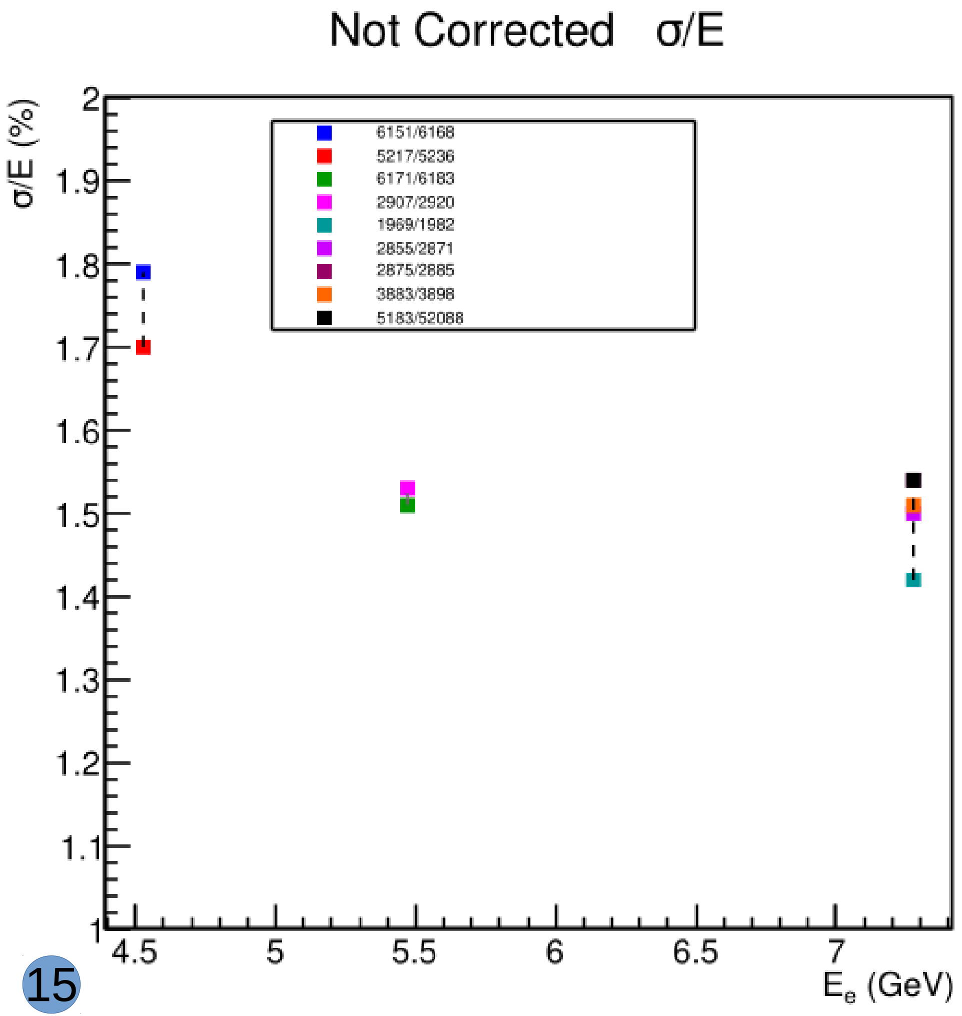
Common cuts used for comparison

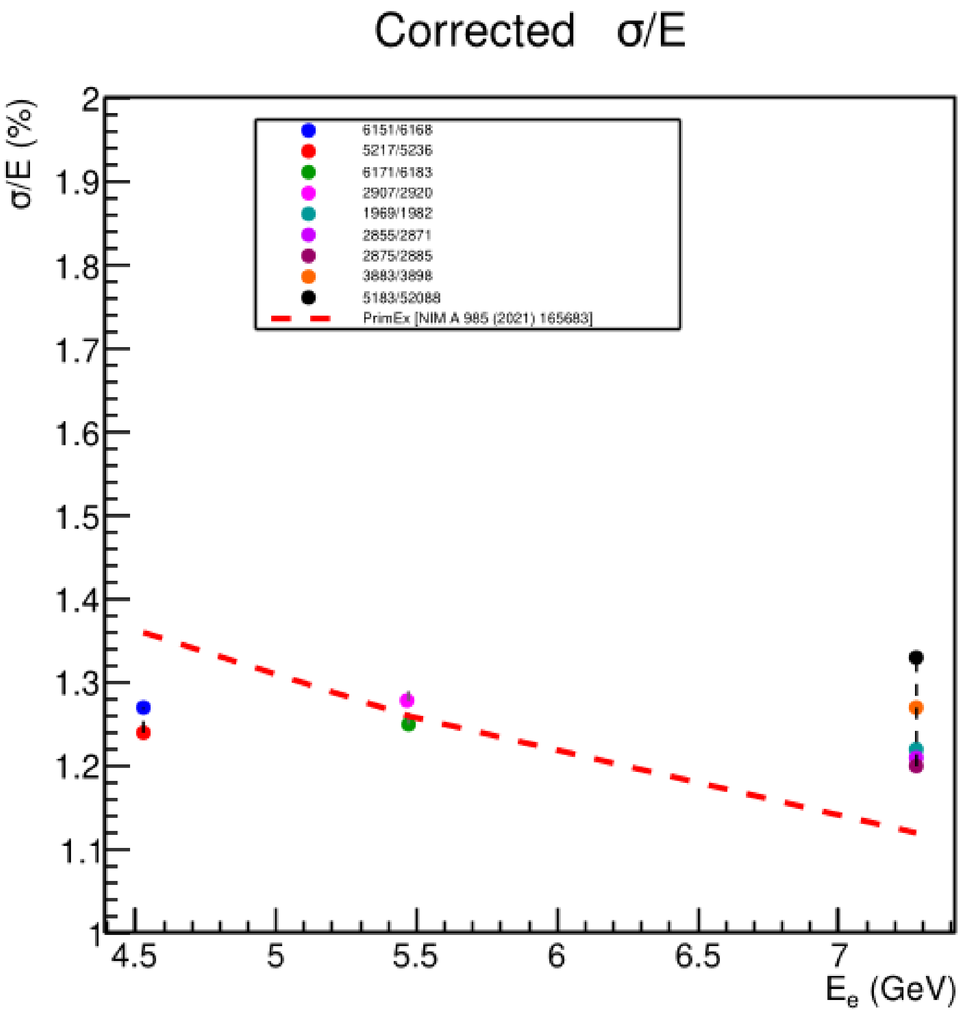
Setting	σ_{NC} (Step5)	$(\sigma/E)_{NC}$ (Step5)	σ_C (Step5)	$(\sigma/E)_C$ (Step5)
6151/6168	$81.31\pm2.13\times10^{-4}$	1.80	$64.71 \pm 1.48 \times10^{-4}$	1.43
5217/5236	$76.26\pm2.25\times10^{-4}$	1.68	$61.22\pm1.58\times10^{-4}$	1.35
6171/6183	$88.21\pm6.68\times10^{-4}$	1.55	$73.88 \pm 6.53 \times10^{-4}$	1.29
2907/2920	$78.20\pm3.64\times10^{-4}$	1.45	$70.04\pm3.11\times10^{-4}$	1.36
1969/1982	$102.30\pm6.5\times10^{-4}$	1.41	$88.56\pm4.84\times10^{-4}$	1.22
2855/2871	$109.5\pm4.73\times10^{-4}$	1.49	$89.10\pm3.21\times10^{-4}$	1.22
2875/2885	$113.45\pm6.95\times10^{-4}$	1.54	$90.09\pm6.11\times10^{-4}$	1.23
3883/3898	$110.68\pm6.05\times10^{-4}$	1.51	$93.29\pm4.43\times10^{-4}$	1.28
5183/5208	$110.40\pm8.02\times10^{-4}$	1.55	$96.79\pm5.98\times10^{-4}$	1.36

Energy Resolution



Energy Resolution

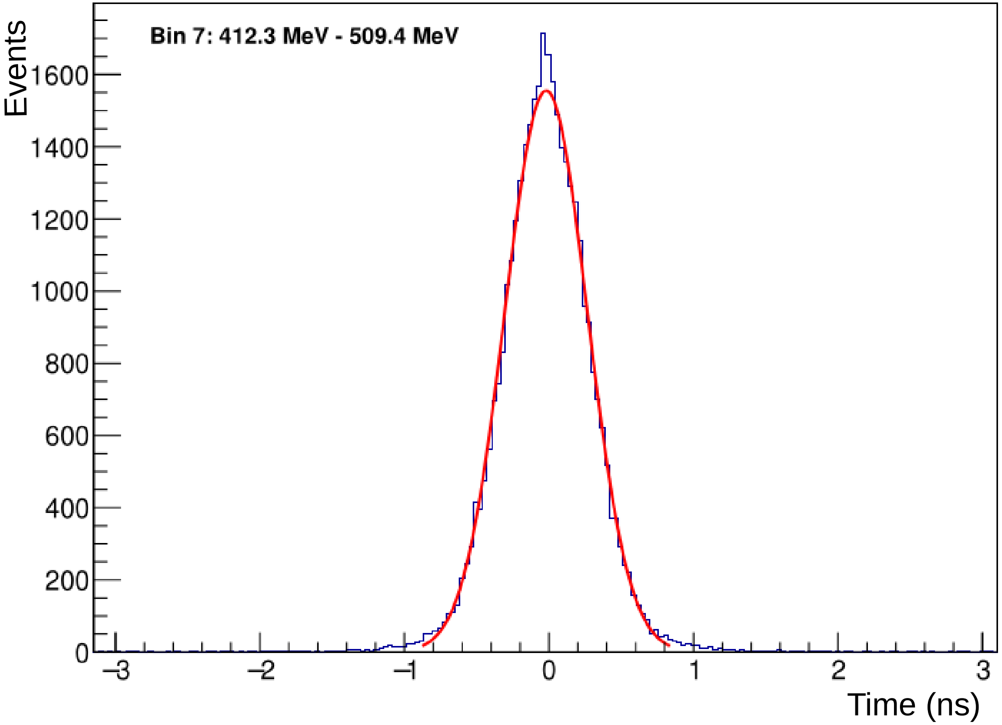




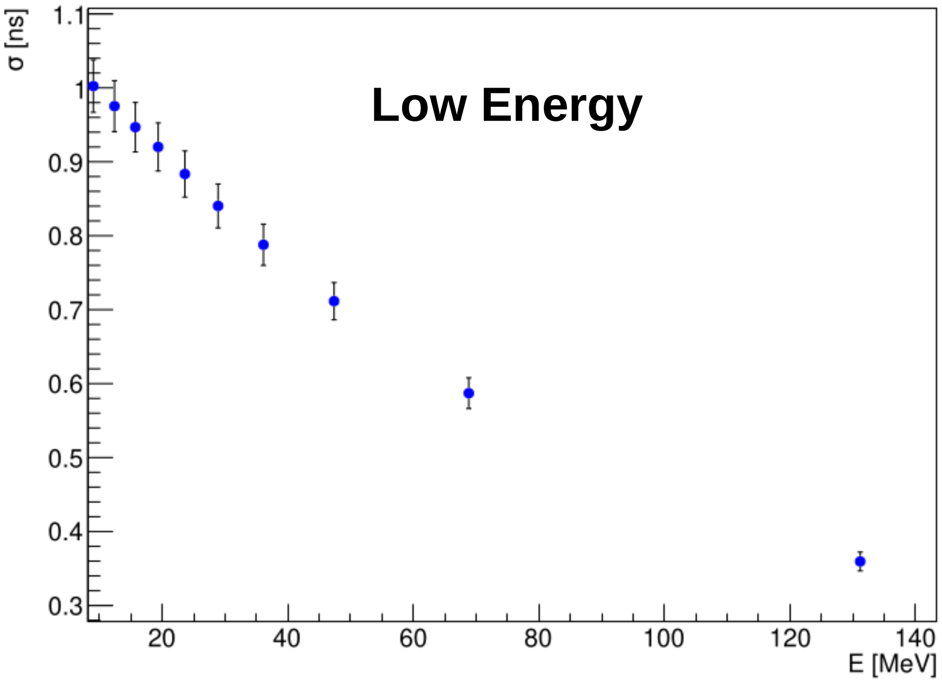
Time Resolution

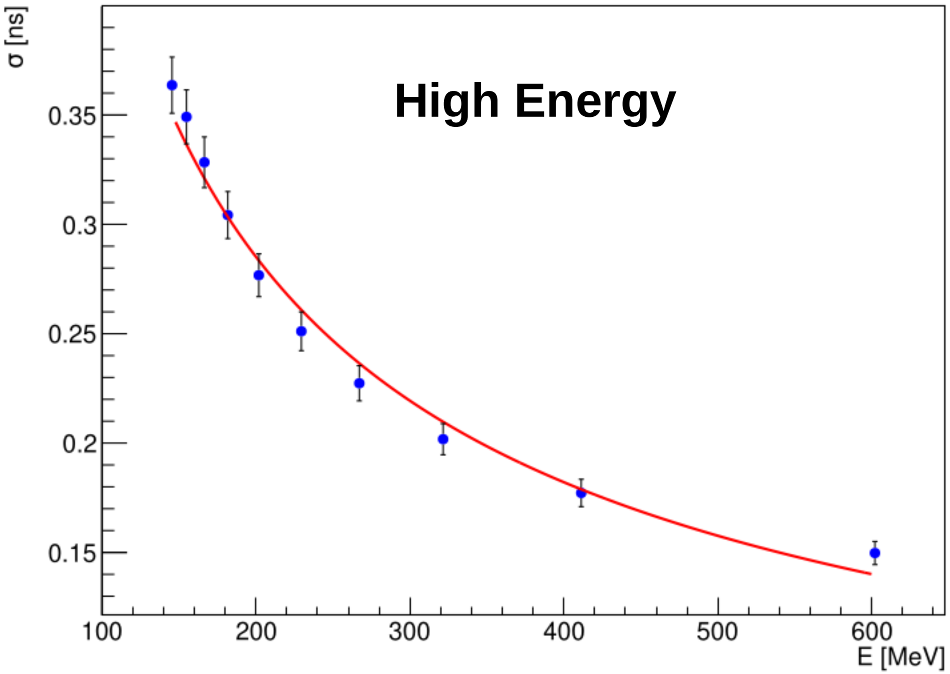
Method:

- **Goal : determine the intrinsic time resolution of a single calorimeter block using the elastic data**
- **Choose multiple intervals of energies with the same statistics**
- **Computed the time difference between every pair of blocks belonging to the same cluster and the same energy interval**
- **Applied a fit to the histograms to get the values of sigma**



Time Resolution





- **These are the intrinsic time resolution results. The sigma values obtained from the fit of the time distributions are divided by the square root of 2.**
- **The resolution is always less than 1 ns no matter the energy and obeys the following power law at high energies:**

$$\sigma(E) = 8.79 \cdot E^{-0.647}$$

Conclusion

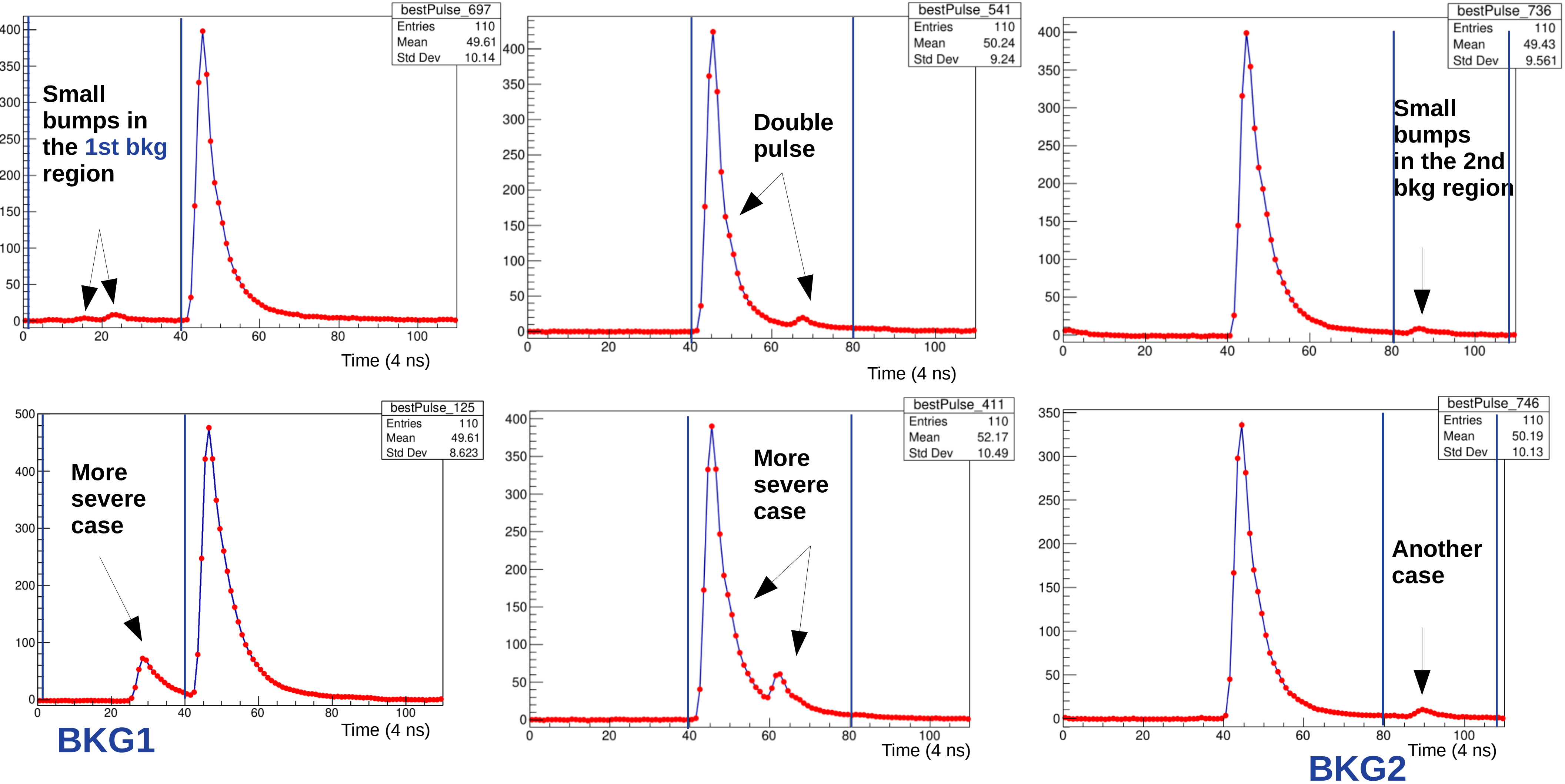
- The NPS temperature was very stable during elastic runs, but a correction might be needed for production runs (which will be very challenging to implement)
- Energy Resolution that ranges from 1.2% to 1.3% for all the settings which goes along with the Primex prototype results
- Less than 1ns time resolution for all the energies with the following power law for high energies:

$$\sigma(E) = 8.79 \cdot E^{-0.647}$$

Backup

Reference Shape Selection

Problems:



- **For the missing 1%:**

+ Had to use some severe conditions for few blocs (1 ascending sample) to get rid of the small bumps

+ Display the 10% highest amplitude waveforms and chose the best one even if it's not the highest amplitude one (- 50 mV at most from the highest waveform)

+ Removed background conditions on some of them since they are so noisy

+ Removed all the pulse conditions and left the major constraints on the time and amplitude which brought a higher and more stable pulse shape

=> Now we have the best reference shapes for one setting

=> Same procedure was done for 10 settings

=> More than 10000 reference shapes in pocket!

Solutions:

- **BKG1+BKG2:**

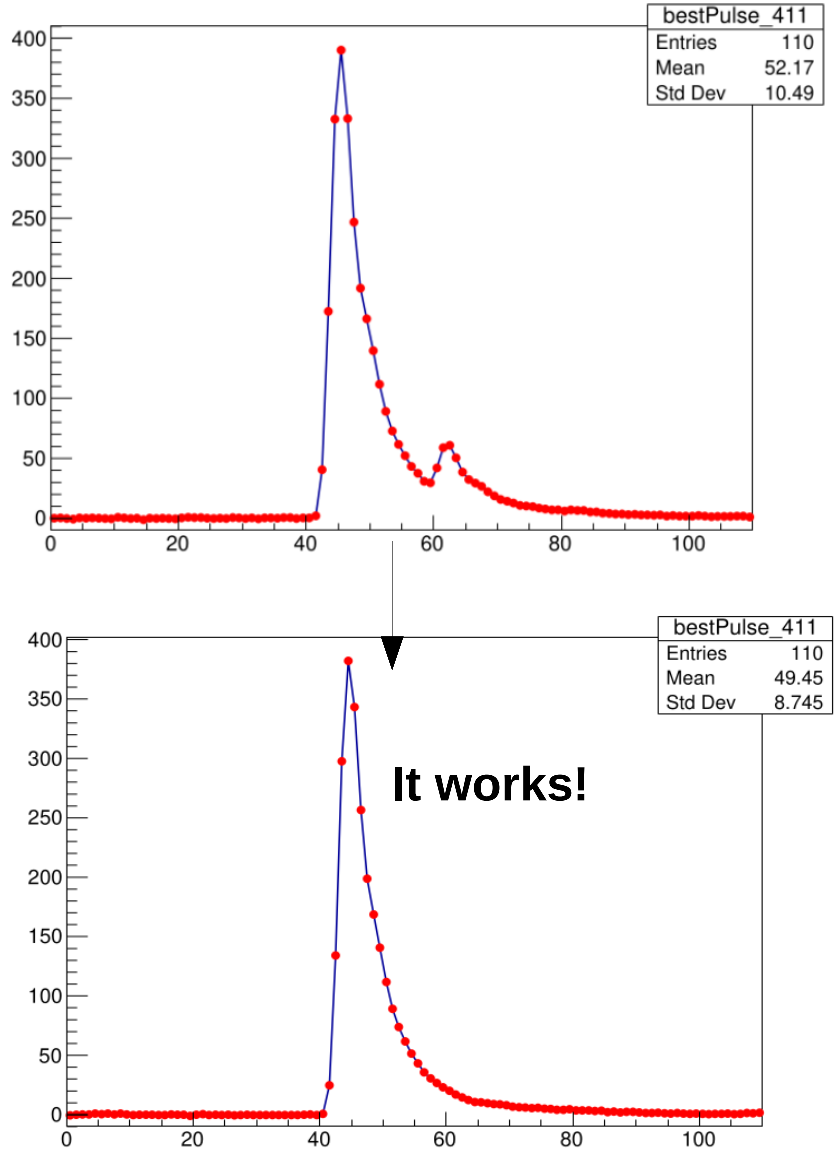
+ A maximum of 2 consecutive ascending samples

- **Pulse region:**

+ A maximum of 3 ascending consecutive samples in the region between the peak sample and the 80th sample

=> 99% of the pulses were in a perfect shape (checked every one of them!)

=> We need that 1% too!!



Reference Shape Check

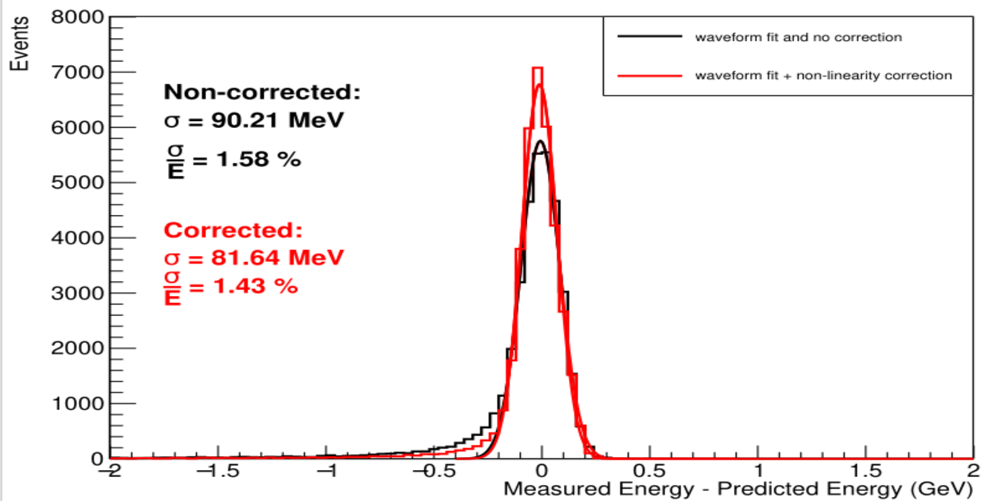
- **Analyzed elastic runs: 6172 to 6179**
- **Mean energy of electrons: 5.7 GeV**
- **HMS central Momentum: 3.1615**

- Expected resolution: $\sigma/E = \frac{2.4\%}{\sqrt{E}} \oplus 1\%$

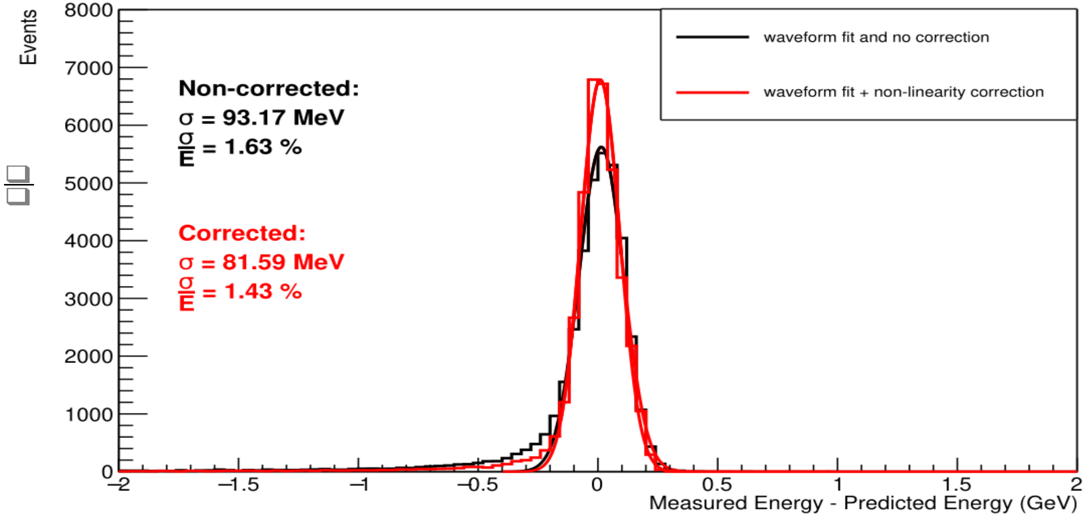
From literature for the case of PW04

From the first setting analyzed by Malek

Samples Logic Method



Mean of All Waveforms Method

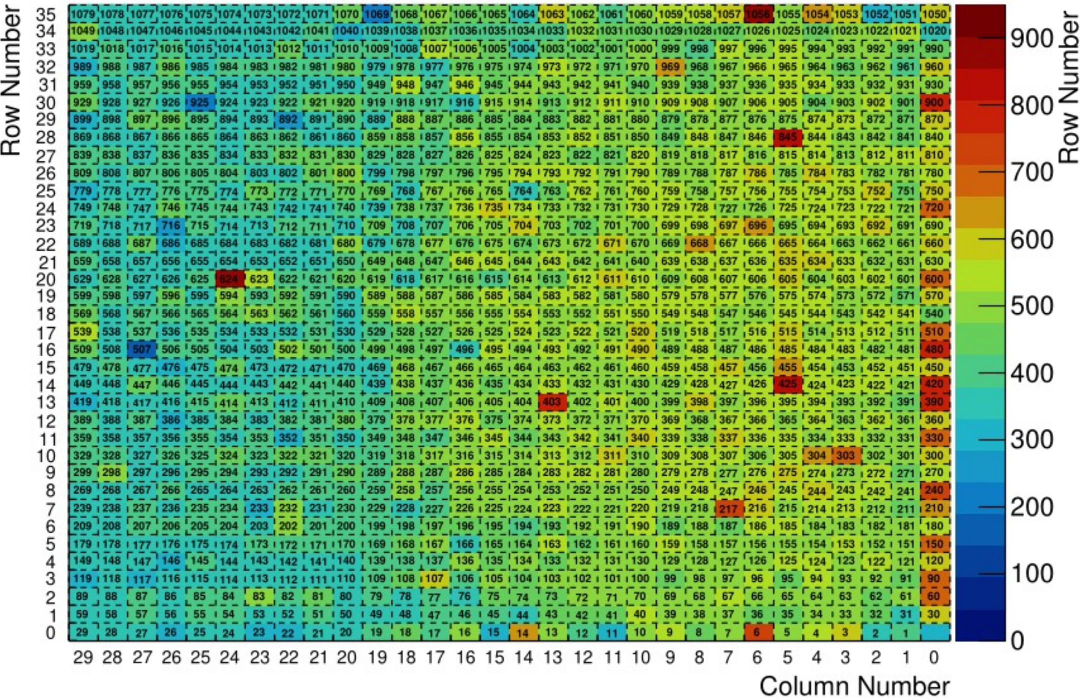


- **Found the expected energy resolution for this setting**
- **Almost the same energy resolution using both methods**

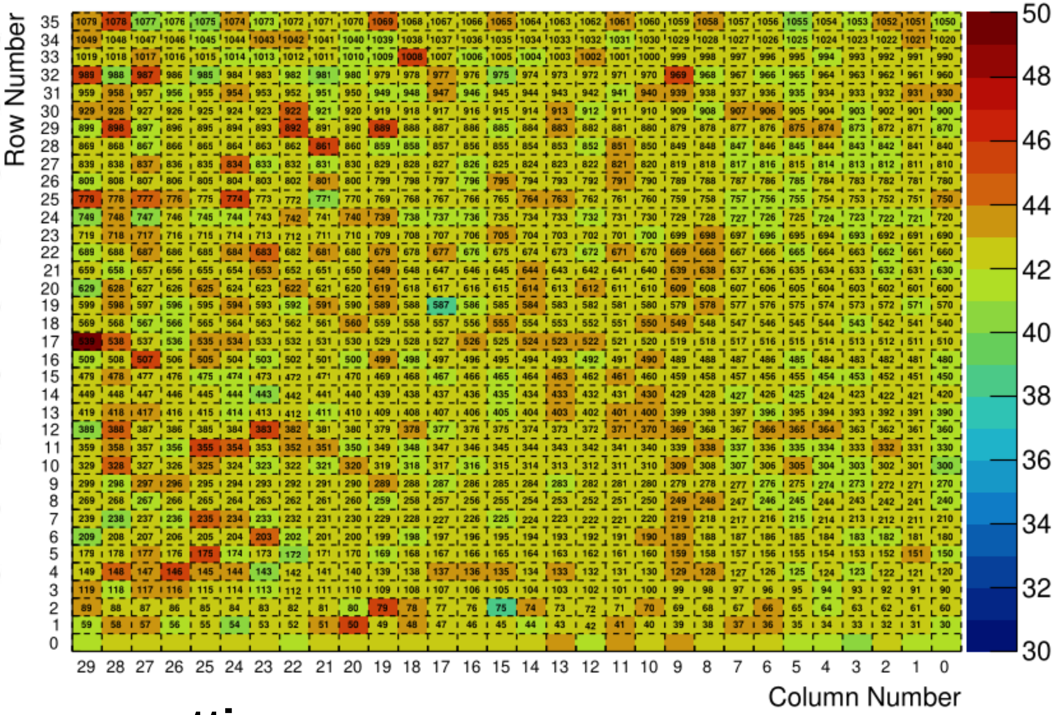
RESULTS

Runs: 1423/1511

Pulse Peak Amplitude — **Ee = 7.072 GeV**



Time of the 1st sample > threshold



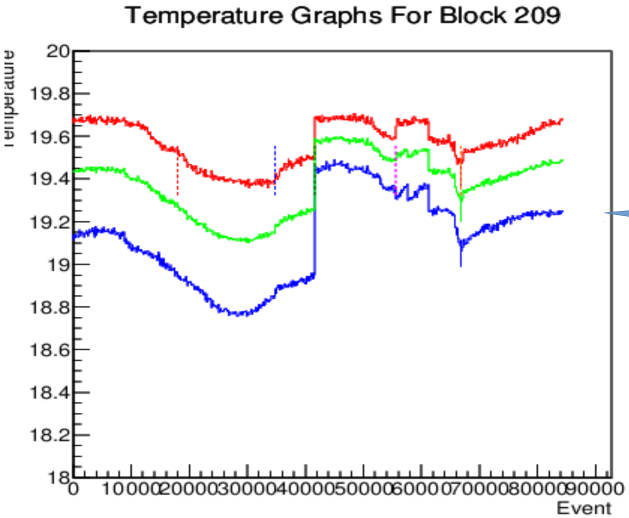
=> Now we have the best reference shapes for one setting

=> Same procedure was done for 10 settings

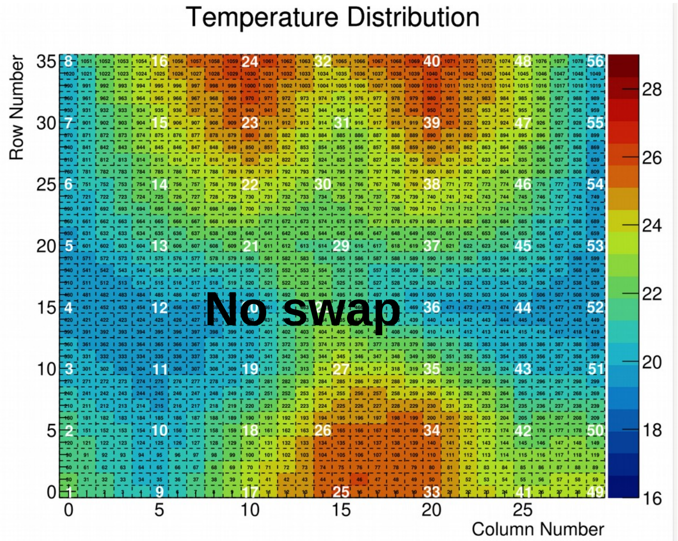
=> More than 10000 reference shapes in pocket!

Note: You can check all the plots for all the other settings in the back up slides

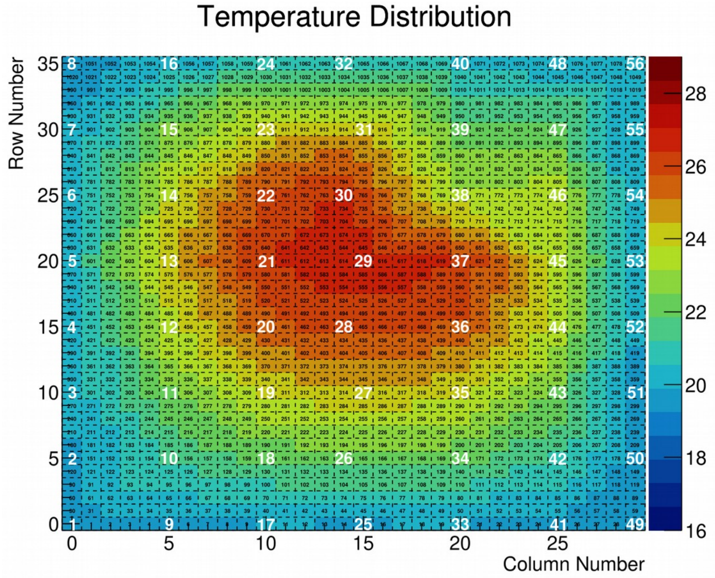
Temperature Sensors Readout problem



First sensor's temperature was stored in the second sensor and so on for the others



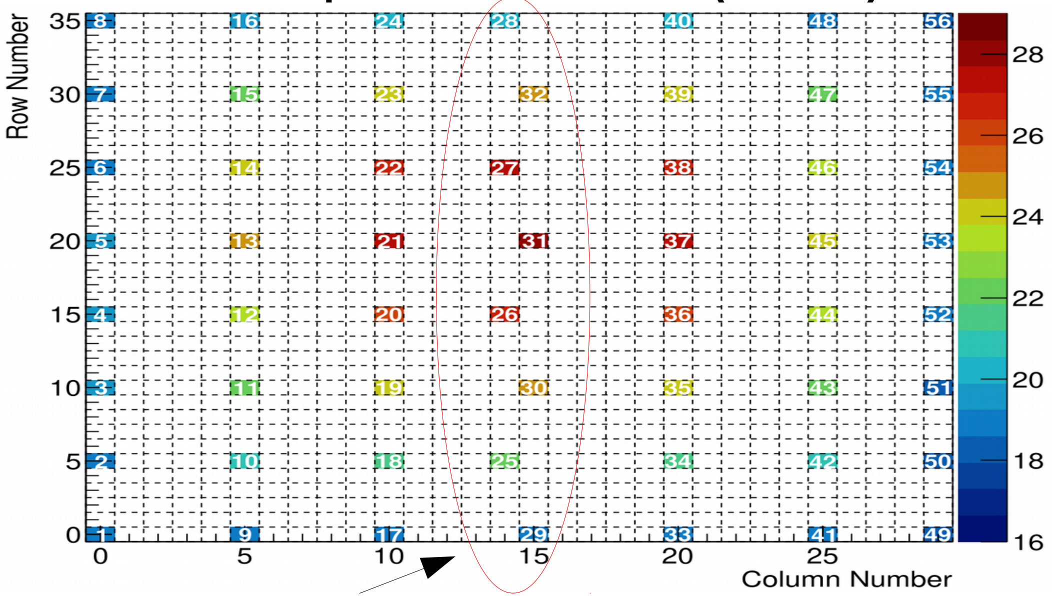
3 swaps => Solved



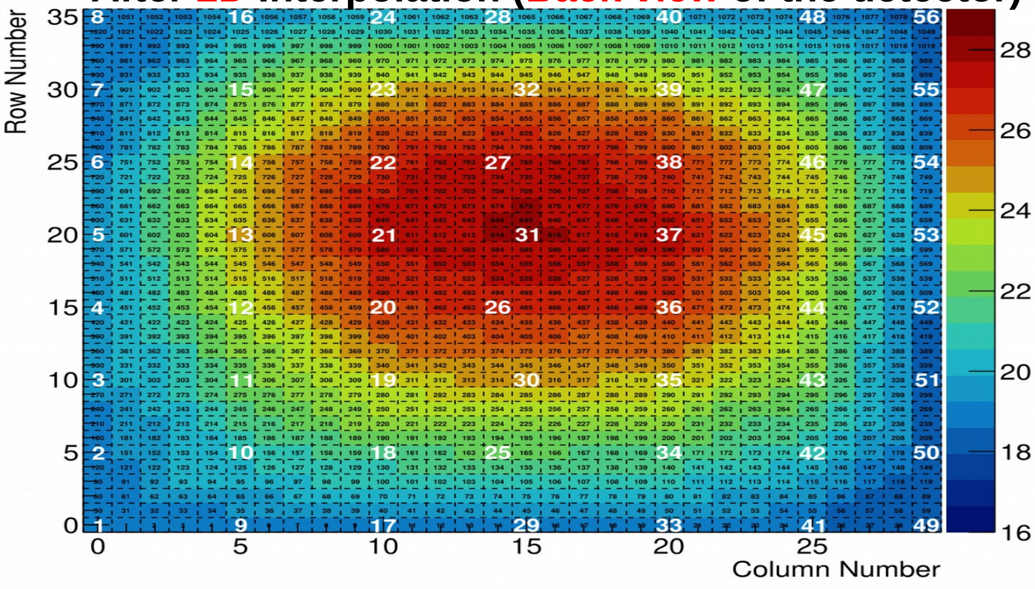
Temperature Interpolation Results

Back Sensors

Temperature of Sensors (1 event)



After 2D Interpolation (Back view of the detector)



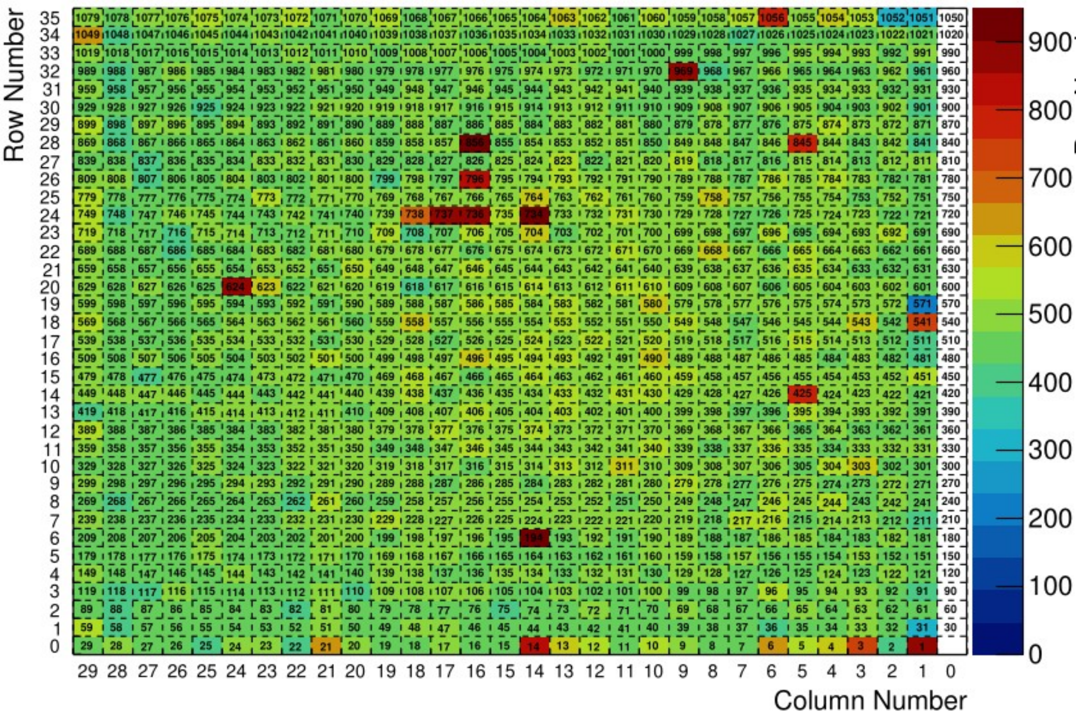
Swap in the map (first problem found)

RESULTS

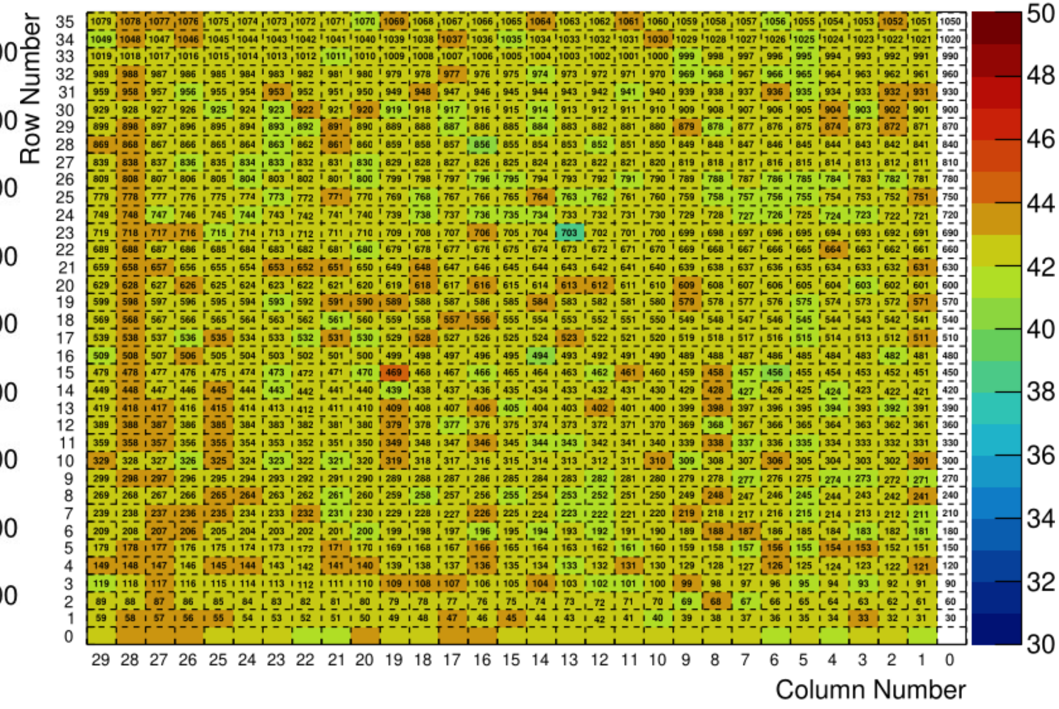
Runs: 1969/1982

Pulse Peak Amplitude

Ee = 7.072 GeV



Time of the 1st sample > threshold

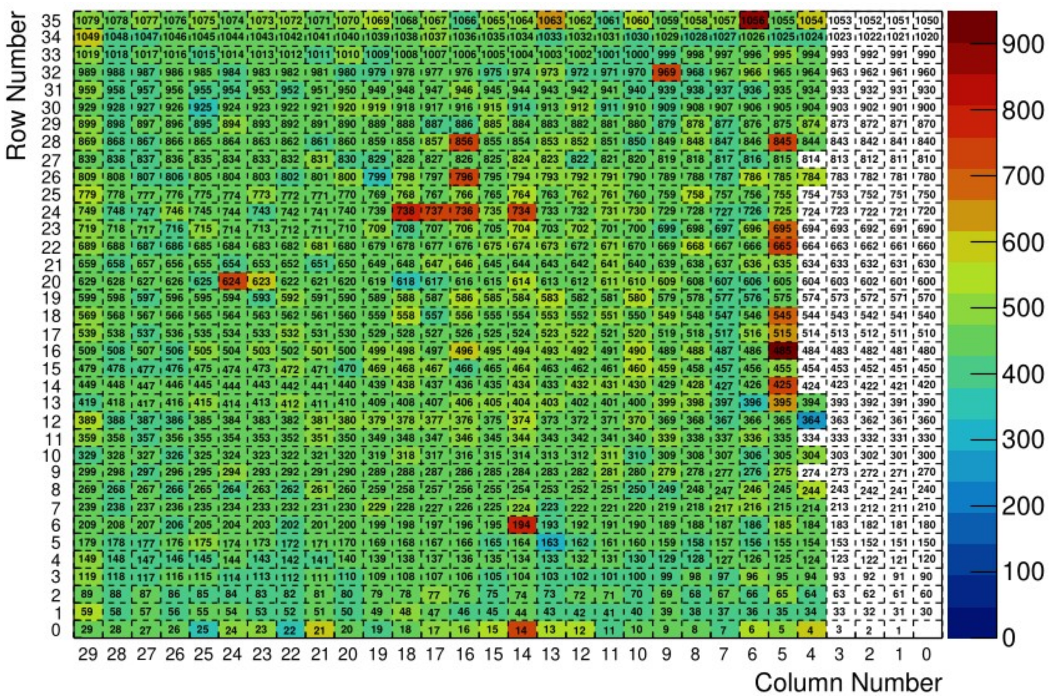


RESULTS

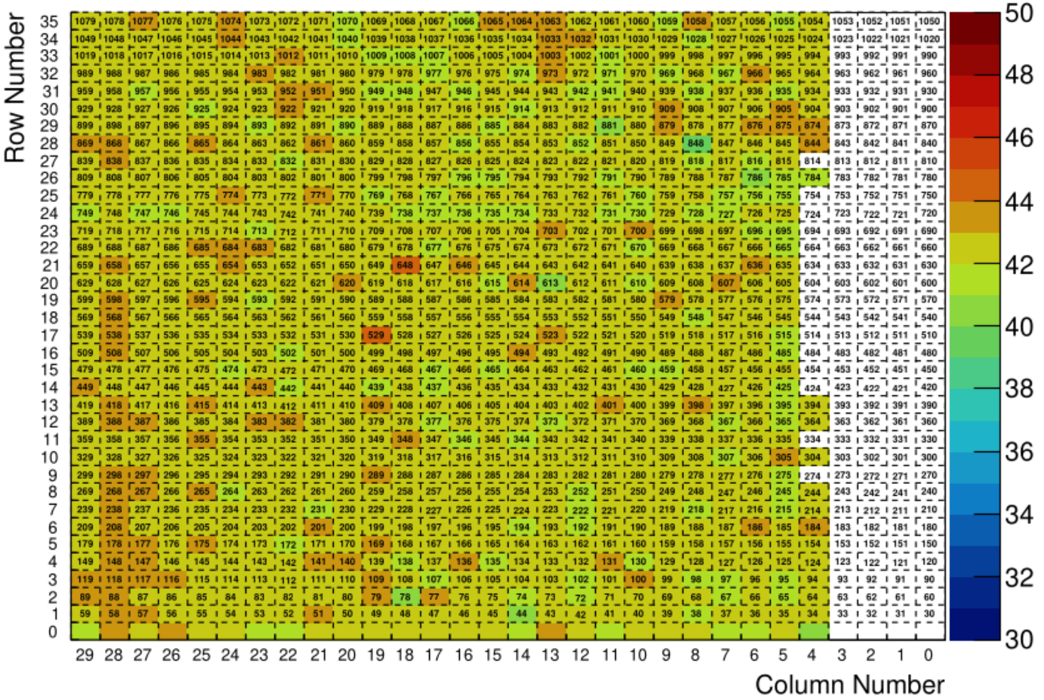
Runs: 2855/2871

Pulse Peak Amplitude

Ee = 7.072 GeV



Time of the 1st sample > threshold

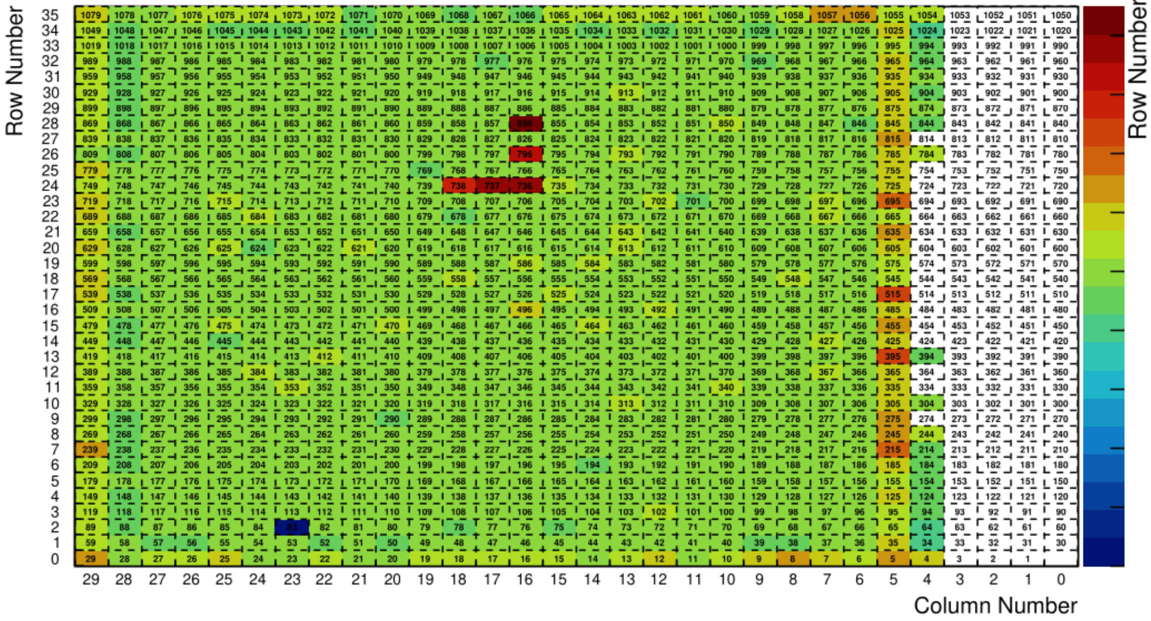


RESULTS

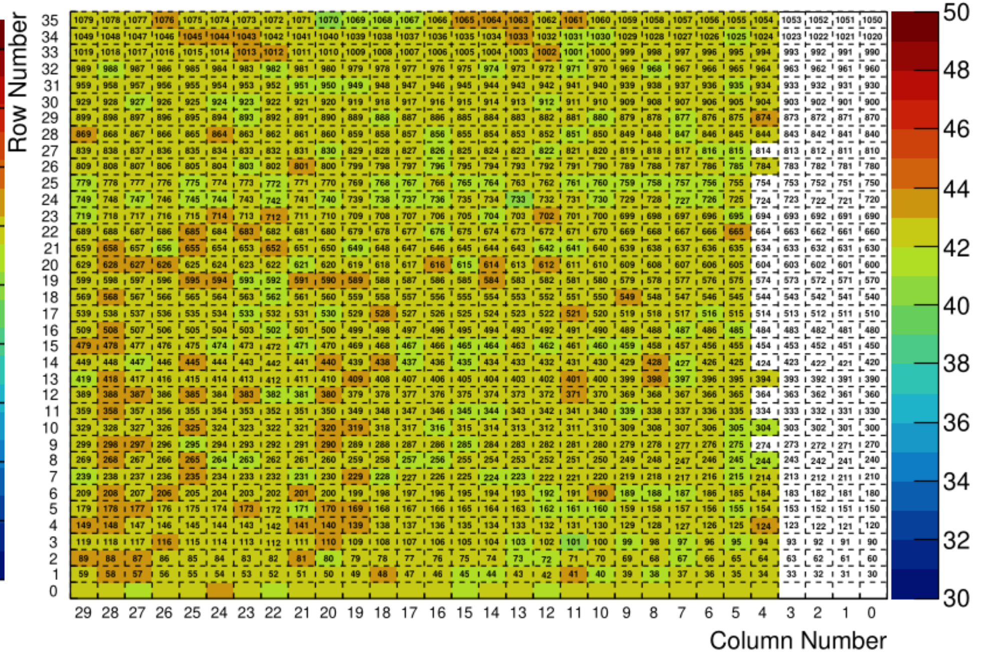
Runs: 2875/2885

Pulse Peak Amplitude

Ee = 7.072 GeV



Time of the 1st sample > threshold



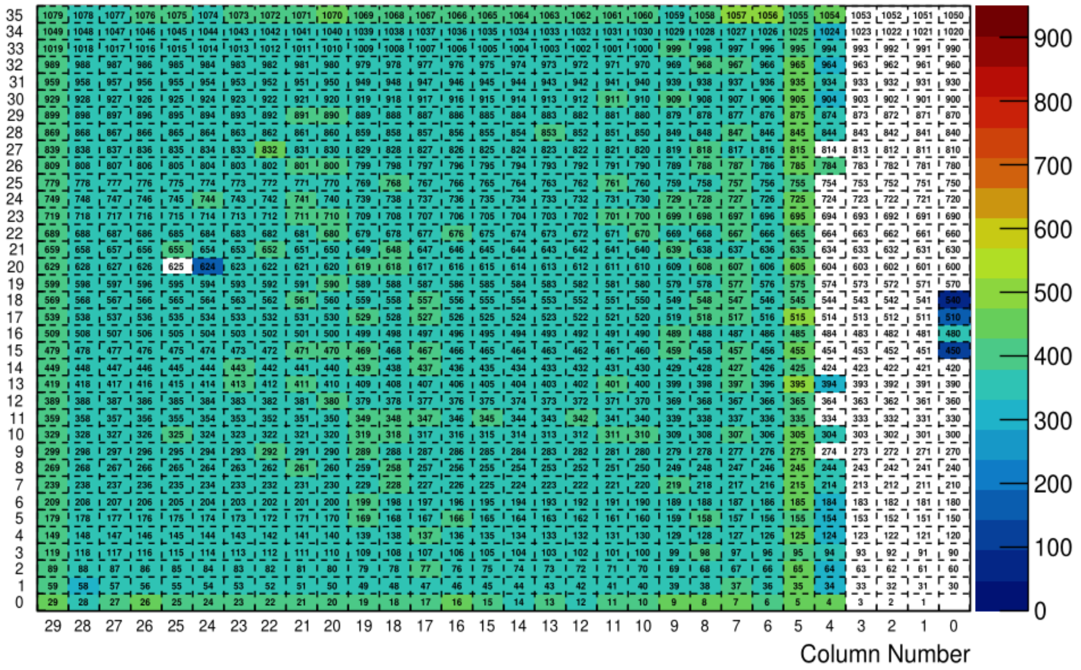
+ A low amplitude for Block 83

RESULTS

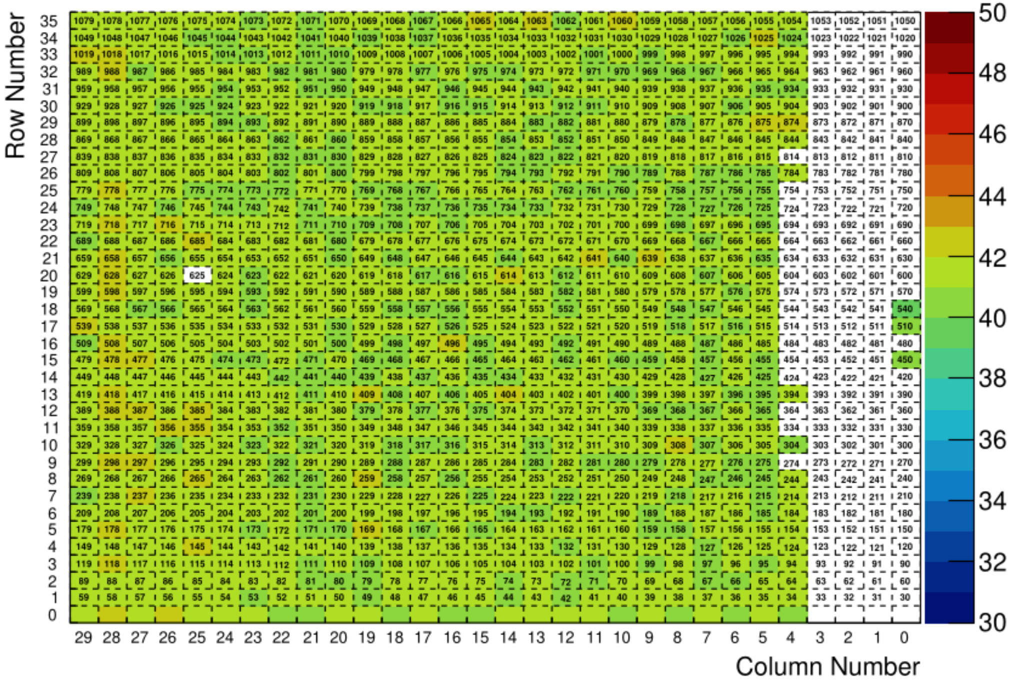
Runs: 2900/2920

Ee = 5.681 GeV

Pulse Peak Amplitude



Time of the 1st sample > threshold



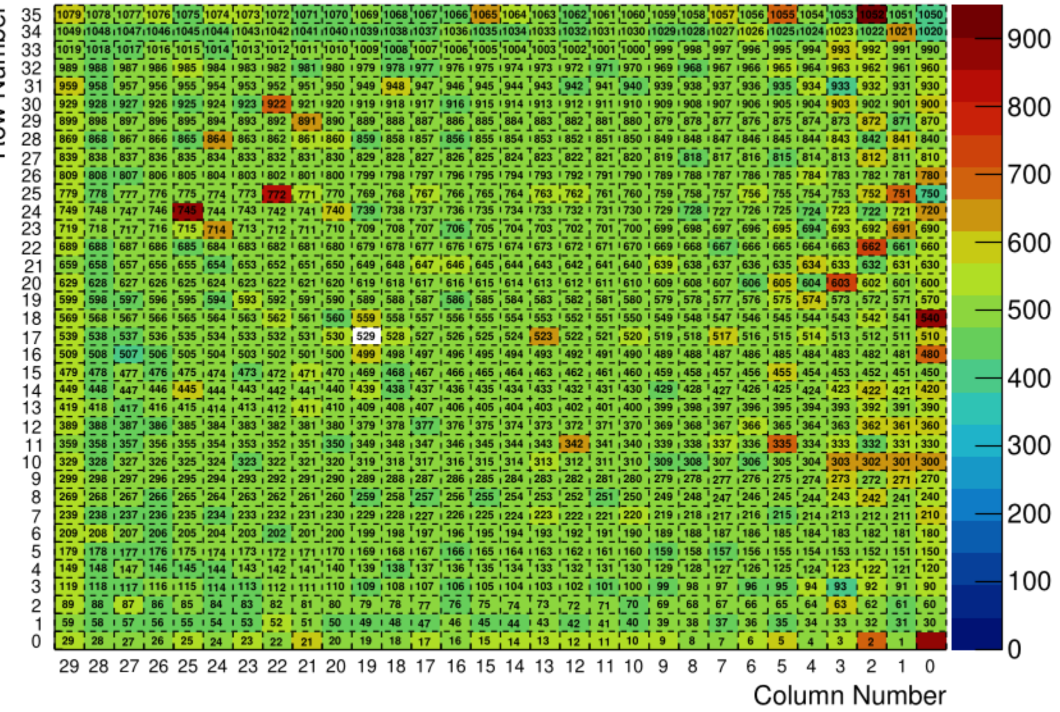
+ Block 625 missing!!
+ A low amplitude for Block 624

RESULTS

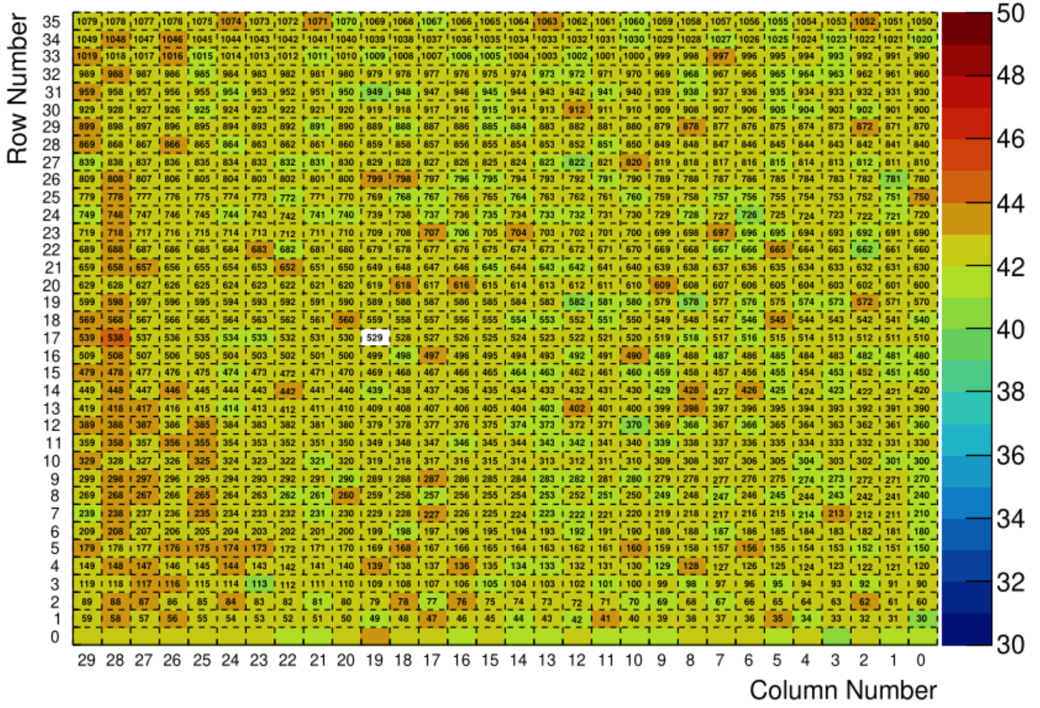
Runs: 3883/3898

Pulse Peak Amplitude

Ee = 7.072 GeV



Time of the 1st sample > threshold



Block 529 missing!!

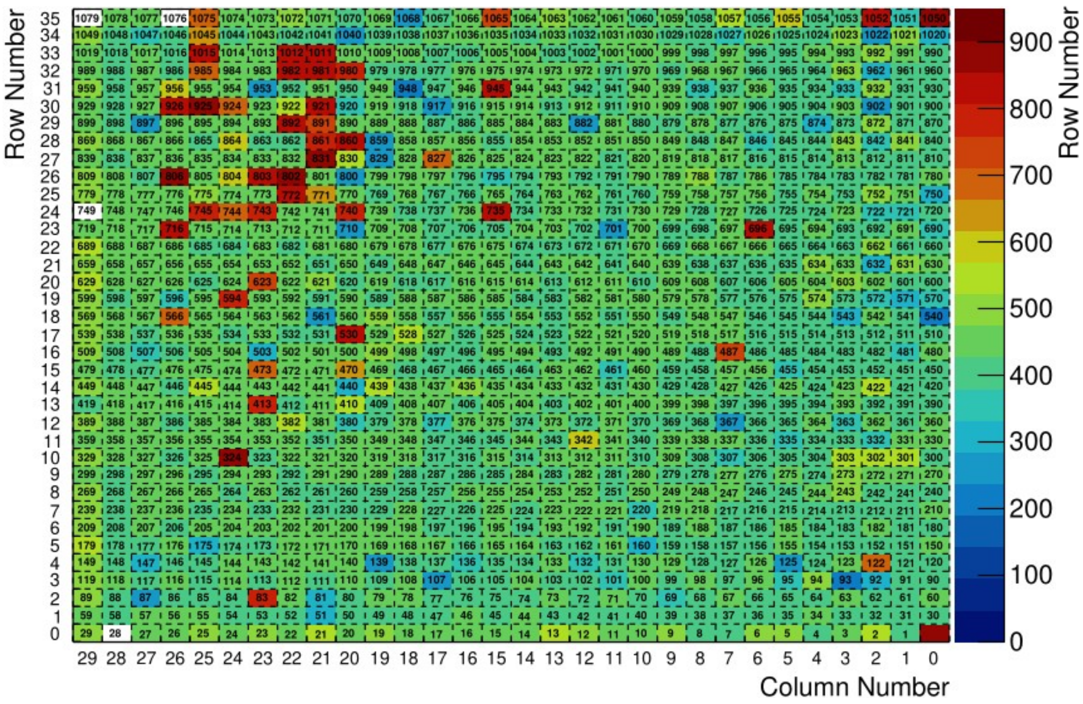
RESULTS

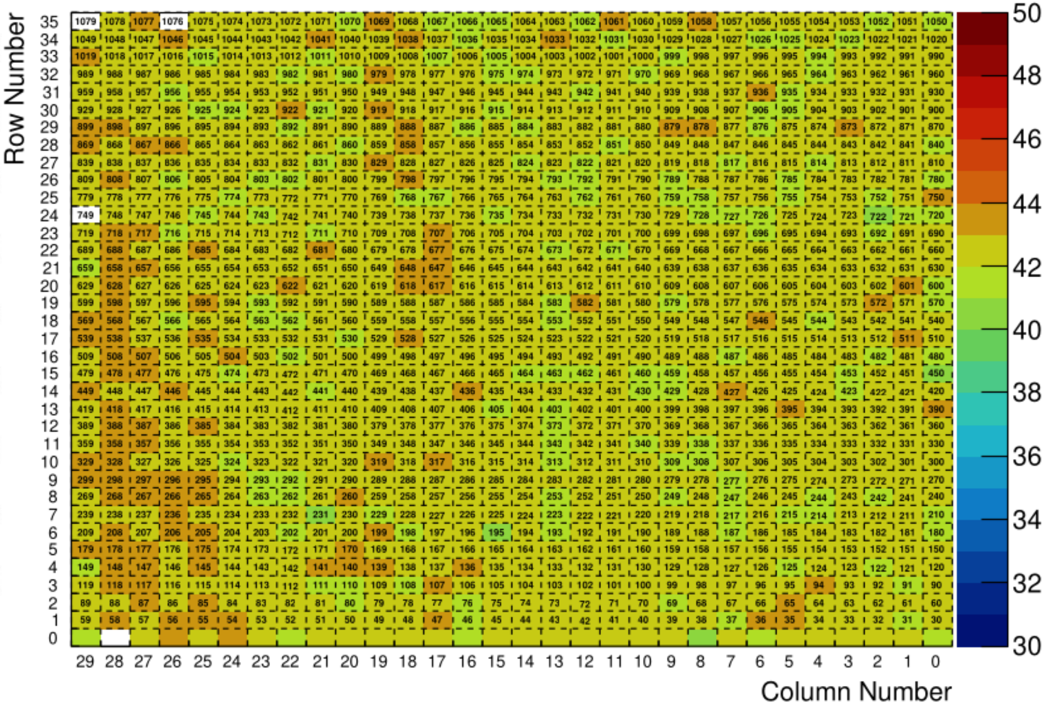
Runs: 5183/5208

Pulse Peak Amplitude

Ee = 7.072 GeV

Time of the 1st sample > threshold





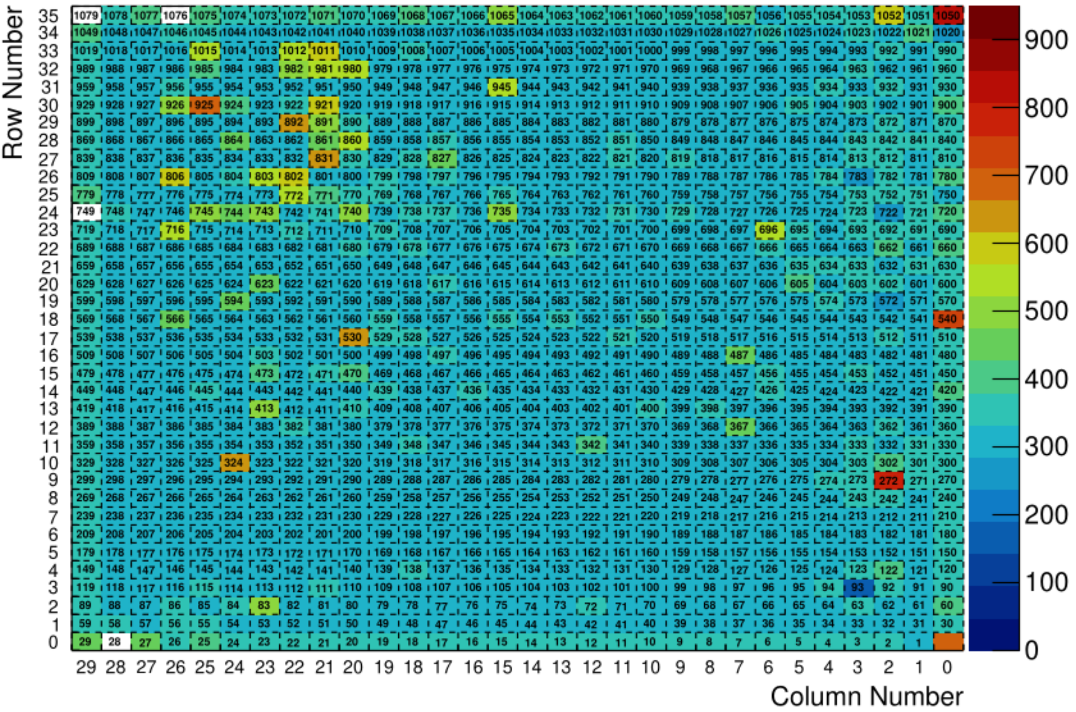
+ 4 dead blocks!

RESULTS

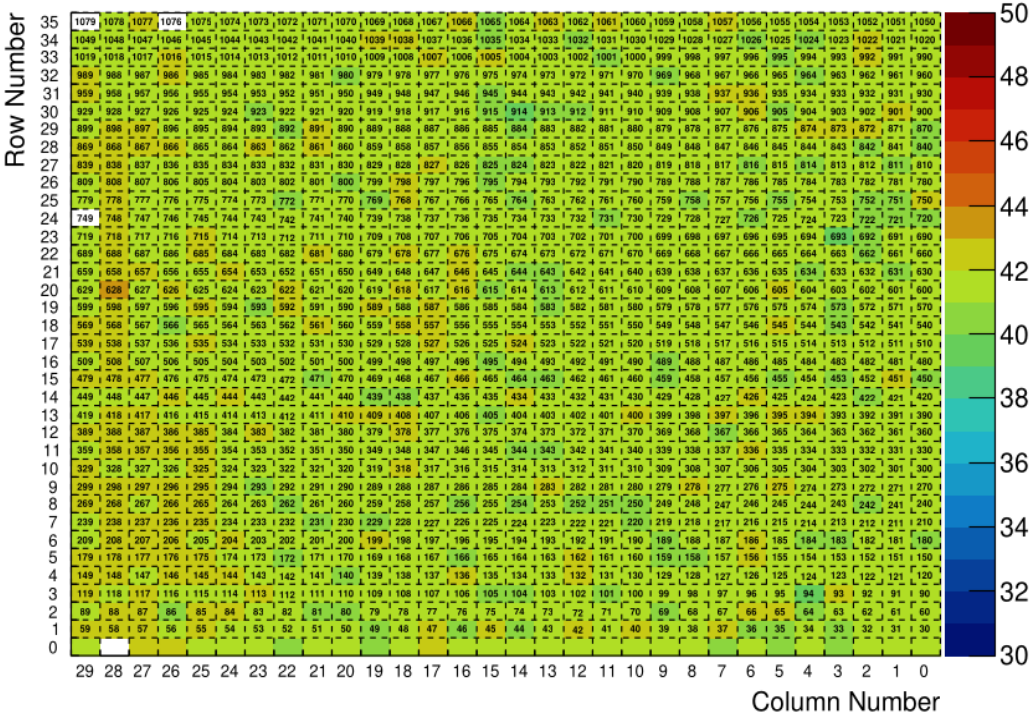
Runs: 5217/5236

Ee = 4.598 GeV

Pulse Peak Amplitude



Time of the 1st sample > threshold



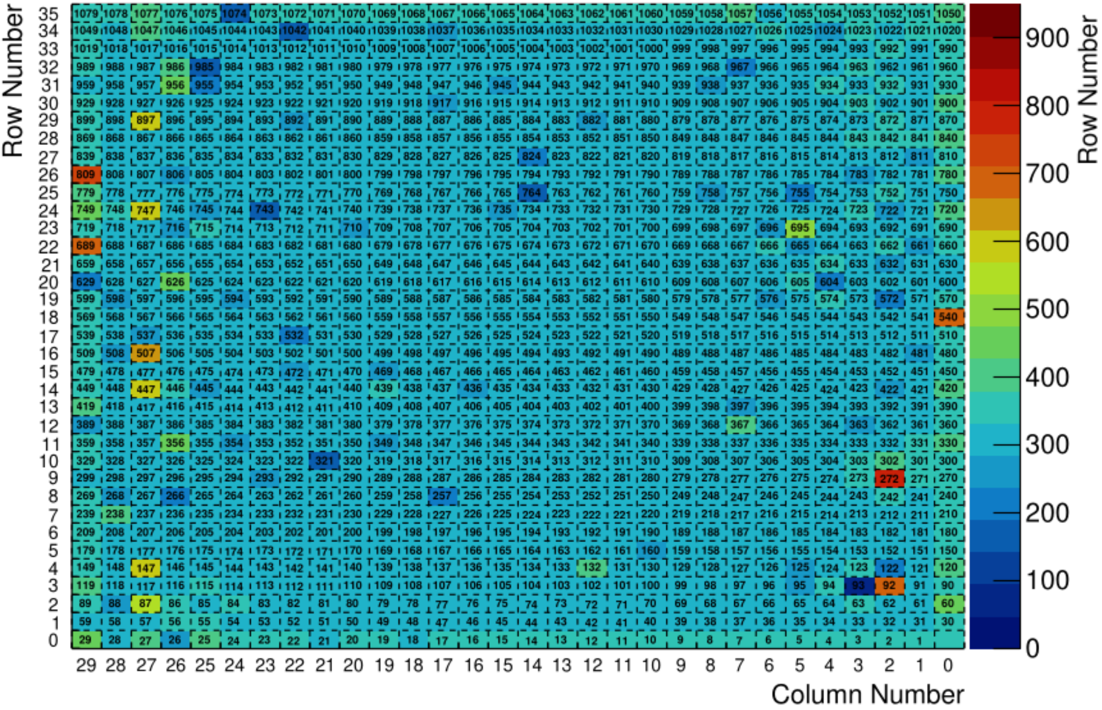
+ 4 dead blocks!

RESULTS

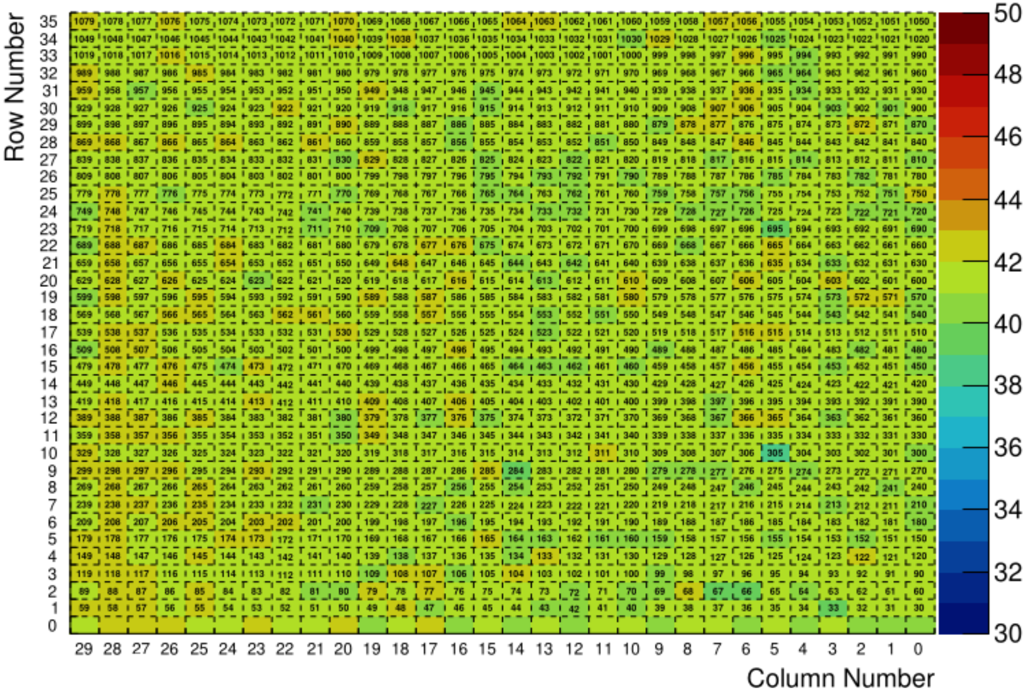
Runs: 6151/6168

Ee = 4.598 GeV

Pulse Peak Amplitude



Time of the 1st sample > threshold

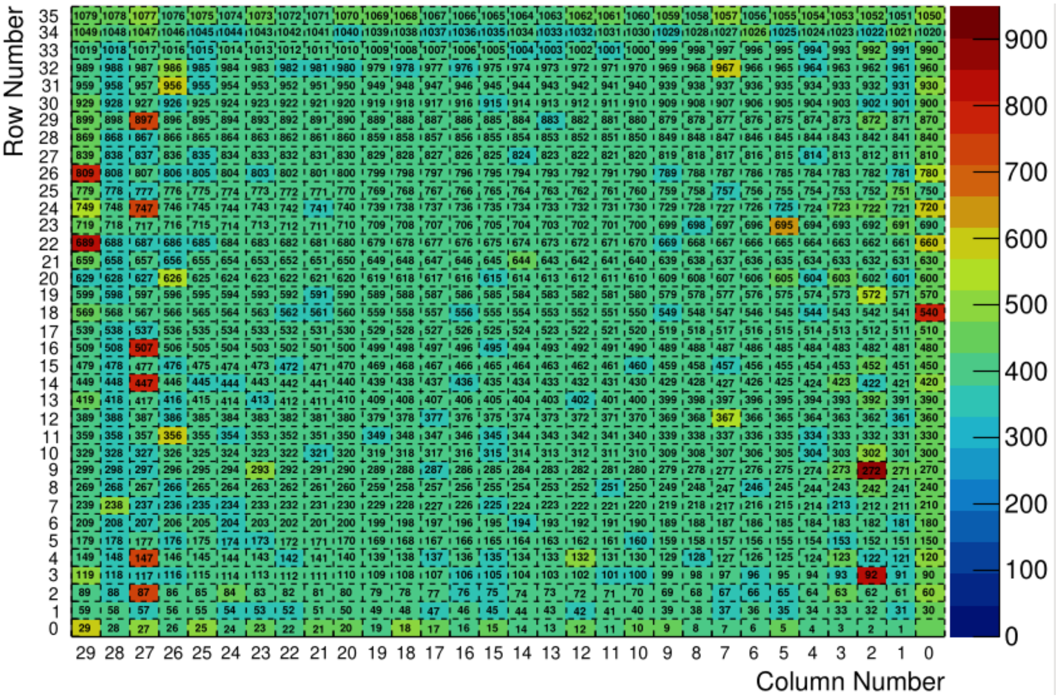


RESULTS

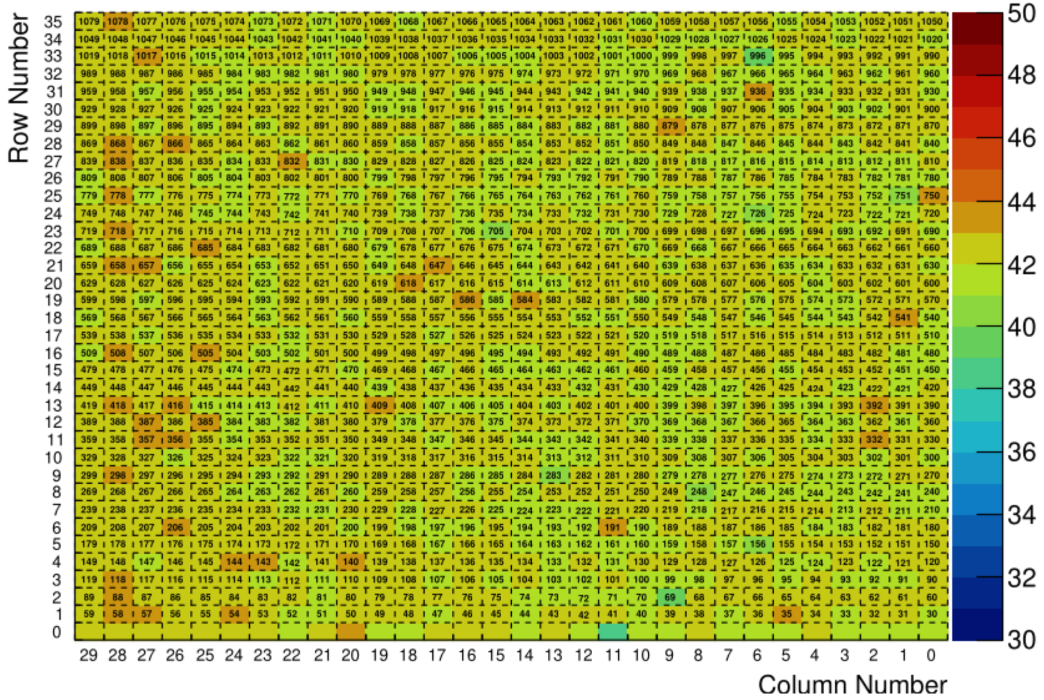
Runs: 6171/6183

Pulse Peak Amplitude

Ee = 5.681 GeV



Time of the 1st sample > threshold



Energy Resolution

Setting	Start Date	Beam (GeV)	E_e (GeV)	N.Runs	Run Numbers	Detector	Geometrical Cuts (plots)	Geometrical Cuts (minimization)
6151/6168	2024/04/22	6.397	4.524	18	6151 $\rightarrow$ 6168	All on	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 0 + 1 & icol $<$ ncol - 1 - 1
							colc[0] $\geq$ 0 + 2 & colc[0] $\leq$ 30 - 1 - 2	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1
5217/5236	2024/03/11	6.395	4.532	11	5226 $\rightarrow$ 5236	28,749,1076 off	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 0 + 1 & icol $<$ ncol - 1 - 1
							colc[0] $\geq$ 4 + 2 & colc[0] $\leq$ 30 - 1 - 2	ilin $\geq$ 0 + 3 & ilin $\leq$ nlin - 1 - 1
6171/6183	2024/04/24	8.477	5.706	8	6172 $\rightarrow$ 6179	All on	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 0 + 1 & icol $<$ ncol - 1 - 1
							colc[0] $\geq$ 0 + 2 & colc[0] $\leq$ 30 - 1 - 2	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1
2907/2920	2023/11/14	8.477	5.236	13	2907 $\rightarrow$ 2920	5 columns + 625 off	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2 + cut 625	icol $\geq$ 4 + 1 & icol $\leq$ ncol - 1 - 1+ cut 625
							colc[0] $\geq$ 4 + 2 & colc[0] $\leq$ 30 - 1 - 2	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1
1423/1560	2023/09/25	10.543	7.298	6	1437 $\rightarrow$ 1442	All on	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 0 + 1 & icol $<$ ncol - 1 - 1
							colc[0] $\geq$ 0 + 2 & colc[0] $\leq$ 30 - 1 - 2	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1
1969/1982	2023/10/20	10.543	7.270	9	1974 $\rightarrow$ 1982	1 column off	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 1 + 1 & icol $\leq$ ncol - 1 - 1
							colc[0] $\geq$ 0 + 2 & colc[0] $\leq$ 30 - 1 - 2	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1
2855/2871	2023/11/11	10.544	7.325	14	2856 $\rightarrow$ 2871	4 columns off	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 4 + 1 & icol $\leq$ ncol - 1 - 1
							colc[0] $\geq$ 4 + 2 & colc[0] $\leq$ 30 - 1 - 2	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1
2875/2885	2023/11/12	10.544	7.353	9	2875 $\rightarrow$ 2885	4 columns off	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 4 + 1 & icol $\leq$ ncol - 1 - 1
							colc[0] $\geq$ 4 + 2 & colc[0] $\leq$ 30 - 1 - 2	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1
3883/3898	2024/01/25	10.544	7.305	14	3883 $\rightarrow$ 3892	All on + 529	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 0 + 1 & icol $\leq$ ncol - 1 - 1 + cut 529
							colc[0] $\geq$ 0 + 2 & colc[0] $\leq$ 30 - 1 - 2 + cut 529	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1
5183/5208	2024/03/08	10.542	7.108	18	5183 $\rightarrow$ 5200	28,749,1076 off	linc[0] $\geq$ 0 + 2 & linc[0] $\leq$ 36 - 1 - 2	icol $\geq$ 0 + 1 & icol $\leq$ ncol - 1 - 2
							colc[0] $\geq$ 0 + 2 & colc[0] $\leq$ 30 - 1 - 3	ilin $\geq$ 0 + 1 & ilin $\leq$ nlin - 1 - 1