Beam events photodetectors response

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ProtoDUNE DRA meeting
April 24th, 2019

In these slides is shown the ProtoDUNE photodetectors response to beam events.

Hadronic and Electromagnetic showers have a different behavior.

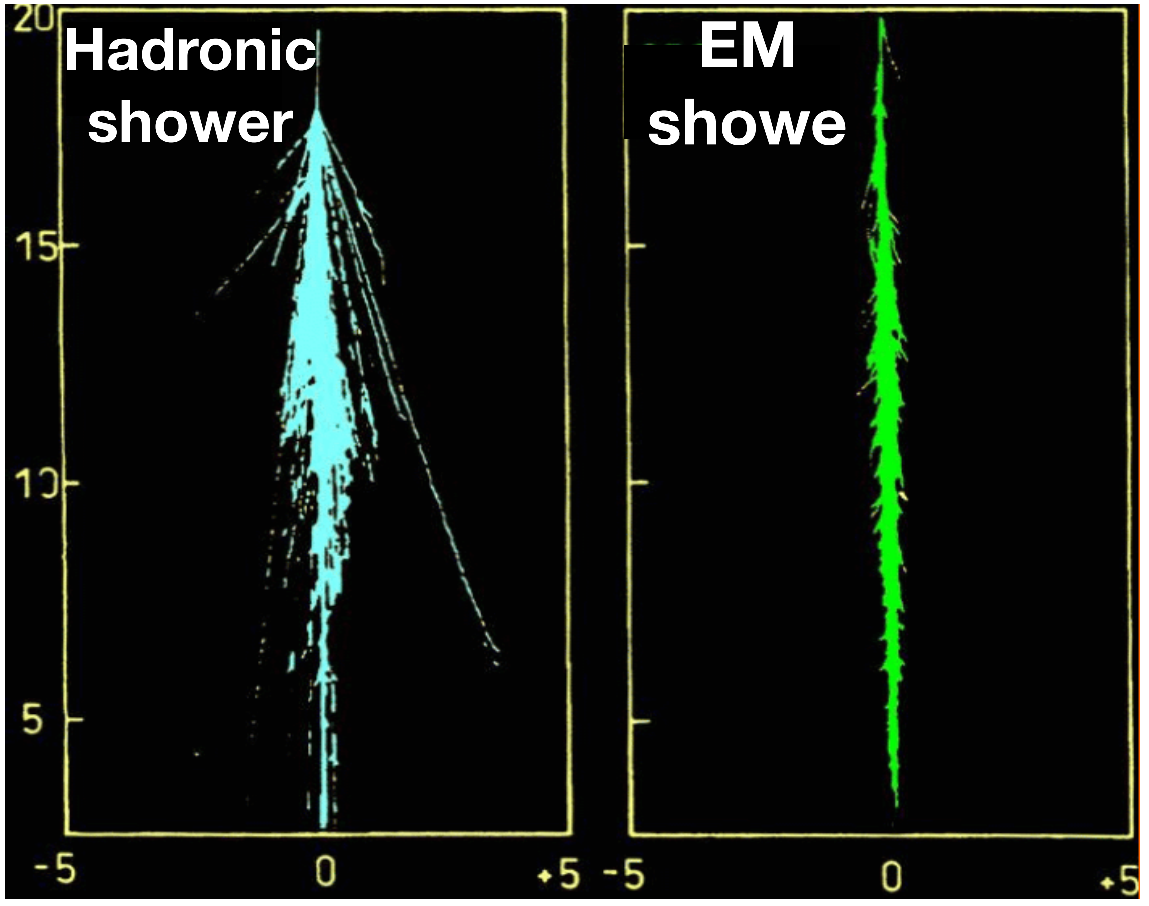
In hadron interactions a large fraction of the energy released goes into "invisible energy" (ie undetectable energy deposit): *nuclear binding energy, neutrino energy, slow/escaping neutrons,..*
The average invisible fraction is usually large O(30%) or more - depends on the material, not well known in LAr - with very large fluctuations event by event, mainly due to the fluctuation of the π^0 (EM) component in the hadronic shower (this reflects on hadronic energy resolution)

Muons does not produce shower. Track like energy deposition.
From 2 GeV/c to up, muons escape the TPC -> constant energy deposition

Hadronic vs EM shower

- many particle species
- central em component
- sizeable transverse size

- e and gamma only
- limited transverse size



- 2 scales for hadronic cascade development:
  - λabs for strongly interacting part
  - Xo for the EM part

Particle identification

Based on Justin Hugon (Louisiana State University) talk : [ProtoDUNE Sim/Reco Meeting 2018-11-28]
(https://indico.fnal.gov/event/19185/contribution/2/material/slides/0.pdf)

- Cherenkov PID

6/7 GeV/c	High Pressure Cherenkov	Low Pressure Cherenkov	**3 GeV/c**	High Pressure Cherenkov	Low Pressure Cherenkov	**0.3/0.5/1/2 GeV/c**	Low Pressure Cherenkov
Electron / Pion	1	1	Electron	1	1	Electron	1
Kaon	1	0	Pion	1	0	Pion	0
Proton	0	0	Proton	0	0	Proton	0

- Time of Flight

For 2 GeV/c:
TOF < 160 ns: pions
Else: protons

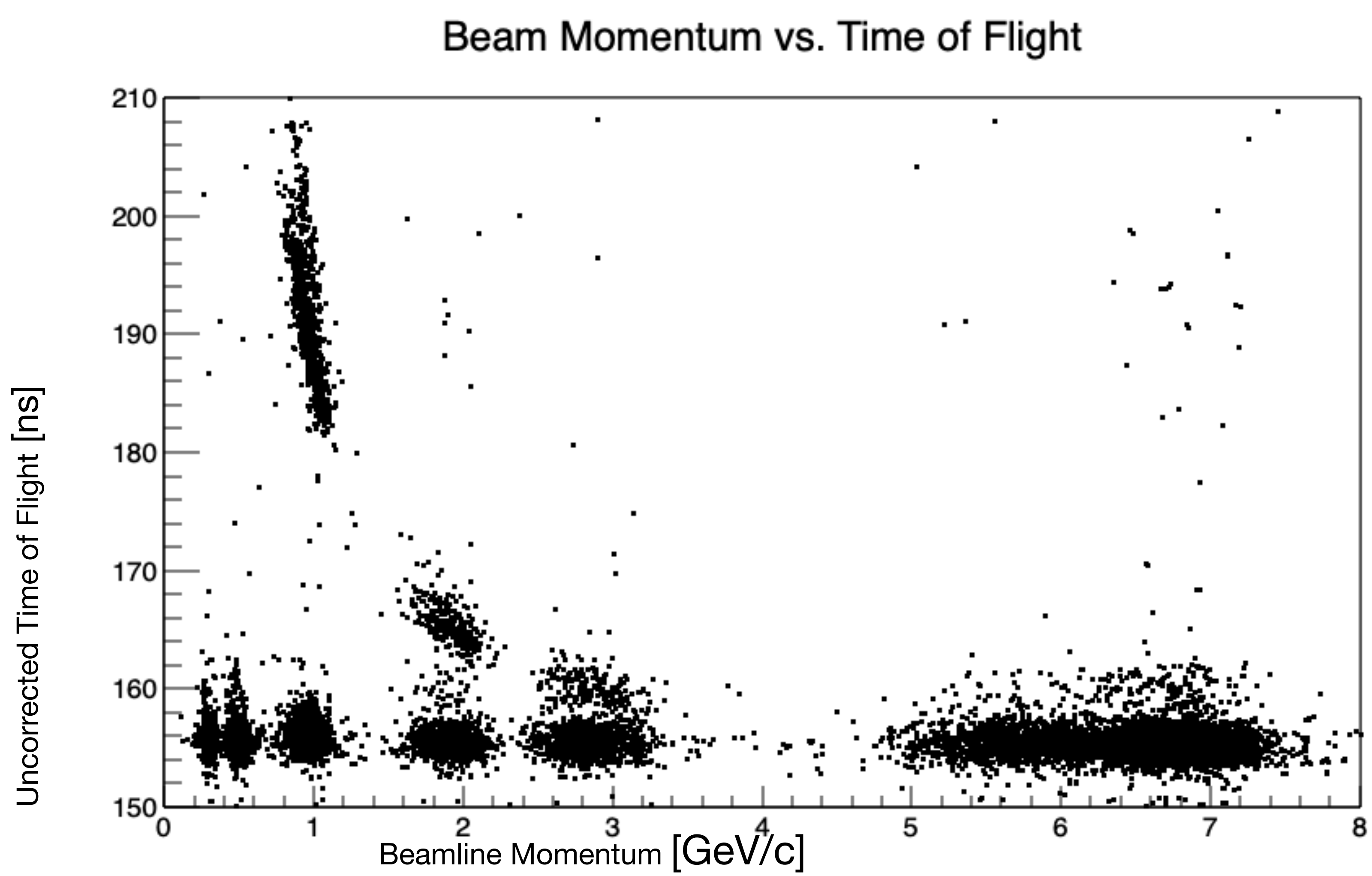
For 0.3/0.5/1 GeV/c:
TOF < 170 ns: pions
Else: protons

- Pandora reconstruction

For 6/7 GeV/c: pions and electrons

- Spectra selections

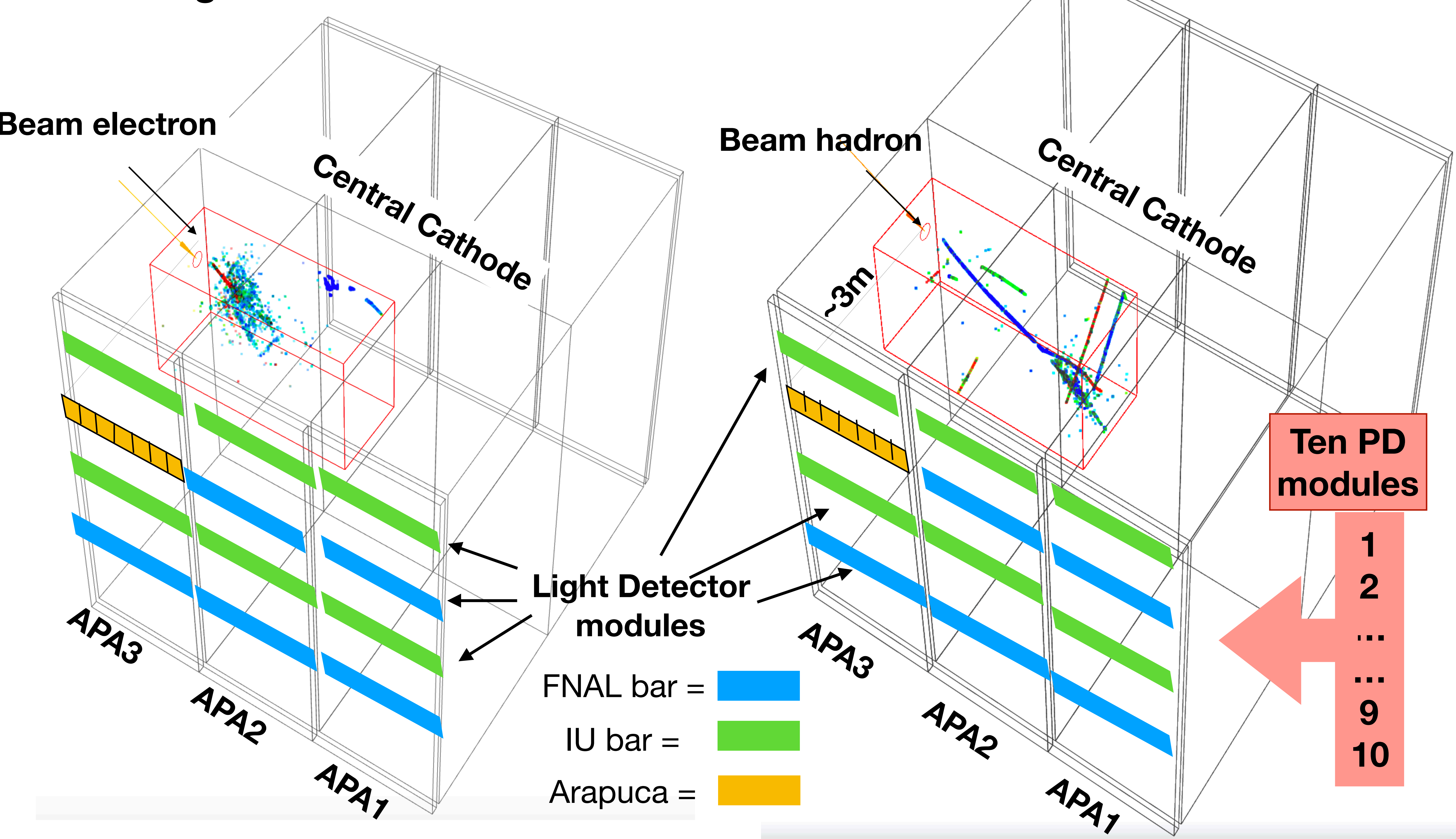
Muons peak from pions and kaons spectra



Hadronic vs EM shower

Electromagnetic shower - localized in front of APA 3 and pencil like

Hadronic shower - more elongated and spread, larger shape fluctuation, leakage across the central cathode

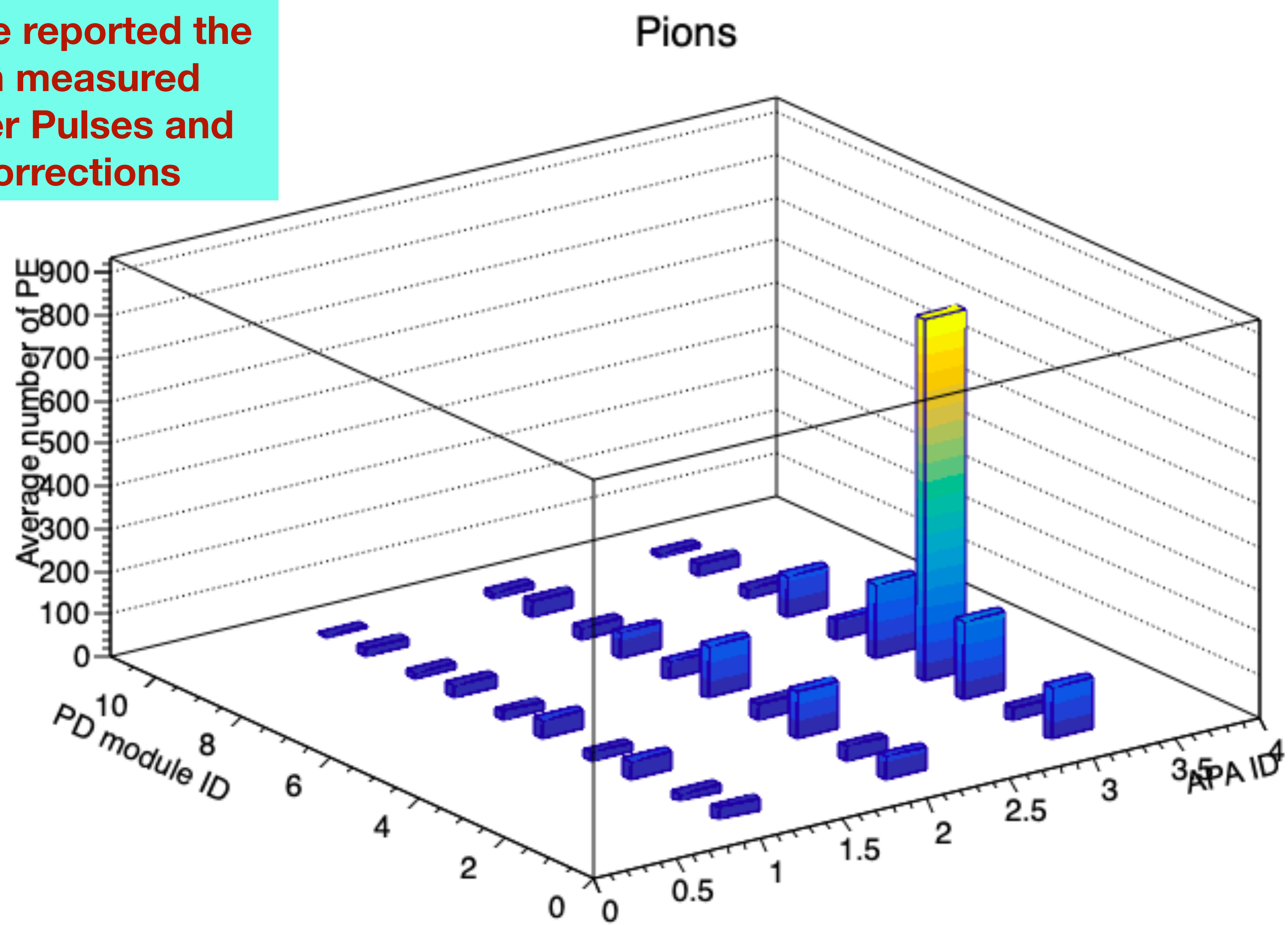


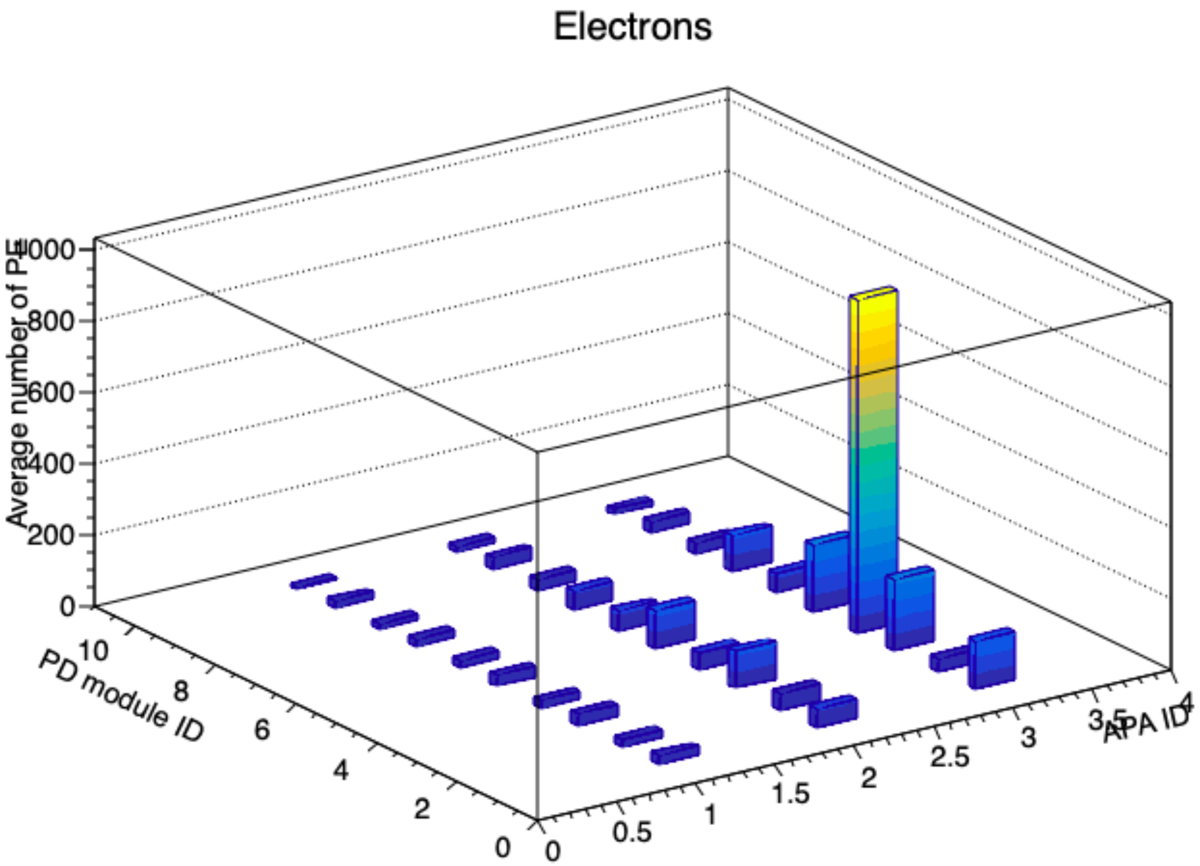
All PD modules response to 7 GeV/c beam momentum events particle by particle

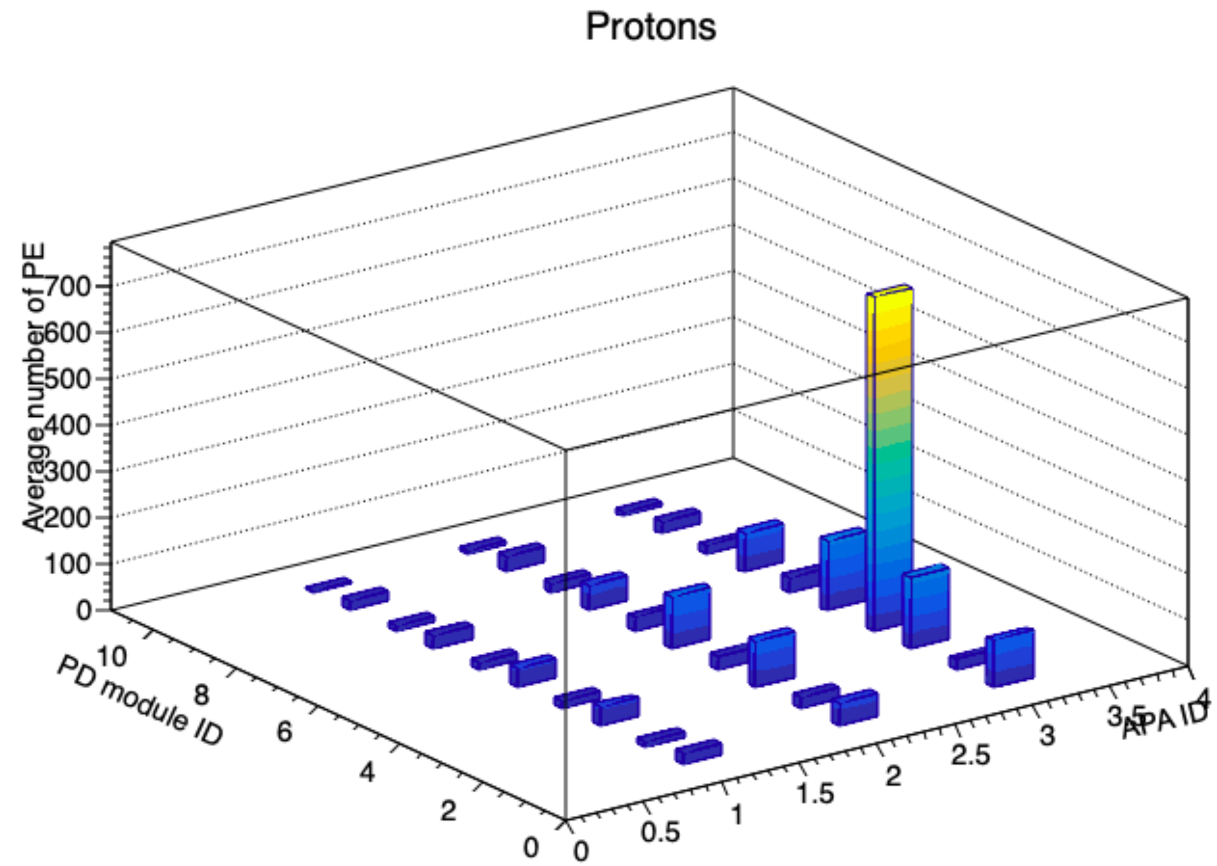
In these plots are reported the photoelectron measured without the After Pulses and Cross Talk corrections

The photons detected will be reduced after these corrections (work in progress) of a factor
~37% MPPC
~?% SensL.

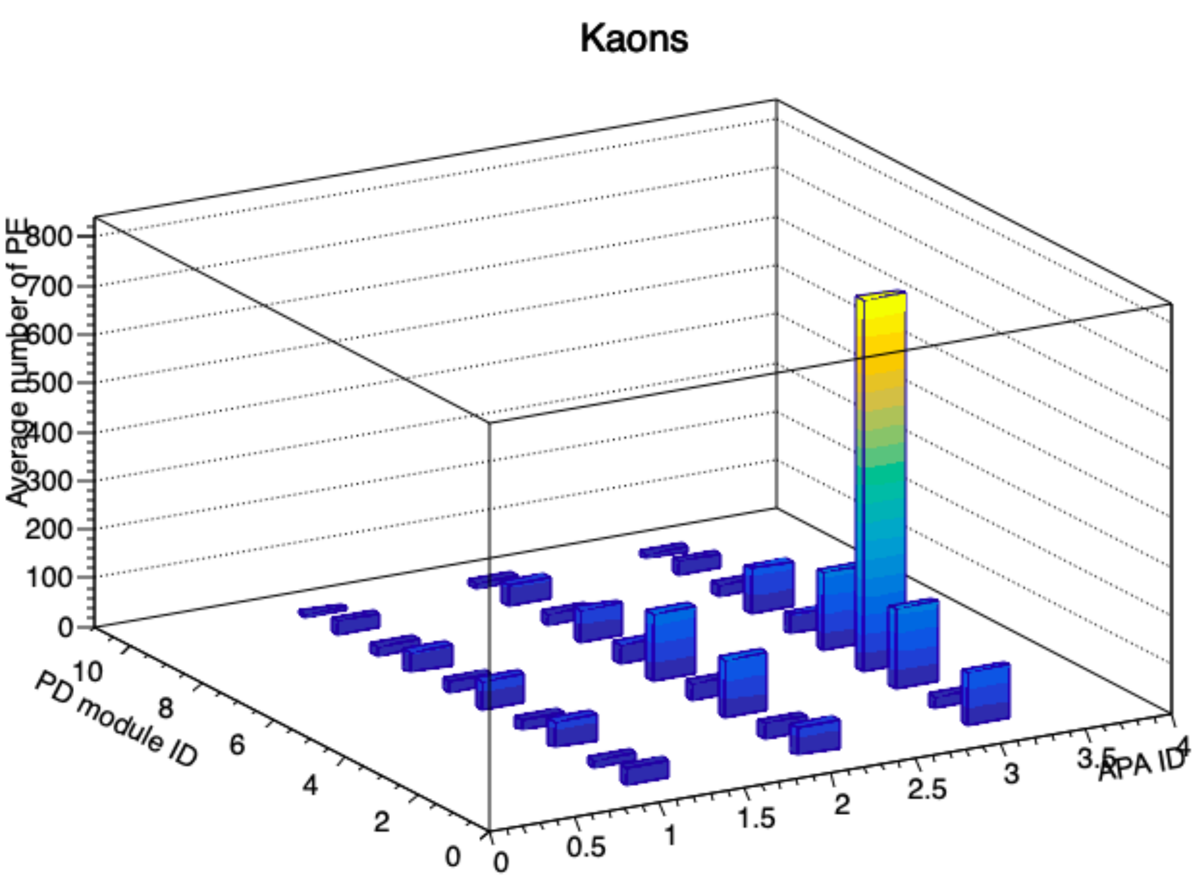
The SensL calibration I used was made by Chris and Bryan

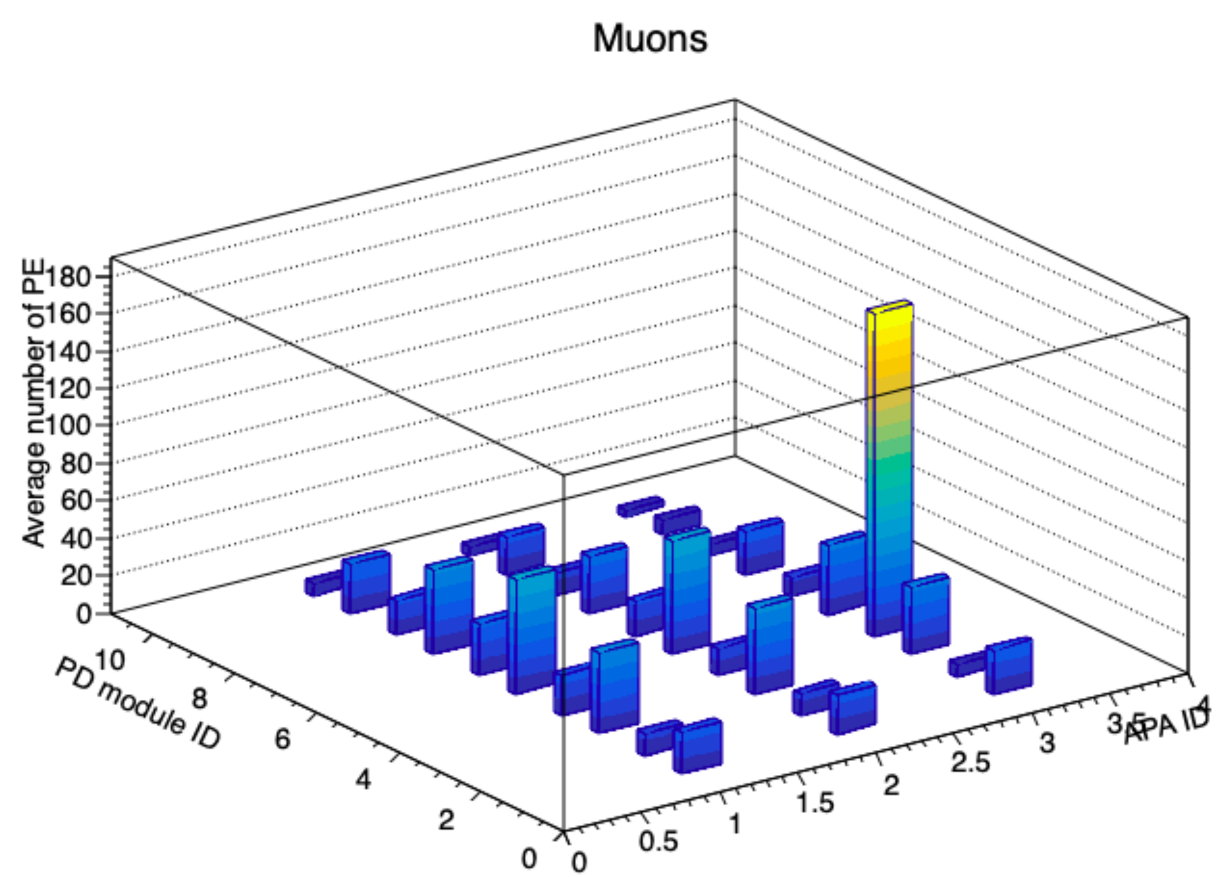




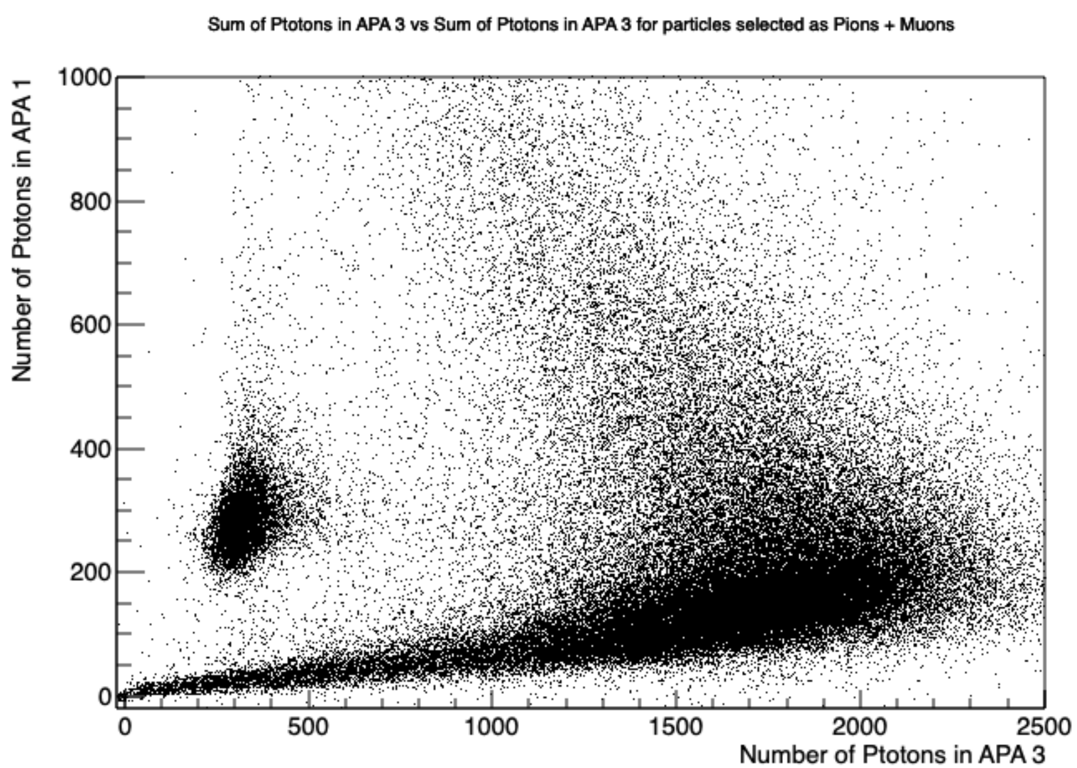


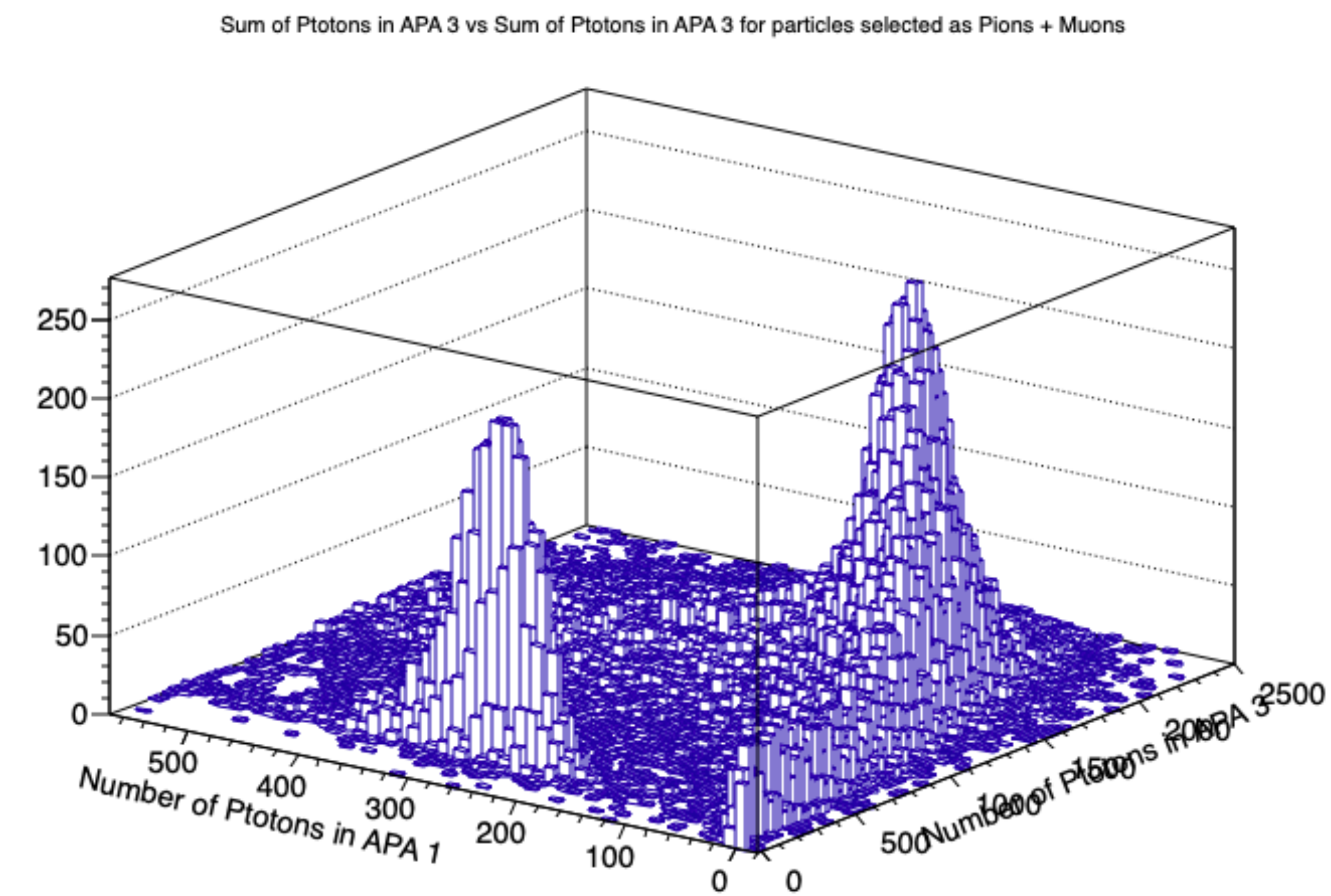
Independently from the PD efficiency, is possible to note difference in the PD response structure between e and P,K,pi focusing on APA2 and APA1.
Differences became huge comparing muons (tracks traversing the TPC) with the other particles.

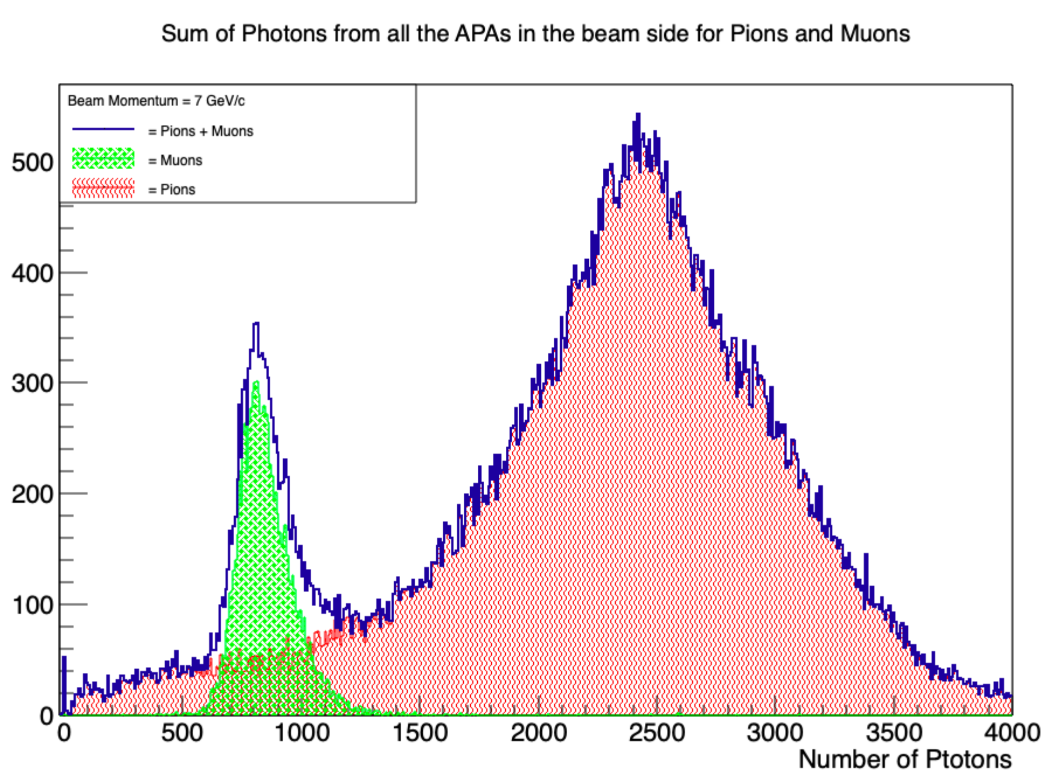




APA 3 vs APA 1 response to 7 GeV/c beam momentum events particle by particle

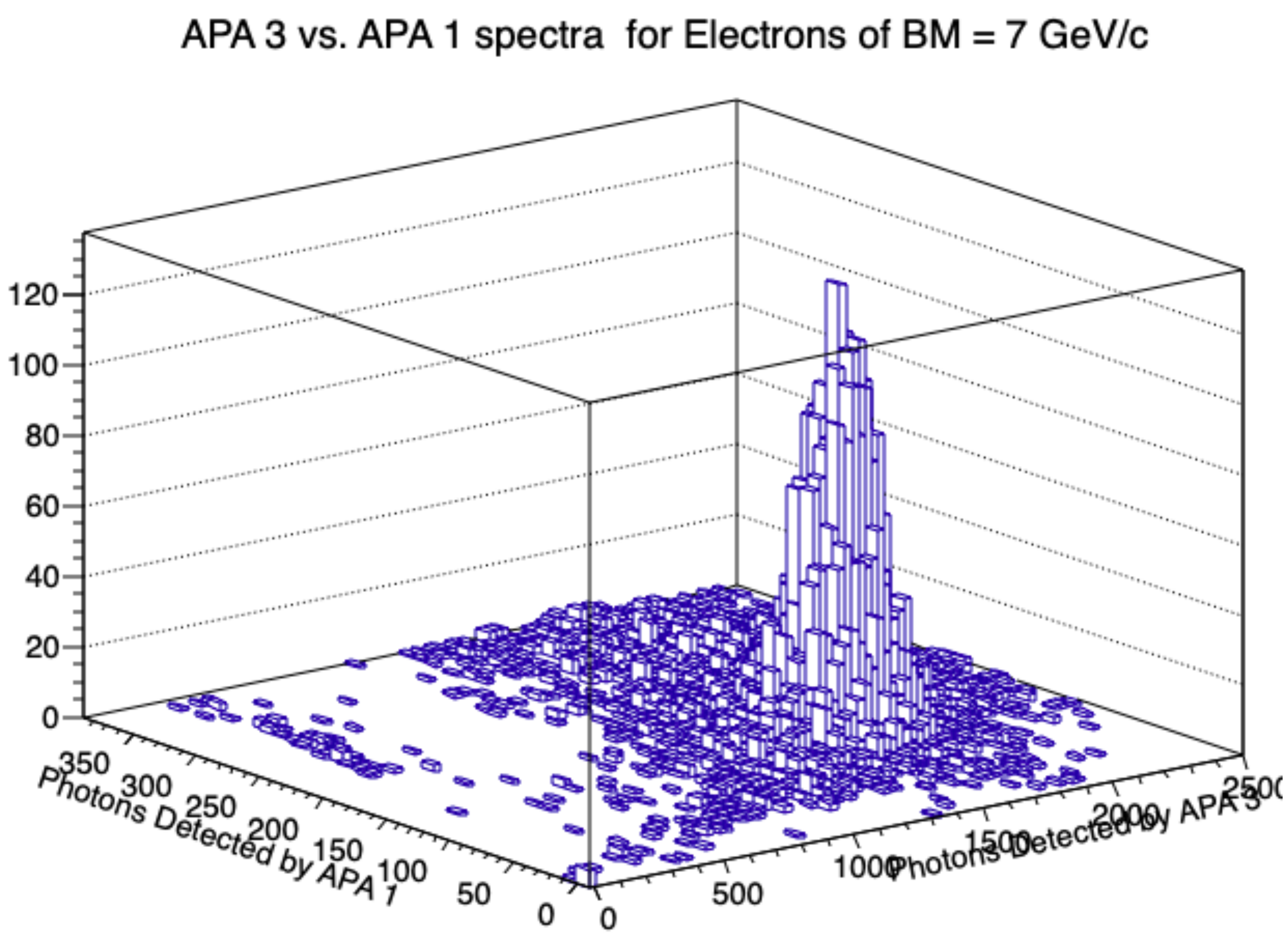


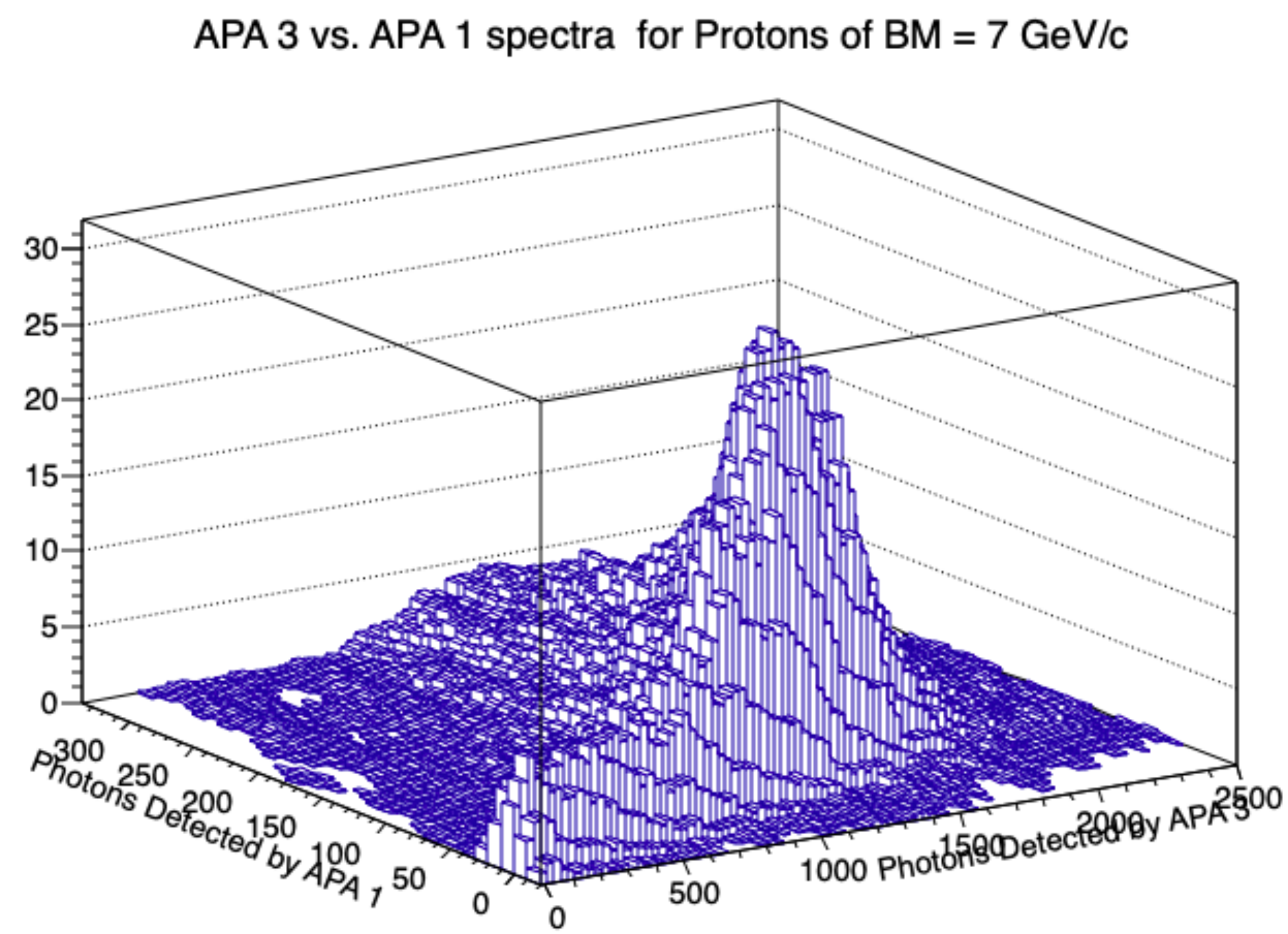


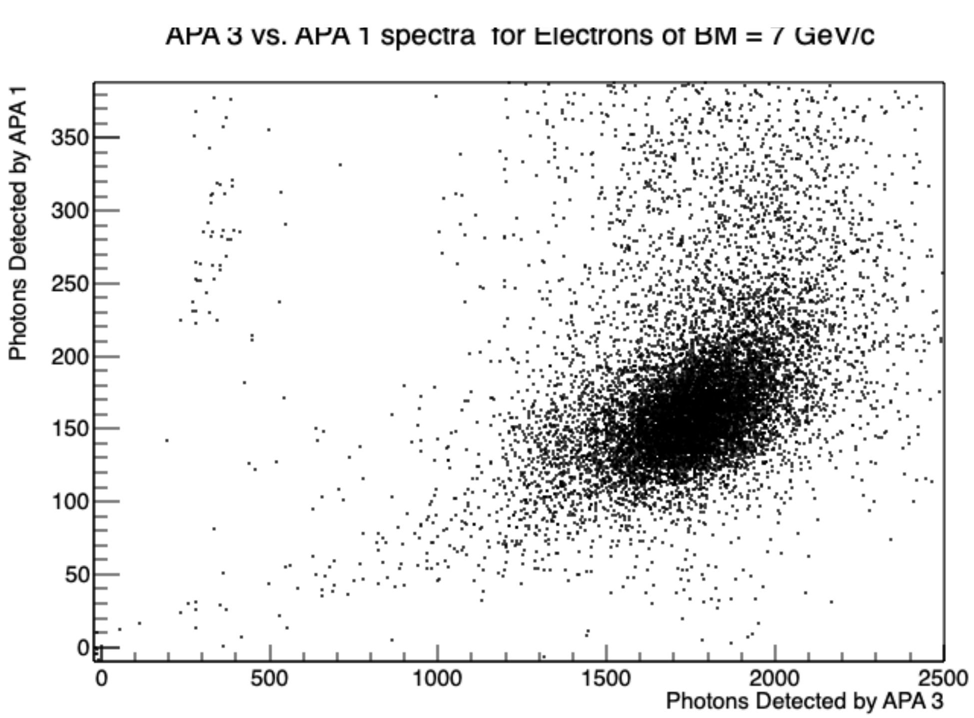


In pions and kaons spectra, the muons peak can be selected very well using scatter plots
(in this case APA3 vs APA1 for pions).

Electrons are well localized, protons present a tail to zero.

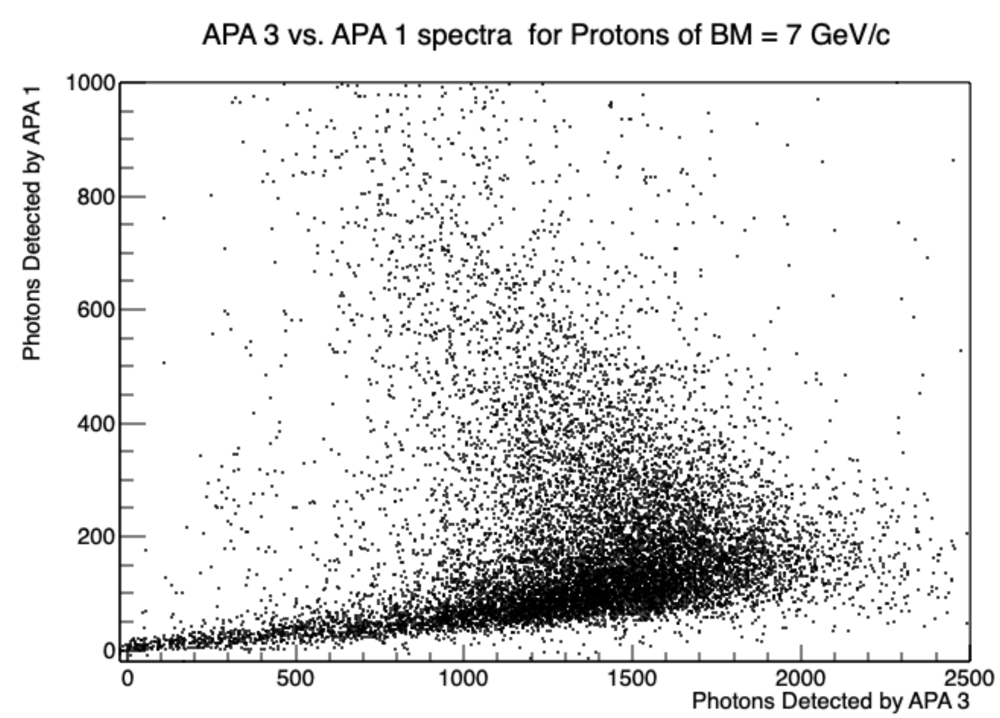


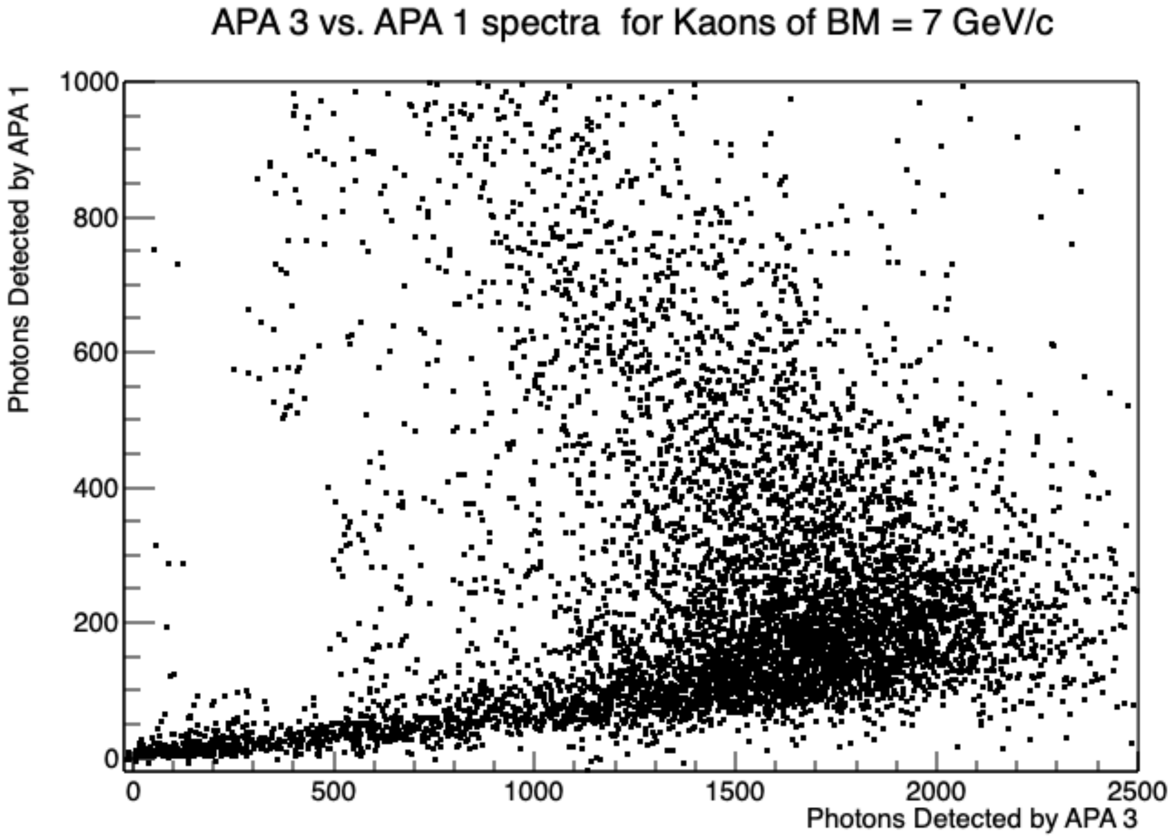


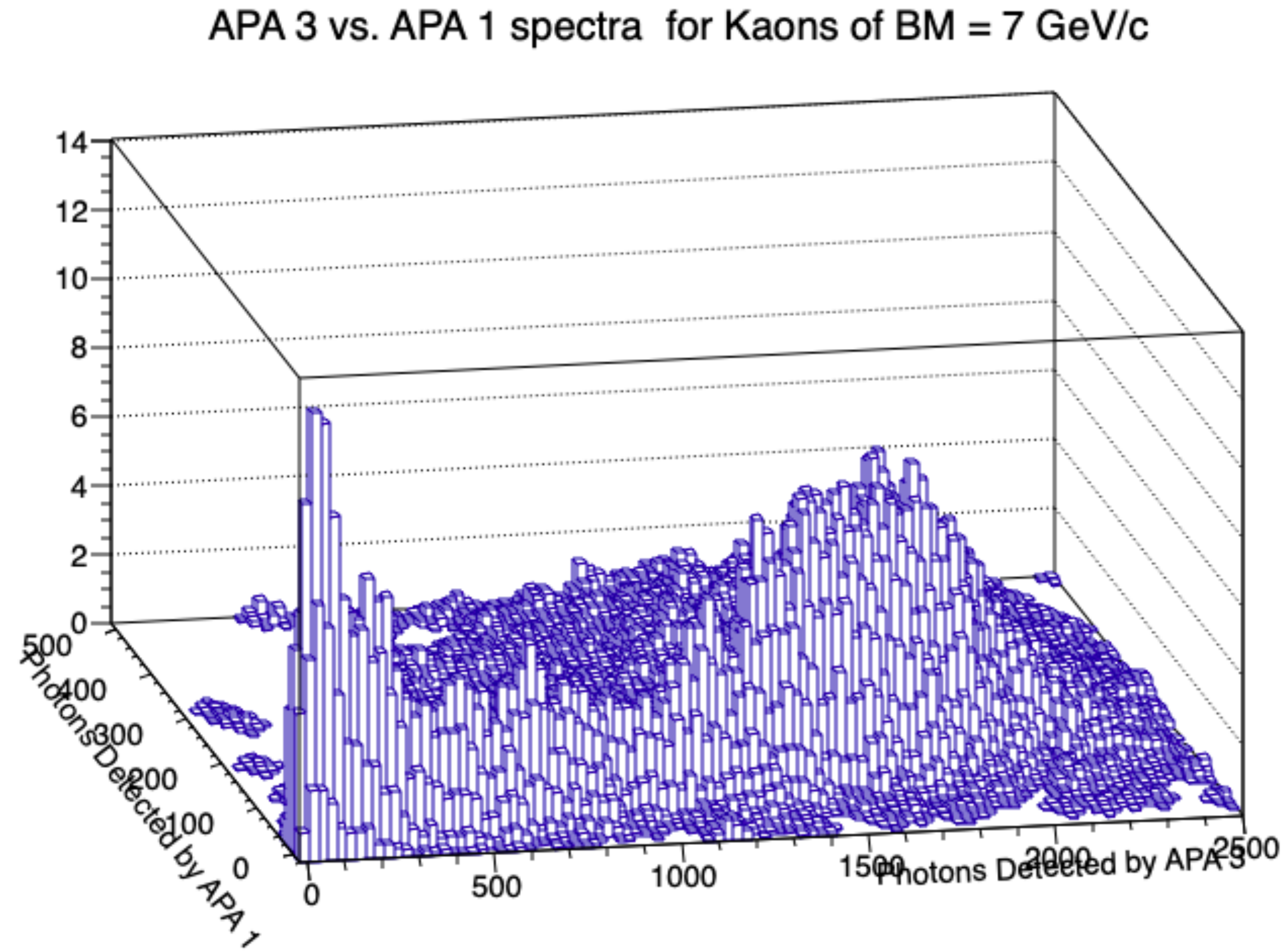


P and e plots have similar statistic

Electrons = 13143
Protons = 13277







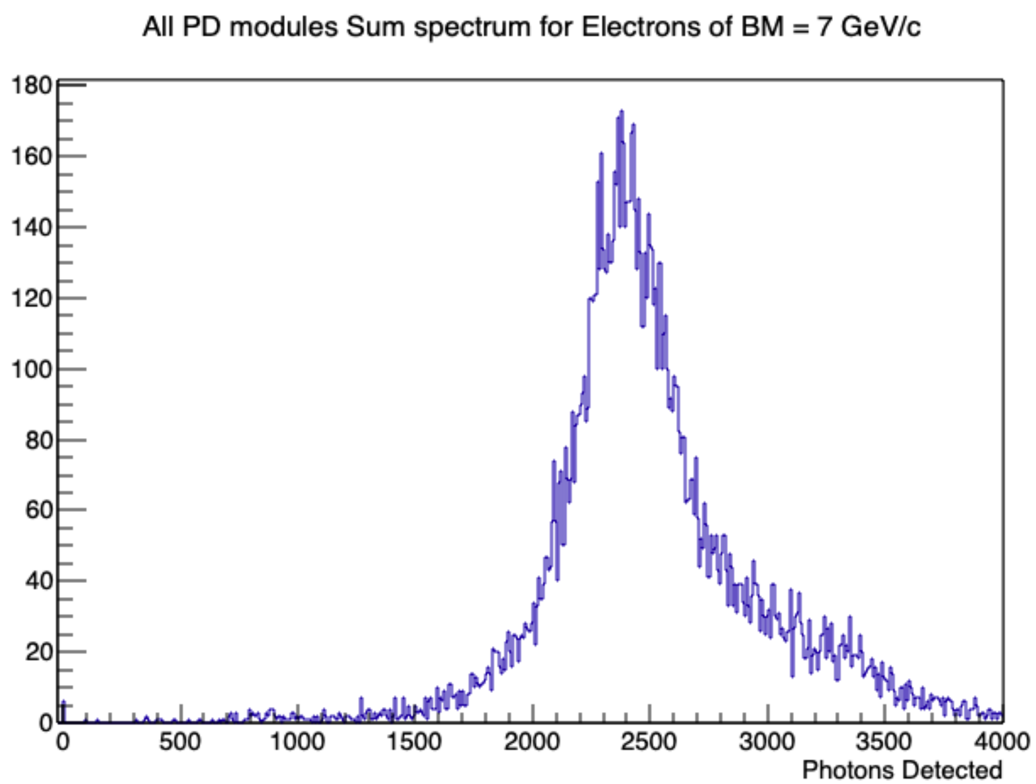
The tail in hadrons spectra is completely absent in the electrons spectrum (and muons).

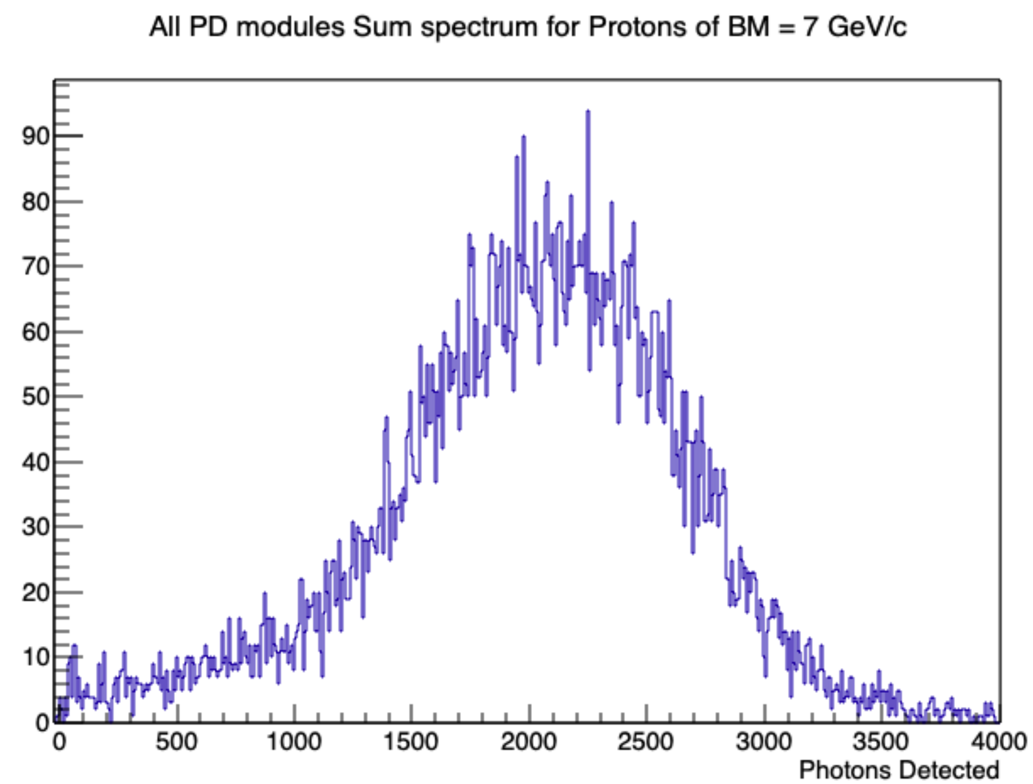
Comparing the protons and electrons spectra, and taking into account that the two datasets have the same statistic:

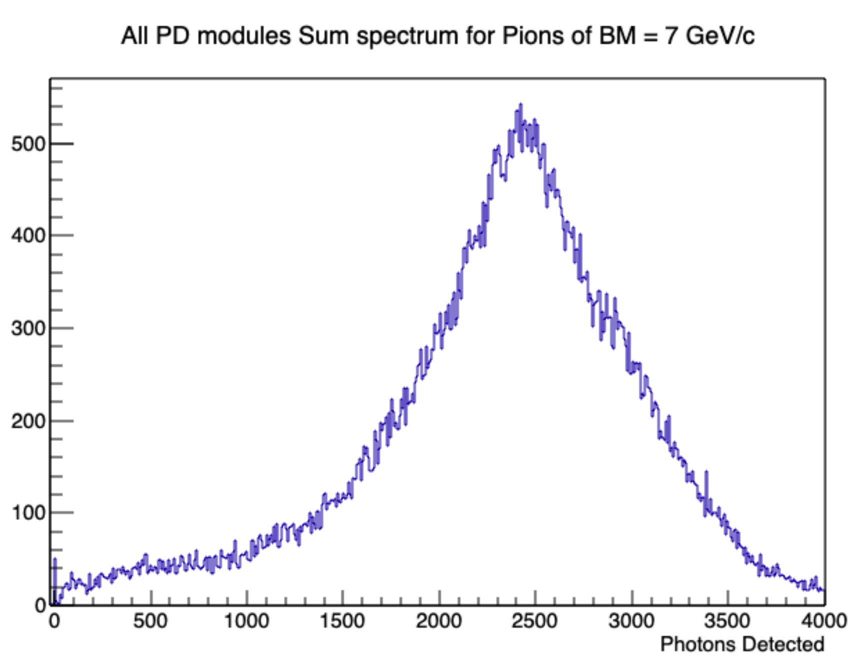
- Bias in the analysis can be excluded
- Background effects can be excluded

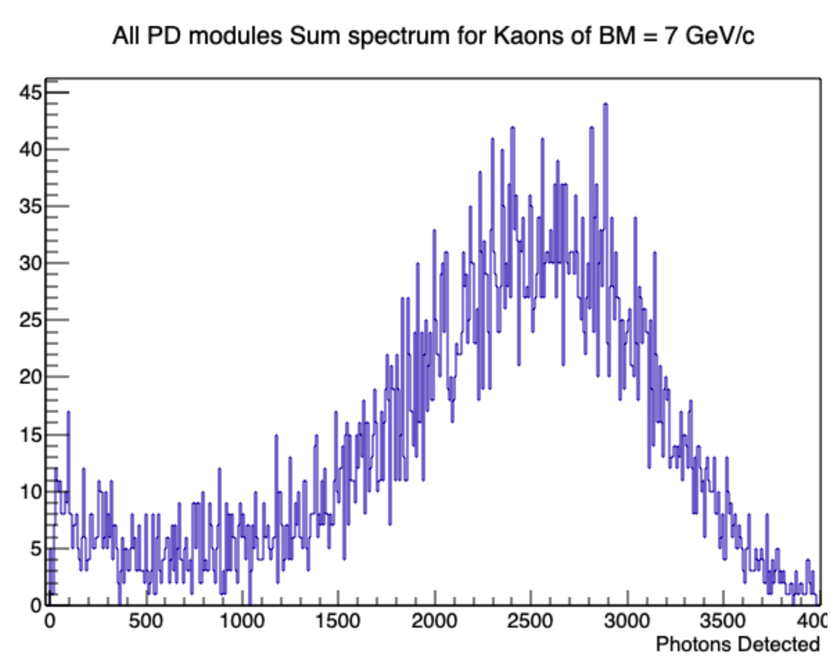
Hadronic "no-visible" energy deposition? "UNDER INVESTIGATION"

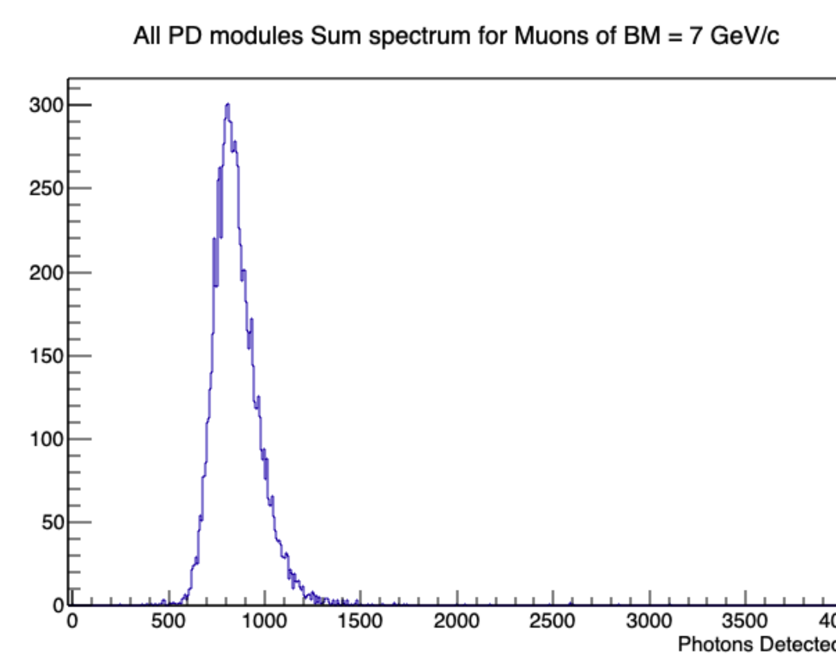
All PD modules "beam-side” sum spectra for 7 GeV/c beam momentum events particle by particle







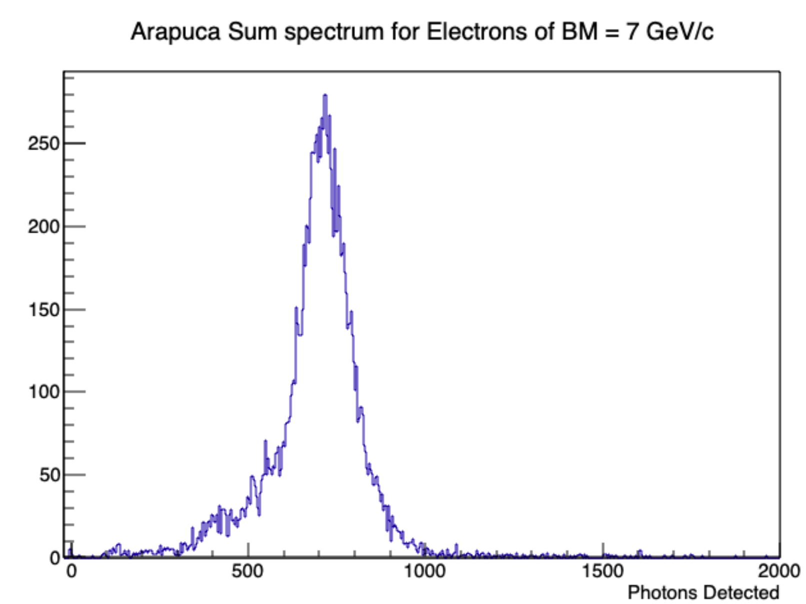


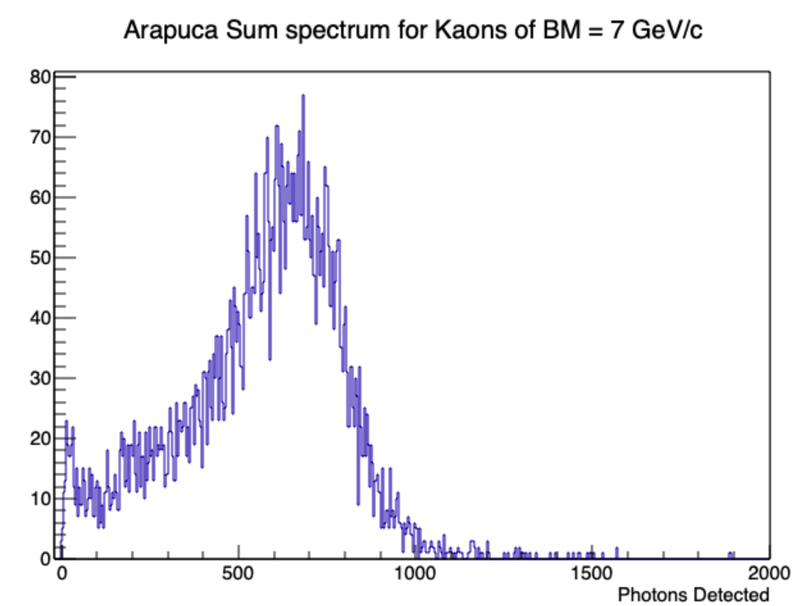


Arapuca spectra

Focusing on Arapuca response for 7 GeV/c beam momentum events, we can notice some difference respect the all PD module sum spectra. The Arapuca PD module geometrical position makes less evident the differences in hadron-electromagnetic showers structure.

From here for the Arapuca calibration, After Pulses and Cross Talks correction are take into account. The numbers reported are an estimation of the effective number of photons detected.

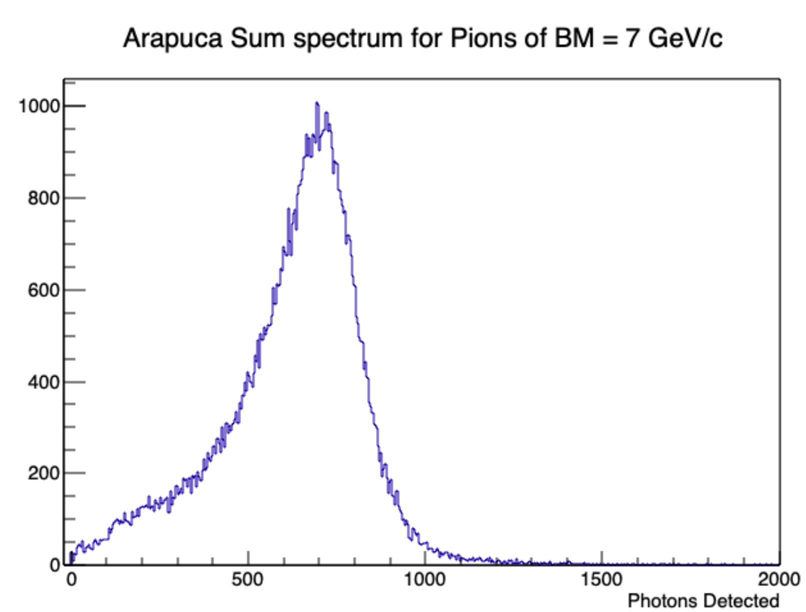


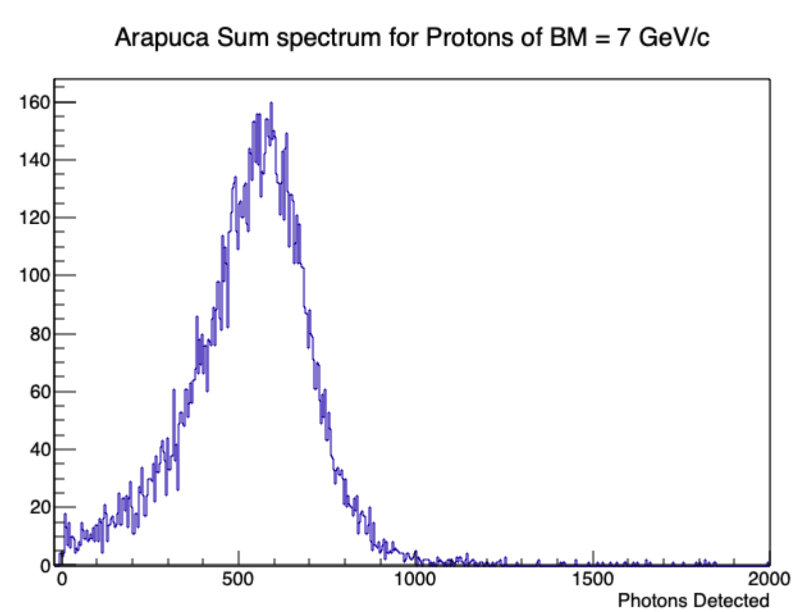


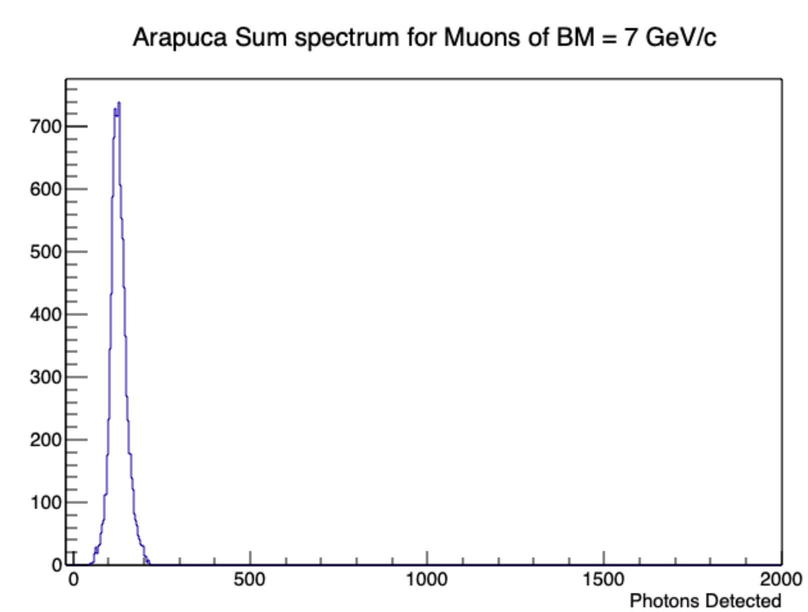
Average number of photons per particles:

Electros: <N_ph> = 693
Muons: <N_ph> = 128
Pions: <N_ph> = 627
Kaons: <N_ph> = 564
Protons: <N_ph> = 534

Remind: the momentum is fixed, the Kinetic Energy depends on the particle

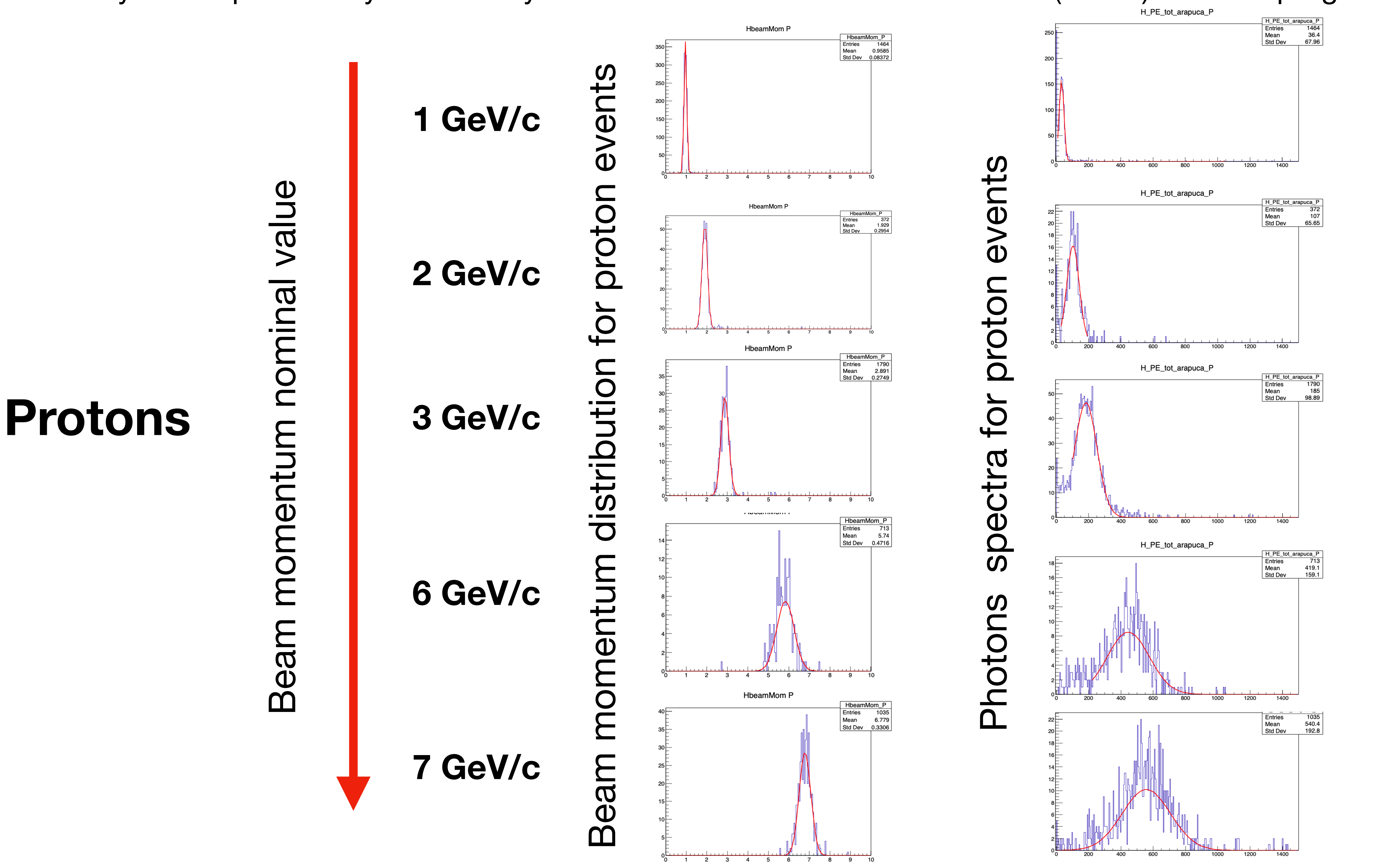






Arapuca spectra vs beam momentum

This analysis is a preliminary result. Only a small fraction of events where used (~10%) “work in progress”



A fit with a Gaussian of the spectra for all the particles and all the beam momentum values is made.

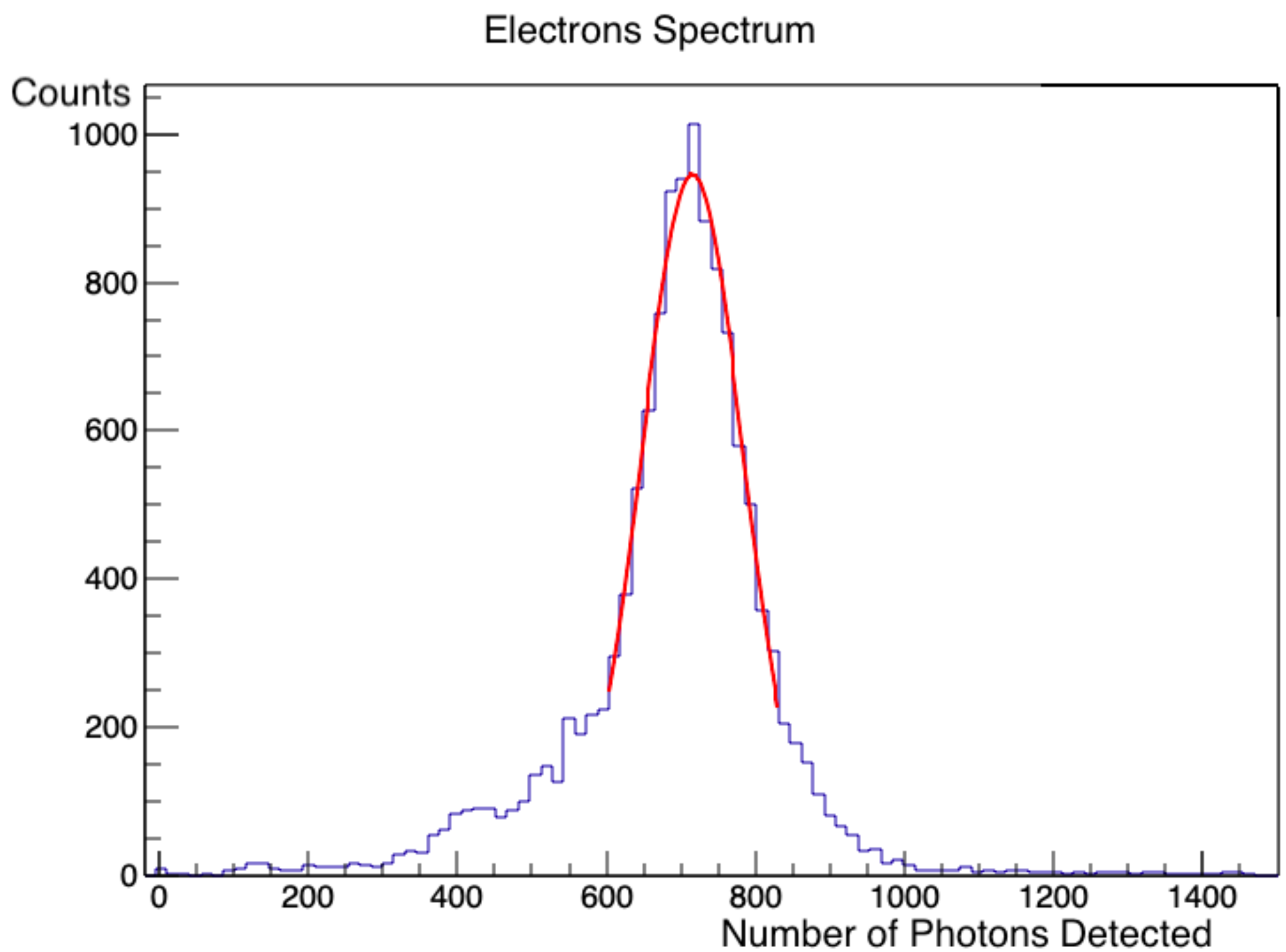
Two quantities have been analyzed :

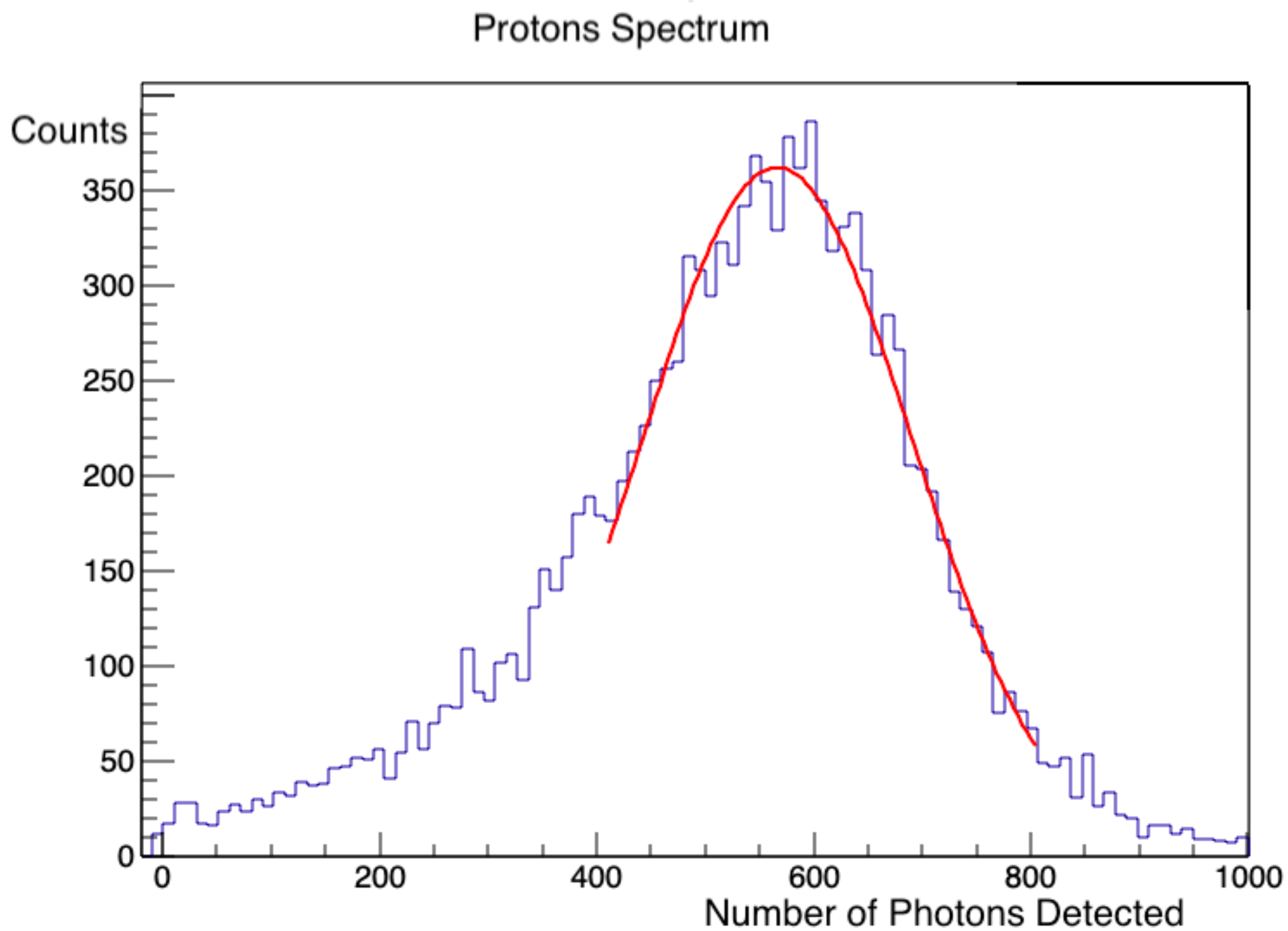
-mean value vs kinetic energy
-standard deviation/ mean vs kinetic energy

Only a fraction of data have been analyzed, the rustles are partials and more consideration have been made.

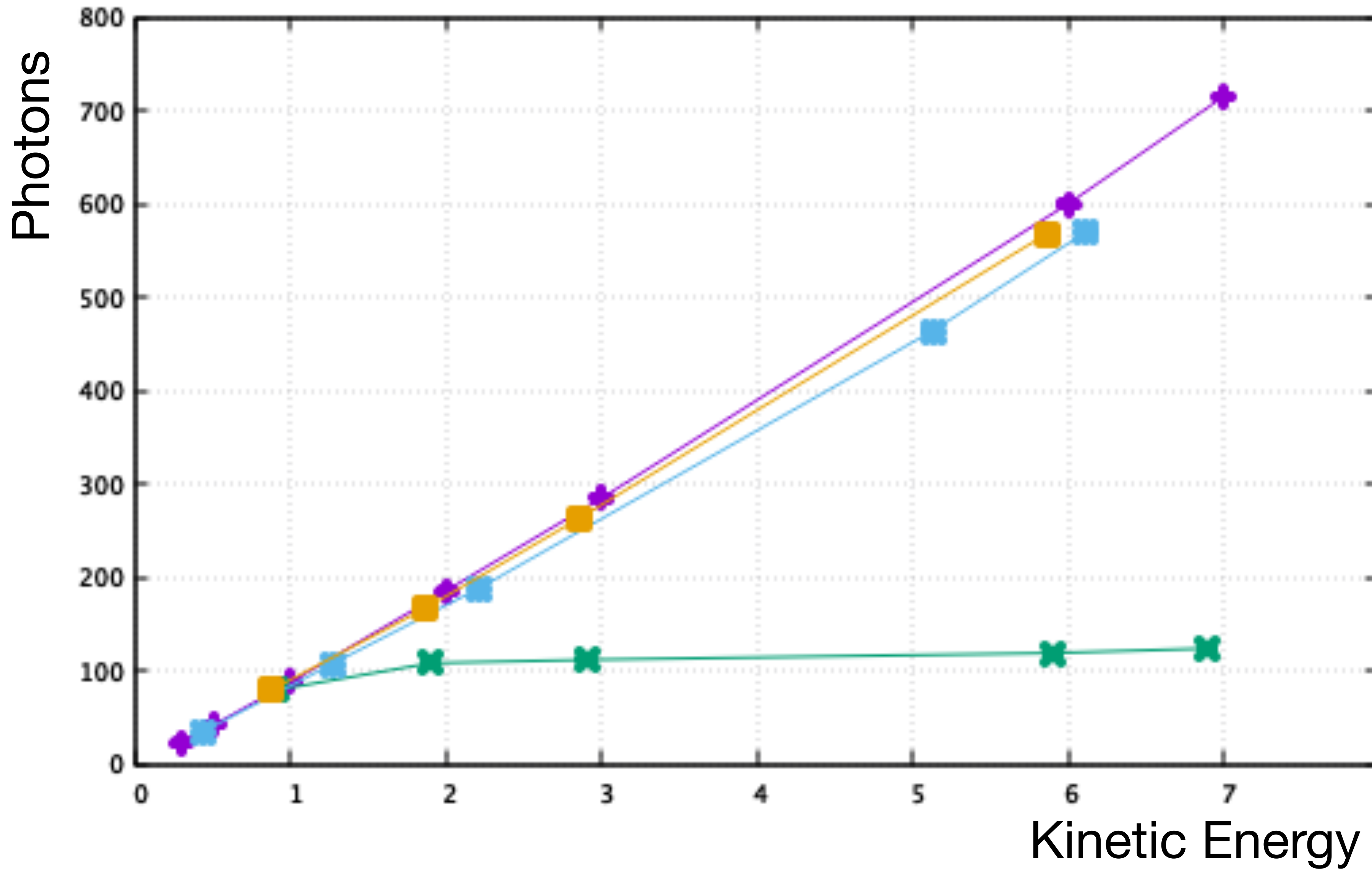
One of the point under investigation is the reliability of a Gaussian fit.
-It is useful for how concern the background. The peak is not affected by the pileup
-But further investigation is needed in order to solve the hadronic “not-visible” energy depositions that make the spectra asymmetric and push the average value to a small number respect the mean of a Gaussian used to fit the peaks.

Example of how the Gaussian fit match the data.
In the electron case it is very good.
For protons there is a clearly mismatch in the left side of the spectrum



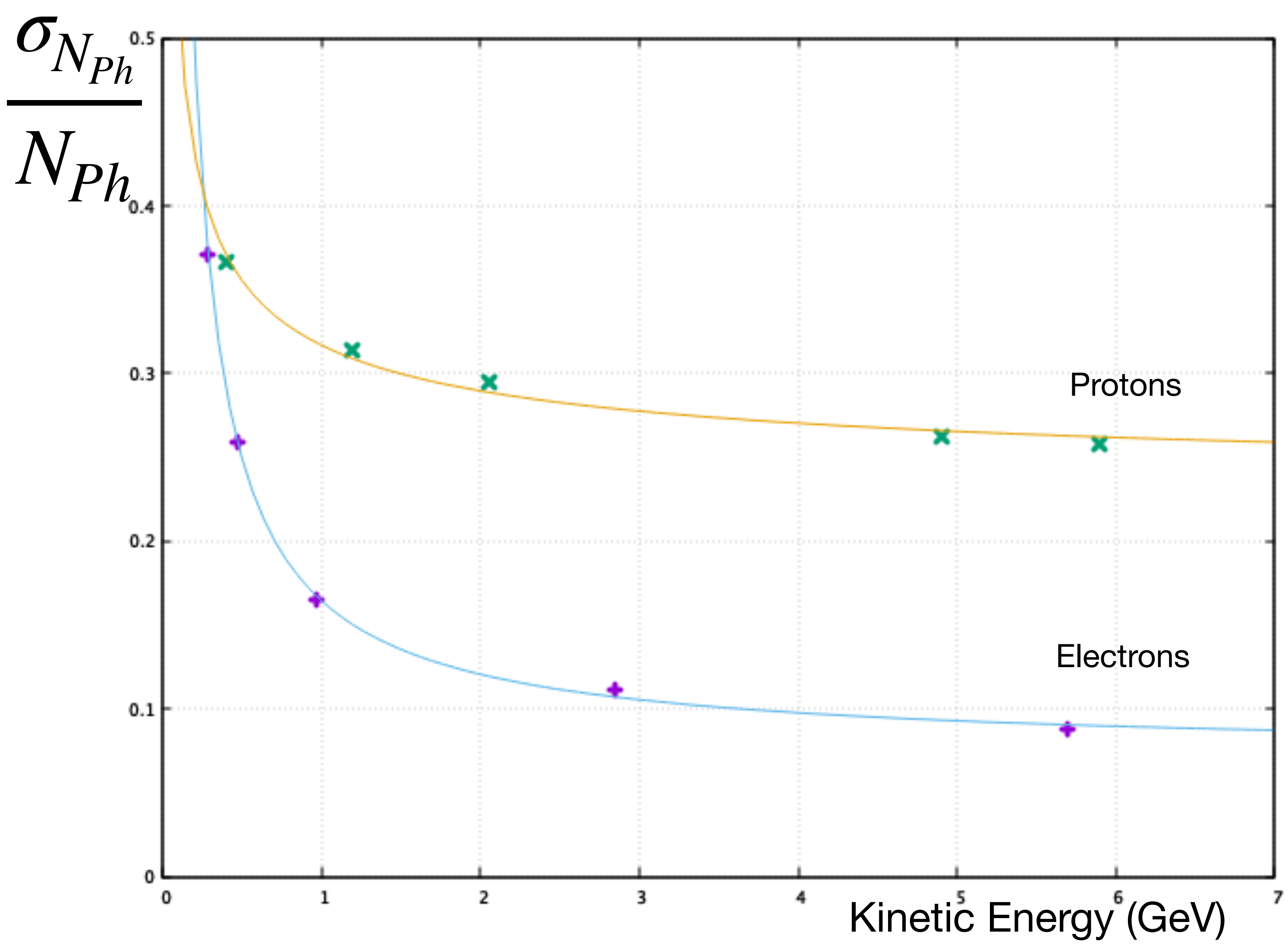


Mean value vs kinetic energy



Green = Muons Purple = Electrons Blue = Protons Yellow = Pions

Resolution vs kinetic energy



Data Fitting

Protons:
k_1 = 0.26 +/- 0.02
k_2 = 0.17 +/- 0.07
k_3 = 0.0004 +/- 9

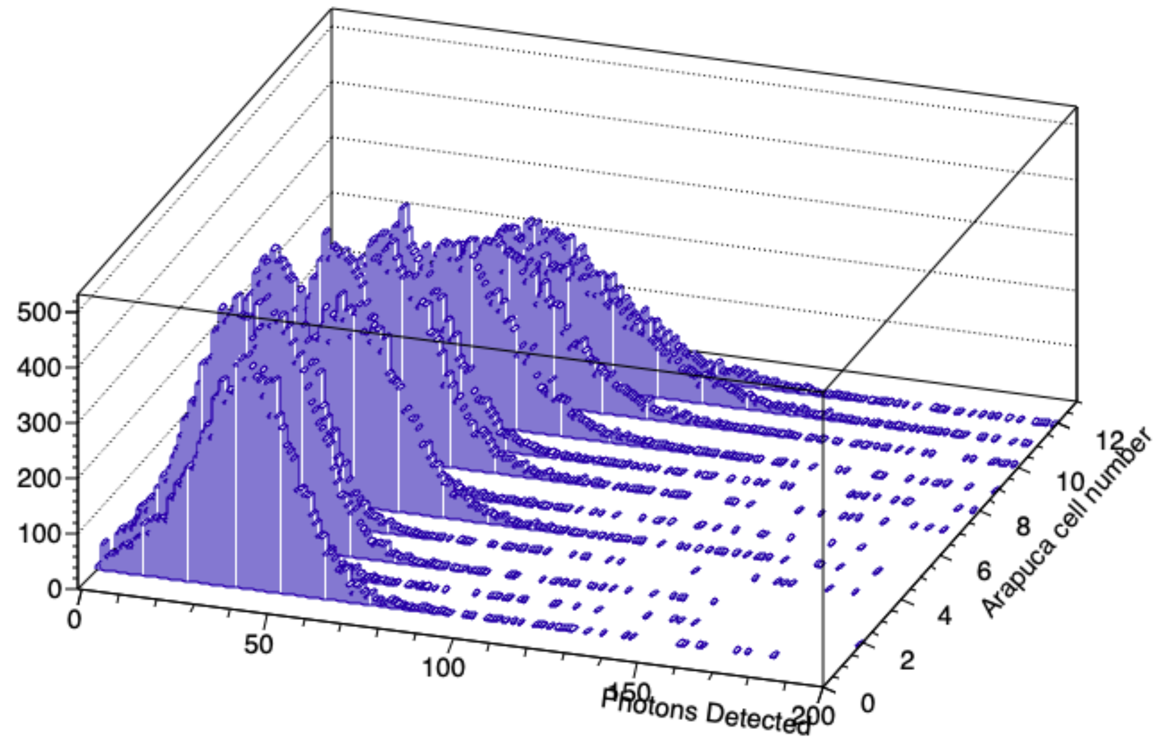
Electrons:
k_1 = 0.073 +/- 0.006
k_2 = 0.12 +/- 0.01
k_3 = 0.082 +/- 0.004

Standard fit equation :

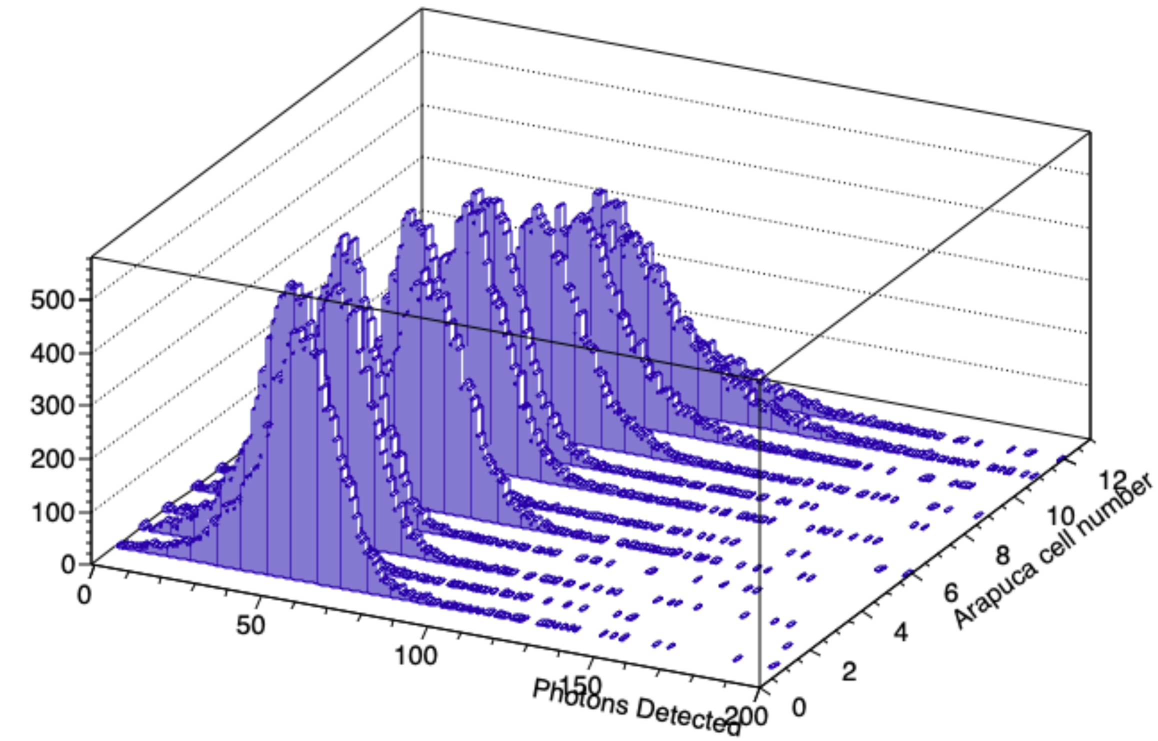
$$\frac{\sigma_{N_{Ph}}}{N_{Ph}} = \sqrt{k_1^2 + \left(\frac{k_2}{\sqrt{KE}}\right)^2 + \left(\frac{k_3}{KE}\right)^2}$$

Arapuca spectra cell by cell

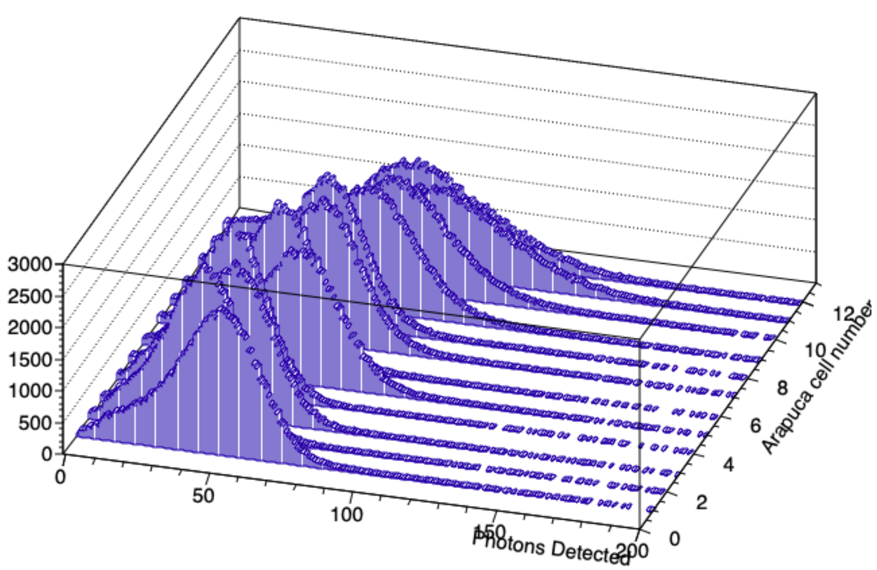
Arapuca signle cell spectra for Protons of BM = 7 GeV/c



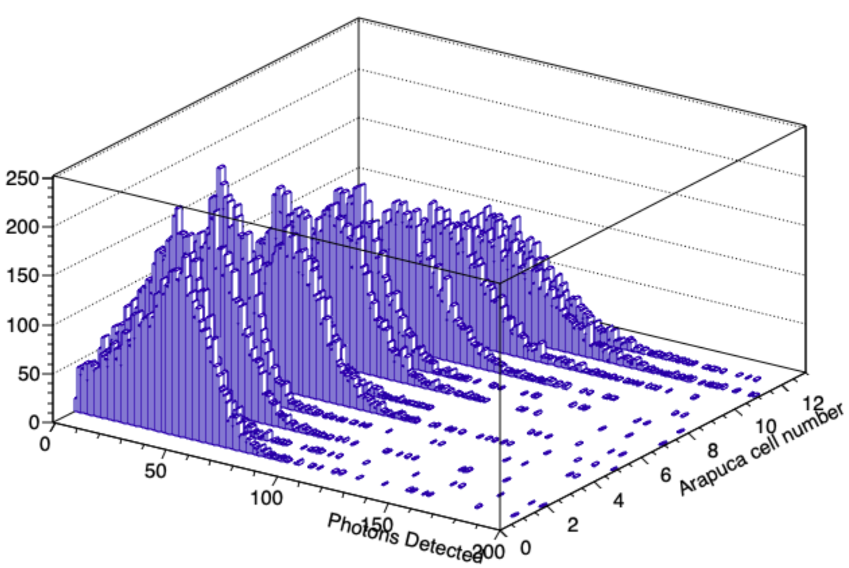
Arapuca signle cell spectra for Electrons of BM = 7 GeV/c



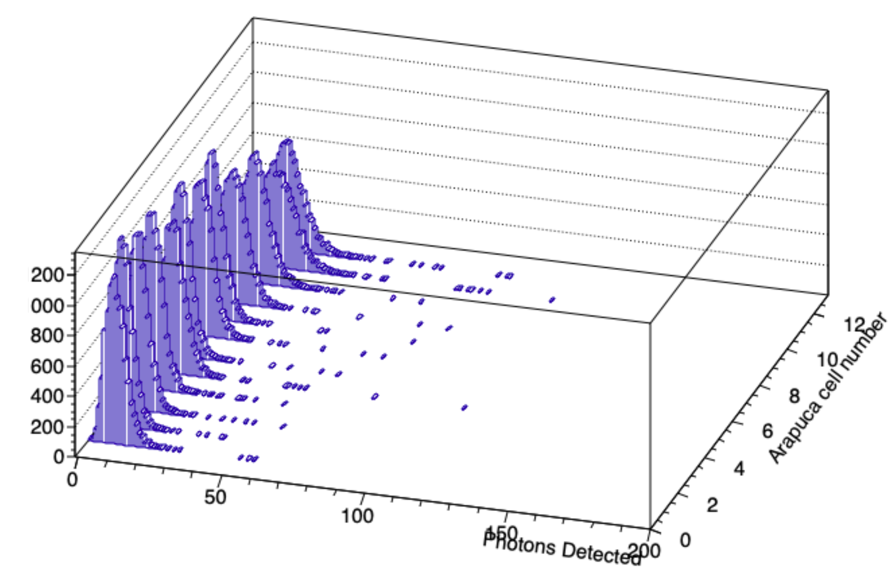
Arapuca signle cell spectra for Pions of BM = 7 GeV/c



Arapuca signle cell spectra for Kaons of BM = 7 GeV/c

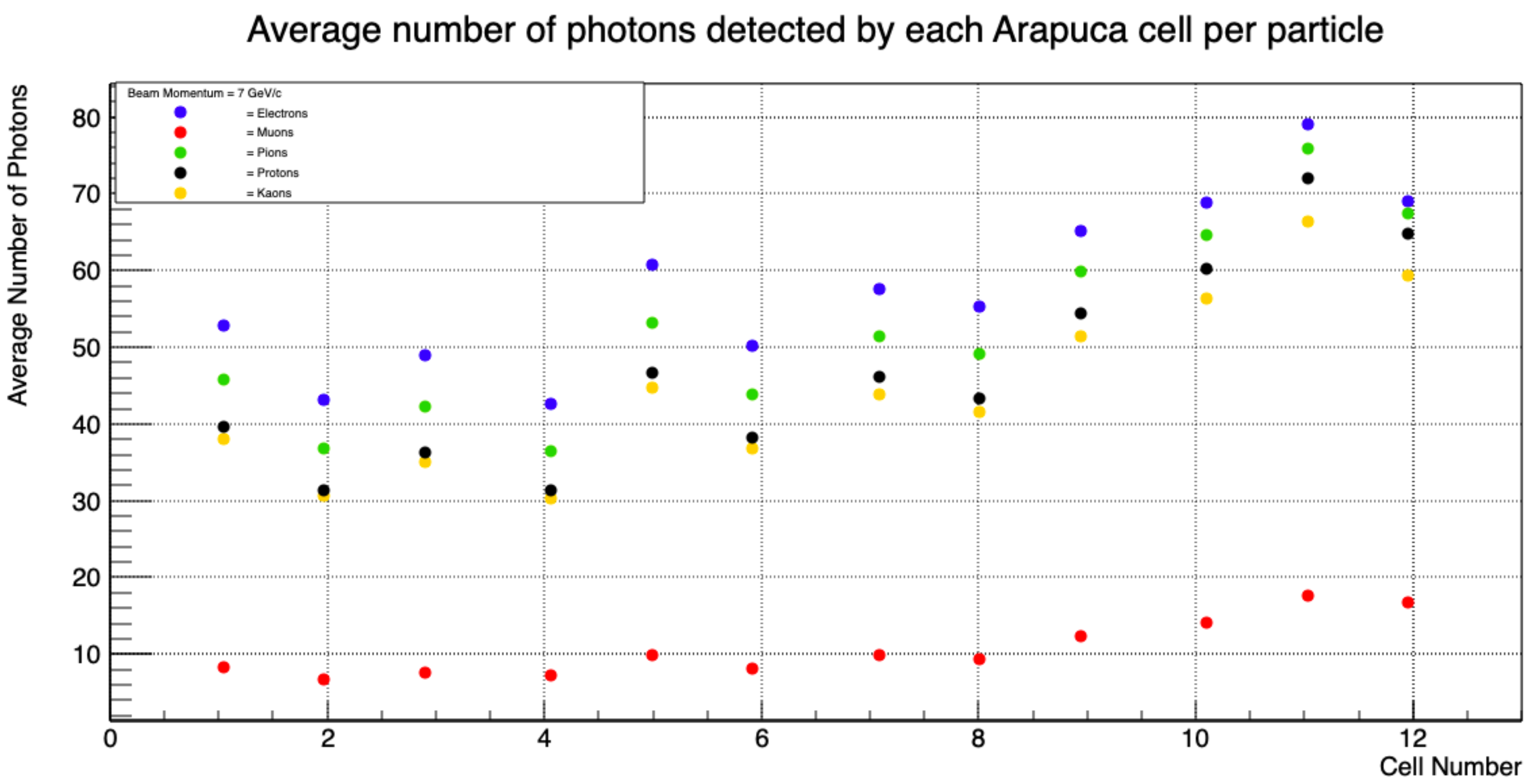


Arapuca signle cell spectra for Muons of BM = 7 GeV/c



Arapuca <Ph> Detected cell by cell

Cell 1 = DAQ channel 132 , Cell 2 = DAQ ch 133 , ….
The geometrical position have to be fixed, as well as, what are the channels with two Arapuca connected in parallele and the channels with only one Arapuca



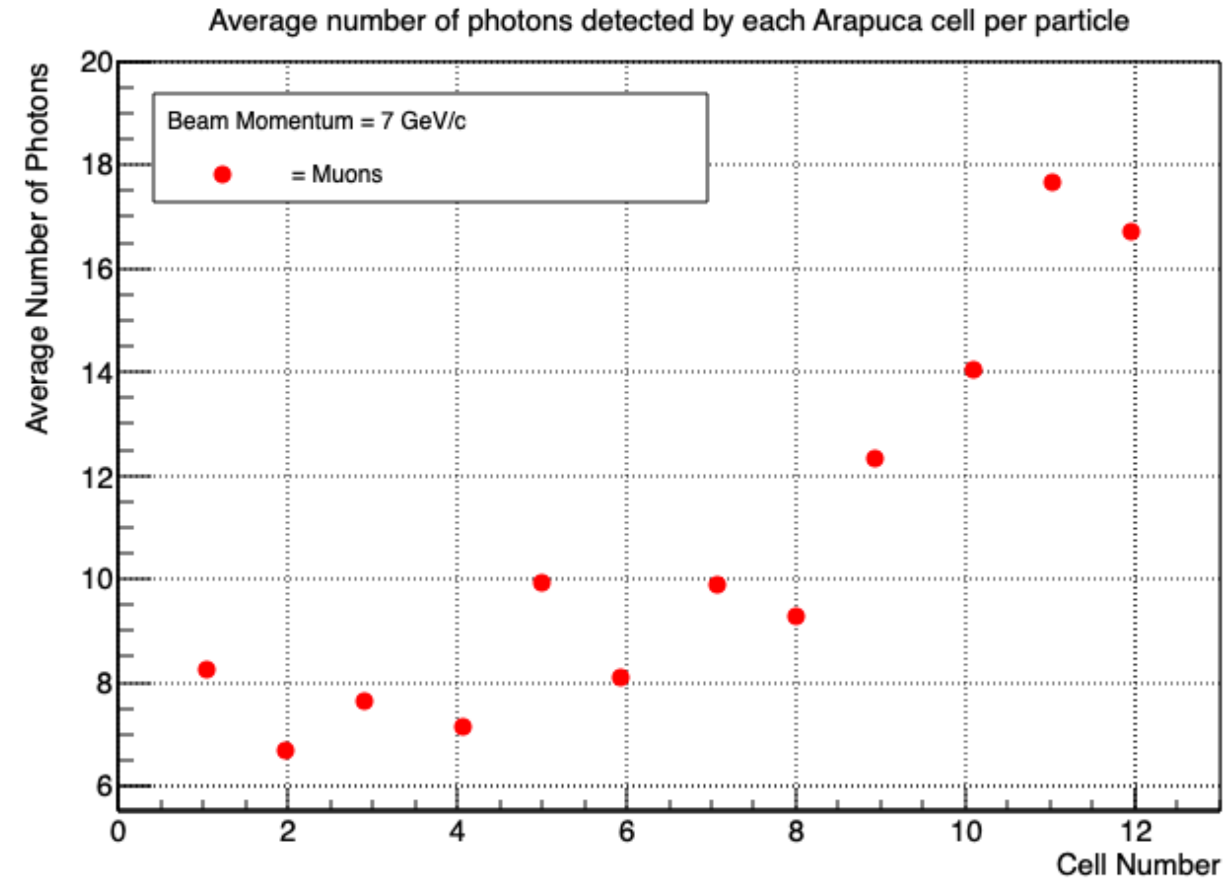
Muons: data & simulation

MC simulation has been made by **Laura Paulucci** and **Franciole Marinho**

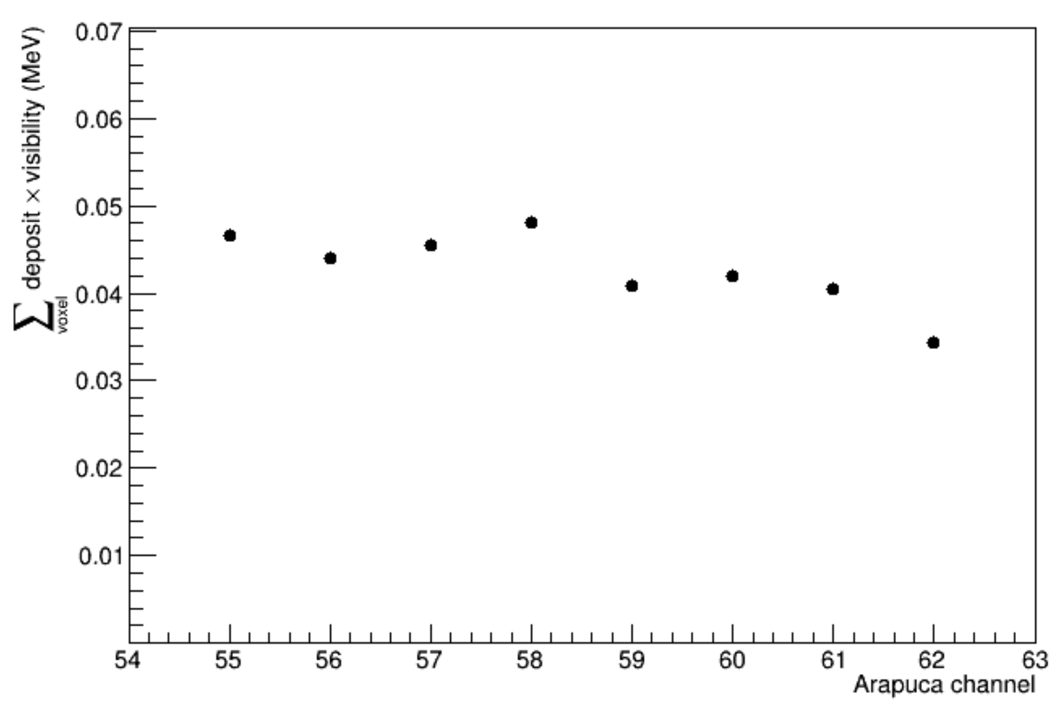
The plots below show the fraction of energy deposited normalized the acceptance of each cell.

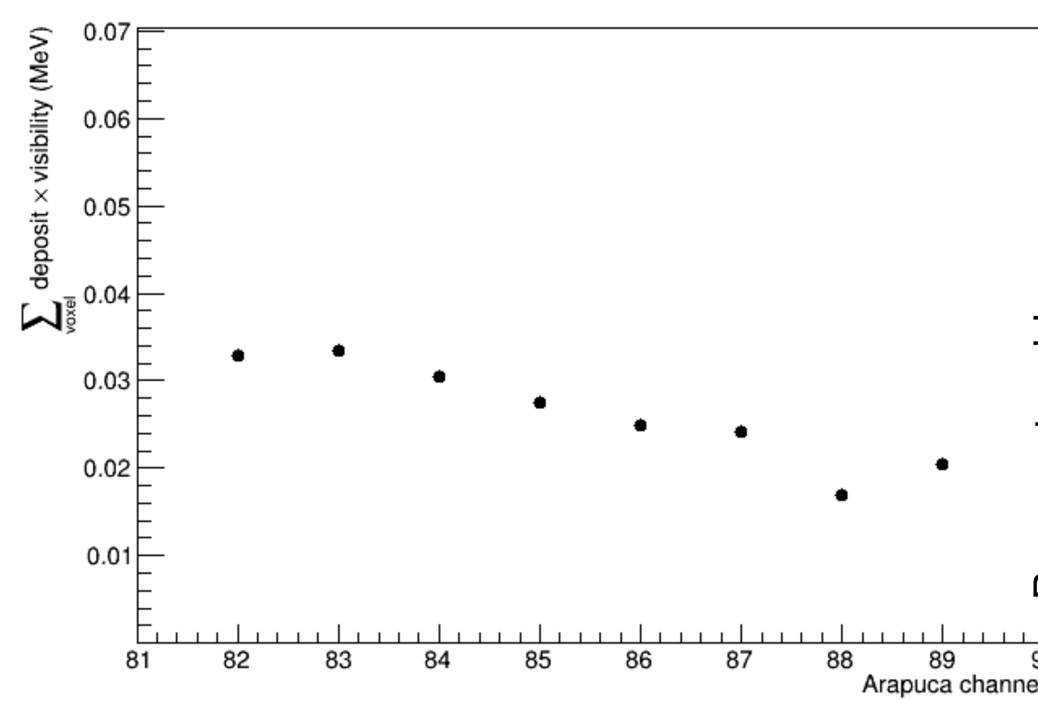
The channel in MC have another labeling and the points are relatives to the Arapuca cells and not to the channels (12 channels for 16 Arapuca).

Data



Simulation

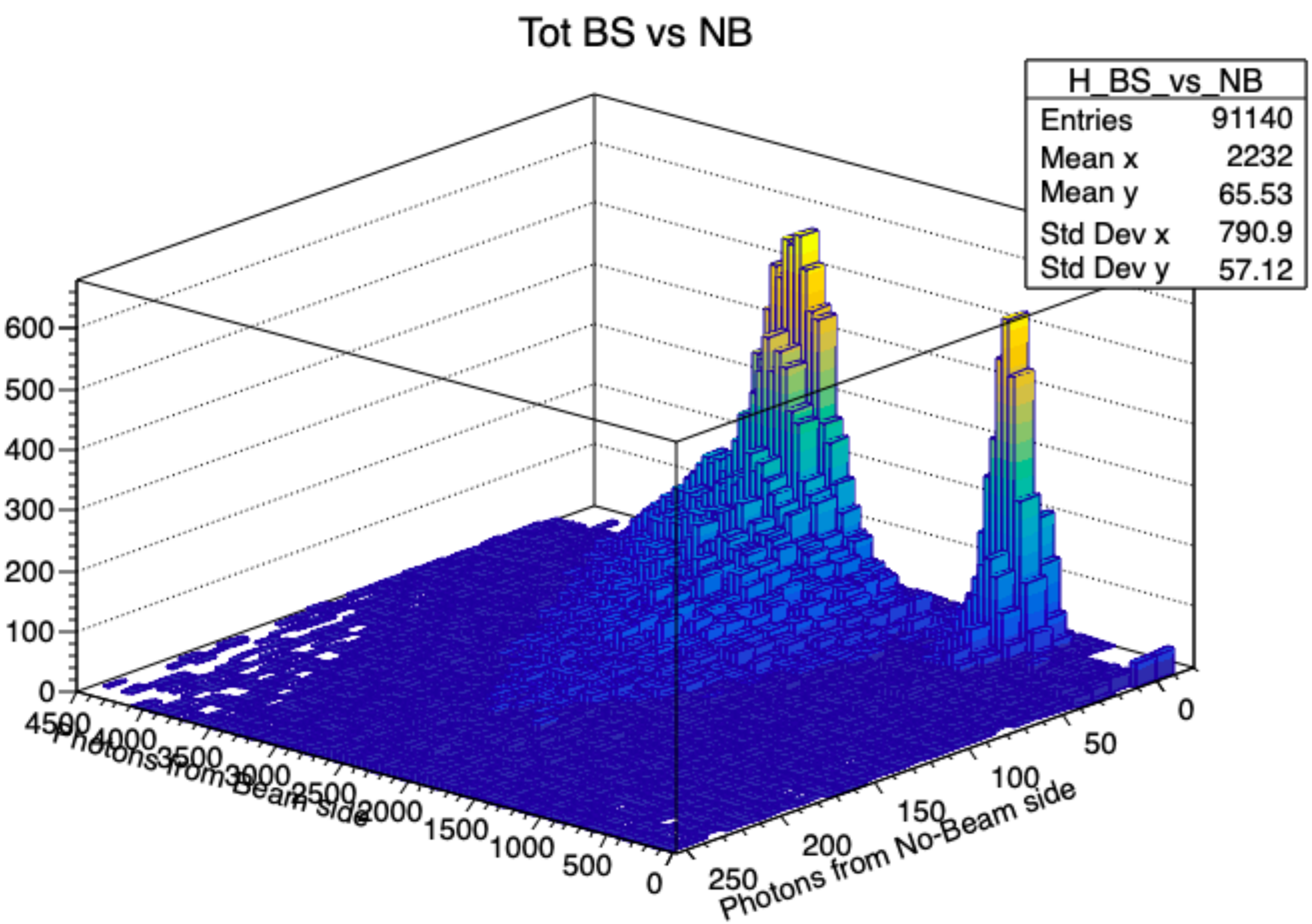




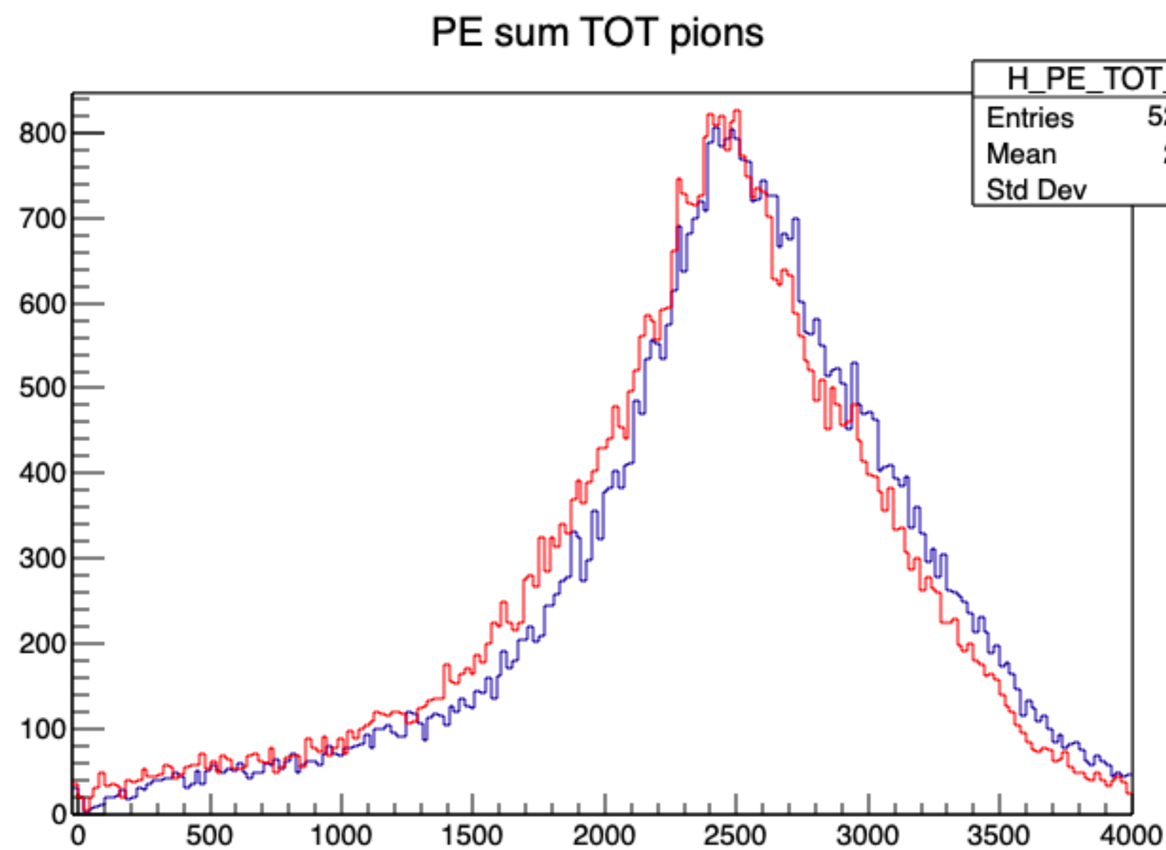
Beam entry side

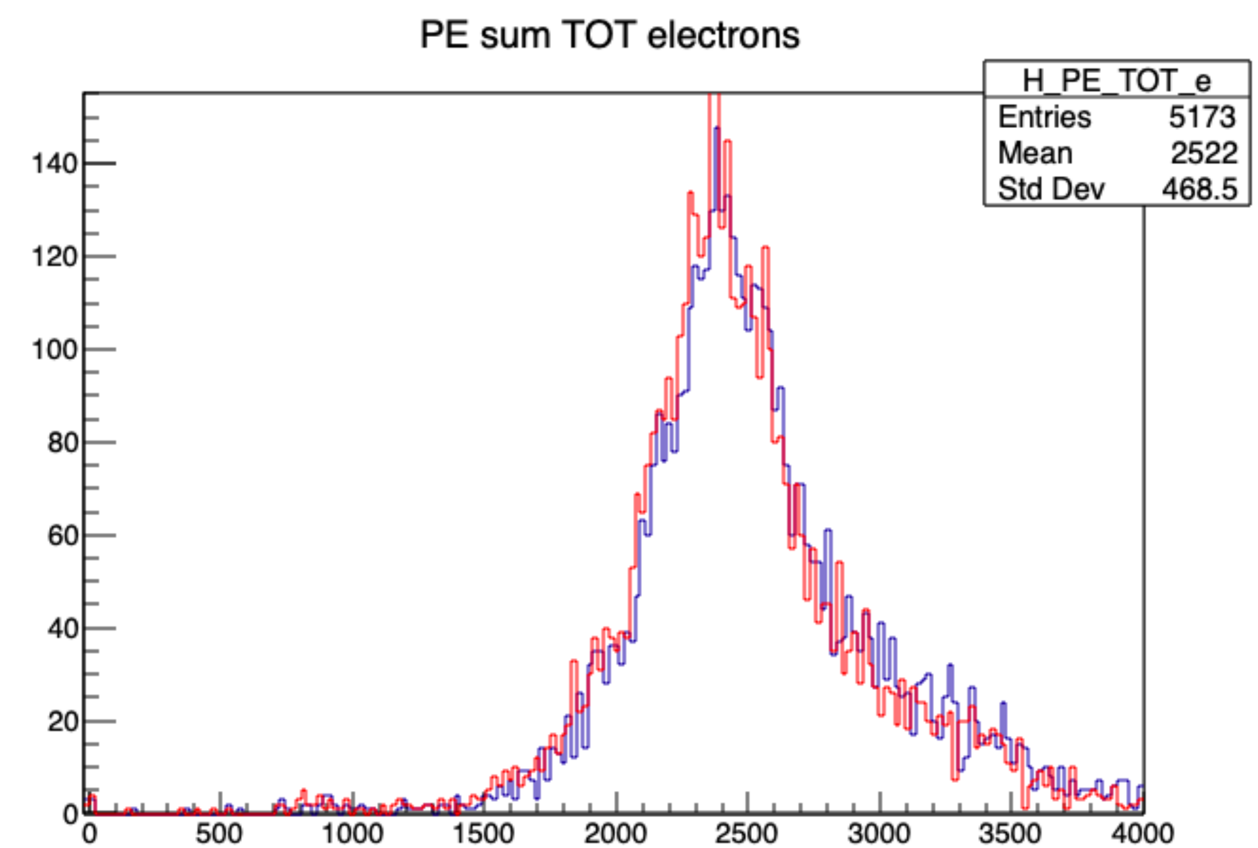
Z axis

Next step:
investigation about No-Beam side ionization particle escape



Summing all the six APAs.
(in this plots are missing some PD modules: all APA 4 and four PD modules in APA 5)



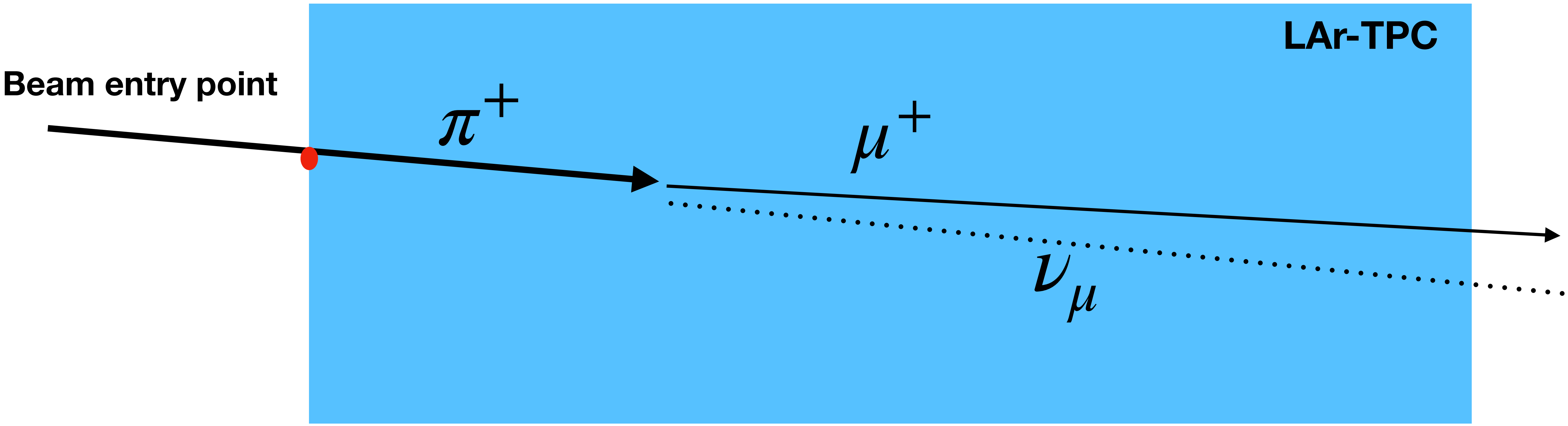


In these plots are reported the Spectra for sum in APA 1,2,3
And spectra for sum in APA 1,2,3,5,6.
When we add No-Beam side APAs we can see a shift in the Pions spectra but not in the Electrons spectra.

Some ionizing particles from hadronic shower cross the cathode, we are investigating about it

Back up

Muons from pions and kaons decay



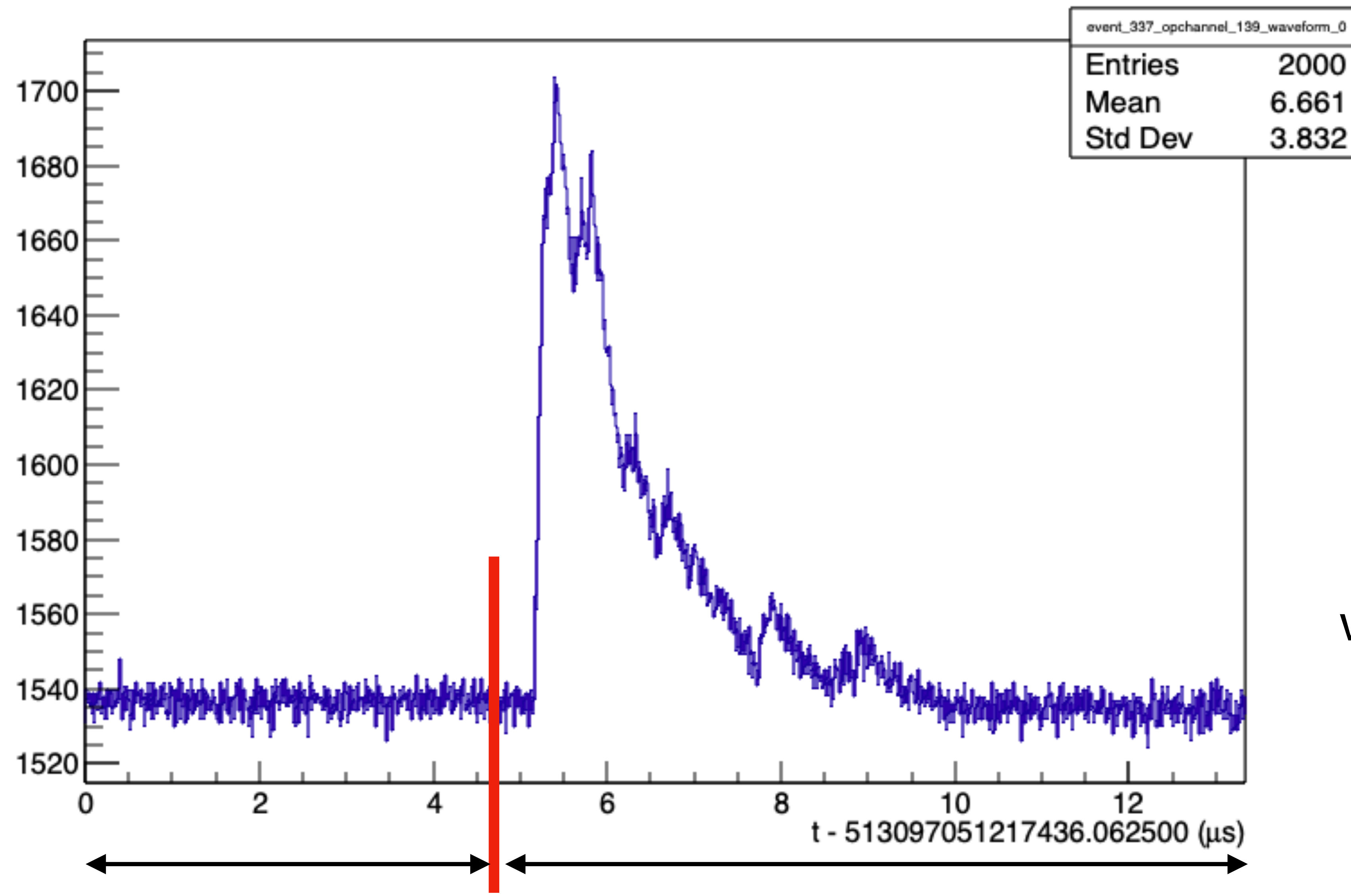
Pions and kaons, which decay in a muon before triggering a shower, ionize as a muon (~ as a MIP).

The final spectra is ~ equivalent to an entry muon.

$BR\left(k^+ \to \mu^+ + \nu_\mu\right) \simeq 63\,\%$ $\quad$ $BR\left(\pi^+ \to \mu^+ + \nu_\mu\right) \simeq 100\,\%$

Waveforms analysis

Original waveform triggered by the beam, as recorded by the SSP (channel 139, Arapuca).



Pre trigger window
700 ticks = 4.666 μs

Integration window
1300 tiks = 8.666 μs

Pre trigger window is used to evaluate the waveform baseline

The charge integral window starts before the trigger point (~300 ns) until the end of the waveform