# First calorimetric energy reconstruction of beam events from LAr scintillation light in protoDUNE-SP and single photon rate observation

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on behalf of the DUNE collaboration

LIDINE August 29th, 2019

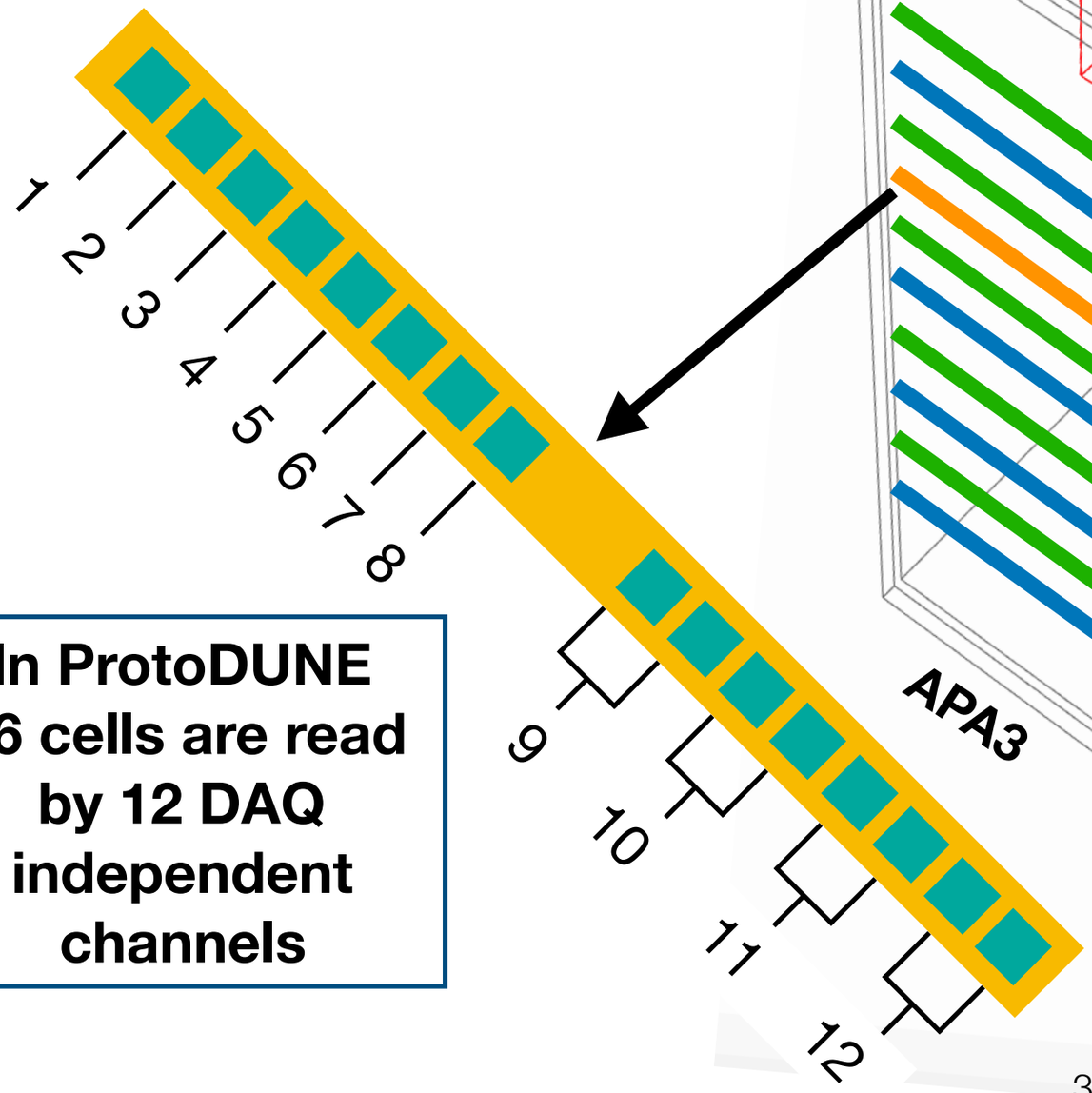
# Outline

- **ProtoDUNE photodetector system**
- **Particle identification**
- **Photodetector response to beam electrons**
- **Arapuca response to beam electrons**
- **Single photon rate from space charge**

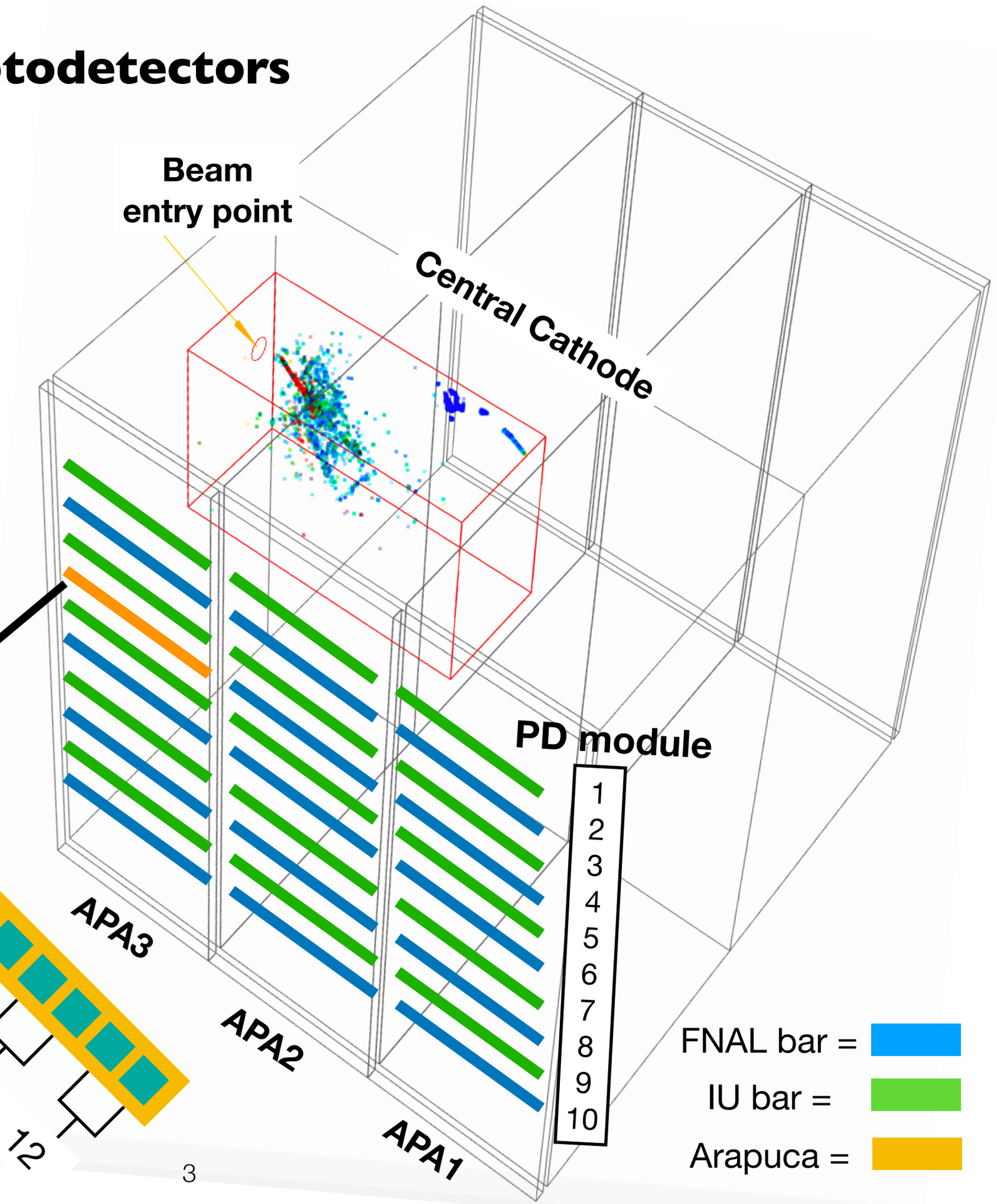
# ProtoDUNE-SP photodetectors

## Arapuca detector

**One Arapuca module is composed by 16 independent cells 8x10cm^2**




**In ProtoDUNE 16 cells are read by 12 DAQ independent channels**



# Particles identification

## - Cherenkov PID

| 6, 7 Gev/c | HP | LP | 3 GeV/c | HP | LP | 2, 1, 0.5, 0.3 GeV/c | LP |
|---|---|---|---|---|---|---|---|
| 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** |

LP (HP)= Low (Hi) pressure

## - Time of Flight

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

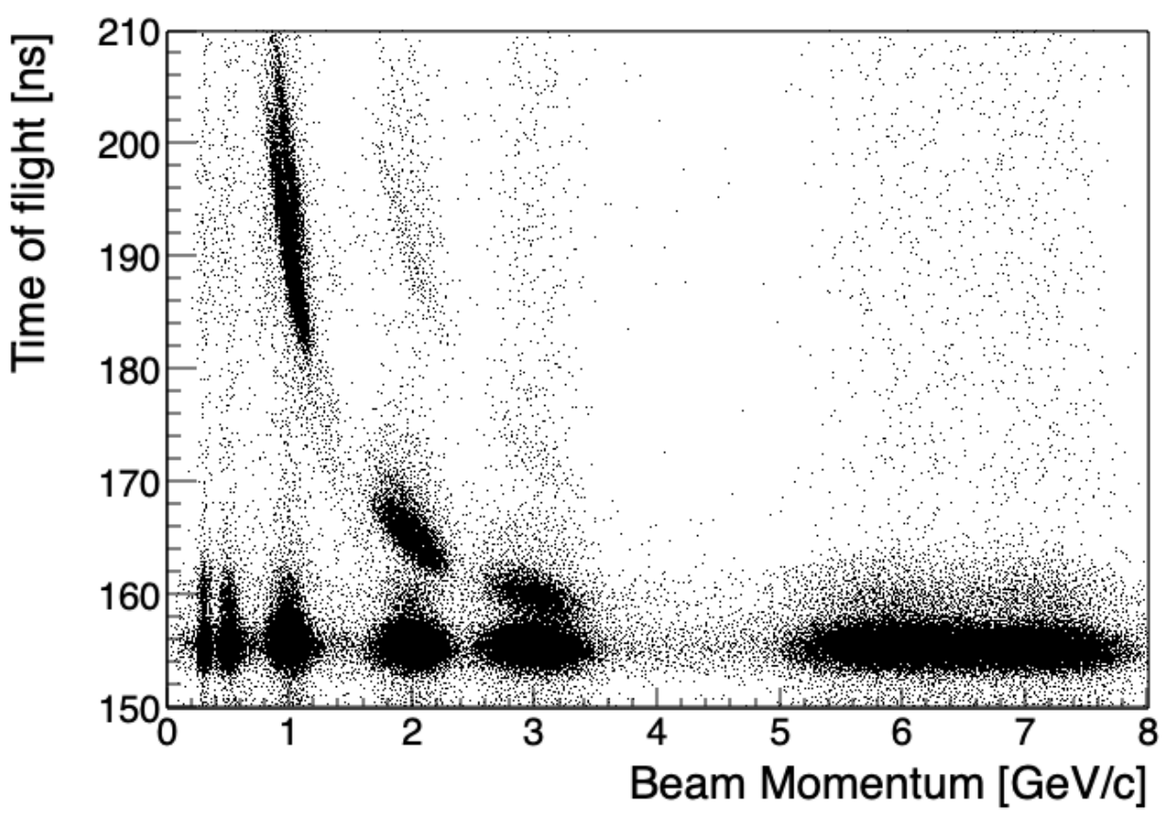
For 0.3/0.5/1 GeV/c:
TOF < 170 ns: pions
Else: protons

## - TPC reconstruction

For 6/7 GeV/c, pions and electrons are classified thanks the signature given by Pandora, a multi-algorithm approach to automated pattern recognition

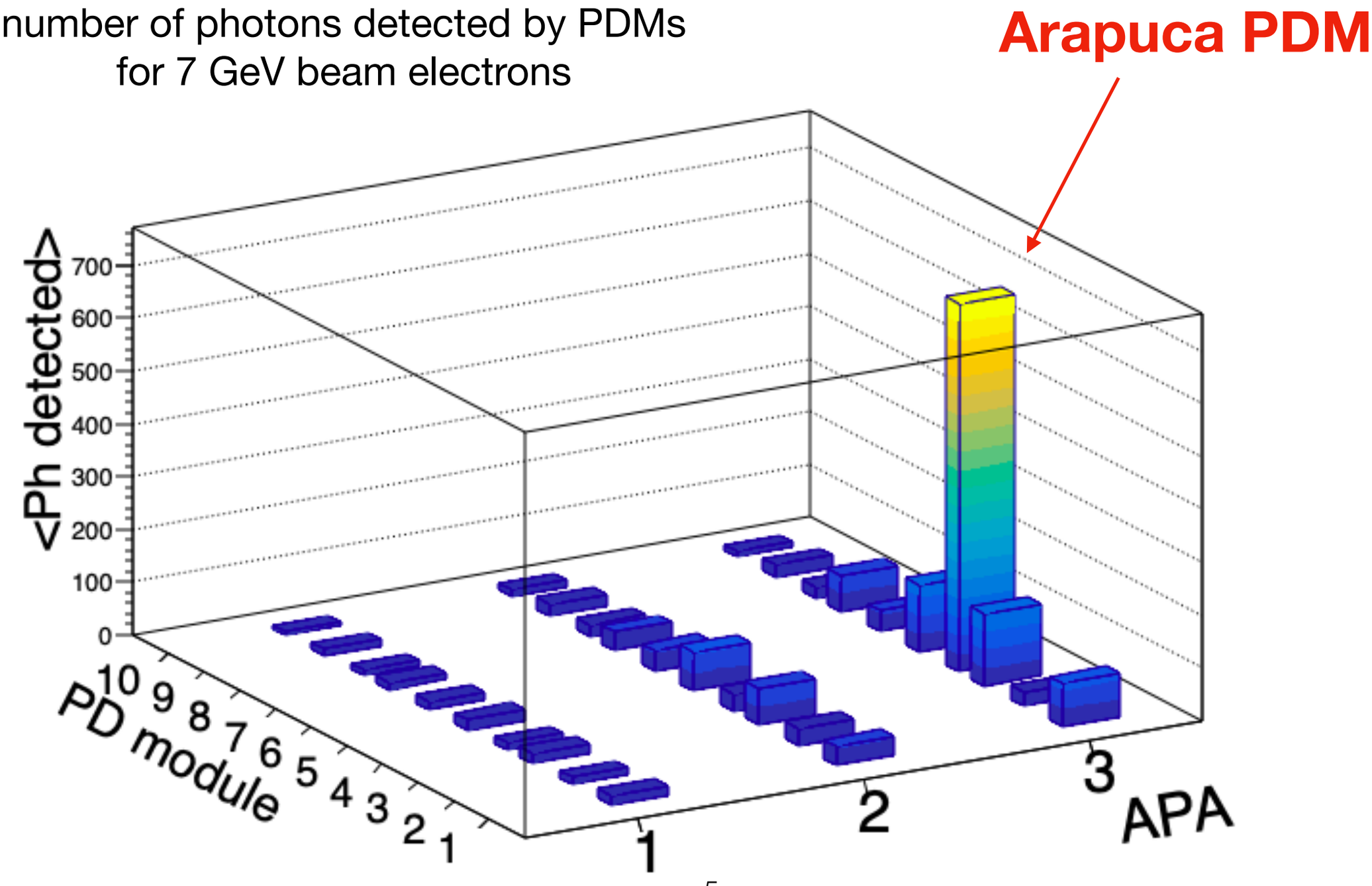
## - Spectra analysis

Muons peak from pions and kaons spectra,  out layer events removal



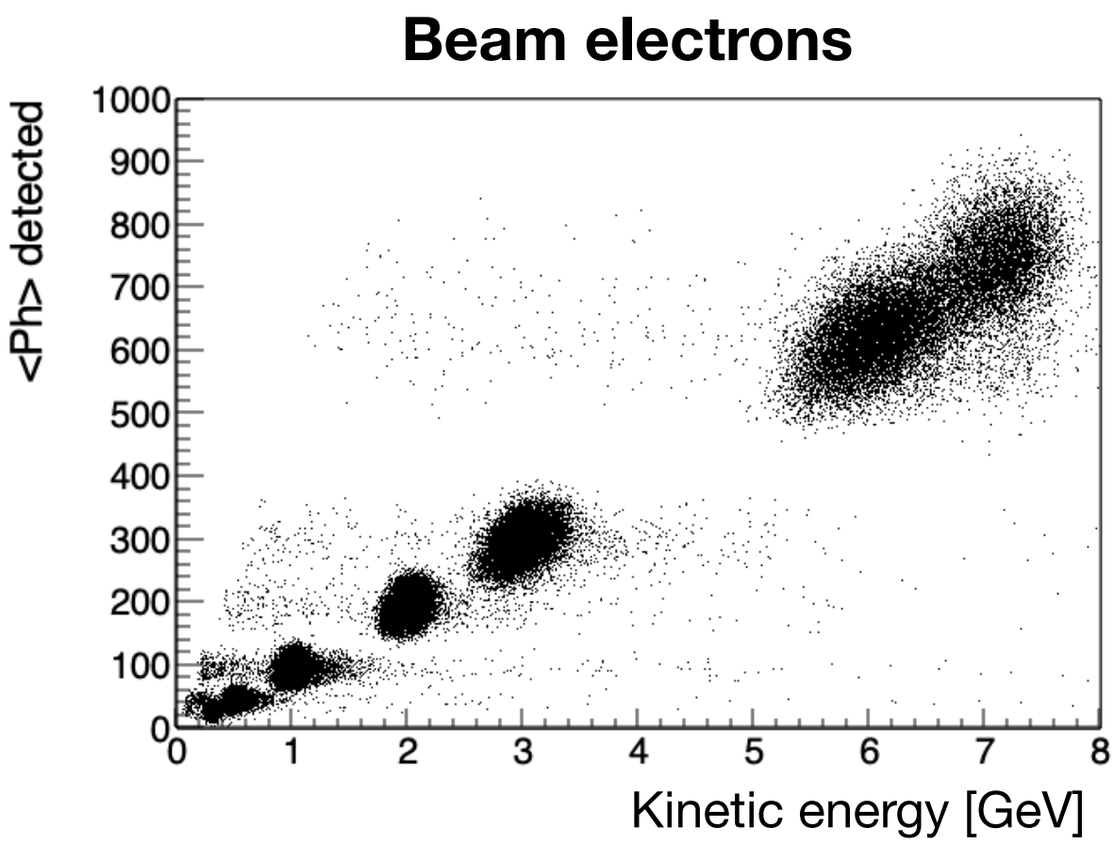
# PD response to 7 GeV beam electrons

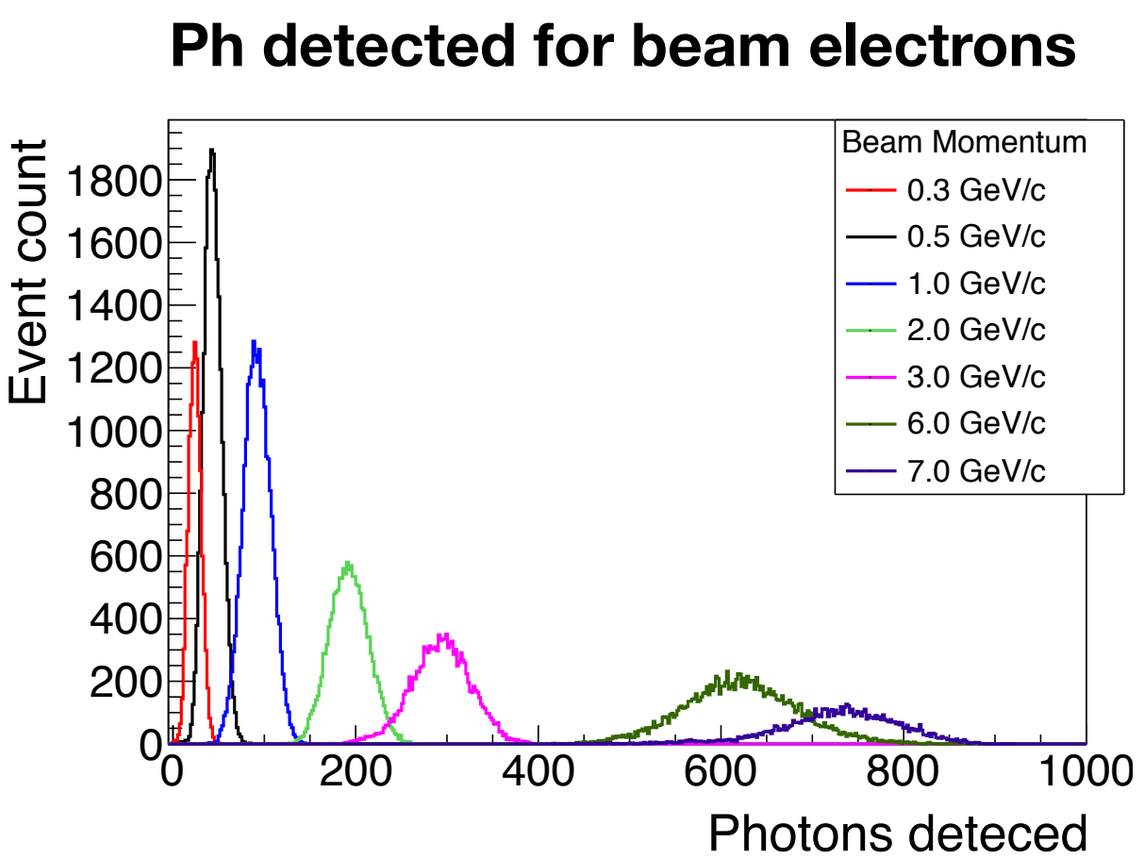
Electrons showers localize in front of the first APA (APA3). Here are reported the average number of photons detected by PDMs for 7 GeV beam electrons

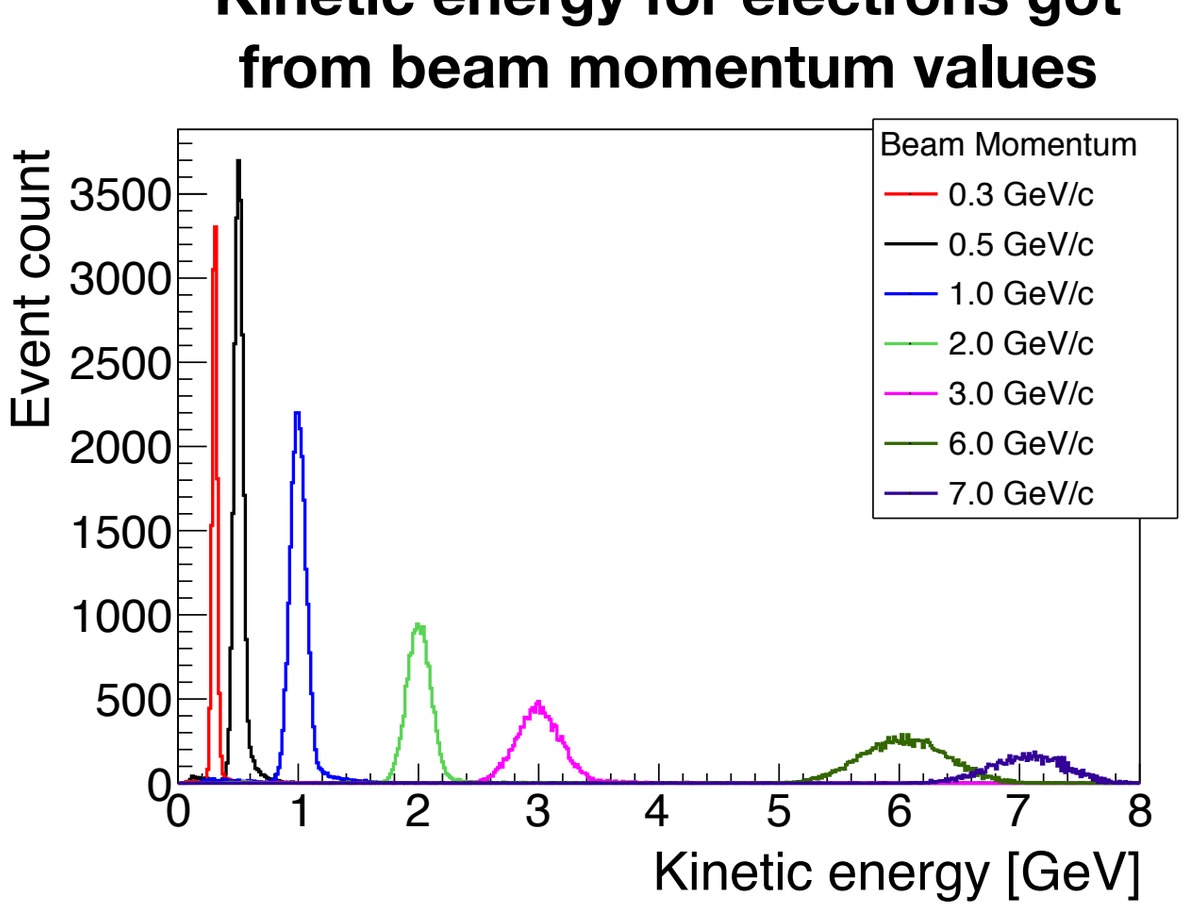


# Arapuca PDM response to beam electrons

For each beam momentum nominal value photon detected spectra and kinetic energy spectra are fitted with gaussian distributions. Two quantities are then analyzed: linear response and resolution.



# Arapuca linear response to electrons kinetic energy

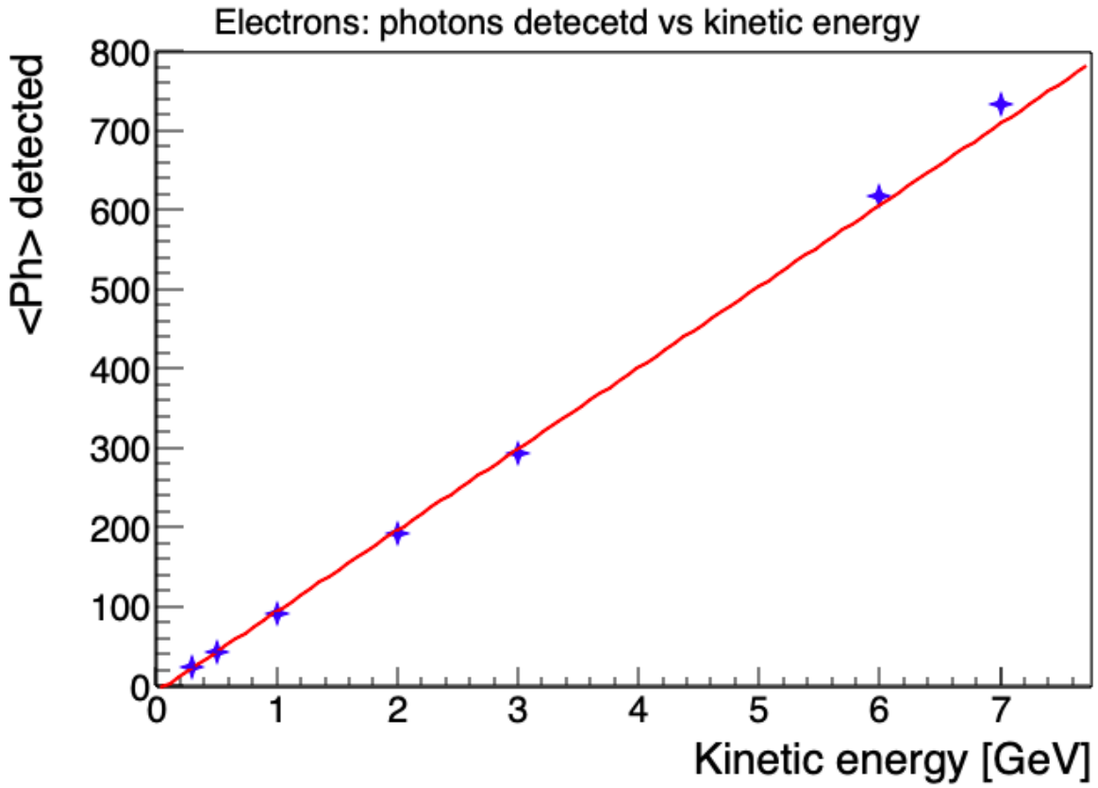
Linearity between photon detected and electrons kinetic energy is checked using the mean values got from the gaussian fit for both quantities.

A linear fit is made using the function: $N_{ph} = m \cdot KE + q$

Getting for the parameters:

$$m = 102.44 \pm 0.05 \left[\frac{Ph}{GeV}\right]$$

$$q = -8.25 \pm 0.05 \, [Ph]$$




The constant term is needed and expected negative, since there is lose of energy due:

- material to cross before particles entering TPC
- small fraction of particles in the showers can cross the cathode

# Arapuca intrinsic resolution to beam electrons

The detector resolution $\frac{\sigma_{Ph}}{\mu_{Ph}}(KE)$ depends from more factors. It can be parametrized with the general equation:

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

The fit result gives:

$k_1 = 0.060 \pm 0.007$

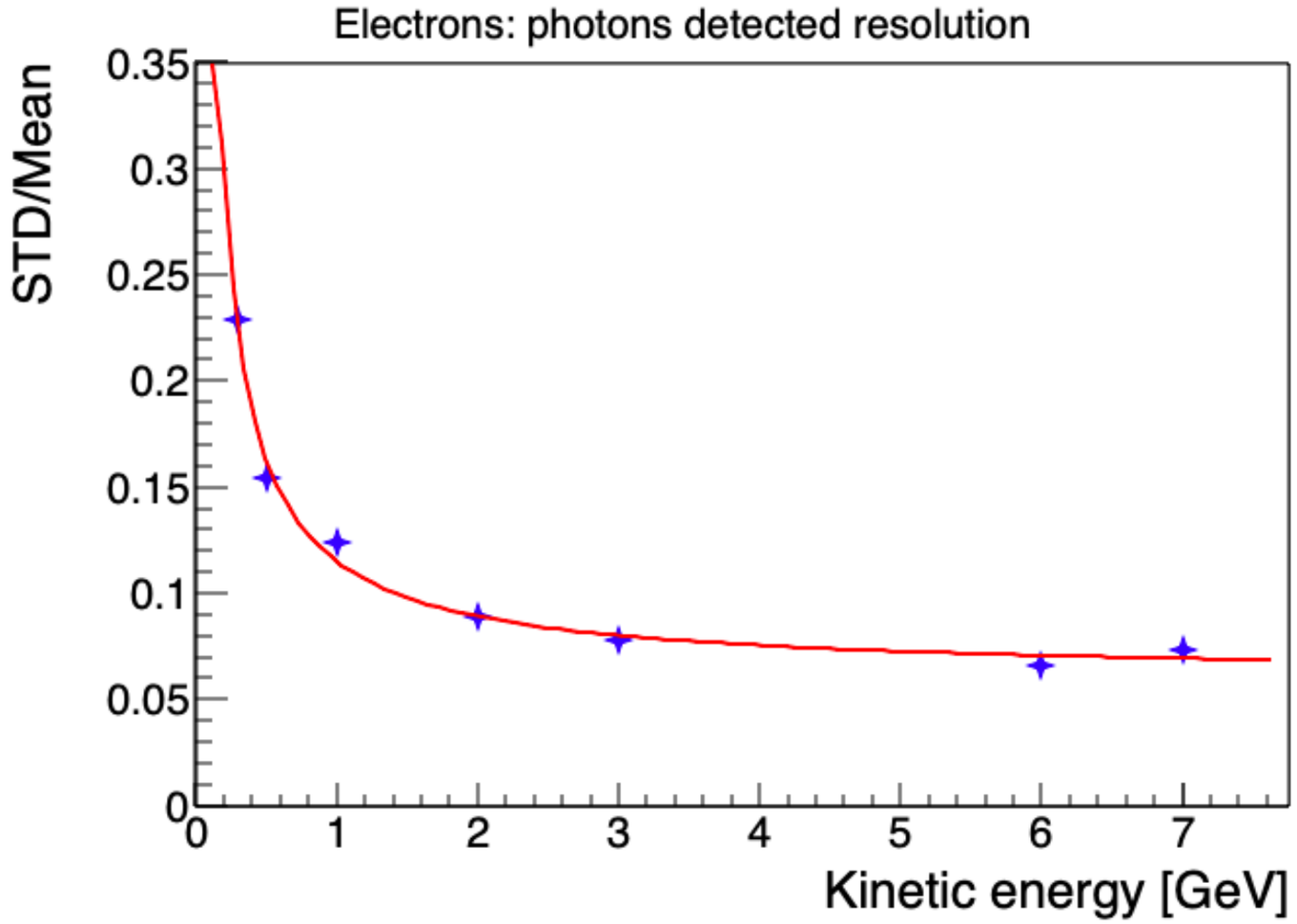
$k_2 = 0.08 \pm 0.01 \left[\sqrt{GeV}\right]$

$k_3 = 0.04 \pm 0.01 \, [GeV]$

The intrinsic resolution $\propto \frac{1}{\sqrt{KE}}$

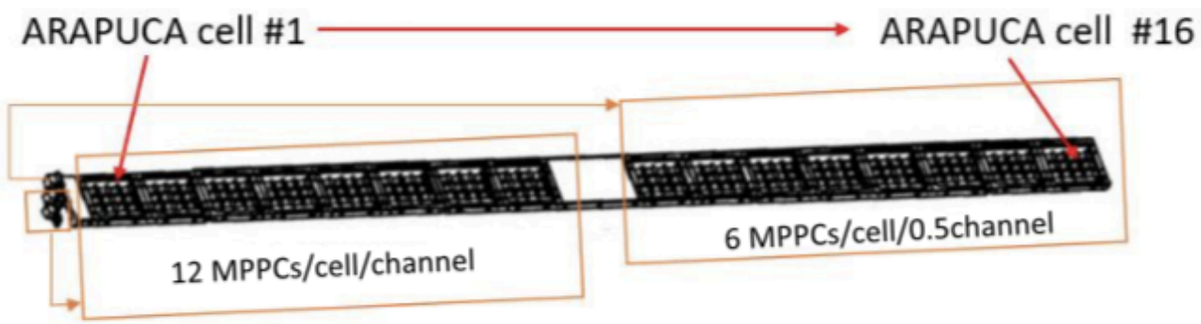
and can be identified with:

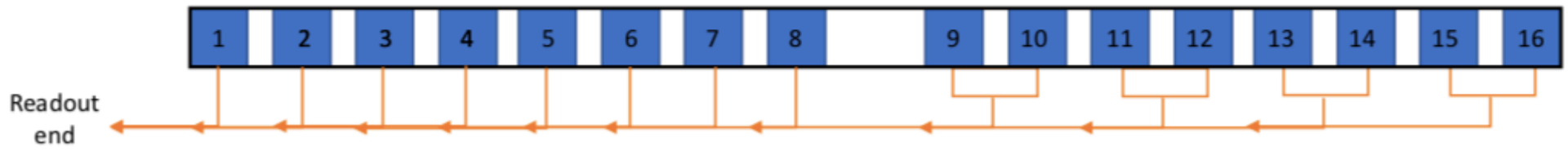
$$k_2 = 0.08 \pm 0.01 \left[\sqrt{GeV}\right]$$



# Single photon rate: first results in ProtoDUNE
# The Arapuca detector granularity

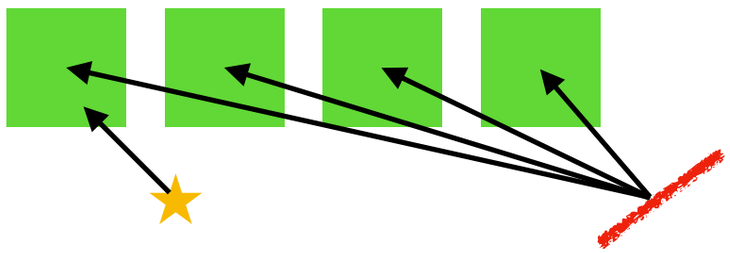
**In protoDUNE the 2 Arapuca modules installed consist in 16 cells 8 read by a single channel and 8 read in couples**




Arapuca granularity can be exploited for more applications: an example is **Space Charge dependence from the electric field** about which a model developed by **Flavio Cavanna** and **Xiao Luo** has just been presented by Xiao in the previous talk

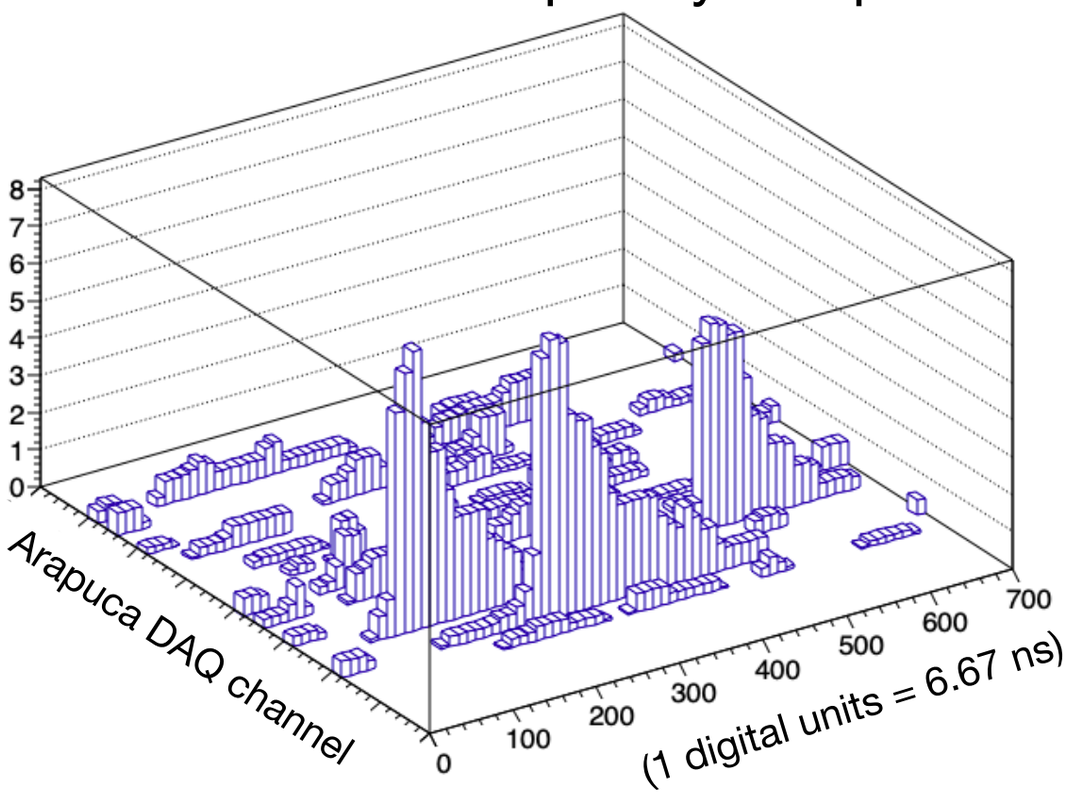
# Single photons and ionizing events



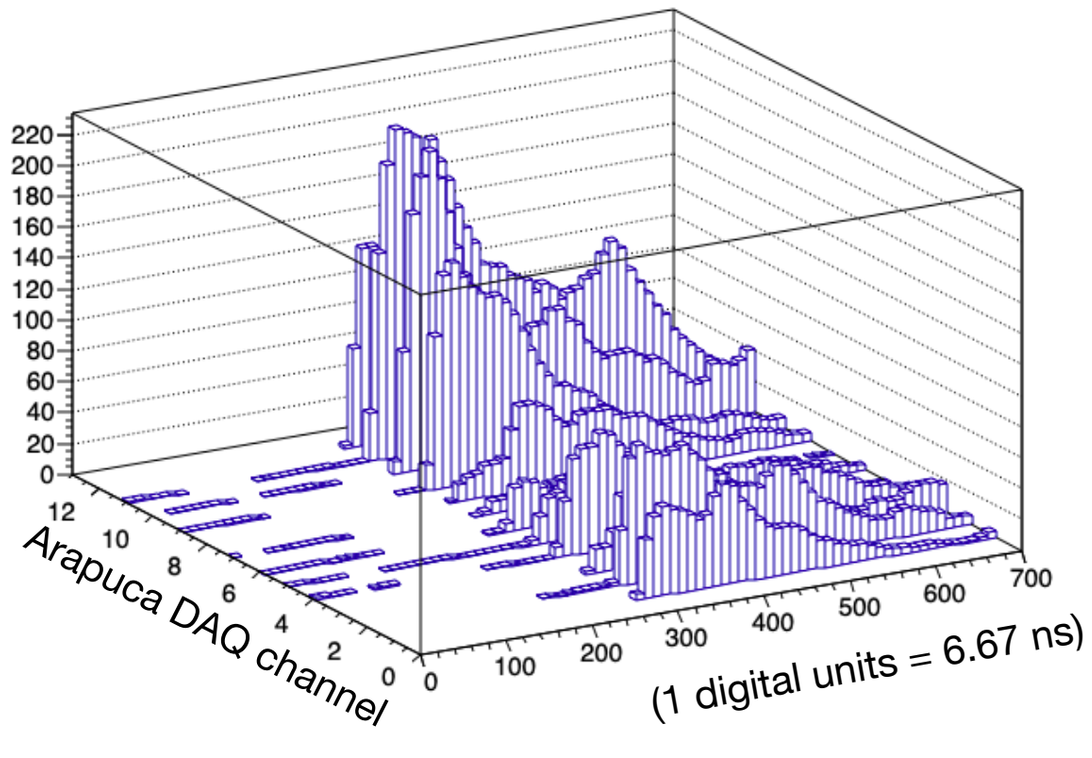
We can distinguish two kind of light events in a LAr TPC:

- **Light from ionizing events**
- **Single photons from recombination**

Photons from electrons-ions and ion-ion recombination are completely independents

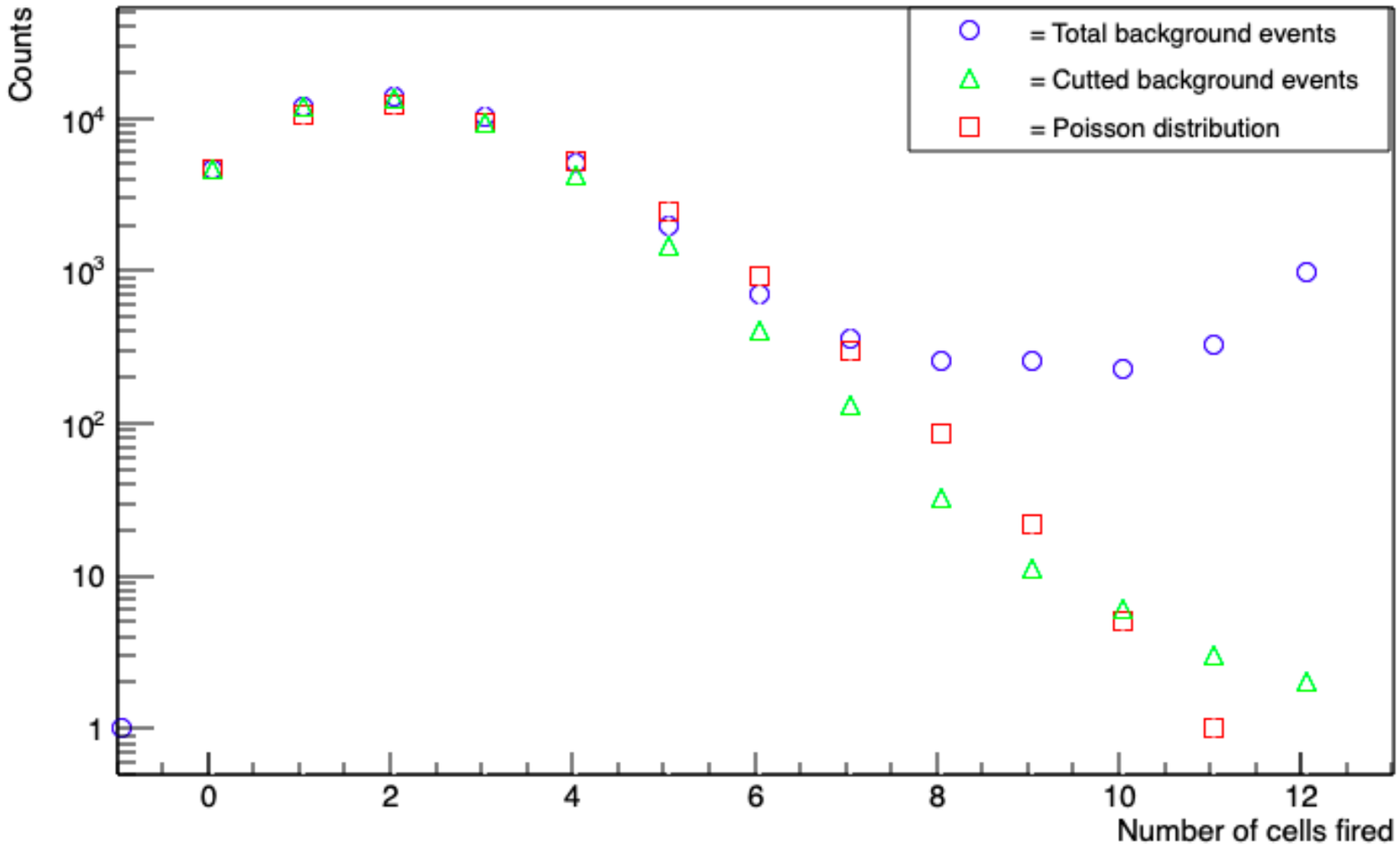



Ionizing events produce a certain amount of photons, which reach the light detectors at the same time




**The granularity of Arapuca detector allow to distinguish them and make an estimation of their rate**

# Single photons will fire each single cell with a probability given by Poisson distribution.




**Excluding events where two or more cells presents signals in a defined time window (~60 ns) we can get the amount of single photons rate**

# Single photon rate vs electric field

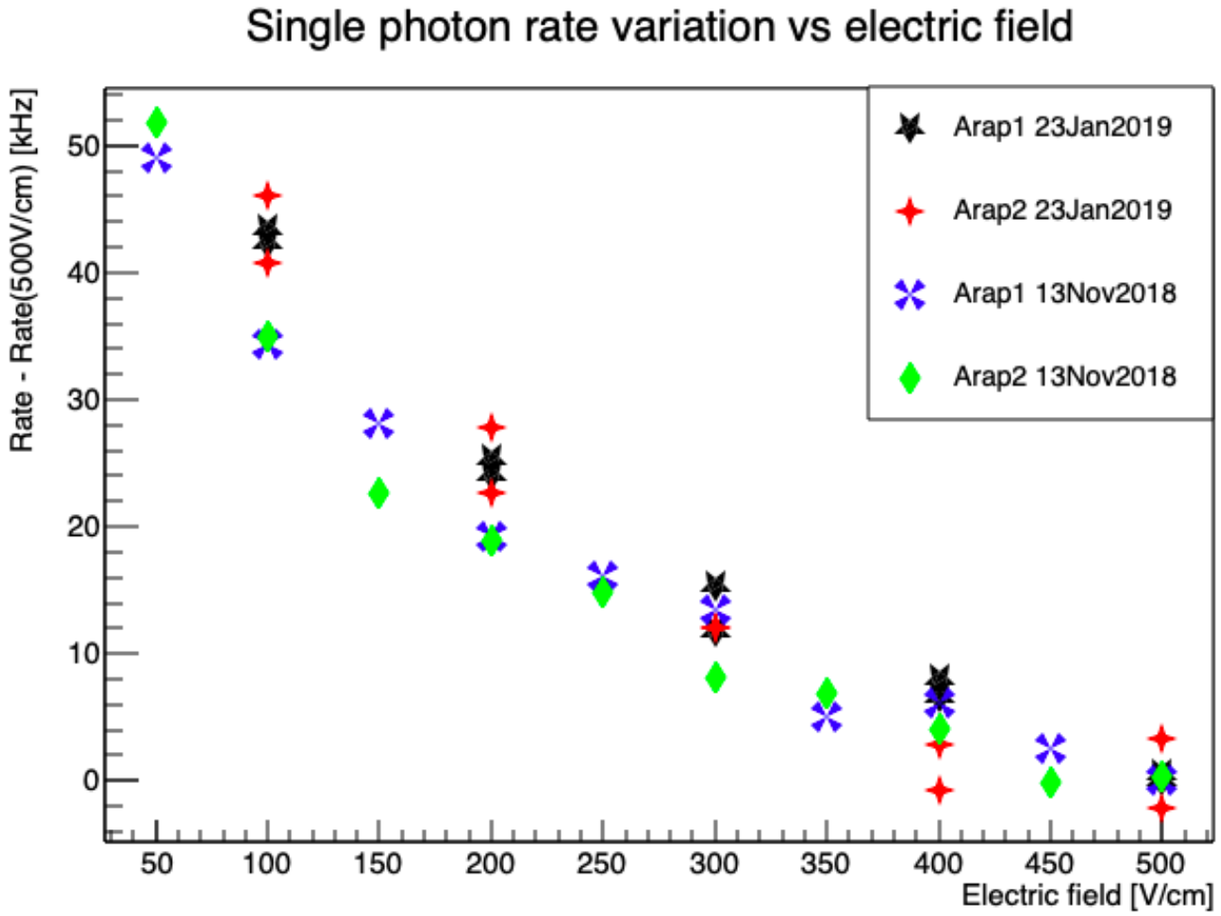
**During the protoDUNE operation period two “ramps” in electric field values were performed to study the space charge effects.**

The absolute value measured at standard protoDUNE conditions :
- electric field: 500 V/cm
- purity:  6 ms (electrons lifetime)

$$< Rate > = 176 \pm 5\, kHz$$

(Average over 15 runs Arapuca PD module 1)

folding in the detector geometric acceptance and photon sensor efficiency (preliminary value) the single photon rate measurement is well aligned with the total photon generation rate predicted from the model: $2 \cdot 10^{10}\, Hz$




The rate reported is normalized subtracting the rate at 500 V/cm.

# Summary

- **Arapuca photodetector has shown good linearity and resolution to beam electrons, as well as high photons collection capability**

$$\frac{N_{ph}}{KE} = 102.4 \frac{Ph}{GeV} \qquad \frac{\sigma_{ph}}{N_{ph}} = \frac{0.08}{\sqrt{KE}}$$

- **Arapuca granularity opens the way to new applications for LAr-TPC photodetector**

- **Single photon rate vs electric field measurements to crosscheck the ions transport model**

- **Single photon rate absolute value from Arapuca PD module 1:**

$$< Rate > = 176 \pm 5\, kHz$$

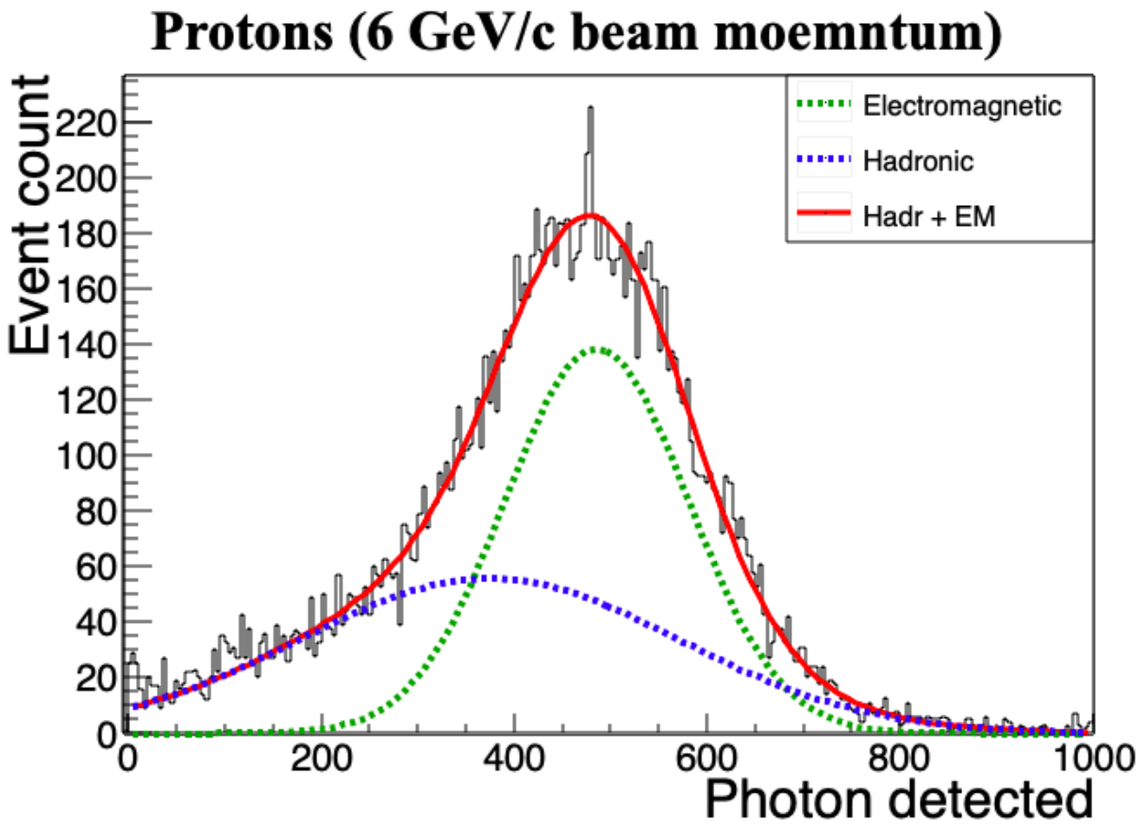
**at ProtoDUNE standard condition (E field = 500 V/cm)**

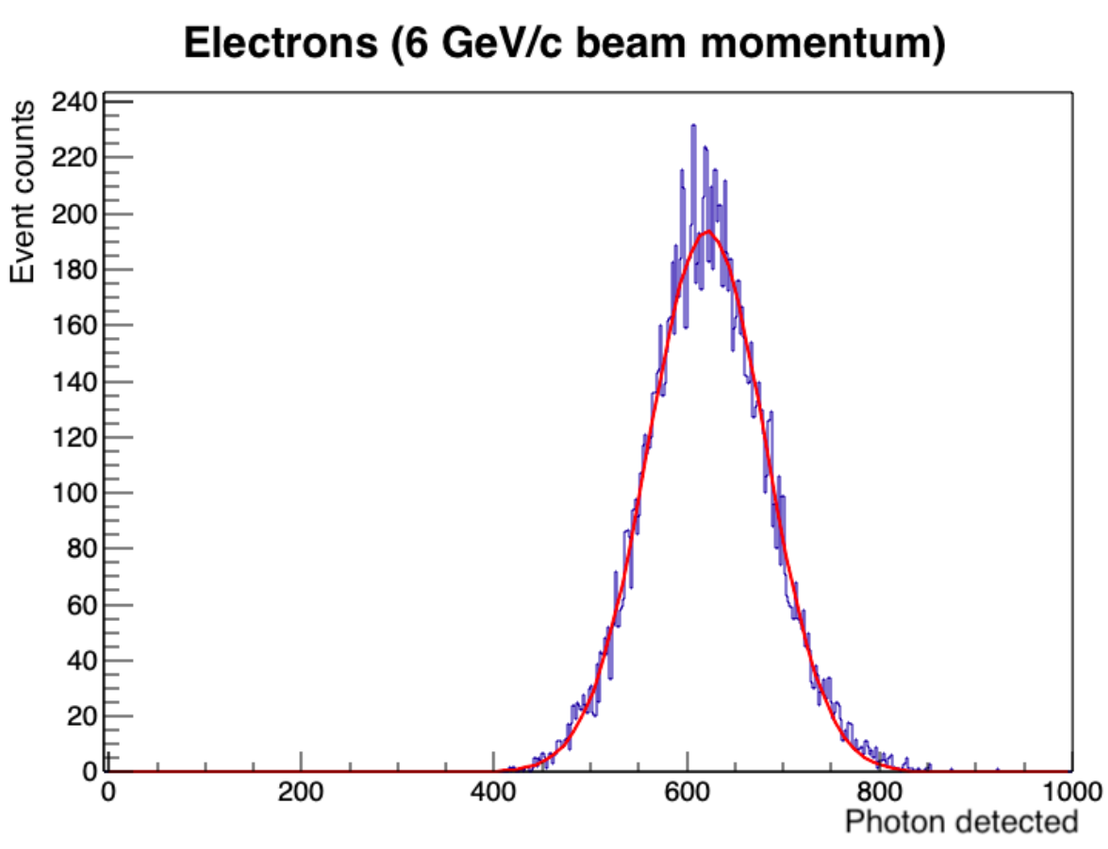
# Thank you

# Back up slides

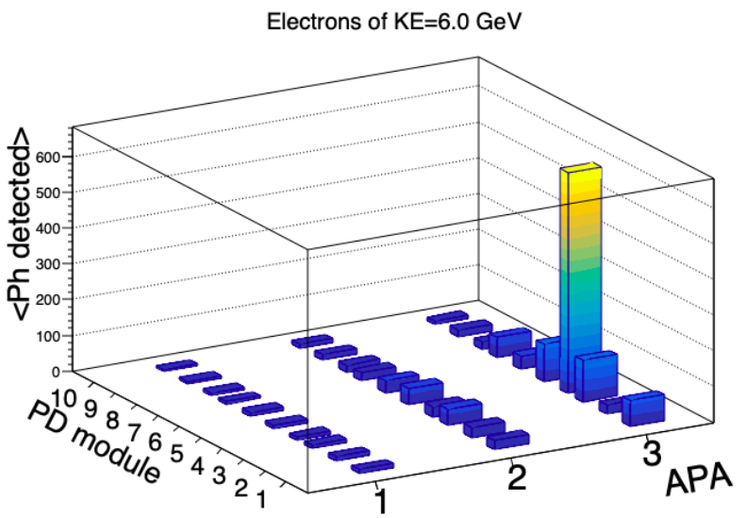
# Electrons vs Protons spectra

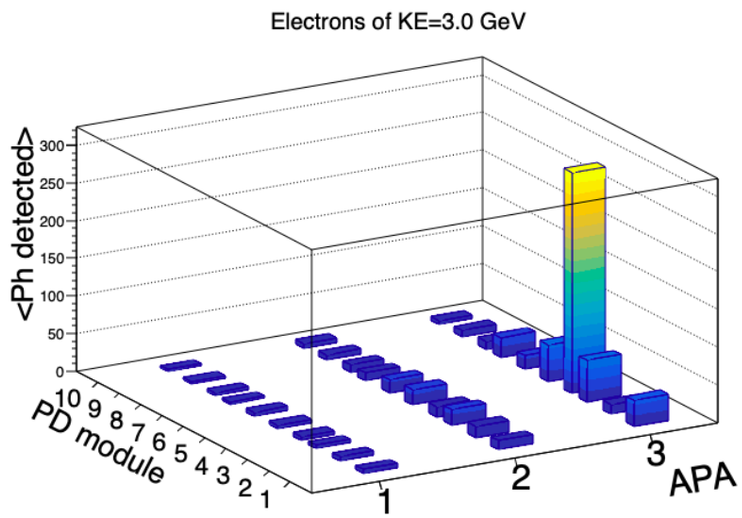
**Protons produce showers where is present the hadronic component, giving a spectrum that is the sum of an hadronic and electromagnetic components. For electrons only the electromagnetic component is present**

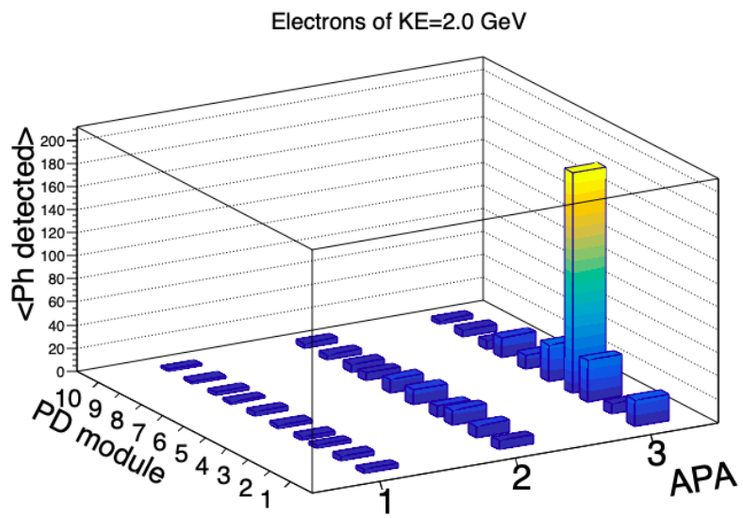


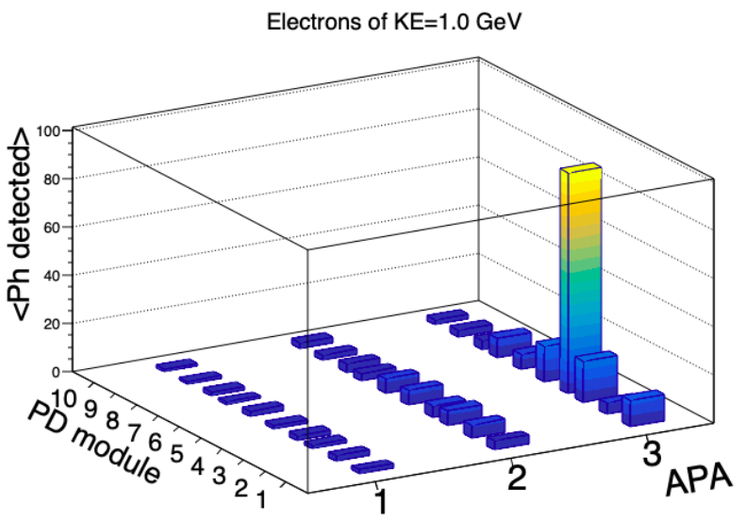



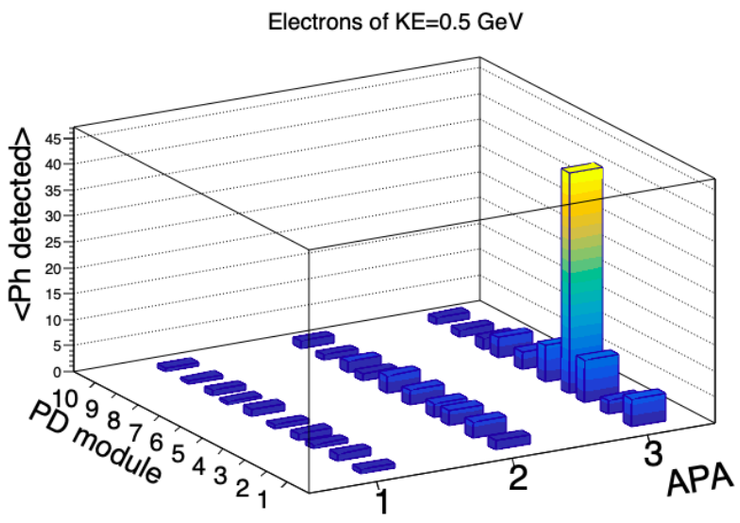
# PD system response to beam electrons

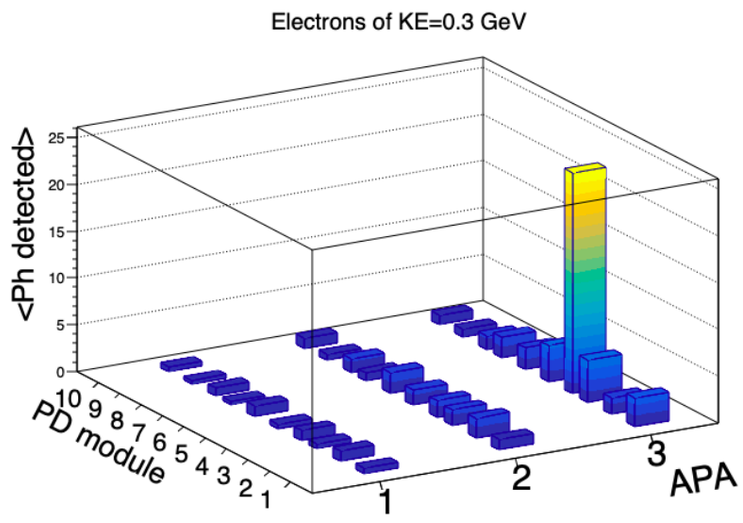


# Arapuca resolution corrections

The kinetic energy too has a spread around its mean values: $\sigma_{KE}$

In the upper plots is reported $\frac{\sigma_{KE}}{\mu_{KE}}\left(\mu_{KE}\right)$

Calling:

$C_d$ : the detector response $\left(N_{ph} = C_d \cdot KE\right)$

$R_d$ : the detector intrinsic resolution:

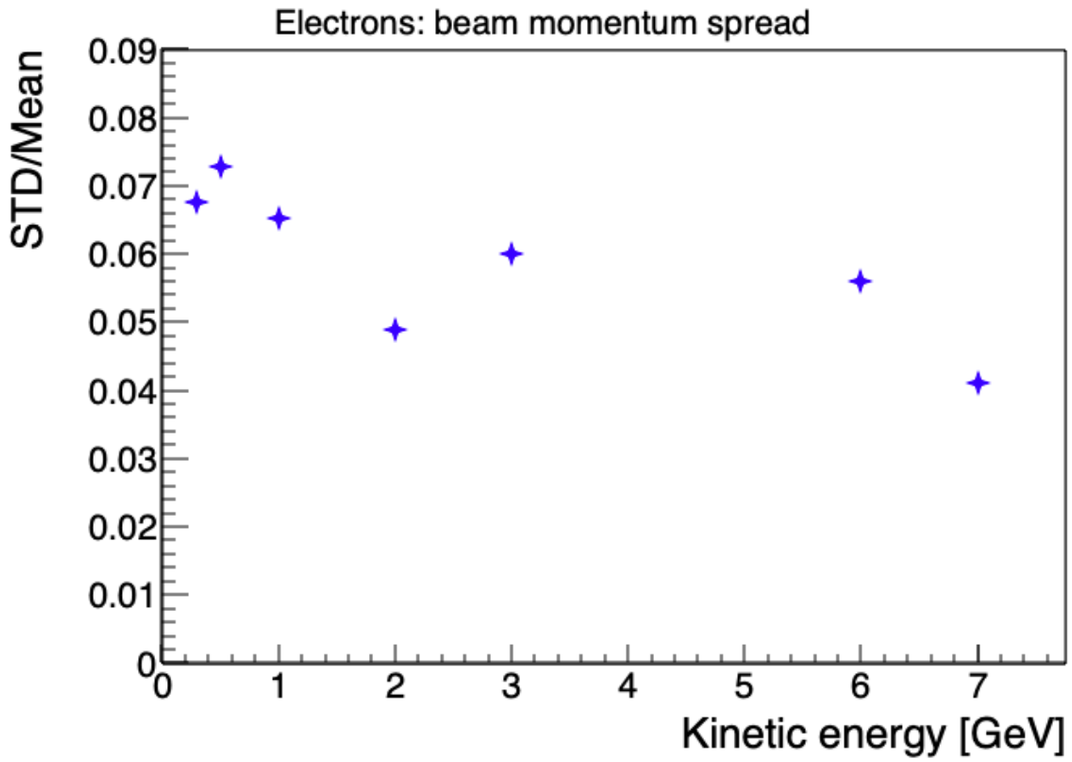
$$R_d = \sqrt{\left(\frac{\sigma_{N_{ph}}}{N_{ph}}\right)^2 - \left(\frac{\sigma_{KE}}{KE}\right)^2}$$

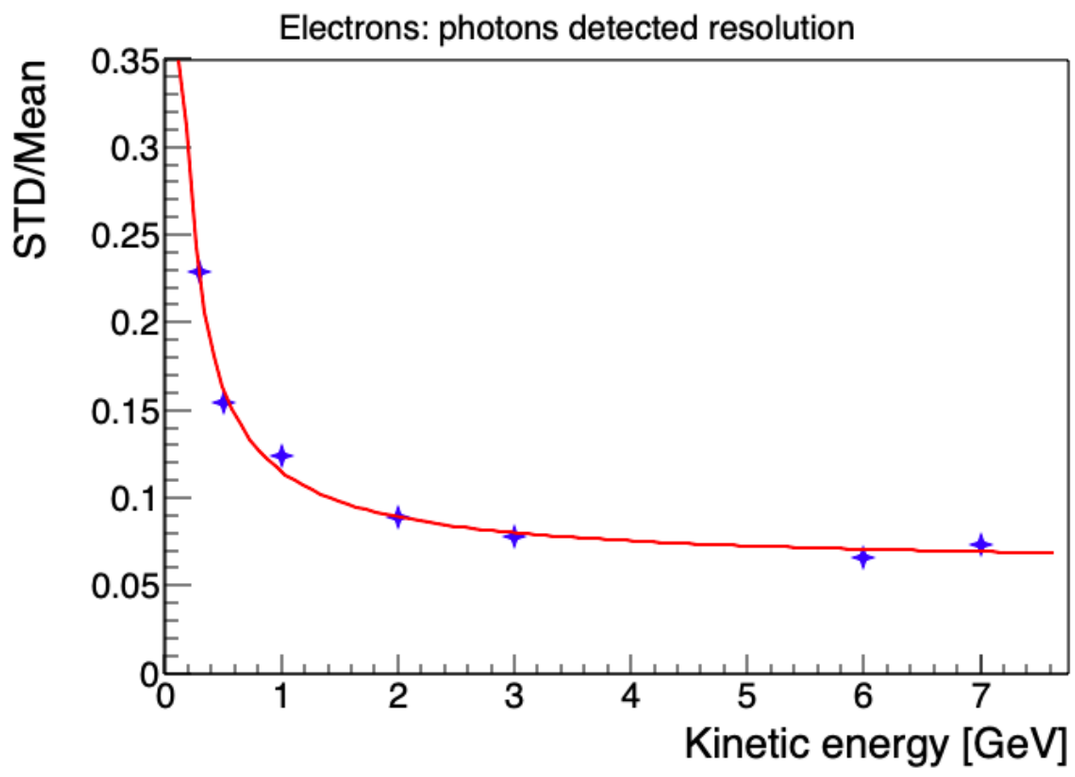
using the general equation for the fit we have:

$k_1 = 0.060 \pm 0.007$

$k_2 = 0.08 \pm 0.01 \ \left[\sqrt{GeV}\right]$

$k_3 = 0.04 \pm 0.01 \ [GeV]$



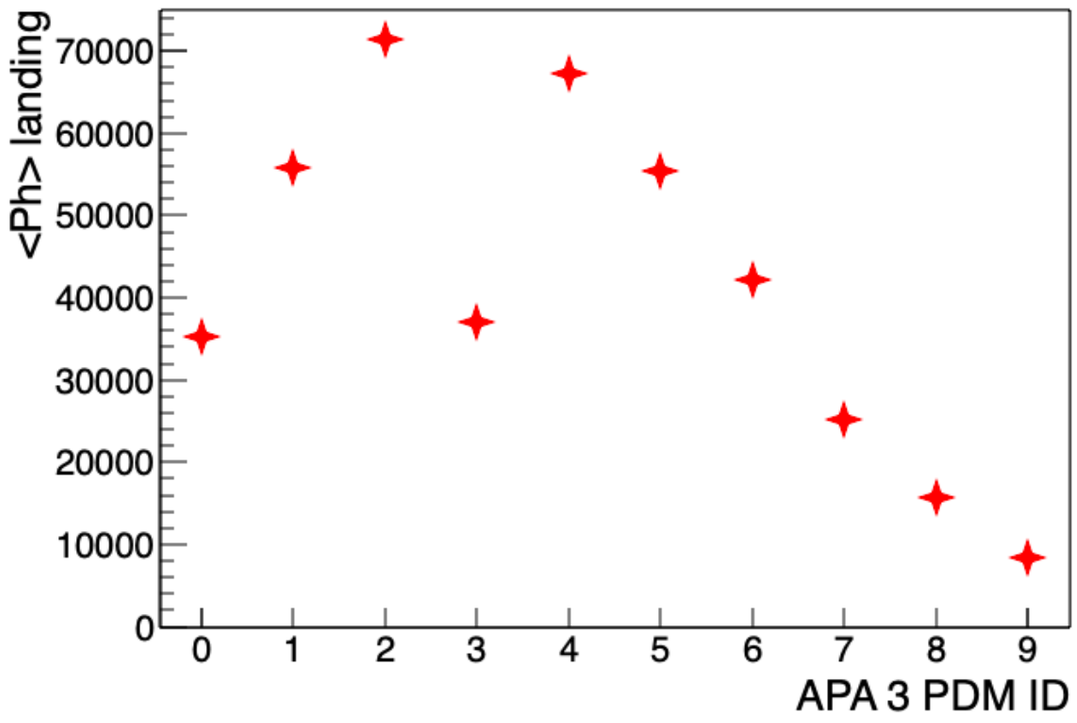
# Arriving photons estimation for 7 GeV beam electrons

**Arriving photons simulation is not completed yet.**

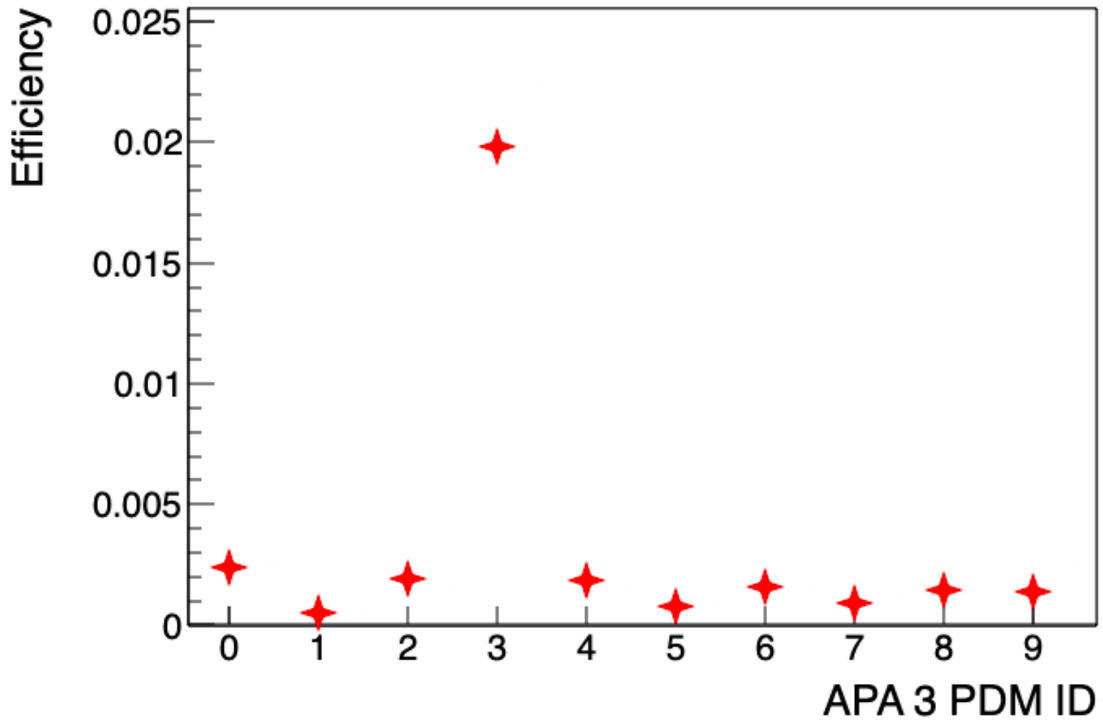
- for the mash shadow is used a average value
- for some channels more statistic is needed

However a very preliminary result on efficiency shows a value ~ 2%

**Landing photons**

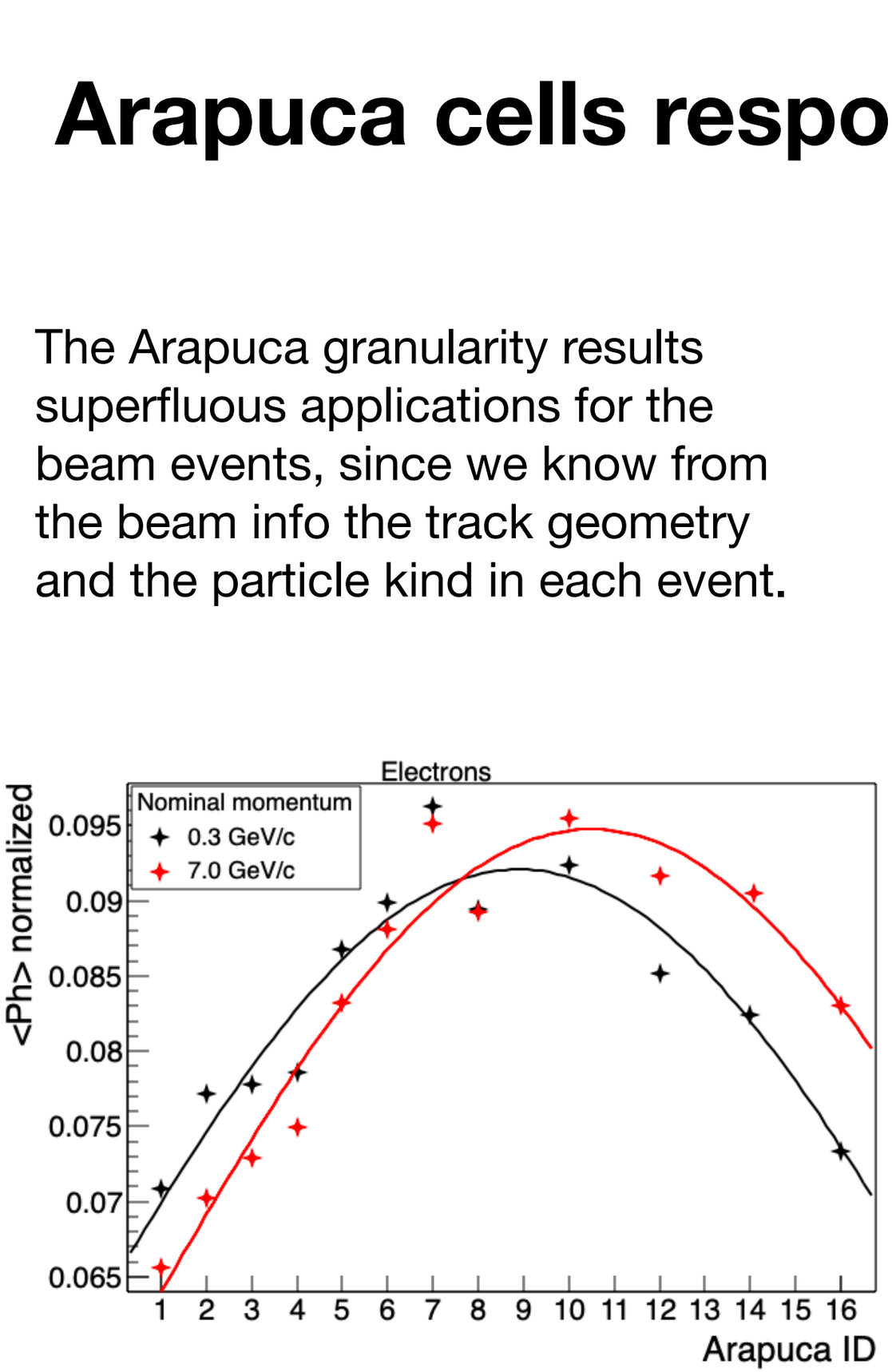


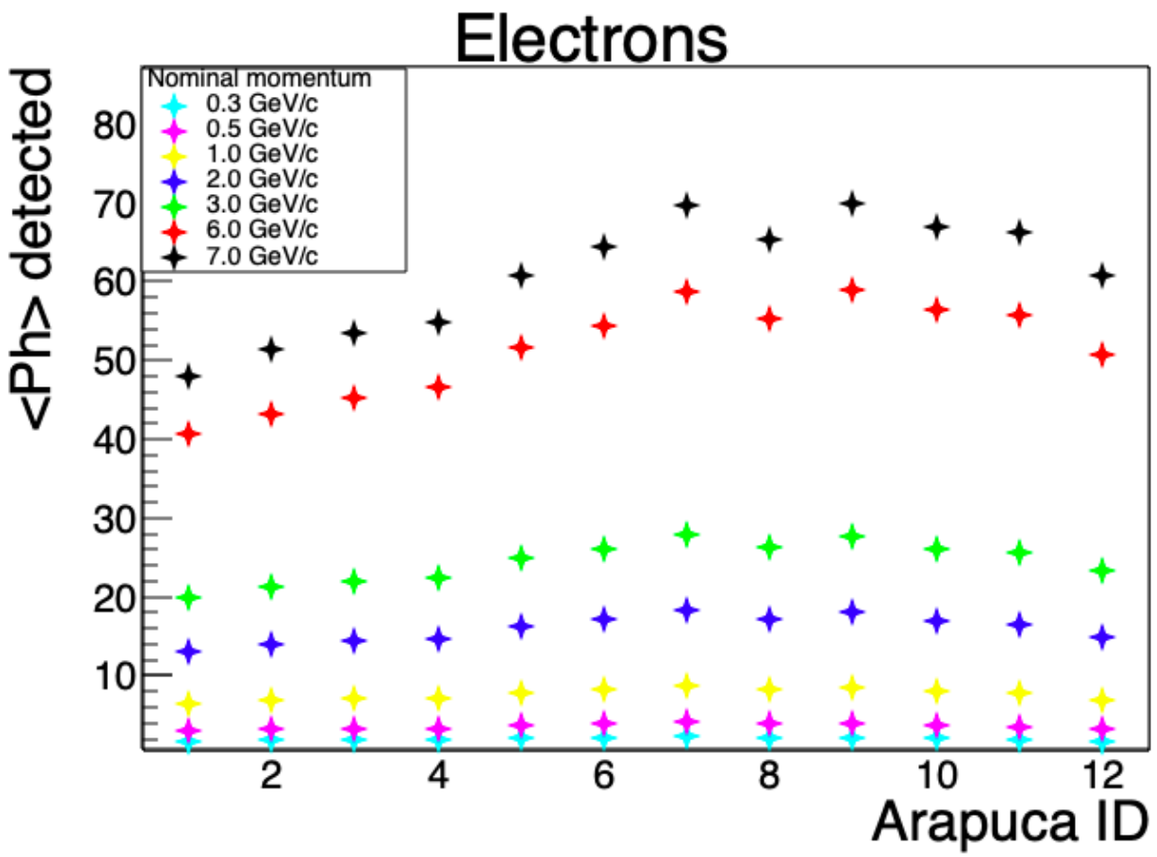

**Efficiency**



# Arapuca cells response to beam electrons

The Arapuca granularity results superfluous applications for the beam events, since we know from the beam info the track geometry and the particle kind in each event.

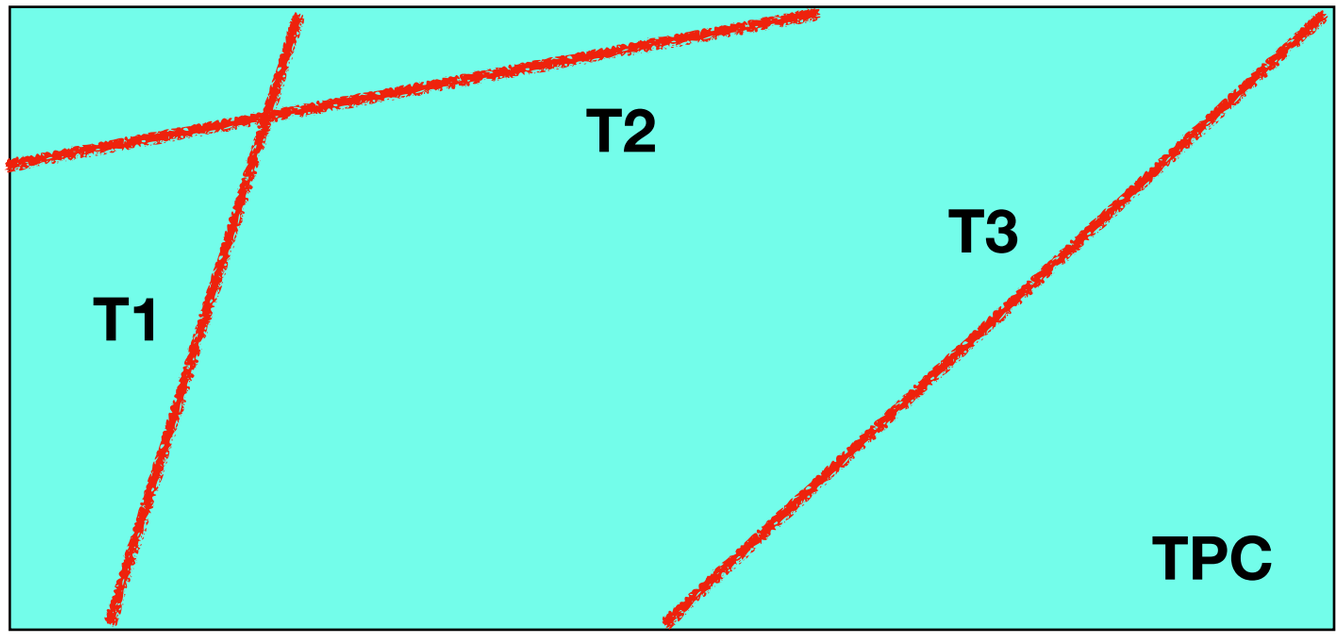



**One of the possible applications could be the determination of the showers length from the light pattern detected by the cells.**

# Arapuca granularity power

**A possible useful application for the Arapuca granularity could be the track identification in the TPC.**

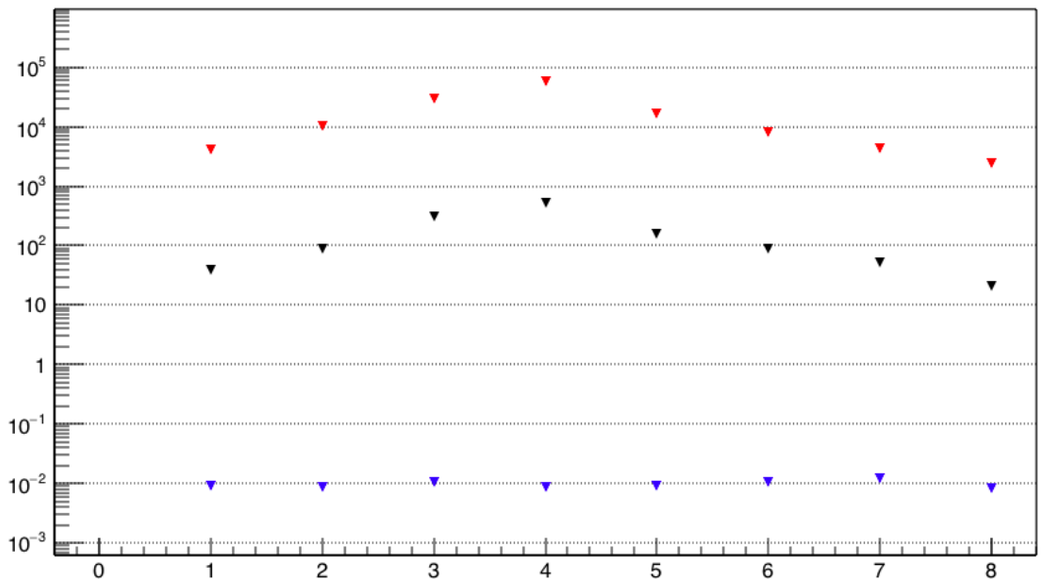



The TPC time window is $\sim 3\,ms$.
More tracks are recorded together.
The photodetectors have a much smaller window $\sim 13\,\mu s$ with resolution of $6.67\,ns$

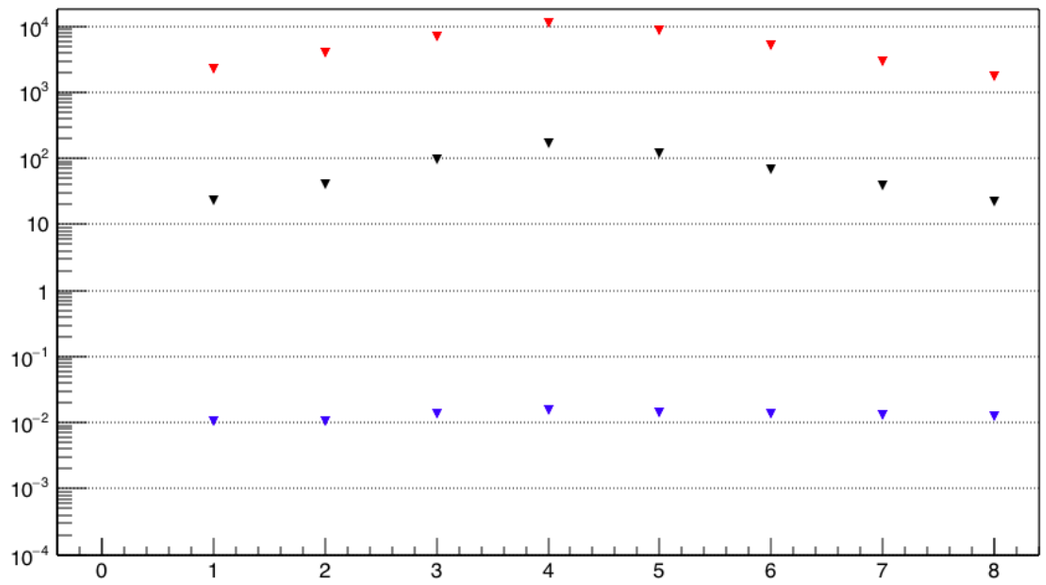
Using the tracks geometry given by the TPC we can reconstruct the light pattern produced by each track. Comparing these patterns with the light observed in the PD system it is possible associate each set of waveforms (PD event) to a given track, and hence getting its timing (t0).

# TallBo experiment: Arapuca granularity application

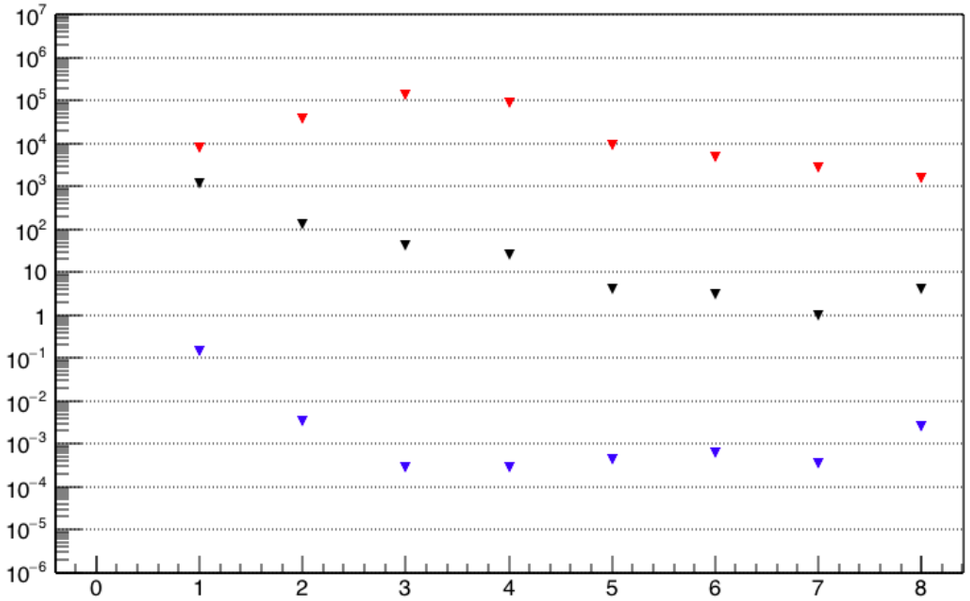
## Good event



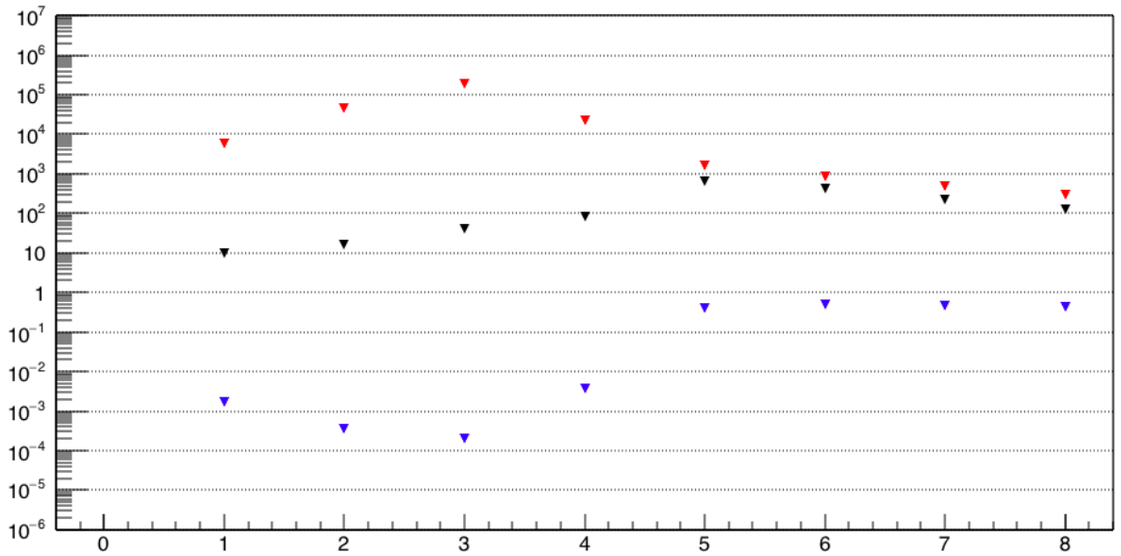
## Good event



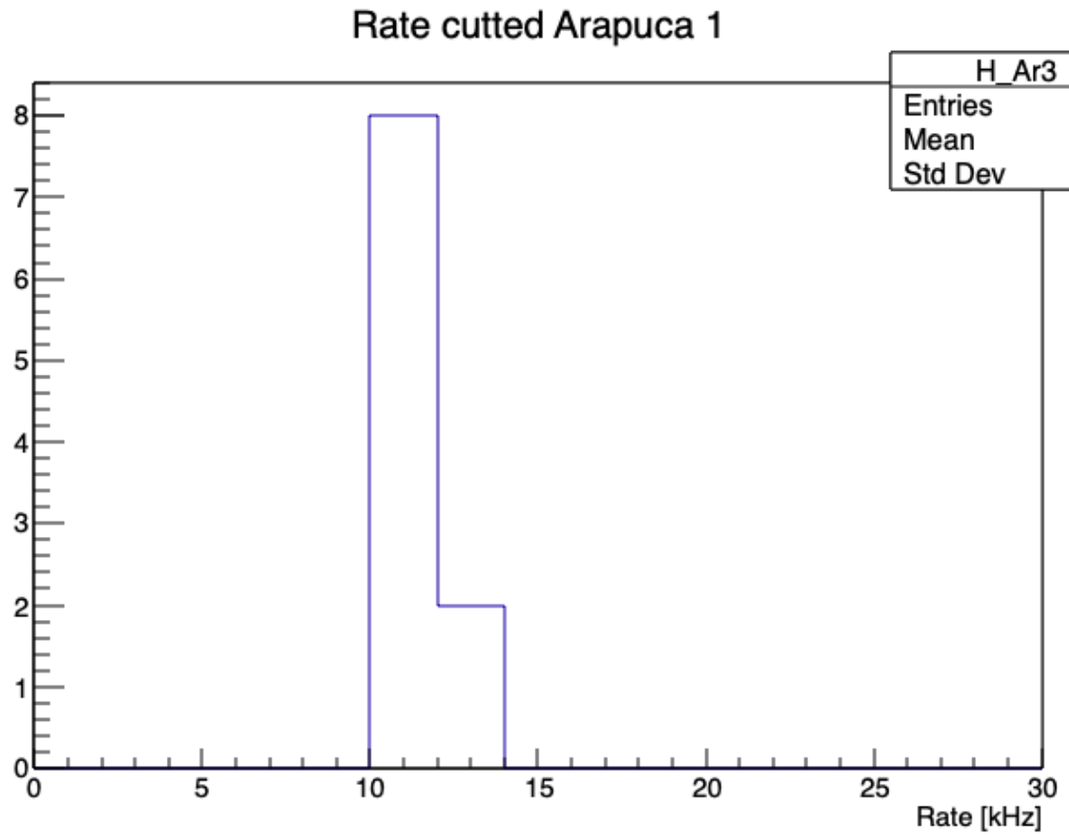
## Bad event

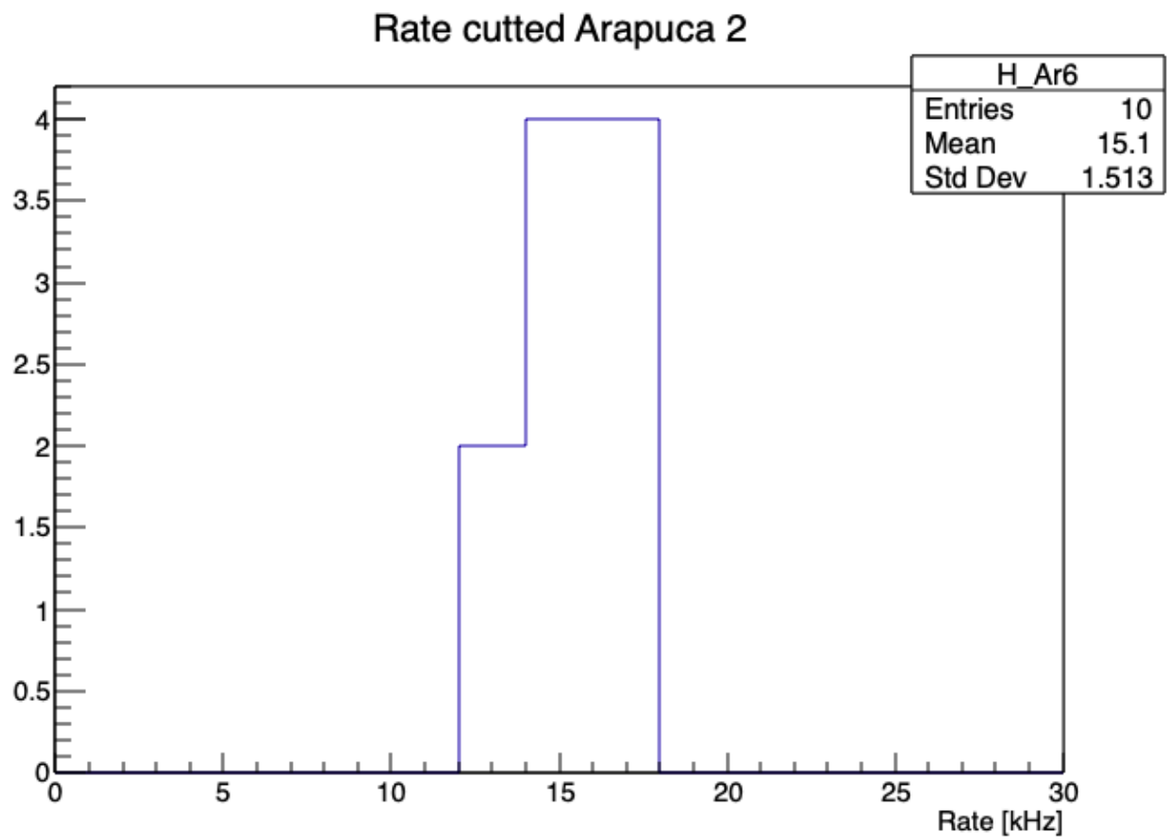


## Bad event

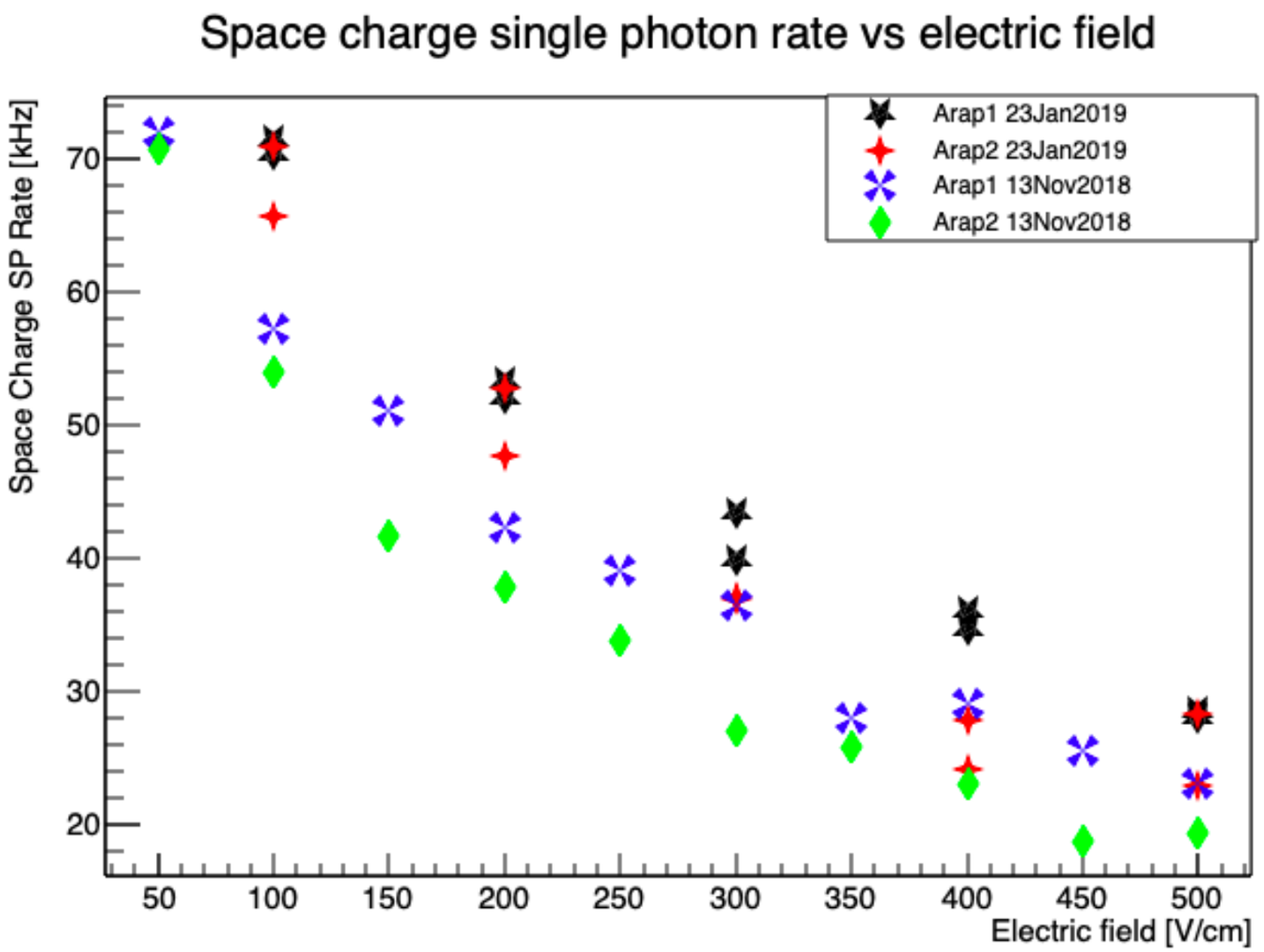


# Ionizing events cut rate are independent from the electric field



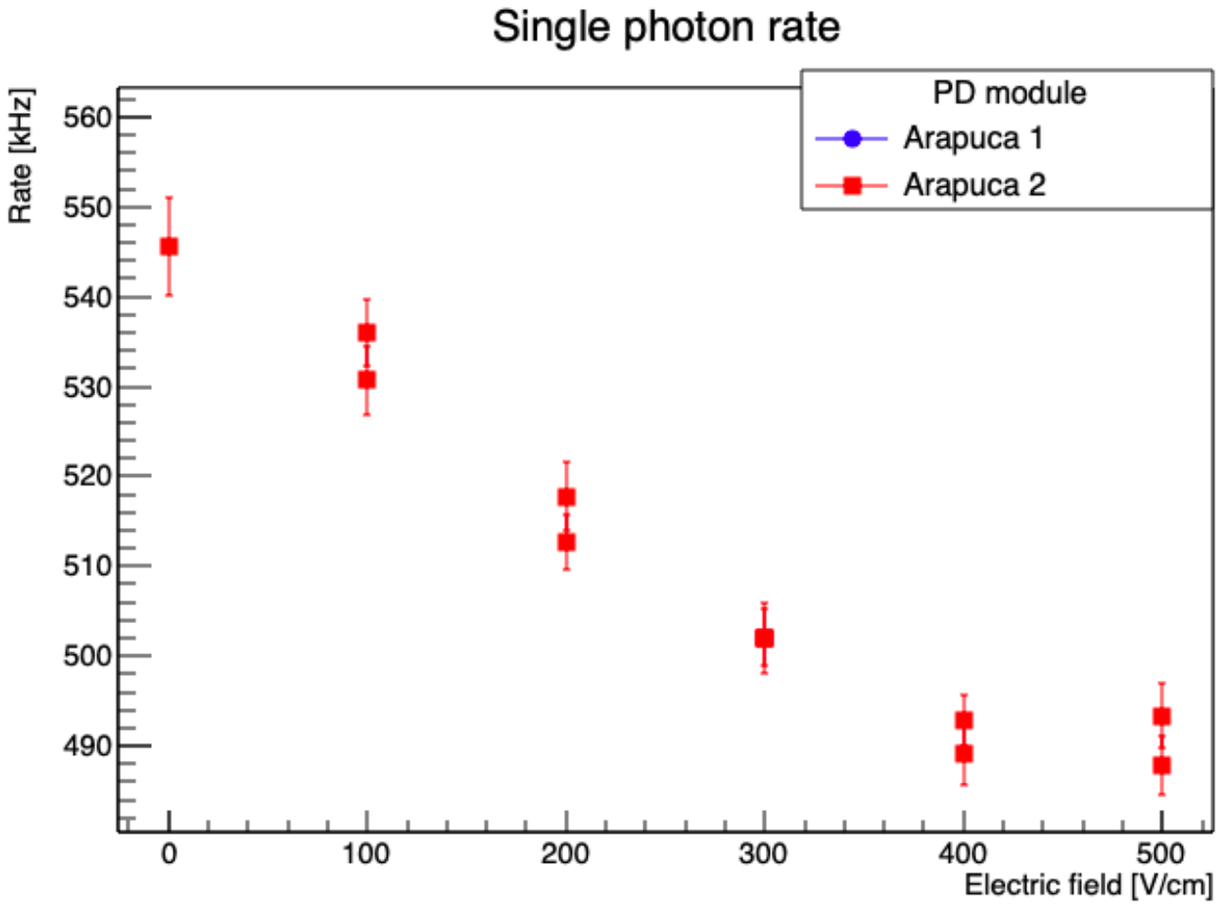



# Offset and single photon rate from space charge absolute values



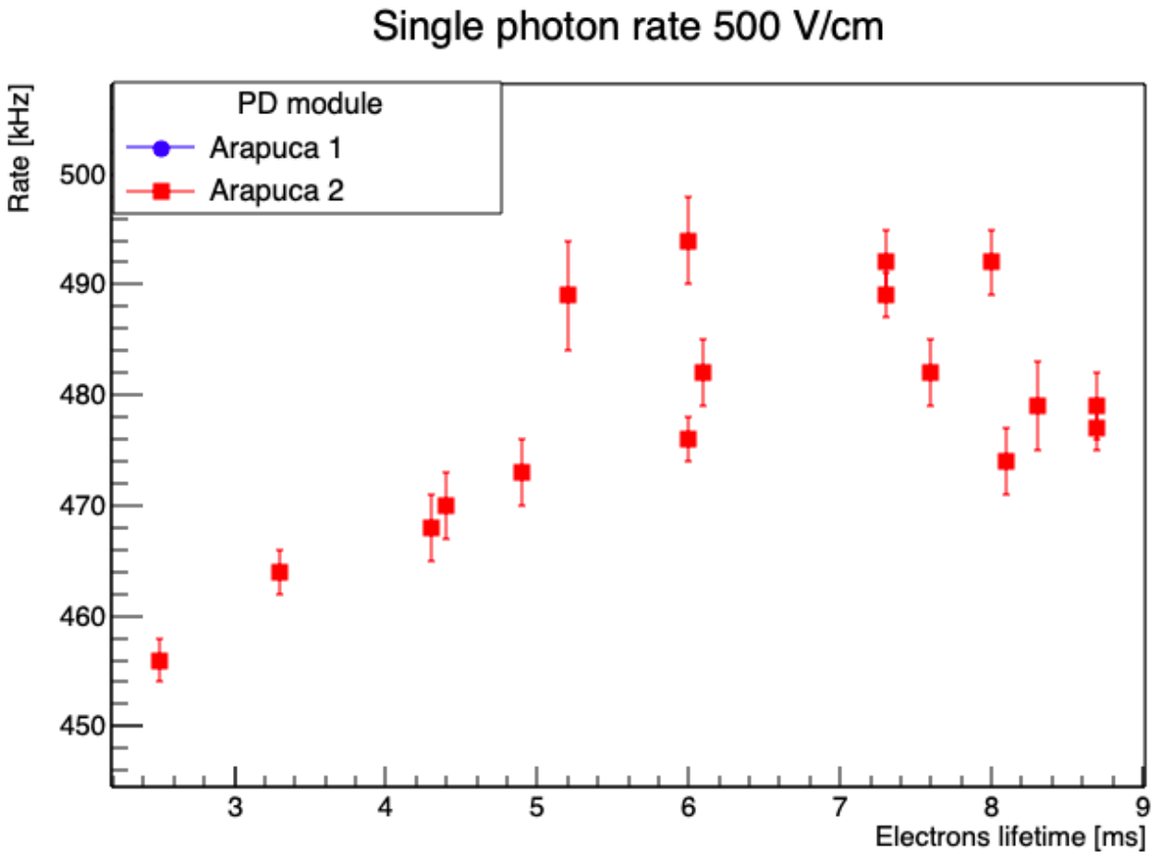

| Ramp | Arapuca | OffSet |
|---|---|---|
| Nov 2018 | 1 | 70 kHz |
| Nov 2018 | 2 | 84 kHz |
| Jan 2019 | 1 | 154 kHz |
| Jan 2019 | 2 | 465 kHz |

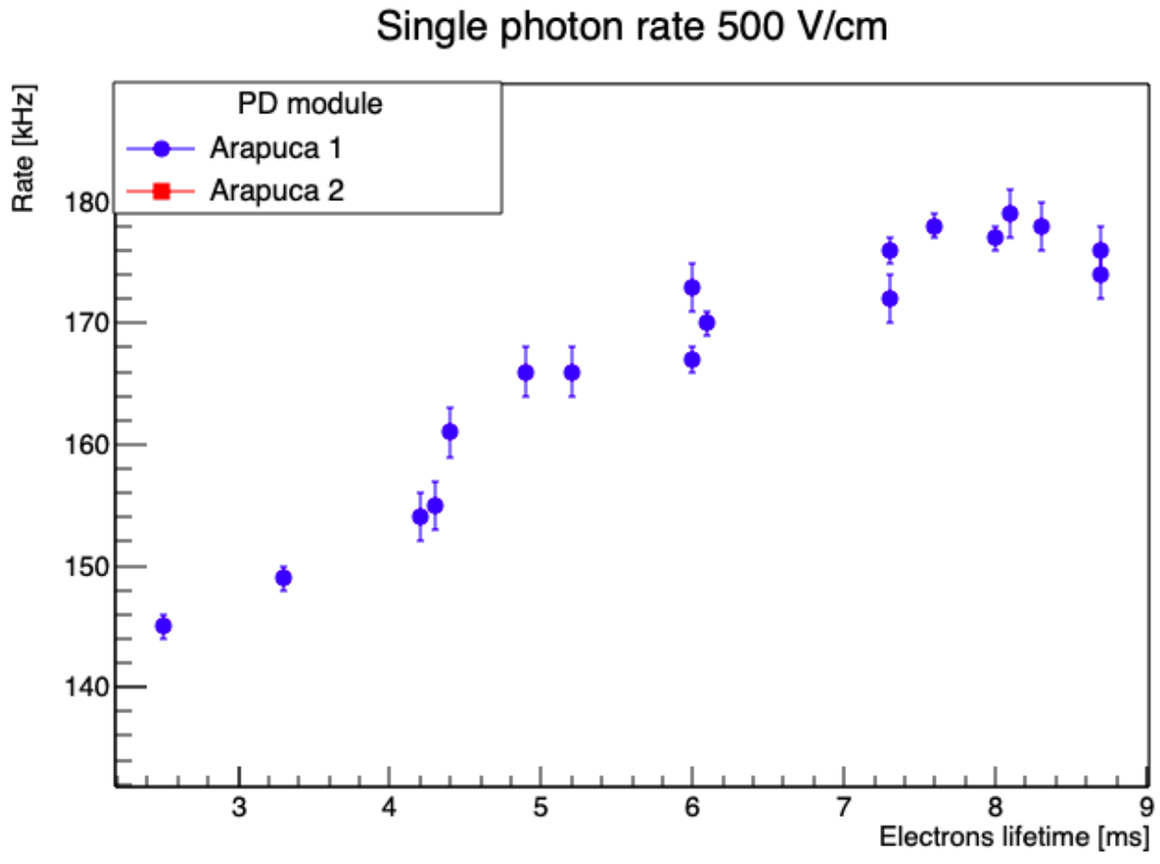
**Subtracting that offset from the data measured we have:**


Single photon rate
PD module
Arapuca 1
Arapuca 2
Rate [kHz]
560
550
540
530
520
510
500
490
0
100
200
300
400
500
Electric field [V/cm]

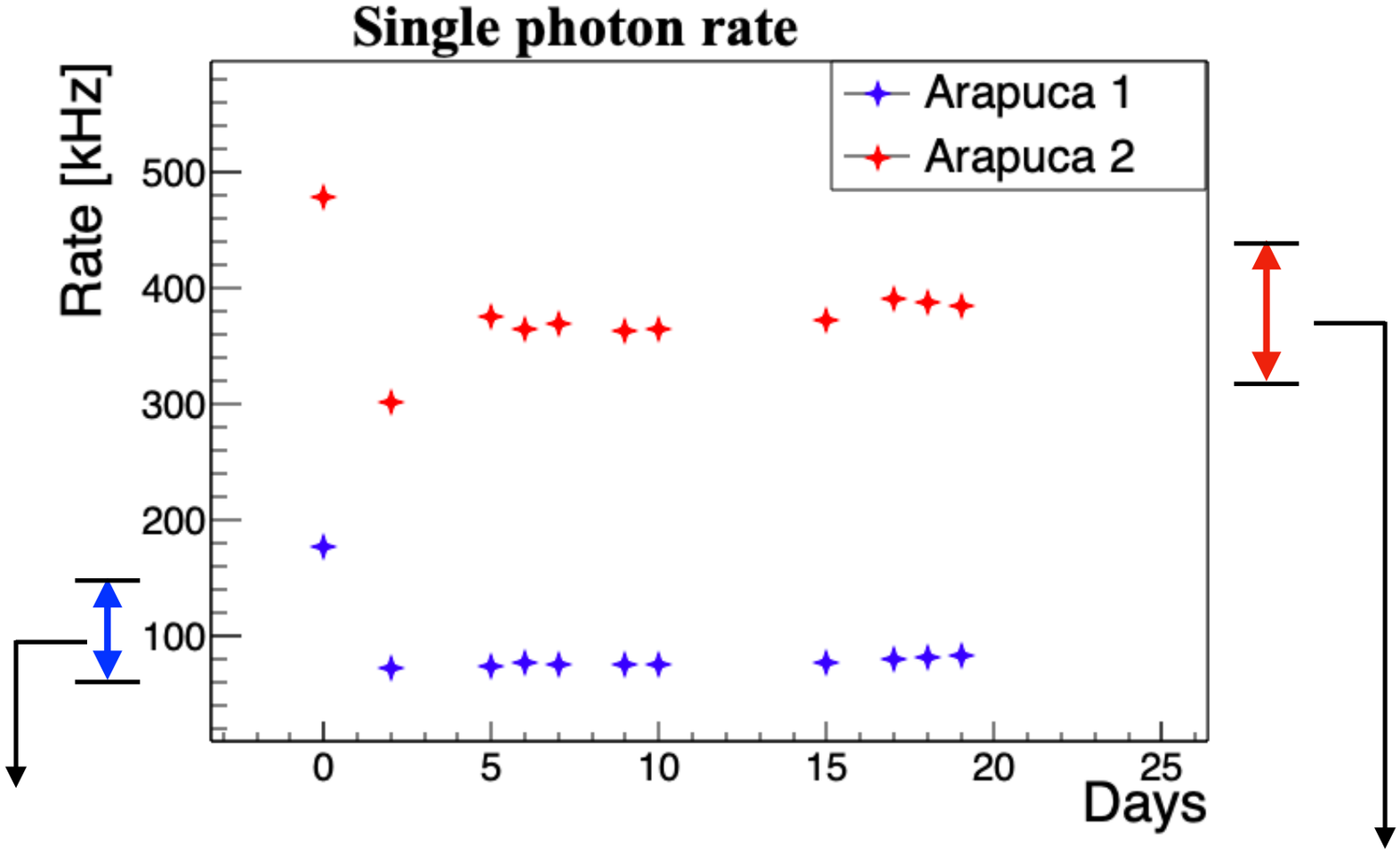

Single photon rate
PD module
Arapuca 1
Arapuca 2
Rate [kHz]
280
260
240
220
200
180
0
100
200
300
400
500
Electric field [V/cm]

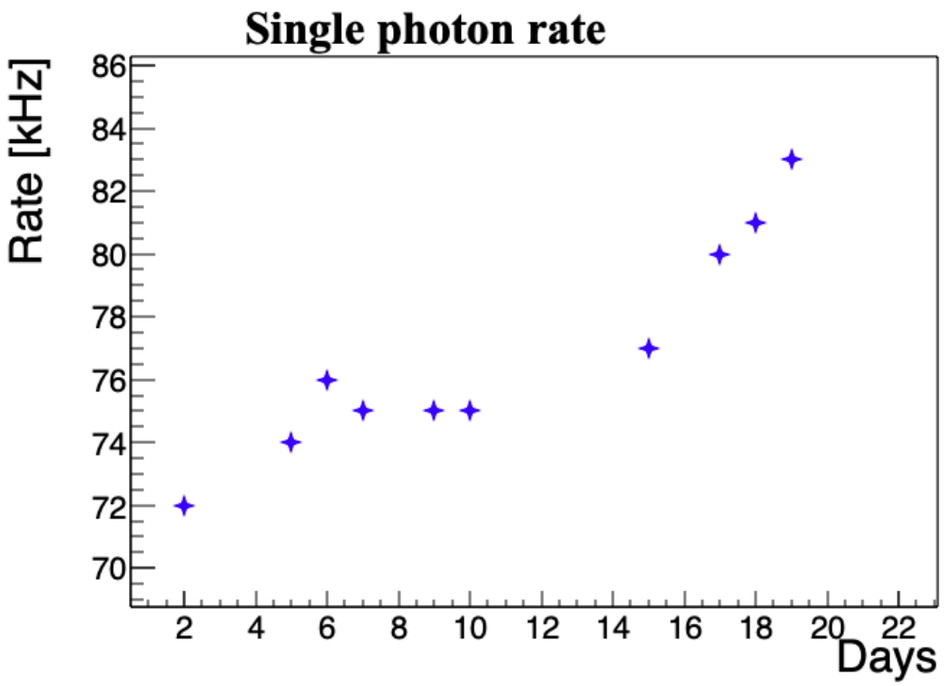
# Rate vs purity (in electrons lifetime)

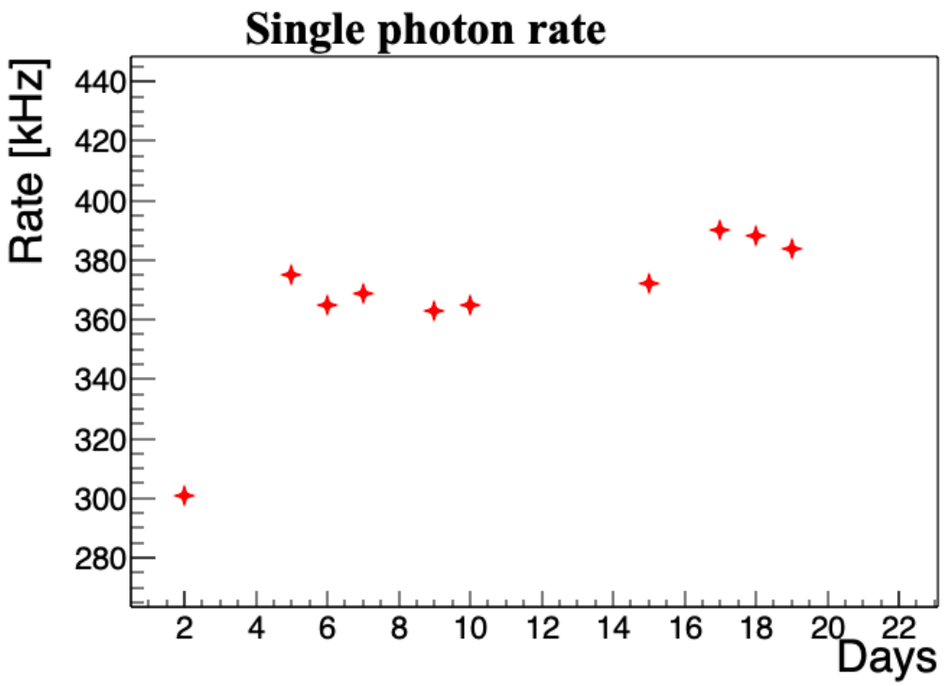


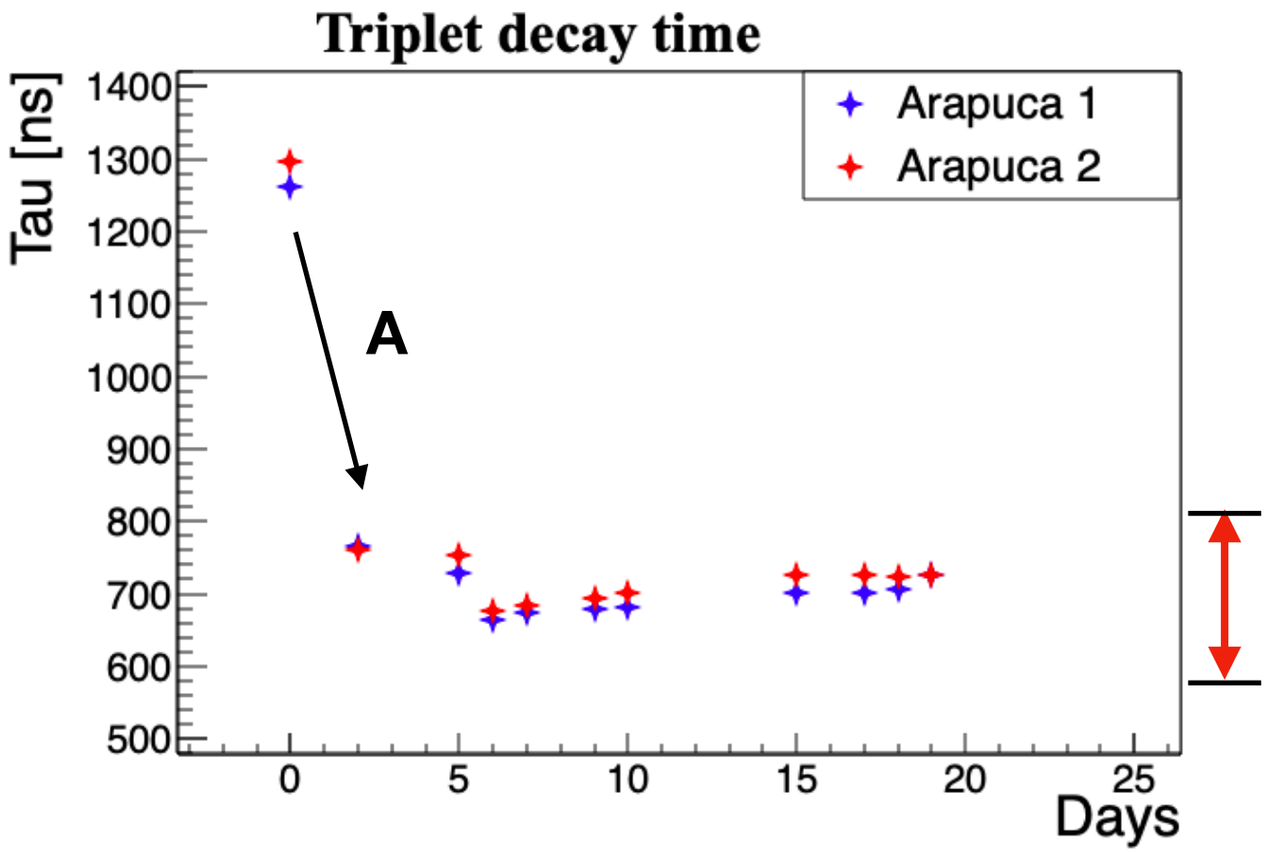



# Rate after purity drop off





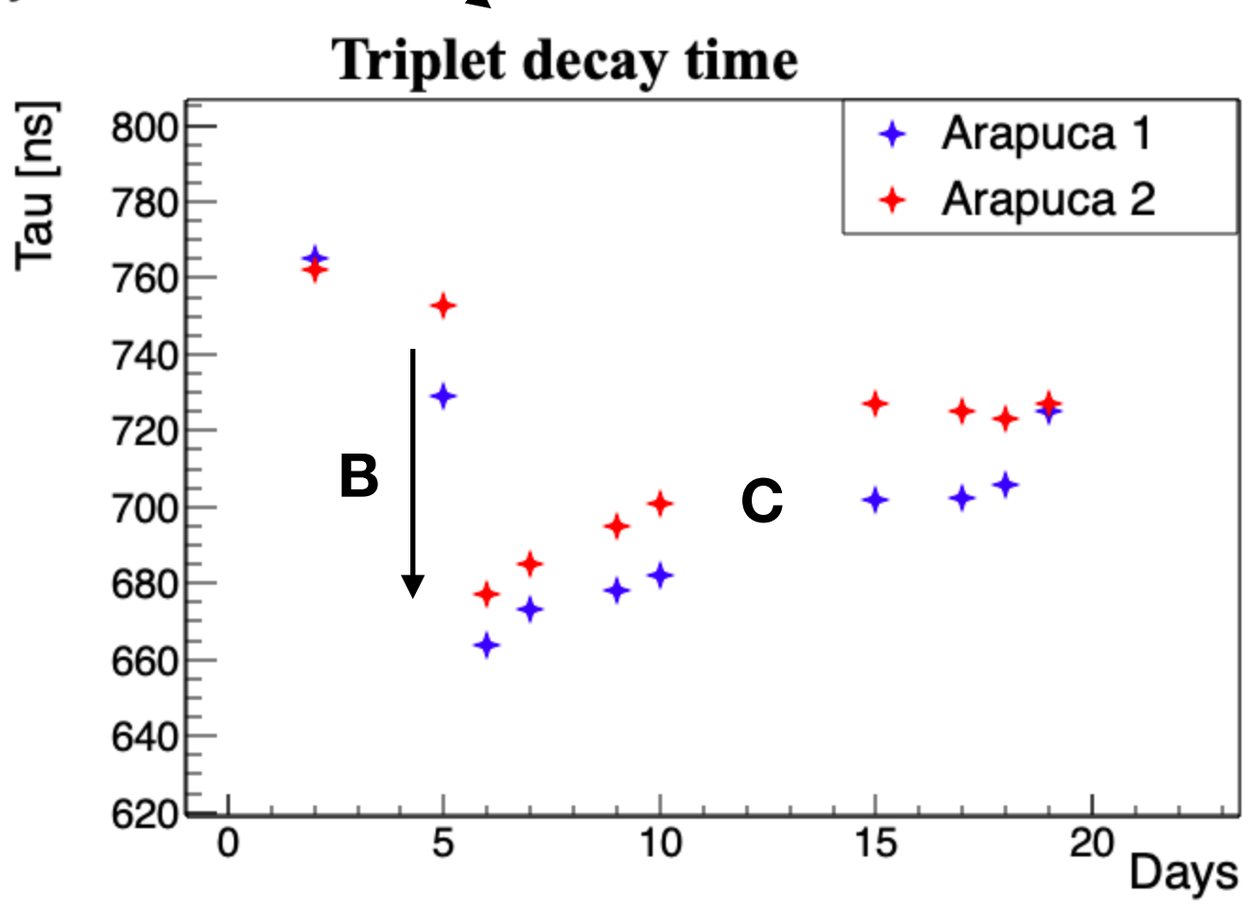

Days means 2=July 22
3=July 23 and so on.

(The reference value at day=0 was taken some weeks before the July 20)

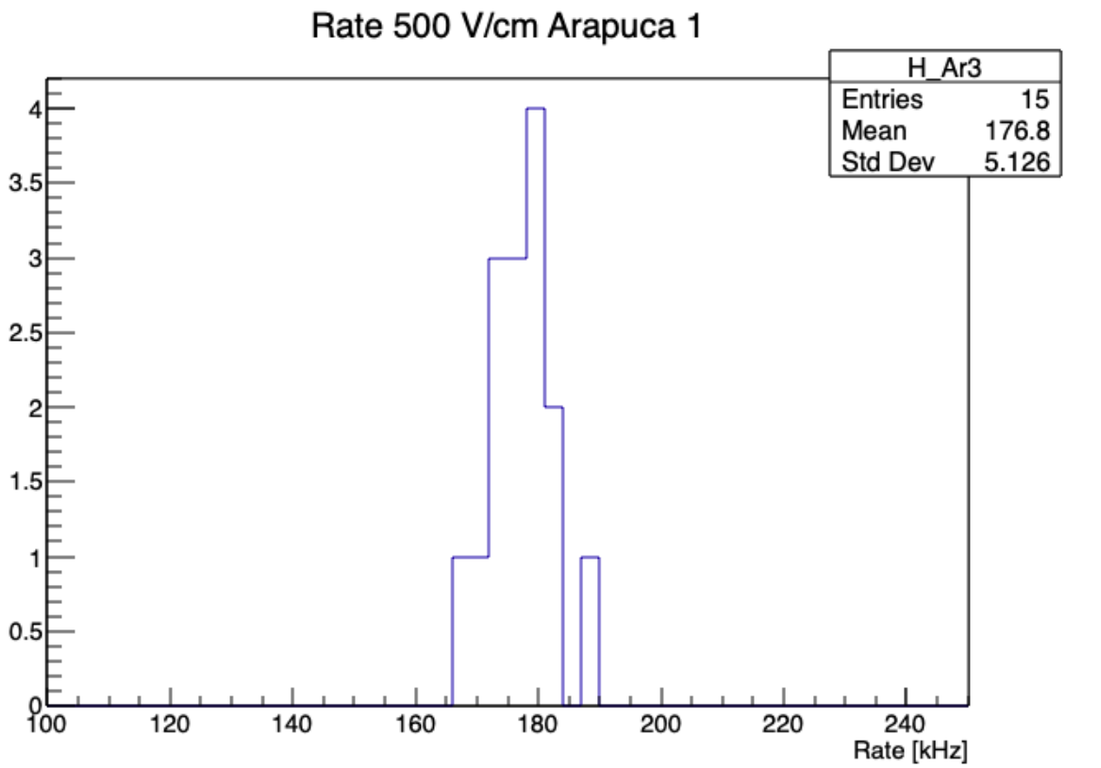
**A: First drop from the first contamination event**

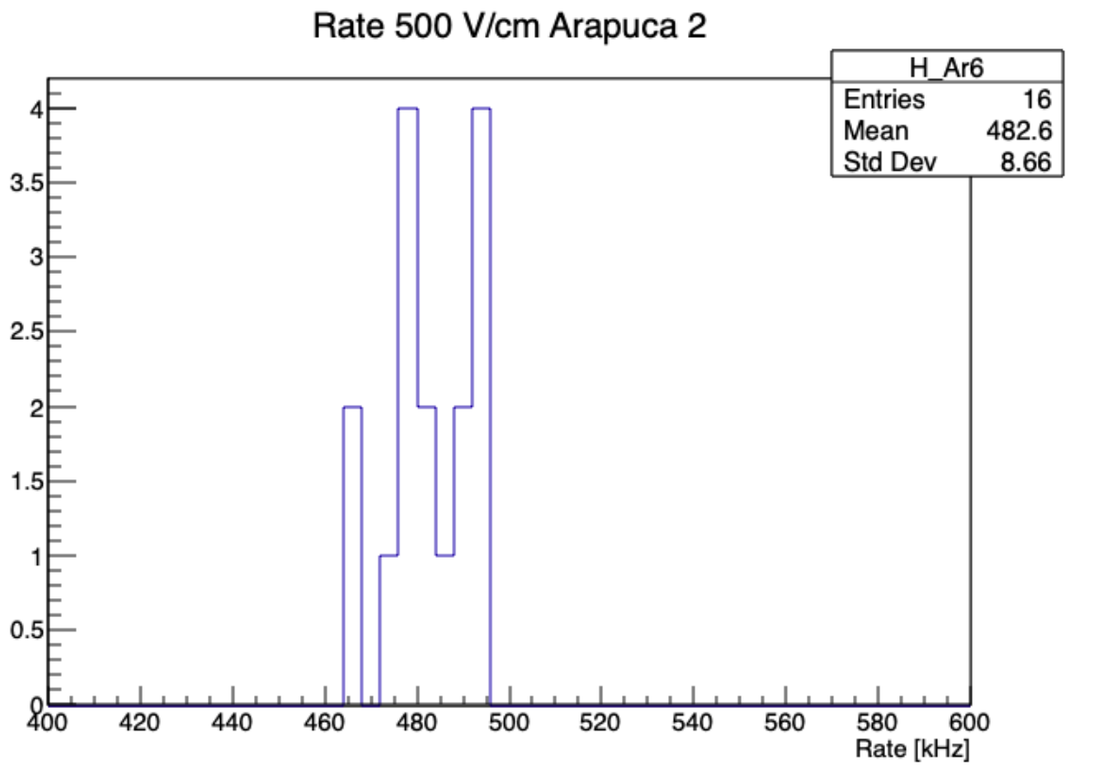
**B: Second drop from the second contamination event**

**C: Recovery from filtering oxygen**



# Absolute single photon rate
# 500 V/cm,  6 ms (e lifetime)




$$Arapuca\,1\ <Rate>=176\pm5\,kHz$$

$$Arapuca\,2\ <Rate>=483\pm9\,kHz$$