Fall and Resurrection: Light Analysis

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DUNE collaboration meeting
Fermilab
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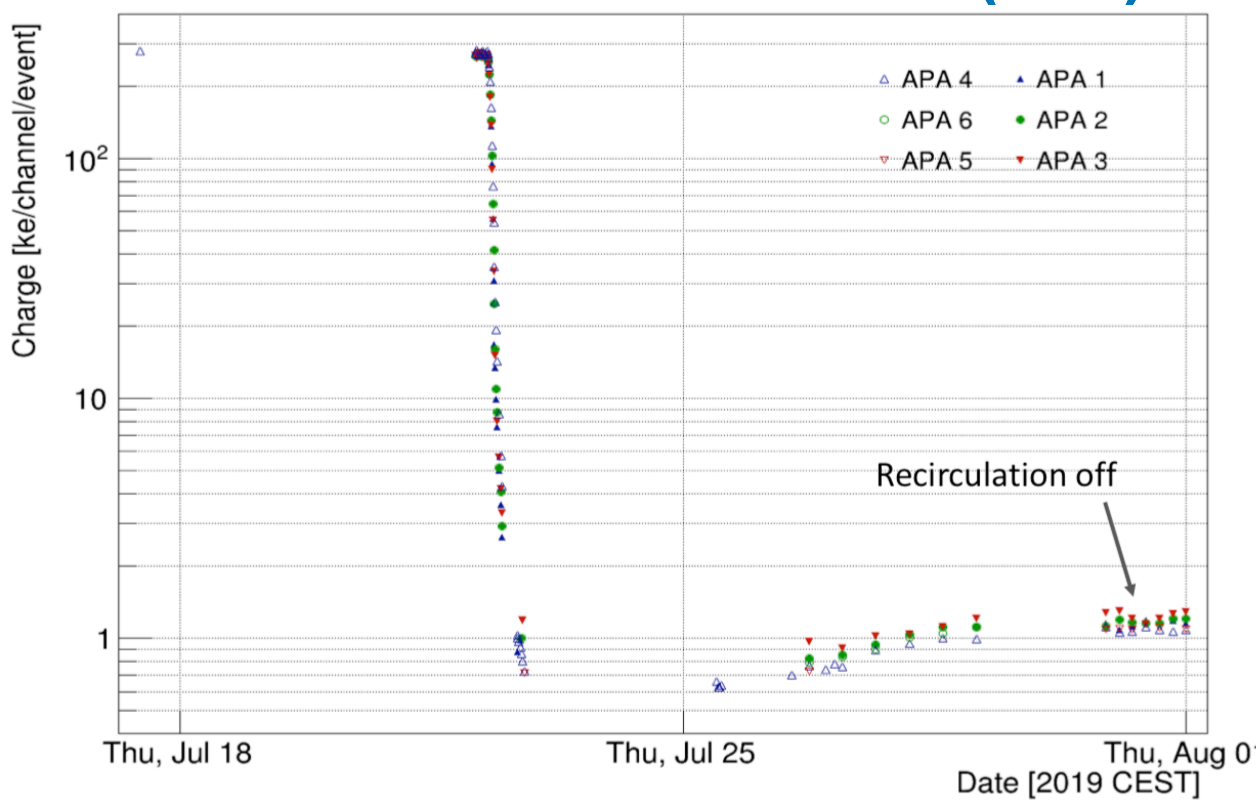
Outline

During the weekend July 20th - 21st 2019 a drop in Liquid Argon purity happened in ProtoDUNE cryostat

Plot from David Adams (BNL)



Charge (produced by cosmic ray) measured by TPC fall down of two orders of magnitude until it disappeared.

The photon detection system played a fundamental role to monitor what was happen in the detector

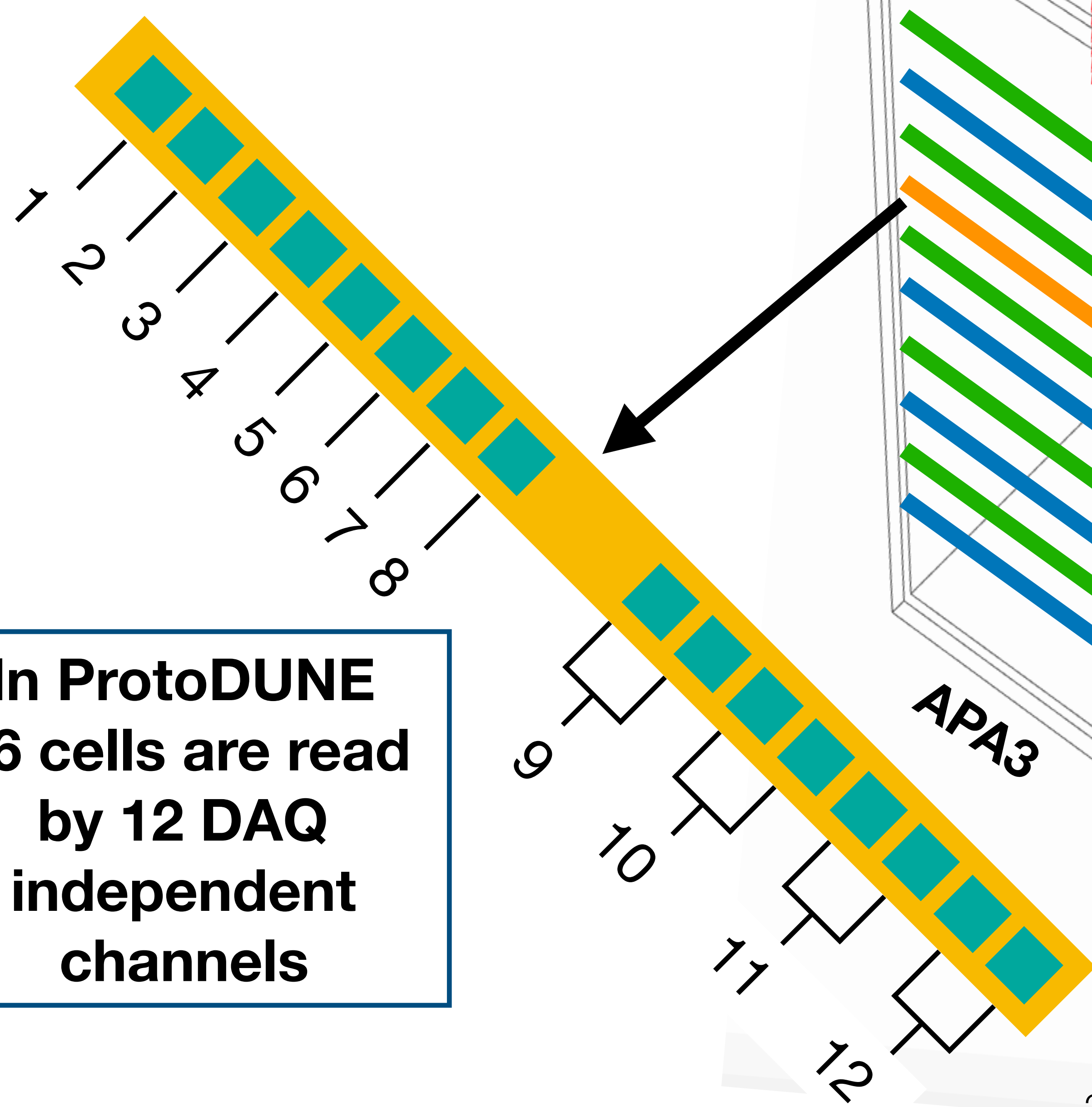
These slides focus on the Arapuca PD modules signals used to study:

- **triplet component decay time**
- **single photon rate**

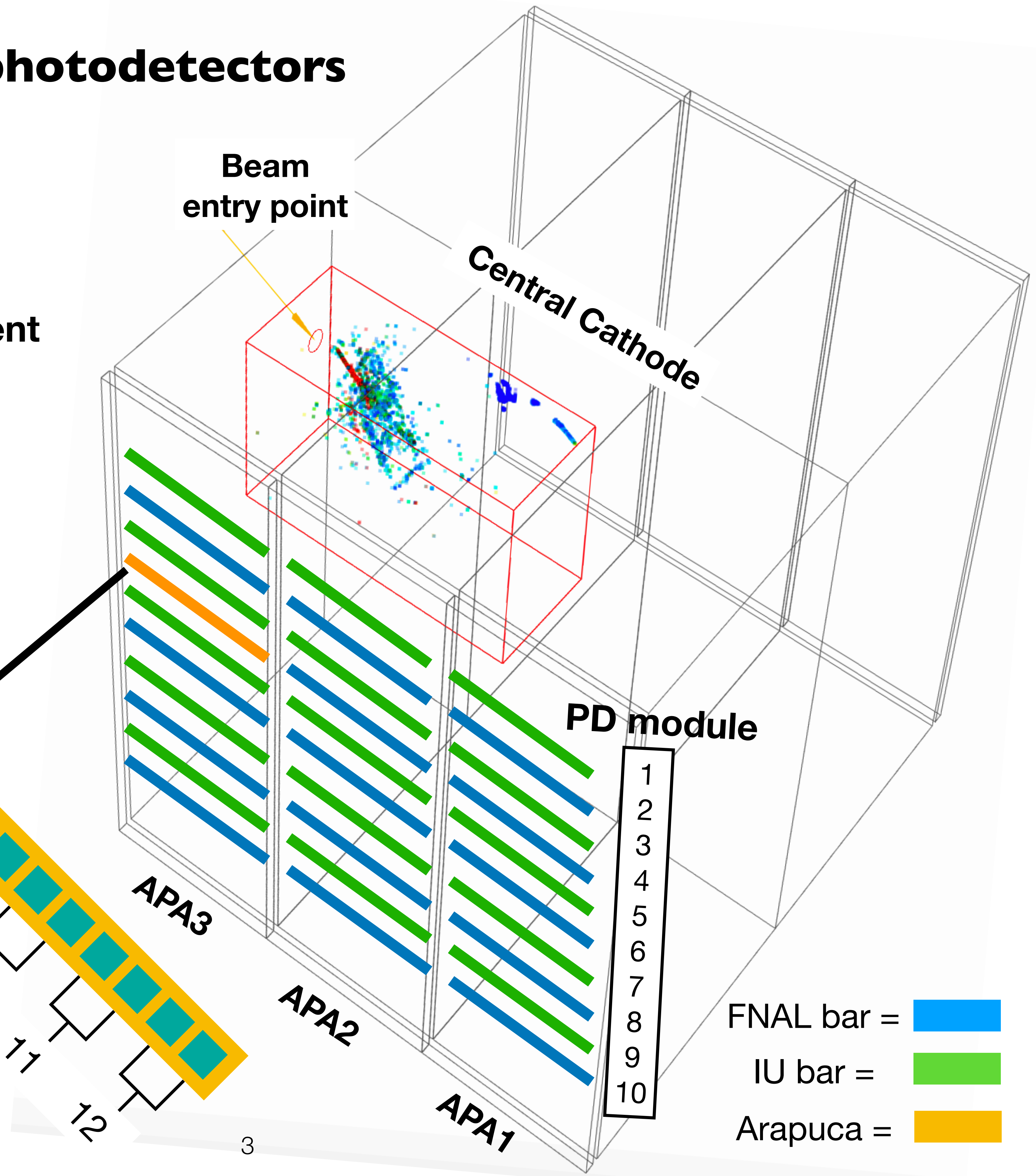
ProtoDUNE-SP photodetectors

Arapuca detector

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



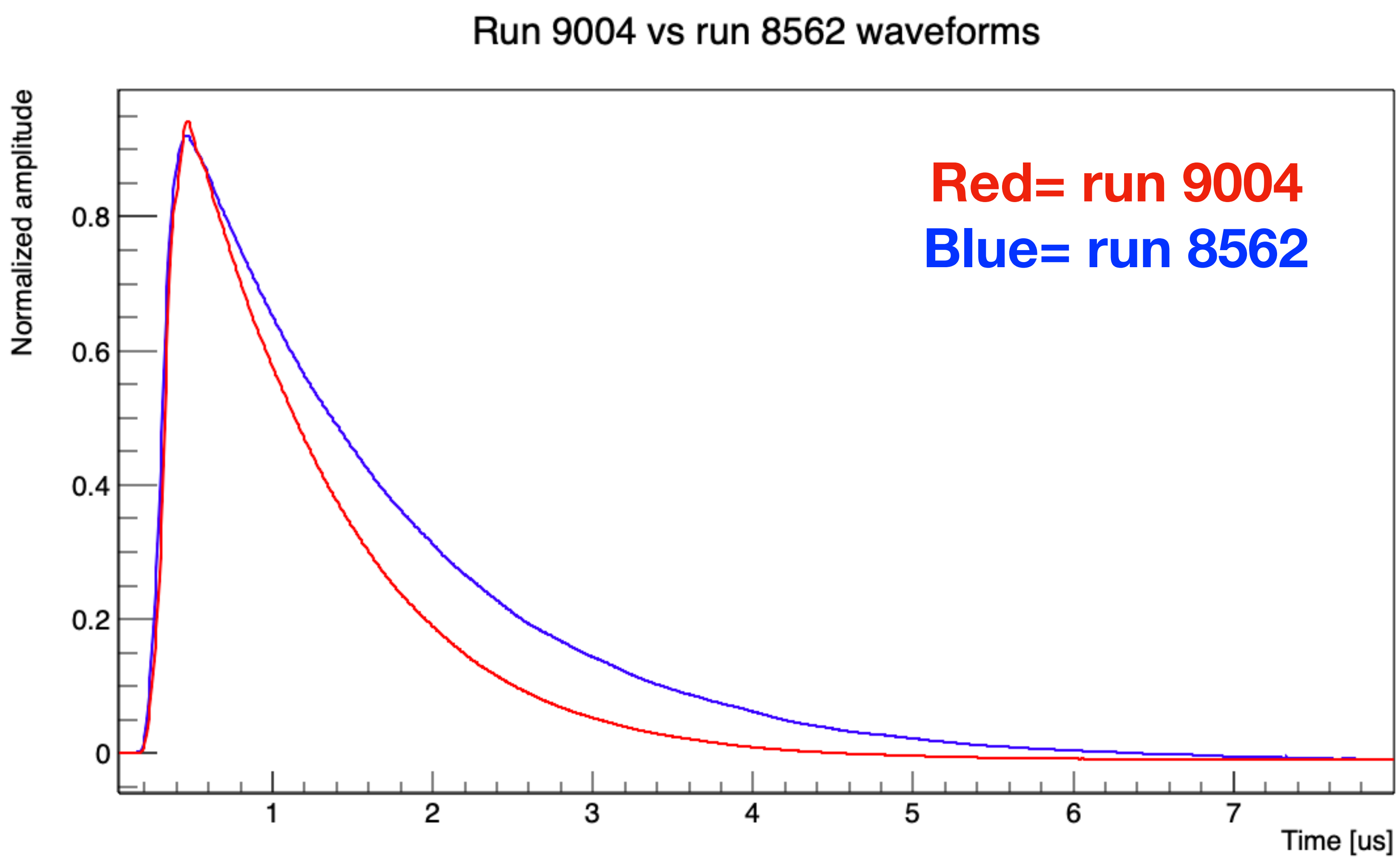
In ProtoDUNE 16 cells are read by 12 DAQ independent channels



Light signals before and after the purity drop

The PD system internal trigger (based on amplitude threshold) allowed to acquire waveforms after the purity drop produced by a similar numbers of photons (~ 35 ph) as in the standard situation

(the impurity increase is reflected in a decrease of the CR rate passing the threshold)

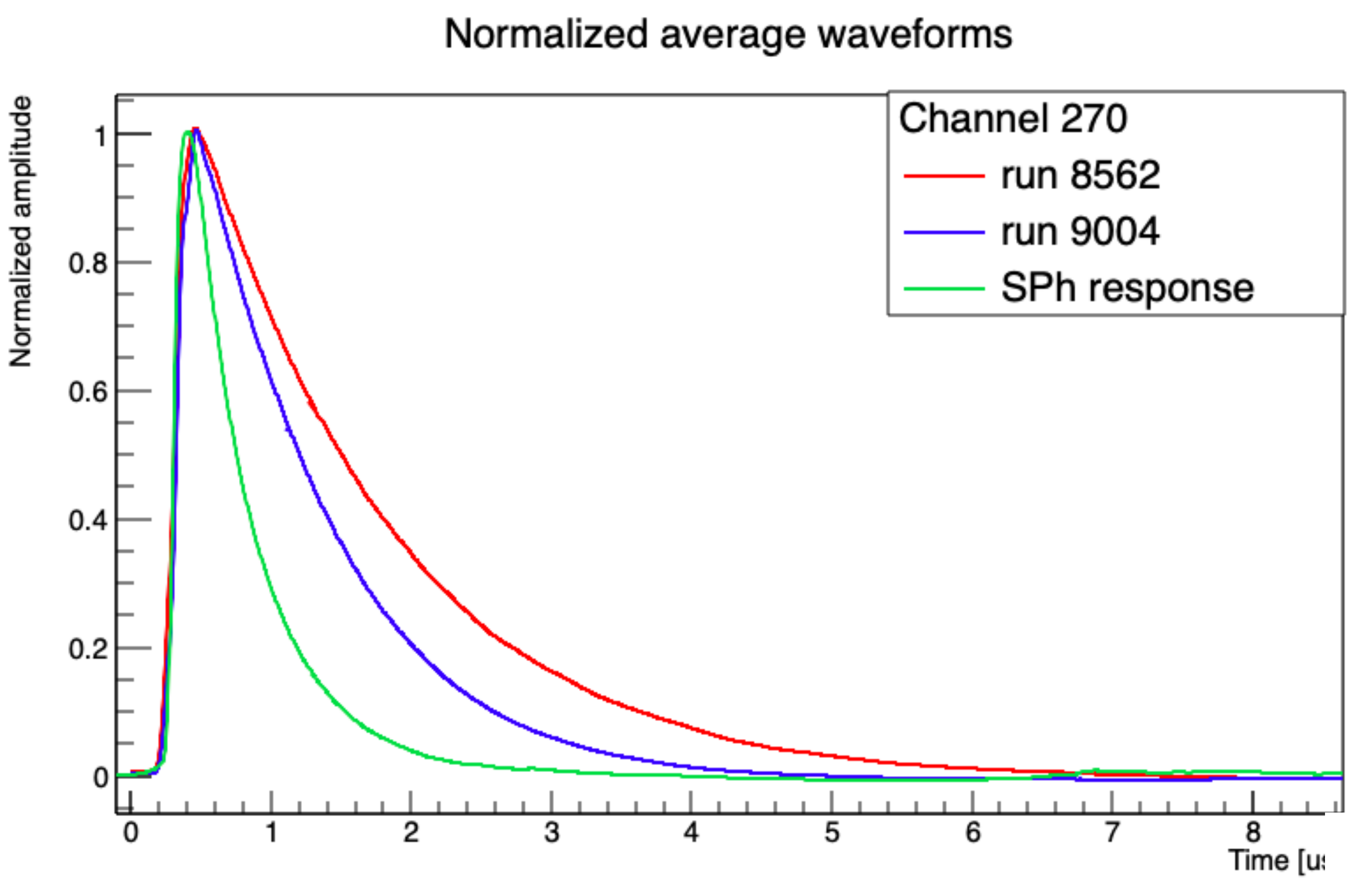


Average waveform normalized from a single Arapuca cell (DAQ ch 270):

Run 9004 -After drop 22nd July 2019

Run 8562 -Before drop 27nd June 2019
(high purity - 8.7 ms electrons lifetime)

Triplet component decay time

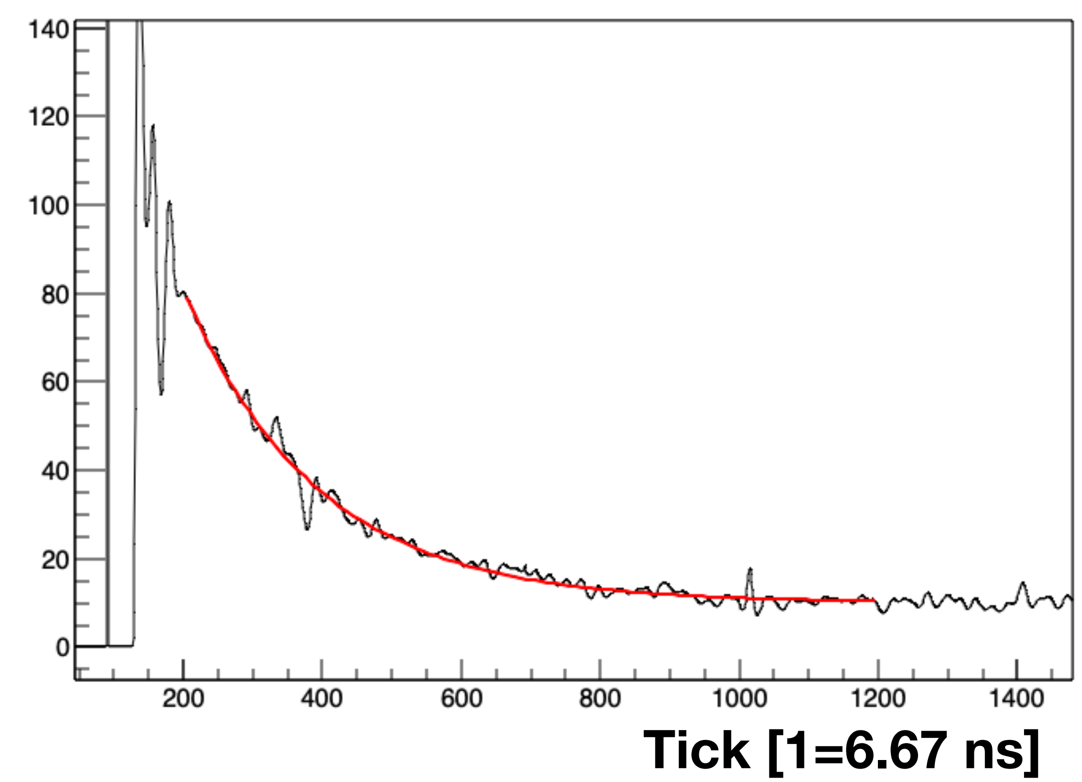


The average waveforms are deconvoluted using the single photon response fitted with the function:

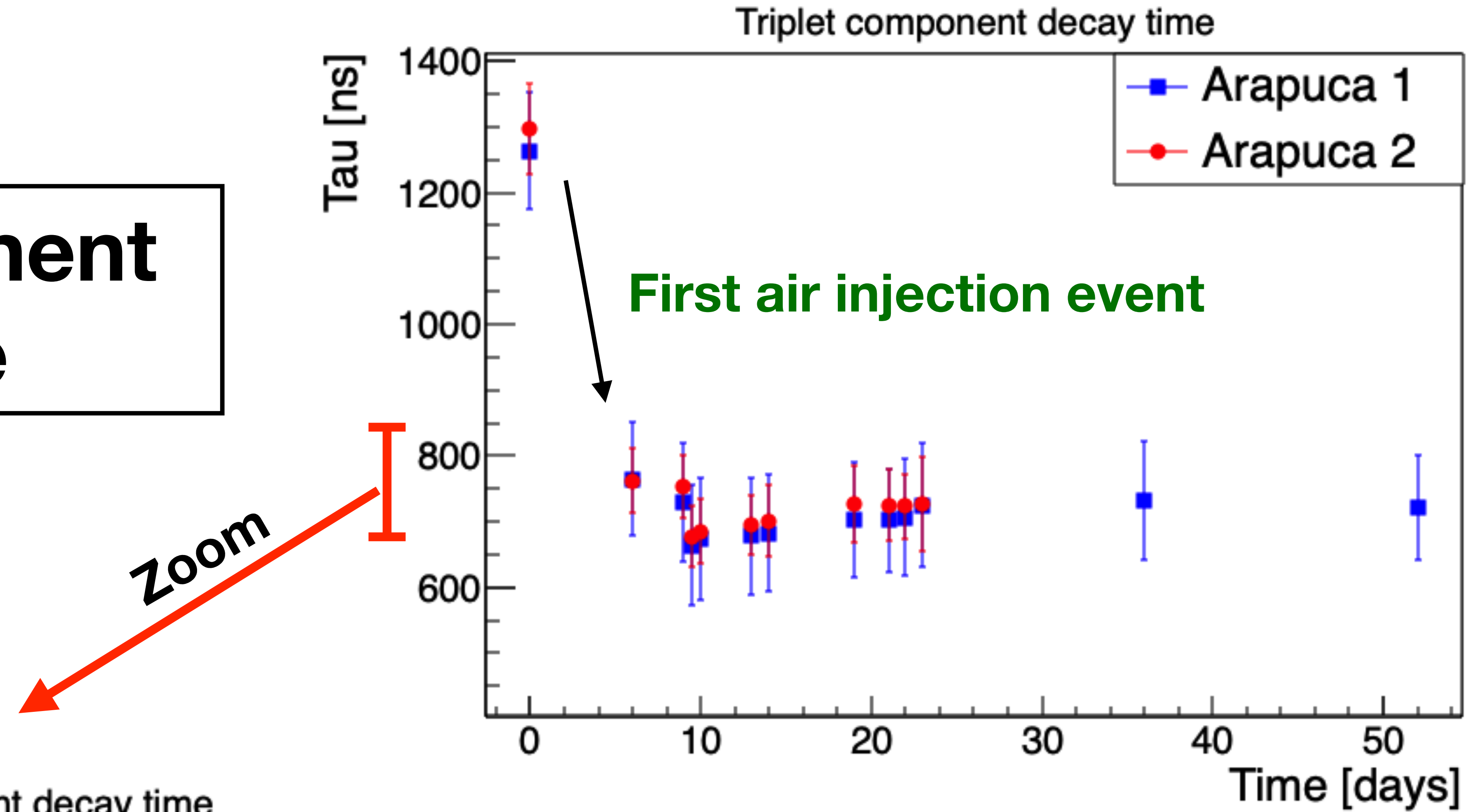
$$f(t) = A + B \cdot \exp(-t/\tau)$$

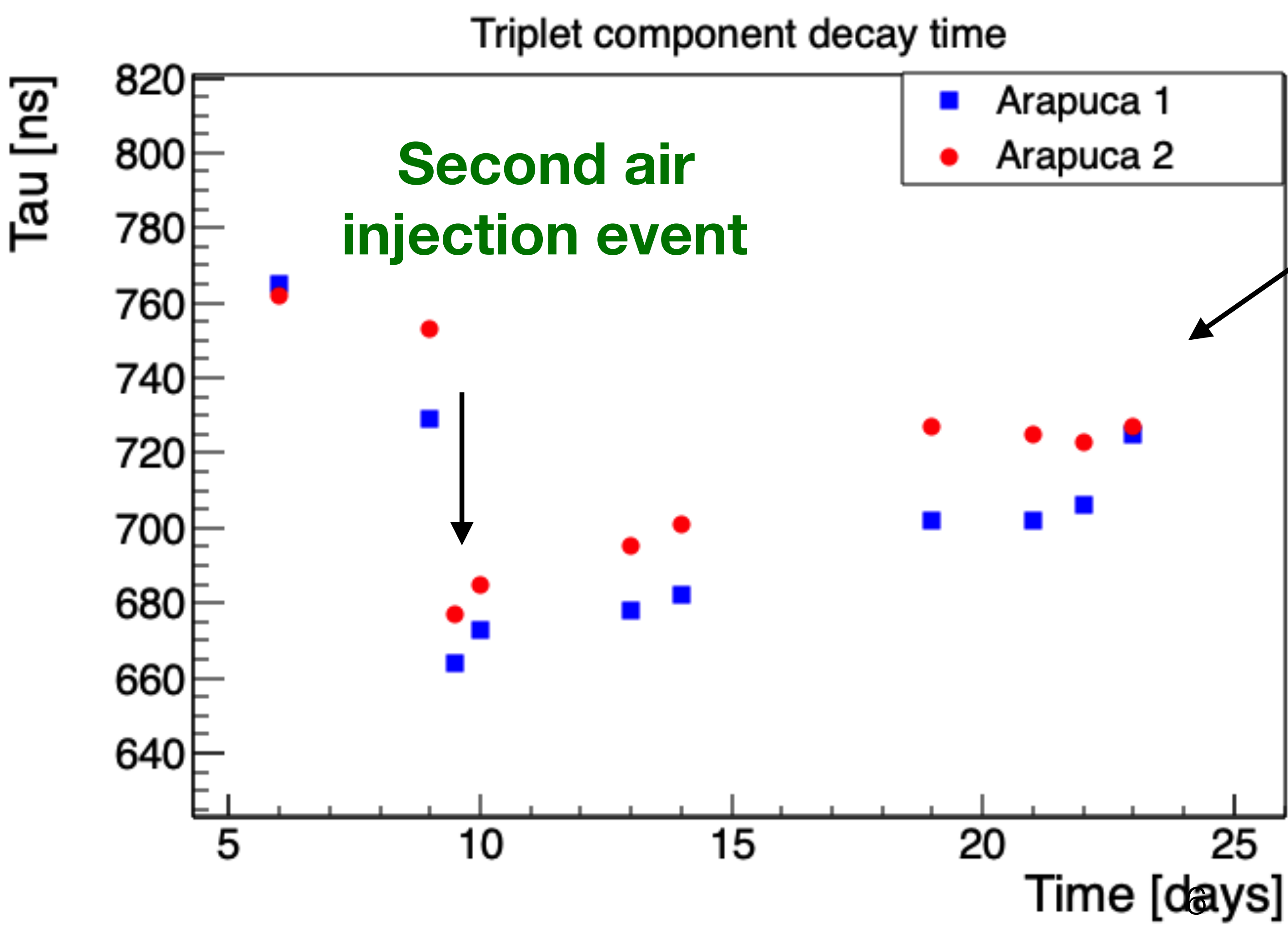
Green = single photon response
Red = before purity drop
Blue = after purity drop

Deconvoluted waveform



Triplet component decay time





Triplet component slow recovery.

The recovery process is partial because the filters can remove only oxygen and water.

The nitrogen is the bigger fraction of impurities

Single photon rate

A huge single photon rate is observed in protoDUNE detector as well as in others LAr TPC detectors. Follow the most valid interpretation that rate comes from space-charge recombination.

Thanks Arapuca granularity is possible to measure and distinguish events of single photon of space-charge recombination, from light produced by ionizing events

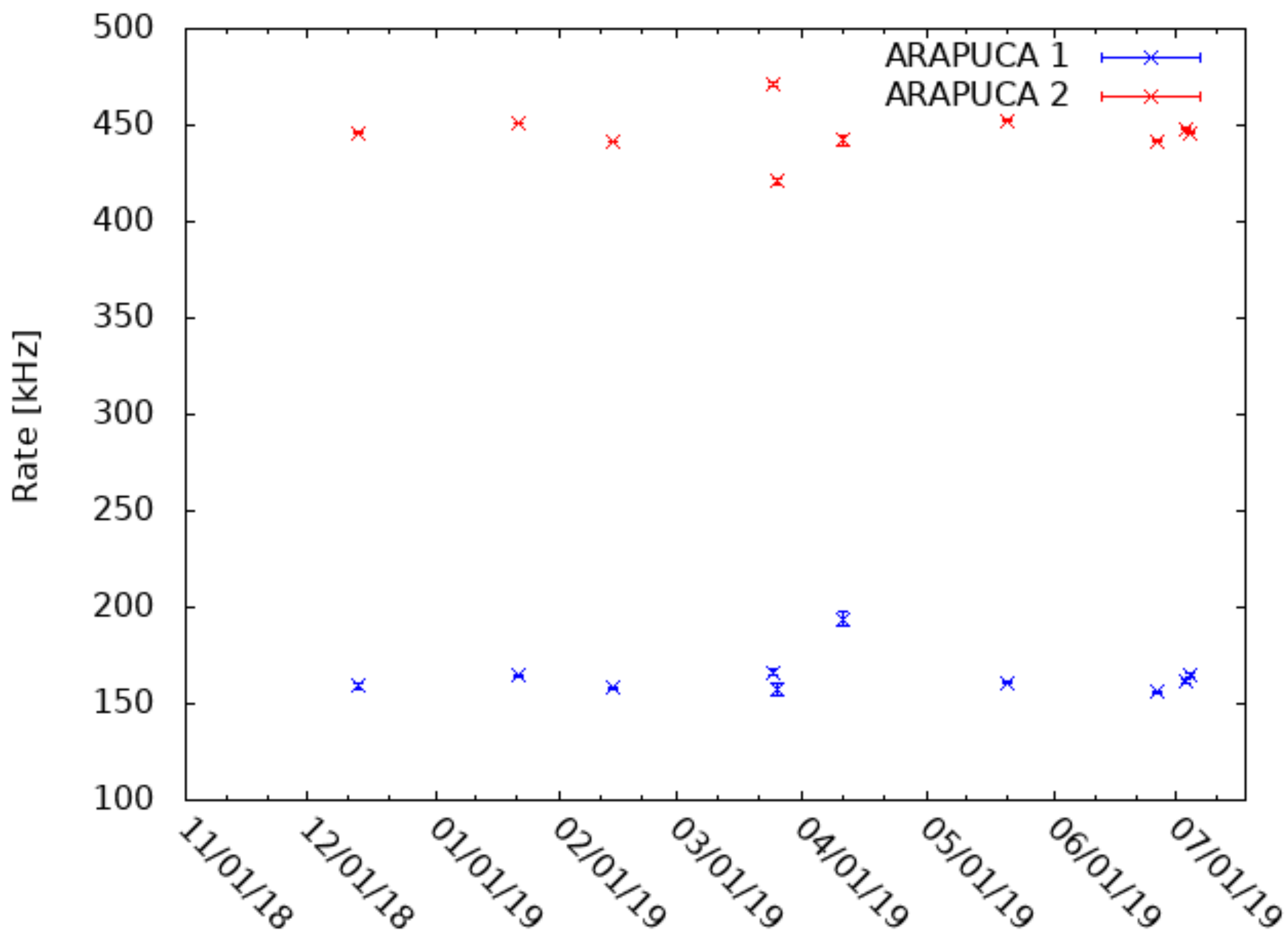
The analysis is ongoing and a lot of things are still not understood.

However we observed a certain stability for the single photon rate in a long period

Plot shows runs in standard situations:

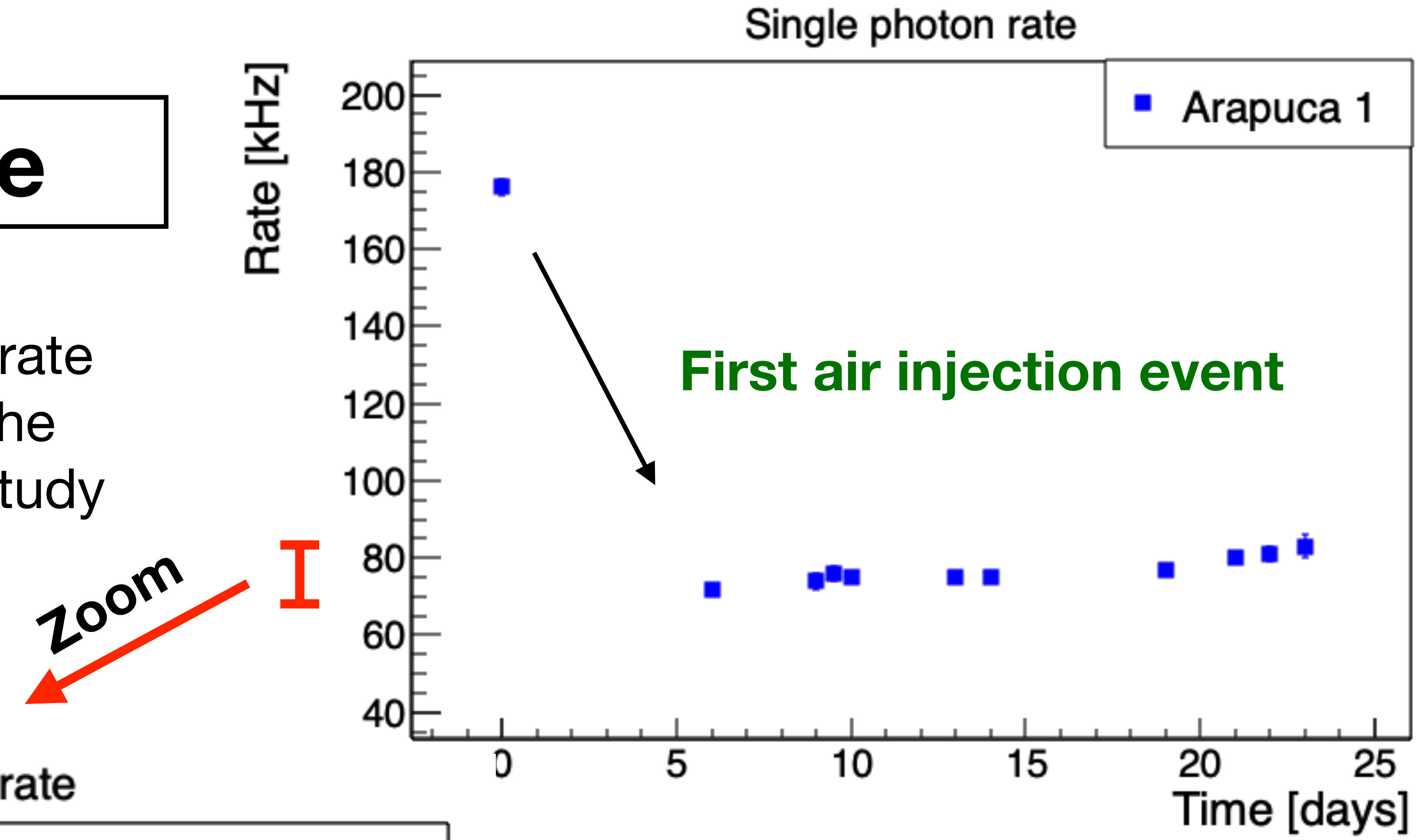
Purity = 6 ms electrons lifetime
Electric field = 500 V/cm

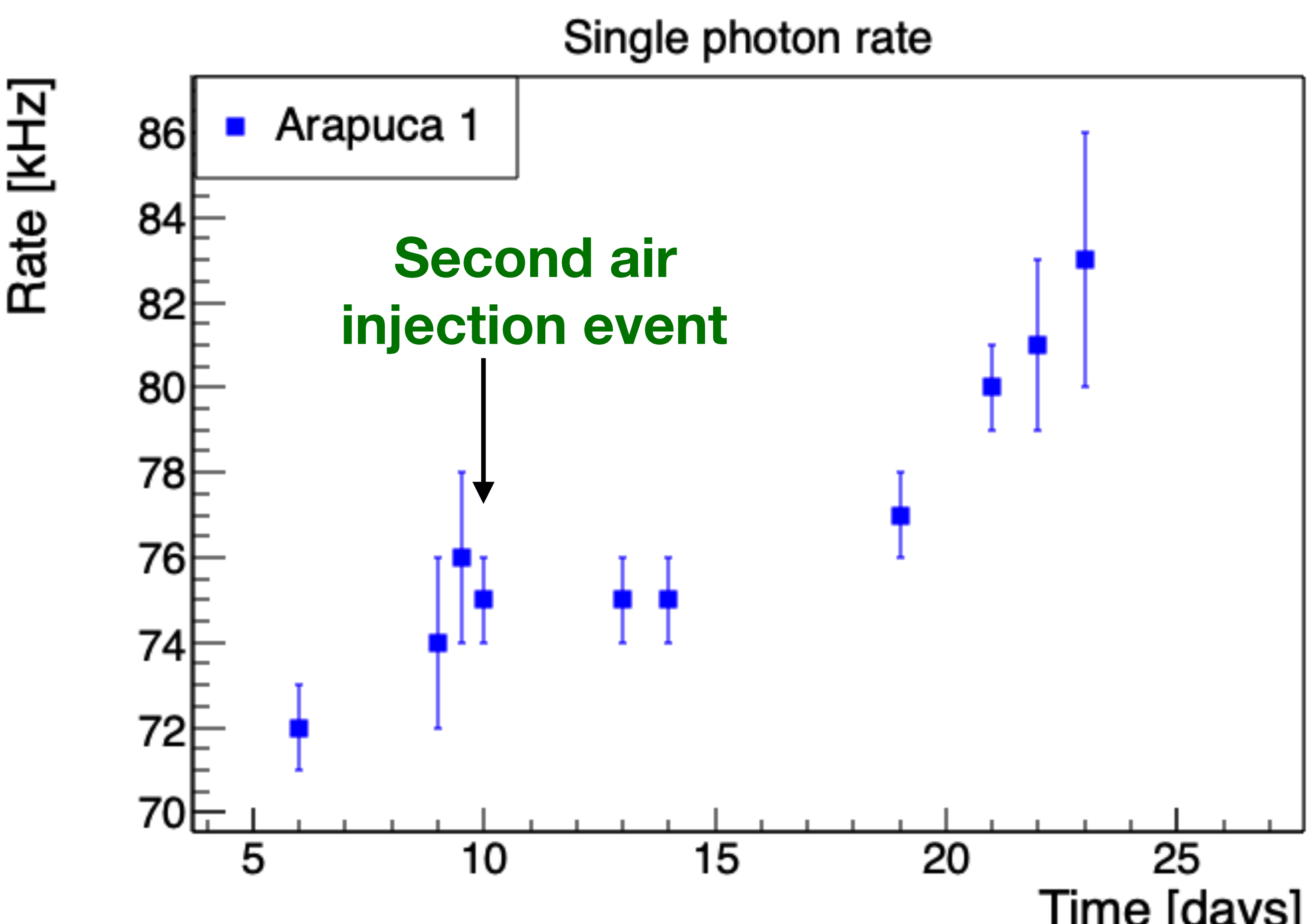
Plot from Niccolo' Gallice
(University of Milan - INFN)



Single photo rate

Plots show the single photon rate observed by Arapuca 1 for the same runs used in the triplet study

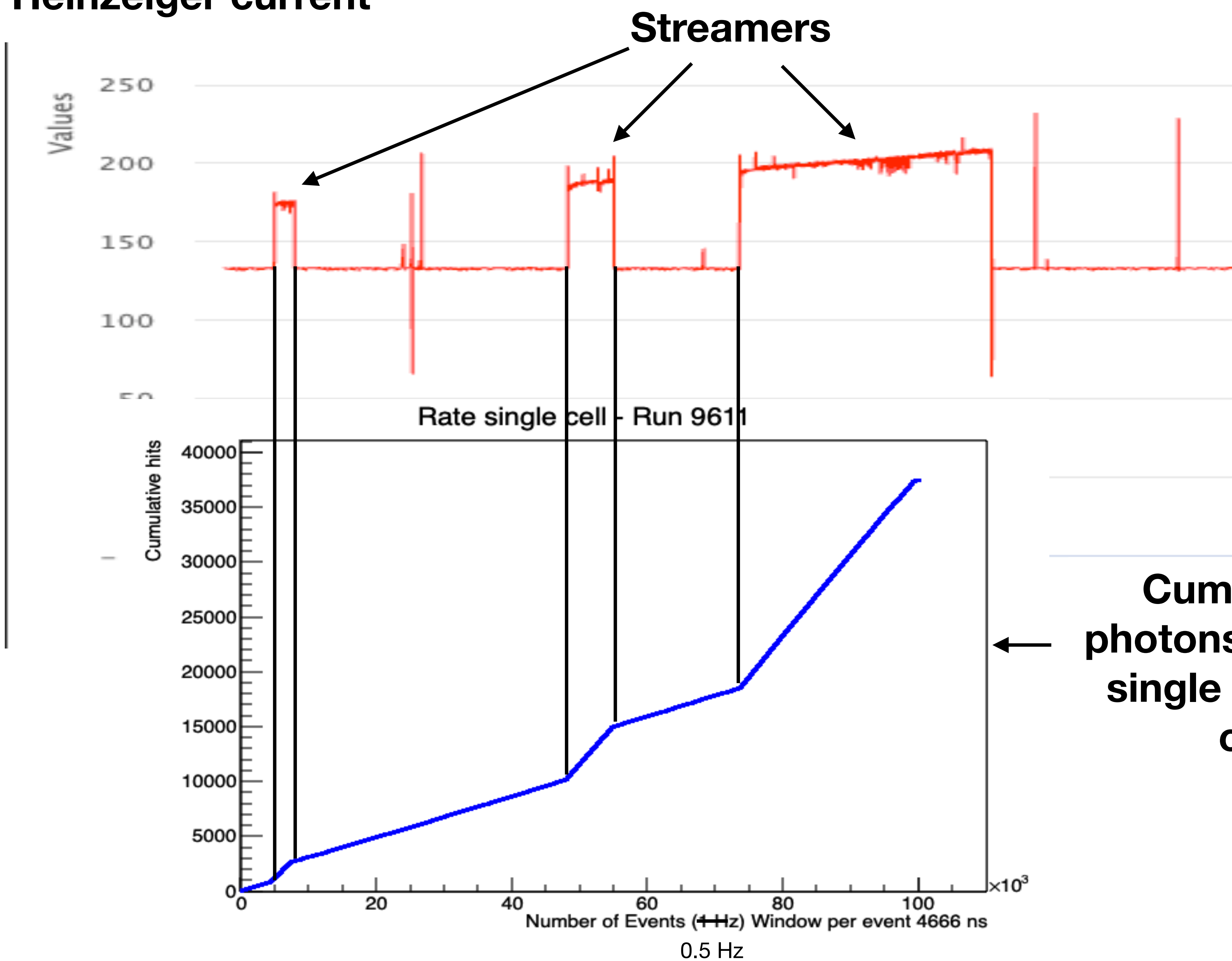




As well for the triplet decay time the single photon rate shows a drop and a partial recovery.

Streamers-light correlation

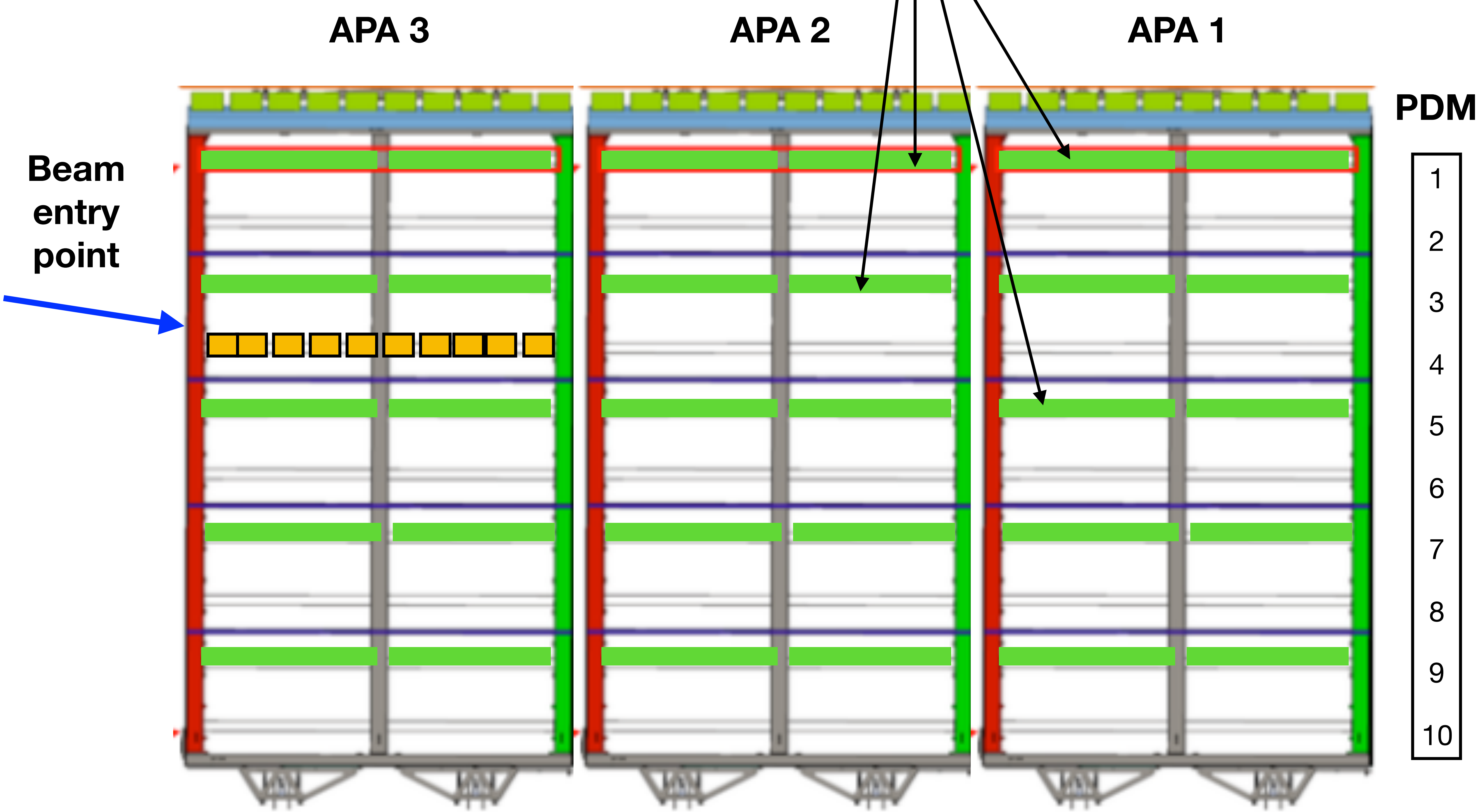
Heinzeiger current

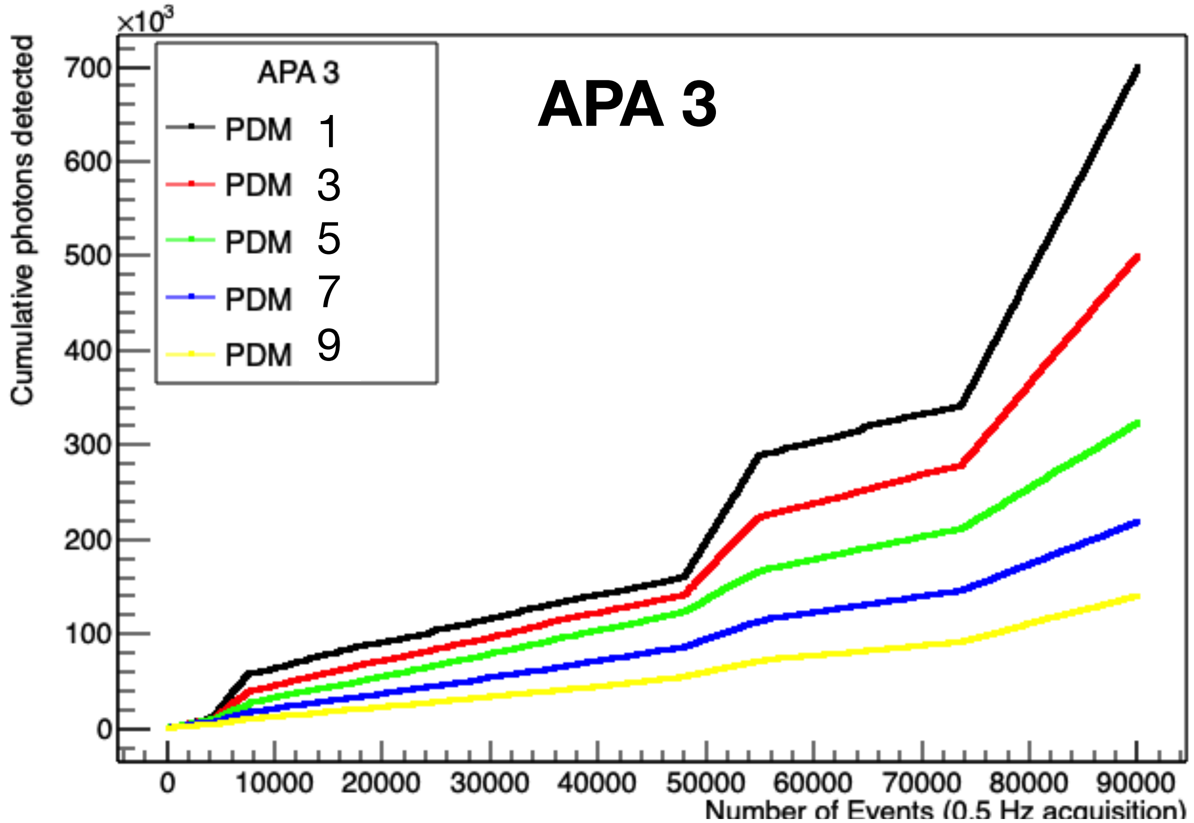


Cumulative photons hits on a single Arapuca cell

The PD module used for the analysis are the IU bars, the green slots in the pictures

15 PD modules

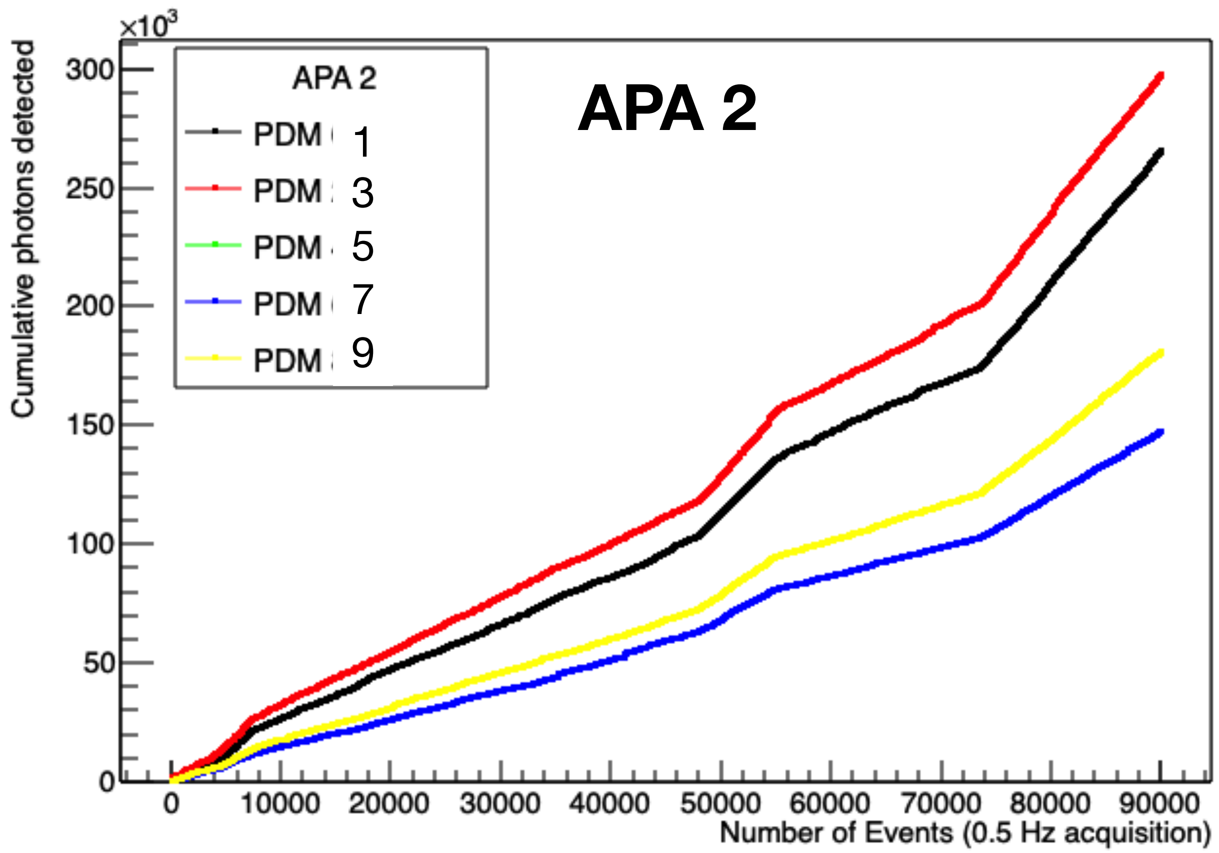


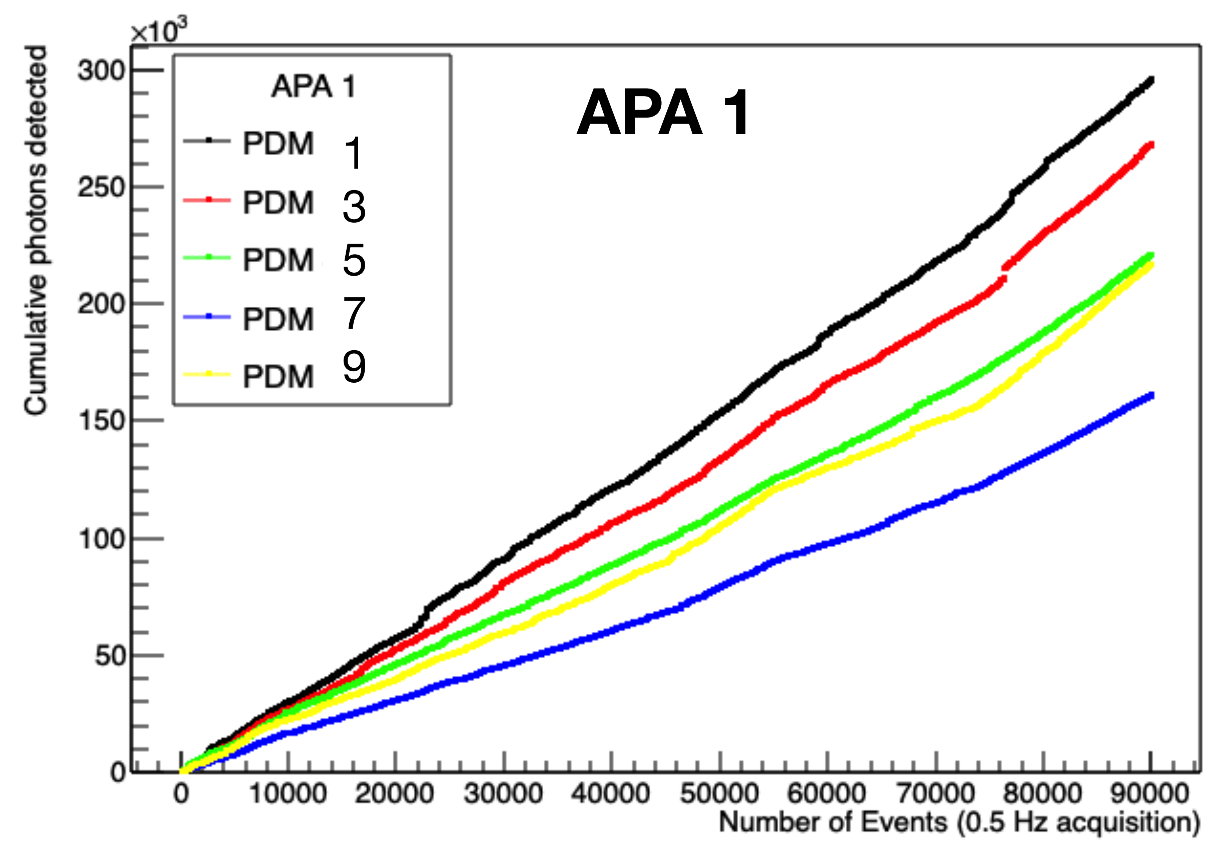


Cumulative number of photons detected per waveform run 9611

Waveform : $13.6\,\mu s$

Rate acquisition = $0.5\,Hz$



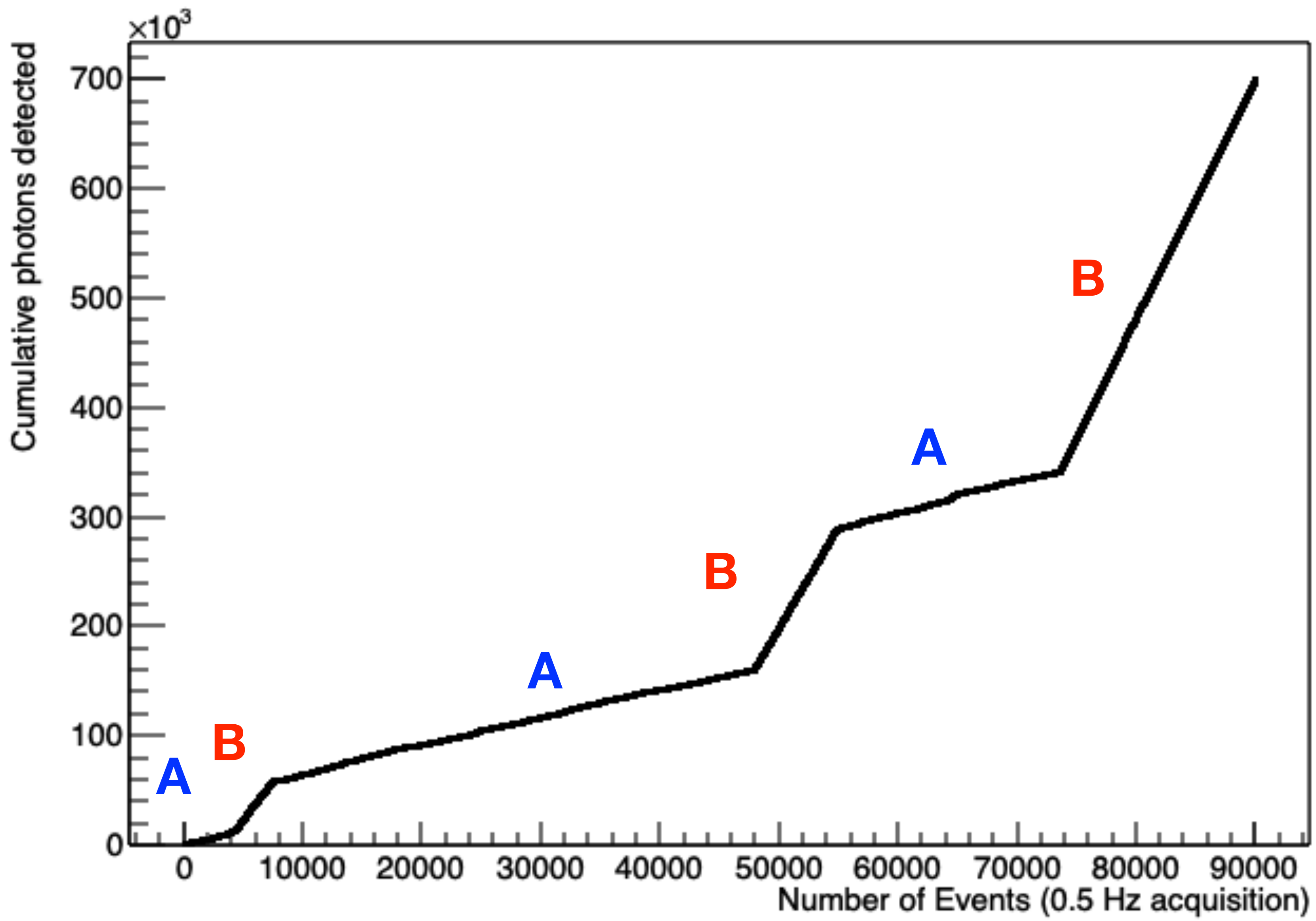


The regions A of “Offset” light observed, shows a uniform amount of light in all the detectors (whit some small dependence from the vertical position in the APA)

The regions B in coincidence with streams, seems to be produced by a localized source

In the next plots will be shown the quantities:

<Ph>/wfm **(A)** and <Ph>/wfm **(B)** - <Ph>/wfm **(A)**

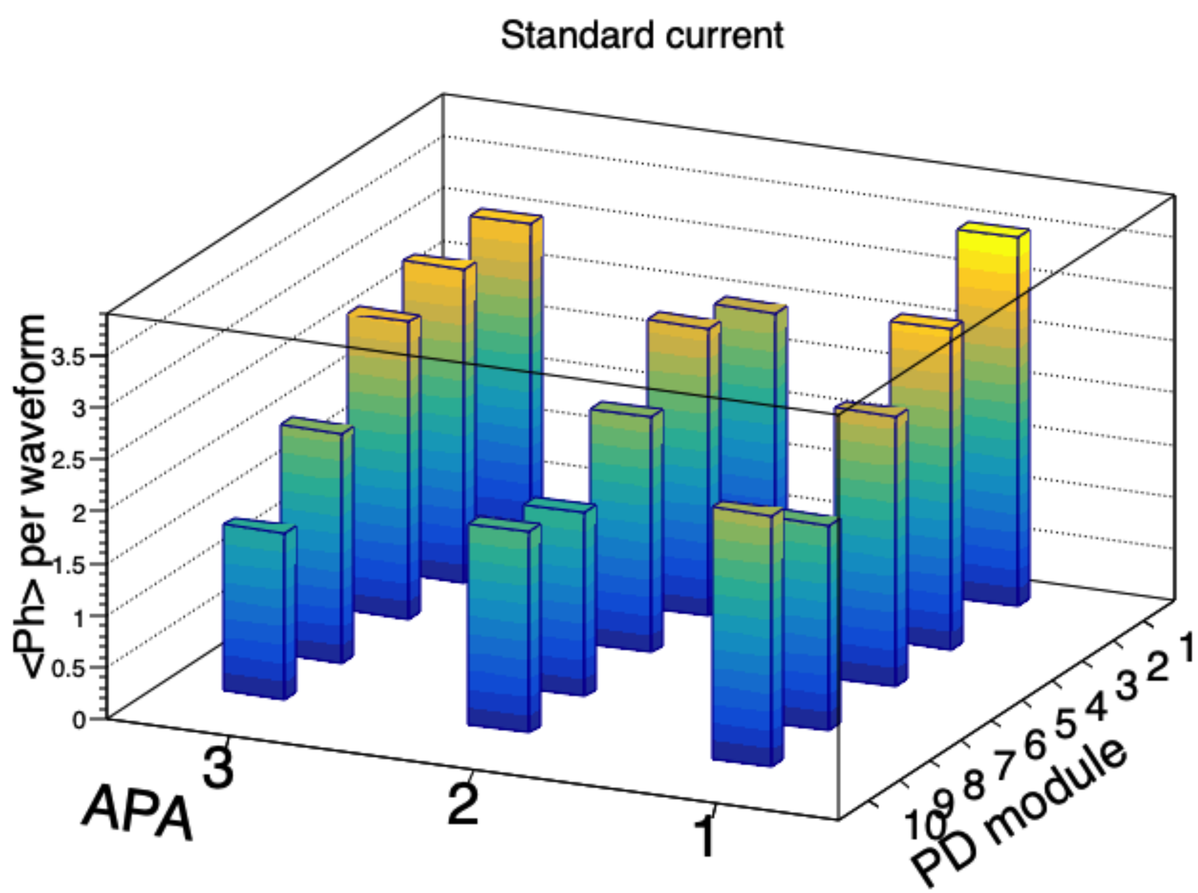


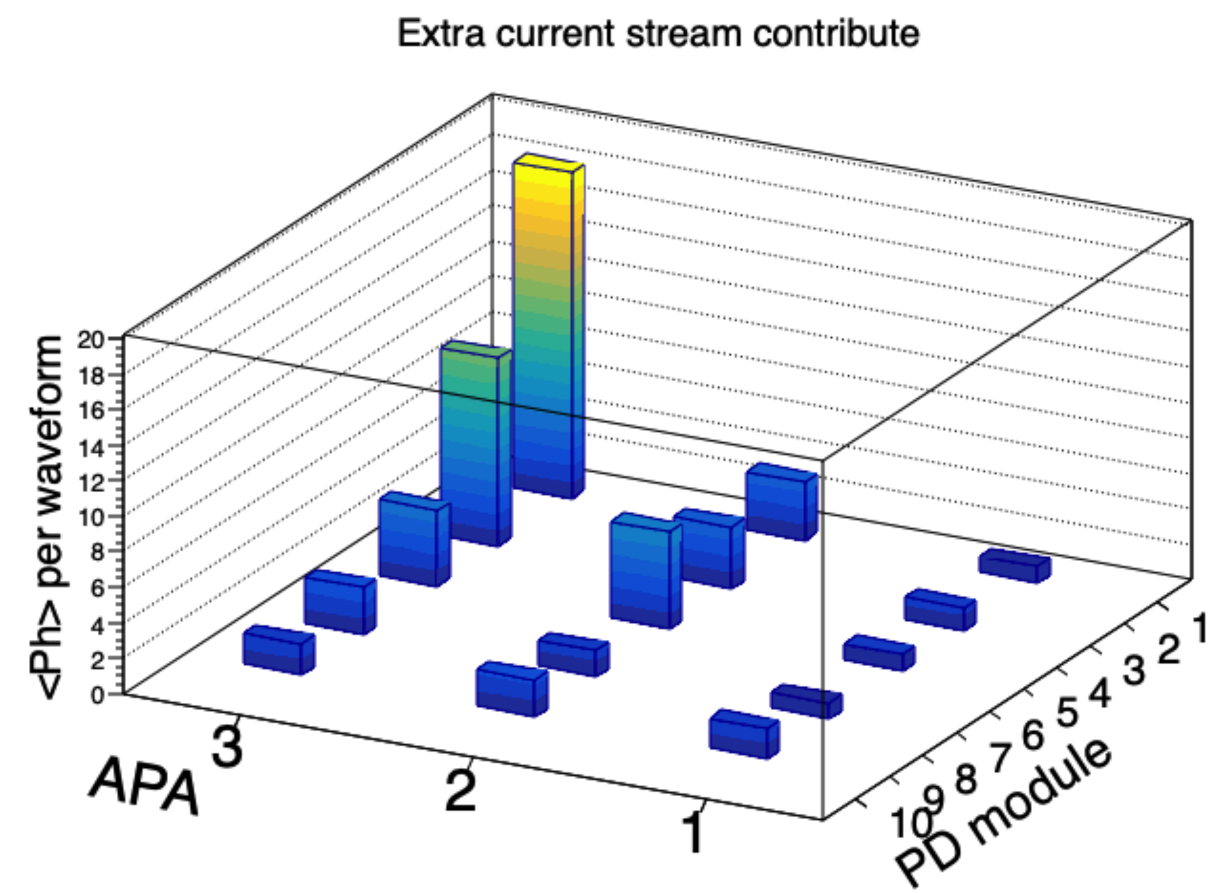
Offset rate

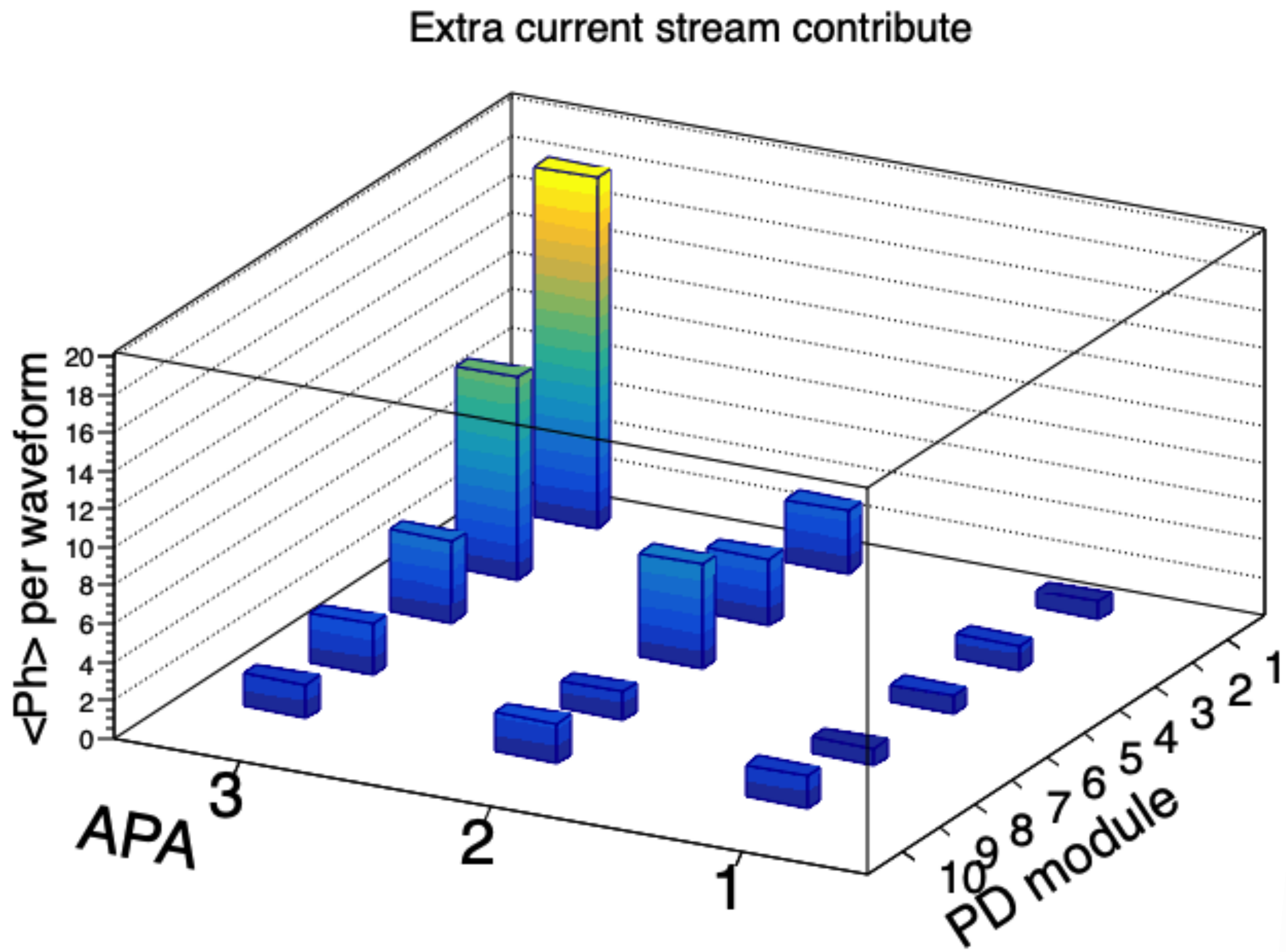
<Ph>	APA 3	APA 2	APA 1
PDM 1	3.03	2.49	3.54
PDM 3	3.01	2.77	3.08
PDM 5	2.86	2.26	2.60
PDM 7	2.21	1.77	1.97
PDM 9	1.60	1.94	2.41

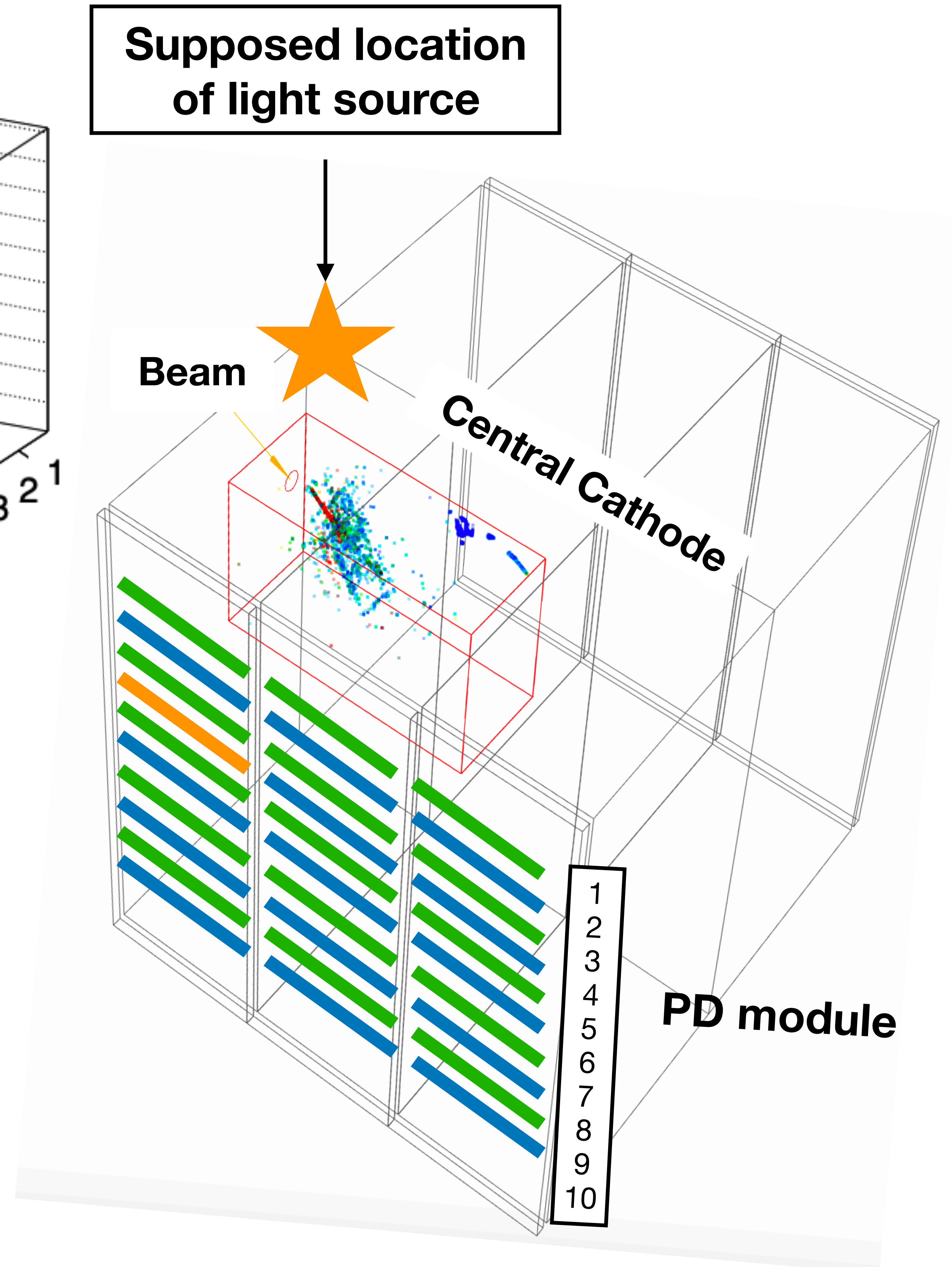
Current stream contribute

<Ph>	APA 3	APA 2	APA 1
PDM 1	18.38	3.29	0.90
PDM 3	10.59	3.46	1.31
PDM 5	4.30	5.46	0.93
PDM 7	2.62	1.45	0.90
PDM 9	1.73	2.07	1.71







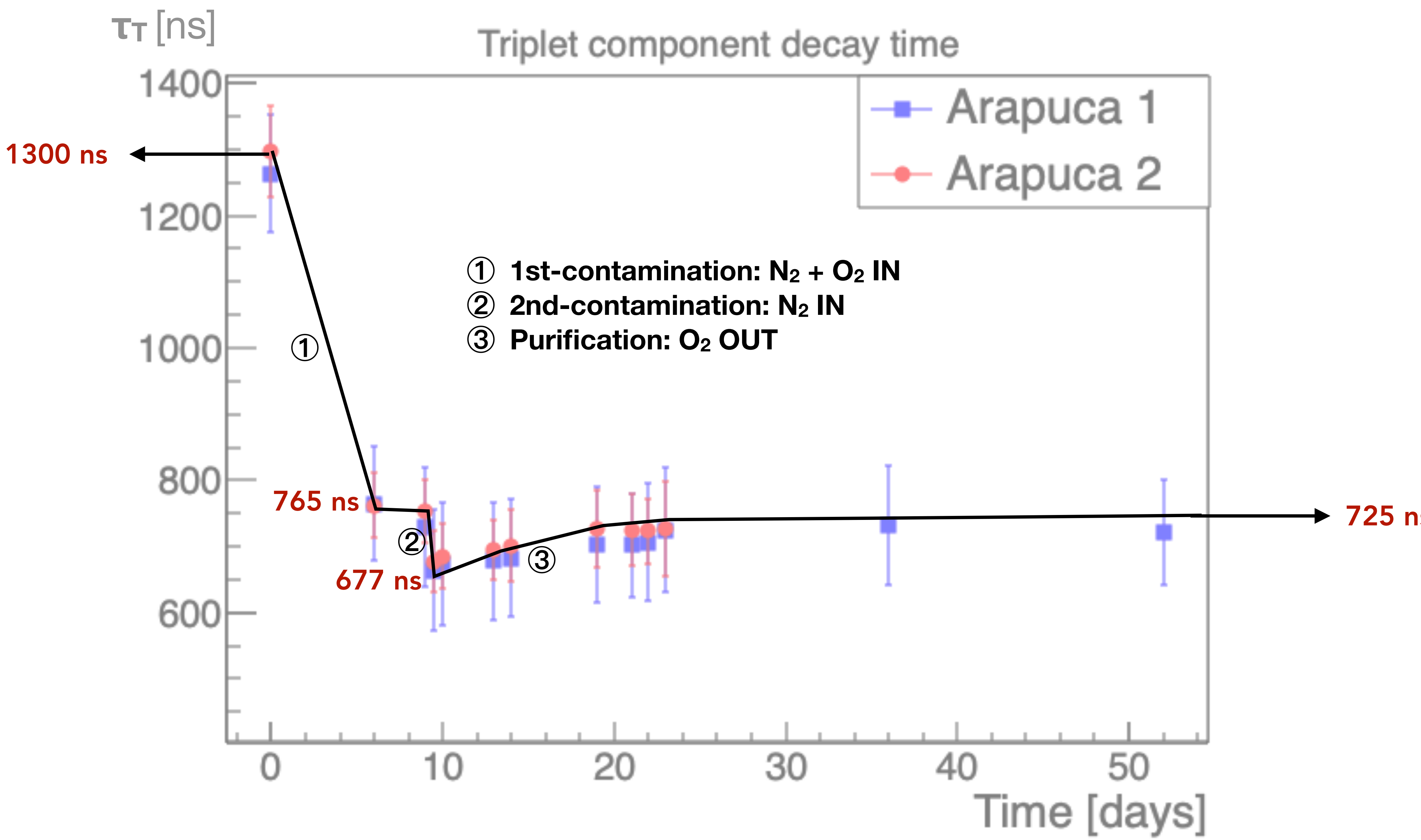


The 15 PD module used for the analysis are the IU bars, the green slots in the pictures

Argon scintillation light triplet component decay time in presence of O_2 and N_2 contaminant

DETERMINATION OF RESIDUAL N_2 CONTAMINATION

Flavio Cavanna
Dante Totani



τT [ns]
Triplet component decay time
Arapuca 1
Arapuca 2
1300 ns
765 ns
677 ns
725 ns
① 1st-contamination: N2 + O2 IN
② 2nd-contamination: N2 IN
③ Purification: O2 OUT
1400
1200
1000
800
600
0
10
20
30
40
50
Time [days]

① 1st-contamination: Air IN (N_2 + O_2)

Sun. Jul.21 - h. 12:00 pm: START Air leak into GAr O_2-filter

100% N_2 go through into TPC

100% O_2 trapped

Sun. Jul.21 - h.~24:00: GAr O_2-filter saturated

100% N_2 go through into TPC

100% O_2 go through GAr O2-filter but trapped in LAr O_2-filter,

19h Air IN (0% O_2, 100% N_2)

Mon. Jul.22 - h.~7:00: LAr O_2-filter saturated:

100% N_2 go through into TPC

100% O_2 go through into TPC

START purity drop in TPC

5h - Air IN (21% O_2, 78% N_2)

Mon. Jul.22 - h.~12:00 Recirculation closed

STOP Air leak

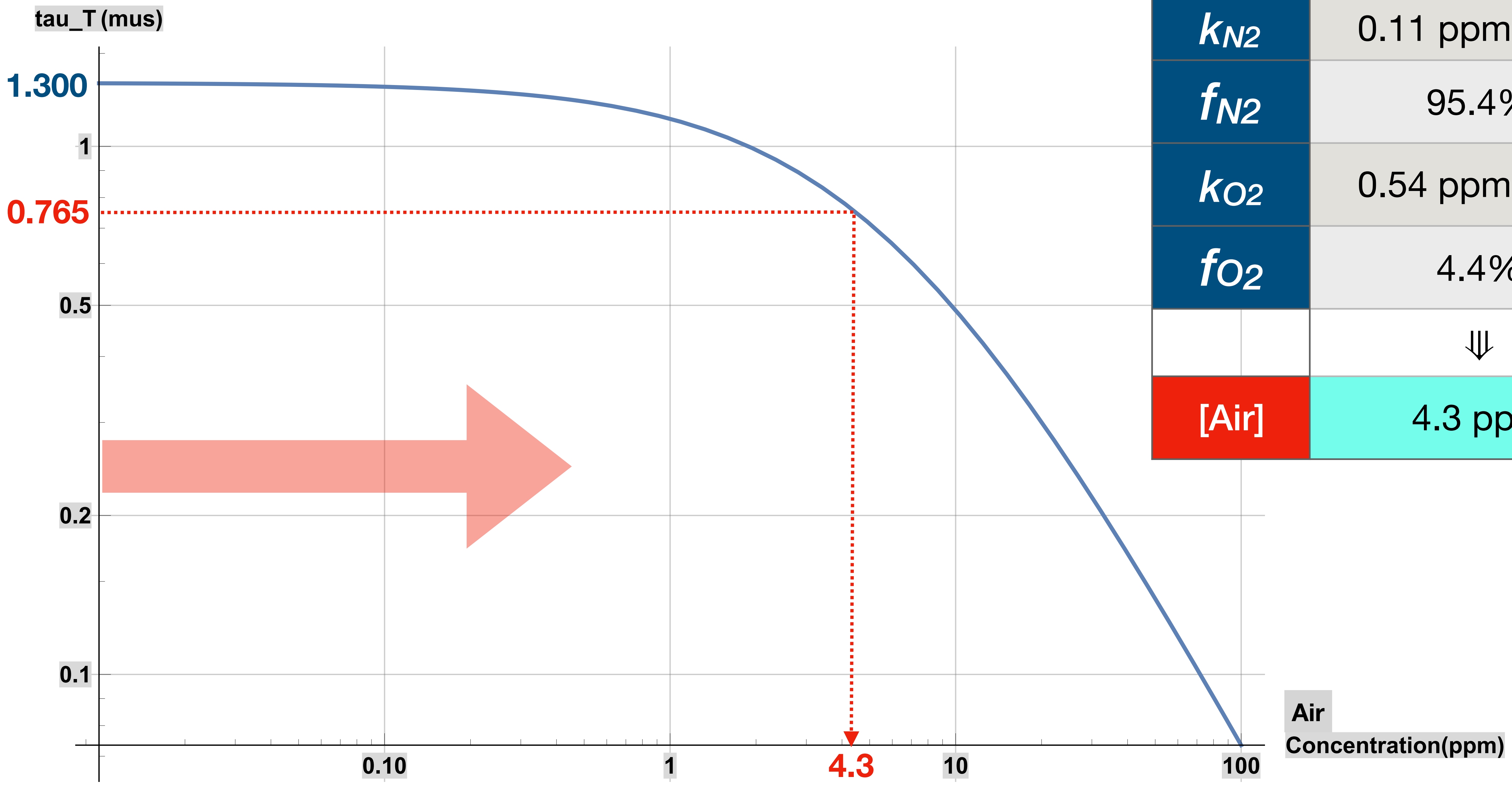
1st Air Contamination in TPC:

N_2 fraction = 95.4%

O_2 fraction = 4.4%

① 1st-contamination: Air ($N_2 + O_2$) IN TPC

$$\frac{1}{\tau_1^T} = \frac{1}{\tau_0^T} + k_{N_2}\, f_{N_2}\, [Air] + k_{O_2}\, f_{O_2}\, [Air]$$



$\tau_0{}^T$	1.300 μs *(meas)*
	1st Air Leak
$\tau_1{}^T$	0.765 μs *(meas)*
k_{N2}	0.11 ppm^{-1} μs^{-1}
f_{N2}	95.4%
k_{O2}	0.54 ppm^{-1} μs^{-1}
f_{O2}	4.4%
	⤋
[Air]	4.3 ppm

$$4.3\ ppm\ (\mathrm{Air}) = 0.2\ ppm\ (\mathrm{O_2}) + 4.1\ ppm\ (\mathrm{N_2})$$

② 2nd-contamination: N_2 IN TPC

Thu. Jul.25 - h.~21: START Air Leak into GAr O_2-filter

100% N_2 go through into TPC

100% O_2 trapped

8h - Air IN
(0% O_2, 100% N_2)

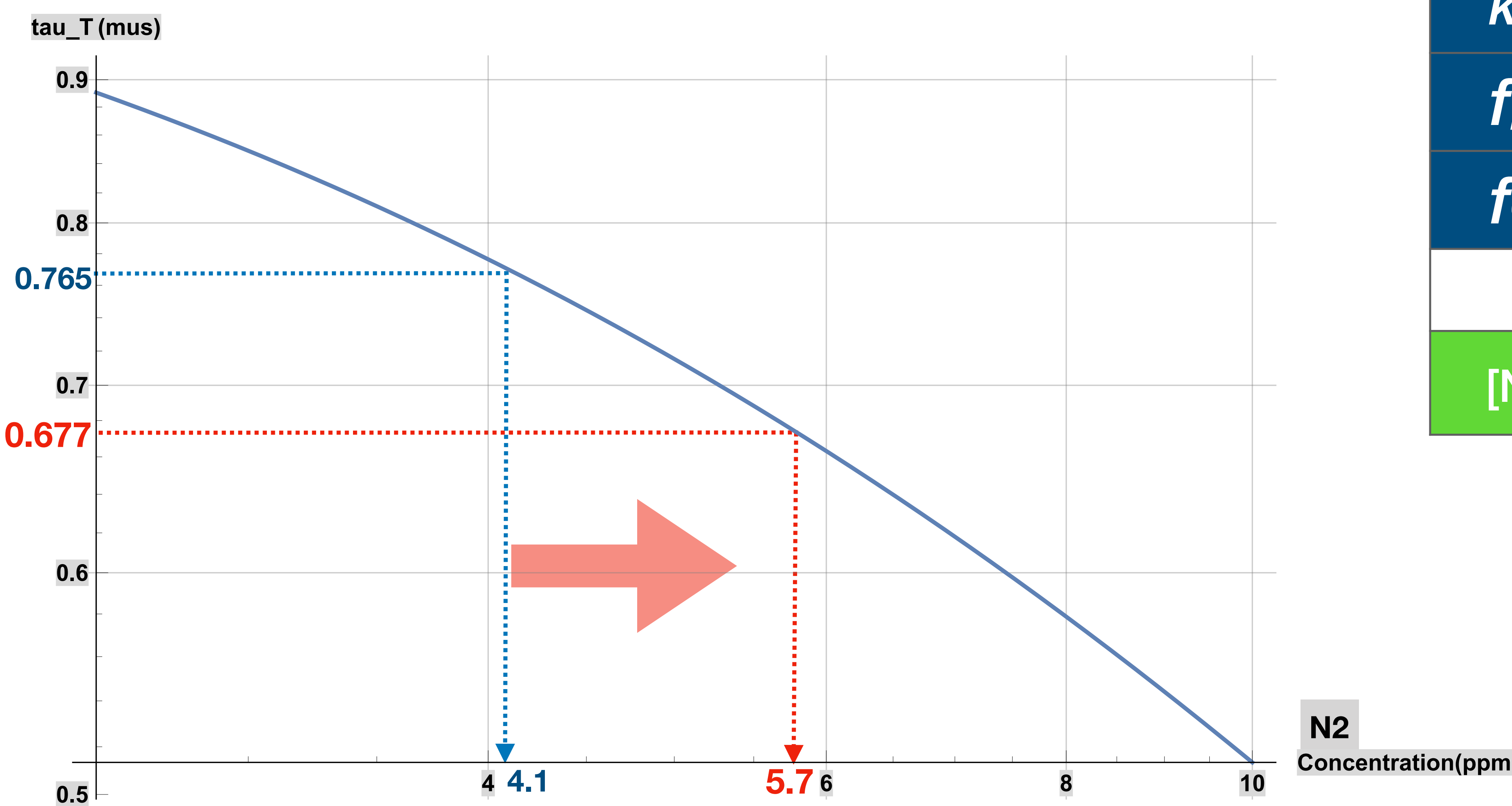
Fri. Jul. 26 - h ~5:00: GAr O_2-filter saturated,
pump failure identified
Recirculation closed

STOP Air leak

2nd Air Contamination in TPC:
N_2 fraction = 100%
O_2 fraction = 0%

② 2nd-contamination: N_2 IN TPC

$$\frac{1}{\tau_2^T} = \frac{1}{\tau_1^T} + k_{N_2}\,[N_2 - 4.1]$$



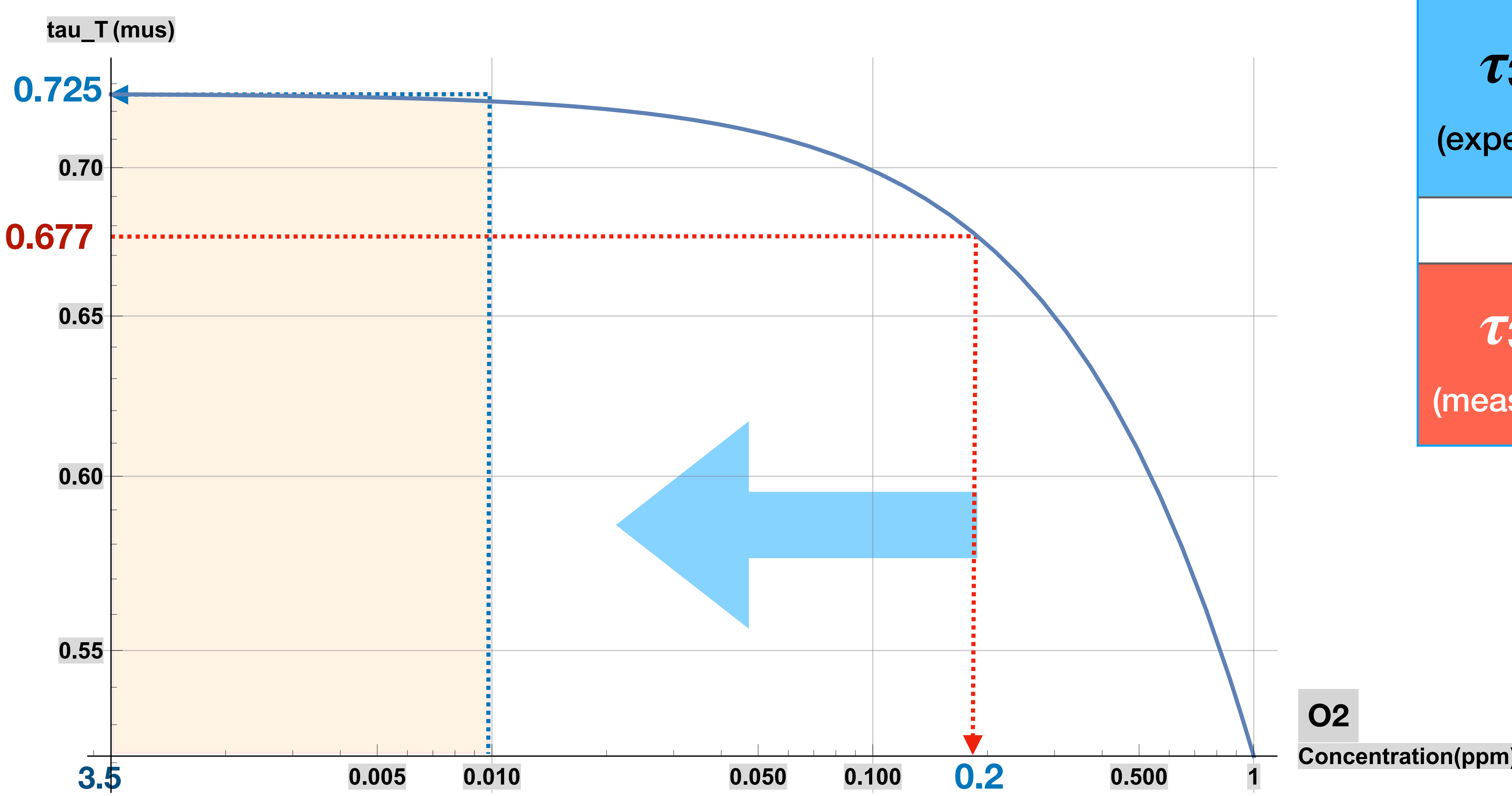
$\tau_1{}^T$	0.765 μs *(meas)*
[N2]	4.1 ppm
	2nd Air Leak
$\tau_2{}^T$	0.677 μs *(meas)*
k_{N2}	0.11 ppm^{-1} μs^{-1}
f_{N2}	100%
f_{O2}	0%
	⤋
[N2]	5.7 ppm

$$5.7\ ppm\ (N_2)\ +\ 0.2\ ppm\ (O_2)$$

③ Purification: O_2 OUT TPC

Recirculation ON: Aug to Mid Sept

$$\frac{1}{\tau_3^T} = \frac{1}{\tau_2^T} + k_{O_2}\,[O_2 - 0.2]$$



τ_2^T	0.677 μs *(meas)*
$[O_2]$	0.2 ppm
	O_2 filtered out
k_{O2}	0.54 ppm^{-1} μs^{-1}
$[O_2]$	<< 0.01 ppm
	⟱
τ_3^T (expected)	0.725 μs
τ_3^T (measured)	**0.722 μs**

$$5.7\ ppm\ (\mathrm{N_2})\ +\ 0\ ppm(\mathrm{O_2})$$

Backup slides

Formula used in Calculation include an initial N_2 contamination term (not reported in slides)

$$\frac{1}{\tau_1^T} = \frac{1}{\tau_0^T} - k_{N_2}[\mathrm{N}_2^{In}] + k_{N_2}\, f_{N_2}\, [Air] + k_{O_2}\, f_{O_2}\, [Air]$$

$$\mathrm{N}_2^{In} = 0.1 \text{ ppm}$$

$$f_{N_2} = f_{N_2}^1\, R^1 + f_{N_2}^2\, R^2 = 95.4\ \%$$

$$f_{O_2} = f_{O_2}^1\, R^1 + f_{O_2}^2\, R^2 = 4.4\ \%$$

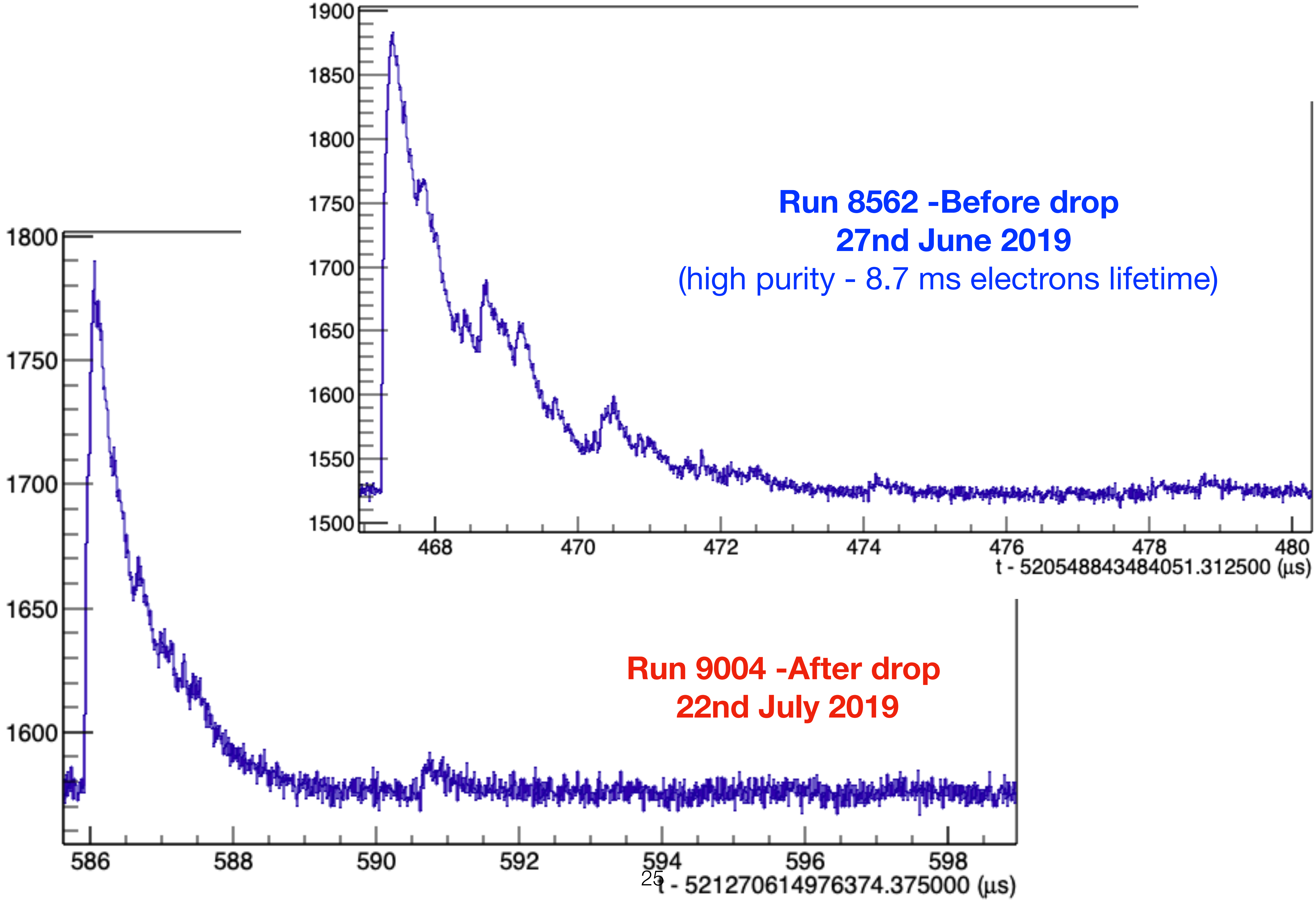
$f_{N_2}^1 = 0.78, \quad f_{O_2}^1 = 0.21, \quad R^1 = \frac{5}{24}$ **Fraction of time after GAr & LAr filters saturated**

$f_{N_2}^2 = 1, \quad f_{O_2}^2 = 0, \quad R^2 = \frac{19}{24}$ **Fraction of time before GAr & LAr filters saturated**

Triplet component decay time

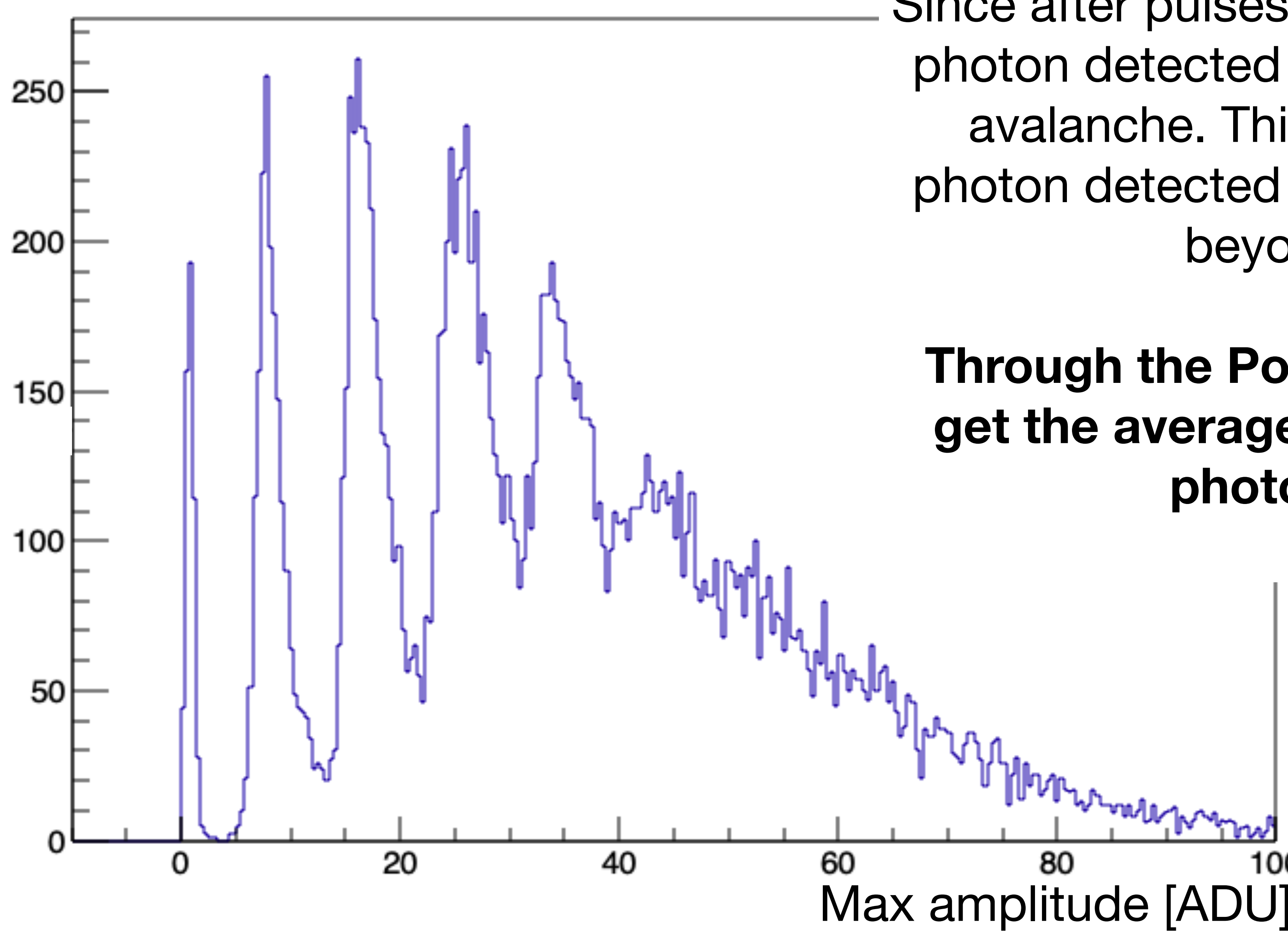
		Arapuca 1 <Tau> (ns)	Arapuca 2 <Tau> (ns)
	Standard condition	1263+/-89	1297 +/- 70
First drop	July 22nd	765+/-87	762 +/- 49
Second drop	July 25th	664+/-91	677 +/- 47
Purity recovering	August 8th	725+/-95	727 +/- 71

Examples of original waveforms for the two runs



Single photon response:

The single photon response comes from calibrations runs.
A pulsed LED lightened the PD modules giving a signal which is totally dependent from the MPPS response to the single photon (or more photons "contemporary")



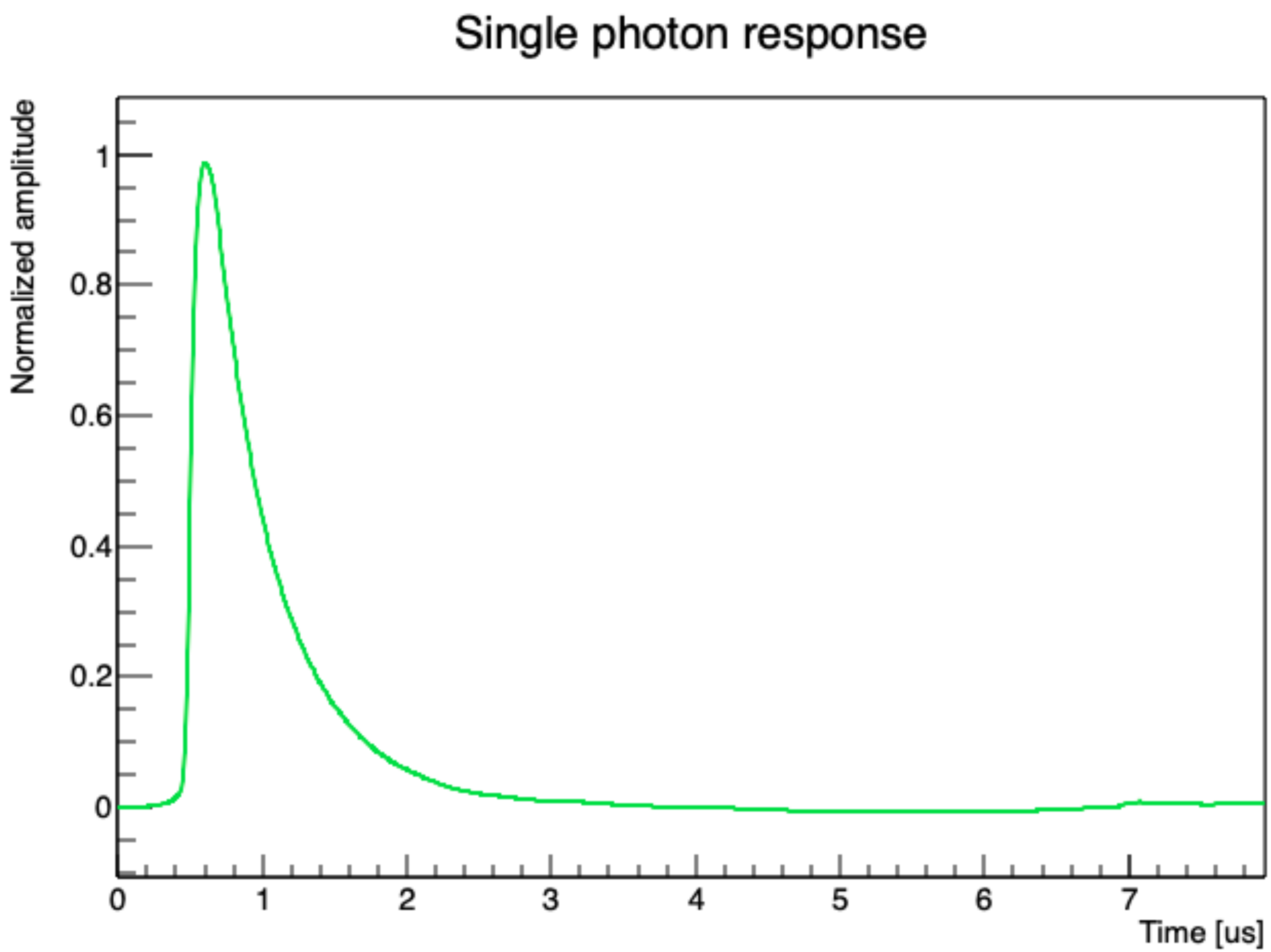
Since after pulses and cross talks, a single photon detected can give more than one avalanche. This means that a single photon detected can populate the peaks beyond the first.

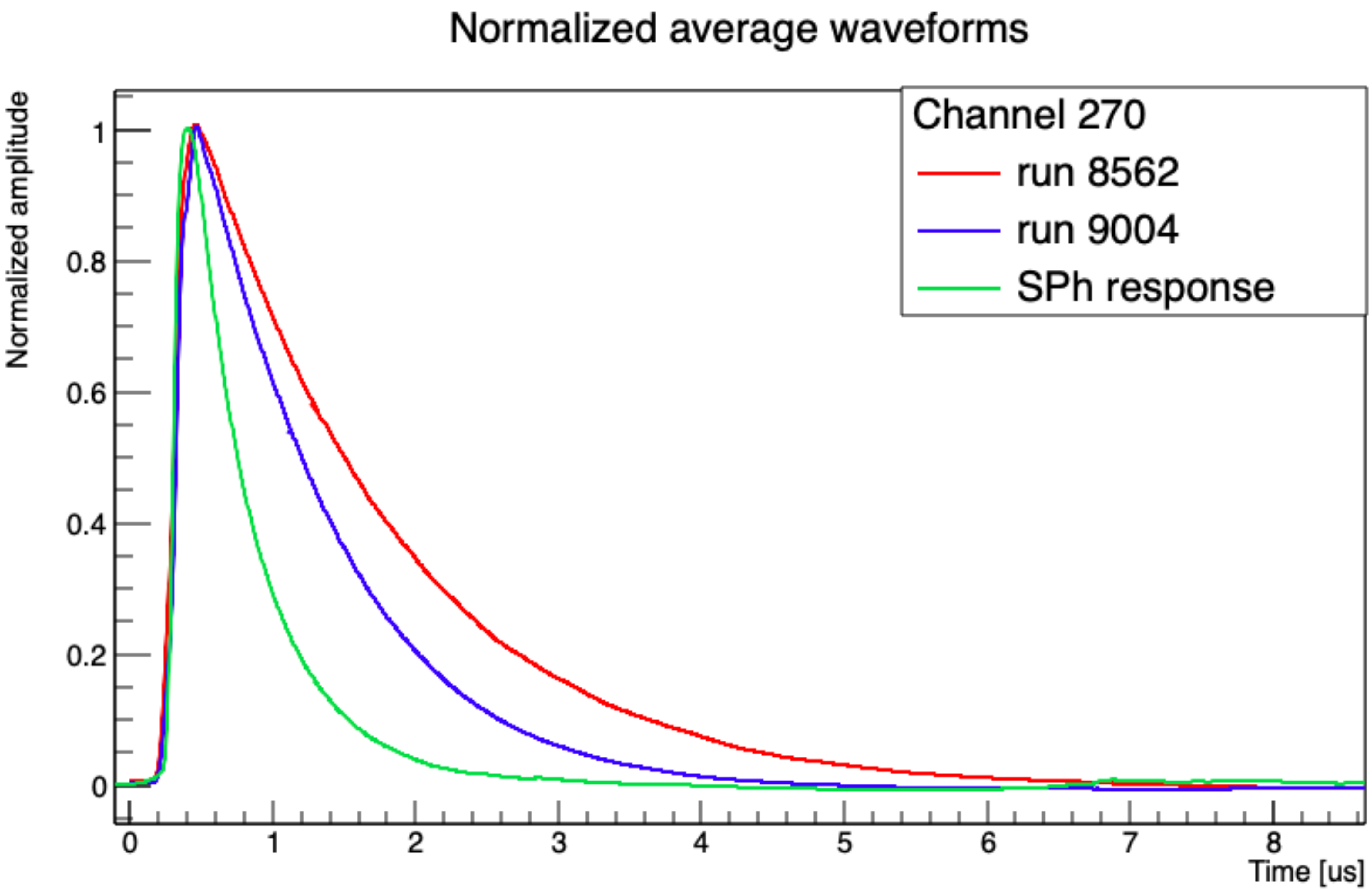
Through the Poisson statistic we can get the average response to a single photon detected

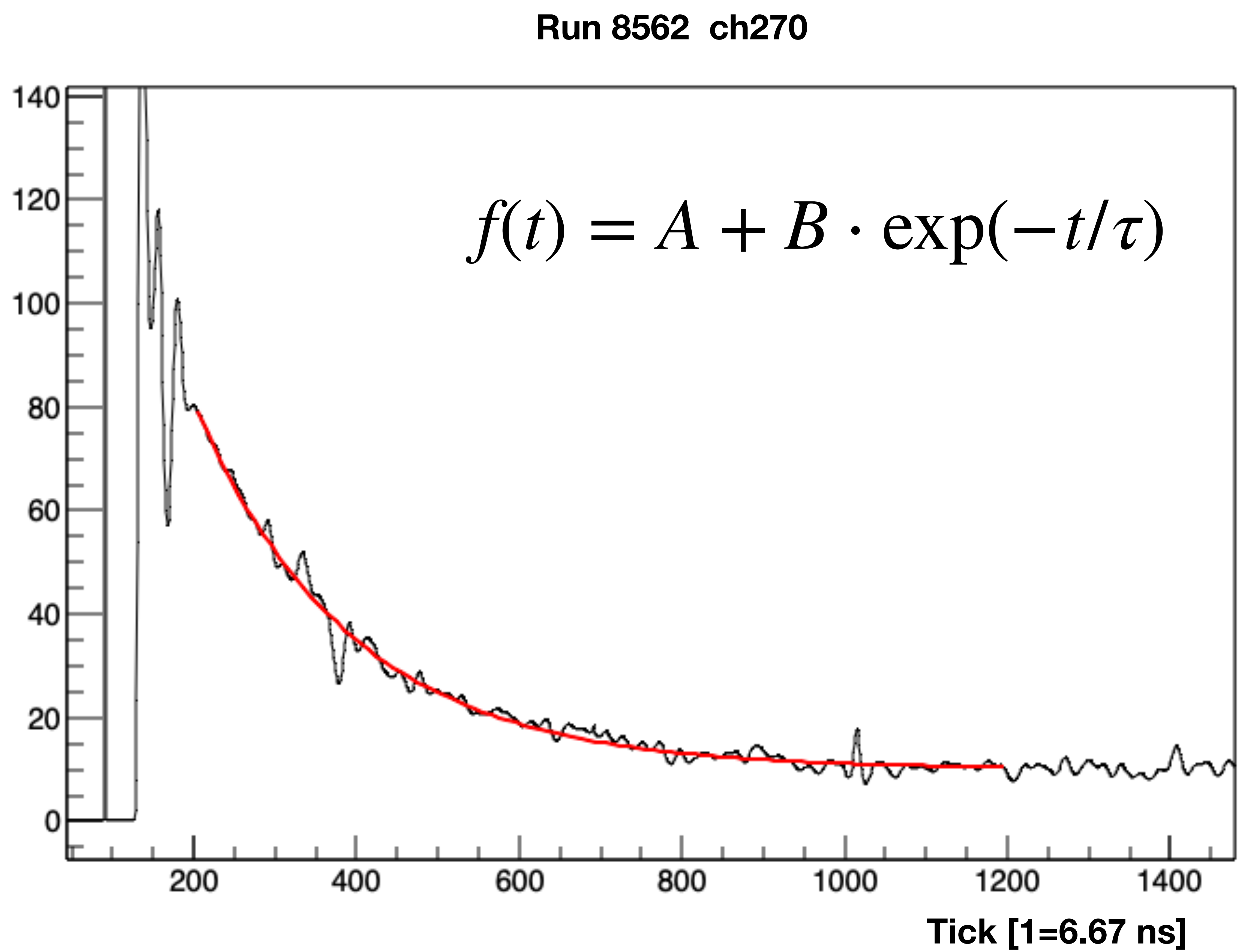
$$\lambda = -\ln\left(\frac{N_0}{N_{Tot}}\right)$$

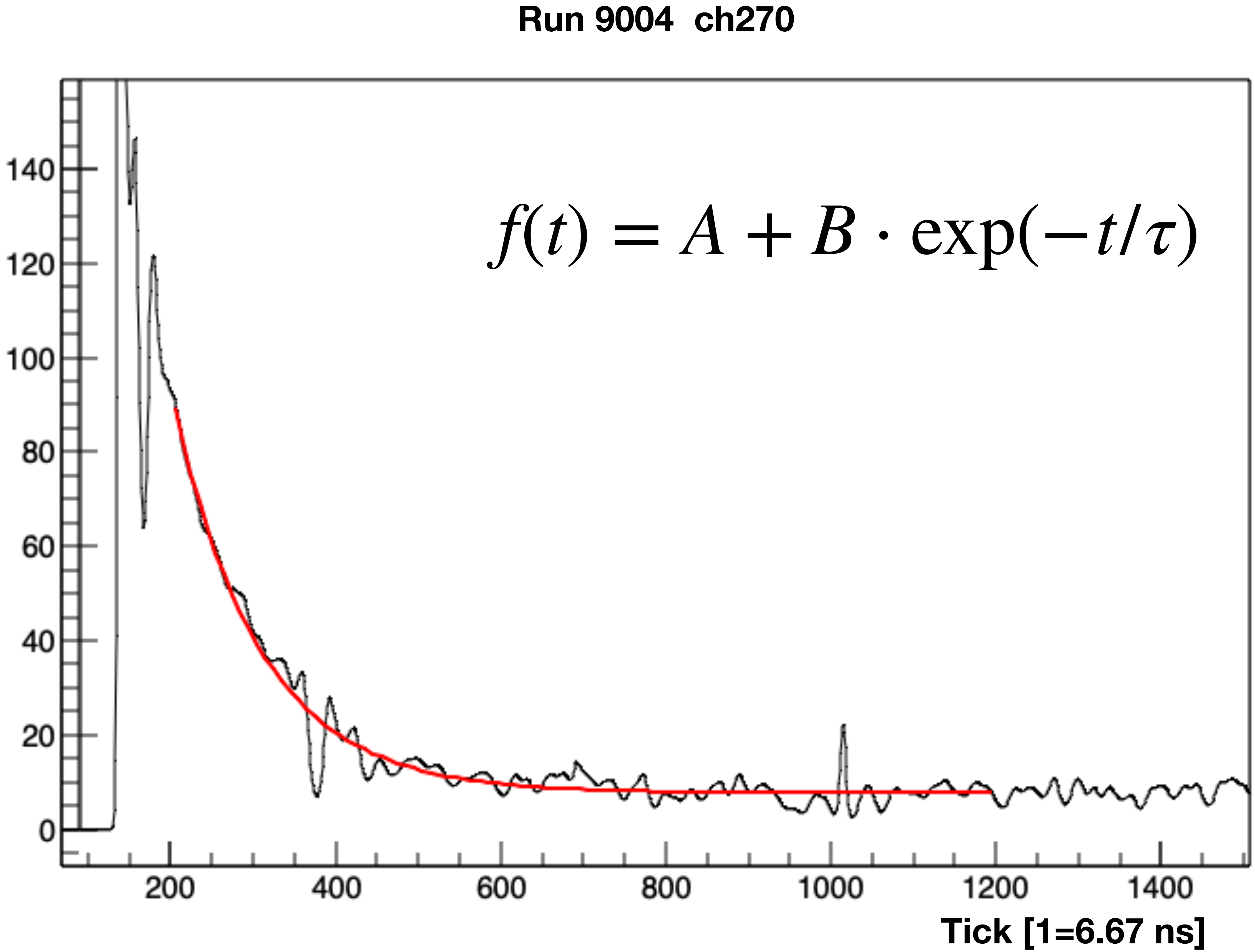
Single photon response normalized from channel 270

(The LED light pulse is assumed to be a delta function)




Normalized average waveforms
Normalized amplitude
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
Time [us]
Channel 270
run 8562
run 9004
SPh response


Run 8562 ch270
$f(t) = A + B \cdot \exp(-t/\tau)$
0
20
40
60
80
100
120
140
200
400
600
800
1000
1200
1400
Tick [1=6.67 ns]


Run 9004 ch270
$f(t) = A + B \cdot \exp(-t/\tau)$
140
120
100
80
60
40
20
0
200
400
600
800
1000
1200
1400
Tick [1=6.67 ns]

Cosmic ray passing threshold

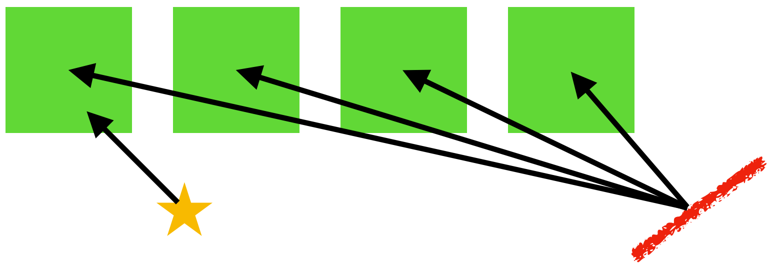
DAQ ch 264: single cell Arapuca 2 (APA 6)

Run number	8562	9004
Internal Trigger (threshold ~35 ph)	170 evt	27 evt
External trigger (random)	62 evt	74 evt
CR triggered per 3 ms window	2.7 evt	0.36 evt
CR triggered rate	0.90 kHz	0.12 kHz

Triplet component decay time

		Arapuca 1	Arapuca 2
		<Tau> (ns)	<Tau> (ns)
Standard	condition	1263+/-89	1297 +/- 70
22	July	765+/-87	762 +/- 49
25	July	729+/-91	753 +/- 48
25.5	July	664+/-91	677 +/- 47
26	July	673+/-93	685 +/- 49
29	July	678+/-89	695 +/- 45
30	July	682+/-89	701 +/- 55
4	August	702+/-88	727 +/- 59
6	August	702+/-79	725 +/- 54
7	August	706+/-89	723 +/- 49
8	August	725+/-95	727 +/- 71
21	August	732+/-89	
6	September	722+/-80	

Single photons and ionizing events

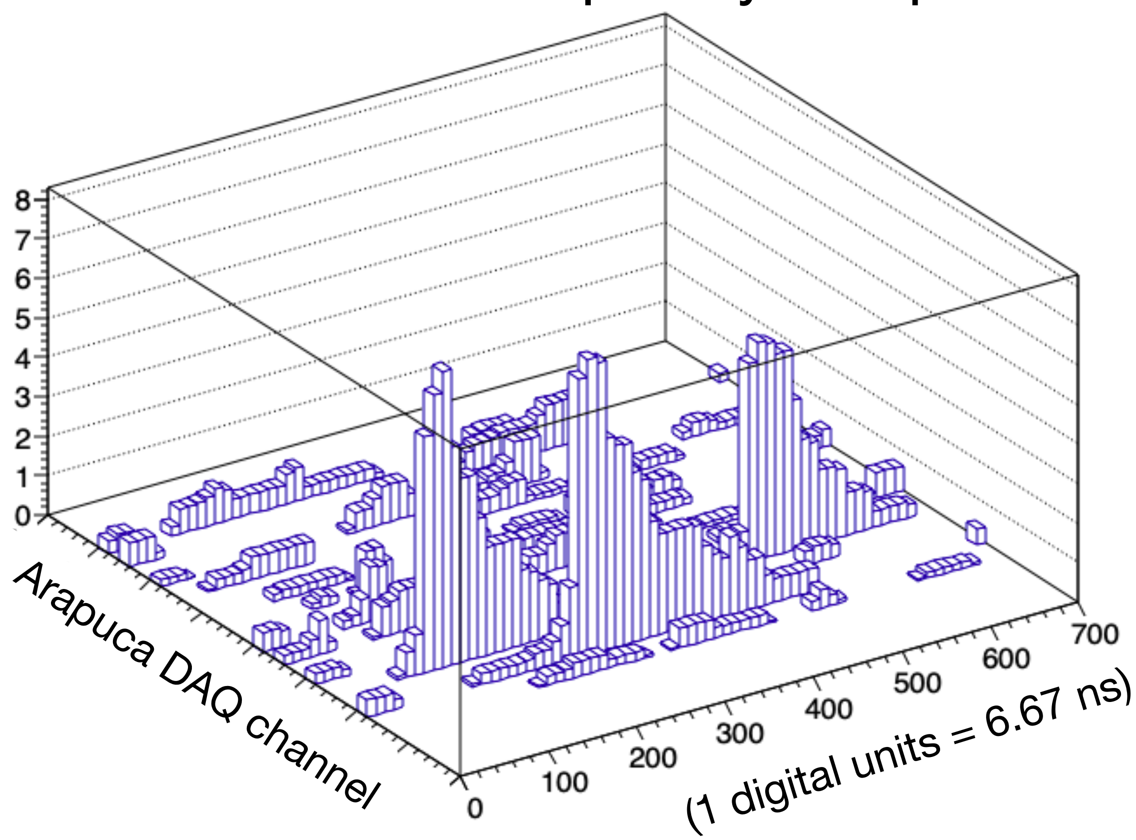


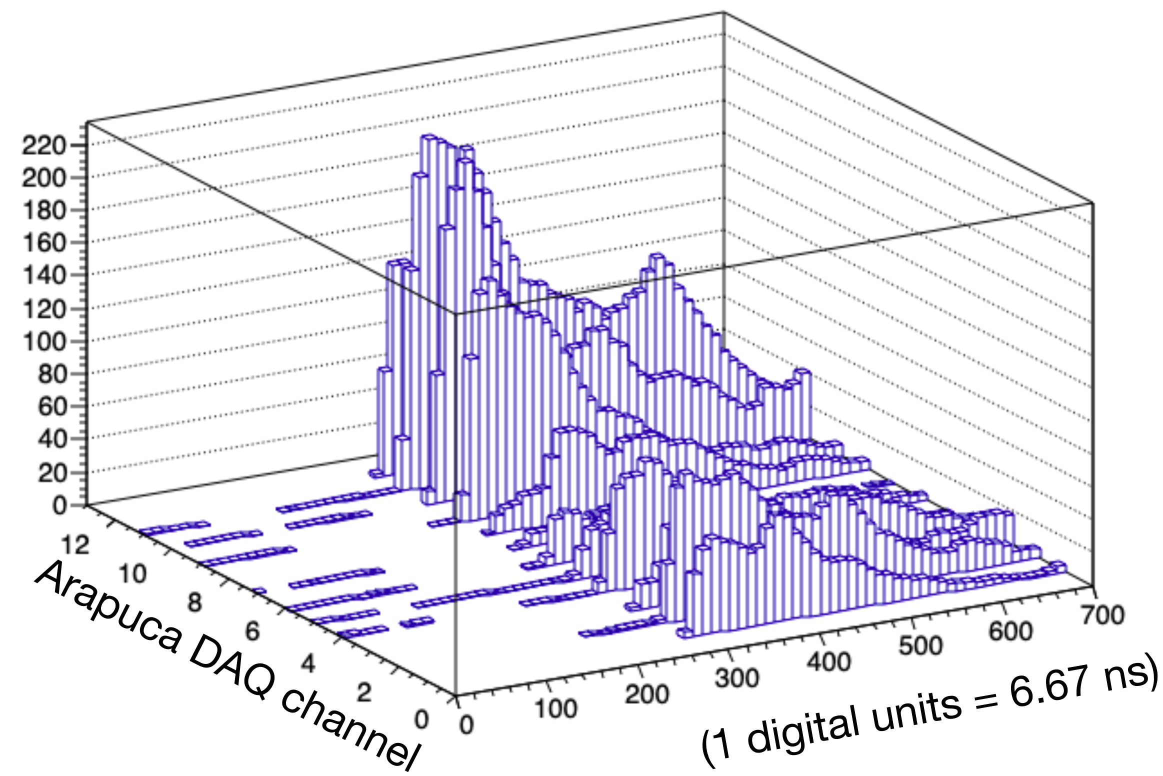
We can distinguish two kind of light events in a LAr TPC:

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

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

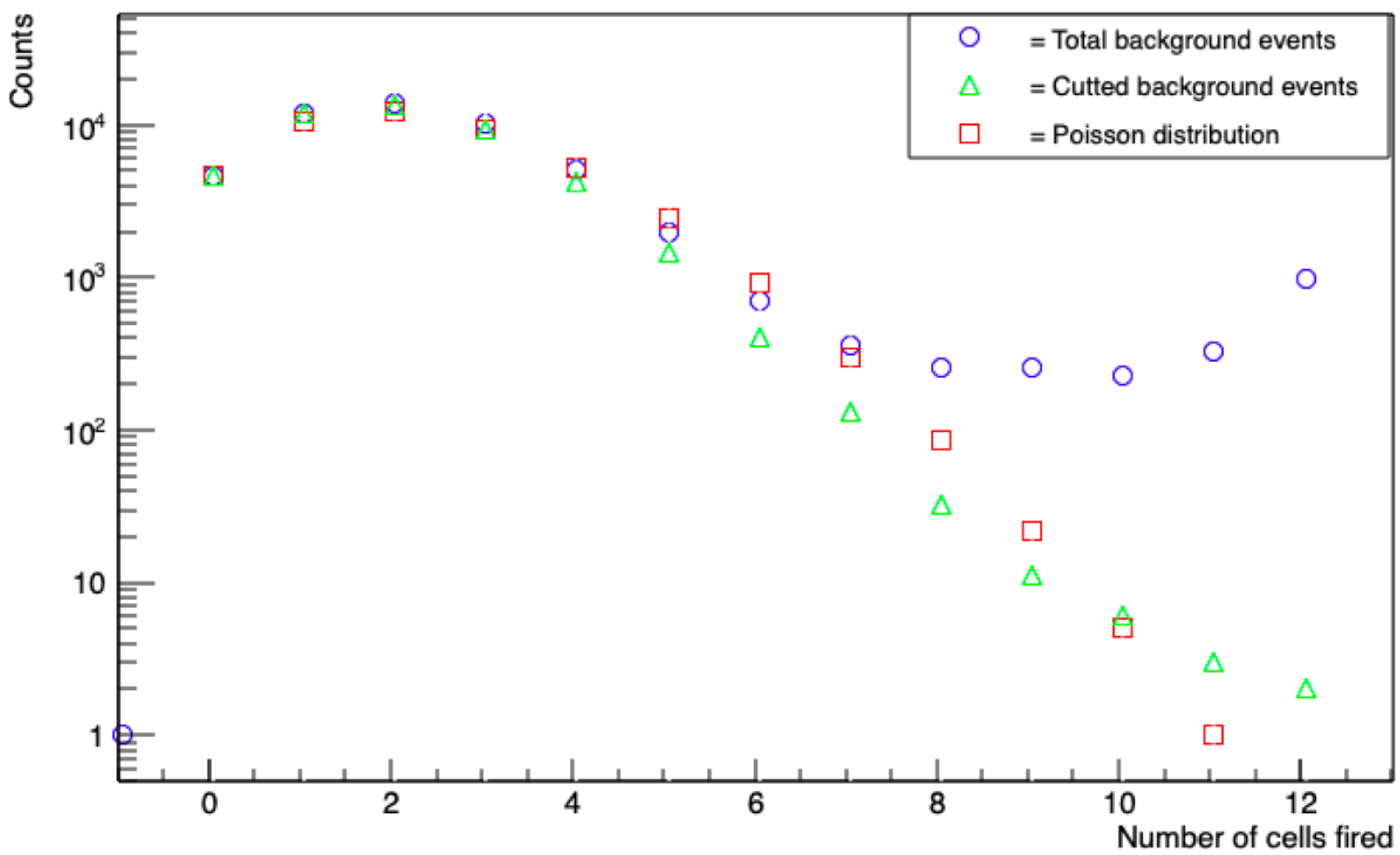
Ionizing events produce a certain amount of photons, which reach the light detectors at the same time





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.

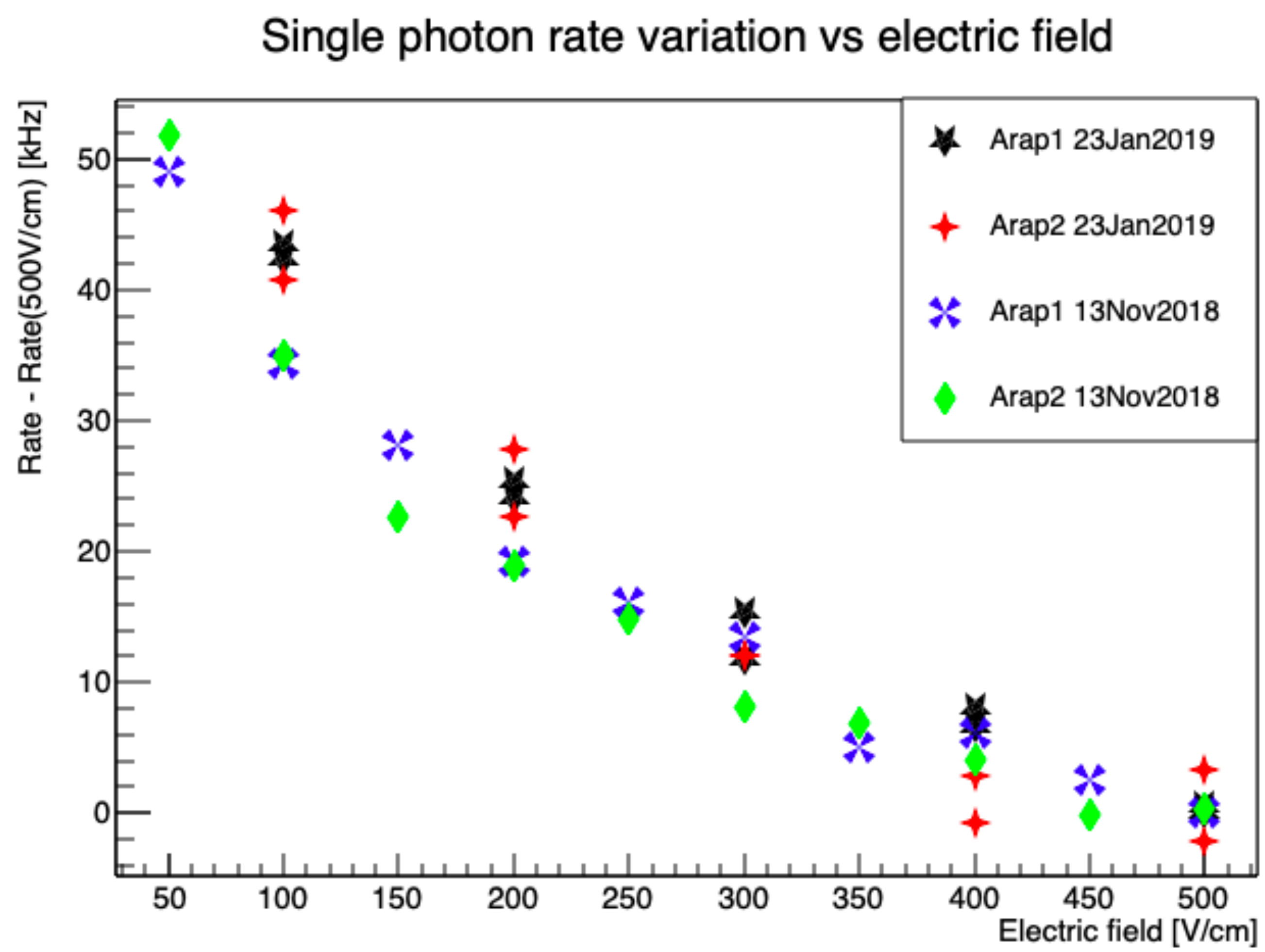
The absolute value measured at standard protoDUNE conditions :

- electric field: 500 V/cm
- purity: 6 ms (electrons lifetime)

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

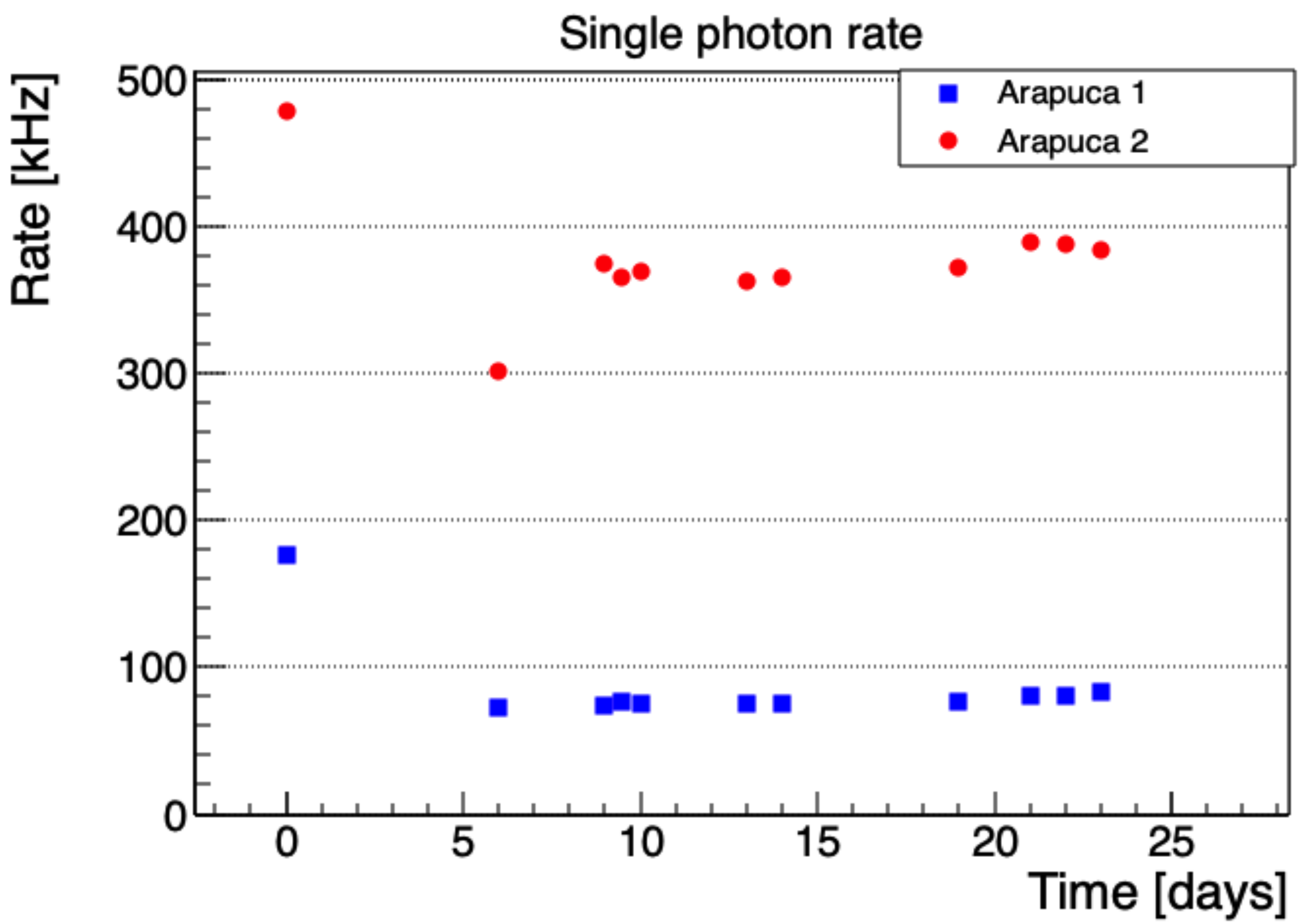
(Average over 15 runs Arapuca PD module 1)

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.

Single photon rate



Rate vs purity (in electrons lifetime)