

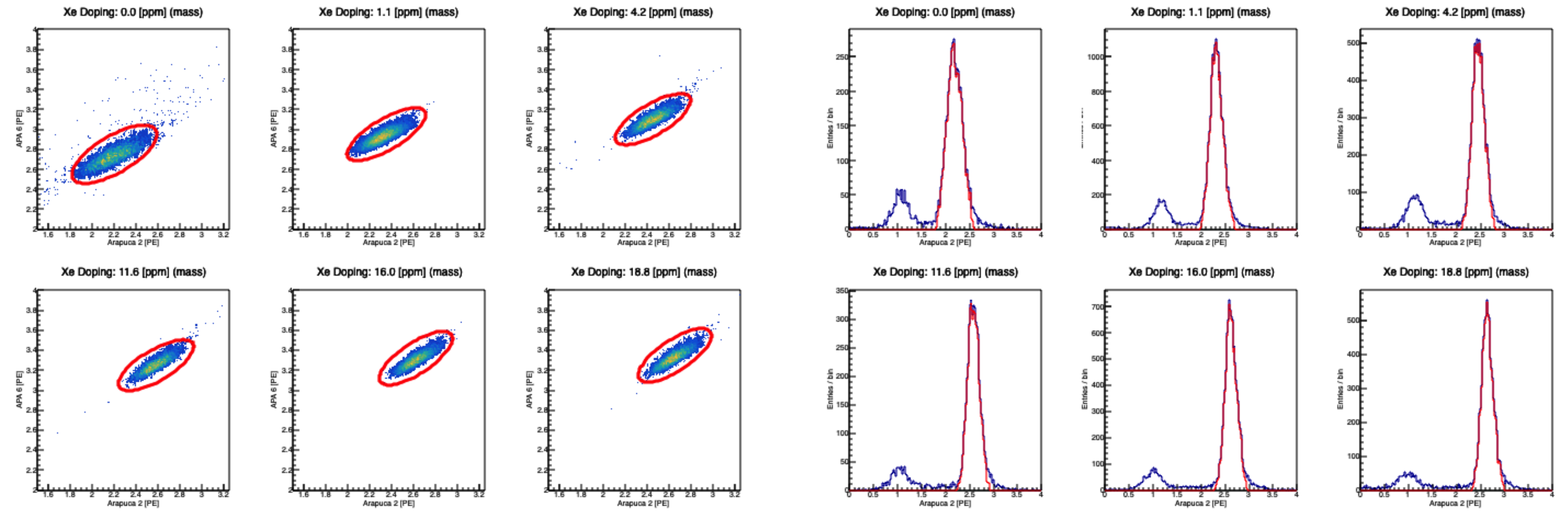
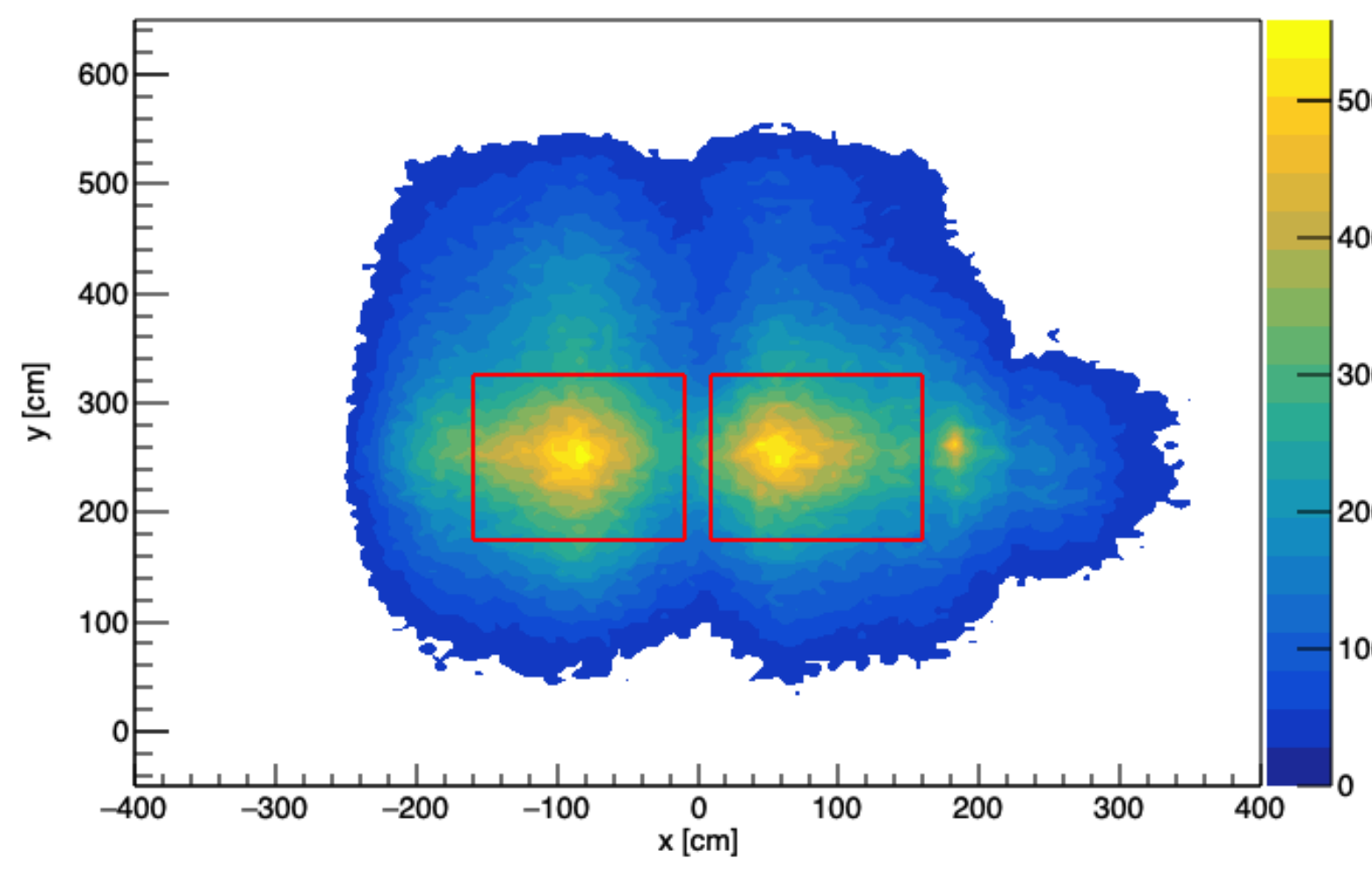
Xe doping.

Waveform analysis

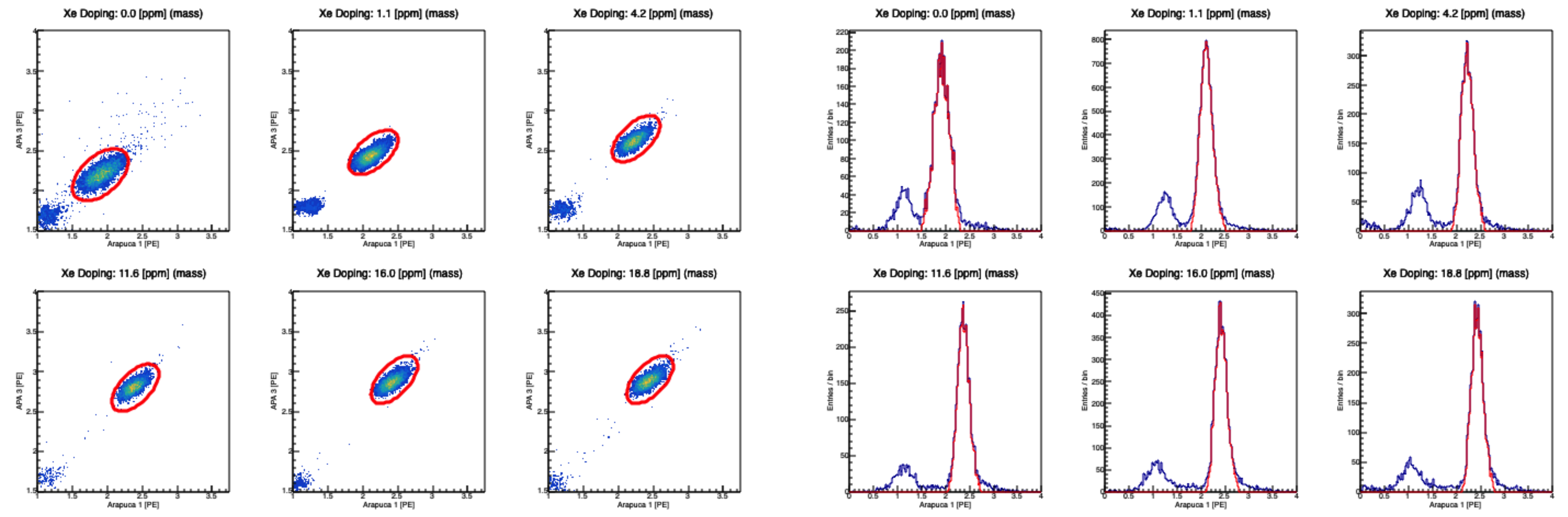
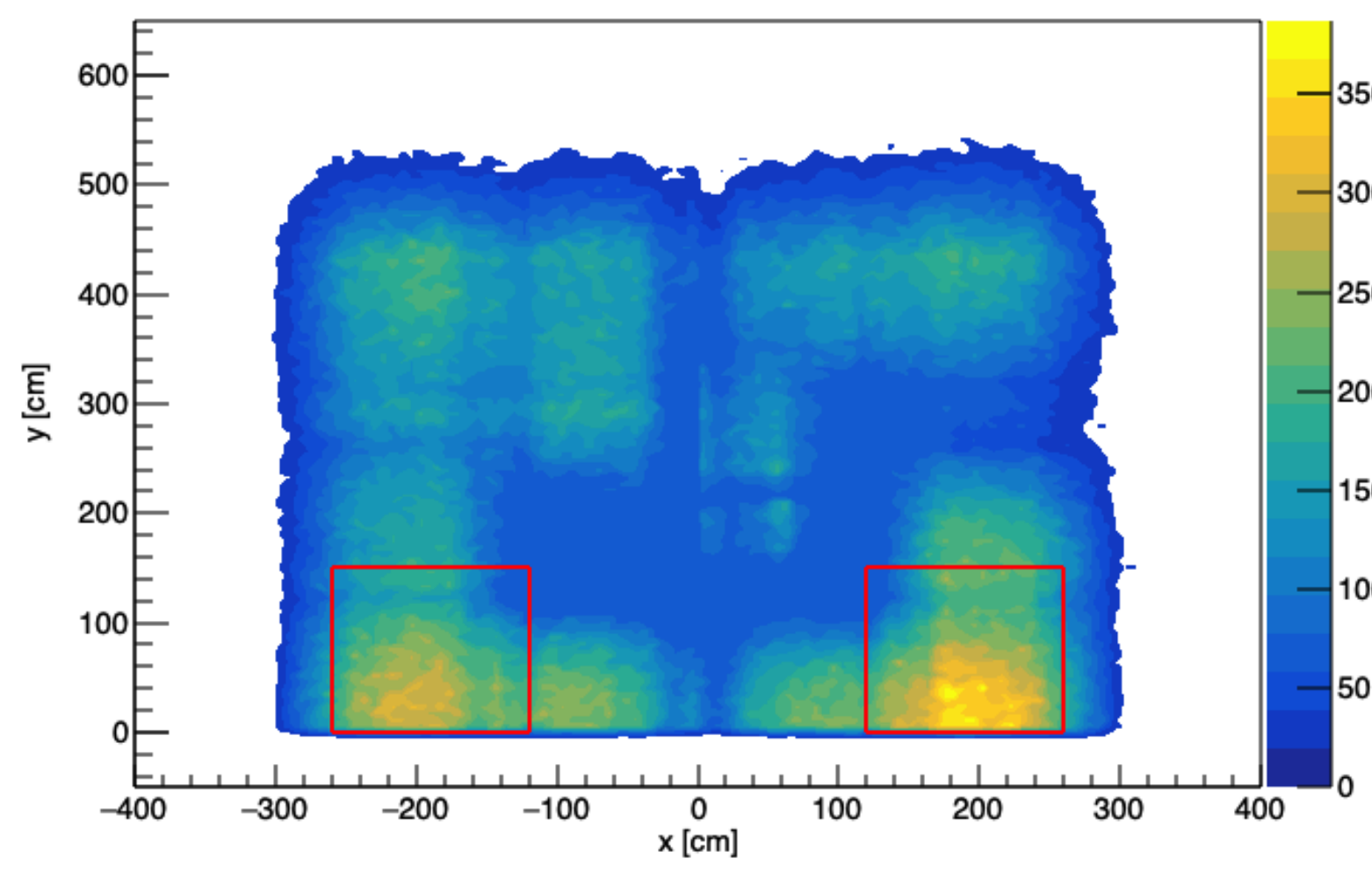
Dante Totani
Dec 18th, 2020

Track geometry selection, and outlier removal

Entry point



Exit point



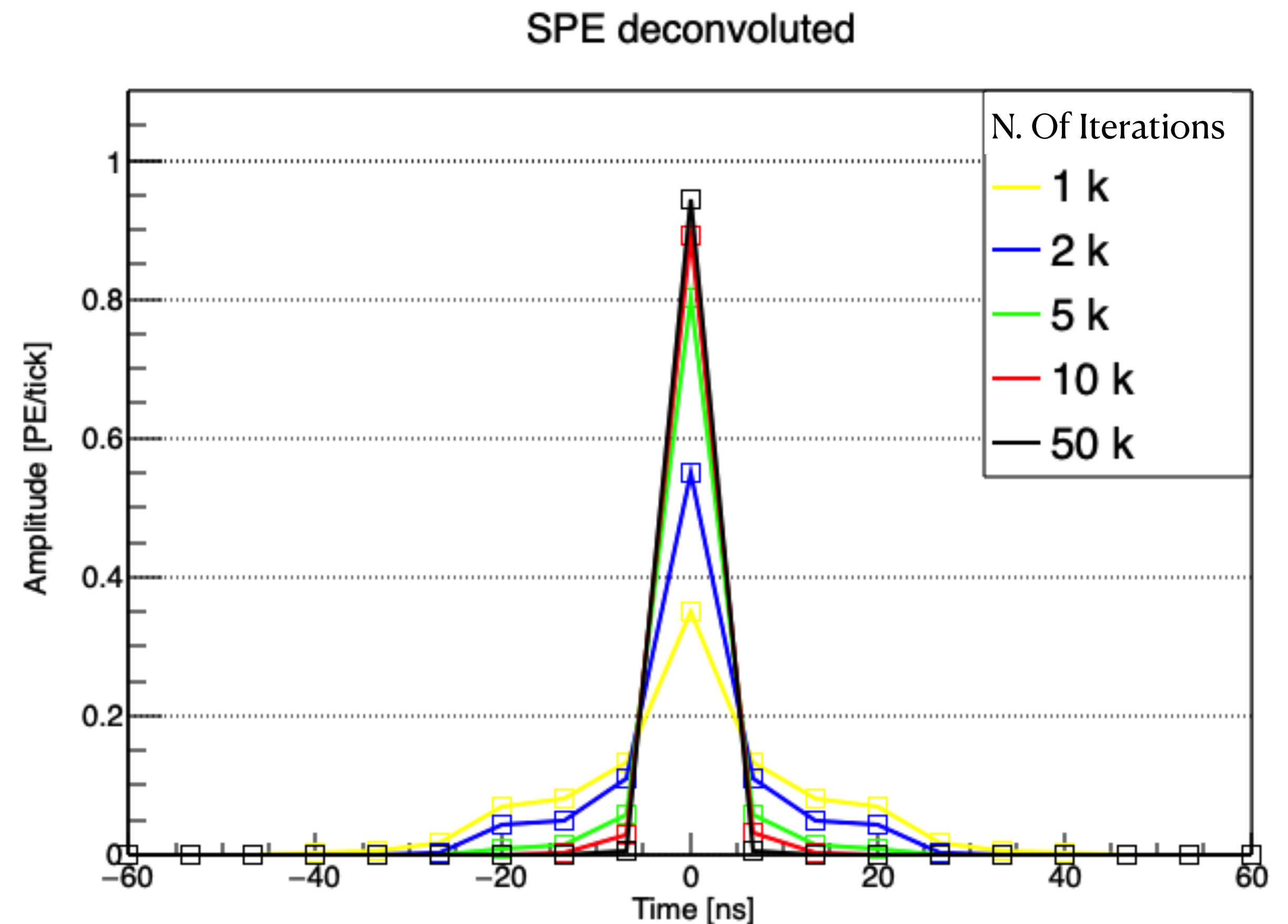
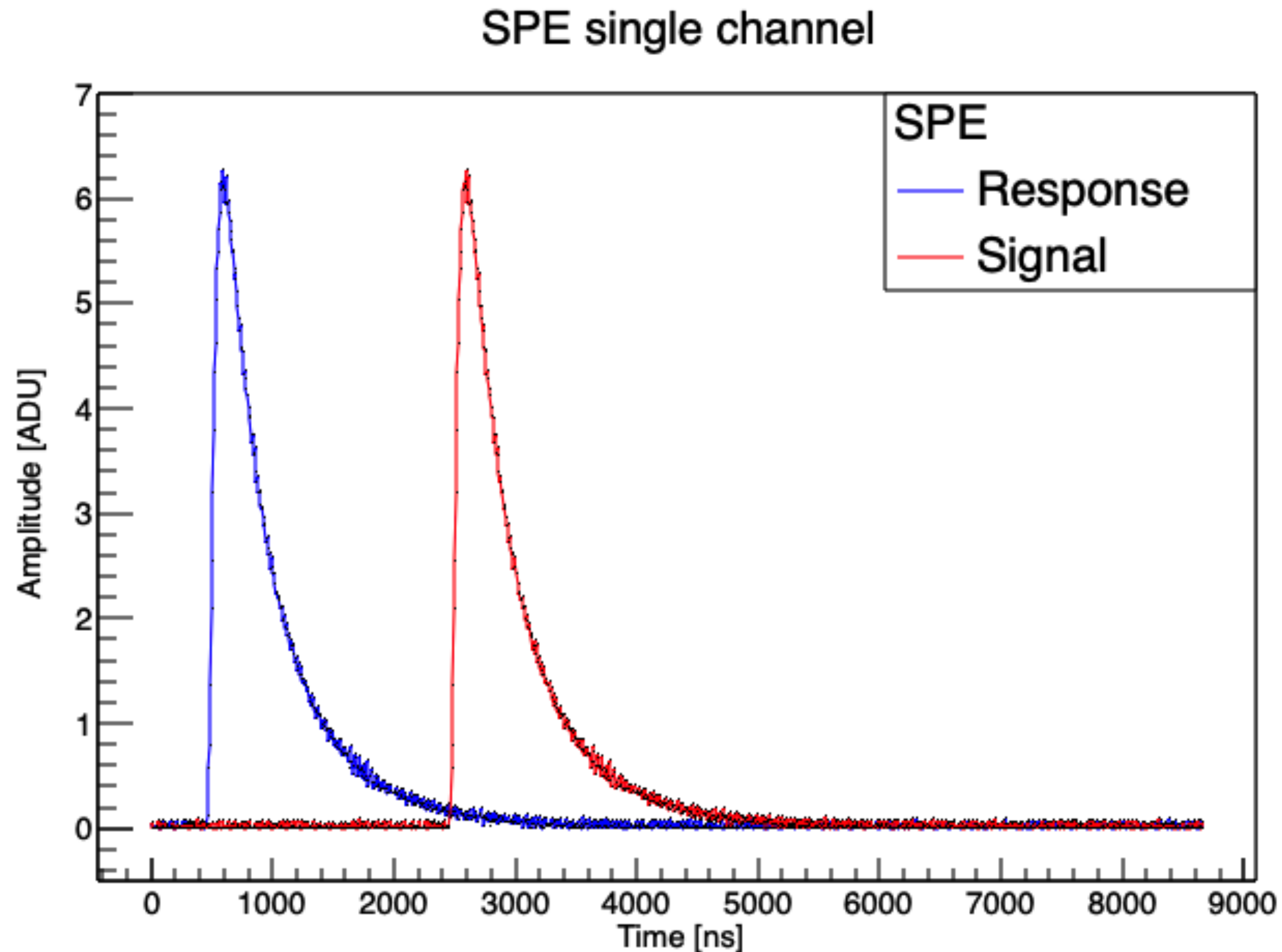
Deconvolution: TSpectrum Class (Root CERN)

SPE is itself deconvoluted to test the algorithm.

A delta is expected with some spread depending on the algorithm parameters.

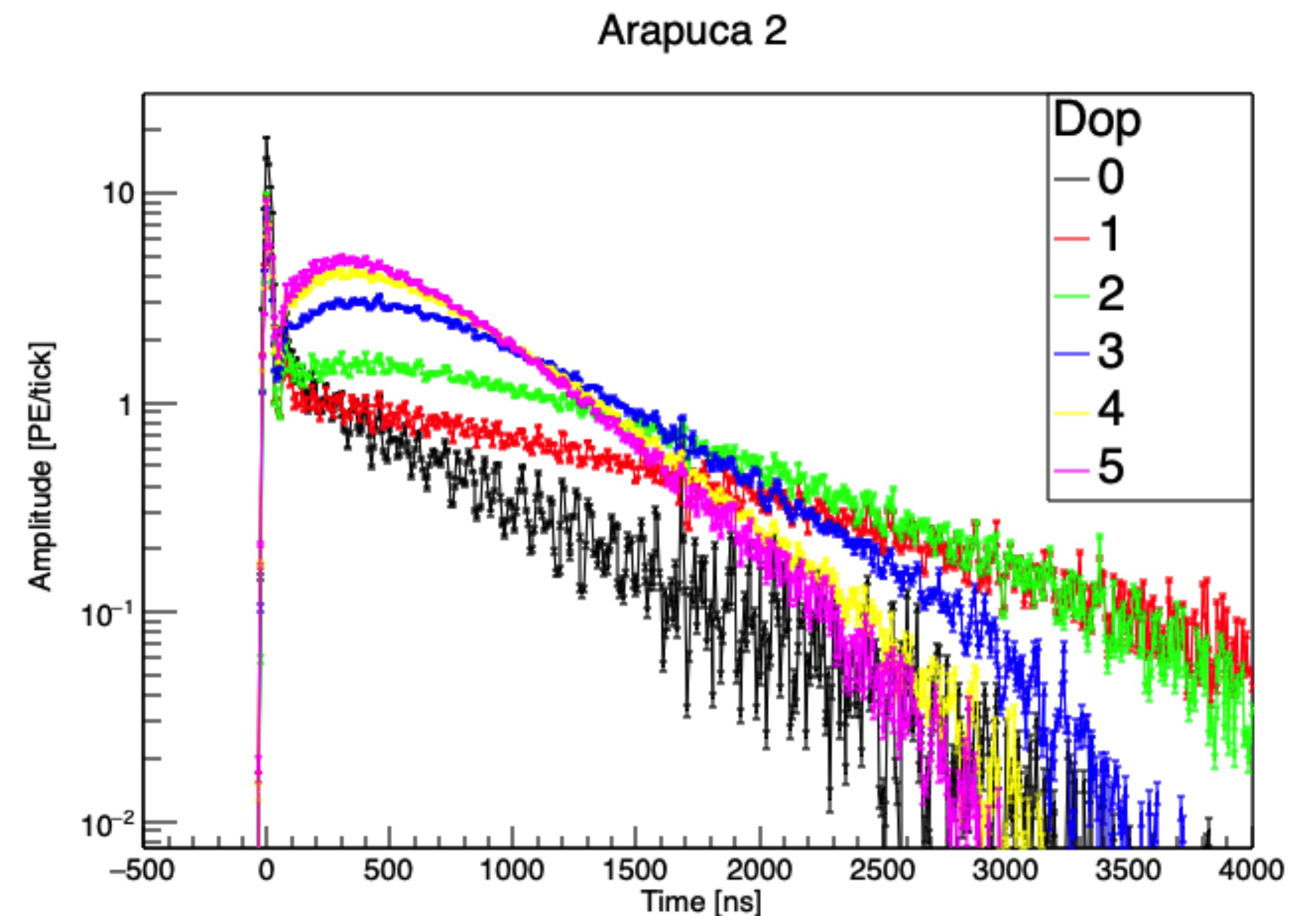
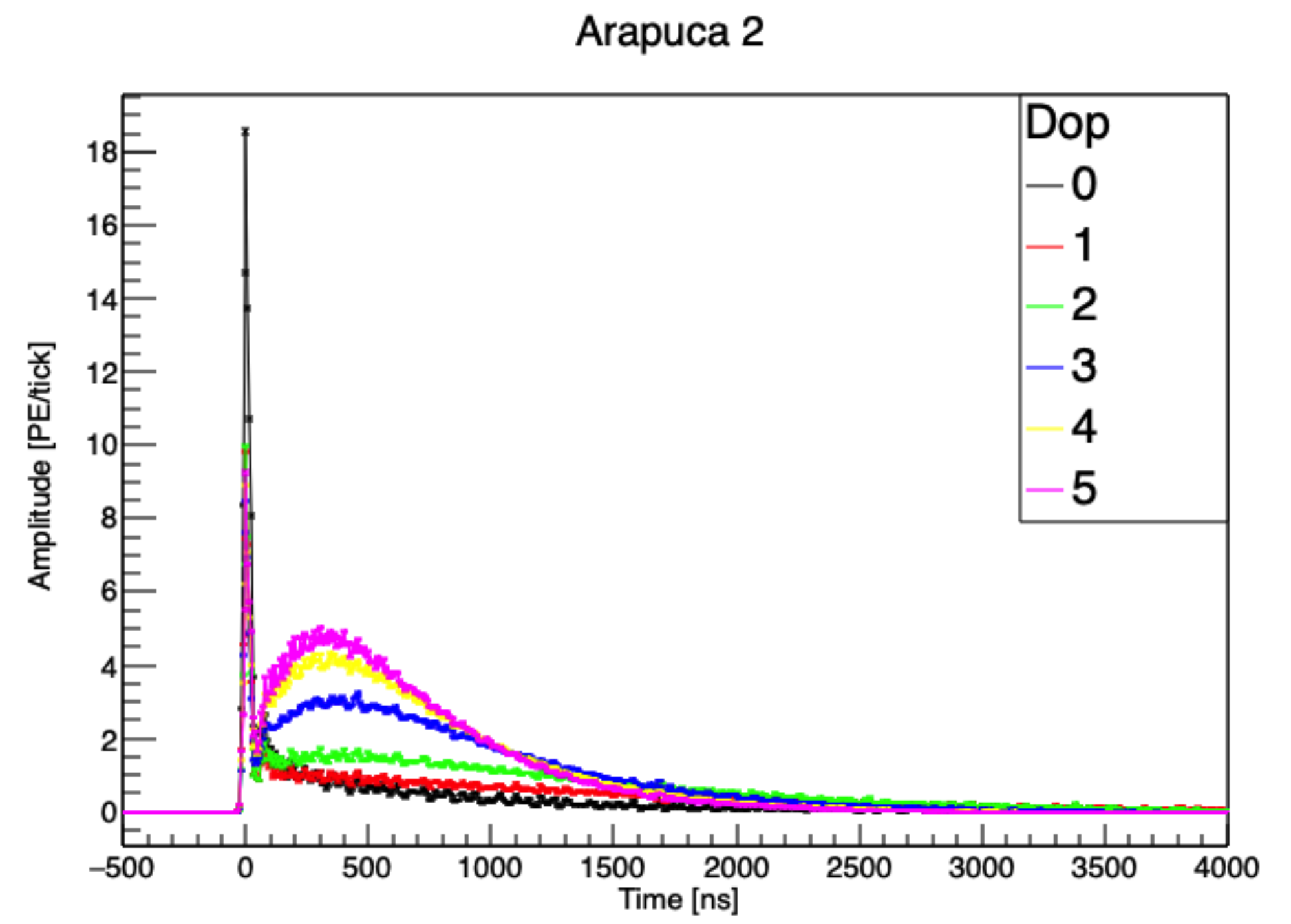
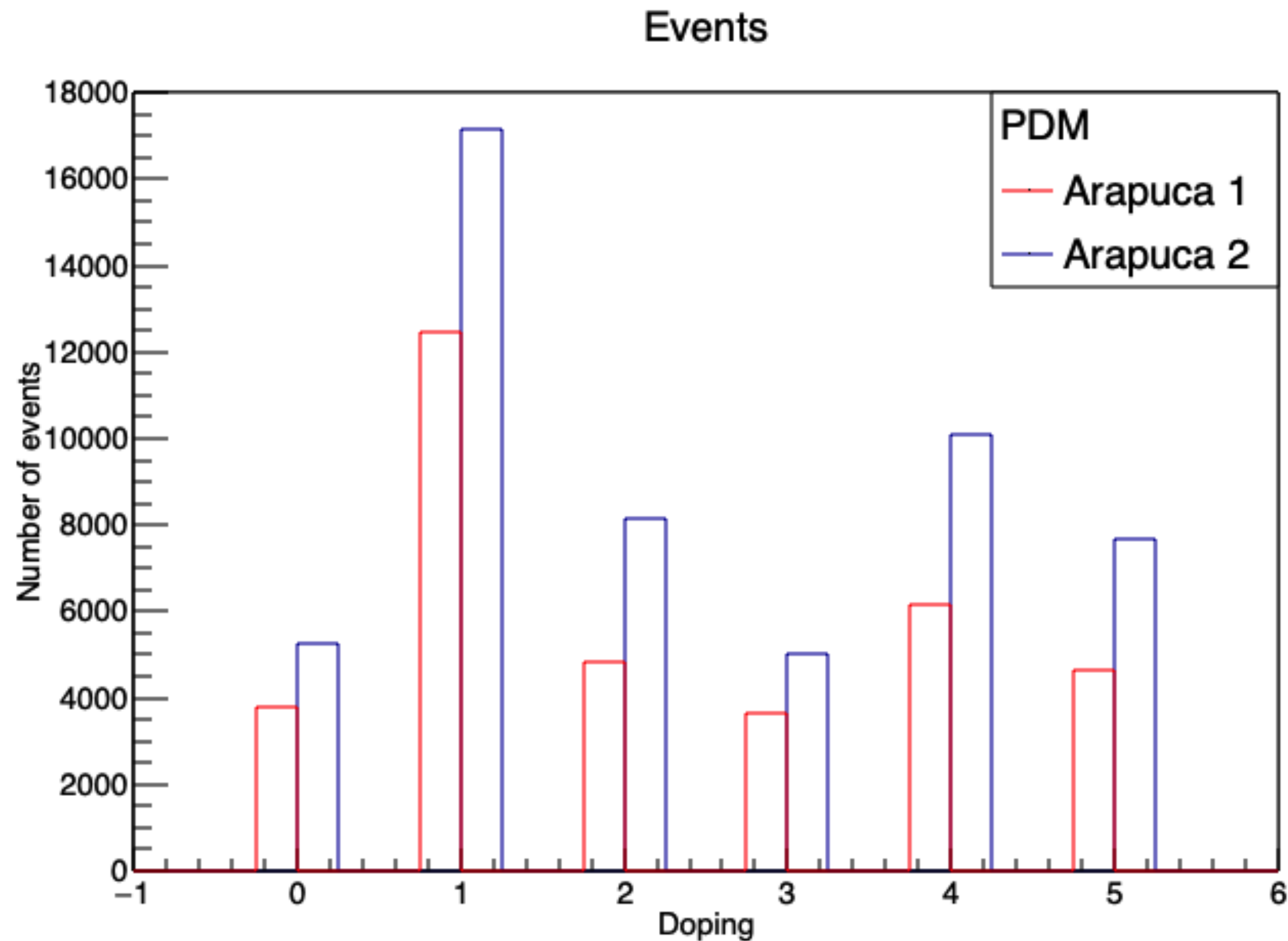
Over $\sim 10k$ iteration small improvement is observed.

50k iterations are used in analysis, getting $\sim 96.4\%$ of the SPE area in a single bin.



Waveforms Deconvolution

The average waveform of each cell is deconvoluted.
After the deconvolution the 12 waveforms of each Arapuca are summed.
The waveform amplitude represents “ N_{Pe} per bin” (1 bin = 6.67 ns).
An error proportional to the square root of amplitude ($\sqrt{N_{Pe}}$) is given,
(The waveform averaging factor is taken into account in the error evaluation).



Integral of the average waveforms.

In the last two column is reported the fast component and the slow/xenon bump component, all values are N of PE.

The fast component integral is obtained integrating for $t < 45 ns$. The Slow component integral for $t \geq 45ns$.

In both Arapuca, since the first doping, a reduction of half is observed in the fast component.

Reduction does not increase with higher Xenon concentration, but remain stable.

Slow Argon component is superimposed with the Xenon bump, but from waveforms it seems to behave as the fast component.

The total light increase with the Xenon concentration going to values much larger than the initial one.

Arapuca 1, Waveform integral

Doping	PE	Fast	Slow
0	112.3	35.5	76.8
1	171.7	18.0	153.7
2	232.2	15.9	216.3
3	347.4	17.6	329.8
4	391.7	18.6	373.1
5	407.3	19.2	388.1

Arapuca 2, Waveform integral

Doping	PE	Fast	Slow
0	232.6	85.3	147.3
1	304.1	43.3	260.8
2	422.1	41.8	380.3
3	581.3	41.2	540.1
4	648.1	42.5	605.6
5	680.2	43.5	636.7

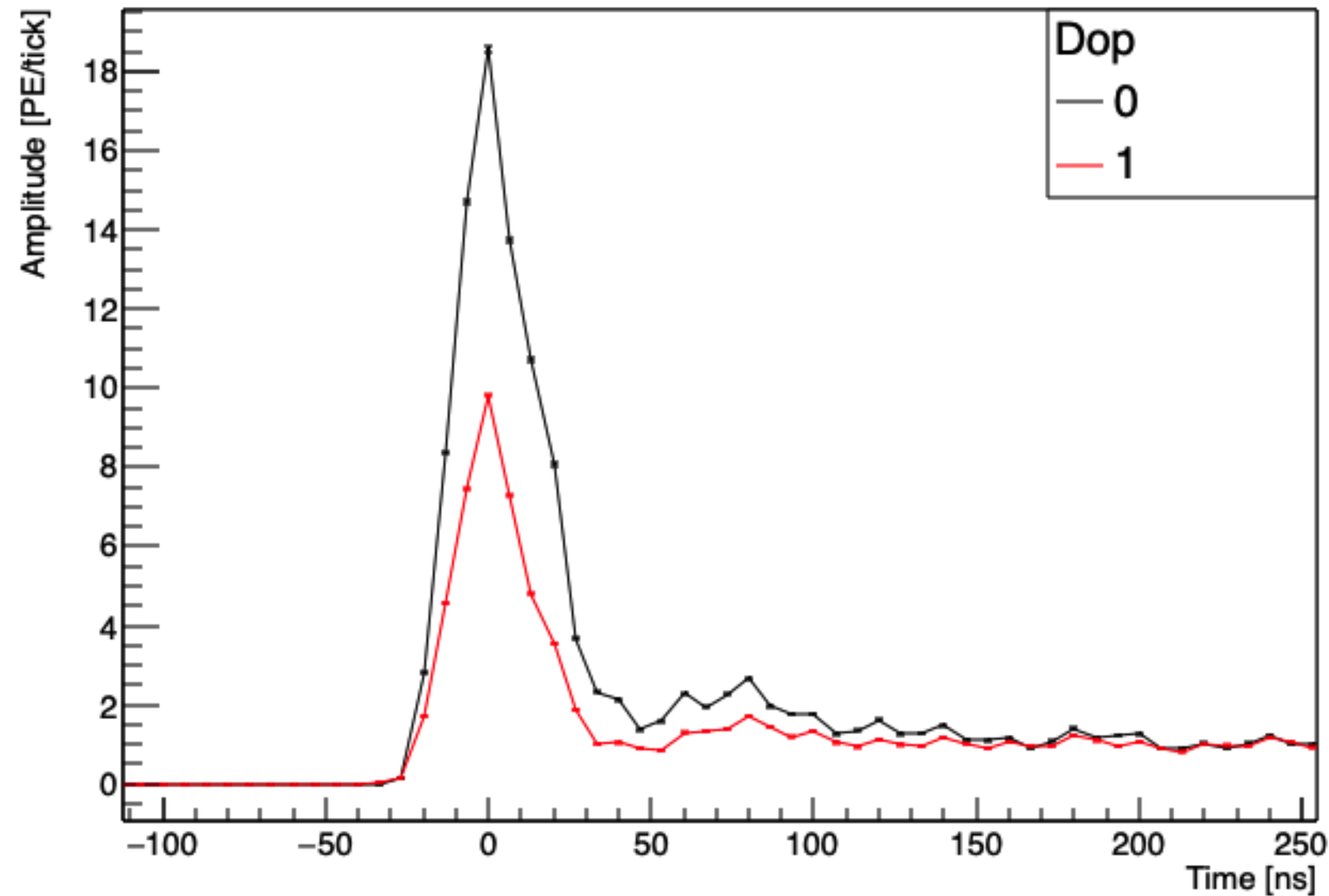
Argon slow component reduction.

As observed in the fast component integral, the Xenon reduce the Argon slow component too, since the first doping.

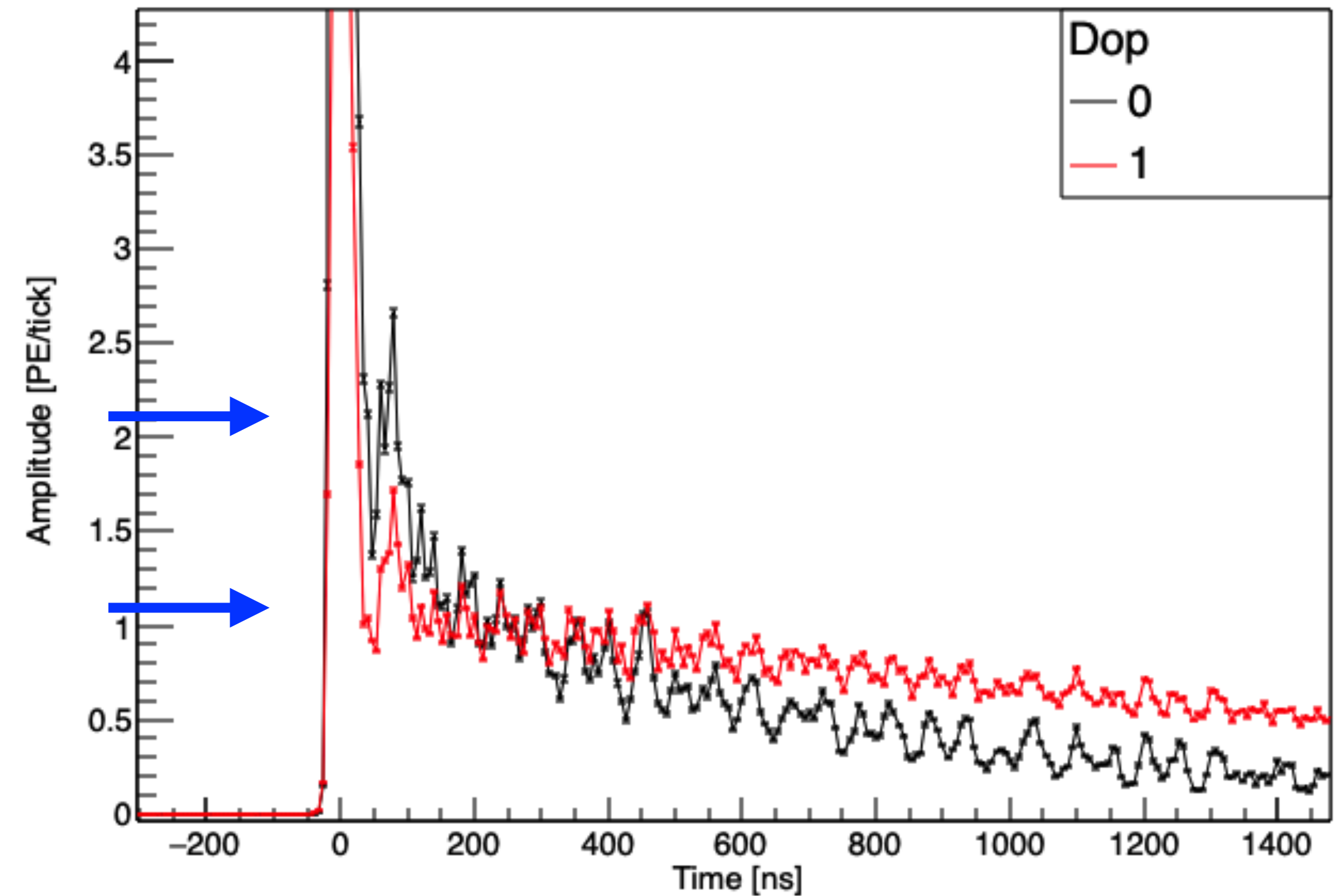
Comparing the waveforms for no Xenon and 1st Xe doping (1.1 ppm (Mass)), the reduction of the slow component becomes evident.

In the Argon+Xenon case, the Argon slow component amplitude got from the fit is compatible with ~half amplitude of no-Xenon case.

Arapuca 2



Arapuca 2



Fit function

Pure Argon: $Ar(t) = C_f \cdot \frac{e^{-t/\tau_f}}{\tau_f} + C_s \cdot \frac{e^{-t/\tau_s}}{\tau_s}$

Argon + Nitrogen: $ArN_2(t) = Ar(t)e^{-t/\tau_{N_2}} = \left[C_f \cdot \frac{e^{-t/\tau_f}}{\tau_f} + C_s \cdot \frac{e^{-t/\tau_s}}{\tau_s} \right] e^{-t/\tau_{N_2}}$ $\tau_{N_2} = \frac{\tau_{N_2}^0}{f_{N_2}}$

$\tau_{N_2}^0 = 9.09 (12.5) \mu s \cdot ppm_{N_2}(Vol)$

There are two values for N_2 rate in literature.

The absolute amount of N_2 depends from the $\tau_{N_2}^0$ value. However it is fixed for the whole Xenon doping period.

What is directly measurable and affects the waveform shape is $\tau_{N_2} = \tau_{N_2}^0 / f_{N_2}$.

Since $\tau_f \ll \tau_{N_2}$ the Argon + Nitrogen waveform can be write as:

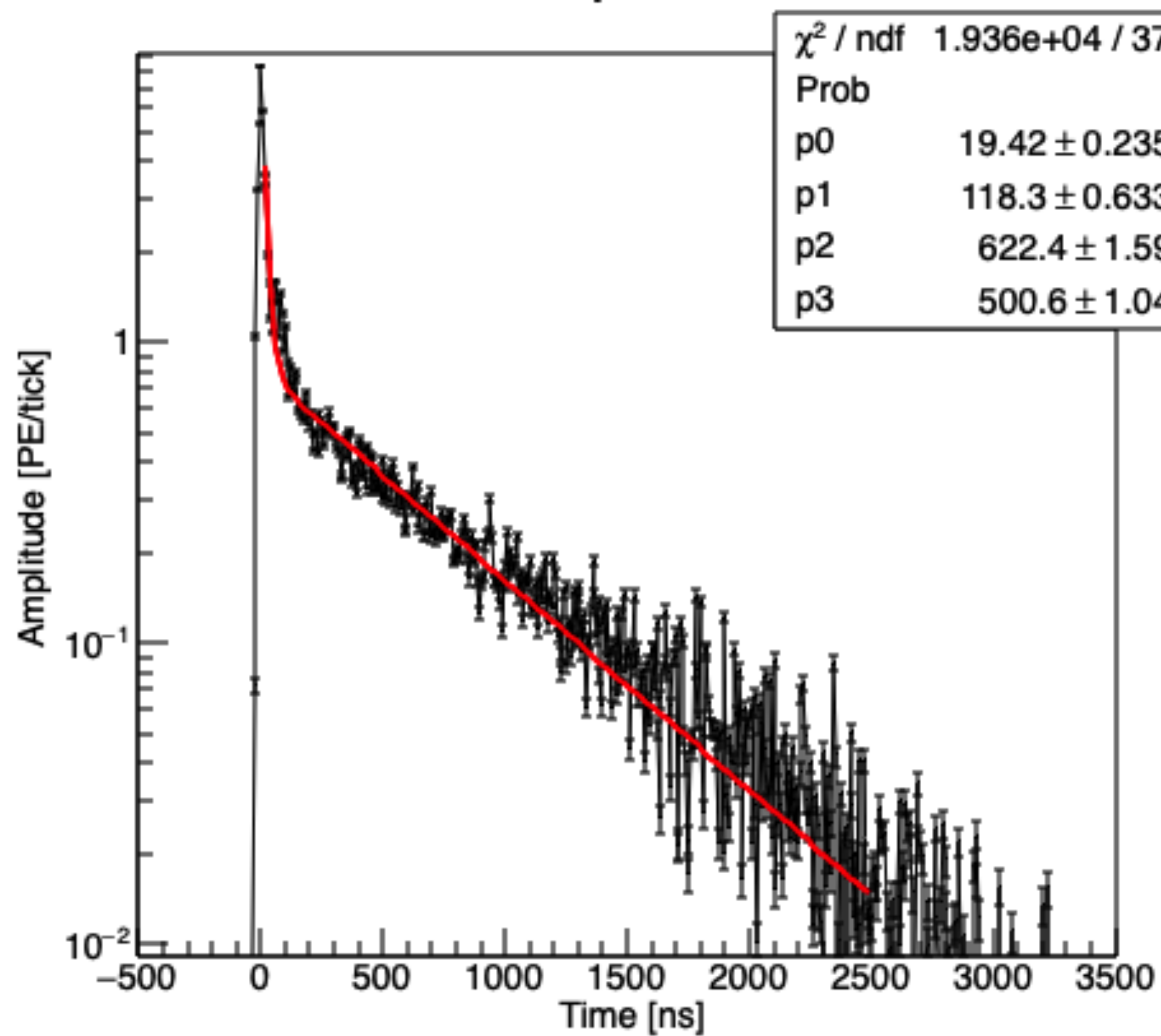
Argon + Nitrogen: $ArN_2(t) = Ar(t)e^{-t/\tau_{N_2}} = C_f \cdot \frac{e^{-t/\tau_f}}{\tau_f} + C_s \cdot \frac{e^{-t/\tau_s^*}}{\tau_s^*}$ where: $\frac{1}{\tau_s^*} = \frac{1}{\tau_s} + \frac{1}{\tau_{N_2}}$

$\tau_s^* = (0.63 \pm 0.01) \mu s$

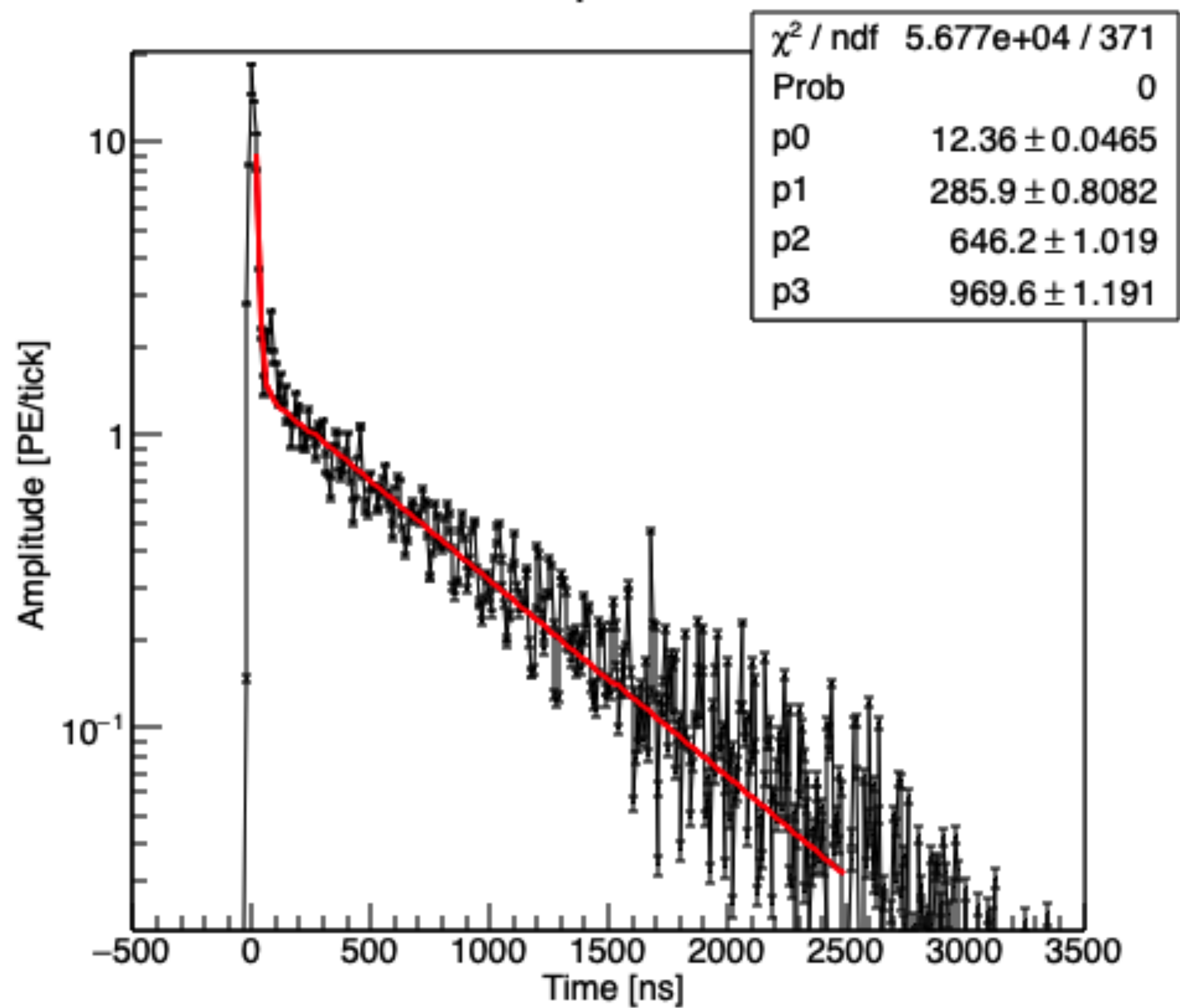
Assuming $\tau_s = 1.3 \mu s$ we got: $\tau_{N_2} = 1.22 \pm 0.01 \mu s$

Doping 0

Arapuca 1



Arapuca 2



Fit function Ar+N2+Xe

When Xenon is present, energy transfer happens from excited ArAr* dimer to Xe before the ArAr* dimer decays.

The first process is energy transfer from ArAr* to ArXe*.

ArXe* can decay through 150 nm light or form the dimer XeXe* .

XeXe* decays through 175 nm.

Standard-Arapucas in protoDUNE can not distinguish the three wavelengths, the function used to describe the waveform shape takes into account the three scintillation light components $SL(t)$:

$$SL(t) = C_a e^{-t/\tau_{TA}} + C_b \cdot (e^{-t/\tau_{TA}^*} - e^{-t/\tau_{TX}})$$

This function is only for the Argon triplet component. The analysis includes an energy transfer from the Argon singlet component.

Photon-mediated and collisional processes in liquid rare gases.

Akira Hitachi

Science and Engineering Research Laboratory, Waseda University, Shinjuku-ku, Tokyo 162, Japan

$$SL(t) = C_a e^{-t/\tau_{TA}} + C_b \cdot (e^{-t/\tau_{TA}^*} - e^{-t/\tau_{TX}})$$

$$\frac{1}{\tau_{TA}} = \frac{1}{\tau_{128}} + \frac{1}{\tau_{N_2}} + \frac{1}{\tau_{AX}}$$

Argon triplet degrades through scintillation, N₂ quenching and ArAr* to ArXe* energy transfer.

The energy transfer τ_{AX} depends on the Xenon concentration.

From Hitachi paper, τ_{AX} is estimated to be 4 times faster for the Argon singlet component.

$$\frac{1}{\tau_{TX}} = \frac{1}{\tau_{150}} + \frac{1}{\tau_{N_2}} + \frac{1}{\tau_{XX}}$$

ArXe* degrades through scintillation at 150 nm, N₂ quenching and ArXe* to XeXe* energy transfer.

The energy transfer τ_{XX} depends on the Xenon concentration.

The XeXe* scintillation process is much faster than others so it is considered immediate

XeXe* scintillation = ~4 ns (Singlet), 22 ns (triplet).

$$\frac{1}{\tau_{TA}^*} = \frac{1}{\tau_{eq}} + \frac{1}{\tau_{AX}}$$

A possible energy transfer from N₂* to ArXe* is taken into account in τ_{TA}^* , replacing $\frac{1}{\tau_{128}} + \frac{1}{\tau_{N_2}}$ with $\frac{1}{\tau_{eq}}$, an independent parameter in the fit.

Xenon Doping

- Five amount of Xenon doping are analyzed: [1.1, 4.2, 11.6, 16.0, 18.8] ppm (Mass).
- Due to the large number of parameters in the light emission equation a simultaneous fit of waveforms from 5 doping values is made.
- The Argon light emission component has been fixed to the values got from the fit for zero-Xenon doping case.
- The coefficient Cb (both for triplet and singlet component) is written as function of Xe doping. Function is got from the fit of the 5 Cb values got independently.

Let's separate the scintillation light function in three components:

- Argon light after Xenon doping: $Ar_X(t)$
- Xenon light (150 nm +175 nm) from Argon Singlet: $Xe_S(t)$
- Xenon light (150 nm +175 nm) from Argon Triplet: $Xe_T(t)$

Argon light after Xenon doping

$$Ar_X(t) = \left(\frac{C_f}{2} \cdot \frac{e^{-t/\tau_f}}{\tau_f} \right) e^{-t \frac{4 \cdot ppm}{\tau_{AX}}} + \left(\frac{C_s}{2} \cdot \frac{e^{-t/\tau_s^*}}{\tau_s^*} \right) e^{-t \frac{ppm}{\tau_{AX}}}$$

Where $\tau_f, \tau_s^*, C_f, C_s$ are the values from the fit for the Argon + Nitrogen and zero-Xe case found.

- The coefficients C_f, C_s are divided by two to take into account the observations made regarding the integral and amplitude reduction of the two Argon components after the doping.
- “ppm” is the amount of Xenon (ppm in Mass), fixed per each doping.
- τ_{AX} is divided by 4 in the fast component to take into account the faster energy transfer from singlet.

τ_{AX} is the only free fit parameter in $Ar_X(t)$ component.

Xenon light from Argon Singlet

$$Xe_S(t) = C_1(ppm) \cdot \left[e^{-t\left(\frac{1}{T} + \frac{ppm}{\tau_{XX}}\right)} - e^{-t\left(\frac{1}{\tau_f} + \frac{4 \cdot ppm}{\tau_{AX}}\right)} \right]$$

- $e^{-t\left(\frac{1}{\tau_f} + \frac{4 \cdot ppm}{\tau_{AX}}\right)}$ is the ArXe* dimer formation from Argon singlet, where the energy transfer rate ($4 \cdot ppm/\tau_{AX}$) depends from the Xenon amount and it is in competition with the Argon singlet scintillation rate $1/\tau_f$
- $e^{-t\left(\frac{1}{T} + \frac{ppm}{\tau_{XX}}\right)}$ is the XeXe* dimer formation from ArXe* dimer, where the energy transfer rate: ppm/τ_{XX} depends from the Xenon amount and it is in competition with ArXe* scintillation at 150 nm and ArXe* \rightarrow N₂ quenching: $\frac{1}{T} = \frac{1}{\tau_{150}} + \frac{1}{T_{N_2}^*}$.
- The coefficient $C_1(ppm)$ depends on the Xenon amount. Using five independent C_1 coefficients it is possible to extrapolate its dependence from Xenon concentration. For $C_1(ppm)$ the best “simple” function is $C_1(ppm) = a_1 + \frac{b_1}{ppm}$.

Xenon light from Argon Triplet

$$Xe_T(t) = C_2(ppm) \cdot \left[e^{-t\left(\frac{1}{T} + \frac{ppm}{\tau_{XX}}\right)} - e^{-t\left(\frac{1}{\tau_{S+R}} + \frac{ppm}{\tau_{AX}}\right)} \right]$$

- $e^{-t\left(\frac{1}{\tau_{S+R}} + \frac{ppm}{\tau_{AX}}\right)}$ is the ArXe* dimer formation from Argon triplet, where the energy transfer rate ppm/τ_{AX} depends from the Xenon amount and it is in competition with the Argon triplet scintillation rate and ArAr* nitrogen quenching $1/\tau_{S+R}$. However the parameter is not exactly the same from $Ar_X(t)$ component ($\tau_{S+R} \neq \tau_S^*$). It is left free in order to take into account an eventual recovery of energy from N_2^* .
- $e^{-t\left(\frac{1}{T} + \frac{ppm}{\tau_{XX}}\right)}$ is the XeXe* dimer formation from ArXe* dimer, where the energy transfer rate: ppm/τ_{XX} depends from the Xenon amount and it is in competition with ArXe* scintillation at 150 nm and ArXe* \rightarrow N₂ quenching: $\frac{1}{T} = \frac{1}{\tau_{150}} + \frac{1}{T_{N_2}^*}$.
- The coefficient $C_2(ppm)$ depends on the Xenon amount. Using five independent C_2 coefficients it is possible to extrapolate its dependence from Xenon concentration. For $C_2(ppm)$ the best “simple” function is $C_2(ppm) = a_2 + b_2 \cdot ppm$.

Coefficients parameters.

Fixing the Argon component to values from no-Xeon fit, and wiring the coefficients as function of Xenon concentration, together the simultaneous fit of the waveforms from the five doping values help to reduce the fit free parameters. Without this procedure the fit usually does not converge, or goes out the iteration range (stop before converging).

The coefficients of energy transfer from Argon Singlet and Triplet:

$$C_1(ppm) = a_1 + \frac{b_1}{ppm} \quad \text{and} \quad C_2(ppm) = a_2 + b_2 \cdot ppm$$

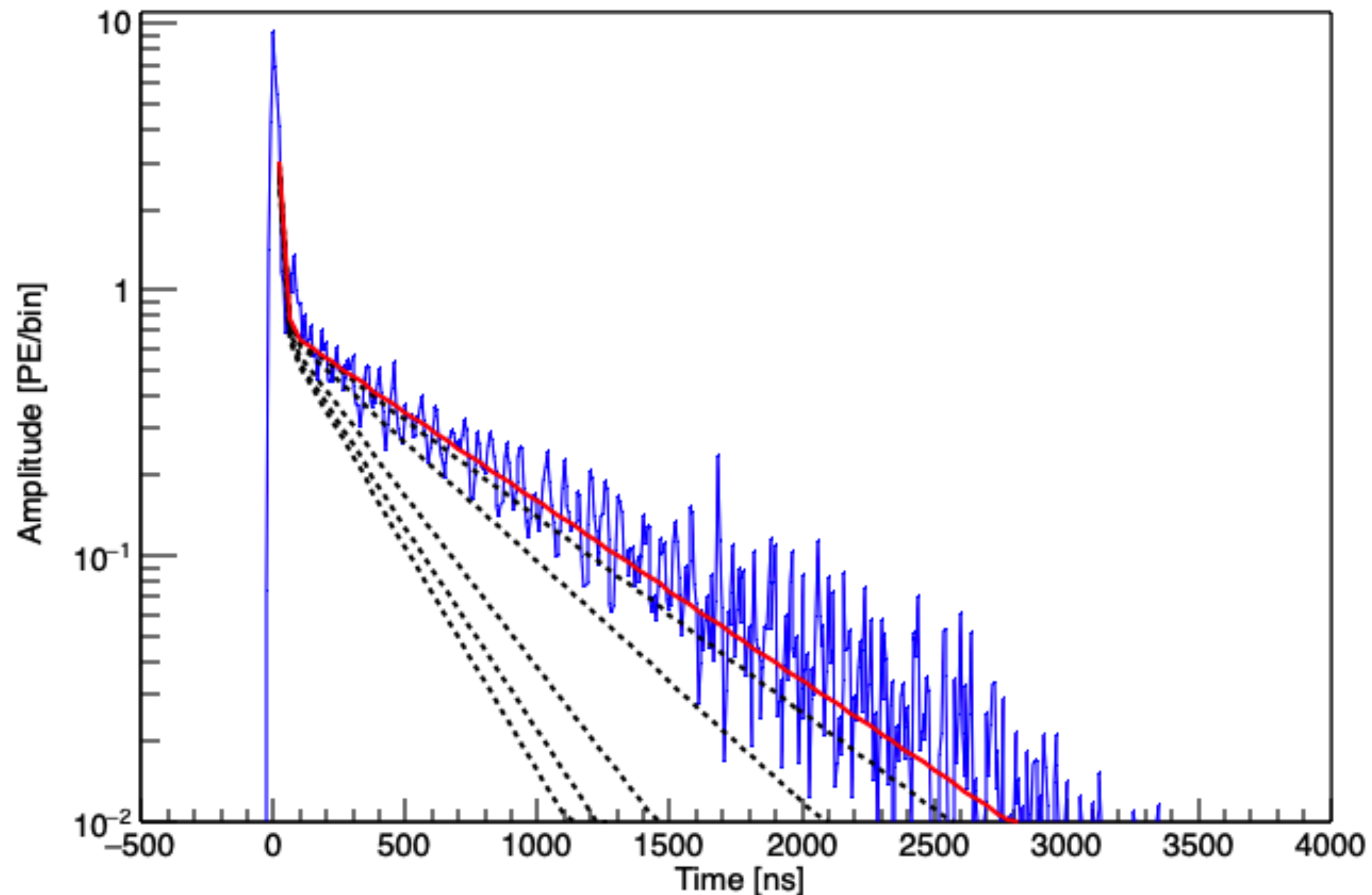
are expressed in that way to follow the fit results. An association with the τ parameters is not trivial.

The larger Xenon light observed, respect the original Argon light, probably introduces some new parameters which are not taken into account in the differential equation solution.

For example, an higher efficiency in photo-detection of Xenon Light respect Argon Light.

Argon light after Xenon doping

Argon Light Component



The black lines are the remains Argon components after the Xenon doping.

The amount of triplet component decreases (as the Tau) when Xenon increases.

The red line is the waveform fit for the no-Xenon case.

The waveform for no-Xenon case (blue) has been divided by 2, in order to be compared with the fit results when Xenon is present, following the previous consideration.

Xenon light from Argon Singlet and Triplet

Green lines are for Triplet and Pink for Singlet. The blue waveform is the case of maximum Xenon doping.

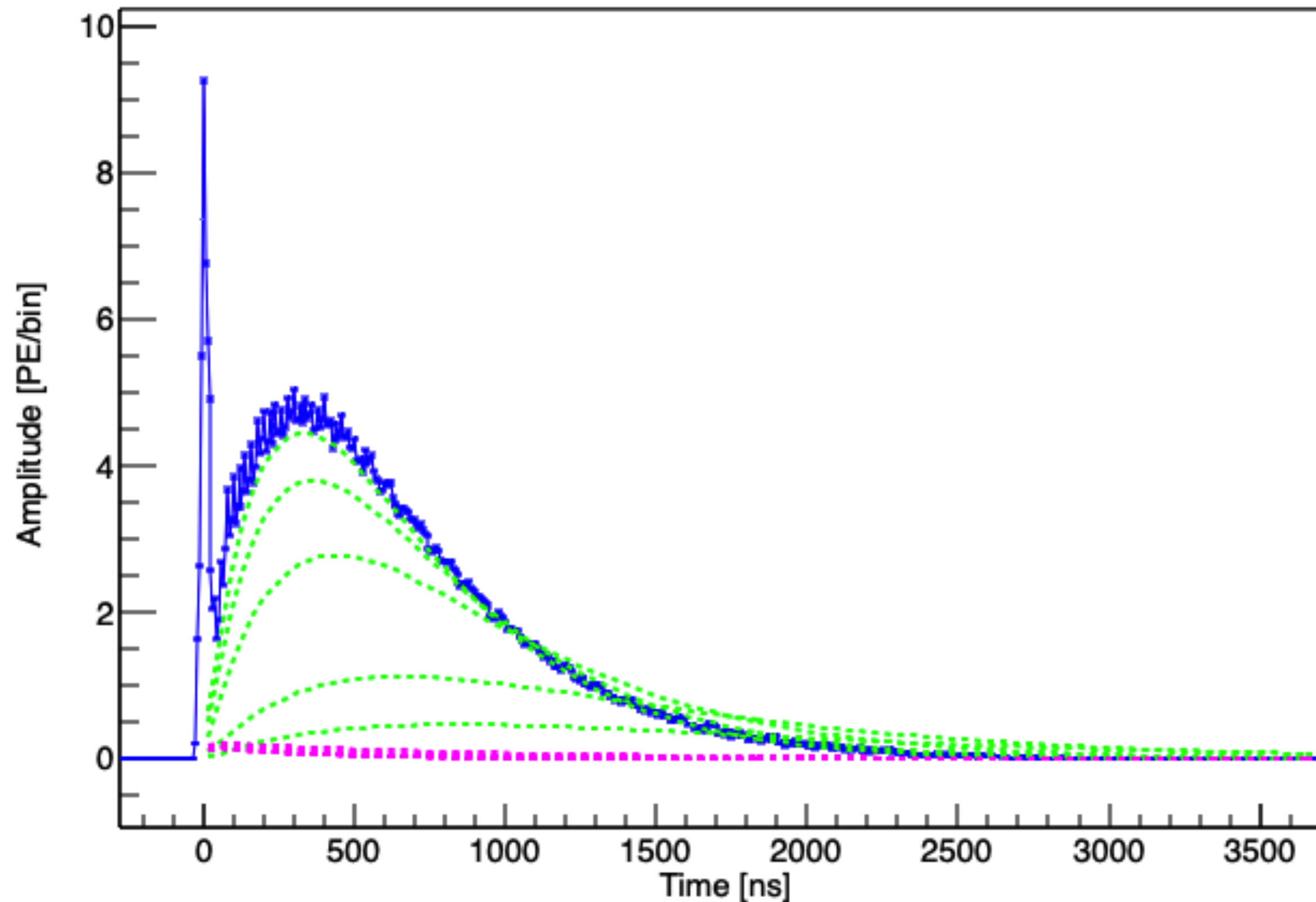
The Triplet component (green) bump increases with the Xenon, reducing its tail, giving an overall increase of the integral

$$\rightarrow C_2(ppm) = a_2 + b_2 \cdot ppm.$$

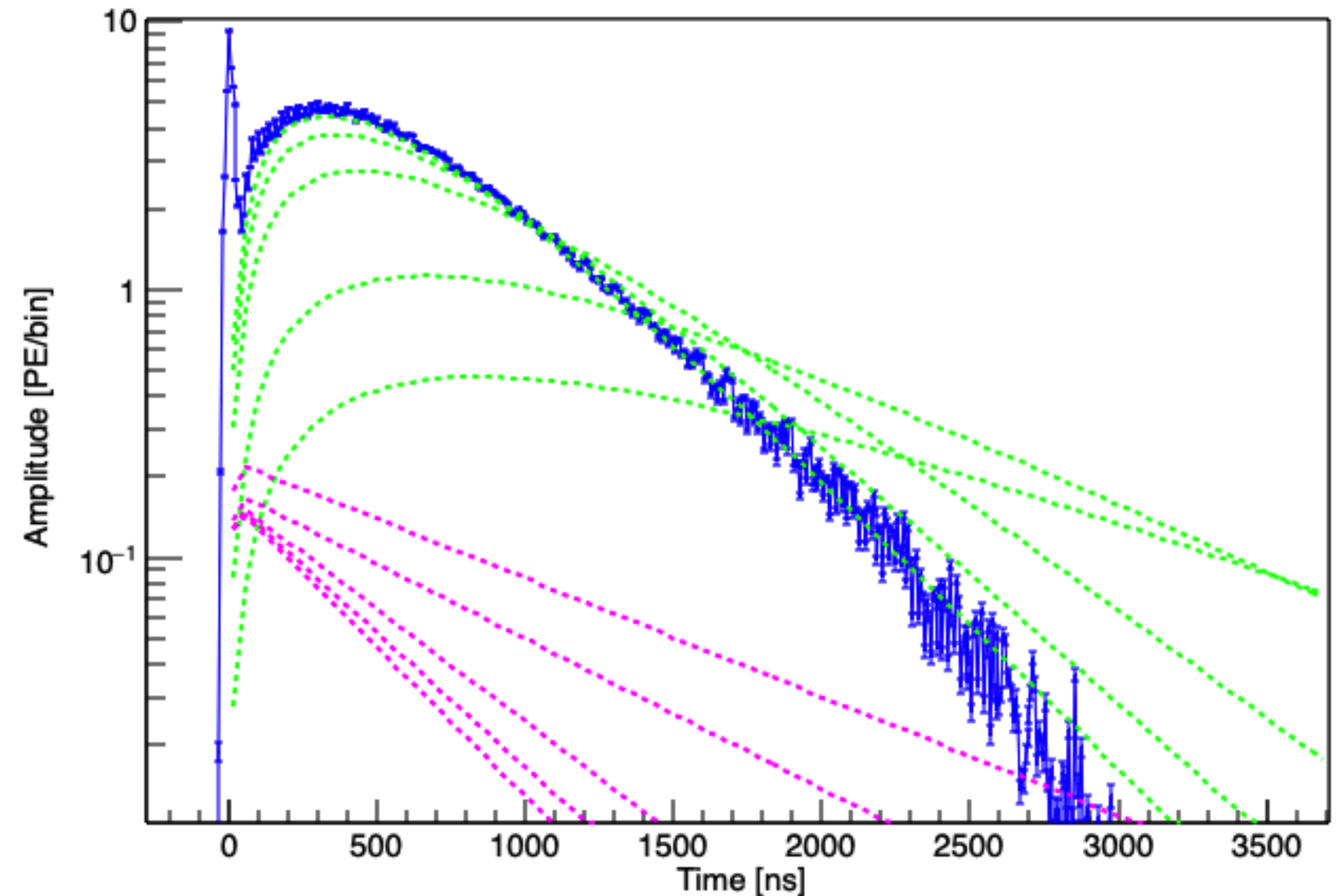
The Singlet component (pink) peak remains similar but the tail reduces with the Xenon amount, giving an overall reduction of the integral:

$$\rightarrow C_1(ppm) = a_1 + \frac{b_1}{ppm}.$$

Argon Light Component



Argon Light Component



Fit results

	Arapuca 1	Arapuca 2	Avg [us]
Tau AX	9488 +/- 20 [ns]	8053 +/- 36 [ns]	8.8 +/- 0.7
T	925 +/- 1 [ns]	1081 +/- 3 [ns]	1.0 +/- 0.07
Tau XX	10682 +/- 22 [ns]	11508 +/- 40 [ns]	11.1 +/- 0.4
Tau SR	862 +/- 1 [ns]	813 +/- 3 [ns]	0.84 +/- 0.02
A1	7.04 +/- 0.2	2.42 +/- 0.07	
B1	3.6 +/- 0.1	1.82 +/- 0.04	
A2	0.053 +/- 0.002	0.162 +/- 0.003	
B2	0.096 +/- 0.003	0.077 +/- 0.004	

$$\tau_{AX} = (8.8 \pm 0.7) \frac{\mu s}{ppm}$$

$$\tau_{XX} = (11.1 \pm 0.4) \frac{\mu s}{ppm}$$

Coefficients are not expected to be the same, since the two Arapuca's geometrical position respect tracks is not the same.

Rayleigh scattering length, reflection and other factors can affect in different way 128 nm light propagation respect 175 nm light.

τ_{SR} value is in the expected range: $0.63 \mu s < \tau_{SR} < 1.3 \mu s$.

It is in a middle way between full N₂ recovery ($\tau_{SR} \simeq 1.3 \mu s$) and no N₂ recovery ($\tau_{SR} \simeq 0.63 \mu s$).

The value found ($\tau_{SR} \simeq 0.84 \mu s$) is compatible with a partial energy recovery from N₂*.



$$\frac{1}{\tau_{TA^*}} = \frac{1}{\tau_{SR}} + \frac{1}{\tau_{AX}} \qquad \frac{1}{\tau_{SR}} = \frac{1}{\tau_{128}} + \frac{1}{\tau_{N_2}} - \frac{1}{\tau_{Rec}} \qquad \tau_{SR} = (0.84 \pm 0.02) \mu s$$

From no Xenon Doping case: $\frac{1}{\tau_s^*} = \frac{1}{\tau_s} + \frac{1}{\tau_{N_2}}$ $\tau_s^* = (0.63 \pm 0.01) \mu s$ $\tau_{N_2} \simeq 1.22 \mu s$
 $\tau_s = 1.3 \mu s$

$$\frac{1}{\tau_{Rec}} = \left(\frac{1}{\tau_{128}} + \frac{1}{\tau_{N_2}} \right) - \frac{1}{\tau_{SR}} \qquad \tau_{Rec} \simeq 2.5 \mu s \qquad \left(\tau_{Rec} > \tau_{N_2} \right)$$

τ_{Rec} (N₂* recovery) is the time constant for the process. $N_2^* + Xe \rightarrow N_2 + Xe^*$

(The process $Xe^* + Ar \rightarrow ArXe^*$ is considered immediate)

$$T = (1.0 \pm 0.07) \mu s$$

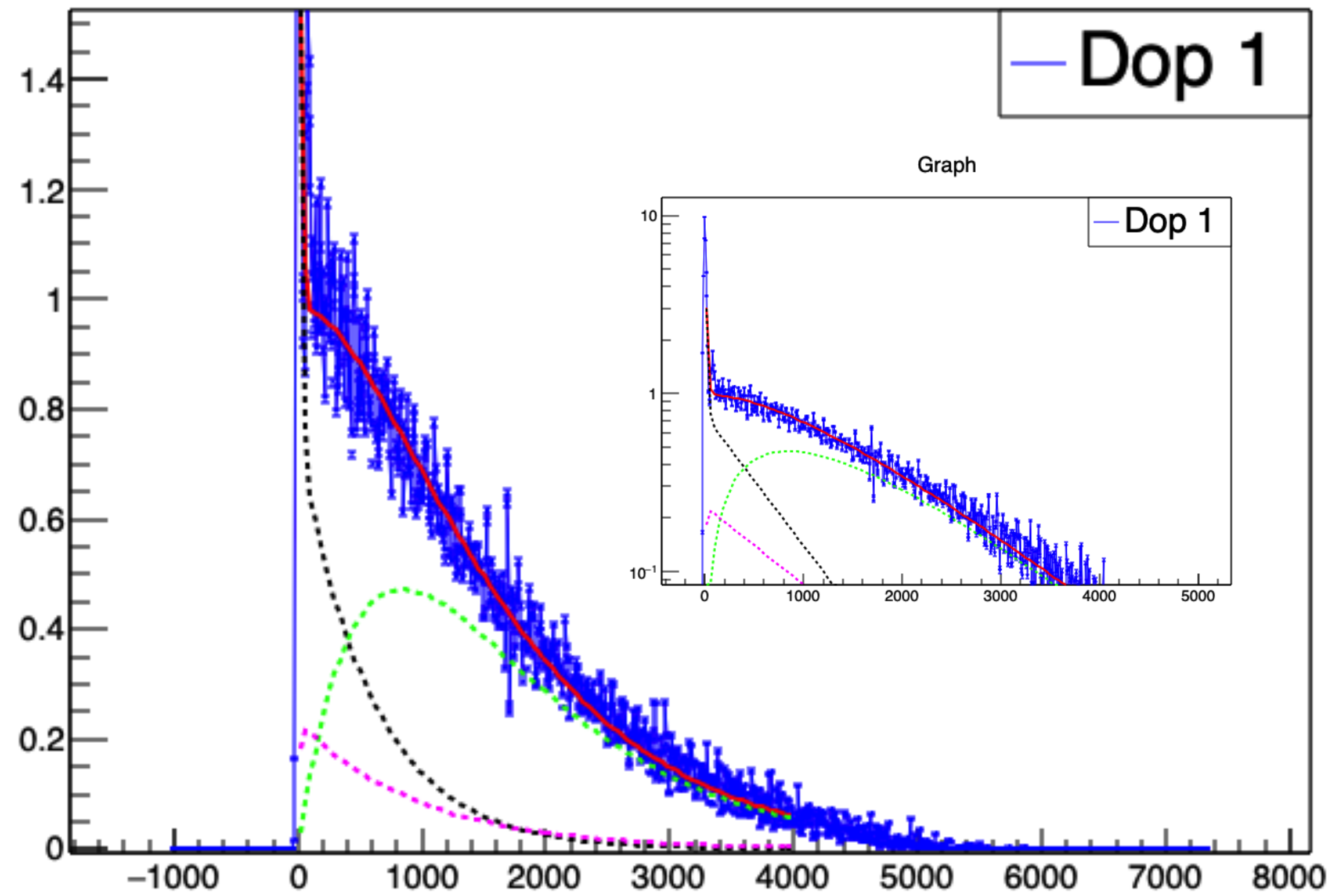
T value includes the ArXe* dimer scintillation process at 150 nm and an eventual N2 quenching of the dimer ArXe*, both of which are in competition with the XeXe* dimer formation.

$$\frac{1}{T} = \frac{1}{\tau_{150}} + \frac{1}{\tau_{N_2}}$$

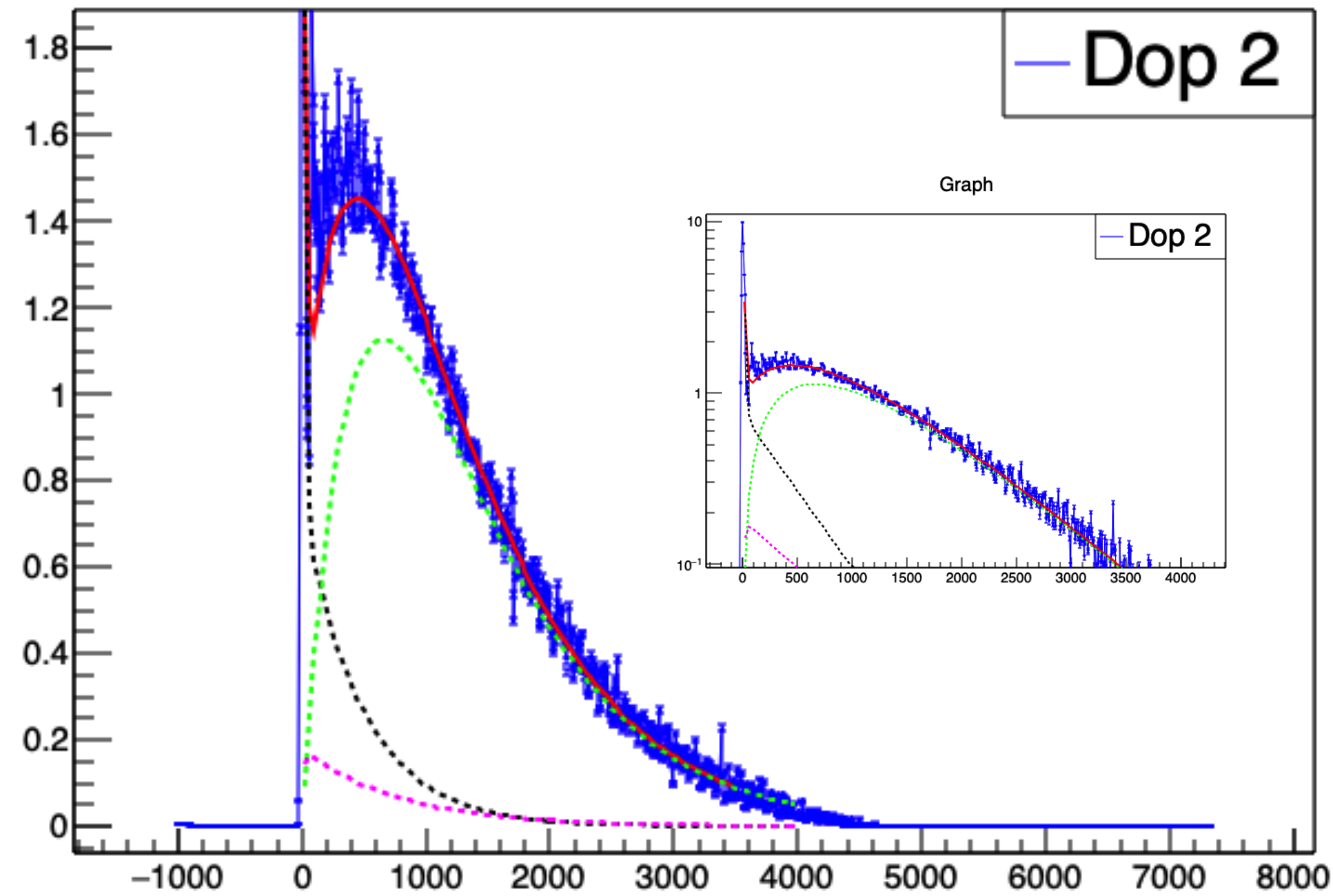
τ_{150} value is not trivial to determinate since it depends from the N2 quenching on XeXe*

Assuming a quenching: similar to ArAr*: $\tau_{N_2} \simeq 1.22 \mu s$, we have: $\tau_{150} \simeq 5.5 \mu s$

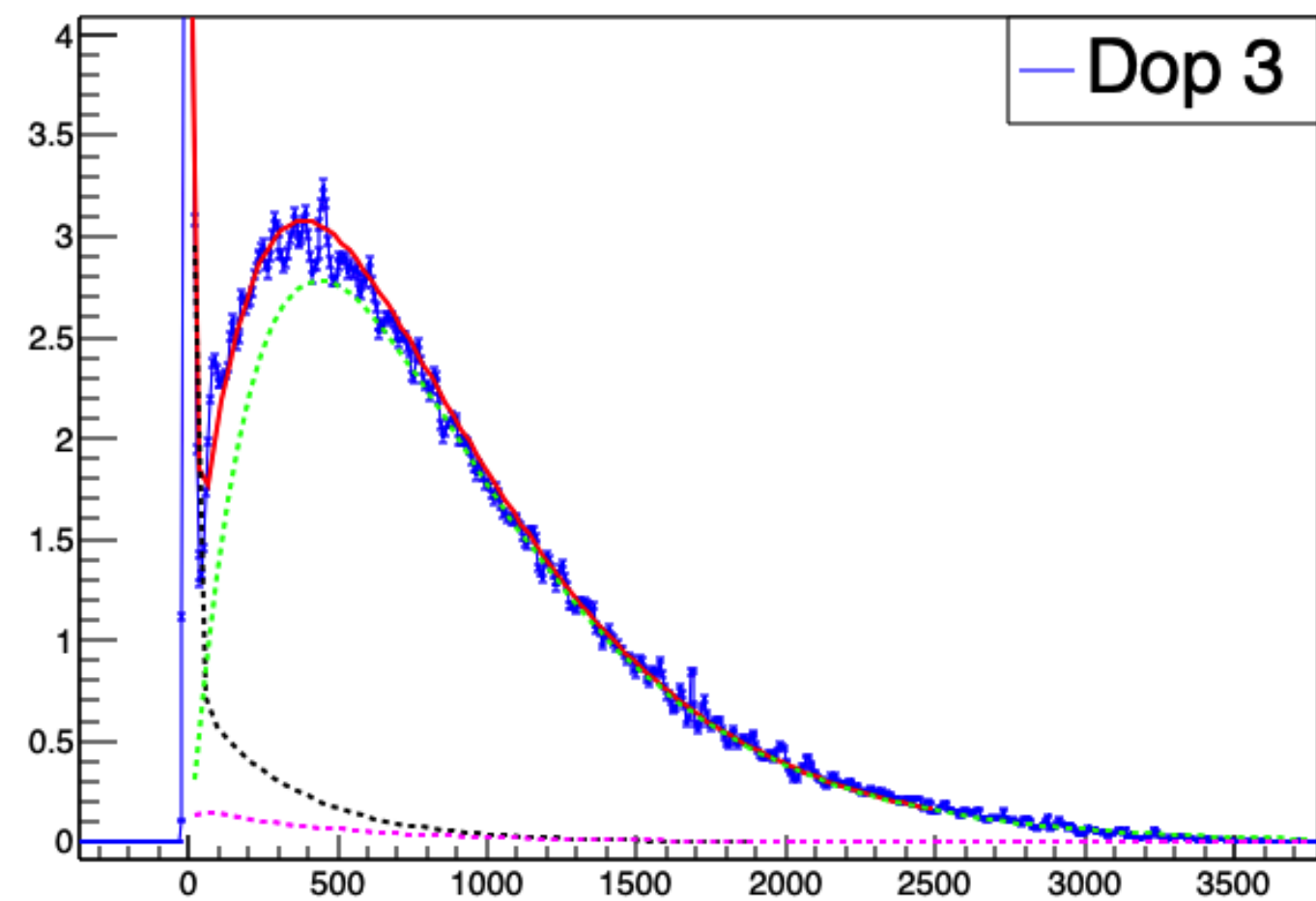
Graph



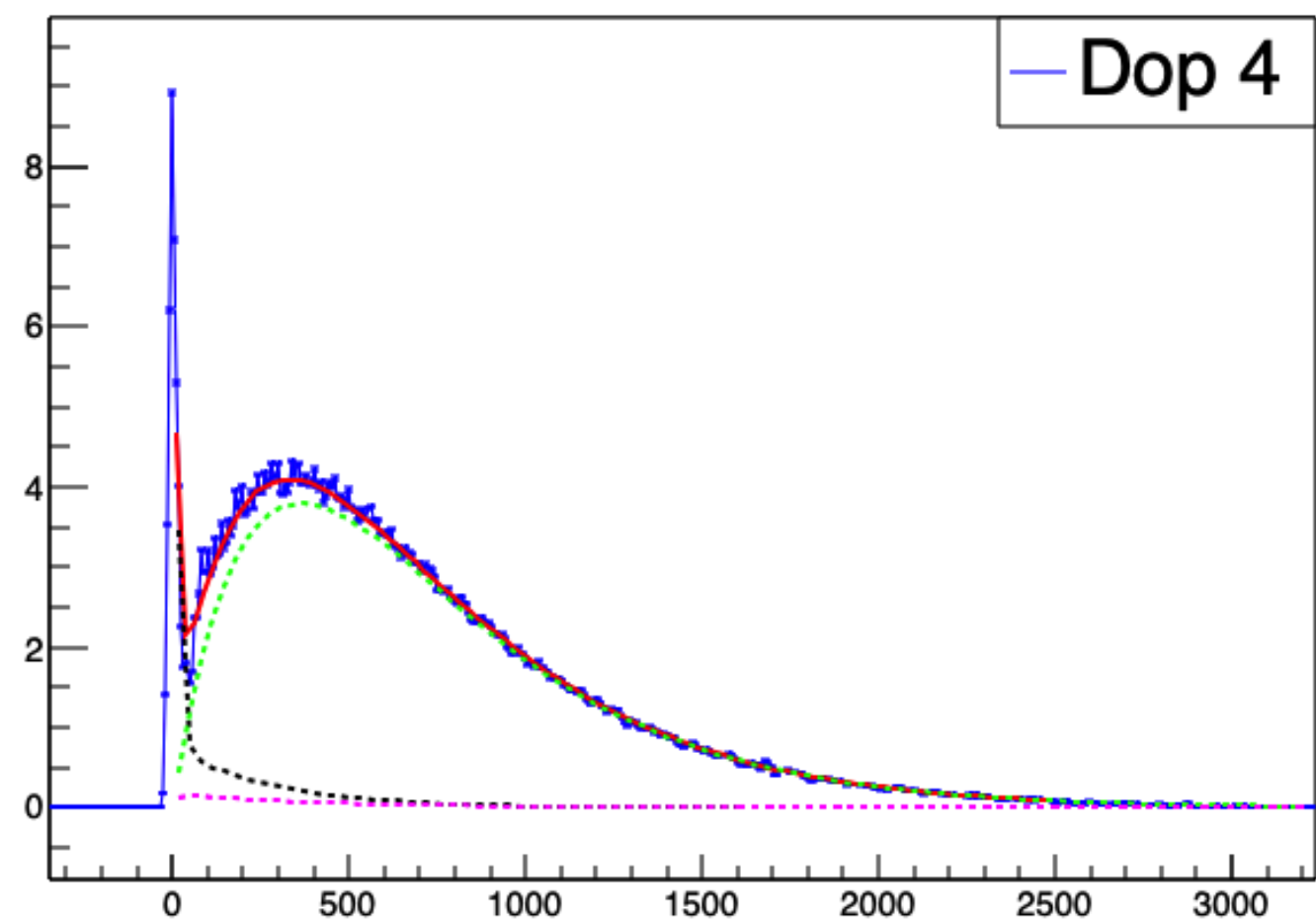
Graph



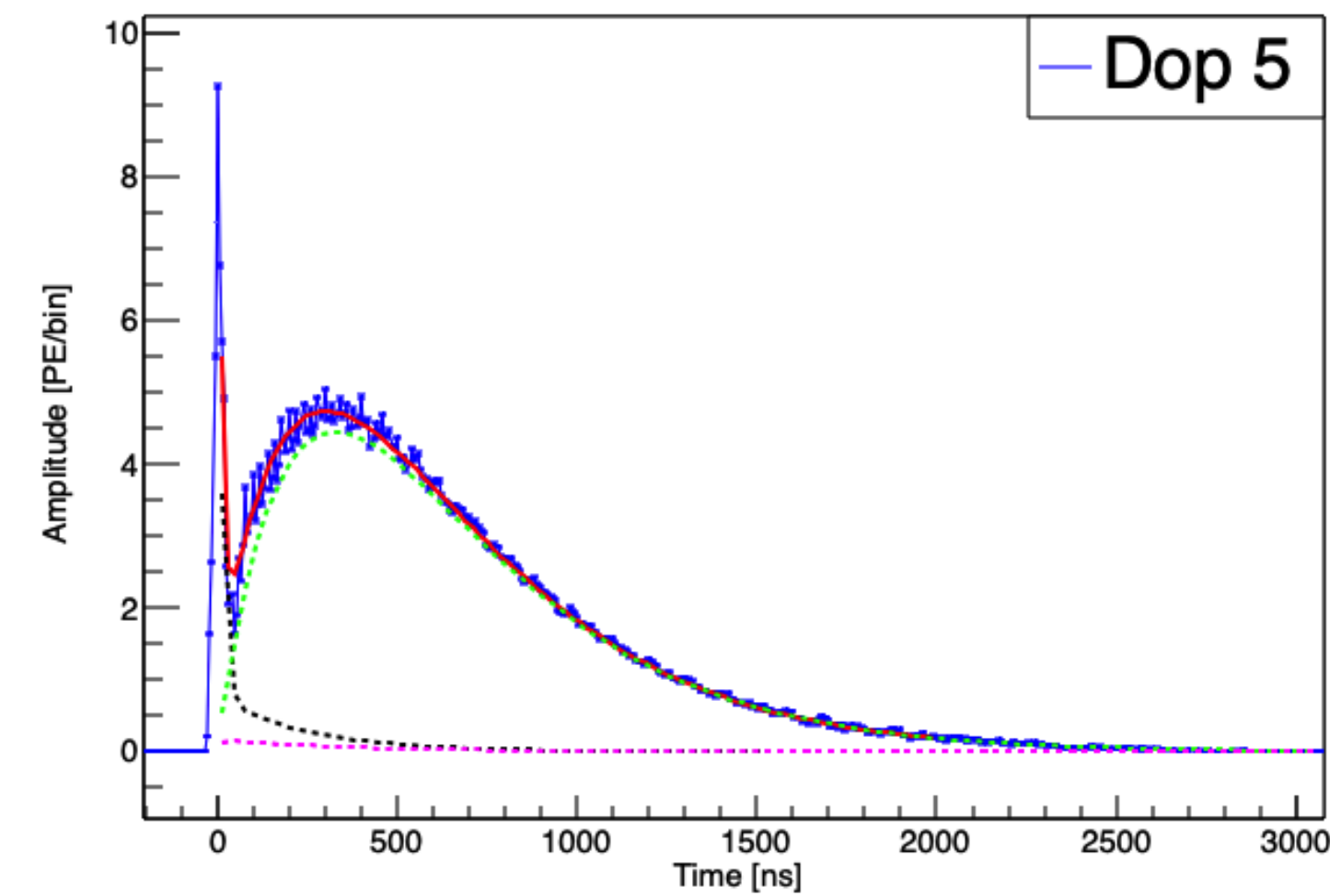
Graph



Graph

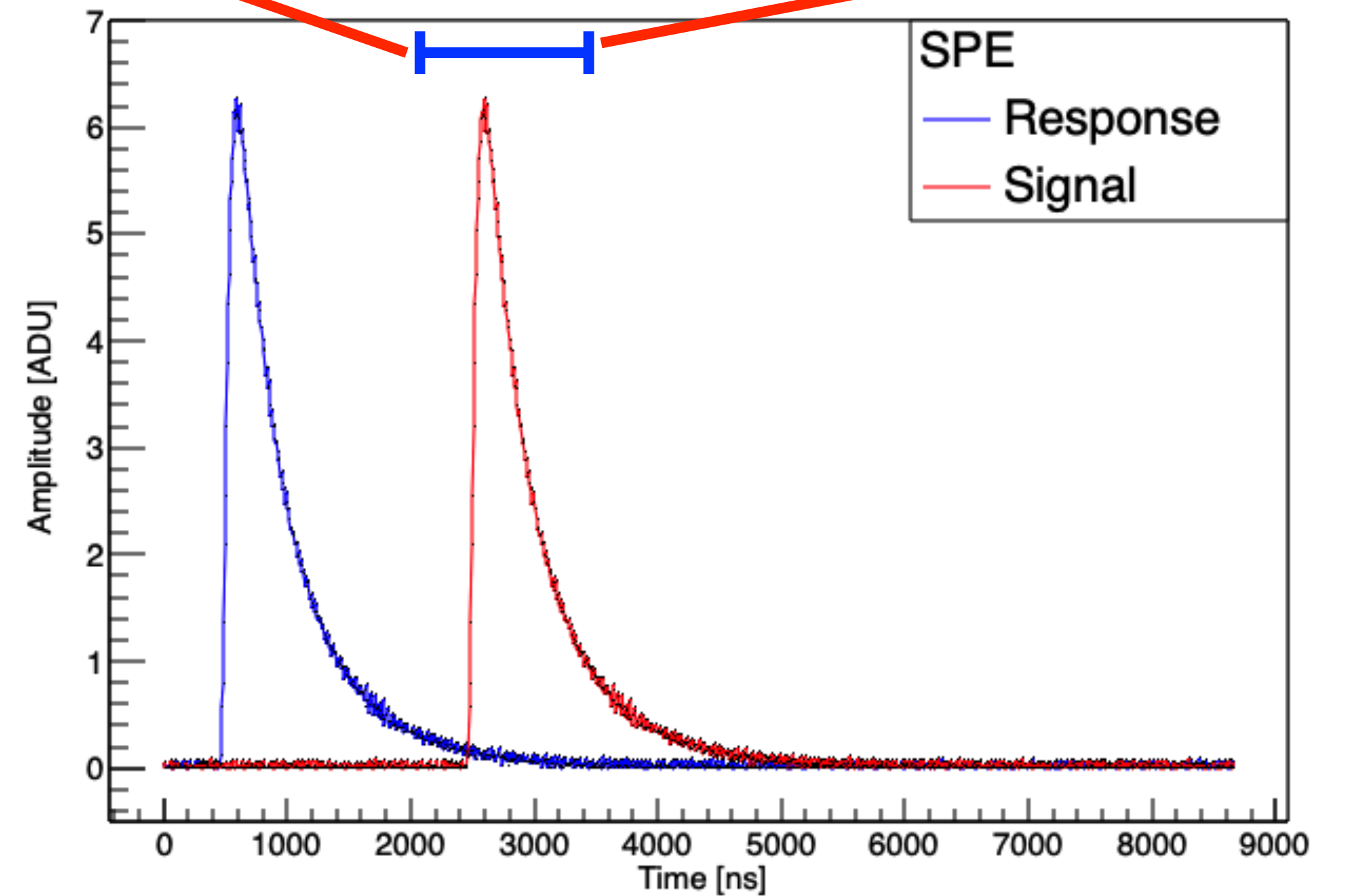
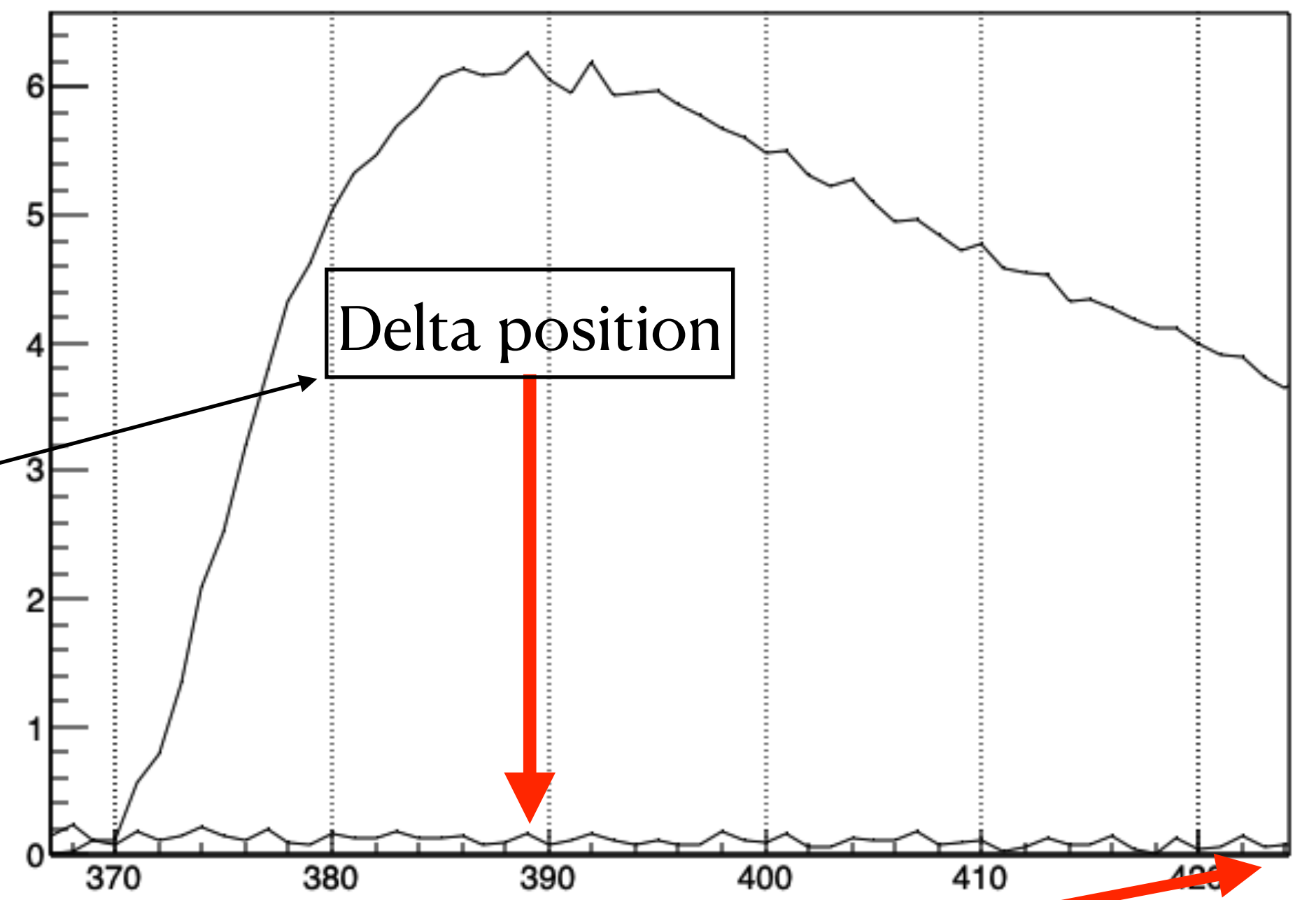
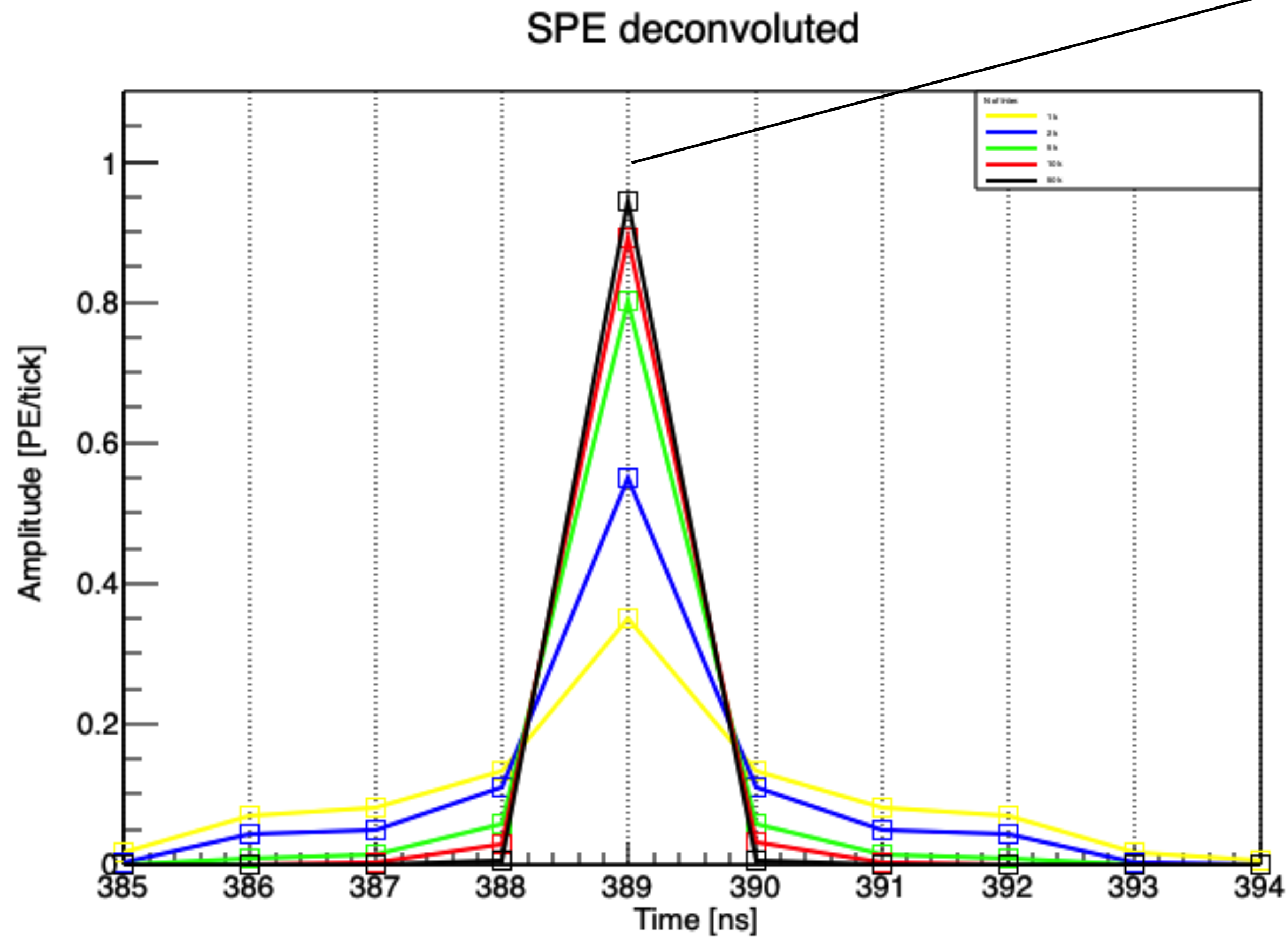


Argon Light Component



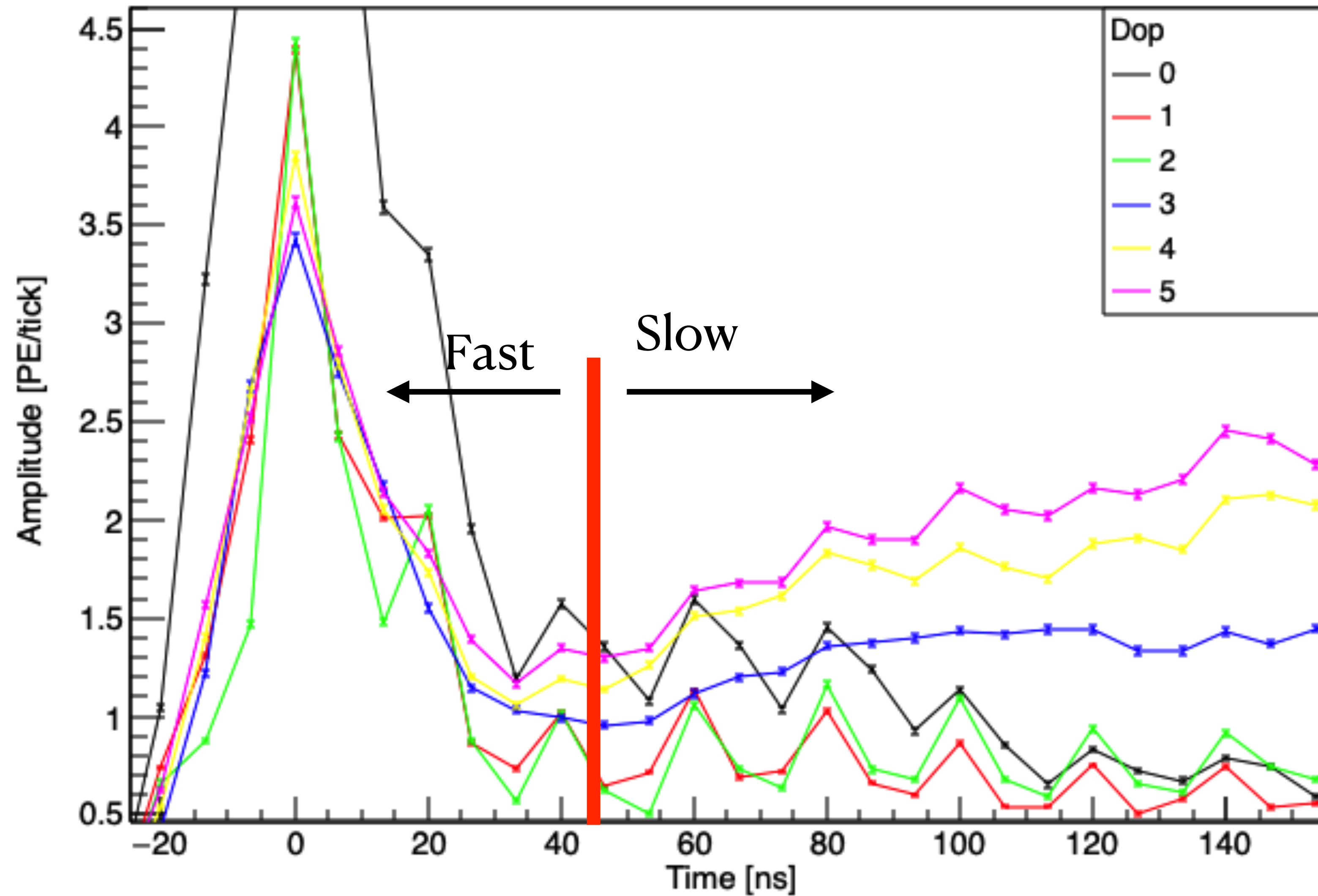
Backup Slides

Deconvolution timing



Integral limit for Fast/Slow component separation

Arapuca 2



Liquid Argon + Nitrogen waveform components

Mip in pure Liquid Argon

Singlet/Triplet = 0.3 Singlet = 23%, Triplet = 77%

A. Hitachi et al., *Effect of ionization density on the time dependence of luminescence from liquid argon and xenon*, *Phys. Rev. B* 27 (1983) 5279.

Lifetimes:

$$\tau_{Fast} = 4.9 \pm 0.2 \text{ ns} \quad \tau_{Int} = 34 \pm 3 \text{ ns} \quad \tau_{Slow} = 1260 \pm 10 \text{ ns}$$

Effects of Nitrogen contamination in liquid Argon
R Acciarri et al 2010 *JINST* 5 P06003

N2 quenching rate constant: $k_Q = 0.11 \pm 0.01 \text{ ppm}^{-1} \mu\text{s}^{-1}$

ppm= parts per million (atomic)

Liquid Argon + Nitrogen waveform components

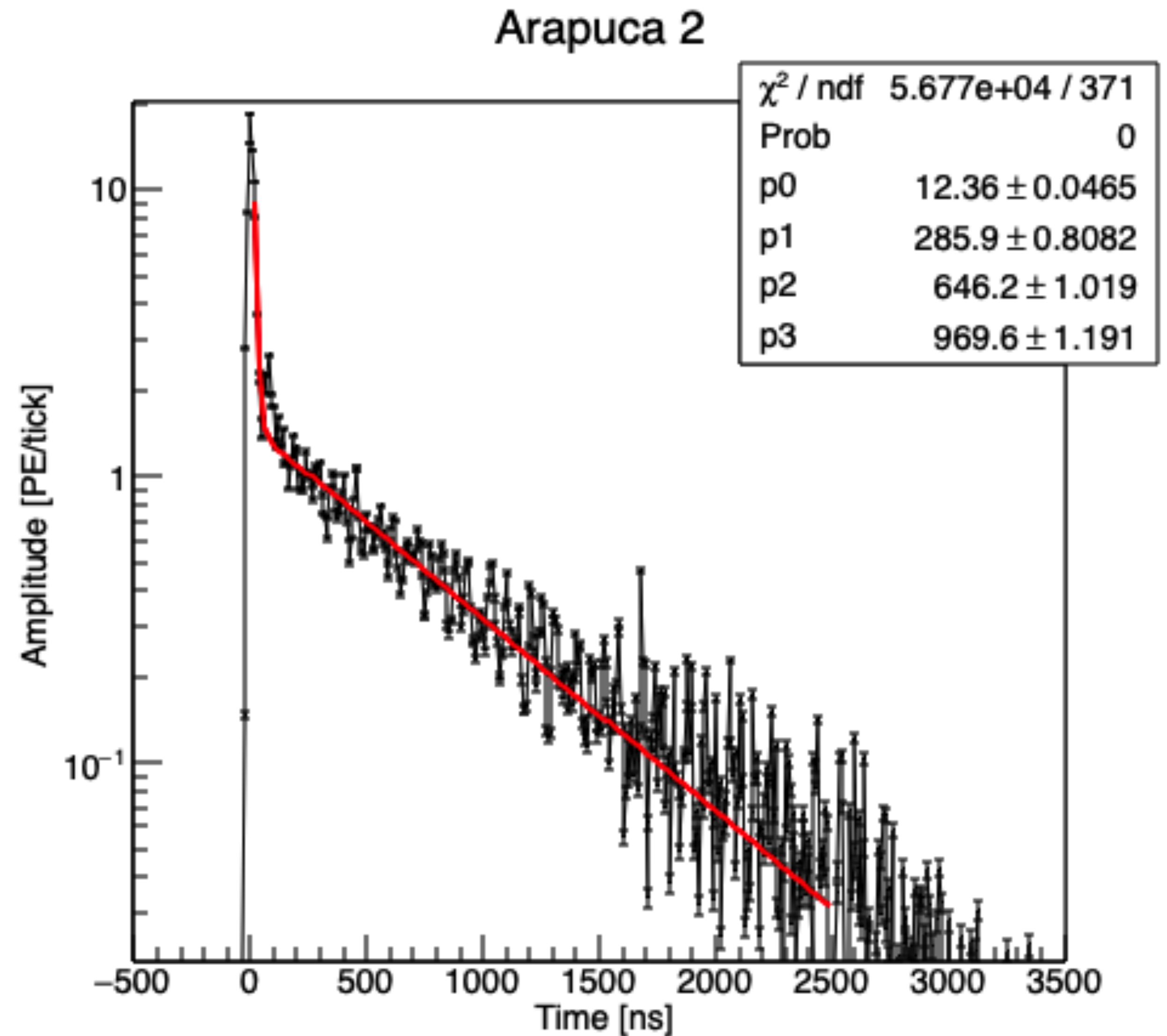
Fit parameters

Component	C	%
Fast	285.9	23%
Slow	969.6	77%
Total	1255.5	

$$A(t) = C_f \cdot \frac{e^{-t/\tau_f}}{\tau_f} + C_s \cdot \frac{e^{-t/\tau_s}}{\tau_s}$$

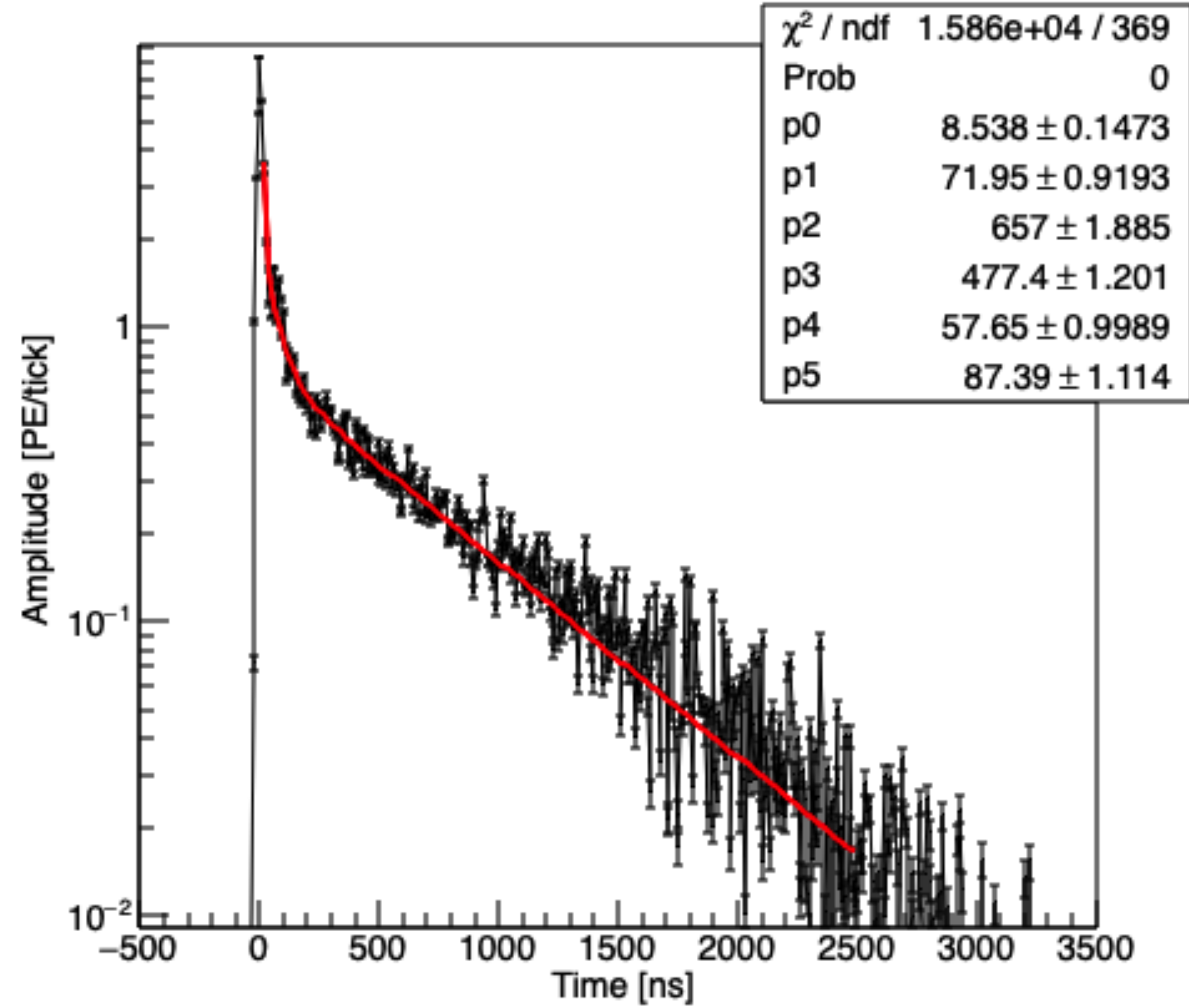
Integral

Component	PE	%
Fast	85.3	36.6%
Slow	147.3	63.4%
Total	232.6	



Doping 0

Arapuca 1



Arapuca 2

