INDIANA UNIVERSITY

Michel e^+ Simulation in protoDUNE-HD

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Content

- Photon yield estimation of Michel electron
- PDS response to Michel electron

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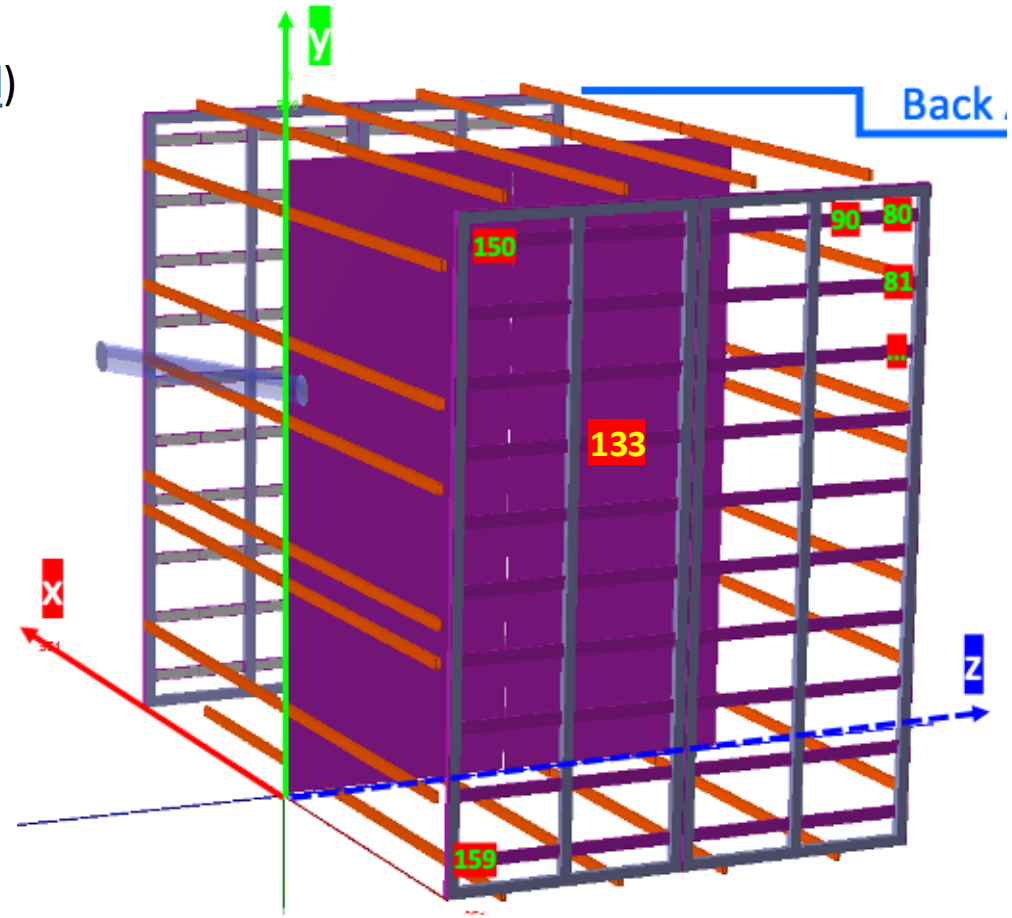
Calculation Details

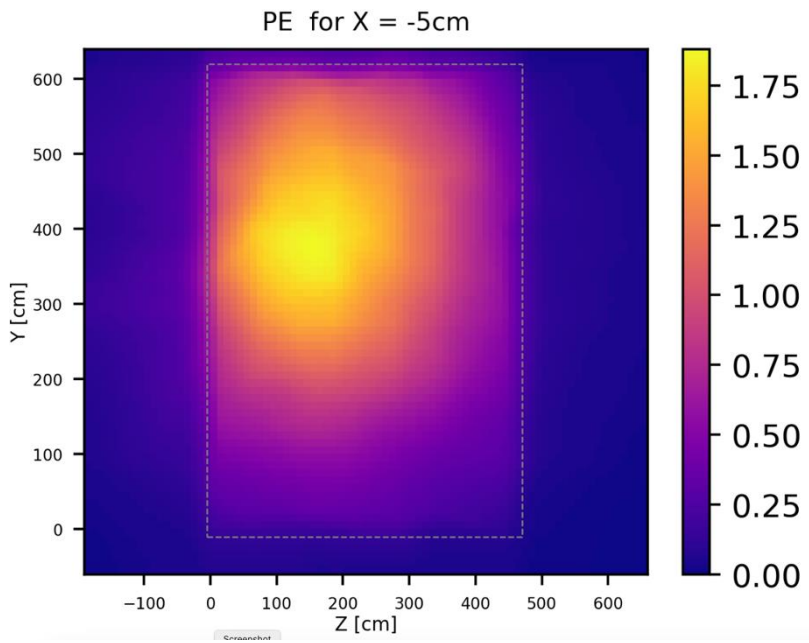
- Geometry: protoDUNE-HD (protodunehd_v6_refactored_nowires.gdml)
- Light yield of Michel e (from Tingjun's presentation [Jul 8, 2024]):

  $\boldsymbol{L = 9.1 \times 10^5}$ for $E_{ME} = 36.7MeV$ and $R = 0.625$
- Transmission efficiency: $T = 0.68$
- PDE: $A = 0.02$
- Photon propagation module: computable graph module for pdhd
- Focus on: opch133

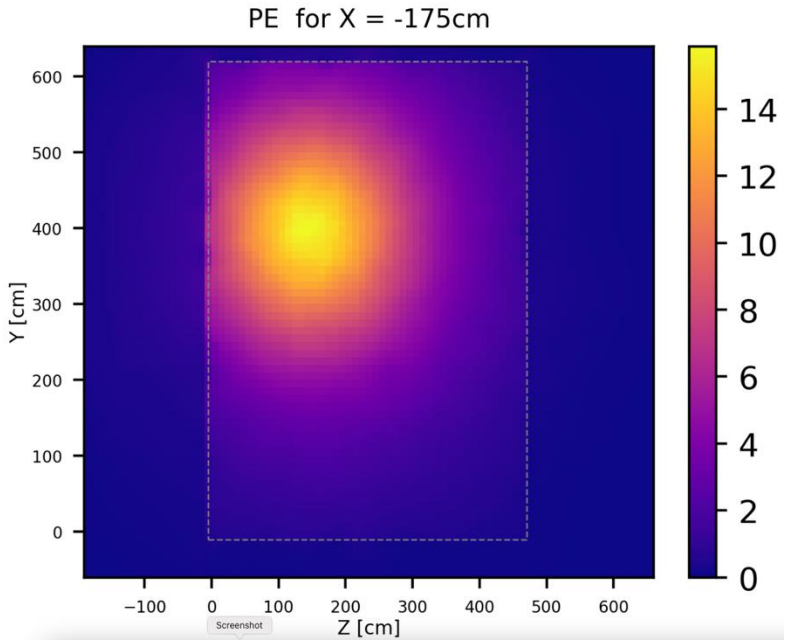


Response of OpCh133

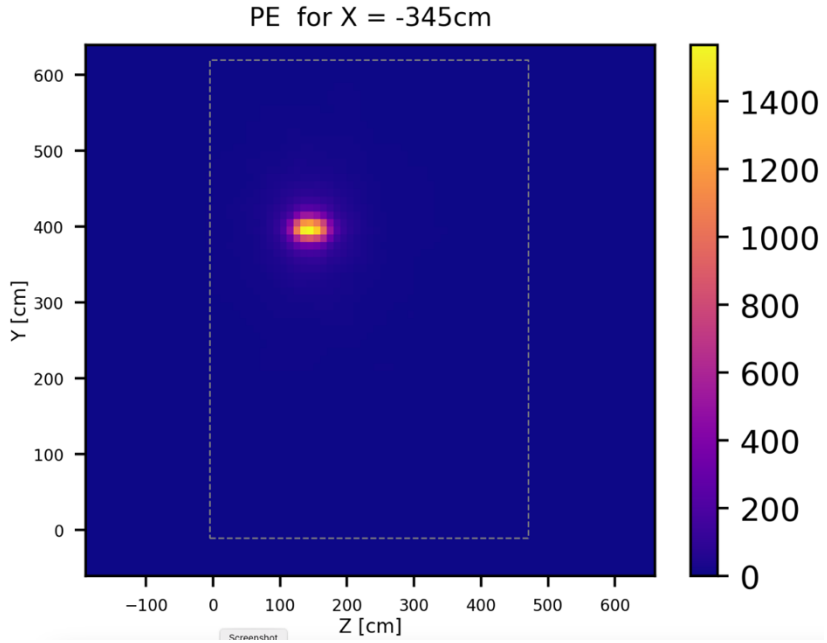
- Position of opch133: $(x, y, z) = (-356.446, 396.659, 145.861)cm$
- Fast component of argon light: $\sim 25\%$ (https://iopscience.iop.org/article/10.1088/1748-0221/5/06/P06003)
- Strong PDS signal expected when distance is short



$Distance = 351cm$



$Distance = 181cm$



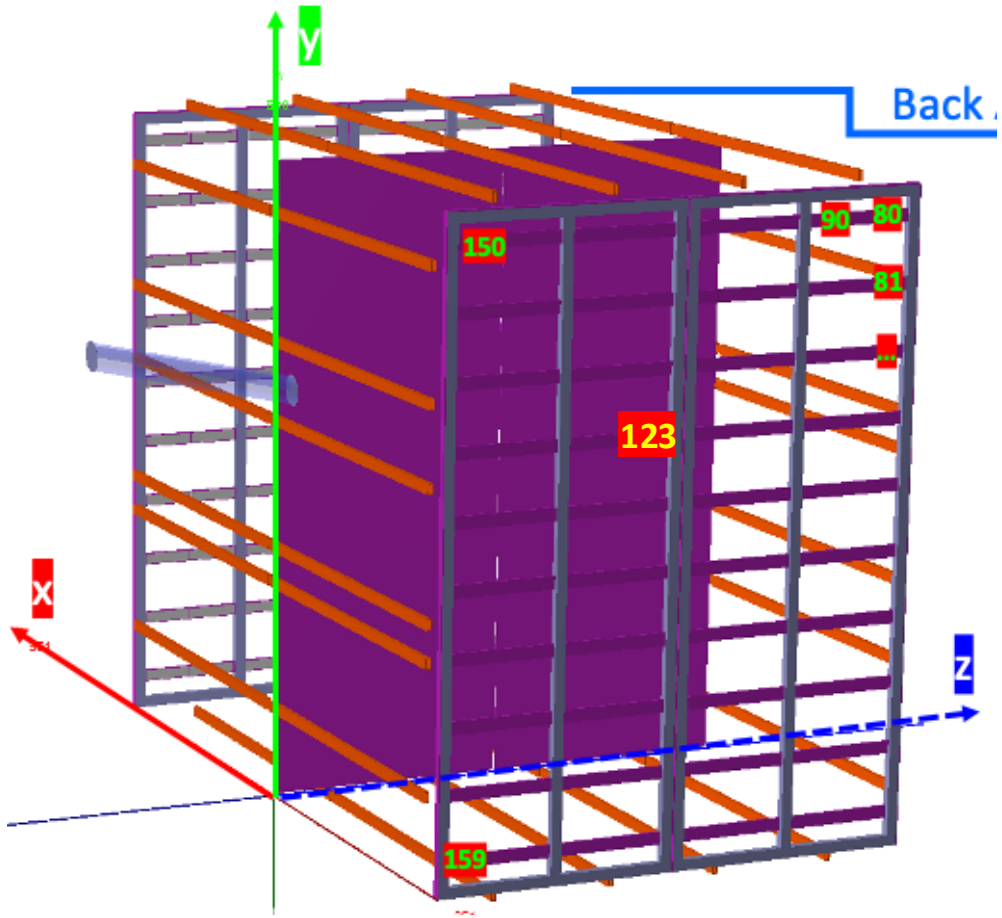
$Distance = 11cm$

- Photon yield estimation of Michel electron
- **PDS response to Michel electron**

Particle Gun (generator):

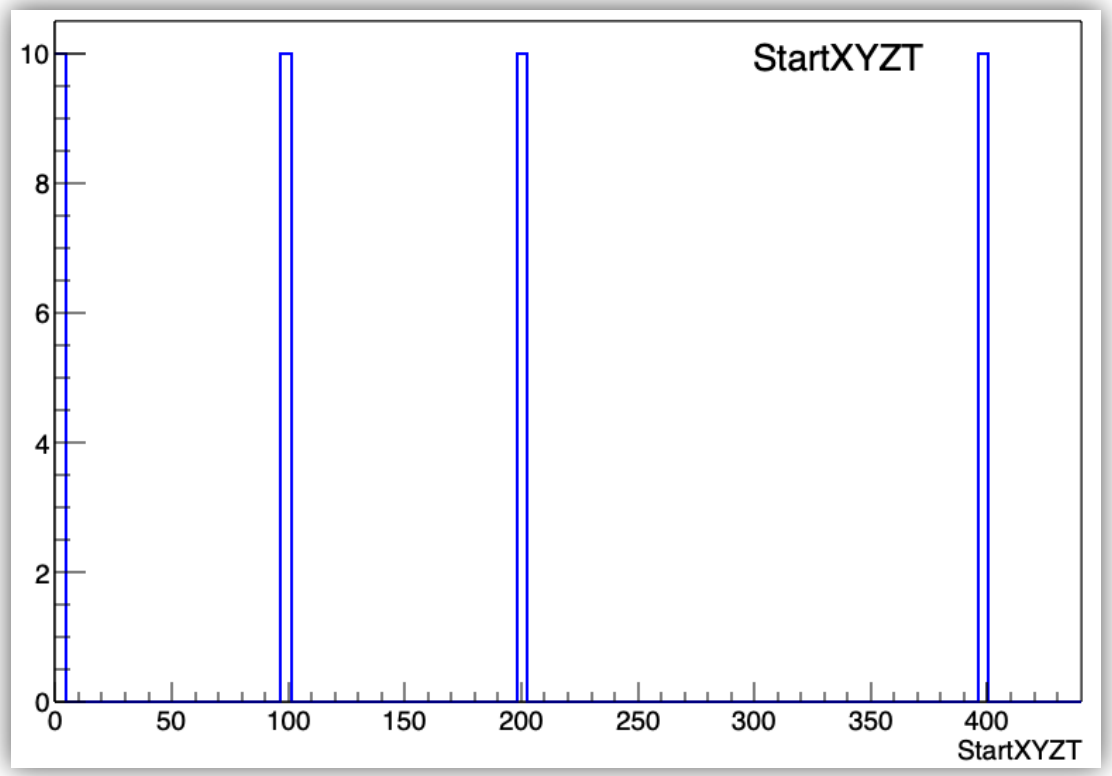
- 10 μ^+ going toward opch123 [$(x, y, z) = (-356.446, 396.659, 195.011)cm$]
- Particle will go through cathode and is expected to stop before APA

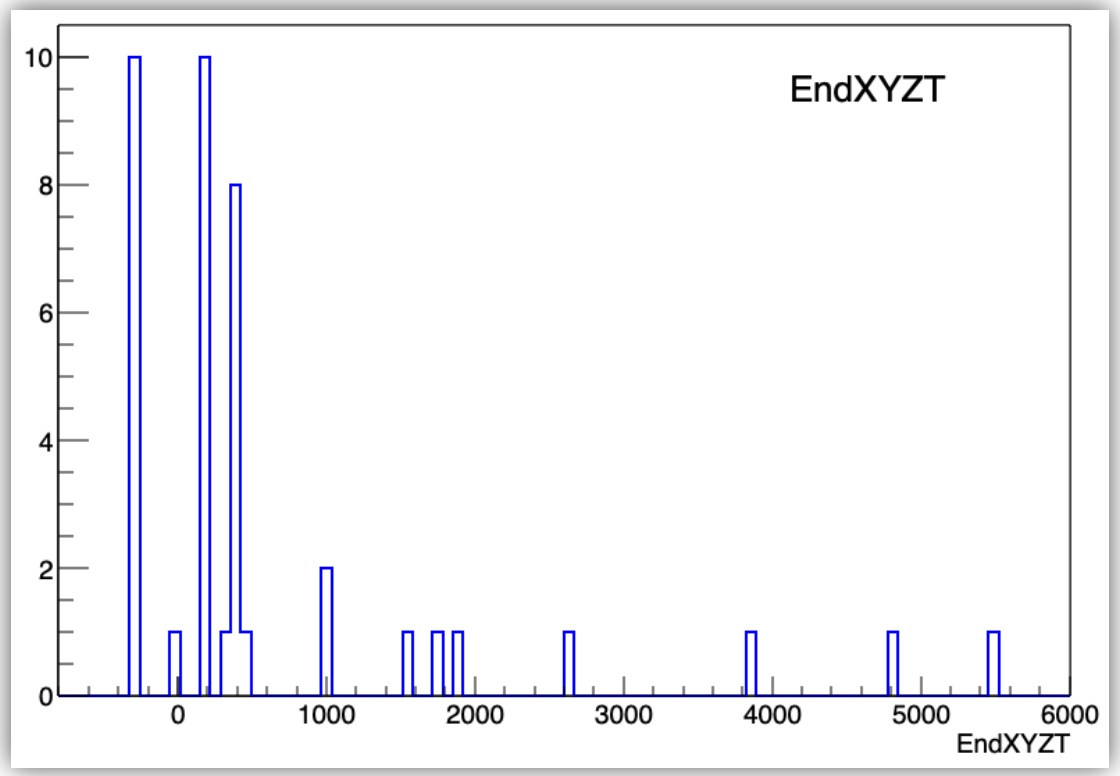
```
#Incident particles:=========
#mu+=-13, mu-=+13, p=2212, pi+=211, K+=321 ---
physics.producers.generator.PDG: [ -13 ]
#Energy (in GeV)---
physics.producers.generator.P0: [ 1.0 ]
#Angle (in degree)---
physics.producers.generator.Theta0XZ: [ -90.0 ]
physics.producers.generator.Theta0YZ: [ 0.0 ]
#Position (in cm)---
physics.producers.generator.X0:     [ 100 ]
physics.producers.generator.Y0:     [ 400.0 ]
physics.producers.generator.Z0:     [ 200.0 ]
```



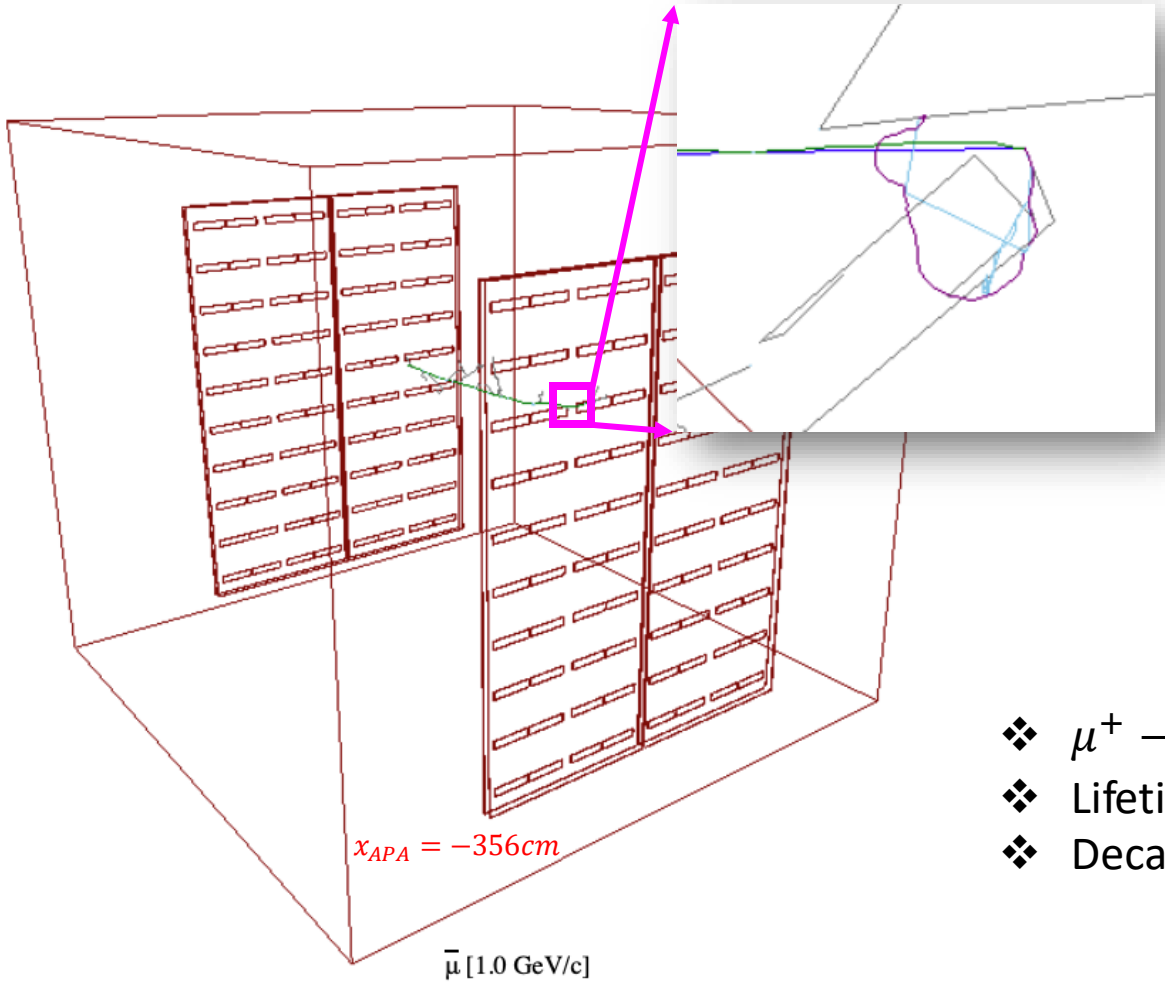
Largeant Simulation:

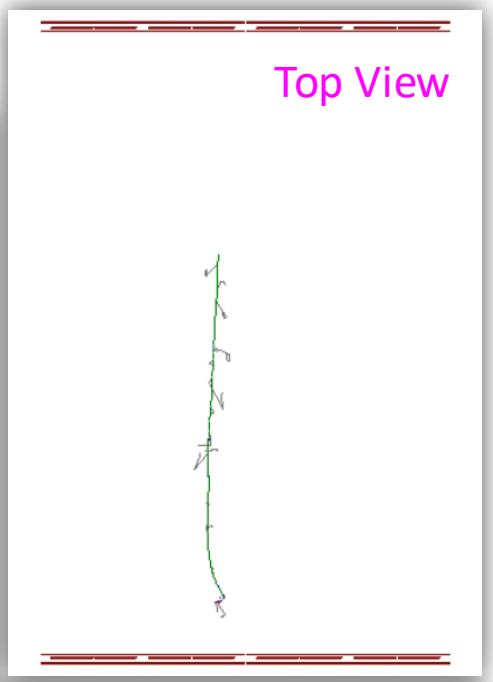
- X, Y, Z: in unit of cm; T: in unit of ns
- Lifetimes of μ^+ : $\tau_1 = 5{,}487.17ns;\quad \tau_2 = 3{,}872ns;\quad \tau_3 = 1{,}764ns;$
  $\tau_4 = 1{,}910ns;\quad \tau_5 = 1{,}540ns;\quad \tau_6 = 12ns;$
  $\tau_7 = 2{,}611ns;\quad \tau_8 = 985ns;\quad \tau_9 = 999ns;\quad \tau_{10} = 4{,}798ns$

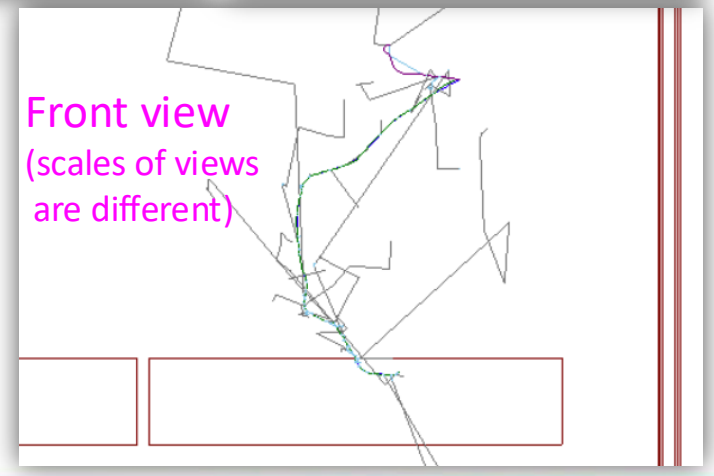




Event 1: mu^+ & e^+ in Space



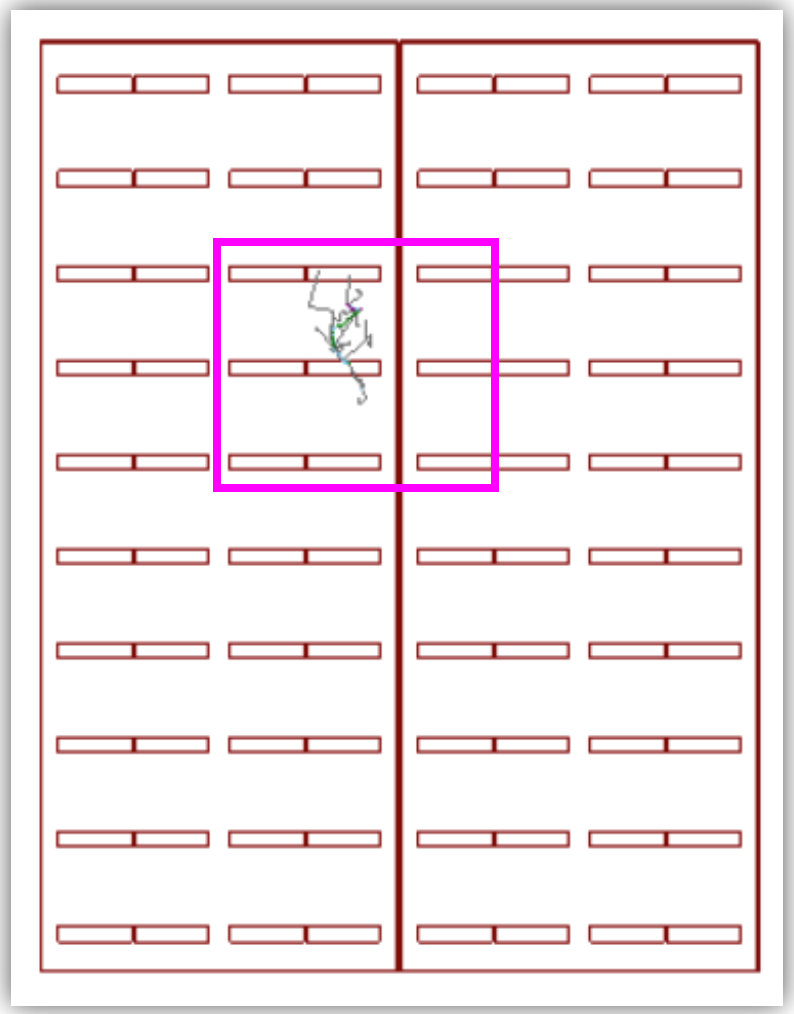


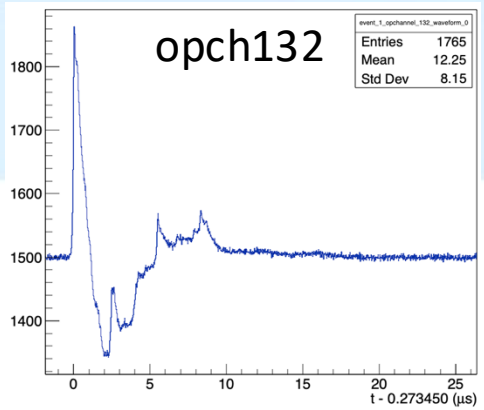


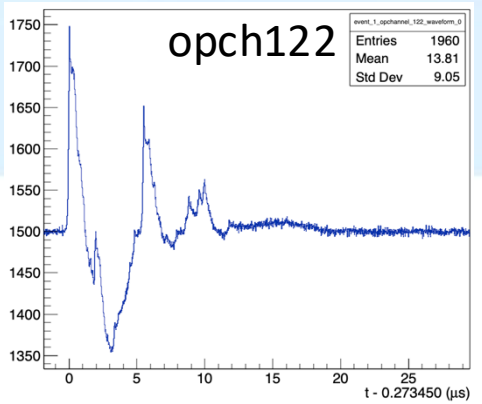
- $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- Lifetime of μ^+: $5{,}487.17ns$
- Decay point: $x = -287cm$

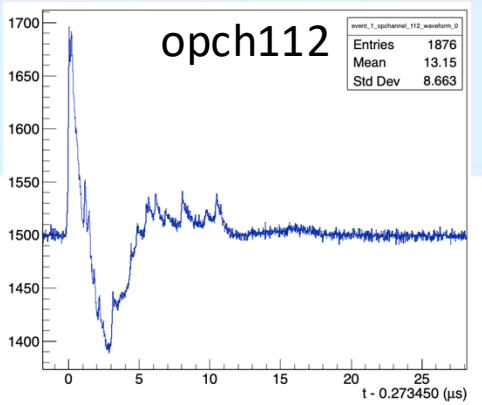
Event 1:

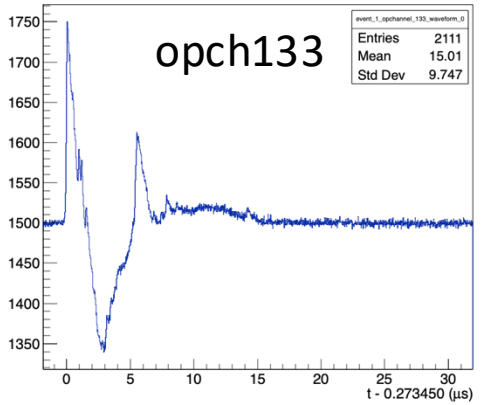
- Lifetime of μ^+: 5,487.17ns

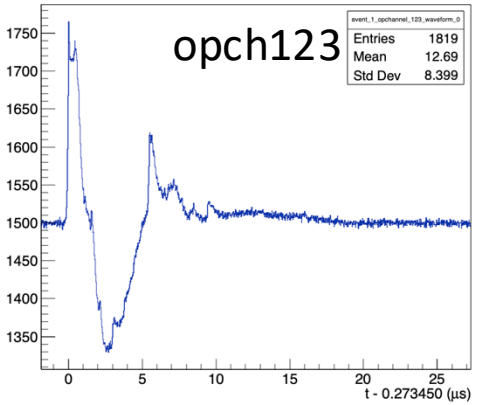


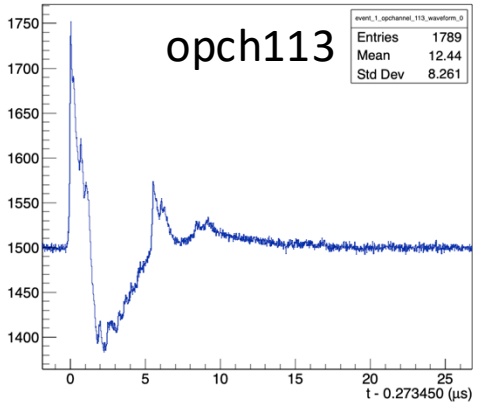


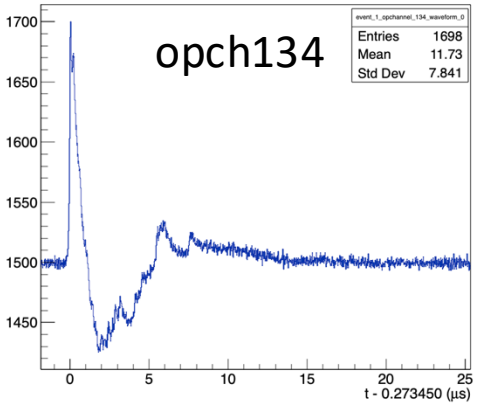


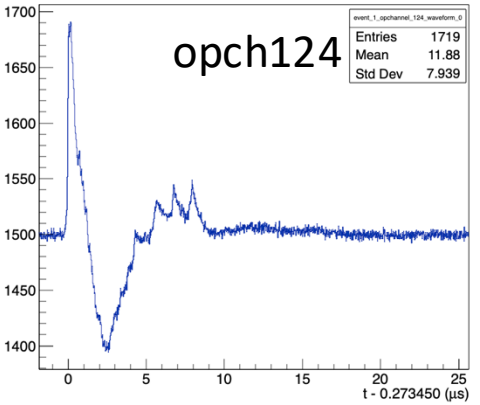


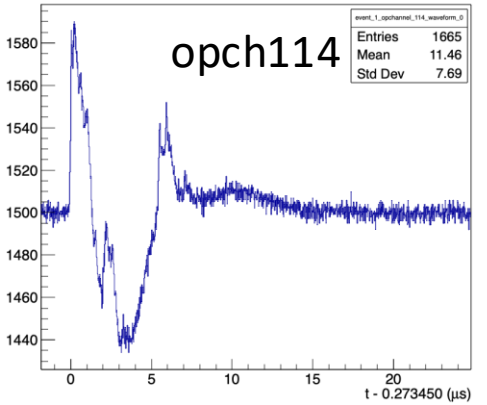




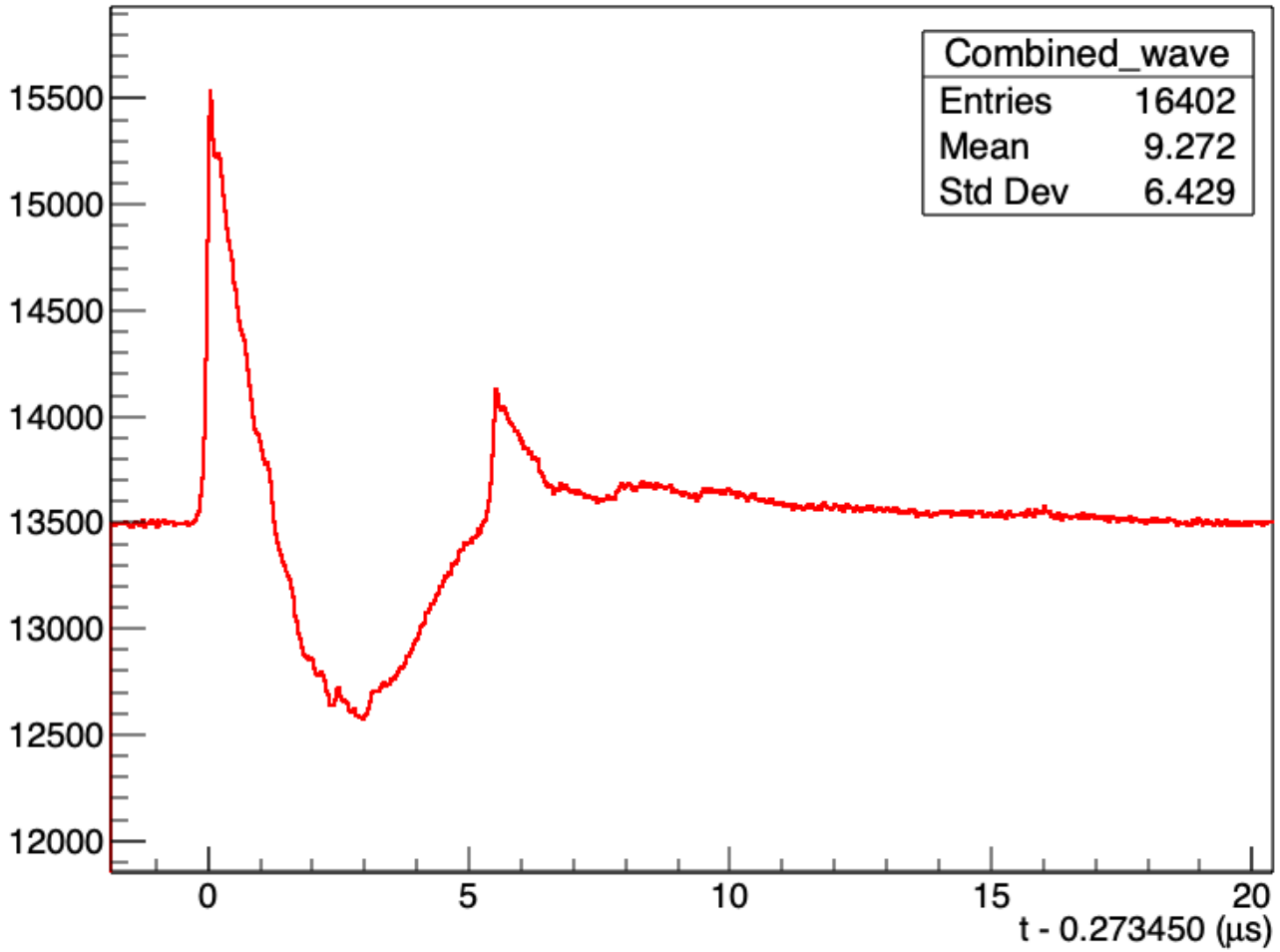




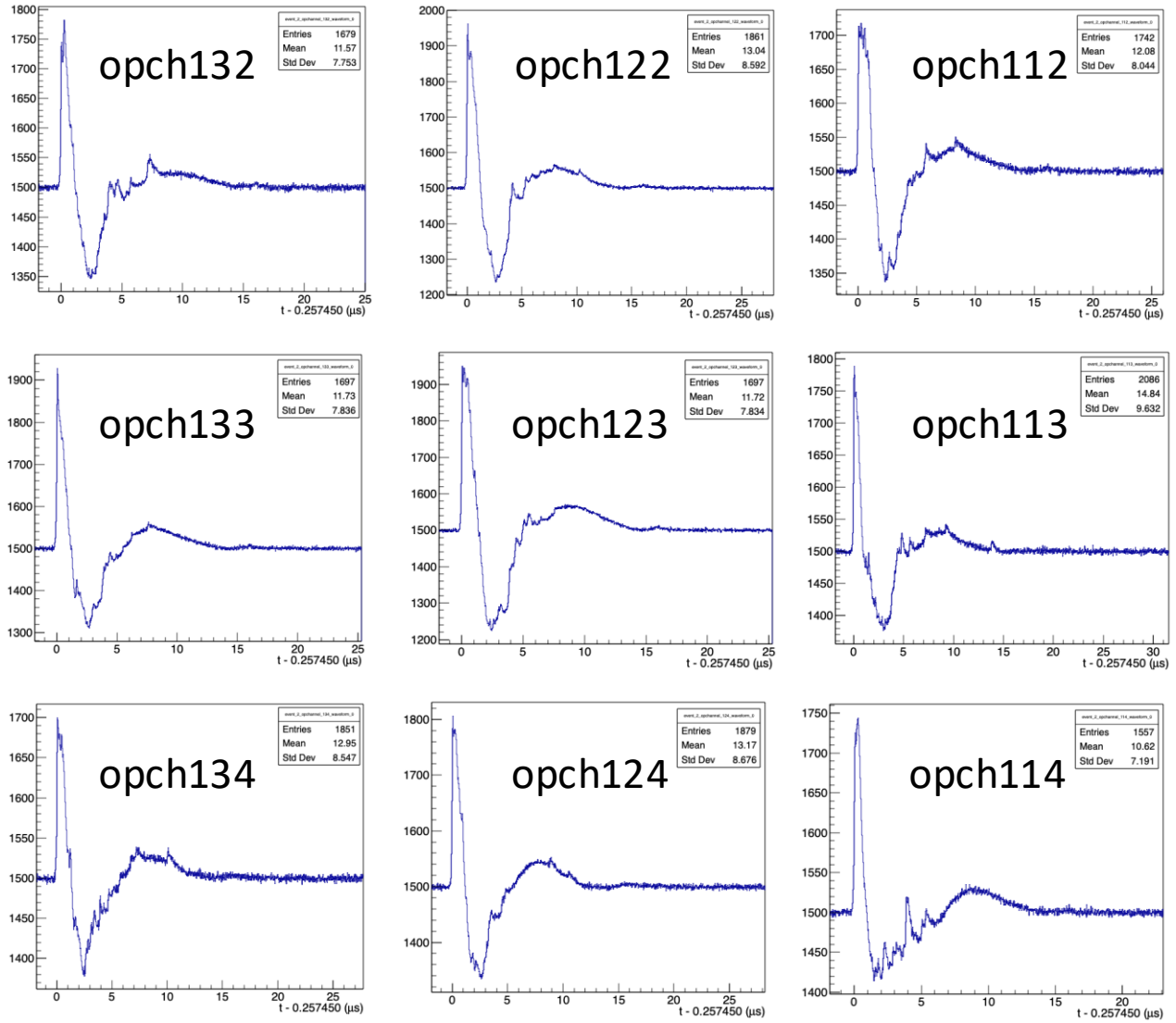




Combine All 9 Channels

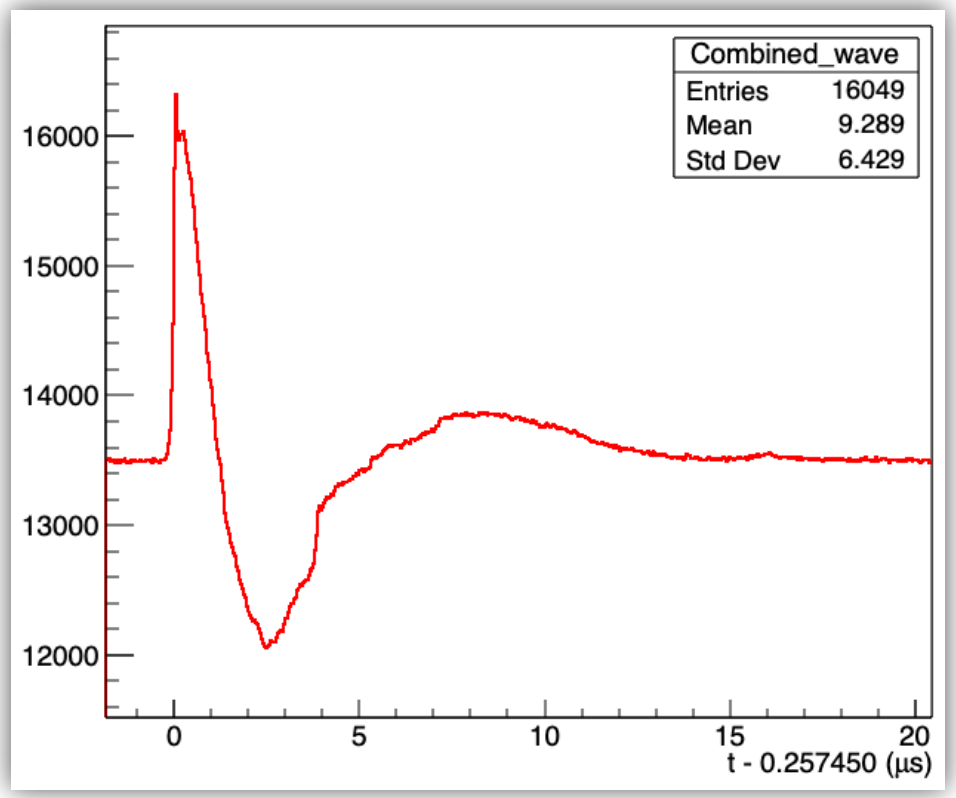


Event 2:

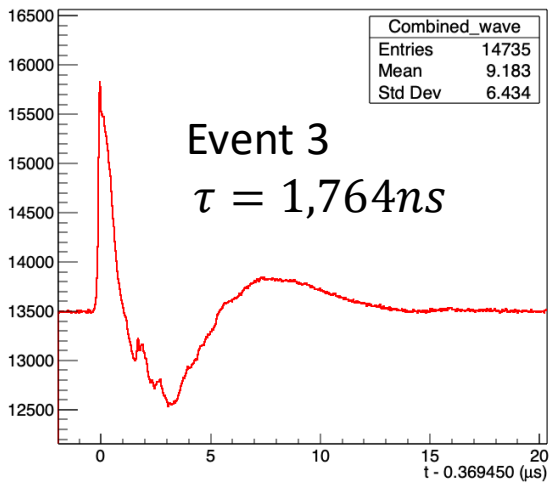


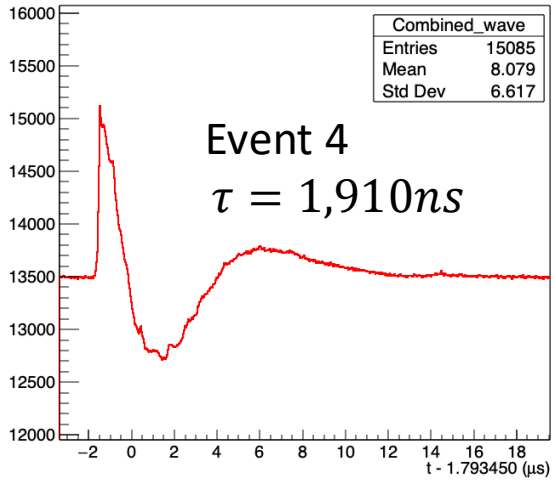
Combine

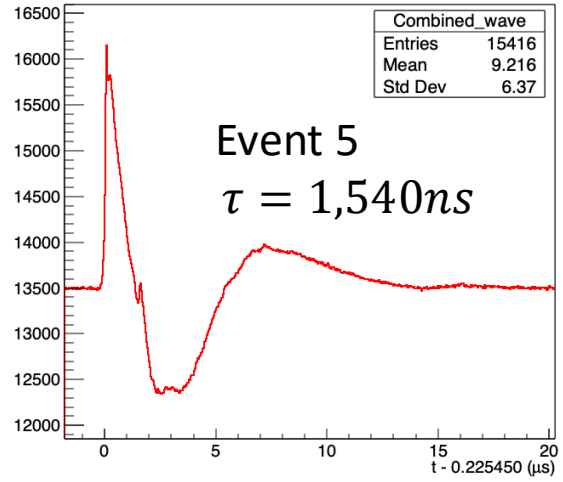
- Lifetime of μ^+: $3{,}872ns$

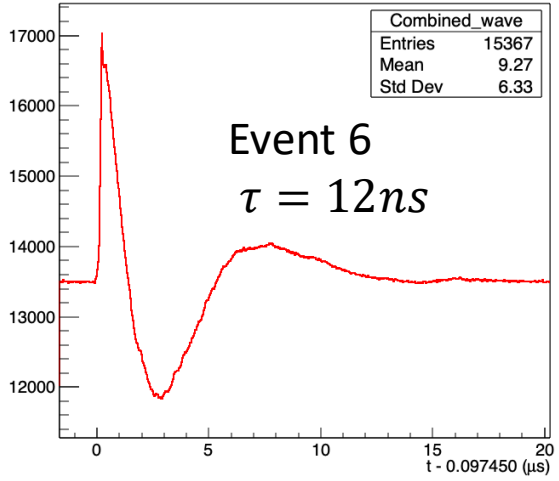


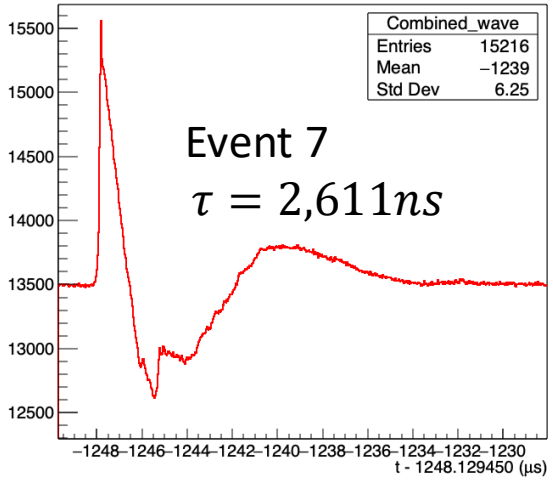
Combined Waveforms

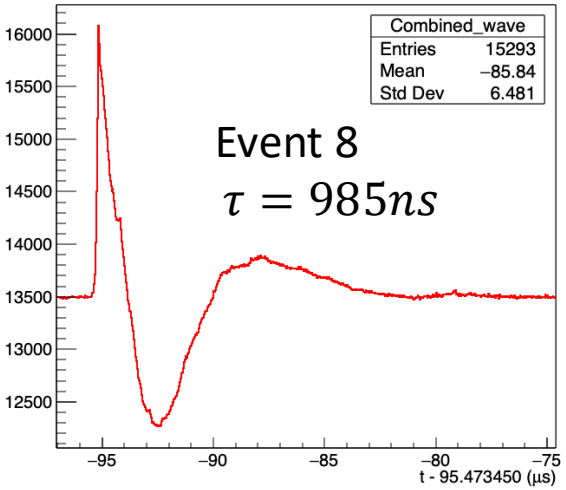


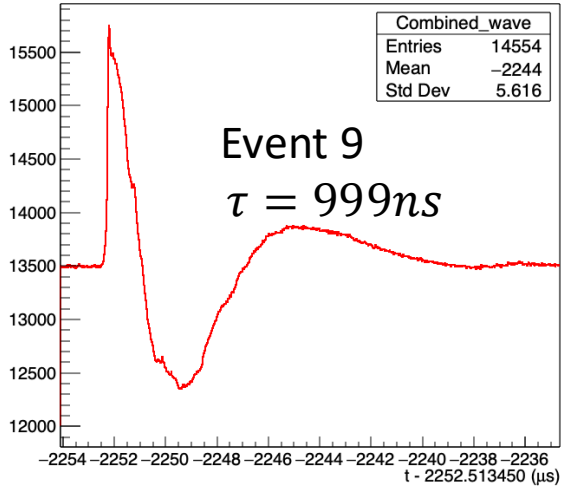


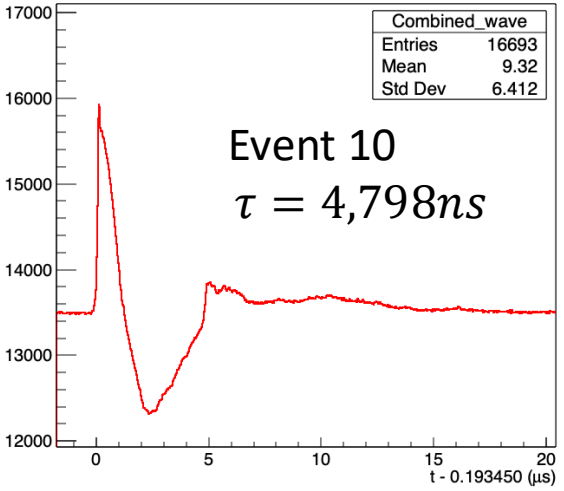






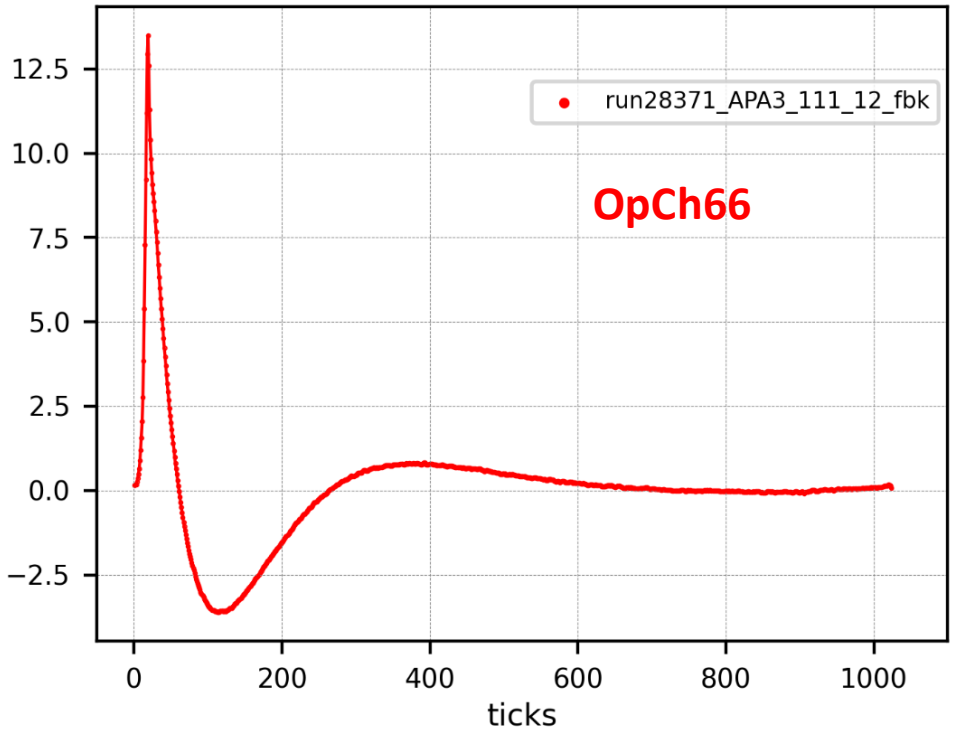


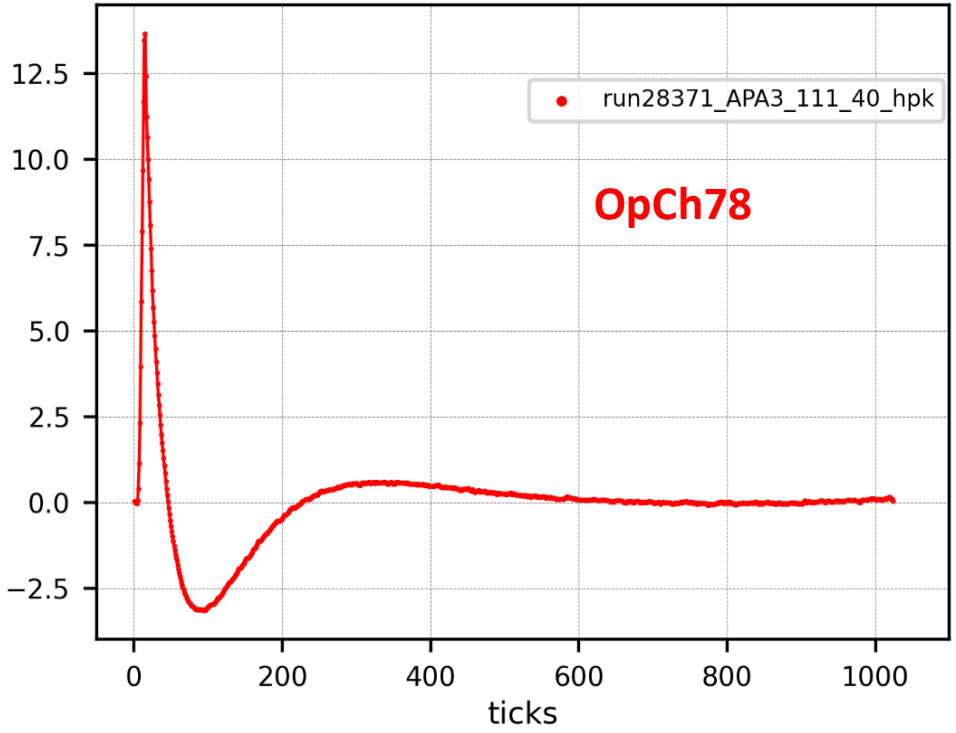




Deconvolution:

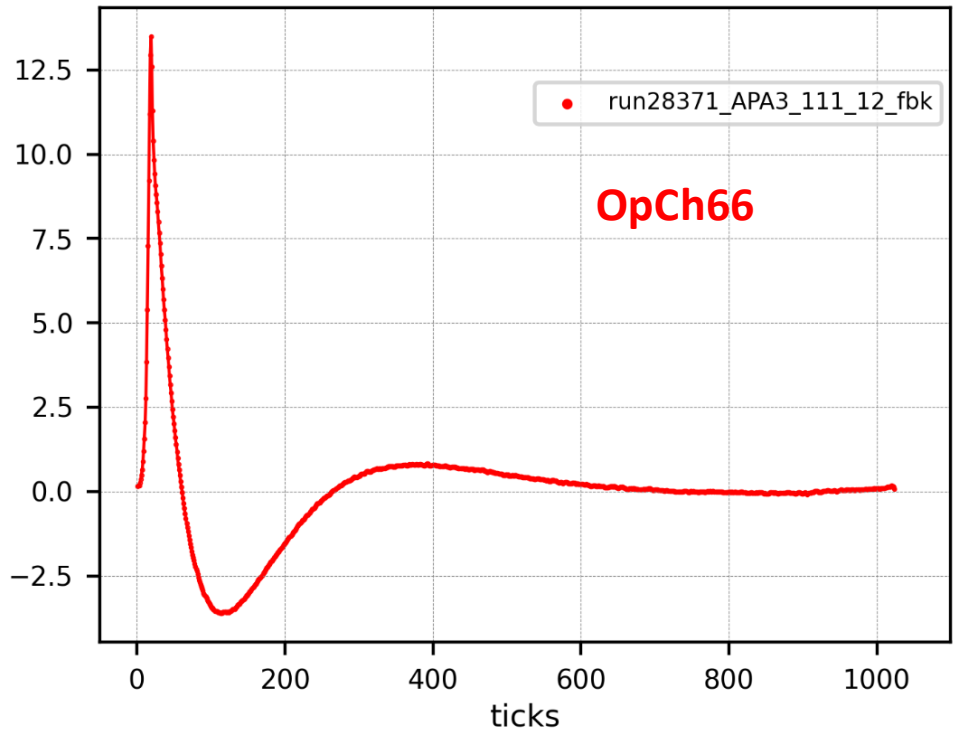
- SPE template: based on data of protoDUNE-HD calibration run
- Example: **SPE_Template_run28371_APA3_111_12_fbk.txt, SPE_Template_run28371_APA3_111_40_hpk.txt**
- Thanks to Maritza's sharing!



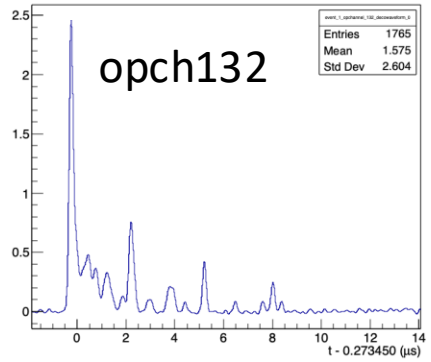


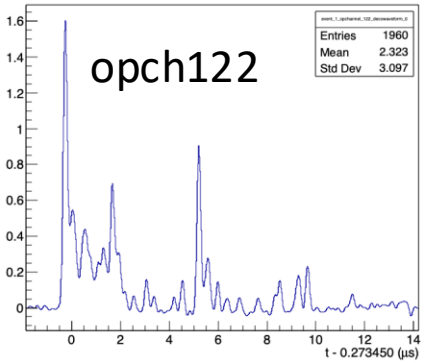
Deconvolution:

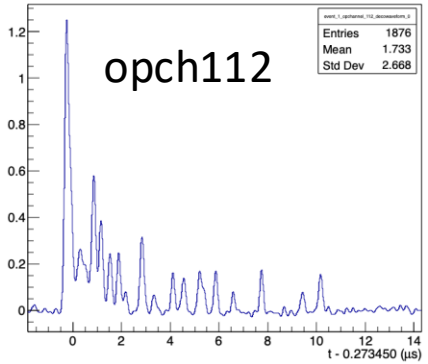
- SPE_Template_run28371_APA3_111_12_fbk.txt is applied to ALL channels

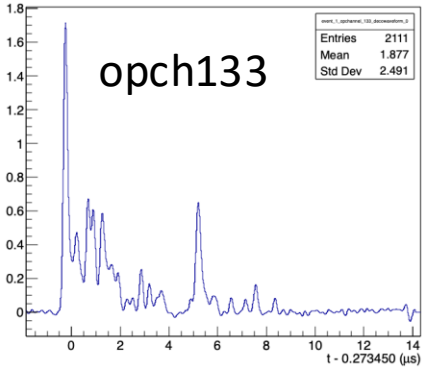


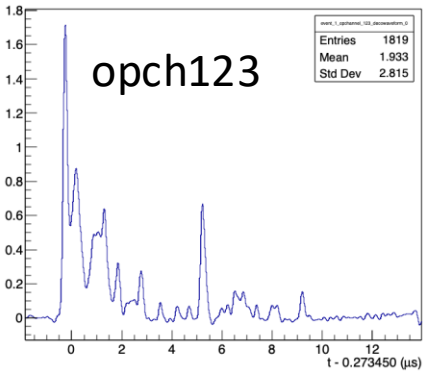
Deconvoluted Wvfs of Event 1:

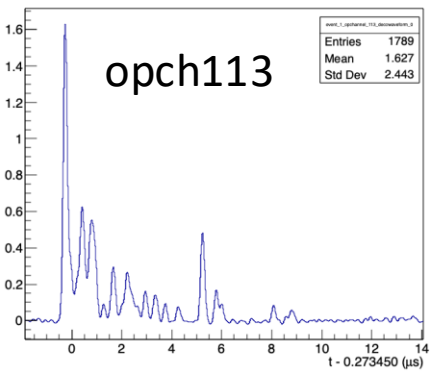


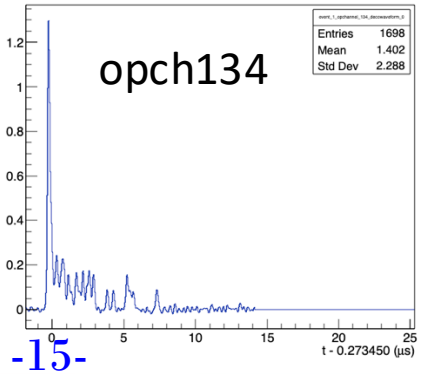


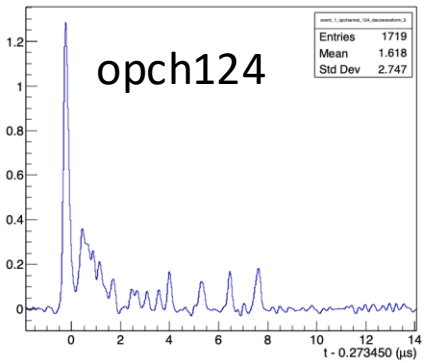


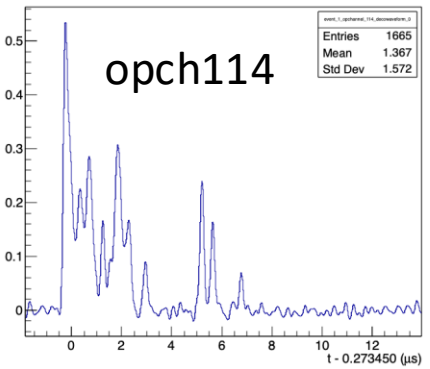






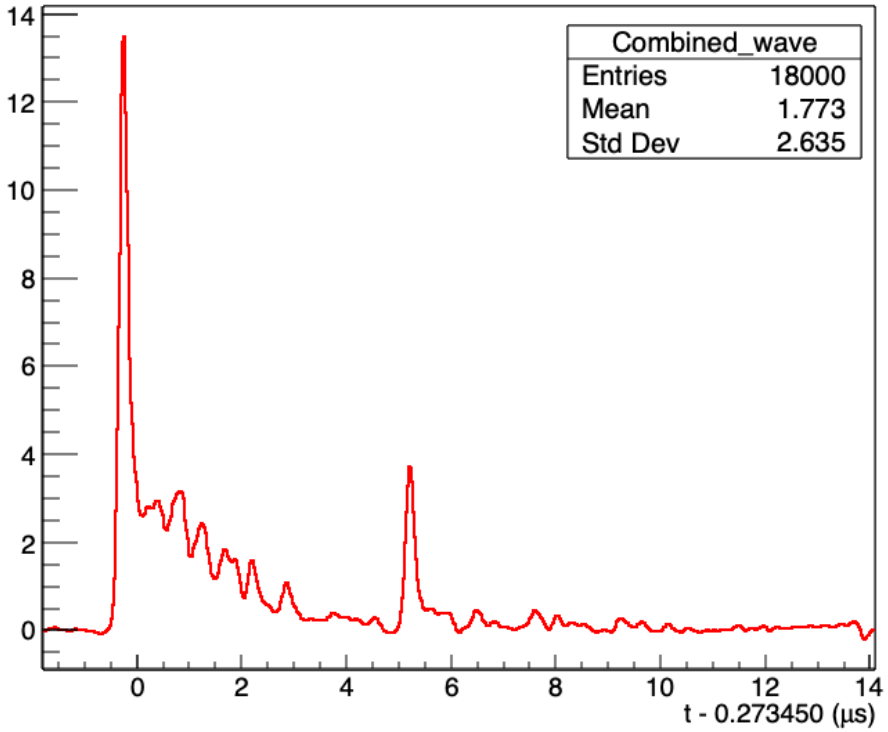






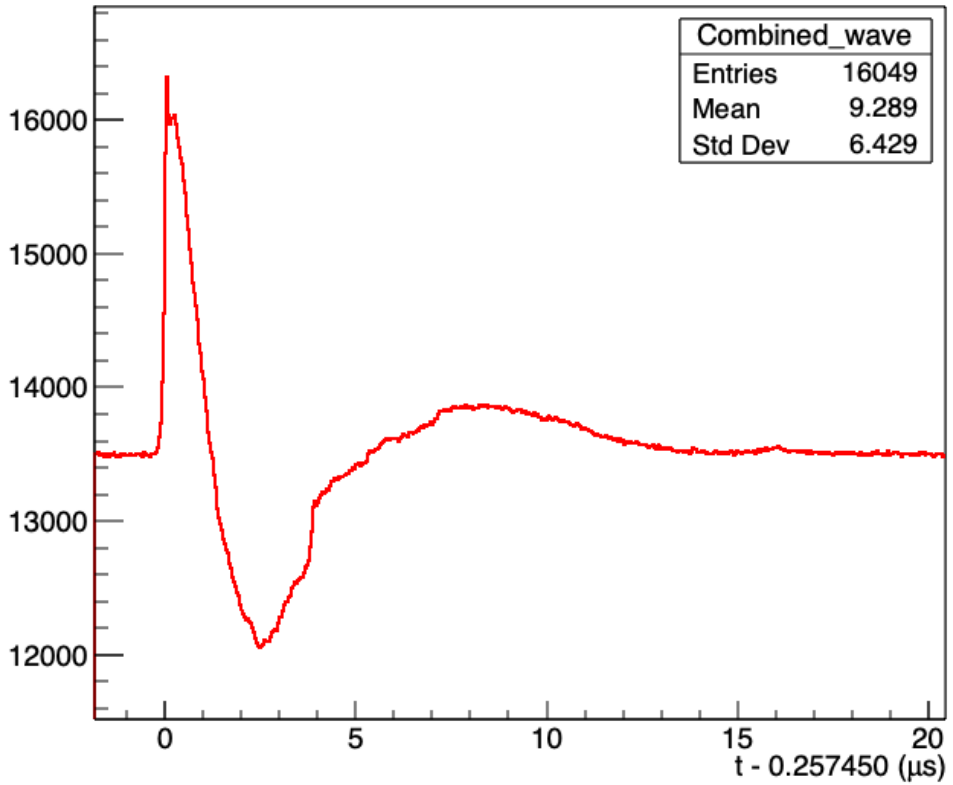
Combine

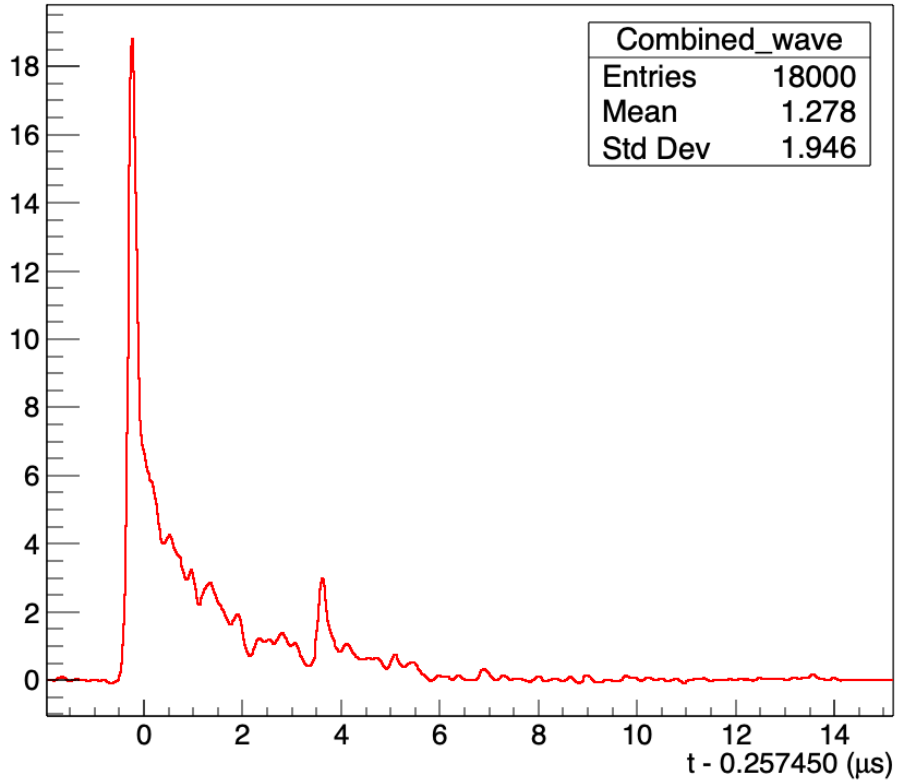
❖ Lifetime of μ^+: $5{,}487.17ns$



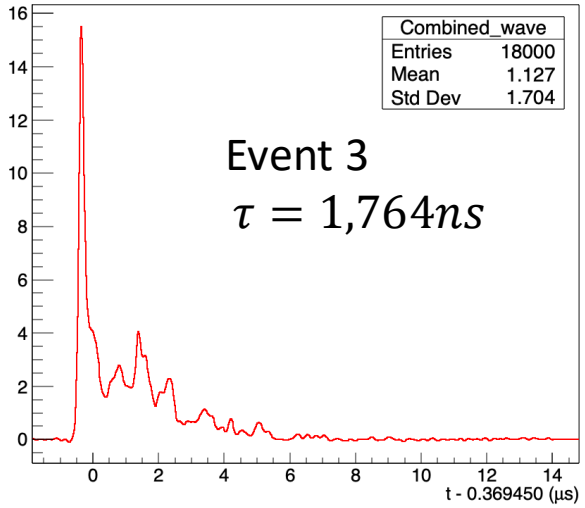
Deconvoluted Wvfs of Event 2:

- Lifetime of μ^+: $3{,}872ns$



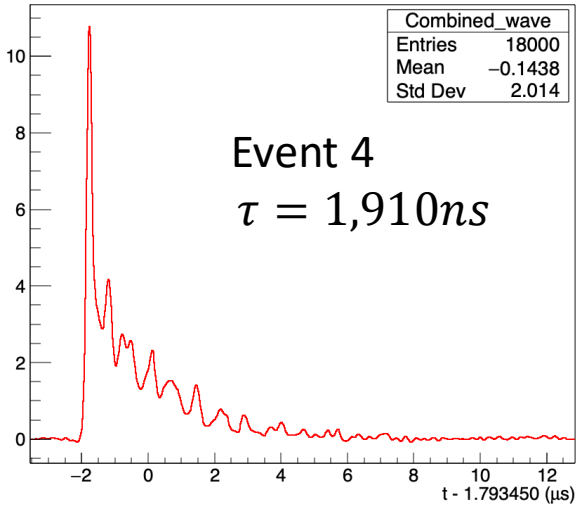


Deconvoluted Waveforms:



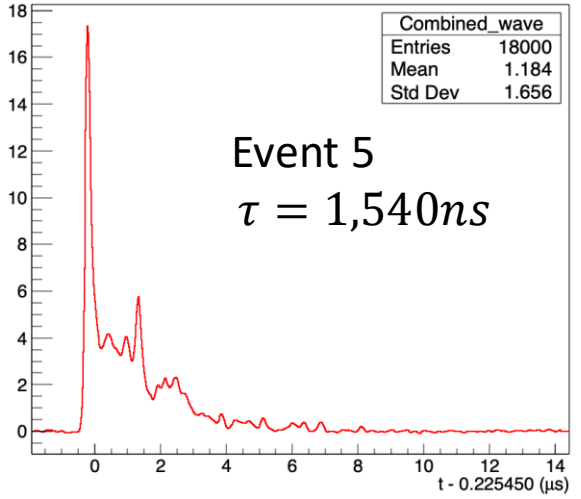
Event 3

$\tau = 1{,}764ns$



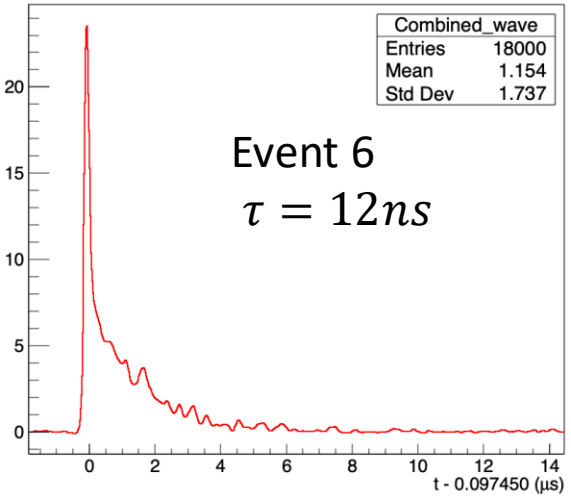
Event 4

$\tau = 1{,}910ns$



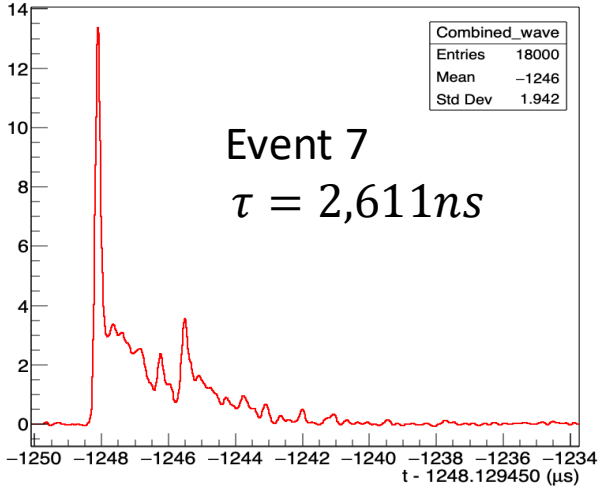
Event 5

$\tau = 1{,}540ns$



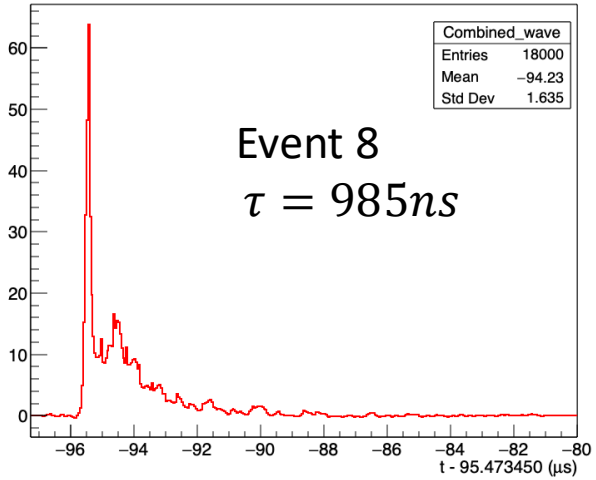
Event 6

$\tau = 12ns$



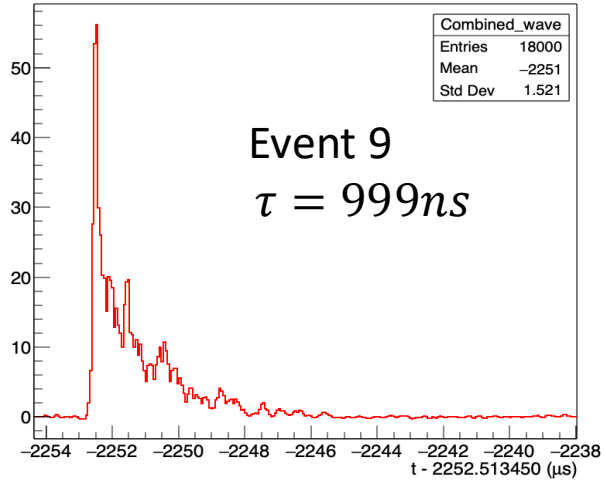
Event 7

$\tau = 2{,}611ns$



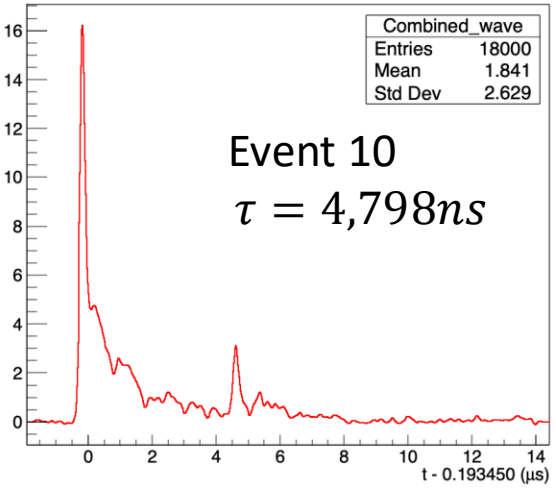
Event 8

$\tau = 985ns$



Event 9

$\tau = 999ns$

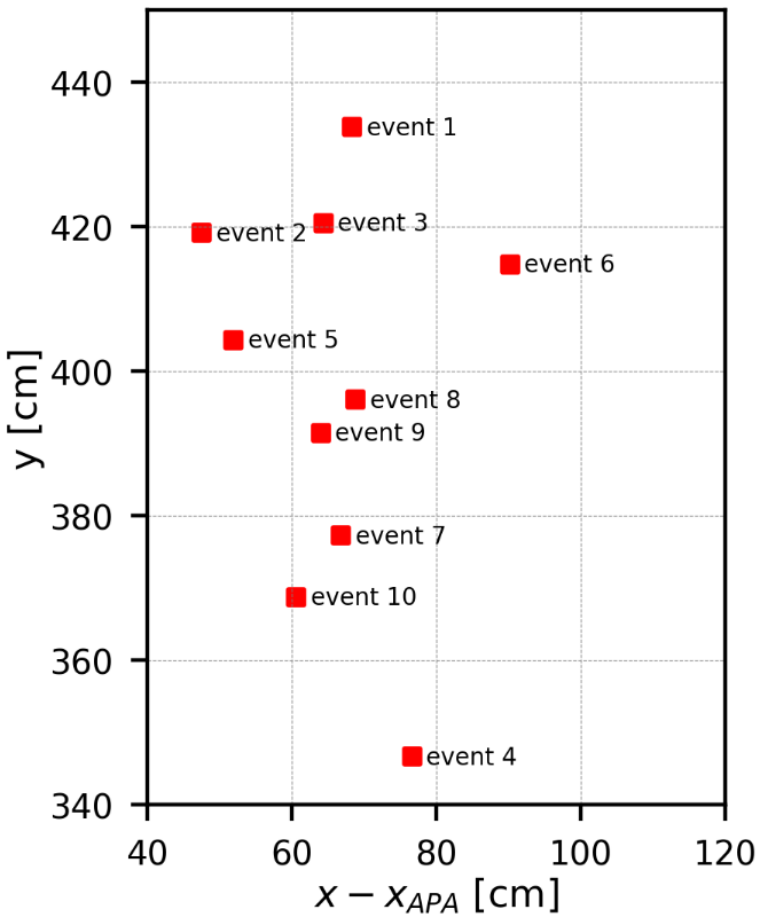


Event 10

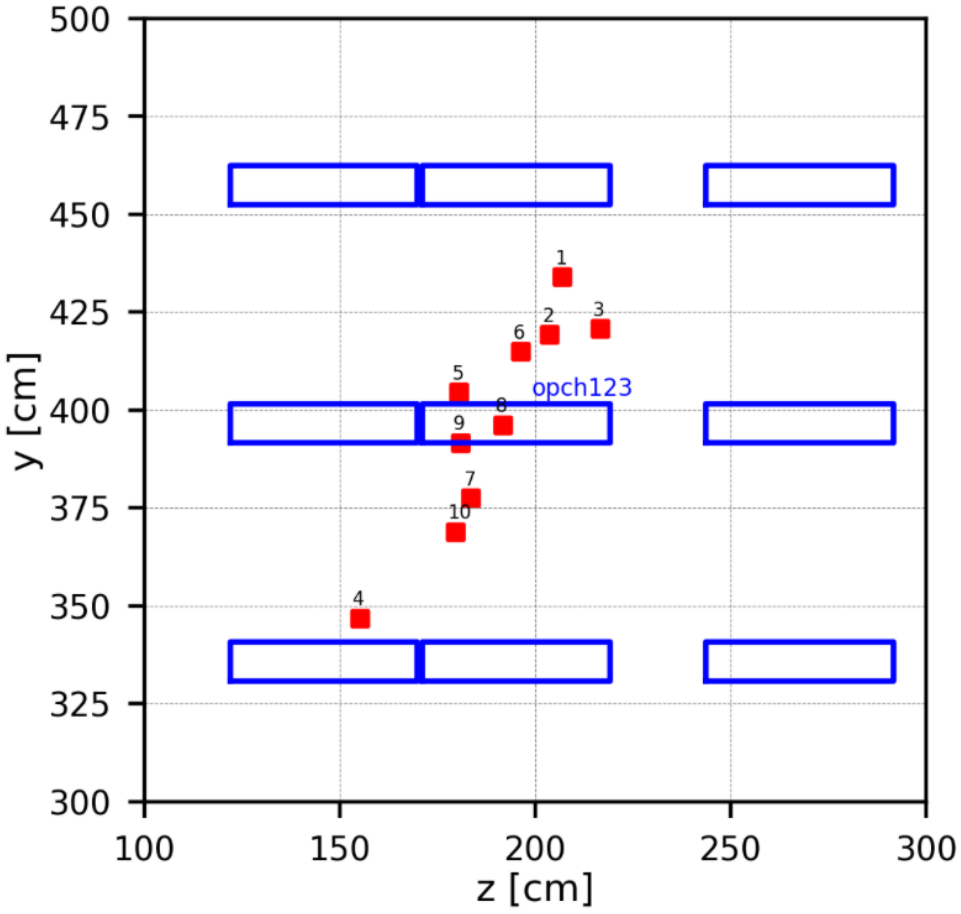
$\tau = 4{,}798ns$

Decay Points of mu^+

Distance to APA plane



Projection to APA plane



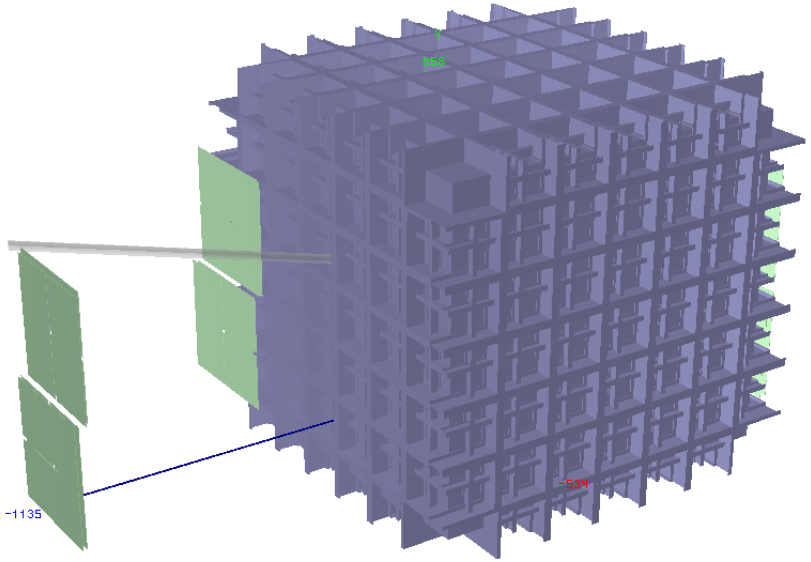
Summary

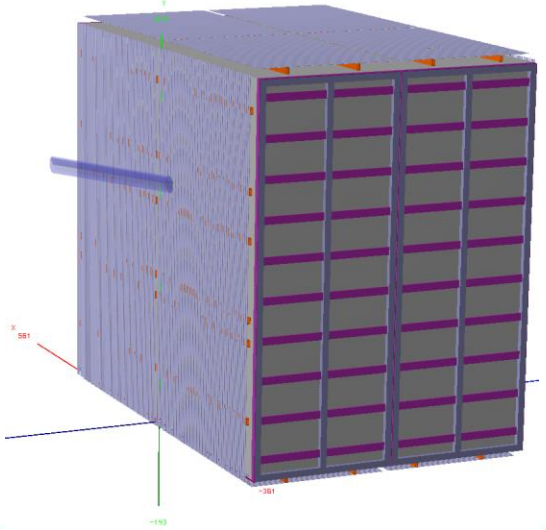
- For energy deposition of Michel e **(<50MeV**), high PE yield expected when distance is short
- For waveform simulation, Michel e signal submersed by undershoot in digitized wvfs when decay time is short
- Michel e signal can be recovered after deconvolution
- Apparent Michel e signal observed against muon bkgs when decay close to X-Arapuca ($\sim 100 cm$)
- Great thanks to Laura (Paulucci), Jose (Soto), Alex (Wilkinson), Maritza, Sergio (Corchado) and Viktor

- Next steps:
  1. muon event with Michel electron selection in pdhd cosmic production
  2. muon selection in pdhd data
  3. PDS and TPC timing matching
  4. Michel electron energy reconstruction with TPC and PDS joint information

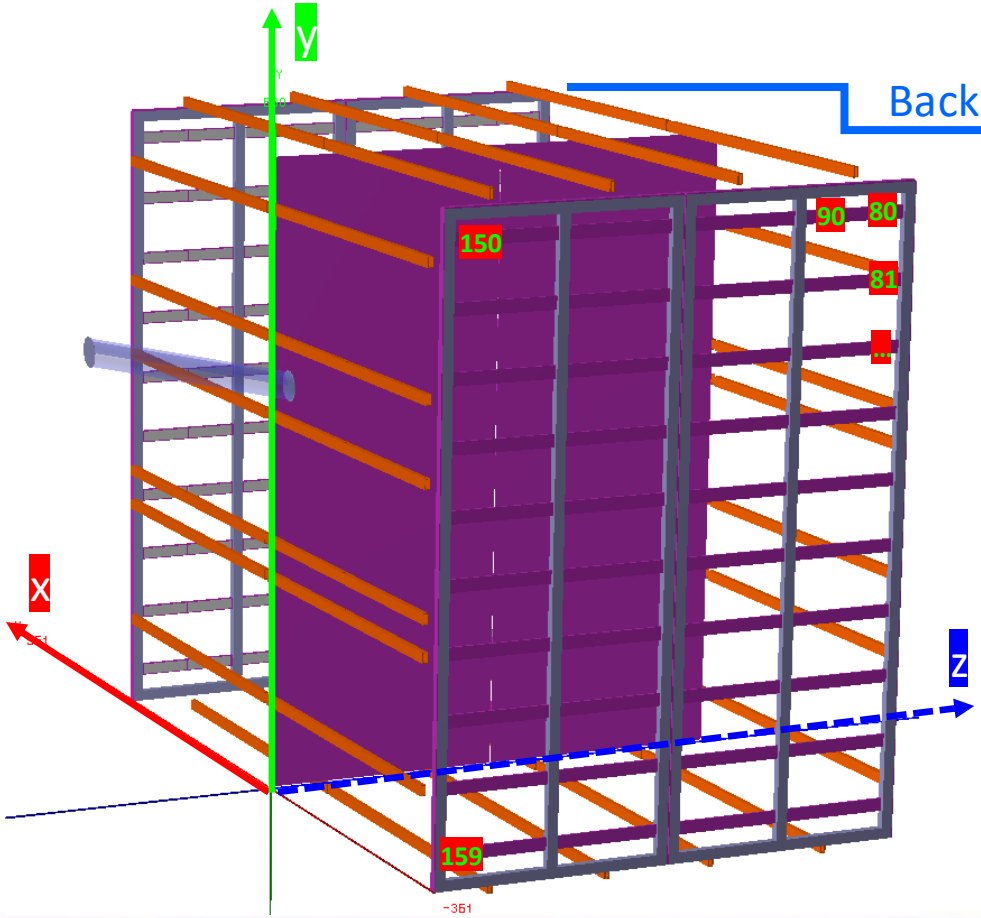
Backups

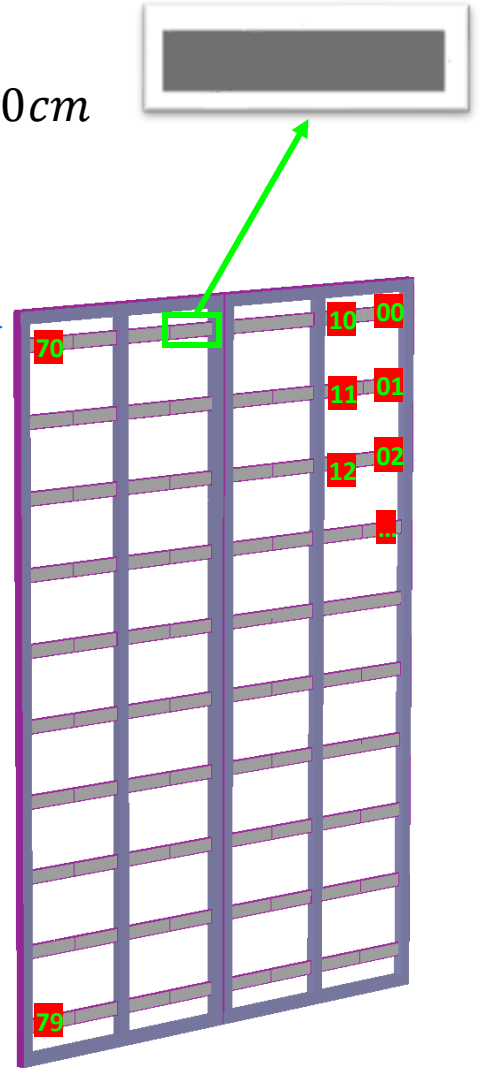
protoDUNE-HD Geometry Review





- protodunehd_v6_refactored_nowires.gdml
- 160 optical channels; All X-Arapuca bars; $48cm \times 10cm$





Optical Channel Labels (I):

- APA and Field cage border: $x \in [-360, 360]cm$, y $\in [-10, 620]cm$, $z \in [-5, 470]cm$

Cryo Boundaries
Xmin: -391.52 Xmax: 463.52 Ymin: -65.1706 Ymax: 725.069 Zmin: -193.854 Zmax: 661.186

Optical Channels positions: 160

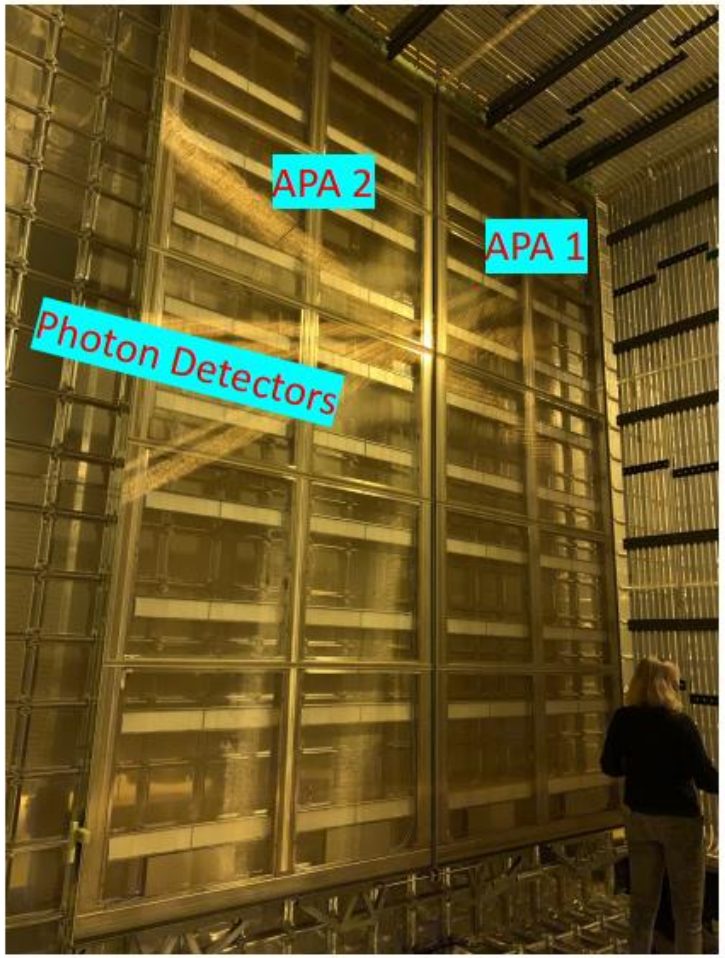
0	356.246	578.909	427.071
1	356.246	518.159	427.071
2	356.246	457.409	427.071
3	356.246	396.659	427.071
4	356.246	335.909	427.071
5	356.246	275.159	427.071
6	356.246	214.41	427.071
7	356.246	153.66	427.071
8	356.246	92.9099	427.071
9	356.246	32.16	427.071
10	356.246	578.909	377.921
11	356.246	518.159	377.921
12	356.246	457.409	377.921
13	356.246	396.659	377.921
14	356.246	335.909	377.921
15	356.246	275.159	377.921
16	356.246	214.41	377.921
17	356.246	153.66	377.921
18	356.246	92.9099	377.921
19	356.246	32.16	377.921
20	356.246	578.909	316.671
21	356.246	518.159	316.671
22	356.246	457.409	316.671
23	356.246	396.659	316.671
24	356.246	335.909	316.671
25	356.246	275.159	316.671
26	356.246	214.41	316.671
27	356.246	153.66	316.671
28	356.246	92.9099	316.671
29	356.246	32.16	316.671
30	356.246	578.909	267.521
31	356.246	518.159	267.521
32	356.246	457.409	267.521
33	356.246	396.659	267.521
34	356.246	335.909	267.521
35	356.246	275.159	267.521
36	356.246	214.41	267.521
37	356.246	153.66	267.521
38	356.246	92.9099	267.521
39	356.246	32.16	267.521
40	356.246	578.909	195.011
41	356.246	518.159	195.011
42	356.246	457.409	195.011
43	356.246	396.659	195.011
44	356.246	335.909	195.011
45	356.246	275.159	195.011
46	356.246	214.41	195.011
47	356.246	153.66	195.011
48	356.246	92.9099	195.011
49	356.246	32.16	195.011
50	356.246	578.909	145.861
51	356.246	518.159	145.861
52	356.246	457.409	145.861
53	356.246	396.659	145.861
54	356.246	335.909	145.861
55	356.246	275.159	145.861
56	356.246	214.41	145.861
57	356.246	153.66	145.861
58	356.246	92.9099	145.861
59	356.246	32.16	145.861
60	356.246	578.909	84.6112
61	356.246	518.159	84.6112
62	356.246	457.409	84.6112
63	356.246	396.659	84.6112
64	356.246	335.909	84.6112
65	356.246	275.159	84.6112
66	356.246	214.41	84.6112
67	356.246	153.66	84.6112
68	356.246	92.9099	84.6112
69	356.246	32.16	84.6112
70	356.246	578.909	35.4612
71	356.246	518.159	35.4612
72	356.246	457.409	35.4612
73	356.246	396.659	35.4612
74	356.246	335.909	35.4612
75	356.246	275.159	35.4612
76	356.246	214.41	35.4612
77	356.246	153.66	35.4612
78	356.246	92.9099	35.4612
79	356.246	32.16	35.4612

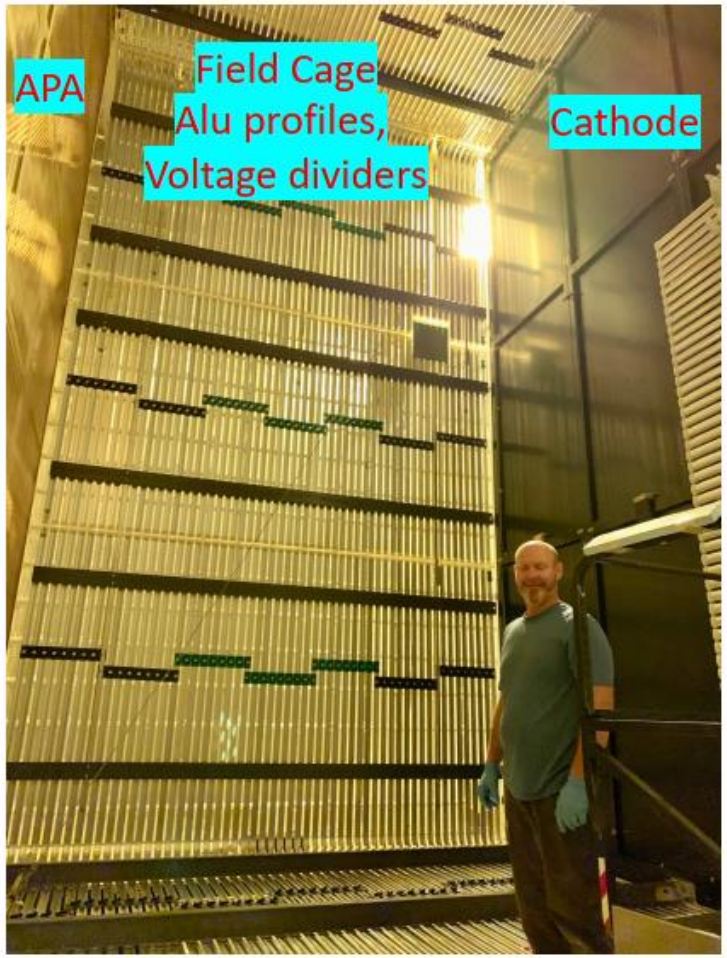
Optical Channel Labels (II):

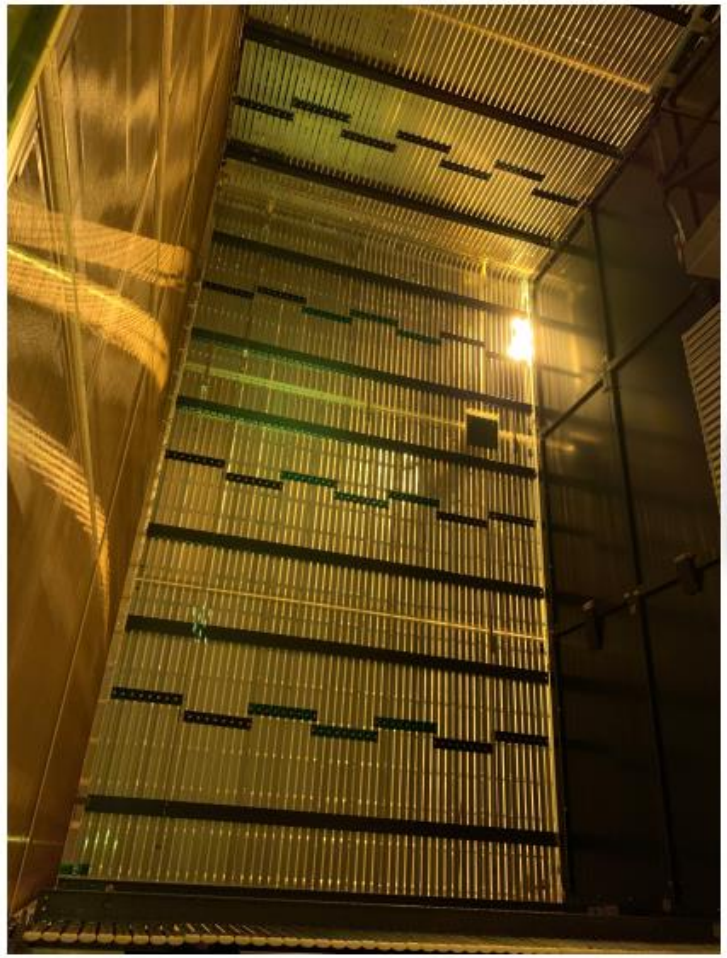
80 -356.446 578.909 427.071	90 -356.446 578.909 377.921	100 -356.446 578.909 316.671	110 -356.446 578.909 267.521
81 -356.446 518.159 427.071	91 -356.446 518.159 377.921	101 -356.446 518.159 316.671	111 -356.446 518.159 267.521
82 -356.446 457.409 427.071	92 -356.446 457.409 377.921	102 -356.446 457.409 316.671	112 -356.446 457.409 267.521
83 -356.446 396.659 427.071	93 -356.446 396.659 377.921	103 -356.446 396.659 316.671	113 -356.446 396.659 267.521
84 -356.446 335.909 427.071	94 -356.446 335.909 377.921	104 -356.446 335.909 316.671	114 -356.446 335.909 267.521
85 -356.446 275.159 427.071	95 -356.446 275.159 377.921	105 -356.446 275.159 316.671	115 -356.446 275.159 267.521
86 -356.446 214.41 427.071	96 -356.446 214.41 377.921	106 -356.446 214.41 316.671	116 -356.446 214.41 267.521
87 -356.446 153.66 427.071	97 -356.446 153.66 377.921	107 -356.446 153.66 316.671	117 -356.446 153.66 267.521
88 -356.446 92.9099 427.071	98 -356.446 92.9099 377.921	108 -356.446 92.9099 316.671	118 -356.446 92.9099 267.521
89 -356.446 32.16 427.071	99 -356.446 32.16 377.921	109 -356.446 32.16 316.671	119 -356.446 32.16 267.521

120 -356.446 578.909 195.011	130 -356.446 578.909 145.861	140 -356.446 578.909 84.6112	150 -356.446 578.909 35.4612
121 -356.446 518.159 195.011	131 -356.446 518.159 145.861	141 -356.446 518.159 84.6112	151 -356.446 518.159 35.4612
122 -356.446 457.409 195.011	132 -356.446 457.409 145.861	142 -356.446 457.409 84.6112	152 -356.446 457.409 35.4612
123 -356.446 396.659 195.011	133 -356.446 396.659 145.861	143 -356.446 396.659 84.6112	153 -356.446 396.659 35.4612
124 -356.446 335.909 195.011	134 -356.446 335.909 145.861	144 -356.446 335.909 84.6112	154 -356.446 335.909 35.4612
125 -356.446 275.159 195.011	135 -356.446 275.159 145.861	145 -356.446 275.159 84.6112	155 -356.446 275.159 35.4612
126 -356.446 214.41 195.011	136 -356.446 214.41 145.861	146 -356.446 214.41 84.6112	156 -356.446 214.41 35.4612
127 -356.446 153.66 195.011	137 -356.446 153.66 145.861	147 -356.446 153.66 84.6112	157 -356.446 153.66 35.4612
128 -356.446 92.9099 195.011	138 -356.446 92.9099 145.861	148 -356.446 92.9099 84.6112	158 -356.446 92.9099 35.4612
129 -356.446 32.16 195.011	139 -356.446 32.16 145.861	149 -356.446 32.16 84.6112	159 -356.446 32.16 35.4612

X-Arapucas in APA:







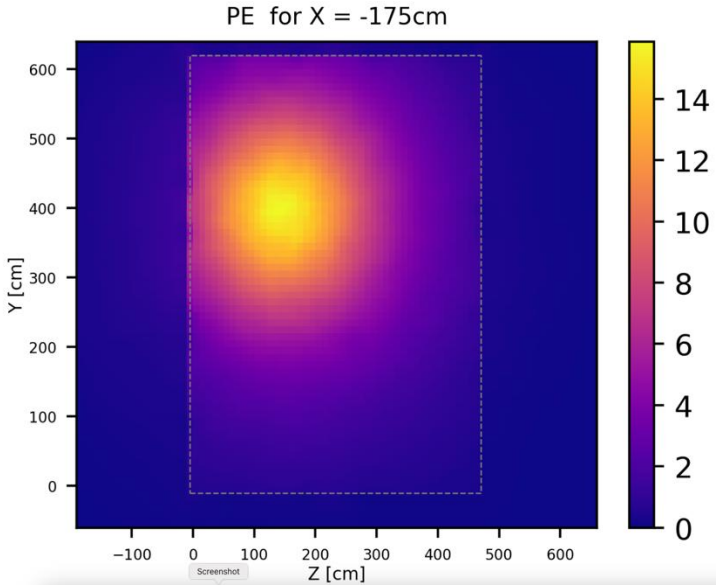
Comparison With Tingjun's Estimation

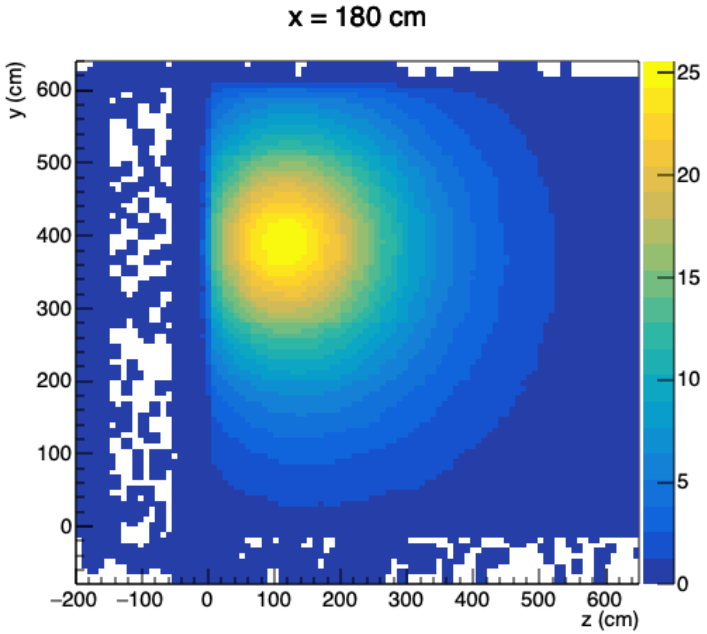
- My results: protoDUNE-HD, comp graph module
- One single X-Arapuca bar; opch133
- Size of opch133: $48cm * 10cm$
- Set PDE as 2%
- Area*PDE [cm^2]: **9.6**

- Tingjun's results: protoDUNE-SP, photon library
- Position: APA3, No.4 bar (Top to bottom)
- 16 Arapuca **cell**s combined; single cell size:

- Area*PDE [cm^2]: **18.6**

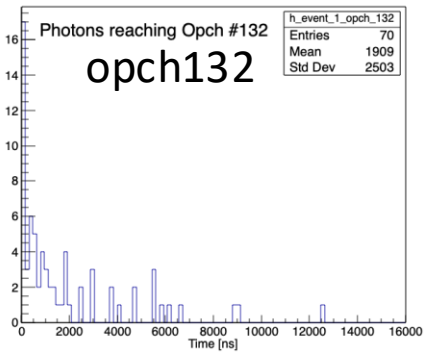
own readout. The first eight cells each have an optical area of 9.8×7.9 cm^2 and the remaining four cells are double-area cells, each with an optical area of 19.6×7.9 cm^2. One ARAPUCA module

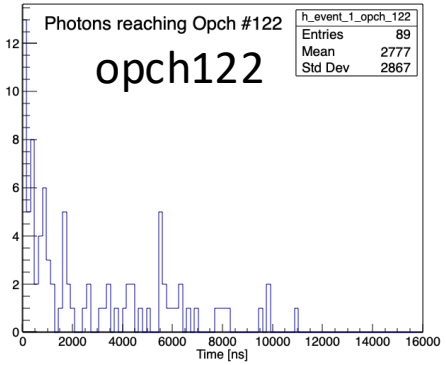


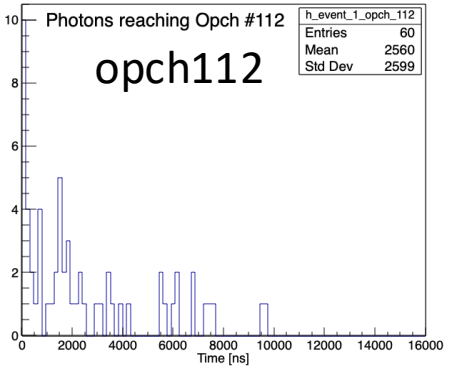


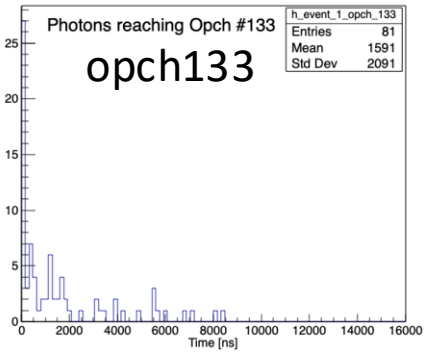
- Not simple double: for SP case, to get max PE, vertex must be at the "middle" of 16 cells

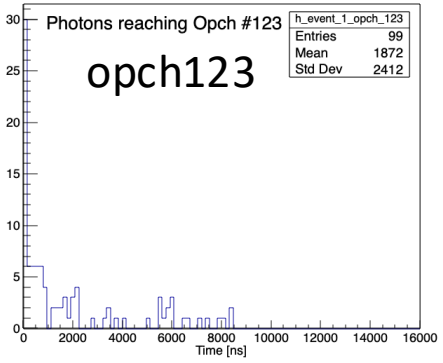
Real Wvfs of Event 1:

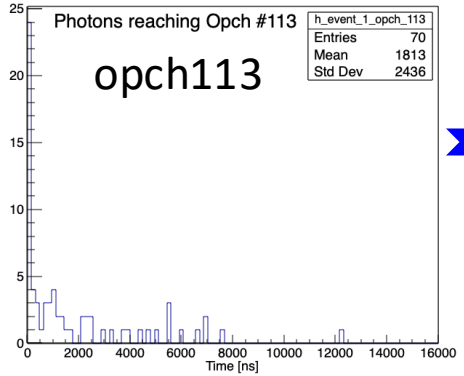


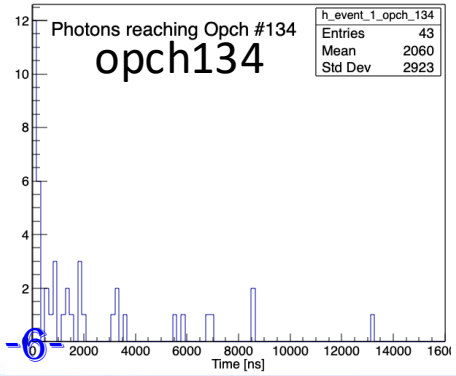


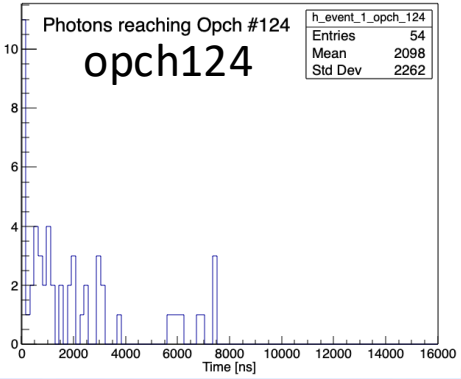


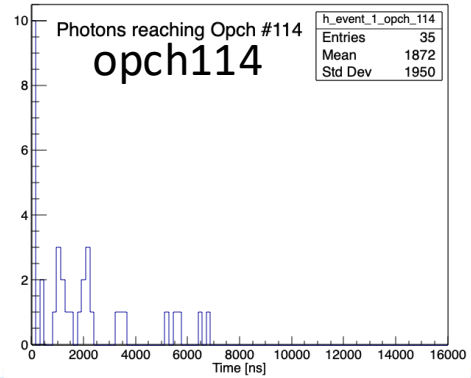






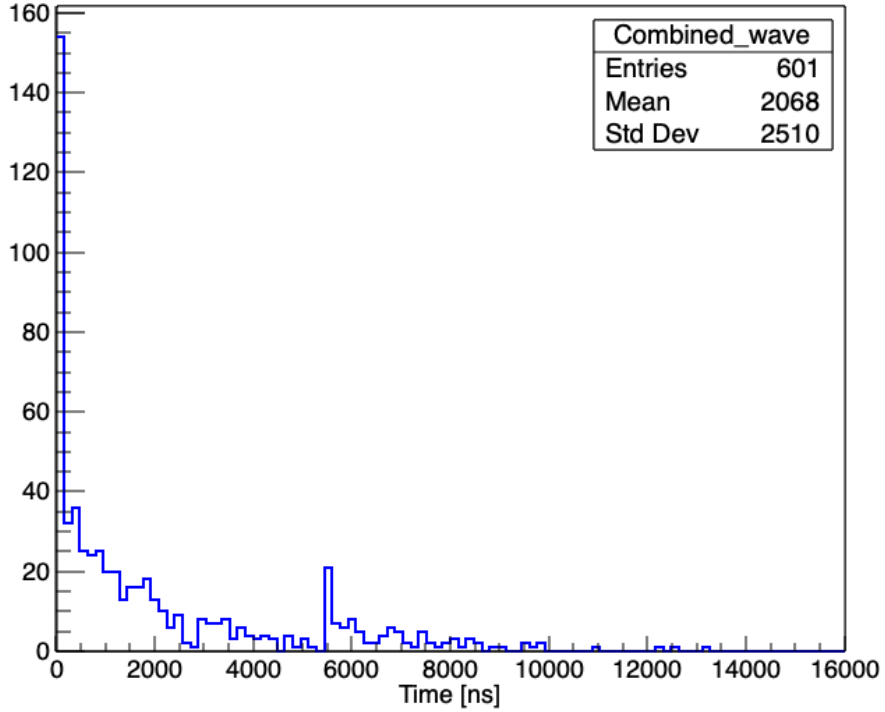






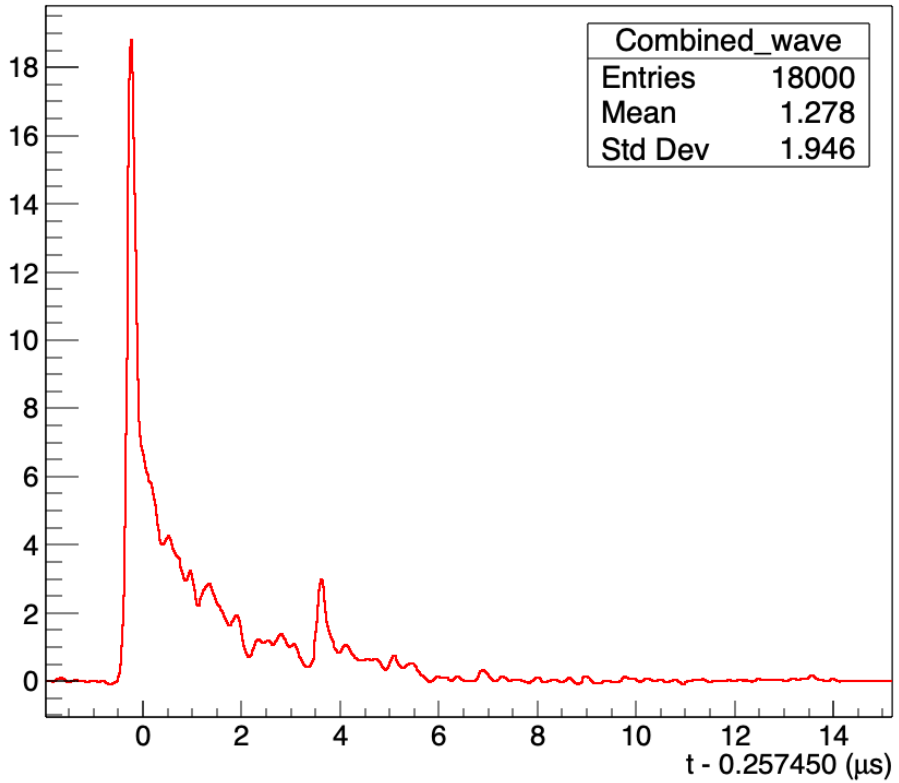
Combine

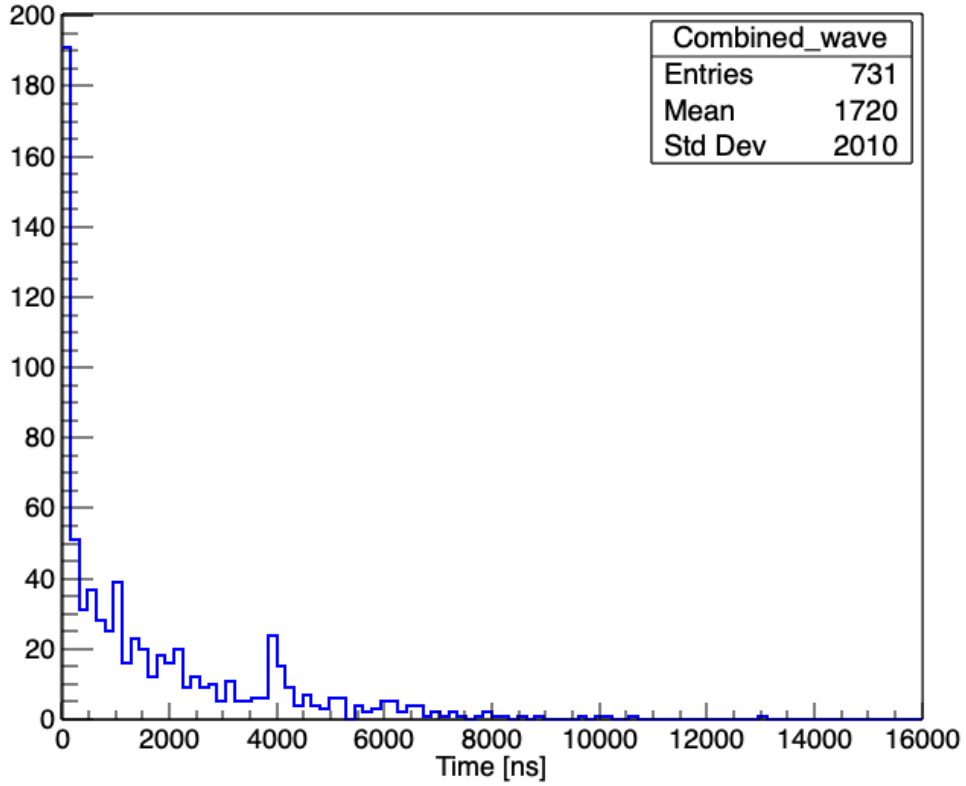
- Lifetime of μ^+: $5{,}487.17ns$



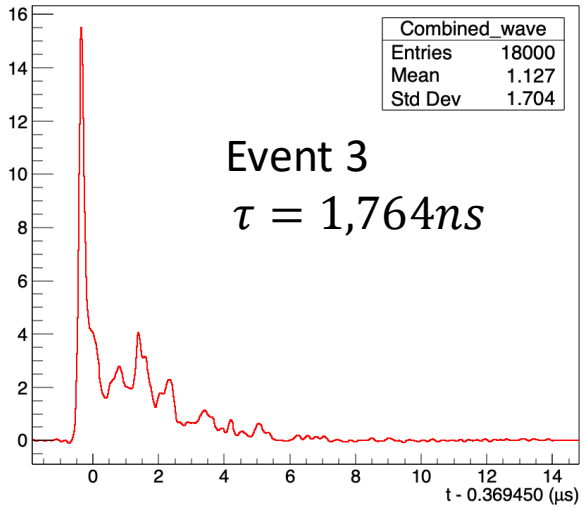
Real Wvfs of Event 2:

- Lifetime of μ^+: $3{,}872ns$



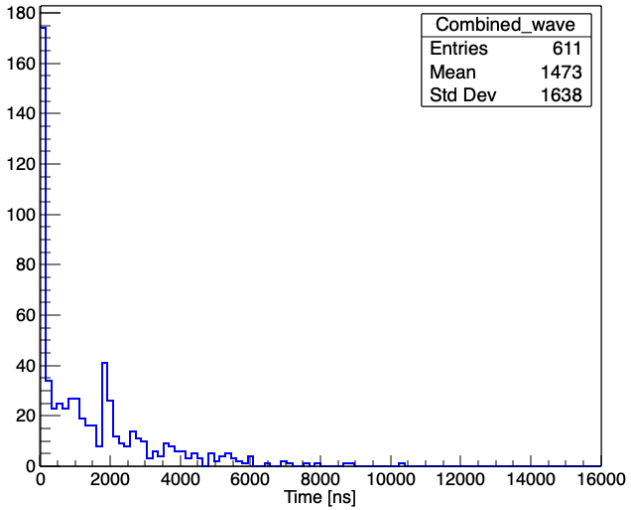


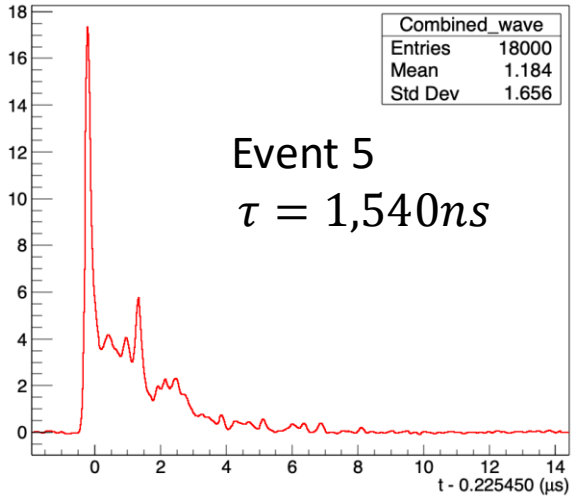
Deconvoluted Wvfs VS Real Wvfs:



Event 3

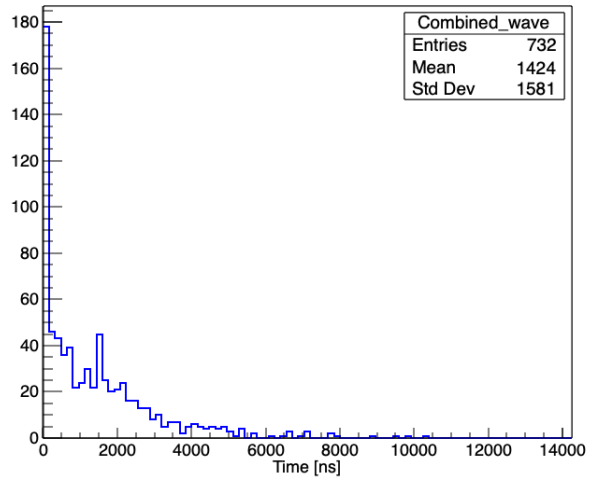
$\tau = 1{,}764ns$

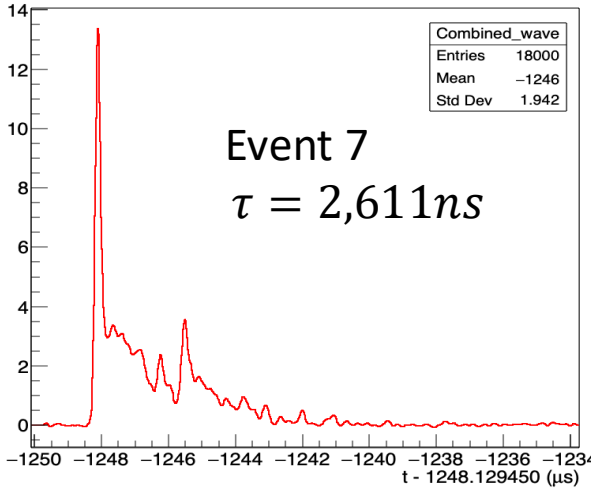




Event 5

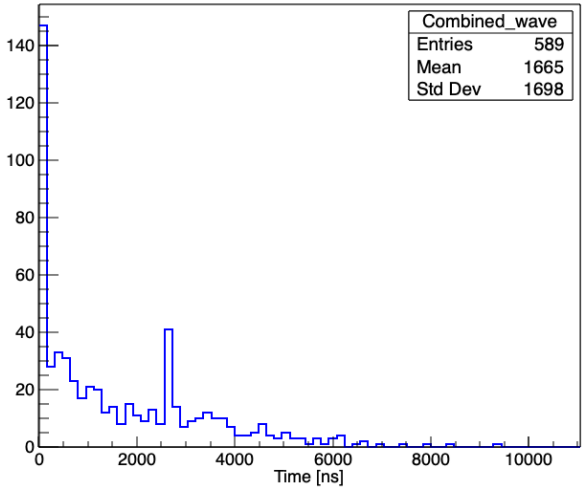
$\tau = 1{,}540ns$

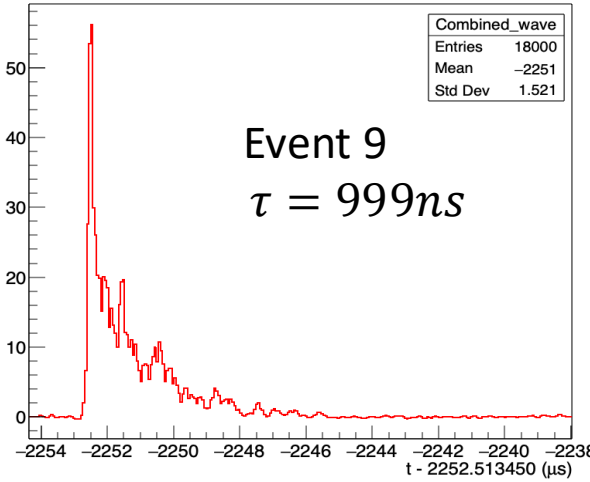




Event 7

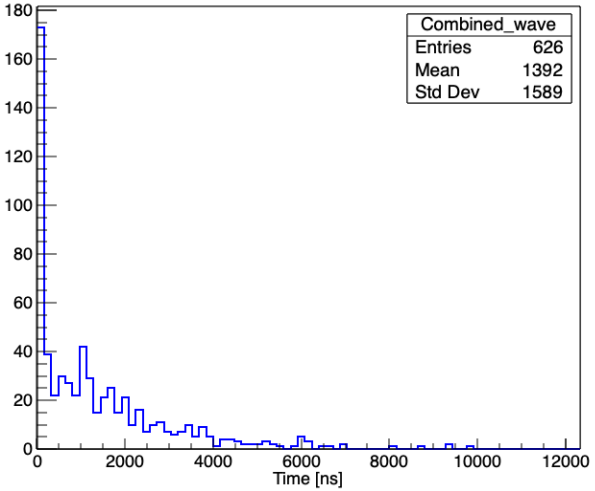
$\tau = 2{,}611ns$



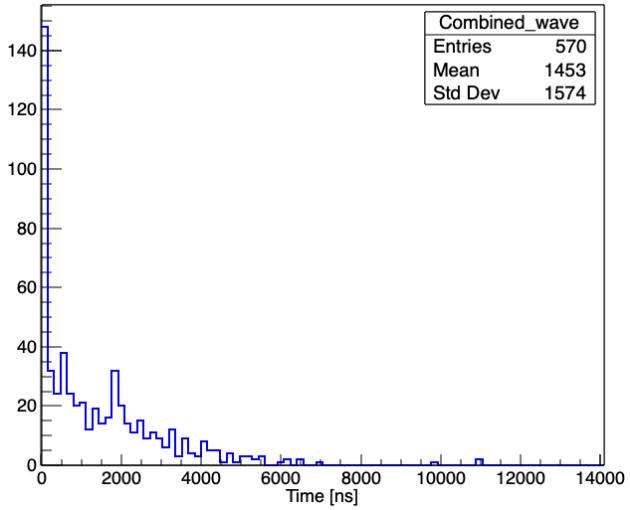


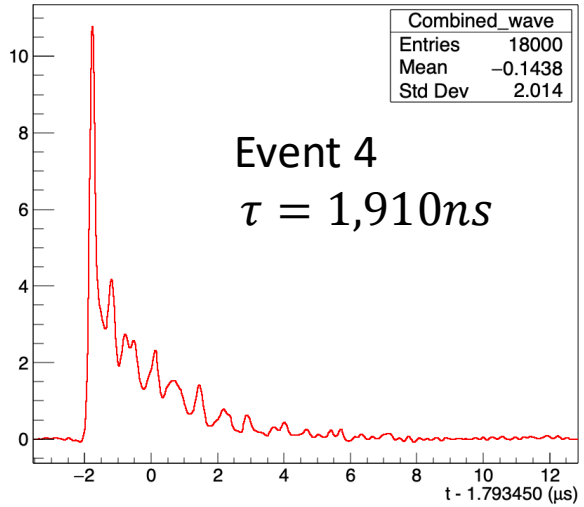
Event 9

$\tau = 999ns$



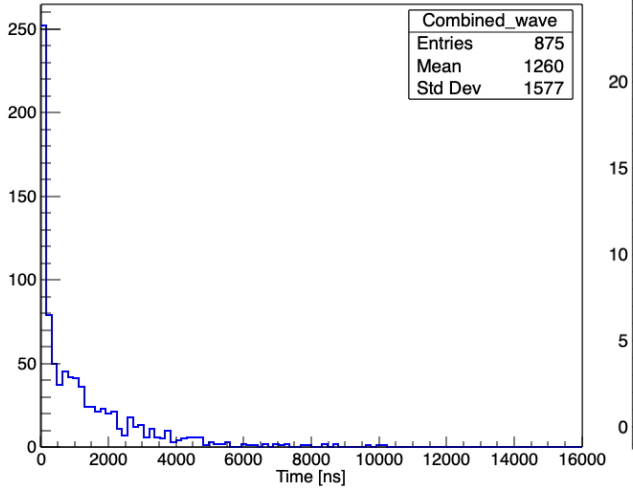
Real Wvfs VS Deconvoluted Wvfs:

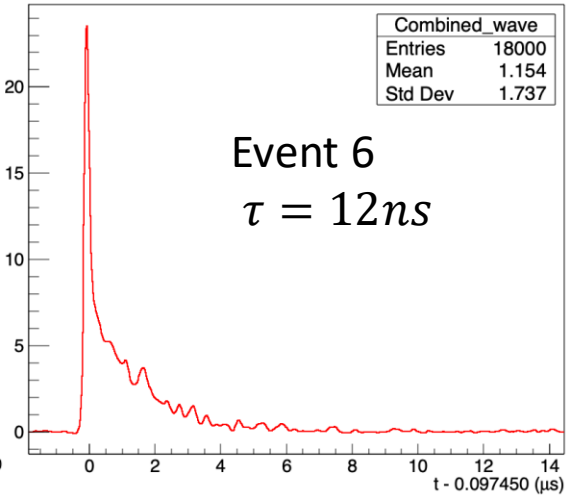




Event 4

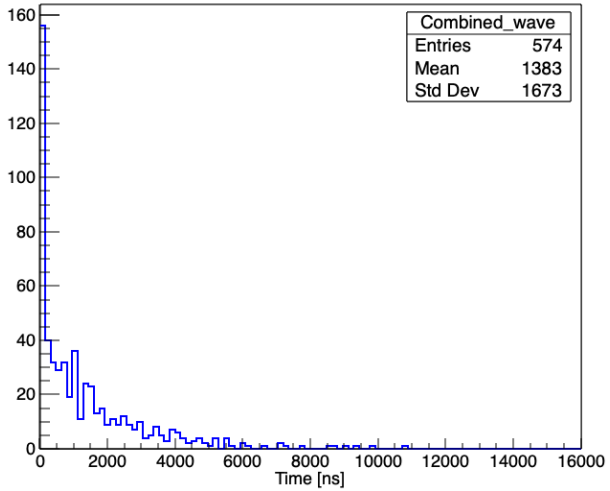
$\tau = 1{,}910ns$

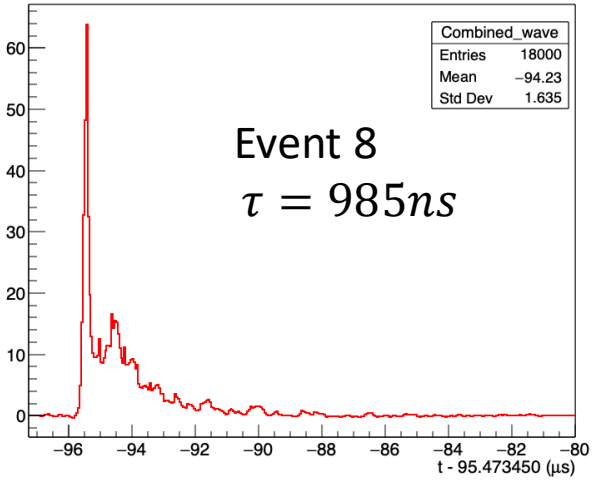




Event 6

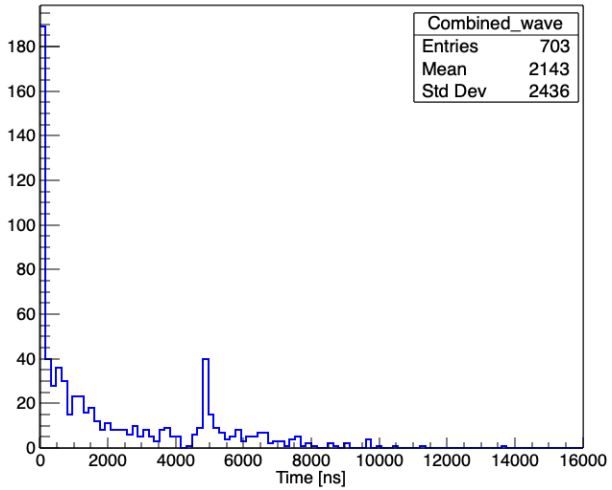
$\tau = 12ns$

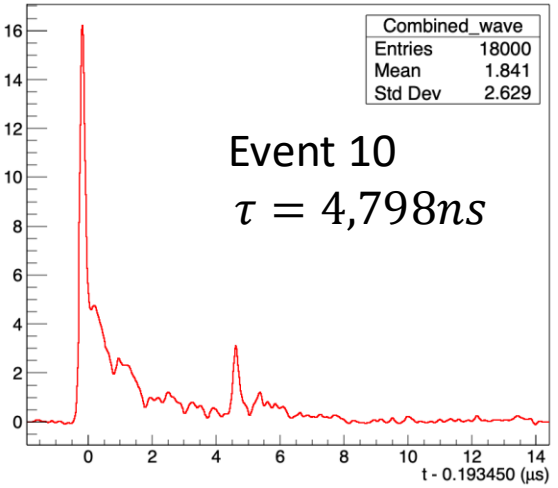




Event 8

$\tau = 985ns$





Event 10

$\tau = 4{,}798ns$

X