# Particle ID with pulse shape discrimination in protoDUNE

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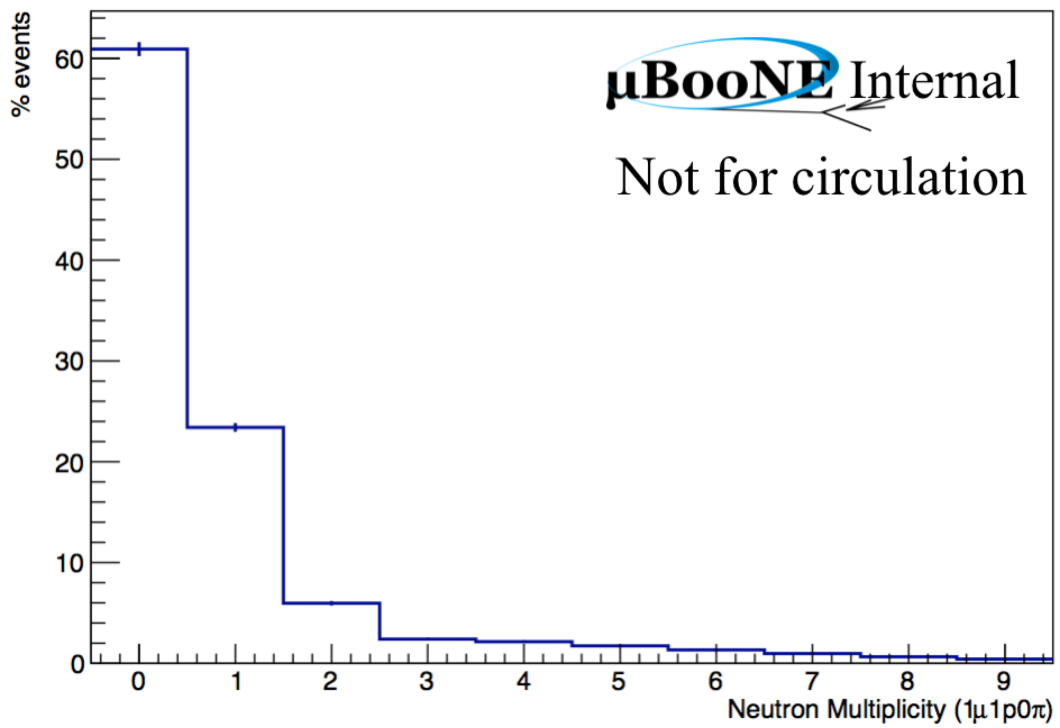
07.06.2023

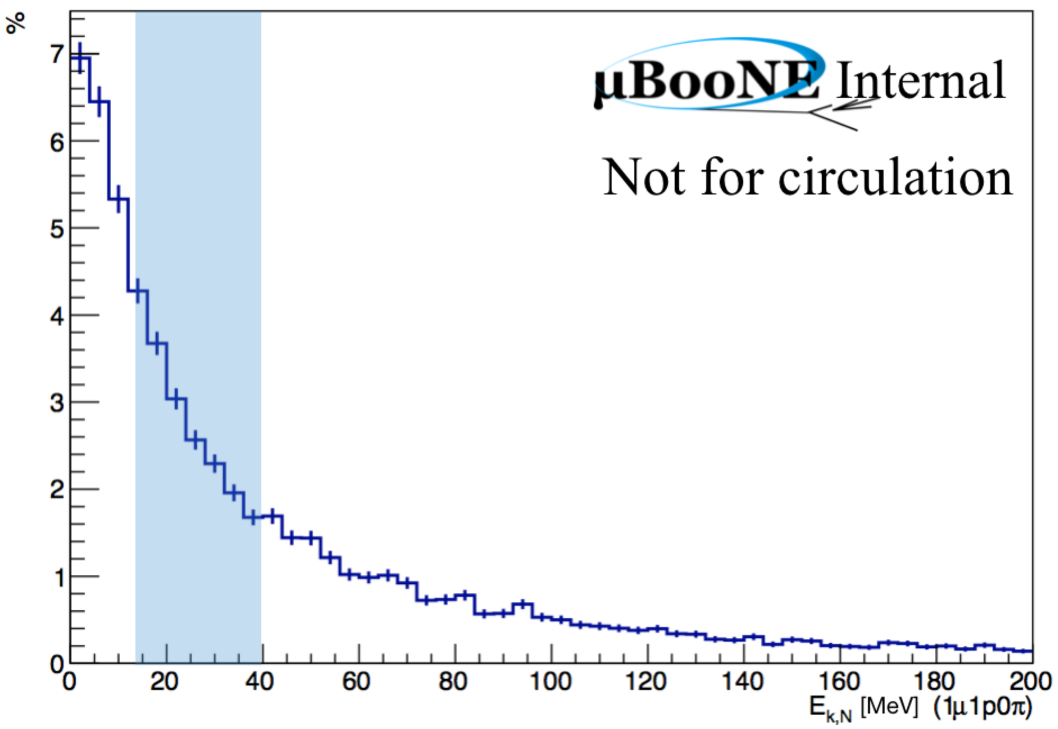
# Motivation

Insufficient knowledge of the energy carried by <u>undetected particles</u> emerging from these interactions, such as neutrons, can skew the reconstructed neutrino energy spectrum and bias the extraction of oscillation parameters, and searches for new physics.

Neutron multiplicity




Neutron kinetic energy

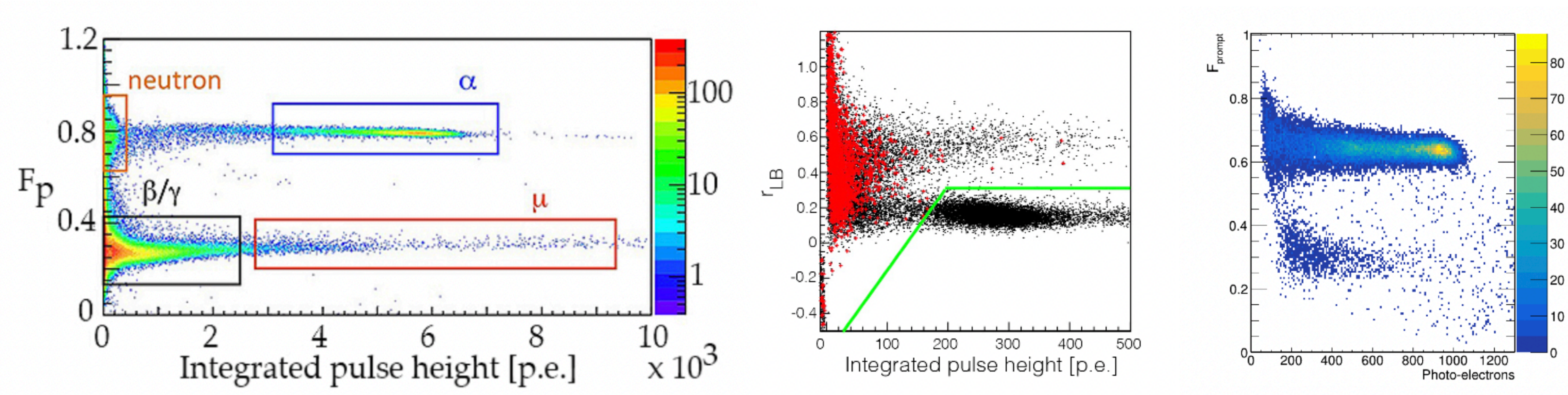



Studies show that ~40% of QE events have at least one neutron.

# Goals

**Main goal:** Neutrons identification in DUNE with light Pulse Shape Discrimination (PSD) technique.

[*JINST 10 (2015) 08, P08002*]
[Phys. Rev. B **27**, 5279]
[*JINST* 16 (2021) 09, P09027]

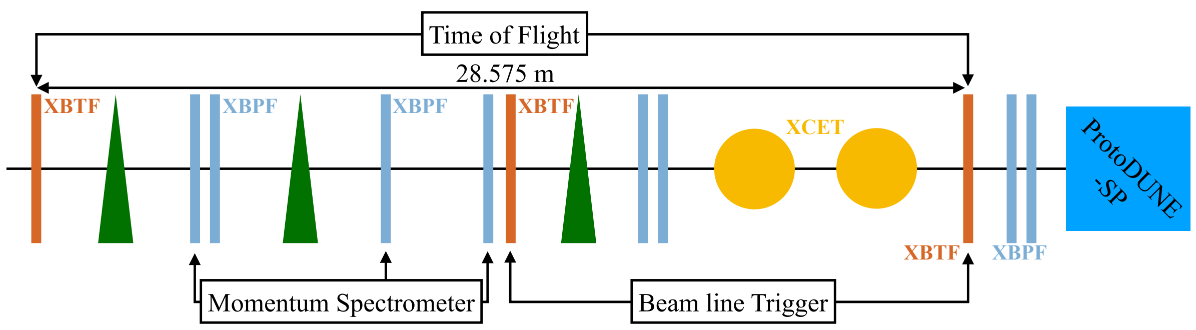



We are currently working on GEANT simulation of neutron interaction in LAr and studying the light yield.

While neutrons are our main goal we are interested in studying PDS response to various particles in protoDUNE environment.

# Beam data

Beamline along with instrumentation provides good conditions for the study PDS signals induced by electrons/muons/pions/protons.

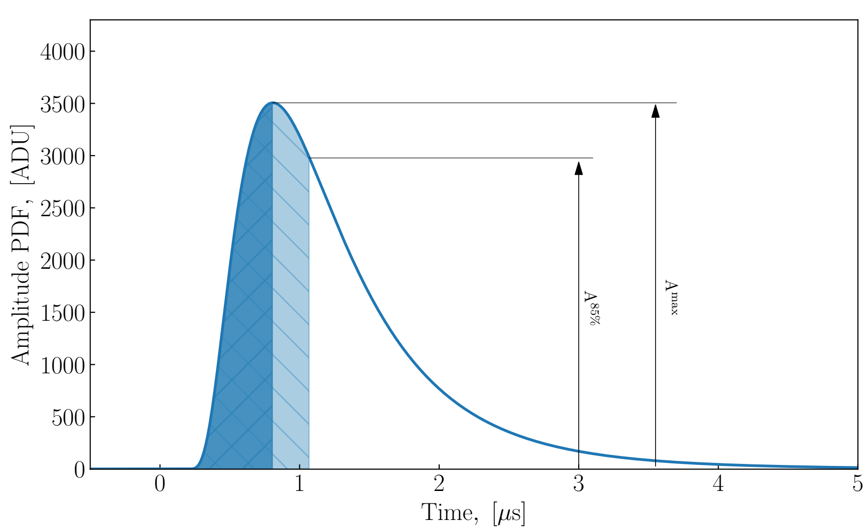


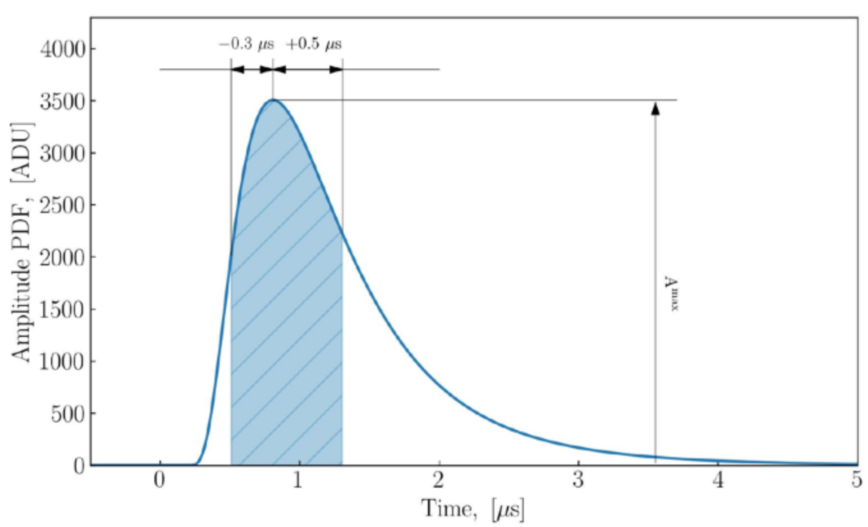

PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 111001 (2017)

TABLE III. Trigger rate at the NP-02 experiment for a W (0.4–3 GeV/$c$) target and a Cu(4–12 GeV/$c$) target for the case of H2-VLE. The rates correspond to $10^6$, 80 GeV/$c$ secondary particles generated at the T2 target.

| Momentum [GeV/$c$] | Electrons | Kaons | Muons | Protons | Pions | Trigger rate [Hz] |
|---|---|---|---|---|---|---|
| 0.4 | 7 | 0 | 0 | 0 | 0 | 7 |
| 1 | 21 | 0 | 0 | 4 | 3 | 28 |
| 2 | 17 | 0 | 0 | 7 | 12 | 36 |
| 3 | 14 | 1 | 1 | 10 | 30 | 56 |
| 3 | 145 | 1 | 1 | 16 | 49 | 213 |
| 4 | 117 | 3 | 1 | 16 | 80 | 218 |
| 5 | 94 | 5 | 2 | 20 | 100 | 222 |
| 6 | 77 | 9 | 2 | 25 | 133 | 247 |
| 7 | 69 | 11 | 2 | 28 | 169 | 279 |
| 8 | 59 | 16 | 3 | 35 | 193 | 305 |
| 9 | 51 | 19 | 3 | 37 | 227 | 337 |
| 10 | 46 | 22 | 3 | 45 | 254 | 370 |
| 11 | 41 | 27 | 3 | 53 | 268 | 393 |
| 12 | 38 | 29 | 3 | 60 | 292 | 422 |

A couple of definitions for the light prompt fraction are used:



# Beam data: 7 GeV runs

Analyzed events have to pass the following selection criteria:

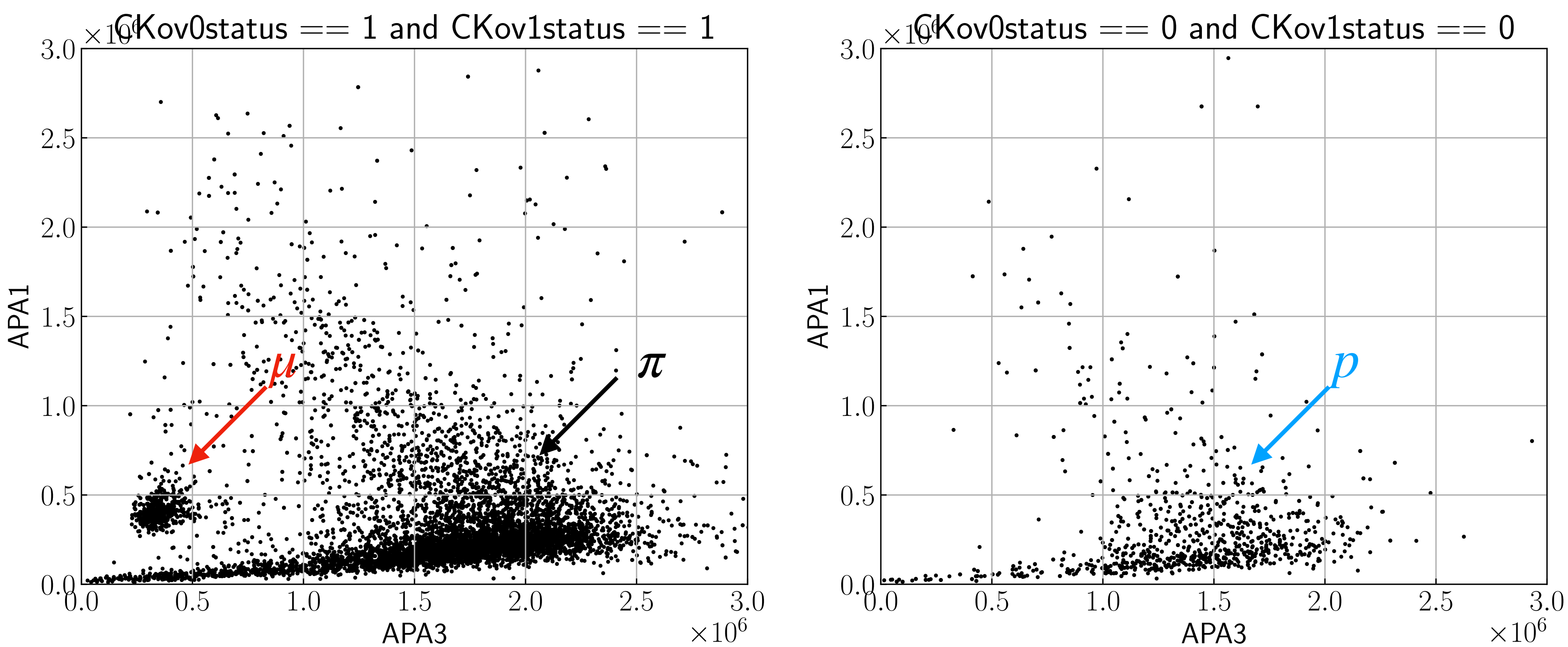
nTracks == 1;

Track_index == 1;

Cherenkov 1 & 2 == 1 (for muons and pions);

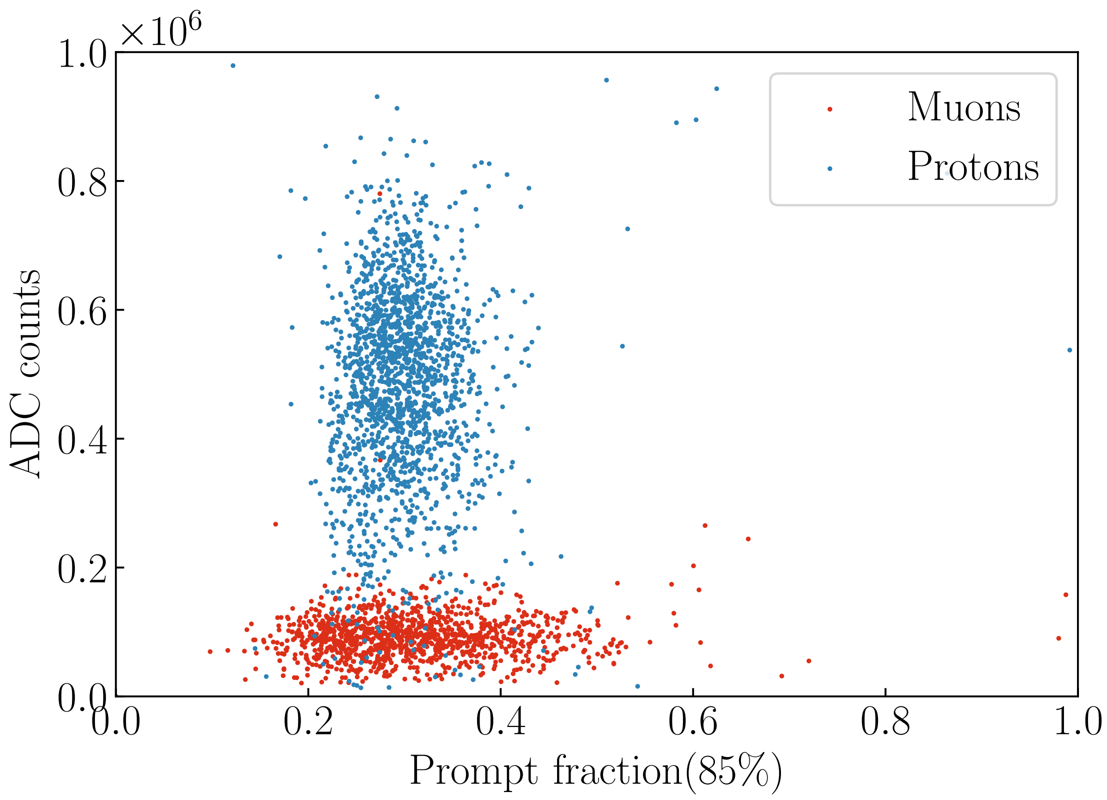
150<TOF<160;

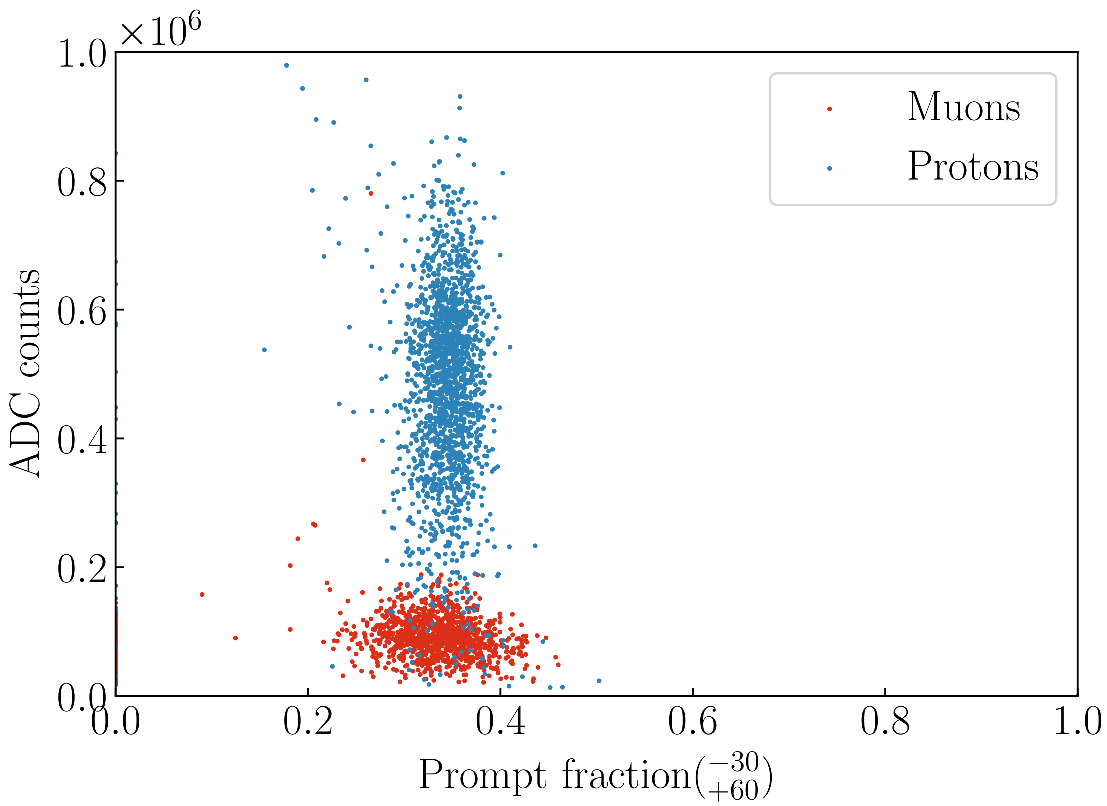
*Technique presented by <u>Dante Totani</u>*



# 7 GeV runs

While muons and protons could be easily distinguished by the amount of light deposited in the detector, prompt fractions for both kinds of waveforms are very similar.



# Neutron source runs

Runs 2020:

- DD generator provides [2, 3] MeV neutrons with intensity peak at 2.5 MeV;

  (Taking into account performance of protoDUNE PDS ~1.6 photons/MeV for $e$ at 3.3 meters )

- Two mode of running: continuous and pulsed; Pulses width was set up to 175 $\mu s$;

  (Much larger than PDS readout window — 13$\mu s$)

Runs 2023:

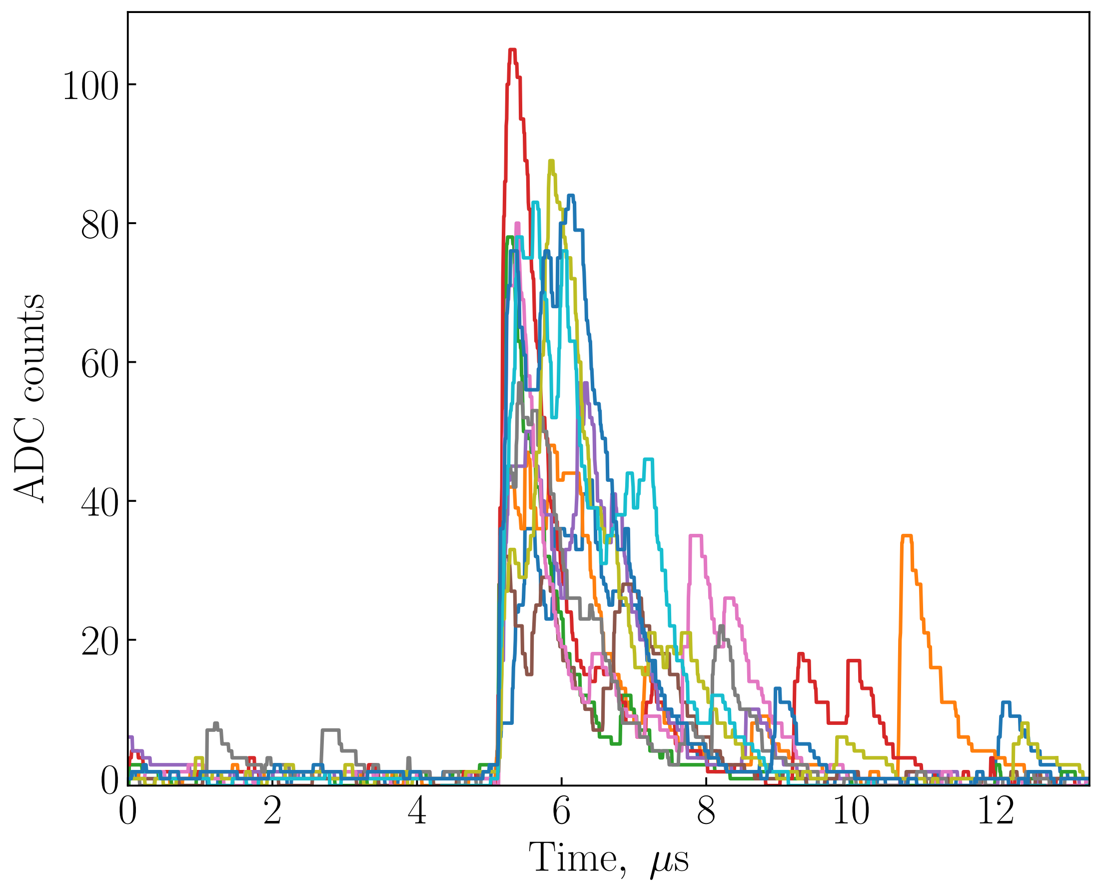
- What will be the configuration: neutron energy, pulse width, intensity?
- Where DD/DT generator will be installed? (My personal concern how far from closest PDS)
- Trigger operation?
- Is there a possibility for muon veto? (Assuming short pulse);
- Is there centrally produced MC simulation for planned runs?

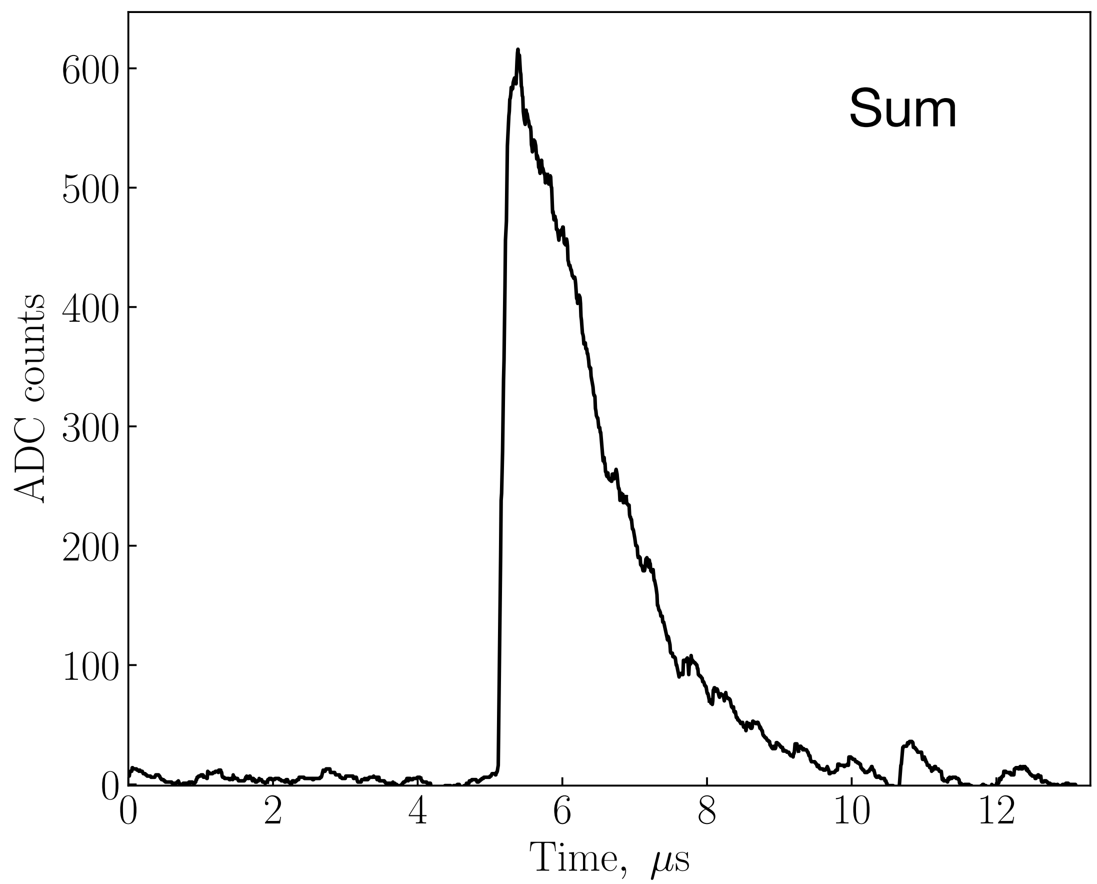
# BACKUP SLIDES

# 7 GeV runs

Moving from analysis of each channel to the sum of all-one-type channel in event. Waveforms from various readout channels shown on the left, sum of all waveforms on the right.

Only one type of sensor is shown on the plots.

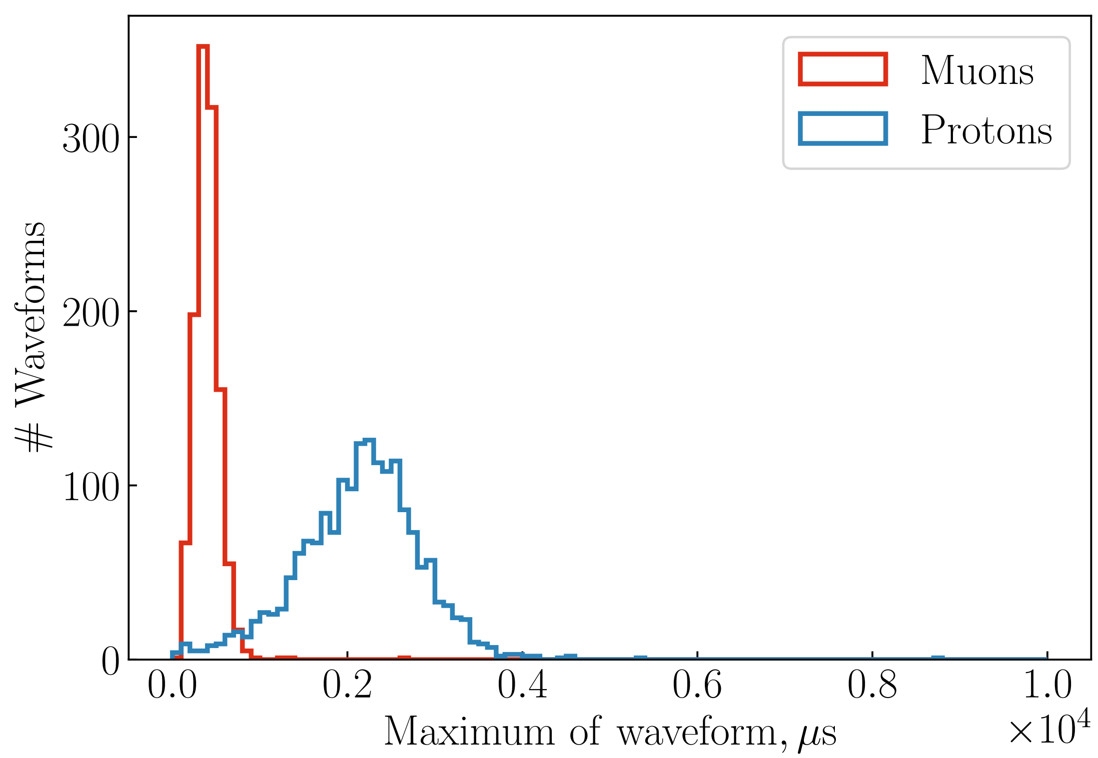


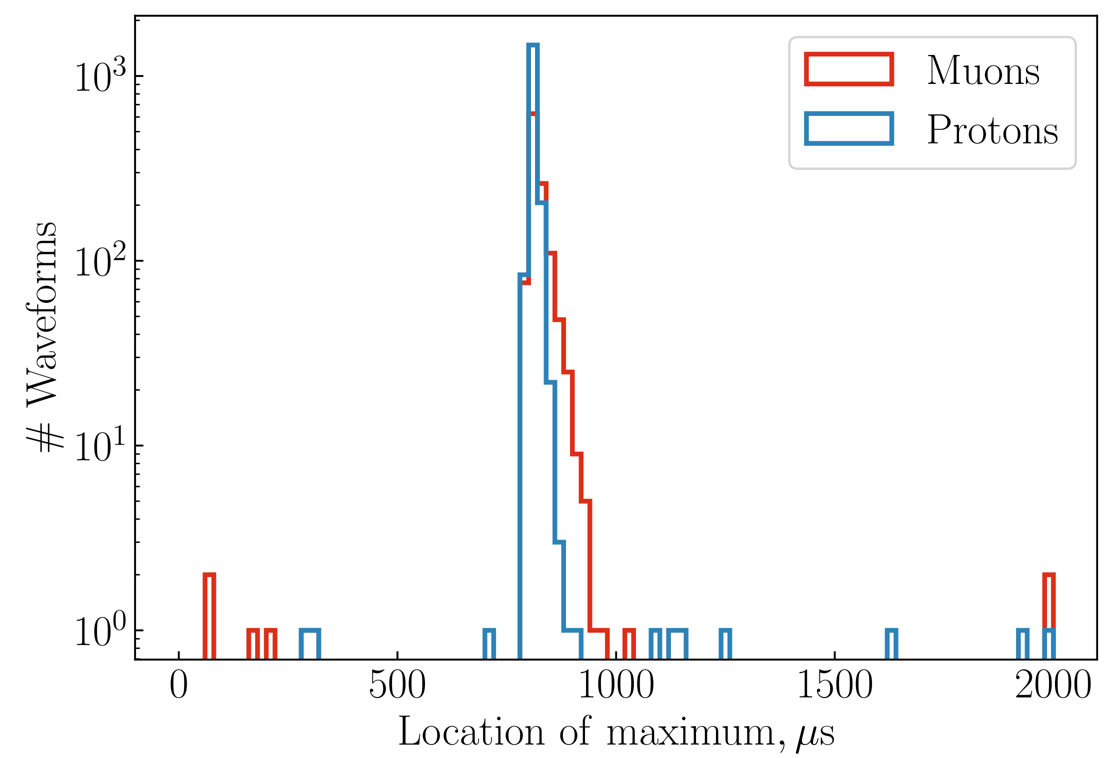



# 7 GeV runs

Distributions of maxima for event makes much more sense then for particular channel in event, meaning time of the signal relative to the trigger time is quite stable.

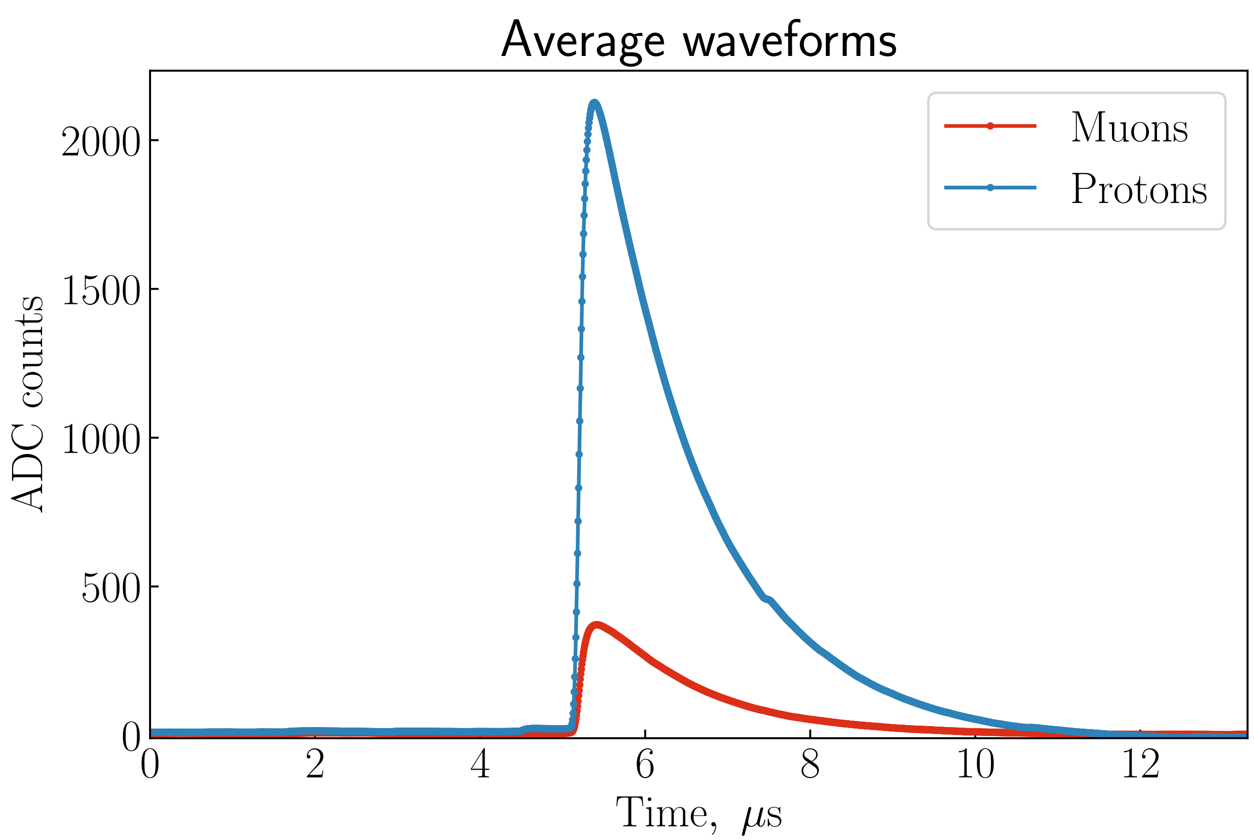
On average protons depose much more light then muons.

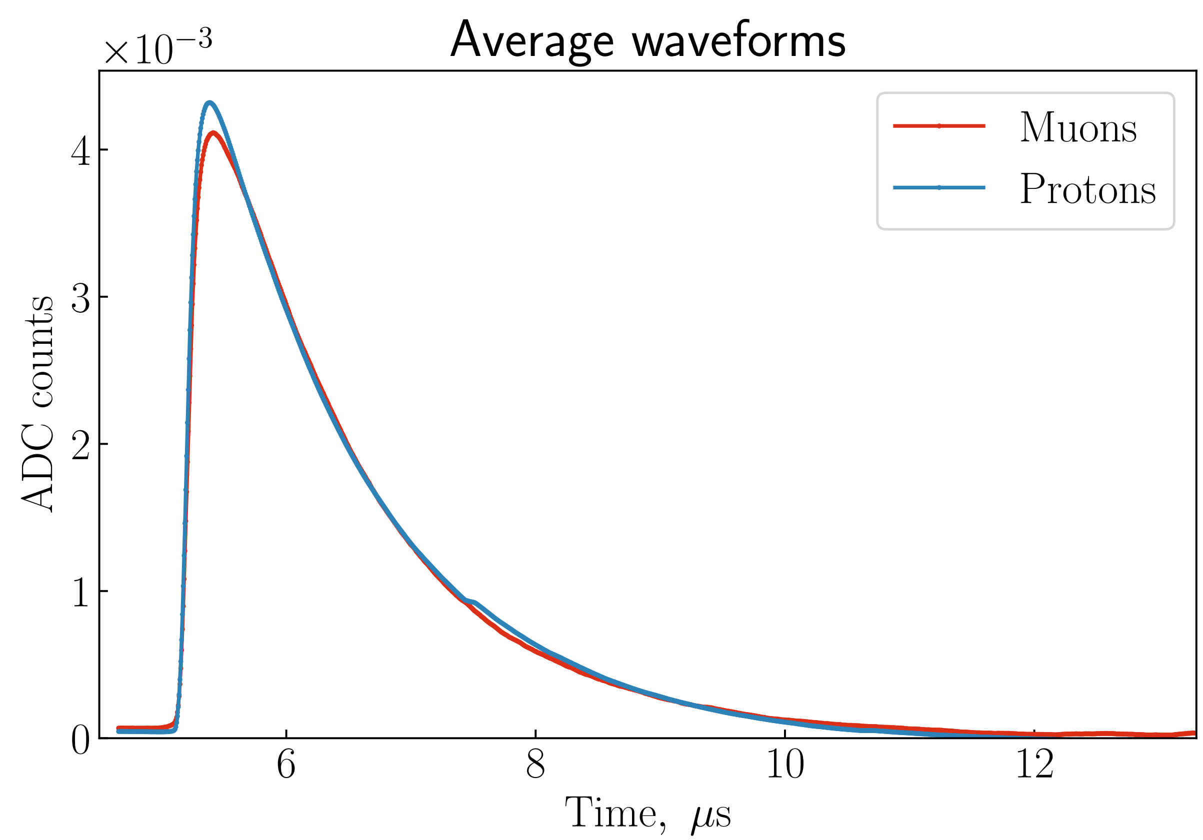


# 7 GeV runs

**NO** significant distinctions on the shape of average waveforms. (Up to scale — left, normalized — right)

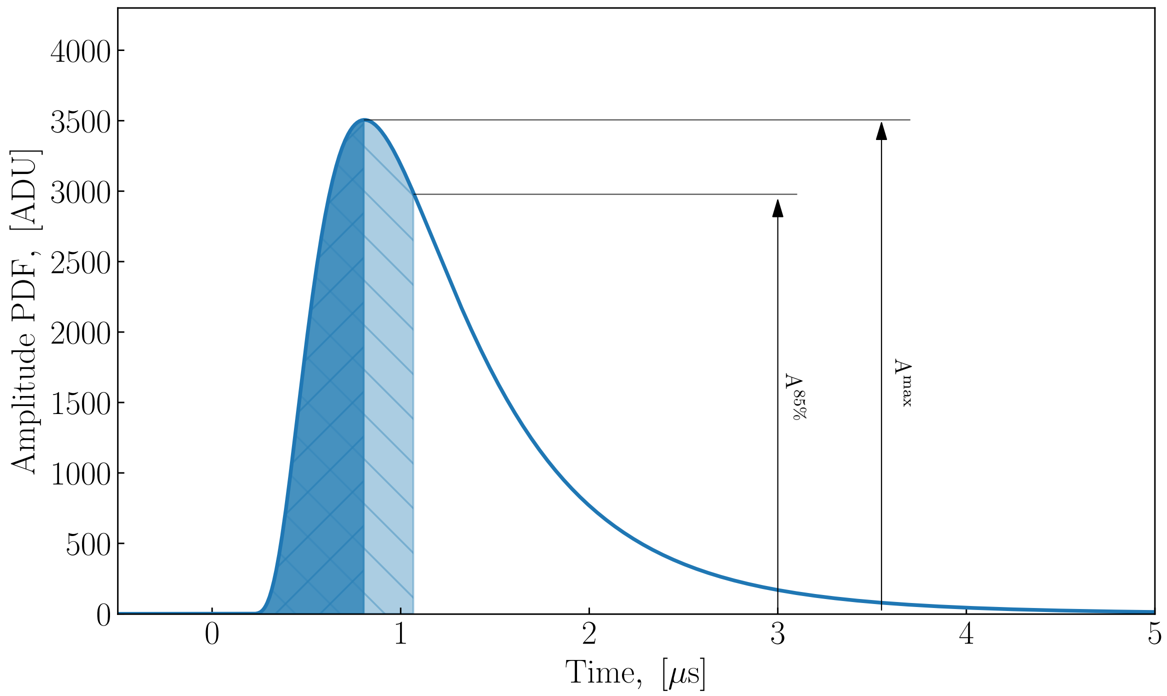


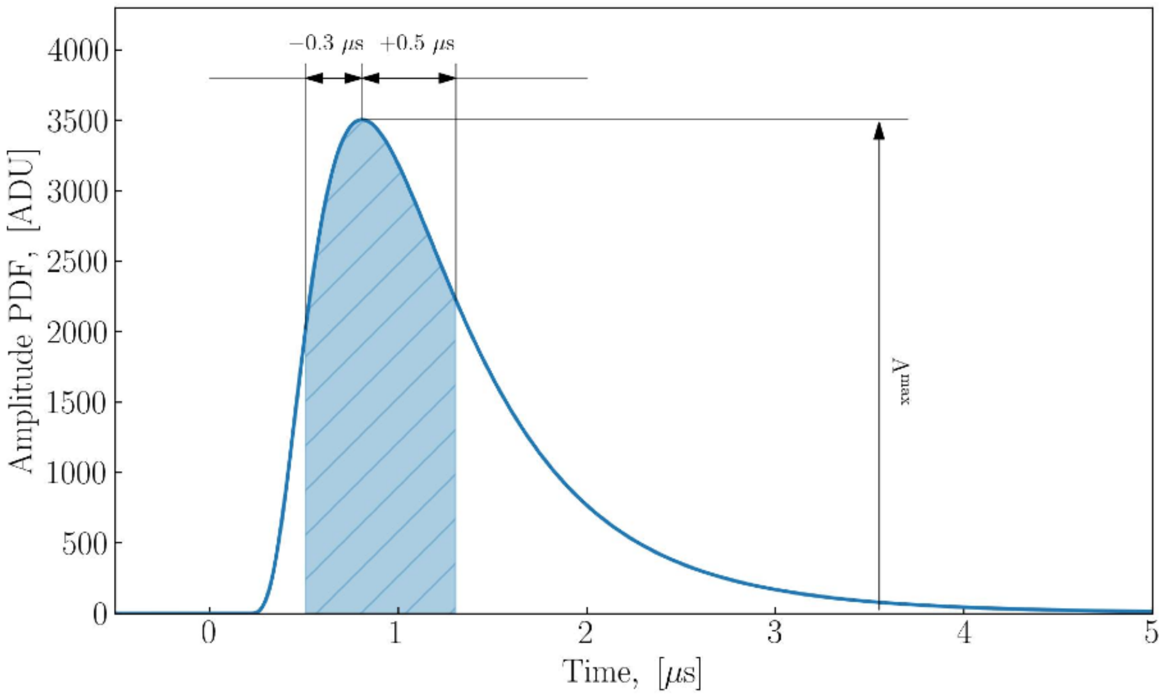



# Prompt fraction definitions

A couple of definitions for the light prompt fraction are used.

$$F_p^{85} = \frac{\int_{t_0}^{t_{85\%}} A(t)dt}{\int_{t_0}^{t} A(t)dt}; \qquad F_p^{100} = \frac{\int_{t_0}^{t_{100\%}} A(t)dt}{\int_{t_0}^{t} A(t)dt}; \qquad F_p' = \frac{\int_{t_{\max}-0.4}^{t_{\max}+0.7} A(t)dt}{\int_{t_0}^{t} A(t)dt};$$



APA3 APA2 APA1

# Entire PD Channel Map

● APA- Face

X APA- Face B

▮ = Readout end

*Modified SSP

TOP of Cryo / Bottom of Cryo — BEAM

| USDaS | | | | | |
|---|---|---|---|---|---|
| PD Module | HB | SSP | SSPch | DAQch | |
| 002-0047-FL34 | Hamamatsu | SSP503 | 0-3 | 216 | 219 |
| 002-0008-IU54 | Hamamatsu | SSP503 | 4-7 | 220 | 223 |
| 002-0058-FL24 | Hamamatsu | SSP503 | 8-11 | 224 | 227 |
| 002-0063-IU19 | Hamamatsu | SSP504 | 0-3 | 228 | 231 |
| 003-0026-FL07* | SensL-C1 | SSP501 | 0-3 | 192 | 195 |
| 002-0014-IU26 | Hamamatsu | SSP504 | 4-7 | 232 | 235 |
| 003-0024-FL33 | SensL-C1 | SSP501 | 4-7 | 196 | 199 |
| 003-0004-IU48 | SensL-C1 | SSP501 | 8-11 | 200 | 203 |
| 002-0041-FL36 | Hamamatsu | SSP504 | 8-11 | 236 | 239 |
| 002-0036-IU47 | SensL-C1 | SSP502 | 0-3 | 204 | 207 |

| MSDaS | | | | | |
|---|---|---|---|---|---|
| PD Module | HB | | SSPch | DAQch | |
| 002-0002-FL22 | Hamamatsu | SSP601 | 0-3 | 240 | 243 |
| 002-0054-IU22 | Hamamatsu | SSP601 | 4-7 | 244 | 247 |
| 002-0059-FL08 | Hamamatsu | SSP601 | 8-11 | 248 | 251 |
| 002-0020-IU09 | Hamamatsu | SSP602 | 0-3 | 252 | 255 |
| 002-0060-FL39 | Hamamatsu | SSP602 | 4-7 | 256 | 259 |
| ARAPUCA-2 | Hamamatsu | SSP603 | 0-3 | 264 | 267 |
| | | SSP603 | 4-7 | 268 | 271 |
| | | SSP603 | 8-11 | 272 | 275 |
| 002-0055-FL40 | Hamamatsu | SSP602 | 8-11 | 260 | 263 |
| 002-0013-IU01 | Hamamatsu | SSP604 | 0-3 | 276 | 279 |
| 002-0011-FL15 | Hamamatsu | SSP604 | 4-7 | 280 | 283 |
| 002-0031-IU02 | Hamamatsu | SSP604 | 8-11 | 284 | 287 |

| DSDaS | | | | | |
|---|---|---|---|---|---|
| PD Module | HB | SSP | SSPch | DAQch | |
| 001-0003-FL01 | SensL-C1 | SSP401 | 0-3 | 144 | 147 |
| 002-0044-IU50 | SensL-C1 | SSP401 | 4-7 | 148 | 151 |
| 002-0039-FL29 | SensL-A1 | SSP401 | 8-11 | 152 | 155 |
| 003-0002-IU27 | SensL-C1 | SSP402 | 0-3 | 156 | 159 |
| 002-0025-FL25 | SensL-C1 | SSP402 | 4-7 | 160 | 163 |
| 003-0011-IU37 | SensL-C1 | SSP402 | 8-11 | 164 | 167 |
| 003-0048-FL42 | SensL-C1 | SSP403 | 0-3 | 168 | 171 |
| 002-0023-IU53 | SensL-C1 | SSP403 | 4-7 | 172 | 175 |
| 002-0038-IU35 | SensL-C1 | SSP403 | 8-11 | 176 | 179 |
| 002-0040-FLP06* | SensL-C1 | SSP404 | 0-3 | 180 | 183 |

| USRaS | | | | | |
|---|---|---|---|---|---|
| PD Module | HB | SSP | SSPch | DAQch | |
| 003-0031-IU20 | SensL-A1 | SSP301 | 0-3 | 96 | 99 |
| 002-0055-FL03 | SensL-A1 | SSP301 | 4-7 | 100 | 103 |
| 002-0020-IU31 | SensL-A1 | SSP301 | 8-11 | 104 | 107 |
| ARAPUCA-1 | Hamamatsu | SSP304 | 0-3 | 132 | 135 |
| | | SSP304 | 4-7 | 136 | 139 |
| | | SSP304 | 8-11 | 140 | 143 |
| 002-0042-IU52 | SensL-A1 | SSP302 | 0-3 | 108 | 111 |
| 002-0056-FL30 | SensL-A1 | SSP302 | 4-7 | 112 | 115 |
| 002-0047-IU17 | SensL-A1 | SSP302 | 8-11 | 116 | 119 |
| 002-0054-FL38 | SensL-A1 | SSP303 | 0-3 | 120 | 123 |
| 001-0039-IU51 | SensL-A1 | SSP303 | 4-7 | 124 | 127 |
| 003-0015-FL04 | SensL-C1 | SSP303 | 8-11 | 128 | 131 |

| MSRaS | | | | | |
|---|---|---|---|---|---|
| PD Module | HB | SSP | SSPch | DAQch | |
| 002-0049-IU16 | SensL-A1 | SSP201 | 0-3 | 48 | 51 |
| 001-0054-FL18 | SensL-A1 | SSP201 | 4-7 | 52 | 55 |
| 002-0035-IU13 | SensL-A1 | SSP201 | 8-11 | 56 | 59 |
| 002-0006-FL14 | SensL-A1 | SSP202 | 0-3 | 60 | 63 |
| 001-0044-IU18 | SensL-A1 | SSP202 | 4-7 | 64 | 67 |
| 002-0012-FL19 | SensL-A1 | SSP202 | 8-11 | 68 | 71 |
| 002-0027-IU12 | SensL-A1 | SSP203 | 0-3 | 72 | 75 |
| 002-0015-FL21 | SensL-A1 | SSP203 | 4-7 | 76 | 79 |
| 001-0052-IU14 | SensL-A1 | SSP203 | 8-11 | 80 | 83 |
| 003-0025-FL06 | SensL-A1 | SSP204 | 0-3 | 84 | 87 |

| DSRaS | | | | | |
|---|---|---|---|---|---|
| PD Module | HB | SSP | SSPch | DAQch | |
| 403-003-0063-IU28 | SensL-A1 | SSP101 | 0-3 | 0 | 3 |
| 403-003-0041-FL9 | SensL-A1 | SSP101 | 4-7 | 4 | 7 |
| 403-002-0001-IU15 | SensL-A1 | SSP101 | 8-11 | 8 | 11 |
| 403-003-0054-FLP12 | SensL-A1 | SSP102 | 0-3 | 12 | 15 |
| 403-001-0006-IU49 | SensL-A1 | SSP102 | 4-7 | 16 | 19 |
| 403-003-0064-FLP13 | SensL-A1 | SSP102 | 8-11 | 20 | 23 |
| 403-001-0061-IU04 | SensL-A1 | SSP103 | 0-3 | 24 | 27 |
| 403-001-0042-FLP4 | SensL-A1 | SSP103 | 4-7 | 28 | 31 |
| 403-001-0025-IU21 | SensL-A1 | SSP103 | 8-11 | 32 | 35 |
| 403-003-0020-FL5 | SensL-A1 | SSP104 | 0-3 | 36 | 39 |

SSP_Serial#

| USDaS | MSDaS | DSDaS |
|---|---|---|
| 127 | 131 | 120 |
| 125 | 130 | 119 |
| 132 | 129 | 118 |
| 121 | 128 | 117 |

| USRaS | MSRaS | DSRaS |
|---|---|---|
| 123 | 113 | 109 |
| 116 | 112 | 108 |
| 115 | 111 | 107 |
| 114 | 102 | 106 |

SSP_IP#

| USDaS | MSDaS | DSDaS |
|---|---|---|
| 504 | 604 | 404 |
| 503 | 603 | 403 |
| 502 | 602 | 402 |
| 501 | 601 | 401 |

| USRaS | MSRaS | DSRaS |
|---|---|---|
| 304 | 204 | 104 |
| 303 | 203 | 103 |
| 302 | 202 | 102 |
| 301 | 201 | 101 |

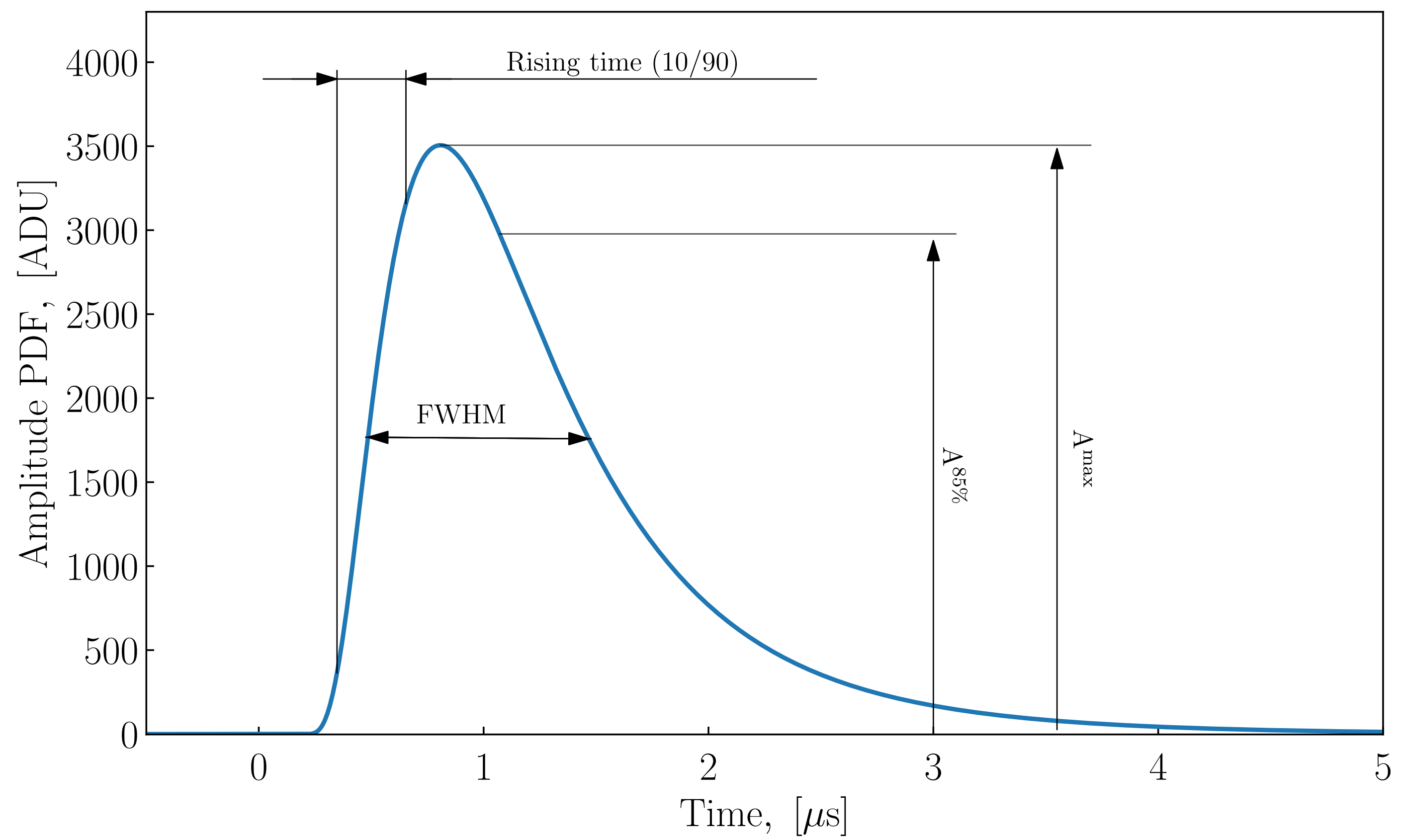


APA5 APA6 APA4

# Signal parameters

To distinguish neutrons a few signal shape parameters are used:

- Rising time (from 10% to 90% of maximum amplitude);
- Full width at half maximum;
- Prompt fractions;

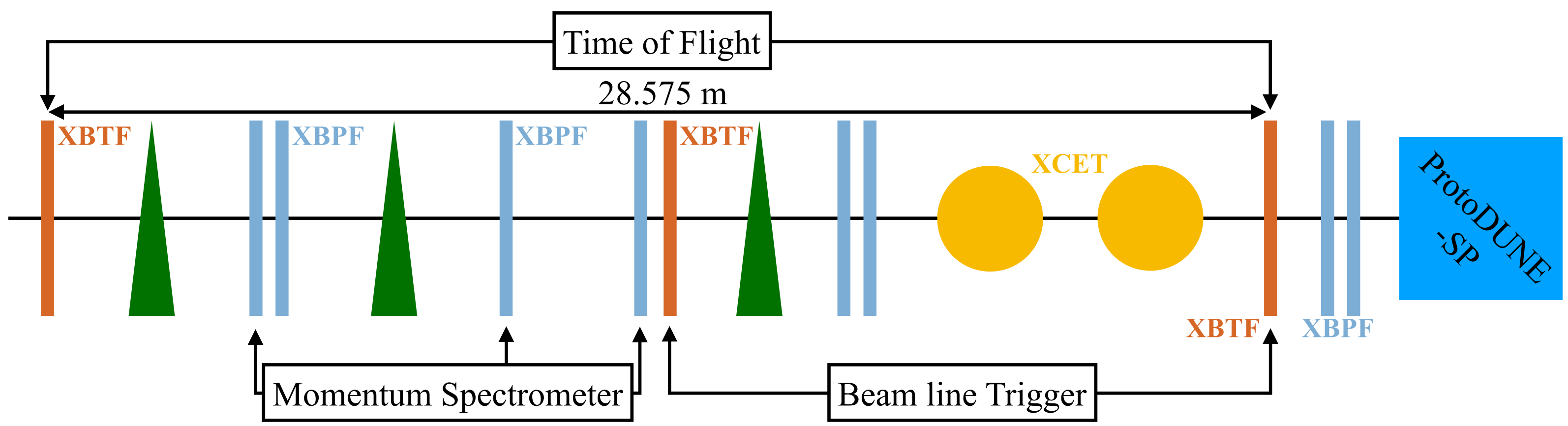


# Beam instrumentation

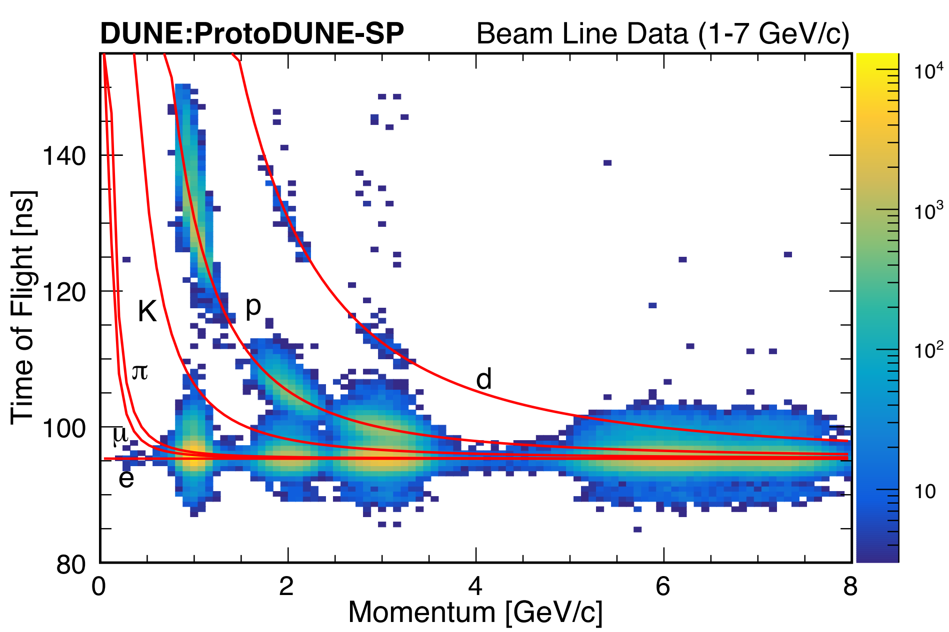
PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 061003 (2019)

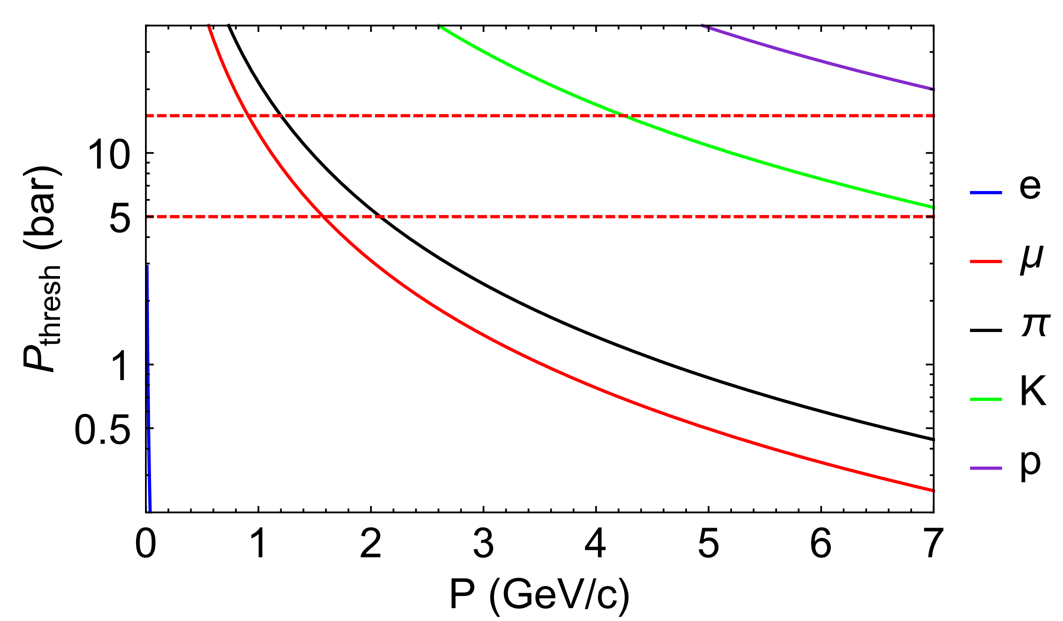
**Particle production, transport, and identification in the regime of 1–7 GeV/c**

A. C. Booth,[1] N. Charitonidis,[2,*] P. Chatzidaki,[2,3,4] Y. Karyotakis,[5] E. Nowak,[2,6] I. Ortega-Ruiz,[2] M. Rosenthal,[2] and P. Sala[2,7]




TOF system allows to ID beam particles below 3 GeV/c and Cherenkov detectors perform ID for momenta > 3 GeV/c



# Neutron energy in DUNE

**Understanding the energy resolution of liquid argon neutrino detectors**

Alexander Friedland[1,*] and Shirley Weishi Li[1,†]
[1] *SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA, 94025*
(Dated: January 21, 2019)

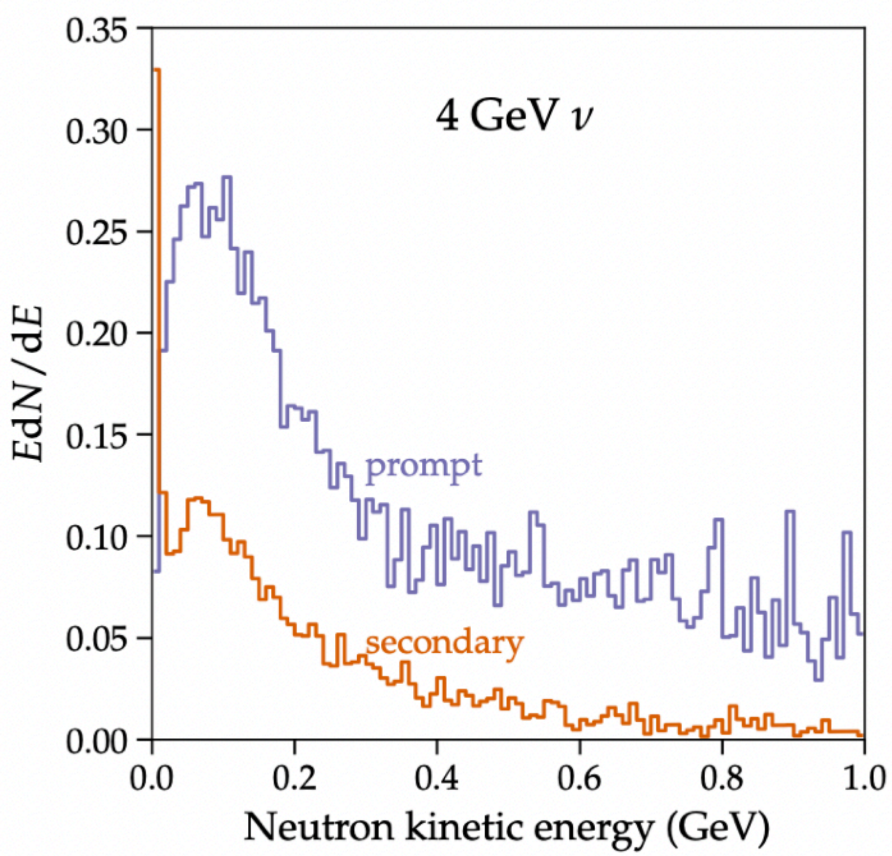



FIG. 8. Energy distribution of the neutrons in 4 GeV neutrino interactions. The top histogram corresponds to prompt neutrons, which come from the nucleus struck by the neutrino; the bottom one corresponds to secondary neutrons, which are knocked out of other argon nuclei as the event develops in the detector.

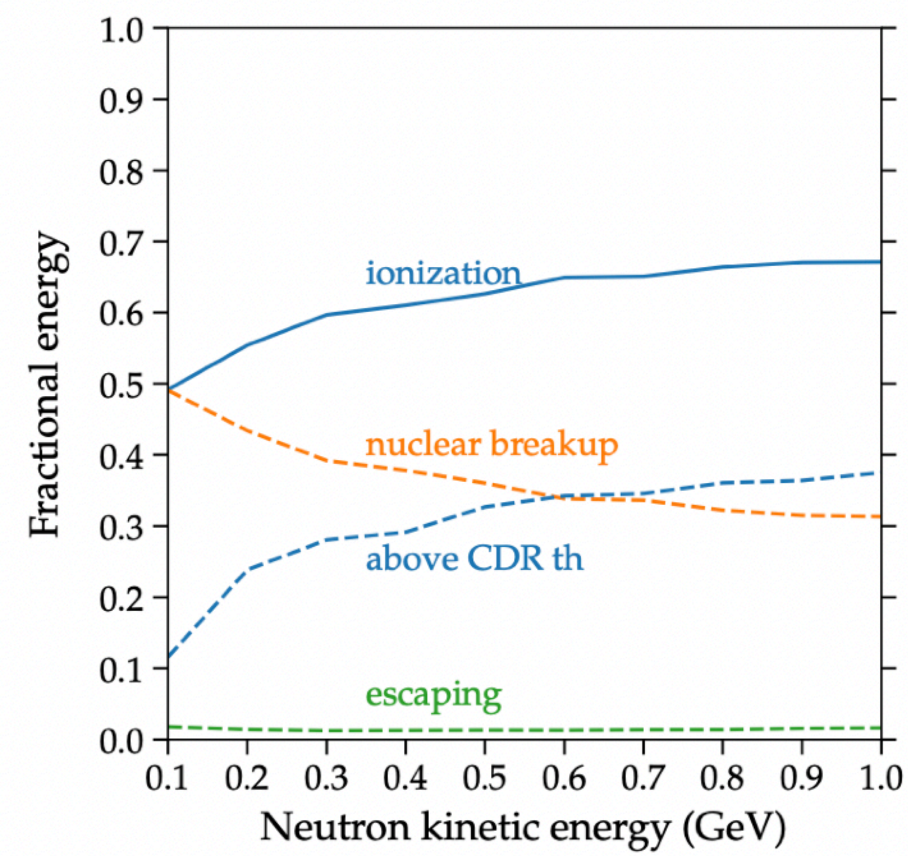



FIG. 9. Energy breakdown of neutrons at different energies. Shown are the energy fractions that go to ionization (*solid blue*) and to nuclear breakup (*dashed orange*). Also shown is the fraction of the ionization energy in particles above the CDR thresholds (*dashed blue*). The ionization charges are given before charge recombination.

# Processed runs

| | |
|---|---|
| **Beam energy** | 0.3, 0.5, 1, 2, 3, 4, 6, 7 [GeV/c] |
| **High Voltage** | 130, 140, 150, 180 [kV] |
| **Sensor type** | SensL SiPM MicroFC- 60035-SMT (35 µm pixel size)<br>Hamamatsu MPPC S13360-6050 (50 µm pixel size) |
| **Particle ID** | $\mu, p, e, \pi$ |