Pulse Shape Discrimination with 2x2 Data

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- ***Excimer formation***
  - Potential well necessary to form excimer occurs for two of the atomic triplet states
    - $^1S_0$ + $^3P_1$ (Singlet excimer, S = 0): Fast decay (~ 7 ns)
    - $^1S_0$ + $^3P_2$ (Triplet excimer, S = 1): Slow decay (~1.45 μs)
    - Decay through photon emission: Broad peak at 128nm

configuration	state	energy [eV]
$[Ne](3s)^2(3p)^6$	$^1S_0$	0.0
$[Ne](3s)^2(3p)^5 \uparrow (4s) \downarrow$	$^1P_1$	11.82
$[Ne](3s)^2(3p)^6 \uparrow (4s) \uparrow$	$^3P_0$	11.72
	$^3P_1$	11.62
	$^3P_2$	11.54

Figure: Energy configuration of the four lowest energy states of Argon, from T. Pollmann's work. [1]

- ***Impact on Singlet-to-Triplet Ratio:***
  - High LET (dE/dx): increases the proportion of singlet excimers.
  - Low LET (dE/dx): increases the proportion of triplet excimers.

Pulse Shape Discrimination

- ***What is PSD?***
  - Technique to distinguish particle types based on scintillation light pulse shapes.
- ***Underlying Principle:***
  - Different particles produce different ratios of singlet to triplet excimers.
- ***Key Parameters:***
  - Decay constants: Time constants for singlet and triplet decay.
  - fprompt: Fraction of prompt light to total light.

fprompt Parameter

$$f_{\text{prompt}} = \frac{\int_{t_0}^{t_{cut}} I(t)\,dt}{\int_{t_0}^{t_{\text{total}}} I(t)\,dt}$$

- ***I (t)*: Scintillation intensity**
- **t_0: *Start time of the signal.***
- **t_{cut}: *Time defining the prompt window.***
- **t_{total}: *Total integration time.***

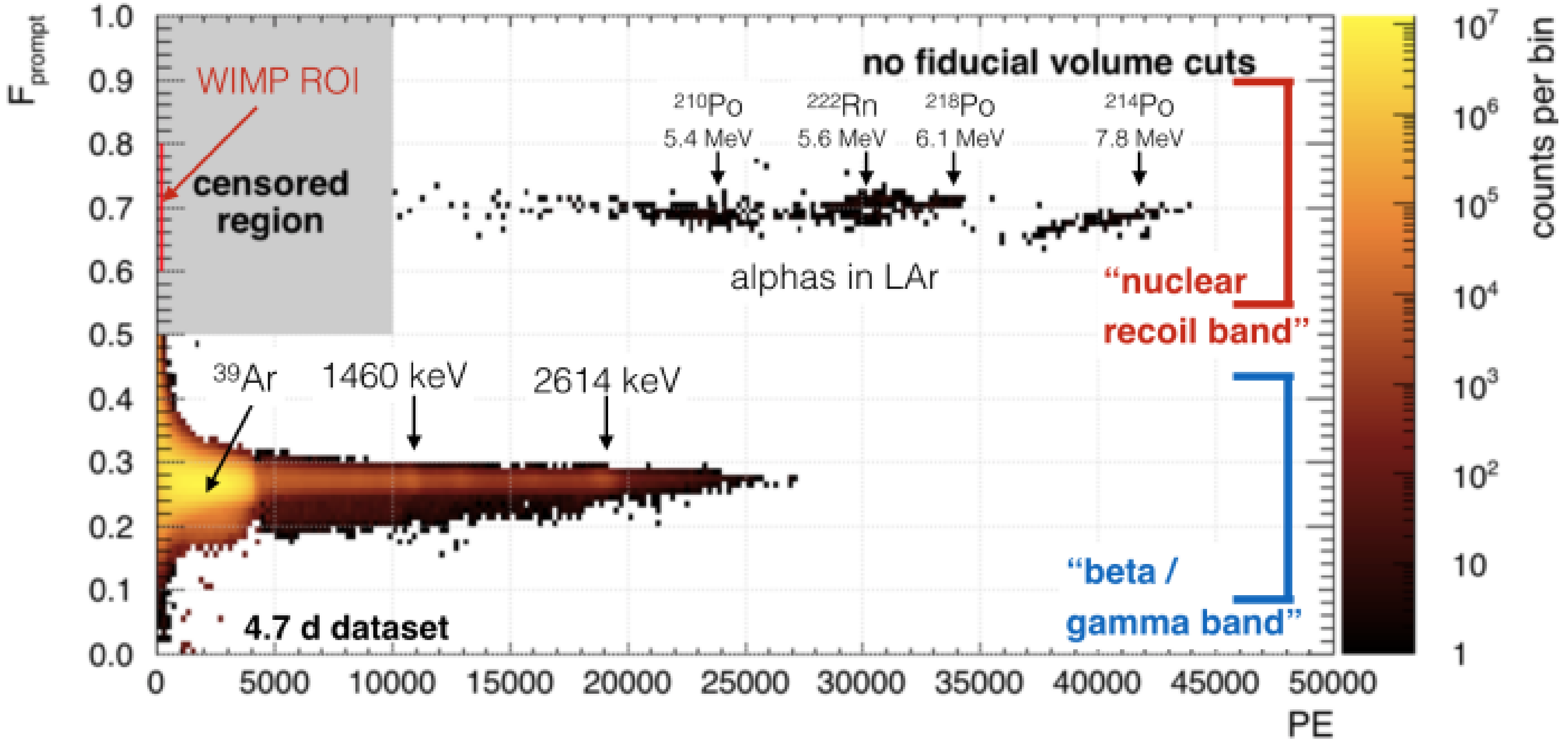


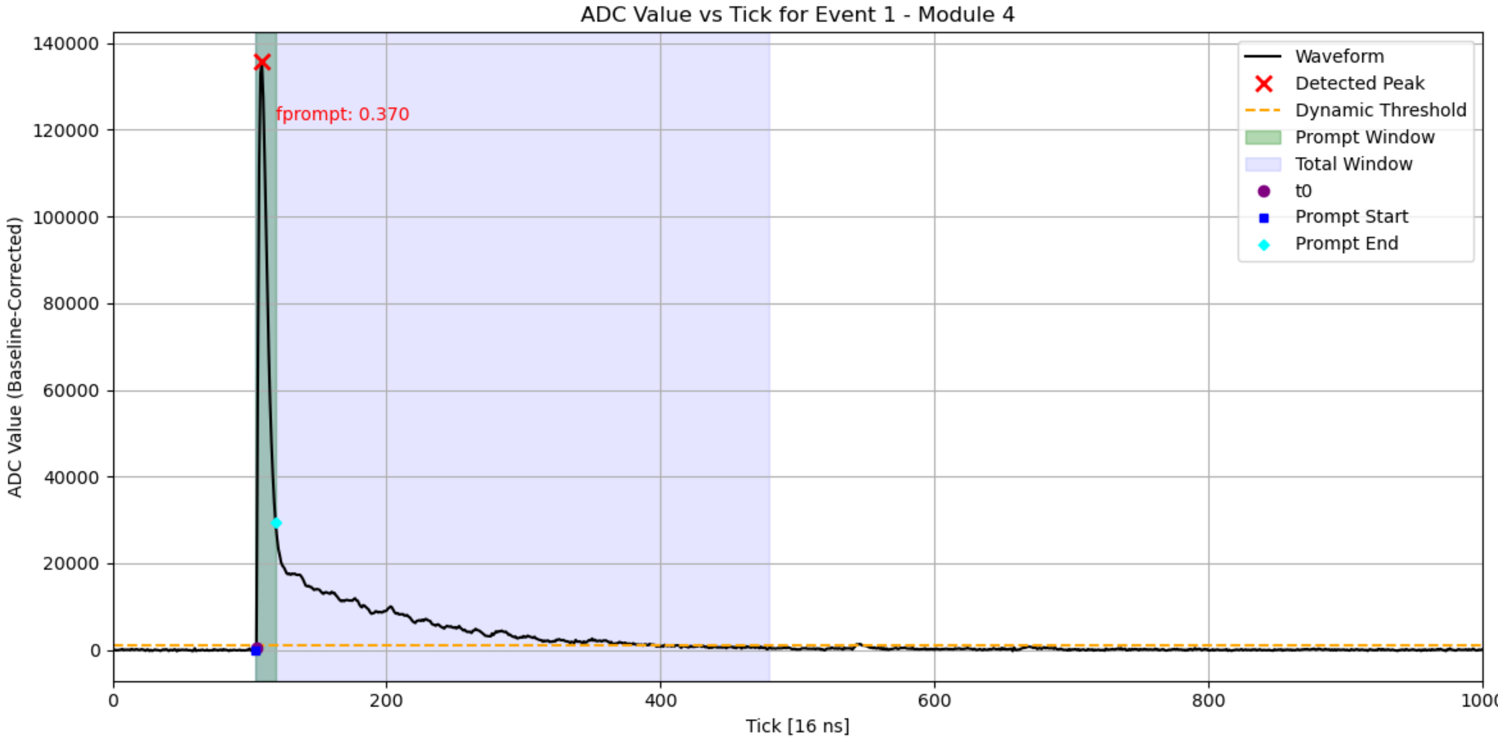
Figure: Frpompt parameter versus detected photo electrons (PE), showing background populations. Taken from B. Lehnert's work for the DEAP-3600 Collaboration [2]

Event Selection Criteria

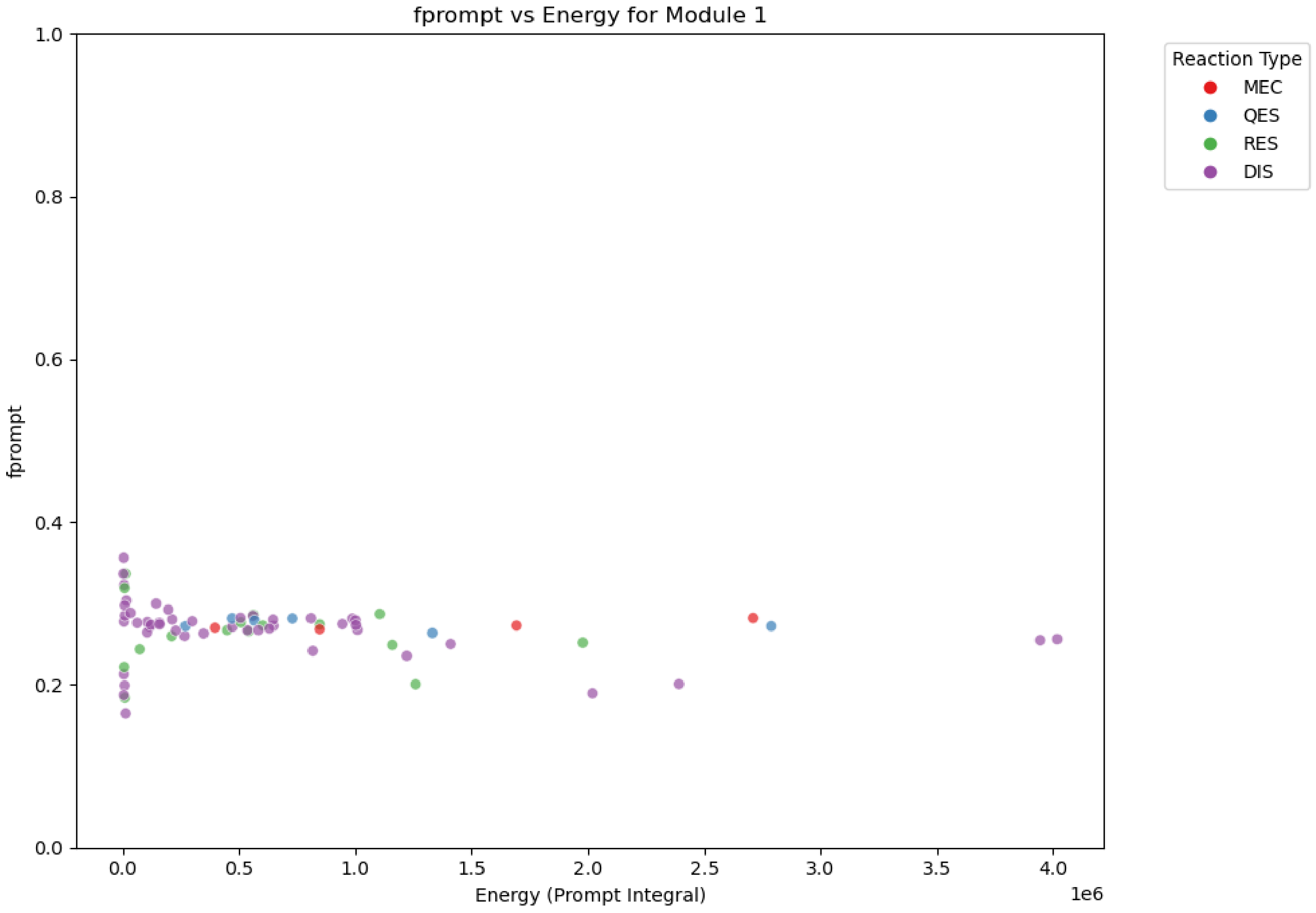
- ***Baseline correction:***
  - *Subtract median waveform value*
- ***Peak finder:***
  - *Noise estimation:*
    - *100 samples -> take 6x above std*
  - *Prominence of 10%*
  - *Single peaks*
- ***Event Selection:***
  - *SNR:*
    - *5x stronger than noise*
    - *More than 5% max value*
  - *Smooth rising edge:*
    - *No dips*

- ***Prompt start:***
  - *Below 10% peak*
  - *1 tick before*

- ***Prompt/total window***
  - ***Arbitrarily chosen***



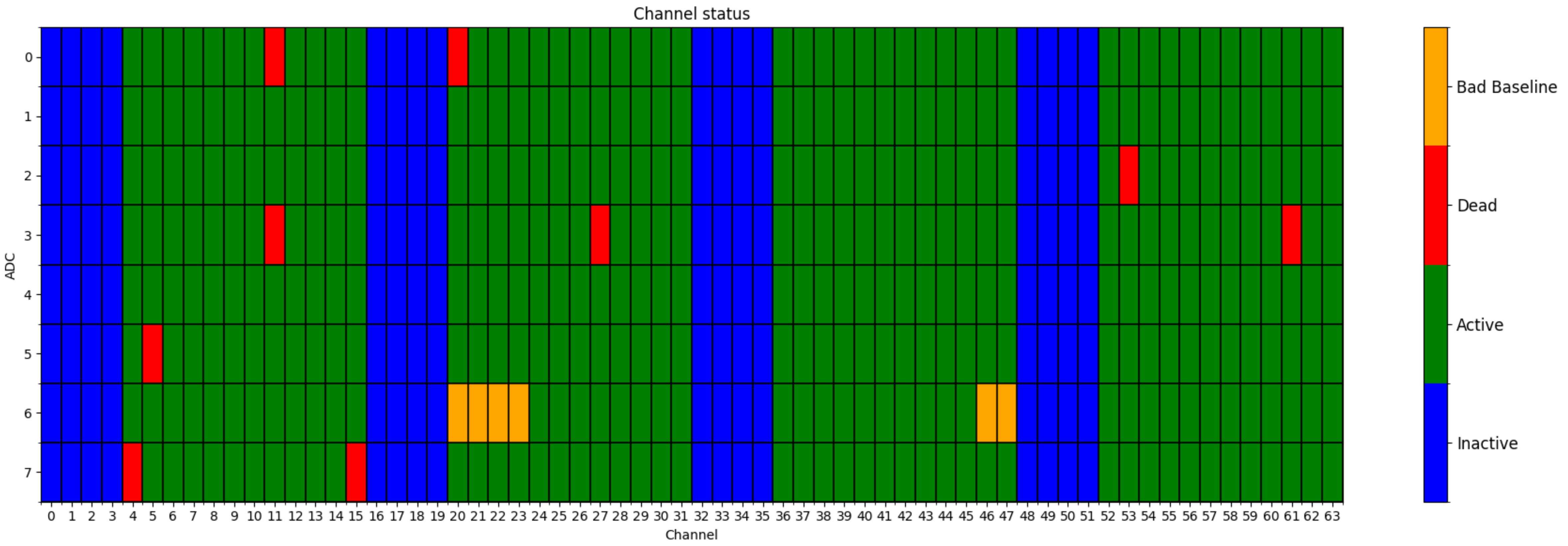
MiniRun5_1E19_RHC.flow.0000055.FLOW.hdf5



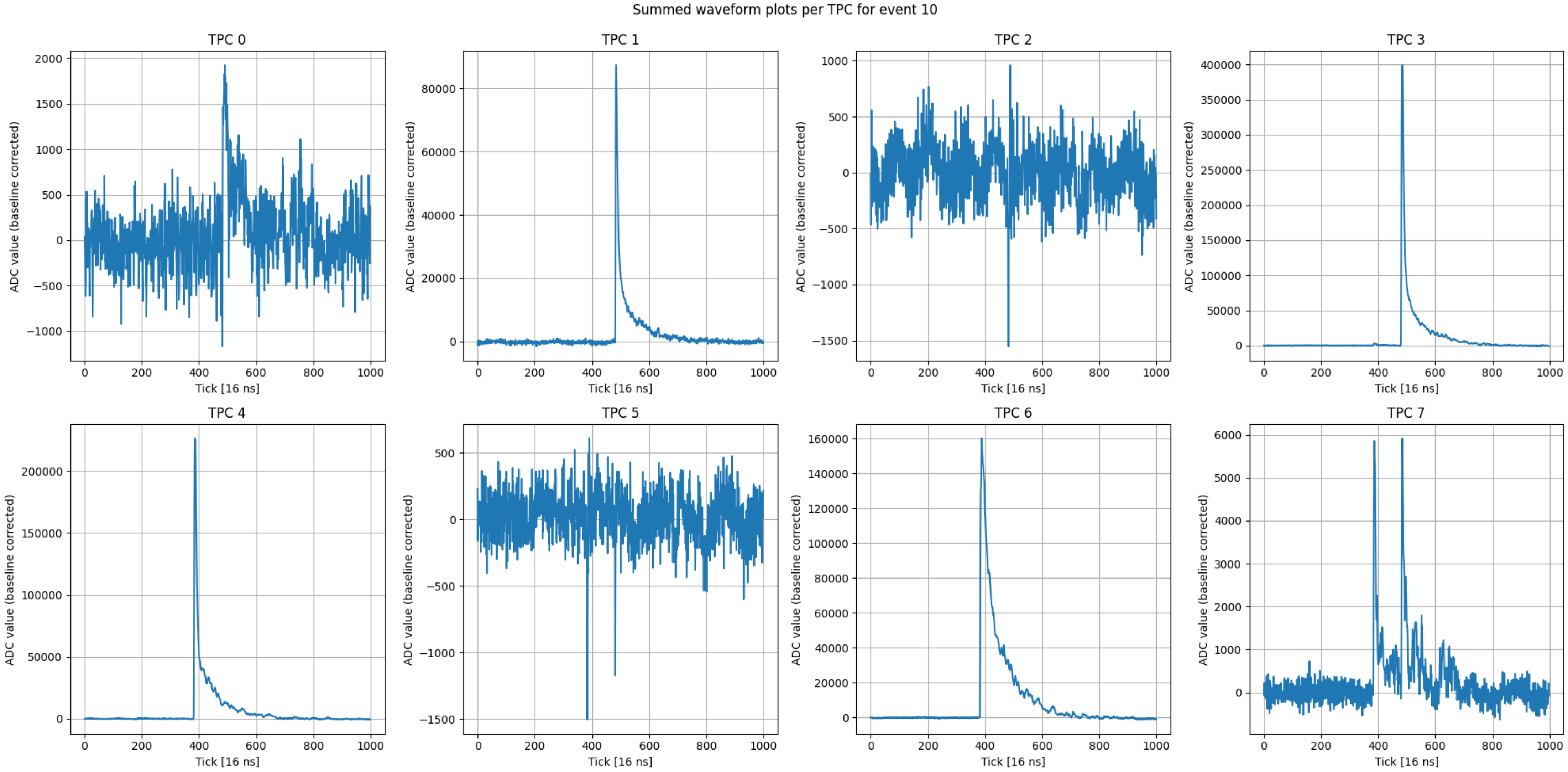
fprompt vs Energy for Module 1
fprompt
Energy (Prompt Integral)
1e6
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Reaction Type
MEC
QES
RES
DIS

```
#: Fraction of total light emitted from singlet state
SINGLET_FRACTION = 0.3
```

2x2 Data: Channel Mapping



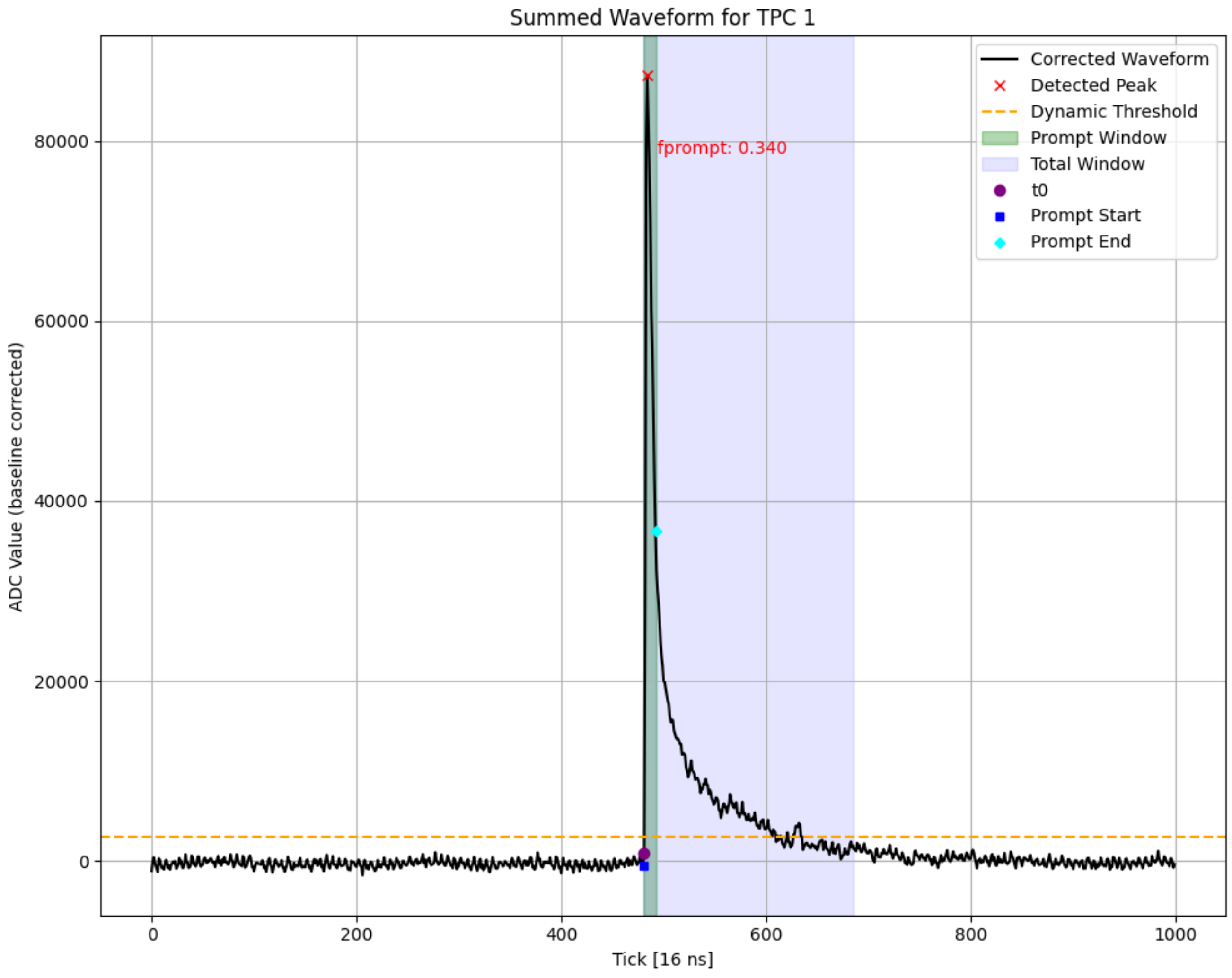
2x2 Data: TPC Waveforms



mpd_run_hvramp_rctl_104_p130.FLOW.hdf5

2x2 Data: fprompt calculation

- ***Baseline correction:***
  - *Subtract median waveform value*
- ***Peak finder:***
  - *Noise estimation:*
    - *100 samples -> take 6x above std*
  - *Prominence of 10%*
  - *Single peaks*
- ***Event Selection:***
  - *SNR:*
    - *5x stronger than noise*
    - *More than 5% max value*
  - *Smooth rising edge:*
    - *No dips*



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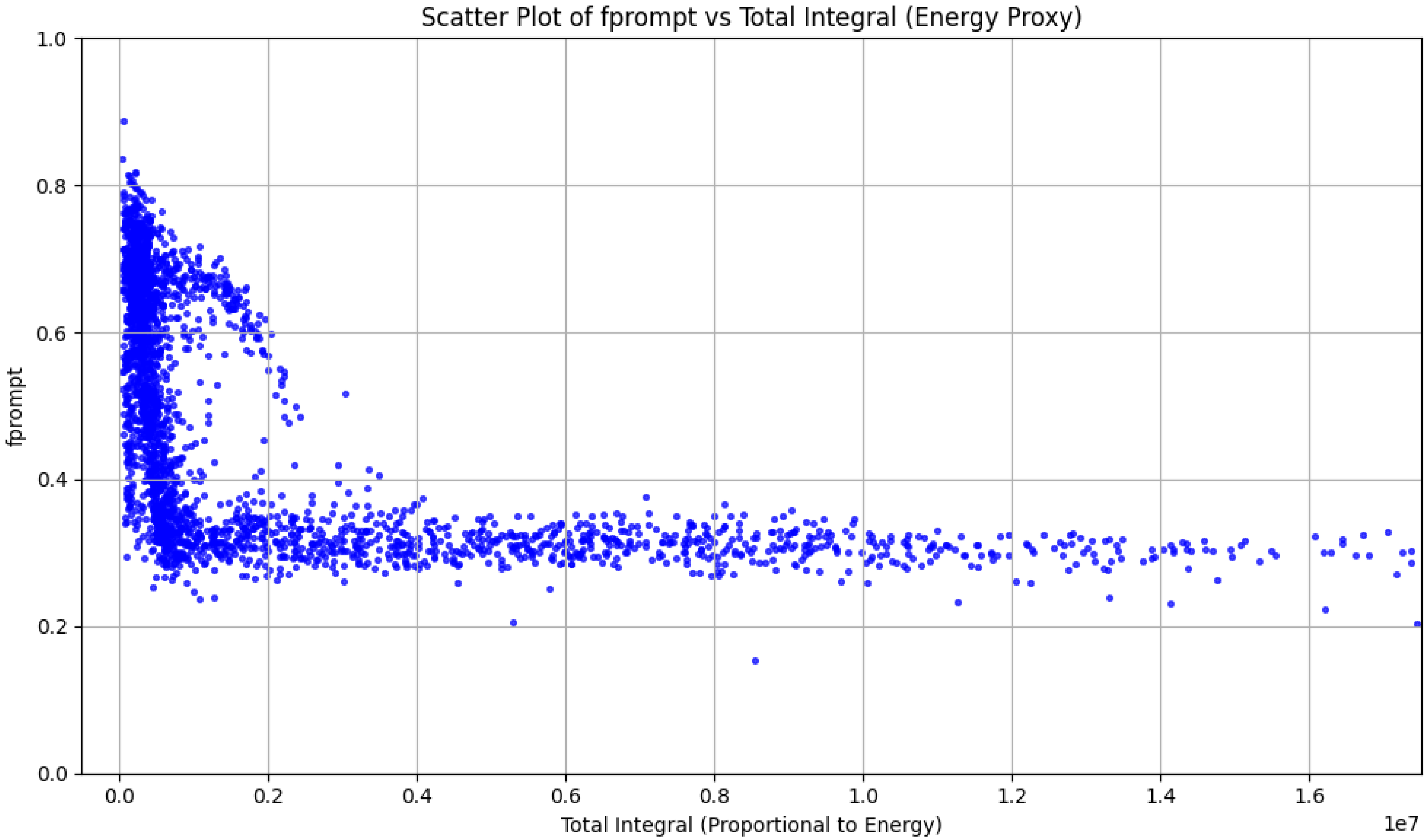
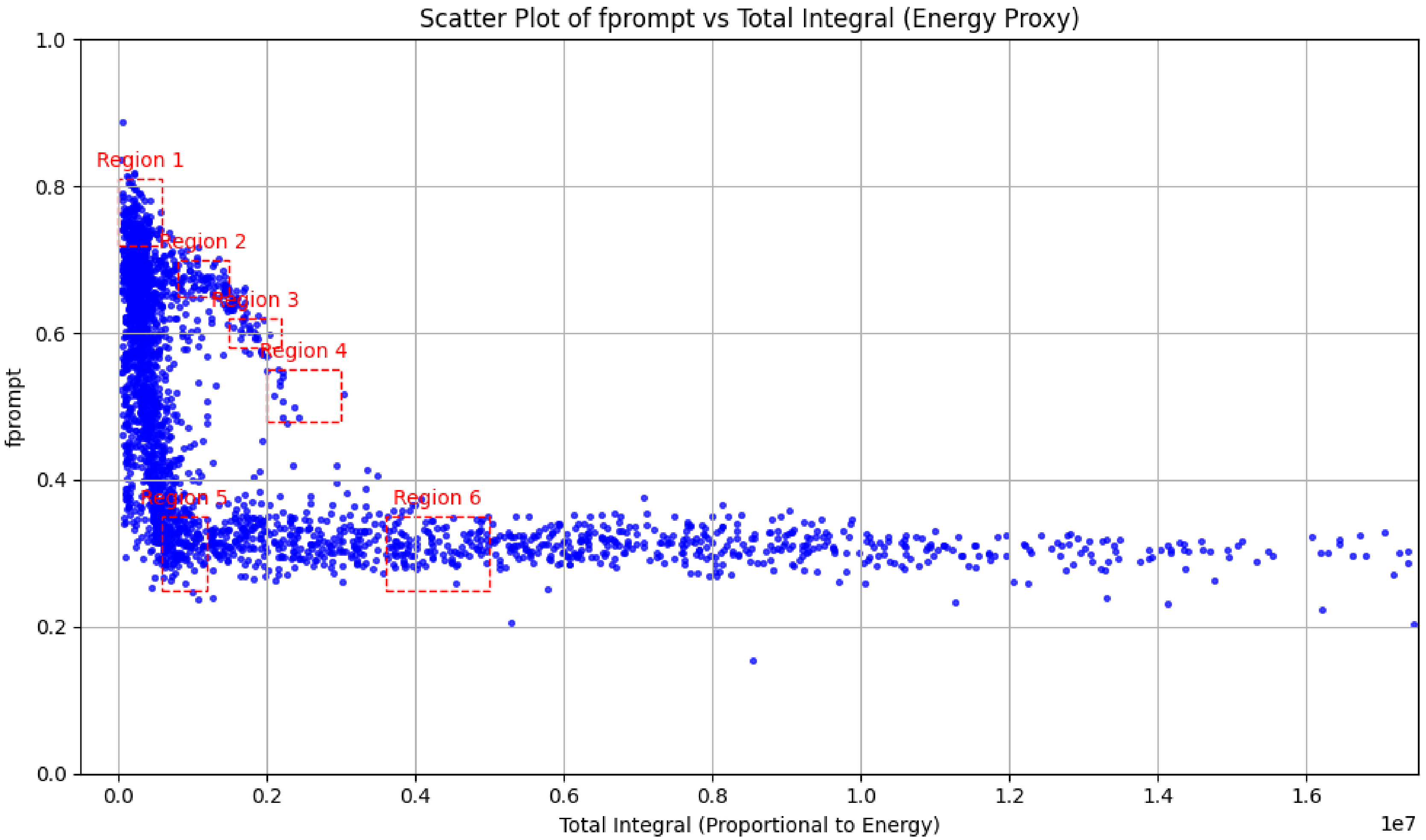
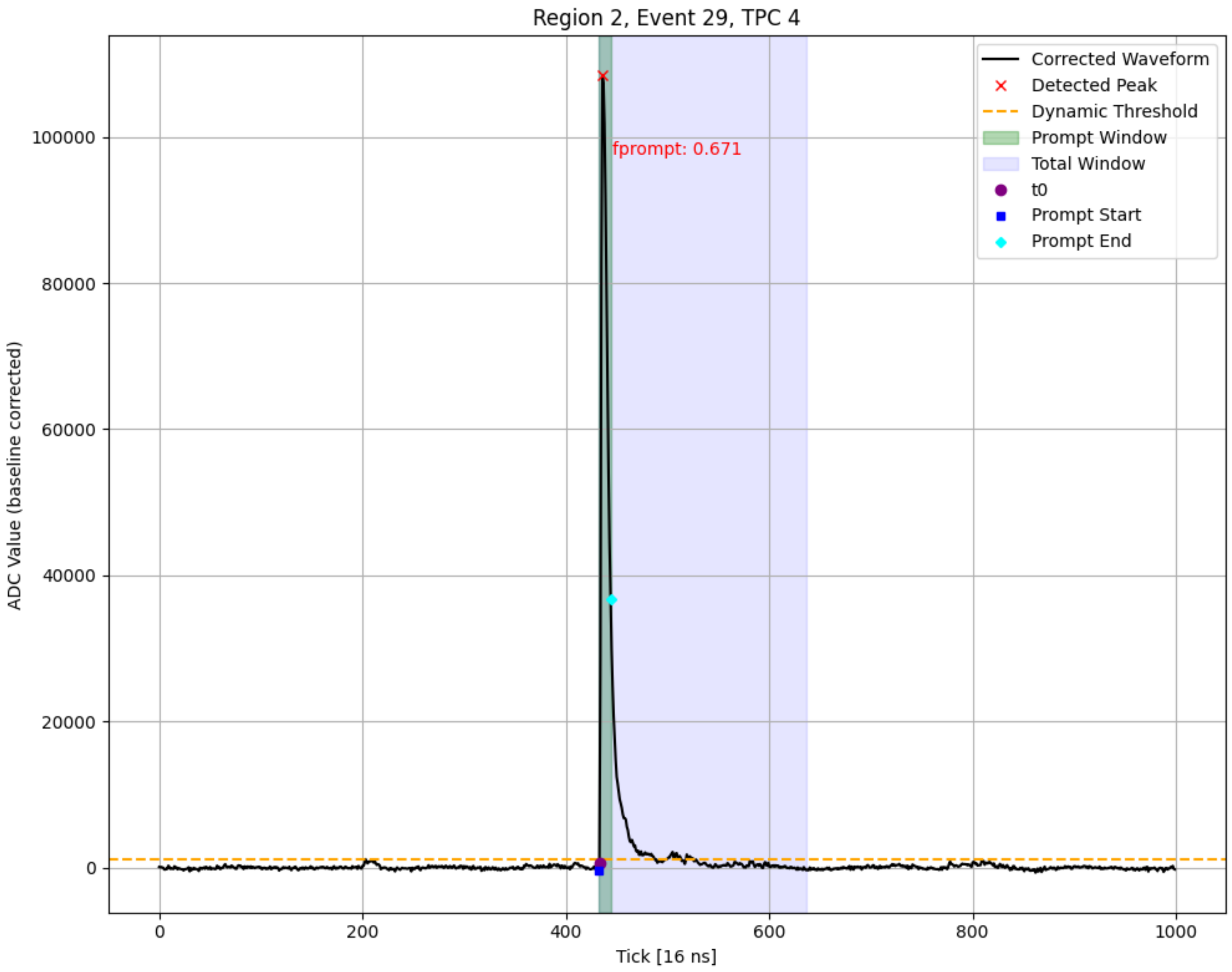


mpd_run_hvramp_rctl_104_p130.FLOW.hdf5

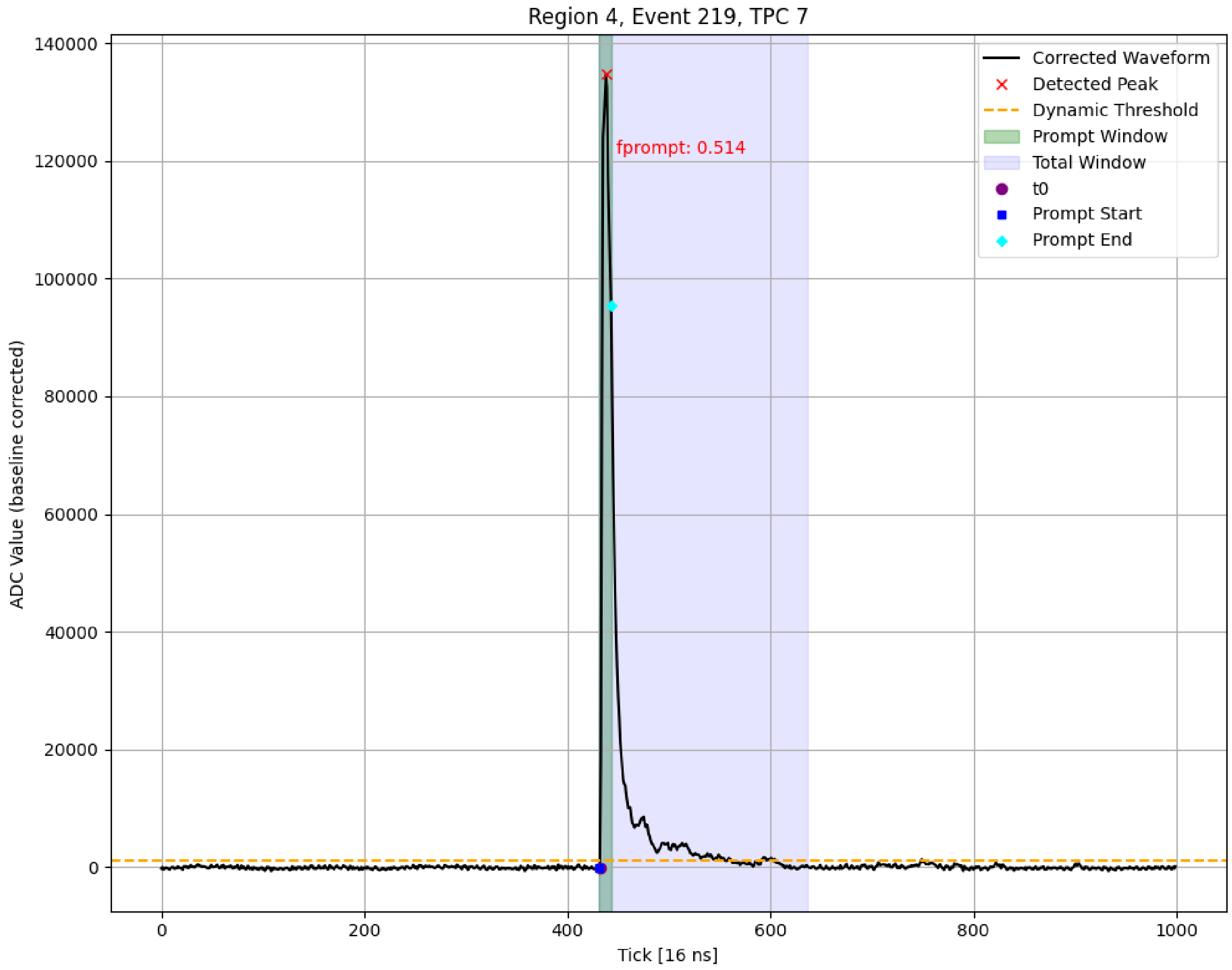
2x2 Data: Scatter plot ROIs



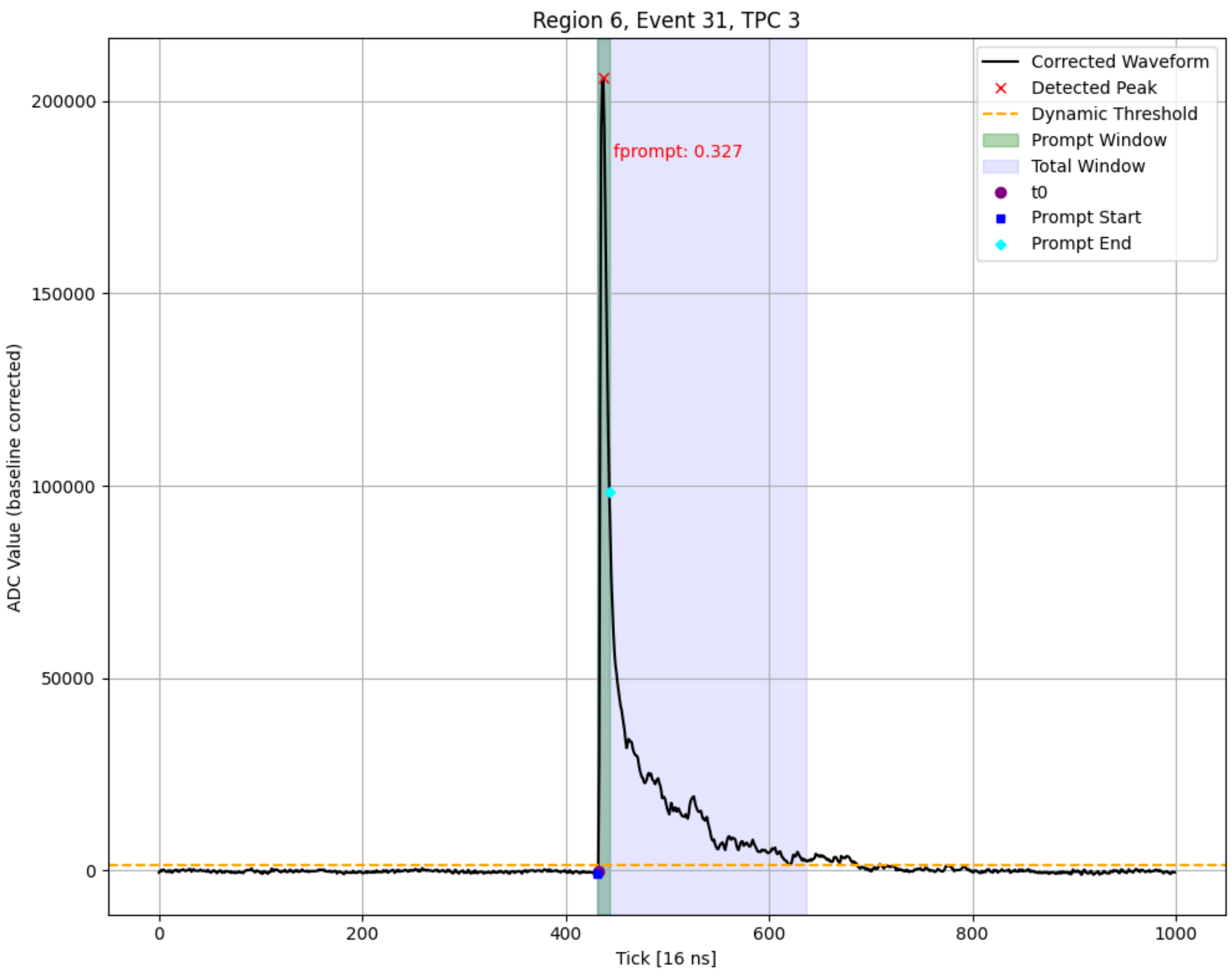
2x2 Data: ROI Pulse Shapes



2x2 Data: ROI Pulse Shapes



2x2 Data: ROI Pulse Shapes



Conclusion + Next Steps

- ***Conclusion***
  - *Clear pulse shapes – fprompt calculations can be applied*
  - *Fprompt – two bands observed (at low energy)*
    - *Likely correlates with nuclear and electron recoils*

- **Next steps**
  - Identify waveforms with pileup – extract event time + fprompt value of each interaction
  - Optimizing the prompt and the total window time
  - Apply energy & gain calibration and compare with own tests
  - Fit the pulseshape to extract the Argon excimer decay times and time resolution (LAr purity test)

[1] T. Pollmann, "Pulse shape discrimination studies in a liquid argon scintillation detector," Max-Planck-Institut für Kernphysik, 2007.

[2] B. Lehnert, Backgrounds in the deap-3600 dark matter experiment, 2018.

Backup Slides

Process A (Excitation):

- Incoming particle excites argon atom. Exciton formed.

Process B (Self-Trapping):

- Exciton becomes self-trapped.

Process C (Excimer Formation):

- Exciton trapped in potential well
- Curves favor excimer formation (singlet or triplet state).

Process D (Emission):

- Excimer decays, emitting 128 nm scintillation light.

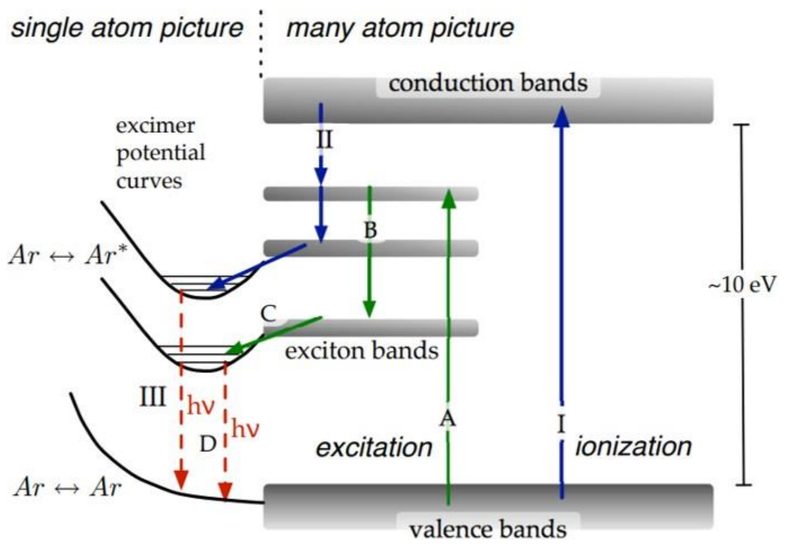


Figure 3: The processes that lead to photon emission, taken directly from T. Pollmann's work [4].

Ionization Process

Process I (Ionization):

- Particle deposits $\sim$10 eV energy, ionizing argon atom

Process II (Recombination):

- Free electron recombines or excites nearby atom

Process III (Excimer Formation and Decay):

- Recombination forms excimer, emits 128 nm light

Spectrum:

- Broad peak at 128 nm - unresolved rotational levels

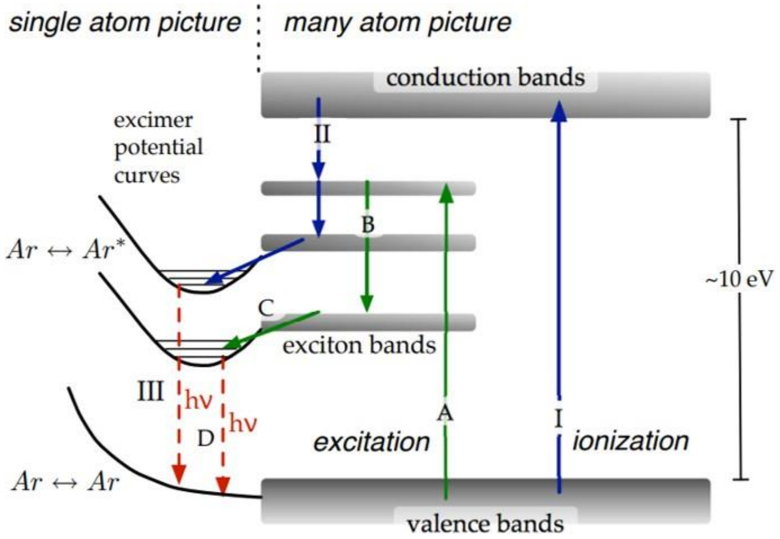


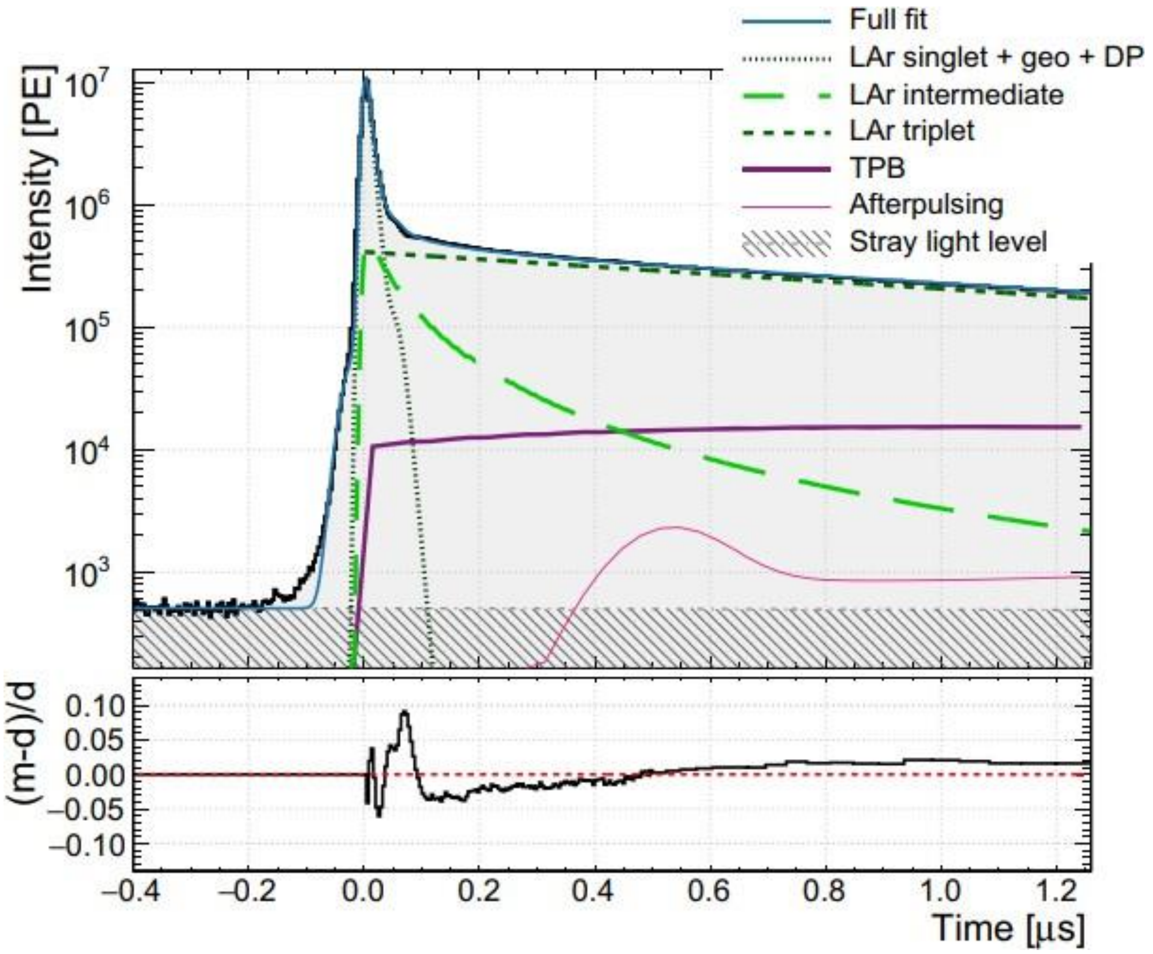
Figure 4: The processes that lead to photon emission, taken directly from T. Pollmann's work [4].

Experiment:

- DEAP-3600 (Ar-39)
- Pulse shape characteristics

Fits:

- geometric effect + detector response
- intermediate (later recomb.)
- TPB late emission
- Afterpulsing (residual charge effects)



Simulation Labels

```
1: 'QES',          # Quasi-elastic scattering
2: '1Kaon',        # Single Kaon production
3: 'DIS',          # Deep inelastic scattering
4: 'RES',          # Resonant pion production
5: 'COH',          # Coherent scattering
6: 'DFR',          # Diffractive scattering
7: 'NuEEL',        # Neutrino-electron elastic scattering
8: 'IMD',          # Inverse muon decay
9: 'AMNuGamma',    # Anomalous neutrino gamma
10: 'MEC',         # Meson exchange current
11: 'CEvNS',       # Coherent elastic neutrino-nucleus scattering
12: 'IBD',         # Inverse beta decay
13: 'GLR',         # Glashow resonance
14: 'IMDAnh',      # Annihilation inverse muon decay
15: 'PhotonCOH',   # Coherent photon production
16: 'PhotonRES',   # Resonant photon production
17: '1Pion',       # Single pion production
101: 'DMEL',       # Dark Matter elastic scattering
102: 'DMDIS',      # Dark Matter deep inelastic scattering
103: 'DME'         # Dark Matter excitation
```