Characterization of Delayed Ionization Backgrounds in the LZ Experiment

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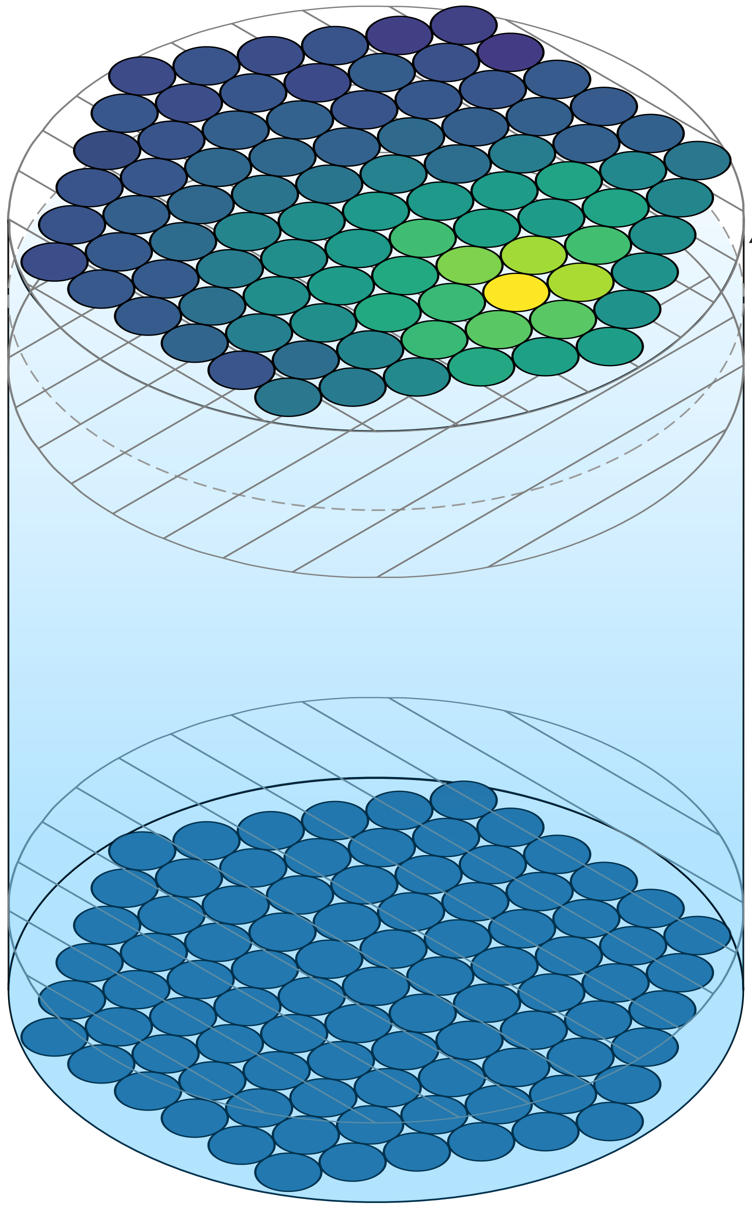
On Behalf of the LZ Collaboration

2023-11-07

Introduction

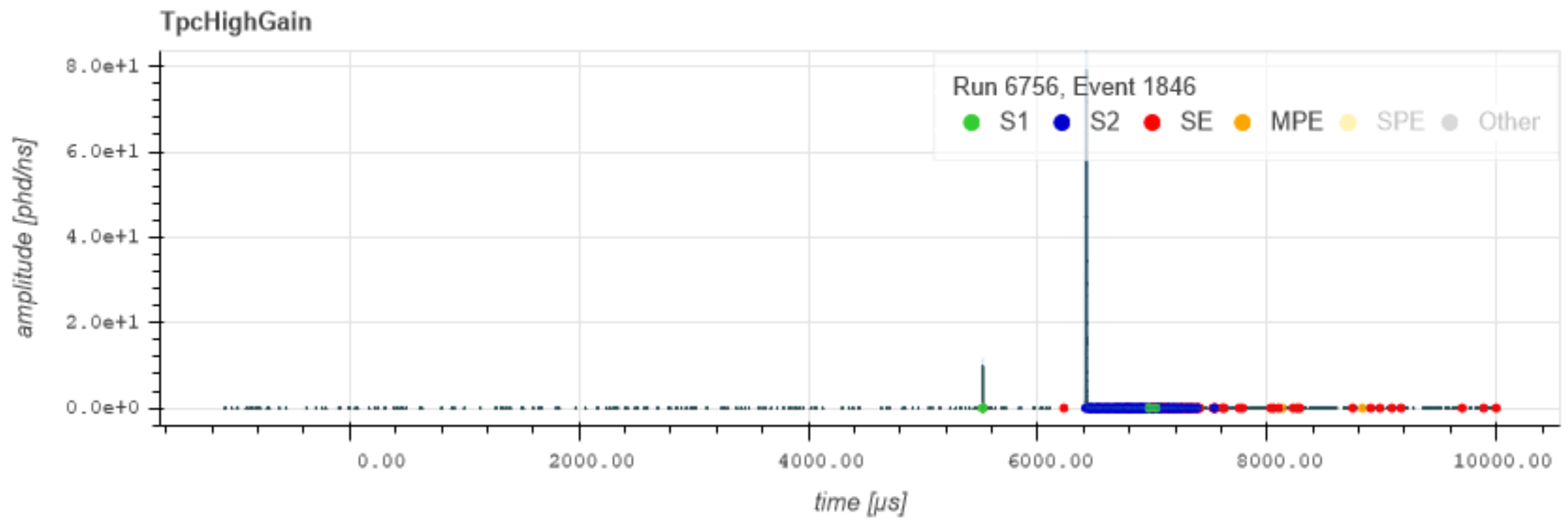
What are Electron Trains?

What do we know about them?

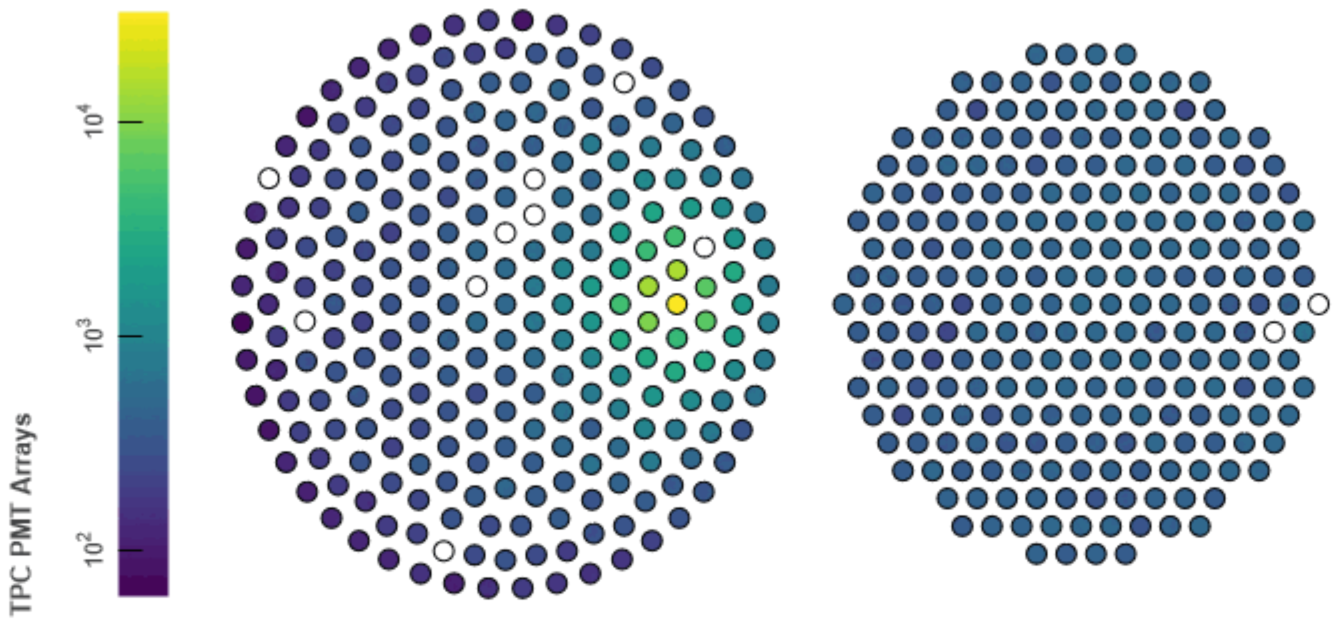


Electron Trains (AKA “e-trains”)

- “Electron trains” are a form of background noise in dual-phase TPCs
- Spurious single electrons (SEs) observed for at least a second after S2s
  - 30% livetime loss vetoing electron/photon-trains in LZ Science Run 1 (SR1) (*Linehan* [1])
- $\Delta t_{S2} < t_{drift} \rightarrow$ dominated by electrons from photoionization of TPC liquid & grids
- $\Delta t_{S2} > t_{drift} \rightarrow$ dominated by electrons captured & released by impurities in drift path?



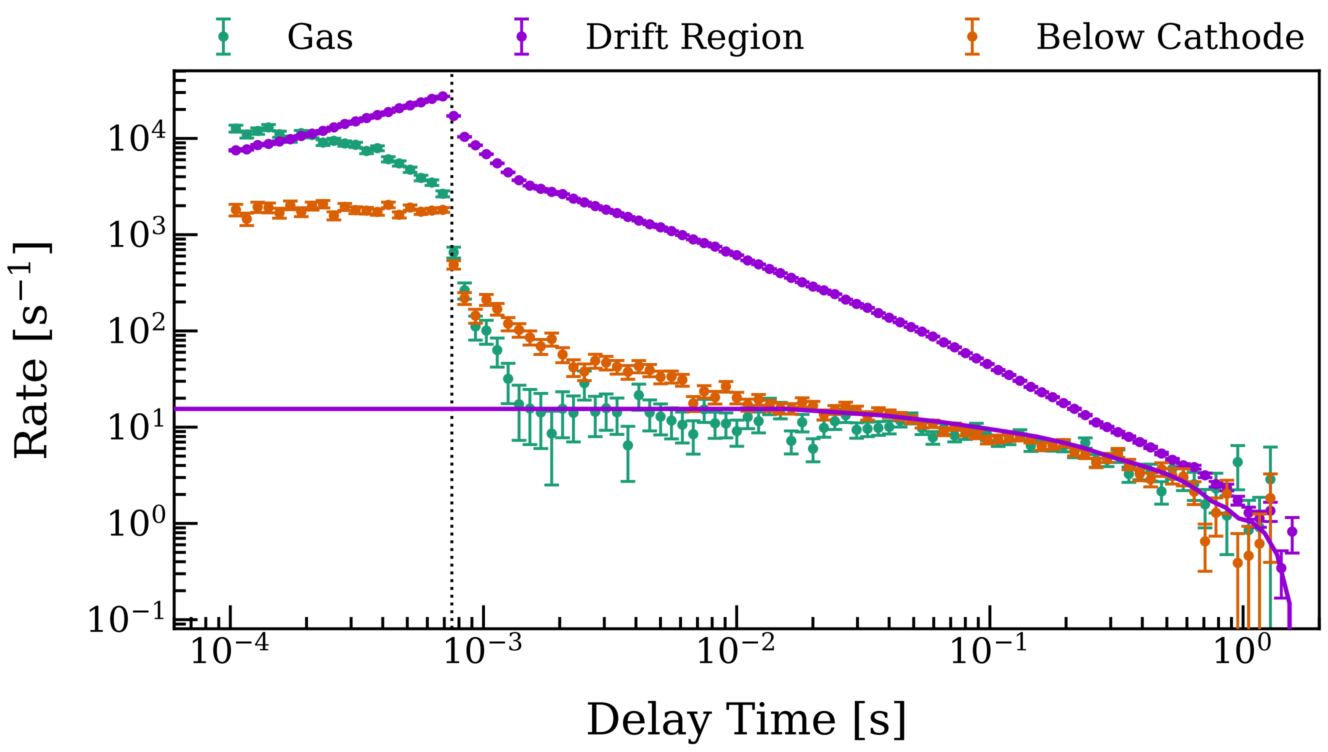
Single scatter S2 followed by SEs for at least 40ms (GIF)



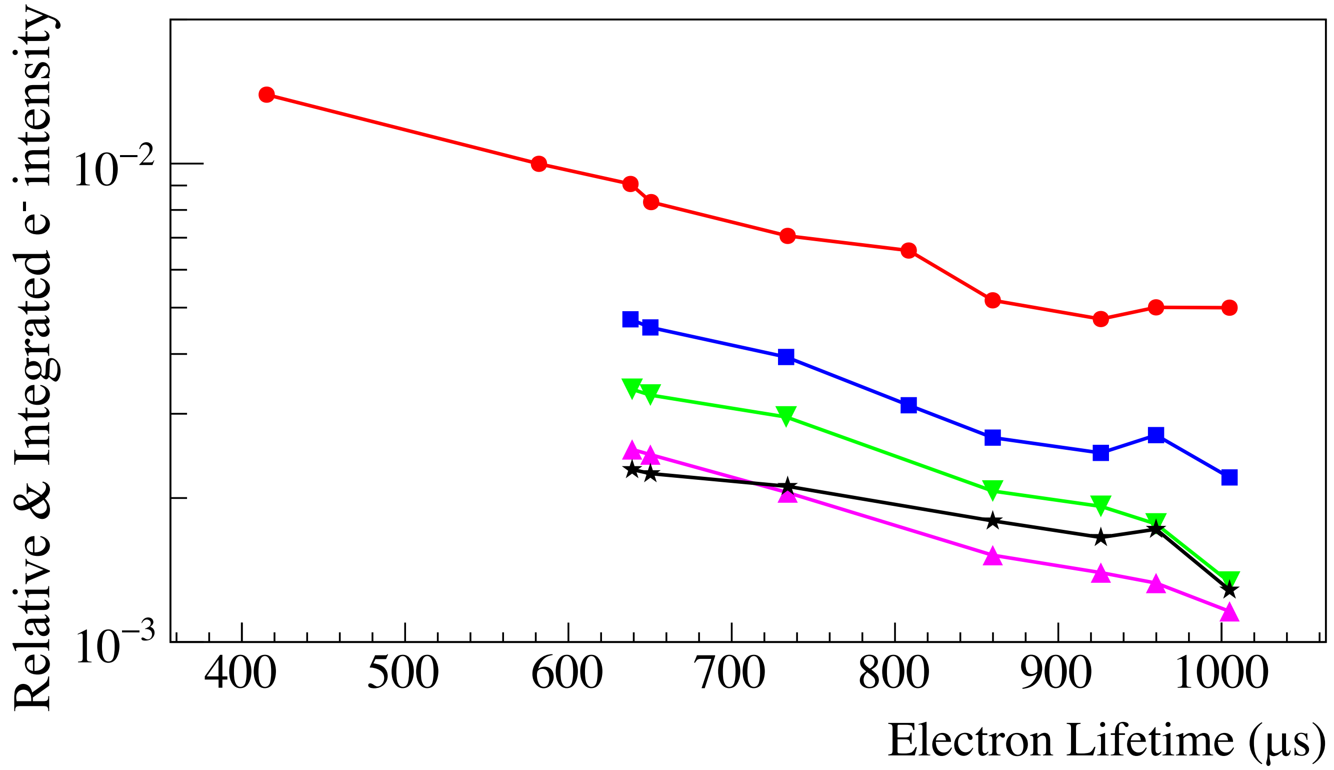
Top PMT array, left, showing position-correlated SEs (GIF)

Electron Train Hypotheses

- **Top**: “Drift” liquid events generate electron trains, not photoionization in gas or below cathode
- E-train rates are [2] [3]:
  - **Bottom**: correlated with electron lifetime
    - $\circ$ $\bullet$ $\rightarrow$ $\star$ $\implies$ increasing time since S2
  - Anti-correlated with drift time of progenitor (shown later)
- $\implies$ Liquid bulk origin, not liquid surface
  - Unclear physics; electrons captured and released by impurities in drift path?

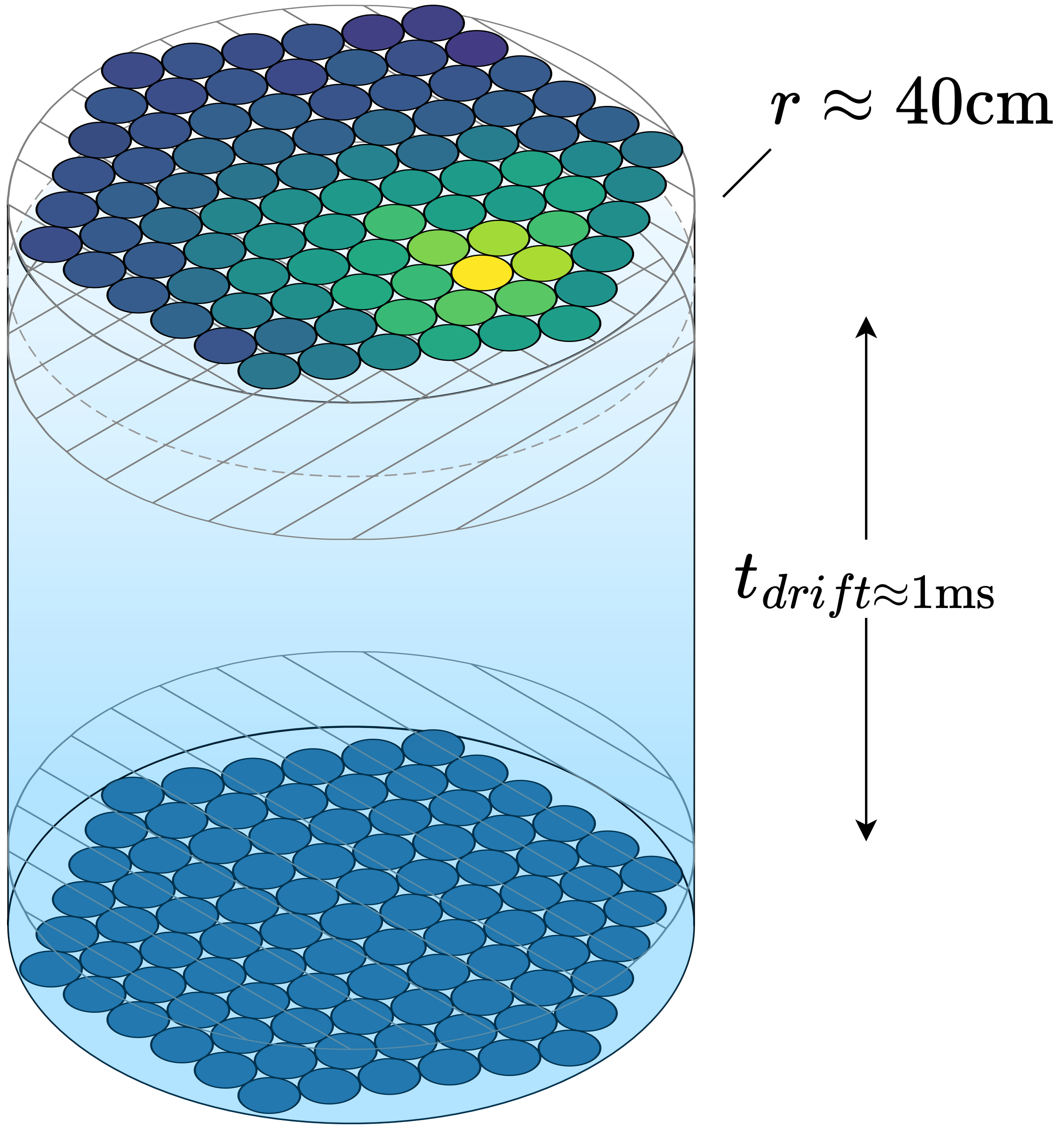


Electron trains in XENON1T [2]



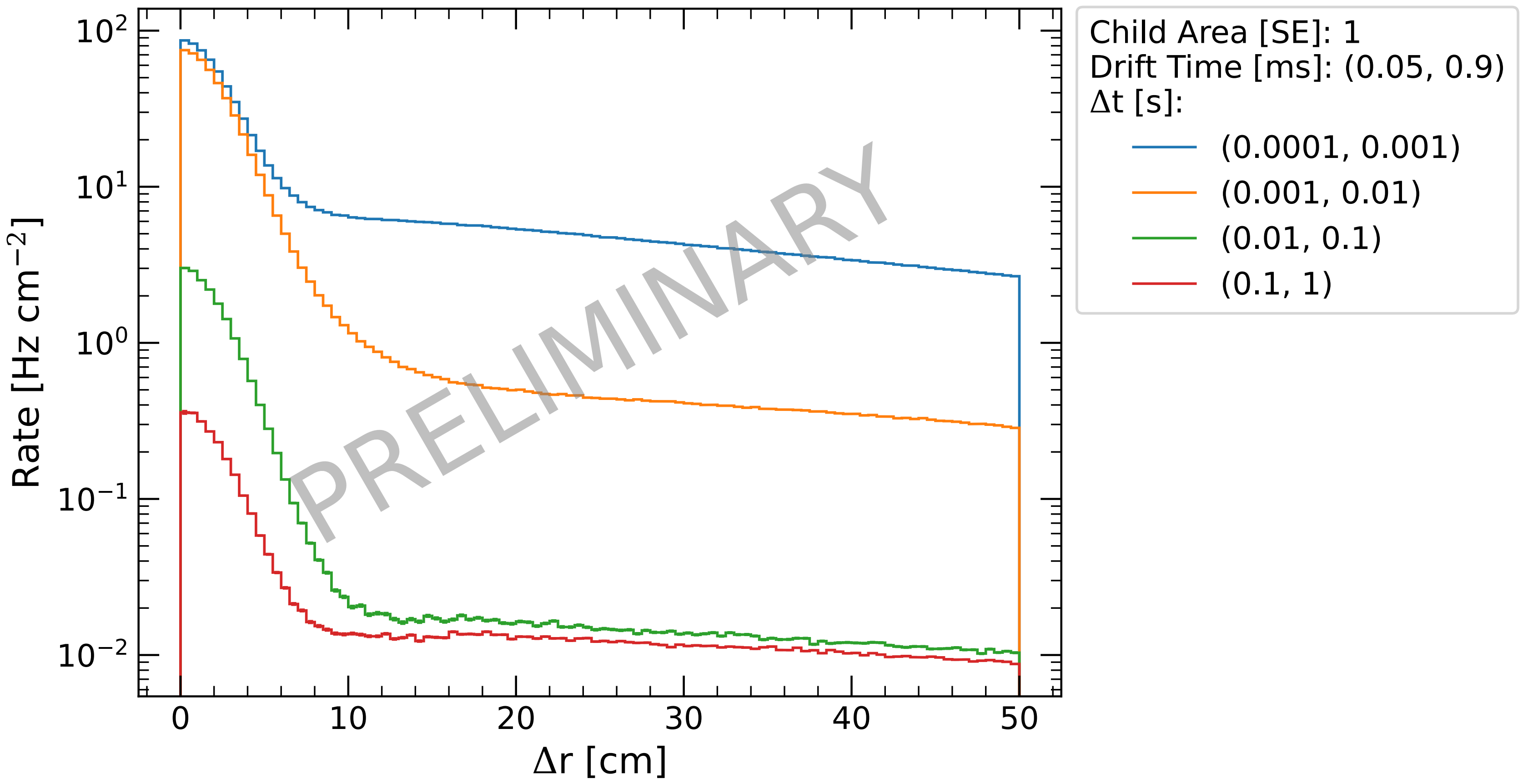
E-train electron lifetime dependence in LUX [3]

Electron Trains in LZ



Position Dependence of SEs after “Progenitor” S2s

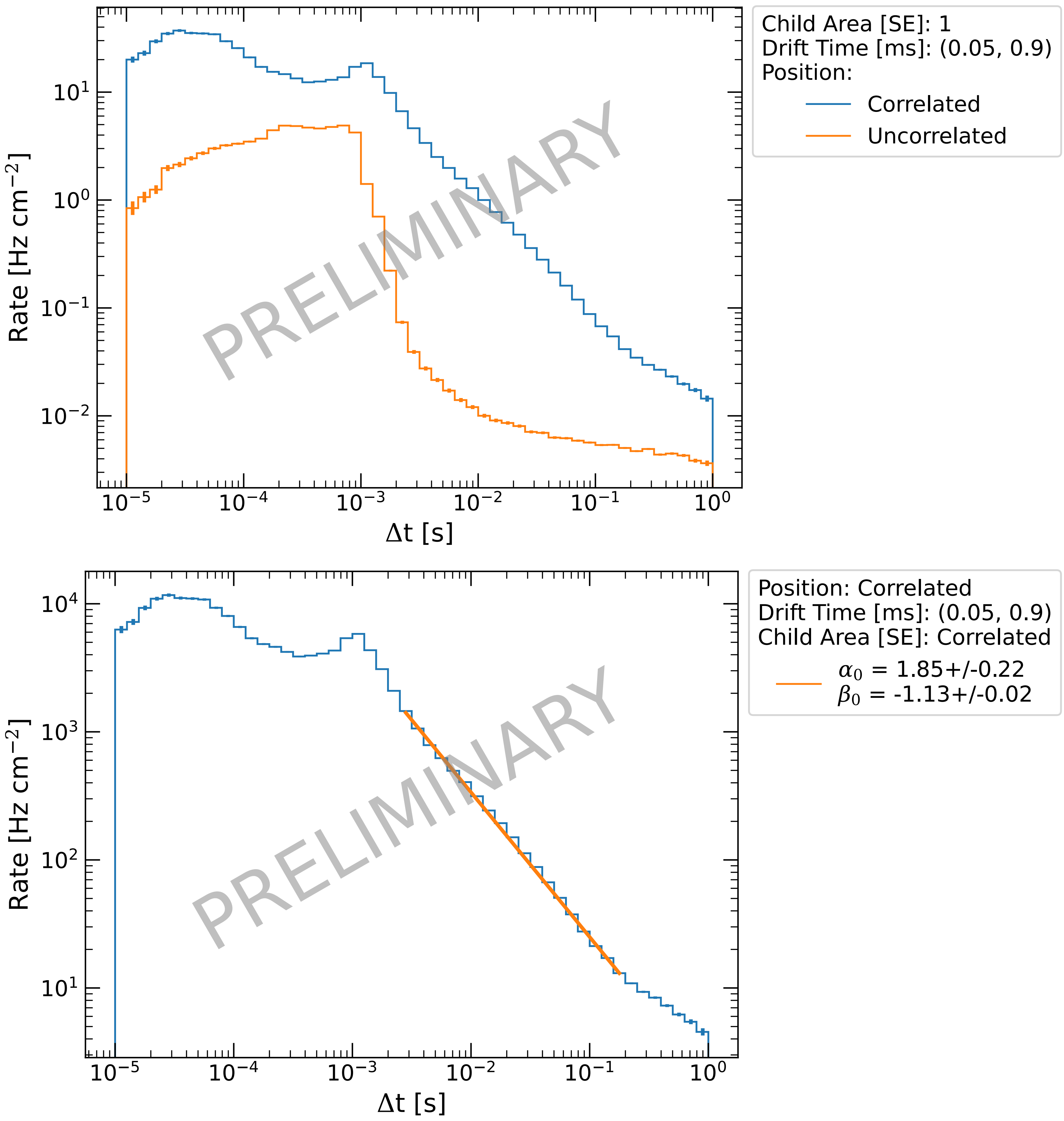
- Prog r < 55cm, area > 1e4 phd (~200 SE)
  - Skip if < 200ms after any pulse > 5e3 phd
- [Hz/cm^2] because larger $\Delta r \implies$ larger area in XY $\implies$ more child pulses
- Define position-correlated and uncorrelated child pulses
  - p-corr: Δr < 10cm
  - p-uncorr: 20cm < Δr < 30cm
- Position-correlated region captures power law (next slide), position-uncorrelated avoids power law and walls
- Prog drift time within fiducial volume



SE Rate vs. radial distance Δr between progenitor and child

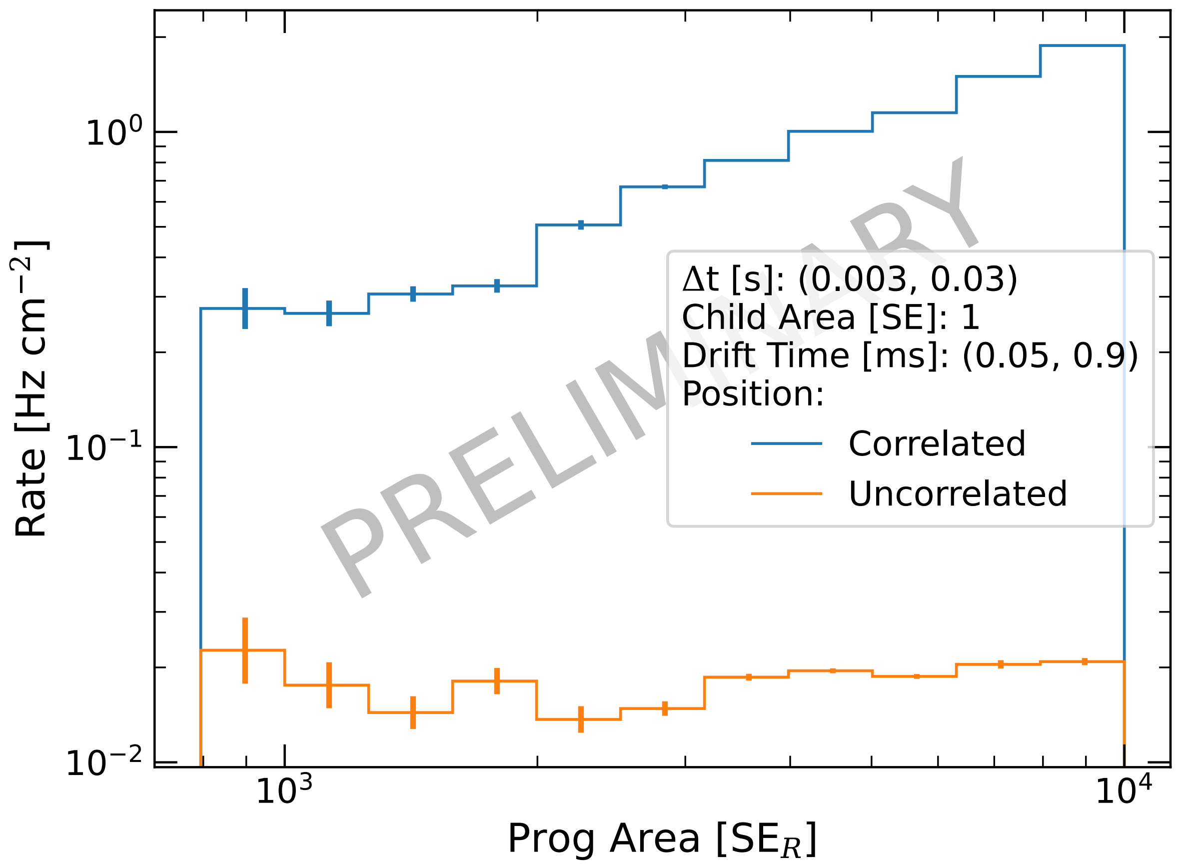
SE Rates vs. Time Since S2

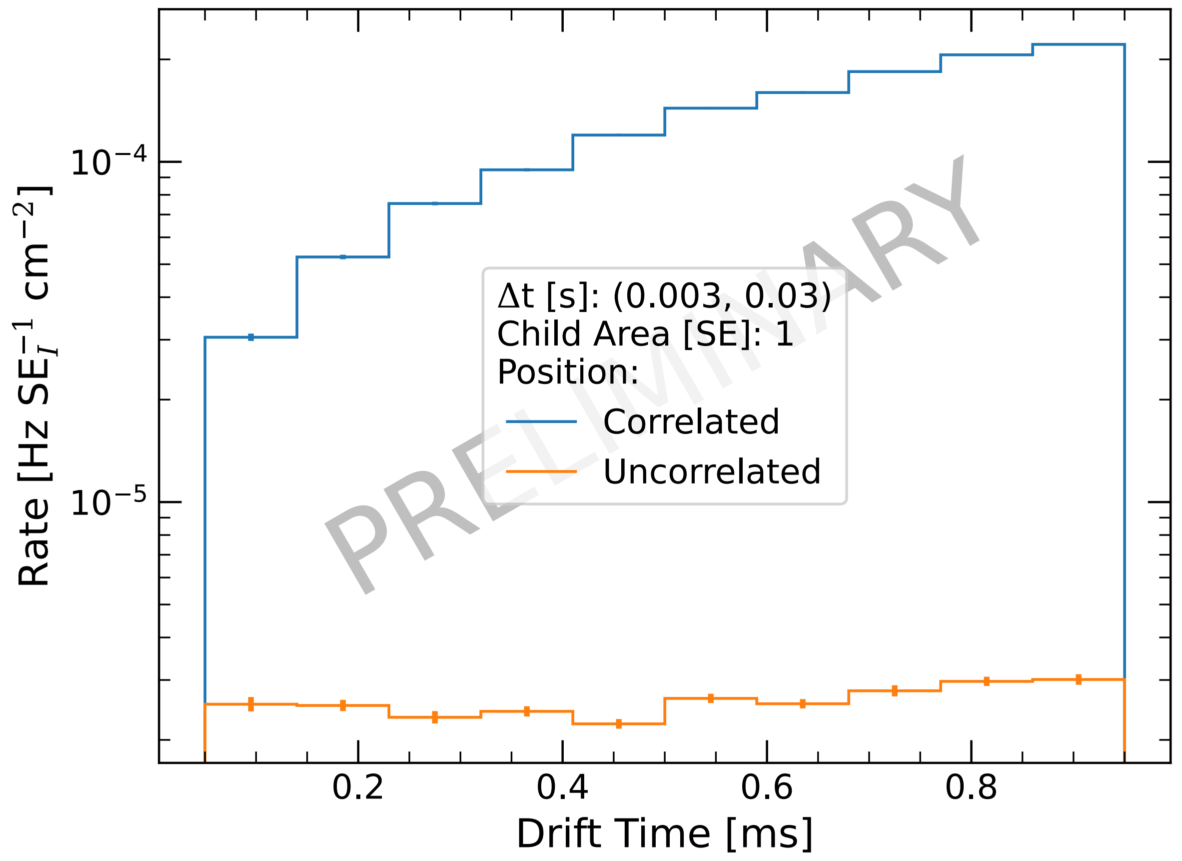
- **Top:** P-corr flux is more intense and appears to follow a power law
- **Bottom:** Fit power law $\alpha t^{-\beta}$ to p-corr rates
  - β consistent with LUX [3], XENON1T [2]
- Dip in rates prior to 1ms is known artifact of pulse pile-up from photoionization



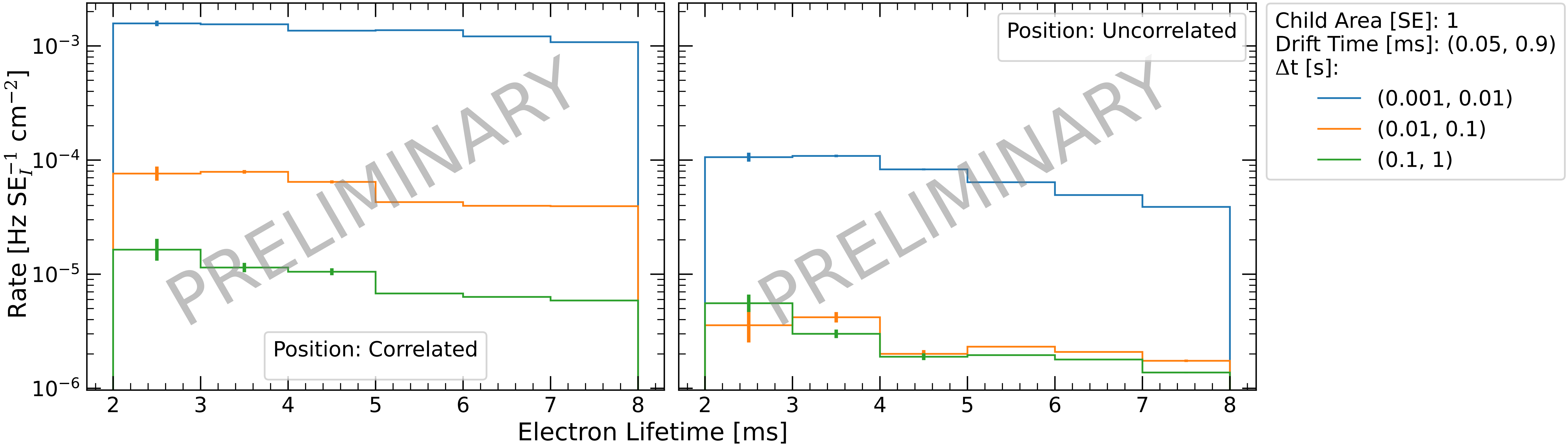
Drift Time and Progenitor Area

- **Top:** SE Rate vs. progenitor area
  - SE_R: Progenitor size in electrons extracted
- **Bottom:** SE Rate vs. progenitor drift time
  - Normalize by $SE_I = SE_S \exp(t_{drift}/\tau_{e^-})$
  - $SE_S \to SE_R$, corrected for extraction efficiency
- Δt [s]: (0.003, 0.3) avoids photoionization in p-uncorr rates
- P-uncorr pulses show virtually no correlation for either prog area or drift time
  - Favors explanation of uncorrelated pulses coming from previous e-trains (*XENON1T* [2])





Electron Lifetime



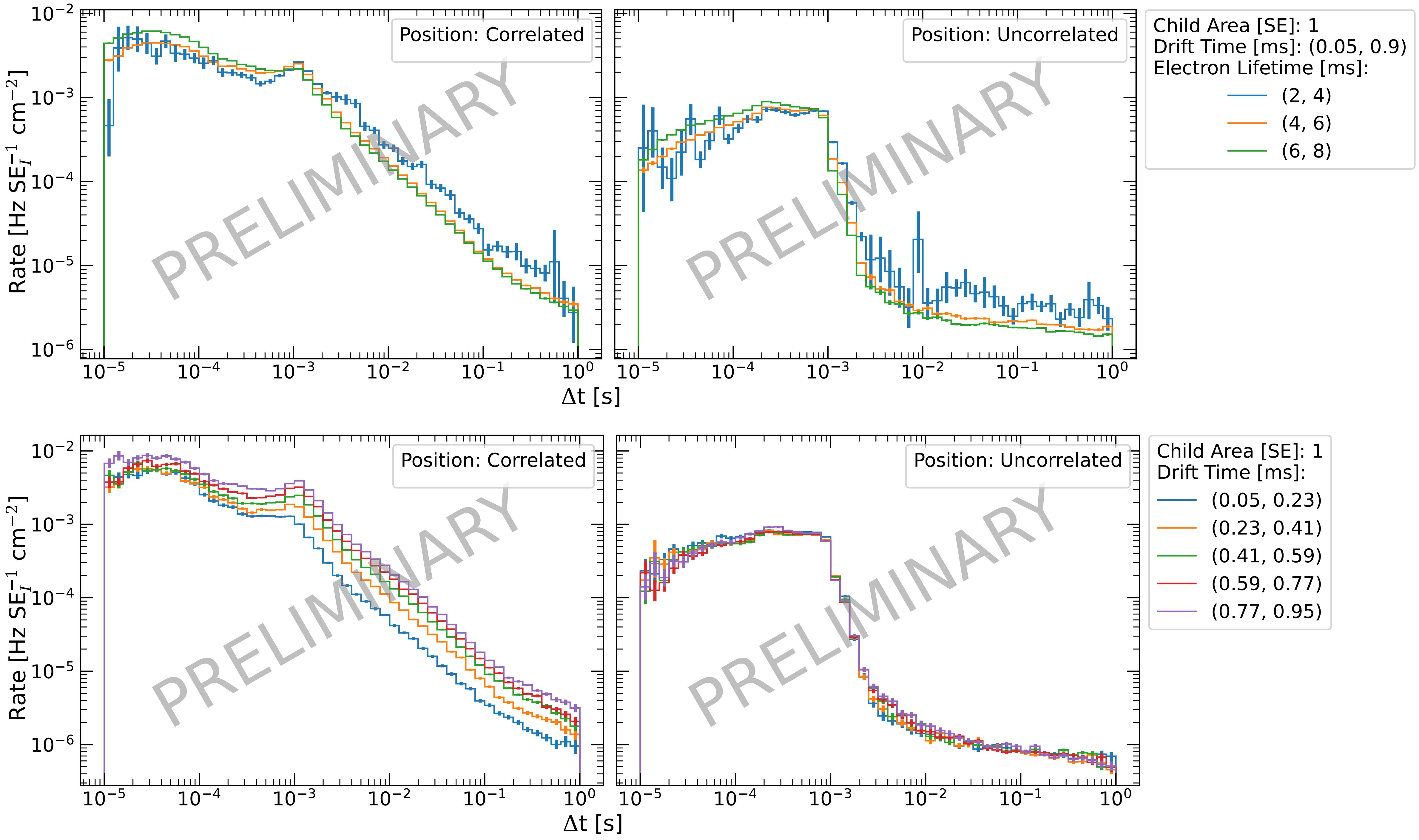
- Rates in SR1 exhibit dependence on electron lifetime up to 8ms

Electron Loss Normalization

Advancing the Liquid Bulk Hypothesis

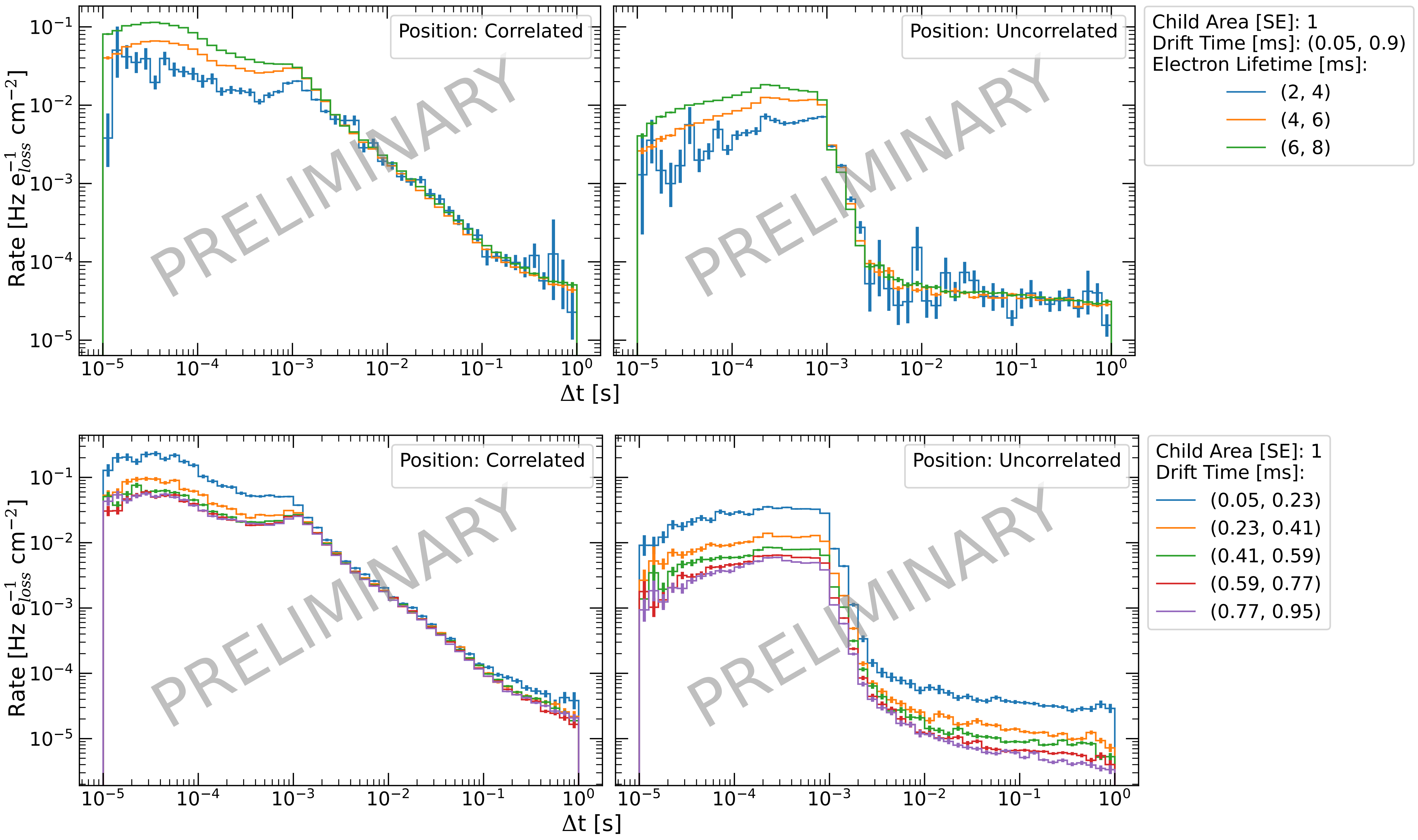
Electron Lifetime and Drift Time

- Electron lifetime and drift time dependence hint at liquid bulk origin
- Normalizing by SE_I does not cancel out dependence



Electron Loss Normalization

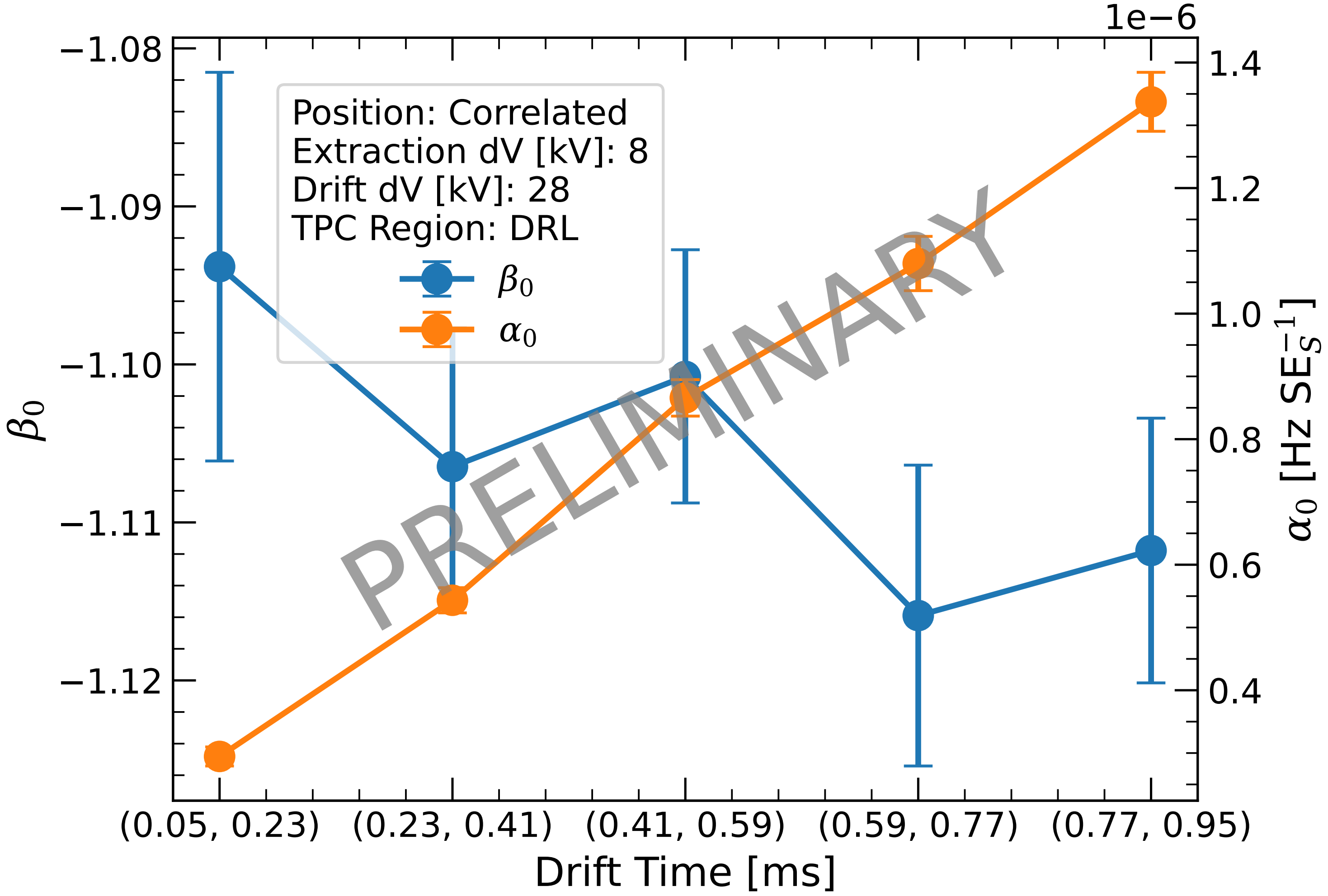
- Normalizing by $e_{loss} = SE_I - SE_S$ unifies drift time and electron lifetime
- Clear indication that power law originates with liquid bulk impurities
- Also shows (again) lack of correlation for uncorrelated backgrounds



“Drift” Field Dependence

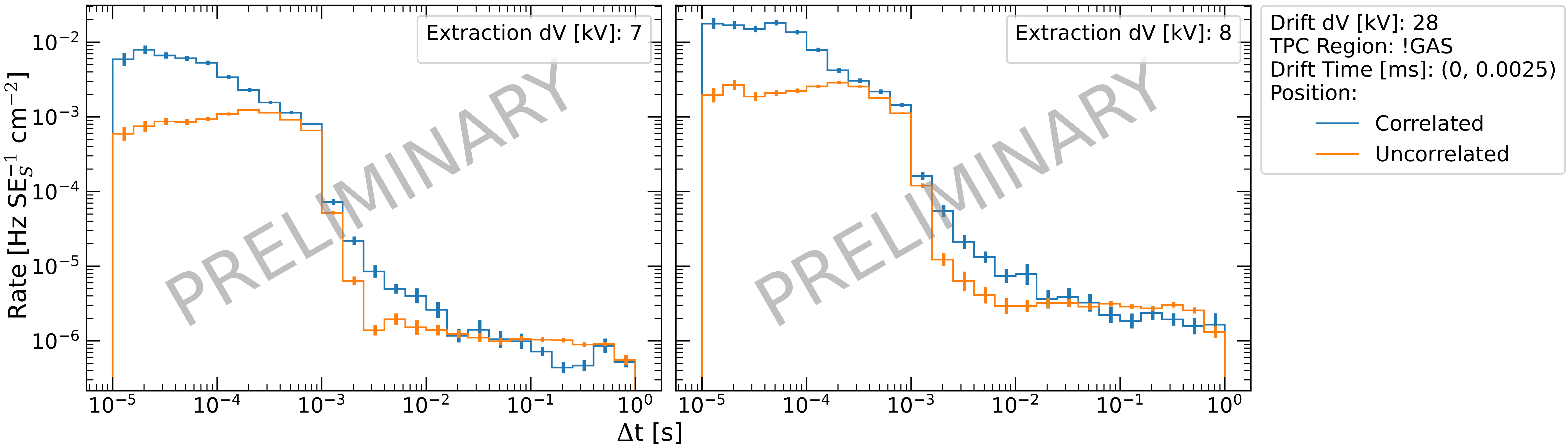
Two TPCs for the Price of One

- Distinguish between extraction liquid (EXL) and drift liquid (DRL) single scatters with drift time
- Use top-bottom asymmetry to exclude gas events
- EXL: a second TPC where the gate is a "cathode" i.e. $E_{drift} = E_{extract}$
- Vary extraction field, compare EXL and DRL e-trains
- Isolate "drift" field dependence with otherwise identical detector conditions!
  - **Right:** Drift time does *not* affect exponent
  - Correct for extraction efficiency and increased charge yield in EXL with SE_S normalization



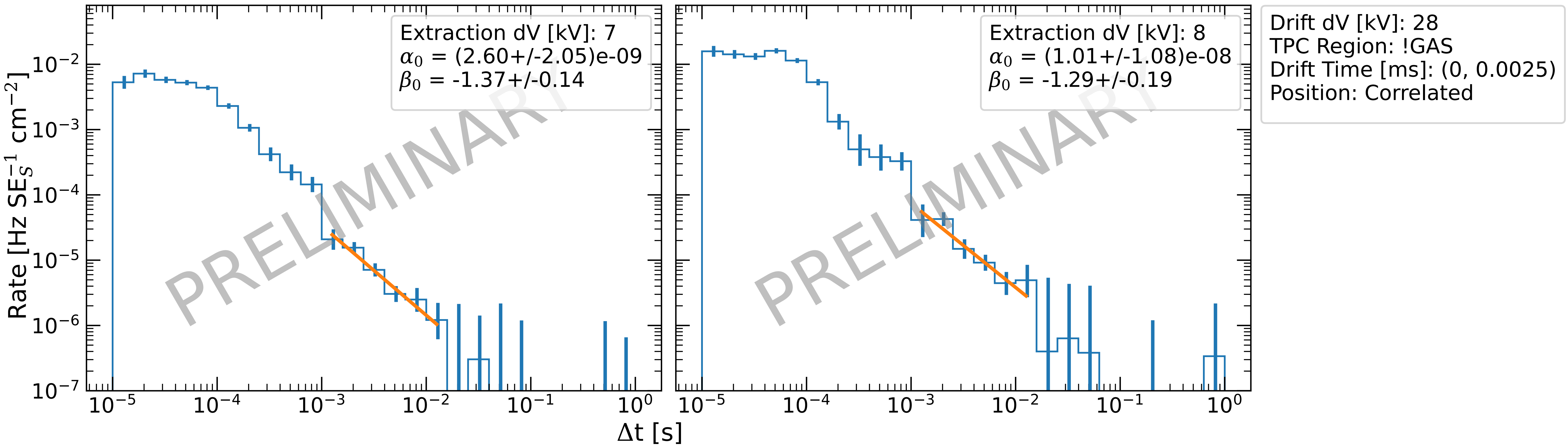
Fits to power law at different drift time bands show exponent does not depend on drift time

$\Delta V_{Extract}$ 7, 8kV - EXL Events



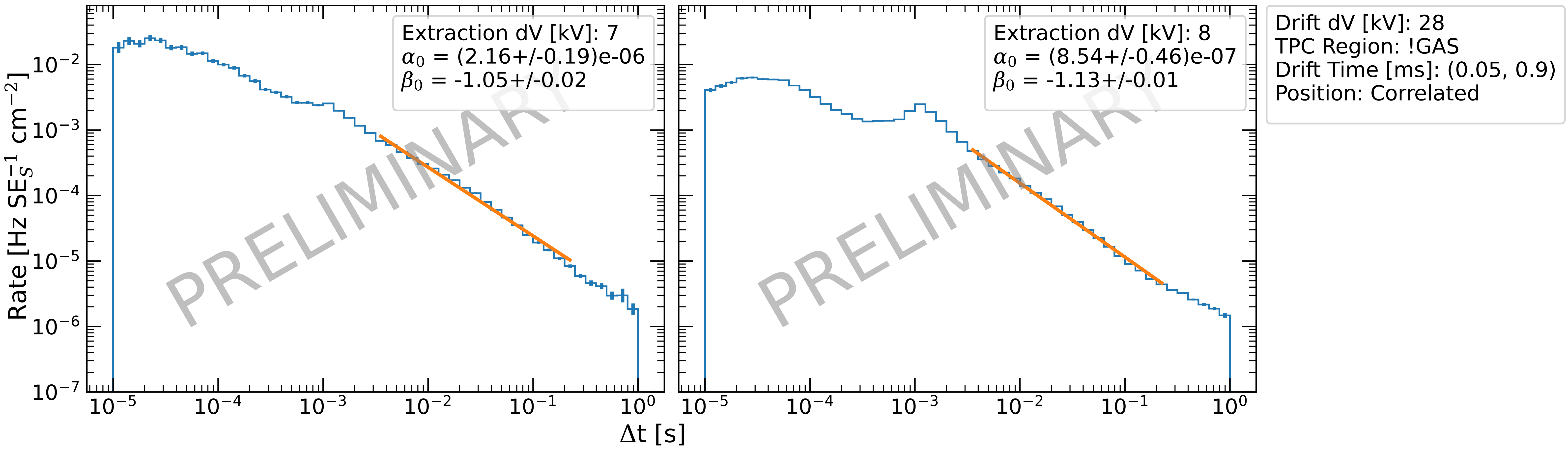
- E-trains from extraction liquid have much weaker delayed correlated pulses
- Try subtracting flux from uncorrelated pulses for slightly cleaner power law
- Liquid field $\approx$ 3400, 3900 V/cm for 7, 8kV respectively; radial field variation ~few %

$\Delta V_{Extract}$ 7, 8kV - Uncorrelated Subtraction



- Exponent is steeper than typical ~1.0-1.1 from drift liquid events (~0.5-1 sigma difference)
- Gate grid at 2.5us drift time; no change in exponents with drift time cut at 2us

$\Delta V_{Extract}$ 7, 8kV - DRL Events

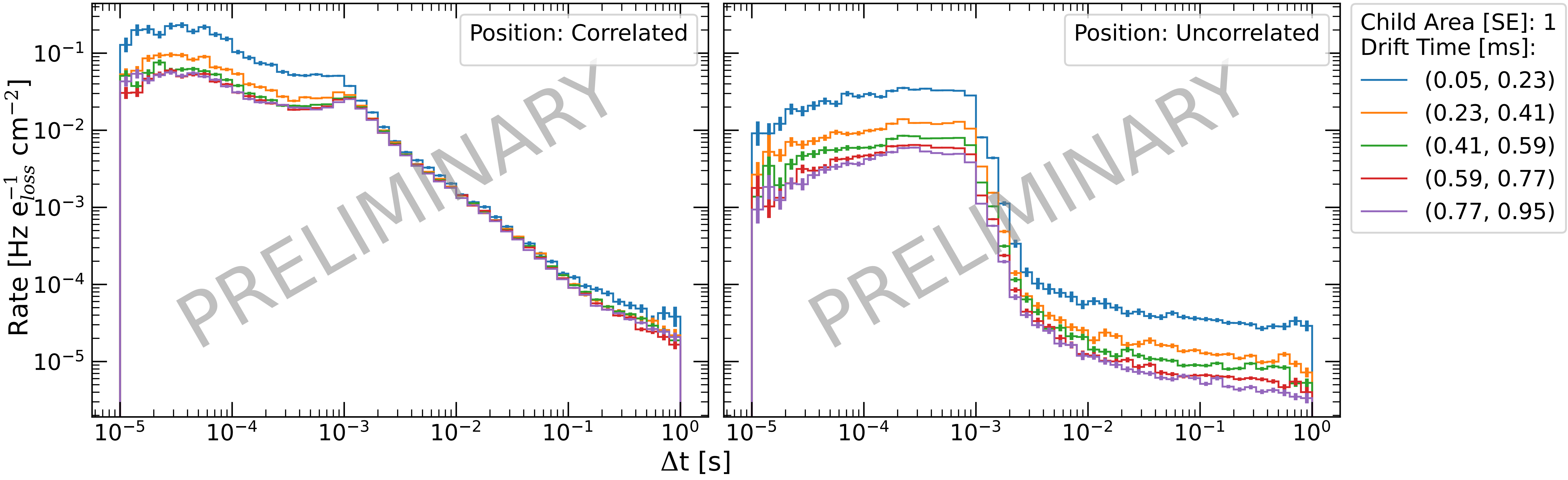


- Rate curves shown here from same datasets, different drift time cut
- Appears compatible with “weak” extraction field dependence reported by XENON1T [2]
- $\implies$ Field in drift path could influence a time constant in power law exponent

Conclusions

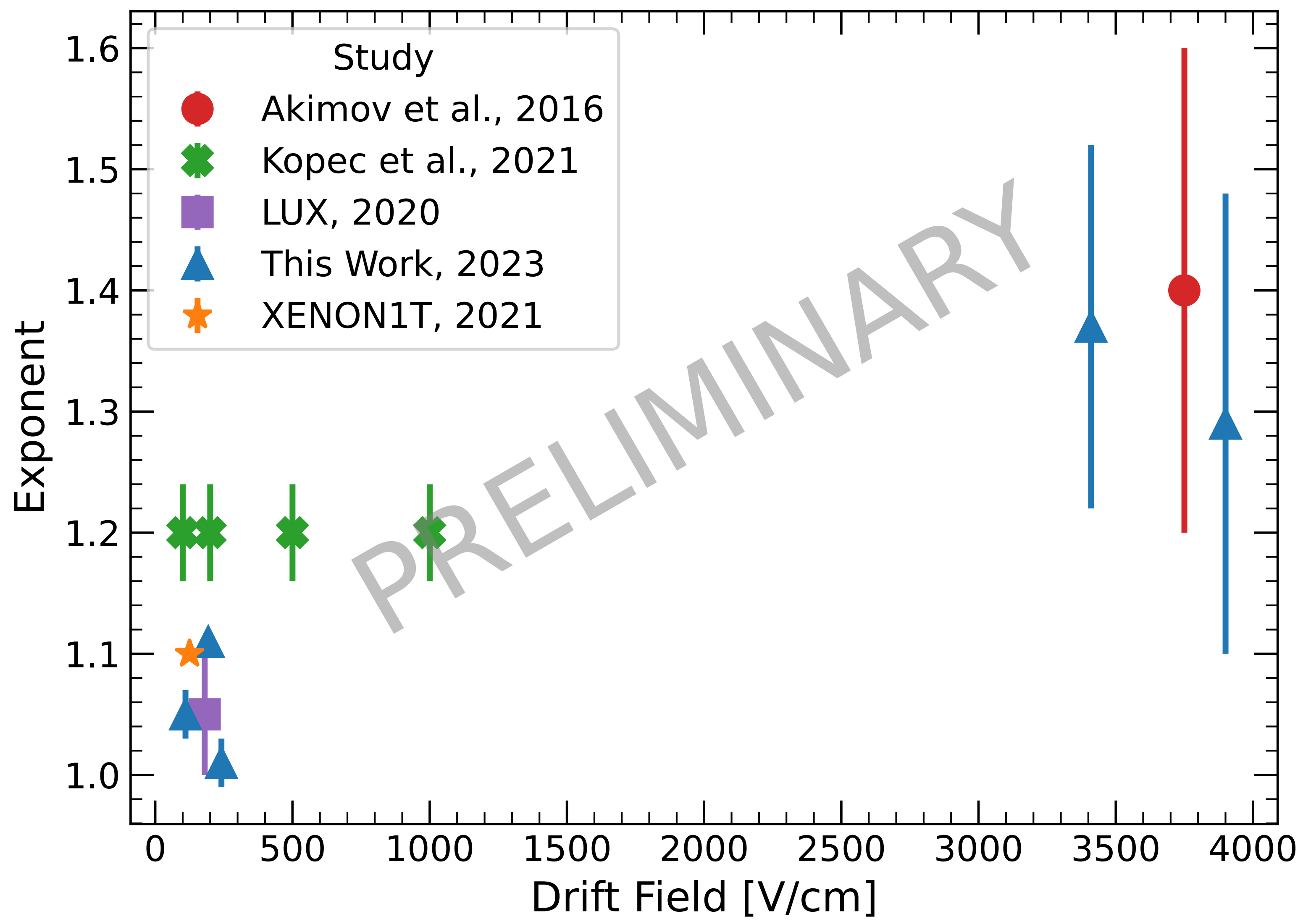
Summary of General Characterization

- Power law observed for rate of single electron pulses following S2s in drift region
- P-uncorr pulses also uncorrelated w/other progenitor characteristics e.g. area and drift time
- **Bottom:** e_{loss} normalization appears to unify electron lifetime and drift time dependence
  - Strong evidence for liquid bulk impurities as dominant factor in power law



Summary of Possible “Drift” Field Dependence

- Simultaneous analysis of e-trains in extraction liquid (EXL) and drift liquid (DRL)
- Steeper exponent at field > 3 kV/cm?
  - Apparent agreement with result from Akimov *et al.* [4]
- Exponent in DRL at field ≈ 180 V/cm matches literature
- Studies of this effect are worth pursuing to gain a better understanding of e-train physics and modeling!



Note: value for study conducted by Kopec et al. [5] was reported for 500 V/cm and “unchanged” for other fields

Acknowledgements 👏

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ibs Institute for Basic Science

Sanford Underground Research Facility
South Dakota Science and Technology Authority

UKRI Science and Technology Facilities Council

Department of Energy · United States of America

Thank you to our sponsors and 37 participating institutions!

References

[1] R. E. Linehan, T. Shutt, D. S. Akerib, P. Burchat, and A. Friedland, High Voltage Electrode Development and the LZ Experiment's WIMP Search, PhD thesis, 2022.

[2] E. Aprile et al., *Emission of Single and Few Electrons in XENON1T and Limits on Light Dark Matter*, (2021).

[3] D. S. Akerib et al., *Investigation of Background Electron Emission in the LUX Detector*, Physical Review D **102**, 092004 (2020).

[4] D. Yu. Akimov et al., *Observation of Delayed Electron Emission in a Two-Phase Liquid Xenon Detector*, Journal of Instrumentation **11**, C03007 (2016).

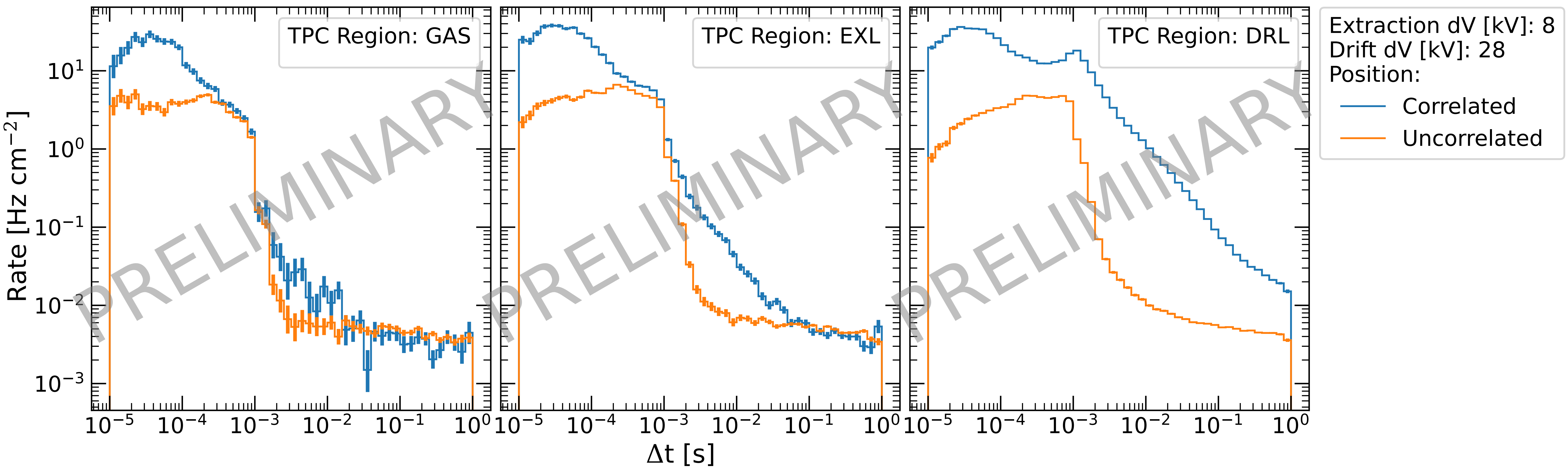
[5] A. Kopec, A. L. Baxter, M. Clark, R. F. Lang, S. Li, J. Qin, and R. Singh, *Correlated Single- and Few-Electron Backgrounds Milliseconds After Interactions in Dual-Phase Liquid Xenon Time Projection Chambers*, Journal of Instrumentation **16**, P07014 (2021).

Backup

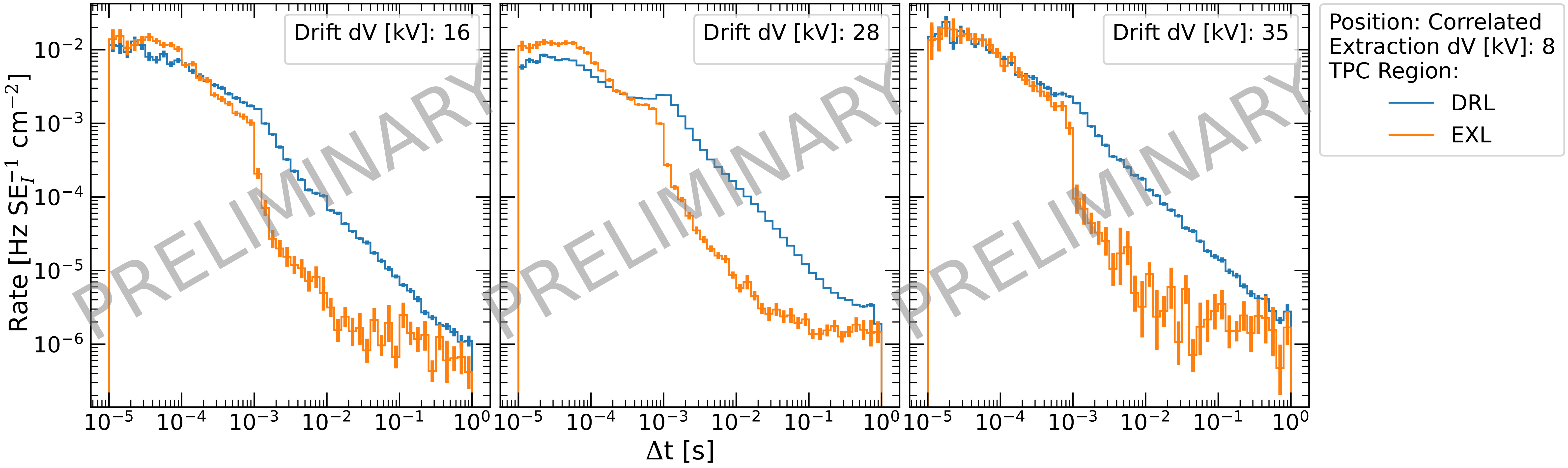
Normalization Reference

Factor	Description
$SE_R = S2_{phd}/n_{phd/SE}$	“Raw” (extracted) S2 area in units of single electrons
$SE_S = SE_R/e_{eee}$	“Surface” S2 area, i.e. SE_R corrected for extraction efficiency
$SE_I = SE_S \exp(t_{drift}/\tau_{e^-})$	“Initial” S2 area, i.e. SE_S corrected for drift losses
$e_{loss} = SE_I - SE_S$	Number of electrons lost while drifting
cm^2	Area of liquid surface subtended by radial selection of pulses

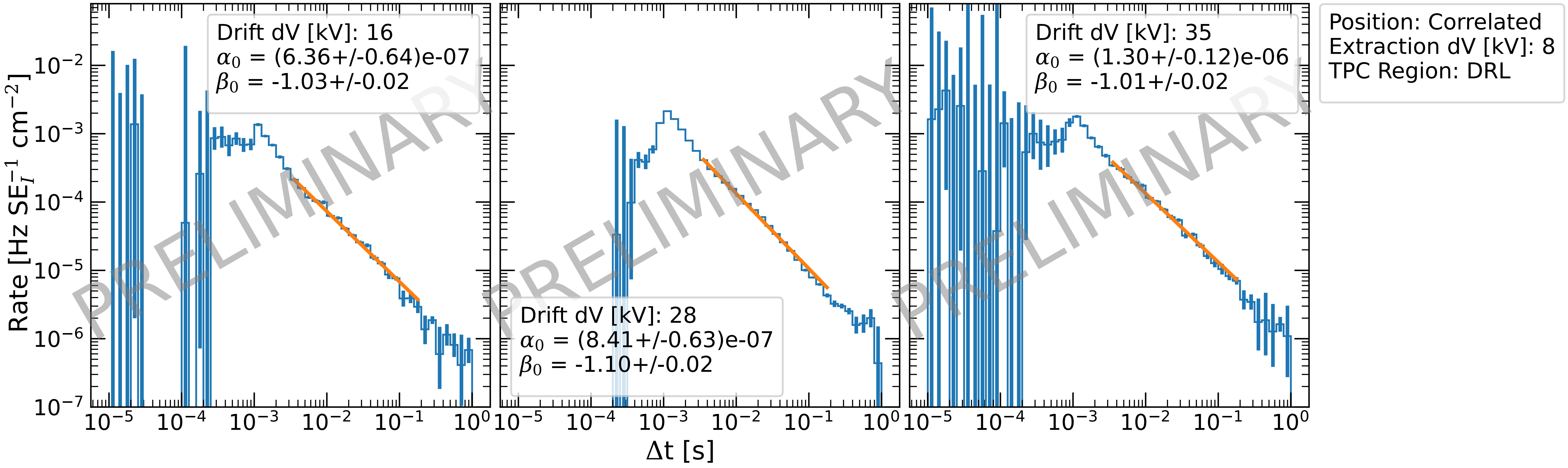
Electron Trains in TPC Regions



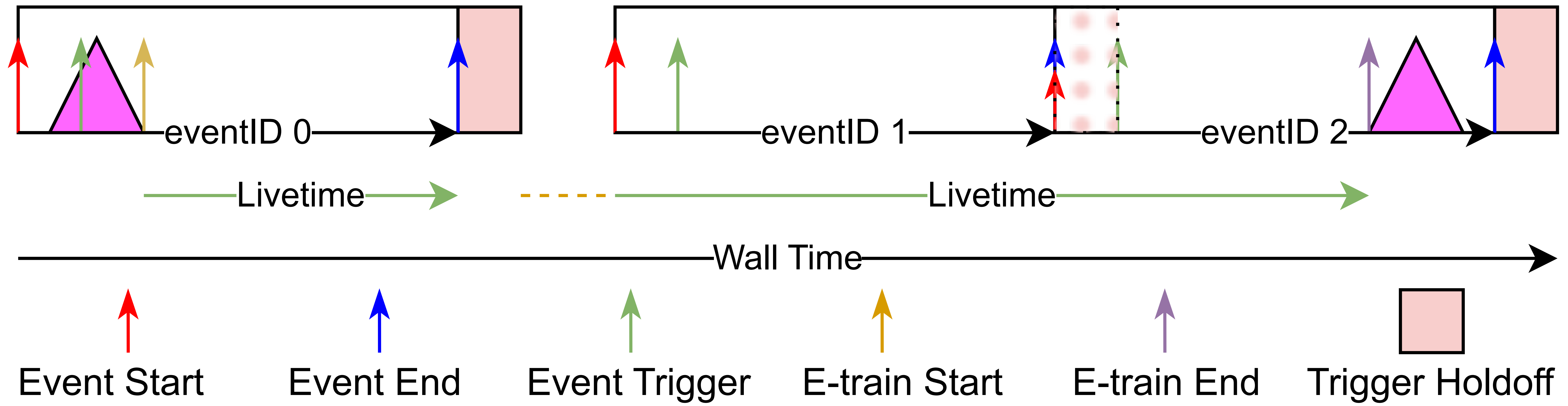
E_{drift} Sweep - DRL Events



E_{drift} Sweep - “Background” Subtraction in DRL Events



BigDEB Main Algorithm



- Livetime between windows is not counted unless trigger efficiency of pulse is ~100%