Modelling the accidental coincidence background in LUX-ZEPLIN for a light dark matter search

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on behalf of the LZ collaboration

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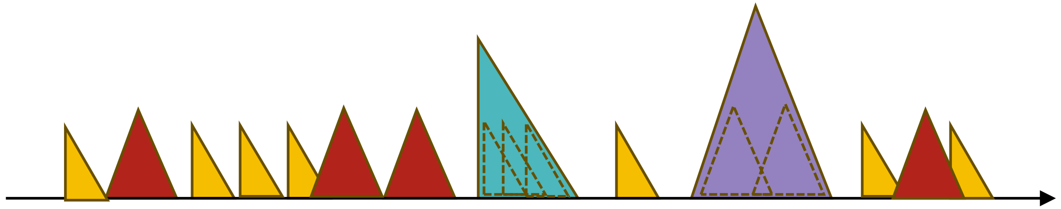
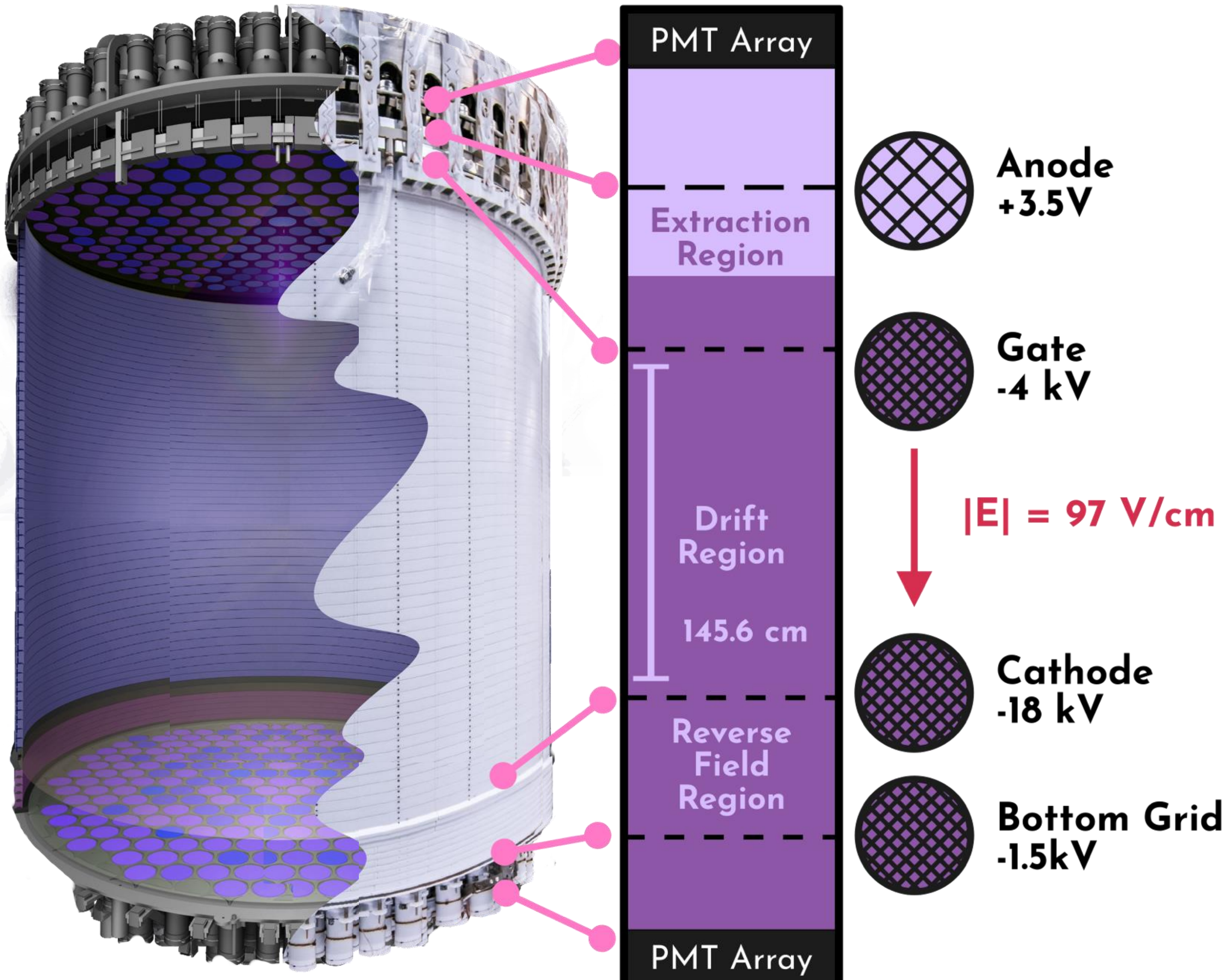


The LUX-ZEPLIN (LZ) experiment

Aims to directly detect dark matter

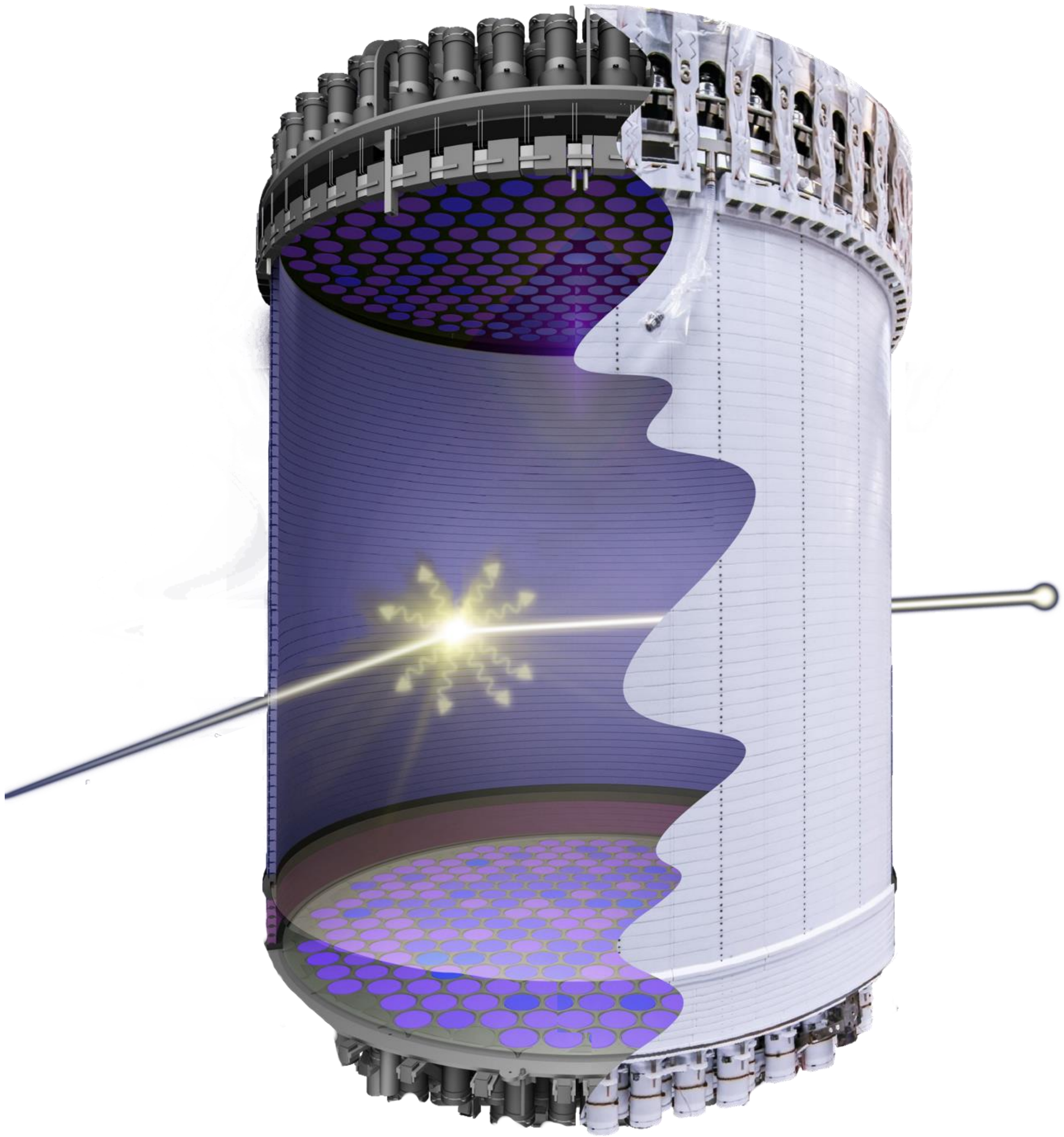
- Dual-phase time projection chamber (TPC)
- 7t of active liquid xenon
- 2 PMT arrays
- 4 high voltage grids



The LUX-ZEPLIN (LZ) experiment

S1: prompt scintillation signal

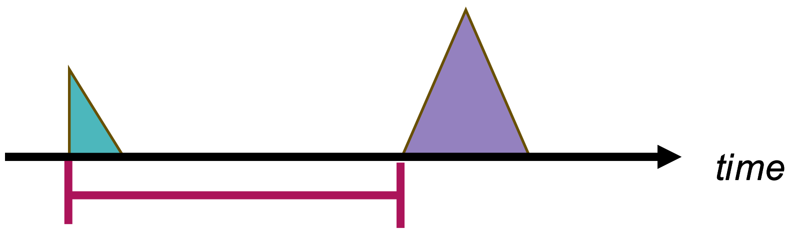
We require coincident hits in 3 PMTs



The LUX-ZEPLIN (LZ) experiment

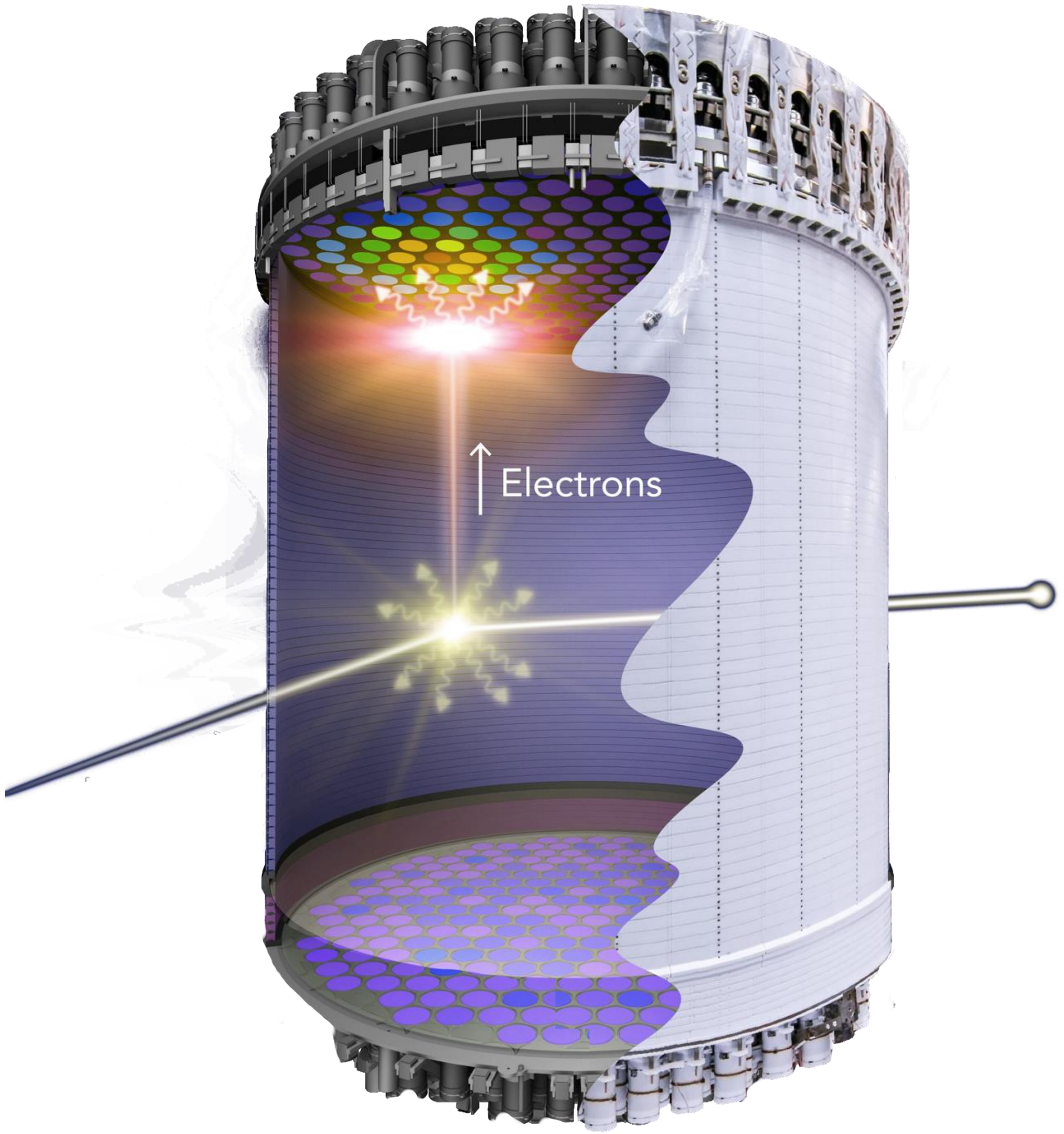
S1: prompt scintillation signal

S2: delayed electroluminescence



Drift time → Z position

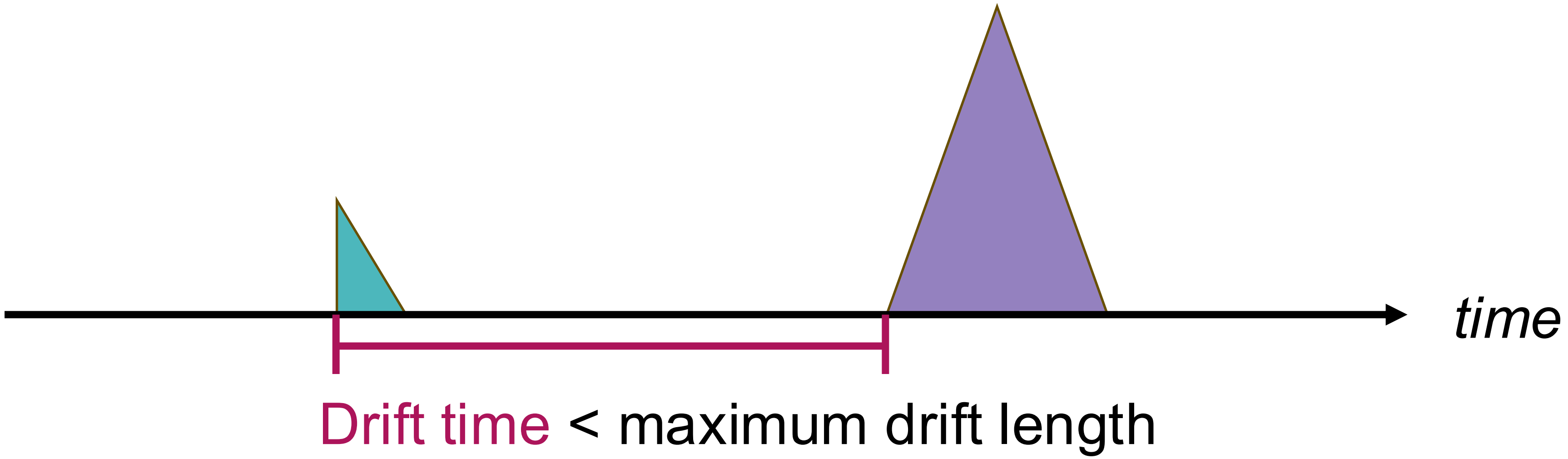
PMT hit map → XY reconstruction



Accidental Coincidence Backgrounds

Also observe S1s and S2s without their counterpart

Accidental coincidence event = **S1 pulse** + **S2 pulse** from a different source



Mistakenly appear as a single signal-like event!

How can you get an isolated pulse?

Isolated S1 (iS1)

Charge insensitive regions
- below cathode
- near walls

Isolated S2 (iS2)

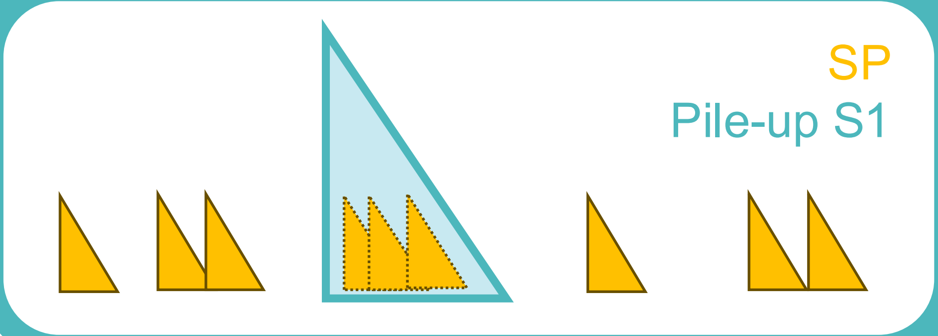
Pulse classification
- S1 merged into S2 due to short drift time
- Events below required 3 PMT coincident threshold for S1

How can you get an isolated pulse?

Isolated S1 (iS1)

Charge insensitive regions
- near walls
- below cathode

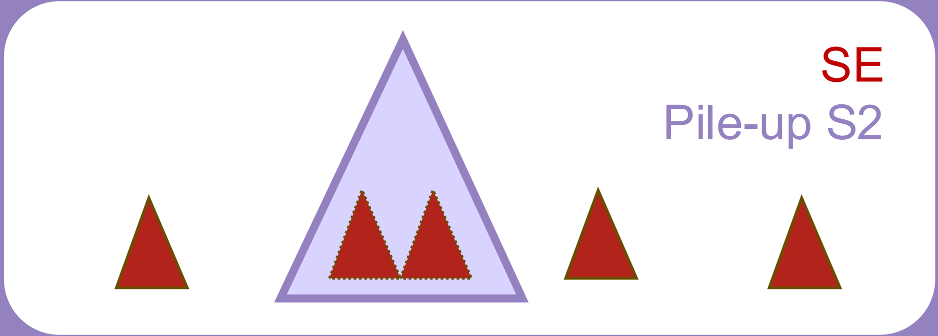
Pile-up of single photons (SPs):



Isolated S2 (iS2)

Pulse classification
- S1 merged into S2 due to short drift time
- Events below required 3 PMT coincidence for S1

Pile-up of single electrons (SEs):



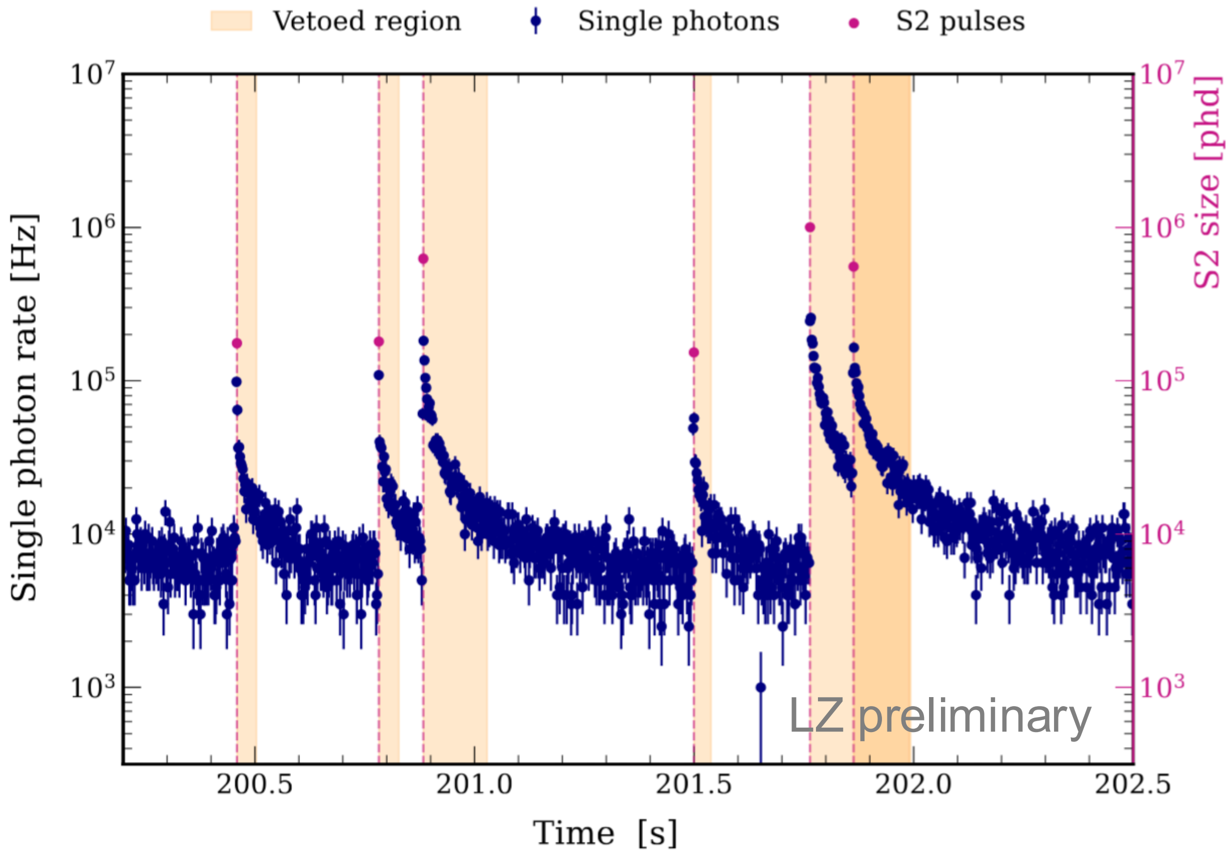
Causes of pile-up

Large S2 → elevated rate of single photons and single electrons

→ Increased rates of both pile-up S1s and S2s

Target with temporal veto

Rate still not constant in time



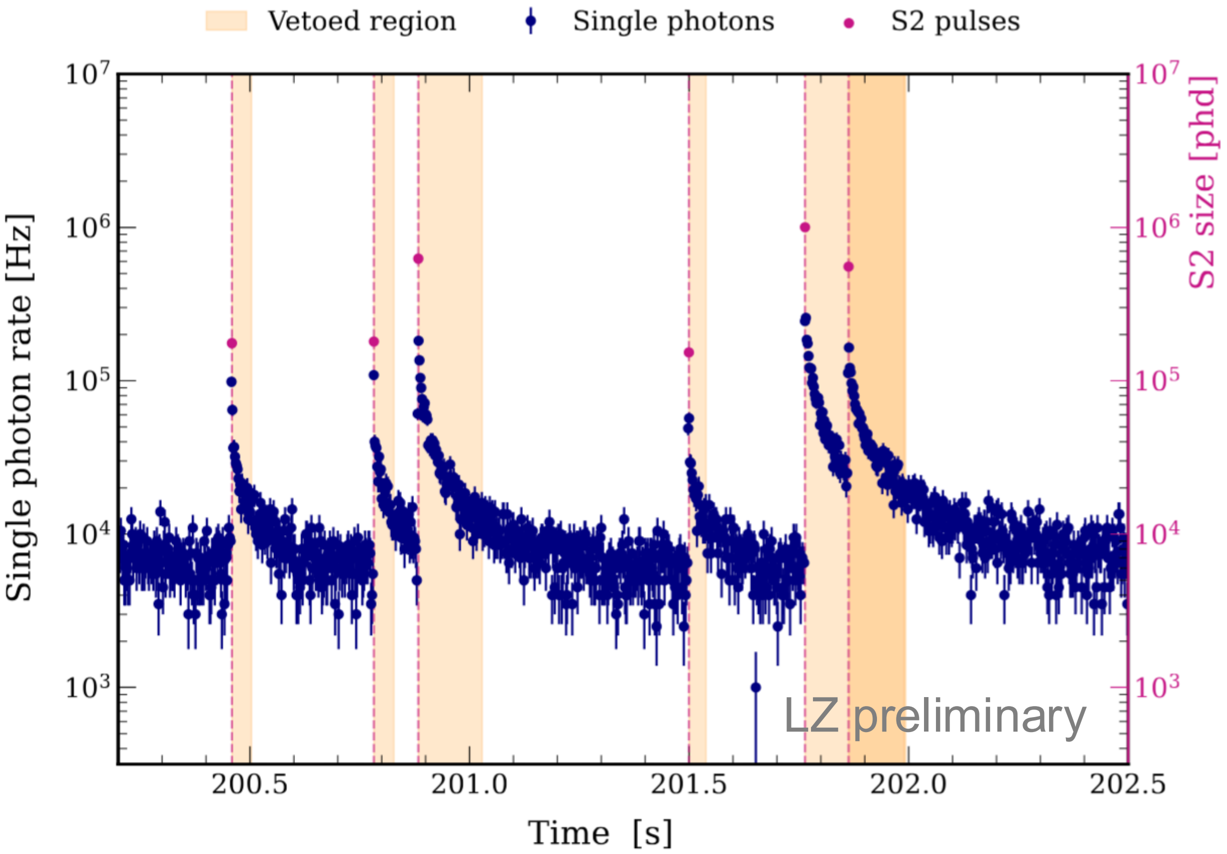
Causes of pile-up

Large S2 → elevated rate of single photons and single electrons
→ Increased rates of both pile-up S1s and S2s

Target with temporal veto

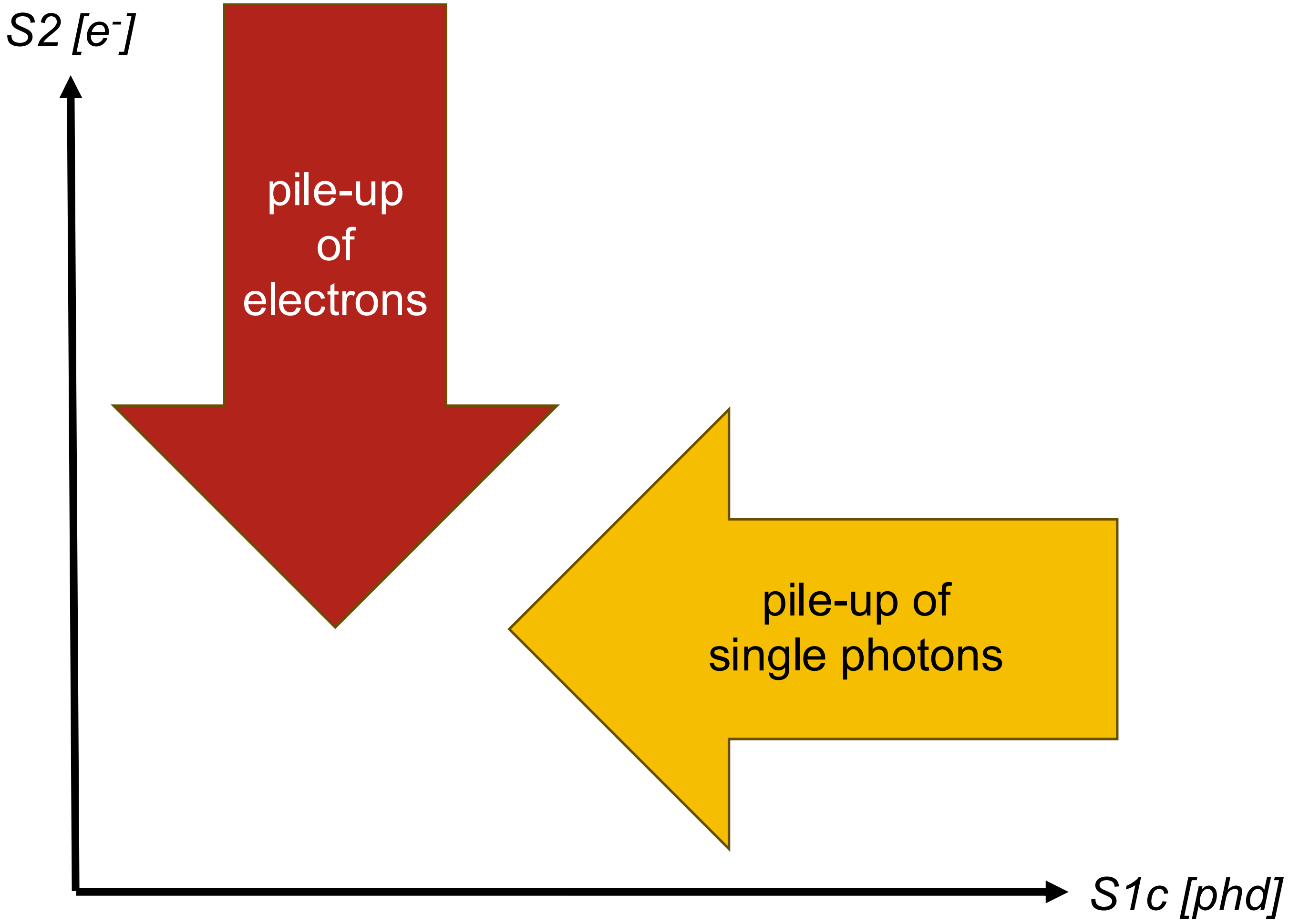
Rate still not constant in time

iS1 and iS2 rate:
- time varying
- correlated



Impact on light dark matter searches

- For S1 and S2 pulses formed via pile-up, smaller pulses are statistically more likely than larger ones
- Rate of accidental coincidence events increases with decreasing S1 and S2 size
- Pile-up pulses can evade the pulse-level cuts that have been effective against larger isolated pulses



Impact on light dark matter searches

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- Rate of accidental coincidence events increases with decreasing S1 and S2 size
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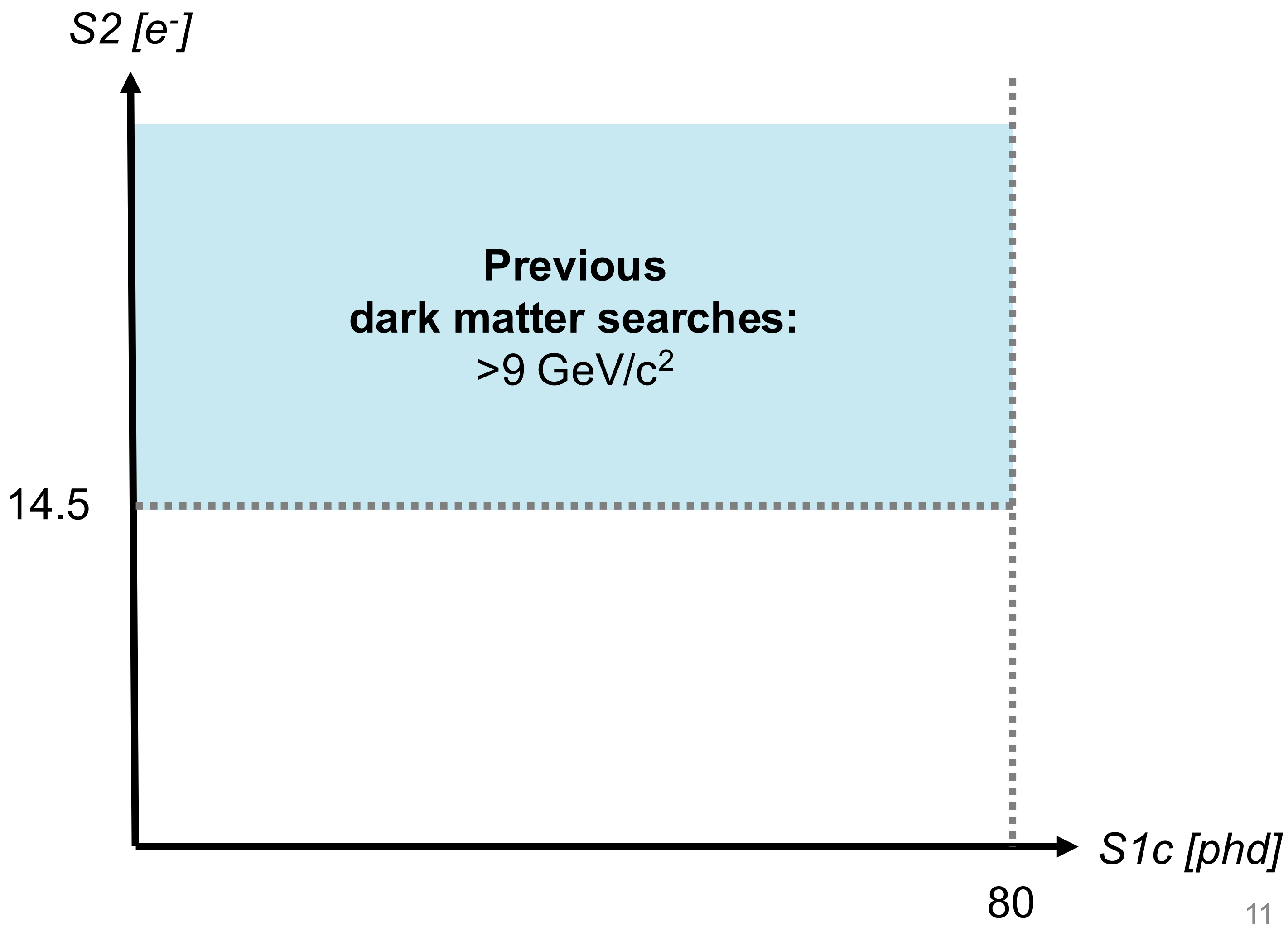
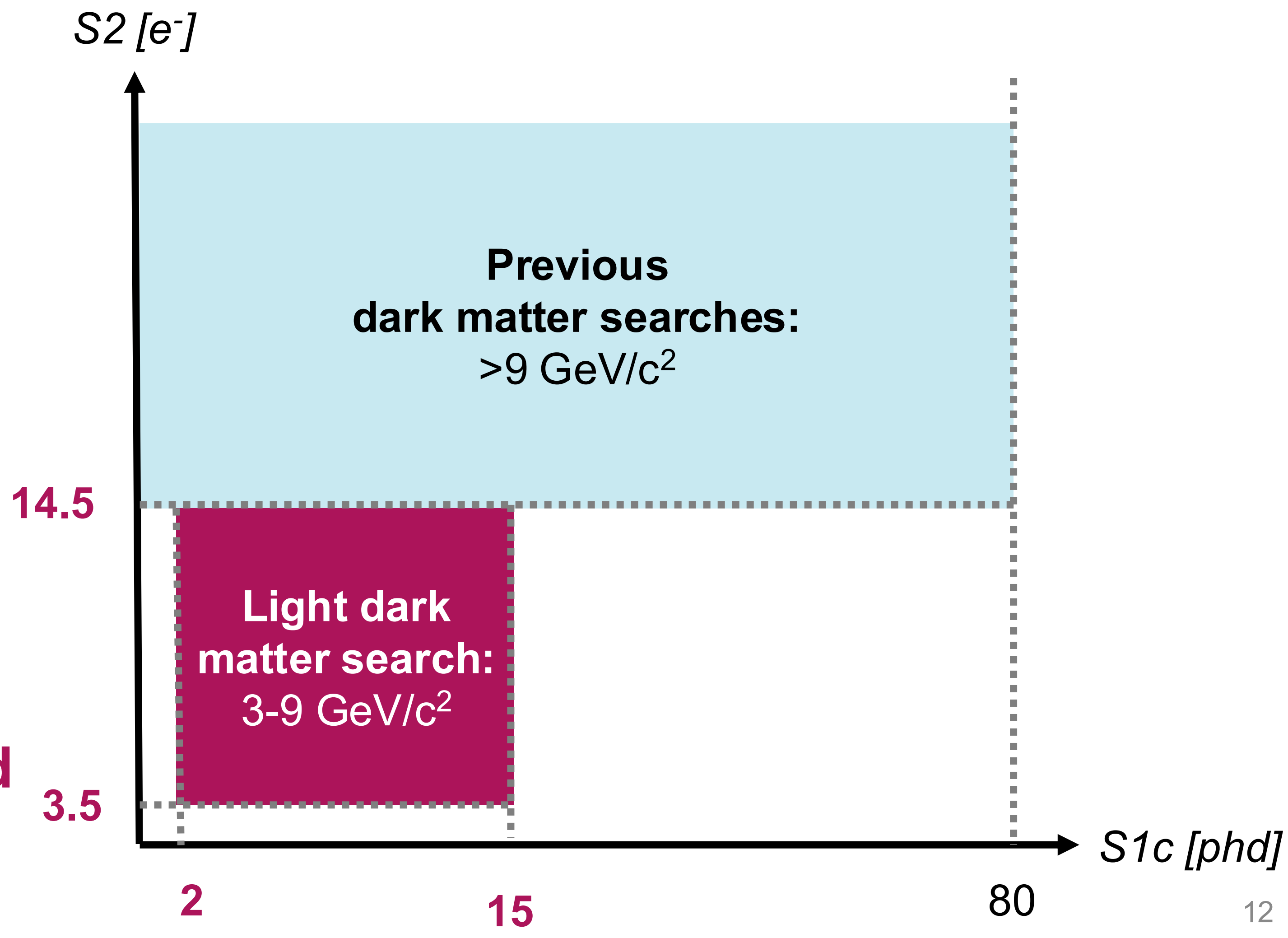
- Subdominant background in previous searches



Impact on light dark matter searches

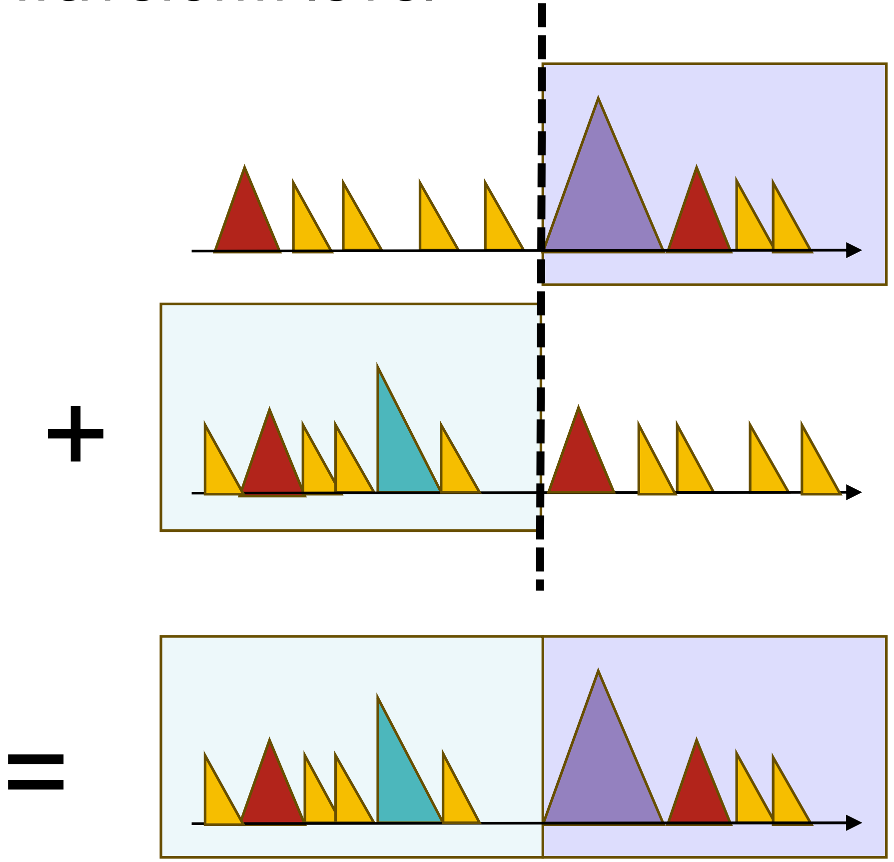
- For S1 and S2 pulses formed via pile-up, smaller pulses are statistically more likely than larger ones
- Rate of accidental coincidence events increases with decreasing S1 and S2 size
- Pile-up pulses can evade the pulse-level cuts that have been effective against larger isolated pulses
- **Dominant source of background for light dark matter searches**



Modelling Procedure

Data-driven approach, pairing real isolated pulses in the detector to create synthetic accidental events at the waveform level

- Previously: iS1s and iS2s were paired randomly together
- Due to the lower ROI we now need to consider that a pile-up S1 is more likely to be paired with a pile-up S2
- Account for this by pairing together iS1s and iS2s from the **same single-photon and single-electron rate environment**



How many events at each rate?

Fraction of events containing an iS1 (at a given SP and SE rate)

$$N_{ac}(r_{SP}, r_{SE}) = k\,\frac{N_{iS1}(r_{SP}, r_{SE})\;N_{iS2}(r_{SP}, r_{SE})}{T(r_{SP}, r_{SE})}$$

How many events at each rate?

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$$N_{ac}(r_{SP}, r_{SE}) = k\,\frac{N_{iS1}(r_{SP}, r_{SE})\,N_{iS2}(r_{SP}, r_{SE})}{T(r_{SP}, r_{SE})}$$

Number of iS2s (at a given SP and SE rate)

How many events at each rate?

Fraction of events containing an iS1 (at a given SP and SE rate)

$$N_{ac}(r_{SP}, r_{SE}) = k \frac{N_{iS1}(r_{SP}, r_{SE}) \; N_{iS2}(r_{SP}, r_{SE})}{T(r_{SP}, r_{SE})}$$

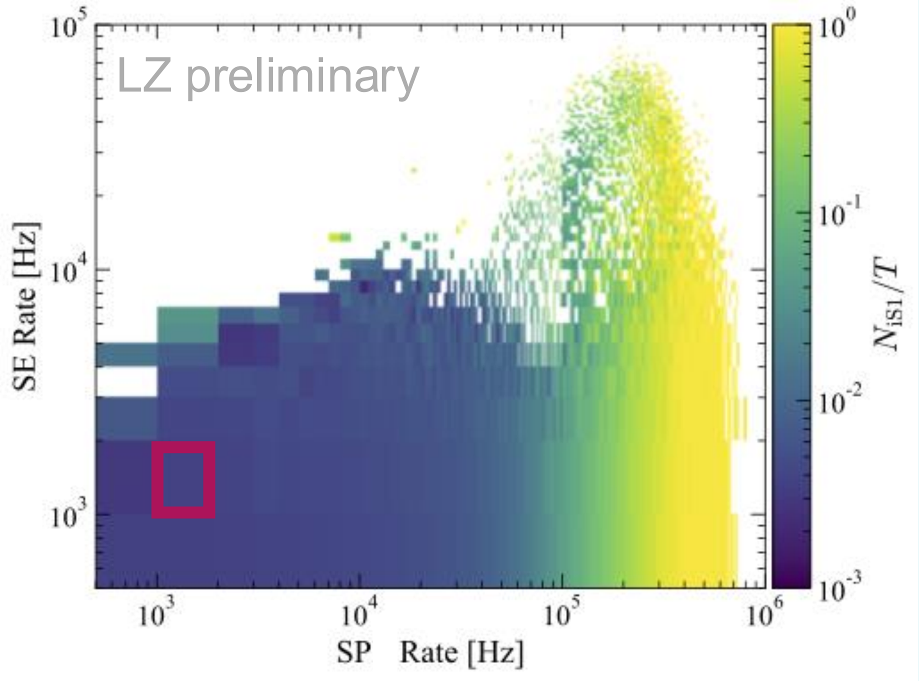
Number of iS2s (at a given SP and SE rate)

Scale this to get the desired statistics for our model

How many events at each rate?

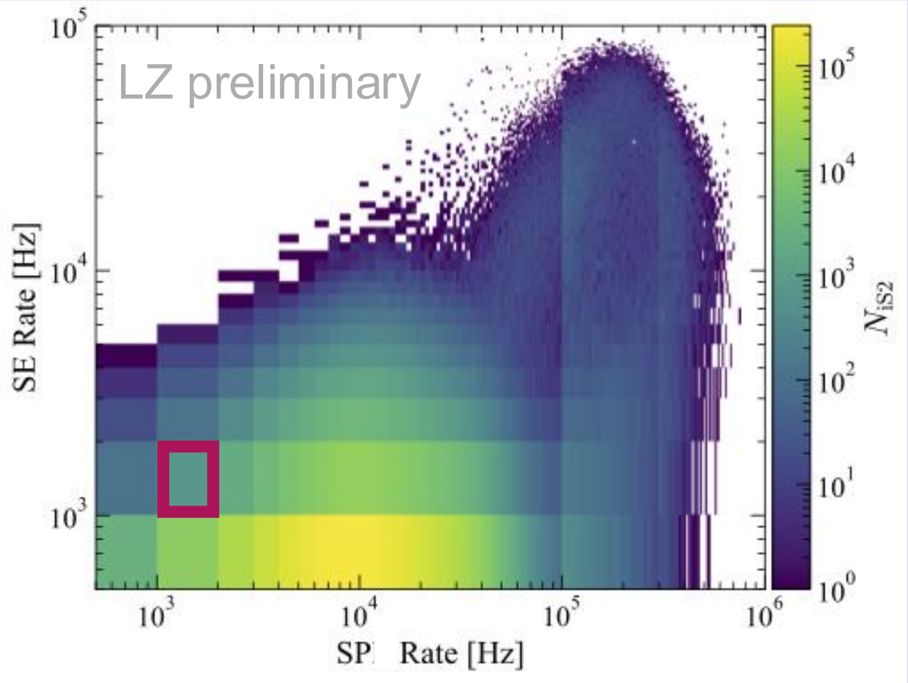
$$N_{ac}(r_{SP}, r_{SE}) = k \frac{N_{iS1}(r_{SP}, r_{SE})}{T(r_{SP}, r_{SE})} N_{iS2}(r_{SP}, r_{SE})$$

N_{iS1} / T



X

N_{iS2}

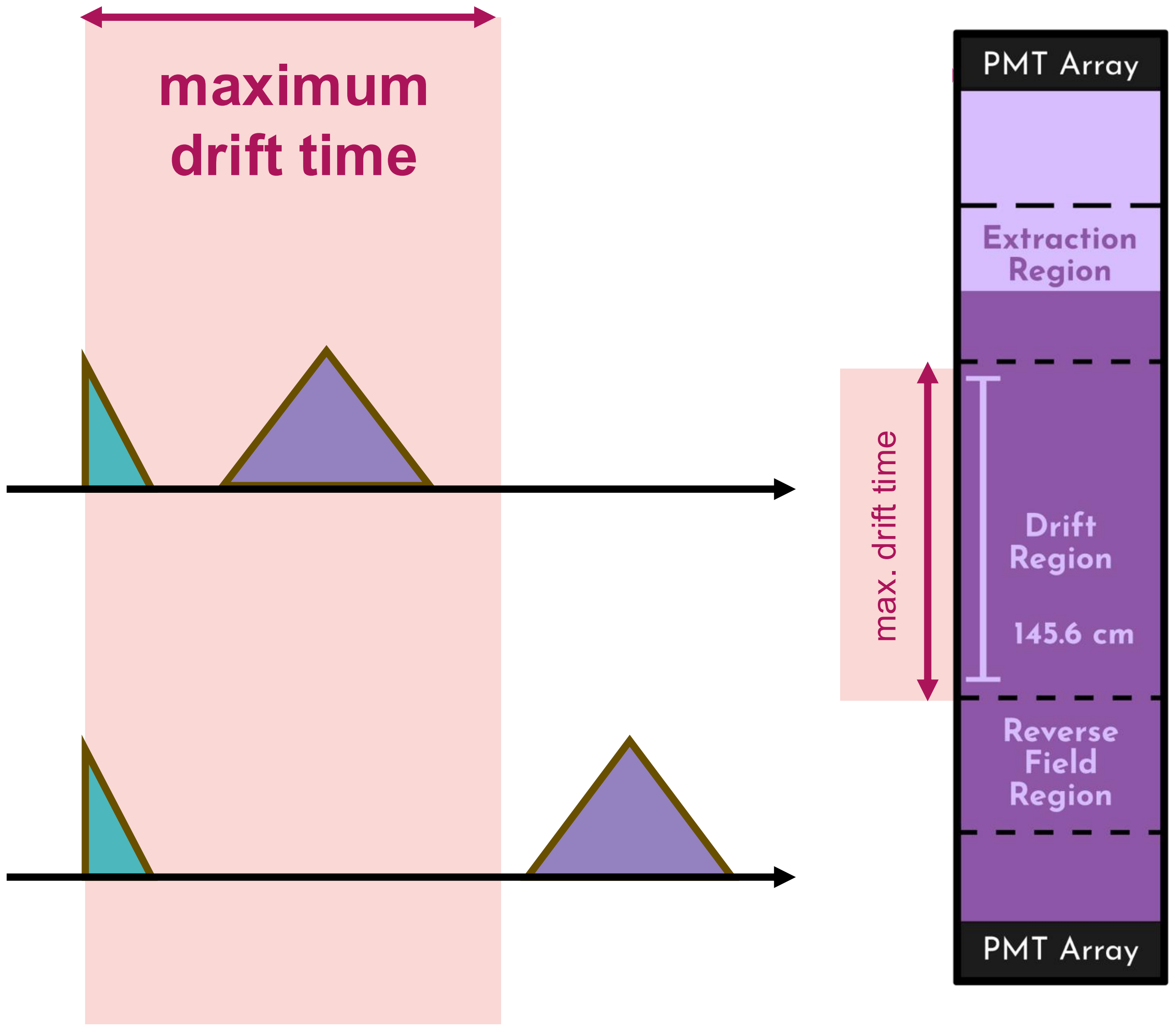


Comparing to data

- Need a sideband of accidental coincidence events

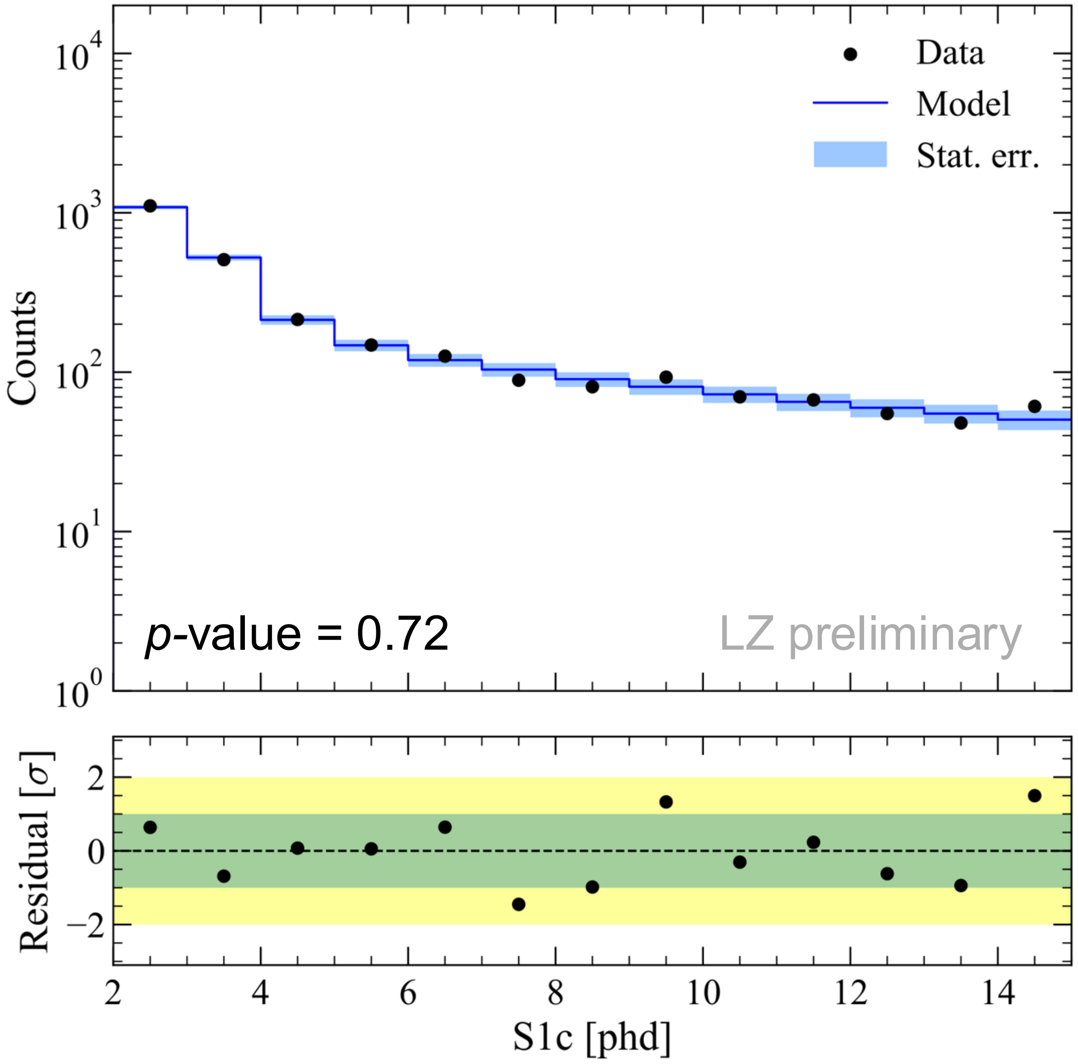
- Unphysical Drift Time (UDT) events:

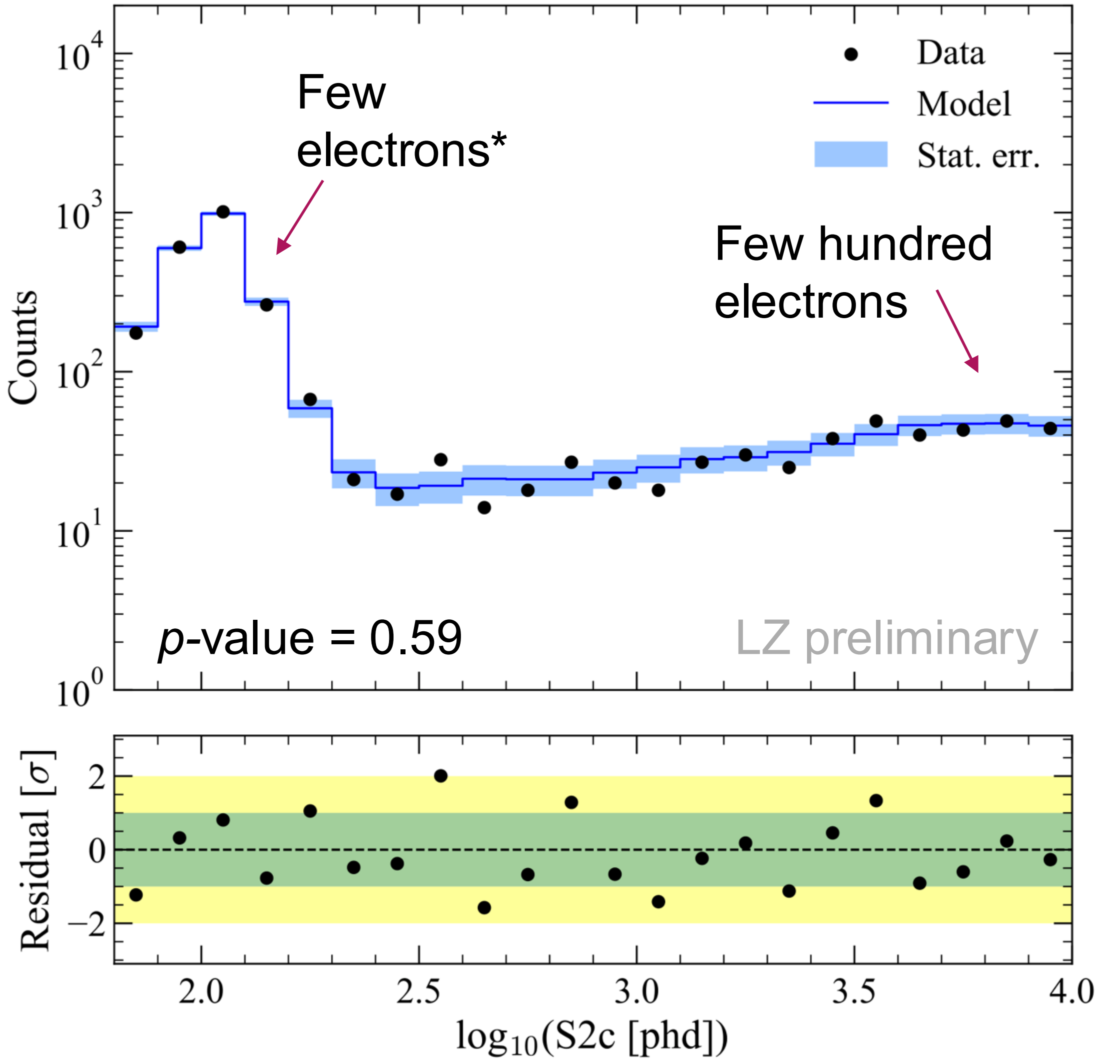
event drift time > max drift time



Comparing to data

**1 electron ~ 44.5 phd*



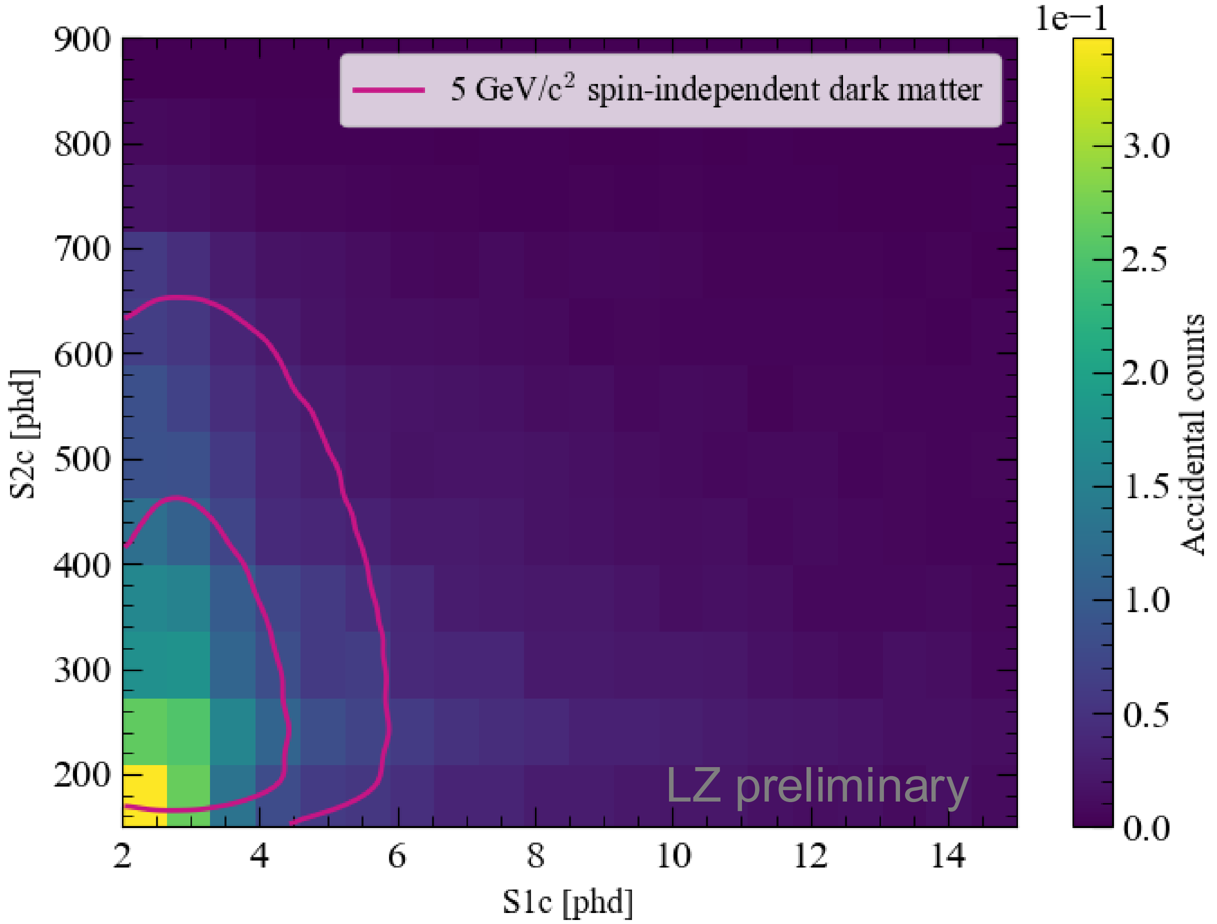


Application to a light dark matter search

The expected accidental coincidence rate is determined from the sideband dataset

Expected # of accidental coincidence events after all cuts

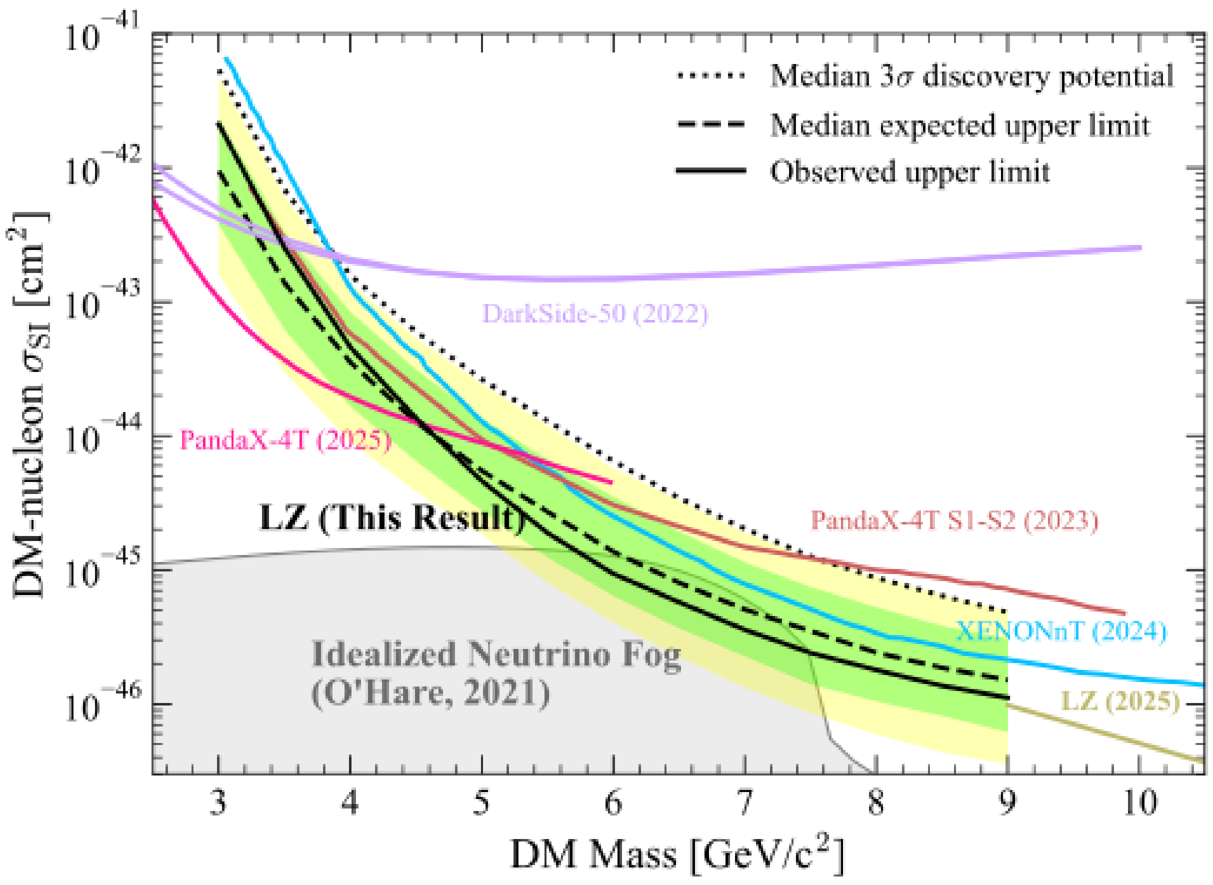
= 6.55 ± 0.29
(1.15 per tonne-year)



Summary

- Accidental coincidence events are the dominant background for light dark matter searches
- Pairing together iS1 and iS2 events
- iS1 and iS2 rates are both correlated and time varying
- Novel approach of pairing events from the same SE and SP environments
- Implemented in the most recent analysis

→ World-leading limits on spin-independent dark matter interactions for masses between 5 and 9 GeV/c^2



More details in Leah Wolf's talk: 11am Friday
Paper: arXiv:2512.08065

LZ (LUX-ZEPLIN) Collaboration,

38 Institutions, 50 scientists, engineers, and technical staff

https://lz.lbl.gov/
@lzdarkmatter

LZ Collaboration Meeting at UCLA, March 2025

Thanks to our sponsors and participating institutions!

- Black Hills State University
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- Brown University
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- Edinburgh University
- Fermi National Accelerator Lab.
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- Lawrence Livermore National Lab.
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- Northwestern University
- Pennsylvania State University
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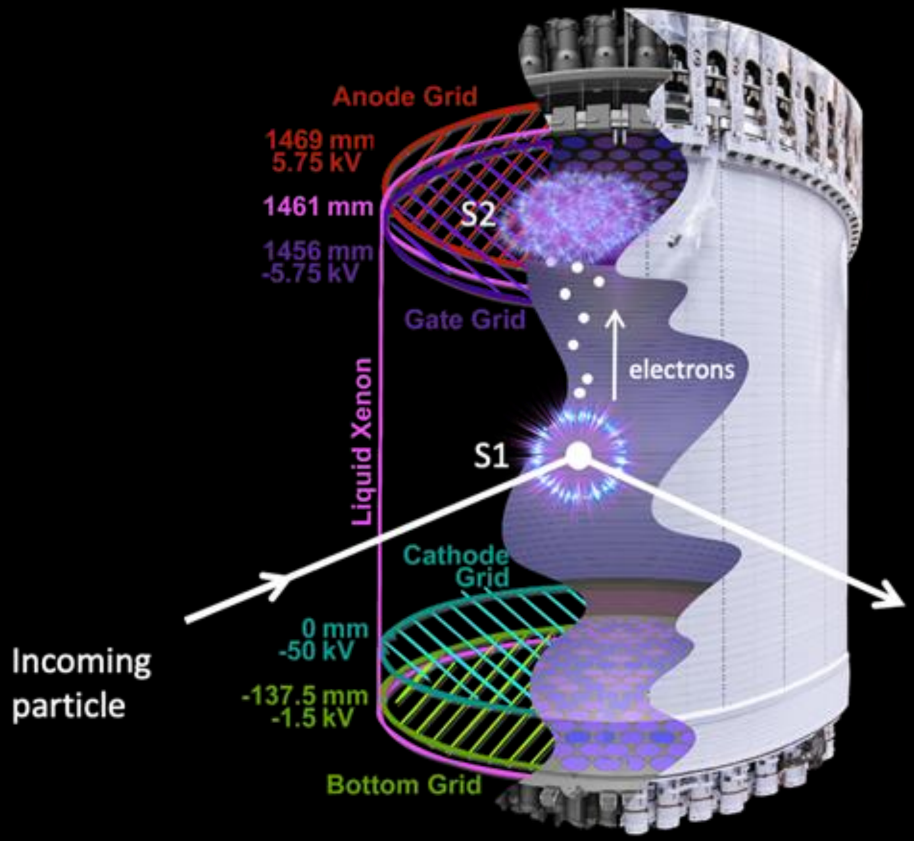

Image by Nicolas A. (Imperial College London)

UCL

Thank you!

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Office of Science

UKRI Science and Technology Facilities Council

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fct Fundação para a Ciência e a Tecnologia

ibs Institute for Basic Science

Swiss National Science Foundation

ARC Centre of Excellence for Dark Matter Particle Physics

Backup

Backgrounds

WS2024: ≥ 9 Gev/c^2

arXiv:2410.17036v3

Source	Pre-fit Expectation	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Solar ν ER	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3	55.9 ± 8.2
^{124}Xe DEC	19.4 ± 2.5	20.4 ± 2.4
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Accidental coincidences	2.8 ± 0.6	2.6 ± 0.6
Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
^{8}B+*hep* ν NR	0.06 ± 0.01	0.06 ± 0.01
Detector neutrons	$^{a}0.0^{+0.2}$	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1202 ± 41

0.2% of final events are **accidental coincidence events**

WS2025: 3-9 Gev/c^2

arXiv:2512.08065

Before pulse-based cuts (in ROI and FV):

- **~3x more accidental coincidence events** than ^{8}B coherent elastic neutrino scatters (CEνNS)

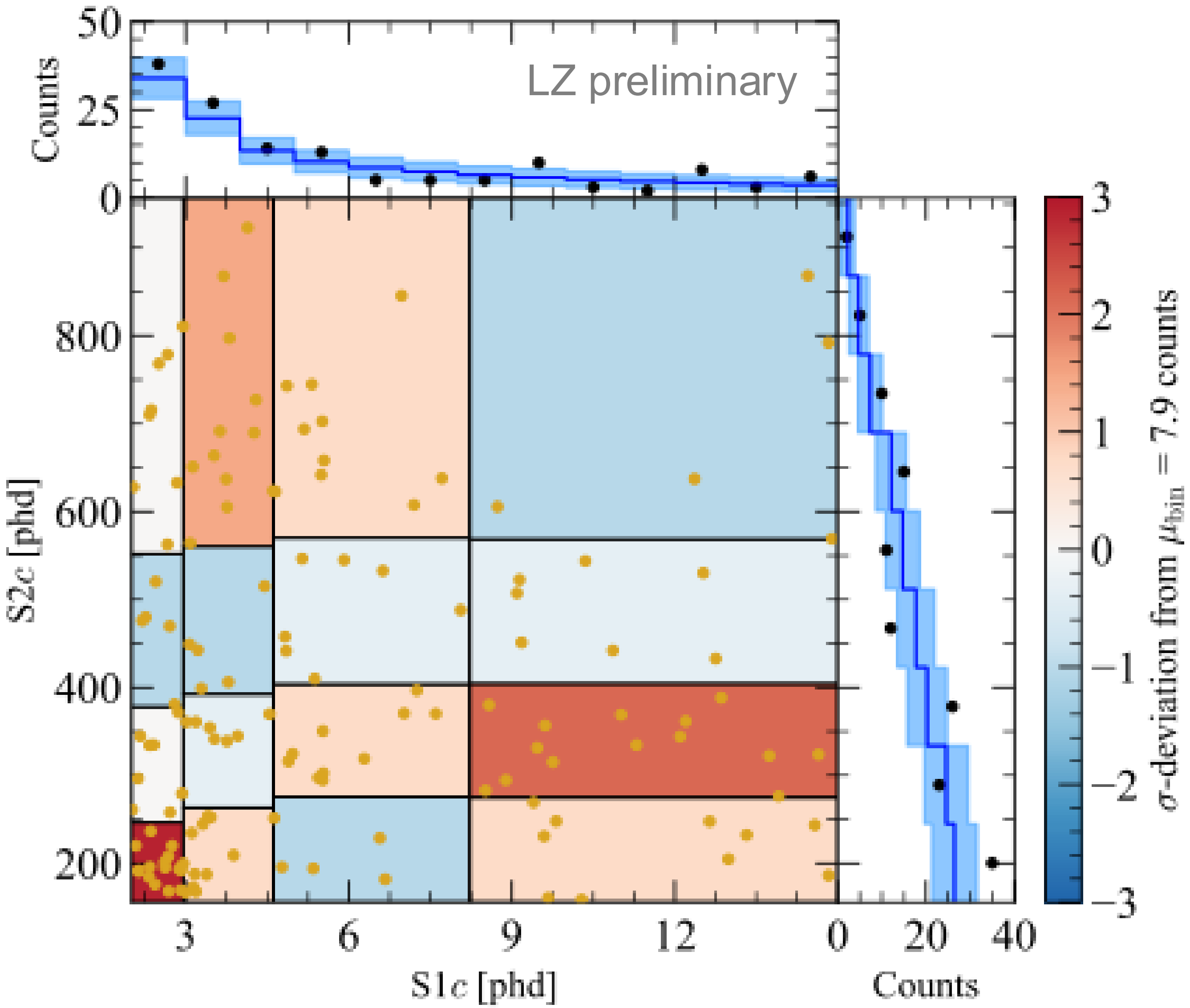
Components	Expectation	Background-Only Fit	3 GeV/c^2 Fit	9 GeV/c^2 Fit	^{8}B CEνNS Unconstrained Fit
SI DM	-	-	$0.4^{+5.4}_{-0.4}$	$0.0^{+4.0}_{-0.0}$	-
^{8}B CEνNS	$20.6^{+8.9}_{-6.8}$	$15.0^{+2.9}_{-2.5}$	$14.7^{+3.0}_{-2.8}$	$15.0^{+2.9}_{-2.5}$	$12.3^{+7.0}_{-5.4}$
Accidental coinc.	6.6 ± 0.3	6.5 ± 0.3	6.5 ± 0.3	6.5 ± 0.3	6.6 ± 0.3
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$
Total	$27.2^{+10.1}_{-7.3}$	$21.6^{+4.7}_{-3.8}$	$21.7^{+6.2}_{-2.8}$	$21.6^{+5.0}_{-2.5}$	$18.9^{+7.0}_{-5.5}$
$\sigma_{\rm eff}$	0 ± 1	$-0.81^{+0.59}_{-0.60}$	$-0.86^{+0.63}_{-0.71}$	$-0.81^{+0.58}_{-0.60}$	0 ± 1

Final events:

- < 0.5% neutrons
- **~30% accidental coincidence events**
- ~70% ^{8}B CEνNS → irreducible neutrino fog

Comparing to data in the ROI

- As the iS1 and iS2 rates are correlated, need to check that the model matches in 2D
- Prior to FV and S1 and S2 pulse-based cuts to maintain statistics
- Perform a Baker-Cousins goodness of fit test with 4x4 equiprobable bins
- Expectation of 7.9 events per bin
- *p*-value of 0.28 in {S1c, S2c}



“High-rate” validation

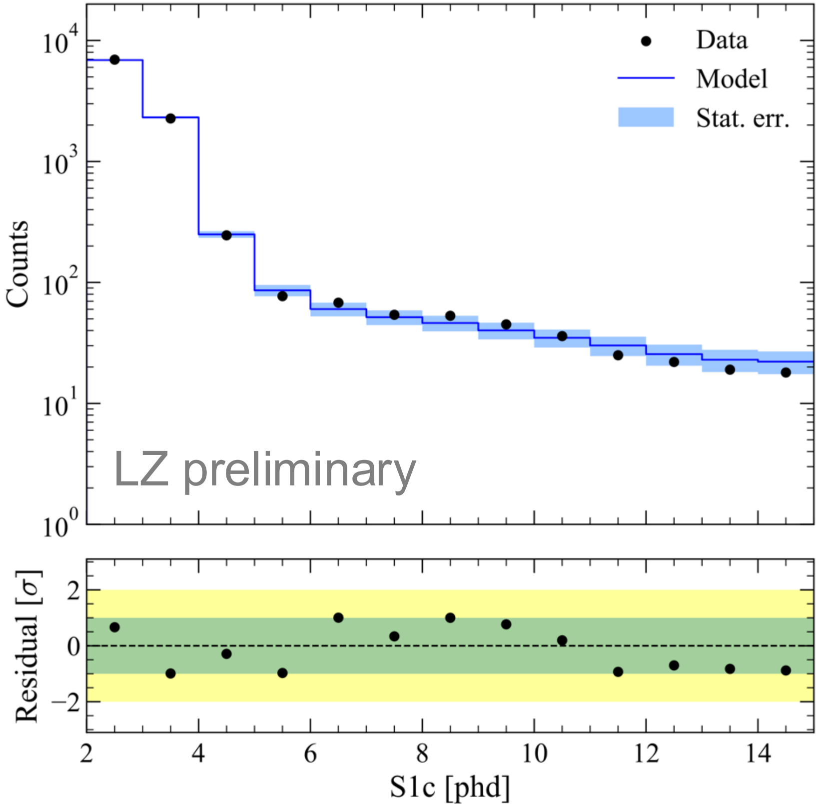
Aim: Stress-test environment matched pairing procedure in elevated photon and electron rate periods → **UDT events failing temporal veto**

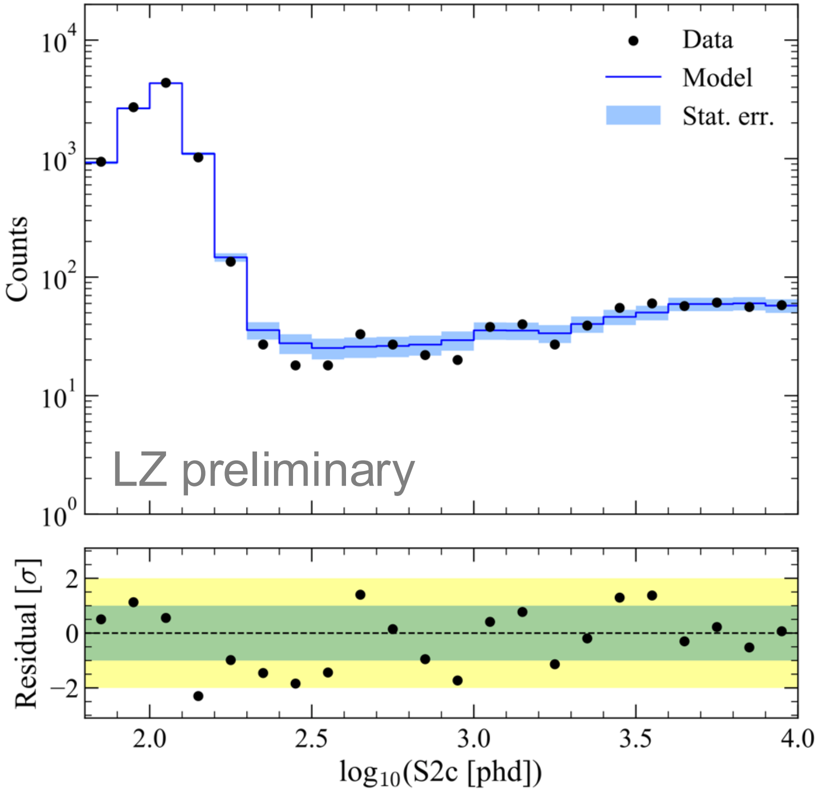
< SPE rate > = 85 kHz
→ factor of 6 increase

< SE rate > = 232 Hz
→ factor of 3 increase

High-rate validation:
~10,000 events

Nominal:
~3000 events

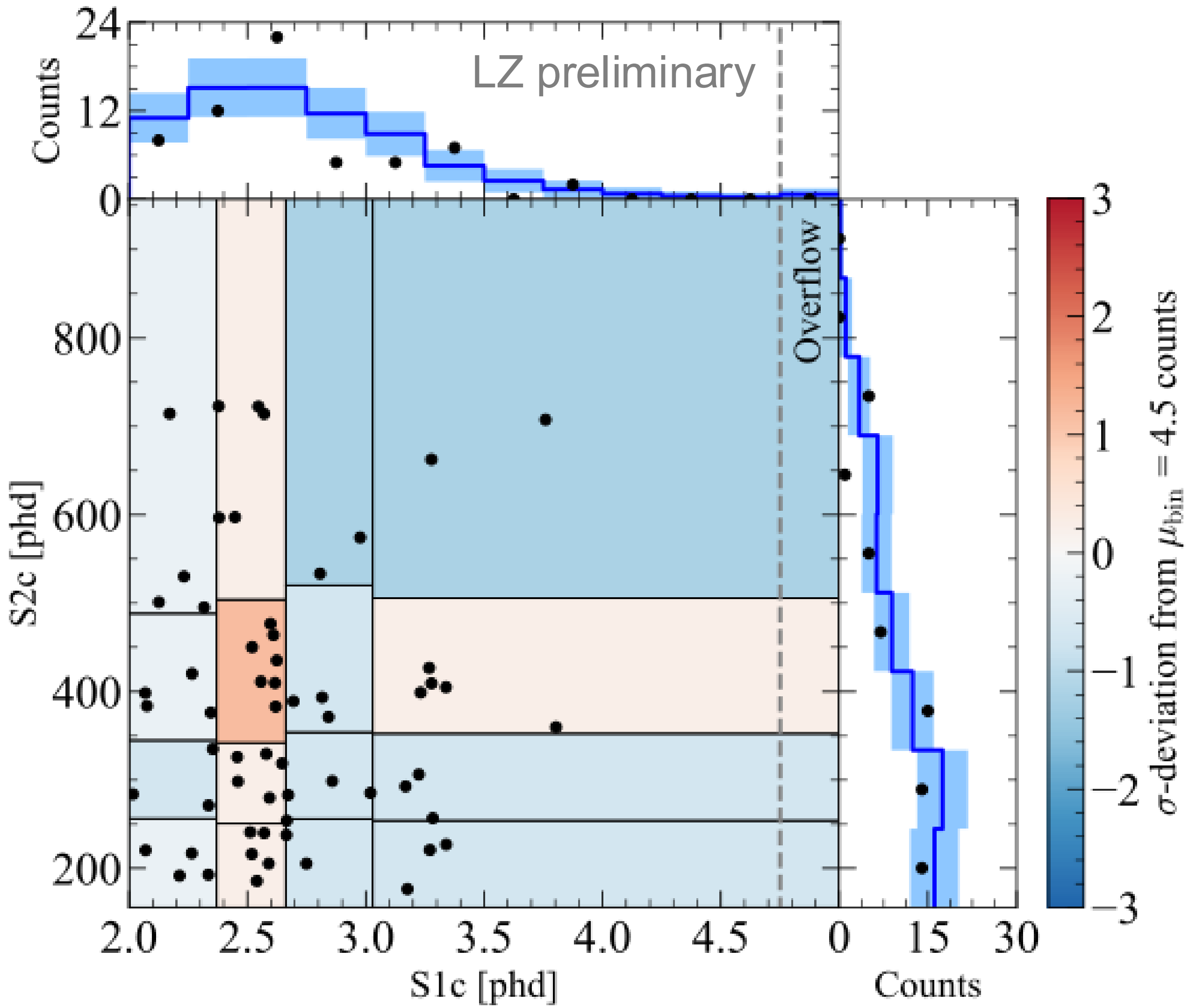




Validation of model post cuts

Aim: Validate the model after data quality cuts with increased statistics → **UDT events during a AmLi neutron calibration campaign**

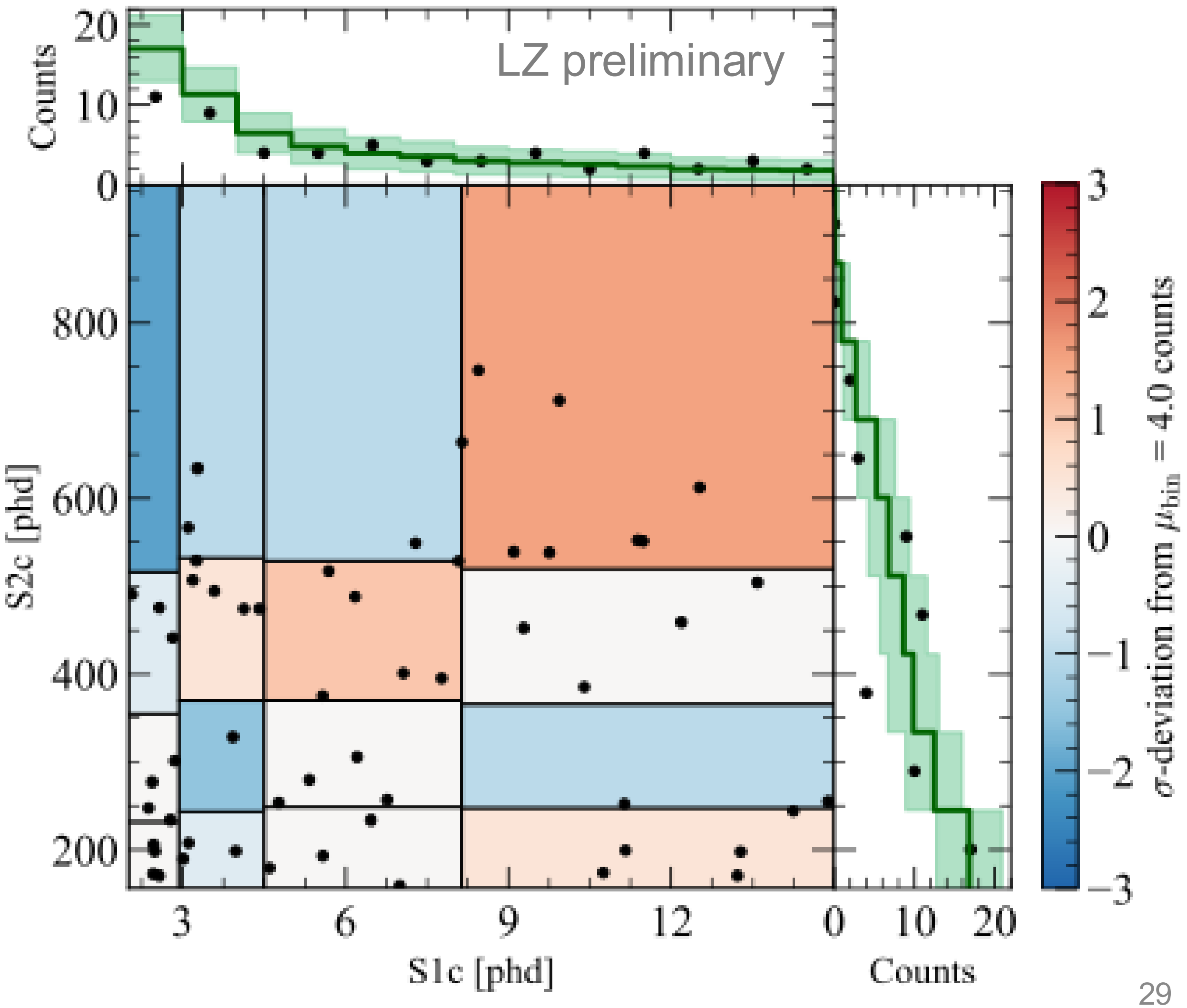
- Factor of 7 more in this calibration data set
- Only 9 events remain in the nominal dataset after all cuts
- High iS2 rate from real interactions where the iS1 is missed due to short drift lengths or coincidence requirements.



Validation of physical drift time region

Aim: Validate the model for accidental events with a physical drift time (PDT)
→ **PDT accidental events in the nominal dataset**

- Select events which fail S1 and S2 pulse-based cuts
- Select events inside the fiducial volume to remove radiogenic backgrounds
- Expect contamination of 3.3 Boron-8 coherent elastic neutrino scattering events
- Include Boron-8 component in background model when comparing to data



Application to a light dark matter search

PDF is normalized such that:

Expected # of UDT events after minimal cuts = # of UDT events after minimal cuts

Expected # of physical drift time (PDT) accidental events after all cuts = # of UDT events after minimal cuts x Ratio of PDT to UDT events x PDT survival fraction after all cuts

as given by the model