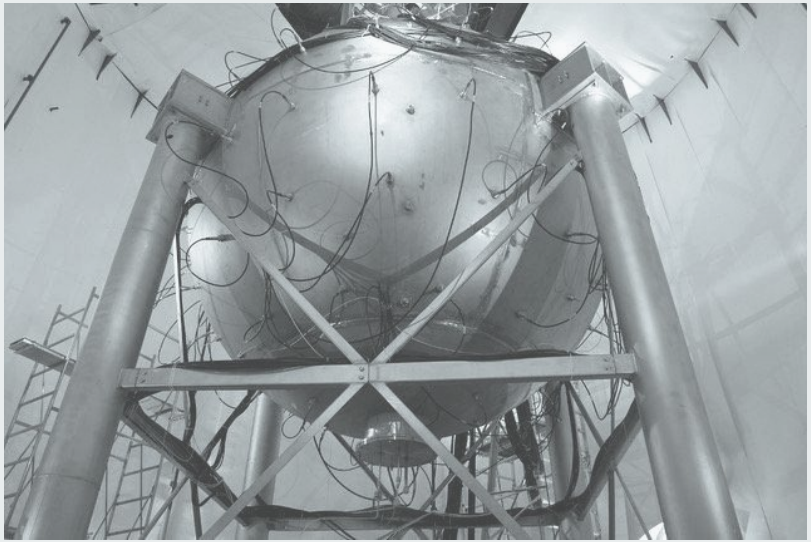
The effect of contamination on the S1 triplet component in DarkSide-50 dark matter experiment



Clea Sunny

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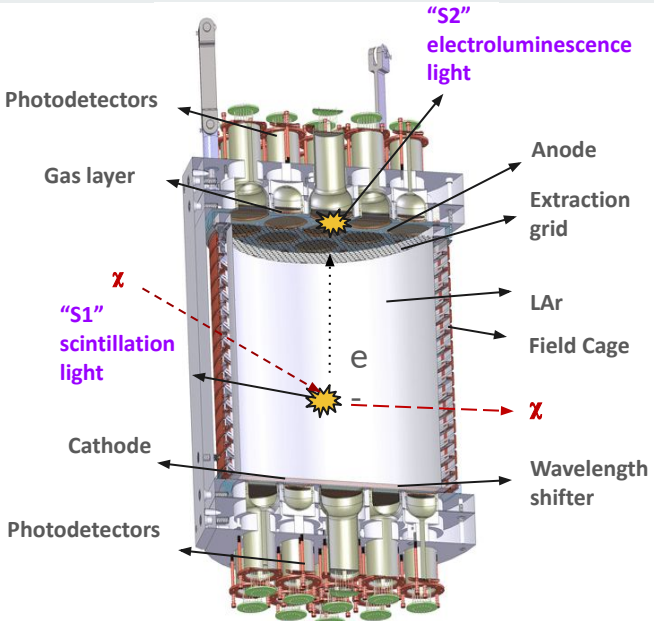
on behalf of the DarkSide-50 Collaboration

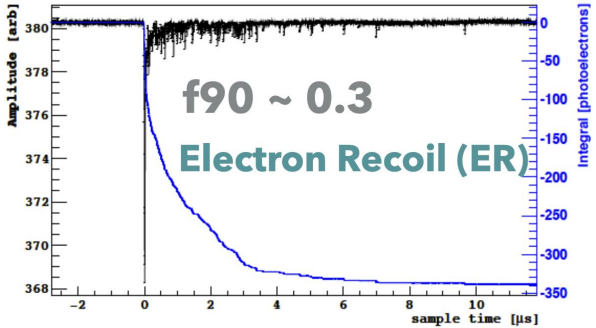
VIEnna Workshop on Simulations 2024 (VIEWS24)

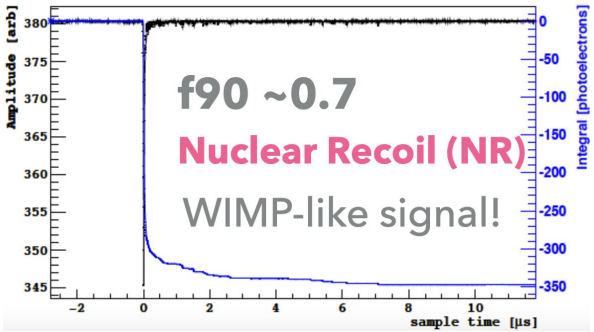
26th April 2024 - Vienna, Austria

Direct detection of WIMPs in DarkSide-50

- Located at Gran Sasso National Laboratory (LNGS), Italy.
- Dual-phase TPC: 46.4 ± 0.6 kg of active Underground Argon (UAr)
- **S1 - Primary scintillation signal in LAr.**
- **S2 - Secondary scintillation (electroluminescence) signal in GAr layer.**
- Precise determination of event positions in all 3-dimensions in TPC.
- DM-induced Nuclear Recoils (NR).
- Background-induced Electron Recoils (ER).
- Excellent signal to background discrimination power based on NR and ER pulse shapes.





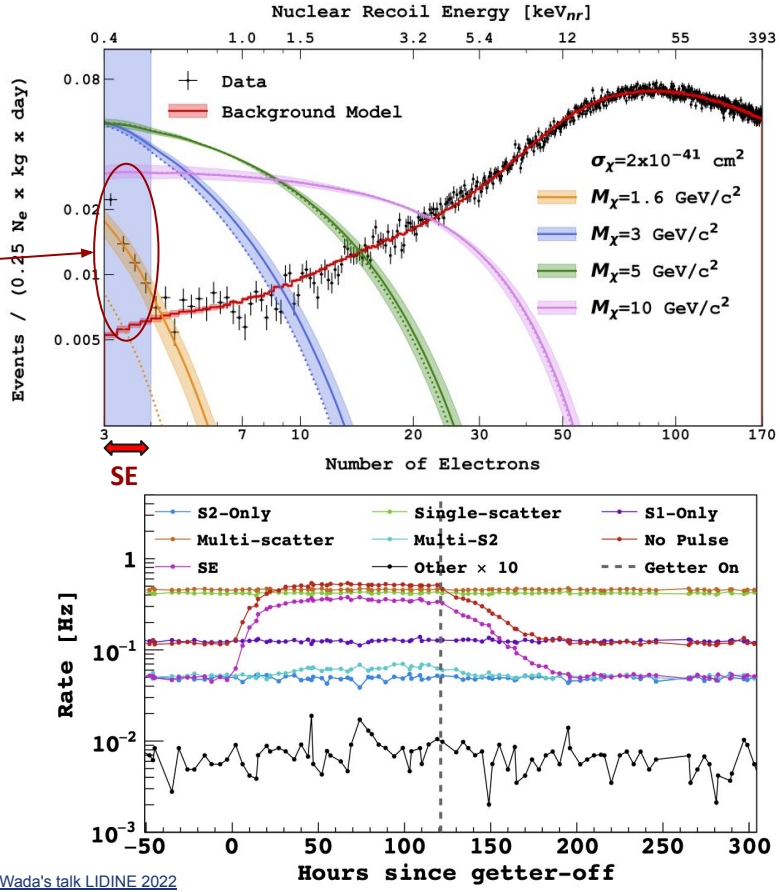


Credits: M. Wada's talk at La Thuile

Hypothesis testing of spurious electron study in DS-50 - Purpose of analysis

- Low energy background analysis in DS-50 encountered an excess number of events at 1-4 Ne, **when the inline getter was bypassed (120 hours).**
- The Spurious Electron (SE) event rate reduced after the getter re-installation.
  - This may imply that the cause of SEs could be an impurity that exist in the gas phase.
  - Given that N_2 is highly volatile at 87 K, it is considered as one of the prime suspects.
  - **N_2 hypothesis testing - Triplet analysis**.

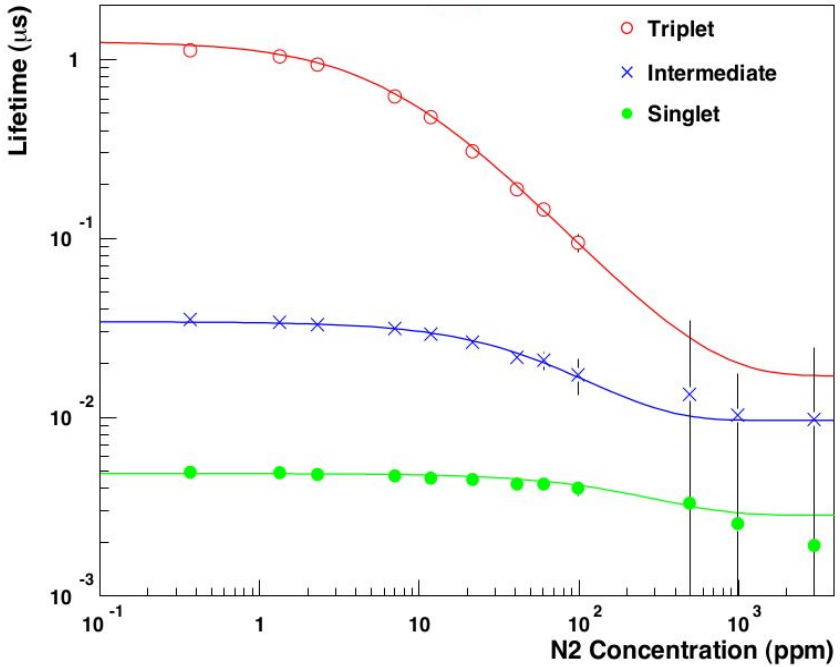
Credits: P. Agnes et al. Phys. Rev. D 107, 063001



Credits: M. Wada's talk LIDINE 2022

Effect of N_2 contamination on the S1 signal - Test study by WArP collaboration

- Contaminants in LAr, such as N_2, O_2, H_2O, CO, etc., quench Ar scintillation photons.
- S1 ⟹ Singlet (~ 6 ns), **triplet (~ 1.6 µs)** components.
- Effect of N_2 contamination in LAr has already been studied (WArP).
- Quenching of light yield in N_2- contaminated LAr is expected.
- $Ar_2^* + N_2 \Longrightarrow 2Ar + N_2$
- The Ar excimers in the **triplet state** are more affected by N_2.
- Thus, analyzing S1 triplet component may help understand the presence of impurities in LAr, **especially N_2**.



Credits: R Acciarri et al 2010 JINST 5 P06003

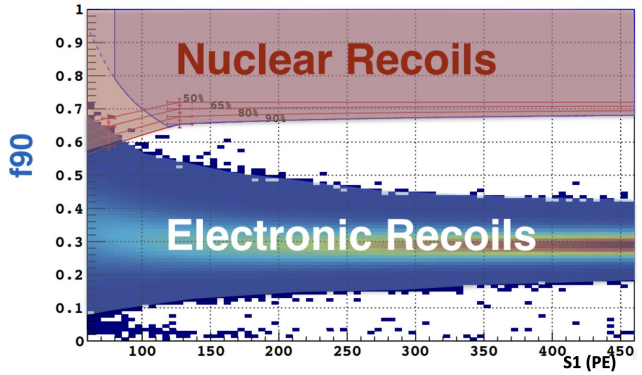
Triplet lifetime event-by-event analysis - Data selection

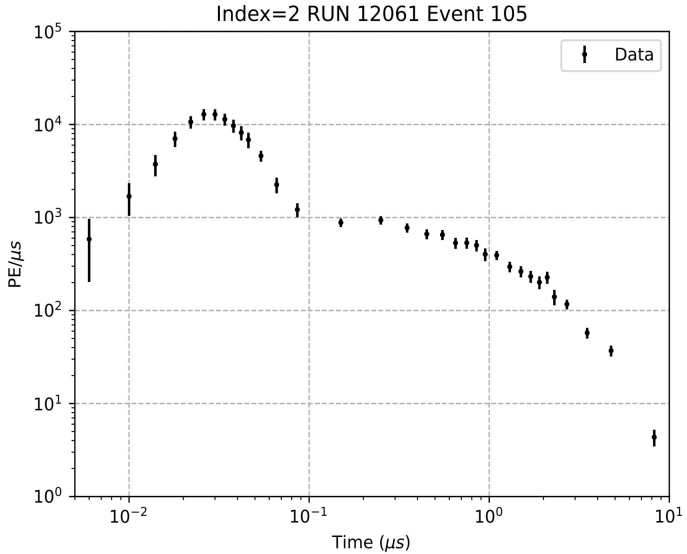
- **UAr data of DS-50 acquired between April 2015 and April 2018.**
- **Event-by-event** analysis.

The selection cuts used are as follows:

1. S2 > 0 : For selecting events with both S1 and S2 signals.
2. $0.1 < S1\_f_{90} < 0.5$: The fprompt for selecting ER events.
3. $\Delta t > 20 \times 10^{-3}$ s : To avoid S1 pile-ups.
4. $t_{drift} > 20$ µs : To avoid overlapping between S1 and S2 signals.
5. **1000 < S1 < 1600 PE**: Lower limit for minimum statistics and upper limit to avoid saturation.
6. $S1_{fwhm} < 0.1$ µs: To avoid pile up in S1 and S2.
7. $S1_{|tba|} < 0.9$: To obtain better events from the center of the fiducial volume.

Credits: M. Cadeddu's talk at La Thuile





The waveform model

Refer: P. Agnes et al 2021 JINST 16 P11026

- To model the waveform, a function which is a convolution of three contributions is considered:
  - Ar scintillation time profile;

$$F\left(t, \tau_s, \tau_t, p_s\right) = \frac{p_s}{\tau_s} e^{-t/\tau_s} + \frac{1-p_s}{\tau_t} e^{-t/\tau_t}$$

where τ_s (τ_t) is the singlet (triplet) decay times, and p_s (1 - p_s) the populating probability of singlet (triplet) state.

  - TPB re-emission contribution;

$$H\left(t, \tau_{TPB}, p_{TPB}\right) = \left(1 - p_{TPB}\right) + \frac{p_{TPB}}{\tau_{TPB}} e^{\frac{t}{\tau_{TPB}}}$$

Here, $p_0 = 1 - p_{TPB}$ is the amplitude of prompt TPB re-emission component. p_{TPB} and τ_{TPB} are the amplitude and lifetime of delayed TPB component, respectively.

TPB (TetraPhenyl Butadiene) is a wavelength shifter used in DS-50. TPB has one prompt and more than one delayed re-emission components. In this analysis, only one delayed component is considered for TPB.

  - Detector response, which is described with a gaussian distribution with a peak at t_0 which is the reference time, and the resolution σ ;

$$G(t, \sigma) = \frac{e^{-t^2/2\sigma}}{\sqrt{2\pi\sigma^2}}$$

The waveform model

- The **total (overall response) function**, which is the convolution of the three contributions, associated with the pulse amplitude (*A*);

$$P\left(t,\ \theta,\ t_0,\ A\right) = A \times R(t',\ \theta)$$

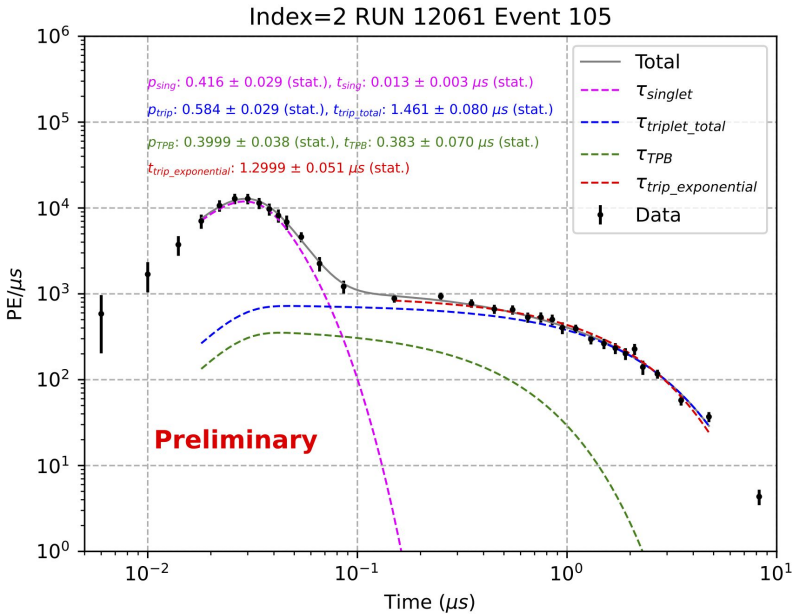
where

$$R(t,\ \theta) = F\left(t,\ \tau_s,\ \tau_t,\ p_s\right) \circledast H\left(t,\ \tau_{TPB},\ p_{TPB}\right) \circledast G(t,\ \sigma)$$

$t' = t - t_0$,

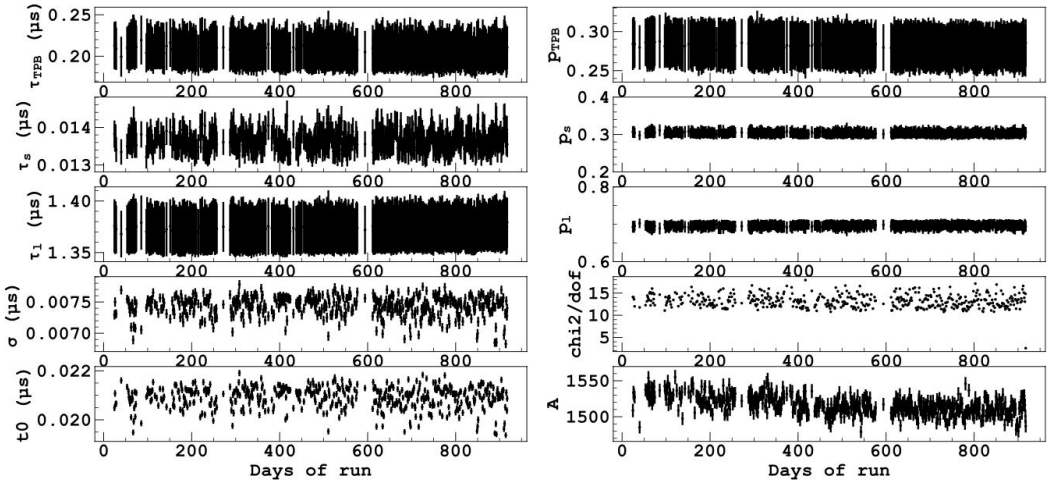
θ is the set of parameters including;

  - p_s , p_t , the probabilities to populate singlet and triplet states, respectively, and
  - τ_s and τ_t , decay times of singlet and triplet states, respectively.



Triplet analysis on the average waveform - A Previous study

- Similar analysis already done by **fitting on the average waveform** (wf).
- Selection cut: **S1 in [100, 20000] PE**.
  - Selected wfs are grouped into sets of 5.10^4.
  - Performed fit on each average wf using the total function in the range **[0.01, 10] µs.**
- Triplet lifetime observed by the average waveform approach is **1.375 ± 0.001 µs.**
- **No reduction in triplet lifetime during getter-off is observed.**

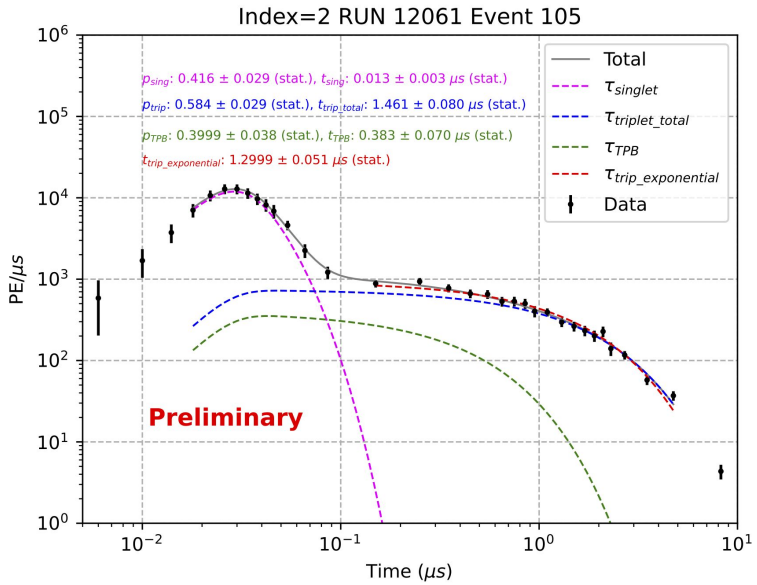


Parameters	Before	During	After
τ_l	1.375 ± 0.005 μs	1.375 ± 0.008 μs	1.375 ± 0.001 μs
p_l	0.694 ± 0.003	0.695 ± 0.005	0.6958 ± 0.0006
τ_s	0.01368 ± 0.00008 μs	0.0136 ± 0.0001 μs	0.01367 ± 0.00002 μs
p_s	0.306 ± 0.003	0.305 ± 0.005	0.3042 ± 0.0006
τ_{TPB}	213 ± 5 ns	212 ± 9 ns	209 ± 1 ns
p_{TPB}	0.285 ± 0.006	0.29 ± 0.01	0.282 ± 0.001

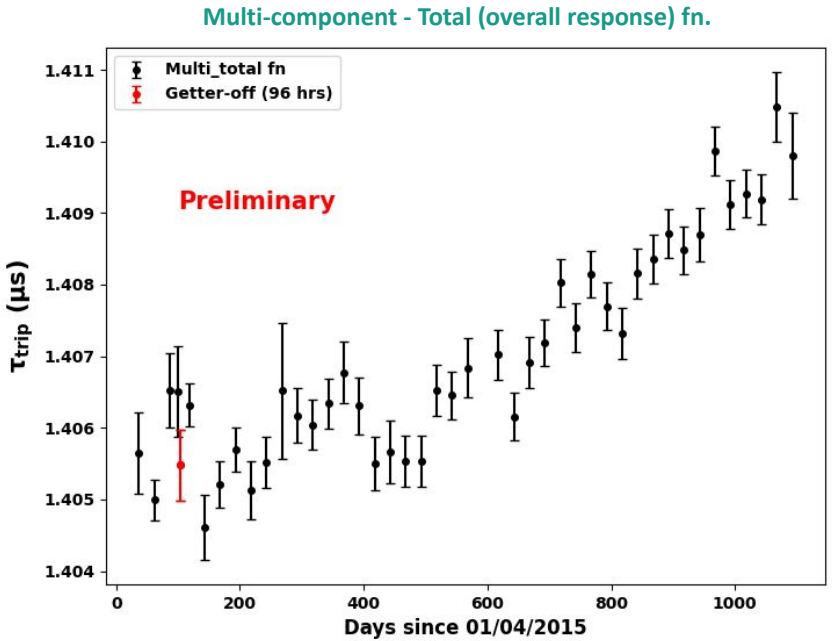
Riccardo Stefanizzi's thesis: https://hdl.handle.net/11584/391996

Triplet lifetime event-by-event analysis - Method of analysis

- Collected 1000 events/run from the whole 3-year dataset, except for getter-off runs.
- **Re-binned**: All bins in the fit ranges have at least 10 PE.
- The error on each wf is the statistical error.
- Modelling the wf;
  - Total fn. for the multi-components
  - Exponential fn. for the single-component.
- Chi-square fitting on each individual wf;
  - Total fn. is fitted over the range **[0.018, 4.75] µs.**
  - Exponential fn. is fitted over the range **[0.15, 4.75] µs.**
- Grouped them into bins of days.



Results from event-wise analysis - Triplet lifetime in DS-50 over 3 years



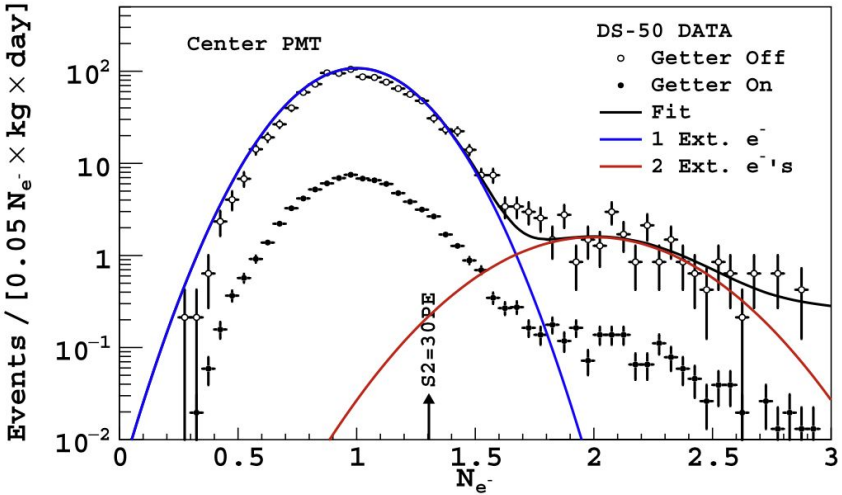
- **Overall increase of τ_{trip} by ~ 0.43%.**
  - May correspond to the purity increase in LAr after getter re-installation.
- **No degradation of τ_{trip} during getter-off period** is observed;
  - **N_2 concentration in DS-50 LAr < 1 ppm**
  - **N_2 may not be the cause of SEs.**
- Event-by-event approach, **τ_{trip} - 1.4070 ± 0.00006 µs**
  Average wf approach, **τ_{trip} - 1.375 ± 0.001 µs**
- Triplet lifetime value from event-wise analysis is **not consistent** with that from the average wf analysis.
  - The difference could be from the **uncertainties in the fit models.**
  - Systematic uncertainty under evaluation.

χ^2/ndof : 0.87 ± 0.0001

Scope of simulations in the analysis

- The few-extracted electrons and their corresponding N_{e^-} distributions are modelled with G4DS.
- One and two *e*- peak well described by Gaussians, and are in good agreement with getter-off data.
- Without understanding the cause of SE, simulating their behavior for predicting occurrences of SE events in future experiments is not feasible.

Credits: Phys. Rev. Lett. 121, 081307



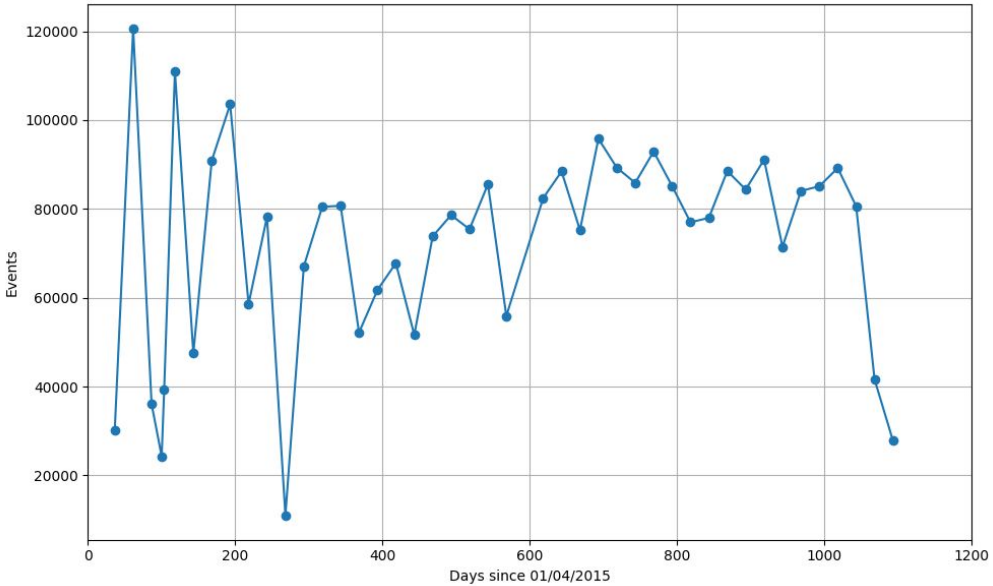
Summary

- The purpose of this S1 triplet component analysis is to test the hypothesis of N_2 causing the SEs.
- This is an event-by-event analysis.
- The decay time of triplet component from our analysis is found to be **1.4070 ± 0.00006 μs.**
- A visible reduction in the triplet lifetime was expected at ~ 1 ppm of N_2 concentration.
- No reduction in the triplet lifetime is observed during the getter-off period;
  - If the LAr in DS-50 is N_2-contaminated, then **the concentration of N_2 in the LAr is less than 1 ppm**.
  - This may also imply that **N_2 may not be the cause of SEs.**
- An **overall increase in the triplet lifetime is observed** over the whole dataset of 3 years after the getter is re-installed;
  - The observed wf change is consistent with the increase in the lifetime of triplet component.
  - This increase **may** correspond to the increase in the purity of the LAr after re-installing getter.


Stay Safe
Thank you !
The Future is Dark

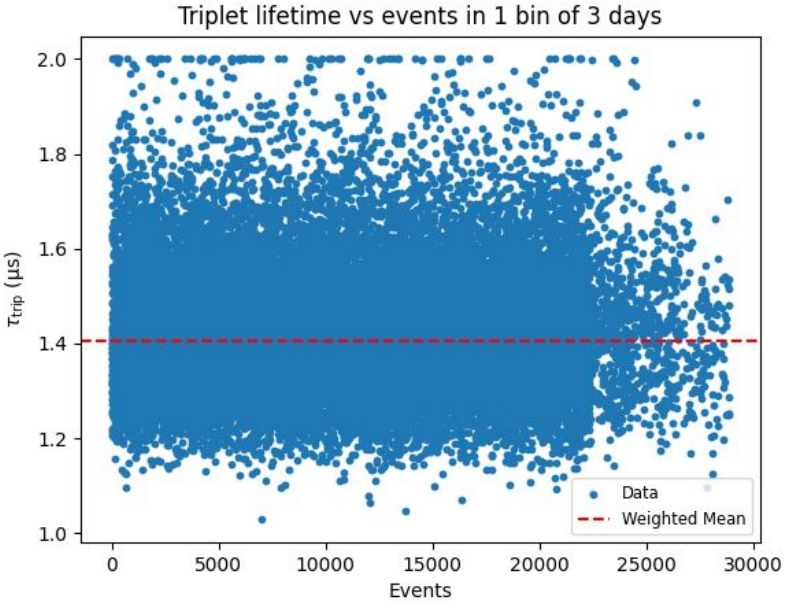
Backup slides

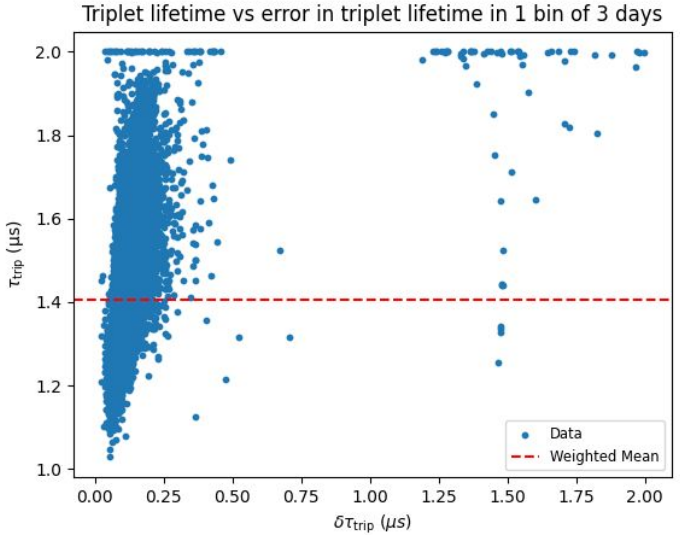
Counts per day-bin



- Grouped each fitted wf in 25-day bins and a 3-day bin from the start till getter-off period.
- Getter-off waveforms are grouped in a 4-day bin from run 12922-12977. Skipped first day to get pure getter-off data
- Rest of the waveforms after getter re-installation are again grouped into 25 days bins.

Statistics in a bin





Exclusion plot

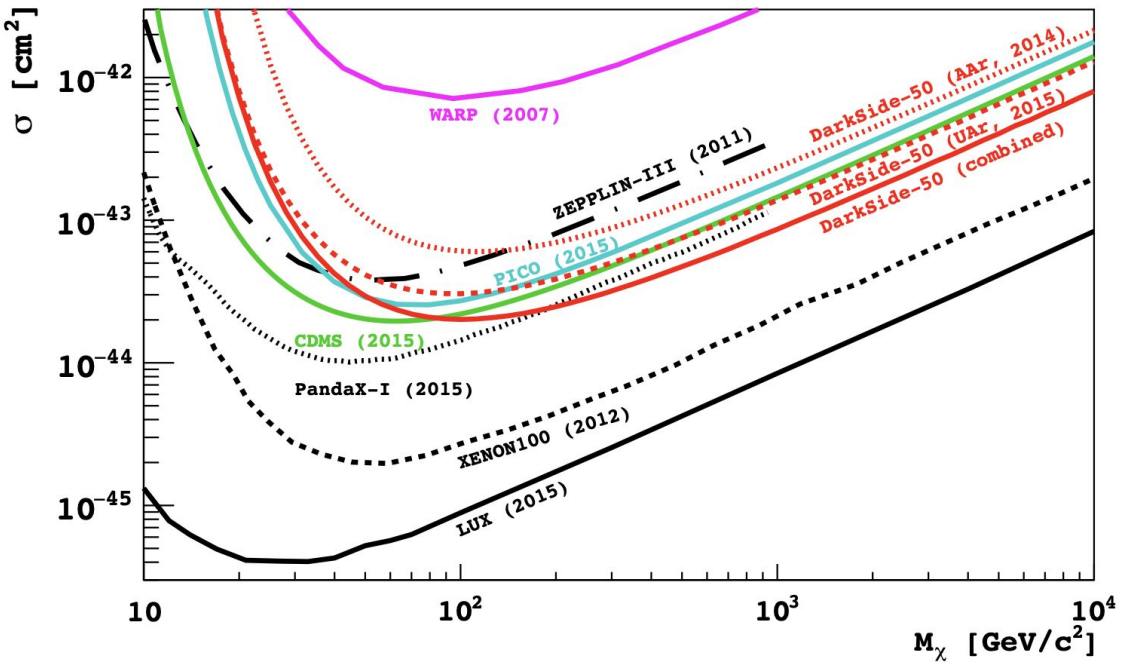


Figure: Spin-independent WIMP- nucleon cross section 90 % C.L. exclusion plots for the DarkSide-50 AAr (dotted red) and UAr campaigns (dashed red), and combination of the UAr and AAr [1] campaigns (solid red).