Extracting the time of core bounce from core-collapse supernovae

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Extracting t_0 using an unbinned maximum likelihood technique

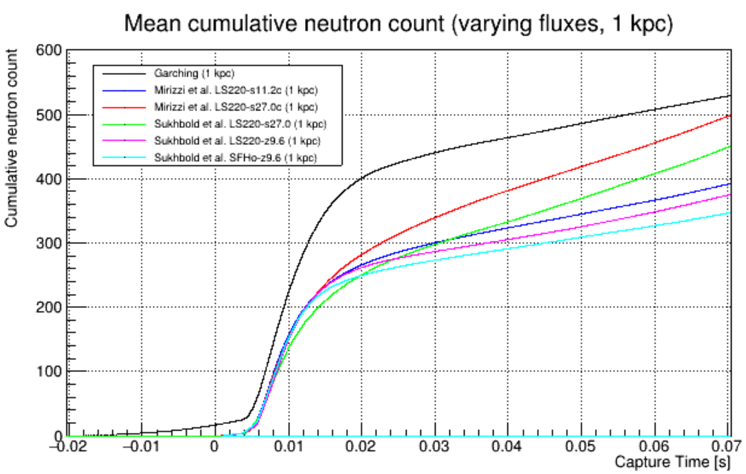
- Assume that the data derives from a Poisson PDF defined by:

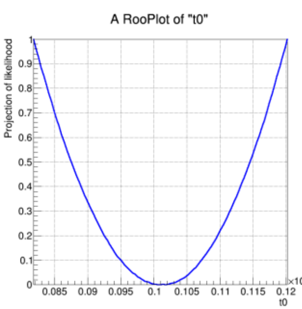
$$P[n(t_i);\bar{n}(t_i - t_0)] = \frac{\bar{n}(t_i - t_0)^{n(t_i - t_0)} \cdot e^{-\bar{n}(t_i - t_0)}}{n(t_i)!}$$

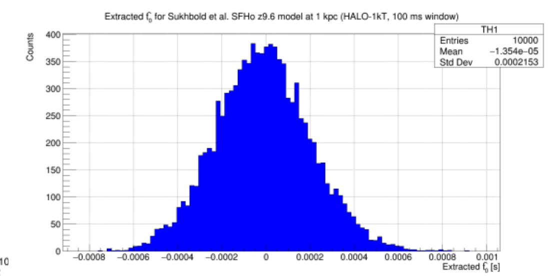
- The negative ln likelihood (NLL) is therefore:

$$\ell(t_0) = 2 \cdot \sum_{i=1}^{N} \eta \cdot \bar{n}(t_i - t_0) + n(t_i) \cdot \ln(\eta \cdot \bar{n}(t_i - t_0))$$

- Here, $n(t)$ is the vector of data with N events (where t_i is the time stamp of the i-th event), η is the normalization condition and $\bar{n}(t)$ is the mean cumulative neutron count.
  - The determination of the mean cumulative count is depicted on the top right (exact technique is left in the backup slides).
- t_0 can be obtained from a minimization of $\ell(t_0)$ using MINOS/Minuit2.
  - An example of this can be found on the bottom left plot (where the errors on the extracted t_0 come from the points at $\ell(t_0) \pm 1$.
- The precision and resolution of the extracted t_0 can be quantified by repeating the NLL fit for 10^4 SN bursts (see bottom right).
  - Fitting data to itself does not account for systematic uncertainties (no knowledge of ‘model of best fit’). To do so, mix and match various models to quantify offset.

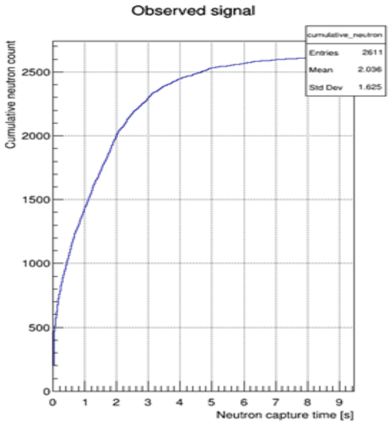


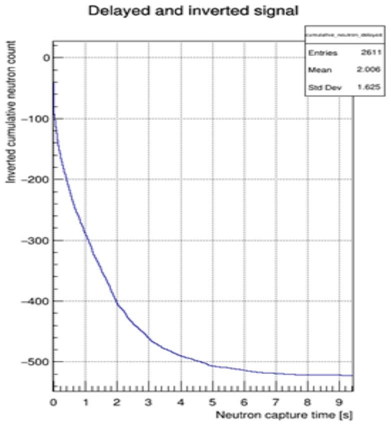




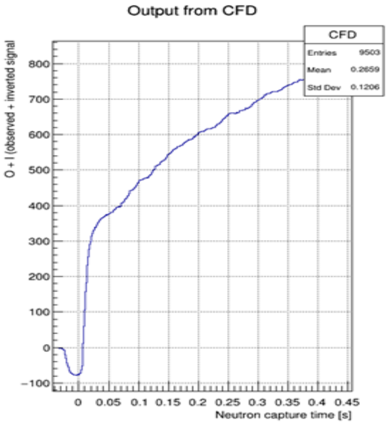
Extracting t_0 using a digital CFD

- We noticed in our analysis that extracting t_0 as a function of distance, introduced some 'walk' from the expected t_0.
  - As will be shown later.
  - Walk was gradual, less than ½ a millisecond from 1-5 kpc.
- Elected to implement a digital constant fraction discriminator (CFD) to attempt a correction for this walk.
  - Feed input signal (cumulative events from entire burst) into CFD.
  - Invert and delay the signal, then scale it down by some value (constant fraction).
  - Sum the two signals together (see right).
  - Locate t_0 from the point where the signal crossed zero.
    - Performance of extracting t_0 is comparable to that the likelihood fit.





The above example is from the Garching model at 1 kpc in HALO-1kT. Depicted on the top left is the cumulative events through the entire burst. The top right is the same signal but shifted 20 milliseconds backwards and with a fractional amplitude of 0.2. These two histograms summed together provide the output from the CFD (bottom right).

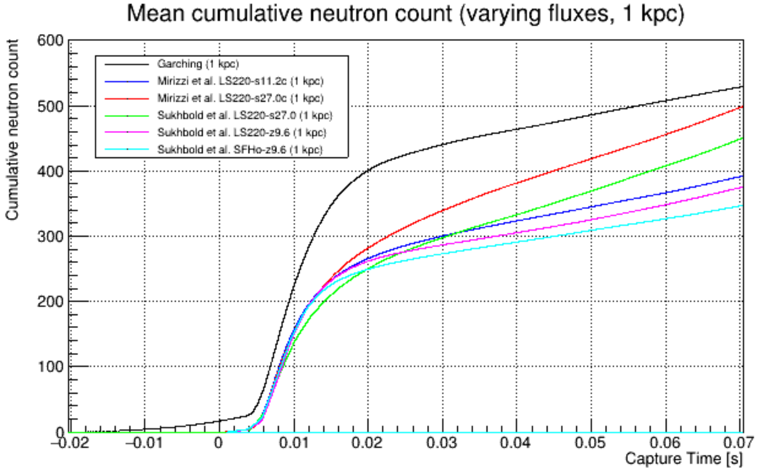


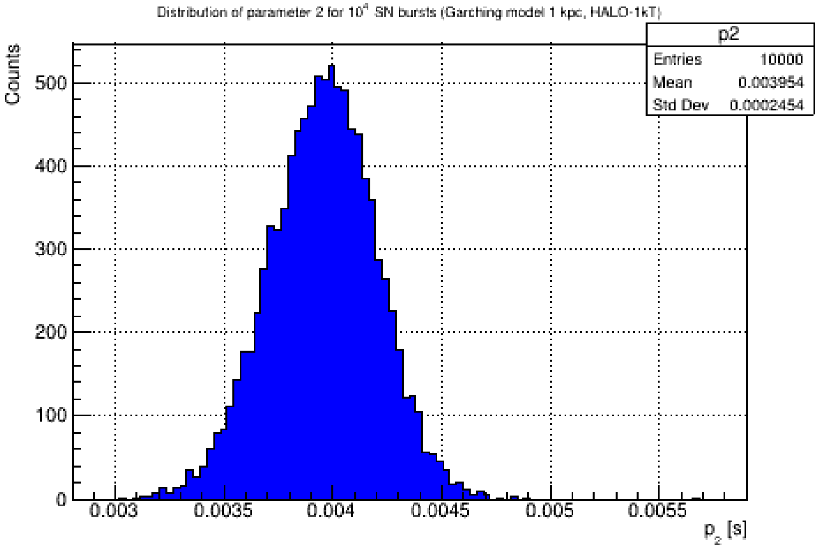
Extracting t_0 with a liner fit

- Linear technique arose as a method of getting around the systematic uncertainties included in the likelihood technique.
  - Use a single function as the cumulative PDF for all models.
- A relatively simple approximation is to treat the cumulative event count in the neutronization region as linear.

$$f(x) = [0] + [1] * (x - [2]) * (x > [2]) * (x < [4] + [2]) + \ldots$$

- Introduce a five-parameter fit (first three parameters constrain fit in neutronization region).
  - [0] – intercept of linear line.
  - [1] – average event rate of the tested models.
  - [2] - offset (wrt time) from the true t_0.
- Final two parameters constrain end point of fit and event rate immediately following neutronization.
- Results for the extraction of parameter [2] for 10^4 bursts from the Garching model at 1 kpc in HALO-1kT can be found on the bottom right plot.





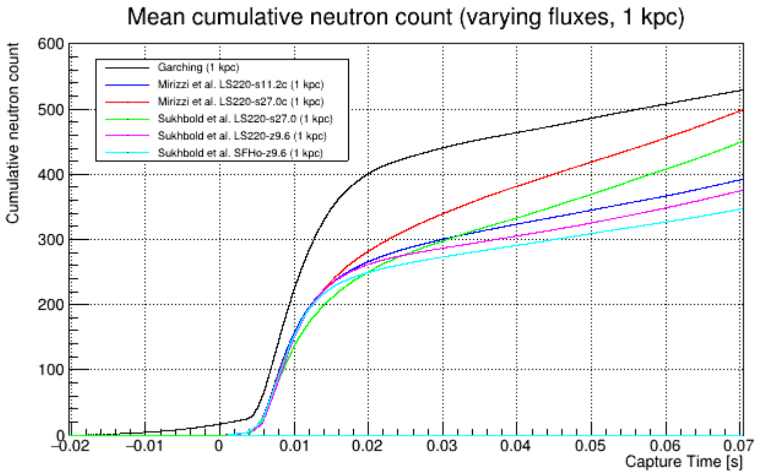
Extracting t_0 with the Anderson Darling test

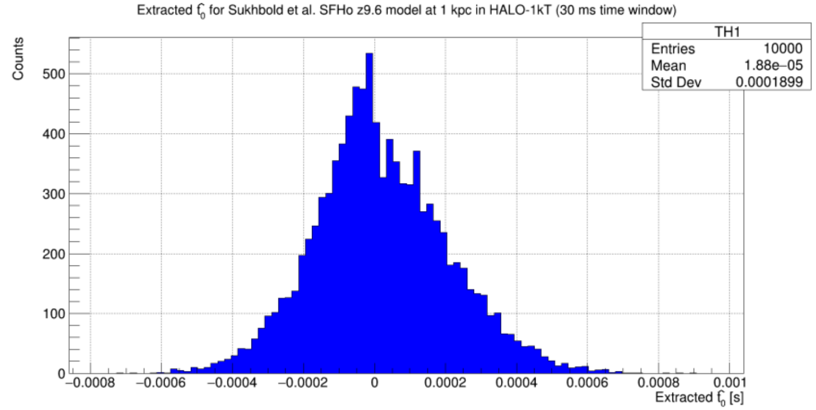
- Anderson Darling (AD) test is intended to determine the probability a sample belongs to some parent CDF.
  - It is an extension of the Kolmogorov Smirnov (KS) test.
  - The KS test was investigated as a candidate technique, performance collapses past 1 kpc in HALO-1kT.
- We implement it here as:

$$A^2(t_0) = -N - S(t_0)$$

$$S(t_0) = \sum_{i=1}^{N} \frac{2i-1}{N} \left[\ln \bar{n}(t_i - t_0) + \ln(1 - \bar{n}(t_{N+1-i} - t_0))\right]$$

- Where N is the number of events (each with timestamp t_i), and $\bar{n}$ is the mean light curve evaluated at some offset.
- Analogous to the NLL technique, must account for systematic uncertainties when mixing model and PDF.
- Distribution of extracted t_0 for the Sukhbold et al. SFHo z9.6 model at 1 kpc can be found in the bottom right.
  - Of the five techniques implemented, the AD test has the most numerical issues.



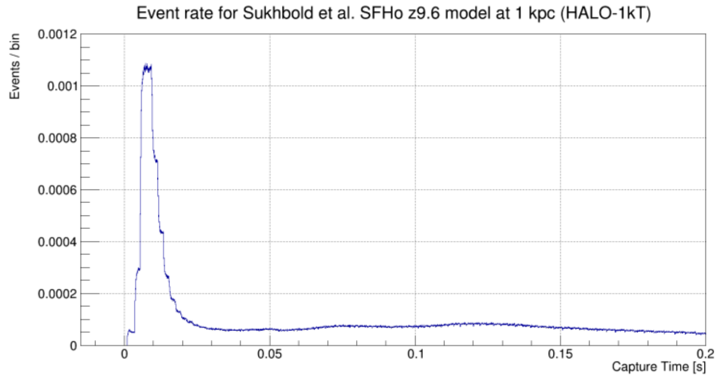


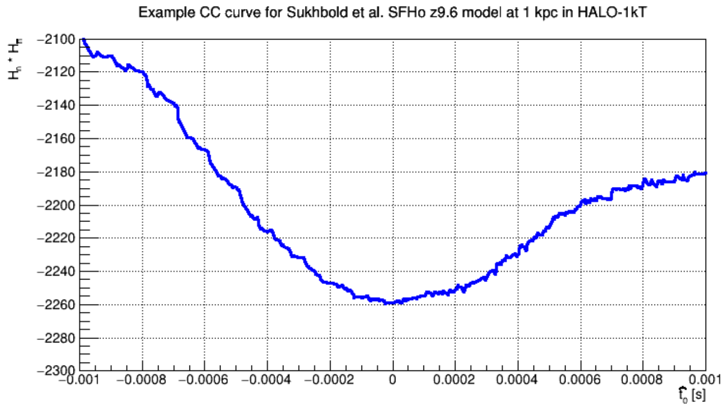
Extracting t_0 via cross-correlation

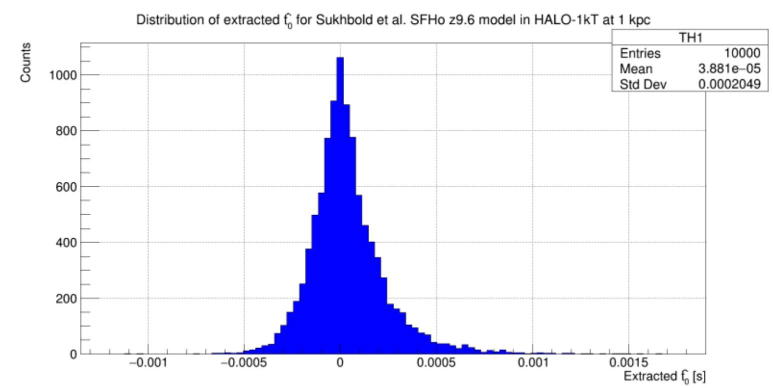
- Originally intended to avoid binning our observed SN signal.
  - For HALO-1kT, relatively low statistics at 10 kpc, bins on the order 1 ms are sparsely populated.
- We implement cross-correlation as:

$$(H_n * H_{\bar{n}})(t - t_0) = -\sum_{\infty}^{-\infty} H_n(t) \cdot H_{\bar{n}}(t - t_0)$$

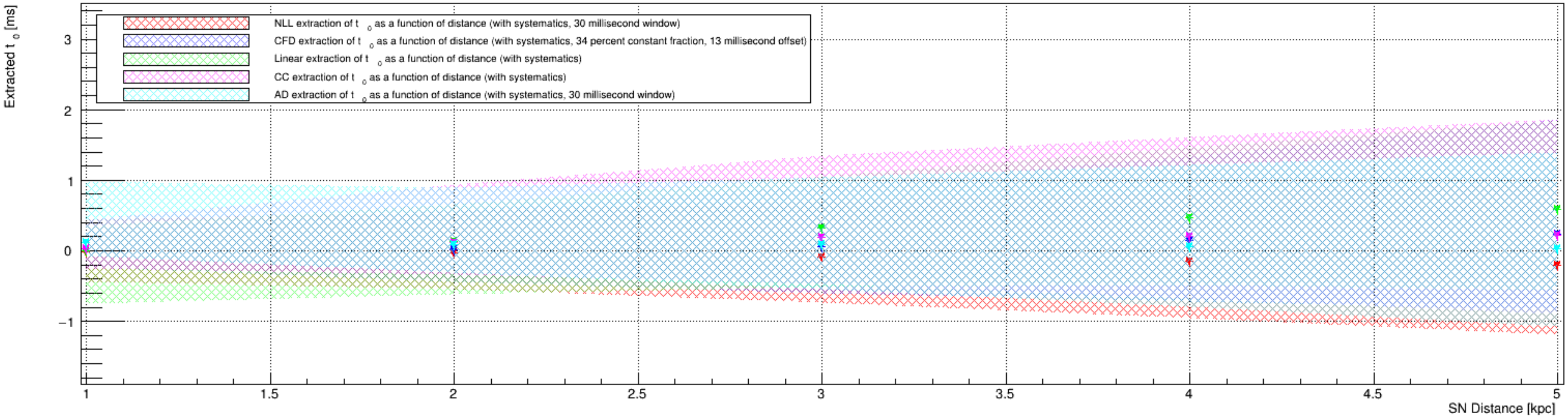
- Where H_n is the 1D histogram of the observed signal, and $H_{\bar{n}}$ is the event rate (top) evaluated at some offset.
  - Observed time series is placed in a histogram with 1 ms bins.
  - $(H_n * H_{\bar{n}})$ should reach a minimum around the Monte Carlo truth $t_0 = 0$.
  - An example can be found in the middle figure.
- The extracted t_0 distribution for the Sukhbold et al. SFHo z9.6 model at 1 kpc in HALO-1kT can be found in the bottom right.

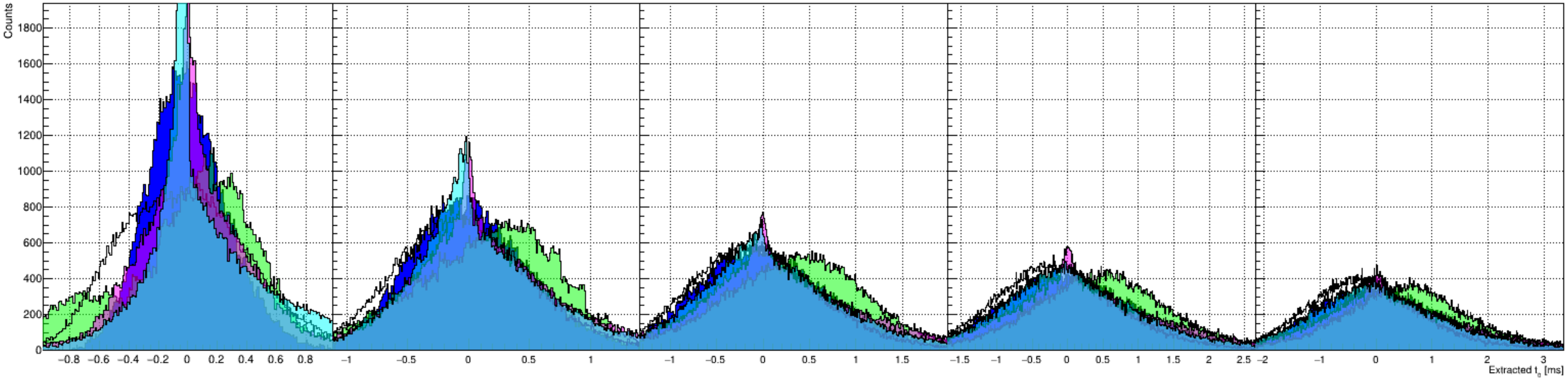




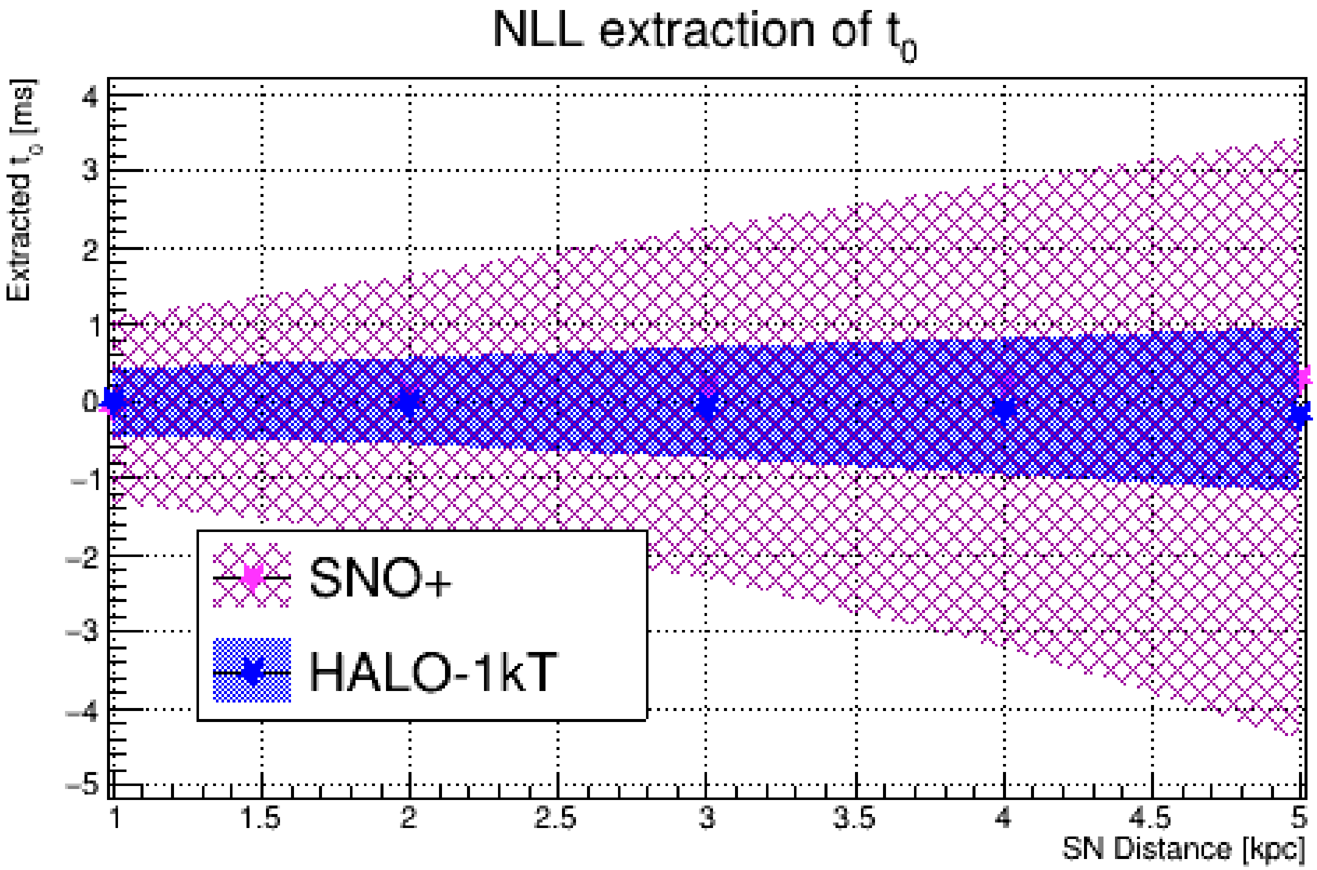


Projection of techniques



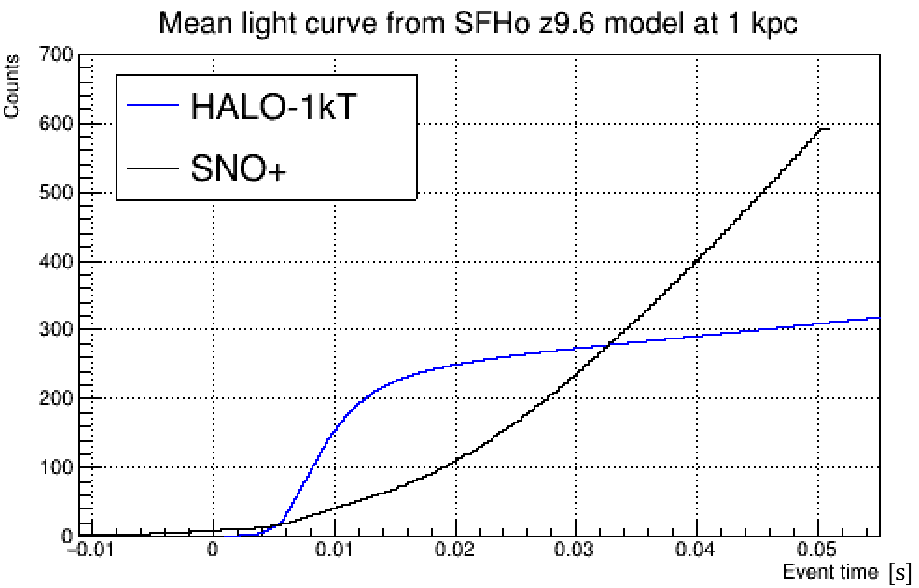


SNO+ vs HALO-1kT



Final remarks on SNO+

- As it stands, SNO+ fails to extract t_0 with the same precision as HALO-1kT.
  - It is not a question of statistics, as SNO+ expects more events in the time window used in this analysis.
- My initial thoughts are that the neutronization burst in HALO-1kT (primarily ν_e sensitive) is much easier to fit.
- A time window is necessary to reduce systematic uncertainties introduced when mixing models.
- However, with the current time window, there isn't a pronounced feature that the likelihood can easily locate.
- I have begun running some preliminary simulations of the entire burst to see if this improves our results.
  - For context, in both HALO-1kT and HALO, performance degrades as more of the burst is used. Maybe things will be different for SNO+.



Depicted above is the mean light curves as observed in HALO-1kT and SNO+ for the SFHo model at 1 kpc. The abrupt cut-off at 50 ms in SNO+ is a result of the upper time in sntools being set to 50 ms. Additionally, for context, in HALO-1kT the time of the events used comes from the capture time on ^3He in the proportional counters. For SNO+, it comes from the event times as registered on the GPS clock in UTC. This is then shifted back to the Monte Carlo truth values.

Integration into SNEWPDAG

- Throughout the hackathon I have worked on implementing some of these techniques into SNEWPDAG.
  - Constant fraction discriminator
  - Negative log likelihood
  - Linear fit
  - Anderson Darling test
  - Cross-correlation
- Will move away from the full Monte Carlo treatment done in HALO-1KT, HALO and SNO+.
  - Will still have to account for detector response, background, etc.
- Run other ν_e sensitive detectors through this pipeline to determine if my initial thoughts regarding the significance of the neutronization burst are true.
  - Will also be running some simulations with ν oscillations.
- Each detector will be unique and formal recommendations on the technique required to extract t_0 can be made once each detector is tested.
  - For HALO-1kT, the ideal candidate appears to be the CFD technique.

Thank you for listening! Questions?

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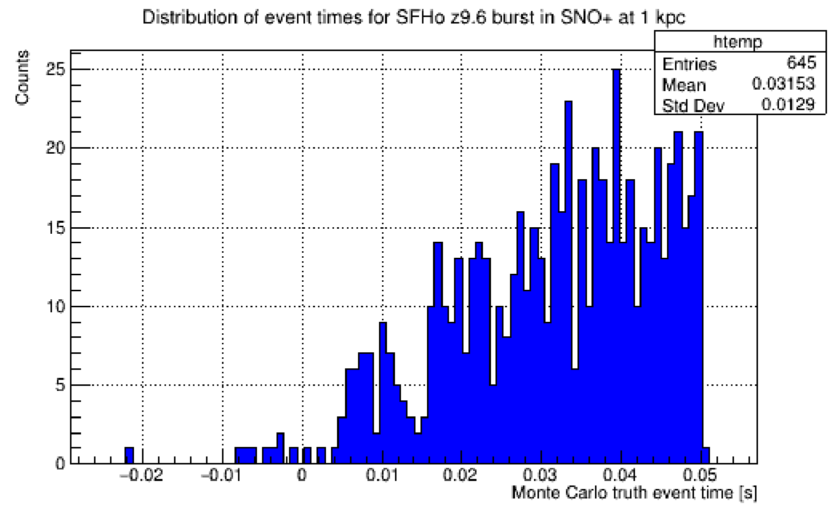
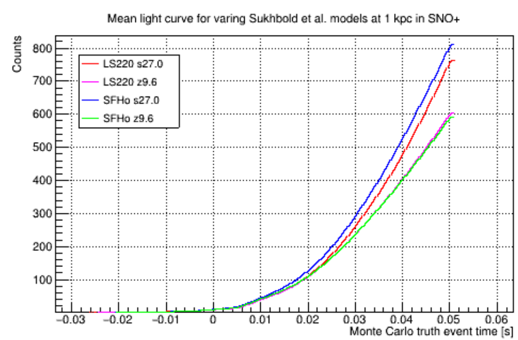
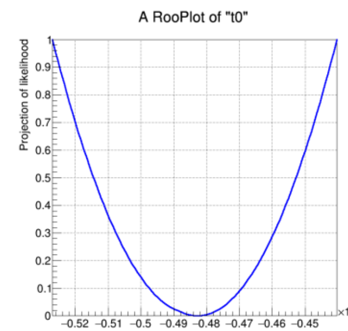
Negative Log Likelihood in SNO+

- We apply the same technique used in HALO-1kT (slide 2) to the output from the SNO+ Monte Carlo.
  - The background is added in, Poisson fluctuated and sampled from a physics run.
  - However, the thresholds of this analysis are raised to a cleaned nhit > 800, effectively removing its contribution.
- On top of the level 2 and level 3 triggers applied to the data, we introduce an additional cut.
  - Require 5 events with greater than 500 nhit each in a rolling 20 ms window.
  - This is intended to remove the sparse neutrino signal in the leading edge.
  - For both the likelihood and CFD technique these events caused severe issues in our extraction techniques.
  - Also cuts out many of elastic scattering on protons as a result.
- Applying these cuts will yield the event distribution on the top right.
  - The resulting likelihood function formed with the mean light curve can be found on the bottom right.







Comparison to HALO-1kT

- Depicted on the top right is the extracted t_0 from the SFHo z9.6 model in both HALO-1kT (left) and SNO+ (right) at 1 kpc.
  - Precision of extracted t_0 is reduced by a factor of 3 in SNO+.
  - Difference in statistics is not attributed to failures to fit but rather the amount of simulations done.
- On the bottom right is the extracted t_0 with the systematics of fitting all models to one another included.
  - With the systematics included the difference in precision is reduced to a factor of ~2.5.
  - With the current techniques, SNO+ does not obtain sub 1 ms precision at 1 kpc.
  - The comparison between the two experiments is not much improved at further distances.