

SNO+: Recovery of IBD Candidates During Bis-MSB Fill Periods

Jaron Cyna

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Abstract

During the bis-MSB fill period, the SNO+ detector scintillator was unmixed, leading to unpredictable energy reconstruction due to optical inhomogeneity. To recover inverse beta decay (IBD) events that occurred within this fill period, the ^{210}Po α -decay peak was used as a local standard candle to derive spatial energy corrections. The methodology evaluated local optical conditions using 1.5 m spherical cuts centered on prompt and delayed IBD events. By stochastically sampling spherical volumes across runs containing IBD candidates, localized correction factors were derived and applied to candidate events, which led to a stochastic restoration efficiency of $60.26\% \pm 0.75\%$ and a candidate recovery efficiency of $\sim 81\%$. This successfully recovered 345 IBD calibration constants for further analysis.

1 Introduction

The SNO+ experiment is a large-scale neutrino detector located at SNOLAB in Sudbury, Ontario. During the course of its three-phase life, from water to scintillator to tellurium, SNO+ has investigated questions in fundamental physics such as the nature of solar neutrinos, neutrinoless double-beta decay ($0\nu\beta\beta$) and Inverse Beta Decay (IBD) [1]. Studying IBD interactions is important because they provide insight into Earth's interior through geoneutrinos [2] and enable measurements of reactor antineutrinos from distant commercial nuclear plants [1].

During the transition to the liquid scintillator phase, the detector volume was initially filled with linear alkylbenzene (LAB) and Diphenyloxazole (PPO) before introducing a secondary wavelength shifter, bis-MSB. During this fill period, the incomplete mixing caused the detector to be optically inhomogeneous, creating position-dependent and time-varying shifts in energy reconstruction. To characterize these variations, the α -decay peak of polonium-210 (^{210}Po), a prominent intrinsic background originating from the natural radon decay chain, serves as a monoenergetic baseline calibration point. Because ^{210}Po is distributed throughout the scintillator with a known decay energy, tracking local shifts in reconstructed energy provides a direct comparison to assess optical changes.

This report presents a methodology for evaluating and recovering IBD candidate events recorded during the bis-MSB fill period. By utilizing the ^{210}Po α -decay peak as a local standard candle, a position-dependent energy correction is derived for prompt and delayed IBD signals.

2 Motivation

IBD occurs when an electron antineutrino interacts with a free proton in the liquid scintillator target:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (1)$$

This interaction produces a characteristic two-fold time-coincident signature. The prompt signal is generated by the positron's kinetic energy and annihilation with an electron, yielding two 511 keV γ -rays ($E_{\text{prompt}} \approx E_{\bar{\nu}} - 0.78 \text{ MeV}$). The neutron subsequently gets captured by a proton ($p+n \rightarrow d+\gamma$), releasing a 2.22 MeV γ -ray after $\sim 50 - 200 \mu\text{s}$, producing the delayed signal.

The dual-stage coincidence, requiring both time separation (Δt) and spatial proximity (Δr), makes uncorrelated radioactive backgrounds unlikely to appear as IBD events. Consequently, IBD candidates remain identifiable, albeit more hidden, in an uncalibrated detector volume.

During the bis-MSB fill phase, optical inhomogeneities throughout the detector complicated event energy reconstruction, making it difficult to declare

an event pair an IBD candidate. However, since position and timing reconstruction remain robust in a poorly mixed detector, by applying looser energy cuts IBD candidates were still identifiable. Rather than attempting a complex, global optical correction for all single-hit events, targeting the correlated IBD sample provides a practical path to salvaging physically meaningful data from this fill period.

3 Methodology

The analysis presented in this report is based on reconstructed data from hundreds of runs in the pre-bis-MSB, bis-MSB fill, and post-bis-MSB phases. The analysis relies on the reconstructed position and energy branches of each event, together with the `fitValid` and data-cleaning flags used for event selection.

3.1 Dataset, Data Quality Cuts, & Processing

The data used was in the range of runs [300000, 364311] where the interval [350000, 354099] corresponds to the bis-MSB fill period, and is the primary data of interest. To properly analyze the data, standard SNO+ cuts were applied which consisted of the criteria summarized in Table 1. The `Nhits` cut is necessary to cut out low energy backgrounds, whereas the radial cut prevents wall optical effects from biasing the data. The `fitValid` requirement ensures convergence of the reconstruction algorithm, while standard data-cleaning masks filter out instrumental noise and non-physical triggers.

Table 1: Event selection criteria applied to data when looking for the ^{210}Po peak.

Cut / Variable	Selection Criterion
N_{hits}	> 80
R (posr)	< 5700 mm
<code>fitValid</code>	<code>== 1</code>
Data Cleaning	<code>(dcApplied & mask) == (dcFlagged & mask)</code> <i>where mask = 0x2100000042C2</i>

Regarding data processing, Reactor Analysis Tool (RAT) Version 7.0.8 was used. RAT is an integrated toolkit for SNO+ that incorporates Geant4 for simulation, ROOT for analysis, and other reconstruction algorithms. For this analysis, RAT is used to correct spatial energy deviations within the detector geometry with `CalibrateEnergyRSP`. This function cancels spatial photomultiplier tube (PMT) effects, allowing the data to correspond purely to optical inhomogeneities.

3.2 IBD Candidate Pre-Selection

Candidate IBD events were identified from a preliminary coincidence search across the stated dataset. Cuts used in the preliminary search were looser than standard IBD searches because of the unpredictable optics. Specifically, the cuts used are presented in Table 2:

Table 2: IBD candidate selection cuts used to tag preliminary IBD candidates.

Cut name	prompt cut		delayed cut		coincidence cut	
	min	max	min	max	min	max
correctedNhits	200	3100	550	1150		
R_{AV} (m)		5.8		6.0		
ΔR (m)						2.0
Δt (μs)						1000
Data Cleaning				pass DC		
fitValid				== 1		
No tagged pairs share events						

Tagged candidate pairs were indexed by run number alongside prompt and delayed Global Trigger IDs (GTIDs). They were then stored in a CSV allowing for simple integration into the analysis scripts. The full list of IBD candidates can be found in Appendix 6.1.

3.3 Local ^{210}Po Standard Candle Fitting

Due to optical stratification during the fill period, evaluating the entire fiducial volume introduces multi-peak reconstructions. Multiple peaks in a single run are shown explicitly in the 2.5 m cut in Figure 1. To mitigate this, evaluating a localized section of a detector around an IBD event would give the immediate energy profile. Knowing the local energy of the ^{210}Po peak would then allow a correction factor to be applied to the IBD candidate, thus determining if it is a true IBD event.

To optimize local cuts around IBD events, sphere radii of 1.0 m to 2.5 m were tested in Figure 1. This graph clearly displays cuts where $R \geq 2.0$ m introduce inhomogeneities within the local cut, resulting in multiple peaks. This is largely resolved at $R = 1.5$ m; decreasing the radius to 1.0 m reduces statistics significantly without providing a measurable improvement in energy resolution. Thus, 1.5 m was chosen to balance enough event entries $\sim 1500\text{--}3000$ with minimal noise.

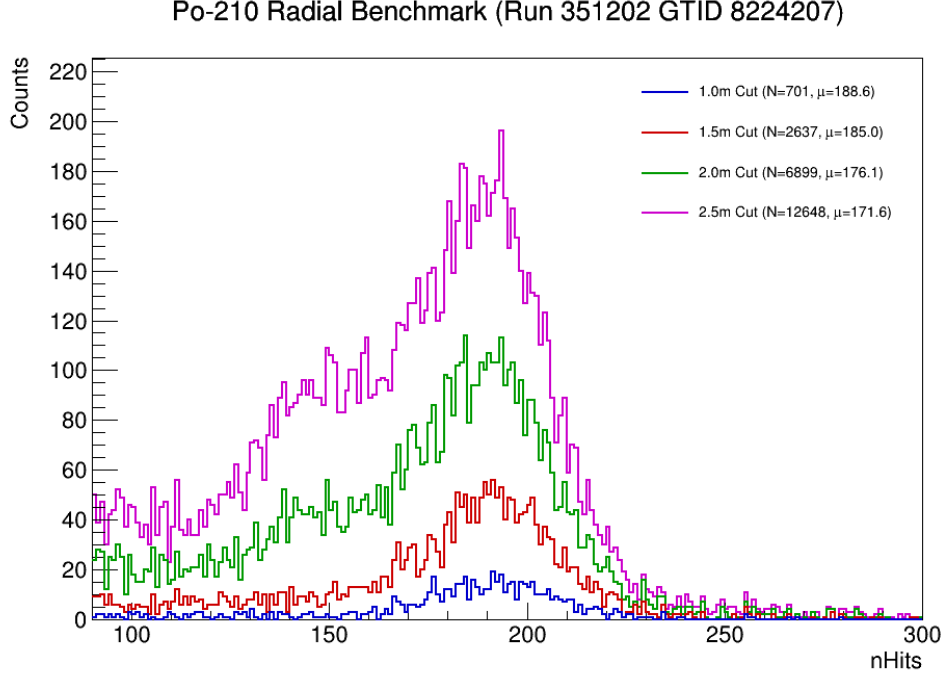


Figure 1: Observed ^{210}Po α -decay nHits spectra for spherical cuts of radius 1.0 m (blue), 1.5 m (red), 2.0 m (green), and 2.5 m (magenta) centered at the IBD candidate of Run 351202 (GTID 8224207). Larger radii ($R \geq 2.0$ m) exhibit secondary low-energy peak structures, whereas the 1.5 m cut isolates the monoenergetic peak with sufficient statistics for fitting.

3.4 Position-Dependent Energy Correction

To quantify local optical gradients around each candidate, a 7-sphere probe geometry was constructed. A central sphere of radius $R = 1.5$ m was centered at the candidate vertex, accompanied by six adjacent 1.5 m spheres displaced along the Cartesian axes at $\pm X$, $\pm Y$, and $\pm Z$ by a center-to-center separation of 3.0 m (such that each boundary sphere is tangent to the central sphere). Peripheral spheres exceeding the fiducial volume were excluded. This geometric configuration was evaluated for both prompt and delayed candidates, producing 14 fitted ^{210}Po peak spheres per candidate pair.

To evaluate local stability, the central fitted mean was compared against the

peripheral sphere with the maximum deviation (excluding failed fits). As shown in Figure 2, the central and peripheral responses follow a rough $y = x$ trendline, with moderate divergence during the bis-MSB fill period.

To calibrate candidate energies, a reference scale E_{ref} was established using the mean RSP-corrected ^{210}Po energy from the stable, fully mixed PPO phase. The corrected energy for each IBD event E_{corr} is calculated via the linear shift shown in Equation 2.

$$E_{\text{corr}} = E_{\text{IBD}} \times \left(\frac{E_{\text{ref}}}{E_{\text{local}}} \right) \quad (2)$$

where E_{local} is the mean of the fitted ^{210}Po peak within the candidate's central 1.5 m sphere. The propagated statistical uncertainty on the correction ratio σ_R is given by Equation 3.

$$\sigma_R = \frac{E_{\text{ref}}}{E_{\text{local}}} \sqrt{\left(\frac{\sigma_{E_{\text{ref}}}}{E_{\text{ref}}} \right)^2 + \left(\frac{\sigma_{E_{\text{local}}}}{E_{\text{local}}} \right)^2} \quad (3)$$

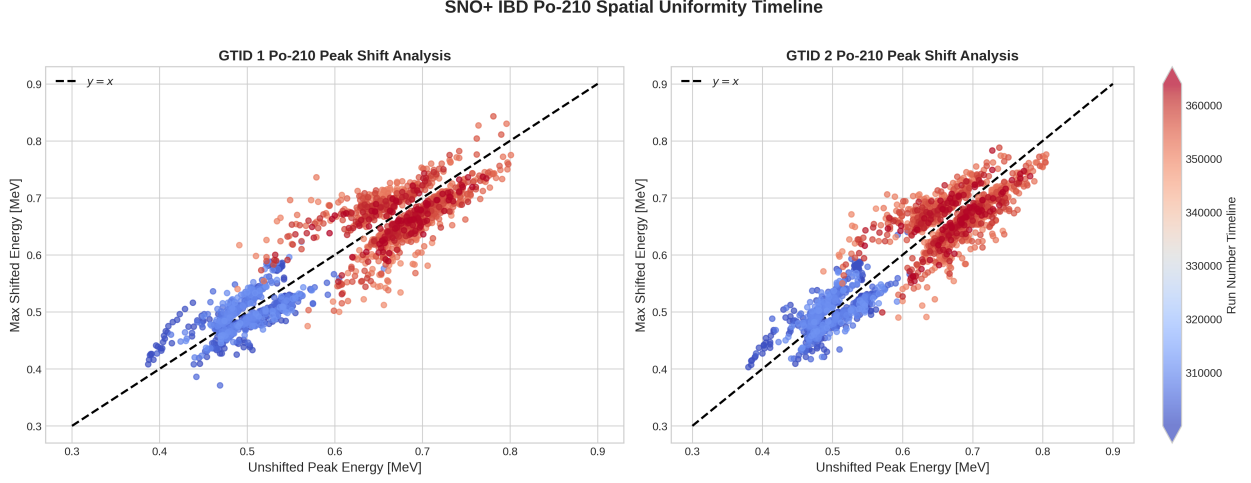


Figure 2: Local optics timeline of the ^{210}Po peak energy for prompt (GTID 1, left) and delayed (GTID 2, right) IBD candidate events across the analyzed run range. The fitted ^{210}Po peak of the central 1.5 m sphere (unshifted) is plotted against the most divergent adjacent sphere (max shifted), with the dashed line denoting ideal $y = x$ optical uniformity.

3.5 Stochastic Sampling & Efficiency Evaluation

To establish an unbiased baseline for local optical gradients and quantify the recovery efficiency of this calibration method, a stochastic sampling method was used for all runs. Rather than evaluating only the GTID coordinates tagged, ten random spatial vertices were uniformly sampled within the fiducial volume ($R_{\text{probe}} < 4.2$ m) for every physics run. This yielded $\sim 18,000$ independent data points, providing a global map of detector optics across runs.

Data from the stable PPO operational phase were used to define a baseline acceptance threshold for local variations ($|E_{\text{local}} - E_{\text{adj}}| < \Delta E_{\text{threshold}}$). Applying this cut to the fill period separates well-behaved, calibratable candidates from poorly mixed regions. Figure 3 displays the central versus maximum-deviated ^{210}Po peaks from stochastically sampled points.

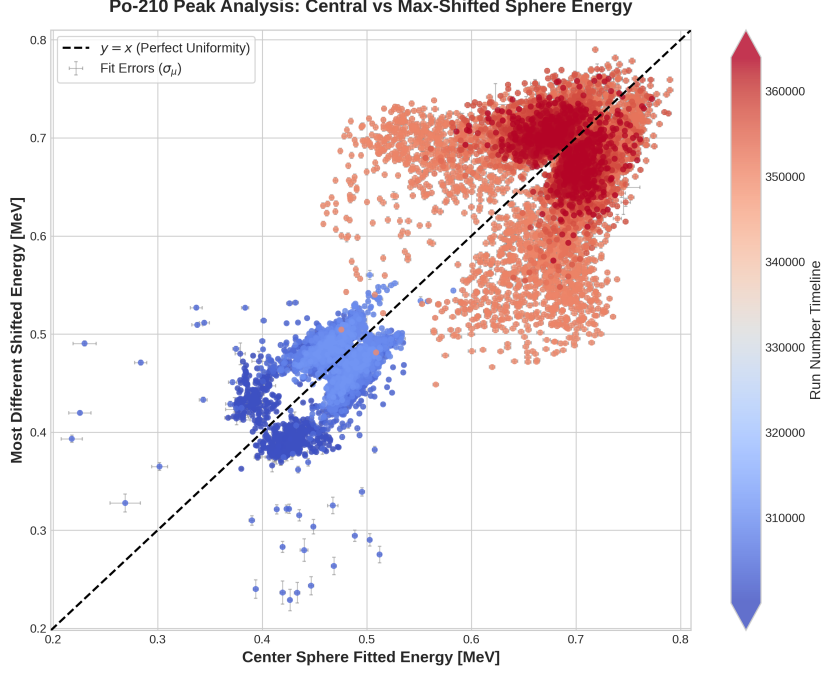


Figure 3: ^{210}Po peak fitted energy of the central 1.5 m sphere versus the most divergent adjacent peripheral sphere ($\pm X, \pm Y, \pm Z$) for $\sim 18,000$ stochastically sampled coordinates across the full dataset timeline. The black dashed line indicates ideal optical uniformity ($y = x$), with grey error bars denoting Gaussian fit uncertainties (σ_μ).

4 Results and Discussion

The ^{210}Po peak was used as a standard candle to calibrate IBD candidates from the bis-MSB fill period. The analysis yielded a point-by-point calibration factor to recover previously unusable IBD events from the inhomogeneous optics of the bis-MSB phase. This section presents the calibration constants derived from stochastic sampling, evaluates the quantity of recovered IBD events, and quantifies the overall event recovery efficiency of this analysis.

4.1 Baseline Calibration & Recovery Efficiency

The acceptance criteria were chosen as a method to eliminate obvious outliers. Figure 4 shows the residuals from the stochastic analysis. The blue points, corresponding to the PPO period, exhibit minimal spread. Based on this, a cut of ± 0.06 MeV was empirically chosen to mitigate outliers while retaining the majority of valid events. (Note that this cut corresponds to $\sim 1.8\sigma$ of the PPO distribution).

By taking the cut of ± 0.06 MeV and applying it broadly to the bis-MSB fill period the efficiency of this method could be determined. In this case, it was $60.26\% \pm 0.75\%$ from an initial sample size of 4,300 points.

To find the calibration constant, the mean of the stochastically sampled points from the PPO phase was taken. This enabled an average of 6,906 data points, which gave a correction factor $E_{\text{ref}} = 0.4734 \pm 0.0003$ MeV. Although ^{210}Po α -decay has a true kinetic energy of ~ 5.3 MeV, its reconstructed equivalent energy is significantly quenched to ~ 0.47 MeV due to the high ionization density of α -particles in LAB/PPO (Birks' law) [1].

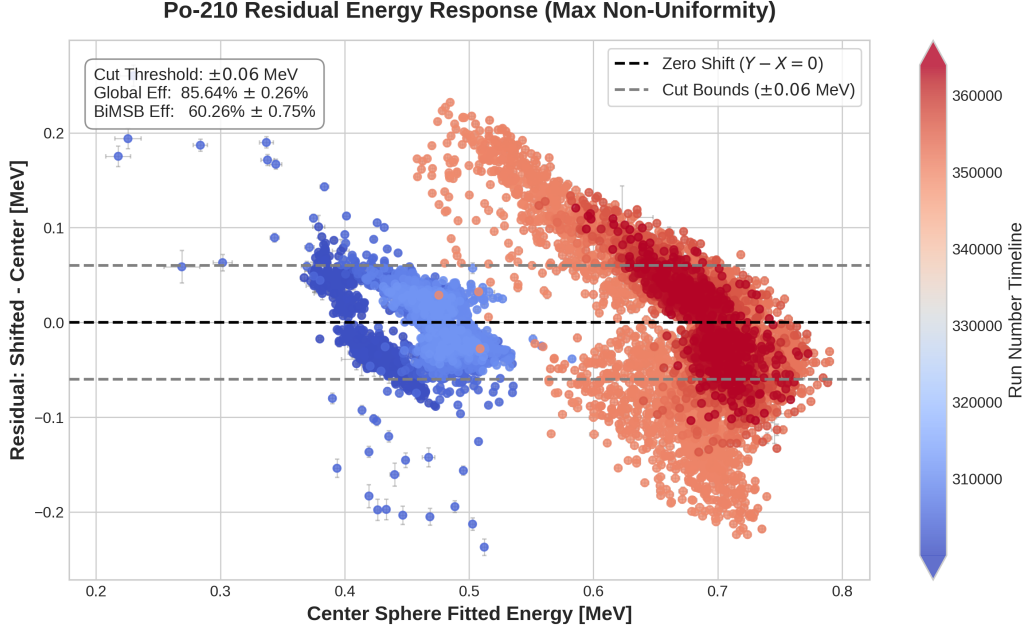


Figure 4: ^{210}Po peak residual energy response ($\Delta E = E_{\text{shift}} - E_{\text{center}}$) as a function of the central 1.5 m sphere fitted energy for $\sim 18,000$ stochastically sampled coordinates across three detector operational phases. The black dashed line denotes zero residual shift ($Y - X = 0$), and the grey dashed lines show the cutoff of $(\pm 0.06$ MeV).

4.2 Position-Dependent IBD Energy Recovery

By combining the errors from Equations 2 and 3, the energy reference constant, and the efficiency cut, the calibration constants per-event were derived. The residuals for Figure 2 are shown in Figure 5. Of the 1,832 candidate pairs across the dataset, 426 fell within the bis-MSB fill interval [350000, 354099], yielding 345 recoverable pairs. This results in a recovery efficiency of approximately 81%, notably higher than the $\sim 60\%$ found from stochastic sampling. This discrepancy likely arises because tagged candidates had already survived initial spatial and coincidence cuts, effectively pre-filtering the noise that degraded the unbiased stochastic sample.

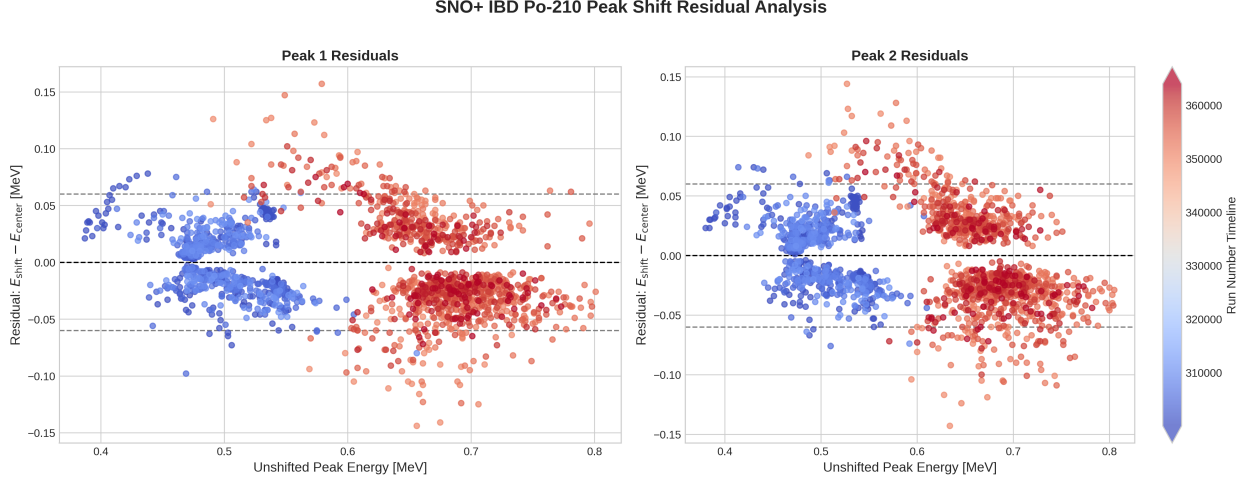


Figure 5: Localized ^{210}Po peak shift residual analysis for candidate IBD prompt (GTID 1, left) and delayed (GTID 2, right) vertices across the analyzed run timeline. Residuals are defined as the energy difference between the maximum-shifted adjacent sphere and the candidate’s central 1.5 m sphere ($\Delta E = E_{\text{shift}} - E_{\text{center}}$) plotted against the central unshifted peak energy. The black dashed line denotes zero spatial shift ($\Delta E = 0$ MeV), and the grey dashed lines mark the ± 0.06 MeV acceptance threshold.

5 Conclusion

This report developed a functional calibration framework for the SNO+ detector when optical inhomogeneities are present in the scintillator. By fitting the local ^{210}Po peak within a 1.5 m sphere around the IBD candidate events, a position-dependent energy scaling factor was derived to normalize event energies to the PPO-phase baseline ($E_{\text{ref}} = 0.4734 \pm 0.0003$ MeV). A stochastic evaluation consisting of $\sim 18,000$ data points determined the recovery efficiency of events in an unmixed detector was a measured $60.26\% \pm 0.75\%$ and $\sim 81\%$ among the actual tagged IBD candidates. This enabled the recovery of 345 IBD candidate events’ correction factors. Future analysis should focus on using these calibration numbers to find the PPO-phase energy of the IBD candidates and apply stricter cuts to discriminate genuine IBD interactions from accidental background coincidences.

6 Appendix

6.1 IBD candidate events

As described in Section 3.2, a loose preliminary coincidence selection was applied across the dataset to avoid pre-filtering genuine interactions. This initial search yielded 1,832 candidate IBD pairs across the analyzed run range. Due to the size of the full dataset, the complete catalog containing all run numbers and prompt and delayed GTIDs is archived in the supplementary repository:

https://github.com/JaronCyna/snoplus-ibd-recovery/blob/main/analysis_files/selected_events.csv

6.2 IBD Candidate Correction Factors

Similar to Section 6.1, the list of correction factors found in Section 4.2 is too long to include in this report. The link for this can also be found below.

https://github.com/JaronCyna/snoplus-ibd-recovery/blob/main/correction_csv/Run_Global_RAT_Energy_Correction.csv

6.3 Fit Logic Used

All peak calibrations were performed using binned log-likelihood Gaussian fits implemented in ROOT. Fits failed when there were too few events (< 100), and in the random case, when the peripheral spheres were outside the fiducial volume, that specific peripheral sphere failed. For more details on the code used, all analysis scripts have been uploaded to GitHub:

<https://github.com/JaronCyna/snoplus-ibd-recovery>

References

- [1] SNO+ Collaboration (V. Albanese *et al.*), *The SNO+ experiment*, JINST **16**, P08059 (2021).
- [2] G. Fiorentini, M. Lissia, and F. Mantovani, *Geo-neutrinos and Earth's interior*, Phys. Rep. **453**, 117–172 (2007).