Event Reconstruction in the SNO+ Experiment

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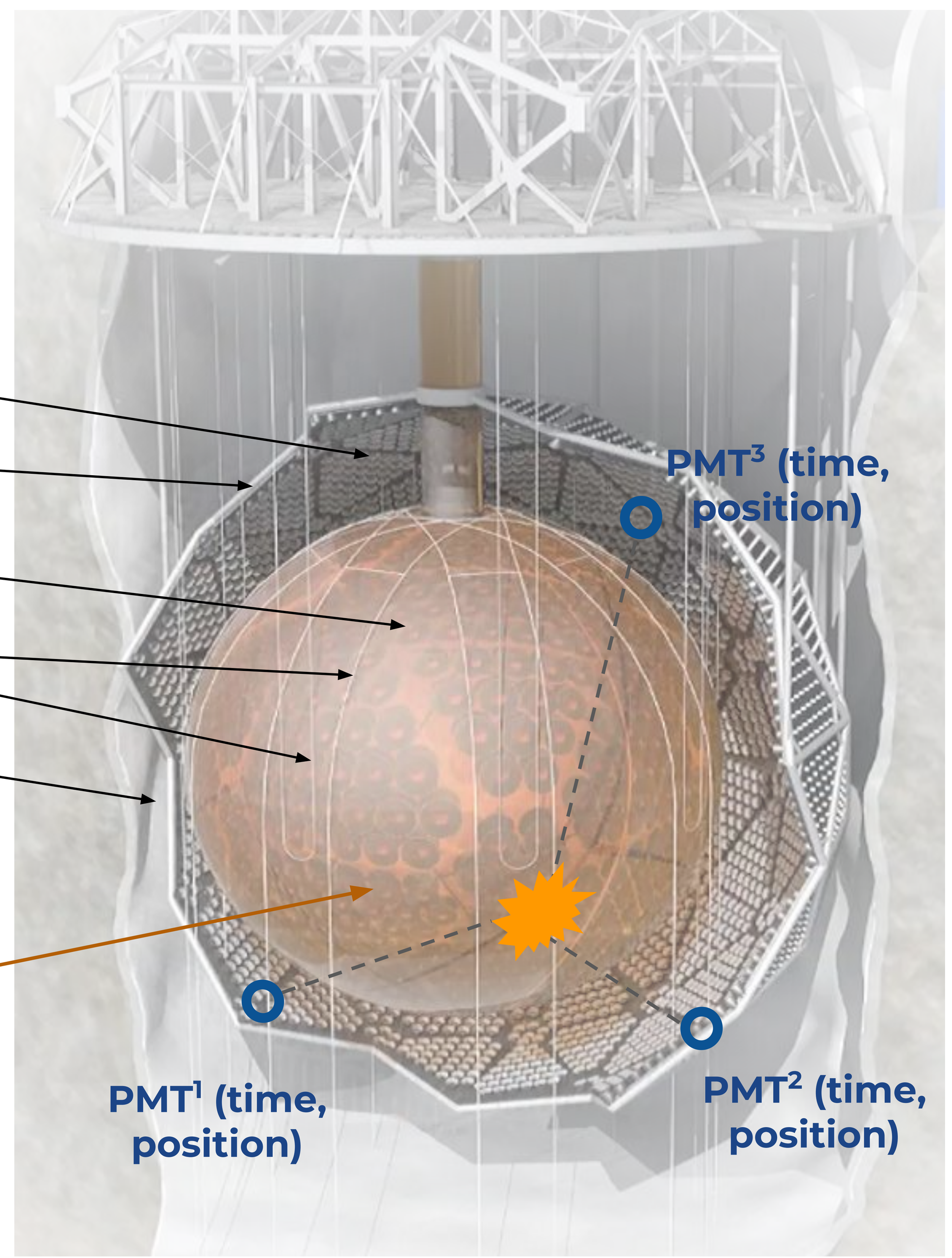
on behalf of the SNO+ Collaboration

The SNO+ Experiment

SNO+ is a multi-purpose neutrino detector located at SNOLAB in Sudbury, Canada. The primary physics goal of the experiment is to search for neutrinoless double beta decay (0νββ) in ^{130}Te. For this rare event search, the acrylic vessel, currently filled with organic liquid scintillator, will be doped with natural tellurium.

2070 m rock overburden



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Physics event
time, position, energy, particle type, direction

Target

Water phase: 905 t ultra-pure water
Unloaded scintillator phase: 780 t liquid scintillator (LS)
Tellurium phase: 4+ t of natural Te loaded to the LS

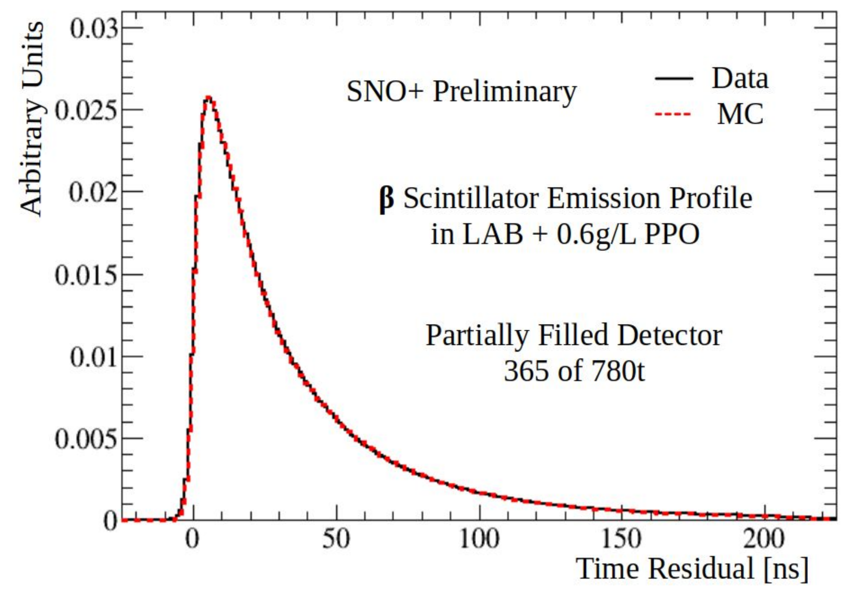
Organic liquid scintillator produces isotropic scintillation light, which is detected by PMTs. The current light yield is ~11800 photons/MeV. The information about the particle type, energy, and position of each interaction is reconstructed using the times and positions of individual triggered PMT hits.

Position & Time Reconstruction

All triggered events in SNO+ are first reconstructed under the hypothesis of a single electron. The position reconstruction utilises the spherical symmetry of the SNO+ detector. It is a likelihood fit to the time residuals, which are calculated as

$$t_{res} = t_{hit} - t_{fit} - t_{tof}$$

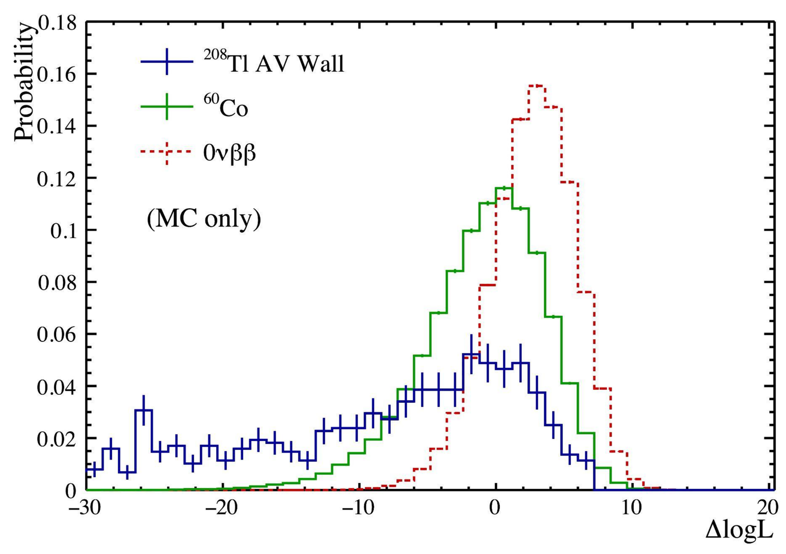
and represent the scintillator timing PDF, accounting for the photon time of flight. Using this method, SNO+ has 3D position resolution of ≤ ~20 cm 3D at 1 MeV and above.

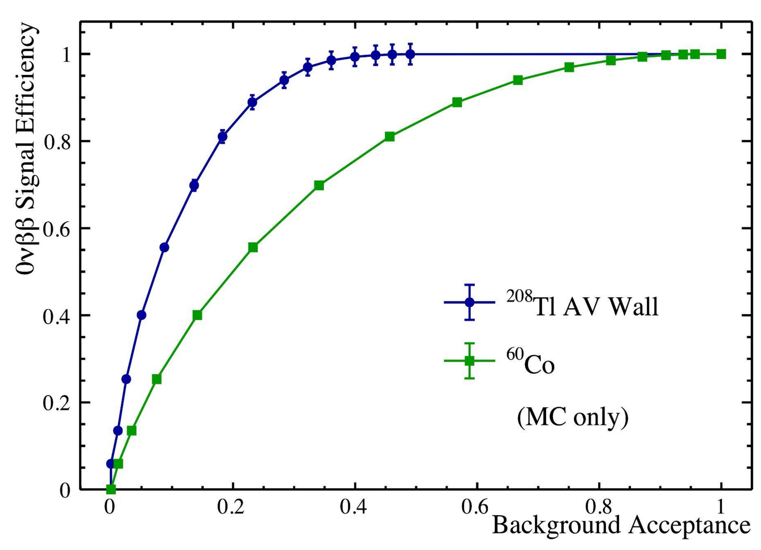


The plot presented above shows the time residuals of ^{214}Bi decays, tagged by their coincidence with daughter ^{214}Po decays in partially filled detector, demonstrating detector calibration and agreement in position reconstruction between data and Monte Carlo.

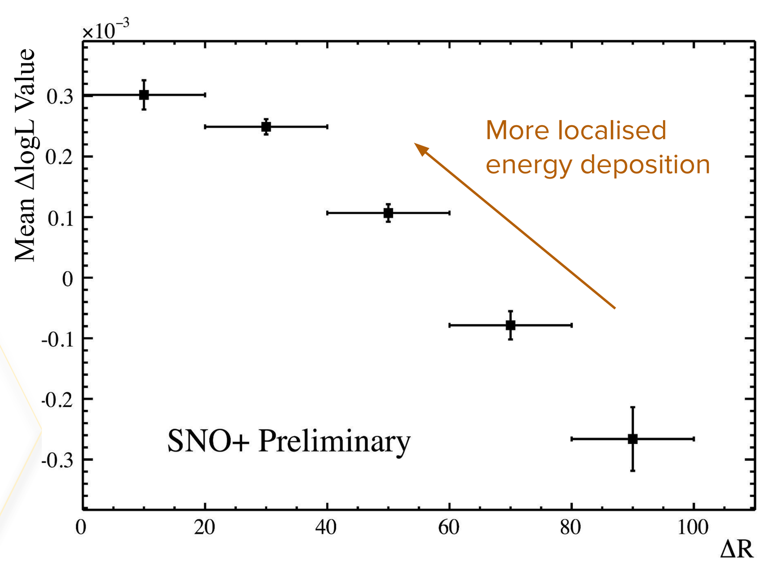
Pulse Shape Discrimination: Multi-site Event Classification

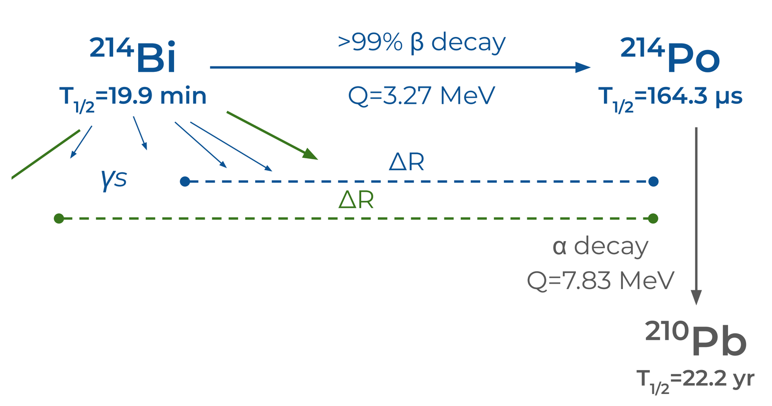
SNO+ has developed a pulse shape discrimination (PSD) technique to classify multi-site (radioactive decays with γs) and single-site (pure β decays, 0νββ) energy depositions based on NIM 943, 2019. Since the position of all events is reconstructed as electrons, the time residual distribution of events with more spread out energy deposition will appear wider compared to true e⁻s of the same energy. A log-likelihood ratio classifier is used to discriminate between single- and multi-site hypotheses using time residual PDFs.



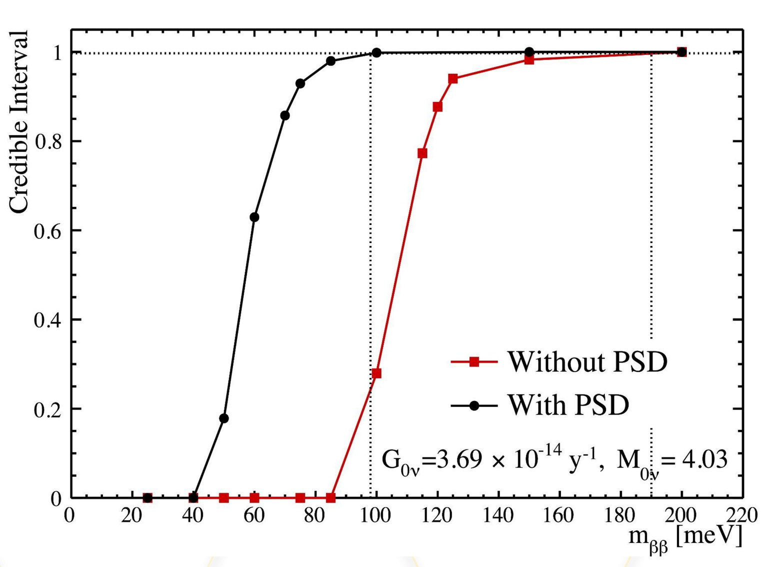


Monte Carlo predictions of the classifier values for the tellurium phase (0.5% Te loading by weight) are shown above on the left for 0νββ and two background event classes with reconstructed energies close to the ^{130}Te Q-value. The figure on the right shows the discrimination potential of the classifier using hard cuts; over 20% of ^{60}Co decays in the scintillator, and 60% of ^{208}Tl decays from the AV wall that reconstruct near the fiducial volume (4.2 m), can be rejected with minimal signal sacrifice.





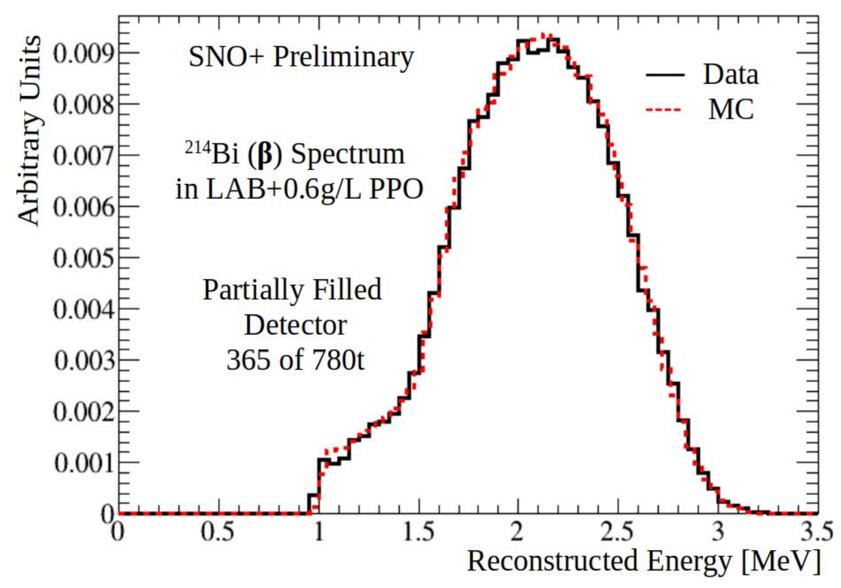
The technique was validated by applying the classifier to tagged ^{214}Bi decays in partially filled detector (365t of LS). ^{214}Bi with more spread-out energy depositions reconstruct on average further away from the daughter decay. The plot above shows that these with higher ΔR have lower discriminant values as expected and presents the first data-driven demonstration of this technique.



Finally, instead of mere hard cuts, the classifier values can also be used as additional dimensions in likelihood fits. The 0νββ 3 year sensitivity with 0.5% Te is plotted on the left, showing significant discovery potential improvement when PSD is included in the fit.

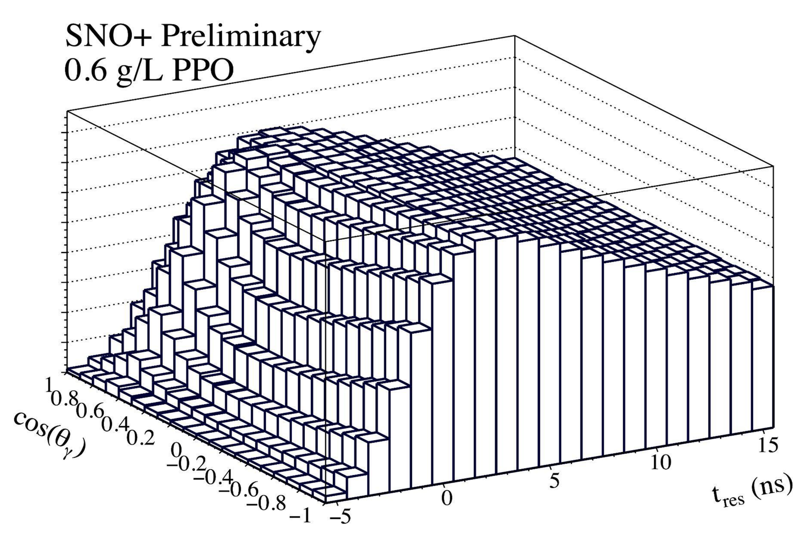
Energy Reconstruction

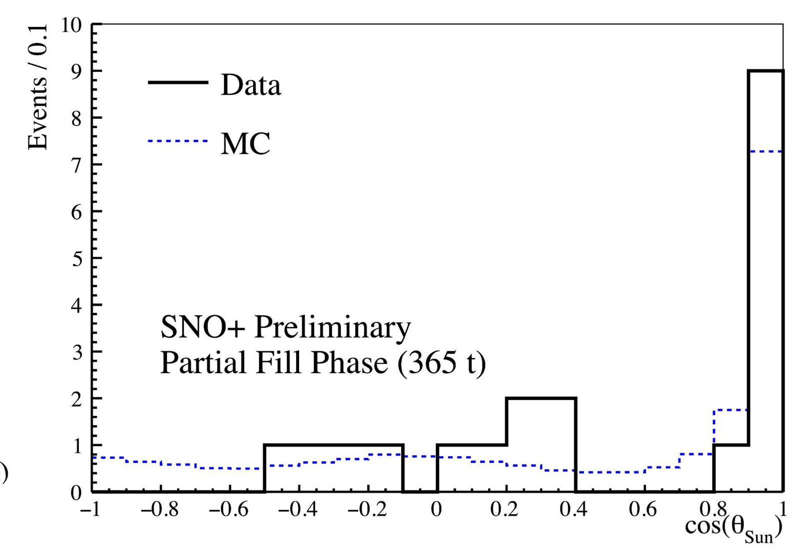
The energy of an event is calculated using the number of hit PMTs. A Poisson correction is applied to subsets of PMTs to obtain a linear energy estimator, accounting for multiple hits of the same PMT. Finally, the reconstructed event position is used to account for optical and geometric effects across the detector. The comparison of data to Monte Carlo reconstructed energy for tagged ^{214}Bi decays is shown below.



Direction Reconstruction

Direction reconstruction in liquid scintillator relies on early Čerenkov light cone emitted in the direction of charged particle's trajectory. The low ratio of Čerenkov to scintillation light makes this reconstruction challenging. During the partial fill phase, a lower concentration of the primary fluor, 2,5-Diphenyloxazole (PPO), led to a slower scintillation emission profile, enhancing the separation between Čerenkov and scintillation components.





θ_γ = angle between event direction and hit PMT with respect to event position
θ_{Sun} = angle between reconstructed event direction and direction from the Sun

A likelihood fitter with a 2D PDF in θ_γ and time residuals using the fitted position was designed to fit the direction of charged particles; the PDF with visible Čerenkov peak is shown above on the left. During 92 days of livetime in partial phase, SNO+ collected 20 events with reconstructed energies above 5 MeV; all expected to be ^{8}B solar neutrino interactions with a scattered electron travelling predominantly in the Sun's direction. The plot on the right displays the fitted directions of these 20 events alongside the MC prediction and demonstrates the first event-by-event direction reconstruction in liquid scintillator.