PMT Timing Calibration with In Situ Radioactive Backgrounds

NPML 25

October 30, 2025

Scott DeGraw, on behalf of the SNO+ collaboration
scott.degraw@physics.ox.ac.uk

UNIVERSITY OF OXFORD

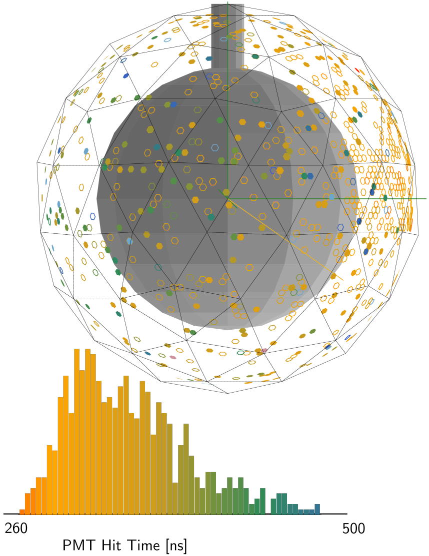
SNO+

UKRI Science and Technology Facilities Council

Introduction

SNO+ is a 780 t general purpose liquid scintillator detector

- Charged particles deposit energy and produce isotropic scintillation light
- Detected by around 9000 PMTs
- Energy reconstruction uses number of PMT hits
- 2nd most important quantity is PMT hit times
  - Position and time
  - Energy corrections
  - Classifiers
- Accurate timing is needed for good event reconstruction



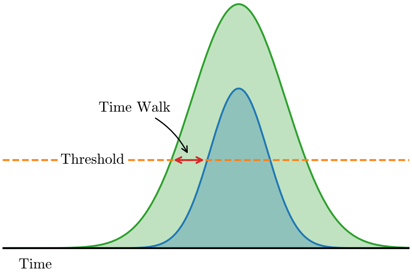
Time Walk and Electronic Delays

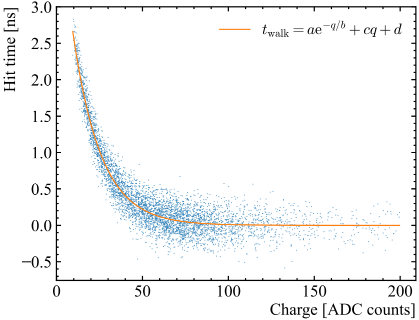
Each PMT has a constant delay and time walk

- Front end electronics give PMTs different delays
- PMTs trigger on individual thresholds
- Time walk: larger pulses biases to earlier hit times
- Parametrize time walk by PMT charge

Standard calibration involves a deployed laserball source

- Requires dedicated calibration runs
- Resource intense
- Contamination risk





Time Residuals

Time residuals correct event position dependence of hit times to first order

For hit i

$$t^i_{\mathrm{res}} = t^i_{\mathrm{hit}} - t^i_{\text{time of flight}} - t_{\mathrm{event}}$$

Find time residual distribution from MC

- Fit skew-t distribution to MC time residuals
- Use fit as likelihood loss function

Dataset we use is $\sim$ 10 million ^{210}Po α events

- Abundant and point like deposition
- Distributed throughout detector

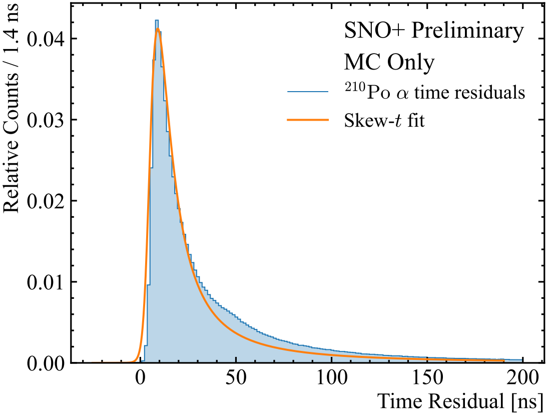


Figure: MC ^{210}Po time residual distributions

PMT Timing Calibration

We want to fit a falling exponential time walk and delay d_i for PMT i

$$t^i_{\text{walk}}(q) = a_i \mathrm{e}^{-q/b_i} + c_i q + d_i$$

If position/time of α from ^{210}Po is known

- Calculate $t^i_{\text{res}} = t^i_{\text{uncal hit}} - t^i_{\text{walk}}(q^i) - t^i_{\text{time of flight}} - t_{\text{event}}$
- Fit time walk against time residual distribution

PMT Timing Calibration

We want to fit a falling exponential time walk and delay d_i for PMT i

$$t^i_{\text{walk}}(q) = a_i \mathrm{e}^{-q/b_i} + c_i q + d_i$$

If position/time of α from ^{210}Po is known

- Calculate $t^i_{\text{res}} = t^i_{\text{uncal hit}} - t^i_{\text{walk}}(q^i) - t^i_{\text{time of flight}} - t_{\text{event}}$
- Fit time walk against time residual distribution

^{210}Po are distributed throughout the detector

- Could reconstruct α position
- Reconstruction depends on PMT timing calibration

PMT Timing Calibration

We want to fit a falling exponential time walk and delay d_i for PMT i

$$t^i_{\text{walk}}(q) = a_i \mathrm{e}^{-q/b_i} + c_i q + d_i$$

If position/time of α from ^{210}Po is known

- Calculate $t^i_{\text{res}} = t^i_{\text{uncal hit}} - t^i_{\text{walk}}(q^i) - t^i_{\text{time of flight}} - t_{\text{event}}$
- Fit time walk against time residual distribution

^{210}Po are distributed throughout the detector

- Could reconstruct α position
- Reconstruction depends on PMT timing calibration

Solution: Train time walk and position reconstruction simultaneously

- As time walk is calibrated, position reconstruction changes with it

ML Based Position/Time Reconstruction

Fitting position and time across 10 million events to t_{res} distribution is challenging

- Alternative: use neural network for event position + time
- Model used is transformer based model (see Cal's talk)

ML Based Position/Time Reconstruction

Fitting position and time across 10 million events to t_{res} distribution is challenging

- Alternative: use neural network for event position + time
- Model used is transformer based model (see Cal's talk)

Procedure for each ^{210}Po batch:

- $t^i_{\text{uncal hit}} - t^i_{\text{walk}}(q^i)$ given to neural network (not pre trained)
- Network predicts event position and time
- Calculate time residuals with current time walks

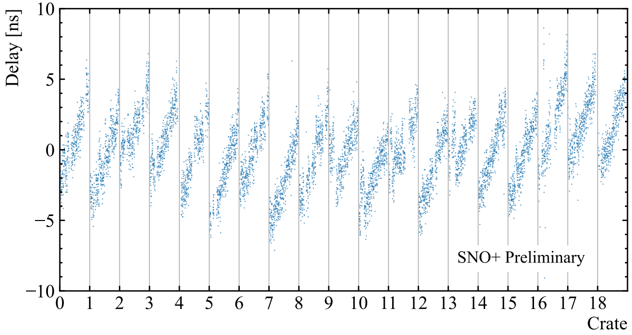
$$t^i_{\text{res}} = t^i_{\text{uncal hit}} - t^i_{\text{walk}}(q^i) - t^i_{\text{time of flight}} - t_{\text{event}}$$

- Loss function is the time residual distribution fit
- Gradient descent simultaneously trains time walks and neural network

Electronic Delays

Delays come from front end electronics

- PMT electronics are grouped in crates, cards and channels
- Can sort PMTs by crate/card/channel number and plot delays
- Calibrated delays show expected crate by crate structure



Data Driven Calibration Comparison

Radioactive ^{214}Bi to ^{214}Po events provide data driven comparison of timing calibrations

- Visible energy $> 1\,\mathrm{MeV}$
- ^{214}Po has short (164 μs) half-life
- Minimal displacement from ^{214}Bi
- Reconstructed displacement of ^{214}Bi to ^{214}Po (ΔR) dominated by position resolution
- Better calibrations → smaller $\Delta R \equiv \|\vec{x}_{\mathrm{Po}} - \vec{x}_{\mathrm{Bi}}\|$

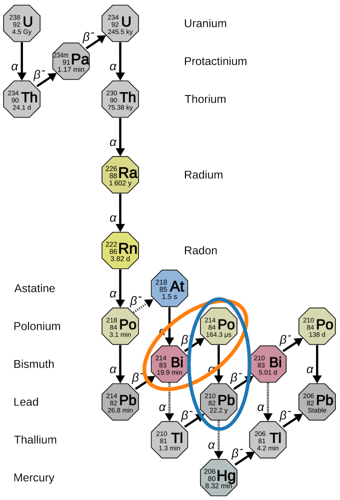
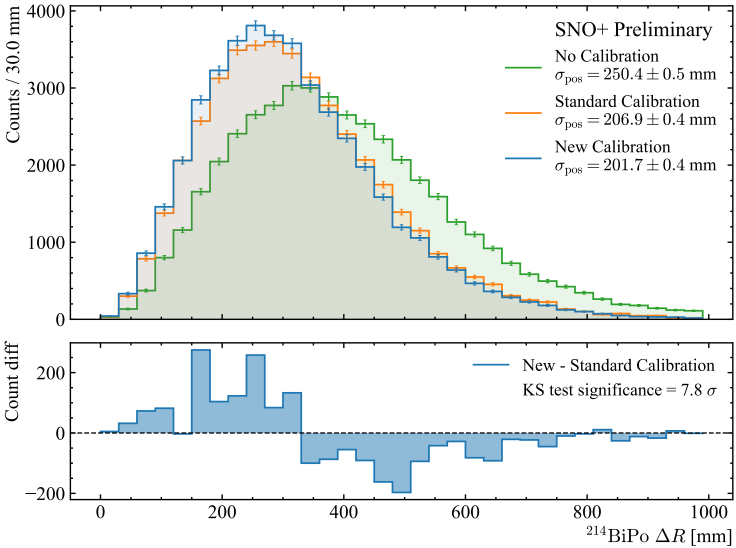


Figure: Uranium-238 decay chain

^{214}BiPo ΔR Comparison

Small ($\sim 5\,$mm), but significant, improvement in position reconstruction resolution.

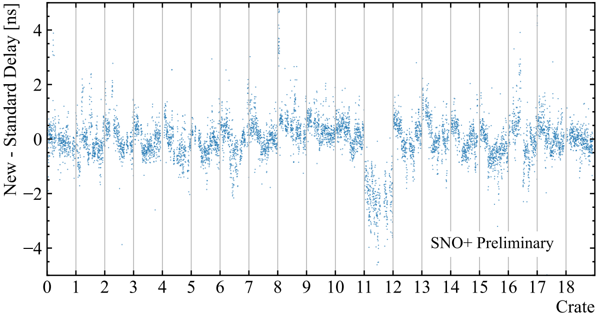
- σ_{pos} assumes $\vec{x}_{\text{Po}} - \vec{x}_{\text{Bi}}$ is an isotropic gaussian

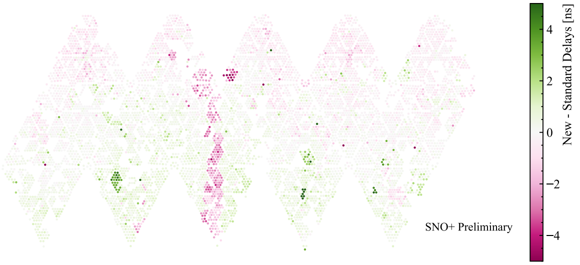


Electronics Monitoring

Change in delays may indicate change in electronics

- Found temporary timing drop in crate 11
- Out dated lower level calibration identified as cause
- Other plots use updated lower level calibration





Summary

New method of calibration performs well

- Reproduces structure of electronics
- Improves ^{214}BiPo ΔR distributions

This calibration has numerous advantages

- Can calibrate using regular physics runs
- Much less resource intensive
- Can perform on a $\lesssim$ weekly basis
- Monitor electronics

Method should be applicable to other large liquid scintillator detectors