A Primitive Water Fitter for Single Vertex Position in SNO+

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(Dated: September 12, 2017)

Event reconstruction of vertices positions in the water phase of SNO+ is currently carried out by the Waterfitter with sophisticated accounting of various optical processes. This paper aims to investigate depreciation of the fitter's results neglecting all physical process but under the assumption that all photons travel in a straight line in the SNO+ detector. Simulated data of photonbombs and N16 runs indicated that the primitive fitter is able to return vertices with position difference to the simulated vertices with a maximum difference of ~ 391.7 % mm and a maximum difference of standard deviation of ~ 524.4 % mm compared to the Waterfitter.

I. INTRODUCTION TO THE SNO+ EXPERIMENT

SNO+ is a large-scale liquid scintillator experiment located underground at the depth of 5890 ± 94 meter water equivalent (m.w.e.) constructed with high radio-purity materials with the main goal to search for the rare neutrinoless double-beta decay ($0\nu\beta\beta$) of ^{130}Te. The large scale experiment also allows the opportunities for other physics investigation including the measurements of geoneutrinos, low energy solar neutrinos and supernova neutrino watch as well as the search for exotic physics.[1]

A. Structure of the SNO+ detector

The underground SNO+ detector centers with a spherical acrylic vessel (AV) of 6 m radius with 5.5 cm of thickness. Concentric to the AV is the geodesic stainless steel structure (PSUP) of around 8.9 m radius supporting 9300 PMTs of two distinct types: OWL-PMTs which are facing outwards to the underground cavity with varied directions and normal PMTs which are facing towards the center.[1]

The cavity outside the PSUP and volume between the PSUP and the AV are filled ultra-pure water to shield the AV from radioactivity of the rock and the PMTs themselves. The AV will be filled with different liquid during different phases. In order to hold up the AV within the PSUP as well as balancing the buoyant force after filling the AV, a system of polyethylene fiber ropes of 38 mm diameter will be used to fix the AV's position.[1]

B. The Water Phase

During the water phase of SNO+, the AV will be filled with ~ 905 tonnes of ultra-pure water and different calibration processes will be ran to test the PMT's performance and characteristics of the data acquisition system, the background radioactive noises and optical properties of water.

Besides, the water phase also provides opportunities to test accuracy of the Geant4-based software package RAT

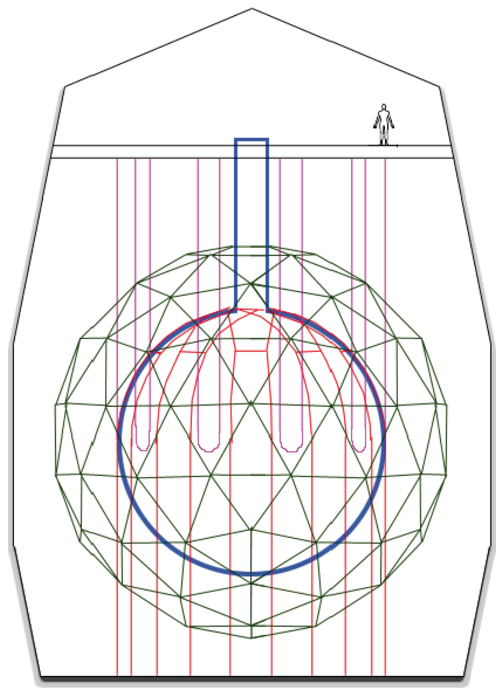

FIG. 1. Structure of SNO+ detector consists of three major components including the spherical acrylic vessel (blue), the geodesic stainless steel structure (green) as well as the rope system (red) suspending the acrylic vessel.

developed to simulate the physics events in the SNO+ detector. In particular, RAT is able to carry out vertex reconstruction determining position of the vertex that is most likely to be responsible for events recorded in the PMT.

C. Events in SNO+

Events in SNO+ is defined by crossing of the analogue trigger threshold, which is adjustable and dependent on purpose of the run. It refers a minimum number of PMTs get hit within a certain time interval. Once the crossing is achieved, information of the PMT hits, including charge and hit time, will be recorded from 180 ns before the trigger latches and 220ns after the trigger latches. [2]Based on the recorded hit time and previously measured positions of the PMTs with the origin set at the center of the AV, the Waterfitter within RAT can be employed to reconstruct a single most likely vertex for the water phase.

II. WATERFITTER

The Waterfitter started with the Quad Method as a seeder of the vertex position which takes four PMT hits in random to solve for the initial vertex assuming all lights travel in a straight line. The fitter then carries out detailed account of light scattering, refraction and reflection as well as the detector's geometry to determine the best fitted vertex position that matches with the PMT info recorded. A typical physics run that lasts for around 1 hour would take up to a day for the detailed fitting.

A. A Primitive Straight Line Fitter

Based on the idea of the Quad Method, one is motivated to look into depreciation of the Waterfitter if all lights are assumed to be travelling in a straight line instead from the vertex to the PMTs. Hence, instead of taking only four PMTs hit to fit for the vertex, one could intend to minimize the following function:

$$\chi^2 = \sum_i [c(t_i - t) - |\boldsymbol{x_i} - \boldsymbol{x}|]^2 \tag{1}$$

, where c is the speed of light in water assumed to be a constant, t and $\boldsymbol{r}$ are the time and position of the vertex respectively and t_i and $\boldsymbol{r_i}$ are the time and position of the PMT hits respectively whereas the number of hits is different for each event.

Refer to Eq.(2), the speed of light in water corresponding to different wavelength should be determined for the iteration method. The refractive index was measured for the water phase and stored into the data base of RAT. In particular, the refractive index for wavelength of 400 mm is 1.31481002573999062 and for wavelength of 700 mm is 1.31481001470856707 which account to a difference of around 6×10^{-9} % difference in c. Since sensitivities of PMTs lie approximately within the visible spectrum and for real data, it is unlikely to detect precisely wavelength of the photon that strikes a particular PMT. The value of c is assumed to be 228.011996 mm/ns following the refractive index for light with the wavelength of 400 mm.

Define

$$r_i(t, \boldsymbol{x}) = c(t_i - t) - |\boldsymbol{x_i} - \boldsymbol{x}| \tag{2}$$

,

$$\boldsymbol{v} = (t, \boldsymbol{x}) \tag{3}$$

and the Jacobean

$$J_{ij} = \frac{\partial r_i}{\partial v_j} \tag{4}$$

, the Gauss-Newton algorithm solves for $\boldsymbol{v}$ by iterations that minimizes χ^2:

$$\boldsymbol{v_{n+1}} = \boldsymbol{v_n} - (\boldsymbol{J^T J})^{-1} \boldsymbol{J^T r}(\boldsymbol{v}) \tag{5}$$

. Computationally, the inverse is handled by turning Eq. (5) into the following linear equation:

$$(\boldsymbol{J^T J})(\boldsymbol{v_n} - \boldsymbol{v_{n+1}}) = \boldsymbol{J^T r}(\boldsymbol{v}) \tag{6}$$

in the standard form of $\boldsymbol{Ax} = \boldsymbol{b}$, where $\boldsymbol{x}$ can be solved by Gaussian elimination.

B. Data for the comparison of fitters

The Straight Line Fitter and the Waterfitter can be compared for their accuracy in fitting a single vertex based on both simulations under RAT and real data obtained in calibration runs. In particular, this paper will look into the simulation of photonbomb and N16 calibration runs.

1. *Photonbomb Simulation in RAT*

RAT is able to simulate a sudden burst of isotropic photons with user-defined wavelength from a user-defined positions which, for convenience, is referred to as a photonbomb. Along with the simulation, user can also turn off selectively different physics process, such as the Rayleigh scattering and reflections of photons by the PMT concentrators. Noises of the PMTs can also be turned off.

2. *N16 Calibration Run*

In the N16 calibration runs, radioactive ^{16}N gas are pumped into a decay chamber with a radius of around 5 cm where the end of it is connected to a PMT to help signify if an event recorded is triggered by a N16 event. The whole setup can be hanged into the AV at a specified position.

III. COMPARISON OF THE STRAIGHT LINE FITTER AND THE WATERFITTER

A. Photonbomb Simulation in RAT

1000 photonbombs are simulated at random and isotropic positions within the AV. Each bomb emitted 1000 photons with the wavelength of 400 mm from each

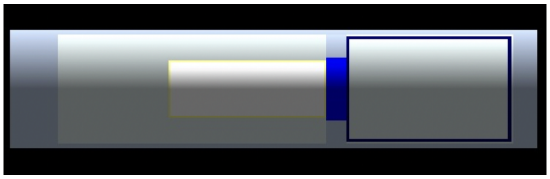

FIG. 2. Side view of the N16 source geometry. The decay chamber is shown as the rectangle on the right while the small rectangle on the left represents the PMT.

position. PMTs noises are turned off for all simulations as no noise handler is implemented within the primitive straight line fitter. Eliminating the noises allow a understanding of the depreciation of the fitting result if physical processes, including refraction, reflection and scattering are neglected. In particular, reflections of the PMTs concentrator and the Rayleigh scattering are turned off for two runs to look into their significance.

1. *Ordinary Runs*

Ordinary runs involve only the turning off of PMTs noise. Difference between the positions of the fitted vertices and the simulated vertices (bias) is calculated and plotted for each component in the Cartesian coordinate system. Results of the Waterfitter are shown from Figure 3 to Figure 5 while results for the straight line fitter are shown in Figure 6 to Figure 8.

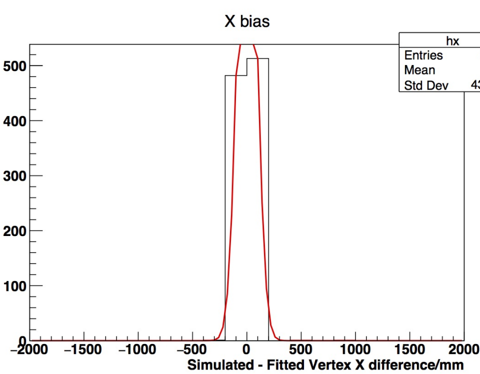

FIG. 3. Difference between x position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise with the Waterfitter.

Results of the Waterfitter give all three means of the biases to be close to zero from -2.694 mm to 2 mm with standard deviations from 29.93 mm to 48.36 mm. Compared to the straight line fitter, means of the biases range from -19.57 mm to 11.2 mm with all standard deviations close to 730 mm. Although the straight line fitter is still about to fix the vertices with a mean of the position biases close to zero, the biases' standard deviations are over 2000% higher which indicated that applying the straight line fitter directly without taking account of major physical processes depreciates quality of the fitter significantly.

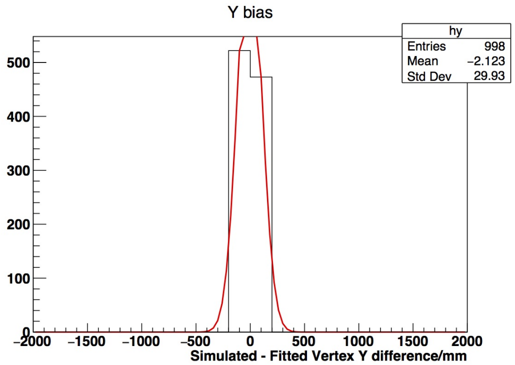

FIG. 4. Difference between y position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise with the Waterfitter.

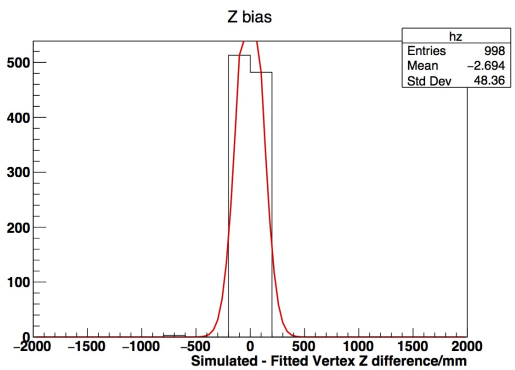

FIG. 5. Difference between z position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise with the Waterfitter.

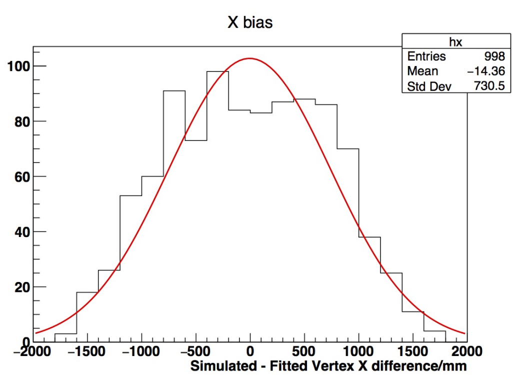

FIG. 6. Difference between x position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise with the straight line fitter.

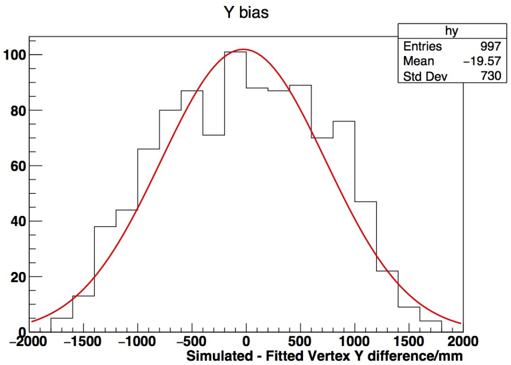

FIG. 7. Difference between y position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise with the straight line fitter.

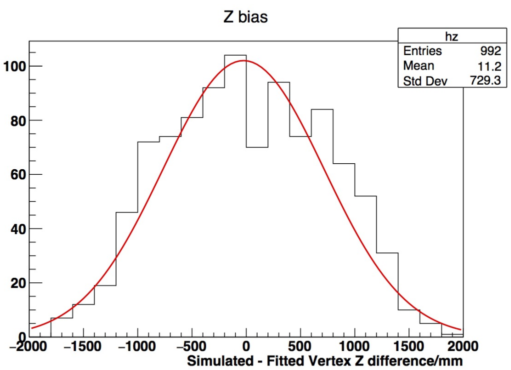

FIG. 8. Difference between z position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise with the straight line fitter.

2. *Omitting Reflections of the PMTs Concentrator*

To look into effects of particular physical processes. Result for the straight line fitter for runs with both the PMTs noise and reflections of the PMTs Concentrator turned off are shown from Figure 9 to Figure 11.

Means of the biases are still close to zero as before ranging from -13.11 mm to 8.066 mm. The standard deviations on the other hand decrease significantly to around 275 mm which lowers the percentage difference to the Waterfitter from over 2000% to 818.8%. This indicated that reflections in the PMTs concentrator shall be a prominent process in determining the photons' path. This is within expectation as purpose of the concentrator is to increase the light yield of the PMTs by allowing photons that are not directed to align to the PMTs' front facing direction to be able to be reflected and collected by the PMTs. Radius of the concentrator used in SNO+ is around 30 cm which in turns refers that distance travelled by the photons reaching the PMTs is different to that predicted by the straight line fitter of the order of 100 cm assuming the photons shall undergo several reflections before hitting the PMTs.

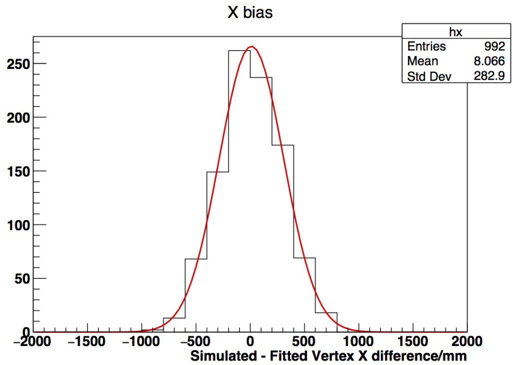

FIG. 9. Difference between x position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise and reflections of the PMTs concentrator with the straight line fitter.

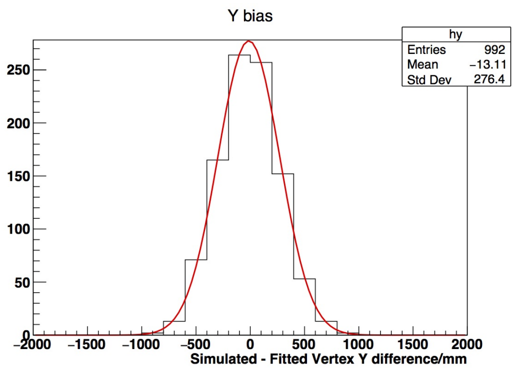

FIG. 10. Difference between y position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise and reflections of the PMTs concentrator with the straight line fitter.

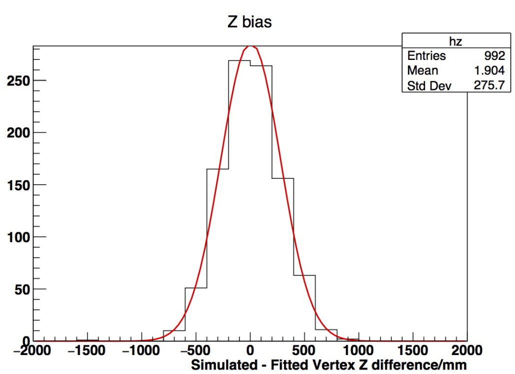

FIG. 11. Difference between z position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise and reflections of the PMTs concentrator with the straight line fitter.

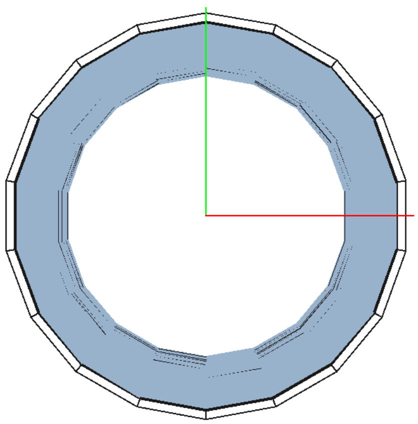

FIG. 12. Front view of the concentrator used in SNO+ simulated in HepRApp.

3. *Omitting Rayleigh scattering*

Effects of turning off both the PMTs noise and the Rayleigh scattering are also investigated with results shown from Figure 13 to Figure 15.

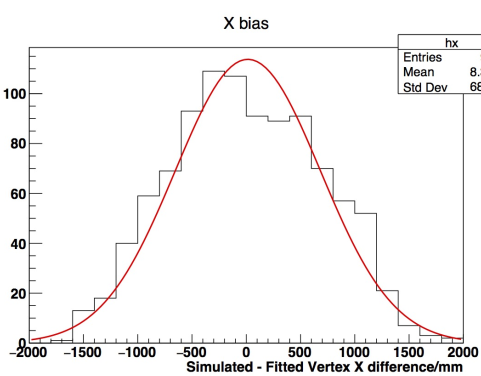

FIG. 13. Difference between x position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise and Rayleigh scattering with the straight line fitter.

Again, means of the biases are close to zero ranging from -8.664 mm to 8.329 mm but the standard deviations are not significantly decreased compared to the ordinary runs. The largest percentage drop is in the x bias of 6.1 %. Effects of the Rayleigh scattering is significanly less than that of concentrator reflections in water.

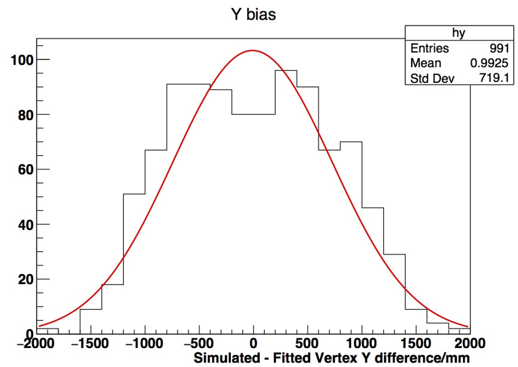

FIG. 14. Difference between y position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise and Rayleigh scattering with the straight line fitter.

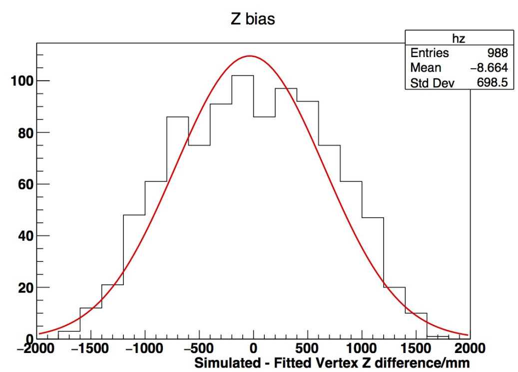

FIG. 15. Difference between z position of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise and Rayleigh scattering with the straight line fitter.

B. N16 Calibration Run

For the N16 runs, precise position of the vertex for each run is not known but can be approximated as the center of the decay chamber which is measured in each run. Seven runs of N16 data are available for the analysis. Positions for each run is listed in Table I.

Results of the Waterfitter are shown from Figure 16

TABLE I. Positions of the decay chamber's center for N16 runs.

Run List			
Run ID	X Position (cm)	Y Position (cm)	Z Position (cm)
100934	-18.6	25.6	2.6
100941	-18.6	25.6	-439.78
100943	-18.6	25.6	-289.82
100945	-18.6	25.6	-139.74
100947	-18.6	25.6	160.22
100949	-18.6	25.6	310.21
100951	-18.6	25.6	460.22

to Figure 18 while results for the straight line fitter are shown in Figure 19 to Figure 21.

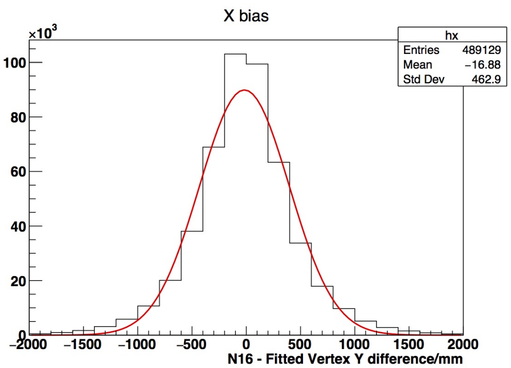

FIG. 16. Difference between the fitted x position of vertices and center of the decay chamber using the Waterfitter.

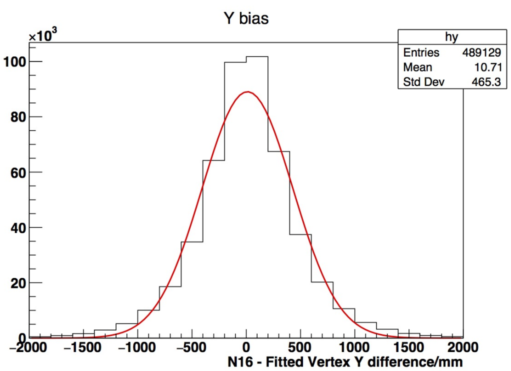

FIG. 17. Difference between the fitted y position of vertices and center of the decay chamber using the Waterfitter.

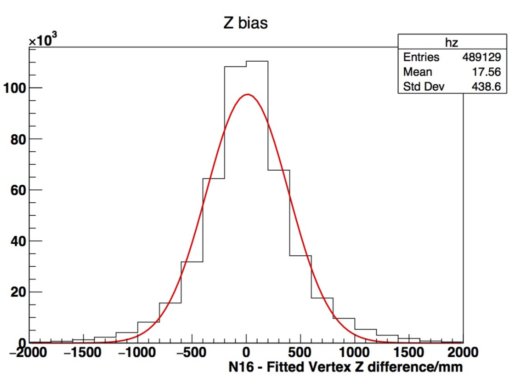

FIG. 18. Difference between the fitted z position of vertices and center of the decay chamber using the Waterfitter.

Performance of the fitters is expected to show a even bigger difference than in simulations given that there are background noises involved in real data, including cross-talking of the PMTs and multiple vertices involved in a single event. Means of the biases for the Waterfitter

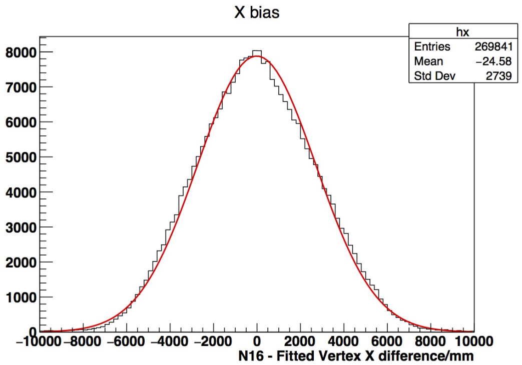

FIG. 19. Difference between the fitted x position of vertices and center of the decay chamber using the straight line fitter.

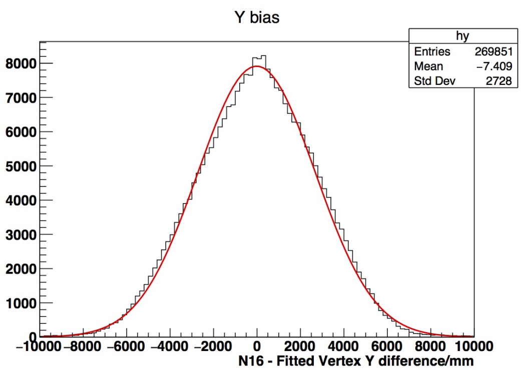

FIG. 20. Difference between the fitted y position of vertices and center of the decay chamber using the straight line fitter.

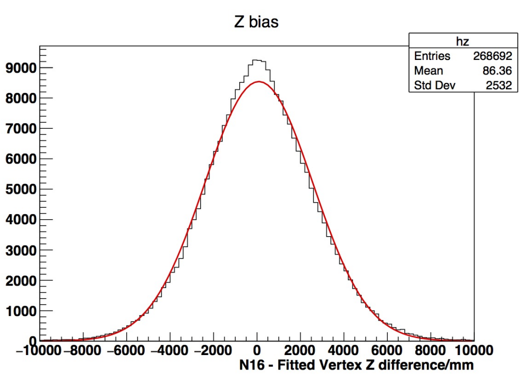

FIG. 21. Difference between the fitted z position of vertices and center of the decay chamber using the straight line fitter.

range from -16.88 mm to 17.56 mm while that of the straight fitter range from -24.68 mm to 86.36 mm. On the other hand, standard deviations of the biases are from 438.6 mm to 465.3 mm for the Waterfitter and 2532 mm to 2739 mm for the straight line fitter. Maximum percentage difference of the standard deviations between the two fitters are around 524.4 % which is in fact less than the simulated data.

IV. CONCLUSIONS AND INDICATIONS FOR AN ALTERNATIVE FITTER

The straight fitter is a much simpler fitter for fitting the position of vertex which reduces the fitting time from around a day for a certain run to a few minutes. Although its performance is significantly depreciated compared to the sophisticated Waterfitter in terms of the standard deviations of the positions biases being over 500 % larger for the N16 data, the straight fitter surprisingly returns vertices with a mean of the position biases close to zero. With the ability to eliminate the effect of noise and hits that undergo multiple reflections before entering the PMTs, the fitter performance can be significantly improved. This provides insights that instead of following the traditional approach of carrying sophisticated accounting of each physical processes when fitting the vertex, methods for eliminating hits can be developed instead to feed the data to a less sophisticated fitter. Future investigations can also be carried out comparing efficiency of the Quad method, which is the current seeder of the Waterfitter, and the straight line fitter. If the extra time needed for the straight line fitter to carry out the fitting can compensate the run time of the Waterfitter due to its better accuracy of the fitted vertex position, the Quad method might be replaced for the overall efficiency of the Waterfitter.

[1] Andringa, S., Arushanova, E., Asahi, S., *et al.*, Advances in High Energy Physics **2016**, 3 (2016).

[2] Jones, P., *Background Rejection for the Neutrinoless Double Beta Decay Experiment SNO+*, Ph.D. thesis (2011).