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Neutron source-based event reconstruction in the JUNO detector

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The Jiangmen Underground Neutrino Observatory (JUNO) is the world's largest underground liquid scintillator experiment, under construction in South China. The primary goal of this experiment is to determine the neutrino mass ordering with the energy spectrum from the reactor anti-electron neutrinos. The JUNO detector consists of a 20-kton liquid scintillator in an acrylic vessel which is viewed by 17,612 20-inch photomultiplier tubes (PMTs) and 25,600 3-inch PMTs. The key component for determining the neutrino mass ordering is to reach a $\sim$ 3% energy resolution at 1 MeV for reactor neutrino events and to understand the non-uniform response of the detector. This proceedings paper describes vertex and energy reconstruction algorithms in the JUNO detector, which have been developed based on neutron source and laser calibration events. Using the JUNO detector simulation, the vertex reconstruction bias has been estimated to be within 4 cm, and the resolution for positrons with $E_{\rm kin}$ = 0 MeV has been evaluated to be about 9 cm. As for the energy reconstruction performance, the non-uniform bias has been estimated to be less than 0.5%.

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1. Introduction

The JUNO detector [1] located in southern China will be the largest underground liquid scintillator detector ever built. The main objective of the experiment is to elucidate the neutrino mass ordering, $m_1 < m_3$ (Normal ordering) or $m_3 < m_1$ (Inverted ordering), through precisely measuring the energy spectrum from electron anti-neutrinos traveling from the nuclear reactor located about 53 km away from the detector. Depending on the neutrino mass ordering, the observed positron energy spectrum will be different, and the energy resolution is one of the crucial components to distinguish the two mass ordering assumptions. The non-uniformity of the energy reconstruction performance across the huge liquid scintillator region in an acrylic vessel (see Figure 1) would be one of the factors deteriorating the energy resolution. This proceedings paper introduces vertex and energy reconstruction algorithms that can be developed mainly using neutron source calibration samples. Since the JUNO experiment has not yet started its operation, the performances of the algorithm have been estimated using simulation samples.

There are other reconstruction algorithms to be used for events in the reactor neutrino energy range in JUNO, and they can be found in [2–9].

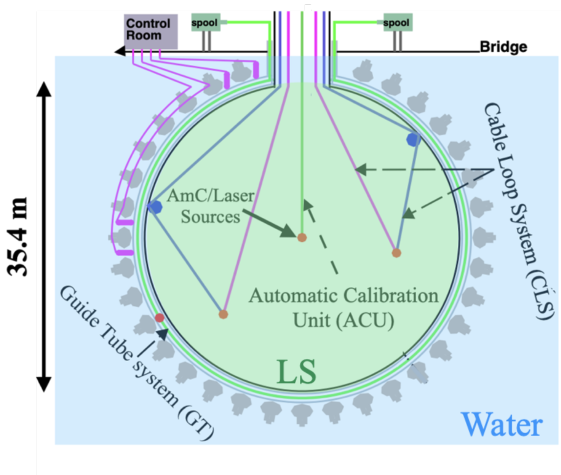

Figure 1: A schematic view of the JUNO detector. The liquid scintillator is contained in an acrylic vessel with a diameter of about 35.4 m. The detector will be equipped with a few different calibration source deployment devices, which will enable us to put the calibration source at multiple positions.

2. Event Reconstruction Algorithm

The event reconstruction algorithm discussed here employs the maximum likelihood method, and by maximizing the following likelihood value, the event vertex position and the visible energy are reconstructed:

$$L = \prod_{j}^{\text{Unhit}} P_j^q(\text{unhit}|\mu_j) \prod_i P_i^q(Q_i|\mu_i) P_i^t(t_{i,\text{residual}}|R, \theta_{i,\text{PMT}}, Q_i^{\text{obs}}),$$

$$t_{i,\text{residual}} = t_{i,\text{first hit time}} - \text{T.O.F.}(x, y, z) - t_0,$$

where $t_{i,\text{first hit time}}$ is the first photon hit time, Q_i^{obs} (μ_i^{exp}) is the observed (expected) charge at the ith PMT, T.O.F. denotes the time-of-flight of the photon from the assumed vertex position (x, y, z) to the ith PMT, R is the vertex position radius $\sqrt{x^2 + y^2 + z^2}$, $\theta_{i,\text{PMT}}$ is the relative angle between the vertex position and ith PMT (see the left figure in Figure 2), and t_0 denotes the event timing to be determined in the maximization process. To apply this event reconstruction algorithm to an event, the expected charge map, which is parameterized as a function of the event vertex position, and the probability density functions (P.D.F., P^q, P^t) need to be prepared beforehand. Those input tables into the algorithm can be obtained from the forthcoming calibration samples taken by various calibration source deployment systems shown in Figure 1.

Monte Carlo samples with the Americium-carbon neutron source (^{241}Am^{13}C) [10], which is envisioned to be used most frequently [11] in JUNO, have been generated using the JUNO detector simulation [12]. Neutrons emitted from the $\alpha - n$ reaction in the AmC source will be captured on hydrogens in the liquid scintillator volume and 2.2 MeV γ-ray is emitted. Besides the 2.2 MeV γ-ray, 6.1 MeV γ-ray is also emitted from the excited state of ^{16}O* produced by the $\alpha - n$ reaction in the AmC source. These γ-ray events have been produced by placing the AmC source along the central axis of the detector in the simulation, and they are used to make the timing P.D.F. (response table) at each PMT.

Other than 2.2 MeV γ-ray from the AmC neutron source, cosmogenic neutrons produced by cosmic-ray muons are expected to be distributed across the detector volume, and they can be used to calibrate the expected charge value at each PMT for the given event position. In this study, uniformly distributed neutron samples have been generated, and 2.2 MeV γ-rays from neutron captures are used to make the expected charge table as a function of the detector position and relative angle to each PMT $(R, \Theta, \theta_{\text{PMT}})$. The parameter definition and an exemplary plot of the expected charge table are shown in Figure 2.

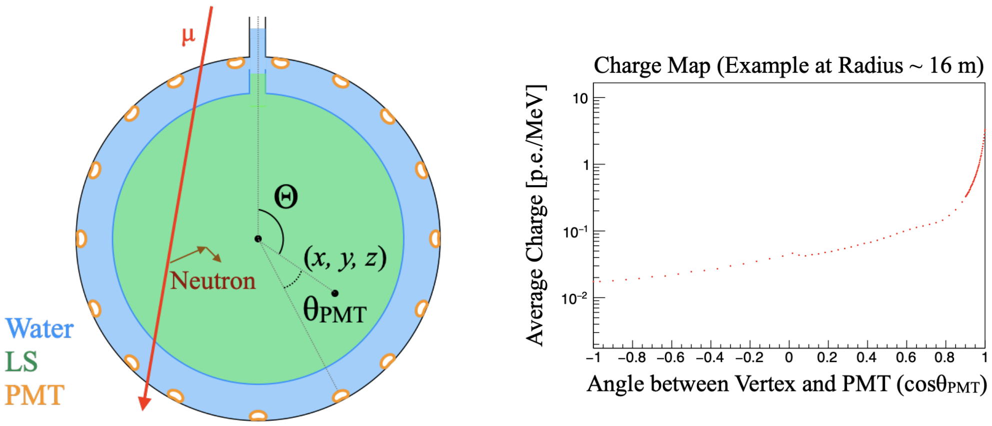

Figure 2: The left schematic view shows the definition of the parameters used to characterize the expected charge table. The right plot shows an example of the expected charge table at $R \sim 16$ m.

As for the charge P.D.F., various intensity laser events have been generated at the center of the detector. Using these laser samples, the probability of observing Q (charge) with the given expected charge μ has been tabulated at each PMT. The mean observed charge at each PMT and at each laser intensity sample is used as μ when tabulating the charge P.D.F.

3. Performance and Summary

We have developed the algorithm to reconstruct the event vertex position and visible energy based on the neutron and laser calibration samples for the reactor neutrino analysis in JUNO. The performance of the event reconstruction algorithm introduced above has been evaluated using uniformly distributed position samples inside the detector. Figure 3 shows the vertex and energy reconstruction performances. The mean vertex bias along the radial direction is estimated to be within ~ 4 cm, and the vertex resolution with $E_{\text{kin}} = 0$ MeV is estimated to be ~ 9 cm. The bias of the energy reconstruction across the detector has been estimated to be within 0.5%, and the energy resolution with $E_{\text{kin}} = 0$ MeV is estimated to be ~ 3.05%.

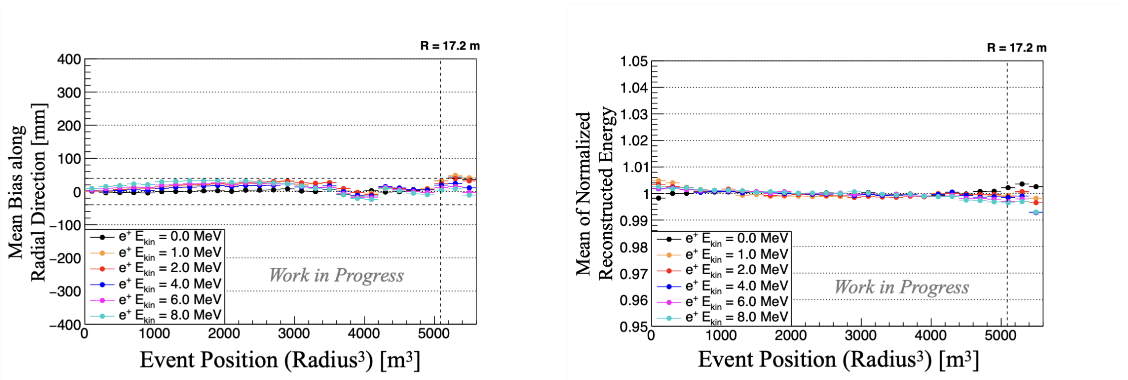

Figure 3: The left (right) plot shows the vertex (energy) reconstruction bias as a function of the detector location. The dashed line at $R = 17.2$ m denotes the fiducial volume boundary.

Acknowledgments

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