

Fast muon simulation in the JUNO central detector^{*}

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Abstract: The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment designed to measure the neutrino mass hierarchy using a central detector (CD), which contains 20 kton liquid scintillator (LS) surrounded by about 17000 photomultiplier tubes (PMTs). Due to the large fiducial volume and huge number of PMTs, the simulation of a muon particle passing through the CD with the Geant4 toolkit becomes an extremely computation-intensive task. This paper presents a fast simulation implementation using a so-called voxel method: for scintillation photons generated in a certain LS voxel, the PMT's response is produced beforehand with Geant4 and then introduced into the simulation at runtime. This parameterisation method successfully speeds up the most CPU consuming process, the optical photon's propagation in the LS, by a factor of 50. In the paper, the comparison of physics performance between fast and full simulation is also given.

Keywords: JUNO, central detector, fast simulation, Geant4

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1 Introduction

The Jiangmen Underground Neutrino Observatory (JUNO)[1, 2] is a multiple purpose neutrino experiment to determine neutrino mass hierarchy and precisely measure oscillation parameters. It is being built in Jiangmen in Southern China and is about 53 km away from Yangjiang and Taishan nuclear power plants, respectively.

A schematic view of the JUNO detector is shown in Fig. 1. The innermost part is called the central detector (CD). The CD is basically an acrylic sphere filled with 20 kt liquid scintillator (LS) and surrounded by about 17000 20-inch photomultiplier tubes (PMTs). An energy resolution of $3\%/\sqrt{E(\text{MeV})}$ is expected. Around the CD, there is a water pool to shield from radioactivity. The PMTs in the water pool are used to detect the Cherenkov light yielded by cosmic ray muons. On top of the water pool, there is a top tracker, made of plastic scintillators, to identify muon tracks.

To meet the requirement of high energy resolution for the CD, reliable and flexible Monte Carlo (MC) simulation software is a necessity, especially for optimizing detector parameters at the design stage. Simulation

software has been developed based on the Geant4 [3] toolkit, which consists of a number of packages to manage event generators, geometry and materials, physics processes, tracking and user interfaces. Both optical parameters and physics processes have been tuned based on the experimental data obtained by the Daya Bay Neutrino Experiment [4]. The simulation software is highly integrated with the underlying software framework of SNIPEr [5] so that it becomes an important component in the full data processing chain.

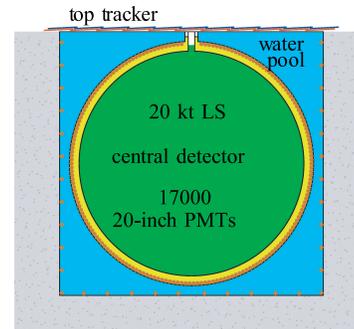


Fig. 1. (color online) Schematic view of the JUNO detector.

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2 Data processing

The raw data recorded by the JUNO detector need to be processed offline in order to be converted to reconstructed data, which are suitable for physics analysis. In the current phase, the raw data are produced by MC simulation and then processed in the same way as real data will be in the future. Following the scheme of SNiPER, various data processing steps shown in Fig. 2 are implemented as corresponding types of algorithms, software components undertaking a certain part of the calculation task. Event data pass between different algorithms via a data buffer. The event data cached in the data buffer can be written to ROOT [6] files for persistent storage. The detector parameters stored in GDML [7] files can be accessed by algorithms through the detector description service in a uniform way.

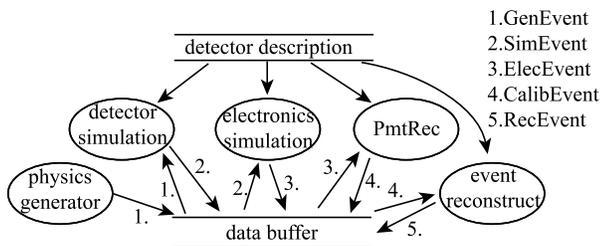


Fig. 2. Work flow for data processing.

As shown in Fig. 2, the physics generator generates simulated physics events such as inverse β decay (IBD), cosmic ray muons, radioactivity events and so on. The generated GenEvent objects, which are in the format of HepMC [8], mainly include kinematics information of the generated final-state particles. Then the detector simulation loads GenEvent objects from the data buffer and starts tracking with Geant4. The information of simulated hits such as charge and time information are saved into SimEvent objects. After inputting SimEvent objects, the electronics simulation performs digitization and generates ElecEvent objects containing information of waveforms with predefined sampling rate. Then the PmtRec algorithm processes the waveforms and converts them into CalibEvent objects using calibration constants. Finally, the event reconstruction algorithm reads in CalibEvent objects, performs event reconstruction and stores the produced RecEvent objects in the data buffer.

3 Challenge of muon simulation

The muon-induced background is one of the main backgrounds in the JUNO experiment. The mean energy of muons that penetrate the overburden is about 215 GeV and they reach the JUNO detector at the rate of about 3 Hz [2].

When a muon travels through the CD, energy is deposited in the LS and both scintillation and Cherenkov photons are emitted: the formers are emitted isotropically, while the latter are produced with a fixed angle with respect to the muon track. The ratio of Cherenkov over scintillation photons is only 5%. The yield for scintillation photons is given by the Birks' Law [9]. The number of scintillation photons, dS , as a function of the visible energy dE_{vis} is given by Chou [10] with a modified form

$$dS = A \cdot dE_{\text{vis}} = A \frac{dE}{1 + C_1 \delta + C_2 \delta^2}, \quad \delta = \frac{dE}{\rho dx} [\text{MeV g}^{-1} \text{cm}^2], \quad (1)$$

where dE is the energy loss, A is the light yield and C_1 and C_2 are Birks constants.

After an optical photon is emitted in the LS, it will travel in the LS and there is a certain possibility for it to reach a PMT after passing through the acrylic sphere and buffering water. During the photon's propagation, it might be absorbed or scattered. At the liquid scintillator and acrylic sphere boundary, it may be refracted, reflected, or a total internal reflection may occur. If it reaches the photo-cathode of a PMT, a photoelectron may be generated. The timing information of photoelectron consists of the initial time, the generation and propagation time of scintillation photon, and the photoelectron's generation time.

The MC simulation of muon particles is important for physics studies, but the full simulation with Geant4 is extremely CPU consuming. To simulate a muon with typical energy passing through the central detector, at least 50 minutes are required using a modern CPU core. So the generation of cosmic ray muons with full simulation becomes a big challenge. The most time consuming part is the propagation of optical photons due to the huge number of photons (at the level of 10^7).

4 Fast muon simulation

The scintillation photons make up the majority of optical photons generated by the muons passing through the CD. To speed up the propagation process of scintillation photons, a fast simulation employing a so-called voxel method has been implemented. Instead of the full simulation, it models the response of the PMTs by sampling the response distributions prepared in advance with the Geant4 simulation. Due to the anisotropy of Cherenkov light emission, the voxel method cannot be applied to Cherenkov photons. The Geant4 toolkit still takes charge of simulating the propagation of Cherenkov photons in both liquid scintillator and water buffer.

4.1 Voxel method

In the voxel method, the volume of the whole liquid scintillator sphere is treated as a regular grid and a voxel

represents the volume element in the grid. By dividing the sphere into voxels, a muon particle encounters a series of voxels along its path when it enters the CD. In Fig. 3, the scintillation photons generated in the shaded voxel (fired voxel) reach the PMT and generate a detector response. The location relationship between the fired voxel and the PMT can be uniquely determined by a pair of variables (R, θ) , where R is the radial position radius of the voxel and θ is the spatial angle between the voxel and the PMT. If there is a certain amount of visible energy of E_{vis} in a voxel, the response of the PMTs with the same (R, θ) pair value follows the same distributions. It is obvious that the response distributions can be easily obtained by running the full simulation. So the core of the voxel method is to build the connection between the E_{vis} in a voxel and the response of the PMTs.

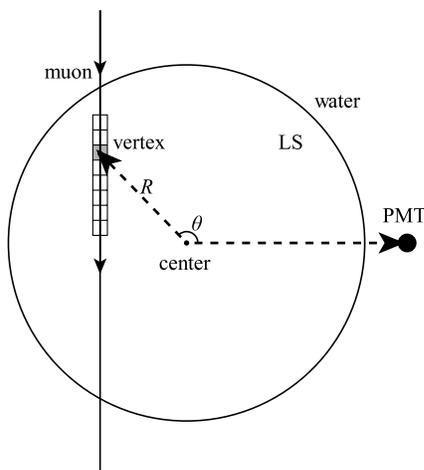


Fig. 3. Illustration of mapping the visible energy within a voxel to the response of the PMTs.

At the stage of preparing response distributions, photons are produced uniformly in all LS voxels with the full simulation. Since photons with different wavelengths behave differently in the detector, the emission spectrum of the LS is used to calculate the wavelength of the photons. For each voxel, the total number of generated photons is equivalent to the light yield of 1 MeV visible energy, which makes it possible for response distributions to contain sufficient information for the fast simulation to simulate a physics event. Photons received by each PMT and the associated timing information are the most important data to reflect an optical photon's transportation process in the LS. So the number of photoelectrons (nPE) and hit time can be regarded as the major parameters of PMT response.

For simplicity, an R - θ parameter space is used to represent the set of possible combinations of (R, θ) values, in which R ranges from 0 to the inside radius of the acrylic sphere and θ is between 0 to π . Both R and θ are divided into a series of intervals, respectively. Each

2-dimensional bin in parameter space is associated with a number of voxels and PMTs. For a specific bin, two histograms, one for nPE distribution and the other for hit time distribution, are generated by the full simulation. After traversing all the bins in the parameter space, a complete set of response distributions are obtained. Figure 4 shows a profile of mean hit time for scintillation photons within a bin in the R - θ parameter space, in which the x -axis represents R^3 , the y -axis represents θ and the z -axis indicates the mean hit time. This figure shows that vertex at the edge of detector is influenced by the total internal reflection, so that the mean hit time is larger than the normal hit time.

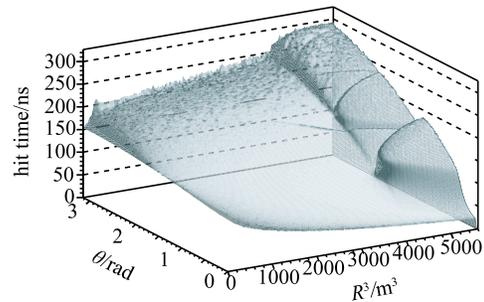


Fig. 4. Profile of mean hit time for scintillation photons within a bin in the R - θ parameter space.

At the stage of using the prepared response distributions to do the fast muon simulation, the procedure is as follows. For every step of muon tracking in LS, the visible energy, E_{vis} , is calculated according to Birks' Law, which is the same as that in the scintillation process. If the E_{vis} value is none-zero, the voxel that the tracking step encounters is identified by the step position and the two associated nPE and hit time histograms are loaded. If E_{vis} is an integer, repeating the nPE histogram sampling will give the number of accepted PEs. However, there is a fractional part of E_{vis} . The number of possible PEs is given by sampling the nPE histogram once. For each possible PE, an extra uniform distribution number is sampled and compared with the fractional part to decide whether to accept it or not. For each accepted PE If the PMT's nPE is greater than zero, its hit time is obtained by sampling the associated hit time histogram.

4.2 Performance measurements

The data sample used in the physics performance studies is single γ s with energy of 1 MeV, which are generated along the vertical z axis with a step of 0.1 m in the LS. To guarantee sufficient statistics, 10000 events are generated at each position.

As shown in Fig. 5, the distributions of nPE and hit time are compared between the fast and full simulation respectively using γ s generated at $z = 16$ m. The agreement is good for both nPE and hit time at the PMT

level. The optical photons received by a PMT should have two components: photons directly from the interaction position and reflected photons. The closer to the acrylic sphere the γ s are generated, the more optical photons are expected to be bounced back at the barrier due to the reflection effect. For γ s generated at $z = 17.3$ m, Fig. 6 shows the hit time distribution of some selected PMTs whose θ varies from 175° to 176° . According to MC truth information of the full simulation, the first peak is caused by the direct photons, but the second is mainly from the reflected photons. So, the fast simulation can effectively reflect the transportation of optical photons in the LS.

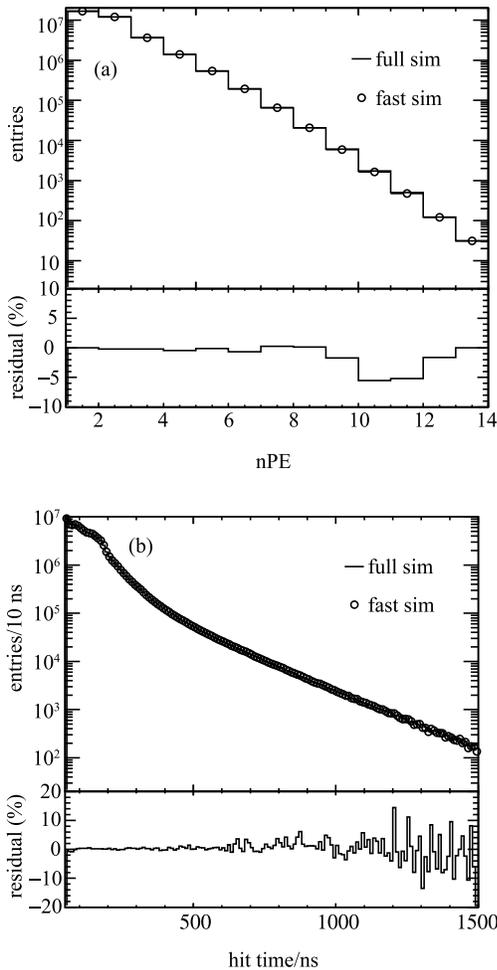


Fig. 5. Comparisons of nPE and hit time between fast and full simulation using γ s generated at $z = 16$ m. (a) nPE of PMT; (b) Hit time of PMT.

Figure 7 shows the average total number of photoelectrons per event (totalPE) as a function of the γ generation position z . The difference between fast and full simulation is less than 0.4%, which again demonstrates a good consistency between them. The totalPE increases when the γ generation position gets closer to the acrylic

sphere. After reaching the turning point, the totalPE drops mainly because of the total internal reflection of photons and because of the so-called energy leak, which means less energy is deposited in the LS while the γ s are crossing the boundary. So the fast simulation can model the change of totalPE with the vertex in a precise way.

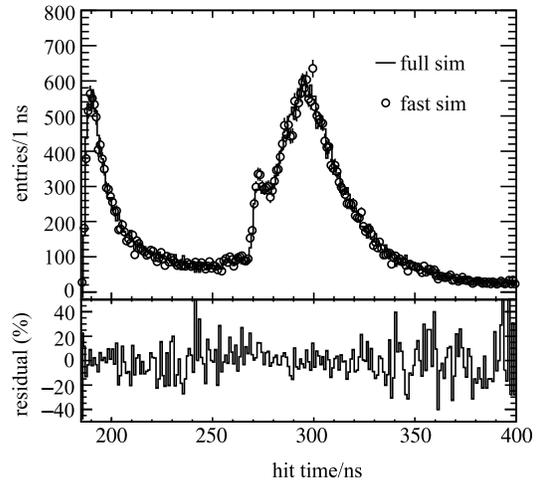


Fig. 6. Hit time of PMTs in the region of 175° to 176° with γ s generated at $z = 17.3$ m.

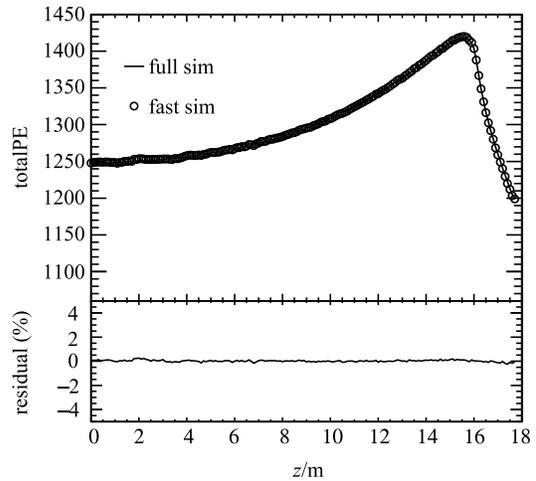


Fig. 7. Average totalPE as a function of γ generation position z .

When a muon passes through the CD, the number of scintillation photons it generates is proportional to its visible energy in the liquid scintillator. So the more energy the muon deposits, the more CPU time is required to simulate the generation and transportation process of scintillation photons. To make a thorough timing measurement, a broad band of energy points covering 10 GeV, 100 GeV, 215 GeV, 500 GeV and 1 TeV is chosen for muon generation. Ahead of timing measurements, a full simulation job is run and during job execution information at each MC simulation step is collected and stored in a data file. The prepared data file

will be used by the subsequent fast simulation so that it can be compared with the full simulation at event level. The measurement of system performance is done on a blade server with the CPU Intel® Xeon® E5-2680 v3 @ 2.50GHz. In order to eliminate interference, the CPU is exclusively used by the timing measurement job and other irrelevant applications such as system monitoring are all suspended.

Figure 8 is a scatter plot of execution time elapsed in generation and transportation of scintillation photons generated by muons passing through the central detector. Each cross represents the fast simulation time versus the full simulation time for a muon particle. The result shows that the elapsed simulation time scales linearly with the muon's visible energy and the fast simulation achieves a speedup ratio of about 50 over the full simulation.

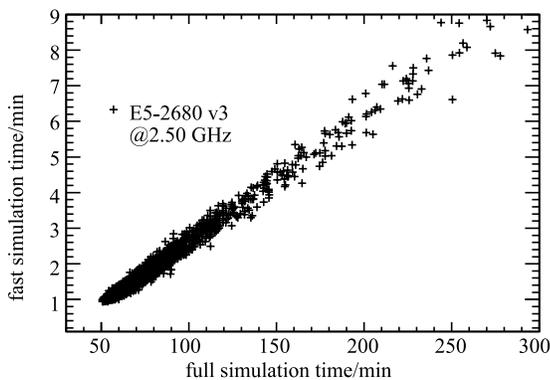


Fig. 8. The fast simulation time versus the full simulation time for muons with momenta varying between 10 GeV and 1 TeV.

4.3 Discussion

The JUNO CD simulation with Geant4 is largely dominated by optical photon transportation in the liquid scintillator. Although the voxel method has been developed to speed up the muon simulation in the central detector, it can also be extended to simulate other

types of events such as IBD because the parameterization approach is related to neither event type nor event energy.

The symmetry of the detector geometry greatly reduces the number of sampling histograms used by the voxel method. But there are many factors that might break this kind of symmetry. For example, supporting struts around the acrylic sphere will block the detection of optical photons. The voxel method can handle this problem by increasing the number of sampling histograms. The response histograms will be organized in a structured way and only the part demanded by the fast simulation algorithm will be loaded to memory dynamically to reduce the memory usage to an acceptable level.

It is easy to use parallel computing techniques such as CUDA [11] to further accelerate execution of the voxel method. Unlike the full simulation application running on GPUs such as Chroma [12], the parallel implementation of the voxel method can only execute histogram sampling with GPUs, which avoids the complexity of geometry translation.

5 Conclusions

Fast muon simulation using the voxel method has been implemented in the JUNO experiment's offline software framework. The applied method is to generate the response of the PMTs beforehand with Geant4 for photons produced in different voxels in the CD, and then to introduce the response into the fast simulation by sampling the response histograms at runtime.

The timing measurement shows that the fast simulation has obtained a speedup ratio of 50 in CPU execution time compared to the full simulation with Geant4. The physics performance has also been examined and validation results show that the agreement between the fast and full simulation is good and no significant discrepancies have been found.

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