

Studies on Muon Veto in the JUNO Liquid Scintillator Neutrino Detector

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Abstract. The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator detector currently under construction near Kaiping, China. It is located 650 m underground with a baseline of 53 km to two nuclear power plants. The reactor neutrinos are measured via inverse beta decay in order to determine the neutrino mass hierarchy. Muons that cross the detector create a correlated background for this measurement. A set of sub-detectors and sophisticated reconstruction algorithms are presented to achieve an efficient veto of cosmogenic backgrounds while keeping a high exposure. On a sample of through-going muons with the expected mean energy of 215 GeV a spatial bias of less than 10 cm and an angular bias better than 0.5° can be reached. There is only 1% additional loss in exposure compared to a perfect tracking.

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a reactor anti-neutrino experiment currently being built close to Kaiping, China. Its main goal is the determination of the neutrino mass hierarchy. For this it will measure anti-neutrinos in the inverse beta decay (IBD) channel via the reaction $\bar{\nu}_e + p \rightarrow n + e^+$. The electron anti-neutrinos are produced by two nuclear power plants (NPP), the Yangjiang NPP and Taishan NPP. In order to maintain the best possible sensitivity, JUNO is placed with a 53 km baseline from both power plants. The chosen experimental site will feature an underground laboratory with 650 m overburden to reduce the incoming muon flux. In order to distinguish the neutrino mass hierarchy with the measured $\bar{\nu}_e$ -energy spectrum an energy resolution of $3\%/\sqrt{E(\text{MeV})}$ is needed. This corresponds to JUNO's design goal of 1200 photoelectrons (p.e.) per MeV of deposited energy.

2. Muon detectors in JUNO

Muons pose a background source for most aspects of the broad physics programme of JUNO. Thus, there are several sub-detectors to tag and track muons in JUNO. The background for the mass-hierarchy measurement due to cosmic muons will be explained in section 3.

2.1. Central Detector

The Central Detector (CD) is the most densely instrumented detector of JUNO. It is an acrylic sphere with a diameter of 35.4 m that holds 20 kton of LAB-based liquid scintillator. It is surrounded by roughly 18000 20-inch photomultiplier tubes (PMTs) and 25000 smaller 3-inch PMTs, held in place by a steel shell. The combined geometrical coverage of both, large PMT



(LPMT) and small PMT (SPMT), systems is 77%. Between the acrylic sphere and the PMT array there is a water buffer of 1.7 m thickness. Muons that cross the CD will illuminate the whole detector and create a signal in the order of 10^7 p.e. per event.

2.2. Water Cherenkov

The CD is submerged in a cylindrical waterpool (WP) of 43.5 m diameter, that is filled with 35 kton of ultra pure water. It is instrumented with 2000 20-inch PMTs to act as a water Cherenkov detector. Their positioning is optimized to maximize light collection from cosmic muons. In addition, the WP is lined with Tyvek on the surface to further increase the light yield. The water also acts as a shielding for the CD, reducing the radioactivity from the surrounding rock, that reaches the liquid scintillator. The residual fast-neutron background is expected to be at 0.1 per day [1].

2.3. Top Tracker

The Top Tracker (TT) is a third system for muon tracking that is placed on top of the WP. It will reuse the former target tracker walls from OPERA and consists of 62 walls of plastic scintillator with a size of 6.8 m \times 6.8 m each. The walls are segmented in 4×64 strips in X and Y and are being stacked in 3 layers with 1 m spacing. This arrangement will cover about half of the WP top area [2]. The fine segmentation allows for a high precision muon tracking above the CD. Although the covered area cannot track every muon, it can provide a valuable calibration sample of well reconstructed muon tracks.

3. Cosmogenic Backgrounds in Liquid Scintillator Detectors

Cosmogenic backgrounds stem from muons created in the atmosphere that traverse the detector and its surrounding rock. Fast neutrons produced by muons in the rock can reach the detector and deposit energy through recoils before being captured. As mentioned earlier, most fast neutrons are stopped in the WP before they can enter the CD. When a muon traverses the CD, it will not only overshadow any other event, but it can create unstable isotopes by spallation on nuclei. In LAB-based scintillator this happens mostly on ^{12}C . Most prominent are ^8He and ^9Li with lifetimes of 172 ms and 256 ms, respectively. They have a (β, n) -decay channel that mimics the correlated IBD signal from $\bar{\nu}_e$ interactions. Since those isotopes are produced by the muon along its trajectory, their decays are correlated with the parent muon in time and space.

In JUNO, the first layer which reduces this background is 650 m of rock overburden to reduce the muon flux. Incorporating a model of the on-site mountain profile, a detailed study gives an expected muon flux of $0.003 \text{ s}^{-1} \text{ m}^{-2}$ with a mean energy of 215 GeV. Taking the size of JUNO into account, the muon rate in the CD will be about 3.5 s^{-1} . Given the rather long lifetime of the cosmogenic isotopes and the muon rate, a veto of the full detector volume is not viable. Instead, the correlation in time and space to the muon is used. A veto of a cylindrical volume with a radius of 3 m around the muon track for 1.2 s can remove most of the produced ^8He and ^9Li [1]. At the same time this veto cylinder removes less than 5% of the detector volume, thus keeping a high signal efficiency. The resulting signal and background rates are summarized in Table 1.

4. Reconstruction Algorithms

The proposed veto strategy of a cylindrical veto around the muon track depends on an accurate reconstruction of the muon trajectory. This can be achieved with the different muon subdetectors and the CD. For the CD, a geometrical track reconstruction was developed that can be seeded with an additional fast reconstruction on the WP data. The CD reconstruction is based on the fastest light information and models the geometrical cone shape that builds up along the muon

Table 1. The muon flux and the corresponding rates of (β, n) -decays from cosmogenic isotopes in comparison with the event rate. The signal-to-background ratio without veto is roughly 1 and can be increased to ~ 37 by the cylindrical veto described in section 3.

Process	Rate without veto	Rate with veto
μ flux in CD		3.5/s
Reactor anti-neutrino signal	83/day	60/day
(β, n) decays	84/day	1.6/day

track. As shown in figure 1, the photons from isotropic emissions around each point along the track add up and build the cone, similar to the construction of a Cherenkov cone. The bottom of the cone is modeled by a sphere for the backwards moving light around the entry point into the LS. The model also takes into account the Cherenkov light, that is created after the muon exits the LS and crosses the waterbuffer towards the PMT array. The reconstruction will find the track parameters for which the intersection of the cone model with the spherical PMT array corresponds to the measured PMT first hit times. The selection of PMTs that are considered in the fit is defined also with help of charge information and the shape of the signal waveform. Low charge PMTs and those with a slowly rising waveform are disregarded in the fit, due to a high uncertainty on their first hit time. The first hit time of a PMT with a slow rise time is likely not due to the fastest light. After the PMT selection, a likelihood fit with MINUIT[3] is executed on the set of 5 track parameters. The entry point is defined by two independent variables, since it is fixed to be on the surface of the LS sphere. Another two parameters define the normalized

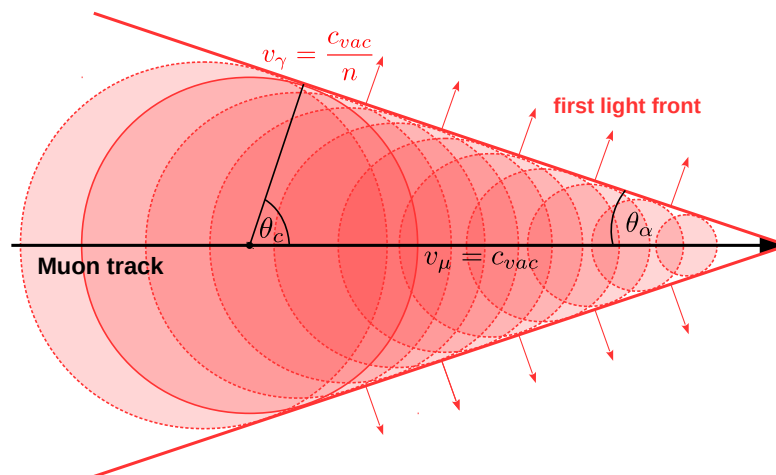


Figure 1. Build up of the first-light surface by isotropic emission of photons along a muon track in liquid scintillator. The opening angle θ_α depends on the photons group velocity and by that on the refractive index n of the traversed medium.

direction and the fifth parameters is the entry time t_0 into the LS, which corresponds to the entry point. The algorithm was developed and features pre-calculated probability density functions for both the LPMTs and SPMTs. Thus, it can be used with each subsystem on its own and with the combination of both systems. For the waterpool reconstruction a less sophisticated, but fast algorithm was implemented. It is based on hit times and charges of the WP PMTs. The algorithm can find charge clusters in an iterative way around the PMTs with the highest charges. In a second step the clusters are counted and merged if too close to each other. Finally the reconstruction can link two clusters to get a muon track. Since the WP is not as densely instrumented as the CD the performance is not as good, but it can be used to get starting parameters for the CD reconstruction.

The Cone Reconstruction was tested with a sample of 5900 Monte Carlo simulated muon tracks through the CD. According to the flux at the experimental site, the muons have an energy of 215 GeV and are oriented to penetrate the detector several different distances and inclinations. The simulation includes a detailed geometrical model of the full detector and the crucial PMT characteristics, detection efficiency and transit time spread. Figure 2 shows the reconstruction performance for the combination of both PMT systems against the track's true distance D from the detector center. The benchmark quantities are the deviation in distance from center $\Delta D = D_{sim} - D_{rec}$ and the angle α between the true and the reconstructed track. The algorithm shows only a small bias of less than 10 cm over the largest part of the detector. Also the angular bias is below 0.5° with a good resolution in this range. Tracks at the very edge of the detector with $D \geq 17$ m show a worse performance due to their short track length.

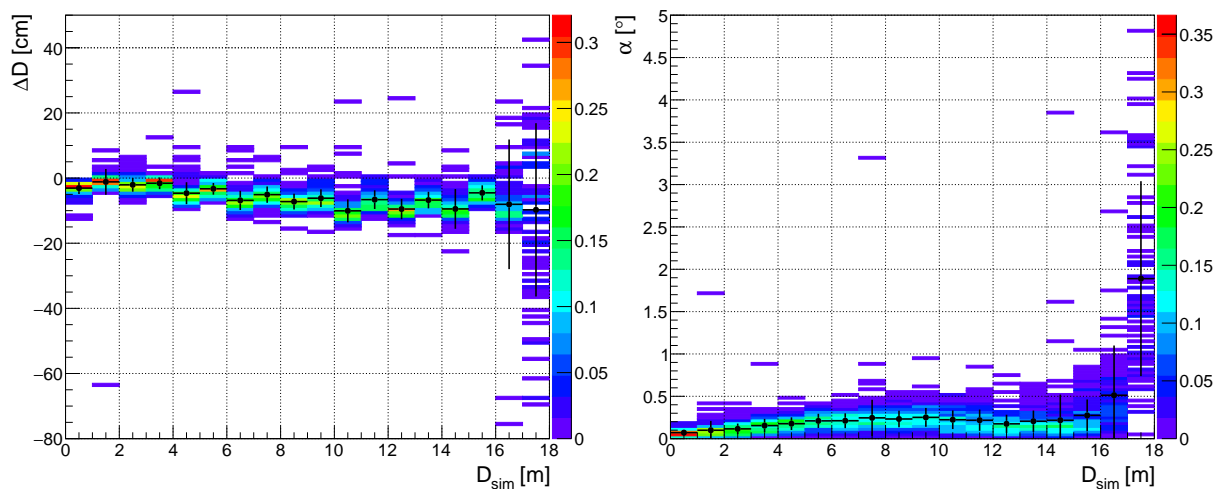


Figure 2. Reconstruction results for a sample of 5900 simulated muon tracks including PMT detection efficiency and time smearing. By combining the LPMTs and SPMTs, the deviation in distance from center ΔD shows a small mean bias of less than 10 cm. The bias in angular reconstruction is better than 0.5° for the largest part of the detector. On the very edge of the sphere, the reconstruction performance declines, because the muon travels only a short distance through the LS.

5. Deadtime estimation

In section 3 was explained that muons are responsible for a substantial amount of detector dead time. A possible solution in form of a cylindrical veto around the muon track could veto most of the cosmogenic backgrounds while maintaining a high exposure. This can only be achieved with

an accurate track reconstruction. In order to benchmark the effect of the cone reconstruction, a toy Monte Carlo is used. It considers the realistic energy and angular distribution as well as muon multiplicity. In addition, various overlapping veto cylinders in time and space are taken into account. With a sample of 75000 tracks, the sensitive detector volume is evaluated whenever a muon enters the detector or when an existing veto volume is released. The baseline veto scheme foresees a cylinder radius of $r_v = 3$ m for 1.2 s after a muon along its track. In order to account for imperfect tracking, the radius is increased according to the bias and resolution in ΔD and α as given above. With perfect tracking, the loss in exposure is found to be 14% in accordance with geometric mean estimation according to the muon rate of 3.5 s^{-1} . This is due to the overburden and could only be further reduced with a different veto strategy. Introducing the imperfection of tracking increases the loss in exposure only by 1% for the combined LPMT and SPMT system. The results are summarized in Table 2

Table 2. Summary of dead time estimation in terms of exposure ratio. The efficiency of 86% for a perfect tracking is in accordance with the reported muon veto efficiency for IBD events [1].

Veto strategy	Exposure ratio
No veto	100%
Perfect tracking	86%
ConeReco LPMT+SPMT	85%

6. Summary

The veto system of JUNO utilizes the combination of several sub-detectors and specialized algorithms. The main goal is to track and veto muons and the cosmogenic isotopes they create inside the LS. While the outer waterpool shields the CD from external radioactivity, it can also provide some muon reconstruction. A more sophisticated algorithm for the densely instrumented CD can reconstruct muon tracks with a bias of less than 10 cm in the track's distance from the detector center and 0.5° in angle, when using both the LPMT and SPMT systems. The additional loss in exposure due to imperfect tracking was estimated to be about 1%. Due to the general model of a light cone intersecting an arbitrary shaped PMT array, the algorithm can also be applied to other liquid scintillator detectors.

Acknowledgments

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References

- [1] An F *et al.* 2016 *Journal of Physics G: Nuclear and Particle Physics* **43** 030401 URL <http://stacks.iop.org/0954-3899/43/i=3/a=030401>
- [2] Djuric Z *et al.* (JUNO) 2015 (*Preprint 1508.07166*)
- [3] James F and Roos M 1975 *Comput. Phys. Commun.* **10** 343–367