Atmospheric neutrinos in JUNO

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Abstract.
This paper explores the JUNO sensitivities to the neutrino mass hierarchy by use of the atmospheric νμ and ¯νμ charged current events with the muon track length \(L_\mu > 5\) m for the physical analysis. It is found that the JUNO’s mass hierarchy sensitivity will reach 0.9 \(\sigma\) for a 200 kton-years exposure, which is complementary to the JUNO reactor antineutrino results. According to the optimistic estimation, atmospheric neutrinos in JUNO may give a better sensitivity to the mass hierarchy.

1. Introduction
The Jiangmen Underground Neutrino Observatory (JUNO) [1], a 20kton multi-purpose underground liquid scintillator (LS) detector, which is located at Kaiping, Jiangmen in South China, is designed to primarily determine the neutrino mass hierarchy (MH) using reactor antineutrinos. In addition, JUNO has also the rich physical potentials in the precision measurement of oscillation parameters, supernova and diffuse supernova neutrinos, solar neutrinos, atmospheric neutrinos, geoneutrinos, dark matter indirect search, nucleon decay and other exotic searches [1]. The JUNO central detector as a LS calorimeter has a very low energy threshold and can measure atmospheric neutrinos with excellent energy resolution. Characteristic signals from Michel electrons, neutron captures and unstable daughter nuclei are helpful for the particle recognition. Note that the JUNO LS detector also has some capabilities to reconstruct the directions of charged leptons in terms of the timing pattern of the first-hit on the PMTs [2]. Based on the above capabilities, JUNO is a promising detector for atmospheric neutrino oscillation measurements. Here we focus on the JUNO MH sensitivities by use of atmospheric neutrinos.

2. Atmospheric neutrinos in JUNO
Considering the neutrino cross sections, fluxes and oscillation parameters [3], we find that JUNO can detect 20790 charged current (CC) and 12255 neutral current (NC) events for the 200 kton-years exposure. On the other hand, we have generated 5 million atmospheric neutrino events and simulated them in the JUNO detector using the Geant4 simulation [4]. Geant4 then provide various quantities for each neutrino event, such as the event vertex radius \(R_\nu\), visible energy \(E_{\text{vis}}\), charged lepton’s zenith angles \(\theta_e\) and \(\theta_\mu\), muon track length in the LS \(L_\mu\), captured neutron numbers \(N_n\) and the Michel electron numbers \(N_e\), etc. Comparing the event numbers per bin of the Monte Carlo (MC) simulation and theoretical prediction, we determine the weight value for every MC event. Then the expected event sample can be obtained for the given neutrino interactions and oscillation parameters. In Fig. 1, we plot the expected spectra as a function of
the visible energy $E_{\text{vis}}$ and indicate the expected event numbers for different interactions. Note that 88.5% of the NC events have visible energies smaller than 1.0 GeV since the final state neutrino does not deposit energy and the final state hadrons have large quenching effect.

Figure 1. The expected neutrino spectra as a function of $E_{\text{vis}}$ for different neutrino interactions with the 200 kton-years exposure. The purple numbers mean the expected event numbers.

Here we only consider the $\nu_\mu/\bar{\nu}_\mu$ CC events and conservatively require the $\mu^\pm$ track length $L_\mu \geq 5$ m. For the selected CC events, the NC backgrounds from the $\pi^\pm$ misidentification as $\mu^\pm$ are negligible based on the following three reasons. Firstly, event rates for the NC interaction is far lower than those from the $\nu_\mu/\bar{\nu}_\mu$ CC interactions for $E_{\text{vis}} > 1$ GeV as shown in Fig. 1. Secondly, the energetic $\pi^\pm$ production rates are largely suppressed since several hadrons share this visible energy. Finally, it is very rare for these $\pi^\pm$ to produce a long straight track for the 1.3m pion interaction length. The selection efficiency of $L_\mu \geq 5$ m is 29.2% for a MC sample of 11798 $\nu_\mu/\bar{\nu}_\mu$ CC events. For these selected events, we assume that the final state $\mu^\pm$ can be fully reconstructed and identified. The corresponding visible energy and $\mu^\pm$ angular resolutions are assumed to be $\sigma_{E_{\text{vis}}} = 0.01\sqrt{E_{\text{vis}}}$/GeV and $1^\circ$, respectively.

| Sample  | $\nu_\mu$ events | $\bar{\nu}_\mu$ events | Total events | $\nu_\mu$ purity |
|---------|-------------------|--------------------------|--------------|-----------------|
| FC $\nu_\mu$-like | 656              | 83                       | 739          | 88.8%           |
| FC $\bar{\nu}_\mu$-like | 652             | 541                      | 1193         | 54.6%           |
| PC $\nu_\mu$-like | 577              | 166                      | 743          | 77.7%           |
| PC $\bar{\nu}_\mu$-like | 383             | 384                      | 767          | 50.0%           |

Table 1. The expected $\nu_\mu$ and $\bar{\nu}_\mu$ event numbers of four samples for 200 kton-years exposure.

According to the characteristics of the reconstructed muon track, the selected $\nu_\mu$ and $\bar{\nu}_\mu$ CC events will be classified as fully contained (FC) or partially contained (PC) events, where FC and PC refers to muon track being fully or partially contained in the LS region. Note that the Michel electron can also help us to distinguish the FC from PC events. On the other hand, we can use the Michel electron number and the relative energy transfer $Y_{\text{vis}} = E_{\text{hadron}}/E_{\text{vis}}$ to statistically distinguish neutrinos from antineutrinos [5] which can improve the JUNO sensitivities to the neutrino mass hierarchy. The principle is that the neutrino statistically shall transfer, on average, more momentum to the hadronic final states than the antineutrino in CC interactions. Therefore we can obtain the FC $\nu_\mu$-like, FC $\bar{\nu}_\mu$-like, PC $\nu_\mu$-like and PC $\bar{\nu}_\mu$-like samples [1]. In Table 1, we list the expected $\nu_\mu$, $\bar{\nu}_\mu$ and total event numbers of four samples for 200 kton-years exposure.
3. The JUNO MH sensitivities

In the $\chi^2$ analysis, we take $\theta_{12}$, $\theta_{13}$ and $\Delta m^2_{23}$ at their best values in Ref. [3], the CP violation phase $\delta = 0^\circ$, and vary $\Delta m^2_{\text{atm}}$. It is found that JUNO has a $0.9\sigma$ MH sensitivity with 10 year data and $\sin^2 \theta_{23} = 0.5$ as shown in the left panel of Fig. 2. The larger $\sin^2 \theta_{23}$ gives better MH sensitivity. In the absence of the statistical separation of neutrinos and antineutrinos, about 20% reduction of the JUNO MH sensitivity is expected. The inverted hierarchy case has the similar results [1].

In addition, we have also discussed an optimistic estimation for the neutrino MH based on few reasonable assumptions. Firstly, the $\nu_e/\bar{\nu}_e$ CC events can be identified and reconstructed very well in the $e^\pm$ visible energy $E^e_{\text{vis}} > 1$ GeV and $Y_{\text{vis}} < 0.5$ case. Secondly, we extend the selection condition $L_{\mu} > 5$ m to $L_{\mu} > 3$ m for the $\nu_\mu/\bar{\nu}_\mu$ CC events. Finally, we replace the charged lepton direction with the neutrino direction and assume $10^\circ$ angular resolution. As shown in right panel of Fig. 2, the combined sensitivity can reach $1.8 \sigma$ for 10 year data [1]. The predicted MH sensitivity will have a 13% reduction when we take $20^\circ$ angular resolution.

![Figure 2. The JUNO conservative (left) and optimistic (right) MH sensitivities as a function of livetime for the true normal hierarchy hypothesis.](image)

4. Summary

We have investigated atmospheric neutrinos in JUNO and discussed their contributions to the neutrino MH. Here we conservatively use the atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ CC events with $L_{\mu} \geq 5$ m for the physical analysis. It is found that the JUNO’s MH sensitivity will reach $0.9 \sigma$ for a 200 kton-years exposure and $\sin^2 \theta_{23} = 0.5$, which is complementary to the JUNO reactor antineutrino results. According to the optimistic estimation, atmospheric neutrinos in JUNO may give a better sensitivity to the neutrino mass hierarchy.

Acknowledgments

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