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Proceeding Paper

Oscillation Physics Potential of JUNO †

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Abstract: The Jiangmen Underground Neutrino Observatory is a 20 kton multipurpose liquid scintillator detector located at a 700 m underground laboratory in South China (Jiangmen City, Guangdong Province). The exceptional energy resolution and the massive volume of the JUNO detector offer great opportunities for addressing many essential topics in neutrino and astroparticle physics. JUNO's primary goals are to determine the neutrino mass ordering and precisely measure the related neutrino oscillation parameters. With reactor neutrino data, JUNO can determine the neutrino mass ordering with significent precision and measure the neutrino oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, and $\Delta m^2_{31}/\Delta m^2_{32}$ to the sub-percent precision level. In addition, the atmospheric and solar neutrino measurements at JUNO can also provide important information for oscillation physics. This paper focuses on the oscillation physics potential of JUNO, including the sensitivity analysis and results based on the recent understanding of the detector.

Keywords: neutrino oscillations; reactor neutrinos; atmospheric neutrinos; solar neutrinos

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1. Introduction

JUNO, short for the Jiangmen Underground Neutrino Observatory, is a multipurpose liquid scintillator (LS) experiment that will be completed in 2023. It is about 700 m underground, and the location is optimized for neutrino mass ordering (NMO) determination using two reactor complexes, the Yangjiang and Taishan nuclear power plants (NPP). The target volume of JUNO is 20 kilo-tons of LS, with an unprecedented energy resolution of better than 3% at 1 MeV [1]. Apart from the main detector, JUNO, we will install a satellite detector, TAO, at approximately 30 m from one core of the Taishan NPP. The detector uses the Gd-LS to suppress the background and operates at −50 °C [2]. The TAO detector has an energy resolution of better than 2% at 1 MeV and thus can provide a high-precision measurement of the reactor neutrino energy spectrum. The measurement is not only important for JUNO but also essential for the nuclear physics community.

JUNO can detect neutrinos for an energy range from a few MeV to tens of GeV from various sources. Among all of these neutrino sources, we can employ the following to extract the oscillation physics with JUNO. With the powerful human-made reactor neutrinos shown in Section 2, whose energy is at a level of a few MeV, we can determine the NMO and precisely measure the oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{13}$. With the atmospheric neutrinos in Section 3, whose energy is in the range of MeV to tens of GeV, we can measure the NMO, the oscillation parameter $\sin^2\theta_{23}$, and the CP-violation phase δ_{CP}. With the solar neutrinos in Section 4, JUNO can measure the oscillation parameters $\sin^2\theta_{12}$ and Δm^2_{21}. With other sources in Section 5, such as core-collapse supernova (CCSN) neutrinos and geo-neutrinos, JUNO can also observe a visible oscillation effect on their spectra.

2. Reactor Neutrinos

The reactor neutrinos are the major signal of the JUNO experiment. The neutrinos at the reactor are the electron antineutrinos, $\overline{\nu}_e$, generated by the decay of the fission fragments in the NPP. For JUNO, the signal source is the 26.6 GW reactor complexes of Yangjiang's six cores and Taishan's two cores. JUNO detects the reactor neutrinos via an inverse beta decay (IBD) interaction. After the interaction, the positron will bring most of the neutrino energy and give a prompt signal to the detector. In JUNO, the neutron will be captured by hydrogen after 200 μs and give a delayed signal of about 2.2 MeV. While at TAO, the delayed signal is the n-Gd signal with an average energy of about 8 MeV. We employ a series of selection criteria by using the time–energy–space correlation between the prompt and delayed signals to suppress the background.

Table 1 shows the estimated signal and background event rate for both JUNO [3] and TAO [2]. Figure 1 shows the expected energy spectra of the signal and background in the JUNO and TAO detectors after selection [2,3].

Table 1. The estimated reactor neutrino signal and background event rate of the JUNO and TAO detectors after selection.

Rate [/day]	Reactor signal	Geo-ν's	Accidental signals	Fast-n
JUNO	47	1.2	0.8	0.1
TAO	2000	-	155	92
Rate [/day]	^{9}Li/ ^{8}He	^{13}C(α ,n) ^{16}O	Global reactors	Atmospheric ν's
JUNO	0.8	0.05	1.0	0.16
TAO	54	-	-	-

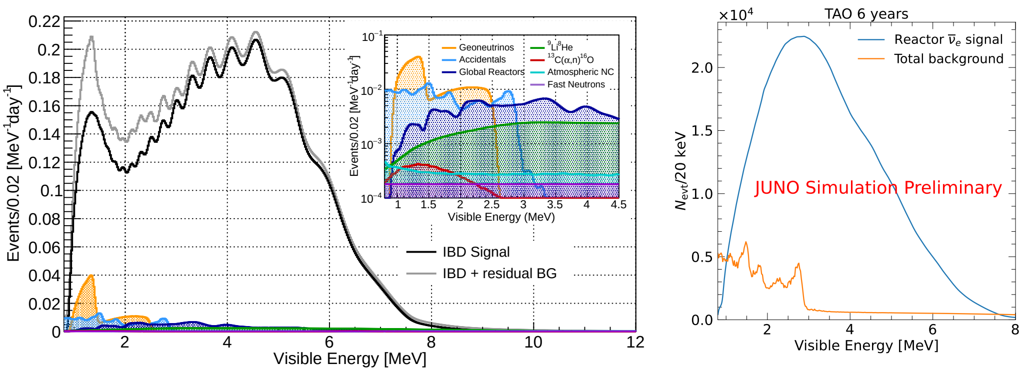

Figure 1. Left: Visible energy spectrum expected in JUNO detector as measured with (grey) and without (black) backgrounds. The inset shows the spectra of the expected backgrounds in log scale. **Right:** Visible energy spectra of reactor $\overline{\nu}_e$ signal (blue) and total backgrounds (orange).

Figure 2 shows the median NMO sensitivity of the JUNO reactor's neutrinos. By considering the most recent knowledge of the detector, we find that the median sensitivity for JUNO when measuring the NMO is 3σ for about 6 years $\times$ 26.6 GW of exposure. The figure also shows the NMO sensitivity for both the NO and IO hypotheses and for the cases of statistical uncertainty only and with all systematics under consideration. Under the exposure of achieving 3σ significance, the right part of Figure 2 shows the impact of the systematic uncertainties. It can be seen that the dominant systematics are the backgrounds, flux uncertainty, and nonlinearity uncertainty. It is worth noting that the background row covers both their statistical and systematic uncertainties.

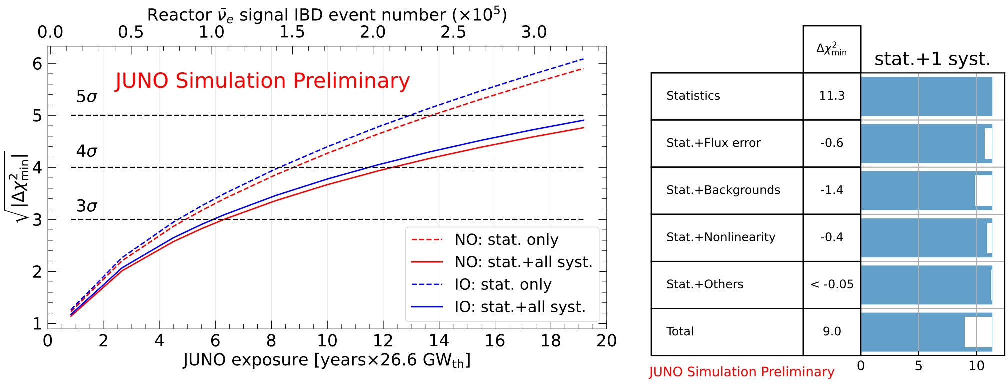

Figure 2. Left: The NMO discriminator $\Delta\chi^2_{\min} \equiv \chi^2_{\min}(\mathrm{IO}) - \chi^2_{\min}(\mathrm{NO})$ as a function of JUNO exposure time for both normal (red) and inverted (blue) ordering Asimov data set. The solid lines are for the cases of full systematic uncertainties, and the dashed lines are for the statistical-only case. **Right:** The impact of individual sources of uncertainty on the NMO sensitivity, for the exposure of JUNO reaches 3σ significance. The filled boxes represent the sensitivity for considering only the statistical uncertainties of the reactor neutrinos. The impact of each source of systematic error is assessed by considering it alone with the statistical uncertainties of the reactor neutrinos, and the $\Delta\chi^2_{\min}$ decrease is represented by the empty boxes.

Figure 3 shows JUNO's sensitivity for precisely measuring four oscillation parameters as a function of data-taking time. It turns out that JUNO can measure $\sin^2\theta_{12}$, Δm^2_{21}, and $\Delta m^2_{31}/\Delta m^2_{32}$ to a sub-percent precision level in about one year and to a level better than 0.5% in six years. Moreover, this is the best measurement of these parameters for the foreseeable future.

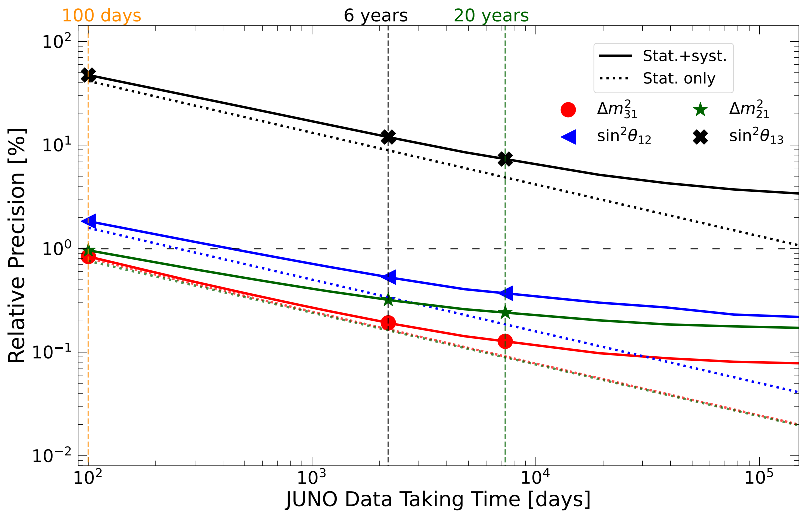

Figure 3. Relative precision sensitivity of the oscillation parameters as a function of JUNO data-taking time. The markers and vertical lines stand for 100 days, 6 years, and 20 years of data taking. The green and red dotted lines are on top of each other since the statistical-only precision is essentially identical for the Δm^2_{31} and Δm^2_{21} parameters.

3. Atmospheric Neutrinos

The atmospheric neutrinos are generated by the decay of secondary particles from the interactions of cosmic rays and the Earth's atmosphere. During propagating to the detector, the neutrino oscillates, and the matter's effect will help us distinguish the NO and IO hypotheses from each other. The atmospheric neutrinos are detected via the charged current (CC) interactions at JUNO. Moreover, the backgrounds will be the neutral current (NC) interactions and the cosmic muons. The numeric calculation shows that after ten years of running, JUNO can detect 8662 ν_μ CC events, 3136 $\overline{\nu}_\mu$ CC events, 6637 ν_e CC events, 2221 $\overline{\nu}_e$ CC events, 90 ν_τ CC events, 44 $\overline{\nu}_\tau$ CC events, and a total of 12,255 NC events [4]. With a high optical coverage of about 78%, JUNO has excellent potential in atmospheric neutrino particle identification (PID), direction, and energy reconstruction.

We have a conservative sensitivity estimation with less than 30% of samples selected for ten years of data for the atmospheric neutrinos [4]. For the NMO determination, the median sensitivity is about $1 \sim 1.8\sigma$. For the mixing angle θ_{23} octant determination, the sensitivity to exclude 35° is 1.8σ for NO and 0.9σ for IO. Moreover, atmospheric neutrinos at JUNO can provide complementary measurements for the CP violation phase δ_{CP}. We are currently developing a more realistic sensitivity analysis with the recent progress and performance of atmospheric neutrino reconstructions [5–8]. We are also performing a combined analysis with the reactor antineutrinos that will further improve JUNO's NMO sensitivity.

4. Solar Neutrinos

The source of the solar neutrinos in the oscillation analysis is mainly the ^{8}B electron neutrinos. The flux is large at a level of $5.25 \times 10^6/\mathrm{cm}^2/\mathrm{s}$. The oscillation effect of the solar neutrino needs to consider two effects. The first one is the MSW resonance in the Sun, and the other is the regeneration of the electron neutrinos due to the Earth matter effect [9,10]. JUNO detects the ^{8}B solar neutrino via several different interactions. With about 200 tons of ^{13}C in the LS, JUNO can detect the solar neutrinos with CC interactions with correlated signals. At the same time, there will also be NC interactions on ^{13}C, which give a single signal. The electron neutrinos can also be detected via elastic scattering (ES) and give a single signal.

Figure 4 shows the expected energy spectrum of the ^{8}B solar neutrino signal and background [10]. The solar neutrinos at JUNO can independently measure the solar neutrino flux and oscillation parameters. Our analysis yields that the sensitivity after ten years of data taking by JUNO on the ^{8}B flux can reach a 5% precision level. When combined with the SNO experiment, the precision can be further improved to a 3% level. For the oscillation parameters, the JUNO ^{8}B solar neutrinos can measure $\sin^2\theta_{12}$ to 8–9% level and Δm^2_{21} to 17–27% precision. Figure 5 shows the χ^2 profile and the allowed regions of the oscillation parameter and the ^{8}B solar neutrino flux measurement, in which the correlations and the improvement in combinations of the different channels can be seen.

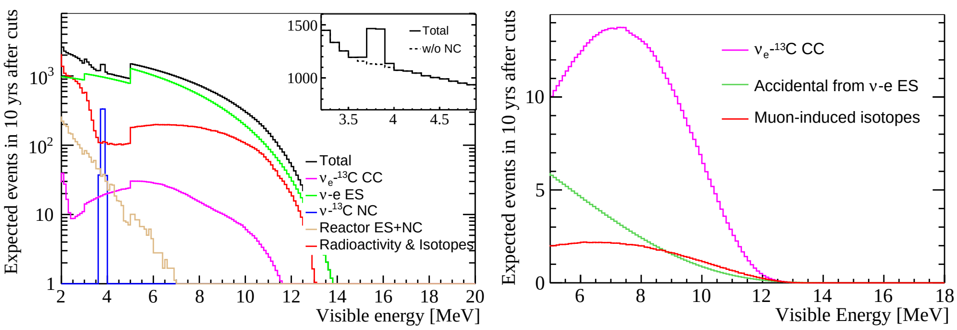

Figure 4. Left: Expected visible energy spectra of all single event sources for 10 years of data taking. The upper right insert plot is illustrated for the energy range between 3 and 5 MeV in the linear scale. **Right:** Expected prompt visible energy spectra of the CC signal and backgrounds after the optimized cuts for 10 years of running.

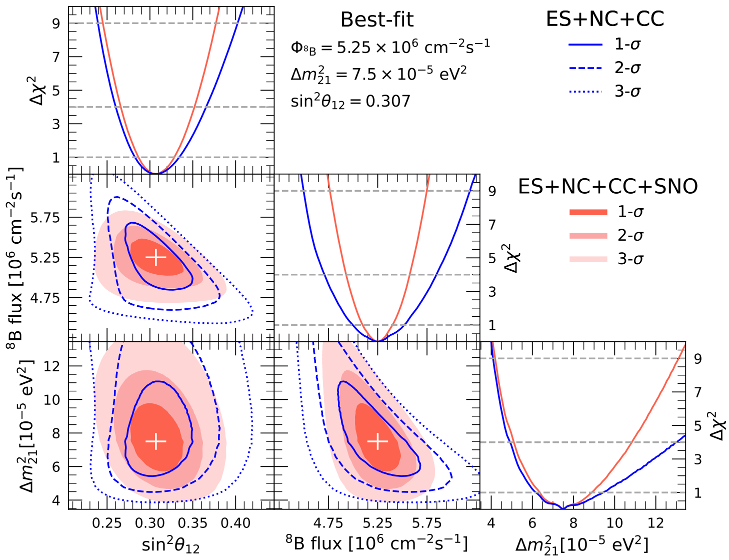

Figure 5. Comparison of the sensitivity on the ^{8}B solar neutrino flux, $\sin^2\theta_{12}$, and Δm^2_{21} between the ES measurement (single events outside [3.5, 4.1] MeV) and the ES+NC measurement (all single events).

5. Oscillation Physic for Other Neutrinos

Apart from the precise sources, we can also observe the oscillation effect with the core-collapse supernova (CCSN) neutrinos at JUNO. For a CCSN that happens 10 kpc from the Earth, JUNO can detect 5000 IBD, 2000 pES, 300 eES, 300 NC on ^{12}C, and 200 CC on ^{12}C events [11]. The predicted spectra are expected to be different from the NO and IO hypotheses due to the oscillation effect. The geoneutrinos are electron antineutrinos generated by the decay chains of U and Th in the Earth, and JUNO can detect about 400 IBD signals per year. In our previous publications [1], we estimate the event rate with an averaged survival probability. A recent study shows that the event rate would be 1–2 Terrestrial Neutrino Units (TNU) larger with the exact survival probability [12].

6. Summary and Prospects

JUNO is a multipurpose large LS detector with great physics potential in oscillation physics using various neutrino sources. With reactor neutrinos, we can determine the NMO with 3σ significance after about 6 years $\times$ 26.6 GW of exposure. At the same time, JUNO can measure the oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, and $\Delta m^2_{32}\Delta m^2_{31}$ to a sub-percent precision level within one year. After six years of data taking, the precision of these parameters will be better than 0.5%. With the atmospheric neutrinos at JUNO, the conservative sensitivity for NMO determination is $1 \sim 1.8\sigma$ for 10 years. Moreover, JUNO can provide complementary measurement for the mixing angle θ_{23} and the CP violation phase δ_{CP}. With the solar neutrinos, JUNO can independently measure the ^{8}B flux and the oscillation parameters $\sin^2\theta_{12}$ and Δm^2_{21}. For other sources of neutrinos, such as CCSN and Geo-ν's, JUNO can observe the visible oscillation effects on their spectra.

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