Solar Neutrinos and Future Experimentss

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29th International Summer Institute on Phenomenology of Elementary Particle Physics and Cosmology (SI 2025)

Aug. 19, 2025

Reference

- P. Bakhti, M. Rajaee, S. H. Seo and S. Shin, "Exploring solar neutrino oscillation parameters with the LSC at Yemilab and JUNO," Phys. Rev. D **109** (2024) no.9, 095030 [arXiv:2307.11582 [hep-ph]].
- S. H. Seo, J. Alonso, P. Bakhti, J. Conrad, *et al.* "Physics Potential of a Few Kiloton Scale Neutrino Detector at a Deep Underground Lab in Korea," [arXiv:2309.13435 [hep-ex]].
- P. Bakhti and A. Y. Smirnov, "Oscillation tomography of the Earth with solar neutrinos and future experiments," Phys. Rev. D **101** (2020) no.12, 123031 [arXiv:2001.08030 [hep-ph]].
- P. Bakhti and M. Rajaee, "Sensitivities of future solar neutrino observatories to nonstandard neutrino interactions," Phys. Rev. D **102** (2020) no.3, 035024 [arXiv:2003.12984 [hep-ph]].
- P. Bakhti and Y. Farzan, "Shedding light on LMA-Dark solar neutrino solution by medium baseline reactor experiments: JUNO and RENO-50," JHEP **07** (2014), 064 [arXiv:1403.0744 [hep-ph]].

Overview

- Solar neutrino problem was the first evidence of neutrino oscillation.
- Neutrino oscillation occurs since Flavor eigenstates (of weak interactions) and mass eigenstates (of free particle Hamiltonian) are not aligned for neutrinos.
- Flavor states and mass states are related by mixing matrix called PMNS matrix. (Pontecorvo-Maki-Nakagawa-Sakata matrix). This matrix can be parametrized by 4 parameters (3 angles and at least one phase).
- In 1978, Wolfenstein, proposed a possibility of flavor change of the massless neutrinos with non-diagonal neutral current non-standard interactions, during propagation in matter.
- For massive neutrinos, standard interactions with matter modify vacuum oscillations, as noted by Wyler.
- The resonance enhancement of neutrino oscillation in matter was proposed by Mikheyev and Smirnov.

Neutrino Oscillation

- There is a mixing between mass and flavor states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \,, \;\; \alpha = e, \mu, \tau, \quad i = 1, 2, 3 \tag{1}$$

- PMNS mixing matrix

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \tag{2}$$

- Mass eigenstates are total Hamiltonian eigestate while flavor eigenstates are not

$$H |\nu_k\rangle = E_k |\nu_k\rangle = i \frac{d}{dt} |\nu_k(t)\rangle \tag{3}$$

$$|\nu_k(t)\rangle = e^{-iE_k t} |\nu_k\rangle \tag{4}$$

Neutrino Oscillation in Vacuum

$$|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t} |\nu_k\rangle = \sum_\beta \sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k} |\nu_\beta\rangle \tag{5}$$

$$E_k \simeq E + \frac{m_k^2}{2E} \quad \& \quad E_k - E_j \simeq \frac{\Delta m_{kj}^2}{2E} \equiv \frac{m_k^2 - m_j^2}{2E} \tag{6}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m_{kj}^2 L}{2E}} \tag{7}$$

- Neutrino oscillations are affected by matter interactions, which introduce a potential term in the Hamiltonian

$$\mathcal{H}_f = \mathcal{H}_{vac} + \mathcal{H}_{mat} \tag{8}$$

Neutrino Oscillation in Matter

$$\mathcal{H}_{mat} = \sqrt{2} G_F N_e diag(1, 0, 0) \tag{9}$$

$$\mathcal{H}_{vac} = U_{\mathrm{PMNS}} \cdot \mathrm{Diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^{\dagger}_{\mathrm{PMNS}} \tag{10}$$

- In the two-flavor approximation, the flavor evolution of neutrinos in matter is governed by the Schrödinger-like equation:

$$i \frac{d}{dx} \psi_\alpha = \mathcal{H}_f \psi_\alpha \tag{11}$$

$$\mathcal{H}_F = \begin{bmatrix} -\Delta m^2 \cos 2\theta + A_{CC} & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta - A_{CC} \end{bmatrix} \tag{12}$$

- where θ is the mixing angle in vacuum and A_{CC} is the charged current potential in matter ($A_{CC} = 2\sqrt{2} G_F N_e E = 2 V_{CC} E$).

Neutrino Oscillation in Matter

- Hamiltonian Diagonalization

$$\mathcal{H}_M = U_M \mathcal{H}_F U_M \tag{13}$$

$$U_M = \begin{bmatrix} \cos 2\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos 2\theta_M \end{bmatrix} \tag{14}$$

$$\mathcal{H}_M = diag(-\Delta m_M^2, \Delta m_M^2) \tag{15}$$

- The effective parameters are given by:

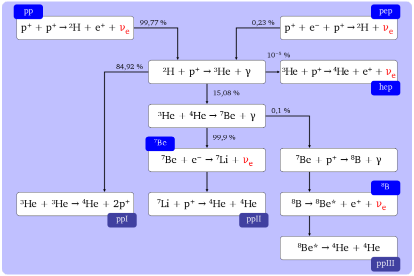
$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \tag{16}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}} \tag{17}$$

- In the case of anti-neutrino $V_{CC} \to -V_{CC}$ $(A_{CC} = 2EV_{CC})$

Solar Neutrino Production

- Solar neutrinos are produced through nuclear fusion reactions occurring in the Sun's core. These neutrinos travel freely to Earth, providing unique insights into solar processes.
- Approximately 98.4% of solar energy is produced via the proton-proton (pp) chain, with the remaining 1.6% originating from the Carbon-Nitrogen-Oxygen (CNO) cycle.



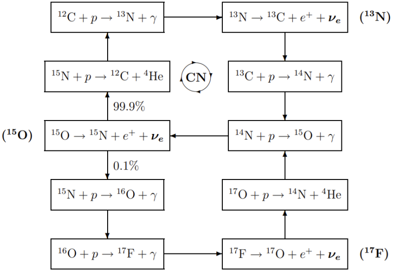
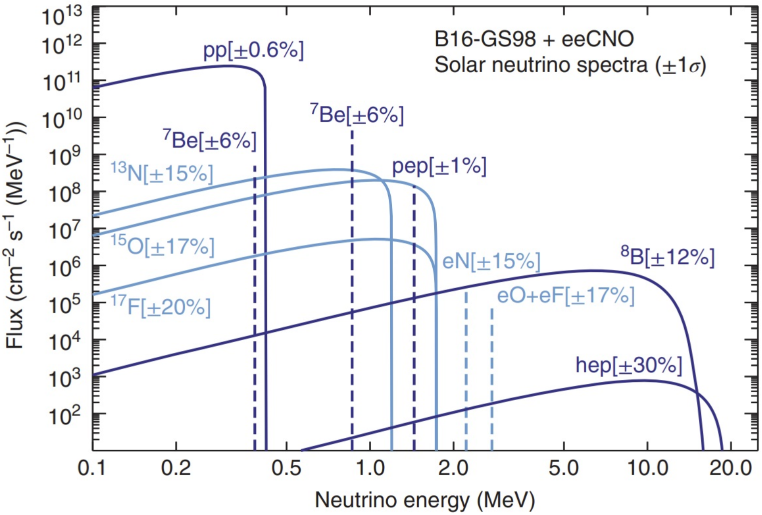


Figure: Left: Proton-proton (pp) chain. Right: CNO cycle.

Solar Neutrino production



Solar Neutrinos on Earth

- Due to loss of coherence during propagation, solar neutrinos arrive at Earth's surface as independent fluxes of mass eigenstates.

$$P_{ee} = \sum_k |U^m_{ek}(n_i) U^{m\dagger}_{ek}(n_f) e^{-i\phi_k}|^2 = \sum_k |U^m_{ek}(n^0_e)|^2 P^E_{ek} \qquad (18)$$

where $|U^m_{e1}| = \cos\theta^m_{13}\cos\theta^m_{12}$, $|U^m_{e2}| = \cos\theta^m_{13}\sin\theta^m_{12}$, $|U^m_{e3}| = \sin\theta^m_{13}$.

- Survival probability at Earth's surface (P^{sur}_{ee}) can thus be expressed as:

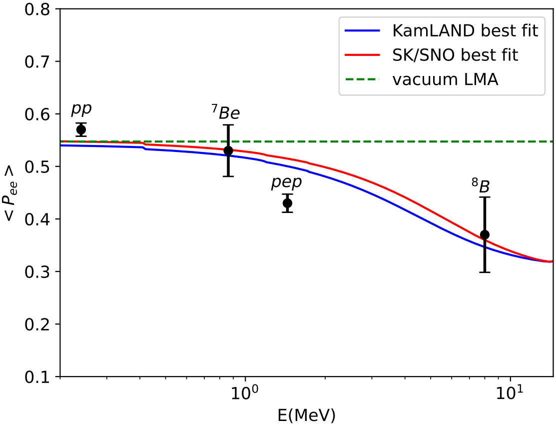
$$P^{\mathrm{sur}}_{ee} = \frac{1}{2} c^2_{13} c^{m2}_{13} (1 + \cos 2\theta_{12} \cos 2\theta^m_{12}) + s^2_{13} s^{m2}_{13} \,. \qquad (19)$$

- The matter-modified mixing angle θ^m_{12} is defined by:

$$\cos 2\theta^m_{12} = \frac{\cos 2\theta_{12} - c^2_{13}\epsilon_{12}}{\sqrt{(\cos 2\theta_{12} - c^2_{13}\epsilon_{12})^2 + \sin^2 2\theta_{12}}} \,, \qquad (20)$$

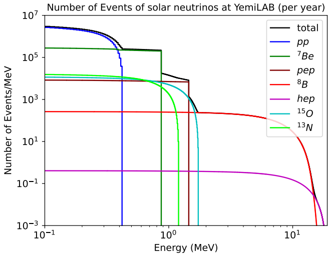
Solar neutrino oscillation probability

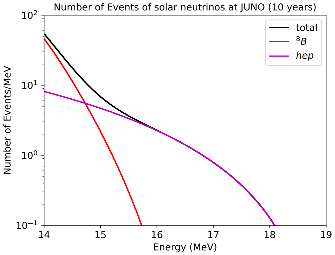
where $\epsilon_{12} \equiv \frac{A_{CC}}{\Delta m^2_{21}}$, with $A_{CC} = 2V_e E$.



Solar Neutrino Event Rates at Yemilab and JUNO

- **Yemilab (Jinping):** A 2.2 kt liquid scintillator detector with 1 kt fiducial volume, optimized for ν_e elastic scattering. It offers excellent energy resolution ($\sim$5%) and a low threshold of 0.2 MeV, enabling detection of low-energy solar neutrinos.
- **JUNO (Reactor Experiment):** Primarily designed to determine mass ordering and measure Δm^2_{21} and θ_{12} with sub-percent precision. JUNO can also detect high-energy solar neutrinos such as ^{8}B, ^{7}Be, and *hep* (with $\sim$0.6 events/year).





Solar neutrino Backgrounds at LS

- ^{14}C: ^{14}C concentration can reach to 10^{-18} gr/gr, below this value has technical challenges
- The activity of ^{14}C in a detector with a mass of m_{det}, ^{14}C concentration C, is expressed as:

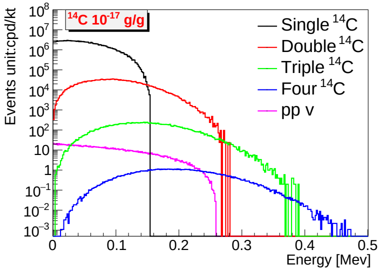
$$A = \frac{m_{det} C N_A}{M \tau}, \tag{21}$$

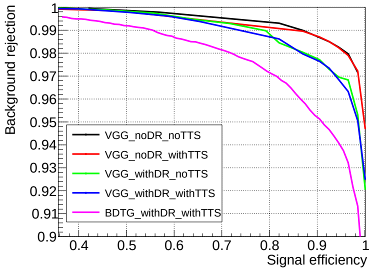
- For concentration of 10^{-18}, for 1kton detector, the ^{14}C activity is 2000 Bq, which million times more than pp events. The Q-value is 156.5 keV, therefore the detector has a threshold depends on the energy reolution.
- Pile-up events: in instances where more than one ^{14}C event occurs within the same time window of detection of pp neutrinos

$$N_{\text{pile-up}} = \frac{e^{-A\delta t} A^n \delta t^{n-1}}{(n-1)!}, \tag{22}$$

Solar neutrino Backgrounds at LS

- For ^{14}C concentrations on the order of 10^{-18} gr/gr, the ratio of double pile-up to pp events for one- and ten-kiloton detectors is around order of ten and a hundred, respectively.

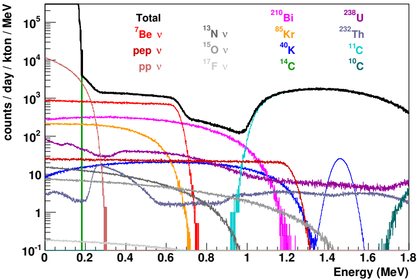


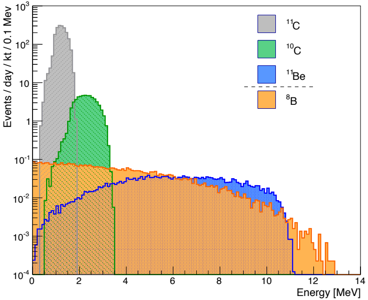


G. M. Chen, et. al. Nucl. Sci. Tech. **34** (2023) no.9, 137 [arXiv:2303.08512 [hep-ex]].

Solar neutrino Backgrounds at LS

- Solar neutrino ES signal and background at JUNO





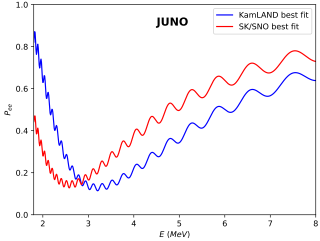
F. An *et al.* [JUNO],“Neutrino Physics with JUNO,” J. Phys. G **43** (2016) no.3, 030401 [arXiv:1507.05613 [physics.ins-det]].

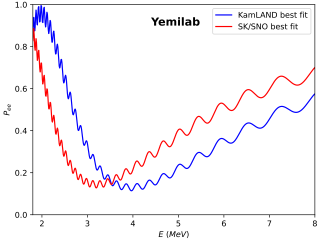
Detection of Reactor Neutrinos at JUNO and YemiLAB

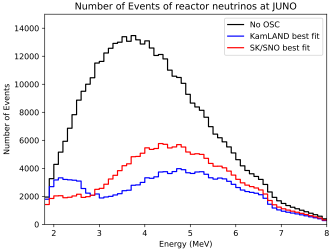
- **JUNO:**
  - 20 kton liquid scintillator (LS) detector.
  - Located $\sim$ 53 km from Yangjiang and Taishan nuclear power plants (total power: 36 GW).
- **YemiLAB:**
  - 2 kton LS detector.
  - Located $\sim$ 65 km from the Hanul Nuclear Power Plant, consisting of six 2.825 GW and two 3.98 GW reactors.
- Reactor neutrino detection allows precise measurement of the neutrino oscillation parameters Δm^2_{21} and θ_{12} with sub-percent accuracy.
- Electron Antineutrino Survival Probability

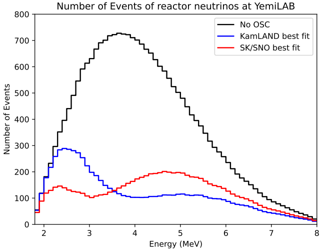
$$P_{\bar{e}\bar{e}} = 1 - \cos^4 2\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E} - \sin^2 2\theta_{13} \left[\cos^2 \theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} \right] \tag{23}$$

Oscillation probabilities and Number of events

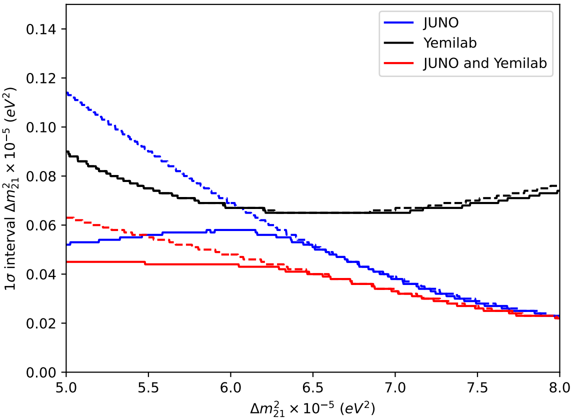




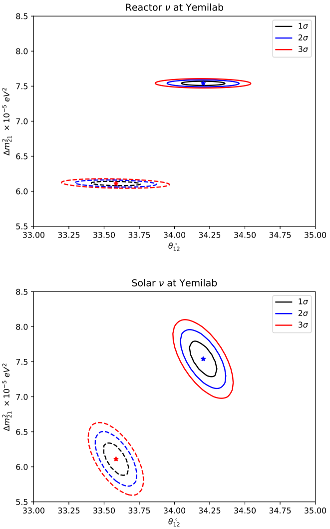




Sensitivity of reactor experiment JUNO and Yemilab to Δm^2_{21} neutrino oscillation parameters



Constraints on solar neutrino oscillation parameters



Solar Neutrino Oscillation parameters measurement

- Reactor and solar neutrino experiments will precisely measure the solar neutrino oscillation parameters with sub-percent accuracy.
  - **Reactor neutrinos (JUNO & Yemilab):**
    - JUNO performs better for larger values of Δm^2_{21}.
    - Yemilab provides higher sensitivity for smaller values of Δm^2_{21}.
  - **Solar neutrinos (Yemilab):**
    - High precision in determining the mixing angle θ_{12}.
    - Background from ^{14}C and double pile-up events significantly affect the detection of pp neutrinos, posing a major challenge for large detectors.
  - Combined solar and reactor data at Yemilab will achieve the best overall precision in measuring both Δm^2_{21} and θ_{12}.
- Future measurements of the entire solar neutrino energy spectrum will offer deeper insights into:
  - Solar interior models.
  - Neutrino propagation mechanisms.
  - Flavor transformations and new physics beyond standard neutrino oscillation scenarios.

Day-Night Asymmetry

- Inside the Earth, the neutrino mass eigenstates oscillate in a multilayer medium with smoothly changing density within layers which leads to the regeneration factor.

$$f_{\text{reg}} = P_{2e}^{Earth} - |U_{2e}|^2 = \frac{1}{2} c_{13}^4 \sin^2 2\theta_{12} \int_0^L dx V(x) \sin \phi^m \tag{24}$$

where ϕ^m is the matter potential phase and L is the total distance traveled by the neutrinos inside the Earth.

- ϕ^m is the adiabatic phase acquired by the neutrino from a given point of trajectory x to a detector at L

$$\phi^m(L - x, E) \equiv \int_x^L dx\ \Delta_{21}^m(x), \tag{25}$$

Day-Night Asymmetry

- During a night the probability equals $P_N = P_D \pm \Delta P$, where the difference of the night and day probabilities is

$$\Delta P(E) = \kappa(E) \left[\int_0^L dx \; V(x) \sin \phi^m(L-x, E) + I_2 \right] . \tag{26}$$

where $\kappa(E) \equiv -\frac{1}{2} c_{13}^6 \cos 2\bar{\theta}_{12}^{\odot}(E) \sin^2 2\theta_{12} \approx 0.5$

- The day-night asymmetry is a function of the nadir angle η

$$A_{ND}(\eta, \Delta E) \equiv \frac{\Delta N(\eta, \Delta E)}{N_D(\Delta E)}, \Delta N \equiv N_N - N_D \tag{27}$$

- $\Delta N(E^r)$ is the difference in the number of events observed during the day and night at a given reconstructed neutrino energy E^r

$$\Delta N(E^r) = D \int dE \; g_\nu(E^r, E) \sigma(E) \Phi(E) \Delta P(E) \tag{28}$$

Attenuation Effect

- Introducing the attenuation factor

$$\int dEG_\nu(E^r, E)\sin\phi^m(L-x, E) = F(L-x)\sin\phi^m(L-x, E^r) \qquad (29)$$

For the Gaussian form of $G_\nu(E^r, E)$, the attenuation factor is given by

$$F(L-x) \simeq e^{-2\left(\frac{L-x}{\lambda_{att}}\right)^2} \qquad (30)$$

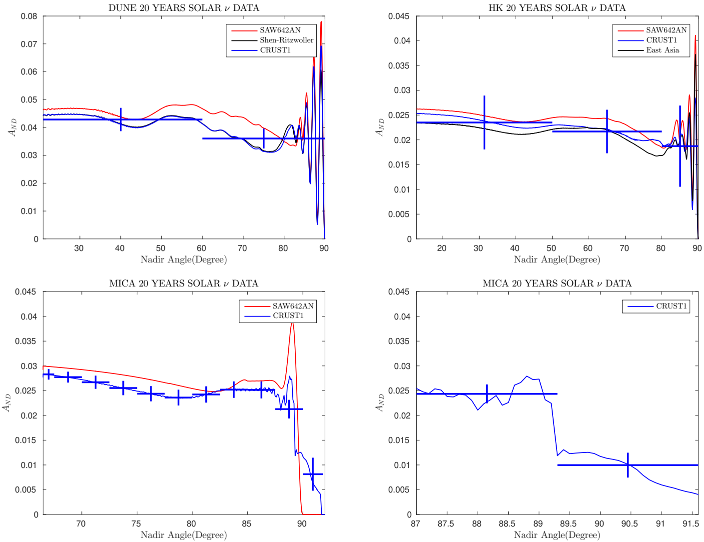
$$\lambda_{att} \equiv l_\nu \frac{E}{\pi\sigma_E} \qquad l_\nu = \frac{4\pi E}{\Delta m^2_{21}}$$

For $L - x \gg \lambda_{att}$, the attenuation factor $F(L-x) \approx 0$, a detector with the energy resolution ΔE is not sensitive to remote structures

Earth Structure and Solar Neutrinos

- Solar neutrinos can be used to probe the Earth's structure through the Day-Night asymmetry, A_{ND}, due to attenuation effect mainly depends on shallow density structures such as the crust, upper mantle, and the crust-mantle border Moho discontinuity.
- The Earth's crust can be divided into two types: the oceanic crust (5-10 km) and the continental crust (20-90 km).
- Models of Earth's structure:
  - Shen-Ritzwoller model: crust and uppermost mantle beneath North America, latitudes $(20^\circ - 50^\circ)$ and longitudes $(235^\circ - 295^\circ)$.
  - FWEA18: Full Waveform Inversion of East Asia model, latitudes $10^\circ - 60^\circ$, longitudes $90^\circ - 150^\circ$, depth up to 800 km.
  - SAW642AN: global model, from Moho depth down to 2900 km.
  - CRUST1: global model, from Earth's surface down to the Moho.

$A_{ND}(\eta)$


DUNE 20 YEARS SOLAR ν DATA
SAW642AN
Shen-Ritzwoller
CRUST1
A_{ND}
Nadir Angle(Degree)
HK 20 YEARS SOLAR ν DATA
SAW642AN
CRUST1
East Asia
A_{ND}
Nadir Angle(Degree)
MICA 20 YEARS SOLAR ν DATA
SAW642AN
CRUST1
A_{ND}
Nadir Angle(Degree)
MICA 20 YEARS SOLAR ν DATA
CRUST1
A_{ND}
Nadir Angle(Degree)

Solar Neutrinos and NSI

- Assuming neutral-current non-standard neutrino interaction

$$\mathcal{L}_{\mathrm{NSI}}^{NC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fC}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f\right) \ , \tag{31}$$

caused flavor change during neutrino propagation in matter

$$H_{mat}^{NSI} = \sqrt{2}G_F N_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \tag{32}$$

$$\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^e + (N_d/N_e)\epsilon_{\alpha\beta}^d + (N_u/N_e)\epsilon_{\alpha\beta}^u \tag{33}$$

- Using 2×2 effective Hamiltonian as following

$$H_{\mathrm{vac}}^{\mathrm{eff}} = \frac{\Delta m_{21}^2}{4E_\nu}\begin{pmatrix} \cos 2\theta_{12} & \sin 2\theta_{12} \\ -\sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix}, \tag{34}$$

$$H_{\mathrm{mat}}^{\mathrm{eff}} = \sqrt{2}G_F N_e(r)c_{13}^2\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2}G_F\sum_f N_f(r)\begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}$$

- The coefficients ϵ_D^f and ϵ_N^f are given

$$\epsilon_D^f = -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) \tag{35}$$

$$+\mathrm{Re}\left[c_{13}s_{13}e^{i\delta}\left(s_{23}\,\epsilon_{e\mu}^f + c_{23}\,\epsilon_{e\tau}^f\right) - \left(1+s_{13}^2\right)c_{23}s_{23}\epsilon_{\mu\tau}^f\right]$$

$$\epsilon_N^f = c_{13}\left(c_{23}\,\epsilon_{e\mu}^f - s_{23}\,\epsilon_{e\tau}^f\right) \tag{36}$$

$$+s_{13}e^{-i\delta}\left[s_{23}^2\,\epsilon_{\mu\tau}^f - c_{23}^2\,\epsilon_{\mu\tau}^{f\,*} + c_{23}s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right]$$

$$\tan 2\tilde{\theta}_{12} = \frac{|\sin 2\theta_{12} + 2\hat{A}_E\epsilon_N|}{\cos 2\theta_{12} - \hat{A}_E(c_{13}^2 - 2\epsilon_D)}\,, \tag{37}$$

Day-Night Asymmetry and NSI

$$P_D(E) = \frac{1}{2} c_{13}^4 \left[1 + \cos 2\theta_{12} \cos 2\tilde{\theta}_{12}(E) \right] + s_{13}^4 \tag{38}$$

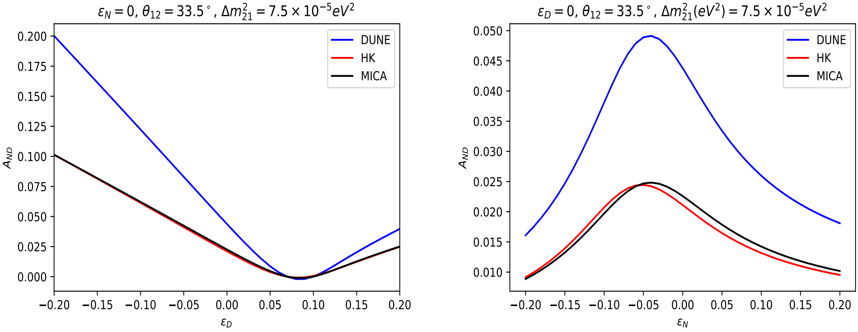
$$N_{D(N)} = A \int dE g_\nu(E^r, E) \sigma(E) f_B(E) P(E)_{D(N)} \tag{39}$$

$$\Delta P(E, \eta) = P_N - P_D = \kappa(E) \left[\int_0^L dx \; V(x) \sin \phi^m(L - x, E) \right] \tag{40}$$

$$\kappa(E) \equiv -\frac{1}{2} c_{13}^4 \cos 2\tilde{\theta}_{12}^s \sin 2\theta_{12} (\sin 2\theta_{12} (c_{13}^2 - 2\epsilon_D^E) + 2 \cos 2\theta_{12} \epsilon_N^E) \tag{41}$$

$$\phi^m(L - x, E) \equiv \int_x^L dx \; \Delta_{21}^m(x) \approx \int_x^L dx \Delta_{21} (1 - c_{13}^2 \cos 2\theta_{12} a_{CC}^E) \tag{42}$$

Day-Night Asymmetry



- constraints on ϵ_N will be 0.014, 0.014, and 0.007 respectively by DUNE, HK, and MICA
- constraints on ϵ_D will be 0.004, 0.004, and 0.002 respectively by DUNE, HK, and MICA

Neutral Current NSI Effect on Electron Neutrino Scattering

$$\frac{d\sigma}{dT}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left[(g_1)^2 + (g_2)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - g_1 g_2 \frac{m_e T_e}{E_\nu^2}\right] \quad (43)$$

within the standard model

$$g_1^{\nu_e} = g_2^{\bar{\nu}_e} = \frac{1}{2} + \sin^2\theta_W = 0.73 \quad (44)$$

$$g_2^{\nu_e} = g_1^{\bar{\nu}_e} = g_2^{\nu_\mu} = g_1^{\bar{\nu}_\mu} = \sin^2\theta_W = 0.23 \quad (45)$$

$$g_1^{\nu_\mu} = g_2^{\bar{\nu}_\mu} = -\frac{1}{2} + \sin^2\theta_W = -0.27 \quad (46)$$

Considering the neutral current NSI

$$g_1^{e\ NSI} = g_1^e + \epsilon_{ee}^{eL} \quad (47)$$

$$g_2^{e\ NSI} = g_2^e + \epsilon_{ee}^{eR} \quad (48)$$

Neutrino Oscillation in Matter and LMA-Dark Solution

- The transformation symmetry under $H \to -H^*$ results in identical neutrino oscillation probabilities. This implies the following parameter transformations:

$$\theta_{12} \to \frac{\pi}{2} - \theta_{12},\ \delta \to \pi - \delta,\ \Delta m^2_{31} \to -\Delta m^2_{13} + \Delta m^2_{21},\ V_{\text{eff}} \to -S V_{\text{eff}} S, \tag{49}$$

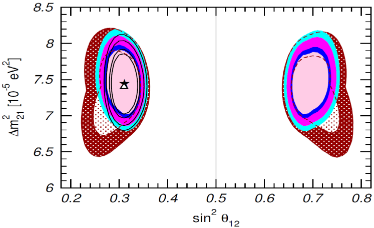
  where $S = \text{Diag}(-1, 1, 1)$.

- At the probability level relevant for JUNO, the survival probability for electron antineutrinos is given by:

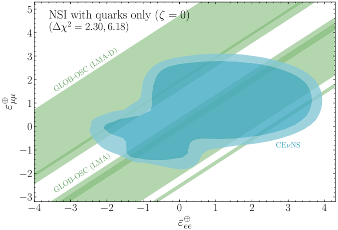
$$P_{\bar{e}\bar{e}} = 1 - \cos^4 2\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \frac{1}{2}\sin^2 2\theta_{13} + \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right] \tag{50}$$

LMA-Dark solution

- M. C. Gonzalez-Garcia and M. Maltoni, "Determination of matter potential from global analysis of neutrino oscillation data," JHEP **1309** (2013) 152 [arXiv:1307.3092].



- P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni, J. P. Pinheiro and S. Urrea, "Global constraints on non-standard neutrino interactions with quarks and electrons," JHEP **08** (2023), 032 [arXiv:2305.07698 [hep-ph]].



Summary and Conclusion

- Solar and reactor neutrino experiments will determine the solar neutrino oscillation parameters with sub-percent precision.
- Solar neutrino observatories can also probe the shallow structure of the Earth, particularly the crust and upper mantle, via the Day-Night asymmetry arising from the attenuation effect.
- When combined with reactor neutrino measurements, solar neutrino observations provide a powerful probe of new physics, such as Non-Standard Interactions (NSI):
  - NSI modify neutrino flavour transitions during propagation through the Sun and the Earth. Neutral-current NSI further affect detection via neutrino-electron scattering.
  - The presence of NSI can lead to the so-called LMA-Dark solution, which cannot be resolved by oscillation experiments alone.