Neutrino Mass Ordering with JUNO
and the impact of
Scalar Non-Standard Interactions

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Partikeldagarna - 2025/11/25

Neutrino Oscillations

- Neutrinos are produced in **flavor eigenstates** but propagate in **mass eigenstates**

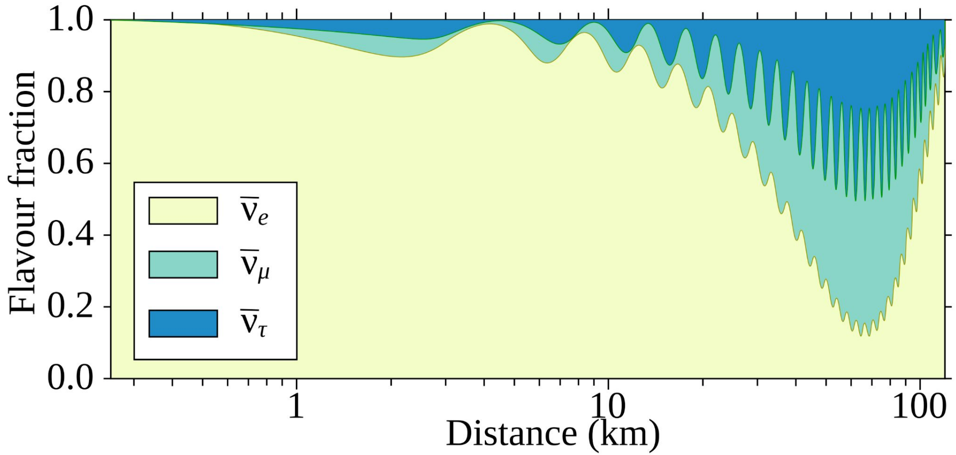
  $\rightarrow$ Flavor oscillations

  P = $sin^2(2\theta)\sin^2(\Delta m^2 L/E)$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Neutrino oscillations require massive neutrinos

  $\rightarrow$ Evidence of BSM!



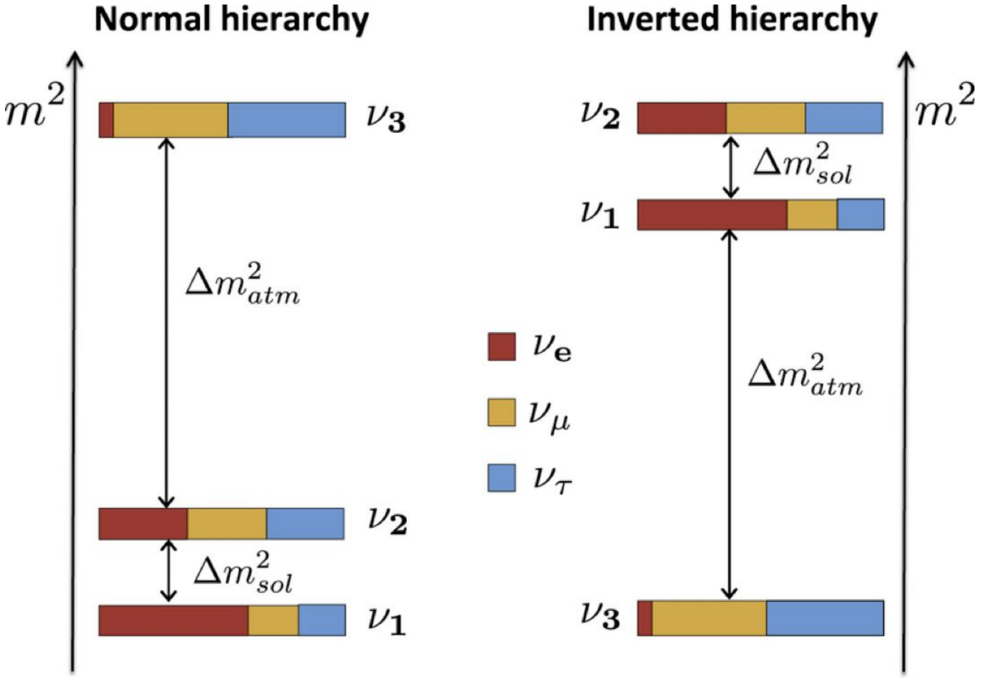
Unresolved question: Mass Hierarchy

- So far we have measured

$$\Delta m^2_{21} \approx 7 \times 10^{-5} eV^2,$$

$$\Delta m^2_{3l} \approx 2.5 \times 10^{-3} eV^2$$

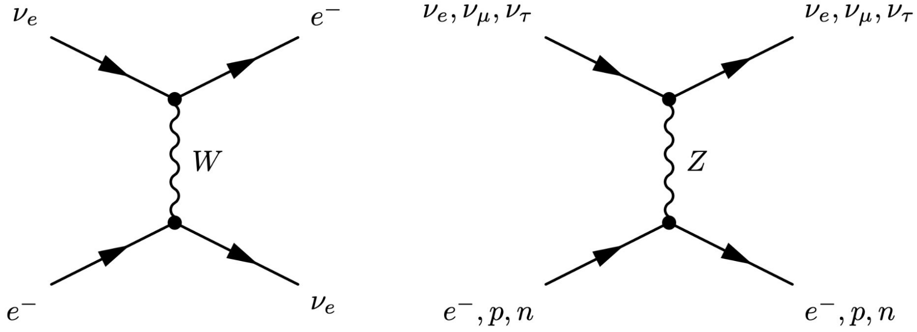
- The hierarchy of mass eigenstates and absolute mass scale remain ambiguous



Neutrino Matter Effects

- Neutrinos propagating through matter (Earth/Sun) experience a potential from coherent elastic forward scattering

- Effective four-fermi interactions
  $\longrightarrow$ Effective propagation Hamiltonian in matter



$$\widetilde{\mathcal{H}}_{\text{eff}} = \frac{1}{2E}\left[U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger - \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}\right] = \frac{1}{2E}\left[\widetilde{U} \begin{pmatrix} \widetilde{m}_1^2 & 0 & 0 \\ 0 & \widetilde{m}_2^2 & 0 \\ 0 & 0 & \widetilde{m}_3^2 \end{pmatrix} \widetilde{U}^\dagger\right]$$

$$A = 2\sqrt{2}\, G_{\mathrm{F}} N_e E \simeq 1.52 \times 10^{-4}\ \mathrm{eV}^2 \cdot Y_e \cdot \frac{\rho}{\mathrm{g/cm^3}} \cdot \frac{E}{\mathrm{GeV}}$$

Non-Standard Neutrino Matter Effects

Vector mediator:

$$\mathcal{L}_{\mathrm{cc}}^{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}}\left[\overline{\nu_e}(p_3)\gamma_\mu P_L \nu_e(p_2)\right]\left[\overline{e}(p_1)\gamma^\mu P_L e(p_4)\right]$$

$$\rightarrow \quad \mathcal{H} \approx E_\nu + \frac{MM^\dagger}{2E_\nu} \pm (V_{\mathrm{SI}} + V_{\mathrm{NSI}})$$

See e.g: (T. Ohlsson, 2013)

Scalar mediator:

$$\mathcal{L}_{\mathrm{eff}}^{s} \propto y_f Y_{\alpha\beta}\left[\bar{\nu}_\alpha(p_3)\nu_\beta(p_2)\right]\left[\bar{f}(p_1)f(p_4)\right]$$

$$\rightarrow \quad \mathcal{H} \approx E_\nu + \frac{(M+\delta M)(M+\delta M)^\dagger}{2E_\nu} \pm V_{\mathrm{SI}}$$

See: (S.-F. Ge and S. J. Parke 2018)

Scalar Non-Standard Interactions (SNSI)

- Correction to mass matrix in matter
- This correction is independent of neutrino energy
- Introduces dependence on lightest neutrino mass

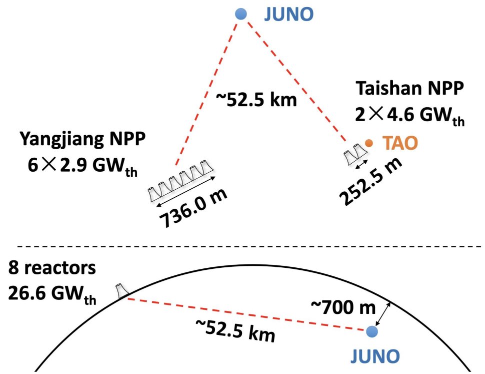
$$\mathcal{H} \approx E_\nu + \frac{(M + \delta M)(M + \delta M)^\dagger}{2E_\nu} \pm V_{\mathrm{SI}}$$

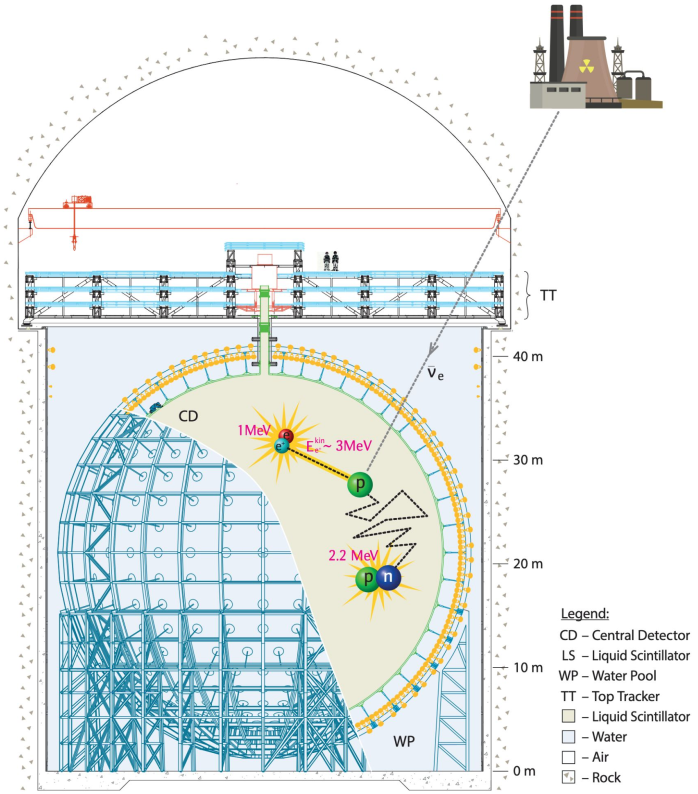
$$\delta M = \sqrt{|\Delta m^2_{31}|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}$$

The JUNO Experiment

- Detector: 20 kton liquidscintillator target surrounded by ~40,000 PMTs

- The primary neutrino sources are nuclear reactors with a thermal energy of 26.6 GW at an approximate baseline length of 52.5 km.





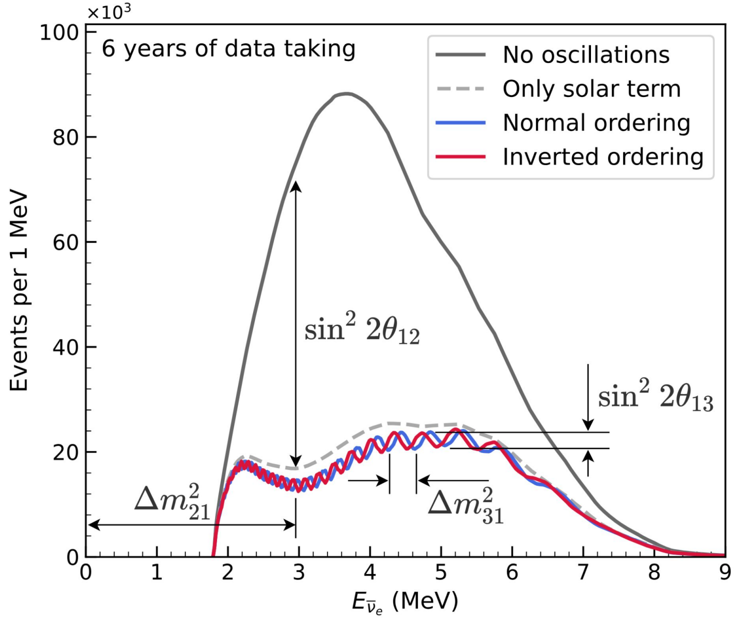
Credit: JUNO Collaboration ArXiv: 2511.14593 / 2204.13249

The JUNO Experiment

- JUNO expects <100,000 IBD events in the coming 6-7 years

- These physics goals rely on JUNO's unprecedented energy resolution (<3% at 1 MeV)

- **Main objectives**
  - Determine neutrino mass ordering with a 3σ confidence
  - Measure $\theta_{12}, \Delta m^2_{21}$ and Δm^2_{31} with sub-percent accuracy.

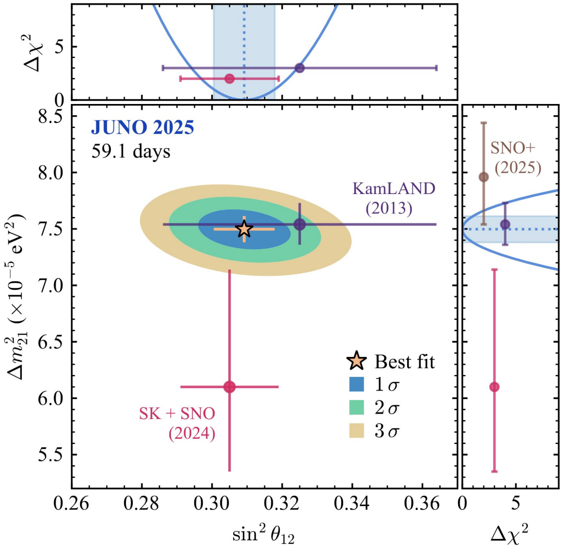


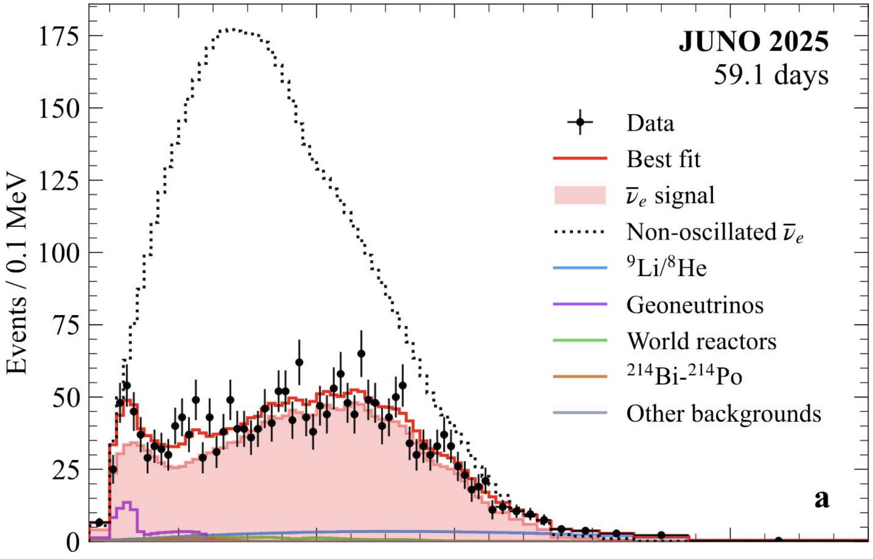
Credit: JUNO Collaboration ArXiv: 2405.18008 / 2204.13249

$$\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \Delta_{21} - \frac{1}{2} \sin^2 2\theta_{13} \left(\sin^2 \Delta_{31} + \sin^2 \Delta_{32}\right) - \frac{1}{2} \cos 2\theta_{12} \sin^2 2\theta_{13} \sin \Delta_{21} \sin(\Delta_{31} + \Delta_{32})$$

JUNO's First Data

- JUNO released their first 2 months of data on 19/11/2025 (last Wednesday!)





- With 2379 candidate events they already passed the precision of previous global fits

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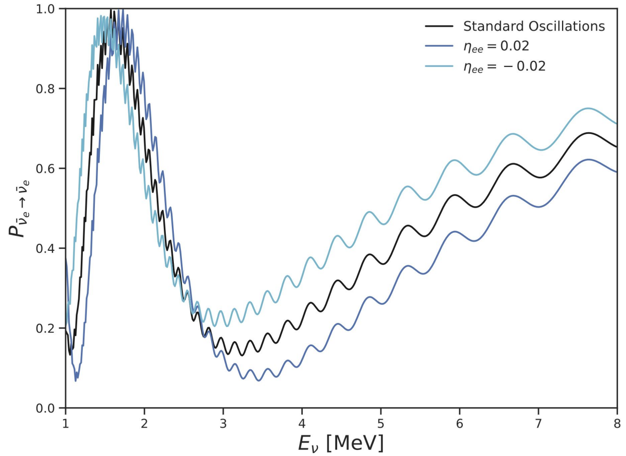
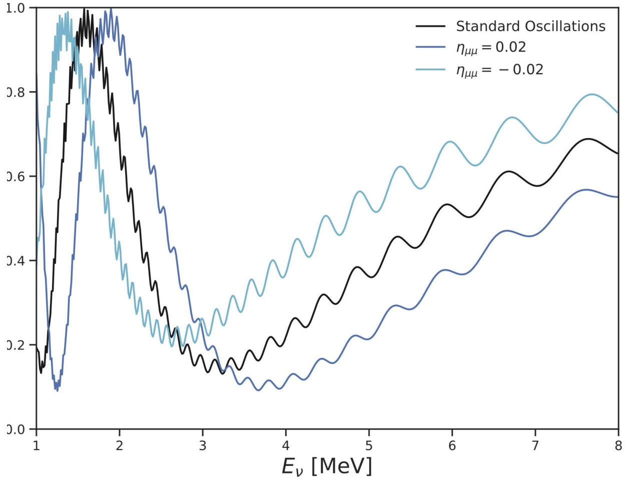
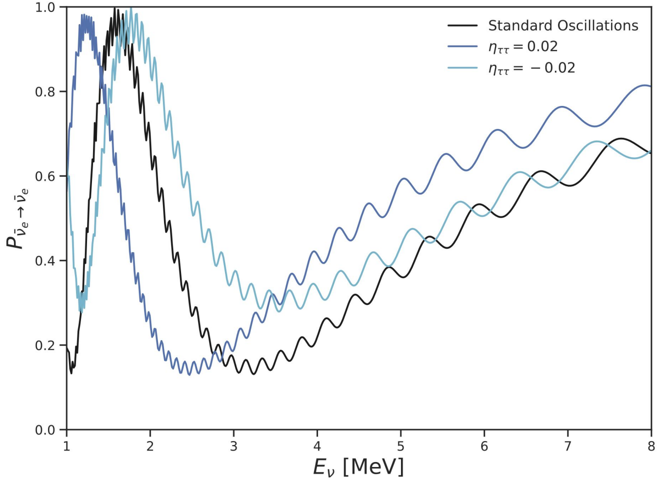
SNSI in JUNO

The oscillation spectrum in JUNO would be severely modified by SNSI parameters



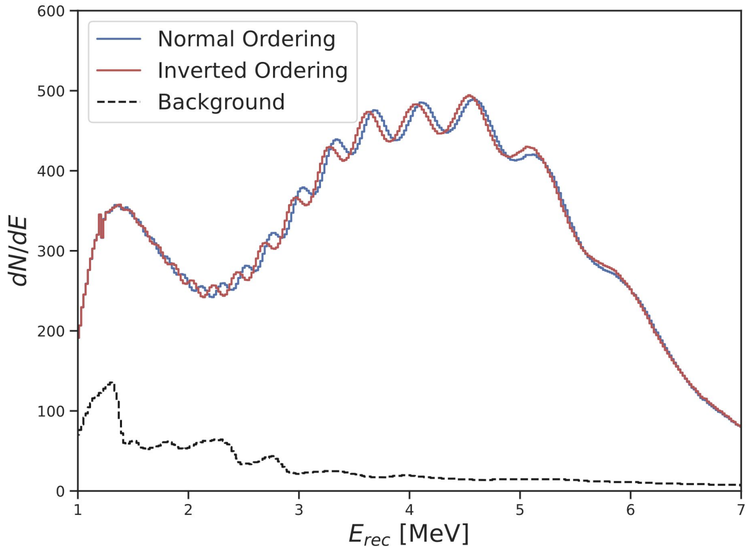




NMO sensitivity in JUNO

- Formulate frequentist hypothesis testing to rule out the wrong mass ordering

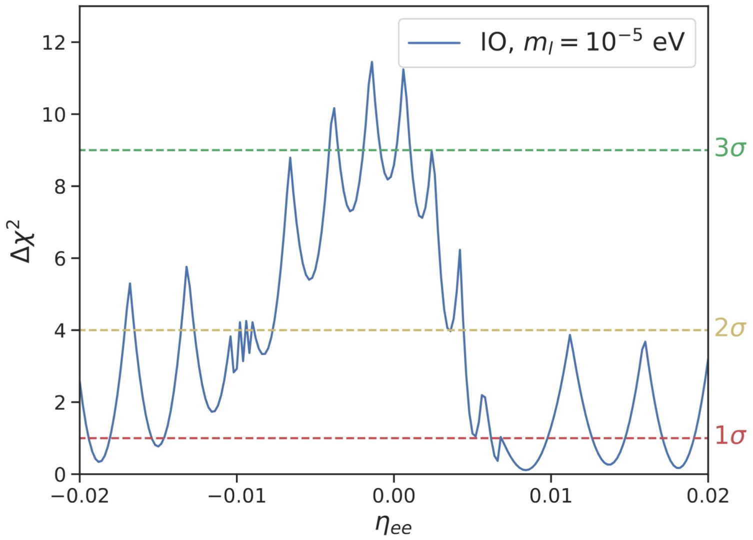
- We focus on the case where SNSI exists in nature, but the fit does not incorporate it
  $\longrightarrow$ Risk of standard analysis to misidentified mass ordering

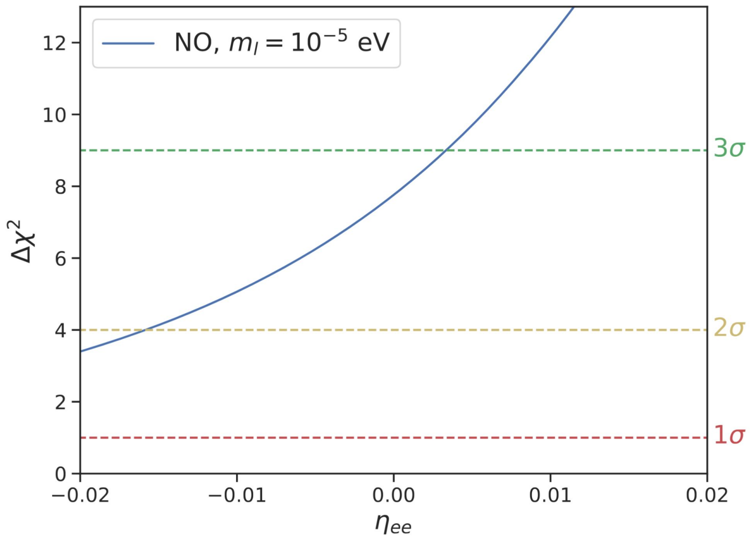


$$\Delta\chi^2_{NO-IO} = \chi^2_{NO}(\mathbf{\Theta}, \eta_{ee}) - \chi^2_{IO}(\mathbf{\Theta})$$

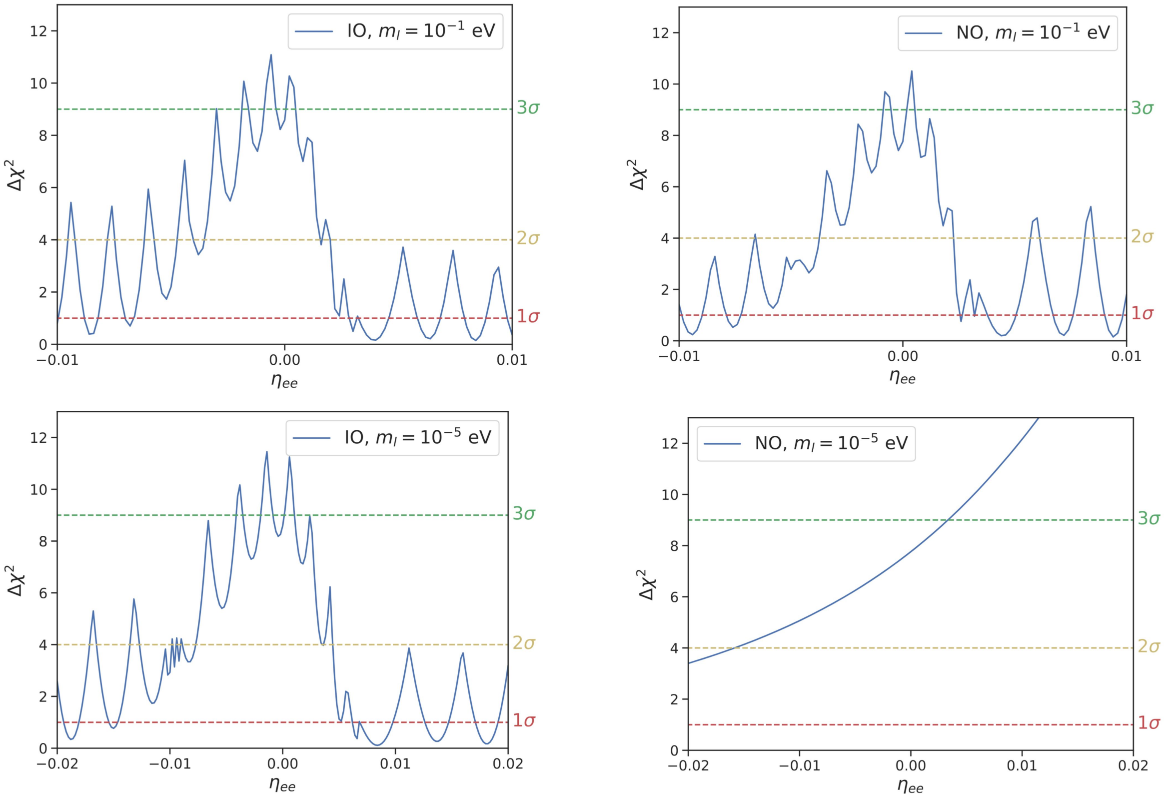
$$\chi^2 = \sum_i \frac{(O_i - P_i)^2}{O_i} + \left(\frac{a}{\sigma_{\text{cor}}}\right)^2 + \left(\frac{a'}{\sigma_{\text{bkg}}}\right)^2 + \sum_k \left(\frac{b_k}{\sigma_{\text{uncor}}}\right)^2 + \sum_i \left(\frac{c_i}{\sigma_{\text{sig shape}}}\right)^2 + \left(\frac{c'_i}{\sigma_{\text{bkg shape}}}\right)^2$$

SNSI in JUNO: Results



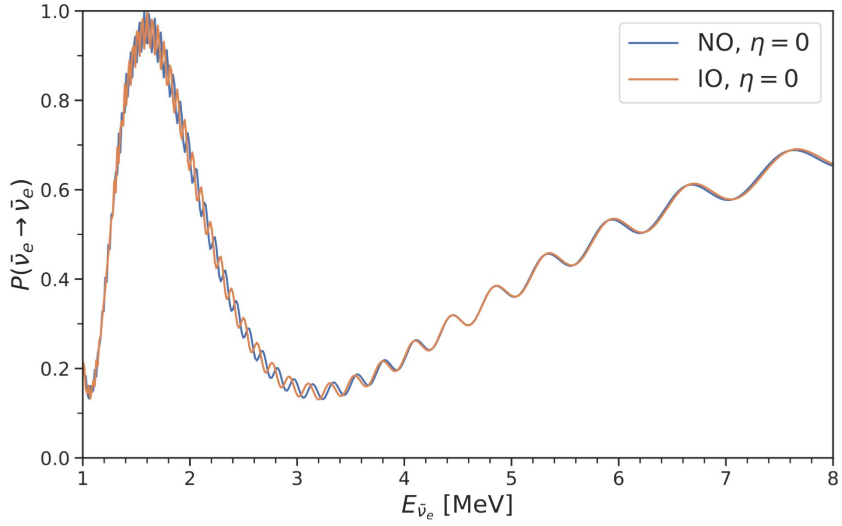


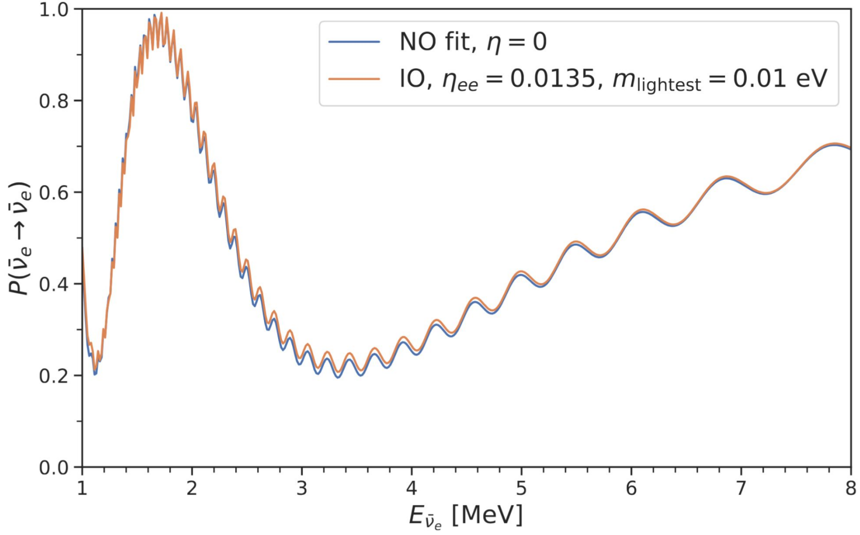
SNSI in JUNO: Results



SNSI in JUNO: The threat of degeneracies

In the currently allowed region of SNSI, JUNO runs the risk of identifying the wrong mass ordering





Conclusion

- The **Jiangmen Underground Neutrino Observatory (JUNO)**
  - JUNO is a next generation neutrino reactor experiment that just released their first two months of data
  - Main goal:
    - Measure **neutrino mass ordering** at 3 sigma confidence
    - Determine oscillation parameters at sub-percent accuracy

- We study **Scalar Non-Standard Interactions (SNSI)**, a model that manifests as sub-leading effects on neutrino oscillations in matter.

- Models like SNSI need to be identified and/or ruled out in various neutrino experiments in order for JUNO to conclusively determine the NMO.

Thank you for listening!