Indirect unitarity violation entangled with matter effects in JUNO

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Outline

- A brief introduction of indirect unitarity violation (UV) effects and matter effects
- Motivation
- Analytical analysis of matter effects and indirect UV effects in JUNO
- Numerical analysis
- Conclusion and outlook

Global analysis of recent neutrino oscillation data

F. Capozzi, E. Lisi, A. Marrone and A. Palazzo, arXiv:1804.09678

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
	IO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
$\sin^2\theta_{12}$	NO	3.04	2.91 – 3.18	2.78 – 3.32	2.65 – 3.46	4.4
	IO	3.03	2.90 – 3.17	2.77 – 3.31	2.64 – 3.45	4.4
$\sin^2\theta_{13}/10^{-2}$	NO	2.14	2.07 – 2.23	1.98 – 2.31	1.90 – 2.39	3.8
	IO	2.18	2.11 – 2.26	2.02 – 2.35	1.95 – 2.43	3.7
$\|\Delta m^2\|/10^{-3}$ eV^2	NO	2.455	2.423 – 2.490	2.390 – 2.523	2.355 – 2.557	1.4
	IO	2.441	2.406 – 2.474	2.372 – 2.507	2.338 – 2.540	1.4
$\sin^2\theta_{23}/10^{-1}$	NO	5.51	4.81 – 5.70	4.48 – 5.88	4.30 – 6.02	5.2
	IO	5.57	5.33 – 5.74	4.86 – 5.89	4.44 – 6.03	4.8
δ/π	NO	1.32	1.14 – 1.55	0.98 – 1.79	0.83 – 1.99	14.6
	IO	1.52	1.37 – 1.66	1.22 – 1.79	1.07 – 1.92	9.3

The octant problem of θ_{23}

Neutrino mass hierarchy

CP-violating phase

Indirect unitarity violation (UV) effects

Type-I seesaw mechanism assuming three heavy sterile neutrinos which do not take part in neutrino oscillations:

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}}\overline{\begin{pmatrix} e & \mu & \tau \end{pmatrix}_{L}}\gamma^{\mu}\left[V\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}_{L} + R\begin{pmatrix}\nu_4\\ \nu_5\\ \nu_6\end{pmatrix}_{L}\right] W_{\mu}^{-} + \text{H.c.}$$

$VV^{\dagger} = \mathbf{1} - RR^{\dagger}$ **Hence V is not unitary**

$V = (\mathbf{1} - \kappa)\,U$ **U is unitary**

Affect the behavior of neutrino oscillations

Conservative neutrino oscillation experimental constraints at the 90% C.L. (S. Antusch et al JHEP 10 (2006) 084):

$$|VV^{\dagger}| \approx \begin{pmatrix} 1.00 \pm 0.04 & < 0.05 & < 0.09 \\ < 0.05 & 1.00 \pm 0.05 & < 0.013 \\ < 0.09 & < 0.013 & ? \end{pmatrix}$$

Strength of Unitarity Violation: maximally a few percent $\kappa \sim \mathcal{O}\,(0.01)$

Matter effects

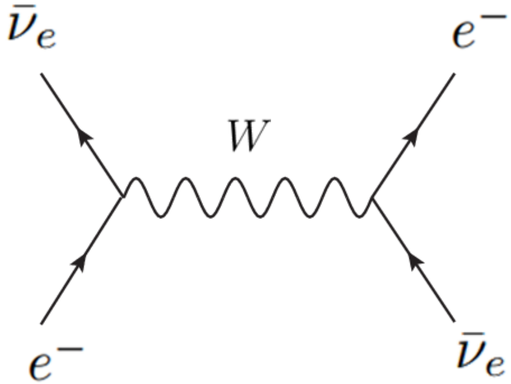
L. Wolfenstein (1978)

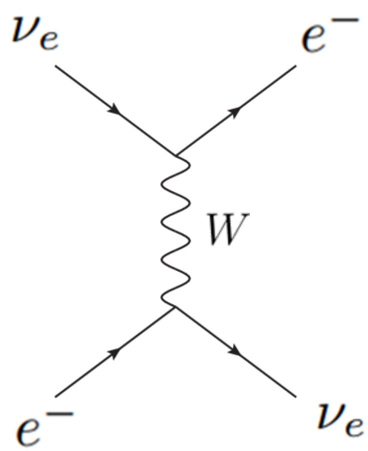
$$\widetilde{\mathcal{H}} = \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} + V^{\mathrm{T}} \begin{pmatrix} V_W^e + V_Z^n & 0 & 0 \\ 0 & V_Z^n & 0 \\ 0 & 0 & V_Z^n \end{pmatrix} V^*$$

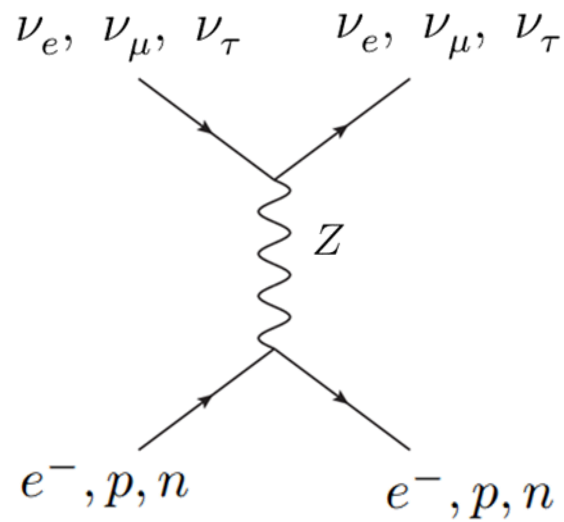
antineutrinos
(matter effects and indirect UV effects)

When traveling in matter, neutrinos can develop different matter potentials due to their NC and CC coherent forward scatterings with electrons, protons and neutrons.

Type of reaction	Matter potential
V_Z^n	$\mp G_F N_n/\sqrt{2}$
V_Z^p	$\pm G_F(1-4\sin^2\theta_W)N_p/\sqrt{2}$
V_Z^e	$\mp G_F(1-4\sin^2\theta_W)N_e/\sqrt{2}$
V_W^e	$\pm\sqrt{2}G_F N_e$







Motivation:

- **To test the standard three-neutrino paradigm or constrain the indirect UV effects induced by heavy sterile neutrinos in JUNO**
- **In Ref. [1], we have known that matter effects are comparable with important systematic uncertainties and hence should not be neglected in JUNO**
- **To study how the indirect UV effects are entangled with matter effects in JUNO and what their magnitude is as compared with matter effects**
- **To study whether the two kinds of effects can be distinguished from each other in JUNO**

[1]Y. F. Li, Y. f. Wang and Z. z. Xing, Chin. Phys. C 40 (2016) no.9, 091001

Analytical analysis

The survival probability of $\overline{\nu}_e \to \overline{\nu}_e$ considering the matter effects and indirect UV effects:

$$\widetilde{P}(\overline{\nu}_e \to \overline{\nu}_e) = \frac{1}{(VV^\dagger)^2_{ee}} \left[\left| (V^* V^{\mathrm{T}})_{ee} \right|^2 - 4 \sum_{j<k} \mathrm{Re}\left(\widetilde{X}^{ee}_j \widetilde{X}^{ee*}_k \right) \sin^2 \left(\frac{\Delta \widetilde{E}_{jk} L}{2} \right) \right]$$

K. Kimura, et al., (2002) ; E. F. Martinez et al., (2007)

$$V = (\mathbf{1} - \kappa)\, U$$

$$\alpha \equiv \frac{\Delta_{21}}{\Delta_{31}} \simeq 0.03$$

$$\beta \equiv \frac{2EV^e_W}{\Delta_{31}} = \frac{A}{\Delta_{31}}$$

$$\gamma \equiv \frac{2EV^n_Z}{\Delta_{31}} = \frac{A}{2\Delta_{31}}$$

Matter effect

$$A \equiv 2\sqrt{2}\, G_{\mathrm{F}} N_e E$$

A few MeV $\beta \sim \gamma \sim \mathcal{O}(\alpha^2)$

$\kappa \sim \mathcal{O}\,(0.01)$ ← **Constraints of Indirect UV parameters from experiments** $\kappa_{ij} \sim \mathcal{O}(\alpha)$

Expand $\widetilde{P}\,(\overline{\nu}_e \to \overline{\nu}_e)$ **in small quantities** $\alpha, \beta, \gamma, \kappa_{ij}$

Analytical approximations of $\widetilde{P}\left(\overline{\nu}_e \rightarrow \overline{\nu}_e\right)$

Vacuum | **Leading order** $\mathcal{O}(\alpha)$ | **Next-to-leading order** $\mathcal{O}(\alpha^2)$

$$\widetilde{P}(\overline{\nu}_e \rightarrow \overline{\nu}_e) \simeq 1 - P_0 - P_* - P_0^{\mathrm{M}_1} - P_*^{\mathrm{M}_1} - P_0^{\mathrm{M}_2} - P_*^{\mathrm{M}_2} - P_0^{\mathrm{UV}} - P_*^{\mathrm{UV}}$$

UV effects

$$\alpha = \frac{\Delta_{21}}{\Delta_{31}} \simeq 0.03$$

$P_0^{\mathrm{M}_1}$, $P_*^{\mathrm{M}_1}$, $P_0^{\mathrm{M}_2}$, $P_*^{\mathrm{M}_2}$ **Matter effects**

$$P_0^{\mathrm{UV}} \simeq A \sin^2 2\theta_{12} \cos^2\theta_{13} \left[1267 \xi_3' \frac{L}{E} \cos^2\theta_{13} \sin 2F_{21} + \frac{2}{\Delta_{21}} \left(\xi_3' \cos 2\theta_{12} \cos^2\theta_{13} + \xi_4'\right) \frac{\cos 2\theta_{12}}{\sin^2 2\theta_{12}} \sin^2 F_{21}\right]$$

Δ_{21}-driven oscillation

$$P_*^{\mathrm{UV}} \simeq \frac{1}{2} A \sin^2 2\theta_{13} \left\{1267 \frac{L}{E} \left[\xi_3' \left(\cos F_* \sin F_{21} + \cos 2\theta_{12} \sin F_* \cos F_{21}\right) - \left(\xi_1' + 2\xi_2'\right) \times \left(\cos 2\theta_{12} \cos F_* \sin F_{21} + \sin F_* \cos F_{21}\right)\right] - \frac{1}{\Delta_{21}} \left(\xi_3' \cos 2\theta_{12} + \frac{1}{\cos^2\theta_{13}} \xi_4'\right) \sin F_* \sin F_{21}\right\}$$

Sensitive to mass hierarchy (MH)

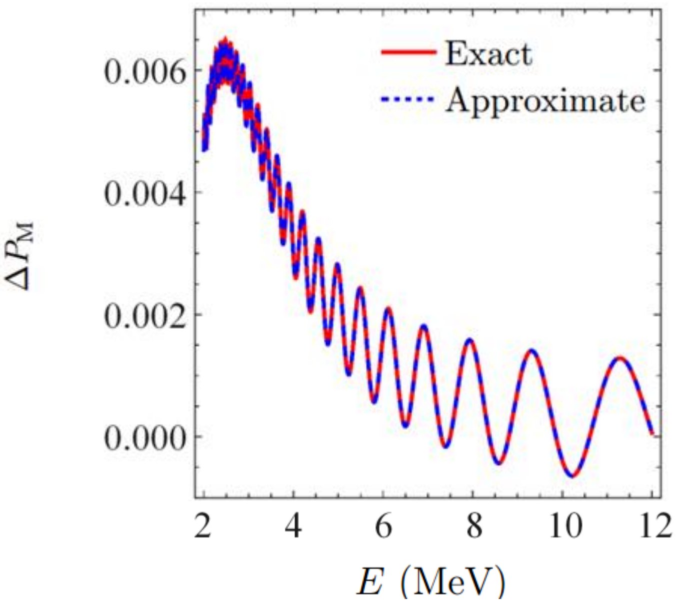
Matter effects → A **UV effects** → $\xi_i' \sim \mathcal{O}(\alpha)$

$$\Delta_* \equiv \Delta_{31} + \Delta_{32}$$
$$F_* = 1267 \Delta_* L/E$$

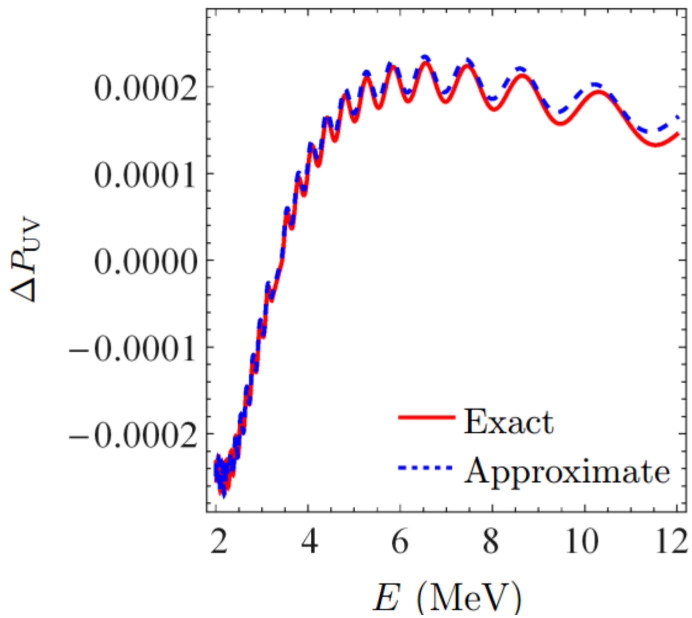
UV effects are much smaller than matter effects and always entangled with matter effects

Numerical analysis

Matter effects



UV effects



Normal mass ordering

L=52.5km

A typical input of considerable UV parameters constrained by experiments

Best-fit values of neutrino oscillation parameters

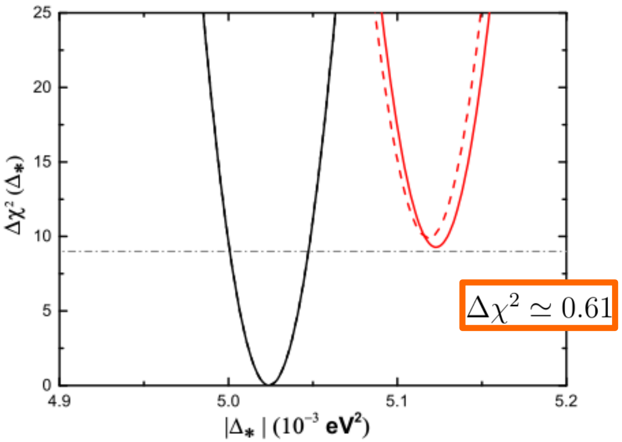
$$\Delta P_{\rm M} = \widetilde{P}(\overline{\nu}_e \to \overline{\nu}_e) - \widetilde{P}(\overline{\nu}_e \to \overline{\nu}_e,\ A=0) \simeq -\left(P_0^{\rm M_1} + P_0^{\rm M_2} + P_0^{\rm UV} + P_*^{\rm M_1} + P_*^{\rm M_2} + P_*^{\rm UV}\right)$$

$$\Delta P_{\rm UV} = \widetilde{P}(\overline{\nu}_e \to \overline{\nu}_e) - \widetilde{P}(\overline{\nu}_e \to \overline{\nu}_e,\ \kappa=\mathbf{0}) \simeq -\left(P_0^{\rm UV} + P_*^{\rm UV}\right)$$

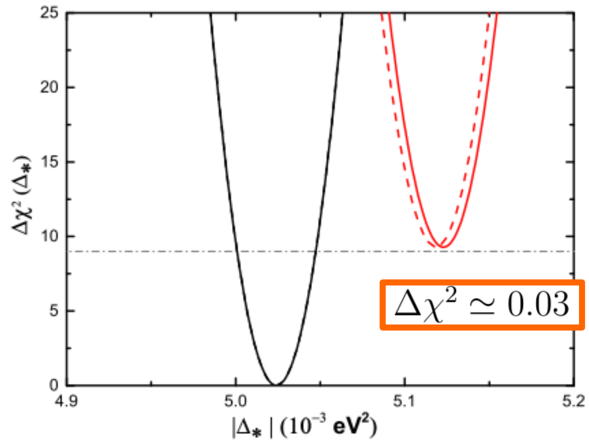
The analytical approximations and the exact values match well

Corrections to the measurements of MH, θ_{12}, and Δ_{21} in JUNO

Matter effects



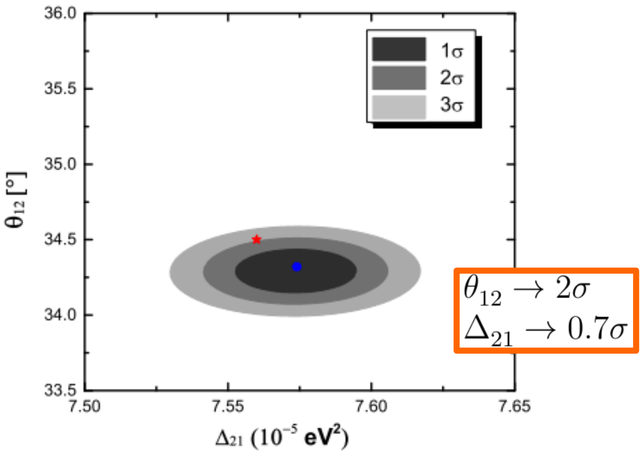
UV effects

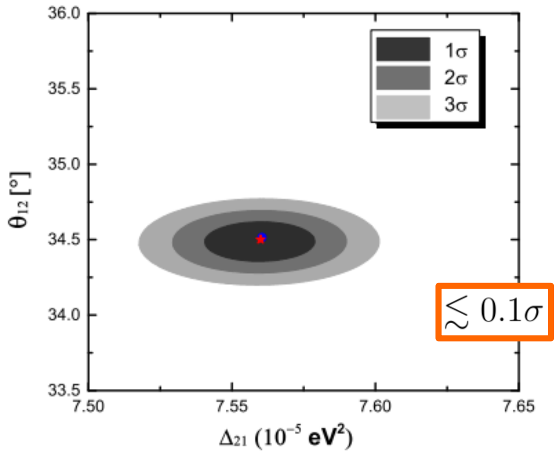


$\Delta\chi^2$the sensitivity of JUNO to MH

Red and black solid lines: Matter and UV effects

Red dashed lines: Ignoring matter effects (left) or UV effects (right)





★ **True value**

● **Best-fit value**

Conclusion and outlook

- **The UV effects are entangled with matter effects and much smaller than matter effects**
- **The fact that terrestrial matter effects should not be neglected in JUNO is reaffirmed**
- **Indirect UV effects make no difference, meaning the experimental sensitivities to MH and a precision measurement of θ_{12} and Δ_{21} are robust in JUNO**
- **The indirect UV effects in long baseline accelerator neutrino experiments may cause multiple parameter degeneracy problems and hence must be taken seriously**

Thank you for your attention!