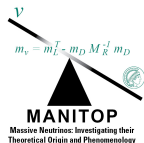


Why matter effects are important for medium baseline reactor neutrino experiments (ICHEP 2020, PRAGUE)

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- * In collaboration with Hiroshi Nunokawa (PUC) and Stephen Parke (Fermilab),
Based on: [arXiv:1910.12900](https://arxiv.org/abs/1910.12900) [hep-ph]

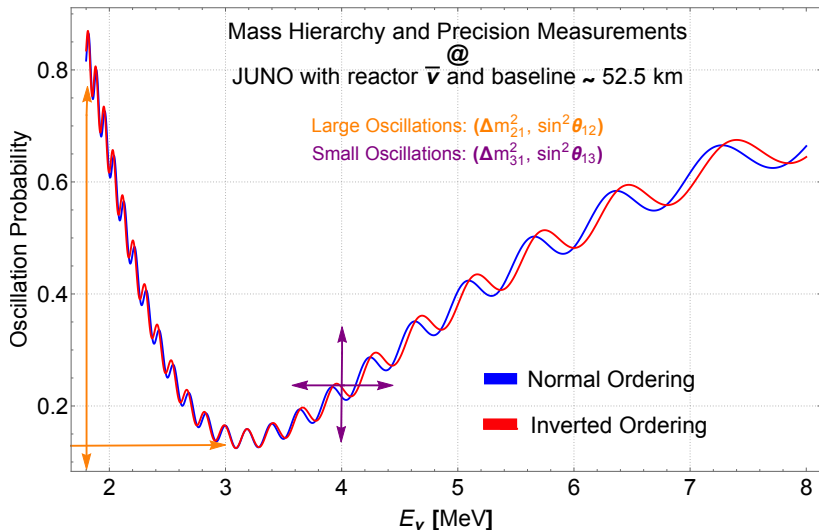
July 31, 2020



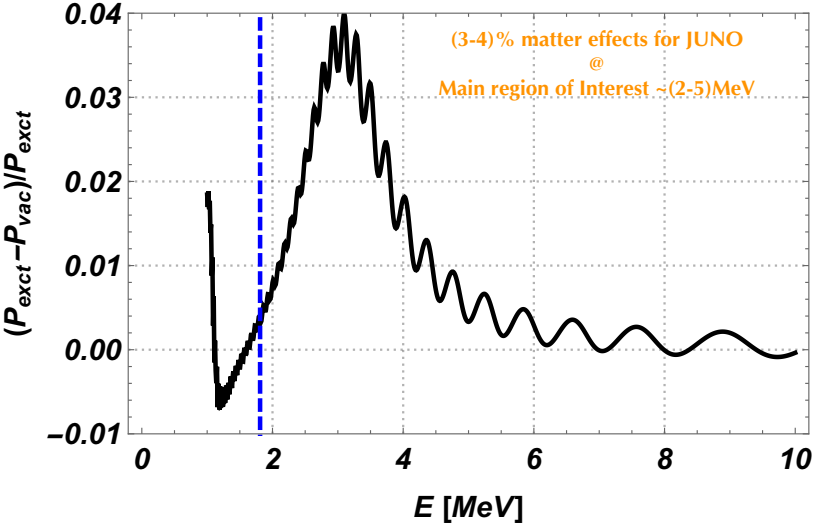
Outline

- ▶ Discuss the approximate oscillation probability including matter effects for Medium Baseline Experiments (MBL)
- ▶ Estimates matter effects on mixing parameters, oscillation probability and differential event energy spectrum
- ▶ Disagreement between the expected and fitted values matter solar parameters, θ_{12} and Δm_{21}^2 , (**Shift Issue**)
- ▶ Independent (Analytical) check of the "**Shift Issue**"
- ▶ Conclusion

Oscillation Probability for a MBL Experiment



Matter effects on oscillation probability for JUNO



Oscillation Probability with Matter Effects

$$\begin{aligned} \tilde{P}_{ee} = & 1 - \cos^4 \tilde{\theta}_{13} \sin^2 2\tilde{\theta}_{12} \sin^2 \tilde{\Delta}_{21} \\ & - \sin^2 2\tilde{\theta}_{13} [\cos^2 \tilde{\theta}_{12} \sin^2 \tilde{\Delta}_{31} + \sin^2 \tilde{\theta}_{12} \sin^2 \tilde{\Delta}_{32}], \end{aligned}$$

where $\tilde{\Delta}_{ij} \equiv \Delta \tilde{m}_{ij}^2 L / 4E$.

The mass-squared differences ($\Delta \tilde{m}_{ij}^2$) and mixing angles ($\tilde{\theta}_{ij}$) in matter can be calculated in any power of $(a/\Delta m_{ee}^2)$ and $(a/\Delta m_{21}^2)$ from exact the expressions found in [3]. We find:

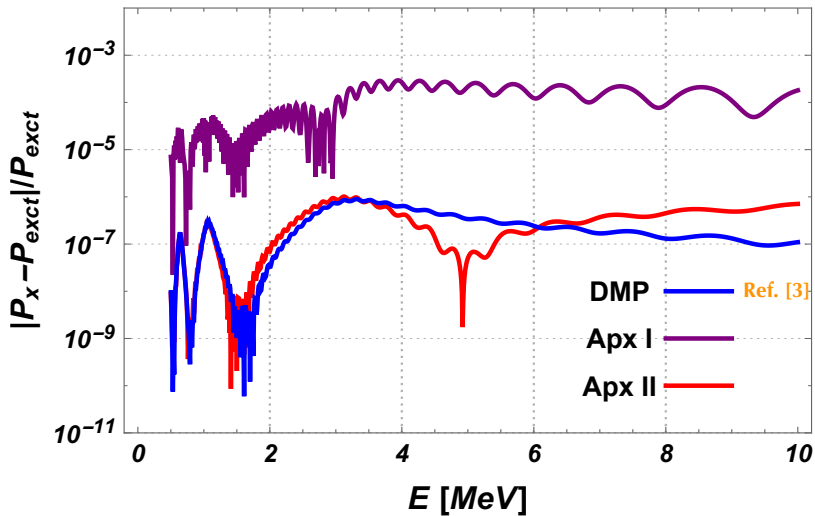
$$\Delta \tilde{m}_{21}^2 = \Delta m_{21}^2 - \Delta m_{21}^2 \left[(1 - 2s_{12}^2) \frac{c_{13}^2 a}{\Delta m_{21}^2} - 2s_{12}^2 c_{12}^2 \left(\frac{c_{13}^2 a}{\Delta m_{21}^2} \right)^2 \right] \dots$$

$$\Delta \tilde{m}_{31}^2 = \Delta m_{31}^2 + \Delta m_{ee}^2 \left[(s_{13}^2 - c_{12}^2 c_{13}^2) \frac{a}{\Delta m_{ee}^2} \right] \dots, \quad a \equiv \pm 2\sqrt{2} G_F N_e E$$

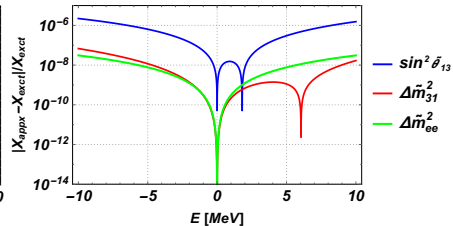
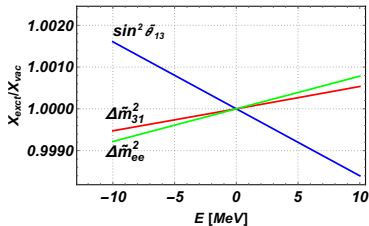
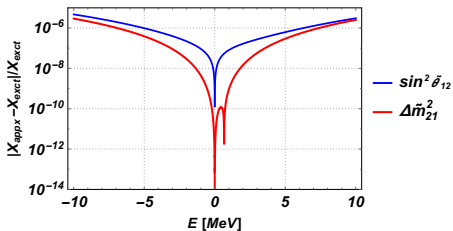
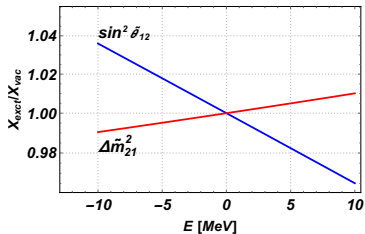
$$\sin^2 \tilde{\theta}_{13} = s_{13}^2 + 2s_{13}^2 c_{13}^2 \frac{a}{\Delta m_{ee}^2} \dots, \quad \Delta m_{ee}^2 \equiv c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2$$

$$\sin^2 \tilde{\theta}_{12} = s_{12}^2 + 2s_{12}^2 c_{12}^2 \frac{c_{13}^2 a}{\Delta m_{21}^2} + 3s_{12}^2 c_{12}^2 \cos 2\theta_{12} \left(\frac{c_{13}^2 a}{\Delta m_{21}^2} \right)^2 \dots$$

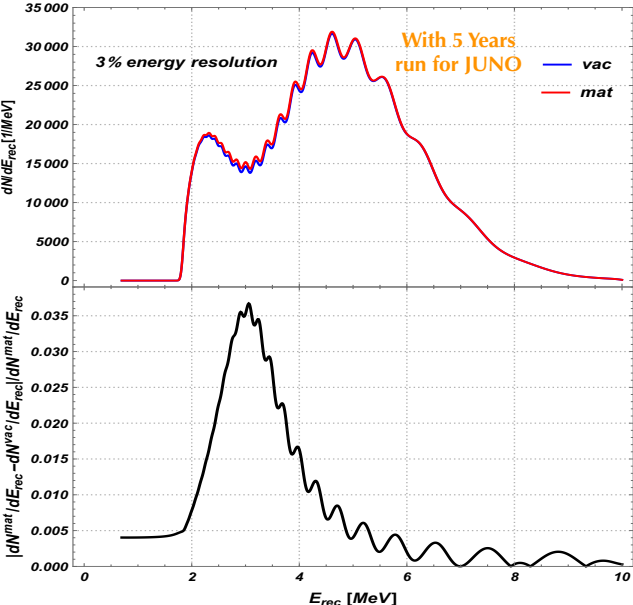
Accuracy of our calculations



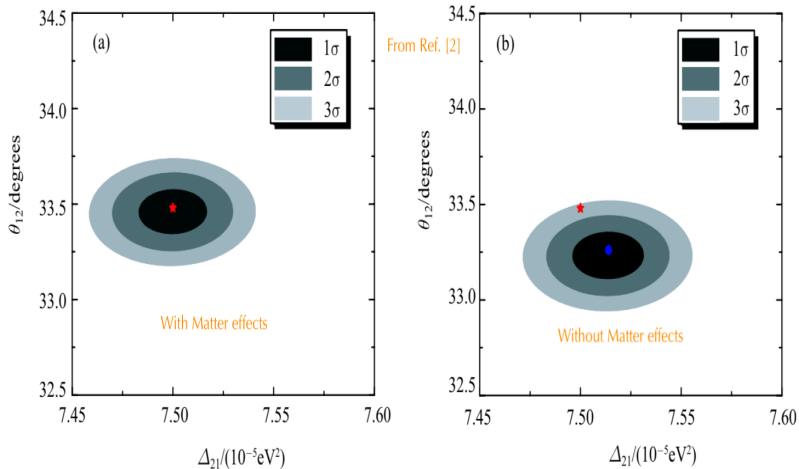
Matter Effects on Mixing Parameters



Matter Effects on Event Energy Spectrum



Shifts of Solar Parameters due to the Matter Effects



The "Shift Issue"

From analysis (and also ref.[2]) we find, assuming the constant matter density 2.6 g/cm^3 , the fractional shifts for the solar parameters are

$$\left(\frac{\delta(\sin^2 \theta_{12})}{\sin^2 \theta_{12}}, \frac{\delta(\Delta m_{21}^2)}{\Delta m_{21}^2} \right) \Big|_{\text{purely numerical } \chi^2} \simeq (-1.1, 0.19)\%. \quad (1)$$

While we find the expected shifts (above formulas) at fixed neutrino energy, E , are

$$\left(\frac{\delta(\sin^2 \theta_{12})}{\sin^2 \theta_{12}}, \frac{\delta(\Delta m_{21}^2)}{\Delta m_{21}^2} \right) \Big|_{\text{naive expectation}} \simeq \begin{cases} (-1.1, 0.30)\% & \text{using } E = 3 \text{ MeV,} \\ (-0.74, 0.21)\% & \text{using } E = 2 \text{ MeV.} \end{cases}$$

Independent Check of the Shift

Expected event number distribution $N(E)$ as function of the neutrino energy E simply written as

$$N(E) = N_0(E) \tilde{P}_{ee}(E),$$

where

$N_0(E) \equiv$ event number distribution without oscillations

$$\tilde{P}_{ee}(E) \approx P_{ee}^{\text{vac}}(E) + \delta P_{ee} \left(\frac{\delta(\sin^2 2\theta_{12})}{\sin^2 2\theta_{12}}, \frac{\delta(\Delta m_{21}^2)}{\Delta m_{21}^2} \right),$$

where the first term

$$P_{ee}^{\text{vac}}(E) \simeq 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right) - \frac{1}{2} \sin^2 2\theta_{13},$$

Independent check of the shift

while the second term is the correction due to matter effects as

$$\delta P_{ee} \left(\frac{\delta(\sin^2 2\theta_{12})}{\sin^2 2\theta_{12}}, \frac{\delta(\Delta m_{21}^2)}{\Delta m_{21}^2} \right) = -c_{13}^4 \sin^2 2\theta_{12} \sin \Delta_{21} \\ \times \left[\sin \Delta_{21} \frac{\delta(\sin^2 2\theta_{12})}{\sin^2 2\theta_{12}} + 2\Delta_{12} \cos \Delta_{12} \frac{\delta(\Delta m_{21}^2)}{\Delta m_{21}^2} \right],$$

where

$$\frac{\delta(\sin^2 2\theta_{12})}{\sin^2 2\theta_{12}} = -2\alpha(\rho)E \\ \frac{\delta(\Delta m_{21}^2)}{\Delta m_{21}^2} = \alpha(\rho)E$$

$$\alpha(\rho) \equiv \frac{2\sqrt{2}G_F N_e c_{13}^2 \cos 2\theta_{12}}{\Delta m_{21}^2}$$

New event energy spectrum

$$N^{\text{obs}}(E) \approx N_0^{\text{tot}} \lambda(E) [P_{ee}^{\text{vac}}(E) + \delta P_{ee}(-2\alpha(\rho)E, \alpha(\rho)E)],$$

where

$N_0^{\text{tot}} \equiv$ Expected total number of events without Osc.

$$\lambda(E) \equiv (S(E) \times \sigma_{IBD}(E)) / N_0^{\text{tot}}$$

Assume the event rate distribution is best fitted with a vacuum oscillation probability, but with a slight dimensionless shifts x and y in the solar mixing parameters as

$$\begin{aligned} \sin^2 2\theta_{12}^{\text{fit}} &= \sin^2 2\theta_{12}(1 + x) \\ \Delta m_{21}^2{}^{\text{fit}} &= \Delta m_{21}^2(1 + y), \end{aligned}$$

New event energy spectrum

Then as if there is no matter effects,

$$N^{\text{fit}}(E) \approx N_0^{\text{tot}} \lambda(E) [P_{ee}^{\text{vac}}(E) + \delta P_{ee}(x, y)],$$

where

$$\delta P_{ee}(x, y) = -c_{13}^4 \sin^2 2\theta_{12} \sin \Delta_{21} \left[\frac{\sin \Delta_{21}}{\sin^2 2\theta_{12}} x + \frac{2\Delta_{12} \cos \Delta_{12}}{\Delta m_{21}^2} y \right]$$

The Task, $x, y = ?$

Define a χ^2 function:

$$\begin{aligned} \chi^2(x, y) &= \int \left(\frac{N^{\text{obs}}(E) - N^{\text{fit}}(E)}{\sqrt{N^{\text{obs}}(E)}} \right)^2 dE, \\ &= N_0^{\text{tot}} \int \frac{[\delta P_{ee}(-2\alpha(\rho)E, \alpha(\rho)E) - \delta P_{ee}(x, y)]^2}{\tilde{P}_{ee}(E)} \lambda(E) dE \end{aligned}$$

Minimizing the χ^2

The minimization condition

$$\frac{\partial \chi^2(x, y)}{\partial x} = \frac{\partial \chi^2(x, y)}{\partial y} = 0$$

leads to coupled linear equations for the two unknowns, x and y ,

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} f \\ g \end{bmatrix},$$

where a, b, c, d, f and g are derived as

$$a \equiv \int (\sin^2 \Delta_{21}) h(E) \lambda(E) dE \approx 2.95,$$

$$b \equiv \int (\Delta_{21} \sin 2\Delta_{21}) h(E) \lambda(E) dE \approx 0.823,$$

$$c \equiv b/2 \approx 0.411,$$

$$d \equiv 2 \int (\Delta_{21}^2 \cos^2 \Delta_{21}) h(E) \lambda(E) dE \approx 1.17,$$

Minimizing the χ^2

$$h(E) \equiv (\sin^2 \Delta_{21})/P_{ee}^{\text{vac}}(E)$$

$$\begin{aligned} f(\rho) &\equiv -\alpha(\rho) \int (2 \sin^2 \Delta_{21} - \Delta_{21} \sin 2\Delta_{21}) h(E) \lambda(E) E dE \\ &\approx -1.75 \times 10^{-2} \left(\frac{\rho}{2.6 \text{ g/cm}^3} \right) \cos^2 \theta_{13} \end{aligned}$$

$$\begin{aligned} g(\rho) &\equiv -\alpha(\rho) \int (\Delta_{21} \sin 2\Delta_{21} - 2\Delta_{21}^2 \cos^2 \Delta_{21}) h(E) \lambda(E) E dE \\ &\approx -3.38 \times 10^{-4} \left(\frac{\rho}{2.6 \text{ g/cm}^3} \right) \cos^2 \theta_{13}, \end{aligned}$$

Summary on the "Shift Issue"

Thus, for the small matter effects, the true and fitted parameters are analytically related as

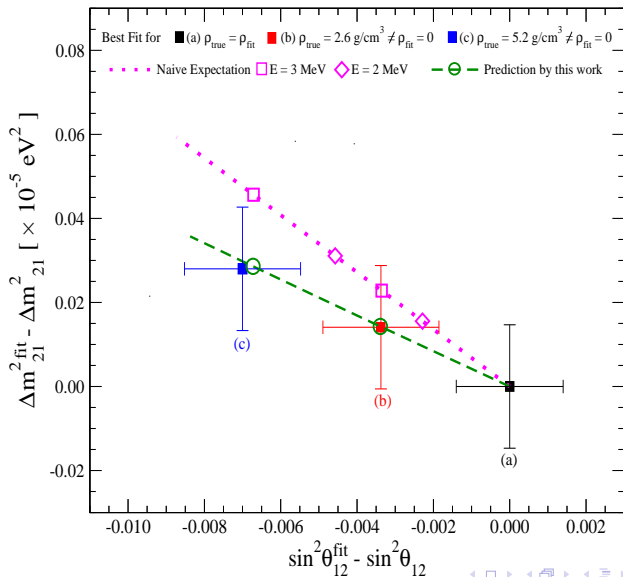
$$\sin^2 \theta_{12}^{\text{true}} \approx \sin^2 \theta_{12}^{\text{fit}} \left[1 - \left(\frac{d.f(\Delta\rho) - b.g(\Delta\rho)}{a.d - b.c} \right) \left(\frac{\cos^2 \theta_{12}}{\cos 2\theta_{12}} \right) \right]$$

and

$$\Delta m_{21}^2{}^{\text{true}} \approx \Delta m_{21}^2{}^{\text{fit}} \left[1 + \left(\frac{a.g(\Delta\rho) - c.f(\Delta\rho)}{a.d - b.c} \right) \right],$$

where $\Delta\rho \equiv (\rho_{\text{true}} - \rho_{\text{fit}})$

Analytical shifts agree with the numerical χ^2 ?



Conclusions

- ▶ We give simple oscillation probability formula and perturbative expansions for oscillation parameters, $\sin^2 \theta$'s and Δm^2 's.
- ▶ We find that the maximum matter effects occur at the solar minimum of around (3-4)%.
- ▶ Argued that solar parameter shifts are in conflict with full χ^2 (Shift Issue)
- ▶ The "Shift Issue" was independently confirmed analytically.
- ▶ Could have some connection with the 2σ mismatch on Δm_{21}^2 's solar and KamLAND measurements (See @MariamTortola Talk slide 9), NSI or something else, yet to know.
- ▶ **Thanks!**

References

- [1] e-Print: arXiv: 1910.12900 [hep-ph],
- [2] e-Print: arXiv: 1605.00900 [hep-ph],
- [3] e-Print: arXiv: 1604.08167 [hep-ph].