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Evolution of Neutrino Mass-Mixing Parameters in Matter with NSIs

Sanjib Kumar Agarwalla[1,2,3], Sudipta Das[1,2], Mehedi Masud[4] Pragyanprasu Swain[1,2],

[1]Institute of Physics (IOP), India; [2]HBNI, India; [3]ICTP, Italy, [4]IBS, South Korea

POSTER ID: 221

sudipta.d@iopb.res.in

AIM OF THIS WORK

- Explore the role of lepton-flavour-conserving and lepton-flavour-violating non-standard interactions (NSIs) in the evolution of oscillation parameters in matter.
- We derive simple approximate analytical expression for the mass-mixing parameters in matter with all real NSIs.
- Demonstrate the utility of our approach in addressing several important features of neutrino oscillation.

EVOLUTION OF MIXING ANGLES

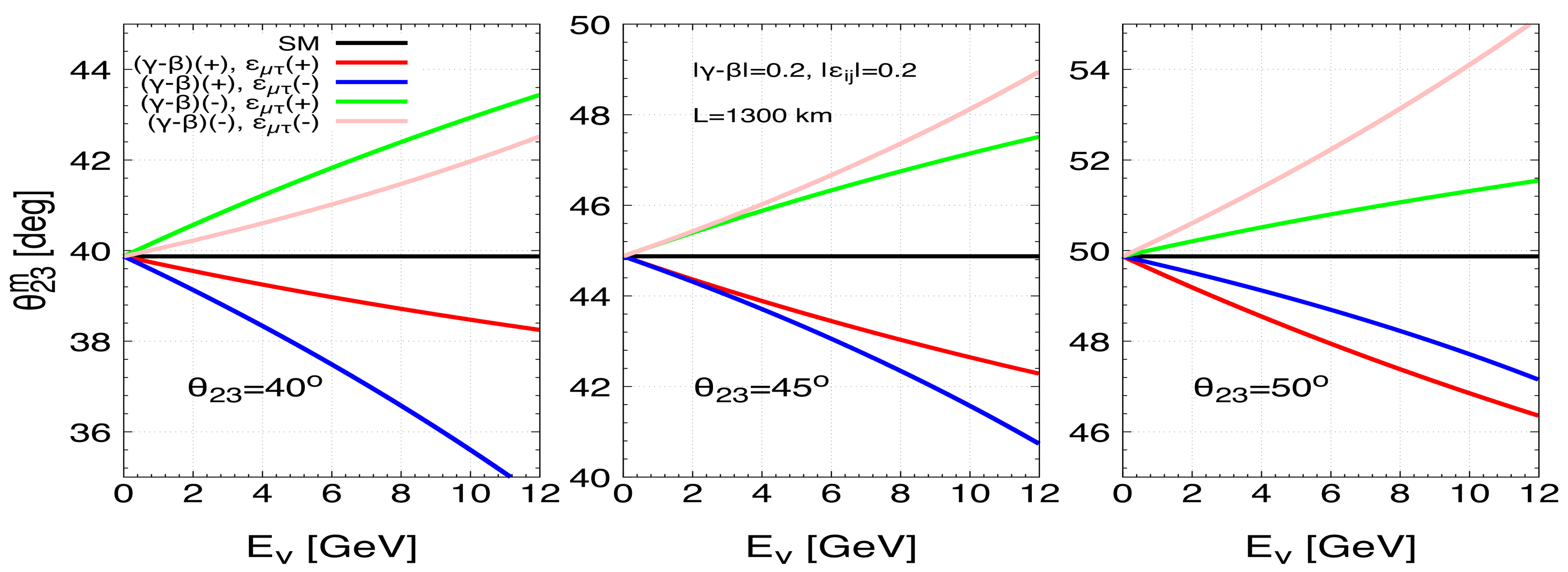
Hamiltonian for the neutrinos propagating in matter with "real NSIs":

$$H_{eff} = \Delta_{31}\left[U\begin{pmatrix}0&0&0\\0&\alpha&0\\0&0&1\end{pmatrix}U^{\dagger} + \hat{A}\begin{pmatrix}1&\varepsilon_{e\mu}&\varepsilon_{e\tau}\\ \varepsilon_{e\mu}&\beta&\varepsilon_{\mu\tau}\\ \varepsilon_{e\tau}&\varepsilon_{\mu\tau}&\gamma\end{pmatrix}\right], \quad \Delta_{ij} \equiv \frac{\Delta m^2_{ij}}{2E}, \quad \hat{A} = \frac{2EV_{cc}}{\Delta m^2_{31}}$$

$$\beta = \varepsilon_{\mu\mu} - \varepsilon_{ee}, \quad \gamma = \varepsilon_{\tau\tau} - \varepsilon_{ee}, \quad \alpha = \Delta_{21}/\Delta_{31} \quad V_{cc} = \sqrt{2}G_F N_e$$

$$\tan 2\theta^m_{23} = \frac{(c^2_{13} - \alpha c^2_{12} + \alpha s^2_{12}s^2_{13})\sin 2\theta_{23} - \alpha \sin 2\theta_{12} s_{13}\cos 2\theta_{23} + 2\varepsilon_{\mu\tau}\hat{A}}{(c^2_{13} - \alpha c^2_{12} + \alpha s^2_{12}s^2_{13})\cos 2\theta_{23} + \alpha s_{13}\sin 2\theta_{12} + (\gamma - \beta)\hat{A}}$$

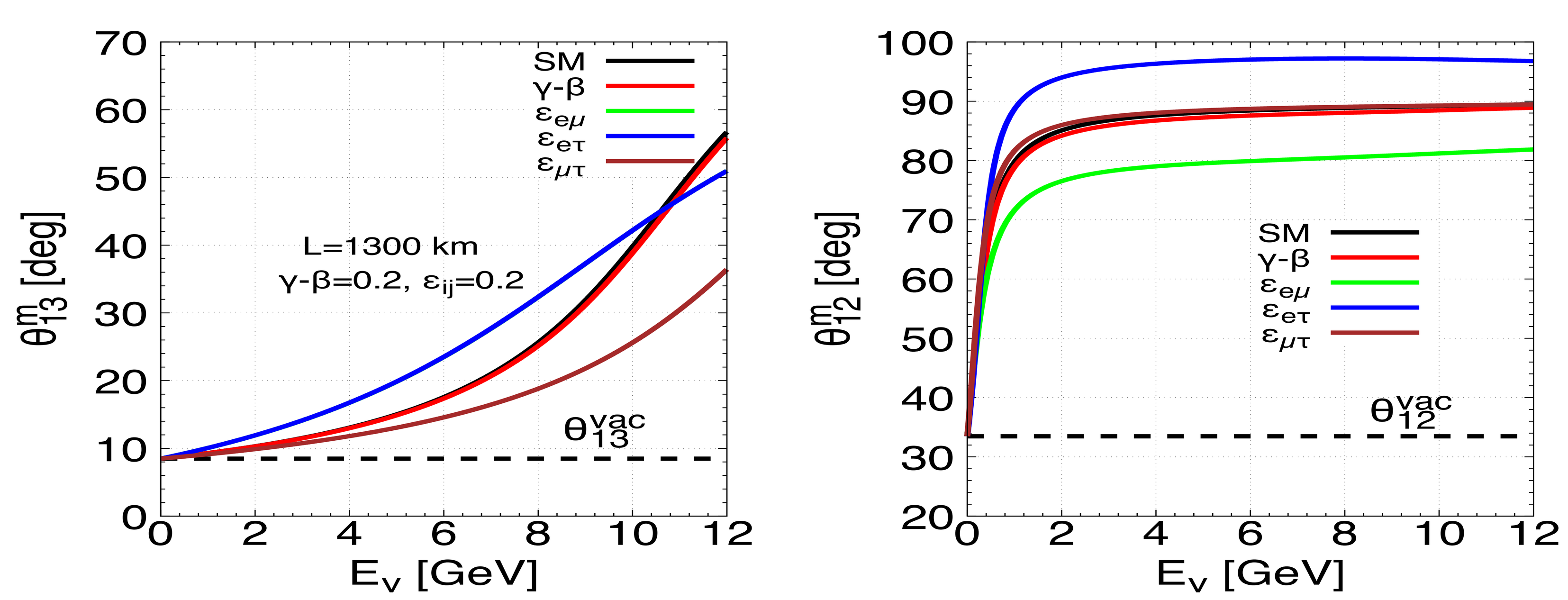
$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, $\theta^m \rightarrow$ mixing angle in matter



Running of θ_{23} in matter in presence of NSIs. Only NSIs in 2-3 block affect θ_{23} in matter.

$$\tan 2\theta^m_{13} = \frac{\sin 2\theta_{13}(1-\alpha s^2_{12})\cos(\theta_{23}-\theta^m_{23}) - \alpha \sin 2\theta_{12} c_{13}\sin(\theta_{23}-\theta^m_{23}) + 2(\varepsilon_{e\mu}s^m_{23} + \varepsilon_{e\tau}c^m_{23})\hat{A}}{(\lambda_3 - \hat{A} - \alpha s^2_{12}c^2_{13} - s^2_{13})}$$

$$\tan 2\theta^m_{12} = \frac{c^m_{13}[\alpha \sin 2\theta_{12} c_{13}\cos(\theta_{23}-\theta^m_{23}) + \sin 2\theta_{13}(1-\alpha s^2_{12})\sin(\theta_{23}-\theta^m_{23}) + 2(\varepsilon_{e\mu}c^m_{23} - \varepsilon_{e\tau}s^m_{23})\hat{A}]}{(\lambda_2 - \lambda_1)}$$



Running of θ_{13} and θ_{12} in matter with NSIs for DUNE.

EVOLUTION OF MASS-SQUARED DIFFERENCES

$$\frac{m^2_{3,m}}{2E} = \frac{\Delta_{31}}{2}\left[\lambda_3 + \hat{A} + s^2_{13} + \alpha s^2_{12}c^2_{13} + \frac{\lambda_3 - \hat{A} - s^2_{13} - \alpha s^2_{12}c^2_{13}}{\cos 2\theta^m_{13}}\right]$$

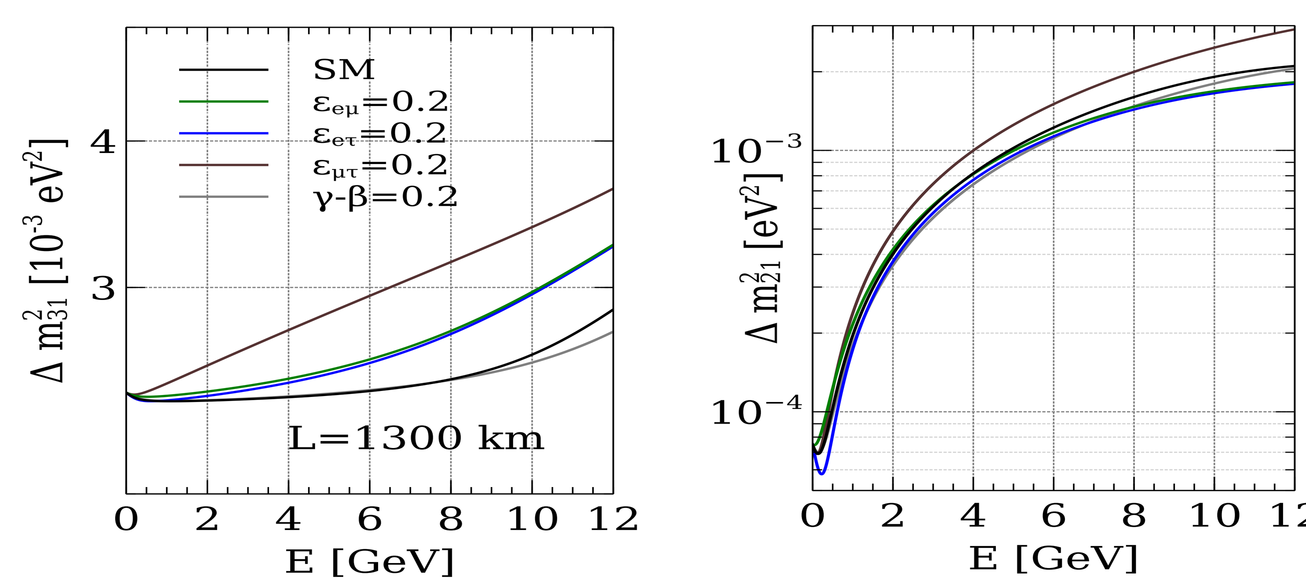
$$\frac{m^2_{2,m}}{2E} = \frac{\Delta_{31}}{2}\left[\lambda_1 + \lambda_2 - \frac{\lambda_1 - \lambda_2}{\cos 2\theta^m_{12}}\right] \qquad \frac{m^2_{1,m}}{2E} = \frac{\Delta_{31}}{2}\left[\lambda_1 + \lambda_2 + \frac{\lambda_1 - \lambda_2}{\cos 2\theta^m_{12}}\right]$$

Expressions of λ_1, λ_2, and λ_3:

$$\lambda_3 = \frac{1}{2}\left[c^2_{13} + \alpha c^2_{12} + \alpha s^2_{12}s^2_{13} + (\beta+\gamma)\hat{A} + \frac{(\gamma-\beta)\hat{A} + \alpha \sin 2\theta_{12}s_{13}\sin 2\theta_{23} + (c^2_{13} - \alpha c^2_{12} + \alpha s^2_{12}s^2_{13})\cos 2\theta_{23}}{\cos 2\theta^m_{23}}\right]$$

$$\lambda_2 = \frac{1}{2}\left[\alpha c^2_{12} + c^2_{13} + \alpha s^2_{12}s^2_{13} + (\beta+\gamma)\hat{A} - \frac{(\gamma-\beta)\hat{A} + \alpha \sin 2\theta_{12}s_{13}\sin 2\theta_{23} + (c^2_{13} - \alpha c^2_{12} + \alpha s^2_{12}s^2_{13})\cos 2\theta_{23}}{\cos 2\theta^m_{23}}\right]$$

$$\lambda_1 = \frac{1}{2}\left[\lambda_3 + \hat{A} + s^2_{13} + \alpha s^2_{12}c^2_{13} - \frac{\lambda_3 - \hat{A} - s^2_{13} - \alpha s^2_{12}c^2_{13}}{\cos 2\theta^m_{13}}\right]$$



Running of Δm^2_{31} and Δm^2_{21} in matter with NSIs for DUNE.

- Parameters $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$ and $\varepsilon_{\mu\tau}$ affect the running of Δm^2_{31} significantly compared to standard model.
- Value of Δm^2_{21} in matter increases rapidly with energy in SM case as well as with NSIs.

"θ_{13}" RESONANCE IN PRESENCE OF NSI

Energy at which reactor mixing angle(θ_{13}) attains the maximal value:

$$E_{res} = \overbrace{\frac{\Delta m^2_{31}\cos 2\theta_{13}}{2V_{cc}}}^{\text{SM case (OMSD)}} \times \frac{(1 - \overbrace{\alpha s^2_{12}}^{\text{solar correction}})}{[1 - \underbrace{0.5 \times (\beta + \gamma + 2\varepsilon_{\mu\tau})]}_{\text{NSIs corrections}}}$$

$V_{cc} \approx 0.76 \times Y_e \times 10^{-14}[\frac{\rho}{\text{gm/cc}}]$ eV $\quad Y_e = \frac{N_e}{N_p + N_n}$=0.5 for earth matter.

OMSD: One Mass Scale Dominance

- 1st term in R.H.S is standard OMSD resonance condition.
- Numerator in the 2nd term gives the solar correction and denominator gives corrections due to NSIs.

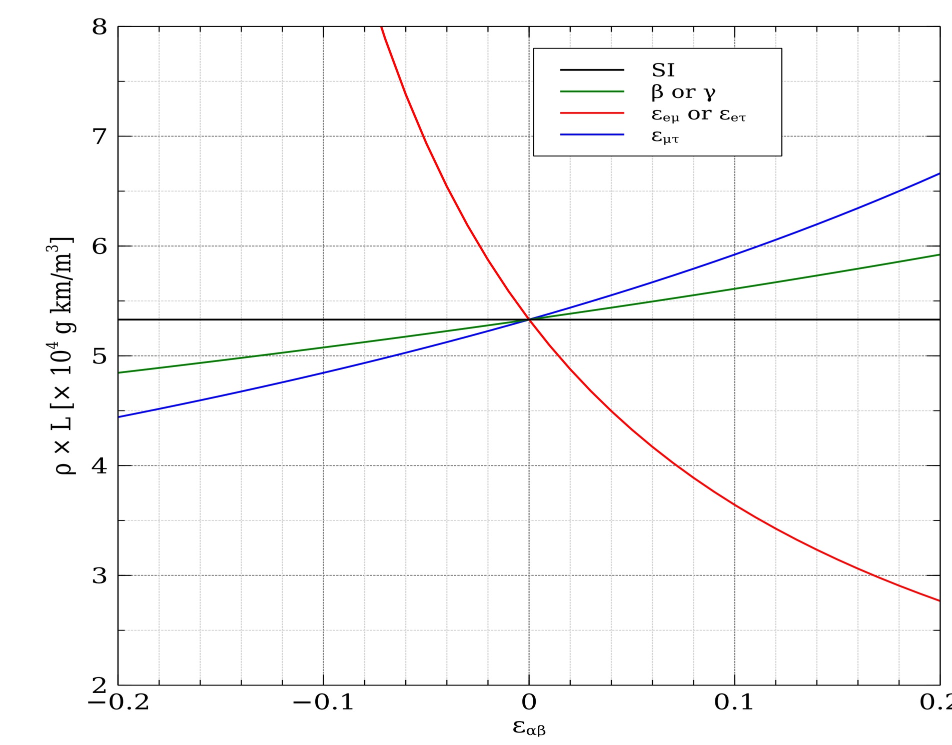
MAXIMISING $\nu_\mu \rightarrow \nu_e$ TRANSITION WITH NSIs

- Under $\theta^m_{12} \rightarrow 90°$, $\nu_\mu \rightarrow \nu_e$ transition probability takes the form:

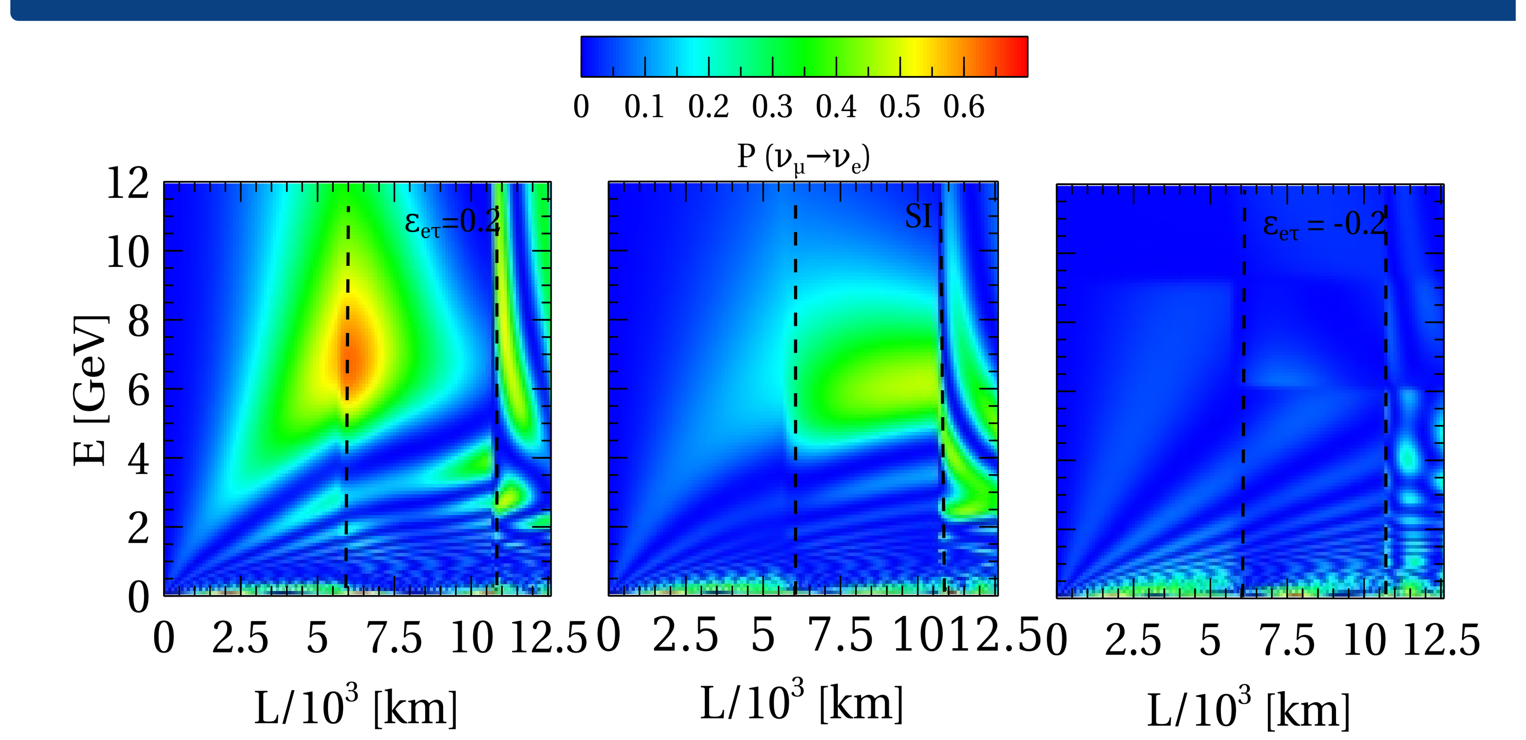
$$P^{NSI}_{\mu e} = \sin^2\theta^m_{23}\sin^2 2\theta^m_{13}\sin^2\frac{1.27\Delta m^2_{32,m}L}{E}$$

- Matter effect is maximmum when $E_{res}(\theta^m_{13} = 45^0)$ is equal to $E_{max} = \frac{1.27\times(\Delta m^2_{32})^m L}{(2p+1)\pi/2}$, p=0,1. After some simplification, we get:

$$(\rho L)^{max} = \frac{5.17\cdot(2n+1)\pi\cdot 10^3}{\tan 2\theta_{13}} \cdot \frac{1}{\underbrace{[1 - \frac{1}{2}(\beta+\gamma+2\varepsilon_{\mu\tau})] + [\sqrt{2}(\varepsilon_{e\mu}+\varepsilon_{e\tau})/\tan 2\theta_{13}]}_{\text{NSIs corrections}}}\,\text{km}\frac{\text{g}}{\text{cm}^3}$$



$\nu_\mu \rightarrow \nu_e$ OSCILLOGRAMS WITH NSIs



SUMMARY AND CONCLUSION

- We observe that NSIs in 2-3 block($\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$, and $\varepsilon_{\mu\tau}$) only affect the running of θ_{23}. $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ has prominent impact on running of θ_{13} at the energy relevant to DUNE.
- We estimate the resonance energy (θ^m_{13}=$\pi/4$).
- Find out the required baseline length and neutrino energies to have maximal matter effect.