Nonstandard Interaction Effects in the Neutrino Propagation in DUNE

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Our Questions

- When DUNE neutrino beam crosses the Earth's crust and mantle, does the matter density distribution has any impact on the sensitivity for the measurements of the oscillation parameters?
- Can an interaction not described in the standard model interfere significantly with DUNE measurements, or can we find strong constraints on such interactions?

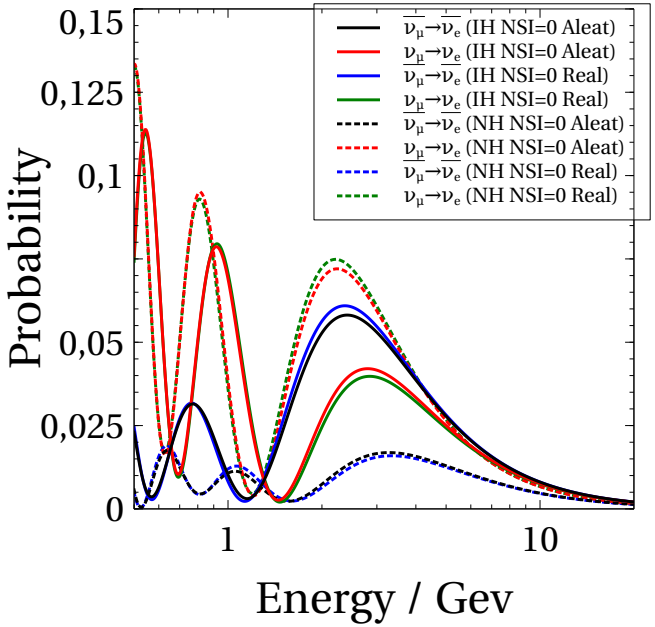
Hamiltonian for Oscillation with NSI

The Hamiltonian on the basis of flavor eigenstates, which describes the oscillations in three families is of the form

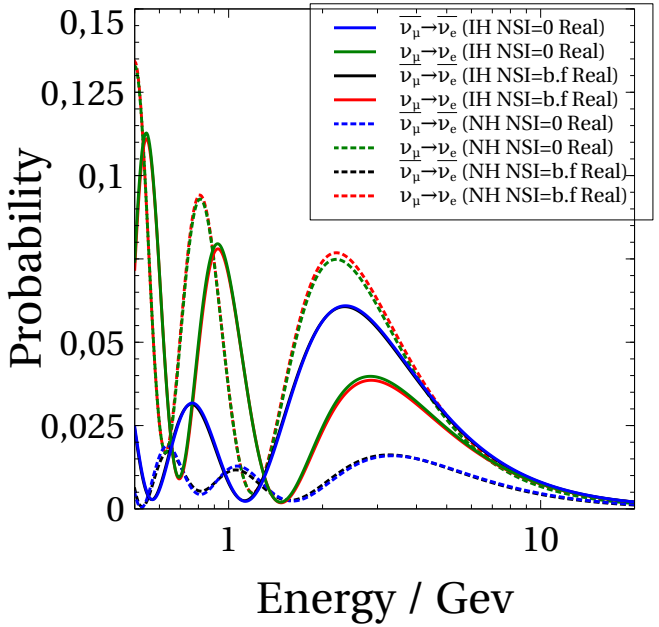
$$H = \underbrace{U \frac{1}{2E} \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger +}_{\text{Vacuum}}$$

$$\underbrace{\underbrace{+\sqrt{2} G_F N_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}}_{\text{Standard Interaction}} \underbrace{+\sqrt{2} G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} e^{i\phi_{e\mu}} & \varepsilon_{e\tau} e^{i\phi_{e\tau}} \\ \varepsilon_{e\mu} e^{-i\phi_{e\mu}} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \varepsilon_{e\tau} e^{-i\phi_{e\tau}} & \varepsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \varepsilon_{\tau\tau} \end{pmatrix}}_{\text{Nonstandard Interaction (NSI)}}}_{\text{Potential for interactions in matter}}$$

Probabilities for different matter density distributions



(a) Probabilities without NSI. The difference between constant and random variation of density in the maximum of probabilities is between 3.8% and 6.0%.



(b) Probabilities for constant density. The difference between the maximum of probabilities is between 0.4% and 3.0% considering NSI and SI.

Figure: Comparison between oscillation probabilities. (a) Constant and random variation of density. (b) Each probability curve is calculated with and without NSI for a constant matter density.

$\sin^2(\theta_{12}) = 0.306$
$\Delta m^2_{12} = 7.5 \cdot 10^{-5}\mathrm{eV}^2$
$\rightarrow$ Normal Hierarchy
$\sin^2(\theta_{13}) = 0.02166$
$\sin^2(\theta_{23}) = 0.441$
$\Delta m^2_{23} = 2.524 \cdot 10^{-3}\mathrm{eV}^2$
$\delta_{CP} = 261\pi/180$
$\varepsilon_{ee} = 0.144$
$\varepsilon_{e\mu} = -0.009$
$\varepsilon_{e\tau} = 0.027$
$\varepsilon_{\mu\tau} = 0.045$
$\varepsilon_{\tau\tau} = 0.022$
$\phi_{e\mu} = 1.85\pi$
$\phi_{e\tau} = 1.4\pi$
$\phi_{\mu\tau} = 1.5\pi$
$\rightarrow$ Inverted Hierarchy
$\sin^2(\theta_{13}) = 0002179$
$\sin^2(\theta_{23}) = 0.587$
$\Delta m^2_{23} = -2.514 \cdot 10^{-3}\mathrm{eV}^2$
$\delta_{CP} = 277\pi/180$
$\varepsilon_{ee} = 0.075$
$\varepsilon_{e\mu} = -0.01$
$\varepsilon_{e\tau} = 0.012$
$\varepsilon_{\mu\tau} = -0.036$
$\varepsilon_{\tau\tau} = -0.004$
$\phi_{e\mu} = 0.0$
$\phi_{e\tau} = 1.5\pi$
$\phi_{\mu\tau} = 0.5\pi$

Method

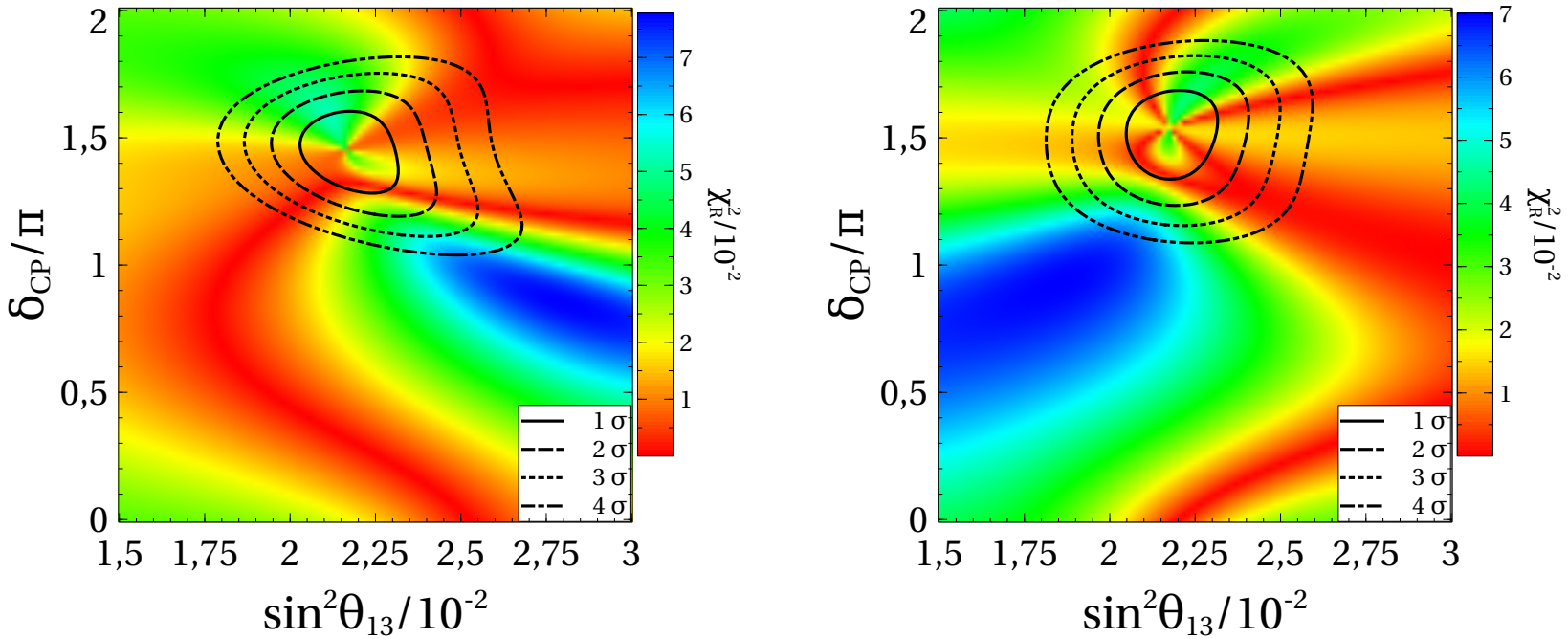
We show next the influence of mass hierarchy, matter density distribution, and nonstandard interactions on δ_{CP} and θ_{13} measurements.

- We compare the sensitivity between standard and nonstandard interactions. Except for δ_{CP} and θ_{13}, all the other standard oscillation parameters are fixed.
- To conduct the analysis we use a χ^2 method for Poisson distribution and compute a relative χ^2 defined as

$$\chi^2_R = \frac{\Delta\chi^2_{standard} - \Delta\chi^2_{analyzed}}{\Delta\chi^2_{standard} + 1} \,. \tag{1}$$

- We consider as systematics only errors in the oscillation channels.

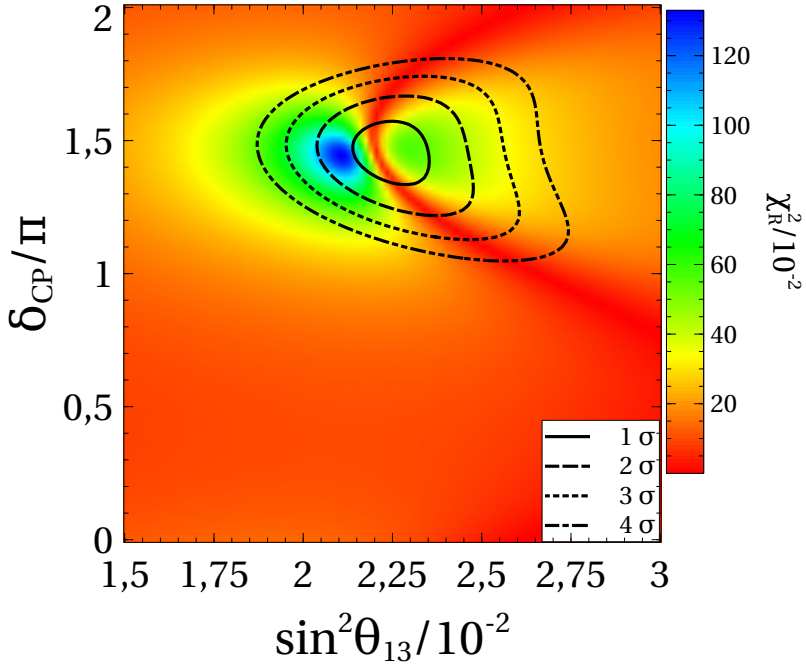
$\delta_{CP} \times \theta_{13}$ sensitivity without NSI



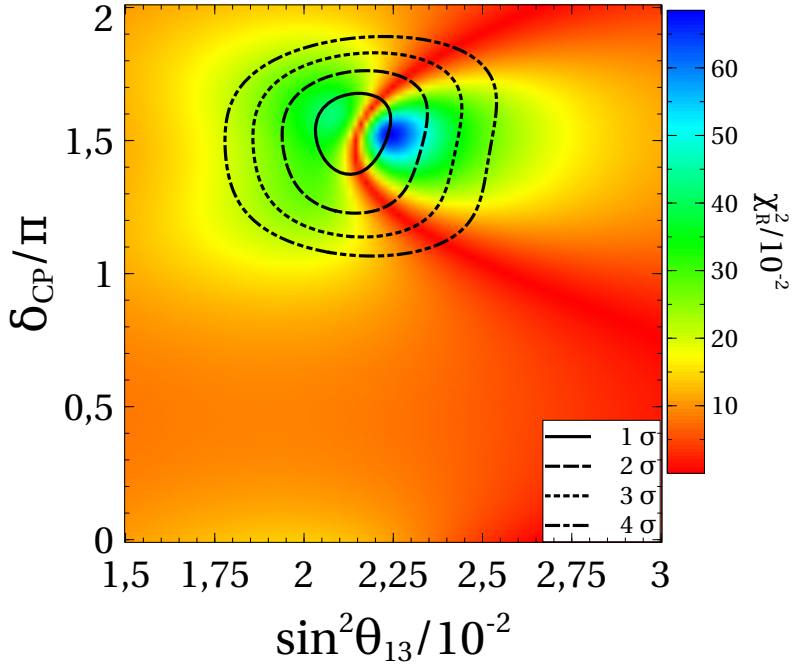
(a) Normal hierarchy. **(b)** Inverted hierarchy.

Figure: Sensitivity lines and color scale for the comparison between constant matter density and a random distribution of matter density, using the relative χ^2_R.

$\delta_{CP} \times \theta_{13}$ sensitivity with constant matter density



(a) Normal hierarchy. The extreme values of θ_{13}, considering 3σ, vary 2.9% and 4.0% for top and bottom regions respectively.



(b) Inverted hierarchy. The extreme values of θ_{13}, considering 3σ, vary 1.8% and 2.4% for top and bottom regions respectively.

Figure: Sensitivity lines and color scale for the comparison between NSI and SI using the relative χ^2_R.

Summary

- The density distribution of matter slightly changes the probability of oscillation and will not interfere significantly with the determination of the oscillation parameters.
- Our simulations with GLoBES indicate that DUNE is more sensitive to the presence of a nonstandard interactions than to the distribution of matter density along the beam line.
- The mass hierarchy is well determined if we use the present constraints on NSI.
- We are still conducting an analysis on how the NSI parameters can change the actual values of the oscillation parameters, if we consider the matter density variation at the same time.