PROCEEDINGS OF SCIENCE

The effect of dark non-standard interaction on the CP-phase measurement at DUNE.

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Several astronomical and cosmological observations confirmed that our universe is vastly composed of dark matter. When neutrinos propagate, they may interact with environmental dark matter particles, giving rise to rich phenomenology in oscillation experiments. When we consider dark matter to be a complex scalar field, the correction due to dark non-standard interaction (NSI) appears as a perturbation to the mass-squared term in the neutrino Hamiltonian. The correction for neutrinos and anti-neutrinos has the opposite sign, which introduces a CPT violation in neutrino oscillations. In this work, we have investigated the effect of dark NSI in the Deep Underground Neutrino Experiment (DUNE). The additional mixing parameters arising as a result of the dark NSI correction introduce degeneracies in the measurement of oscillation parameters. They may also act as additional sources of CP violation apart from the genuine Dirac CP phase. We have investigated the phenomenological consequences of dark NSI in neutrino oscillation and its effect on the CP violation sensitivity of the DUNE experiment.

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1. Introduction

The experimental discovery of the quantum mechanical phenomena of neutrino oscillations plays a pivotal role in particle physics by confirming neutrinos to be massive and thereby opening a portal of physics beyond the standard model (BSM). A large range of neutrino experiments worldwide have been involved in exploring this sector measuring the oscillations parameters with unprecedented accuracy. Despite this tremendous success, we are still left with some intriguing questions like the CP violation in the lepton sector, the quest for dark matter (DM) and dark energy, the baryon asymmetry, the origin and nature of neutrino mass etc. Several astronomical and cosmological studies have established that almost 70% of our universe is composed of DM, although we have no idea about the exact nature of it at present. Astronomical constraint suggests the DM density to be in the range $\rho_x \approx 0.3 - 0.4 GeV/cm^3$ [1] and its number density is inversely proportional to its mass. Therefore, if we consider the light DM ($\lesssim$ 100 GeV), there will be plenty of DM surrounding us. When neutrinos travel through such a DM background, we cannot disregard the possibility of neutrinos interacting with them, regarding DM as a fundamental particle. This non-standard interaction (NSI) of neutrinos with DM [2, 3], is termed dark NSI and it is expected to significantly impact neutrino oscillations phenomenology. This interesting coupling also opens the possibility of exploring dark matter through oscillation experiments. In this work, we have presented the effect of dark NSI on CP violation (CPV) sensitivity in the long baseline (LBL) experiment DUNE [4].

2. Dark NSI formalism

The light DM particles must be Bosons to account for the uncertainty principle. In our analysis, we will be considering light DM particle (ϕ) s represented by a complex scalar field, $\phi = |\phi| e^{i m_\phi t}$. The relevant Lagrangian for the interaction of neutrinos with a scalar DM particle having mass (m_ϕ) is [3],

$$-\mathcal{L}_{DNSI} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c., \tag{1}$$

where

- $\alpha, \beta = e, \mu, \tau$ are the ν flavors,
- $y_{\alpha\beta}$ is the Yukawa coupling between neutrinos and light DM particles, and,
- $M_{\alpha\beta}$ is the neutrino mass matrix.

While propagating through matter, both neutrinos and DM particles are present as real particles. The forward scattering between them introduces an extra potential, which has a concrete form as shown in equation 2.

$$\delta\Gamma_{\alpha\beta} \approx \sum_j y_{\alpha j} y^*_{j\beta} \frac{\rho_x}{m_\phi^2 E_\nu} \gamma_0. \tag{2}$$

with α, β are the flavor indices for the three active neutrino flavors.

The energy dependence of this term allows us to write the effective Hamiltonian as,

$$H_{DNSI} \approx \frac{M^2 \pm \delta M^2}{2E_\nu} \pm V_{SI}, \tag{3}$$

where $\delta M^2_{\alpha\beta} \equiv \mp \frac{2\rho_x}{m_\phi^2} \sum_j y_{\alpha j} y^*_{j\beta}$. Corrections for neutrinos and antineutrinos have complementary signs, which gives rise to an apparent CPT violation, that makes dark NSI even more interesting. Implementing parameterization similar to [5], we can express the dark NSI correction δM^2 as,

$$\delta M^2 = \Delta m^2_{31} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}, \tag{4}$$

where the $\eta_{\alpha\beta}$ are dimensionless parameters which quantify the strength of dark NSI.

3. Methodology

To study the effect of dark NSI on the sensitivity of DUNE, we have used GLoBES [6] and developed a framework by modifying the standard Hamiltonian to incorporate dark NSI effects. We have run the experiment for 5 years in neutrino mode and 5 years in antineutrino mode. The values of the standard oscillation parameters used are listed in table 1.

θ_{12}	θ_{13}	θ_{23}	δ_{CP}	Δm^2_{21} (eV^2)	Δm^2_{31} (eV^2)
$33.45°$	$8.62°$	$47°$	$-\pi/2$	7.54×10^{-5}	2.43×10^{-5}

Table 1: Benchmark values of standard oscillations parameters.

In order to study the CP violation sensitivity in the presence of dark NSI, we have defined the statistical χ^2 as

$$\chi^2 \equiv \min_{\eta} \sum_i \sum_j \frac{[N^{i,j}_{true} - N^{i,j}_{test}]^2}{N^{i,j}_{true}}, \tag{5}$$

where $N^{i,j}_{true}$ and $N^{i,j}_{test}$ are the number of true and test events in the i, j^{th} bins respectively.

4. Results and discussions

We have explored the effect of dark NSI, on neutrino oscillations at the probability level in the long baseline experiment DUNE. Then we investigated how the off-diagonal dark NSI parameters can impact the CP violation sensitivity of DUNE. The results are presented in the following subsections.

4.1 Effect of dark NSI on oscillation probabilities

The muon neutrino appearance probability ($P_{\mu e}$) as a function of neutrino energy is shown in figure 1 for the two off-diagonal parameters $\eta_{e\mu}$ and $\eta_{e\tau}$. The black line represents the standard case without NSI. The blue, cyan and green lines represent the cases with $\eta_{e\mu}$ and $\eta_{e\tau}$ being 0.01, 0.02

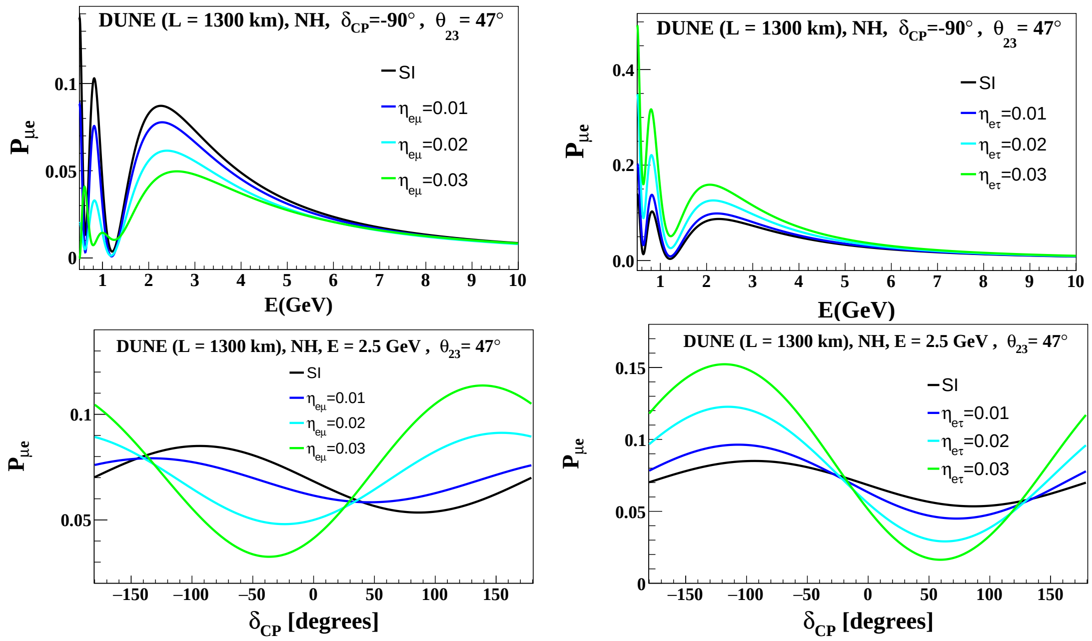

Figure 1: The effect of off-diagonal dark NSI parameters $\eta_{e\mu}$ (left–column) and $\eta_{e\tau}$ (right–panel) at DUNE. $P_{\mu e}$ is shown as a function of neutrino energy (top–panel) with $\delta_{CP} = -\pi/2$ and as a function of δ_{CP} (bottom–panel) with E=2.5 GeV.

and 0.03 respectively. The phase term associated with dark NSI ($\phi_{\alpha\beta}$) is considered to be zero here. We have seen that, for $\eta_{e\mu}$ oscillations probability got more and more suppressed with increasing value of the moduli of the dark NSI term (left –panel). However, $\eta_{e\tau}$ enhances the oscillation probabilities. With increasing moduli values of the dark NSI term probability gets enhanced more. There is also degeneracy in oscillations probability for different sets of δ_{CP}, which may hinder the sensitivities towards CP phase measurement at DUNE.

4.2 Effect on CP–violation sensitivity

In figure 2, we have shown the CP violation sensitivity of DUNE in the presence of the off-diagonal dark NSI term ($\eta_{e\mu}$ = 0.01 (left–panel, 0.03 (middle–panel) and 0.05 (right–panel)) and compare it with the SI case. For, $\phi_{e\mu} = 0$, the sensitivity deteriorates for $\eta_{e\mu} = 0.01$ and 0.03. However, for $\eta_{e\mu} = 0.05$, a nominal effect is observed. Including the phase term, ($\phi_{e\mu} \in [-\pi, \pi]$) broadens the sensitivity region. For different combinations of moduli and phases of $\eta_{e\mu}$, sensitivity can deteriorate in some cases and enhance in others.

In figure 3, the CPV-sensitivity of DUNE for both SI and in presence of dark NSI is shown. The moduli of the dark NSI term $\eta_{e\tau}$ mostly enhance the sensitivity. However, for $\eta_{e\tau}$= 0.01 the SI and NSI sensitivity curves almost overlap. For this particular case, even the presence of the phase term can't enhance the sensitivity. For $\eta_{e\tau}$=0.03 sensitivity can either increase or decrease for particular combinations of the moduli and the phase term. Whereas, for $\eta_{e\tau}$=0.05 the sensitivity received significant enhancement than SI.

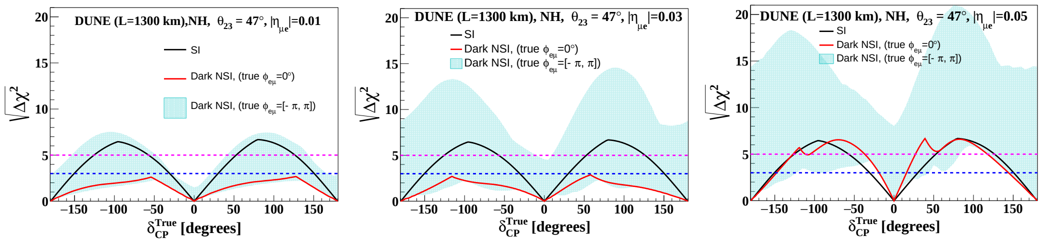

Figure 2: The CP-violation sensitivity of DUNE in the presence of the off-diagonal dark NSI parameter $\eta_{e\mu}$. The black solid line represents the standard case without dark NSI. The moduli and phases are varied as indicated in the legends.

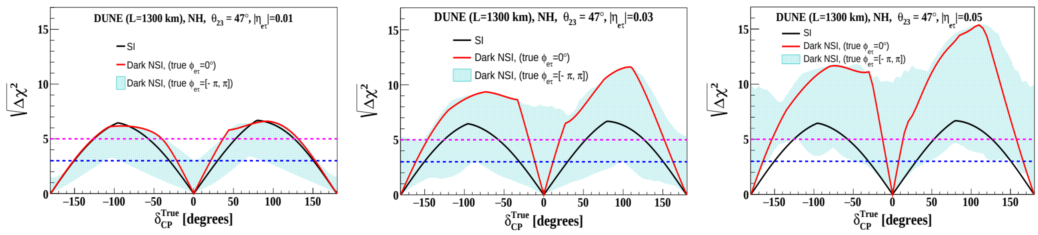

Figure 3: The CP-violation sensitivity of DUNE in the presence of the off-diagonal dark NSI parameter $\eta_{e\tau}$. The black solid line represents the standard case without dark NSI. The moduli and phases are varied as indicated in the legends.

5. Summary and conclusion

In this precision era of neutrino oscillations experiments, it is extremely important that we take into account the subdominant non-standard effects that may affect the precision measurement. Dark matter is an abundant particle in the environment that can couple with neutrinos and this dark NSI can have a notable impact on neutrino oscillations. We have observed that the presence of dark NSI can significantly affect the oscillation probabilities as well as the sensitivity towards CP-phase measurements at DUNE.

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References

[1] P. F. de Salas, K. Malhan, K. Freese, K. Hattori, and M. Valluri, "On the estimation of the local dark matter density using the rotation curve of the milky way," *Journal of Cosmology and Astroparticle Physics*, vol. 2019, no. 10, p. 037, 2019.

[2] A. Berlin, “Neutrino Oscillations as a Probe of Light Scalar Dark Matter,” *Phys. Rev. Lett.*, vol. 117, no. 23, p. 231801, 2016.

[3] S.-F. Ge and H. Murayama, “Apparent CPT Violation in Neutrino Oscillation from Dark Non-Standard Interactions,” 4 2019.

[4] B. Abi *et al.*, “Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics,” 2 2020.

[5] A. Medhi, D. Dutta, and M. M. Devi, “Exploring the effects of scalar non standard interactions on the CP violation sensitivity at DUNE,” *JHEP*, vol. 06, p. 129, 2022.

[6] P. Huber, M. Lindner, and W. Winter, “Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator),” *Comput. Phys. Commun.*, vol. 167, p. 195, 2005.