



Can Violation Of Equivalence Principle Be Probed At DUNE?

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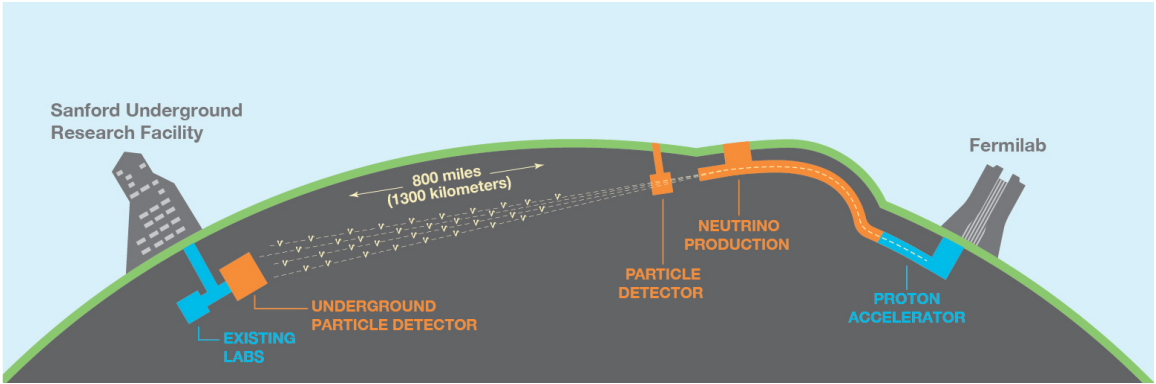
The Deep Underground Neutrino Experiment (DUNE)



DUNE: Experimental Overview

- **Baseline:** 1300 km distance from Fermilab to SURF (South Dakota).
- **Detector:** Liquid Argon (LArTPC) detectors to capture highly detailed particle tracks.
- **Beam:** An adjustable wide-band neutrino beam.
- **Flux Profile:** A Low-Energy (LE) setup, where most neutrinos are around $E_\nu \approx 2.5\,\mathrm{GeV}$.
- **Goal:** Study how gravity affects neutrino mixing, alongside standard mass effects, right where the mixing is strongest.

Neutrino Propagation under VEP

- Under VEP, different neutrino states may feel slightly different gravitational pulls:

$$G_N^{(i)} = \gamma_i G_N \quad \text{or} \quad \Phi_i = \gamma_i \Phi$$

- Total energy of the i-th neutrino state at high speeds:

$$E_i \simeq E + \frac{m_i^2}{2E} + 2E\gamma_i\Phi$$

- Effective Hamiltonian in the flavor basis $\Psi_F = (\nu_e, \nu_\mu, \nu_\tau)^T$:

$$\mathcal{H}_F = \frac{1}{2E}\left[U_{\rm PMNS}\mathbb{M}^2 U_{\rm PMNS}^\dagger + \mathbb{V} + \mathbb{A}\right]$$

The Gravitational Mixing Matrix & Potential

- VEP potential $\mathbb{V}$ introduces new mixing parameters from coupling differences $(\Delta\gamma_{21}, \Delta\gamma_{31})$:

$$\mathbb{V} = U_G \begin{pmatrix} 0 & 0 & 0 \\ 0 & t_1 & 0 \\ 0 & 0 & t_2 \end{pmatrix} U_G^\dagger$$

- Magnitude scales:

$$t_1 = 4E^2\Phi\Delta\gamma_{21}, \qquad t_2 = 4E^2\Phi\Delta\gamma_{31}$$

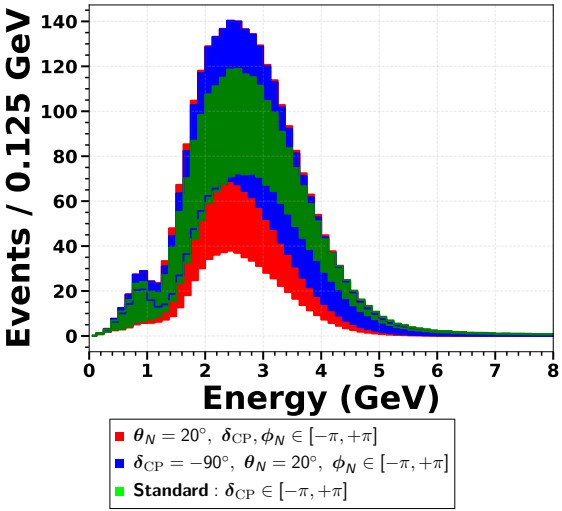
- The gravitational mixing matrix U_G in the (2,3) sector is defined by:
  - θ_N**:** A new gravitational mixing angle.
  - ϕ_N**:** A new gravitational phase.

Energy Scaling & The LE Flux Advantage

- **Standard Mass Contribution ($\mathbb{M}^2$):** Scales inversely with energy ($\propto 1/E$).
- **VEP Contribution ($\mathbb{V}$):** Scales linearly with energy ($\propto E$).

- **Why the Low-Energy (LE) Beam?**
  - Standard CP effects are strongest near $E \sim 2.5\,\mathrm{GeV}$.
  - At higher energies, the VEP term takes over and hides the interference.
  - The LE beam allows us to clearly see the mixing between the standard (δ_{CP}) and exotic (ϕ_N) phases.

Event Envelopes: CP-Phase Degeneracy

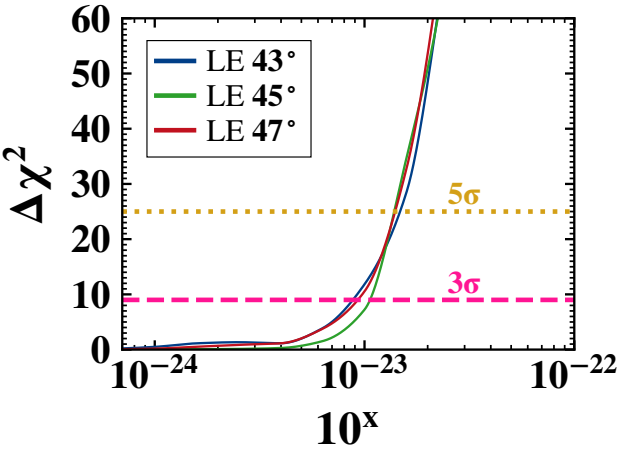


- **Standard CP (Green):** Most events happen near $2.5\,\mathrm{GeV}$ ($\sim$ 65–120 events/bin).
- **Exotic Phase ϕ_N (Blue):** Pushes the maximum number of events higher.
- **Both Phases (Red):** Cancellation drops the minimum number of events down to $\sim$ 38 per bin.
- **Takeaway:** Just counting the total events is not enough to separate the phases; we must look at the whole energy spectrum.

Simulation Framework & Statistical Methodology

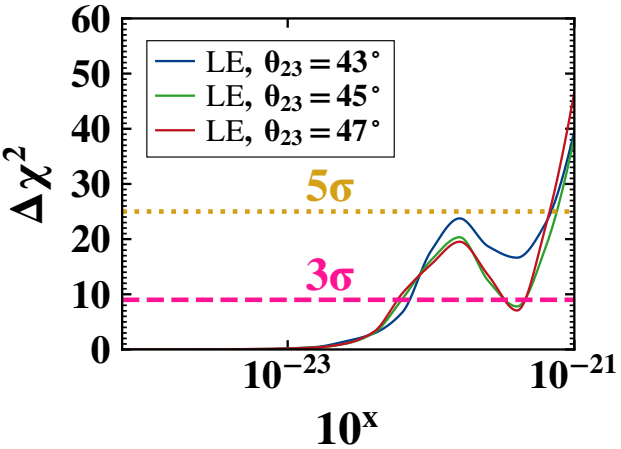
- **Simulation Tool:** We use GLoBES to calculate oscillation probabilities and event rates.
- **Statistical Fit:** We compute $\Delta\chi^2$ to compare the VEP model against standard oscillations.
- **Accounting for Uncertainties:** We minimize $\Delta\chi^2$ by varying over:
  - Standard oscillation parameters within their allowed ranges.
  - New VEP parameters (θ_N, ϕ_N).
- **Octant Check:** We test three values of the atmospheric angle θ_{23}: lower (43°), maximal (45°), and upper (47°) octants.

1D Sensitivity Analysis: Octant Dependence (LE Flux)



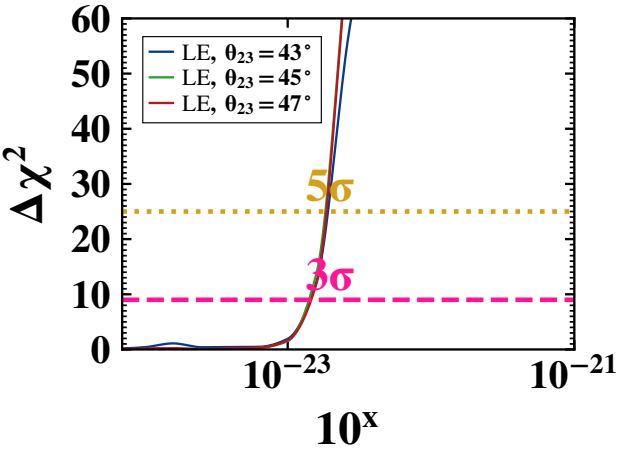
- **Lower Octant ($\theta_{23} = 43°$):** The $\Delta\chi^2$ curve rises sharply, hitting a 3σ limit at a VEP scale of 1.0×10^{-23}.
- **Maximal & Upper Octants:** For $\theta_{23} = 45°$ and $47°$, the LE beam reaches 3σ limits near 1.2×10^{-23} and 5σ levels near 1.5×10^{-23}.
- **Consistency:** The LE setup stays sensitive to VEP across all of these different mixing scenarios.

Individual Channels: Appearance ($\nu_\mu \to \nu_e$)



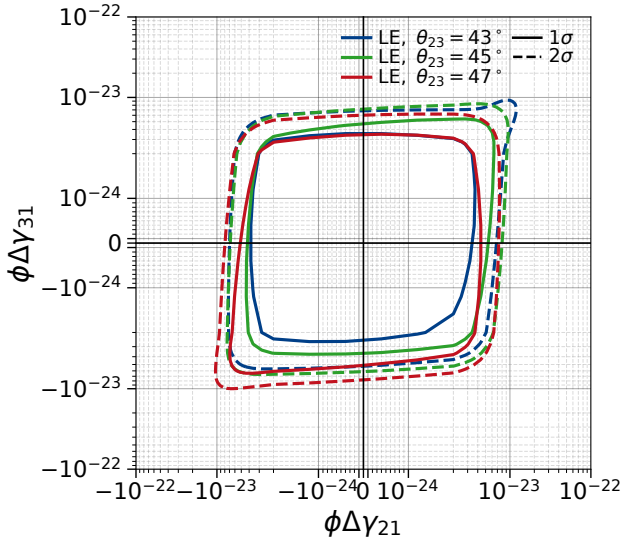
- **Phase Sensitivity:** This channel depends heavily on the mixing phases ($\delta_{\rm CP}$ and ϕ_N).
- **Degeneracy Effects:** The curves split apart for different octants and show dips because of mixed parameter effects ($\sim 10^{-22}$).
- **Role:** While it struggles to set a strict lower bound alone, the appearance channel is essential because it helps us separate the phases.

Individual Channels: Disappearance ($\nu_\mu \to \nu_\mu$)



- **Steady Bound:** Shows a smooth, steady rise to a 3σ limit at 1.0×10^{-23}.
- **Octant Independence:** It is completely unaffected by the octant (notice how all three curves perfectly overlap).
- **Takeaway:** The disappearance channel acts as the anchor—it limits the overall size of VEP, which we then combine with the appearance data.

2D Parameter Space: Full Combined DUNE Analysis



- **Breaking Degeneracy:** Combining both channels joins the strong scale limit from disappearance with the phase information from appearance.
- **Sensitivity Limits:** For the upper octant ($\theta_{23} = 47^\circ$), the setup gives 1σ and 2σ contours, reaching $|\phi\Delta\gamma_{21}| \lesssim 8 \times 10^{-24}$ and $|\phi\Delta\gamma_{31}| \lesssim 6 \times 10^{-24}$ (at 1σ).
- **Implication:** The LE beam limits the possible parameter values to a small, distinct area.

Summary & Conclusions

- **Testing Symmetries:** Long-baseline experiments are great tools for studying fundamental spacetime symmetries.
- **LE Beam Benefit:** The Low-Energy (LE) flux makes it much easier to separate the energy-dependent VEP effects.
- **Combining Channels:** We need to use both appearance and disappearance channels together to solve parameter degeneracies.
- **DUNE Sensitivity:** This approach shows that DUNE can limit equivalence principle violations down to $\mathcal{O}(10^{-24})$.

Thank You!