Long-range interactions in neutrino oscillations

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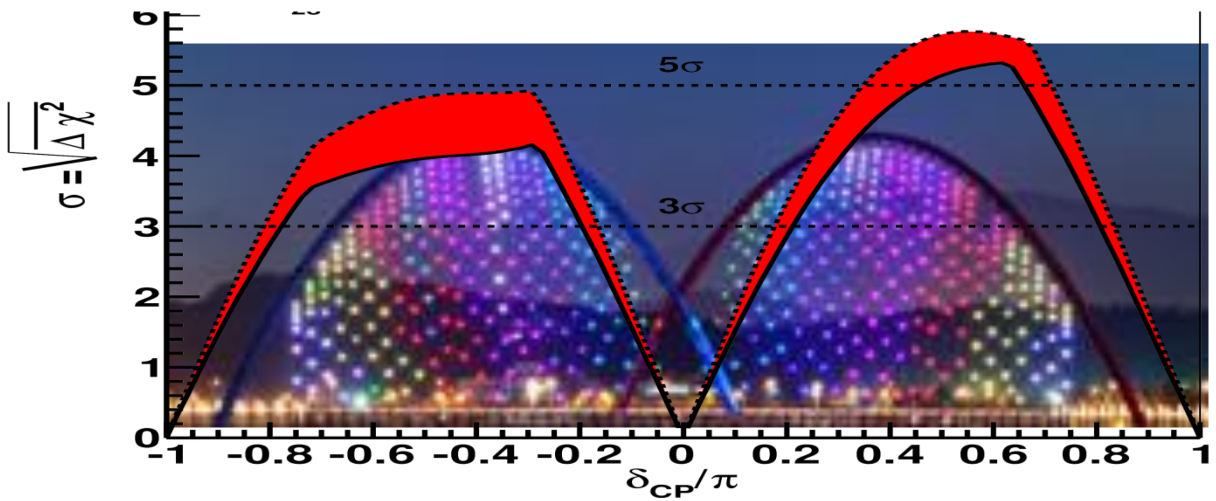
Neutrino oscillations today

- The three-flavour neutrino oscillation framework has been experimentally verified to a very high degree of precision
- Solar, KamLAND: θ_{12}, Δm^2_{21}
- Atmospheric, long-baseline: θ_{23}, $|\Delta m^2_{31}|$
- Reactor: θ_{13}
- NOvA, T2K data: Preference for normal hierarchy, δ_{CP}= -90°.



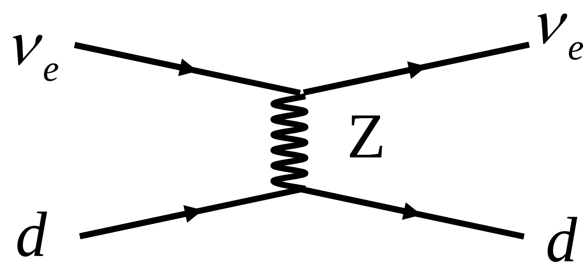
CP Violation discovery sensitivity: DUNE Conceptual Design Report

- Next gen expts like DUNE expected to measure the mass hierarchy and δ_{CP}.

New physics effects

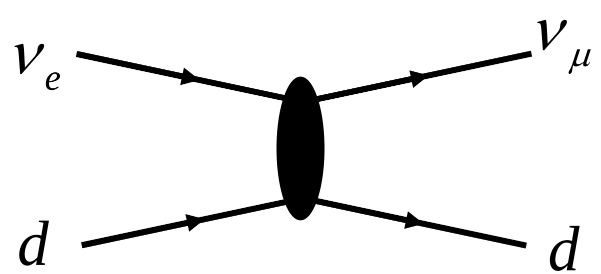
- Extra sterile states
- Non-unitary mixing
- New interactions

- In the Standard Model,



$$\mathcal{L}_{NC} = (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma_\mu P_L f') \sim G_F$$

- With new physics, we could have a flavour violating interaction, modifying the neutrino propagation Hamiltonian



$$\mathcal{L}_{NC} = (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f') \sim \varepsilon_{\alpha\beta} G_F$$

Long-range interactions (LRIs)

- Introduce an anomaly-free $U(1)_X$ extension of the Standard Model, for eg. X = B-L, L_e-L_μ, etc. with gauge boson Z' and fine-structure constant α'.
    - Flavour diagonal but not universal

Joshipura, Mohanty: 0310210

- A very light Z' makes the range of the interaction of terrestrial/astronomical scale
- For example, if $m_{Z'} < 10^{-18}$ eV, the range is > 1 A.U. Neutrino oscillations on earth will then be affected by a potential sourced by the electrons and quarks in the sun

- Q1: Can long-baseline experiments like DUNE constrain LRIs?
- Q2: Will CP measurement at DUNE be affected by affected by the presence of LRIs?

Outline

- General formalism of neutrino oscillations in the presence of LRIs
- Measuring CP violation in the presence of LRIs
- Constraints on LRIs from long-baseline neutrino oscillation experiments

[with Hooman Davoudiasl, Hye-Sung Lee, William J. Marciano]

General LRI formalism

- Most general anomaly-free combination:

$$\eta(B-L)+\beta(L_e-L_\mu)+\gamma(L_\mu-L_\tau)+\delta(L_\tau-L_e)$$

$$\equiv p_0 B+p_1 L_e+p_2 L_\mu+p_3 L_\tau$$

- Potential at earth because of matter in the sun and earth:

$$V^{\odot}=\frac{\alpha' N_N^{\odot}}{R_{ES}}(p_0+p_1 Y_e^{\odot})\ , \quad V^{\oplus}=\frac{\alpha' N_N^{\oplus}}{R_E}(p_0+p_1 Y_e^{\oplus})\ , \quad V_{LR}=V^{\odot}+V^{\oplus}$$

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- The neutrino propagation Hamiltonian is

$$\begin{bmatrix} V_{\rm MSW} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} p_1 V_{\rm LR} & 0 & 0 \\ 0 & p_2 V_{\rm LR} & 0 \\ 0 & 0 & p_3 V_{\rm LR} \end{bmatrix} = \frac{\Delta m^2_{31}}{2E} \left\{ \begin{bmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} p & 0 & 0 \\ 0 & \xi/2 & 0 \\ 0 & 0 & -\xi/2 \end{bmatrix} \right\}$$

$$A \equiv 2EV_{\rm MSW}/\Delta m^2_{31} \qquad p = 2E(p_1 - \frac{p_2+p_3}{2})V_{\rm LR}/\Delta m^2_{31} \qquad \xi = 2E(p_2-p_3)V_{\rm LR}/\Delta m^2_{31}$$

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- Potential at earth because of matter in the sun and earth:

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Probability formula

We derived an analytic formula for the oscillation probability $P_{\mu e}$ as a perturbative expansion in the small parameters $r = \Delta m^2_{21} / \Delta m^2_{31}$ and $\sin\theta_{13}$

$$P_{\mu e} \approx \frac{P_1 Q_1 + P_2 Q_2 + P_3 Q_3}{\omega^2\, \omega_+^2\, \omega_-^2}$$

$$P_1 \equiv 4 \sin^2\theta_{13} \sin^2\theta_{23}$$
$$P_2 \equiv 2r \sin\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$
$$P_3 \equiv r^2 \sin^2 2\theta_{12} \cos^2\theta_{23}$$

$$\Delta \equiv \Delta m^2_{31} L / 4E$$

$$\omega \equiv \sqrt{1 + \xi^2 - 2\xi \cos 2\theta_{23}}$$
$$\omega_\pm \equiv \omega \pm (1 - 2B)$$
$$B \equiv A + p$$

$$Q_1 = -4\xi\omega_+\omega_- \cos^2\theta_{23} \sin^2(\omega\Delta) + 2\omega\omega_-(\xi + 2B)(\omega + \xi + 1) \sin^2\left(\frac{\omega_+}{2}\Delta\right) - 2\omega\omega_+(\xi + 2B)(\omega - \xi - 1) \sin^2\left(\frac{\omega_-}{2}\Delta\right) ,$$

$$Q_2 = \omega_-^2 \left[(\omega + \xi)^2 - 1\right] \cos\delta_{CP} \sin^2\left(\frac{\omega_+}{2}\Delta\right) + \omega_+^2 \left[(\omega - \xi)^2 - 1\right] \cos\delta_{CP} \sin^2\left(\frac{\omega_-}{2}\Delta\right) + 2\omega_+\omega_- \left\{(\omega^2 - \xi^2 + 1) \cos\delta_{CP} \cos(\omega\Delta) - 2\omega \sin\delta_{CP} \sin(\omega\Delta)\right\} \sin(\omega_+\Delta) \sin(\omega_-\Delta) ,$$

$$Q_3 = 4\xi\omega_+\omega_- \sin^2\theta_{23} \sin^2(\omega\Delta) + 2\omega\omega_- \left[\xi - 2(1 - B)\right] (\omega + \xi - 1) \sin^2\left(\frac{\omega_+}{2}\Delta\right) - 2\omega\omega_+ \left[\xi - 2(1 - B)\right] (\omega - \xi + 1) \sin^2\left(\frac{\omega_-}{2}\Delta\right) .$$

Probability formula

- There are now three sources of CP violation: intrinsic δ_{CP}, 'normal' MSW matter effect and LRIs

- If we assume that LRIs are small in nature and expand this formula up to second order in ξ, the resulting expression is simply the standard oscillation probability with the replacement A → A+p=B, i.e. just a shift in the MSW potential

$$P_{\mu e} \approx P_1 \frac{\sin^2([1-B]\Delta)}{(1-B)^2} + P_2 \cos(\Delta + \delta_{CP}) \frac{\sin(B\Delta)}{B} \frac{\sin([1-B]\Delta)}{1-B}$$

- Can a future experiment like DUNE distinguish between intrinsic CP violation and that induced by LRIs? We use the CP asymmetry to check this

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

Details of our LRI

- As a concrete example, we consider the L_e-L_τ gauge group
- Bounds from black hole super-radiance and neutrino decay lifetime disfavour ultralight vector bosons with mass around 1/A.U.

Baryakhtar, Lasenby, Teo: 1704.05081

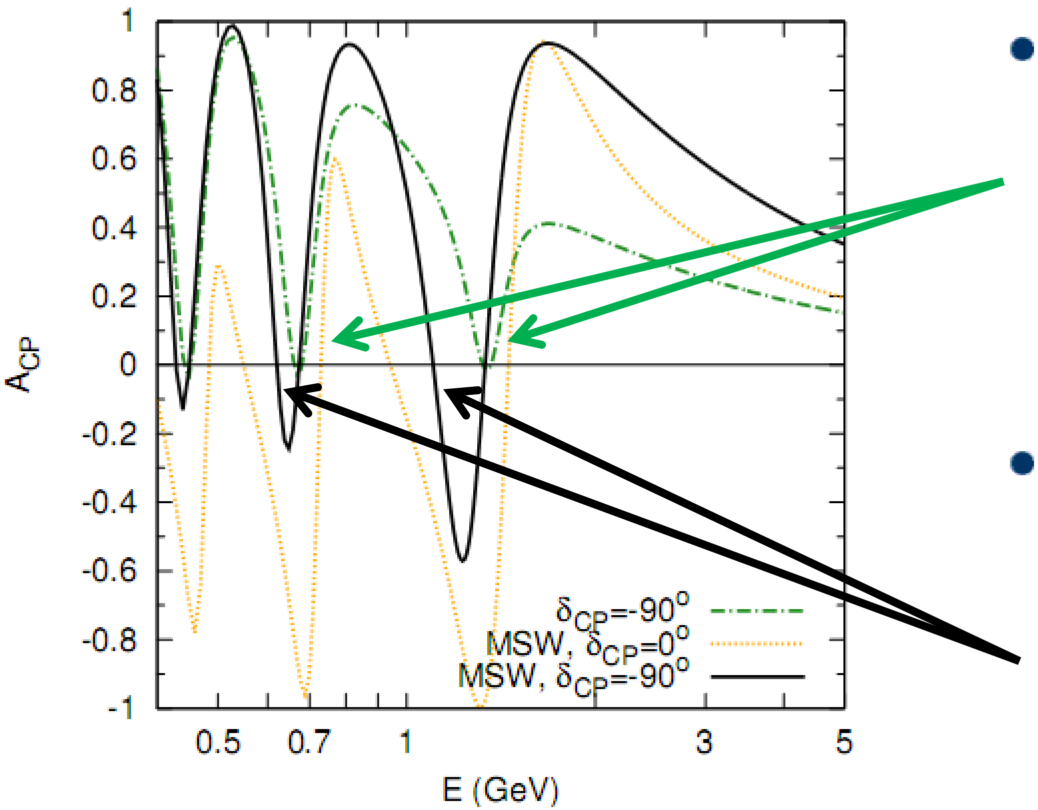
- We assume the $m_{Z'}$ range to be 10^{-14}-10^{-16} eV, or the range to be around 10^6-10^8 km. Thus all the electrons in the earth contribute to the LRI potential, but those in the sun do not
- Best upper bound on the coupling α' in this range are from tests of the equivalence principle, at around 10^{-49}.

Jeong, Kim, Lee: 1512.03179

- The range of α' that can be probed by GeV-scale oscillation experiments is around 10^{-51}-10^{-53}.

CP asymmetry

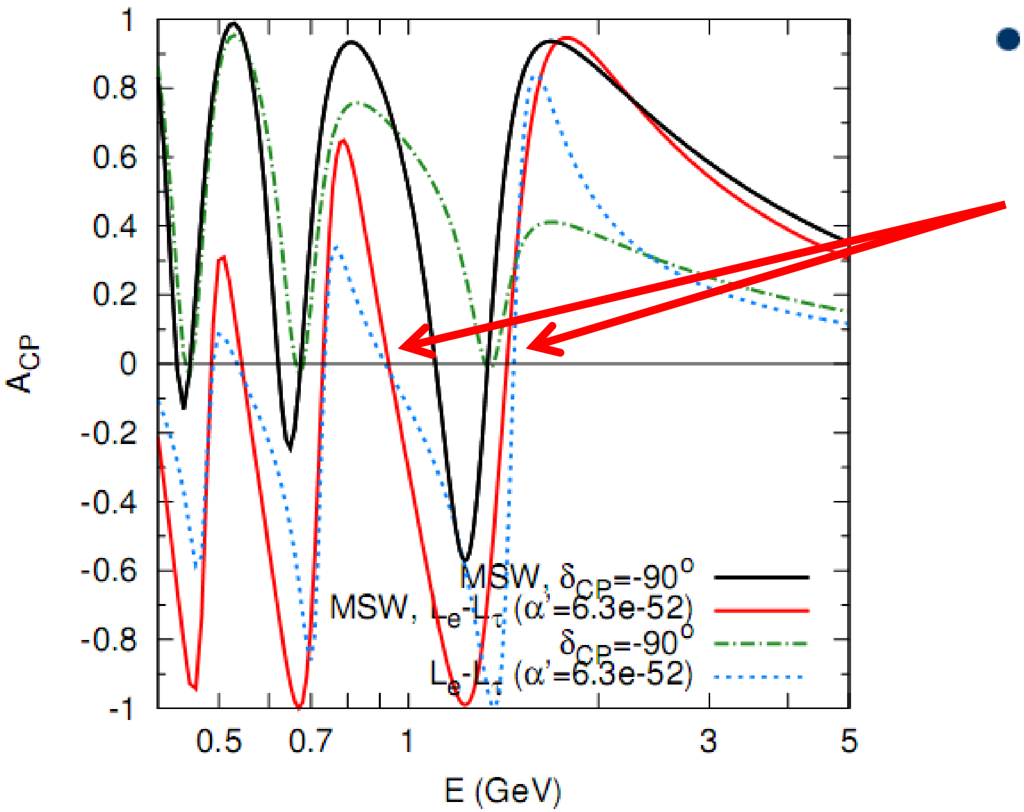
A_{CP}: standard oscillations



- For only δ_{CP} and no matter effect, A_{CP} is zero when $\Delta=n\pi$, independent of the value of δ_{CP} itself
- For δ_{CP} along with matter effect, every alternate zero of A_{CP} occurs at an energy depending on the value of δ_{CP}

CP asymmetry

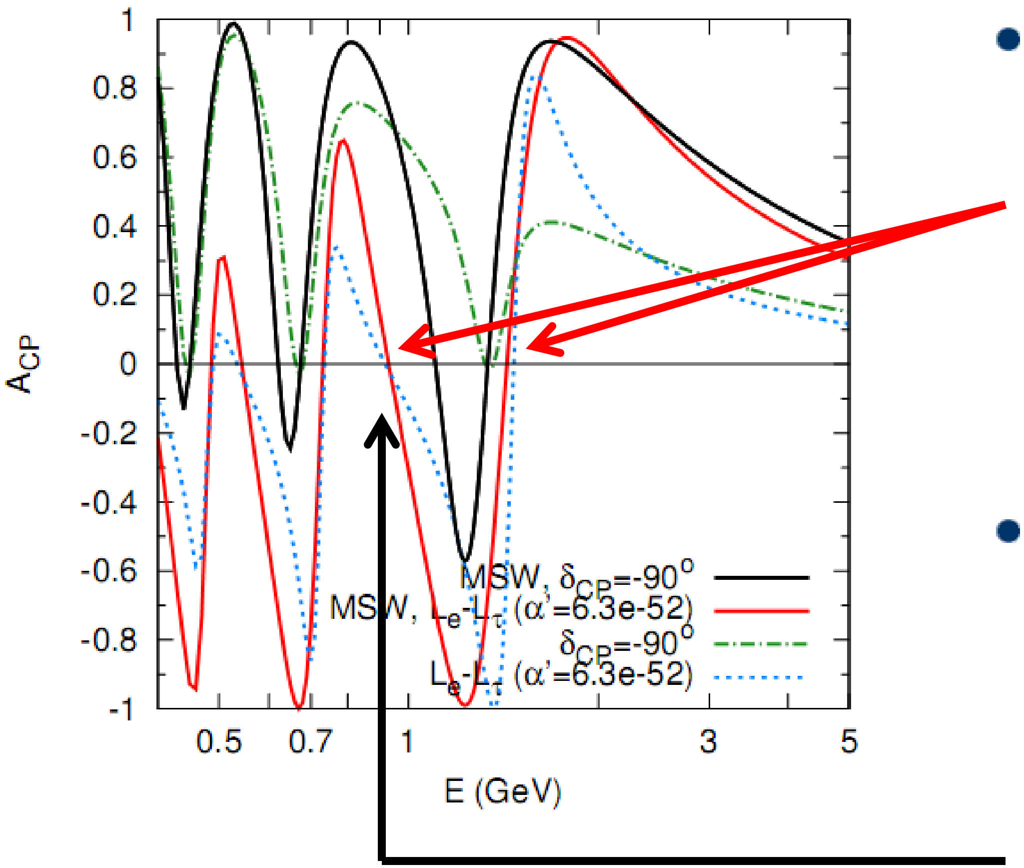
A_{CP}: in the presence of LRIs



- When CP violation is induced by LRIs instead of δ_{CP}, the zeros of A_{CP} are found to be independent of the matter effects or LRIs

CP asymmetry

A_{CP}: in the presence of LRIs



- When CP violation is induced by LRIs instead of δ_{CP}, the zeros of A_{CP} are found to be independent of the matter effects or LRIs
- Around 0.9 GeV the asymmetry induced by δ_{CP} is large while that due to LRIs is small. This can be used to distinguish between the two scenarios

Statistical analysis (F.O.M.)

- We choose for DUNE a total exposure of 300 kt-MW-yr, divided into 1.75 yrs (neutrino) + 5.25 yrs (antineutrino)

- We use the statistical figure of merit (F.O.M.) defined as

$$F.O.M. = (A_{CP} / \delta(A_{CP}))^2 = A_{CP}^2 N_{tot} / (1 - A_{CP}^2)$$

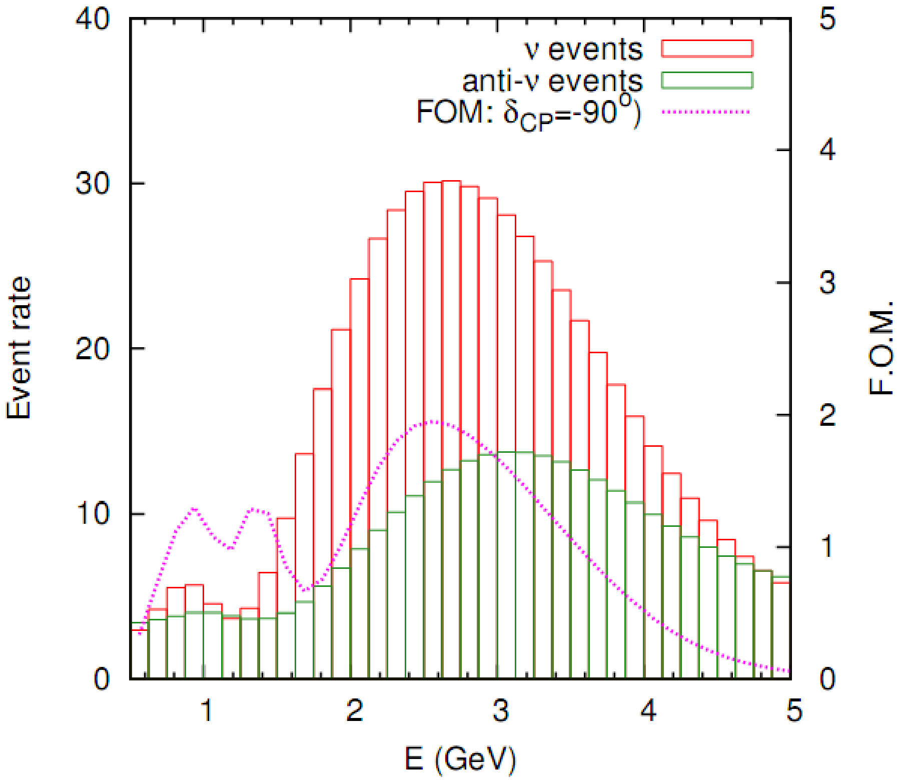
$$\text{with} \quad N_{tot} = N + \bar{N} \quad , \quad A_{CP} = \frac{N - r\bar{N}}{N + r\bar{N}}$$

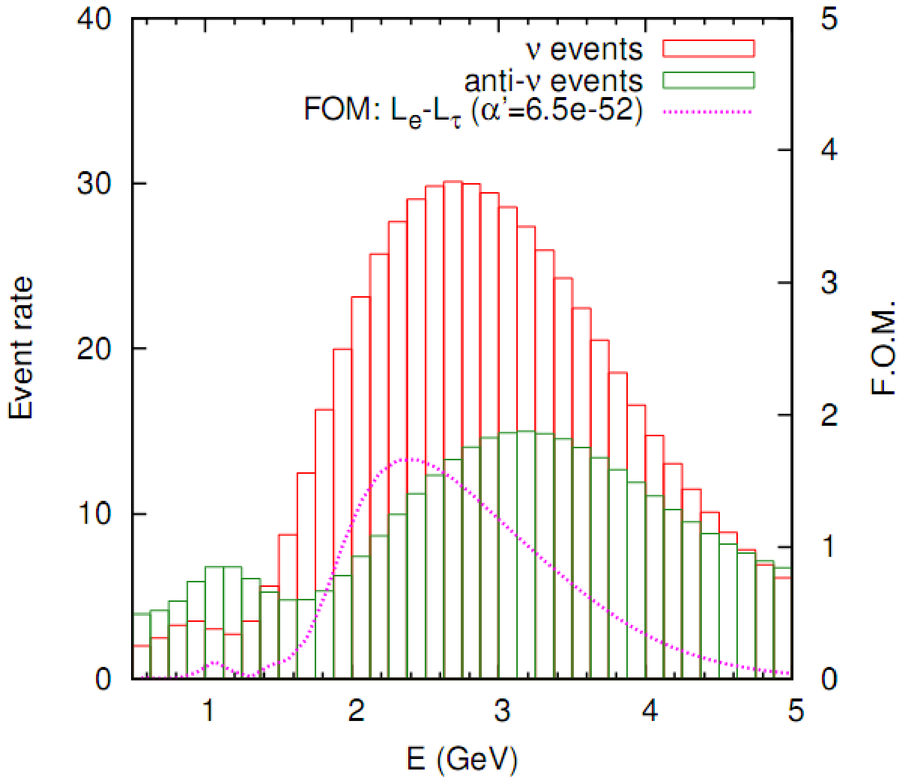
Marciano: 0108181

- The number r is the ratio of (simulated) neutrino:antineutrino events with only matter effect (no δ_{CP}, no LRI). By using this definition, the effect of matter is 'factored out', leaving only asymmetry due to δ_{CP} or LRI

Statistical analysis (F.O.M.)

Event spectrum and F.O.M. for (a) δ_{CP} induced CPV and (b) LRI induced CPV





Additional low energy data from (a) DUNE setup optimized for low energy, or (b) low energy experiment like T2HK will further enhance our sensitivity

Distinguishing 'real' from 'fake' CP

- Our F.O.M. analysis shows that the low energy region (sub-GeV) can be used to distinguish between LRIs and intrinsic δ_{CP}
- Optimize DUNE beam for more low energy flux? Low energy off-axis detector?

- Synergy with low energy experiments: The value of δ_{CP} and θ_{23} measured at DUNE will deviate from those measured at low energy experiments like T2HK, indicative of new physics

Bounds from ν_μ disappearance

- Effect of LRIs at NOvA > Effect of LRIs at T2K

$$\sin^2 2\tilde{\theta}_{23} = \frac{\sin^2 2\theta_{23}}{(\xi - \cos 2\theta_{23})^2 + \sin^2 2\theta_{23}}$$

- If LRIs are sizeable, the effective value of θ_{23} measured by NOvA should deviate from maximal mixing

- NOvA sees a deviation, but is still compatible with T2K, consistent with maximal mixing

- We obtain the bound $\alpha' < 2.1 \times 10^{-51}$ from a χ^2 analysis of the NOvA+T2K data
- DUNE can constrain it further by an order of magnitude

Bounds from NSI analyses

- Note similarity with non-standard interactions (NSIs) in matter

LRI potential:

$$\begin{bmatrix} V_{\rm MSW} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} p_1 V_{\rm LR} & 0 & 0 \\ 0 & p_2 V_{\rm LR} & 0 \\ 0 & 0 & p_3 V_{\rm LR} \end{bmatrix}$$

NSI potential:

$$\sqrt{2} G_F n_e \left\{ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{bmatrix} \right\}$$

$$\varepsilon_{ee} = \frac{p_1 V_{LR}}{\sqrt{2} G_F n_e} \, , \; \varepsilon_{\mu\mu} = \frac{p_2 V_{LR}}{\sqrt{2} G_F n_e} \, , \; \varepsilon_{\tau\tau} = \frac{p_3 V_{LR}}{\sqrt{2} G_F n_e}$$

$$\text{and } \varepsilon_{\alpha\beta} = 0 \text{ for } \alpha \neq \beta \; .$$

Bounds from NSI analyses

ϵ_{ee}^{eL}	$[-0.021, 0.052]$	solar + KamLAND
ϵ_{ee}^{eR}	$[-0.07, 0.08]$	TEXONO
$\epsilon_{\mu\mu}^{eL}$, $\epsilon_{\mu\mu}^{eR}$	$[-0.03, 0.03]$	reactor + accelerator
$\epsilon_{\tau\tau}^{eL}$	$[-0.12, 0.06]$	solar + KamLAND
$\epsilon_{\tau\tau}^{eR}$	$[-0.98, 0.23]$ [-0.25, 0.43]	solar + KamLAND and Borexino reactor + accelerator
$\epsilon_{\tau\tau}^{eV}$	$[-0.11, 0.11]$	atmospheric

90% C.L. bounds on NSI parameters: 1710.09360

A naive translation of the NSI bound $\varepsilon_{ee} < 0.1$ gives $\alpha' < 1.9 \times 10^{-51}$

Caveats: The correspondence between bounds on NSIs and LRIs is not exact.

- Two-flavour vs three-flavour analyses
- Number of non-zero diagonal NSIs

Summary

- Long-range interactions can arise out of U(1) extensions of the Standard Model with very light Z'
- We consider the L_e-L_τ model, with range around 10^6-10^8 km, making the earth the source of the potential. The coupling α' is currently constrained to be less than $\mathcal{O}(10^{-49})$
- We have derived the analytic formula for the $P_{\mu e}$ oscillation probability. The formula exact in LRI parameters is complicated, but when expanded up to second order in them, it reduces to the standard oscillation formula with a shift of the MSW potential
- The CP asymmetry can be a useful tool in measuring CP violation induced by intrinsic δ_{CP}, MSW matter effect or LRIs.

Summary...

- The analytic formula allows us to pinpoint the zeros of A_{CP}, and the regions where a distinction between intrinsic and fake CP violation is possible. At DUNE, this is around 0.9 GeV
- A low energy optimized beam and/or synergy with T2HK will allow us to probe the existence of new physics
- We derive the bound $\alpha' < 2.1 \times 10^{-51}$ from T2K/NOvA data. This is comparable to the naive bound translated from NSI constraints: $\alpha' < 1.9 \times 10^{-51}$.
- Connecting NSI bounds to LRI bounds is straightforward but not necessarily accurate

THANK YOU