Long-Range Lepton Flavor Interactions and Neutrino Oscillations

[with H. Davoudiasl and W. Marciano (PRD 2011)]

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Goal of this talk

MINOS $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance experiments.

$(L = 735 \text{ km}, E_\nu \sim \text{GeV scale})$

\[
|\Delta m^2| < |\Delta \bar{m}^2| \\
\sin^2(2\theta) > \sin^2(2\bar{\theta})
\]

[MINOS Collaboration] arXiv:1104.0344

Likely due to statistics ($N_\nu \sim 2000$, $N_{\bar{\nu}} \sim 100$). Yet, it could be a hint of New Physics that can affect $\nu$ oscillation (differently for $\nu$ and $\bar{\nu}$).

In this talk, we go over a possible explanation and discuss its implications for other $\nu$ experiments.
Long-Range Lepton Flavor Interactions and $\nu$ Oscillations

Outline

- Long-Range Interaction & $\nu$ oscillation
- Implication for atmospheric $\nu$ at IceCube DeepCore (ongoing)
- Implication for Future Long Baseline $\nu$ experiments
- Brief comment on the implications for the charged lepton sector
What type of New Physics?

\[ H = H_{\text{vac}} + H_{\text{SM}} \]

\[ H_{\text{SM}} = V_W(1, 0, 0) + V_Z(1, 1, 1) \]

with \( V_W = \sqrt{2} G_F n_e \), \( V_Z = -\frac{G_F}{\sqrt{2}} n_n \)

Flavor-universal potential (such as \( Z \) boson effect) is irrelevant to \( \nu \) flavor oscillation.

We will consider a Lepton Flavor Long-Range Interaction (LRI):

(i) lepton flavor-dependent \( U(1)' \),  (ii) almost massless gauge boson \( Z' \).

\[ H_{\text{LRI}} = V_{Z'}(Q_e, Q_\mu, Q_\tau) \]

(No sterile \( \nu \), No CPT violation, etc.)
Related works

Some related works prior to our study: LRI effects on $\nu$ oscillation, MINOS anomaly explanation with a new interaction, etc.

Joshipura, Mohanty (2003); Grifols, Masso (2003); Gonzalez-Garcia, Holanda, Masso, Funchal (2006); Bandyopadhyay, Dighe, Joshipura (2006); Engelhardt, Nelson, Walsh (2010); Mann, Cherdack, Musial, Kafka (2010); Kopp, Machado, Parke (2010); Heeck, Rodejohann (2010); · · ·
Effective $\nu_\mu$ survival probability in 2-flavor ($\nu_\mu - \nu_\tau$) oscillation

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\tilde{\theta}_{23}) \sin^2 \left( \frac{\Delta \tilde{m}^2_{23} L}{4E_\nu} \right) \]

with effective mass splitting and mixing angle under New Potential

\[ \Delta \tilde{m}^2_{23} = \Delta m^2_{23} \sqrt{[\xi - \cos(2\theta_{23})]^2 + \sin^2(2\theta_{23})} \]
\[ \sin^2(2\tilde{\theta}_{23}) = \frac{\sin^2(2\theta_{23})}{([\xi - \cos(2\theta_{23})]^2 + \sin^2(2\theta_{23}))} \]

\[ \xi \equiv -\frac{2W_\tau E_\nu}{\Delta m^2_{23}}, \quad W_\tau = Q_\tau V_{Z'} \text{ (potential energy, in } \nu_\mu - \nu_\tau) \]

(In analogy of the standard matter effect in $\nu_e$ oscillation: $\xi = \frac{2\sqrt{2}G_F n_e E_\nu}{\Delta m^2}$)

$\xi$ flips sign for $\bar{\nu}$ causing different effects on $\nu$ and $\bar{\nu}$ unless $\sin^2(2\theta_{23}) = 1$.}

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LRI should be extremely weak
T.D. Lee & C.N. Yang (1955): LRI gets constraints from Eötvös-type expt.
\[ \alpha' < 10^{-47} \text{ (baryons), } \alpha' < 10^{-49} \text{ (leptons) } \]

Okun, Dolgov (1990’s)

LRI needs large (astronomical) source to have sizable effects.

We assume \[ m_{Z'} \lesssim \frac{1}{\text{AU}} \sim 10^{-18} \text{ eV } \]
to include the Sun (but not much smaller).

\( U(1)' \) charge
\[ Q = a_0 (B - L) + a_1 (L_e - L_\mu) + a_2 (L_e - L_\tau) + a_3 (L_\mu - L_\tau) \]
: a linear combination of anomaly-free gauge symmetries

We choose \[ Q = (B - L) + (L_\mu - L_\tau) = B - L_e - 2L_\tau. \]

\[ H_{\text{LRI}} = V_{Z'} (-1, 0, -2) \]

(Neutrons in the Sun and the Earth are the source of New Potential.
Flavor-dependent charges affect \( \nu \) oscillation.)
Astronomical source of New Potential

\[ \text{Sun (⊙) } \quad r \quad \text{→ Earth (⊕)} \]

\[ (N^\odot_n = 1.7 \times 10^{56}) \quad (N^{⊕}_n = 1.8 \times 10^{51}) \]

\[ V_{Z'} = \alpha' \left( \frac{N^\odot_n}{r} + \frac{N^{⊕}_n}{R^{⊕}} \right) = \left( \frac{\alpha'}{10^{-50}} \right) \times \left( \frac{AU}{r} + 0.25 \right) \times (2.2 \times 10^{-12} \text{ eV}) \]

\[ \sim \left( \frac{\alpha'}{10^{-50}} \right) \times \mathcal{O}(10^{-12} \text{ eV}) \]

(1) Since the MINOS $\nu$ oscillation is relevant to $\frac{\Delta m^2_{23}}{E_\nu} \sim \mathcal{O}(10^{-12} \text{ eV})$, LRI with $\alpha' \sim \mathcal{O}(10^{-50})$ level can affect MINOS experiments.

(In other words, $\nu$ oscillation is a good probe of an extremely weak LRI.)

(2) Annual modulation in New Potential due to $r = (1.47 \sim 1.52) \times 10^8 \text{km}$
Our fit to MINOS data with LRI

\[\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2\]
\[\sin^2(2\theta_{23}) = 0.9\]
\[\alpha' = 1.0 \times 10^{-52} \quad \text{(or } W_\tau = 5.6 \times 10^{-14} \text{ eV})\]

\[\alpha' \lesssim 5 \times 10^{-52} \text{ at } 3\sigma \text{ level}\]

Using simplified MINOS data from Kopp, Machado, Parke (2010).
Not positively ruled out by solar+KamLAND \(\nu\) and atmospheric \(\nu\) data.
(There is a tension between the potential for MINOS data and SK atmospheric \(\nu\) data though.)

Note: The best-fit does not really improve MINOS data fitting, but we take it a motivated benchmark point to explore other experiments to test the LRI idea.
(Optional slide) Constraints

MINOS best-fit: \( \alpha' = 1.0 \times 10^{-52} \rightarrow W_\tau = 5.6 \times 10^{-14} \text{ eV} \)

(cf. \( \alpha' = 0.5 \times 10^{-52} \rightarrow W_\tau = 2.8 \times 10^{-14} \text{ eV} \))

(1) Solar+KamLAND \( \nu \) data constraints on LRI:
\[ \alpha' \lesssim 5 \times 10^{-52} \quad (\text{at } 3\sigma) \]
Gonzalez-Garcia, Holanda, Masso, Funchal (2006); Bandyopadhyay, Dighe, Joshipura (2006)

(2) Atmospheric \( \nu \) data (Super-Kamiokande):
\[ W_\tau = \epsilon_{\tau\tau} \sqrt{2} G_F n_e. \quad \epsilon_{\tau\tau} \lesssim 0.2 \quad (\text{at } 95\% \text{ CL}) \]
Friedland, Lunardini, Maltoni (2004)

It depends on \( n_e \) (electron number density).
In the core (\( R \lesssim 3400 \text{ km} \)): \( n_e \approx 12 \text{ g/cm}^3 \) \( (W_\tau \lesssim 9 \times 10^{-14} \text{ eV}) \)
In the mantle (\( R \gtrsim 3400 \text{ km} \)): \( n_e \approx 5 \text{ g/cm}^3 \) \( (W_\tau \lesssim 4 \times 10^{-14} \text{ eV}) \)
Where are good places to test LRI?

$L = 2 \times 6400 \text{ km} \quad \text{(DeepCore)}$

$L = 1300 \text{ km} \quad \text{(Future LBNE)}$

(for MINOS best-fit values)

LRI effects on $\nu$ oscillations are energy-dependent.

The effects on $\nu$ (red solid) and $\bar{\nu}$ (green dashed) are different.

$\nu$ and $\bar{\nu}$ are the same in standard oscillation (black dotted).
DeepCore at IceCube

[Atm $\nu_\mu$ disappearance at DeepCore (simulation)]

C. Wiebusch [IceCube Collaboration] (arXiv:0907.2263)

DeepCore: 6 additional densely instrumented strings + 7 IceCube strings. Recently commissioned. Running and taking data now.

“Analysis of the first year DeepCore data is in progress” F. Halzen (NuFact’11).

$\mathcal{O}(10^5) \nu_{\text{atm}} / \text{year}$ in $E_\nu \approx 1 - 100 \text{ GeV}$ triggered.

Complementary to IceCube (optimized for $E_\nu \gtrsim 10 \text{ TeV}$).
LRI effects on atmospheric $\nu_\mu$ at DeepCore

[reproduction of standard oscillation]  
(with different input values)

[for MINOS best-fit]

We assume $\nu : \bar{\nu} = 2 : 1$, isotropic flux, zenith angle $0.7\pi \leq \phi \leq \pi$.

Red solid: $\alpha' = 1.0 \times 10^{-52}$ (MINOS best-fit)

(Red dashed: $\alpha' = 0.5 \times 10^{-52}$, Red dotted: $\alpha' = 0.1 \times 10^{-52}$)

$\rightarrow$ LRI effect on atmospheric $\nu_\mu$ can be quite distinct at DeepCore.
Annual modulation at DeepCore (due to Sun-Earth distance variation)

Annual modulation effect $\left| \frac{N_a - N_p}{N_a + N_p} \right|$ (events in summer — winter)

(15 < $E_\nu$ < 30 GeV, 120 days for each season, for uniform flux).

MINOS best-fit ($\alpha' = 10^{-52}$): Total 2700 events (1 year). 1.2% seasonal variation.

→ Annual modulation at DeepCore can point the Solar origin of New Potential.
Future Long Baseline $\nu$ Experiment (DUSEL)

- $L = 1300$ km, 200 kton Water Cherenkov detector
- 5-years run unoscillated beam profile from M. Diwan’s talk at DURA annual meeting (2010)

MINOS best-fit (red solid): For $E_\nu \sim \mathcal{O}(\text{GeV})$, $\nu_\mu$ has less events ($\bar{\nu}_\mu$ has more events) than the standard oscillation (solid black).

$\rightarrow$ DUSEL can tell the different LRI effects on $\nu$ and $\bar{\nu}$. 

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Annual modulation at DUSEL

Annual modulation effect \( \left| \frac{N_a - N_p}{N_a + N_p} \right| \) for accelerator \( \nu_\mu \) at Long Baseline. (\( 2 < E_\nu < 3 \text{ GeV} \), 180 days for each season, for uniform flux).

MINOS best-fit (\( \alpha' = 10^{-52} \)): Total 1100 (\( \nu_\mu \)), 2100 (\( \bar{\nu}_\mu \)) events (5 years) with 0.5\%, 0.4\% seasonal variation.

→ We may need enhanced capability to see annual modulation.
Comment on the implication of the LRI for the charged lepton sector

Lepton flavor-dependent $U(1)'$ gauge symmetry with nearly massless $Z'$ implies

1. $Z'$-mediated FCNC at tree-level is present, *in general*.  
   : For instance, $\mu$-$e$-$Z'$ vertex may exist in mass eigenstate.

2. Even for tiny coupling ($\alpha' \lesssim 10^{-50}$), its effect is not negligible, *in general*.  
   : $\mu \rightarrow e Z'$ decay is enhanced since $m_{Z'} \ll m_{\mu}$ (Goldstone boson equivalence theorem).  
   \[ \Gamma(\mu \rightarrow e Z') \sim \alpha' m_{\mu} \left( \frac{m_{\mu}^2}{m_{Z'}^2} \right), \]  
   \[ \text{not } \Gamma \sim \alpha' m_{\mu}. \]

Here, "*in general*" means that it depends on the Higgs sector.

Explicit model buildings with Higgs sector should address this. (For instance, separate Higgses for $\nu$ and $\ell^\pm$ sectors as in SUSY or 2HDM).
Summary

1. MINOS data (difference in $\nu_\mu$ and $\bar{\nu}_\mu$):
   a possible hint for New Physics which distinguishes $\nu$ and $\bar{\nu}$.

2. Lepton Flavor LRI with $\alpha' \sim 10^{-52}$ is a possibility.
   ($\nu$ oscillation is sensitive to Lepton Flavor LRI.)

3. IceCube DeepCore (ongoing expt.): can test LRI possibility. Annual modulation (percent-level) can point solar origin of New Potential.

4. DUSEL (future expt.): can tell difference of LRI effects on $\nu$ and $\bar{\nu}$.

5. LRI effect on the charged lepton sector is not negligible, in general.
   (It depends on the explicit Higgs sector model building.)

- Thank you -