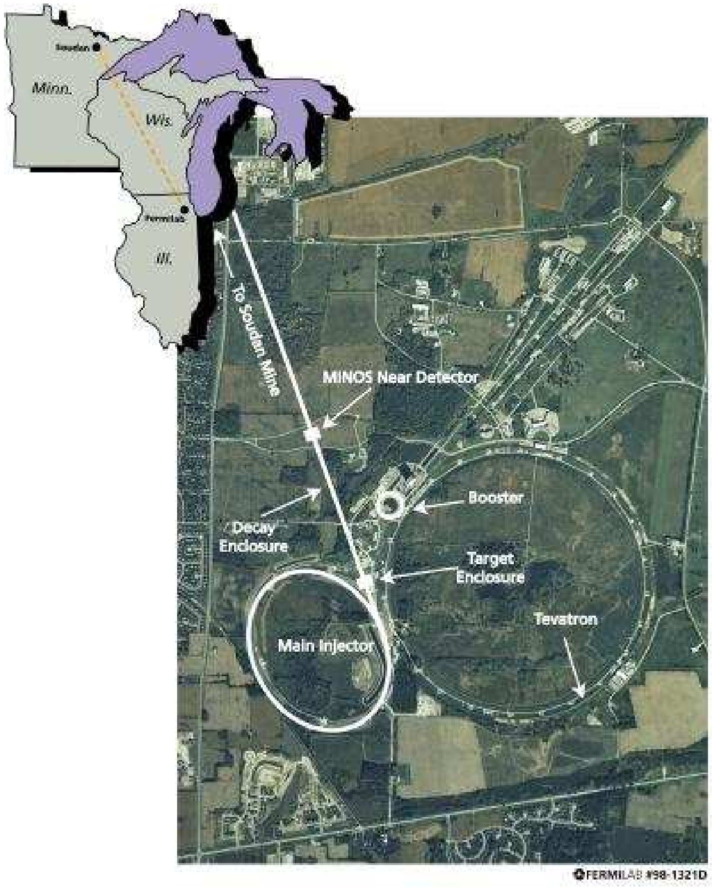
Long-Range Lepton Flavor Interactions and Neutrino Oscillations

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

Hye-Sung Lee

(Brookhaven National Lab)



NuFact 2011

(CERN/UNIGE, August 2011)

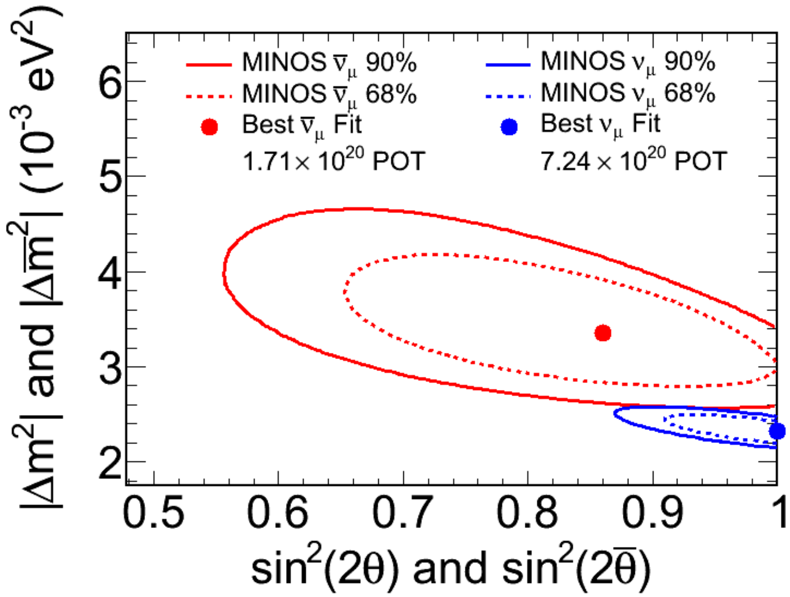
Goal of this talk

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

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

$$\begin{array}{ccc} \nu & & \bar{\nu} \\ |\Delta m^2| & < & |\Delta \bar{m}^2| \\ \sin^2(2\theta) & > & \sin^2(2\bar{\theta}) \end{array}$$

[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 ν oscillation (differently for ν and $\bar{\nu}$).

In this talk, we go over a possible explanation and discuss its implications for other ν experiments.

Outline

- Long-Range Interaction & ν oscillation
- Implication for atmospheric ν at IceCube DeepCore (ongoing)
- Implication for Future Long Baseline ν experiments
- Brief comment on the implications for the charged lepton sector

What type of New Physics?

$$H = H_{\rm vac} + H_{\rm SM}$$
$$H_{\rm SM} = V_W(1,0,0) + V_Z(1,1,1)$$

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 ν flavor oscillation.

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

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

$$H_{\rm LRI} = V_{Z'}(Q_e, Q_\mu, Q_\tau)$$

(No sterile ν, No CPT violation, etc.)

Related works

Some related works prior to our study: LRI effects on ν 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); $\cdots$

Effective ν_μ survival probability in 2-flavor ($\nu_\mu - \nu_\tau$) oscillation

Joshipura, Mohanty (2003)

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

with effective mass splitting and mixing angle under New Potential

$$\begin{aligned} \Delta \tilde{m}^2_{23} &= \Delta m^2_{23} \sqrt{[\xi - \cos(2\theta_{23})]^2 + \sin^2(2\theta_{23})} \\ \sin^2(2\tilde{\theta}_{23}) &= \sin^2(2\theta_{23}) / \left([\xi - \cos(2\theta_{23})]^2 + \sin^2(2\theta_{23}) \right) \end{aligned}$$

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

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

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

LRI should be extremely weak

T.D. Lee & C.N. Yang (1955): LRI gets constraints from Eötvös-type expt.

$\alpha' < 10^{-47}$ (baryons), $\alpha' < 10^{-49}$ (leptons) Okun, Dolgov (1990's)

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

We assume $m_{Z'} \lesssim \frac{1}{AU} \sim 10^{-18}\ \mathrm{eV}$ 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 $Q = (B - L) + (L_\mu - L_\tau) = B - L_e - 2L_\tau$.

$$H_{\mathrm{LRI}} = V_{Z'}(-1, 0, -2)$$

(Neutrons in the Sun and the Earth are the source of New Potential.

Flavor-dependent charges affect ν oscillation.)

Astronomical source of New Potential

$$\text{Sun } (\odot) \quad \longleftarrow r \longrightarrow \quad \text{Earth } (\oplus)$$

$$(N_n^{\odot} = 1.7 \times 10^{56}) \qquad\qquad (N_n^{\oplus} = 1.8 \times 10^{51})$$

$$V_{Z'} = \alpha' \left(\frac{N_n^{\odot}}{r} + \frac{N_n^{\oplus}}{R_{\oplus}} \right) = \left(\frac{\alpha'}{10^{-50}}\right) \times \left(\frac{AU}{r} + 0.25\right) \times (2.2 \times 10^{-12}\,\mathrm{eV})$$

$$\sim \left(\frac{\alpha'}{10^{-50}}\right) \times \mathcal{O}(10^{-12}\,\mathrm{eV})$$

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

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

(2) Annual modulation in New Potential due to $r = (1.47 \sim 1.52) \times 10^8 \mathrm{km}$

Our fit to MINOS data with LRI

$$\begin{aligned} \Delta m^2_{23} &= 2.4 \times 10^{-3}\,\mathrm{eV}^2 \\ \sin^2(2\theta_{23}) &= 0.9 \\ \alpha' &= 1.0 \times 10^{-52} \qquad (\text{or } W_\tau = 5.6 \times 10^{-14}\,\mathrm{eV}) \end{aligned}$$

($\alpha' \lesssim 5 \times 10^{-52}$ at 3σ level)

Using simplified MINOS data from Kopp, Machado, Parke (2010).

Not positively ruled out by solar+KamLAND ν and atmospheric ν data.

(There is a tension between the potential for MINOS data and SK atmospheric ν 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: $\alpha' = 1.0 \times 10^{-52} \quad \longrightarrow \quad W_\tau = 5.6 \times 10^{-14}\,\mathrm{eV}$

(cf. $\alpha' = 0.5 \times 10^{-52} \quad \longrightarrow \quad W_\tau = 2.8 \times 10^{-14}\,\mathrm{eV}$)

(1) Solar+KamLAND ν data constraints on LRI:

$\alpha' \lesssim 5 \times 10^{-52}$ (at 3σ)

Gonzalez-Garcia, Holanda, Masso, Funchal (2006); Bandyopadhyay, Dighe, Joshipura (2006)

(2) Atmospheric ν data (Super-Kamiokande):

$W_\tau = \epsilon_{\tau\tau}\sqrt{2}G_F n_e.\quad \epsilon_{\tau\tau} \lesssim 0.2$ (at 95% CL)

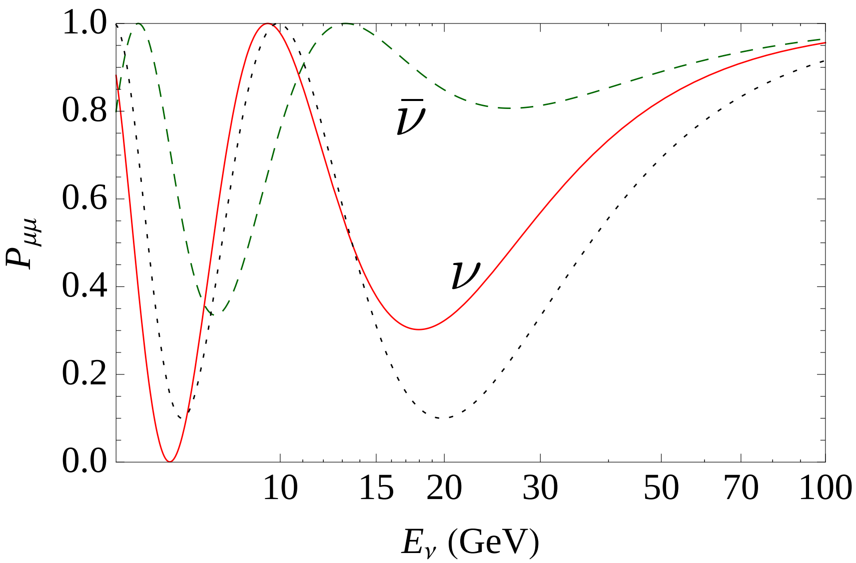
Friedland, Lunardini, Maltoni (2004)

It depends on n_e (electron number density).

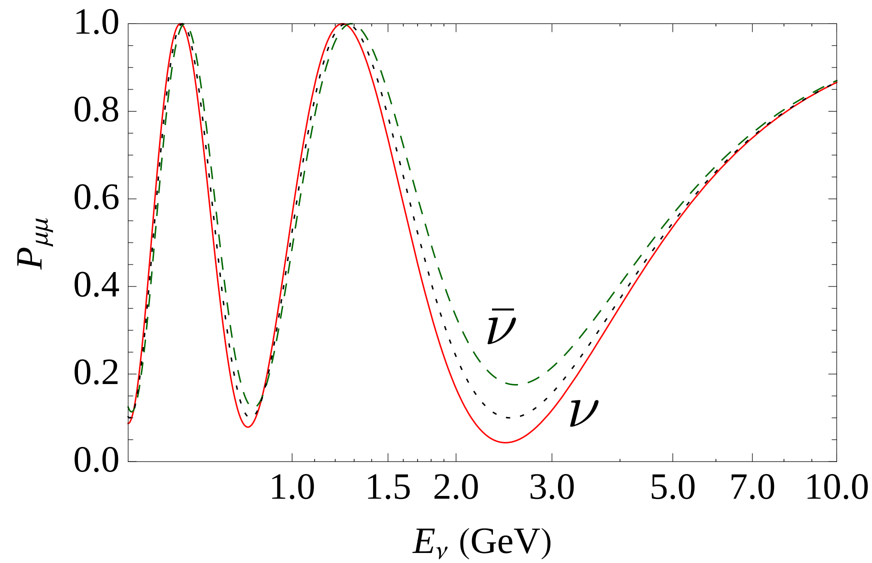
In the core ($R \lesssim 3400\,\mathrm{km}$): $n_e \approx 12\,\mathrm{g/cm^3}$ ($W_\tau \lesssim 9 \times 10^{-14}\,\mathrm{eV}$)

In the mantle ($R \gtrsim 3400\,\mathrm{km}$): $n_e \approx 5\,\mathrm{g/cm^3}$ ($W_\tau \lesssim 4 \times 10^{-14}\,\mathrm{eV}$)

Where are good places to test LRI?



[$L = 2 \times 6400$ km (DeepCore)]



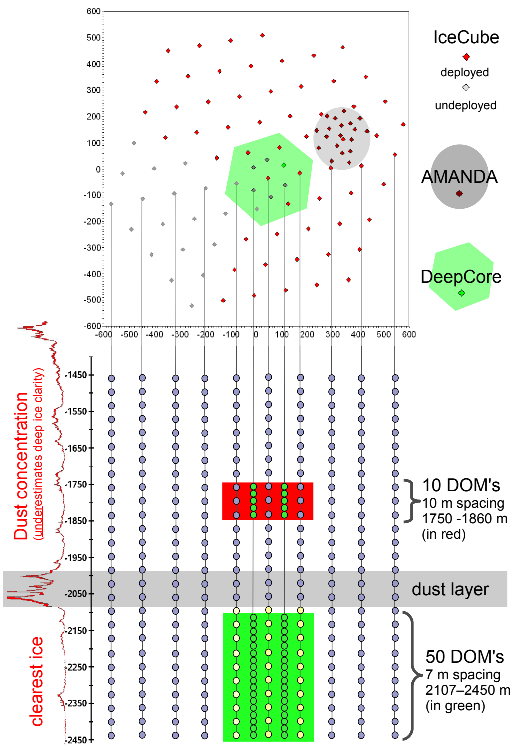
[$L = 1300$ km (Future LBNE)]

(for MINOS best-fit values)

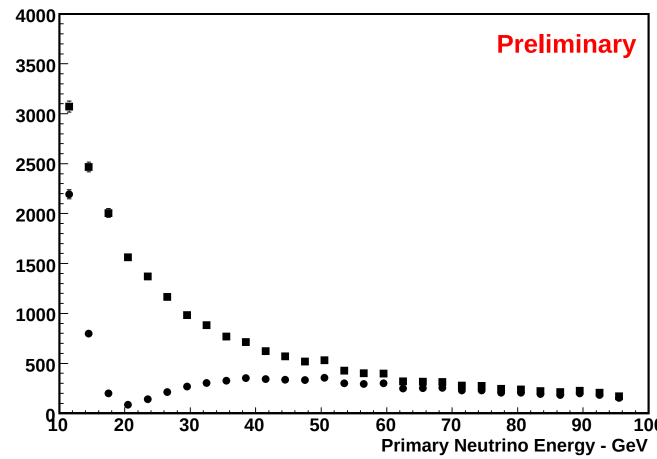
LRI effects on ν oscillations are energy-dependent.

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

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



DeepCore at IceCube



[Atm ν_μ disappearance at DeepCore (simulation)]

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

DeepCore: 6 additional densely instrumented strings + 7 IceCube strings.

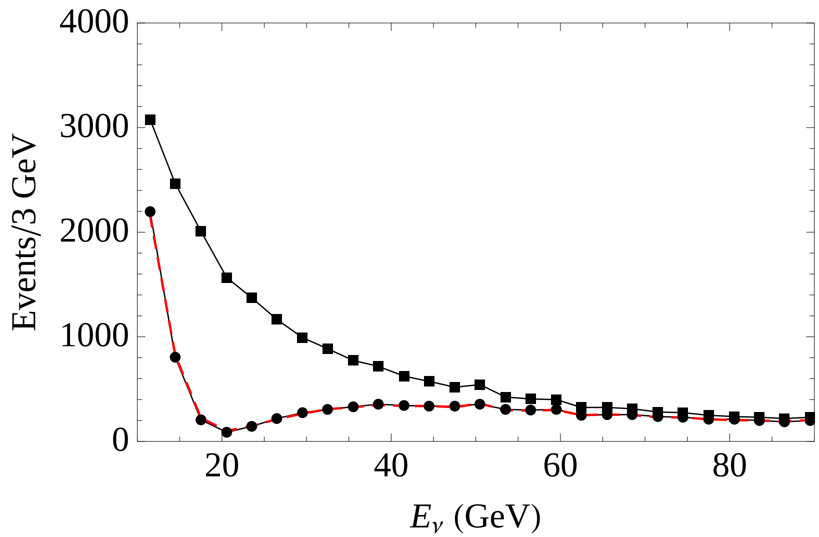
Recently commissioned. Running and taking data now.

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

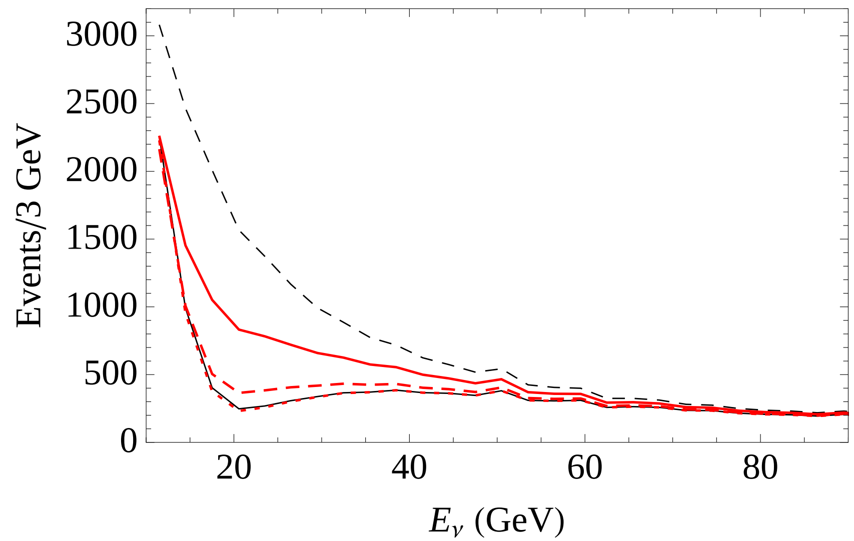
$\mathcal{O}(10^5)$ $\nu_{\rm atm}$ / year in $E_\nu \approx 1 - 100$ GeV triggered.

Complementary to IceCube (optimized for $E_\nu \gtrsim 10$ TeV).

LRI effects on atmospheric ν_μ at DeepCore



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



[for MINOS best-fit]

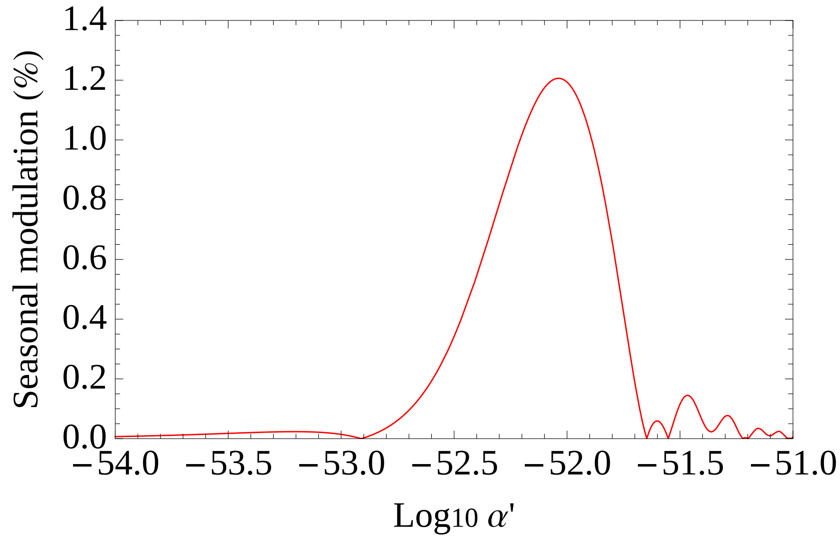
We assume $\nu : \bar{\nu} = 2 : 1$, isotropic flux, zenith angle $0.7\pi \lesssim \phi \leq \pi$.

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

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

$\longrightarrow$ LRI effect on atmospheric ν_μ can be quite distinct at DeepCore.

Annual modulation at DeepCore (due to Sun-Earth distance variation)



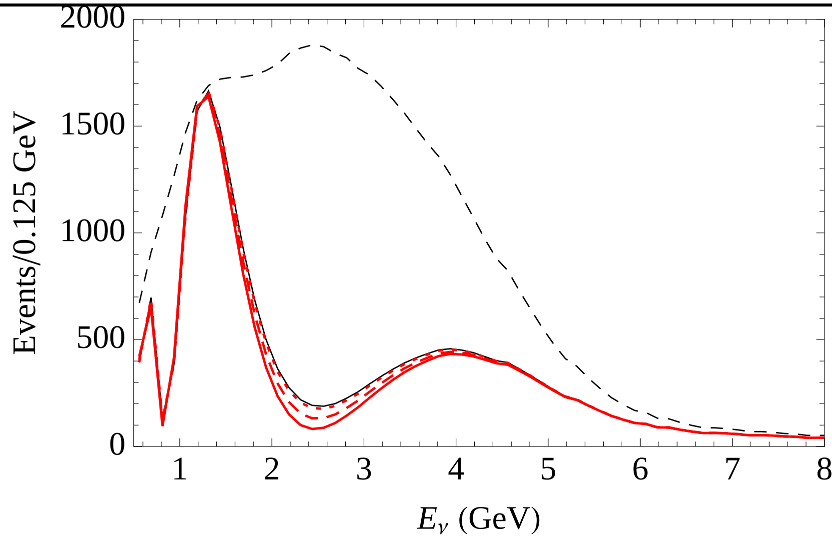
Annual modulation effect $\left|\frac{N_a - N_p}{N_a + N_p}\right|$ (events in summer − winter)

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

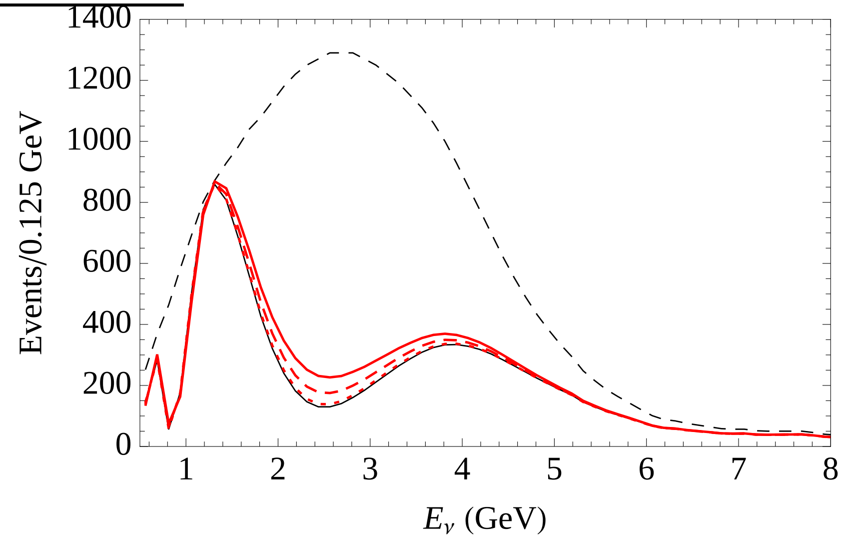
MINOS best-fit ($\alpha' = 10^{-52}$): Total 2700 events (1 year). 1.2% seasonal variation.

$\longrightarrow$ Annual modulation at DeepCore can point the Solar origin of New Potential.

Future Long Baseline ν Experiment (DUSEL)



[ν_μ disappearance]



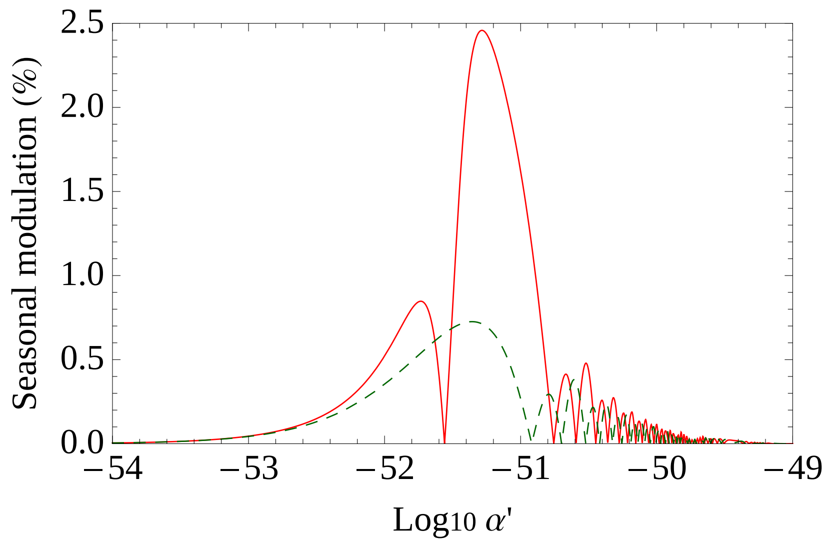
[$\bar{\nu}_\mu$ disappearance]

- $L = 1300$ 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 $E_\nu \sim \mathcal{O}(\mathrm{GeV})$, ν_μ has less events ($\bar{\nu}_\mu$ has more events) than the standard oscillation (solid black).

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

Annual modulation at DUSEL



Annual modulation effect $\left|\frac{N_a - N_p}{N_a + N_p}\right|$ for accelerator ν_μ at Long Baseline.

($2 < E_\nu < 3\ \mathrm{GeV}$, 180 days for each season, for uniform flux).

MINOS best-fit ($\alpha' = 10^{-52}$): Total 1100 (ν_μ), 2100 ($\bar{\nu}_\mu$) events (5 years)

with 0.5%, 0.4% seasonal variation.

$\longrightarrow$ 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, μ-e-Z' vertex may exist in mass eigenstate.

(2) Even for tiny coupling ($\alpha' \lesssim 10^{-50}$), its effect is not negligible, *in general*.

: $\mu \rightarrow eZ'$ decay is enhanced since $m_{Z'} \ll m_\mu$ (Goldstone boson equivalence theorem). $\Gamma(\mu \rightarrow eZ') \sim \alpha' m_\mu \left(\frac{m_\mu^2}{m_{Z'}^2}\right)$, 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 ν and $\ell^\pm$ sectors as in SUSY or 2HDM).

Summary

1. MINOS data (difference in ν_μ and $\bar{\nu}_\mu$):
   a possible hint for New Physics which distinguishes ν and $\bar{\nu}$.
2. Lepton Flavor LRI with $\alpha' \sim 10^{-52}$ is a possibility.
   (ν 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 ν 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 -