Long-Range Neutrino Interactions

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Based on:

H.D., H.-S. Lee, and W. Marciano, work in progress.

February 4, 2011

Recent MINOS accelerator results (2010):

$$|\Delta m^2_{23}| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \text{eV}^2\ ;\ \sin^2(2\theta_{23}) > 0.91$$

and

$$|\Delta \bar{m}^2_{23}| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2\ ;\ \sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11$$

- $L = 735$ km.
- Suggest asymmetry, but $N(\nu) \sim 2000, N(\bar{\nu}) \sim 100$.
- Not very conclusive, but interesting.
- Motivating our discussion.

MINOS atmospheric results (2010):

$$|\Delta m^2| - |\Delta \bar{m}^2| = 0.4^{+2.5}_{-1.2} \times 10^{-3}\ \text{eV}^2$$

- New physics: distinguish ν and $\bar{\nu}$.
- Possibility: a long-range $U(1)'$ force acting on neutrinos.
  - Opposite signs for ν and $\bar{\nu}$.
  - Extremely weak interactions, need large (astronomical) sources.
  - Ultra light Z' (astronomical range).

Some related works:

Joshipura, Mohanty, 2003; Gonzalez-Garcia, Holanda, Massó, Zukanovich Funchal, 2006; Bandyopadhyay, Dighe, Joshipura, 2006; Heeck, Rodejohann, 2010.

- New long-range interactions: Lee and Yang, 1955.
- Can lead to deviations in Eötvös-type tests of gravity.
- Bounds on α':
  - $\alpha' < 10^{-49}$ (leptons).
  - $\alpha' < 10^{-47}$ (baryons). Okun, 1996; Dogov, 1999.
- Truly feeble coupling.

  Gravitational coupling between two protons $\propto m_p^2/M_P^2 \sim 10^{-38}$.
- Can such negligible interactions be of any consequence?

- Remarkably, the answer is yes!

- Tiny coupling $\alpha' \sim 10^{-50} \rightarrow$ large number of sources.
- $M_\odot \sim 10^{57}$ GeV $\rightarrow N_\odot \sim 10^{57}$ sources.
- Example: gauge anomaly free $L_e - L_\ell$, $\ell = \mu, \tau$. Joshipura, Mohanty, 2003.
- Earth-Sun distance: $R_{ES} \sim 10^{18}$ eV^{-1}.
- Potential energy at Earth $W = QV$:

$$W_\odot \sim \alpha' N_\odot / R_{ES} \sim 10^{-11} \text{ eV}.$$

- Neutrino oscillation experiments: $\Delta m^2 \sim 10^{-3}$ eV^2, $E_\nu \sim 1$ GeV.

$$\Delta m^2 / E_\nu \sim 10^{-12} \text{ eV} \ .$$

- $W_\odot$ could be important in neutrino oscillation experiments!
- Recent work motivated by MINOS.

Heeck, Rodejohann, arXiv:1007.2655 [hep-ph].

- We adopt gauged $(B-L)+(L_\mu-L_\tau)=B-L_e-2L_\tau$.
  - Avoid some constraints.
- Source: neutrons in the Sun $(B-L)$.
  - $m_{Z'}\lesssim 1/R_{\rm AU}$ (but not much smaller).

$$\boldsymbol{V_n=\alpha'\left(\frac{N_n^\oplus}{R_\oplus}+\frac{N_n^\odot}{R_{\rm ES}}\right)=2.24\times10^{-12}\ {\rm eV}\left(\frac{\alpha'}{10^{-50}}\right)\left[0.25+\left(\frac{R_{\rm AU}}{R_{\rm ES}}\right)\right]}$$

$N_n^\odot=1.70\times10^{56}$ and $N_n^\oplus=1.78\times10^{51}$.

$R_\oplus=6.4\times10^3$ km

$R^a_{\rm ES}\simeq1.52\times10^8$ km, aphelion ($\sim$ July 4)

$R^p_{\rm ES}\simeq1.47\times10^8$ km, perihelion ($\sim$ January 4).

- Annual modulation of the effect.

- 2-flavor $\nu_\mu - \nu_\tau$ oscillation: Joshipura, Mohanty, 2003.

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

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

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

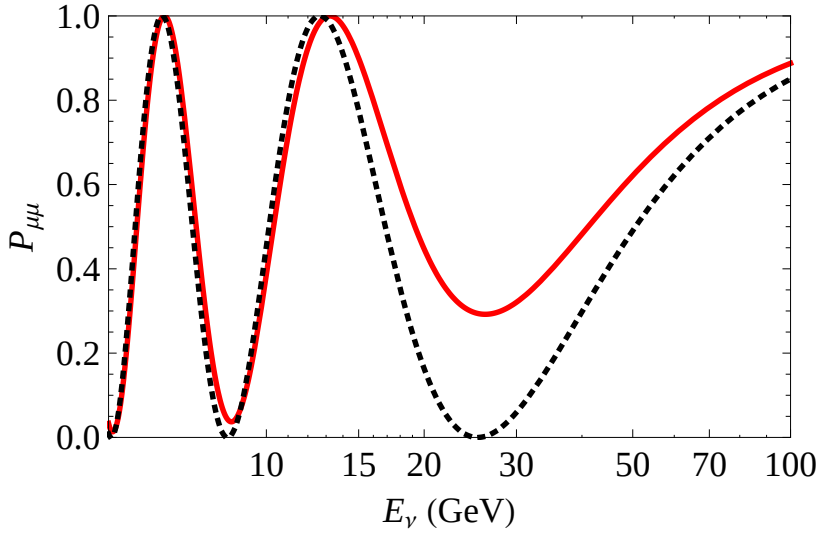
$$\xi \equiv \frac{2W_\tau E_\nu}{\Delta m^2_{23}}$$

- $\Delta\tilde{m}^2_{23}$ and $\sin^2(2\tilde{\theta}_{23})$ energy-dependent.

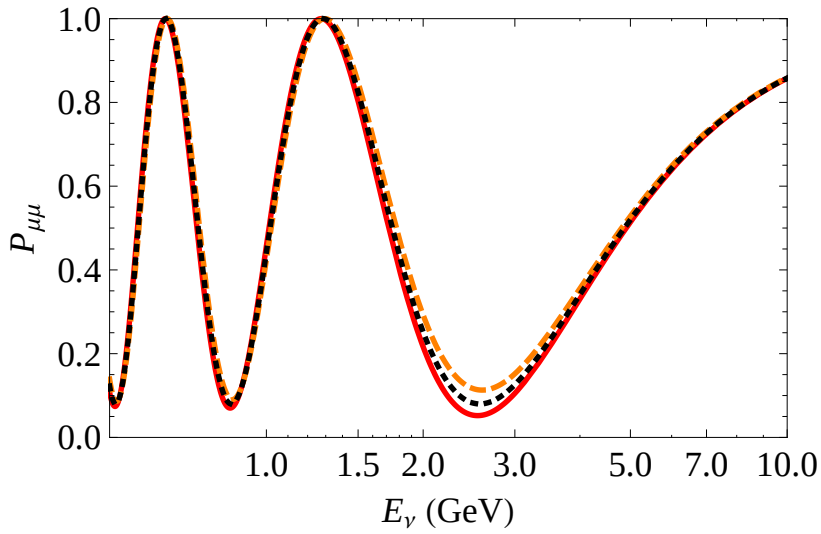
Vacuum quantities tilde-free. $W_\tau = -\mathcal{Q}_\tau V_n$ potential energy for ν_τ.

- $\bar{\nu}$ quantities from $\xi \to -\xi$.

- Physics symmetric for $\sin^2(2\theta_{23}) = 1$.

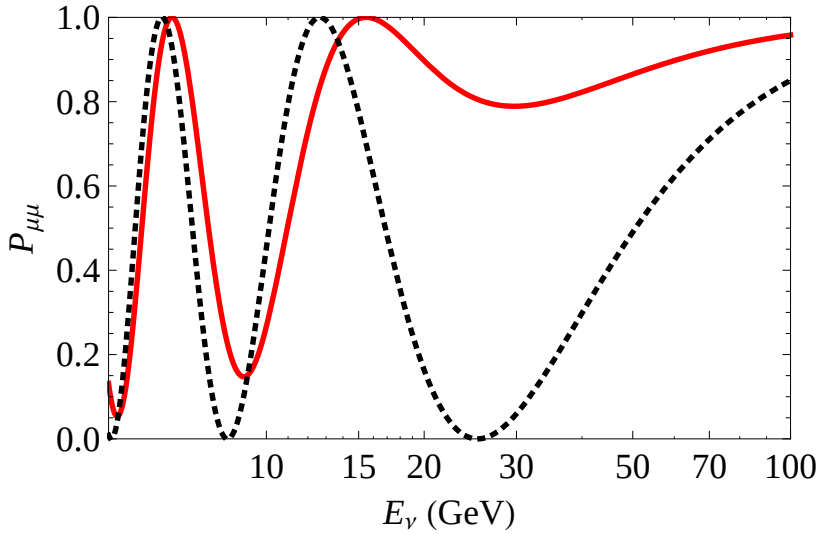


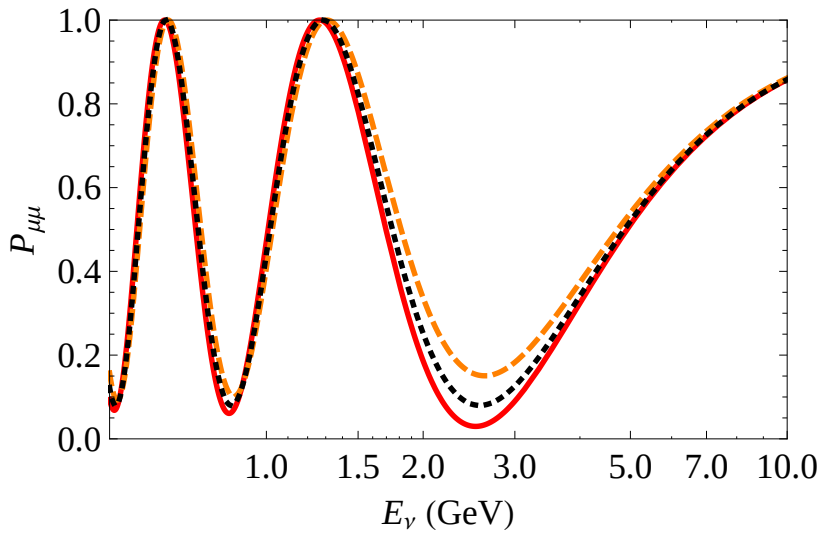
(a)



(b)

Above: SM (black dotted), LRI (red solid) with $\Delta m^2_{23} = 2.45 \times 10^{-3}$ eV^2 and $\alpha' = 0.5 \times 10^{-52}$. (a) $L = 2 \times 6400$ km (DEEPCORE experiment) with $\sin^2(2\theta_{23}) = 1$. (b) $L = 1300$ km (DUSEL) with $\sin^2(2\theta_{23}) = 0.92$. ν: red solid, $\bar{\nu}$: dashed orange. Below: $\alpha' = 1.0 \times 10^{-52}$





- Rough MINOS fit:

$\Delta m^2_{23} = 2.4 \times 10^{-3}$, $\sin^2(2\theta_{23}) = 0.89$, and $\alpha' = 1.0 \times 10^{-52}$.

- Simplified data from Kopp, Machado, Parke, [arXiv:1009.0014 [hep-ph]].

- New contributions often parameterized by $\varepsilon_{\ell\ell'}$ in units of $\sqrt{2}G_F n_e$.

- Present bounds $\varepsilon_{\tau\tau} \lesssim 0.2$ from atmospheric data.

Friedland, Lunardini, Maltoni, 2004

For average Earth density of $\rho \approx 6$ g cm^{-3}: $n_e \approx 1.4 \times 10^{10}$ eV^3.

- Our α' for MINOS corresponds to $W_\tau/(\sqrt{2}G_F n_e) \approx 0.2$.

- Roughly consistent with the atmospheric bound.

Note: Our fit is rough and this is a preliminary result.

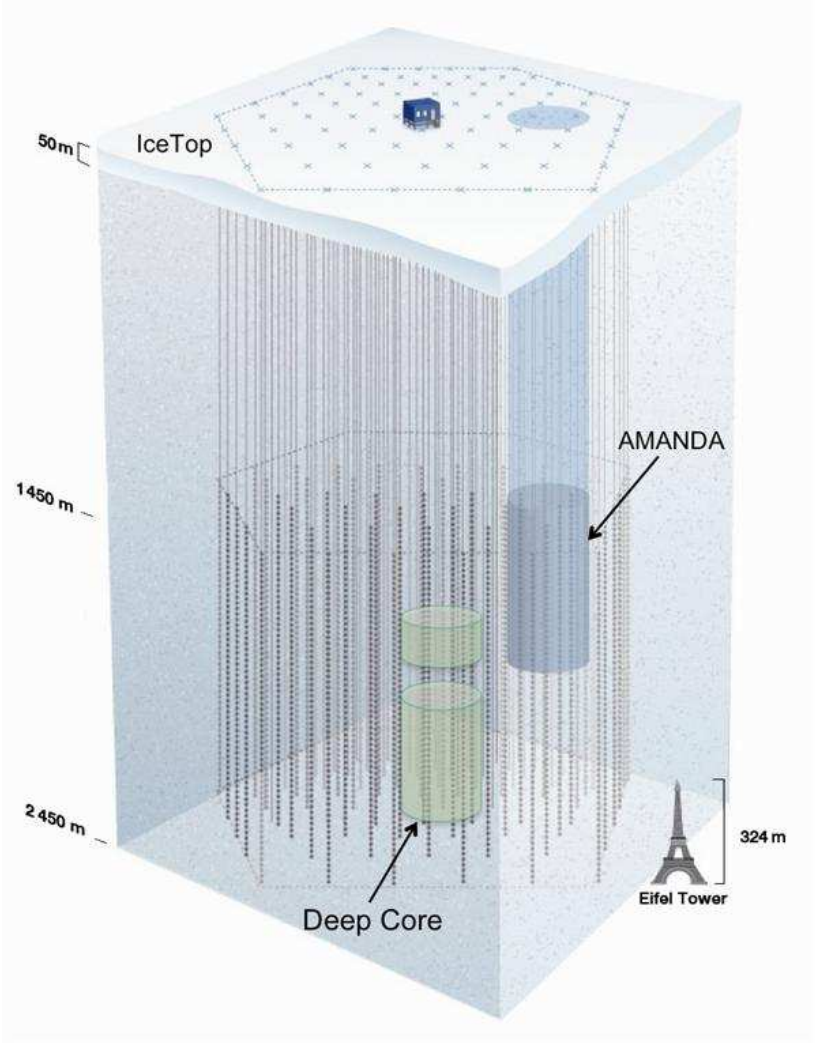
- A more detailed look at constraints is perhaps necessary, but a long-range $U(1)'$ might fit the MINOS results.

- In any event, this type of physics could be probed at current and future experiments.

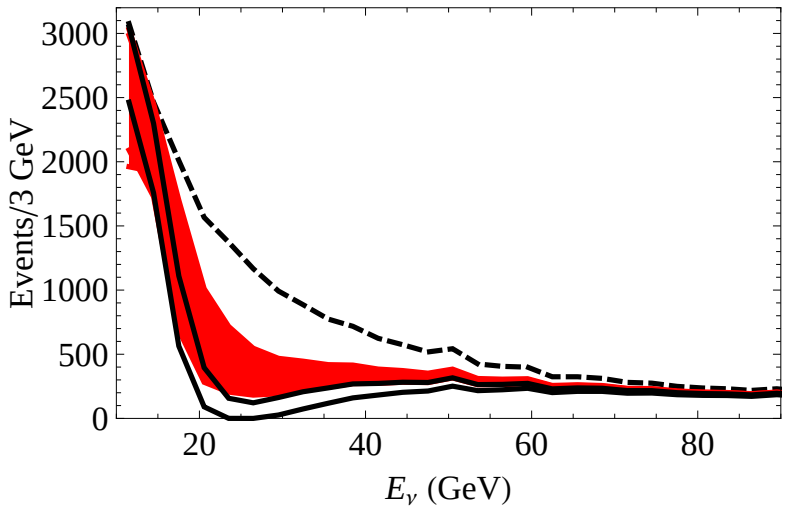
- DeepCore Array at IceCube in Antarctica.

  C. Wiebusch, IceCube Collaboration, [arXiv:0907.2263 [astro-ph.IM]]

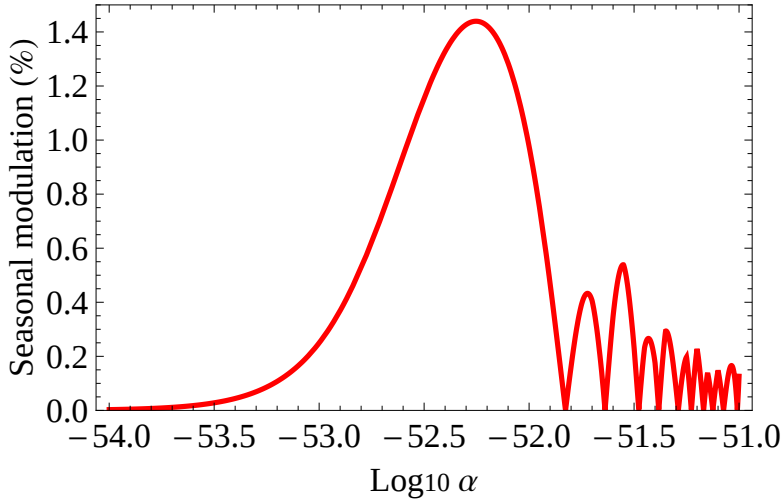
  - 6 extra strings, 360 phototubes + 7 central IceCube strings.
  - Threshold down to about 10 GeV.
  - $\mathcal{O}(10^5)$ atmospheric νs per year.
  - Running now!



- High statistics measurements of neutrino properties.

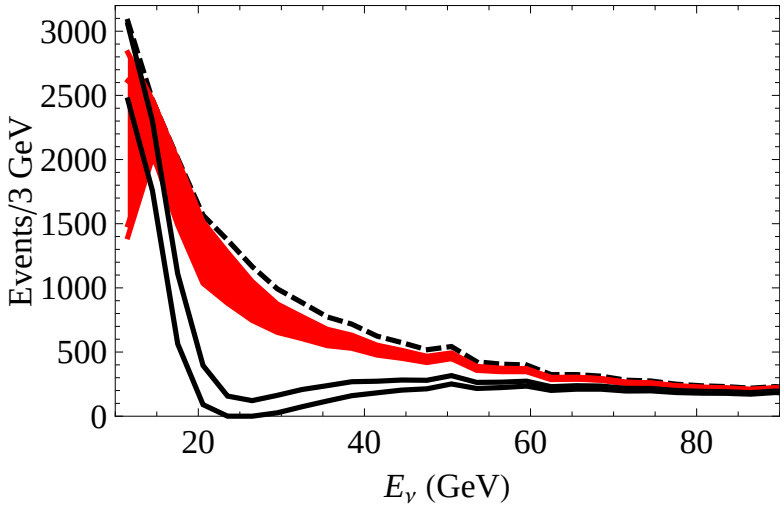


(a)



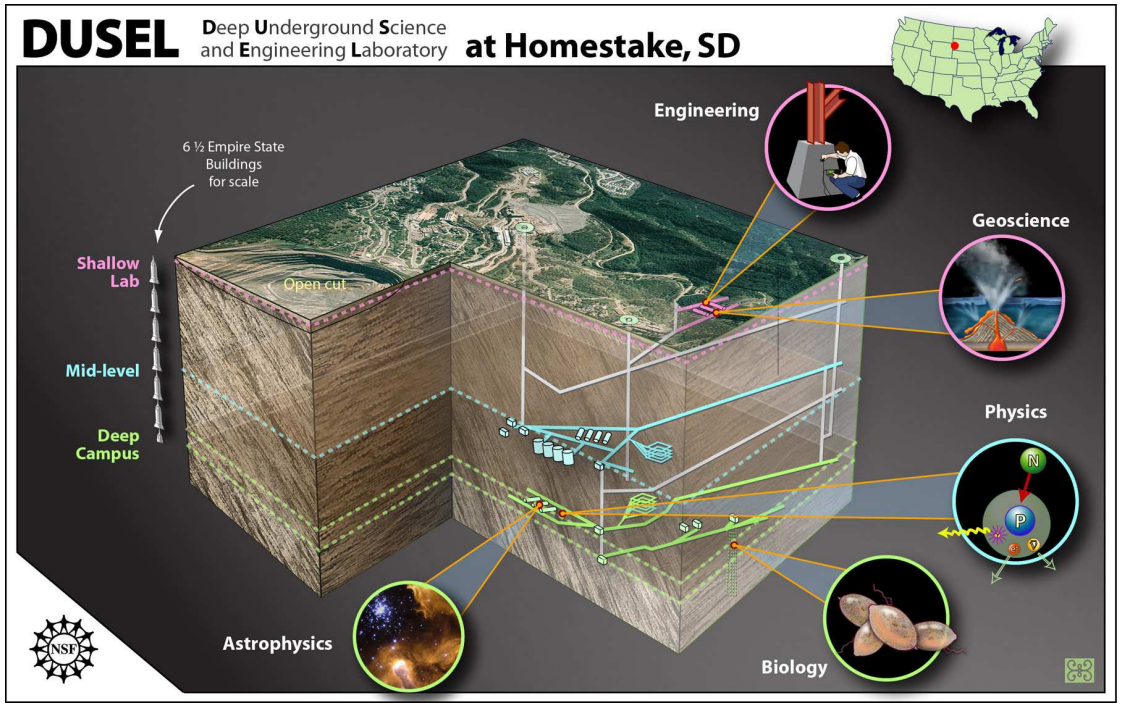
(b)

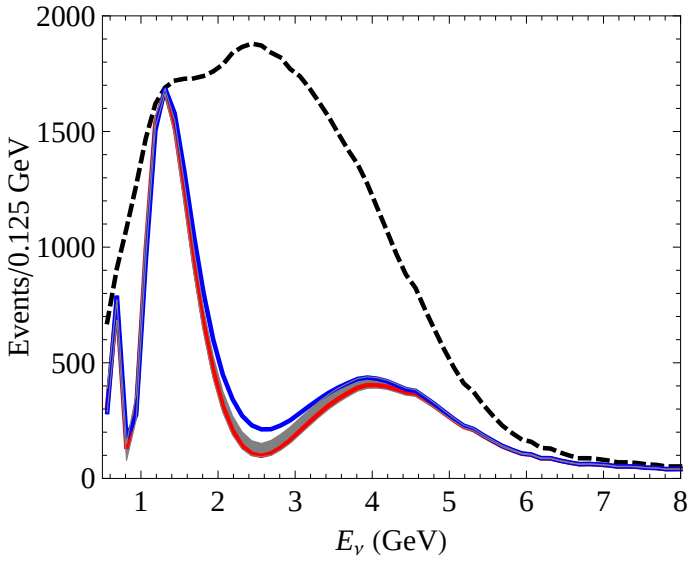
DeepCore: (a) Atmospheric νs/year (per 3 GeV); *vertical path assumed*. Unoscillated (black dashed), standard (black solid), LRI range (red); $\sin^2(2\theta_{23}) > 0.92$, $2.3 \times 10^{-3} < |\Delta m^2_{23}\ (\mathrm{eV}^2)| < 2.56 \times 10^{-3}$, $\alpha' = 0.5 \times 10^{-52}$. (b) Seasonal modulation $|(N_a - N_p)/(N_a + N_p)|$, $20 < E_\nu\ (\mathrm{GeV}) < 40$, 120 days for each season. Below: $\alpha' = 1.0 \times 10^{-52}$.



- DUSEL
  - Assume baseline $L = 1300$ km, 200 kT water Čerenkov detector.
  - ν and $\bar{\nu}$ beams.
  - Beam profile adopted from talk by M. Diwan:

http://www.dusel.org/workshops/fallworkshop10/milind dura talk.pdf.





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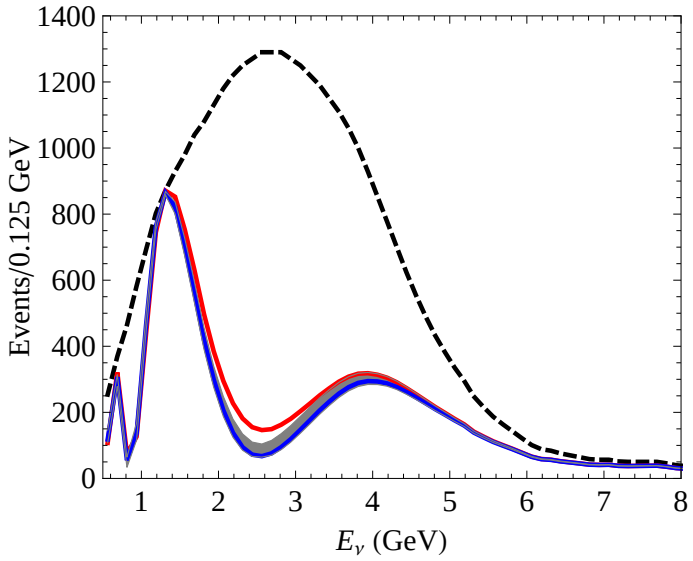
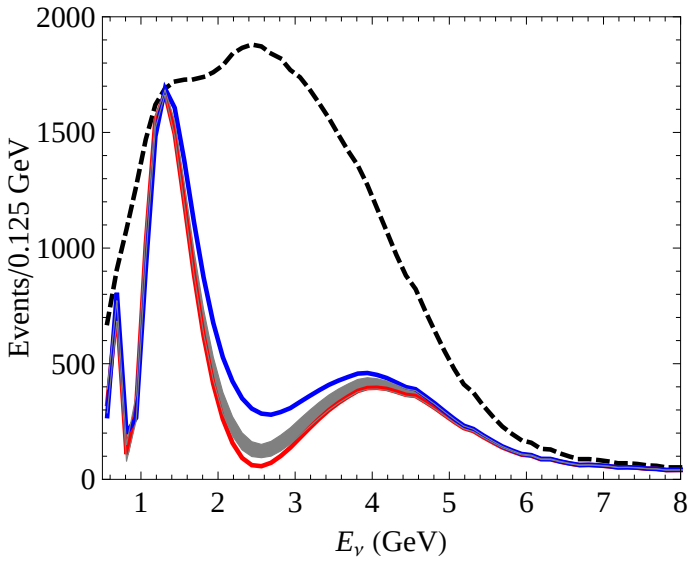
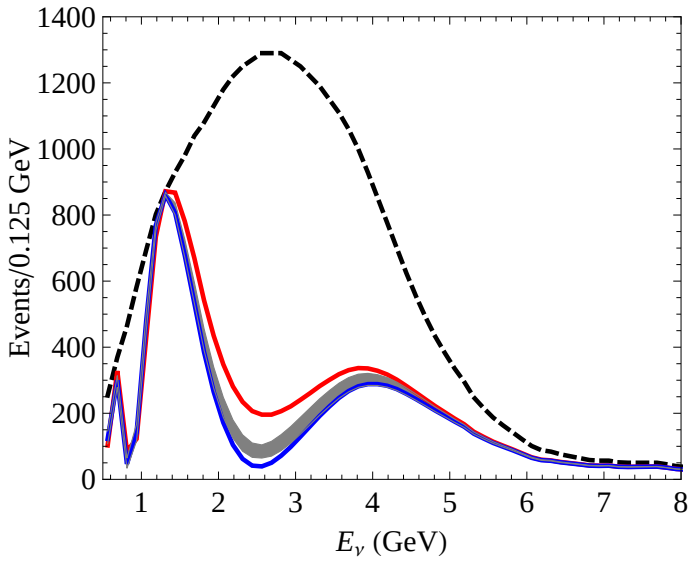
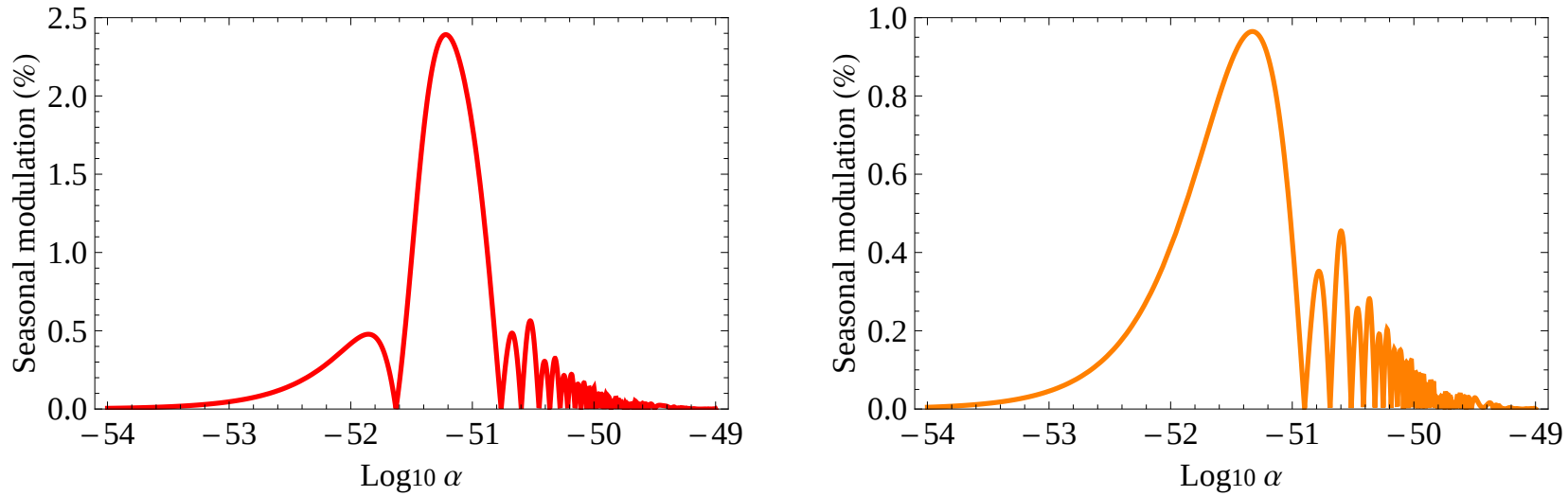


(b)

DUSEL: (a) νs and (b) $\bar{\nu}$s, 5 years. Unoscillated (black dashed), standard (gray band) with $0.92 < \sin^2(2\theta_{23}) < 0.95$, 2.4×10^{-3} eV^2 $< |\Delta m^2_{23}| < 2.45 \times 10^{-3}$ eV^2, LRI (solid), $\alpha' = 0.5 \times 10^{-52}$, $\sin^2(2\theta_{23}) = 0.92$, $\Delta m^2_{23} = \pm 2.45 \times 10^{-3}$ eV^2 (red $+$, blue $-$). Below: $\alpha' = 1.0 \times 10^{-52}$.







(a) (b)

DUSEL: Seasonal modulation $|(N_a - N_p)/(N_a + N_p)|$ for a 5-year run, $2 < E_\nu$ (GeV) $<$ 3.5, 120 days for each season for (a) ν_μ and (b) $\overline{\nu}_\mu$.

Concluding Remarks

- MINOS: Hint of asymmetry in ν and $\bar{\nu}$ oscillation parameters.
- Ultra weak $U(1)'$ could be a possible explanation, $\alpha' < 10^{-50}$.
- Neutrino oscillations: a unique probe of these interactions.
- Annual modulations would point to a solar origin.
- DeepCore: operational at IceCube.
  - $\mathcal{O}(10^5)$ atmospheric neutrinos per year.
  - Sensitivity to long-range interactions.
  - Percent level annual modulations could be detected.
- LBNE, DUSEL: Important role in detecting the ν and $\bar{\nu}$ asymmetry.