Energy-Dependent Neutrino Mixing Parameters at Oscillation Experiments

based on 2108.11961, in collaboration with
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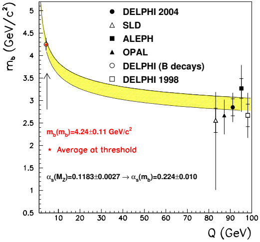
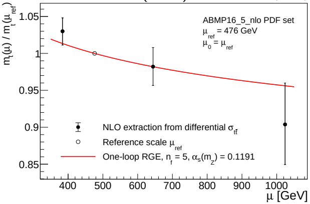
Energy Dependence of the Standard Model Parameters

- couplings and mass parameters in the Standard Model and Beyond are energy dependent
- while we know that from theoretical perspective (renormalization in QFT) it should be stressed that "running" of various parameters has actually been observed

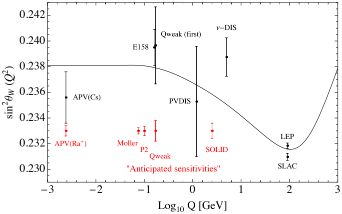
DELPHI, EPJC 46 (2006) 569



CMS PLB 803(2020)135263 35.9 fb^{-1} (13 TeV)



Davoudiasl et al., arXiv:1507.00352

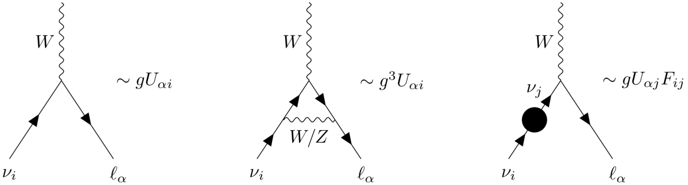


- What about neutrino sector?

Energy Dependence of the PMNS Matrix

$$\nu_\alpha(Q^2) = U_{\alpha i}(Q^2)\nu_i$$

$\alpha = e, \mu, \tau$
$i, j = 1, 2, 3$

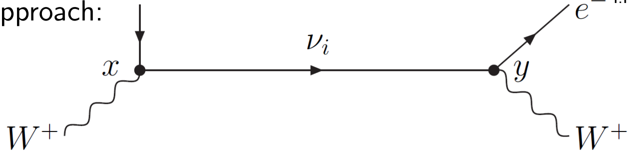


- when higher-order quantum effects are included, do $U_{\alpha i}$ matrix elements change relative to one another?
- higher-order electroweak corrections lead to very minor effects but in neutrino mass models $U_{\alpha i}$ can change in a flavor-dependent way
- this was already extensively studied for many models with heavy BSM degrees of freedom, see *e.g.* Antusch et al. (JHEP 03 (2005) 024) Casas et al. (NPB 573 (2000)) Goswami et al. (PRD 80 (2009)) Balaji et al. (PLB 481 (2000))
- we are however interested here in relatively light new physics where masses of new particles are comparable or lighter with respect to the neutrino energies at various experiments

Connection to Neutrino Experiments

M. Beuthe, arXiv:hep-ph/0109119
I.P. Volobuev, arXiv:1703.08070

QFT approach:



- amplitude: $\sum_i U^*_{\alpha i}\, e^{-i\frac{m_i^2-p^2}{2|\vec{p}|}L}\, U_{\beta i} \to P_{\alpha\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\, e^{-i\frac{m_j^2-m_k^2}{2|\vec{p}|}L}$
- Energy dependence of oscillation parameters:
- propagating neutrino is on shell ($Q^2 = p_\nu^2 = m_\nu^2 \approx 0$) $\to m_i$ in formula is the mass at $\sqrt{Q^2} = m_i$
- at production, contribution to the amplitude should be Lorentz invariant; in the rest frame of decaying pion $E = m_\pi \to U_{\alpha i} = U_{\alpha i}(Q_p^2 = m_\pi^2)$
- at detection site we take $U_{\beta i}(Q_d^2)$ where Q_d^2 is Mandelstam t which has no dependence on m_π^2

Neutrino Oscillations in Vacuum

2 flavors:

$$U(Q^2) = \begin{pmatrix} \cos\theta(Q^2) & \sin\theta(Q^2) \\ -\sin\theta(Q^2) & \cos\theta(Q^2) \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\tilde{\beta}(Q^2)} \end{pmatrix}$$

$$\theta(Q_p^2) \equiv \theta_p, \quad \theta(Q_d^2) \equiv \theta_d, \quad \text{and} \quad \tilde{\beta}(Q_d^2) - \tilde{\beta}(Q_p^2) \equiv \beta$$

Grossman, PLB 359 (1995)

$$P_{\mu e} = \sin^2(\theta_p - \theta_d) + \sin 2\theta_p \sin 2\theta_d \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right)$$

- β appears due to the CP-violating couplings in the new physics sector and has nothing to do with the nature of active neutrinos $\Longrightarrow$ it appears also in Dirac neutrino models
- β "shifts" the oscillation phase: $\Delta m^2 L/2E \to \Delta m^2 L/2E + \beta$

In the small new physics effect, $\epsilon_\theta = \theta_d - \theta_p \ll 1$ and $\beta = \epsilon_\beta + \mathcal{O}(\epsilon_\beta^2) \ll 1$:

$$P_{\mu e} = \epsilon_\theta^2 + \mathcal{O}(\epsilon_\theta^4) + \left[\sin^2 2\theta_d - \sin 4\theta_d \epsilon_\theta + \mathcal{O}(\epsilon_\theta^2)\right]\left[\sin^2\left(\frac{\Delta m^2 L}{4E}\right) + \frac{\epsilon_\beta}{2}\sin\left(\frac{\Delta m^2 L}{2E}\right) + \mathcal{O}(\epsilon_\beta^2)\right]$$

- In the zero-baseline limit, $L \to 0$, the new-physics effects are $\mathcal{O}(\epsilon_\theta^2, \epsilon_\beta^2)$
- for a finite baseline, instead, the new-physics effects are $\mathcal{O}(\epsilon_\theta, \epsilon_\beta)$

Neutrino Oscillations in Vacuum

3 flavors:

- more CP-odd phases when compared to 2-flavor case: β, α, $\delta(Q_p^2)$, $\delta(Q_d^2)$
- expressions for 3 flavor oscillation probabilities are lengthy but looking at $P_{\alpha\beta} - P_{\bar{\alpha}\bar{\beta}}$ gives simple and useful results:

$$\epsilon_{ij} \equiv \theta_{ij}(Q_d^2) - \theta_{ij}(Q_p^2),\ \epsilon_\delta = \delta(Q_d^2) - \delta(Q_p^2),\ \epsilon_\alpha = \alpha,\ \epsilon_\beta = \beta \qquad \Delta_{ij} \equiv \Delta m_{ij}^2 L/2E$$

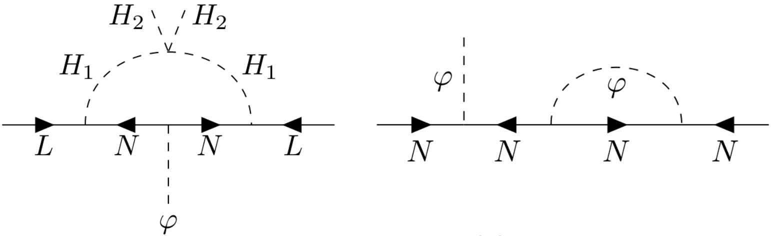
$$P_{\mu e} - P_{\bar{\mu}\bar{e}} \simeq -8\, J\, \Delta_{21} \sin^2\left(\frac{\Delta_{31}}{2}\right) \left[1 + \left(2\frac{\epsilon_{12}}{\sin 2\theta_{12}} + \epsilon_\alpha \frac{c_\delta}{s_\delta}\right) \frac{\cot(\Delta_{31}/2)}{\Delta_{21}}\right]$$

- in the $\delta \to 0$ limit, in which there is no standard CP violation in the lepton sector, new RG induced CP violation is still present and nonzero

$$P_{ee} - P_{\bar{e}\bar{e}} \simeq (\epsilon_\beta - \epsilon_\delta) \sin^2 2\theta_{13} \sin\Delta_{31} - \epsilon_\alpha \left(s_{12}^2 \sin^2 2\theta_{13} \sin\Delta_{31} - \sin^2 2\theta_{12} \sin\Delta_{21}\right)$$

- apparent violation of CPT symmetry but CPT invariance, $P(\nu_\alpha(Q_p^2) \to \nu_\alpha(Q_d^2)) = P(\bar{\nu}_\alpha(Q_d^2) \to \bar{\nu}_\alpha(Q_p^2))$, is satisfied
- for T2K and NOvA matter effects are included in our analysis

Model



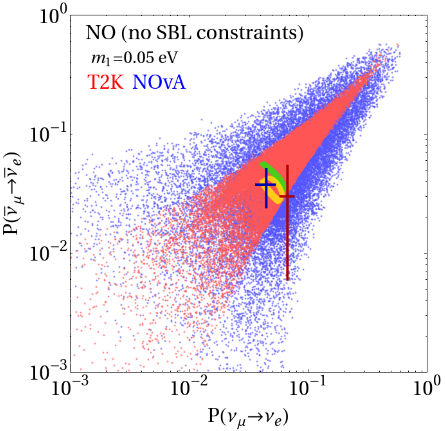
- We consider scotogenic-like model with $U(1)$ and $\mathbb{Z}_2$ symmetry

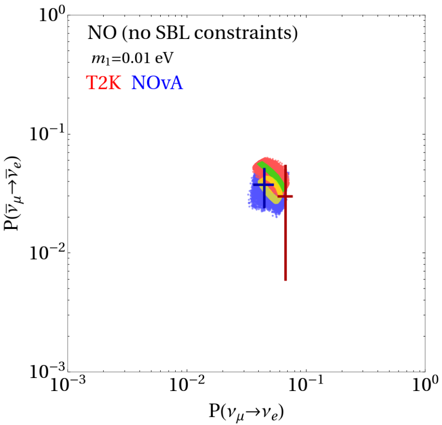
$$-\mathcal{L}_\nu^{(1)} = \overline{L} Y_\nu \tilde{H}_1 N_R + \varphi \overline{N_R^c} Y_N N_R + \mathrm{h.c.}$$

$$\text{for } M_N^i = Y_N^i v_\varphi / \sqrt{2} \ll M_{H,A}, \quad M_\nu \simeq \frac{v_\varphi}{16\sqrt{2}\pi^2} Y_\nu Y_N Y_\nu^T \ln \frac{M_H^2}{M_A^2}$$

- $16\pi^2 \beta(Y_N) \equiv 16\pi^2 \frac{dY_N}{d \ln |Q|} = 4 Y_N \left[Y_N^2 + \frac{1}{2}\mathrm{Tr}(Y_N^2) \right] \Longrightarrow$ obtain Y_N and hence M_ν at $\sqrt{Q_p^2}$ and $\sqrt{Q_d^2}$; Y_N has $\mathcal{O}(1)$ entries to maximize RG effect
- Y_ν is obtained using Casas-Ibarra parametrization

RGE Effect





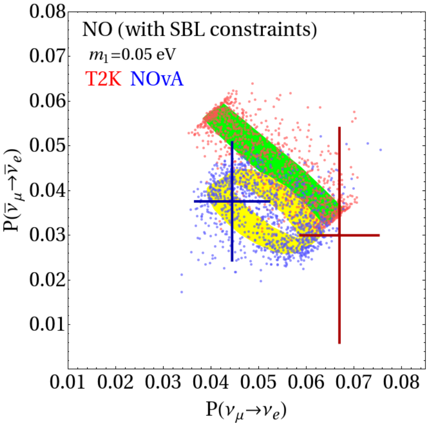
- we take parameters at Q_p^2 in accord with NuFIT, evolve mass matrix between Q_p^2 and Q_d^2 and extract oscillation parameters at the latter scale
- RG effect is largest for quasidegenerate masses

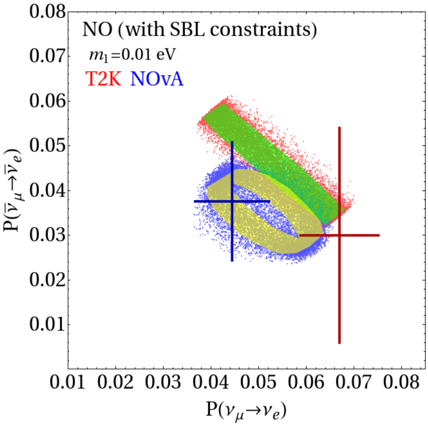
Constraints from Short Baseline Experiments

- RG running leads to zero baseline effects since $U(Q_p^2)U^\dagger(Q_d^2) \neq \mathbb{1}$
- experiments with high average neutrino energy are especially sensitive due to the larger difference between $Q_p^2 = m_\pi^2$ and Q_d^2
- while we found successful explanations or LSND and MiniBooNE, constraints from short baseline experiments rule out such possibilities

Experiment	E (GeV)	$\sqrt{Q_d^2}$ (GeV)	channel	constraint
ICARUS	17	3.94	$\nu_\mu \to \nu_e$	3.4×10^{-3}
CHARM-II	24	4.70	$\nu_\mu \to \nu_e$	2.8×10^{-3}
NOMAD	47.5	6.64	$\nu_\mu \to \nu_e$	7.4×10^{-3}
			$\nu_\mu \to \nu_\tau$	1.63×10^{-4}
NuTeV	250	15.30	$\nu_\mu \to \nu_e$	5.5×10^{-4}
			$\nu_e \to \nu_\tau$	0.1
			$\nu_\mu \to \nu_\tau$	9×10^{-3}

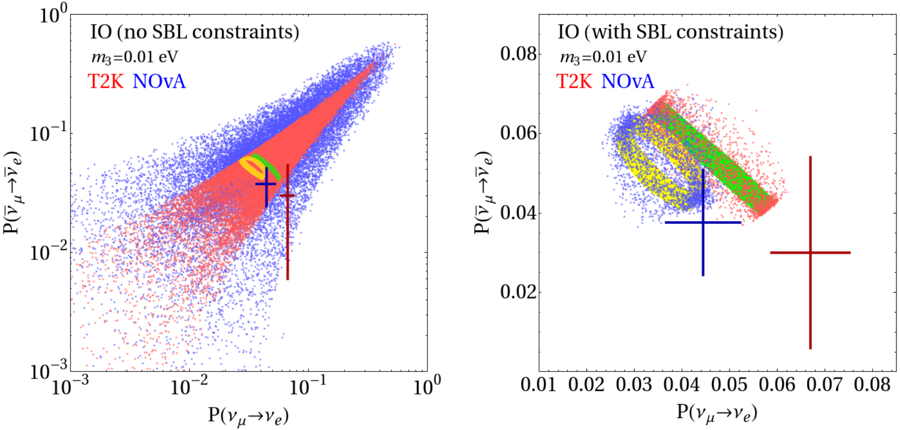
Constraints from Short Baseline Experiments





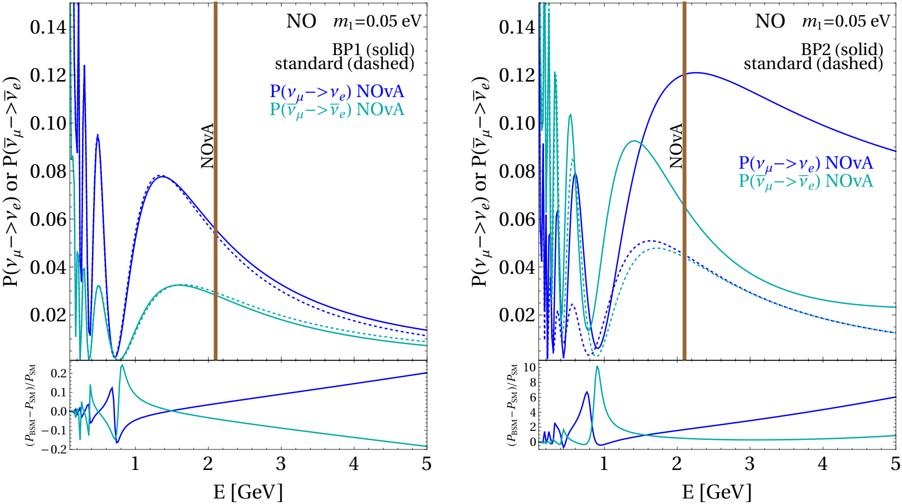
- short baseline constraints remove parameter points with strongest RG running

Inverted Ordering



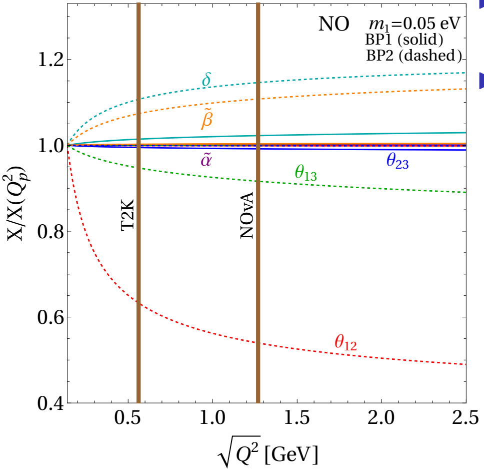
- for fixed lightest neutrino mass, RG running in the inverted ordering is stronger than in the normal one

Oscillation Probabilities

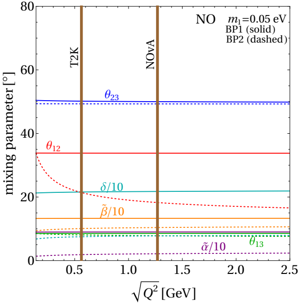


- BP1 best fits T2K and NOvA data and BP2 is strongly disfavoured by both short and long baseline experiments

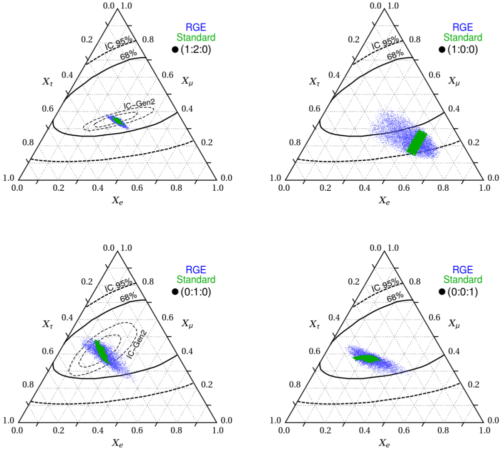
RG Evolution of the Mixing Parameters



- the strongest effects are in running of θ_{12}
- variation of θ_{12} relative to the other mixing angles θ_{13} and θ_{23} is enhanced by $|\Delta\theta_{12}/\Delta\theta_{13}|$, $|\Delta\theta_{12}/\Delta\theta_{23}| \propto |\Delta m^2_{31}/\Delta m^2_{21}|$

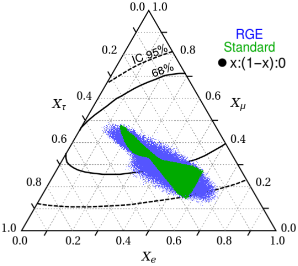


Ultra-High Energy Neutrinos - Flavor Ratios



- we postulate that Q_p^2 is above the detection scale in accelerator-based experiments; Q_d^2 is fixed to $(1000\,\mathrm{GeV})^2$
- detected neutrinos are incoherent superposition of mass eigenstates

$$P_{\alpha\beta} = \sum_{j=1}^{3} \left|U_{\alpha j}(Q_p^2)\right|^2 \left|U_{\beta j}(Q_d^2)\right|^2$$

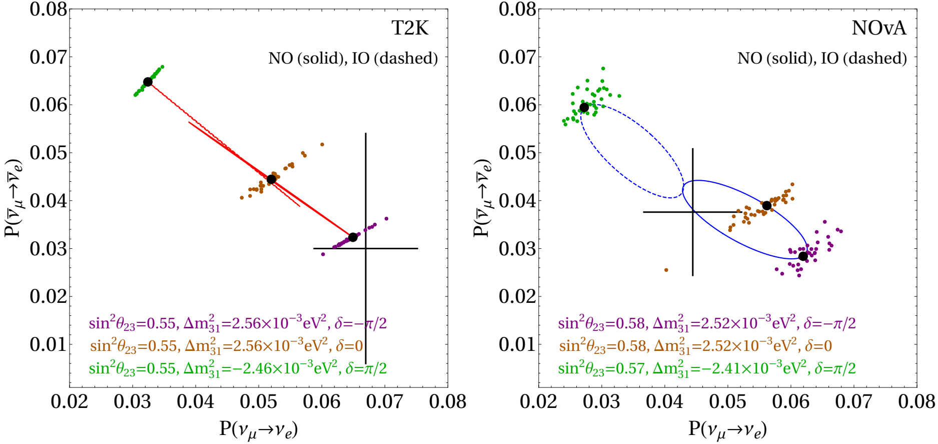


Conclusion

- we considered the effects of scale-dependent lepton mixing parameters at neutrino oscillation experiments
- mismatch between $U(Q_p^2)$ and $U(Q_d^2)$ leads to novel phenomenology
- signatures include difference between mixing angle measurements at various experiments, zero-baseline flavor transition, new sources of CP violation and apparent but not actual violation of CPT
- all of this can be induced by light new physics sector that does not need to be produced at experiments - such light particles can remain undiscovered and only impact neutrino experiments through quantum corrections that induce non-trivial energy depedence of $U(Q^2)$
- we showed that the renormalization group evolution of the mixing parameters can induce observable effects at T2K and NOvA and in the flavor composition of ultra-high energy neutrinos

BACKUP SLIDES

Bi-probabilities Plots



Oscillation Probabilities - T2K