Energy-Dependent Neutrino Mixing Parameters at Oscillation Experiments

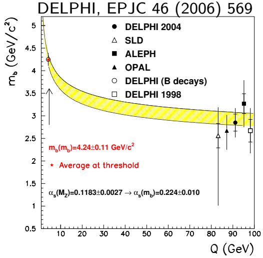
Vedran Brdar

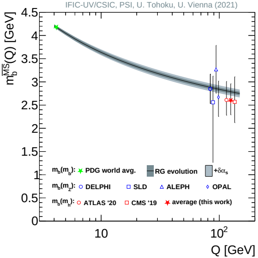
Fermilab

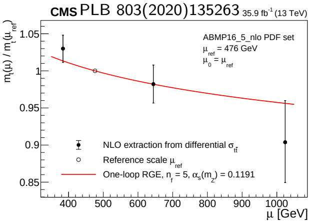
Northwestern University

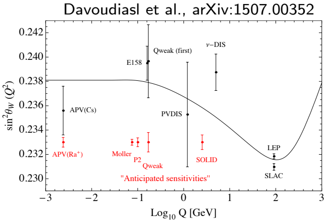
Examples for Running in SM

- parameters in the Standard Model and Beyond are energy dependent







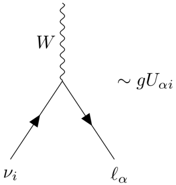


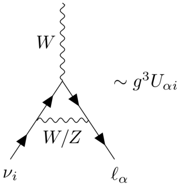
What about the Neutrino Sector?

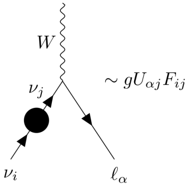
Energy Dependence of the PMNS Matrix

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

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







- 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))

Energy-Dependent Neutrino Mixing Parameters at Oscillation Experiments

K. S. Babu,[1] Vedran Brdar,[2,3] André de Gouvêa,[2] and Pedro A. N. Machado[3]

[1] *Department of Physics, Oklahoma State University, Stillwater, OK, 74078, USA*

[2] *Northwestern University, Department of Physics & Astronomy, 2145 Sheridan Road, Evanston, IL 60208, USA*

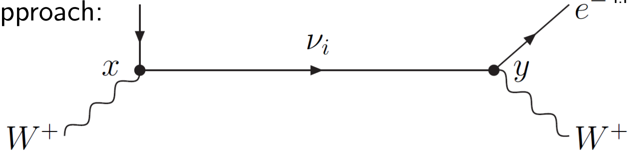
[3] *Theoretical Physics Department, Fermilab, P.O. Box 500, Batavia, IL 60510, USA*

Neutrino mixing parameters are subject to quantum corrections and hence are scale dependent. This means that the mixing parameters associated to the production and detection of neutrinos need not coincide since these processes are characterized by different energy scales. We show that, in the presence of relatively light new physics, the scale dependence of the mixing parameters can lead to observable consequences in long-baseline neutrino oscillation experiments, such as T2K and NOvA, and in neutrino telescopes like IceCube. We discuss some of the experimental signatures of this scenario, including zero-baseline flavor transitions, new sources of CP-invariance violation, and apparent inconsistencies among measurements of mixing angles at different experiments or oscillation channels. Finally, we present simple, ultraviolet-complete models of neutrino masses which lead to observable running of the neutrino mixing matrix below the weak scale.

Connection to Neutrino Experiments

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

QFT approach:



- amplitude: $\sum_i U^*_{\alpha i}\, e^{-i\frac{m_i^2-p^2}{2|\vec{p}|}L}\, U_{\beta i} \to P_{\alpha\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\, e^{-i\frac{m_j^2-m_k^2}{2|\vec{p}|}L}$

PRODUCTION: contribution to the amplitude should be Lorentz invariant; in the rest frame of decaying pion $E = m_\pi \to U_{\alpha i} = U_{\alpha i}(Q_p^2 = m_\pi^2)$

DETECTION: $U_{\beta i}(Q_d^2)$ where Q_d^2 has no dependence on m_π^2

PROPAGATION: neutrino is on shell $(Q^2 = p_\nu^2 = m_\nu^2 \approx 0)$
$\Longrightarrow m_i$ in formula is the mass at $\sqrt{Q^2} = m_i$

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
- β "shifts" the oscillation phase: $\Delta m^2 L/2E \to \Delta m^2 L/2E + \beta$

3 flavors:

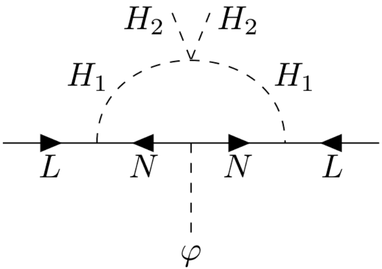
- CP-odd phases β, α, $\delta(Q_p^2)$, $\delta(Q_d^2)$

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

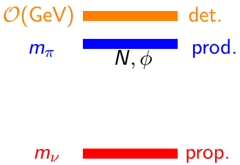
$$P_{\mu e} - P_{\bar{\mu}\bar{e}} \simeq -8\, J\, \Delta_{21} \sin^2\left(\frac{\Delta_{31}}{2}\right)\left[1 + \left(2\frac{\epsilon_{12}}{\sin 2\theta_{12}} + \epsilon_\alpha \frac{c_\delta}{s_\delta}\right)\frac{\cot(\Delta_{31}/2)}{\Delta_{21}}\right]$$

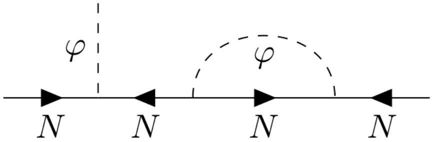
- in the $\delta \to 0$ limit, CP violation is present

The Model



	$U(1)_L$	$\mathbb{Z}_2$
L	0	$+$
H_2	0	$+$
H_1	$+1$	$-$
N_R	$+1$	$-$
ϕ	-2	$+$





Scotogenic-like realization

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

for $M_N^i = Y_N^i v_\varphi / \sqrt{2} \ll M_{H,A}$,

$$M_\nu \simeq \frac{v_\varphi}{16\sqrt{2}\pi^2} Y_\nu Y_N Y_\nu^T \ln \frac{M_H^2}{M_A^2}$$

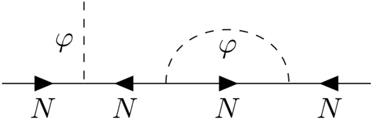
$$16\pi^2 \beta(Y_N) \equiv 16\pi^2 \frac{dY_N}{d\ln|Q|} = 4Y_N \left[Y_N^2 + \frac{1}{2}\mathrm{Tr}(Y_N^2)\right]$$

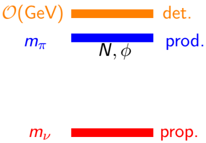
Strategy

$$H = \sum_i \frac{m_i^2}{2E} |\nu_i\rangle\langle\nu_i| + \sqrt{2} G_F N_e |\nu_e(Q^2 = 0)\rangle\langle\nu_e(Q^2 = 0)|$$

- at Q_p^2 scale mixing parameters are sampled using NuFIT values
- $Y_N \sim \mathcal{O}(1)$
- Y_ν is obtained using Casas-Ibarra parametrization

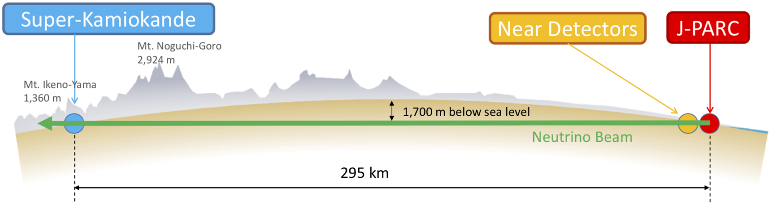
$$16\pi^2 \beta(Y_N) \equiv 16\pi^2 \frac{dY_N}{d \ln |Q|} = 4 Y_N \left[Y_N^2 + \frac{1}{2} \mathrm{Tr}(Y_N^2) \right]$$

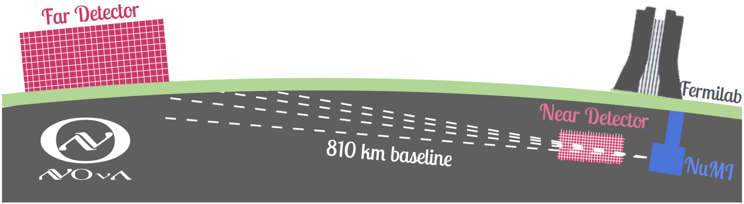




- at Q_d^2 scale, Y_N and hence $M_\nu(Q_d^2)$ is found
- diagonalize M_ν to get PMNS matrix at higher scale

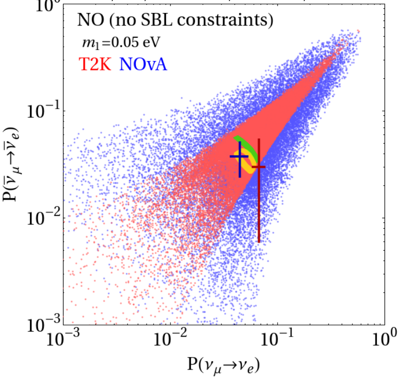
Long-Baseline Neutrino Experiments

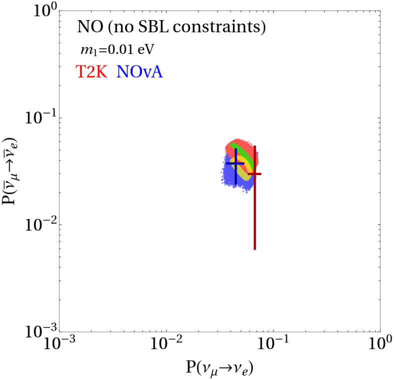




RGE Effect

Babu, VB, de Gouvea, Machado, arXiv:2108.11961





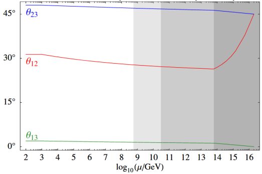
Ohlsson, Zhou, Nature Commun. 5 (2014) 5153

$$8\pi^2 \frac{\mathrm{d}}{\mathrm{d}t}\theta_{12} \approx -C_\kappa y_\tau^2 \frac{m_1^2}{\Delta m_{21}^2} s_{23}^2 \sin 2\theta_{12}$$

$$8\pi^2 \frac{\mathrm{d}}{\mathrm{d}t}\theta_{13} \approx -C_\kappa y_\tau^2 \frac{m_1^2}{\Delta m_{31}^2} c_{23}^2 \sin 2\theta_{13}$$

$$8\pi^2 \frac{\mathrm{d}}{\mathrm{d}t}\theta_{23} \approx -C_\kappa y_\tau^2 \frac{m_1^2}{\Delta m_{31}^2} \sin 2\theta_{23}$$

Antusch et al. (JHEP 03 (2005) 024)



Constraints from Short Baseline Experiments

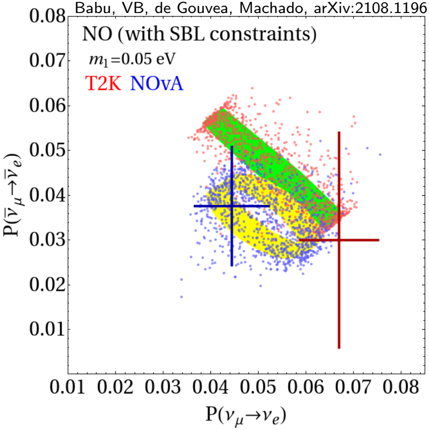
$$P_{\mu e} = \sin^2(\theta_p - \theta_d) + \sin 2\theta_p \sin 2\theta_d \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right)$$

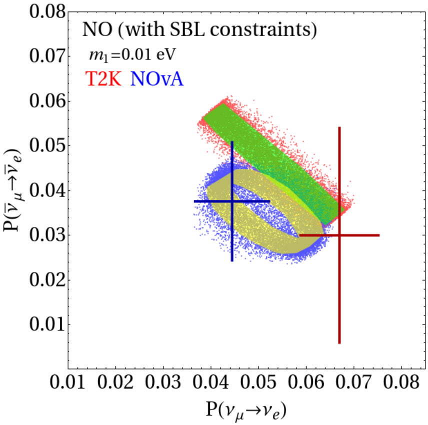
- experiments with high average neutrino energy are especially sensitive due to the larger difference between $Q_p^2 = m_\pi^2$ and Q_d^2
- while we found successful explanations or LSND and MiniBooNE, constraints from short baseline experiments rule out such possibilities

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

Babu, VB, de Gouvea, Machado, arXiv:2108.11961

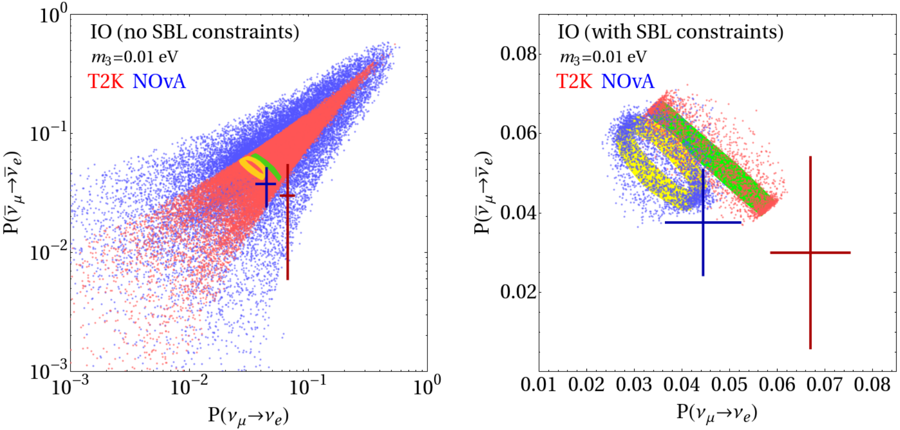




- short baseline constraints remove parameter points with strongest running

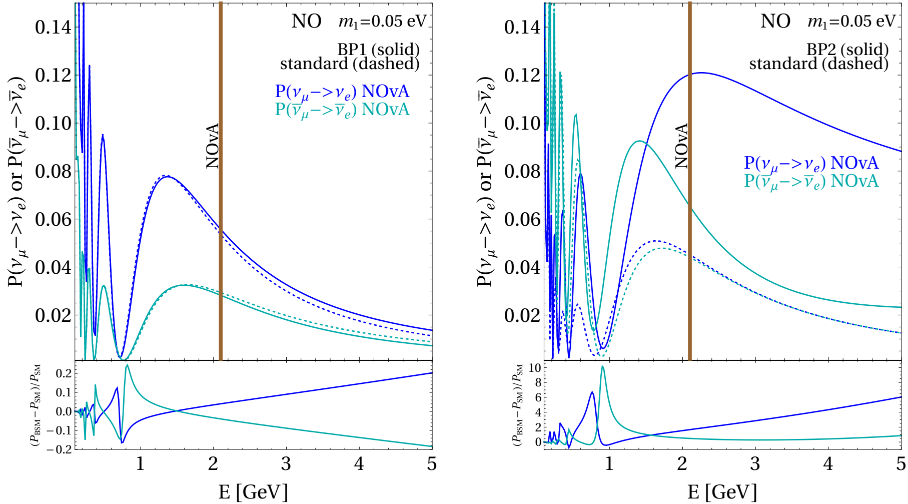
Inverted Ordering Case

Babu, VB, de Gouvea, Machado, arXiv:2108.11961



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

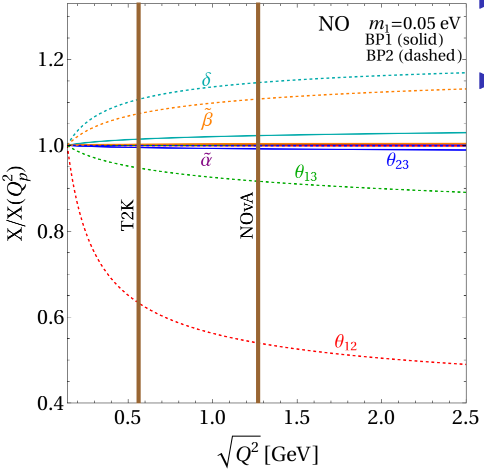
Oscillation Probabilities – NOvA



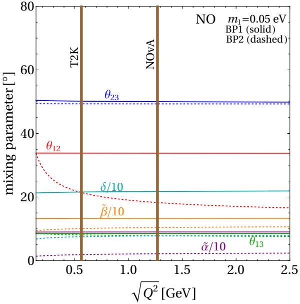
- BP1 best fits T2K and NOvA data and BP2 is strongly disfavoured by both short and long baseline experiments

RG Evolution of the Mixing Parameters

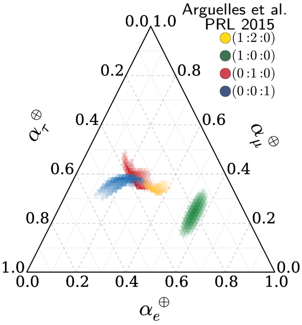
Babu, VB, de Gouvea, Machado, arXiv:2108.11961

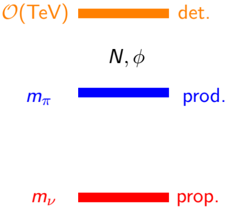


- the strongest effects are in running of θ_{12}
- variation of θ_{12} relative to the other mixing angles θ_{13} and θ_{23} is enhanced by $|\Delta\theta_{12}/\Delta\theta_{13}|$, $|\Delta\theta_{12}/\Delta\theta_{23}| \propto |\Delta m^2_{31}/\Delta m^2_{21}|$



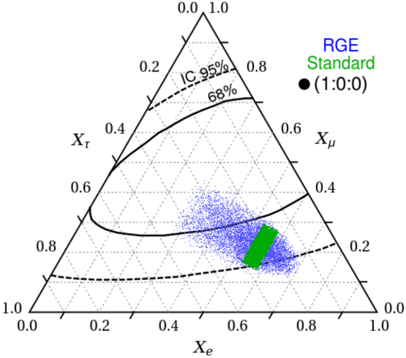
Ultra-High Energy Neutrinos - Flavor Ratios





- detected neutrinos are incoherent superposition of mass eigenstates

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



Summary

- mismatch between $U(Q_p^2)$ and $U(Q_d^2)$ leads to novel phenomenology

Summary

- mismatch between $U(Q_p^2)$ and $U(Q_d^2)$ leads to novel phenomenology
- this is induced by light new physics sector that does not need to be produced at experiments but only impacts through quantum corrections that induce non-trivial energy depedence of $U(Q^2)$

Summary

- mismatch between $U(Q_p^2)$ and $U(Q_d^2)$ leads to novel phenomenology
- this is induced by light new physics sector that does not need to be produced at experiments but only impacts through quantum corrections that induce non-trivial energy depedence of $U(Q^2)$
- signatures include:
  (*i*) difference between mixing angle measurements at various experiments (e.g. θ_{13} at reactor and beam experiments)
  (*ii*) zero-baseline flavor transition
  (*iii*) new sources of CP violation

Summary

- mismatch between $U(Q_p^2)$ and $U(Q_d^2)$ leads to novel phenomenology
- this is induced by light new physics sector that does not need to be produced at experiments but only impacts through quantum corrections that induce non-trivial energy depedence of $U(Q^2)$
- signatures include:
  (i) difference between mixing angle measurements at various experiments (e.g. θ_{13} at reactor and beam experiments)
  (ii) zero-baseline flavor transition
  (iii) new sources of CP violation
- 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

Summary

- mismatch between $U(Q_p^2)$ and $U(Q_d^2)$ leads to novel phenomenology
- this is induced by light new physics sector that does not need to be produced at experiments but only impacts through quantum corrections that induce non-trivial energy depedence of $U(Q^2)$
- signatures include:
  (*i*) difference between mixing angle measurements at various experiments (e.g. θ_{13} at reactor and beam experiments)
  (*ii*) zero-baseline flavor transition
  (*iii*) new sources of CP violation
- 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
- neutrino mass models are testable at oscillation experiments!