Probing NLO Effects at Neutrino Experiments

Vedran Brdar

Outline

- Energy-dependent Neutrino Mixing Parameters

- Towards Measuring CP Violation with Solar Neutrinos

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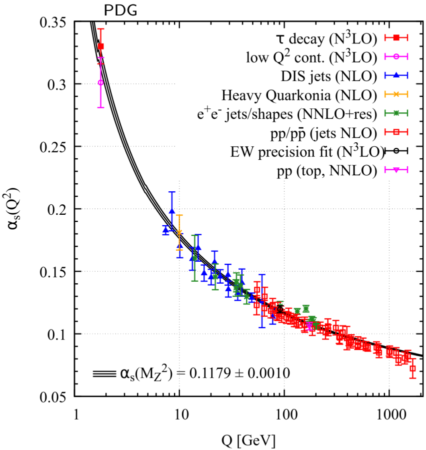
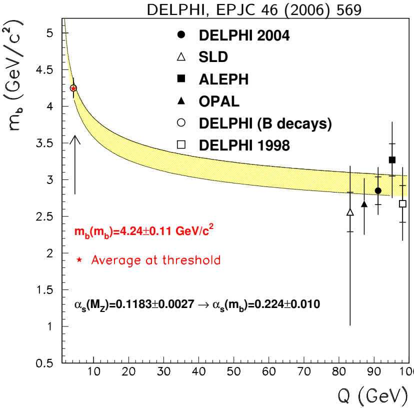
Energy-Dependence of parameters in the Standard Model



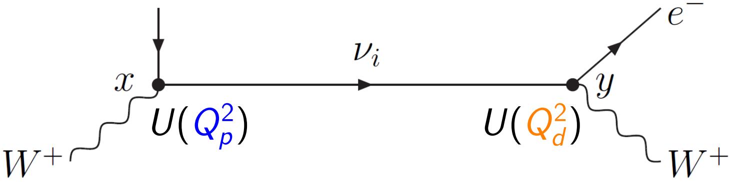


What about the Neutrino Sector?

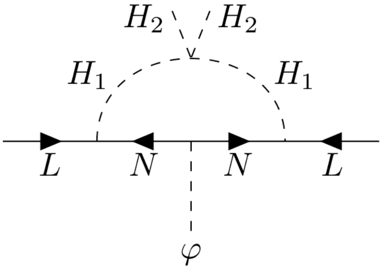
Energy-Dependent Neutrino Mixing Parameters

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

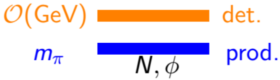
Babu, VB, de Gouvea, Machado, PRD 2022

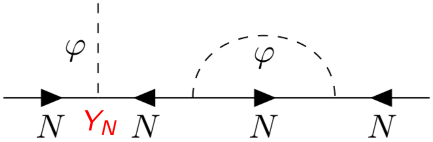


$$U_{\alpha j} \neq U_{\beta j}$$



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





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

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

- diagonalize M_ν to get $U(Q^2)$

Oscillations in Vacuum. 2 Flavors

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

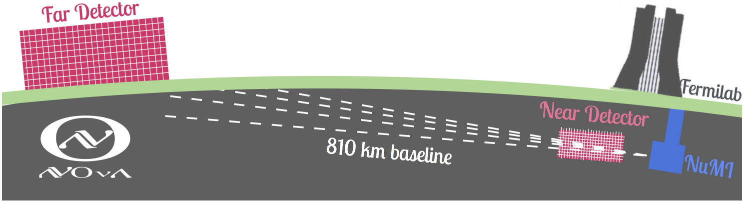
$$\theta(Q_p^2) \equiv \theta_p, \quad \theta(Q_d^2) \equiv \theta_d, \quad \text{and} \quad \tilde{\beta}(Q_d^2) - \tilde{\beta}(Q_p^2) \equiv \beta$$

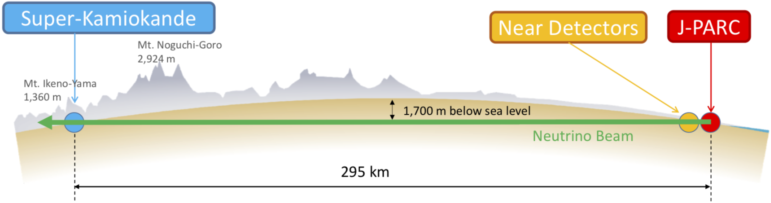
Grossman, PLB 359 (1995)

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

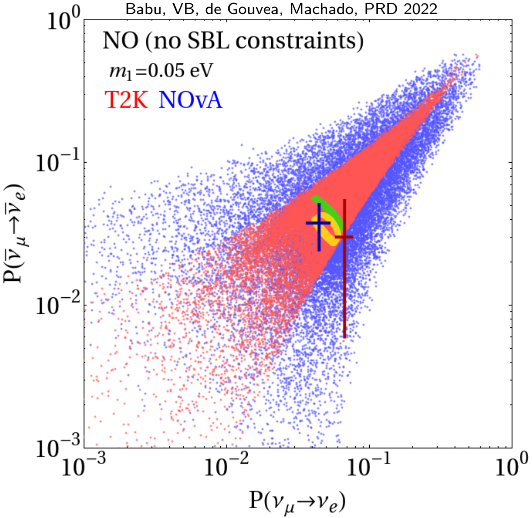
- smoking gun signature would be e.g. θ_{12} (solar) $\neq \theta_{12}$ (beam)

Long-Baseline Experiments





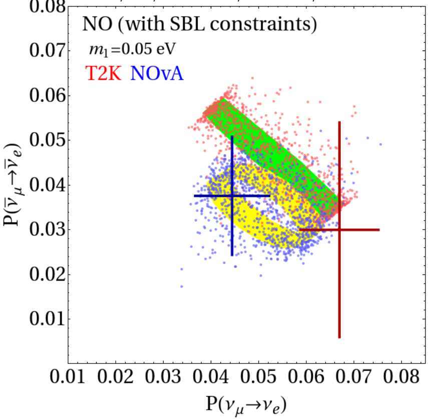
Imprint of the Energy-Dependence

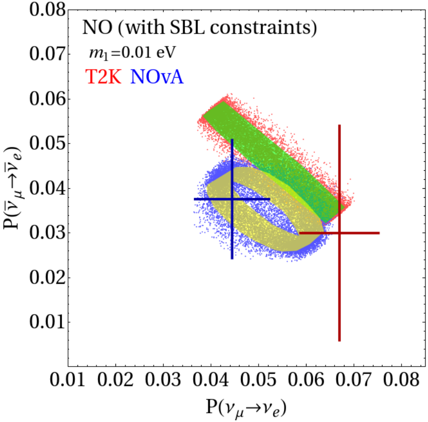


Constraints from Short Baseline Experiments

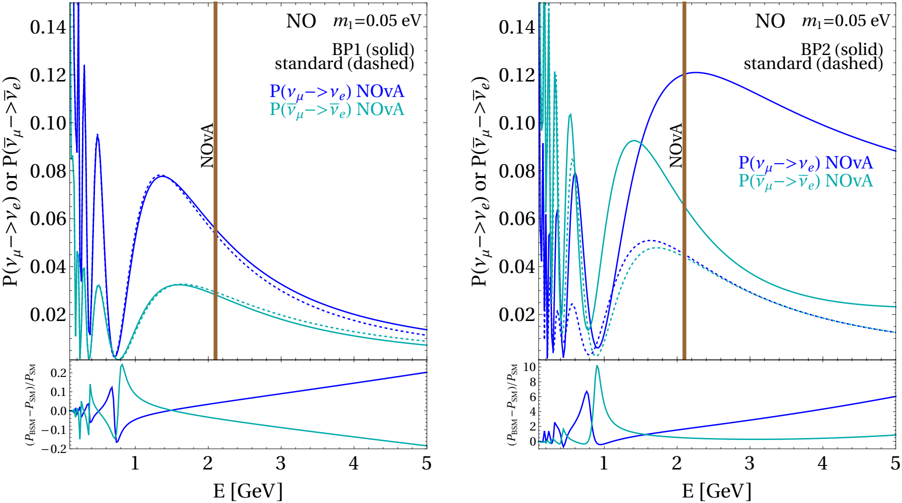
$$P_{\mu e} = \sin^2(\theta_p - \theta_d) + \sin 2\theta_p \sin 2\theta_d \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right)$$

Babu, VB, de Gouvea, Machado, PRD 2022

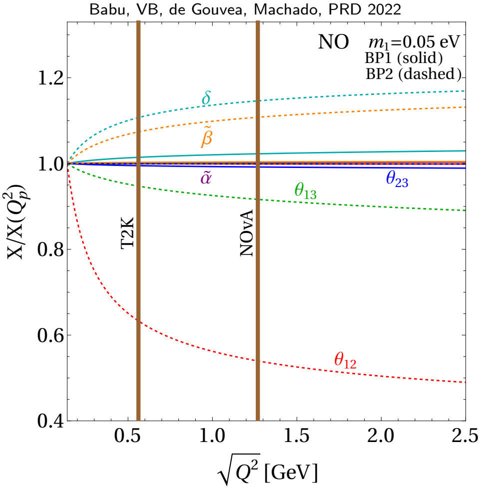




Oscillation Probabilities – NOvA



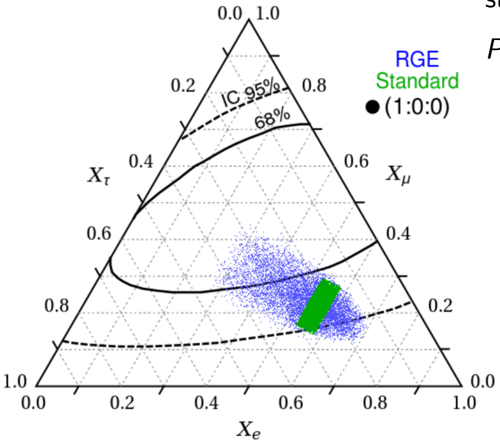
Energy-dependence of the Mixing Parameters



- the strongest effects are in the running of θ_{12}

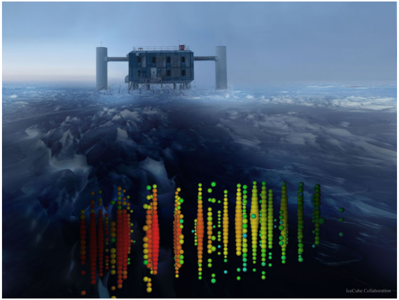
Ultra-High Energy Neutrinos - Flavor Ratios

Babu, VB, de Gouvea, Machado, PRD 2022



- detected neutrinos are incoherent superposition of mass eigenstates

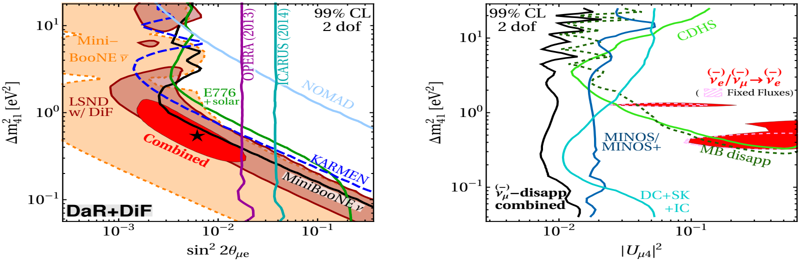
$$P_{\alpha\beta} = \sum_{j=1}^{3} \left|U_{\alpha j}(Q_p^2)\right|^2 \left|U_{\beta j}(Q_d^2)\right|^2$$



eV-scale ν_s for LSND and MiniBooNE Anomalies?

- Oscillation maxima for standard oscillations expected at
  - $L/E \sim 500$ km/GeV (from $\Delta m^2_{31} \sim 2.4 \times 10^{-3}\text{eV}^2$)
  - $L/E \sim 15000$ km/GeV (from $\Delta m^2_{21} \sim 7.5 \times 10^{-5}\text{eV}^2$)
- the minimal solution for LSND and MiniBooNE requires an additional mass squared difference $\Delta m^2_{41} \sim 1\,\text{eV}^2$; this calls for an introduction of eV-scale sterile neutrino (3+1 scheme)

Dentler et al., arXiv:1803.10661



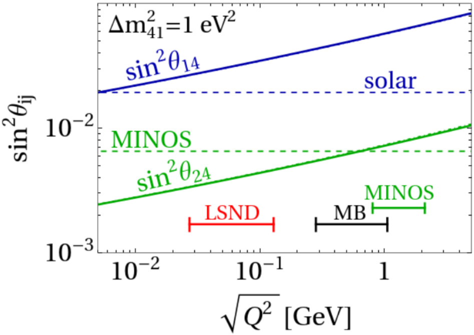
- while ν_e appearance data supports eV-scale ν_s explanation of LSND and MiniBooNE, ν_μ disappearance data puts such solution in strong tension

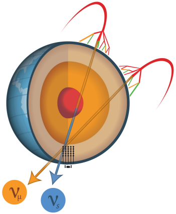
Energy Dependent $U_{\mathrm{PMNS}}+\nu_s$ for Addressing Anomalies

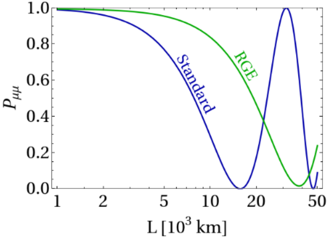
$\sin\theta_{14} = U_{14}$
$\sin\theta_{24}\cos\theta_{14} = U_{24}$

- $\tan\theta_{14} \simeq \frac{\mu_e}{M}$, $\tan\theta_{24} \simeq \frac{\mu_\mu}{M}$
- M decreases with energy if ν_s interacts with Z', like e^- mass in QED
- θ_{14} and θ_{24} increase with energy

Babu, VB, de Gouvêa, Machado, PRD 2023

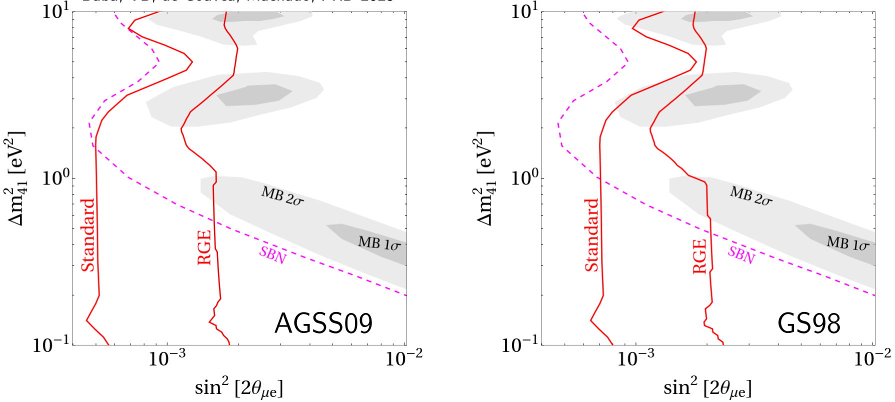






Energy Dependent $U_{\mathrm{PMNS}}+\nu_s$ for Addressing Anomalies

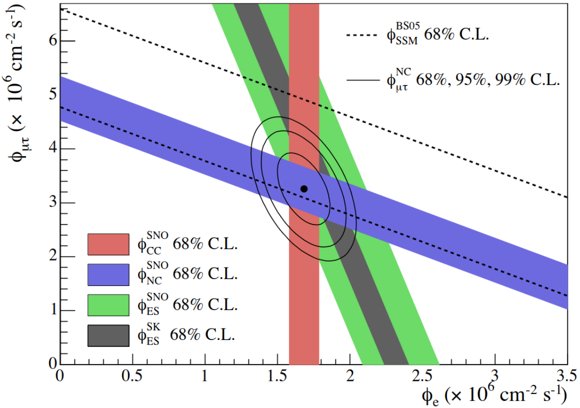
Babu, VB, de Gouvêa, Machado, PRD 2023



- Energy-dependent Neutrino Mixing Parameters

- Towards Measuring CP Violation with Solar Neutrinos

Solution to the Solar Neutrino Problem



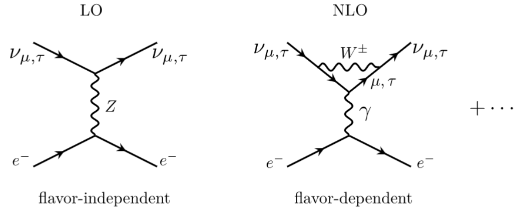
CC: $\nu_e d \to ppe^-$

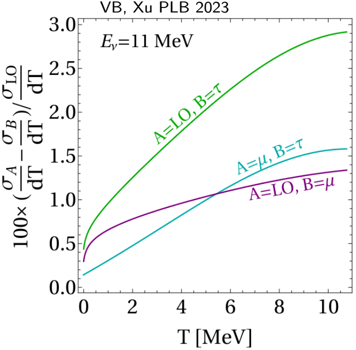
NC: $\nu_\alpha d \to pp\nu_\alpha$

ES: $\nu_\alpha e^- \to \nu_\alpha e^-$

- ϕ_e and $\phi_\mu + \phi_\tau$ are measured
- Can we access ϕ_μ and ϕ_τ separately and measure the full flavor composition of solar neutrinos?

Radiative Corrections for $\nu_\alpha - e^-$ Scattering





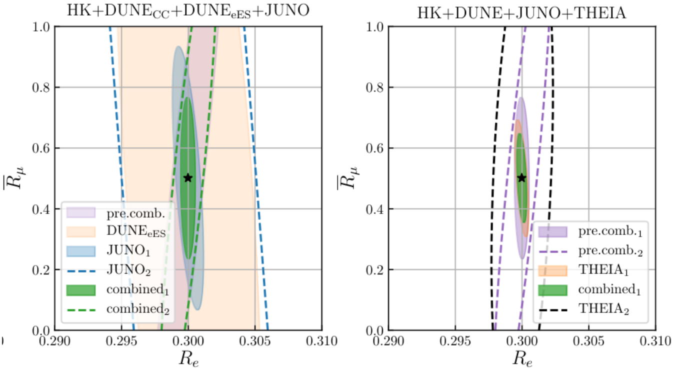
LO: $N_{\nu e} = \phi_e \sigma_e + (\phi_\mu + \phi_\tau)\sigma_{\mu\tau}$

$\sigma_{\mu\tau} = \sigma_\mu = \sigma_\tau$

NLO: $N_{\nu e} = \phi_e \sigma_e + \phi_\mu \sigma_\mu + \phi_\tau \sigma_\tau$

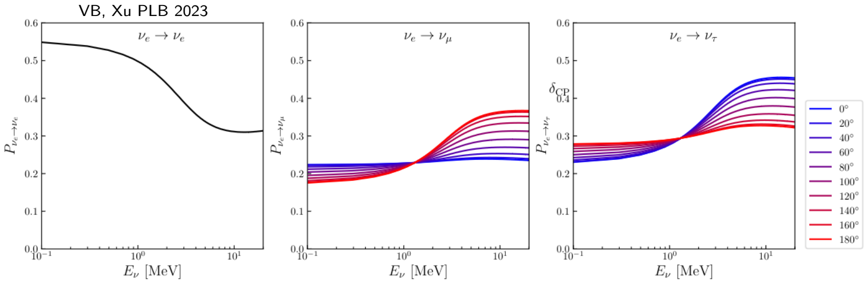
$\sigma_\mu \neq \sigma_\tau$

Measuring the Flavor Composition



$$R_e = \phi_e/\phi_{\text{total}} \qquad \overline{R}_\mu = \phi_\mu/(\phi_\mu + \phi_\tau)$$

Solar neutrinos as a probe of CP violation



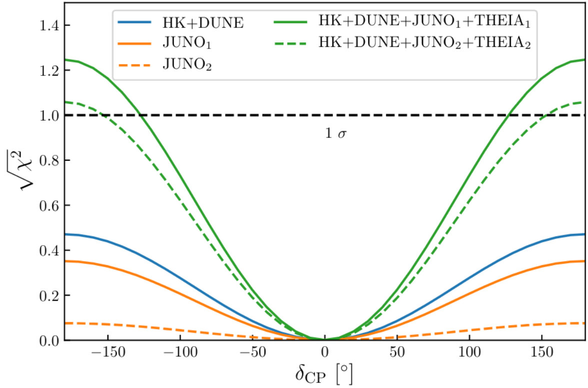
LO: $N_{\nu e} = \phi_e^0 P_{ee}\sigma_e + \phi_e^0 (P_{e\mu} + P_{e\tau})\sigma_{\mu\tau} = \phi_e^0 P_{ee}\sigma_e + \phi_e^0 (1 - P_{ee})\sigma_{\mu\tau}$

NLO: $N_{\nu e} = \phi_e^0 P_{ee}\sigma_e + \phi_e^0 P_{e\mu}\sigma_\mu + \phi_e^0 P_{e\tau}\sigma_\tau$

- sensitivity to $\delta_{\rm CP}$

Solar neutrinos as a probe of CP violation

VB, Xu PLB 2023



Summary

- mismatch between $U(Q_p^2)$ and $U(Q_d^2)$ leads to novel phenomenology: difference between mixing angle measurements at various experiments, zero-baseline flavor transition...
- it can be induced by light new particles that do not need to be produced but only impact through quantum corrections
- the leptonic CP violation can be probed with solar neutrinos when the flavor-dependent radiative corrections are taken into consideration
- upcoming JUNO and proposed THEIA will be the most sensitive experiments to test δ_{CP} via this method