Neutrino Decay, Sterile Mass Ordering and Quantumness at DUNE

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DUNE-India meeting

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Based on Dibya S. Chattopadhyay, A.Dighe, ++

1. Invisible neutrino decay

Invisible decay

$\nu_\alpha \rightarrow \psi\phi$

$\nu_\alpha \rightarrow \psi\psi\bar{\psi}$

- The inclusion of decay makes the effective Hamiltonian non-Hermitian:

$$\tilde{H} = H - i\Gamma/2$$

- The decay and the mass eigenstates need not be the same ⇒ *Mismatch*

$$[H, \Gamma] \neq 0$$

- Even if there's no mismatch in vacuum, due to matter effects, the components will invariably become non-commuting.

- Then $$e^{-i\tilde{H}t} \neq e^{-iHt}\, e^{-\Gamma/2}$$

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Decay of ν_3 mass eigenstate

- Strong constraints from solar neutrino data on ν_1 and ν_2 decay.

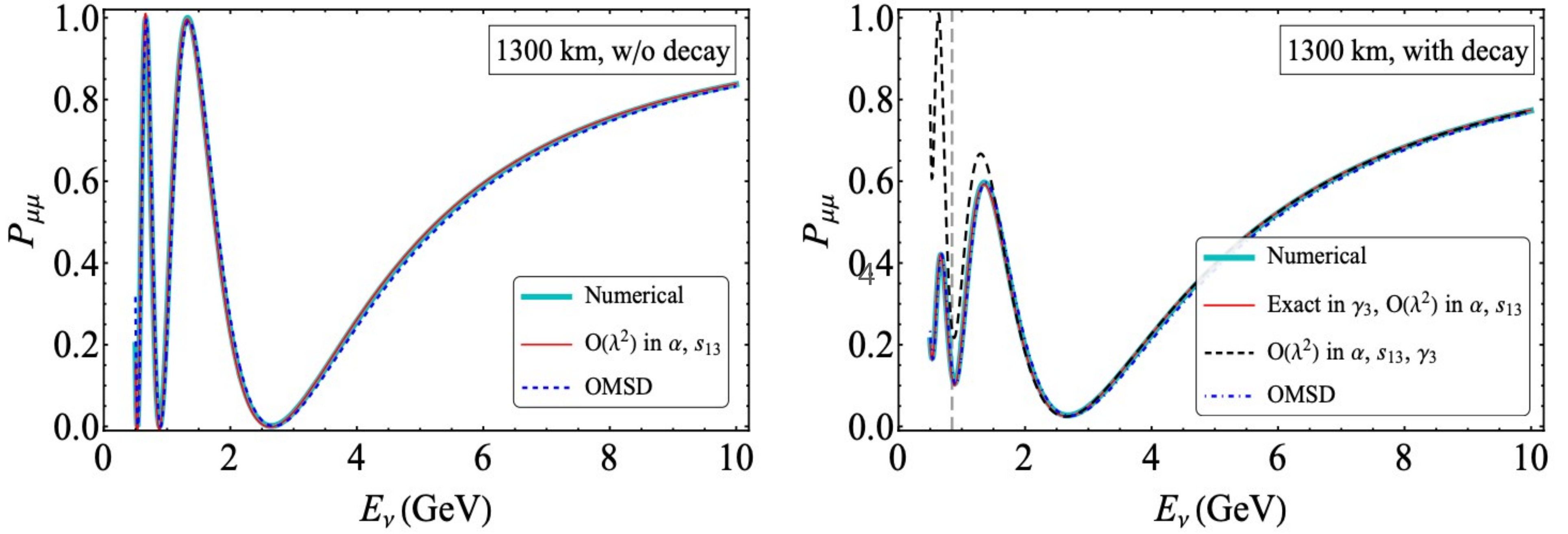
- Therefore, the special case where only ν_3 mass eigenstate in vacuum decays:

- $H_f = \frac{1}{2\,E_\nu}\,U\left[\Delta m_{31}^2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & 1-\gamma_3 \end{pmatrix}\right]U^\dagger + \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

$$\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}\,,\gamma_3 \equiv \frac{m_3}{\tau_3\,\Delta m_{31}^2}$$

- Current long-baseline constraints: $\frac{\tau_3}{m_3} > 1.5 \times 10^{-12}\ s/eV$

(Apparent) increase of $P_{\mu\mu}$ at oscillation dips due to decay!



- Non-zero oscillation dip in spite of maximal mixing of $\theta_{23} = 45°$.

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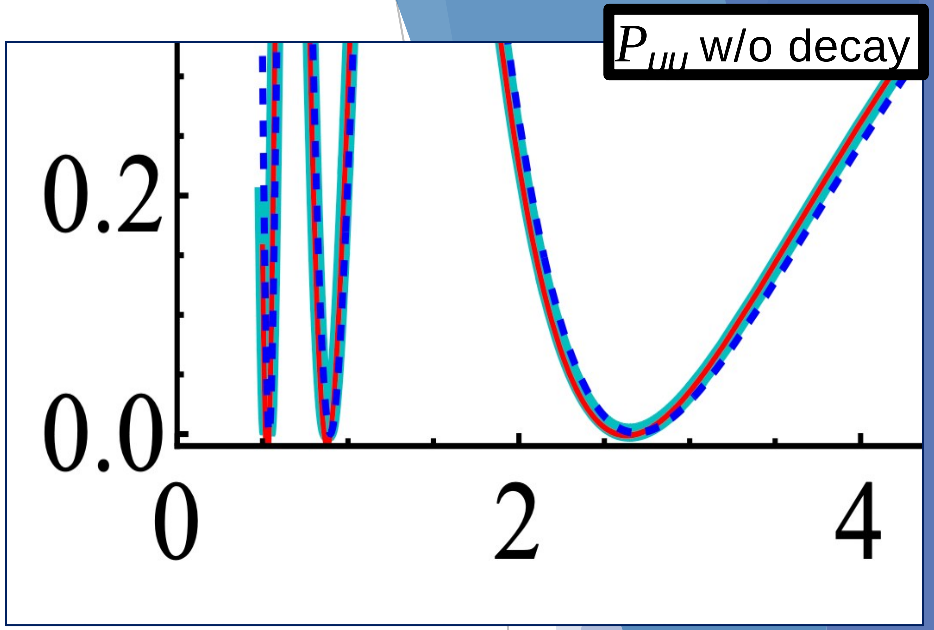
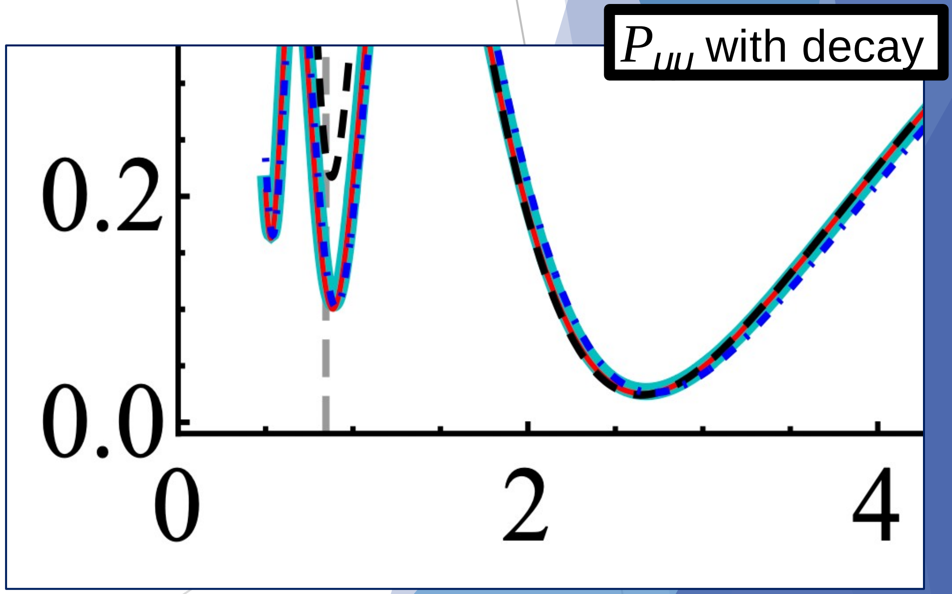
Analytical connection of $P_{\mu\mu}$ at dip to γ_3

$$P_{\mu\mu}(\text{first dip}) \simeq P_{\mu\mu}^{\text{leading}}(\Delta \simeq \pi/2) = \frac{1}{4}\left(1 - e^{-\pi\gamma_3}\right)^2 \geq 0$$

$$P_{\mu\mu}(\text{second dip}) \simeq P_{\mu\mu}^{\text{leading}}(\Delta \simeq 3\pi/2) \simeq \frac{1}{4}\left(1 - e^{-3\pi\gamma_3}\right)^2 \geq 0$$





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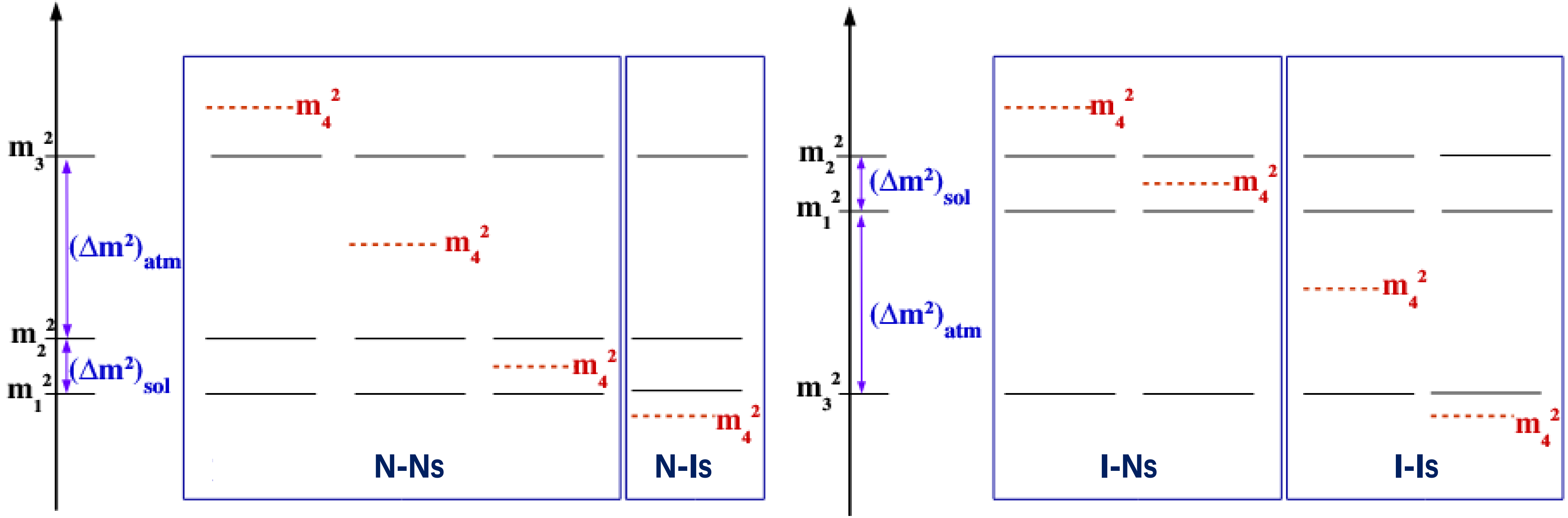
2. Sterile mass ordering

N vs I : sign of Δm_{31}^2

Ns vs Is : sign of Δm_{41}^2

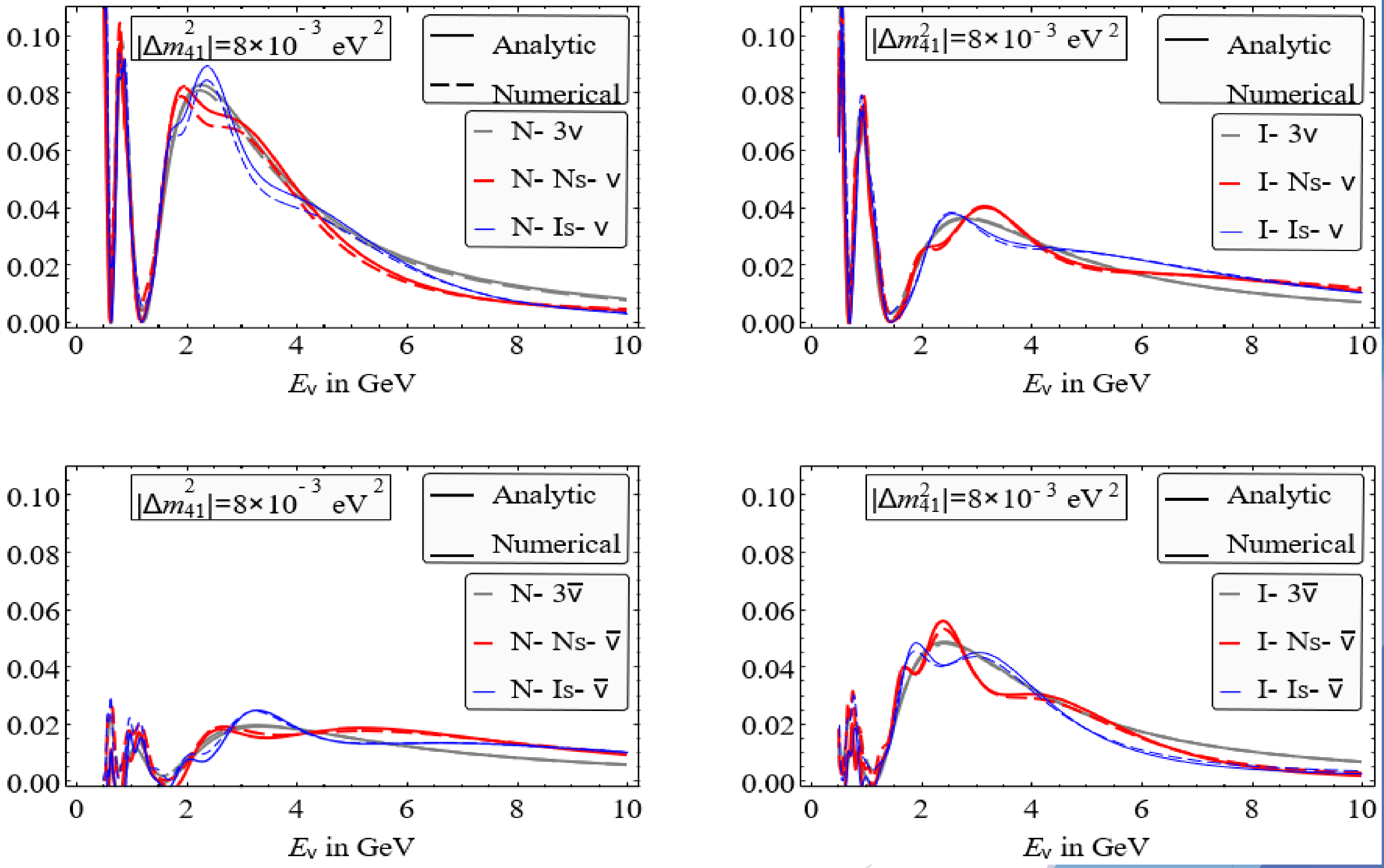


Peaks and Dips at DUNE

$P_{\mu e}$

$P_{\bar{\mu}\bar{e}}$

The effects of Mass Ordering in the Sterile sector is clearly visible.



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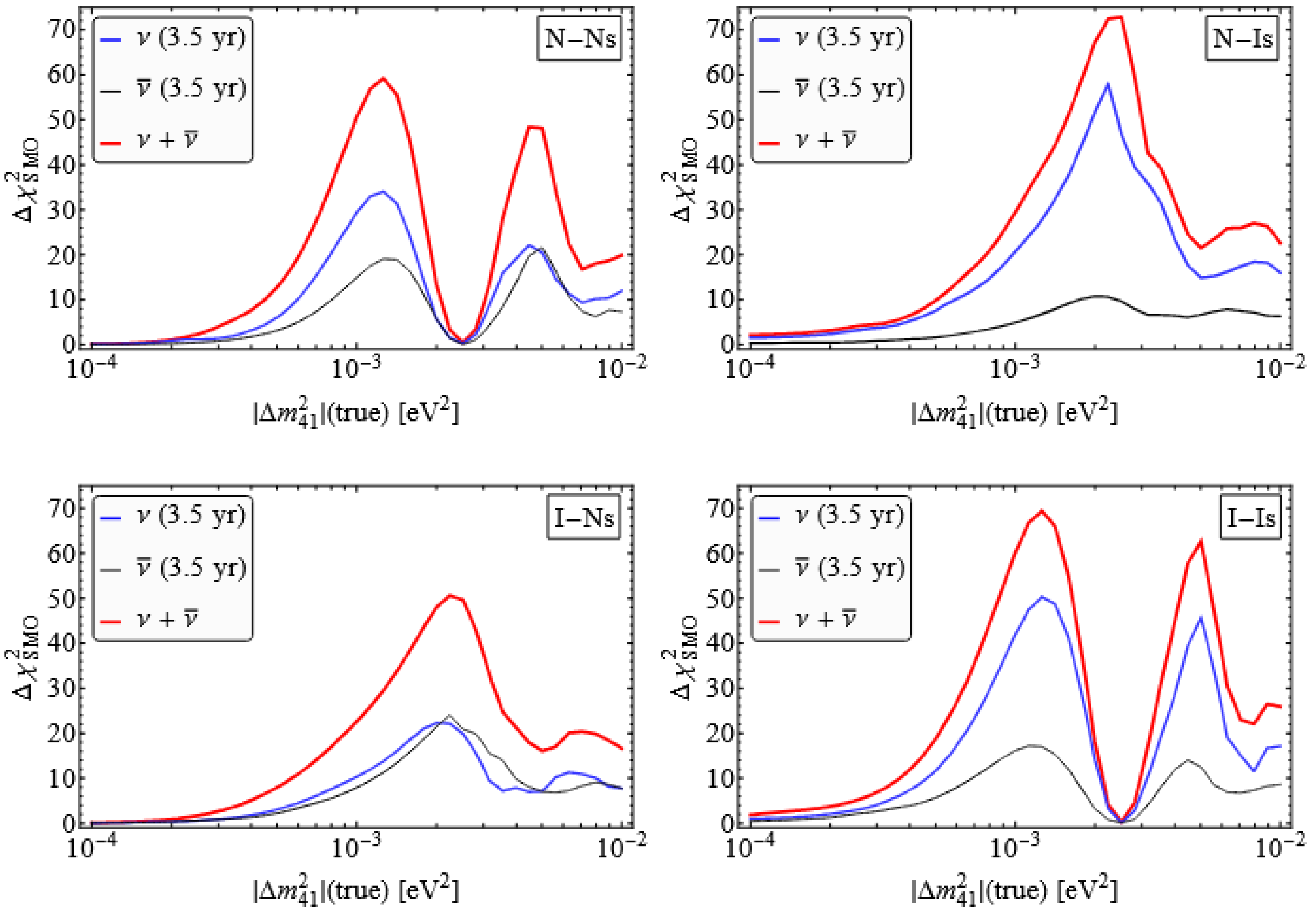
DUNE sensitivity to sterile mass ordering

DUNE is sensitive to sterile mass ordering in the range $|\Delta m^2| \sim 10^{-4} - 10^{-2}$eV^2



All the features in this sensitivity plot can be analytically understood

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3. Quantumness in neutrino oscillations

“Legett-Garg” measure:

$$C_{ij} \equiv < Q(t_i)\, Q(t_j) >$$

$$K_3 = C_{01} + C_{12} - C_{02}$$

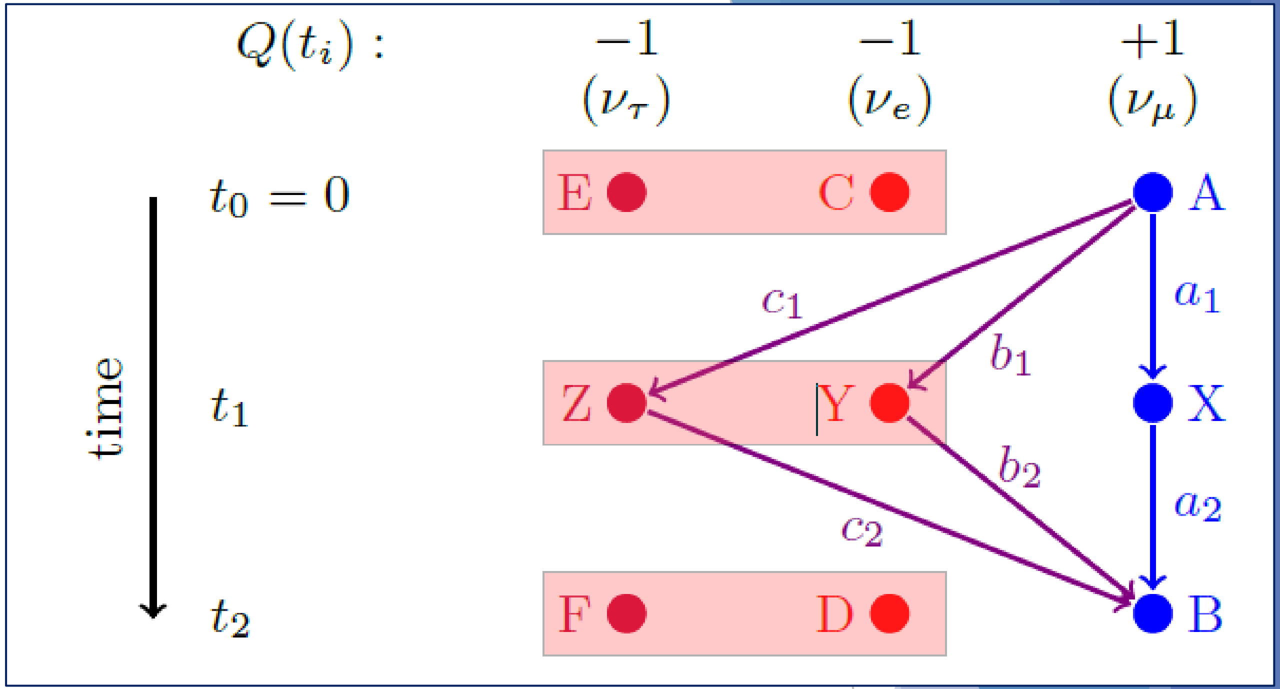
Classical: $K_3 \leq 1$

$K_3 > 1 \;\Rightarrow$ Quantum

<u>Three-ν generalization:</u>

$$\widetilde{K_3} = 2(P_{AX} + P_{XB} - P_{AB}) - 1$$

$$\widetilde{K_3} > 1 \Rightarrow \text{ Quantum}$$



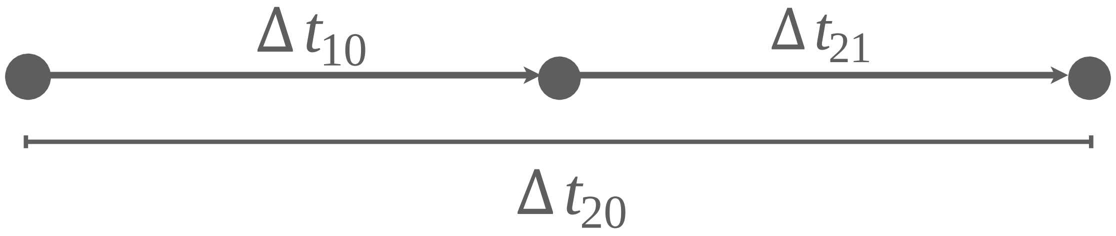
“Quantum mismatch” measure:
Survival probability should be the same with or without an intermediate observation

$$\widetilde{\delta P_{\mu\mu}} = P_{AB} - P_{AX}\, P_{XB} - (1 - P_{AX})(1 - P_{XB})$$

$$\widetilde{\delta P_{\mu\mu}} > 0 \;\Rightarrow \text{ Quantum}$$

Energy as a proxy for intermediate time

- No one is funding such an experiment, **yet!**



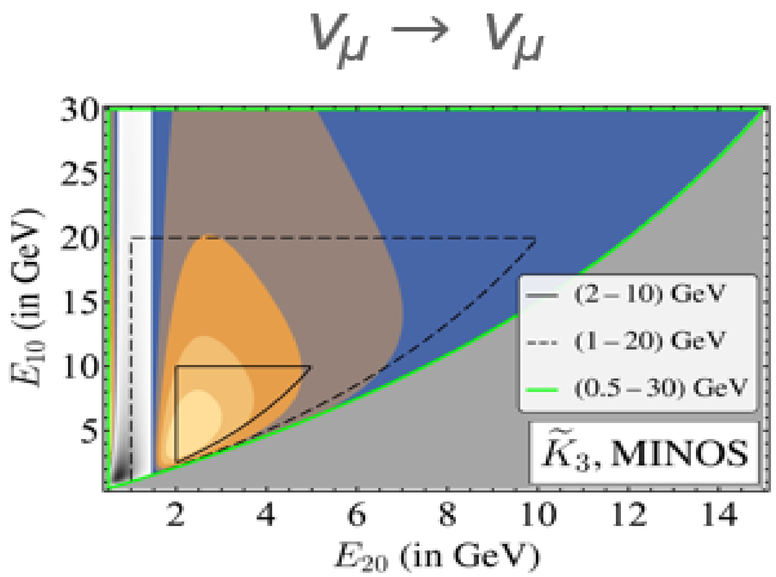
Using only
Special Relativity:
L/E dependence

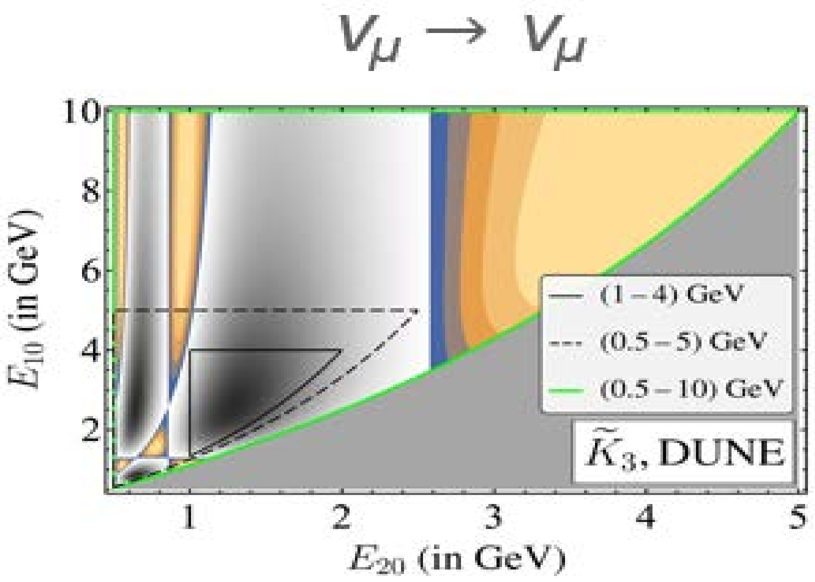
- Different energies can be used as proxies for different baselines…

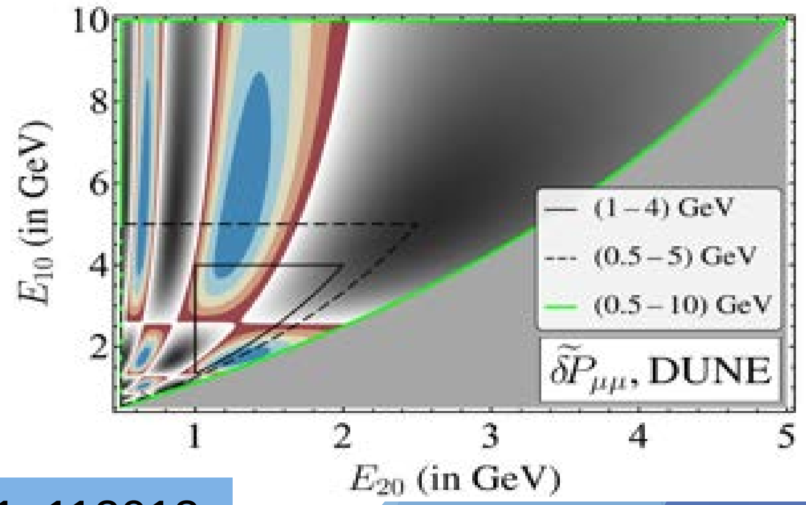
$$\Delta t_{10} + \Delta t_{21} = \Delta t_{20} \quad \Rightarrow \quad 1/E_{10} + 1/E_{21} = 1/E_{20}$$

Quantum measure suitable for DUNE

MINOS has an LG measurement, but hard for DUNE







“Quantum Mismatch” measure to the rescue:
Possible to determine quantumness at DUNE !

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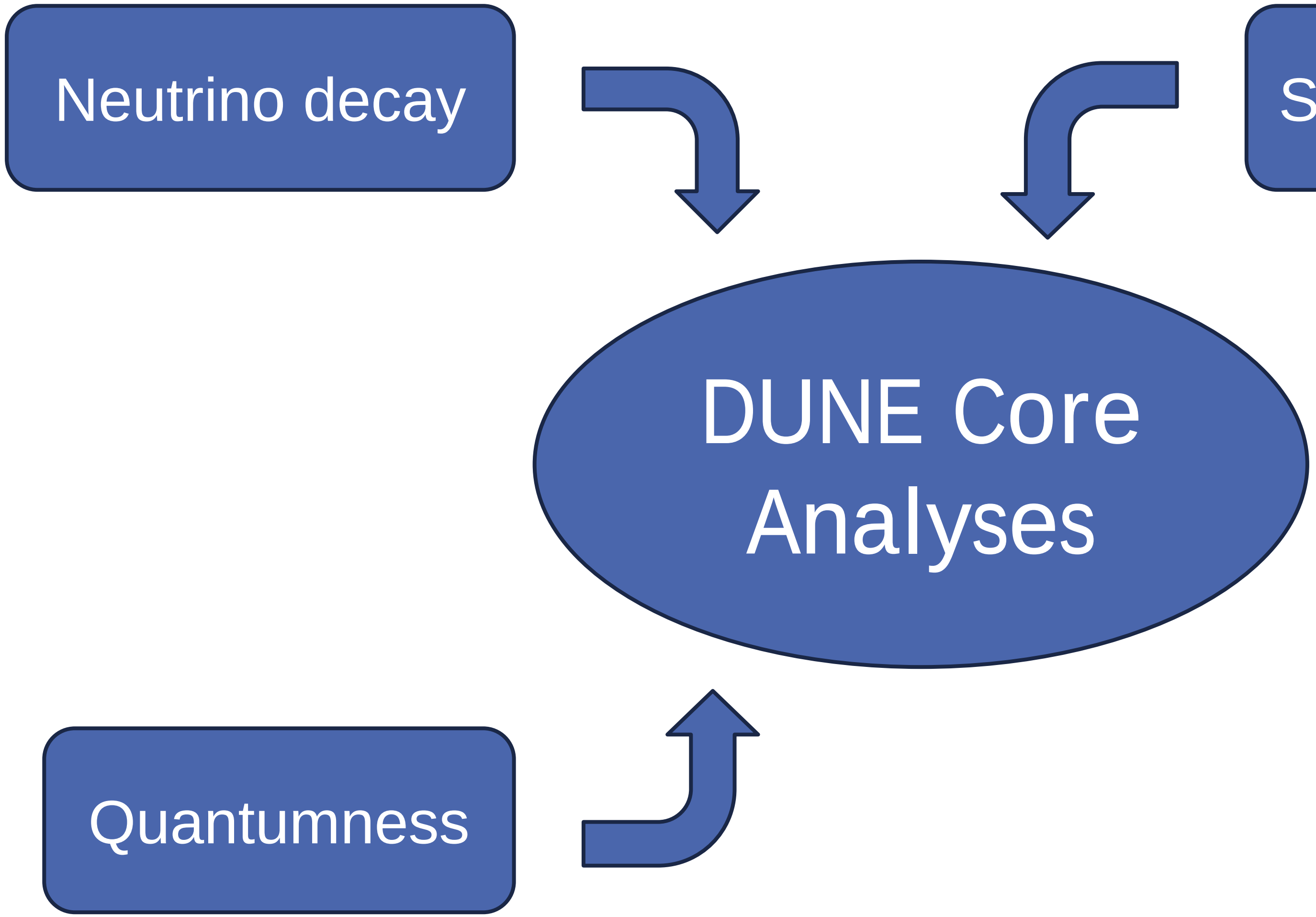
Neutrino decay
Sterile neutrinos
DUNE Core Analyses
Quantumness