Detecting CP Violation in the Presence of Nonstandard Neutrino Interactions

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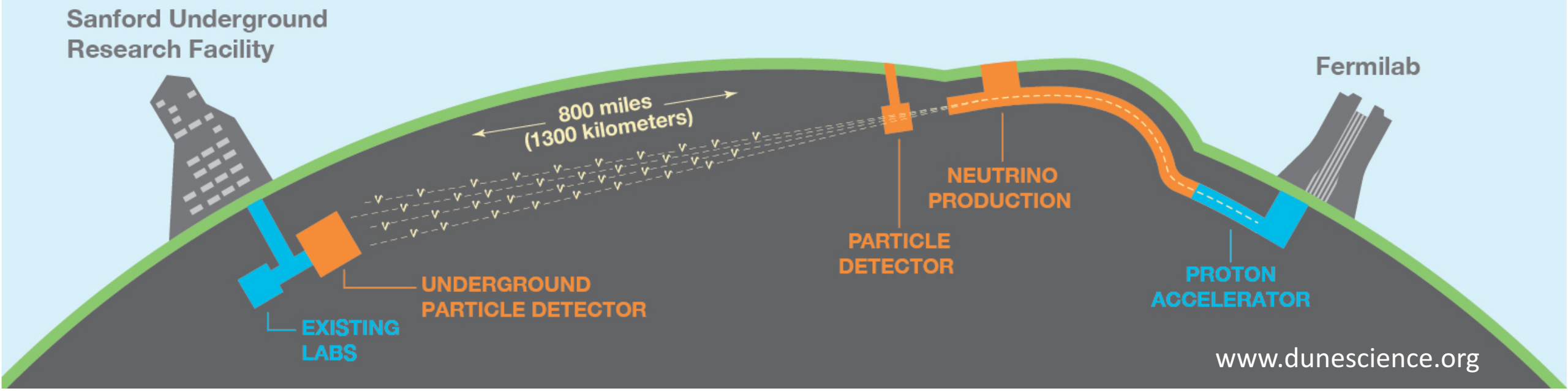
Based on arXiv:1806.09221 & on-going work

Measuring δ_{13} is a big goal for long-baseline experiments.



In vacuum:

If the probability $P(\nu_\mu \to \nu_e) \equiv P$ is different from $P(\bar{\nu}_\mu \to \bar{\nu}_e) \equiv \bar{P}$, then $\delta_{13} \neq 0, \pi$.

In matter:

Propagation through CP-violating potential $V \sim diag(1,0,0)$ generally gives $P \neq \bar{P}$.

Non-standard interactions further complicate things

Beyond-Standard Model physics → “Non-standard Neutrino Interactions” (NSI)

e.g. get off-diagonal elements with CP-violating phases:

$$V \sim \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}\,* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}\,* & \epsilon_{\mu\tau}\,* & \epsilon_{\tau\tau} \end{pmatrix} \qquad (\epsilon_{e\mu} = |\epsilon_{e\mu}| \exp(-i\delta_{e\mu}), \ldots)$$

Non-standard interactions further complicate things

Be NSI)

e

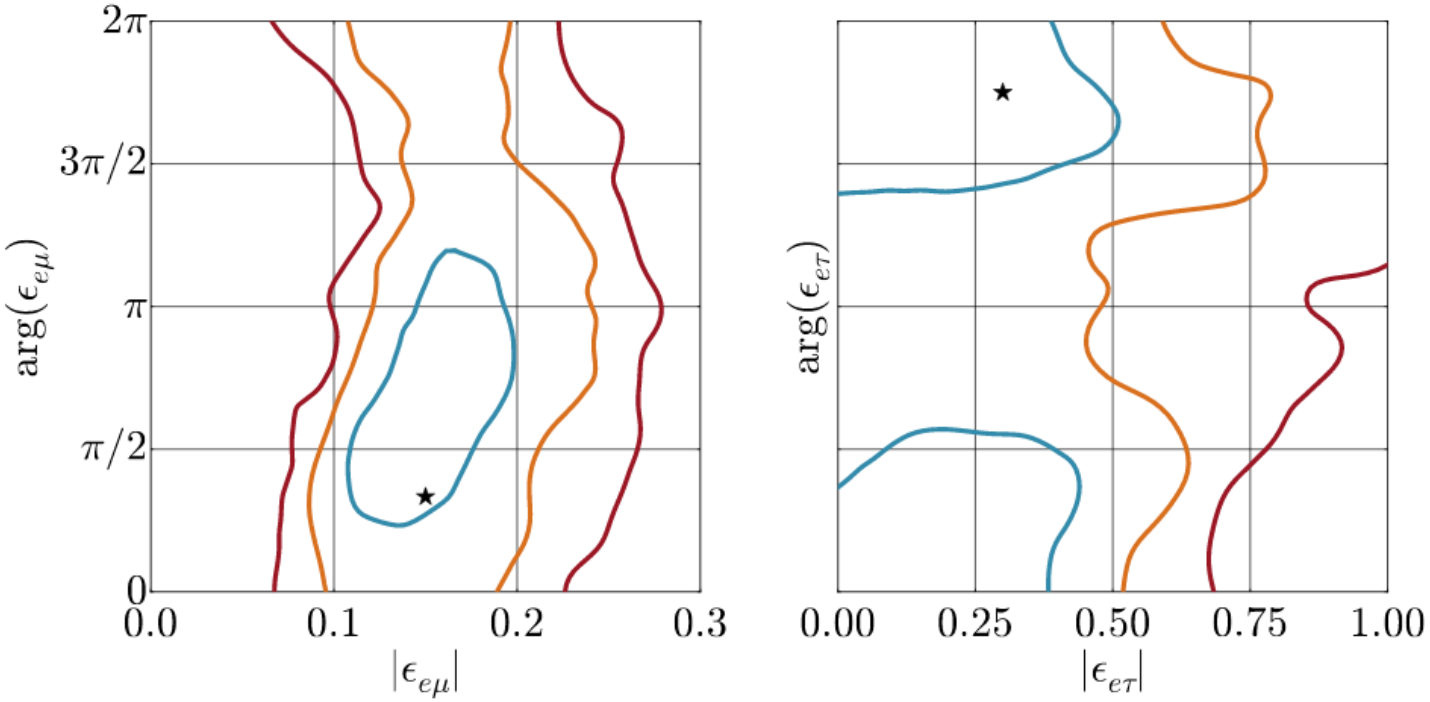
How can we tell whether CP is violated (and determine the underlying parameters) in the presence of nonstandard interactions?

$$V \sim \begin{pmatrix} \epsilon_{e\mu} * & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau} * & \epsilon_{\mu\tau} * & \epsilon_{\tau\tau} \end{pmatrix} \qquad (\epsilon_{e\mu} = |\epsilon_{e\mu}| \exp(-i\delta_{e\mu}), \ldots)$$

It’s common to look at sensitivity of given experiments based on specific parameter choices.

e.g. from de Gouvea & Kelly Nuclear Phys. B908 (2016) arXiv:1511.05562,

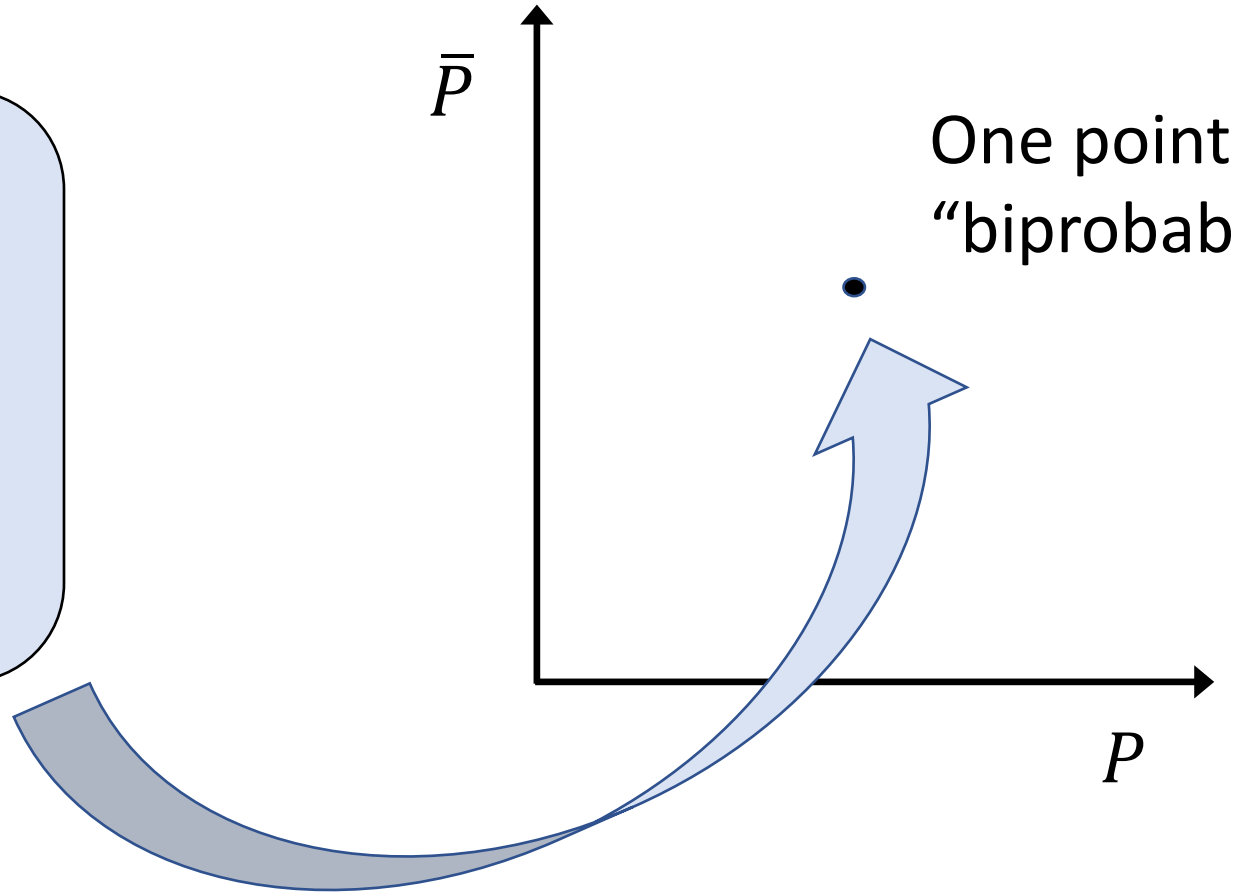
for $\delta_{13} = \pi/3$.



Important, but how to relate possible measurements with effect of individual parameters?

A useful way to visualize parameter degeneracies:

Model parameters
$(\theta_{12}, \delta_{13}, \ldots)$
and experimental
parameters (L, E, …)

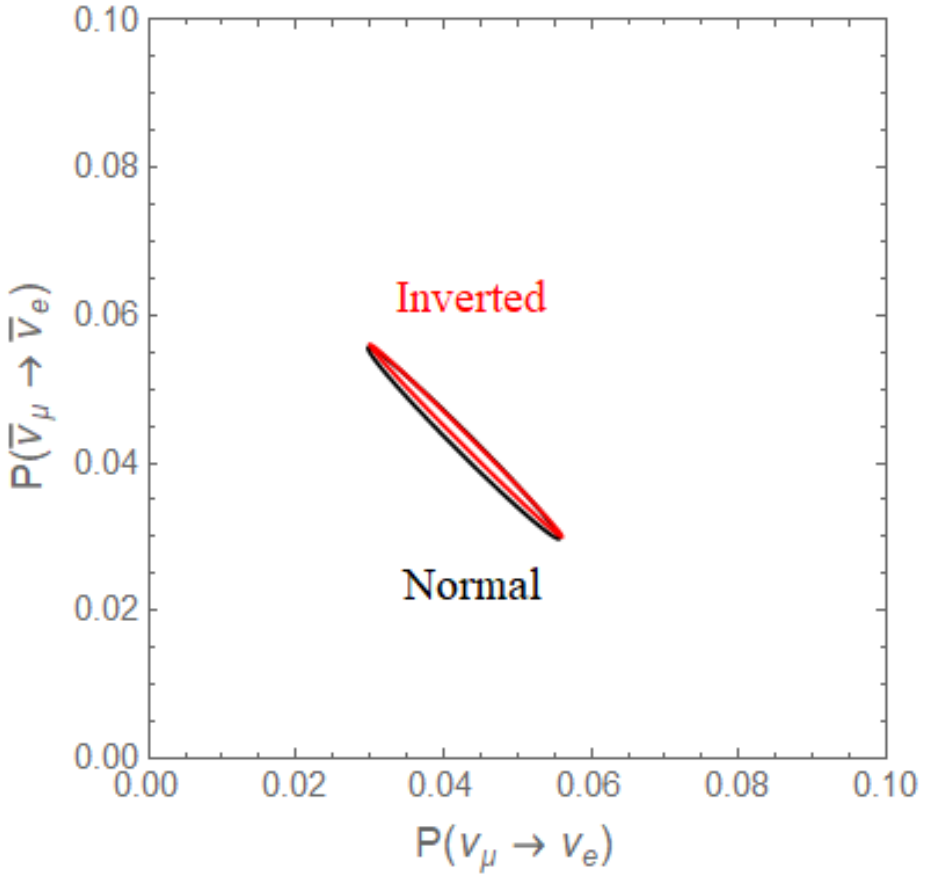


One point on
“biprobability” plot

For example, matter effects lift normal-inverted degeneracy:

[see JHEP 0110 (2001) 001, hep-ph/0108085]

Plot for every value of δ_{13} from 0 to 2π → traces out ellipse on biprobability plot:



Oscillations in vacuum

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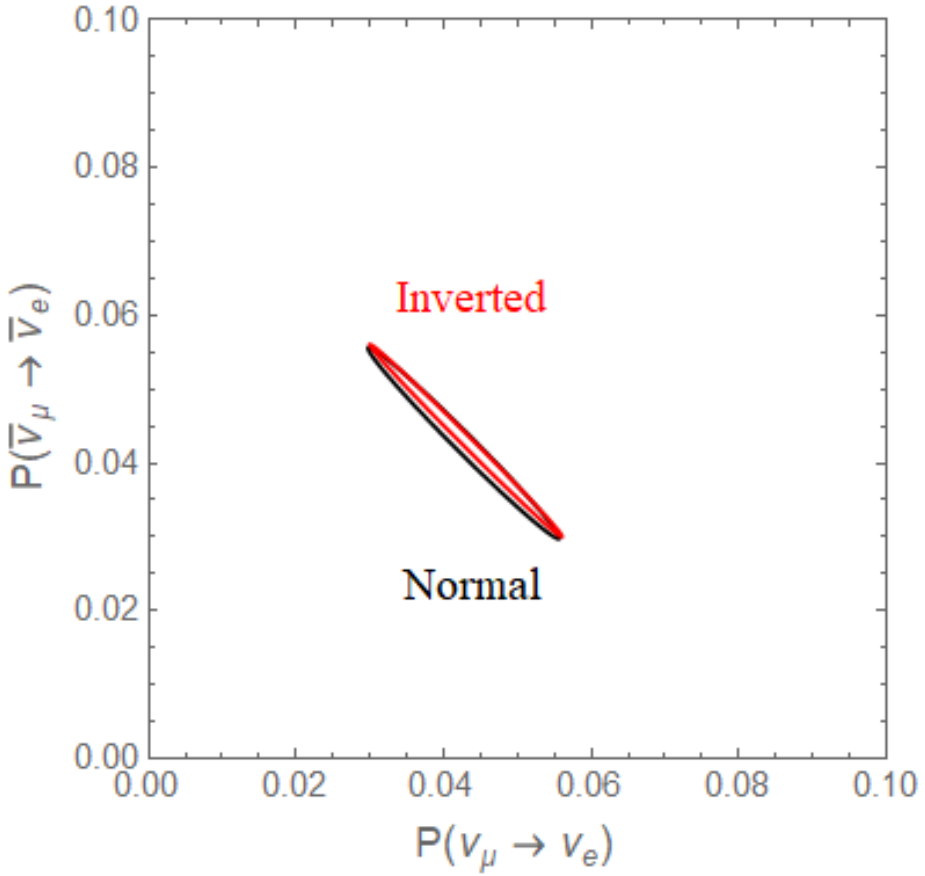
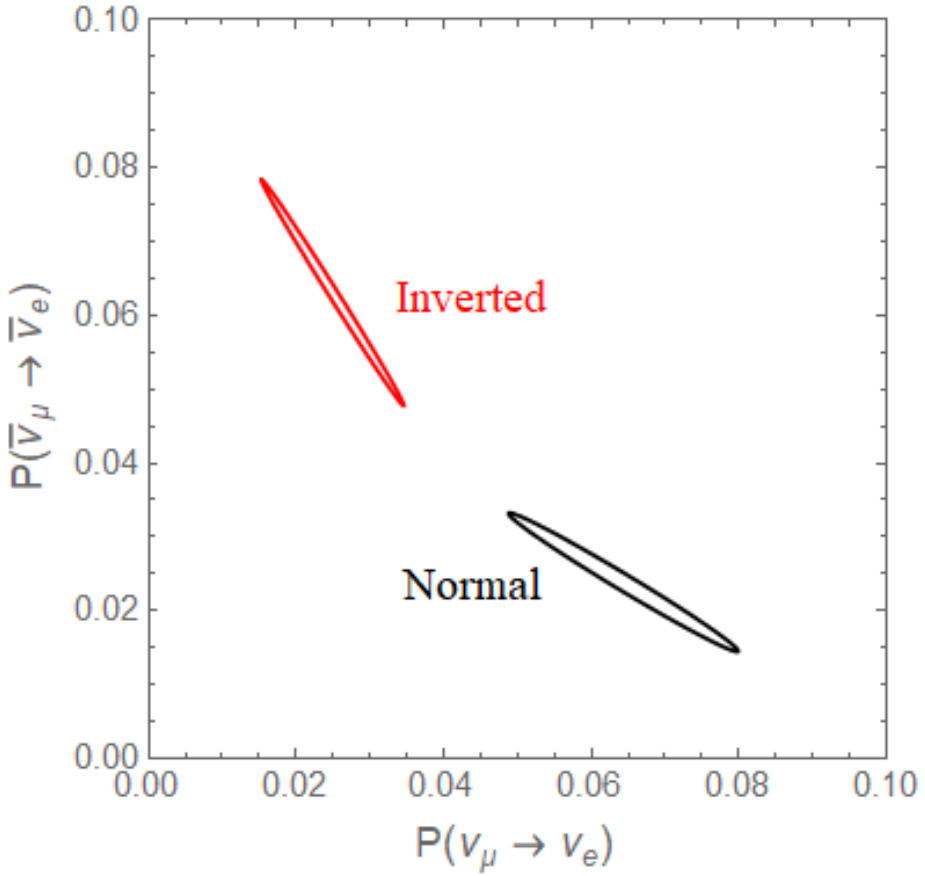
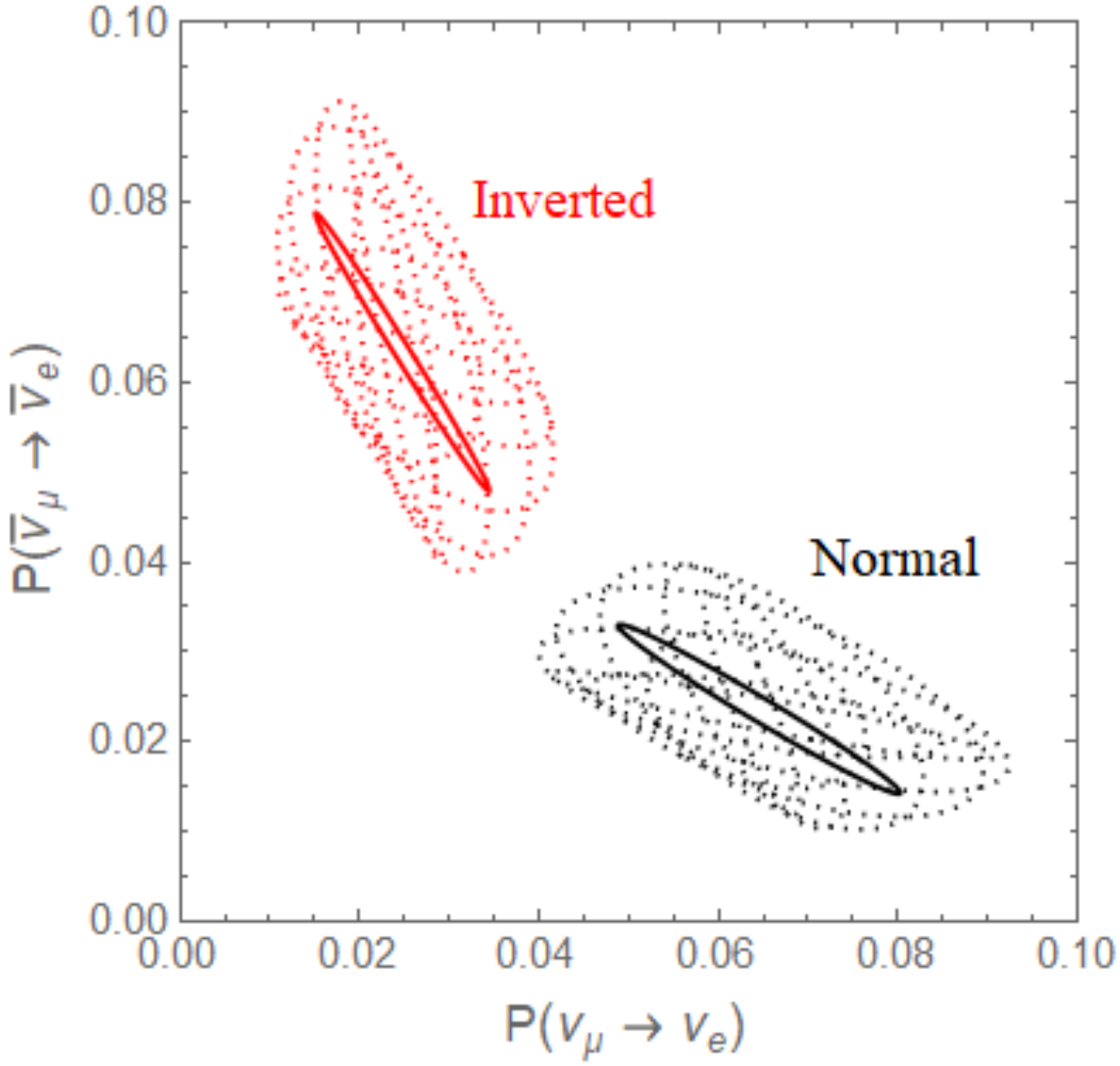


Oscillations in vacuum



Oscillations in matter

Adding NSI significantly complicates the situation:



Oscillation probabilities have form

$$P = \text{(CP-even terms) + (CP-odd terms)}$$
$$\bar{P} = \text{(CP-even terms) - (CP-odd terms)}$$

Therefore, it's natural to choose rotated coordinates

$$P^{+} = \frac{1}{\sqrt{2}}(P + \bar{P}) = \sqrt{2}\,\text{(CP-even terms)}$$
$$P^{-} = \frac{1}{\sqrt{2}}(P - \bar{P}) = \sqrt{2}\,\text{(CP-odd terms)}$$

At L = 1300 km with $\Delta_{31} = \Delta m^2_{31} L/(4E) = \pi/2$ (so E = 2.5 GeV), ρ = 3 g/cm^3:

Without NSI, perturbative expressions for oscillation probabilities give:

$$P^+ \approx 0.059, \qquad P^- \approx 0.027 - 0.017 \sin(\delta_{13})$$

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Proportional to L.

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With NSI, the same approach gives

$$P^+ \approx 0.059 + 0.21|\epsilon_{e\mu}|(-\sin(\delta_+) + 0.099\sin(\delta_{e\mu})),$$
$$P^- \approx 0.027 - 0.017 \sin(\delta_{13}) + 0.22|\epsilon_{e\mu}|\,(0.64\cos(\delta_+) + 0.14\cos(\delta_{e\mu})),$$

in terms of $\delta_+ = \delta_{13} + \delta_{e\tau}$.

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δ_+ dominates over $\delta_{e\mu}$ here.

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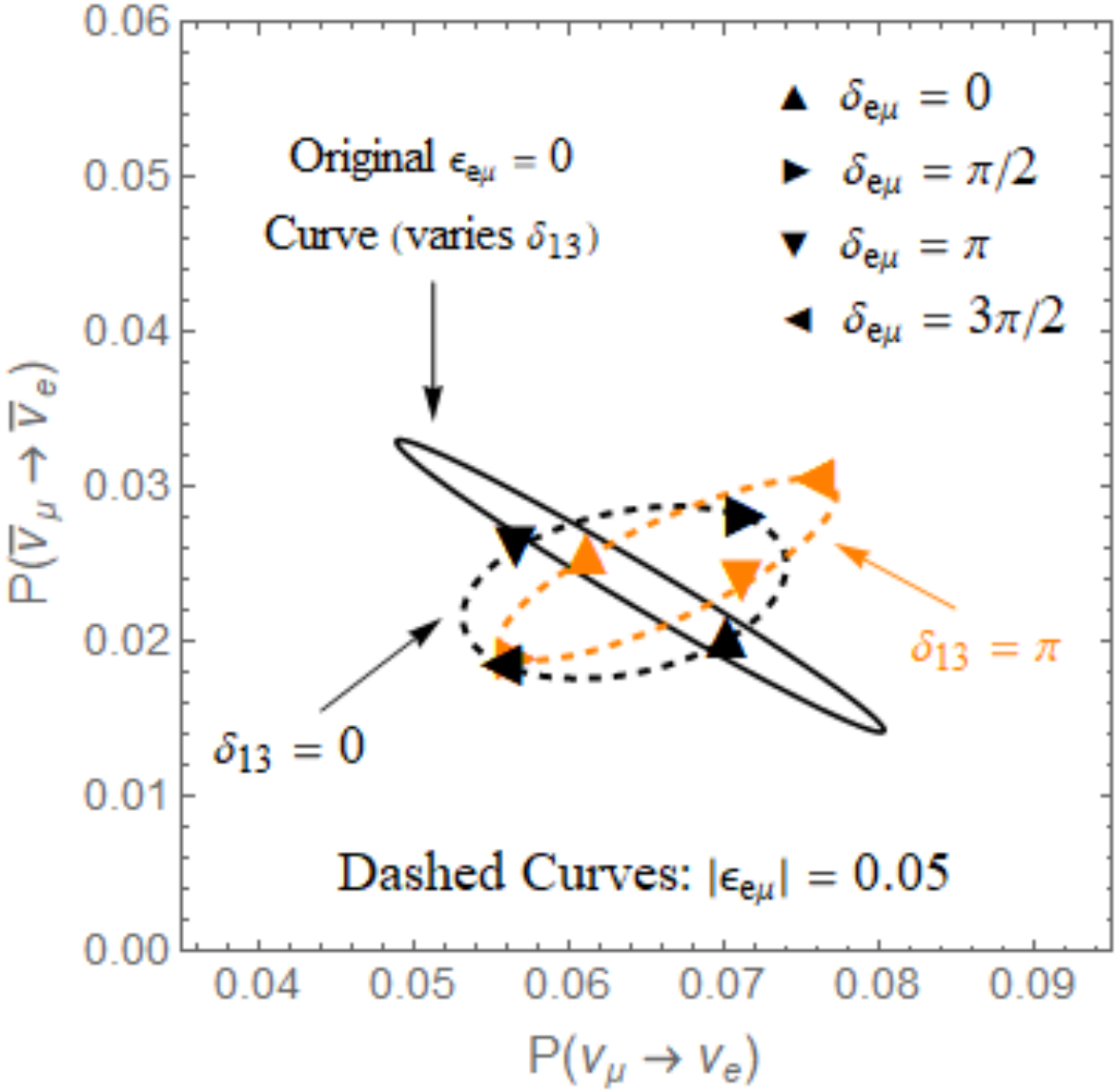
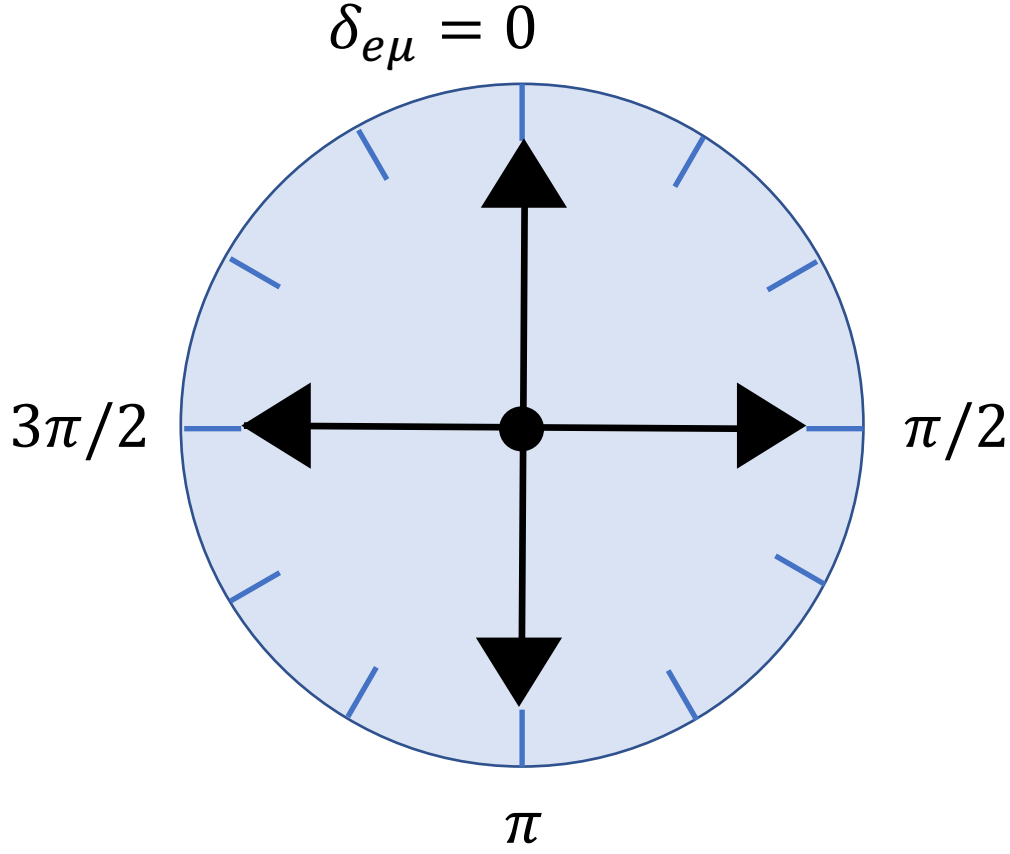
Hold δ_{13} constant, vary $\delta_{e\mu}$:



Dashed curves = constant δ_{13}

Triangles: think of them as "hands on a clock" that go around once per 2π



Look at energies away from $\Delta_{31} = \pi/2$:

For convenience: Fractional shift in energy $x \equiv (E - E_0)/E_0$.

Then P^+ gains a term $0.027x \cos(\delta_{13})$ (and some subleading terms).

→ Separation in P^+ direction according to δ_{13}.

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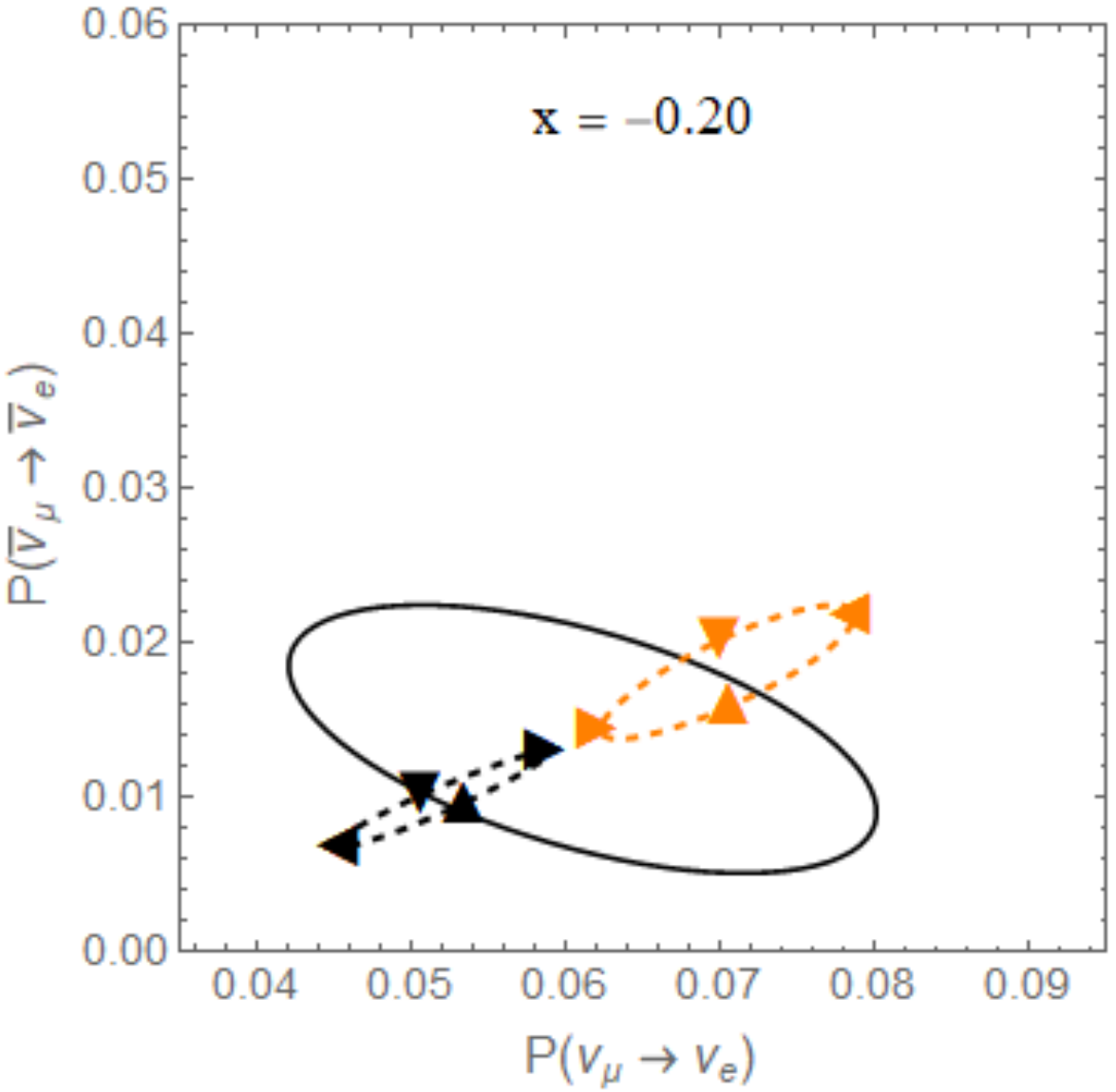
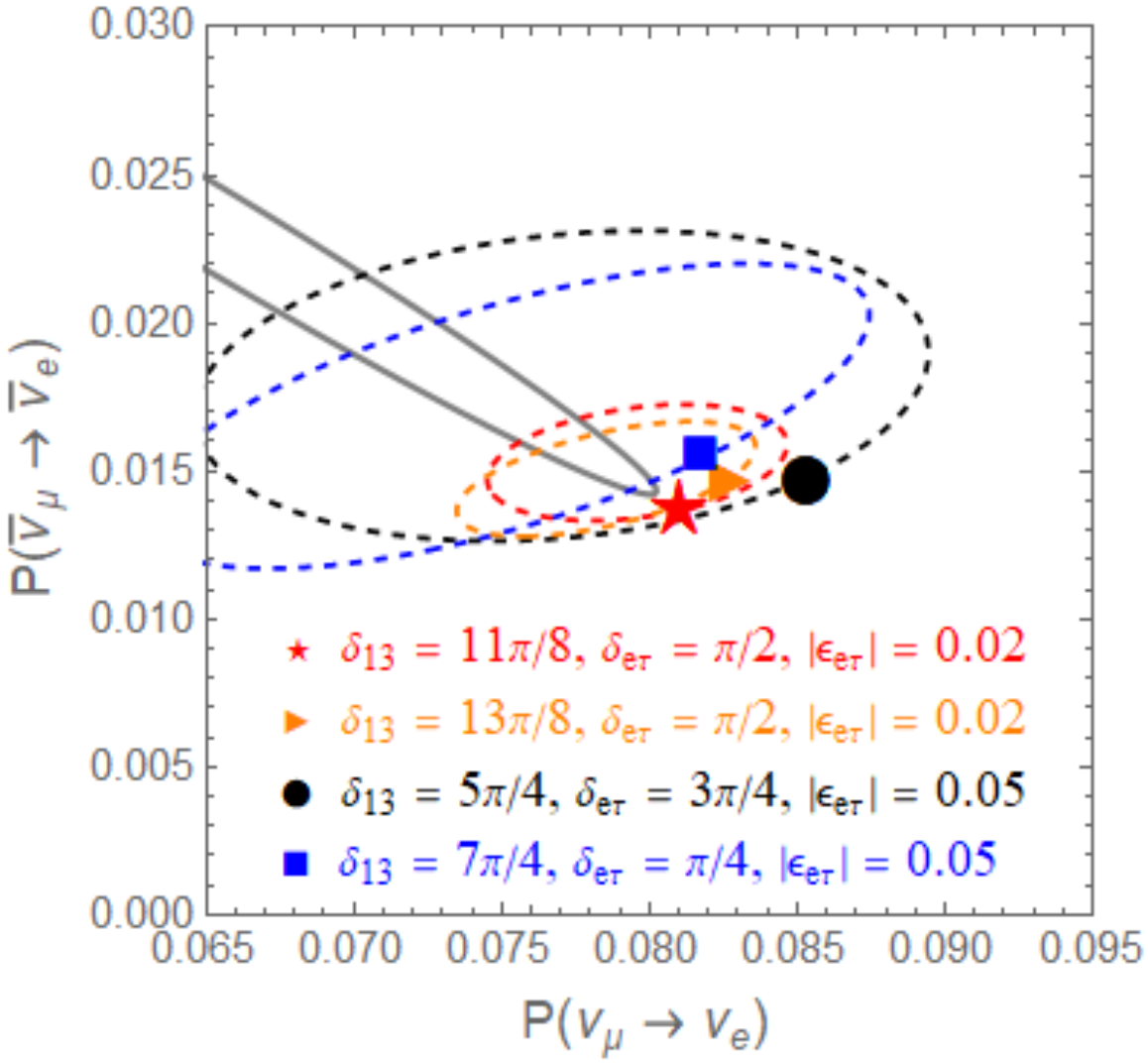


Example: Look at hints for $\delta_{13} \sim -\pi/2$



See also e.g. Forero & Huber PRL 117 (2016) arXiv:1601.03736

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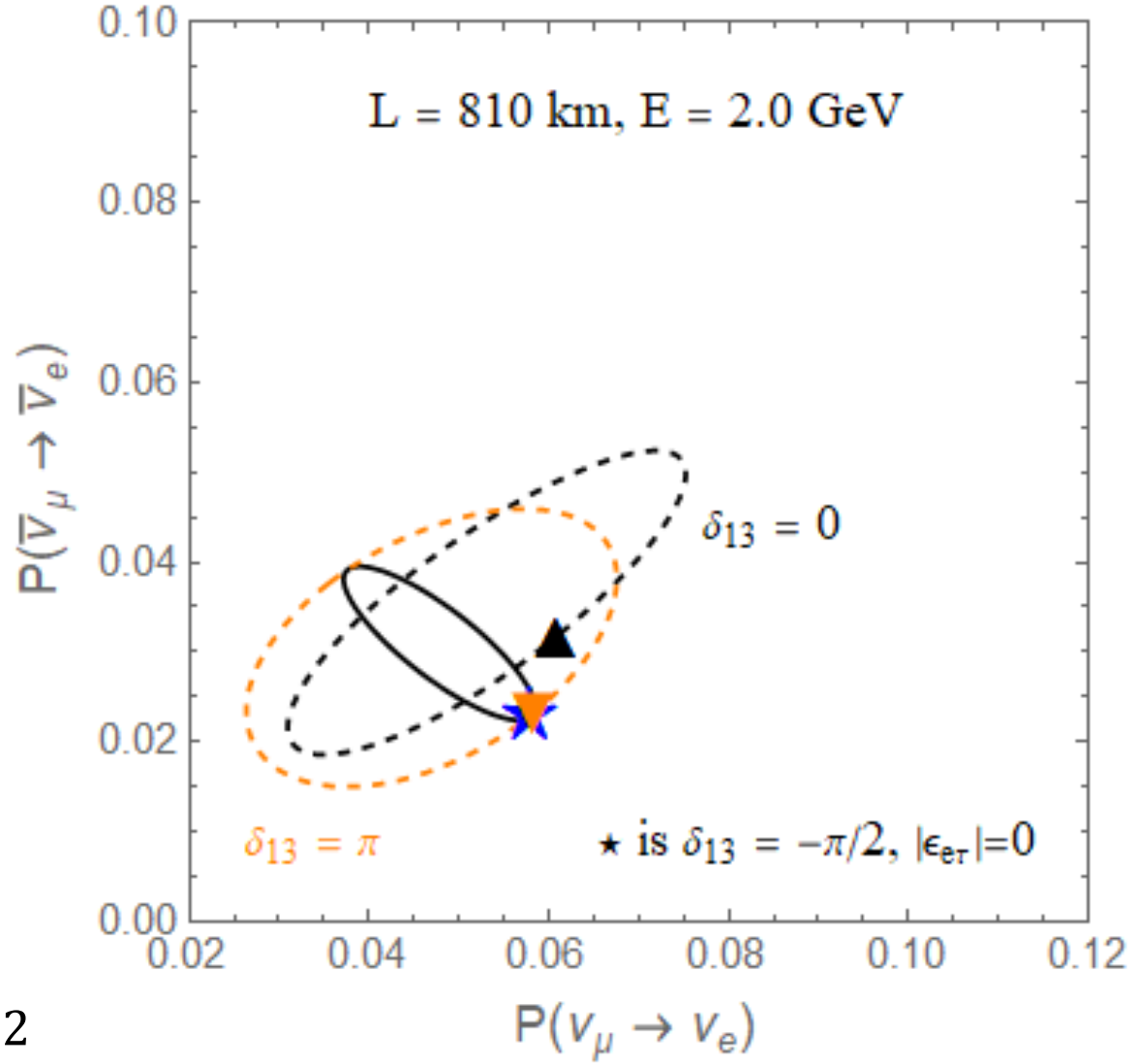

Dashed curves show $\epsilon_{e\tau} = 0.2$

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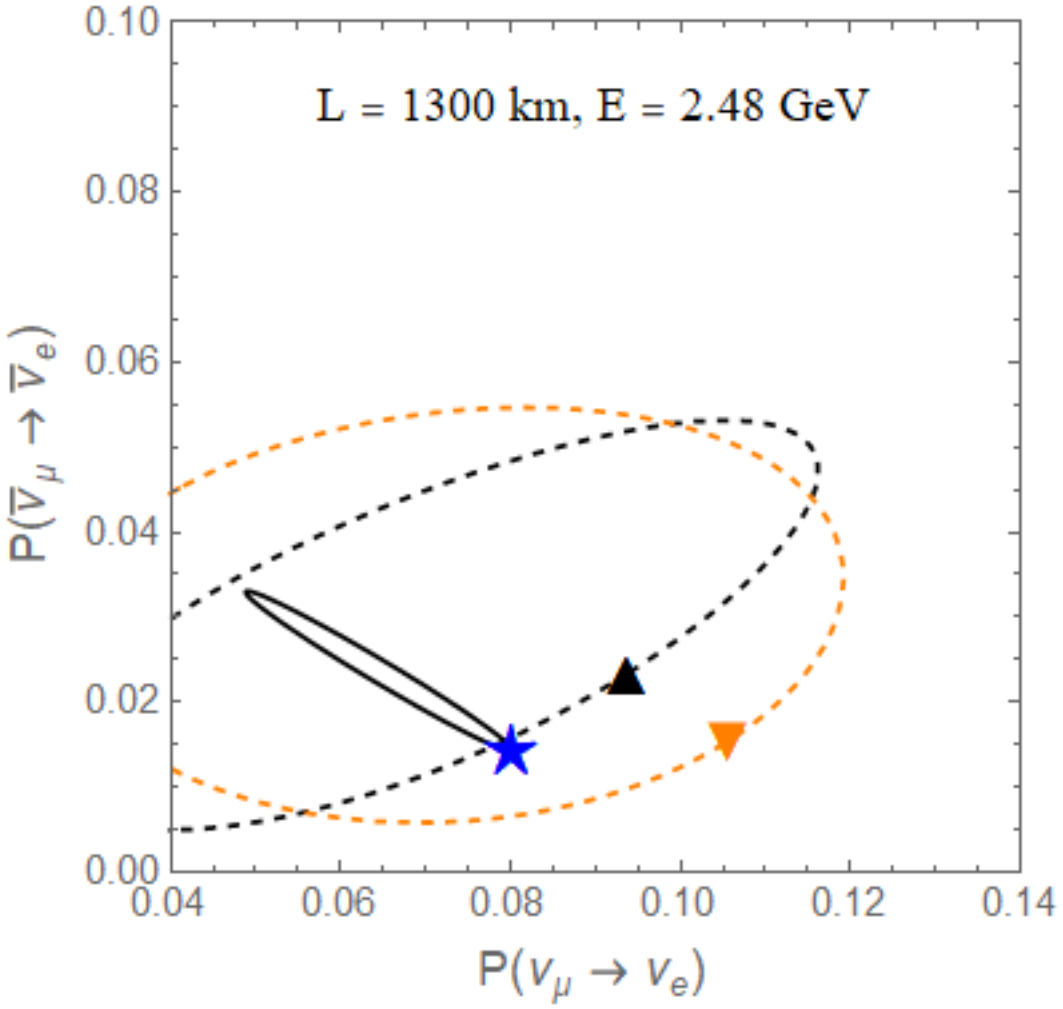
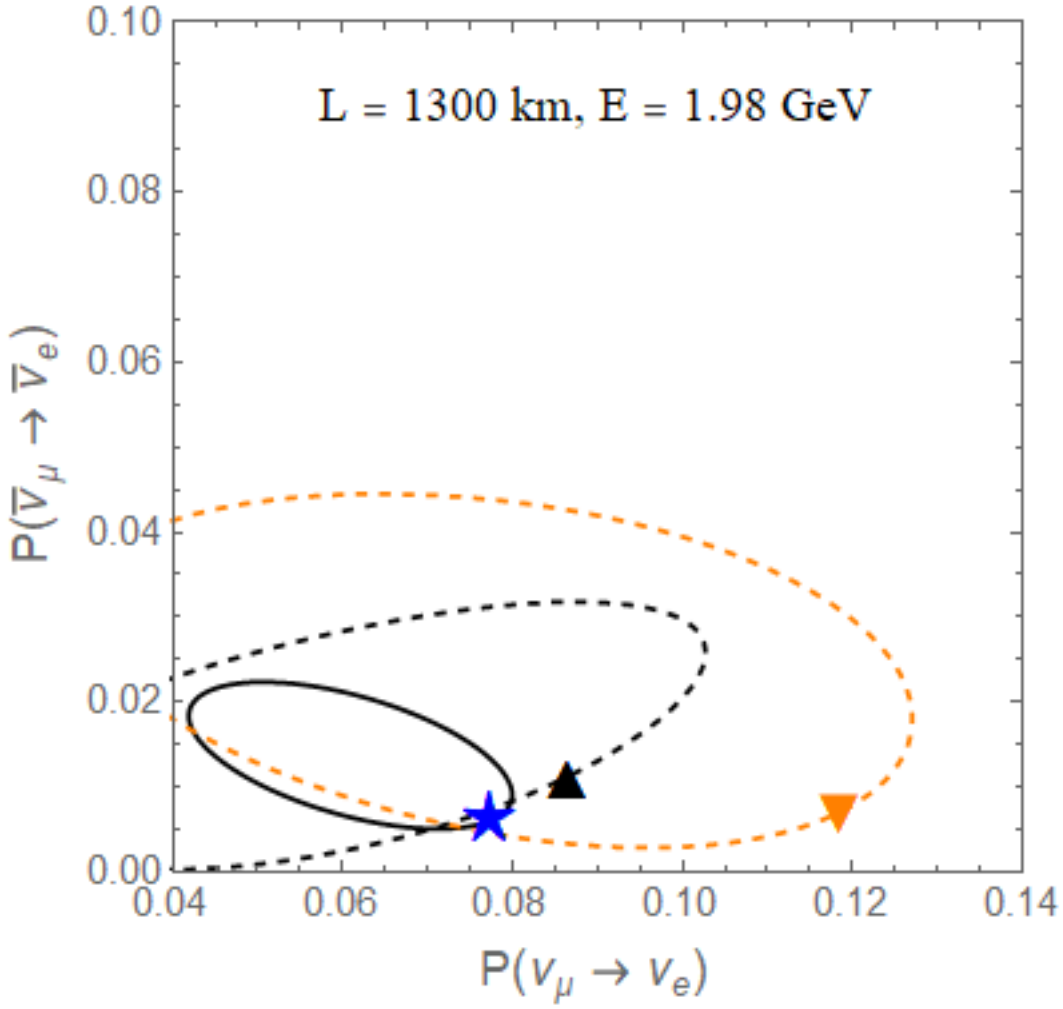
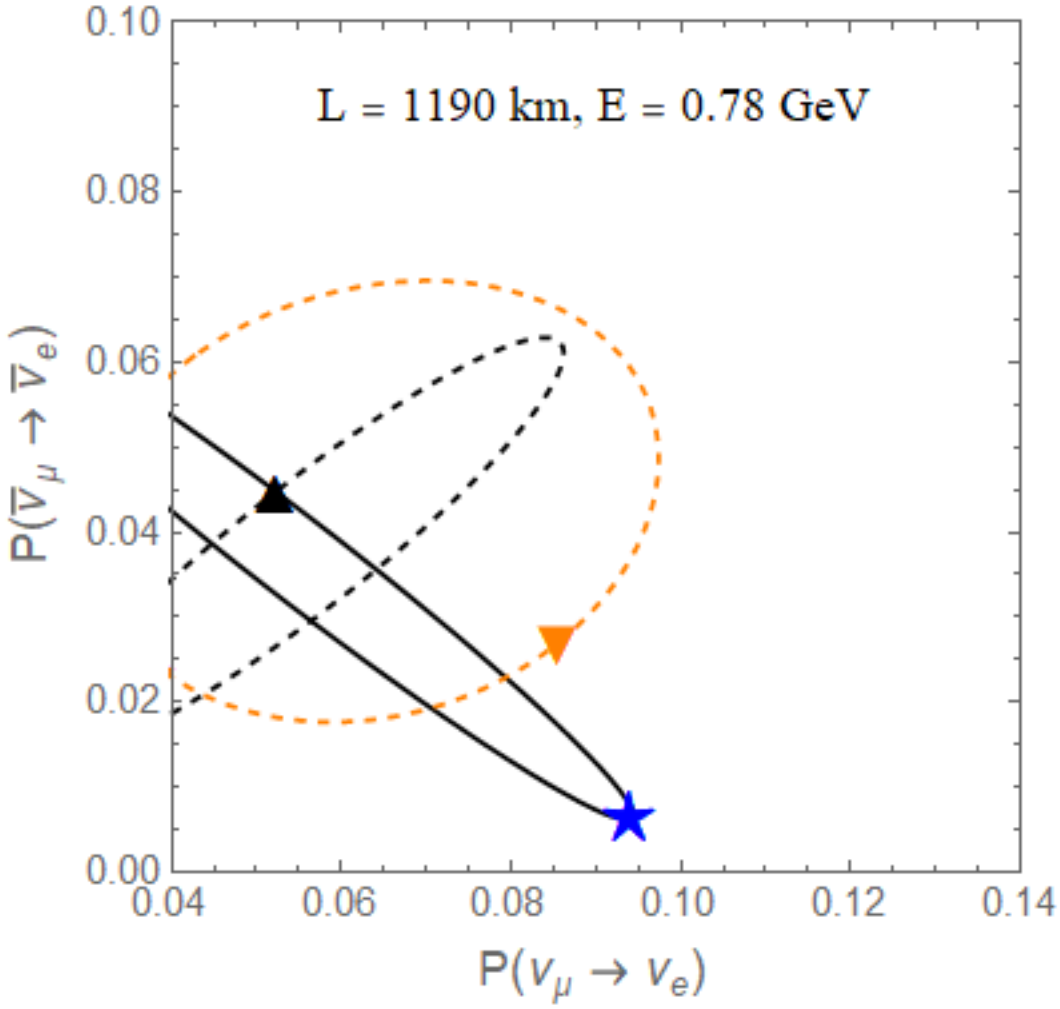




Further help from $\Delta_{31} = 3\pi/2$ (e.g. T2HKK)

In P^- expression, relative importance of δ_+ and $\delta_{e\tau}$ switch

→ breaks δ_+ degeneracy along P^-



Take-away points

- At oscillation max ($\Delta_{31} = \pi/2$), probabilities just depend on δ_+. → Degenerate "hidden sector" ellipses of width $\sim 0.1|\epsilon_{e\mu}|$ or $\sim 0.1|\epsilon_{e\tau}|$.

- Away from the peak, there is an effect in the P^+ direction depending on δ_{13}

  → Shows specific ways energy spectrum helps lift degeneracy.

- Additional "help" from looking near $\Delta_{31} = 3\pi/2$ → relative importance of δ_+ and δ_{13} switched in P^- expression.