CPT violation and neutrino oscillation experiments

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Neutrino oscillations

\[ |\nu_k(t)\rangle = e^{-iE_k t} |\nu_k\rangle \]

\[ |\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle \]

\[ A_{\nu_\alpha \to \nu_\beta}(t) \equiv \langle \nu_\beta |\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k} U_{\beta k} e^{-iE_k t} \]

\[ P_{\nu_\alpha \to \nu_\beta}(t) = |A_{\nu_\alpha \to \nu_\beta}(t)|^2 = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i(E_k - E_j) t} \]
Three-neutrino oscillations

Neutrino mixing matrix

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$

1 Dirac + 2 Majorana CP-phases

Three masses $m_1, m_2, m_3$ for which two orderings are possible

Oscillations are only sensitive to mass splittings
Three-neutrino oscillations

See also:
Bari – 2107.00532, PRD 2021

See also:
NuFit - 2111.03086
CPT violation

CPT from EFT:

Kostelecky and collaborators, many papers, in particular:
Kostelecky, Mewes, PRD 2004, hep-ph/0309025

CPT from non-locality:


CPT from decoherence

Papers by Mavromatos et al, Gago et al, Capolupo et al
Assume that neutrinos oscillate with parameters
\[ \Delta m_{21}^2, \Delta m_{31}^2, \theta_{12}, \theta_{13}, \theta_{23}, \delta \]
while the antineutrinos oscillate with a new set of parameters
\[ \Delta \overline{m}_{21}^2, \Delta \overline{m}_{31}^2, \overline{\theta}_{12}, \overline{\theta}_{13}, \overline{\theta}_{23}, \overline{\delta} \]
Different parameters for neutrinos and antineutrino would indicate a violation of CPT symmetry.
Current experiments
Current experiments

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020
If CPT is not conserved a measurement of CP violation is currently not possible. The different event spectra could be explained with different reactor mixing angles.

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020
Combining accelerator and reactor data does not improve the situation.

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020
The same data allows us to bound CPT-violating neutrino oscillation parameters:

\[
\begin{align*}
|\Delta m_{21}^2 - \Delta m_{21}^2| &< 4.7 \times 10^{-5} \text{ eV}^2, \\
|\Delta m_{31}^2 - \Delta m_{31}^2| &< 2.5 \times 10^{-4} \text{ eV}^2, \\
|\sin^2 \theta_{12} - \sin^2 \bar{\theta}_{12}| &< 0.14, \\
|\sin^2 \theta_{13} - \sin^2 \bar{\theta}_{13}| &< 0.029, \\
|\sin^2 \theta_{23} - \sin^2 \bar{\theta}_{23}| &< 0.19.
\end{align*}
\]

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020
Future perspectives at DUNE
Future perspectives at DUNE

How will this improve with DUNE?

Poor sensitivity to CP phases and reactor angles

Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018

Valencia - 2017 Global Fit, 1708.01186, PLB 2018

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.56 \times 10^{-5} \text{eV}^2$</td>
</tr>
<tr>
<td>$\Delta m_{31}^2$</td>
<td>$2.55 \times 10^{-3} \text{eV}^2$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.321</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.43, 0.50, 0.60</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.02155</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$1.50\pi$</td>
</tr>
</tbody>
</table>
Future perspectives at DUNE

Good improvement for the atmospheric mass splitting and mixing angle

Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018
Future perspectives at DUNE

We could obtain

$$\Delta(\Delta m_{31}^2) < 8.1 \times 10^{-5} \text{eV}^2$$

at 3σ C.L.
Future perspectives at DUNE

For the atmospheric angle we obtain increasing sensitivity for maximal mixing.
Future perspectives at DUNE

For the atmospheric angle we obtain increasing sensitivity for maximal mixing.

For the other values instead it increases and then decreases again.

This is due to degenerate solutions.
Obtaining impostor solutions
Assume $\sin^2 \theta_{23} = 0.5$, $\sin^2 \bar{\theta}_{23} = 0.43$

The combined best fit value is now

$$\sin^2 \theta^{\text{comb}}_{23} = 0.467$$

The real true values are disfavored at close to $3\sigma$ and more than $5\sigma$ confidence levels

Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018
Obtaining impostor solutions
This can also happen for other parameters

Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018
Observing CPT violation
Observing CPT violation

What if the values obtained in T2K and NOvA turn out to be true?

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

Barenboim, Ternes, Tórtola 1712.01714, PLB 2018
If the different different best fit values obtained for neutrino and antineutrino oscillations turned out to be true, DUNE could observe CPT violation at very high significance.
Observing CPT violation

CPT violation effects can be mimicked by nonstandard interactions

\[ \mathcal{H}_F = \frac{1}{2E} \left\{ U \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2 \end{pmatrix} U^\dagger + A_{CC} \begin{pmatrix} \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^m_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix} \right\} \]

Oscillation probability

\[ P_{\mu\mu} = 1 - \sin^2 2\tilde{\theta} \sin^2 \left( \frac{\Delta \tilde{m}^2}{4E} \right) \]

Matter parameters given by

\[ \Delta m^2_\nu \cos 2\theta_\nu = \Delta m^2 \cos 2\theta + \epsilon^m_{\tau\tau} A \]
\[ \Delta m^2_\nu \sin 2\theta_\nu = \Delta m^2 \sin 2\theta + 2\epsilon^m_{\mu\tau} A \]
\[ \Delta m^2_{\bar{\nu}} \cos 2\theta_{\bar{\nu}} = \Delta m^2 \cos 2\theta - \epsilon^m_{\tau\tau} A \]
\[ \Delta m^2_{\bar{\nu}} \sin 2\theta_{\bar{\nu}} = \Delta m^2 \sin 2\theta - 2\epsilon^m_{\mu\tau} A \]

Barenboim, Ternes, Tórtola, 1804.05842, EPJC 2019
Need to be careful to disentangle CPT violation and neutrino non standard interactions, since they can mimic CPT effects.

Barenboim, Ternes, Tórtola, 1804.05842, EPJC 2019
Conclusions

Determination of neutrino oscillation parameters worsens when CPT is not conserved

DUNE will improve the current bounds on CPT violation in the neutrino sector

Impostor solutions can arise in the determination of oscillation parameters when combining channels

DUNE might distinguish CPT violation from NSI
Thanks!
Solar sector

\[\Delta \chi^2\]

\[\sin^2 \theta_{12}\]

\[\Delta m_{21}^2 [10^{-5} \text{ eV}^2]\]
Solar sector
\[ H = \frac{1}{2E} \left[ U \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2 \end{pmatrix} U^\dagger + A \begin{pmatrix} \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{\mu\tau}^m & \epsilon_{\tau\tau}^m \end{pmatrix} \right] \]

\[
\Delta m_{\nu}^2 \cos 2\theta_{\nu} = \Delta m^2 \cos 2\theta + \epsilon_{\mu\tau}^m A,
\]

\[
\Delta m_{\nu}^2 \sin 2\theta_{\nu} = \Delta m^2 \sin 2\theta + 2\epsilon_{\mu\tau}^m A,
\]

\[
\Delta m_{\bar{\nu}}^2 \cos 2\theta_{\bar{\nu}} = \Delta m^2 \cos 2\theta - \epsilon_{\tau\tau}^m A,
\]

\[
\Delta m_{\bar{\nu}}^2 \sin 2\theta_{\bar{\nu}} = \Delta m^2 \sin 2\theta - 2\epsilon_{\mu\tau}^m A,
\]