Testing CPT Invariance with Neutrinos

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- CPT violation is connected with the search for physics beyond the SM.
- So far, no CPT violation has been found.
- However, neutrinos have been suggested as a source of CPT violation.

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Prior Papers on CPT Violation with Neutrinos

- S.R. Coleman and S.L. Glashow,
  PLB **405**, 249 (1999), `hep-ph/9703240` &
  PRD **59**, 116008 (1999), `hep-ph/9812418`
- V.D. Barger, S. Pakvasa, T.J. Weiler, and
  K. Whisnant,
  PRL **85**, 5055 (2000), `hep-ph/0005197`
- H. Murayama and T. Yanagida,
  PLB **520**, 263 (2001), `hep-ph/0010178`

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Neutrinos as a Source of CPT Violation

- M.C. Bañuls, G. Barenboim, and J. Bernabéu, hep-ph/0102184
- G. Barenboim, L. Borissov, J. Lykken, and A.Yu. Smirnov, hep-ph/0108199
- Z.-z. Xing, hep-ph/0112120
- S. Skadhauge, hep-ph/0112189
- S.M. Bilenky, M. Freund, M. Lindner, T. Ohlsson, and W. Winter, hep-ph/0112226

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Neutrinos as a Source of CPT Violation

- G. Barenboim, L. Borissov, and J. Lykken, `hep-ph/0201080`
- J.N. Bahcall, V. Barger, and D. Marfatia, `hep-ph/0201211`
- A. Strumia, `hep-ph/0201134`
- I. Mocioiu and M. Pospelov, `hep-ph/0202160`
- G. Barenboim, J.F. Beacom, L. Borissov, and B. Kayser, `hep-ph/0203261`

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CPT Violation with Neutrinos (beyond the SM)

S.R. Coleman and S.L. Glashow:

Lorentz violation $\rightarrow$ CPT violation

Allow the most general CPT-violating interaction: $u^\dagger b u$, where b is a Hermitian matrix $\quad\Rightarrow\quad$ The energies of the ultra-relativistic neutrinos with definite momentum p are the eigenvalues of the matrix: $cp + \frac{m^2}{2p} + b$, where c is also a Hermitian matrix (velocity-mixing)

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CPT Violation with Neutrinos (beyond the SM)

V.D. Barger *et al.*:

The effective Lorentz-violating and CPT-violating interaction for neutrinos is: $\bar{\nu}_L^\alpha b^\mu_{\alpha\beta} \gamma_\mu \nu_L^\beta$

$$\Rightarrow \qquad \Delta P^{\rm CPT}_{\alpha\alpha} \equiv P_{\alpha\alpha} - P_{\bar{\alpha}\bar{\alpha}} = -2\sin^2 2\theta \sin\left(\frac{\Delta m^2 L}{2E}\right)\sin(\delta b L)$$

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CPT Violation with Neutrinos (beyond the SM)

G. Barenboim *et al.*:

CPT violation (but Lorentz invariance) so strong that the mass spectra of neutrinos and antineutrinos are completely different $\Rightarrow$ Possible to describe solar, atmospheric, and LSND neutrino data

$$H_0 = \int \frac{d^3p}{(2\pi)^3} (\mathbf{p}^2 + m^2) \sum_s \left[a_{\mathbf{p}}^{s\,\dagger} a_{\mathbf{p}}^s + b_{\mathbf{p}}^{s\,\dagger} b_{\mathbf{p}}^s \right]$$

$$\rightarrow$$

$$H_0 = \int \frac{d^3p}{(2\pi)^3} \sum_s \left[(\mathbf{p}^2 + m^2) a_{\mathbf{p}}^{s\,\dagger} + (\mathbf{p}^2 + \bar{m}^2) b_{\mathbf{p}}^{s\,\dagger} b_{\mathbf{p}}^s \right],$$

$$m \neq \bar{m}$$

CPT-Violating Effects

S.M. Bilenky, M. Freund, M. Lindner, T. Ohlsson, and W. Winter, Phys. Rev. D **65**, 073024 (2002).

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- CPT violation was used to accommodate the LSND result
- Here: Precision measurements $\Rightarrow$ Interesting limits

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Sensitivity to small CPT-Violating Effects at NuFact

CPT invariance $\Rightarrow$

$$\mathrm{P}(\nu_\alpha \to \nu_{\alpha'}) = \mathrm{P}(\overline{\nu_{\alpha'}} \to \overline{\nu_\alpha})$$

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Consequence:

$$\mathrm{P}(\nu_\alpha \to \nu_{\alpha'}) \neq \mathrm{P}(\overline{\nu_{\alpha'}} \to \overline{\nu_\alpha})$$

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CPT invariance test at NuFact:

NuFact: Neutrinos produced in muon decays $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ (or $\mu^- \to e^- \bar{\nu}_e \nu_\mu$).

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Straightforward test: Check the appearance relation $\mathrm{P}(\nu_e \to \nu_\mu) = \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)$ [or $\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_\mu) = \mathrm{P}(\nu_\mu \to \nu_e)$]

Require to measure the sign of the charge of the produced lepton.

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INSTEAD: Check the equality

$$\mathrm{P}(\nu_\mu \to \nu_\mu) = \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

Sensitivity to small CPT-Violating Effects at NuFact

Limit CPT violation in the disappearance channels at NuFact:

- high event rates
- no beam contamination
- small matter effects
- large oscillation effects

$\Rightarrow$ Exclusion limits for tiny CPT-violating effects

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Asymmetries

Consider ν and $\bar{\nu}$ channels as independent experiments:

$$\delta \equiv \left|\Delta m_{32}^2 - \Delta \overline{m}_{32}^2\right| , \quad \epsilon \equiv \left|\sin^2 2\theta_{23} - \sin^2 2\bar{\theta}_{23}\right|$$

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For $m_1 \ll \sqrt{\Delta m_\odot^2}$ (hierarchical) and $|m_3 - \overline{m}_3| \ll (m_3)_{\text{average}}$:

$$\delta \simeq 2\, a_{\text{CPT}}\, \Delta m_{32}^2 \text{ with } a_{\text{CPT}} \equiv \frac{|m_3 - \overline{m}_3|}{(m_3)_{\text{average}}}$$

$$\epsilon \simeq 2\, b_{\text{CPT}} \sqrt{\sin^2 2\theta_{23}} \sqrt{1 - \sin^2 2\theta_{23}} \text{ arcsin} \sqrt{\sin^2 2\theta_{23}}$$

$$\text{with } b_{\text{CPT}} \equiv \frac{|\theta_{23} - \bar{\theta}_{23}|}{(\theta_{23})_{\text{average}}}$$

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Sensitivities of Asymmetries

- Sensitivity to possible CPT violation $\Leftrightarrow$ Accuracy of a_{CPT} and/or b_{CPT}

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- Compare δ and ϵ with corresponding relative statistical error $\delta \Delta m^2_{32}$ or $\delta \theta_{23}$

Sensitivities of Asymmetries

- Sensitivity to possible CPT violation $\Leftrightarrow$ Accuracy of a_{CPT} and/or b_{CPT}
- Compare δ and ϵ with corresponding relative statistical error $\delta\Delta m_{32}^2$ or $\delta\theta_{23}$
- Sensitivities δa_{CPT} and δb_{CPT} for a_{CPT} and b_{CPT} are given by:

$$\delta a_{\mathrm{CPT}} \sim \frac{\delta\Delta m_{32}^2}{2}$$

$$\delta b_{\mathrm{CPT}} \sim \delta\theta_{23}$$

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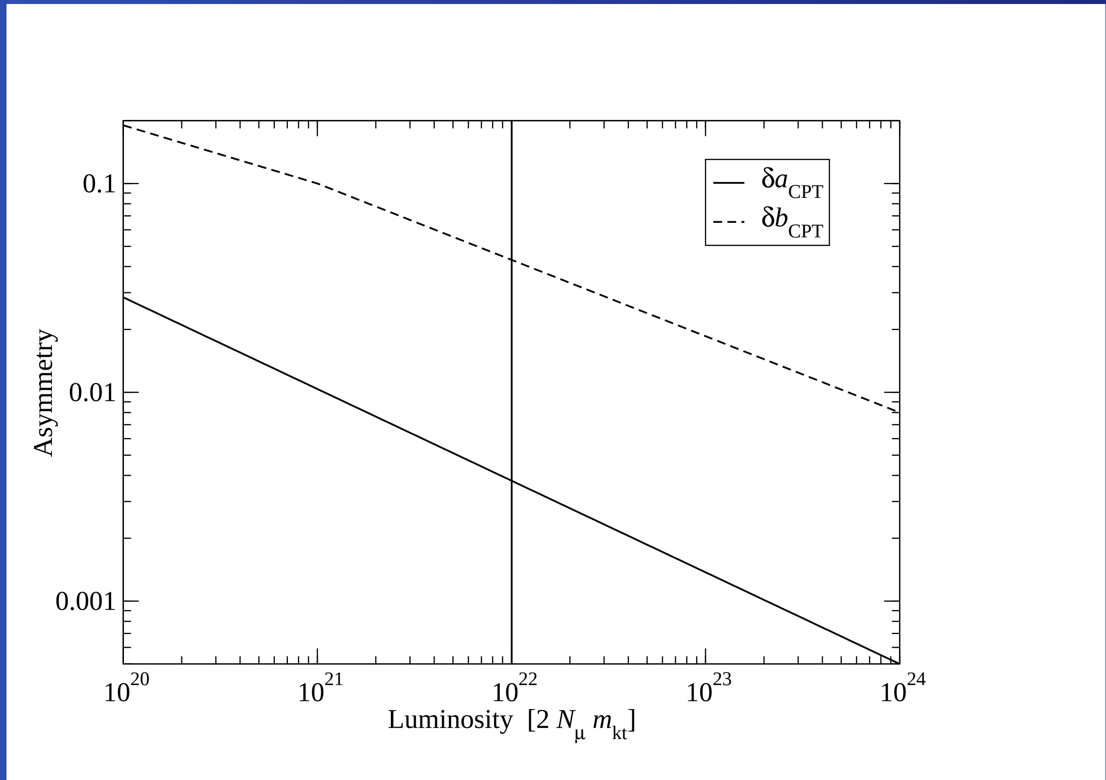
The Sensitivities of an Estimate of the Asymmetries



$E_\nu = 50\,\mathrm{GeV}$, $L = 3000\,\mathrm{km}$ (Δm^2_{23}) / $L = 7000\,\mathrm{km}$ (θ_{23}), 10^{20} muons/year, 5 years, 10kt

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Obtained Upper Bounds

$a_{CPT} \leq 3.8 \cdot 10^{-3} \ \wedge \ (m_3)_{\text{average}} \simeq \sqrt{\Delta m^2_{\text{atm}}} \leq 5 \cdot 10^{-2} \text{ eV}$

$$\Rightarrow \quad |m_3 - \bar{m}_3| \lesssim 1.9 \cdot 10^{-4} \text{ eV}$$

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$b_{CPT} \leq 4.3 \cdot 10^{-2} \;\wedge\; (\theta_{23})_{\text{average}} \simeq \theta_{\text{atm}} = 45^\circ$

$$\Rightarrow \quad |\theta_{23} - \bar{\theta}_{23}| \lesssim 2^\circ$$

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Summary & Conclusions

CPT violation:

- ✔ In local QFT not allowed
- ✔ Fundamental CPT violation $\Leftrightarrow$ Planck scale physics
- ✔ $|m_3 - \bar{m}_3| \lesssim 1.9 \cdot 10^{-4}\ \mathrm{eV}$ and $|\theta_{23} - \bar{\theta}_{23}| \lesssim 2^\circ$

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Reference:

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