Disentangling genuine from matter-induced CP violation in neutrino oscillations

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Based on:

J. Bernabeu and AS, Phys.Rev.Lett. **121** (2018) 211802 [arXiv:1806.07694 [hep-ph]]

J. Bernabeu and AS, JHEP **1811** (2018) 063 [arXiv:1807.11879 [hep-ph]]

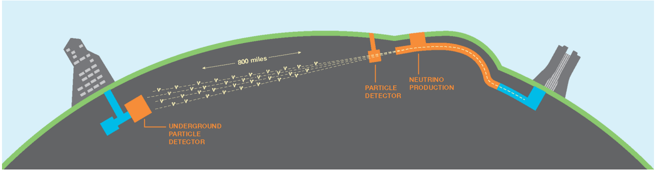
Introduction

Neutrino Mixing: Standard Parametrization

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Testing CP in neutrino oscillations
A direct evidence of Symmetry Violation means the measurement, in a single experiment, of an observable odd under the symmetry.

But... Matter induces *fake* CPV effects



CP Asymmetry Disentanglement

Neutrino Hamiltonian in Matter

$$H = \frac{1}{2E}\left\{U\begin{bmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{bmatrix}U^\dagger \pm \begin{bmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\right\} = \frac{1}{2E}\,\tilde{U}\tilde{M}^2\tilde{U}^\dagger\,,$$

CP Asymmetry Disentanglement Theorem

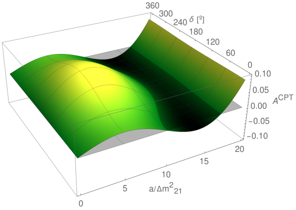
$$\mathcal{A}^{\mathrm{CP}}_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) =$$

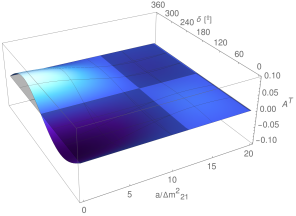
$$\mathcal{A}^{\mathrm{CPT}}_{\alpha\beta} : \quad -4\sum_{j<i}\left[\mathrm{Re}\,\tilde{J}^{ij}_{\alpha\beta}\,\sin^2\tilde{\Delta}_{ij} - \mathrm{Re}\,\tilde{\bar{J}}^{ij}_{\alpha\beta}\,\sin^2\tilde{\bar{\Delta}}_{ij}\right]$$

$$\mathcal{A}^{\mathrm{T}}_{\alpha\beta} : \quad -2\sum_{j<i}\left[\mathrm{Im}\,\tilde{J}^{ij}_{\alpha\beta}\,\sin 2\tilde{\Delta}_{ij} - \mathrm{Im}\,\tilde{\bar{J}}^{ij}_{\alpha\beta}\,\sin 2\tilde{\bar{\Delta}}_{ij}\right]$$

$\mathcal{A}^{\mathrm{CPT}}_{\alpha\beta}$ is T-invariant, CPT-odd: L-even
$\sin\delta$-even, a-odd
Vanishes when $a = 0\ \forall\delta$

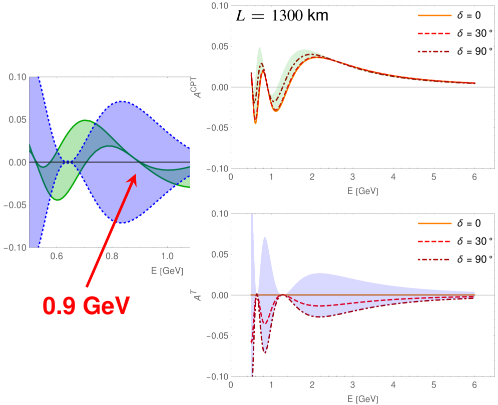
$\mathcal{A}^{\mathrm{T}}_{\alpha\beta}$ is T-odd, CPT-invariant: L-odd
$\sin\delta$-odd, a-even
Vanishes when $\sin\delta = 0\ \forall a$



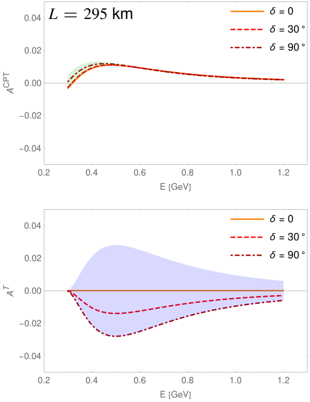


Disentangled $\mathcal{A}_{\mu e}^{\rm CPT}$ and $\mathcal{A}_{\mu e}^{\rm T}$ components

DUNE



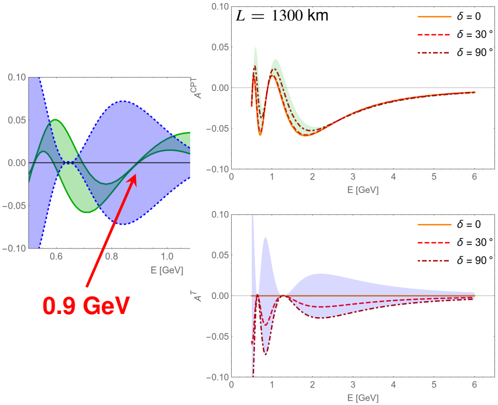
T2HK



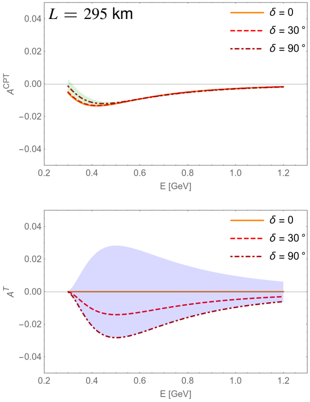
Normal Hierarchy

Disentangled $\mathcal{A}^{\mathrm{CPT}}_{\mu e}$ and $\mathcal{A}^{\mathrm{T}}_{\mu e}$ components

DUNE



T2HK



Inverted Hierarchy

Accelerator neutrinos: $\Delta m^2_{21} \ll a \ll \Delta m^2_{31}$

Perturbative expansion $\frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim 0.030\,, \qquad |U_{e3}|^2 \sim 0.022\,,$

$$\left[\frac{\Delta m^2_{21}}{a}\right]^2 \sim \frac{0.12}{(E/\mathrm{GeV})^2}\,, \quad \left[\frac{a}{\Delta m^2_{31}}\right]^2 \sim 0.008\,(E/\mathrm{GeV})^2\,, \quad \left[\frac{aL}{4E}\right]^2 \sim 0.084\left(\frac{L}{1000\mathrm{km}}\right)^2\,.$$

Both $\mathcal{A}^{\mathrm{CPT}}_{\alpha\beta}$ and $\mathcal{A}^{\mathrm{T}}_{\alpha\beta}$ have **definite a-parity**: quadratic corrections

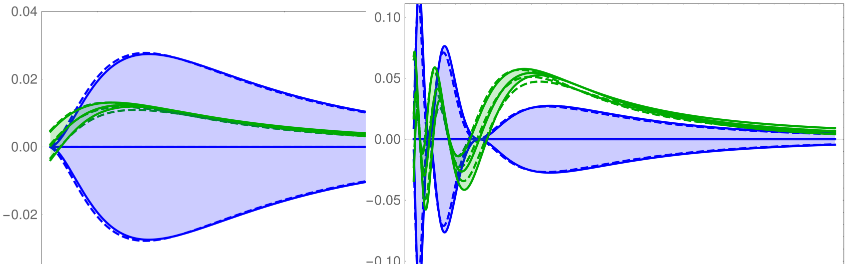
Approximated expressions for both components of the CP Asymmetry:

$$\mathcal{A}^{\mathrm{CPT}}_{\mu e} = 16\,A\left[\frac{\sin\Delta_{31}}{\Delta_{31}} - \cos\Delta_{31}\right]\left(S\sin\Delta_{31} + J_r\cos\delta\,\Delta_{21}\cos\Delta_{31}\right) + \mathcal{O}(A^3)\,,$$

$$\mathcal{A}^{\mathrm{T}}_{\mu e} = -16\,J_r\sin\delta\,\Delta_{21}\sin^2\Delta_{31} + \mathcal{O}(A^2)\,,$$

where $S \equiv c^2_{13}s^2_{13}s^2_{23}$, $J_r \equiv c_{12}c^2_{13}c_{23}s_{12}s_{13}s_{23}$, $A \equiv \frac{aL}{4E} \propto L$ and $\Delta_{ij} \equiv \frac{\Delta m^2_{ij}L}{4E} \propto L/E$.

Accelerator neutrinos: $\Delta m^2_{21} \ll a \ll \Delta m^2_{31}$



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Analytical expressions for $\mathcal{A}_{\mu e}^{\rm CPT}$ and $\mathcal{A}_{\mu e}^{\rm T}$ components

Genuine (a-even)

$$\mathcal{A}_{\mu e}^{\rm T} = -16\, J_r \sin\delta\, \Delta_{21} \sin^2 \Delta_{31} + \mathcal{O}(A^2)$$

Same as in vacuum
Proportional to $\sin\delta$
Hierarchy-independent
Maximum $\left|\mathcal{A}_{\mu e}^{\rm T}\right|$: $\tan\Delta_{31} = -2\Delta_{31}$
Zeros: $\sin\Delta_{31} = 0$

Vanishes in vacuum
Proportional to L
Hierarchy-odd at high E
δ-independent zeros: $\tan\Delta_{31} = \Delta_{31}$
δ-dependent zeros

$$\mathcal{A}_{\mu e}^{\rm CPT} = 16\, A \left[\frac{\sin\Delta_{31}}{\Delta_{31}} - \cos\Delta_{31}\right] (S \sin\Delta_{31} + J_r \cos\delta\, \Delta_{21} \cos\Delta_{31}) + \mathcal{O}(A^3)$$

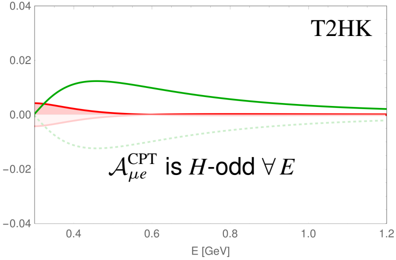
Matter-induced (a-odd)

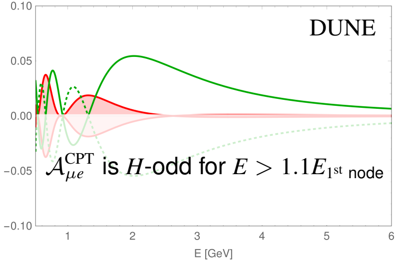
Hierarchy discrimination

$$\mathcal{A}^{\rm CPT}_{\mu e} = 16A\left[\frac{\sin\Delta_{31}}{\Delta_{31}} - \cos\Delta_{31}\right](S\sin\Delta_{31} + J_r\cos\delta\,\Delta_{21}\cos\Delta_{31}) + \mathcal{O}(A^3)$$

Hierarchy-odd, δ-independent

Hierarchy-even, δ-dependent





Genuine CP asymmetry

$$\mathcal{A}^{\mathrm{T}}_{\mu e} = -16\, J_r \sin\delta\, \Delta_{21} \sin^2\Delta_{31} + \mathcal{O}(A^2)$$

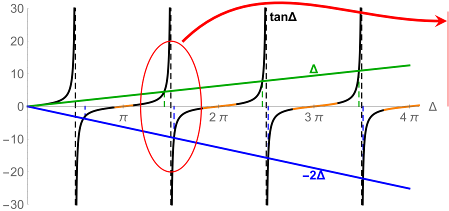
Max: $\tan\Delta_{31} = -2\Delta_{31}$

$$\mathcal{A}^{\mathrm{CPT}}_{\mu e} = 16\, A \left[\frac{\sin\Delta_{31}}{\Delta_{31}} - \cos\Delta_{31}\right] \left(S \sin\Delta_{31} + J_r \cos\delta\, \Delta_{21} \cos\Delta_{31}\right) + \mathcal{O}(A^3)$$

δ-independent zeros: $\tan\Delta_{31} = \Delta_{31}$

$\Delta_{31} \equiv \Delta m^2_{31} L/4E$

δ-dependent zeros: $\tan\Delta_{31} = -0.09 \cos\delta\, \Delta_{31}$

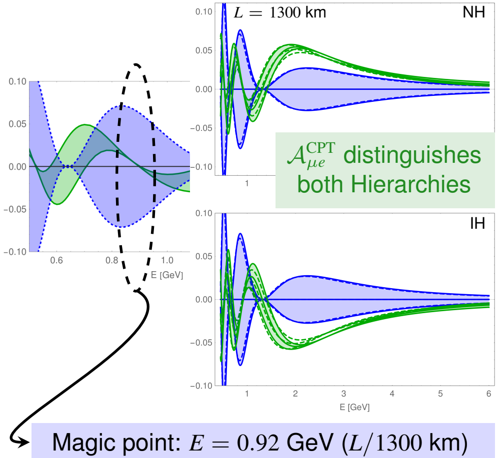


$$E = 0.92\,\mathrm{GeV}\, \frac{L}{1300\,\mathrm{km}}\, \frac{|\Delta m^2_{31}|}{2.5\times 10^{-3}\,\mathrm{eV}^2}$$

$L/E = 1420$ km/GeV,
near 2[nd] oscillation max.

Signatures of the disentangled components of the $\mathcal{A}_{\mu e}^{\rm CP}$

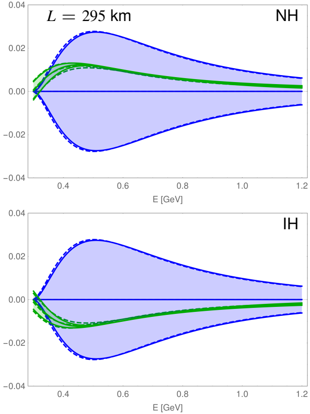
DUNE



$\mathcal{A}_{\mu e}^{\rm CPT}$ distinguishes both Hierarchies

Magic point: $E = 0.92$ GeV ($L/1300$ km)
$\mathcal{A}_{\mu e}^{\rm CP} \propto \sin\delta$ probes genuine CP violation!

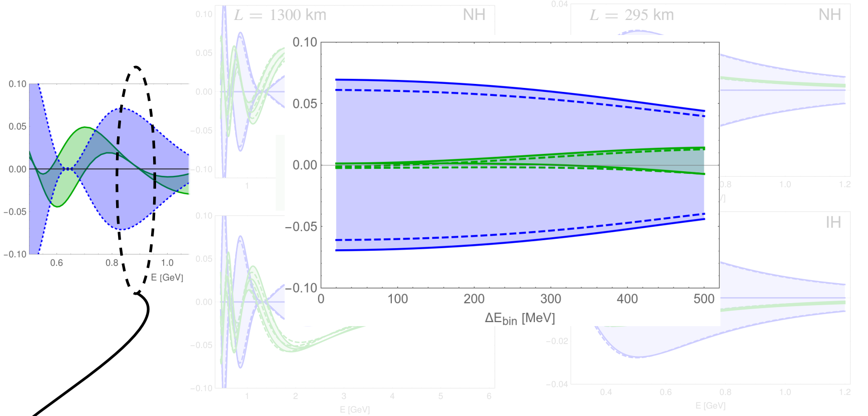
T2HK



$\mathcal{A}_{\mu e}^{\rm CPT}$ nearly δ-independent: theoretical background in $\mathcal{A}_{\mu e}^{\rm CP}$

Signatures of the disentangled components of the $\mathcal{A}_{\mu e}^{\rm CP}$

DUNE	T2HK



Magic point: $E = 0.92$ GeV $(L/1300$ km$)$
$\mathcal{A}_{\mu e}^{\rm CP} \propto \sin\delta$ probes genuine CP violation!

$\mathcal{A}_{\mu e}^{\rm CPT}$ nearly δ-independent: theoretical background in $\mathcal{A}_{\mu e}^{\rm CP}$

Conclusions

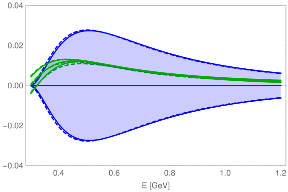
- Decomposition of CP asymmetry into:

$\mathcal{A}^{\rm CPT}_{\alpha\beta}$	T-invariant, CPT-odd,	L-even,	$\sin\delta$-even, a-odd, $\approx$H-odd
$\mathcal{A}^{\rm T}_{\alpha\beta}$	T-odd, CPT-invariant,	L-odd,	$\sin\delta$-odd, a-even, H-even

- Definite a-parity allows for compact expansions: quadratic corrections!

- **T2HK** $L = 295$ km

  Nearly δ-independent and small $\mathcal{A}^{\rm CPT}_{e\mu}$: theoretical background to test CP (provided known Hierarchy)



- **DUNE** $L = 1300$ km

  The experimental CP asymmetry tests:

  - Hierarchy: E above first node.
  - Genuine CP violation at

$$E = 0.92\ \text{GeV}\ \frac{L}{1300\ \text{km}}\ \frac{|\Delta m^2_{31}|}{2.5\times 10^{-3}\ \text{eV}^2}$$