CPT INVARIANCE AND NEUTRINOS

Gabriela Barenboim
UV-IFIC

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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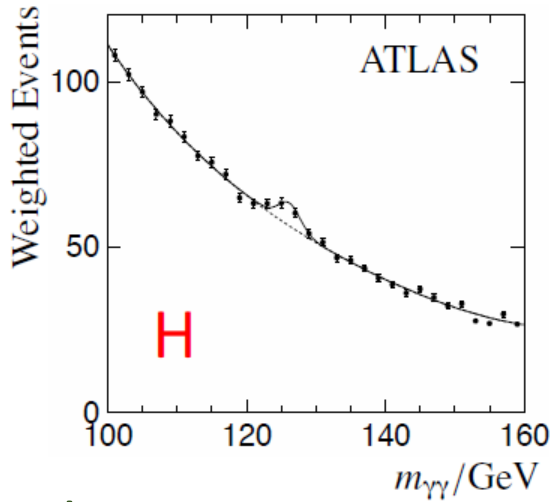
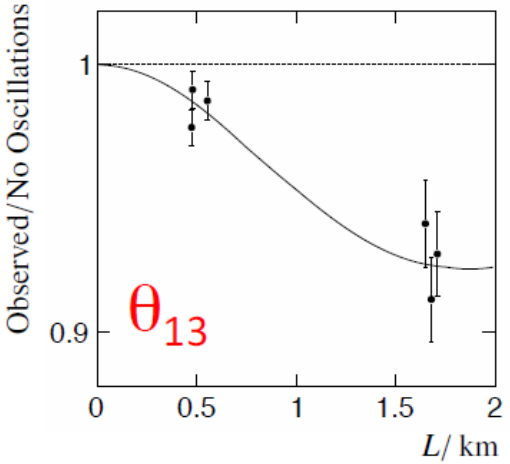
2012 ~~One~~ two major discoveries in particle physics

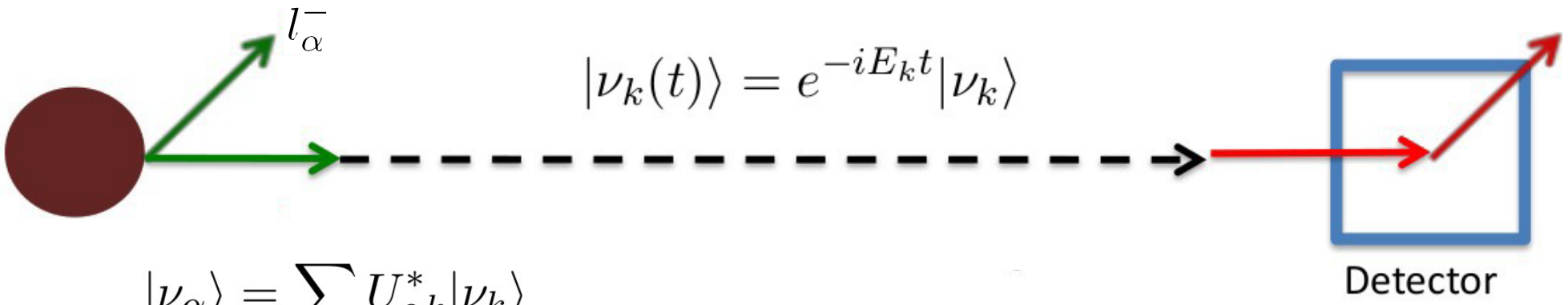
- A SM-like Higgs boson (ATLAS, CMS)
  The key to EWSB and a possible window to





- $\theta_{13} \sim 10^{o}$ (T2K, MINOS, Daya Bay, RENO)
  about as large as it could have been !
  The door to CP Violation in the leptonic sector

Neutrino oscillations



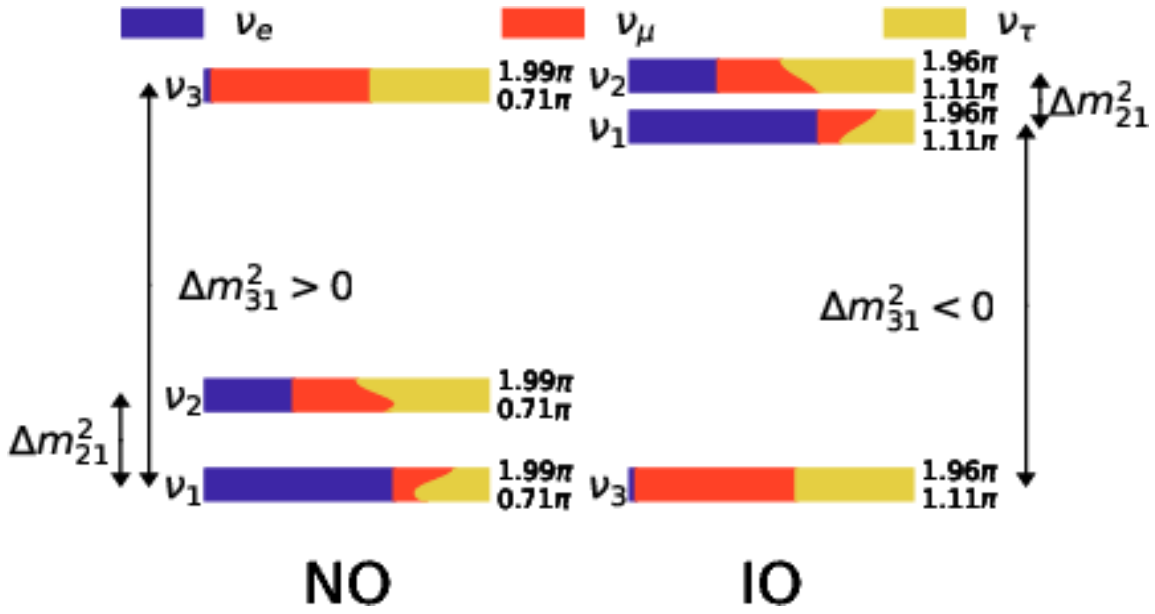
$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{k>j} \mathrm{Re}[\mathrm{W}_{\alpha\beta}^{\mathrm{jk}}] \sin^2\left(\frac{\Delta \mathrm{m}_{\mathrm{jk}}^2 \mathrm{L}}{4\mathrm{E}_\nu}\right)$$

$$\pm \quad 2 \sum_{k>j} \mathrm{Im}[\mathrm{W}_{\alpha\beta}^{\mathrm{jk}}] \sin\left(\frac{\Delta \mathrm{m}_{\mathrm{jk}}^2 \mathrm{L}}{2\mathrm{E}_\nu}\right)$$

Three-neutrino oscillations

Neutrino mixing matrix

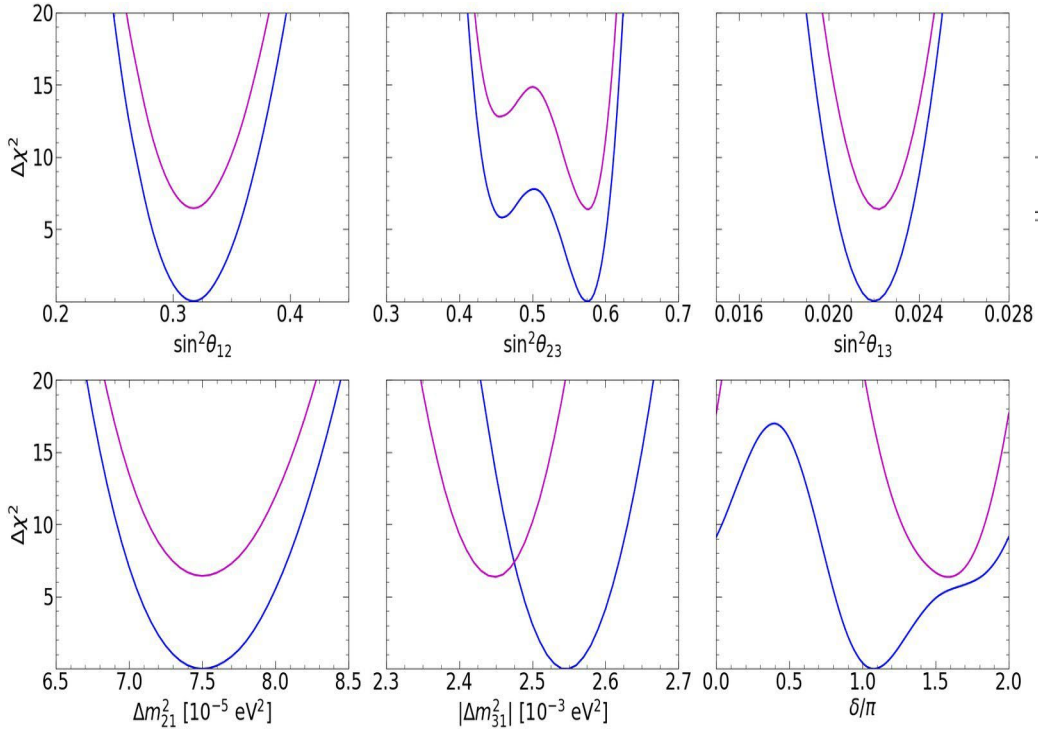
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Parameter	Main contribution	Other contributions
θ_{12}	SOL	KamLAND
θ_{13}	REAC	ATM+LBL and SOL+KamLAND
θ_{23}	ATM+LBL	-
δ_{CP}	LBL	ATM
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
MO	LBL+REAC and ATM	-

SOL: Solar
ATM: Amtopsheric neutrinos
LBL: Long baseline accelerator experiments
REAC: Short-baseline reactor experiments

https://globalfit.astroparticles.es/



de Salas et al, JHEP 02 (2021) 071 [arXiv:2006.11237]

parameter	best fit ± 1σ	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

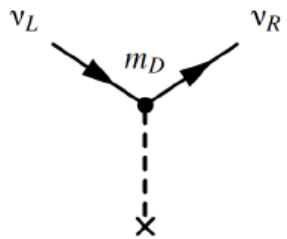
Relative 1σ uncertainty

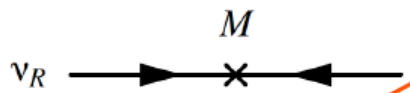
2.7%	PRECISION
1.1%	ORDERING?
5.2%	PRECISION
5.1%	OCTANT?
3.0%	PRECISION
20%	CPV?
9.0%	

a connection to BSM physics

★ **Is there a connection to the GUT scale?**

- If both Dirac and Majorana mass terms are pres





violation

$$\mathcal{L} \sim -\frac{1}{2}\left(\overline{\nu_L} \quad \overline{\quad} \right) \qquad \left(\nu_R \right)$$

- The seesaw m… ysical "mass eigenstates" are thos… re the mass matrix is diagonal

…ino $m_\nu \approx \dfrac{m_D^2}{M}$ + heavy **RH neutrino** $m_N \approx M$

$m_D \sim m_\ell$ to get to right range of small neutrino masses:

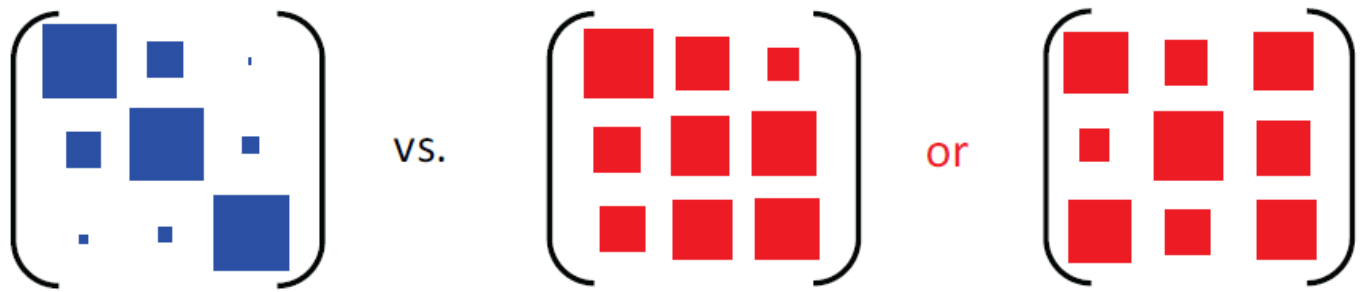
$$M \sim 10^{12} - 10^{16}\,\text{GeV}$$

Neutrinos may provide a window to GUT-scale physics
argues for a precision neutrino physics program

The Known Unknowns

★ **Next generation Long-Baseline experiments (such as DUNE) can address three of these questions:**

- **Are neutrinos Dirac or Majorana ?**
  - Is there a connection to the GUT scale?
- **Are there light sterile neutrino states ?** → Breaks 3-flavor paradigm
  - No clear theoretical guidance on mass scale, M, …
- **What is the neutrino mass hierarchy ?**
  - An important question in flavor physics, e.g. CKM vs. PNMS



- **Is CP violated in the leptonic sector ?**
  - Are νs key to understanding the matter-antimatter asymmetry?

In principle, it is straightforward

★ CPV ⇨ different oscillation rates for νs and $\overline{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = 4 s_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \times \left[\sin\left(\frac{\Delta m^2_{21} L}{4E}\right) \times \sin\left(\frac{\Delta m^2_{23} L}{4E}\right) \times \sin\left(\frac{\Delta m^2_{31} L}{4E}\right)\right]$$

vacuum osc.

★ Requires $\{\theta_{12}, \theta_{13}, \theta_{23}\} \neq \{0, \pi\}$

- now know that this is true, $\theta_{13} \approx 9^\circ$
- but, despite hints, don't yet know "much" about δ

★ So "just" measure $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$?

★ Not quite, there is a complication…

Neutrino Oscillations in Matter

★ Accounting for this potential term, gives a Hamiltonian that is not diagonal in the basis of the mass eigenstates

$$\mathcal{H}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = \begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} + V|\nu_e\rangle$$ ← ME

★ Complicates the simple picture !!!!

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) =$$

ME $$\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

ME $$-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

CPV $$-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta\; s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$

with $A = 2\sqrt{2}G_F n_e E = 7.6\times10^{-5}\mathrm{eV}^2\cdot\frac{\rho}{\mathrm{g\,cm^{-3}}}\cdot\frac{E}{\mathrm{GeV}}$

Experimental Strategy

EITHER:

★ Keep L small (~200 km): so that matter effects are insignificant

- First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\mathrm{GeV}$$

- Want high flux at oscillation maximum

⇨ **Off-axis beam:** narrow range of neutrino energies

OR:

★ Make L large (>1000 km): measure the matter effects (i.e. MH)

- First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2\,\mathrm{GeV}$$

- **Unfold CPV from Matter Effects through E dependence**

⇨ **On-axis beam:** wide range of neutrino energies

Non standard neutrino interactions

They can be described by effective four-fermion operators of the form

$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R} f'\right)$$

normalizing the operator with the Fermi constant

$$\varepsilon_{\alpha\beta} = \frac{M_W^2}{M_{NSNI}^2}$$

We are left "only" with neutral current NSNI

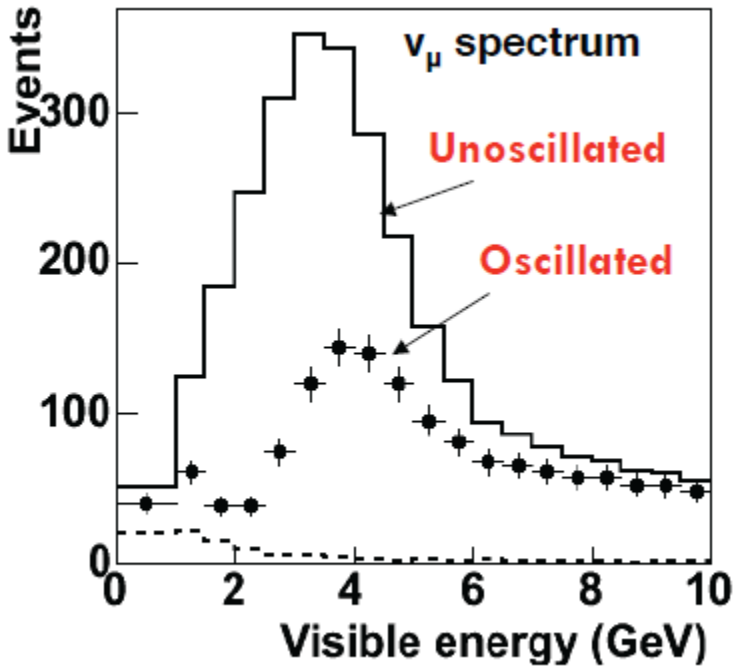
$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\overline{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$$

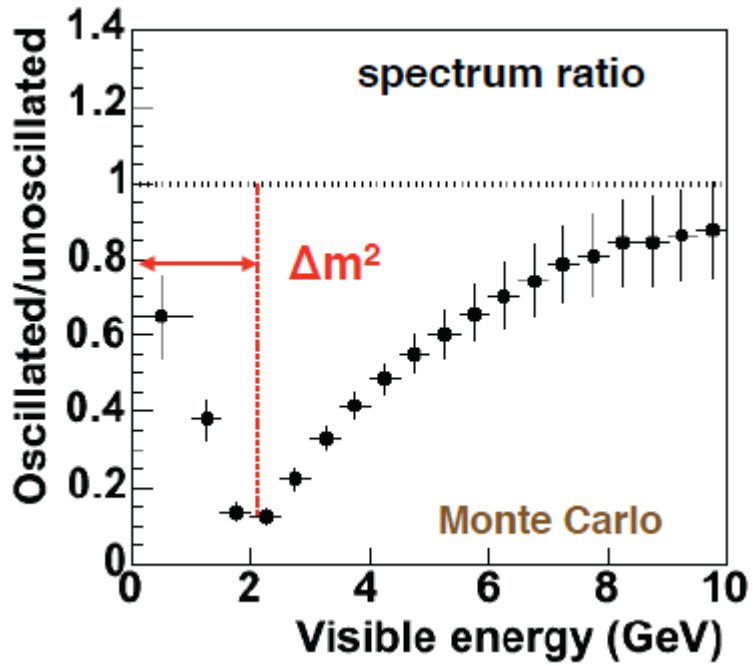
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger+a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

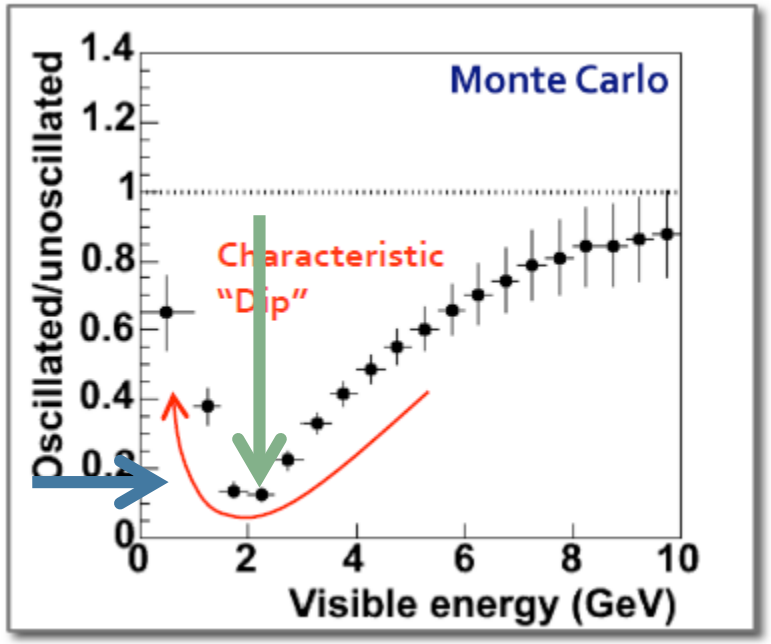
$$a\equiv 2\sqrt{2}G_F n_e E$$

$$H=\frac{1}{2E}\left[U\begin{pmatrix}0 & \\ & \Delta m^2_{32}\end{pmatrix}U^\dagger+a\begin{pmatrix}\epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{\mu\tau}{}^* & \epsilon_{\tau\tau}\end{pmatrix}\right]$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$







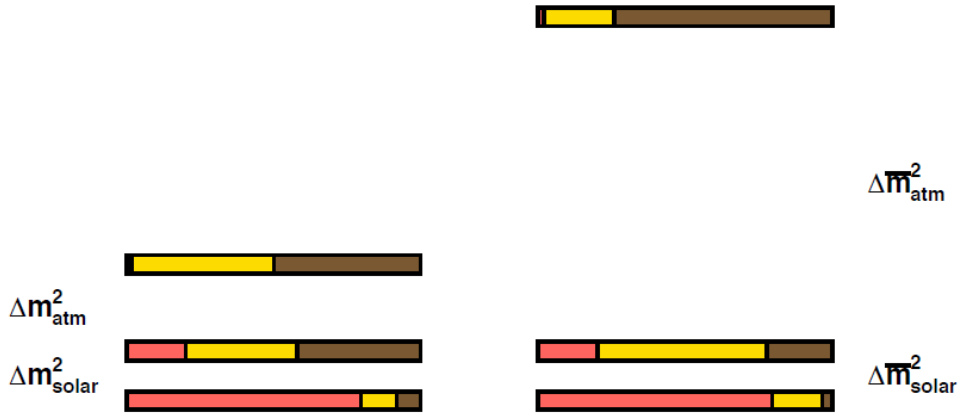
$\varepsilon_{\mu\tau}$ changes the disspearence probability at large energies shifts the position of the minimum in energy

$$\Delta m^2$$

$\varepsilon_{\tau\tau}$ modifies the dissapearence probability near the first oscillation minimum, especially the depth of the minimum

$$sin^2(2\,\theta_{23})$$

CPT violation



$$\frac{|\, m(K_0) - m(\overline{K_0}\,)\,|}{m_{K-av}} < 10^{-18}$$

$$m_{K-av} \approx \frac{1}{2}\ 10^{9}\ \text{eV}$$

$$(m(K_0) - m(\overline{K_0}\,))(m(K_0) + m(\overline{K_0}\,)) < 2\ \ 10^{-18}\, {m_{K-av}}^2$$

$$|m^2(K_0) - m^2(\overline{K_0}\,)| \approx \frac{1}{2}\ \text{eV}^2$$

CPT tests

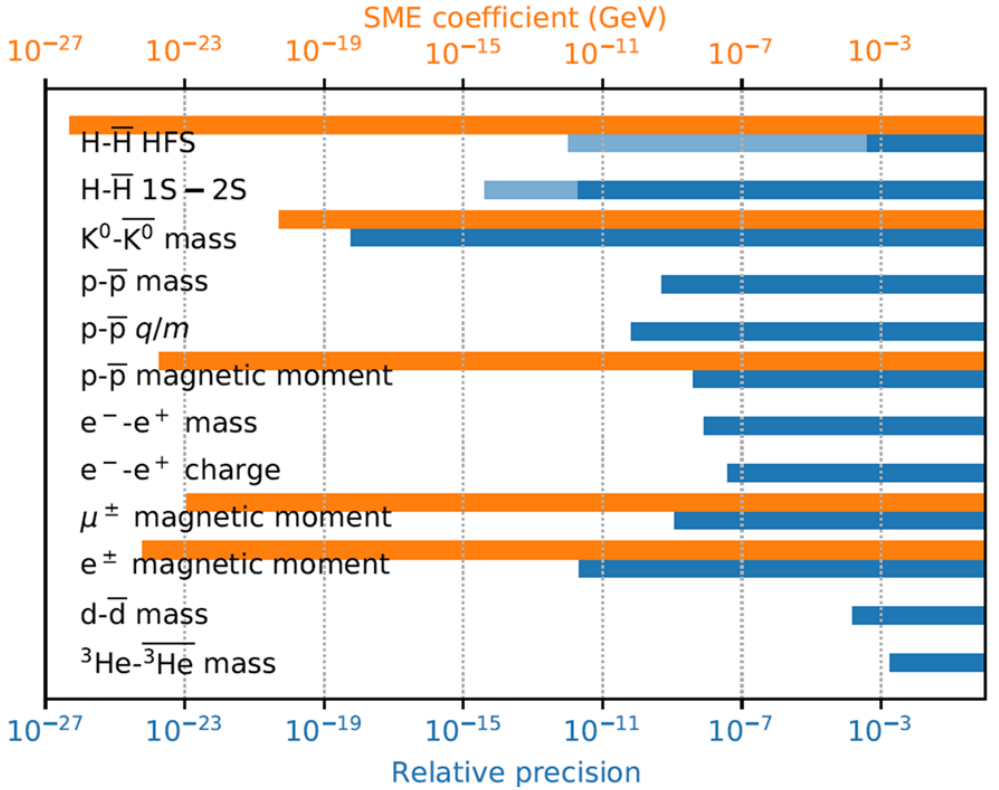
CPT invariance tested in several matter-antimatter systems:

neutral kaons

electron/positron

proton/antiproton

H/anti-H



E. Widmann, arXiv:2111.04056 [hep-ex]

Several experiments at the Antiproton Decelerator and ELENA(Extra Low Energy Antiproton) @CERN

Current bounds

- We can use data of various experiments to calculate the neutrino and antineutrino oscillation parameters:
  - Solar neutrino data: $\theta_{12}, \Delta m^2_{21}, \theta_{13}$
  - Neutrino mode in LBL: $\theta_{23}, \Delta m^2_{31}, \theta_{13}$
  - KamLAND data: $\overline{\theta}_{12}, \Delta \overline{m}^2_{21}, \overline{\theta}_{13}$
  - SBL reactors: $\overline{\theta}_{13}, \Delta \overline{m}^2_{31}$
  - Antineutrino mode in LBL: $\overline{\theta}_{23}, \Delta \overline{m}^2_{31}, \overline{\theta}_{13}$
- No bounds on CP-phases since all values are allowed

Parameter	Main contribution	Other contributions
θ_{12}	SOL	KamLAND
θ_{13}	REAC	ATM+LBL and SOL+KamLAND
θ_{23}	ATM+LBL	-
δ_{CP}	LBL	ATM
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
MO	LBL+REAC and ATM	-

SOL: Solar
ATM: Amtopsheric neutrinos
LBL: Long baseline accelerator experiments
REAC: Short-baseline reactor experiments

Current bounds

- We use the same data (except atmospheric neutrinos) as for the global fit to obtain

$$
\begin{aligned}
|\Delta m^2_{21} - \Delta \overline{m}^2_{21}| &< 4.7 \times 10^{-5}\ \mathrm{eV}^2, \\
|\Delta m^2_{31} - \Delta \overline{m}^2_{31}| &< 2.5 \times 10^{-4}\ \mathrm{eV}^2, \\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14, \\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.029, \\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.19.
\end{aligned}
$$

G.B., C. Ternes and M. Tortola, 2005.05975, JHEP2020

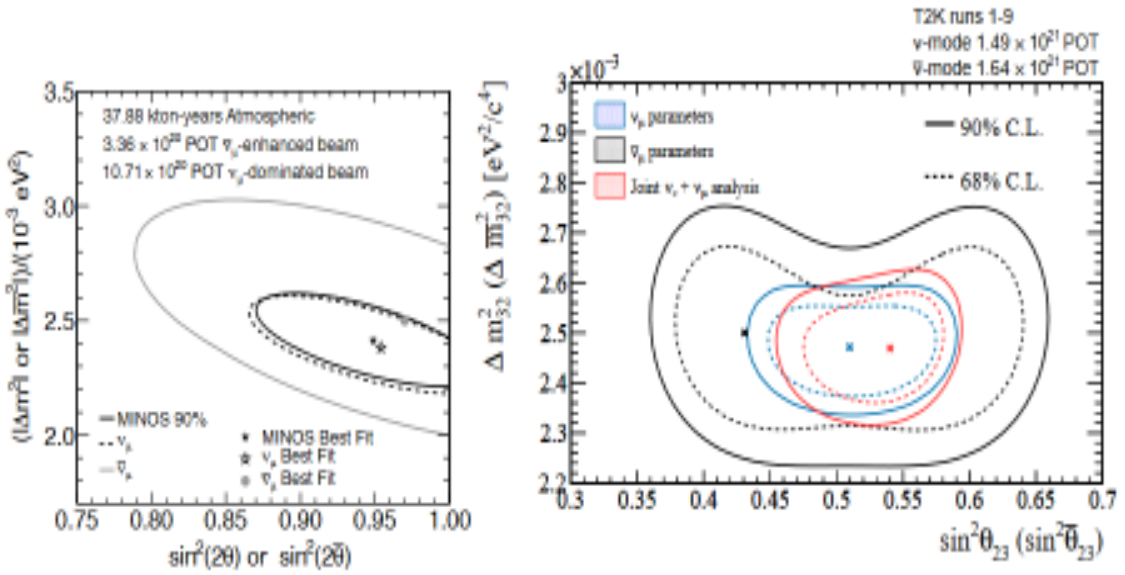
T2K results, a hint ?

- T2K studied neutrino and anti-neutrino oscillations separated

$$\sin^2\theta_{23} = 0.51, \quad \Delta m^2_{32} = 2.53 \times 10^{-3}\mathrm{eV}^2$$

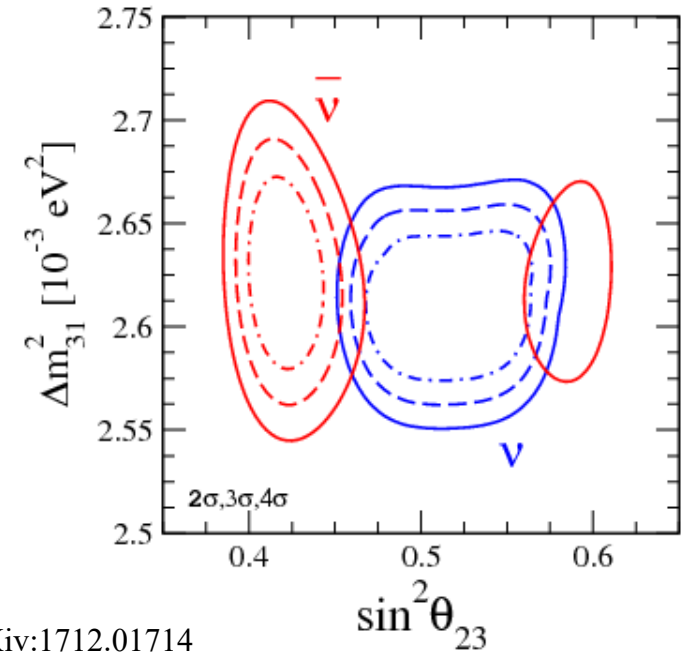
$$\sin^2\overline{\theta}_{23} = 0.42, \quad \Delta \overline{m}^2_{32} = 2.55 \times 10^{-3}\mathrm{eV}^2$$

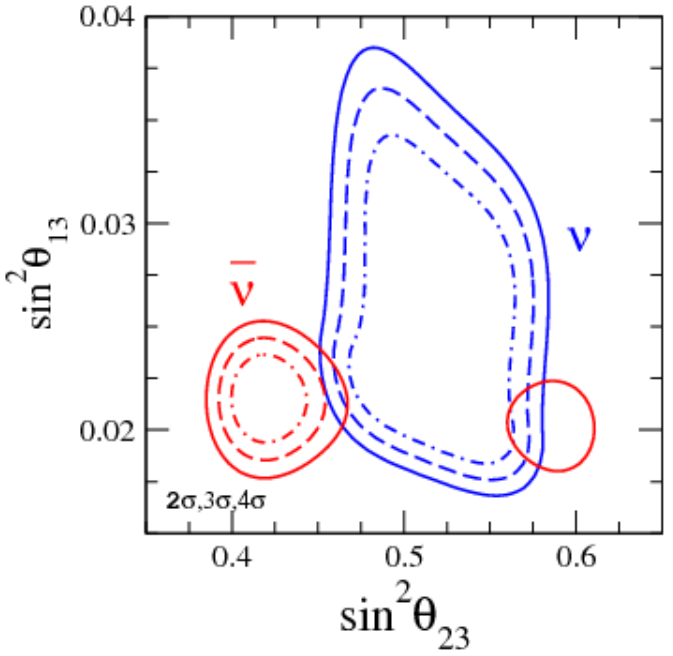
- Results are consistent with
- CPT-conservation



DUNE about T2K

- We find, that if these values turn out to be the true values, DUNE would measure CPT-violation at more than 3σ confidence level





ArXiv:1712.01714

- In experiments and in fits normally you assume CPT-conservation
- If CPT is not conserved this leads to impostor (fake) solutions in the fits

- To perform the standard fit you would calculate

$$\chi^2_{\text{total}} = \chi^2(\nu) + \chi^2(\overline{\nu})$$

and then minimize this function

$$h(x,y) = f(x) + g(y)$$

$$\partial_x f(x) = 0 \qquad \partial_y g(y) = 0$$

$$x = y$$

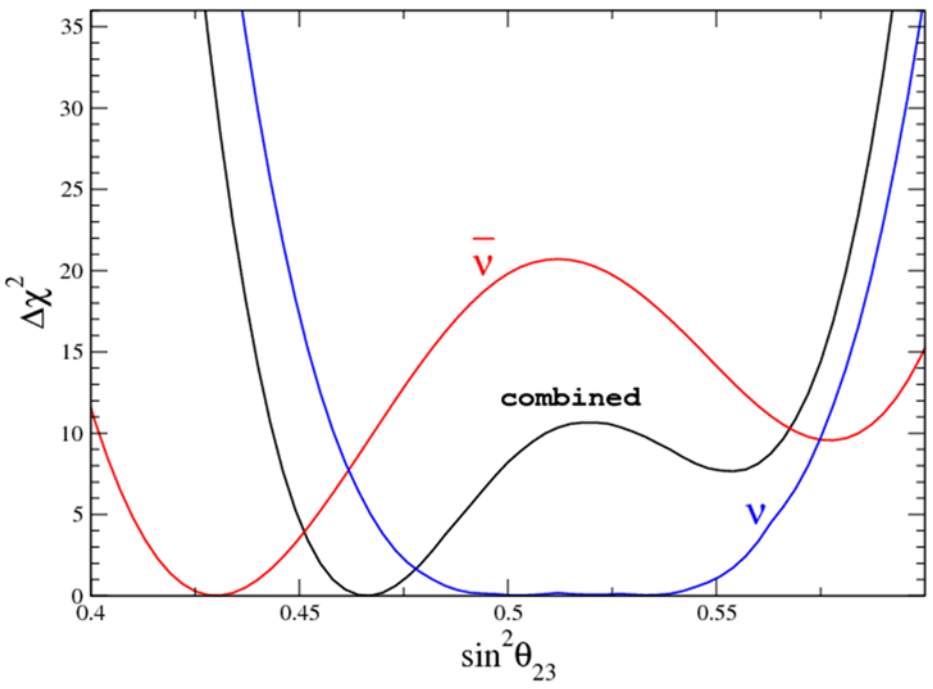
$$h(x) = f(x) + g(x)$$

$$\partial_x f(x) = \partial_x g(x) = 0$$

$$\partial_x f(x) = -\partial_x g(x)$$

Obtaining impostor solutions

- This was done for $\sin^2(\theta_{23}) = 0.5,\ \sin^2(\overline{\theta}_{23}) = 0.43$



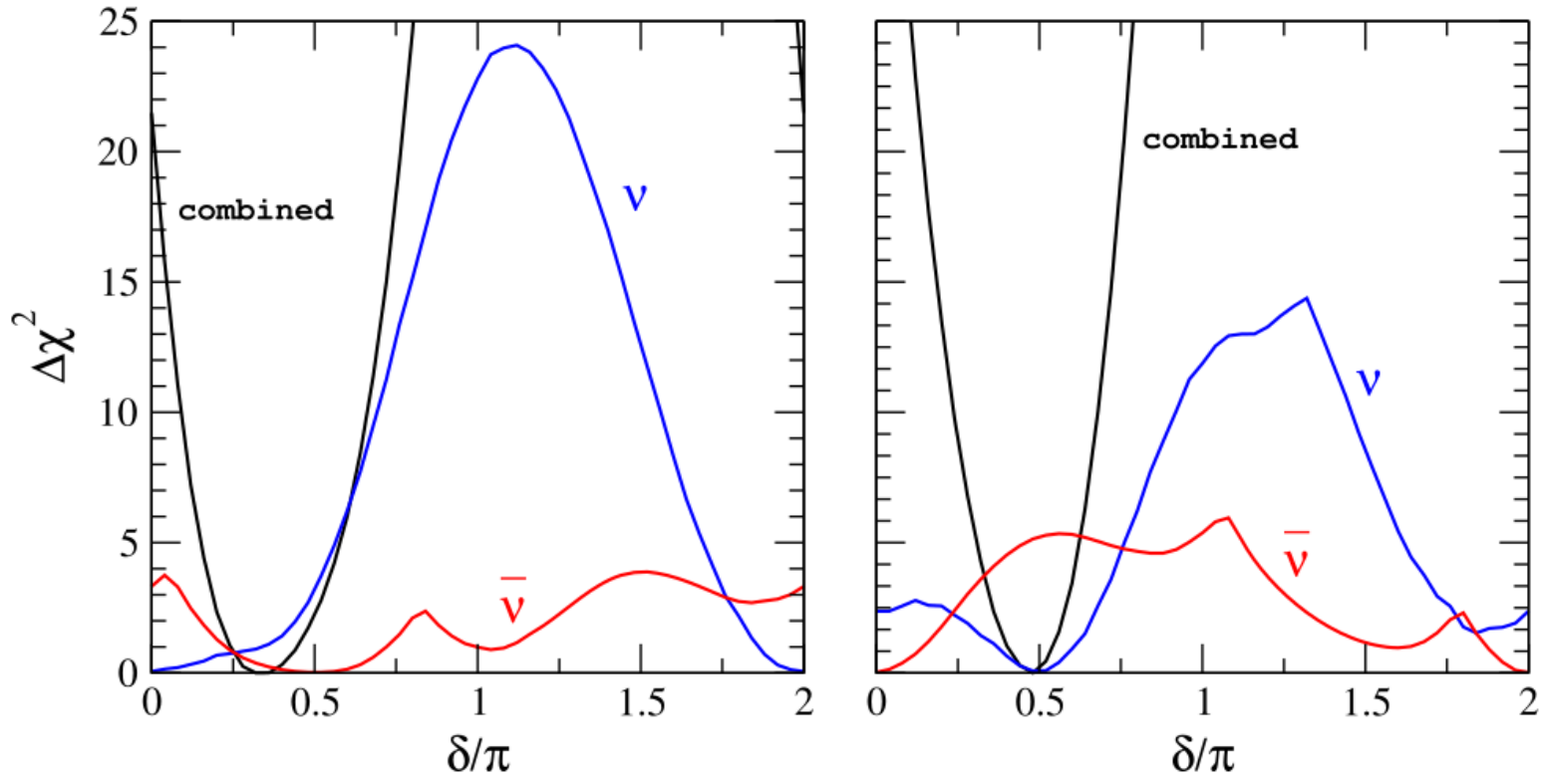
Combined best fit value is now

$$\sin^2(\theta_{23}^{\rm comb}) = 0.467$$

Real true values are disfavored at close to 3σ and more 5σ confidence levels

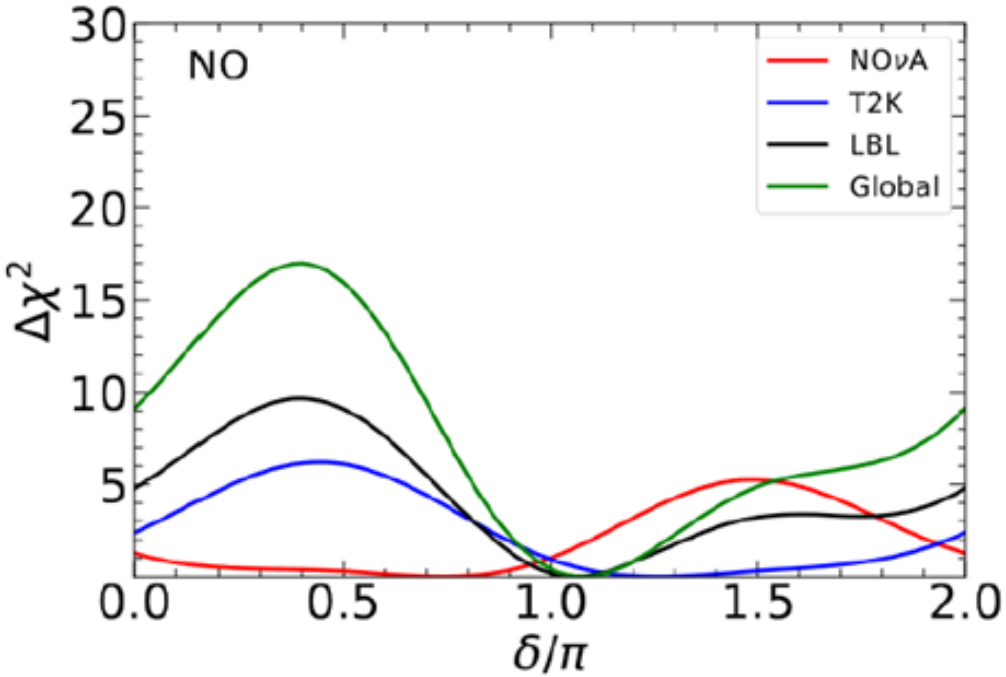
This can also happen

$$\delta = \begin{cases} \pi/2 \\ 0 \end{cases} \quad \text{and} \quad \bar{\delta} = \begin{cases} 0 \\ \pi/2 \end{cases}$$



G.B., C. Ternes and M. Tortola, JHEP 07 (2020) 155

$\theta_{13} \neq \theta_{13}$ can account for different behavior in neutrino and antineutrino channels



Tension between NOvA, T2K and SK atm. and $\delta_{bf} = 1.08\pi$

- Disfavours:
  - $\delta = \pi/2$ at 4.0σ
  - $\delta = 0$ at 3.0σ
  - $\delta = 3\pi/2$ with $\Delta\chi 2 = 4.9$

all values of δ and $\overline{\delta}$ remain allowed at ~ 1σ

The increasing precision in neutrino oscillation measurements requires a thorough analysis of the assumptions considered.

Distinguishing CPT violation from NSNI

The muon neutrino survival probability in matter can be written as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_\nu \sin^2\left(\frac{\Delta m^2_\nu L}{4E}\right).$$

in matter

$\Delta m^2_\nu \cos 2$ $\Delta m^2_\nu \sin 2$

$$4\Delta m^4 = \Delta m^4_\nu + \Delta m^4_{\bar\nu} + 2\Delta m^2_\nu \Delta m^2_{\bar\nu} \cos(2\theta_\nu - 2\theta_{\bar\nu})$$

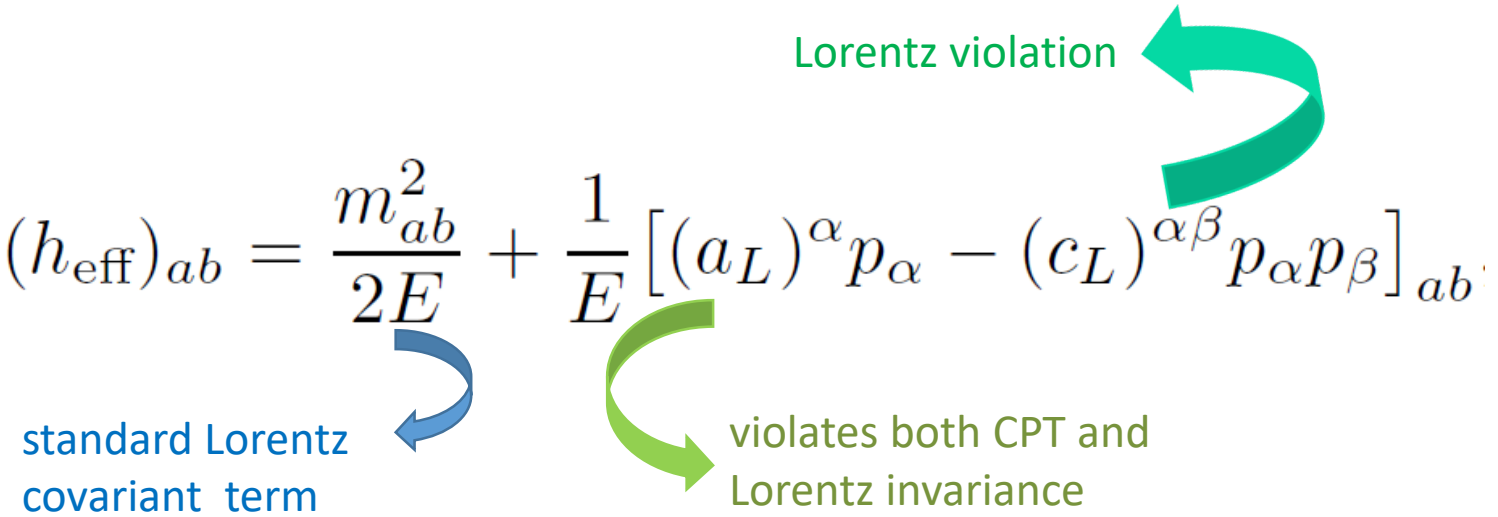
$- \epsilon_{\tau\tau} A\,,$
$- 2\epsilon_{\mu\tau} A\,.$

$$\sin^2(2\theta) = \frac{\left(\Delta m^2_\nu \sin(2\theta_\nu) + \Delta m^2_{\bar\nu} \sin(2\theta_{\bar\nu})\right)^2}{\Delta m^4_\nu + \Delta m^4_{\bar\nu} + 2\Delta m^2_\nu \Delta m^2_{\bar\nu} \cos(2\theta_\nu - 2\theta_{\bar\nu})}$$

$$\begin{aligned} 2\epsilon^m_{\tau\tau} A &= \Delta m^2_\nu \cos(2\theta_\nu) - \Delta m^2_{\bar\nu} \cos(2\theta_{\bar\nu}) \\ 4\epsilon^m_{\mu\tau} A &= \Delta m^2_\nu \sin(2\theta_\nu) - \Delta m^2_{\bar\nu} \sin(2\theta_{\bar\nu}) \end{aligned}$$

G.B., C. Ternes and M. Tortola, Eur.Phys.J.C 79 (2019) 5, 390

Violations of Lorentz invariance



Conclusions: Neutrino physics will continue delivering results

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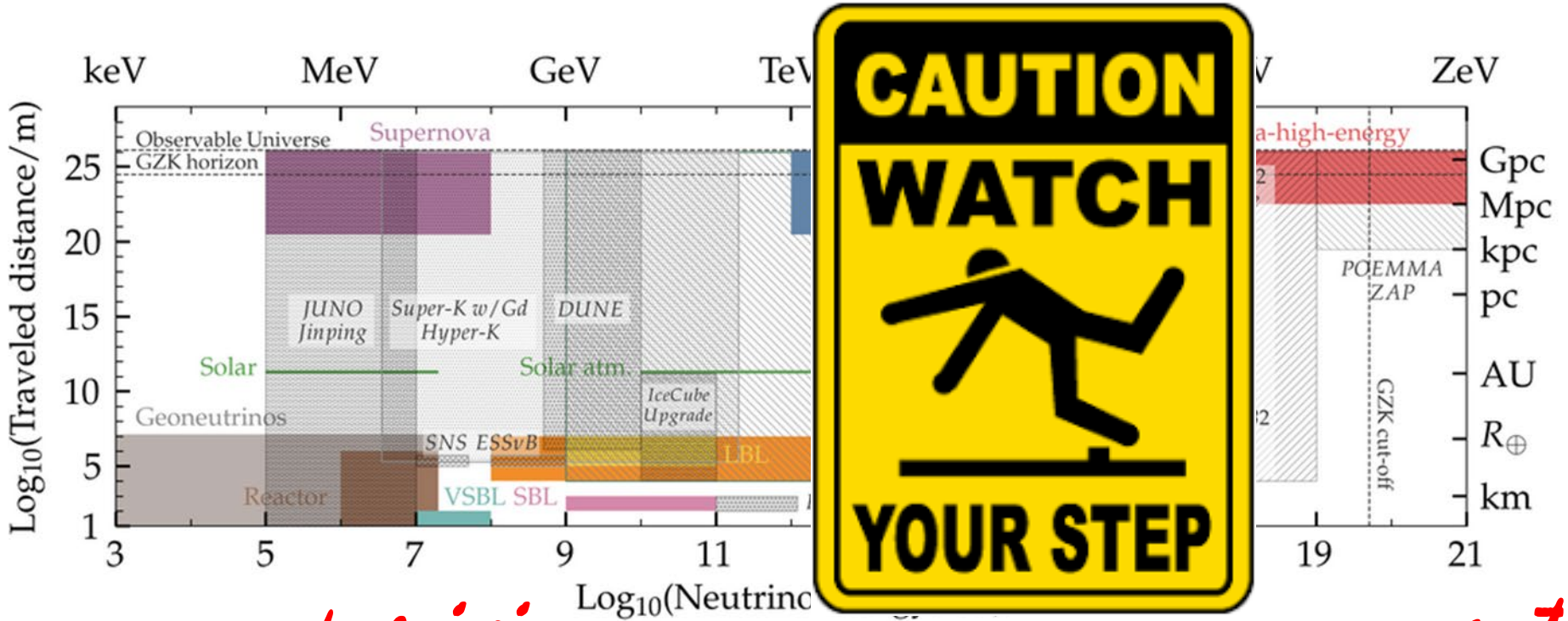

precision caution

Extraordinary claims requires extraordinary evidence

CPT invariance check should come BEFORE any CP violation claim….

Mariam Tortola

Christoph Ternes

Pablo Martinez-Mirave