

LIVE

LIVE COVERAGE

BREAKING NUS

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10:27 | 75°F

HIDDe1

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1

Is The Whole Universe made of—

Electrons **Protons** **Neutrons ?**

NO!

Electrons **Protons are rareties!** **Neutrons**

For every one of them, the universe contains a **billion** neutrinos v!

2

Passing through each person on earth every second:
One hundred trillion neutrinos from the sun.

The sun shines because of nuclear fusion in its core.

This fusion produces—

- Energy, including visible light
- Neutrinos
- The atoms more complicated than hydrogen

3



Almost all neutrinos zipping through us do nothing at all.

Typically, a solar neutrino would have to zip
through 10,000,000,000,000,000 people
before doing anything.

The probability that a particular solar neutrino
will interact as it zips through one of us is
 $1 / 10,000,000,000,000,000$.

4

Are Neutrinos Important to Our Lives?

If there were no ν s, the sun and stars would not shine.

- No energy from the sun to keep us warm.
- No atoms more complicated than hydrogen.
No carbon. No oxygen. No water.
No earth. No moon. No us.

No ν s is very **BAD** news.

5

Particle physics was not a hard course to take

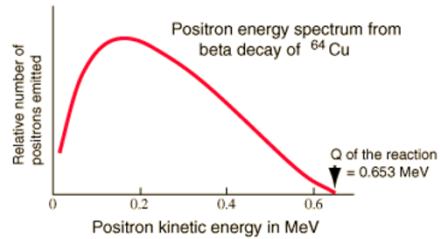
β decay was supposed to be a two body decay



$$E_e = \frac{m_n^2 + m_e^2 - m_p^2}{2 m_n}$$

6

Studies of β decay revealed a continuous energy spectrum.



Another anomaly was the fact that the nuclear recoil was not in the direction opposite to the momentum of the electron.

The emission of another particle was a probable explanation of this behaviour, but searches found no evidence of either mass or charge.

7



8

...desperate remedy to save the law of conservation of energy...

Neutron Decay:

$$n \rightarrow p + e^- + \bar{\nu}_e$$



Fermi postulated a theory for β decay in terms of spinors

$$H_{ew} = \frac{G_F}{\sqrt{2}} \bar{\Psi}_p \gamma_\mu \Psi_n \bar{\Psi}_e \gamma^\mu \Psi_\nu$$

9

A Dirac field is described by a four component spinor

$$\begin{pmatrix} e_L \\ e_R \\ \hat{e}_L \\ \hat{e}_R \end{pmatrix}$$

10

Standard Model of Particle Physics

Gauge Theory based on the group:

$$SU(3) \times SU(2) \times U(1)$$

$$\underline{SU_L(2) \times U_Y(1) \Rightarrow U_{EM}(1)}$$

Force Carriers: W^\pm , Z^0 and γ masses: 80, 91 and 0 GeV

quark, SU(2) doublets: $\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L$

up-quark, SU(2) singlets: u_R, c_R, t_R

down-quark, SU(2) singlets: d_R, s_R, b_R

lepton, SU(2) doublets: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$

neutrino, SU(2) singlets: — — —

charge lepton, SU(2) singlets: e_R, μ_R, τ_R

11

Electron mass

comes from a term of the form

$$\bar{L}\phi e_R$$

Absence of ν_R

forbids such a mass term (dim 4)

for the Neutrino

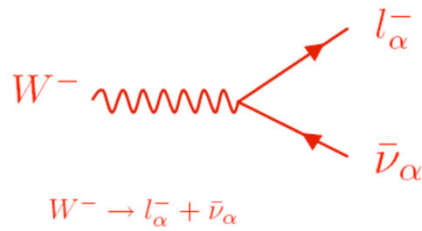
Therefore in the SM neutrinos are massless

and hence travel at speed of light.

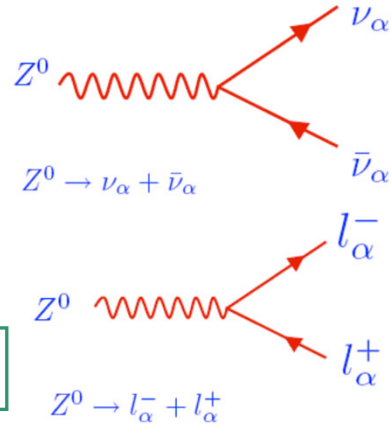
12

Interactions:

Charge Current (CC)



Neutral Current (NC)



$$\Gamma(Z^0 \rightarrow f + \bar{f}) = K \frac{g_Z^2 M_Z}{48\pi} [|c_V^f|^2 + |c_A^f|^2]$$

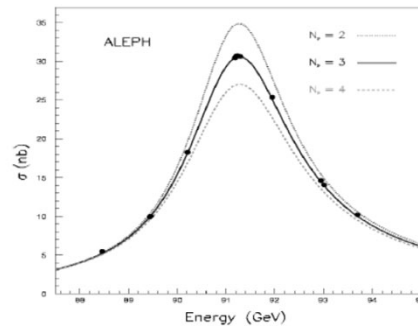
$\alpha = e, \mu, \text{ or } \tau$

13

Invisible width of Z plus other data from LEP:

$$Z^0 \rightarrow \nu \bar{\nu}$$

Implies $N_\nu = 2.99 \pm 0.01$



Three Active Neutrinos!!!

Sterile Neutrinos don't couple to Z^0

14

Note That

$W^- \rightarrow l^- + \bar{\nu}_\alpha$

Implies

ν_e, ν_μ, ν_τ
 e, μ, τ

15

Standard Model

couplings conserve the **Lepton Number L**
 defined by—
 $L(\nu) = L(l^-) = -L(\bar{\nu}) =$ Left Handed Nature of The Neutrino

Actually $L_e, L_\mu,$ and L_τ separately

spin
 momentum

ν
 $\bar{\nu}$

16

Beyond the SM

What if Neutrino have a MASS?

speed is less than c therefore time can pass

and

Neutrinos can change character!!!

What are the stationary states?

How are they related to the interaction states?

17

NEUTRINO OSCILLATIONS:

Two Flavors

flavor eigenstates \neq mass eigenstates

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

W's produce ν_μ and/or ν_τ 's

but ν_1 and ν_2 are the states

that change by a phase over time, mass eigenstates.

$$|\nu_j\rangle \rightarrow e^{-ip_j \cdot x} |\nu_j\rangle \quad p_j^2 = m_j^2$$

$\alpha, \beta \dots$ flavor index

$i, j \dots$ mass index

18

Production:

$$|\nu_\mu\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

Propogation:

$$\cos\theta e^{-ip_1 \cdot x}|\nu_1\rangle + \sin\theta e^{-ip_2 \cdot x}|\nu_2\rangle$$

Detection:

$$|\nu_1\rangle = \cos\theta|\nu_\mu\rangle - \sin\theta|\nu_\tau\rangle$$

$$|\nu_2\rangle = \sin\theta|\nu_\mu\rangle + \cos\theta|\nu_\tau\rangle$$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = |\cos\theta(e^{-ip_1 \cdot x})(-\sin\theta) + \sin\theta(e^{-ip_2 \cdot x})\cos\theta|^2$$

19

$$P(\nu_\mu \rightarrow \nu_\tau) = |\cos\theta(e^{-ip_1 \cdot x})(-\sin\theta) + \sin\theta(e^{-ip_2 \cdot x})\cos\theta|^2$$

$$\text{Same } E, \text{ therefore } p_j = \sqrt{E^2 - m_j^2} \approx E - \frac{m_j^2}{2E}$$

$$e^{-ip_j \cdot x} = e^{-iEt} e^{-ip_j L} \approx e^{-i(Et - EL)} e^{-im_j^2 L/2E}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2\theta \cos^2\theta |e^{-im_2^2 L/2E} - e^{-im_1^2 L/2E}|^2$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

$$\delta m^2 = m_2^2 - m_1^2 \text{ and } \frac{\delta m^2 L}{4E} \equiv \Delta \text{ kinematic phase:}$$

20

$$P(\nu_\mu \rightarrow \nu_\tau) = |\cos\theta(e^{-ip_1 \cdot x})(-\sin\theta) + \sin\theta(e^{-ip_2 \cdot x})\cos\theta|^2$$

Same E, therefore $p_j = \sqrt{E^2 - m_j^2} \approx E - \frac{m_j^2}{2E}$

$$e^{-ip_j \cdot x} = e^{-iEt} e^{-ip_j L} \approx e^{-i(Et - EL)} e^{-im_j^2 L/2E}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2\theta \cos^2\theta |e^{-im_2^2 L/2E} - e^{-im_1^2 L/2E}|^2$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E} \frac{c^4}{\hbar c}$$

21

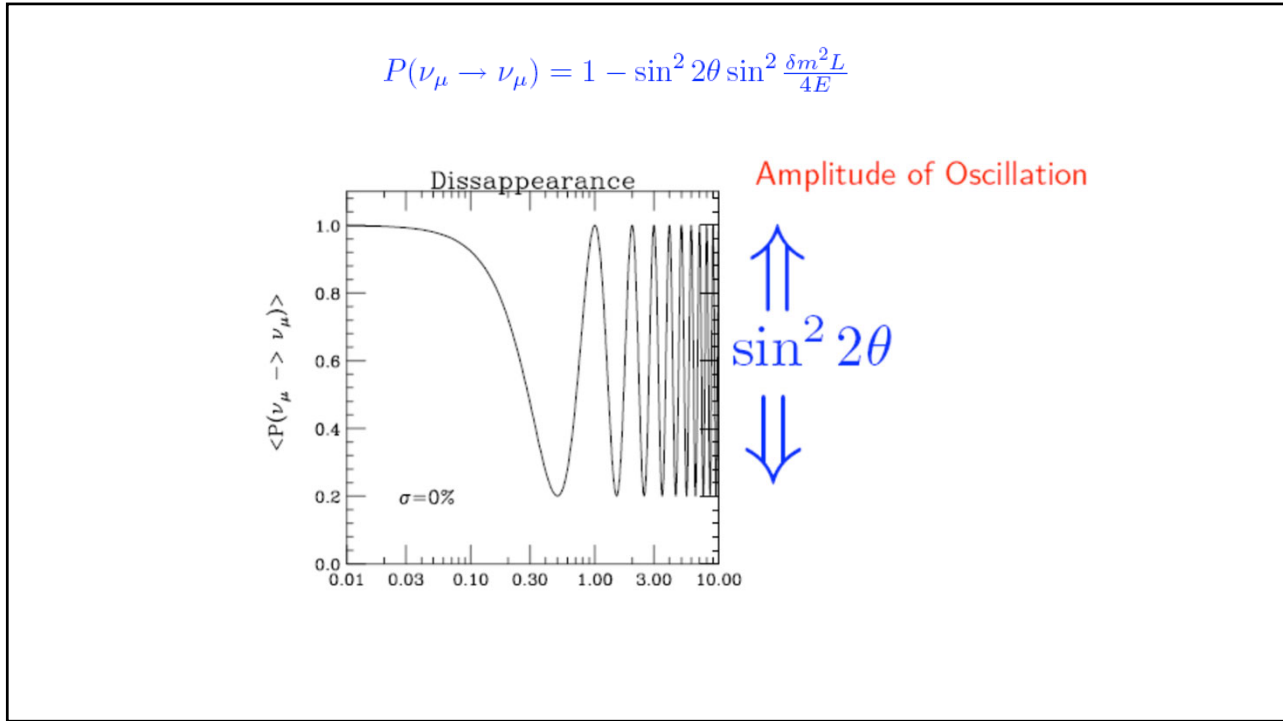
Appearance:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

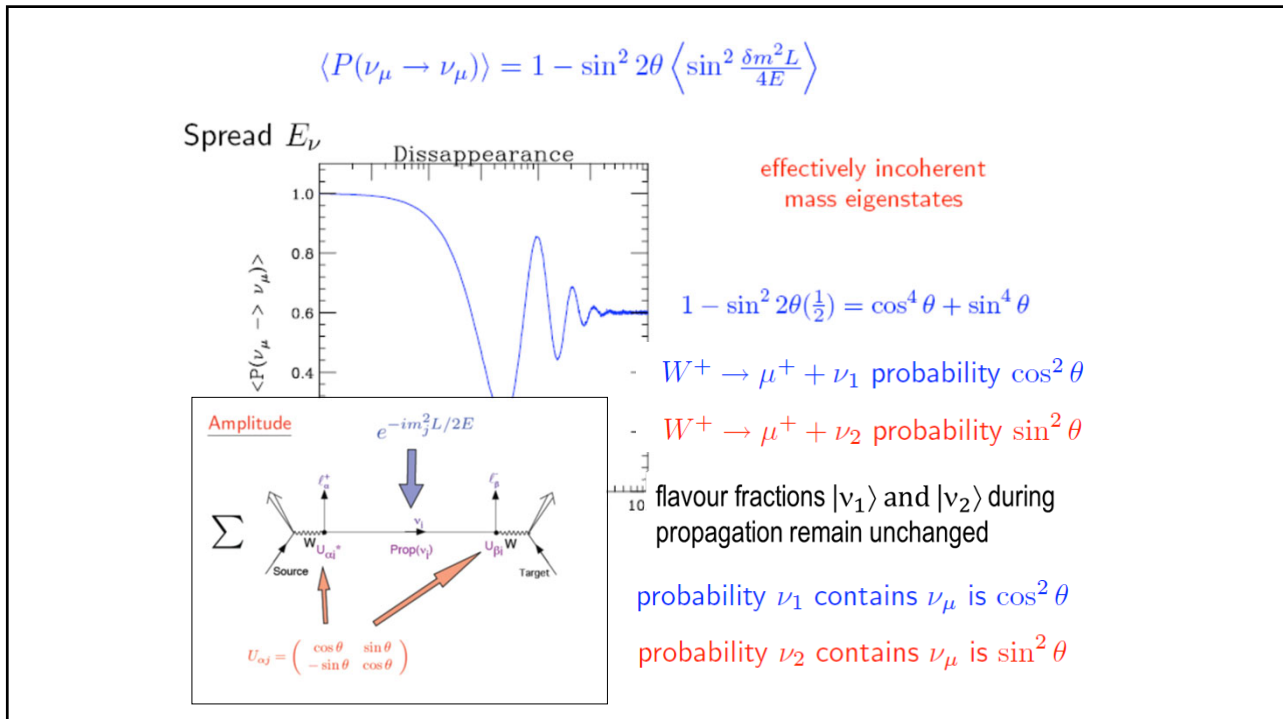
Disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

22



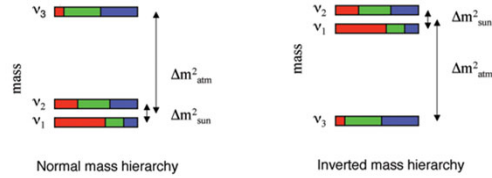
23



24

The ν Standard Model

- 3 light ($m_i < 1$ eV) Majorana Neutrinos:
 \Rightarrow only 2 δm^2



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \curvearrowright \frac{n(n+1)}{2}$$

• **Chirality breaking matrix:**

3 angles ($\theta_{12}, \theta_{23}, \theta_{13}$), 1 Dirac phase (δ),

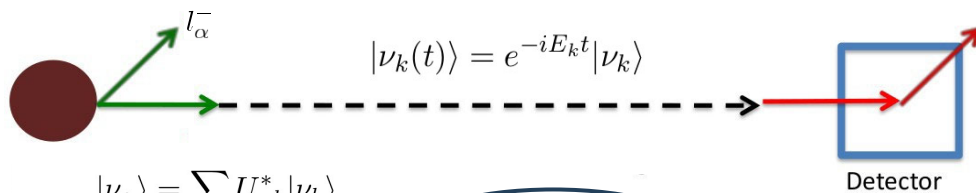
2 Majorana phases (α_2, α_3)

$$2n - 1 \quad n$$

$$\frac{(n-2)(n-1)}{2} \quad + (n-1)$$

25

Neutrino oscillations



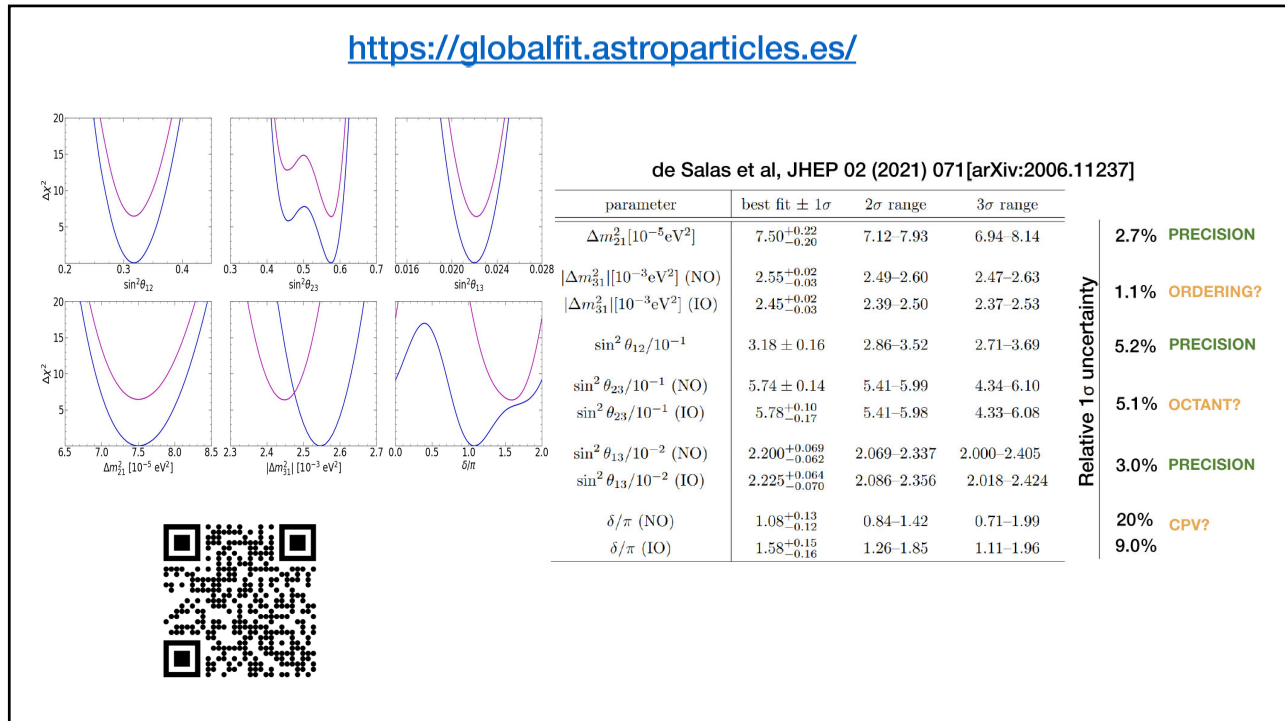
$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle$$

$$W_{\alpha\beta}^{jk} = U_{\alpha j} U_{\beta j}^* U_{\alpha k} U_{\beta k}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{k>j} \text{Re}[W_{\alpha\beta}^{jk}] \sin^2 \left(\frac{\Delta m_{jk}^2 L}{4E_\nu} \right)$$

$$\pm 2 \sum_{k>j} \text{Im}[W_{\alpha\beta}^{jk}] \sin \left(\frac{\Delta m_{jk}^2 L}{2E_\nu} \right)$$

26



27

a connection to BSM physics

- ★ Is there a connection to the GUT scale?
 - If both Dirac and Majorana mass terms are present

$\mathcal{L} \sim -\frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R \end{pmatrix} \begin{pmatrix} m_D & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$

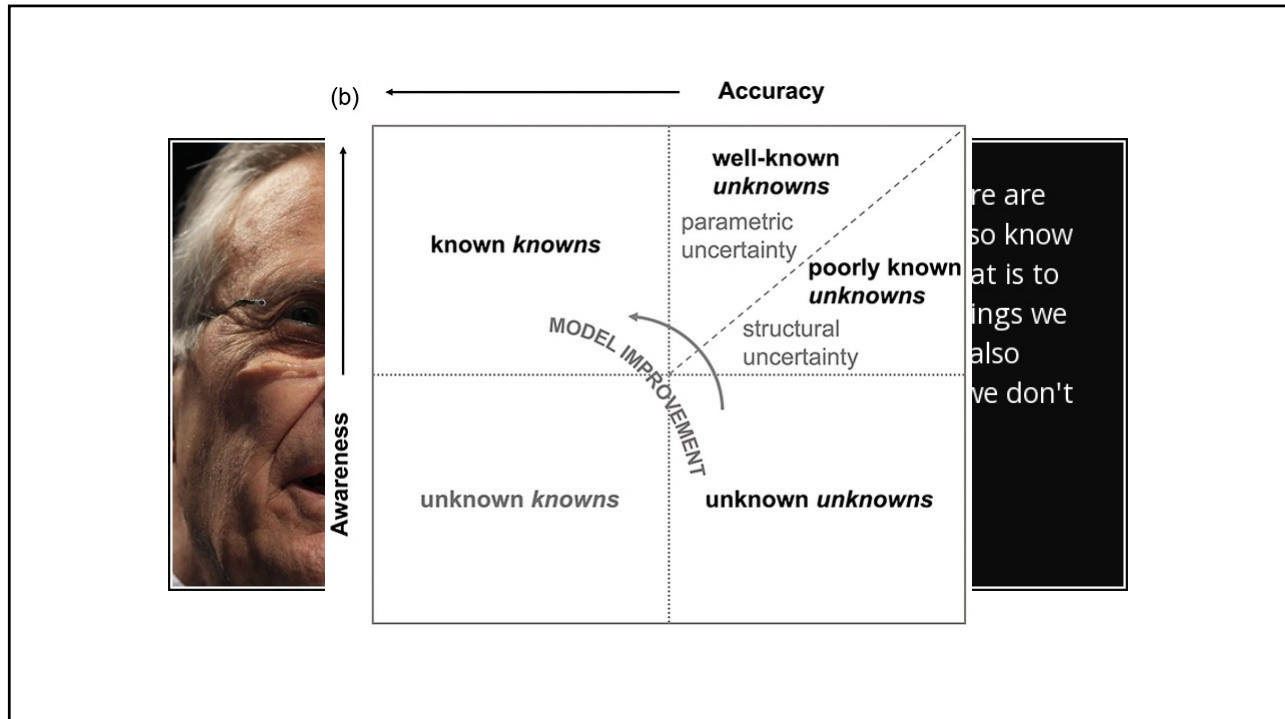
- The seesaw mechanism provides physical “mass eigenstates”
 - are those for which the mass matrix is diagonal

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

light neutrino $m_\nu \approx \frac{m_D^2}{M}$ + heavy RH neutrino $m_N \approx M$

$m_D \sim m_\ell$ to get to right range of small neutrino masses:
 $M \sim 10^{12} - 10^{16} \text{ GeV}$

28

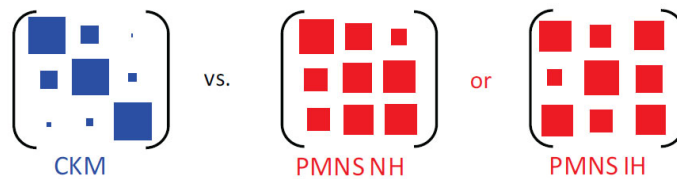


29

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. PMNS



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

30

In principle, it is straightforward

- ★ CPV \Rightarrow different oscillation rates for ν s and $\bar{\nu}$ s

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4s_{12}s_{13}c_{13}^2s_{23}c_{23}\sin\delta \quad \leftarrow \text{vacuum osc.}$$

$$\times \left[\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \times \sin\left(\frac{\Delta m_{23}^2 L}{4E}\right) \times \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \right]$$

- ★ 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 $P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?
- ★ Not quite, there is a complication...

31

Neutrino Oscillations in Matter

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

$$\mathcal{H} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} = i \frac{d}{dt} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} = \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} + V|\nu_e\rangle \quad \leftarrow \text{ME}$$

- ★ Complicates the simple picture !!!!

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) =$$

$$\text{ME} \quad \frac{16A}{\Delta m_{31}^2} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$

$$\text{ME} \quad - \frac{2AL}{E} \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$

$$\text{CPV} \quad - 8 \frac{\Delta m_{21}^2 L}{2E} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\delta \cdot s_{13} c_{13}^2 c_{23} s_{23} c_{12} s_{12}$$

with $A = 2\sqrt{2}G_F n_e E = 7.6 \times 10^{-5} \text{eV}^2 \cdot \frac{\rho}{\text{g cm}^{-3}} \cdot \frac{E}{\text{GeV}}$

32

CPT violation



33

$$\frac{|m(K_0) - m(\overline{K}_0)|}{m_{K-av}} < 10^{-18}$$

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

$$(m(K_0) - m(\overline{K}_0))(m(K_0) + m(\overline{K}_0)) < 2 \cdot 10^{-18} m_{K-av}^2$$

$$|m^2(K_0) - m^2(\overline{K}_0)| \approx \frac{1}{2} \text{ eV}^2$$

34

CPT tests

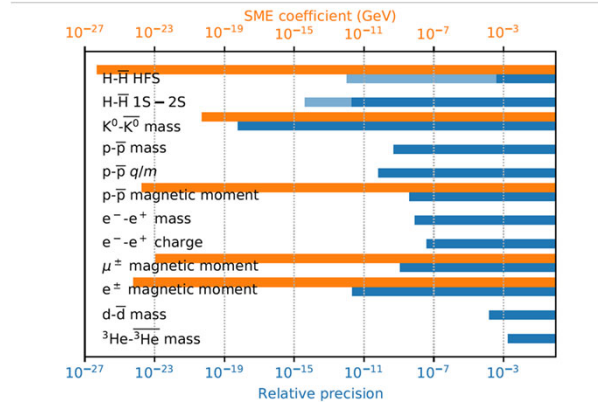
CPT invariance tested in several matter-antimatter systems:

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

35

Current bounds

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

36

Current bounds

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

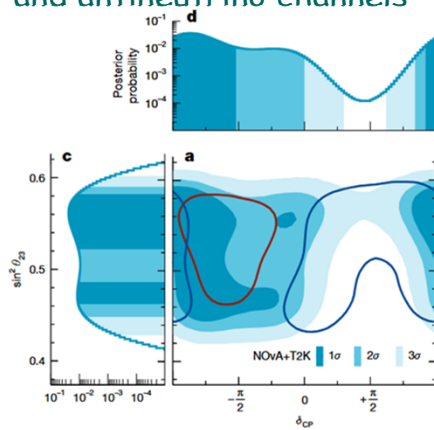
$$\begin{aligned}
 |\Delta m_{21}^2 - \Delta \bar{m}_{21}^2| &< 4.7 \times 10^{-5} \text{ eV}^2, \\
 |\Delta m_{31}^2 - \Delta \bar{m}_{31}^2| &< 2.5 \times 10^{-4} \text{ eV}^2, \\
 |\sin^2 \theta_{12} - \sin^2 \bar{\theta}_{12}| &< 0.14, \\
 |\sin^2 \theta_{13} - \sin^2 \bar{\theta}_{13}| &< 0.029,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

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



37

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



The NOvA Collaboration & The T2K Collaboration

Nature **646**, 818–824 (2025)

all values of δ and $\bar{\delta}$
remain allowed at $\sim 1\sigma$

38

Violations of Lorentz invariance

$$(h_{\text{eff}})_{ab} = \frac{m_{ab}^2}{2E} + \frac{1}{E} [(a_L)^\alpha p_\alpha - (c_L)^{\alpha\beta} p_\alpha p_\beta]_{ab}$$

standard Lorentz covariant term Lorentz violation
violates both CPT and Lorentz invariance

39

Violations of Lorentz invariance

$$(h_{\text{eff}})_{ab} = \frac{m_{ab}^2}{2E} + \frac{1}{E} [(a_L)^\alpha p_\alpha - (c_L)^{\alpha\beta} p_\alpha p_\beta]_{ab}$$

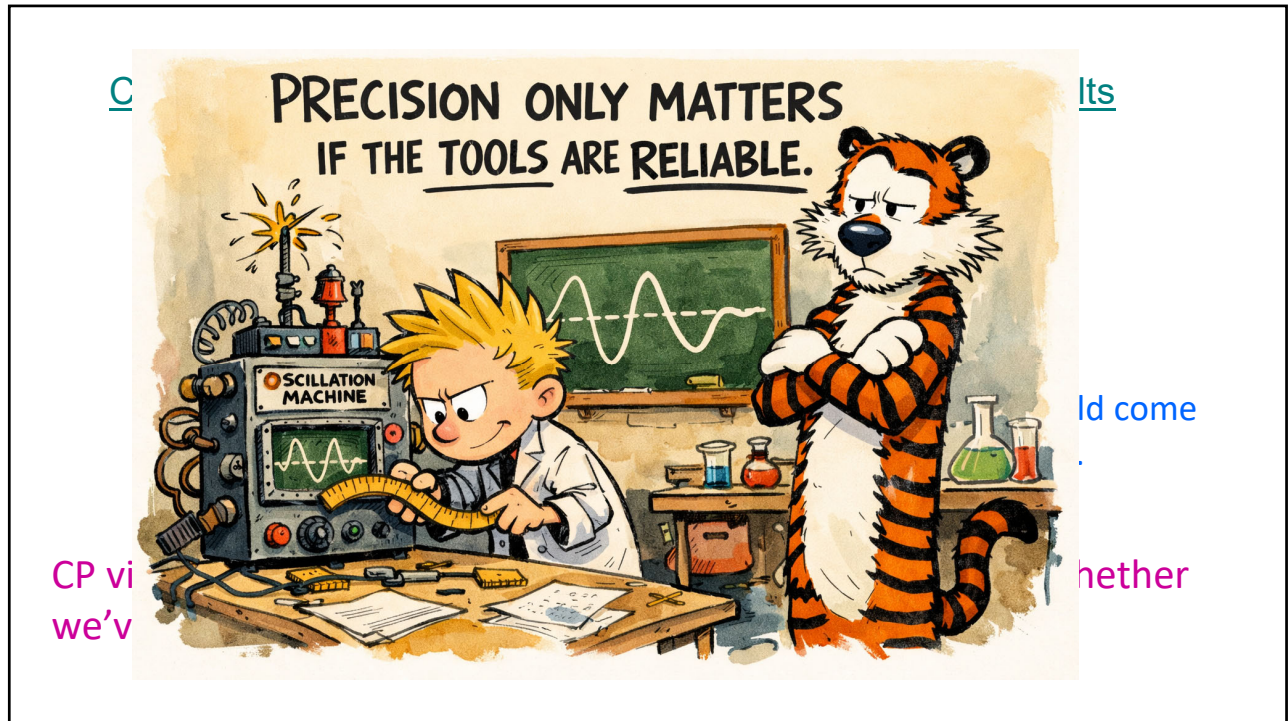
standard Lorentz covariant term Lorentz violation
violates both CPT and Lorentz invariance

As usual, the oscillation probability is governed by the difference of the eigenvalues of the effective hamiltonian.

$$\sin^2(\Delta_{ab} L/2)$$

$m_{ab}^2 L/E$ $(a^\alpha)_{ab} L$ $(c^{\alpha\beta})_{ab} L E$

40



41