NEUTRINOS: WHERE WE ARE.
WHERE WE ARE HEADING TO.

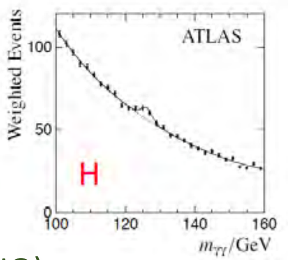
중성미자: 우리는 어디에 있습니까
우리는 어디로 향하고 있습니까

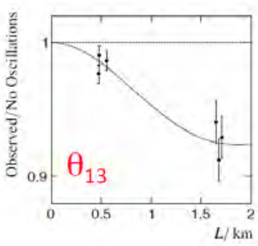
Gabriela Barenboim
(UV-IFIC and KIAS)
ChungAng University, August 17

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

2012 Two major discoveries in particle physics

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



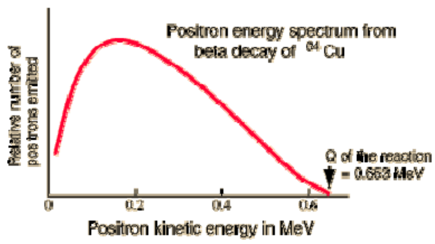


- θ_{13} ~ 10^o (T2K, MINOS, Daya Bay, RENO)
  about as large as it could have been !
  The door to CP Violation in the leptonic sector

Some 100 years ago …..

β de

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.

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

Fermi postulated ... n terms of spinors

$$H_{ew} = \ldots \, {}_e\gamma^{\mu} \ \psi_{\nu}$$

A Dirac field is described by a four component spinor

$$\begin{pmatrix} e_L \\ e_R \\ \widehat{e_L} \\ \widehat{e_R} \end{pmatrix}$$

Standard Model of Particle Physics

Gauge Theory based on the group:

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

$SU(3) \Rightarrow$ Quantum Chromodynamics

Strong Force (Quarks and Gluons)

$SU_L(2) \times U(1) \Rightarrow$ ElectroWeak Interactions broken to $U_{EM}(1)$

by HIGGS

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

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

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)

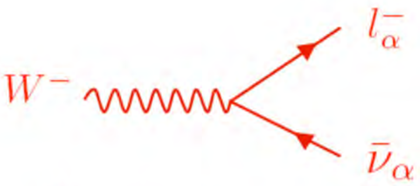
for the Neutrino

Therefore in the SM neutrinos are massless

and hence travel at speed of light.

Interactions:

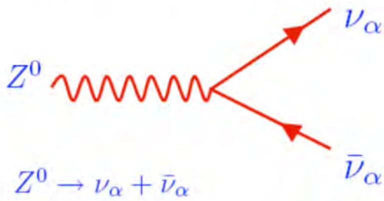
Charge Current (CC)



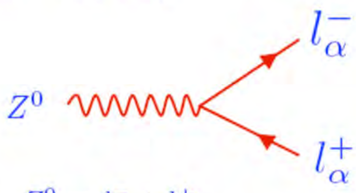
$W^- \rightarrow l^-_\alpha + \bar{\nu}_\alpha$

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

Neutral Current (NC)



$Z^0 \rightarrow \nu_\alpha + \bar{\nu}_\alpha$



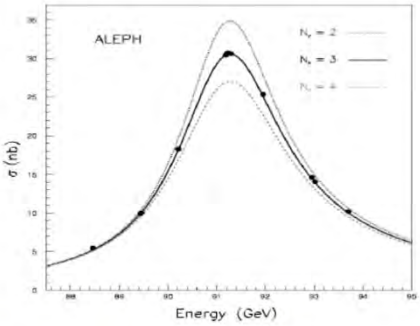
$Z^0 \rightarrow l^-_\alpha + l^+_\alpha$

$\alpha = e, \mu,\ or\ \tau$

Invisible width of Z plus other data from LEP:

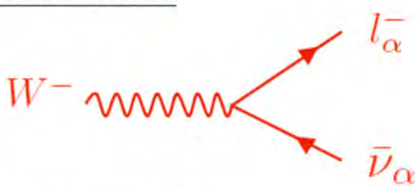
$Z^0 \to \nu\bar{\nu}$

Implies $N_\nu = 2.99 \pm 0.01$



Three Active Neutrinos!!!   Sterile Neutrinos don't couple to Z^0

Note That



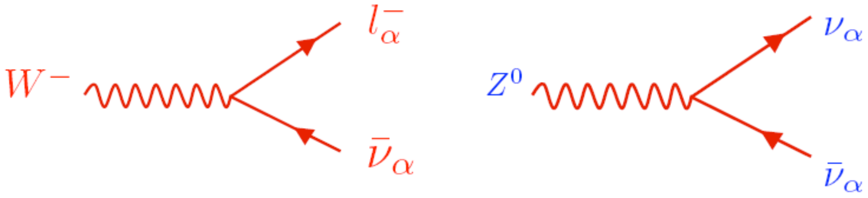
$W^- \to l_\alpha^- + \bar{\nu}_\alpha$

ν_e , ν_μ , ν_τ

Implies ↕ ↕ ↕

e , μ , τ

Standard Model

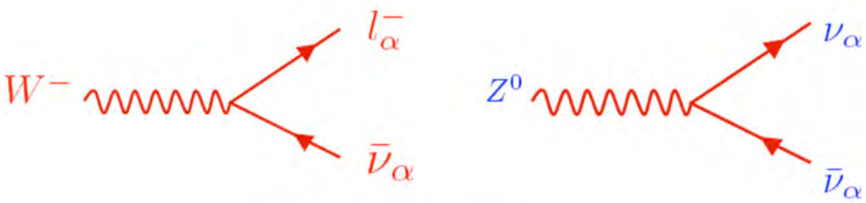


couplings conserve the Lepton Number L
defined by—

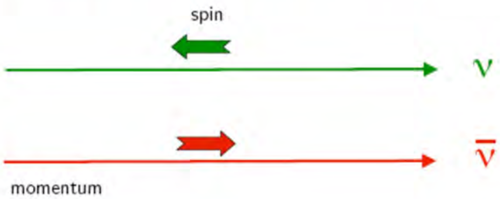
L(ν) = L(ℓ^-) = – L($\bar{\nu}$) = – L (ℓ^+) = 1.

Actually L_e, L_μ, and L_τ
separately

Left Handed Nature of The Neutrino



Produce Left-Handed Neutrinos
and Right-Handed Anti-Neutrinos



What about the RH neutrinos and LH anti-neutrino ????

There exist three fundamental and discrete transformations in nature:

- **Parity** $\mathcal{P}$ $\vec{x} \to -\vec{x}$
- **Time reversal** $\mathcal{T}$ $t \to -t$
- **Charge conjugation** $\mathcal{C}$ $q \to -q$

$\mathcal{P}$, $\mathcal{T}$ and $\mathcal{C}$ are conserved in the classical theories of mechanics and electrodynamics!

$\mathcal{CPT} \leftrightarrow$ Lorentz invariance $\oplus$ unitarity: is an essential building block of field theory

$\mathcal{CPT}$: L particle $\leftrightarrow$ R antiparticle

Neutrinos in the MSM are massless and exist only in two states: particle with negative helicity and antiparticle with positive one: Weyl fermion

Summary of ν's in SM:

Three flavors of massless neutrinos

$$W^- \to l_\alpha^- + \bar{\nu}_\alpha$$

$$W^+ \to l_\alpha^+ + \nu_\alpha$$

$$\alpha = e, \mu, \ or \ \tau$$

Anti-neutrino, $\bar{\nu}_\alpha$, has +ve helicity, Right Handed

Neutrino, ν_α, has -ve helicity, Left Handed

ν_L and $\bar{\nu}_R$ are CPT conjugates

massless implies helicity = chirality

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?

NEUTRINO OSCILLATIONS:

Two Flavors

flavor eigenstates $\neq$ mass eigenestates

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

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.

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

$\alpha, \beta \ldots$ flavor index $\qquad$ $i, j \ldots$ mass index

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{\delta m^2 L}{4E}\,\frac{c^4}{hc}\right)$$

Appearance:

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

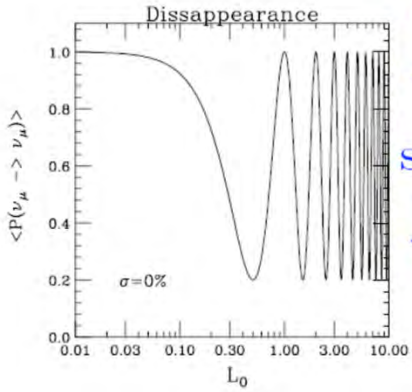
Disappearance:

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

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

Oscillation Length $L_0 = 4\pi E/\delta m^2$

Fixed E_ν

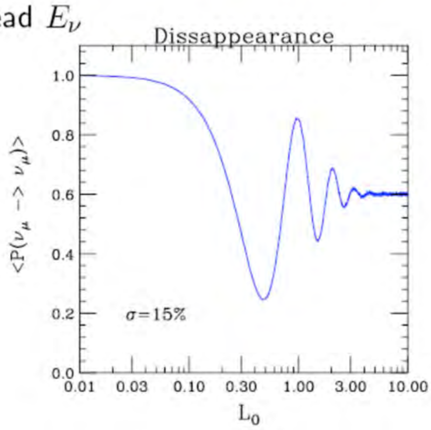


Amplitude of Oscillation

$\Uparrow$ $\sin^2 2\theta$ $\Downarrow$

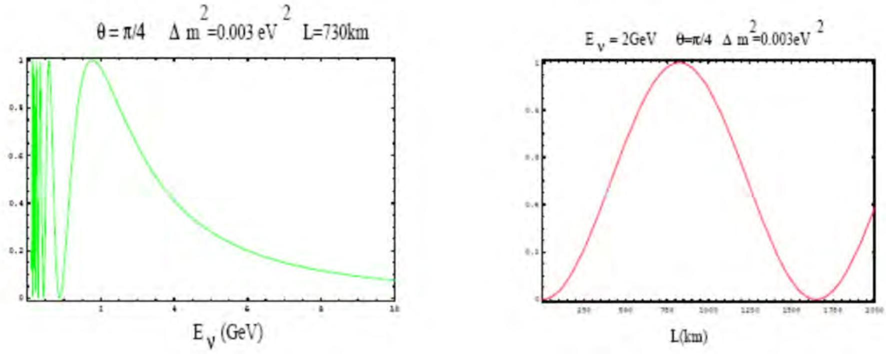
$$\langle P(\nu_\mu \rightarrow \nu_\mu)\rangle = 1 - \sin^2 2\theta \left\langle \sin^2 \frac{\delta m^2 L}{4E} \right\rangle$$

Spread E_ν



effectively incoherent
mass eigenstates

$1 - \sin^2 2\theta(\frac{1}{2}) = \cos^4\theta + \sin^4\theta$



Oscillation probabilities show the expected GIM suppression of any flavour changing process: they vanish if the neutrinos are degenerate

Probability for Neutrino Oscillation in Vacuum

$$P(\nu_\alpha \to \nu_\beta) = |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2 =$$

$$P_{\alpha\beta} = \sin^2 2\theta \;\; \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \to \text{appearance}$$

$$P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1 \to \text{disappearance}$$

Probability for Neutrino Oscillation in Vacuum

$$P(\nu_\alpha \to \nu_\beta) = |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2 =$$

$P_{\alpha\beta} = \sin^2 2\theta$ s... pearance

$P_{\alpha\alpha} = 1 - P_{\alpha\beta}$ ...nce

$$\left(\frac{\Delta m^2\, L}{4\, E}\right)$$

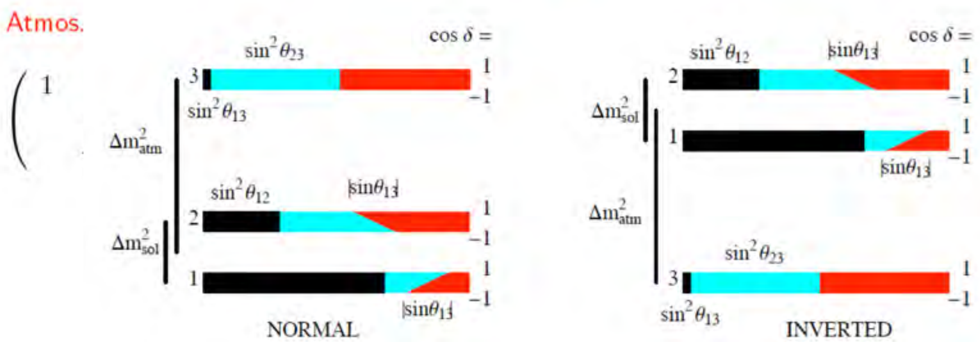
$$\left(1.27\ \frac{\Delta m^2\,(eV^2)\, L(km)}{E(GeV)}\right)$$

L/E becomes crucial !!!

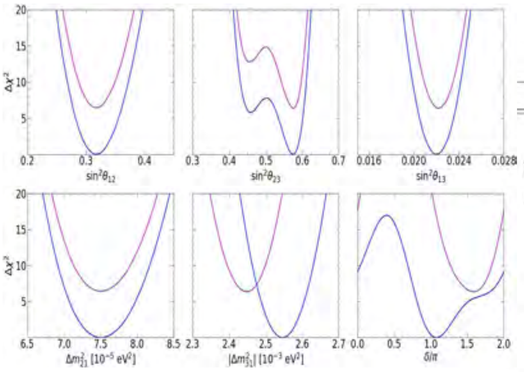
Using the unitarity of the mixing matrix: ($W^{jk}_{\alpha\beta} \equiv [V_{\alpha j} V^*_{\beta j} V^*_{\alpha k} V_{\beta k}]$)

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

ν_e ■ ν_μ ■ ν_τ ■



https://globalfit.astroparticles.es/



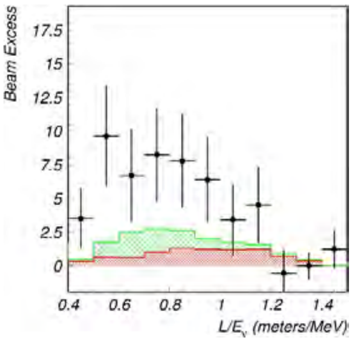
de Salas et al, JHEP 02 (2021) 071[arXiv:2006.11237]

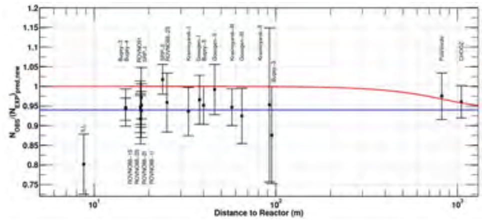
parameter	best fit $\pm 1\sigma$	2σ range	3σ range	Relative 1σ uncertainty	
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14	2.7%	PRECISION
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63	1.1%	ORDERING?
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (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	5.2%	PRECISION
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10	5.1%	OCTANT?
$\sin^2\theta_{23}/10^{-1}$ (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	3.0%	PRECISION
$\sin^2\theta_{13}/10^{-2}$ (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	20%	CPV?
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96	9.0%	

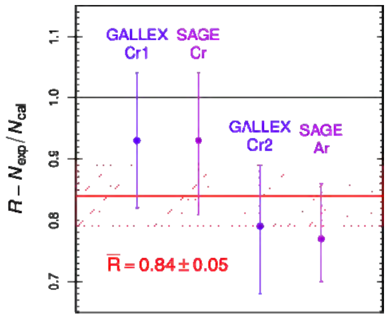
Parameter	Main contribution	Other contributions
θ_{12}	SOL	KamLAND
θ_{13}	REAC	ATM+LBL and SOL+KamLAND
θ_{23}	ATM+LBL	-
δ_{CP}	LBL	ATM
Δm^2_{21}	KamLAND	SOL
$\|\Delta m^2_{31}\|$	LBL+ATM+REAC	-
MO	LBL+REAC and ATM	-

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

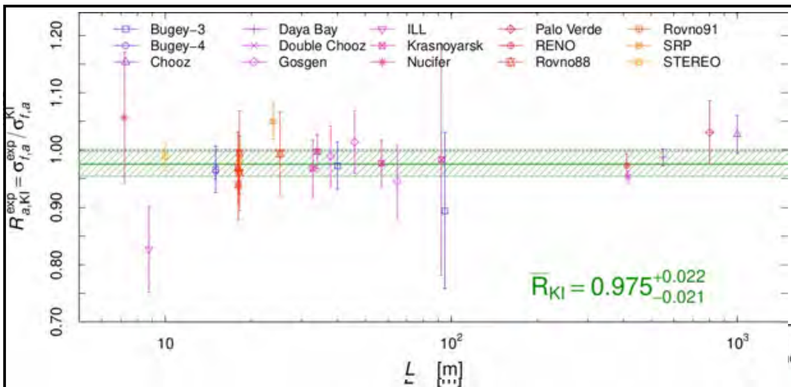
Anomalies

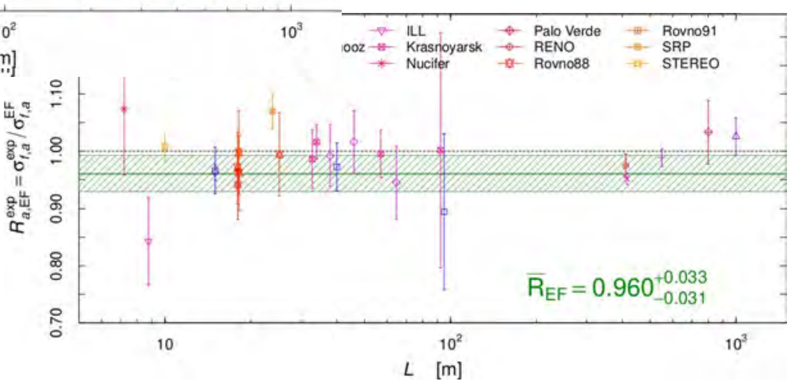






Need extra states !!!

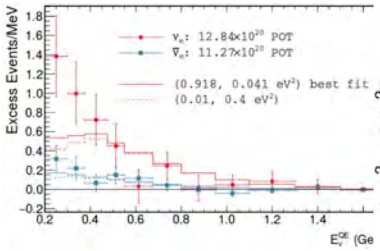




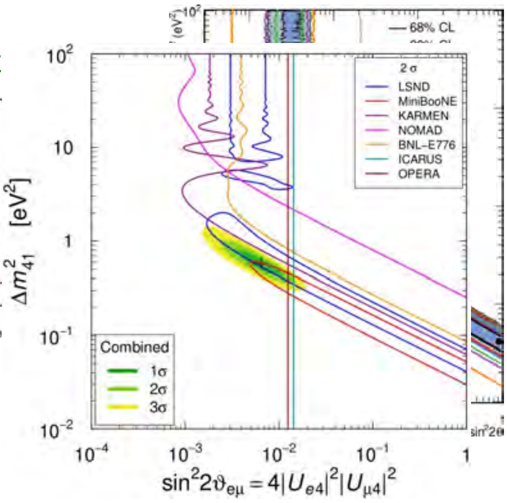
MiniBooNE

MiniBooNE was built to check the LSND results with a different baseline, but similar L/E

MiniBooNE has no near det



MiniBooNE sees an excess at ~5σ at low energies



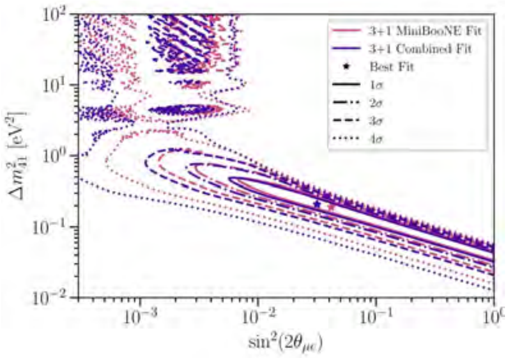
MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels

The collaboration did not perform an oscillation analysis

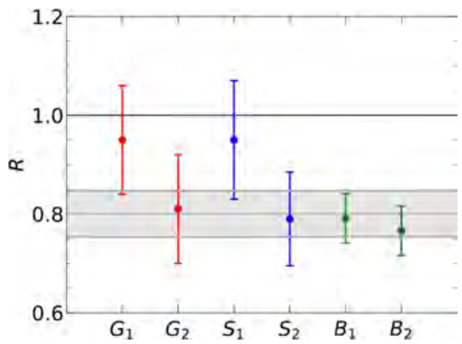
A combined analysis shows that MicroBooNE can not exclude the region of parameter space preferred by MiniBooNE

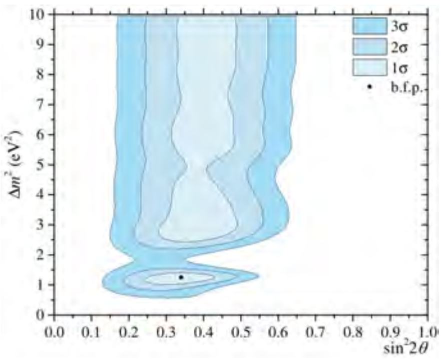


2201.01724

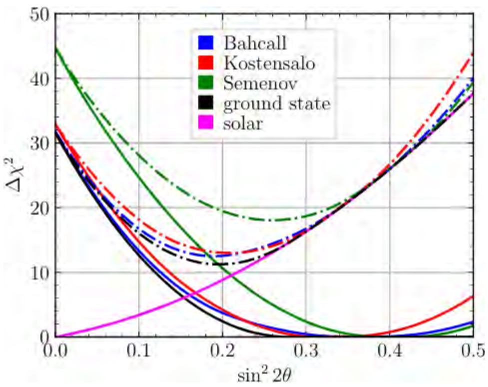
The Gallium anomaly

BEST coll., 2109.11482





The Gallium anomaly is now at more than 5σ significance



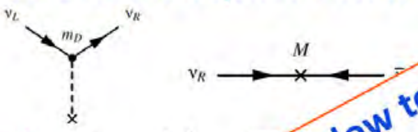
Berryman et al, 2111.12530, JHEP 2022

Can not be explained due to cross section mistakes

a connection to BSM physics

★ Is there a connection to the GUT scale?

- If both Dirac and Majorana mass terms are pres…



…violation

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

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

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

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

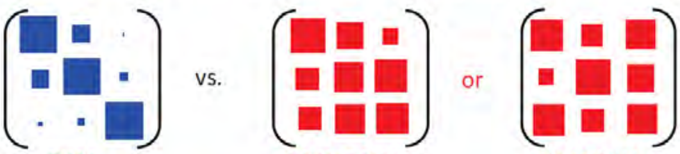
$$M \sim 10^{12} - 10^{16}\,\text{GeV}$$

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



CKM — PMNS NH — PMNS IH

- **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

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

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

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

ME

★ Complicates the simple picture !!!!

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

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

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

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

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

Experimental Strategy

EITHER:

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

- First oscillation maximum:

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

- Want high flux at oscillation maximum

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

OR:

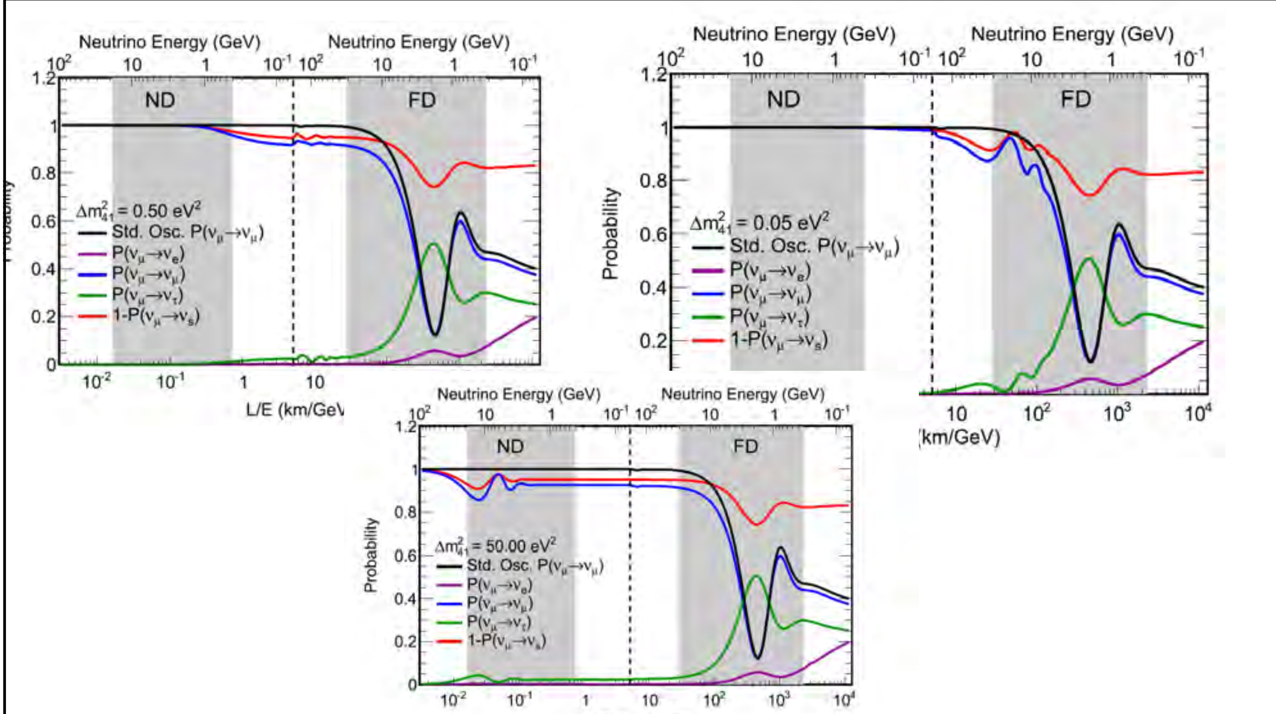
★ Make L large (>1000 km): measure the matter effects (i.e. MH)

- First oscillation maximum:

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

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

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



Non unitarity

$$N = \begin{bmatrix} 1-\alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{bmatrix} U$$

CPT violation

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

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

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

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

$$|\Delta m^2_{21} - \Delta \overline{m}^2_{21}| < 4.7 \times 10^{-5}\,\mathrm{eV}^2,$$
$$|\Delta m^2_{31} - \Delta \overline{m}^2_{31}| < 3.7 \times 10^{-4}\,\mathrm{eV}^2,$$
$$|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| < 0.14,$$
$$|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| < 0.03,$$
$$|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| < 0.32.$$

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

Violations of Lorentz invariance

Lorentz violation

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

standard Lorentz covariant term

violates both CPT and Lorentz invariance

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

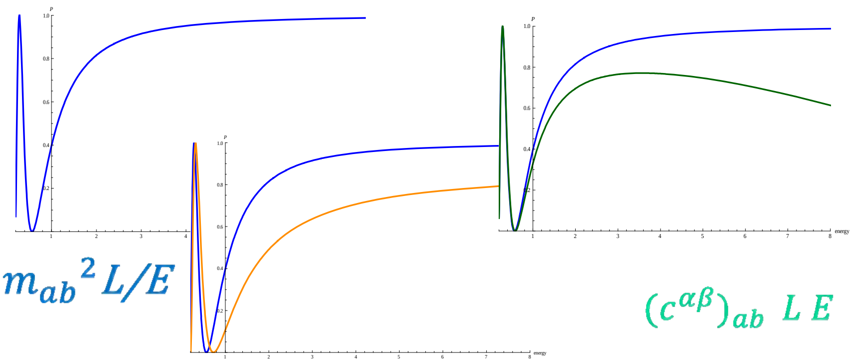
$$\sin^2(\Delta_{ab}\ L/2)$$

${m_{ab}}^2 L/E$

$(a^\alpha)_{ab}\ L$

$(c^{\alpha\beta})_{ab}\ L\ E$

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

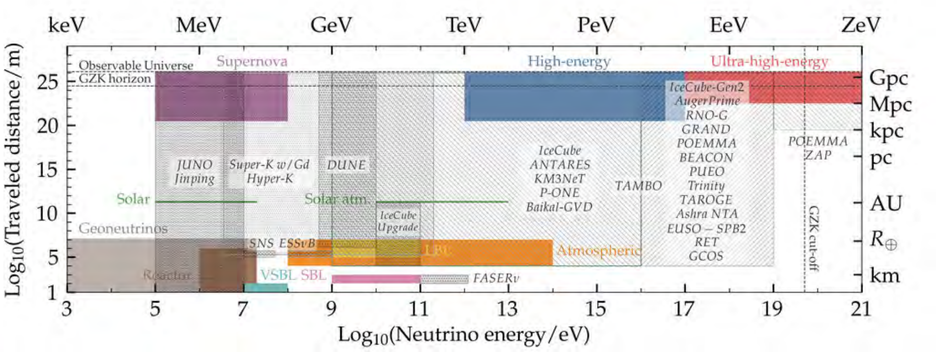


${m_{ab}}^2 L/E$

$(c^{\alpha\beta})_{ab}\ L\ E$

$(a^\alpha)_{ab}\ L$

Conclusions: Neutrino physics is alive and kicking !!!



고맙습니다