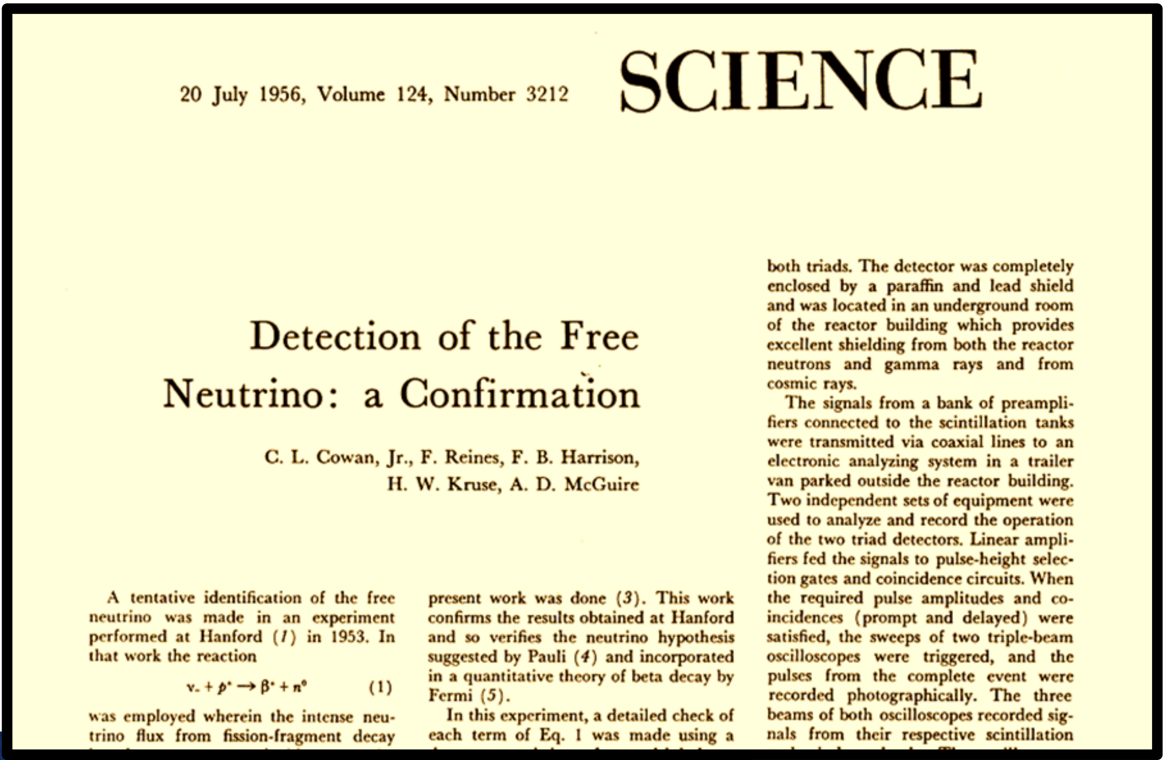
NEUTRINOS AT 66



20 July 1956, Volume 124, Number 3212 SCIENCE

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

A tentative identification of the free neutrino was made in an experiment performed at Hanford (1) in 1953. In that work the reaction

$$\nu_- + p^+ \rightarrow \beta^+ + n^0 \qquad (1)$$

was employed wherein the intense neutrino flux from fission-fragment decay

present work was done (3). This work confirms the results obtained at Hanford and so verifies the neutrino hypothesis suggested by Pauli (4) and incorporated in a quantitative theory of beta decay by Fermi (5).

In this experiment, a detailed check of each term of Eq. 1 was made using a

both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

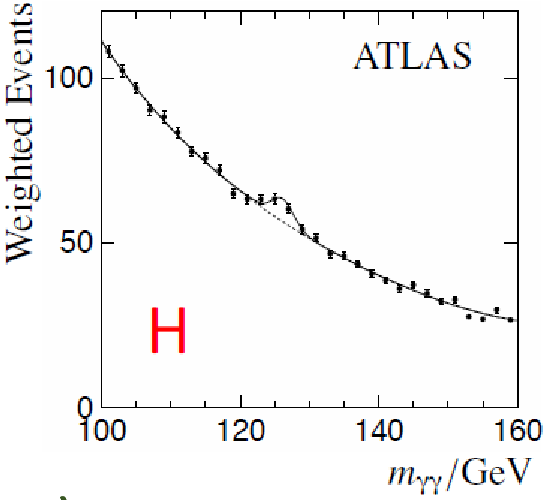
The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were used to analyze and record the operation of the two triad detectors. Linear amplifiers fed the signals to pulse-height selection gates and coincidence circuits. When the required pulse amplitudes and coincidences (prompt and delayed) were satisfied, the sweeps of two triple-beam oscilloscopes were triggered, and the pulses from the complete event were recorded photographically. The three beams of both oscilloscopes recorded signals from their respective scintillation

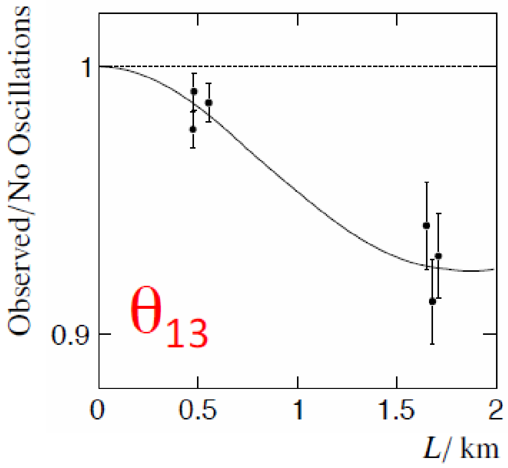
Gabriela Barenboim
UV-IFIC

XIV Latin American Symposium on High Energy Physics
USFQ,Quito, November 15, 2022

2012 ~~One~~ two major discover~~y~~ies in particle physics

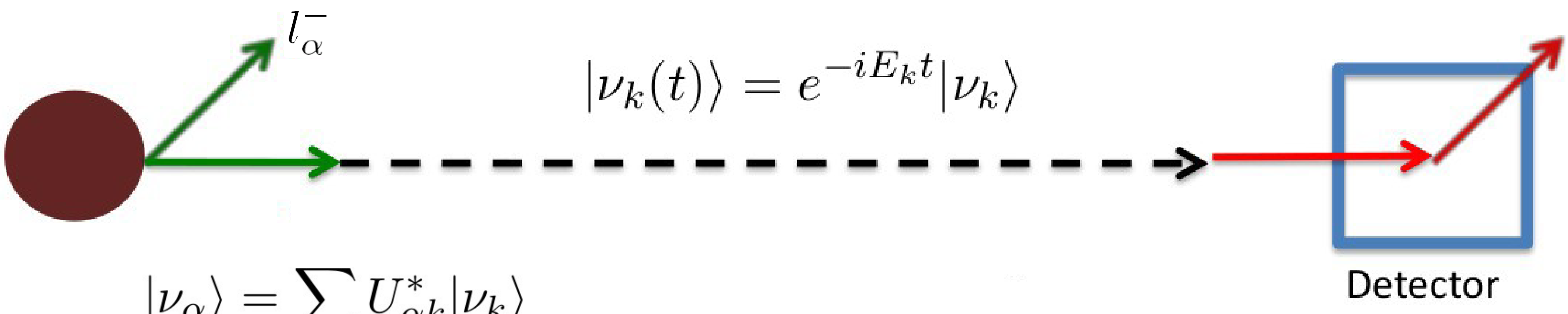
- A SM-like Higgs boson (ATLAS, CMS)
  The key to EWSB and a possible window to





- 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

Neutrino oscillations



$$|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle$$

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

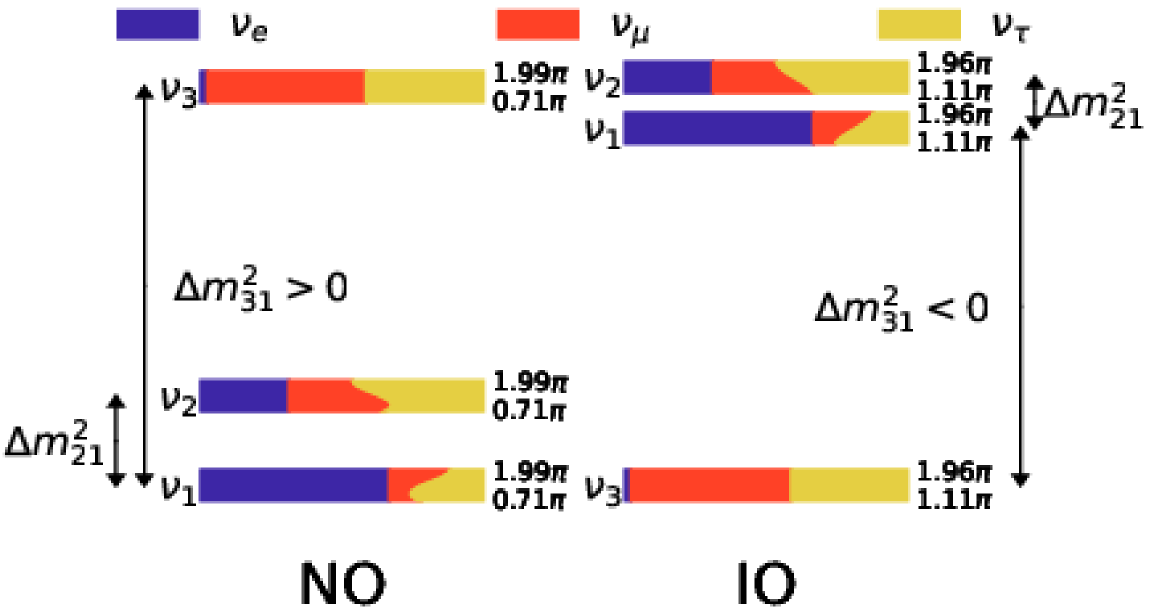
$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{k>j} \mathrm{Re}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}]\sin^2\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}}\,\mathrm{L}}{4\mathrm{E}_\nu}\right)$$

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

Three-neutrino oscillations

Neutrino mixing matrix

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

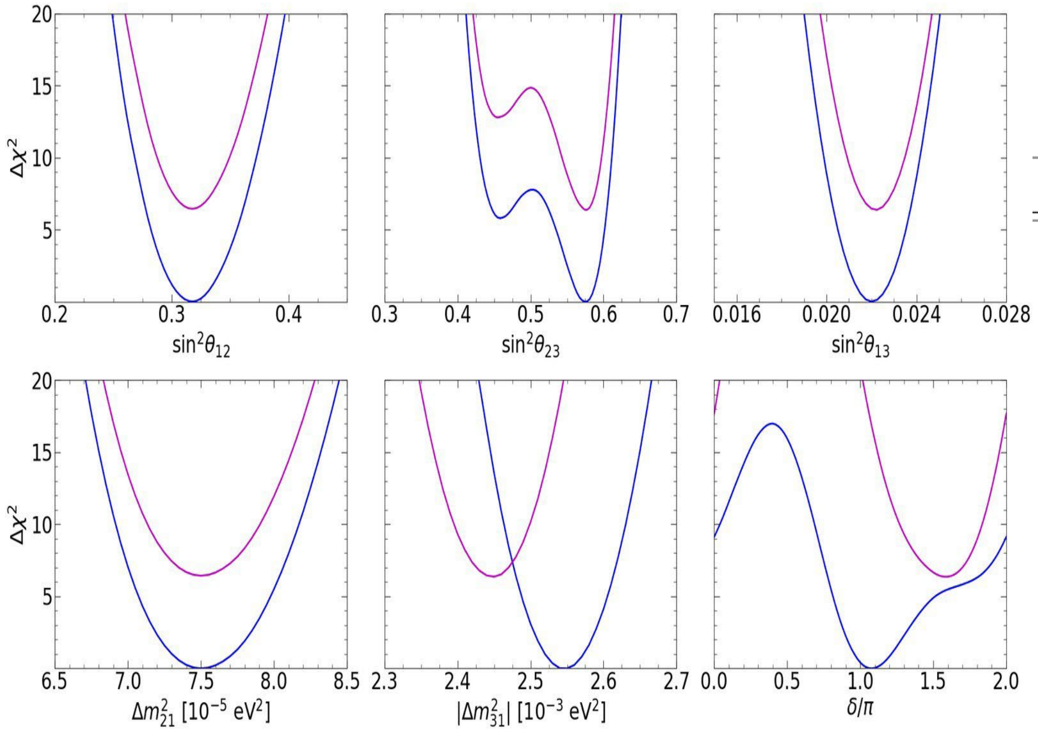


Parameter	Main contribution	Other contributions
θ_{12}	SOL	KamLAND
θ_{13}	REAC	ATM+LBL and SOL+KamLAND
θ_{23}	ATM+LBL	-
δ_{CP}	LBL	ATM
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
MO	LBL+REAC and ATM	-

SOL: Solar
ATM: Amtopsheric neutrinos

LBL: Long baseline accelerator experiments
REAC: Short-baseline reactor experiments

https://globalfit.astroparticles.es/



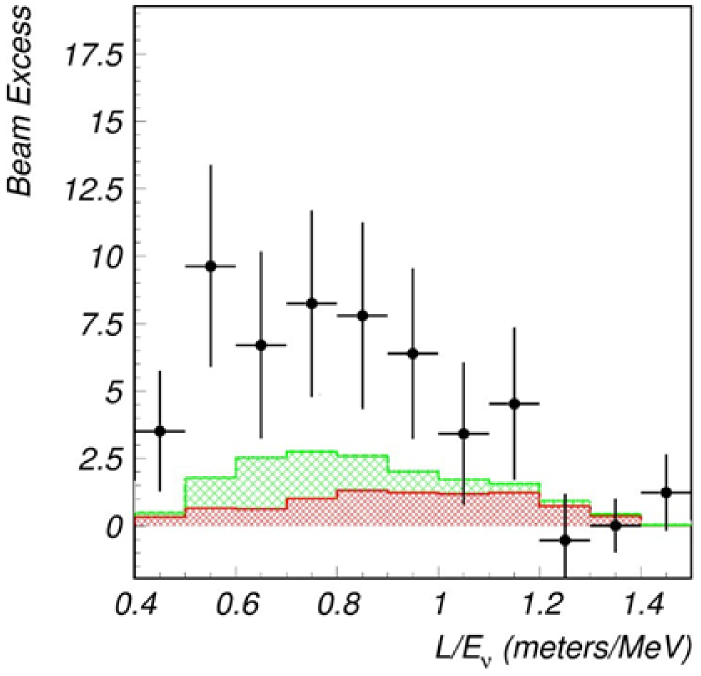
de Salas et al, JHEP 02 (2021) 071[arXiv:2006.11237]

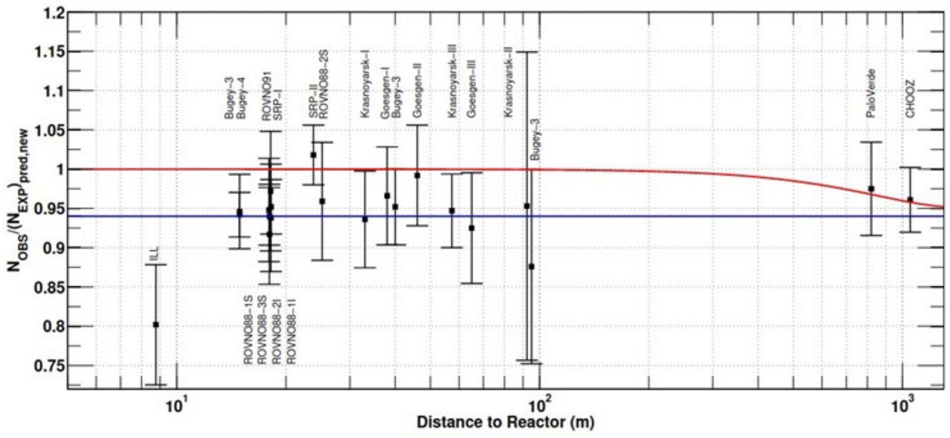
parameter	best fit $\pm$ 1σ	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\vert\Delta m^2_{31}\vert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\vert\Delta m^2_{31}\vert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (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

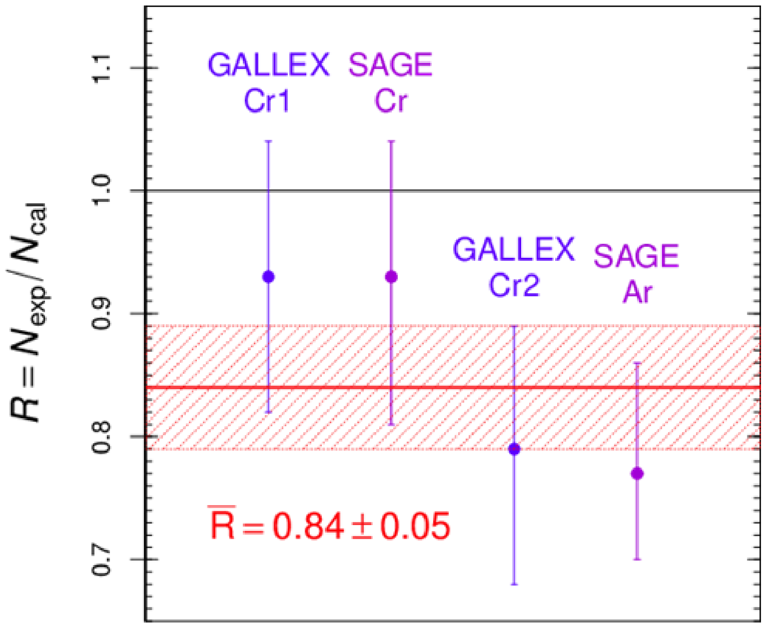
Relative 1σ uncertainty

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

Anomalies

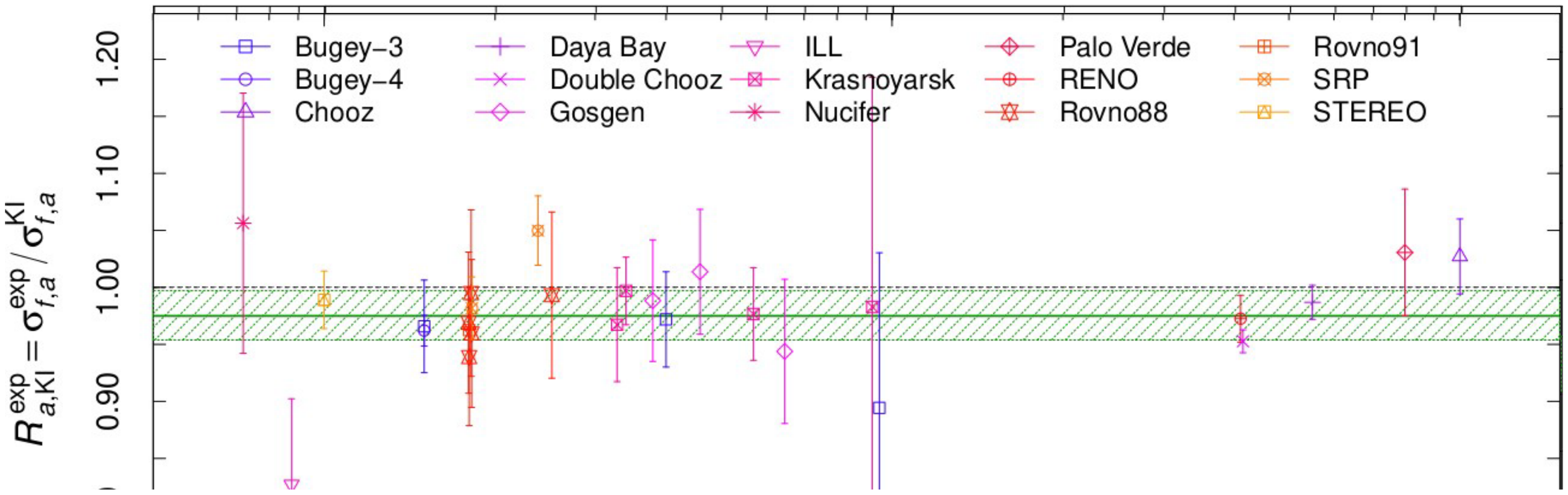






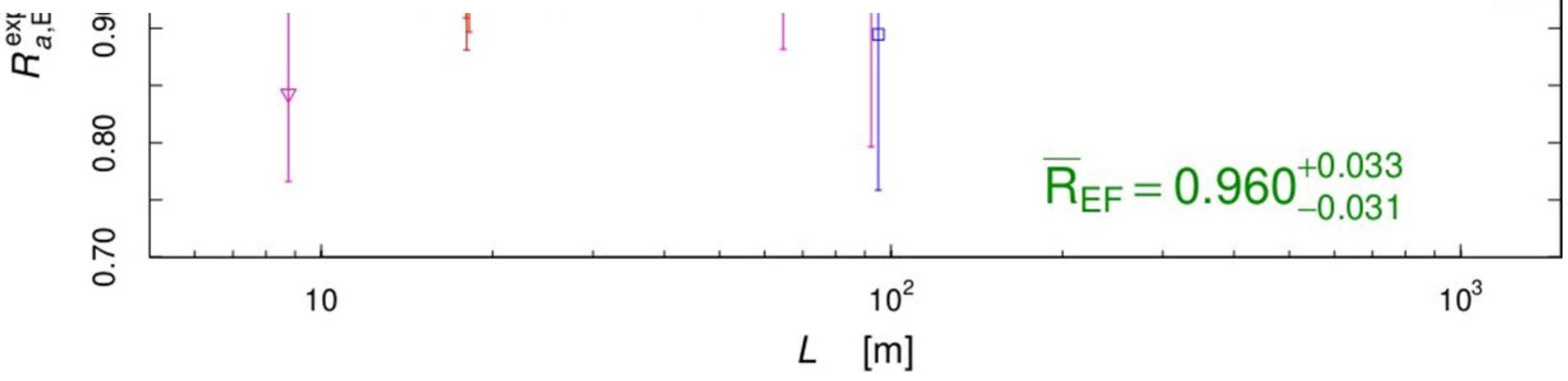
Need extra states !!!

V. Kopeikin, et al, 2103.01684, PRD 2021



Model	Rates		Evolution		Rates + Evolution	
	$\overline{R}_{\text{mod}}$	RAA	$\overline{R}_{\text{mod}}$	RAA	$\overline{R}_{\text{mod}}$	RAA
HM	$0.936^{+0.024}_{-0.023}$	$2.5\,\sigma$	$0.933^{+0.025}_{-0.024}$	$2.6\,\sigma$	$0.930^{+0.024}_{-0.023}$	$2.8\,\sigma$
EF	$0.960^{+0.033}_{-0.031}$	$1.2\,\sigma$	$0.975^{+0.032}_{-0.030}$	$0.8\,\sigma$	$0.975^{+0.032}_{-0.030}$	$0.8\,\sigma$
HKSS	$0.925^{+0.025}_{-0.023}$	$2.9\,\sigma$	$0.925^{+0.026}_{-0.024}$	$2.8\,\sigma$	$0.922^{+0.024}_{-0.023}$	$3.0\,\sigma$
KI	$0.975^{+0.022}_{-0.021}$	$1.1\,\sigma$	$0.973^{+0.023}_{-0.022}$	$1.2\,\sigma$	0.970 ± 0.021	$1.4\,\sigma$
HKSS-KI	$0.964^{+0.023}_{-0.022}$	$1.5\,\sigma$	$0.955^{+0.024}_{-0.023}$	$1.9\,\sigma$	$0.960^{+0.022}_{-0.021}$	$1.8\,\sigma$

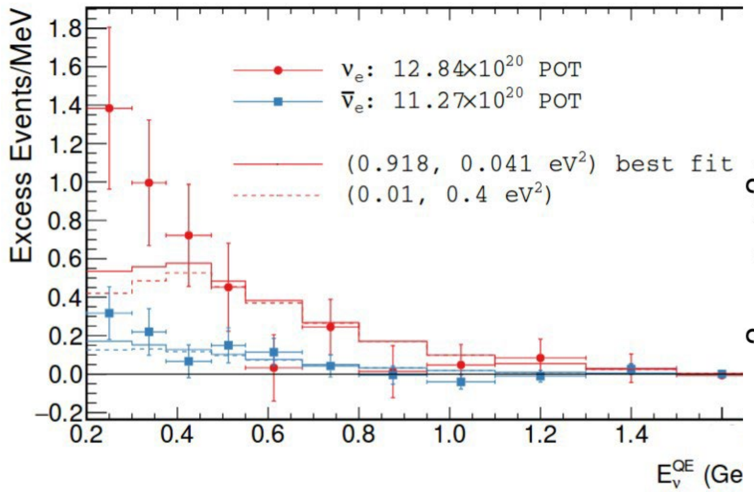
Estienne et al,

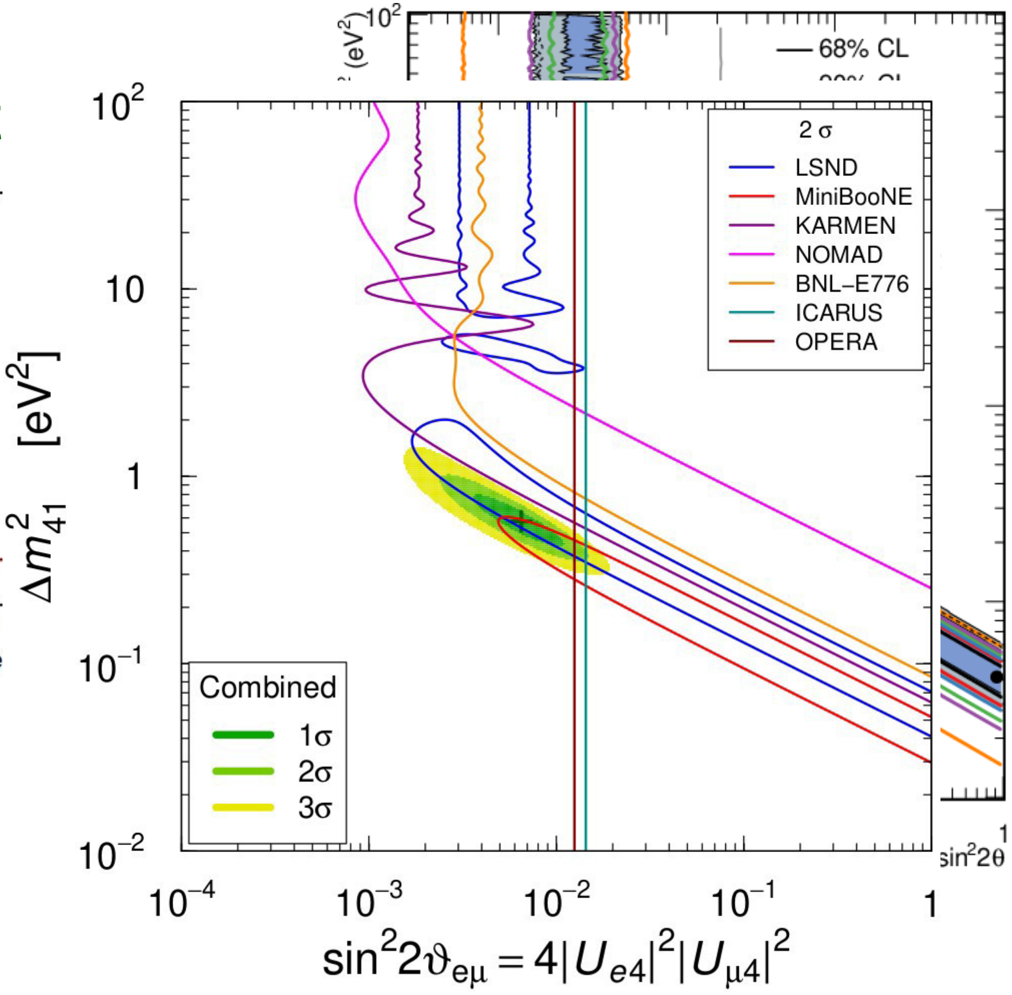


MiniBooNE

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

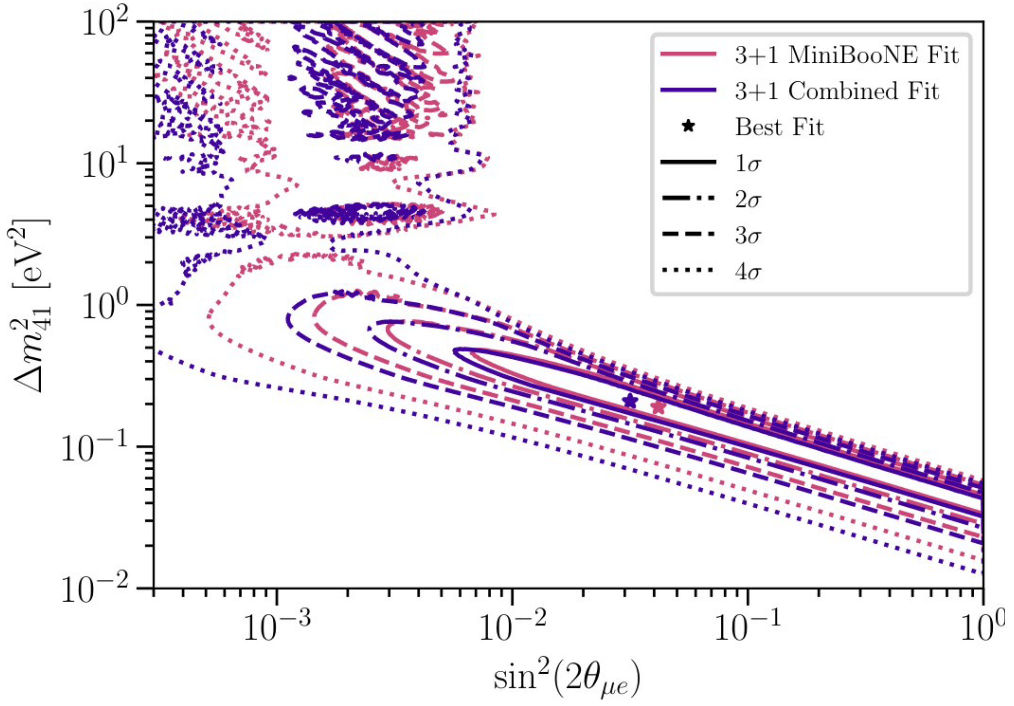
MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels

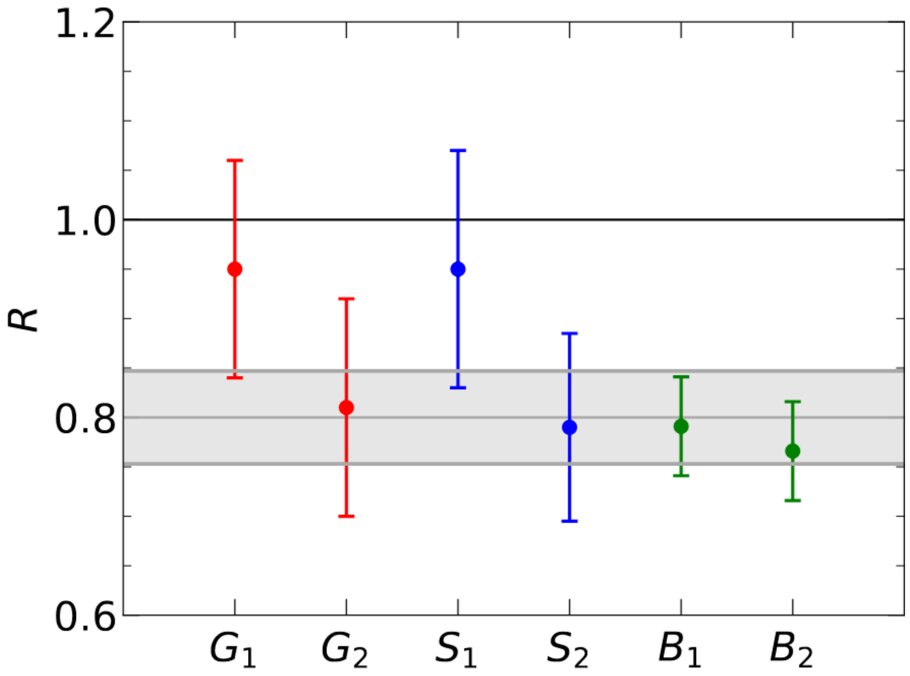
The collaboration did not perform an oscillation analysis

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

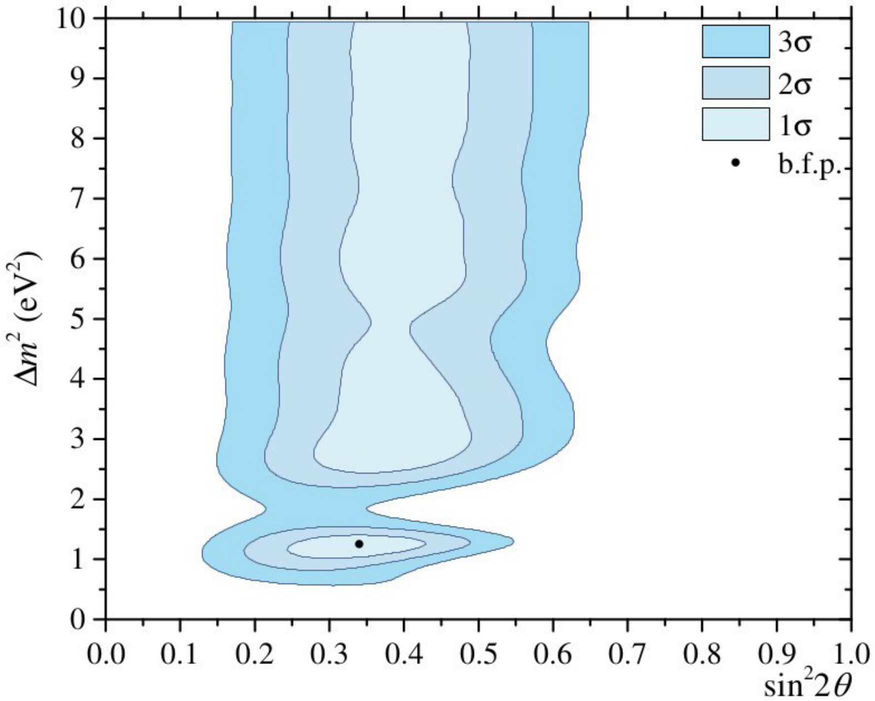


2201.01724

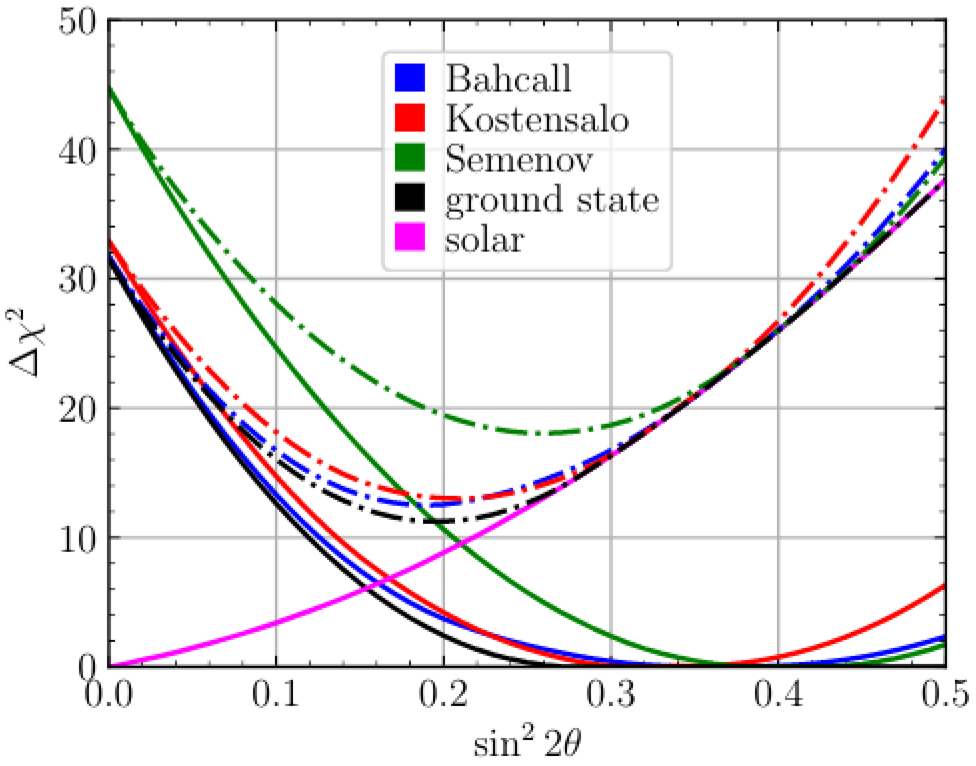
The Gallium anomaly



BEST coll., 2109.11482



The Gallium anomaly is now at more than 5σ significance



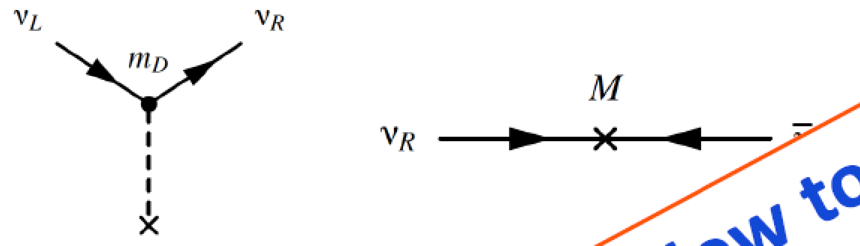
Berryman et al, 2111.12530, JHEP 2022

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…



…ns)

… violation

$$\mathcal{L} \sim -\tfrac{1}{2} \left(\overline{\nu_L} \; \ldots \right) \ldots \begin{pmatrix} \ldots \\ \nu_R \end{pmatrix}$$

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

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

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

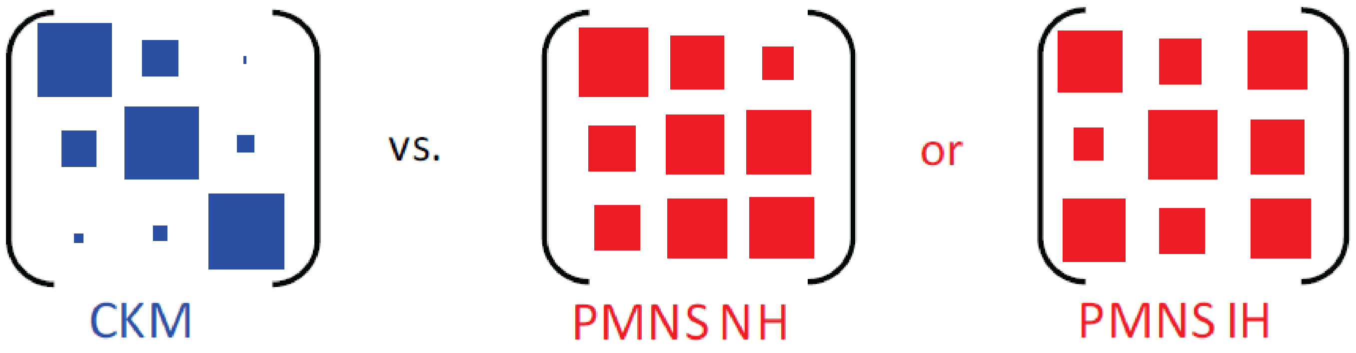
…$m_D \sim m_\ell$ to get to right range of small neutrino masses:

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

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 $\bar{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4 s_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta$$

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 $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$?

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

Experimental Strategy

EITHER:

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

- First oscillation maximum:

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

- Want high flux at oscillation maximum

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

OR:

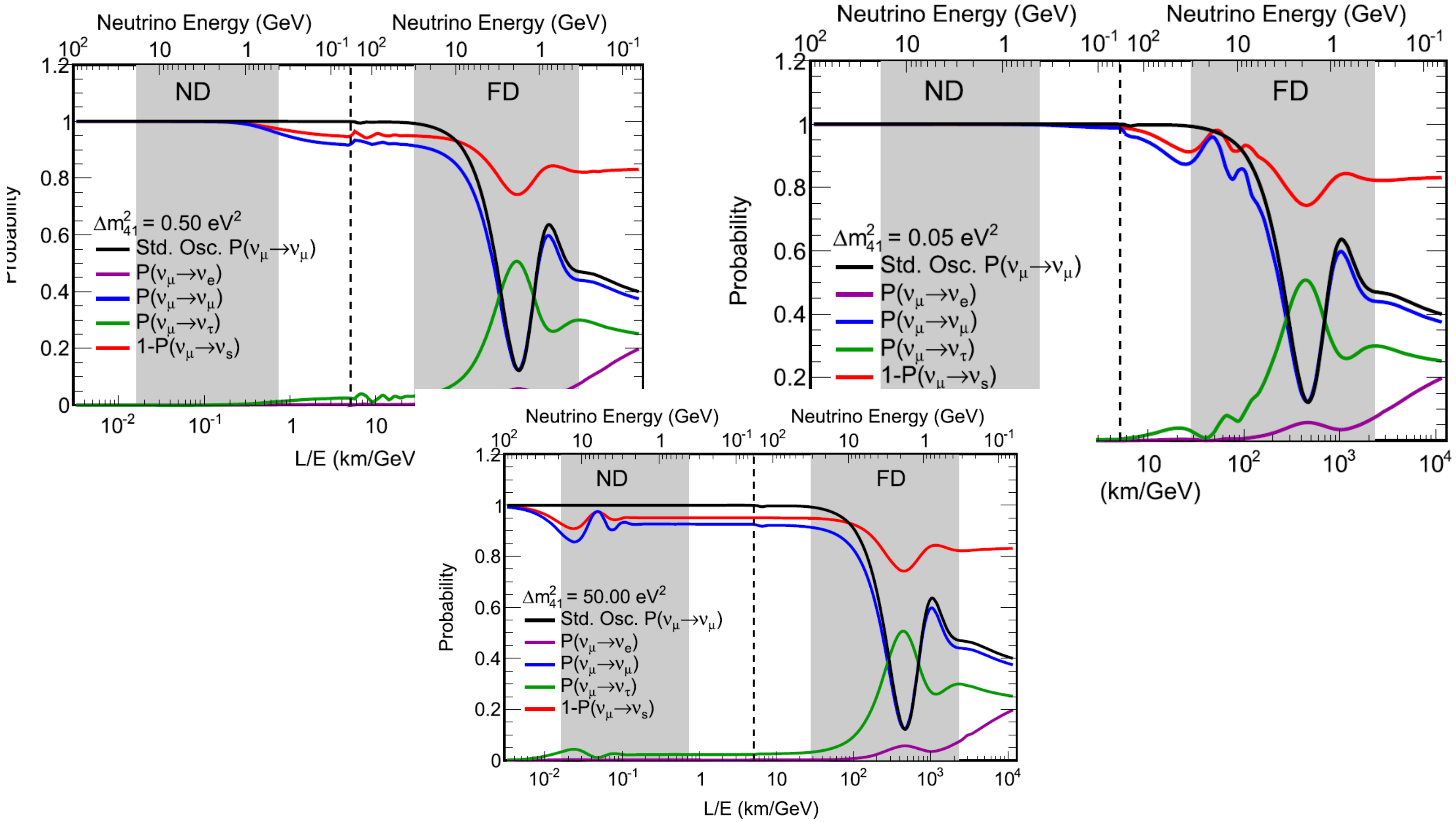
★ Make L large (>1000 km): measure the matter effects (i.e. MH)

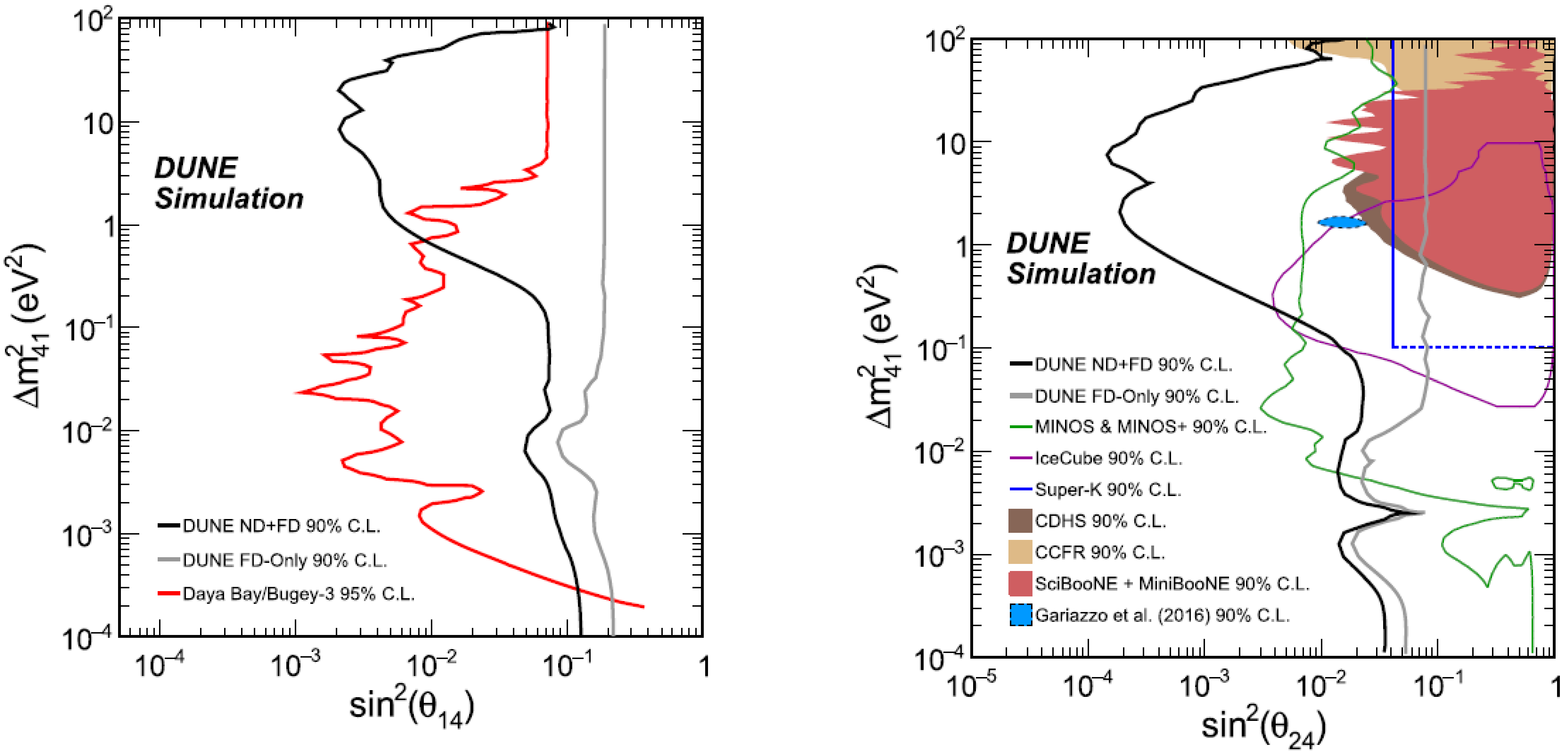
- First oscillation maximum:

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

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

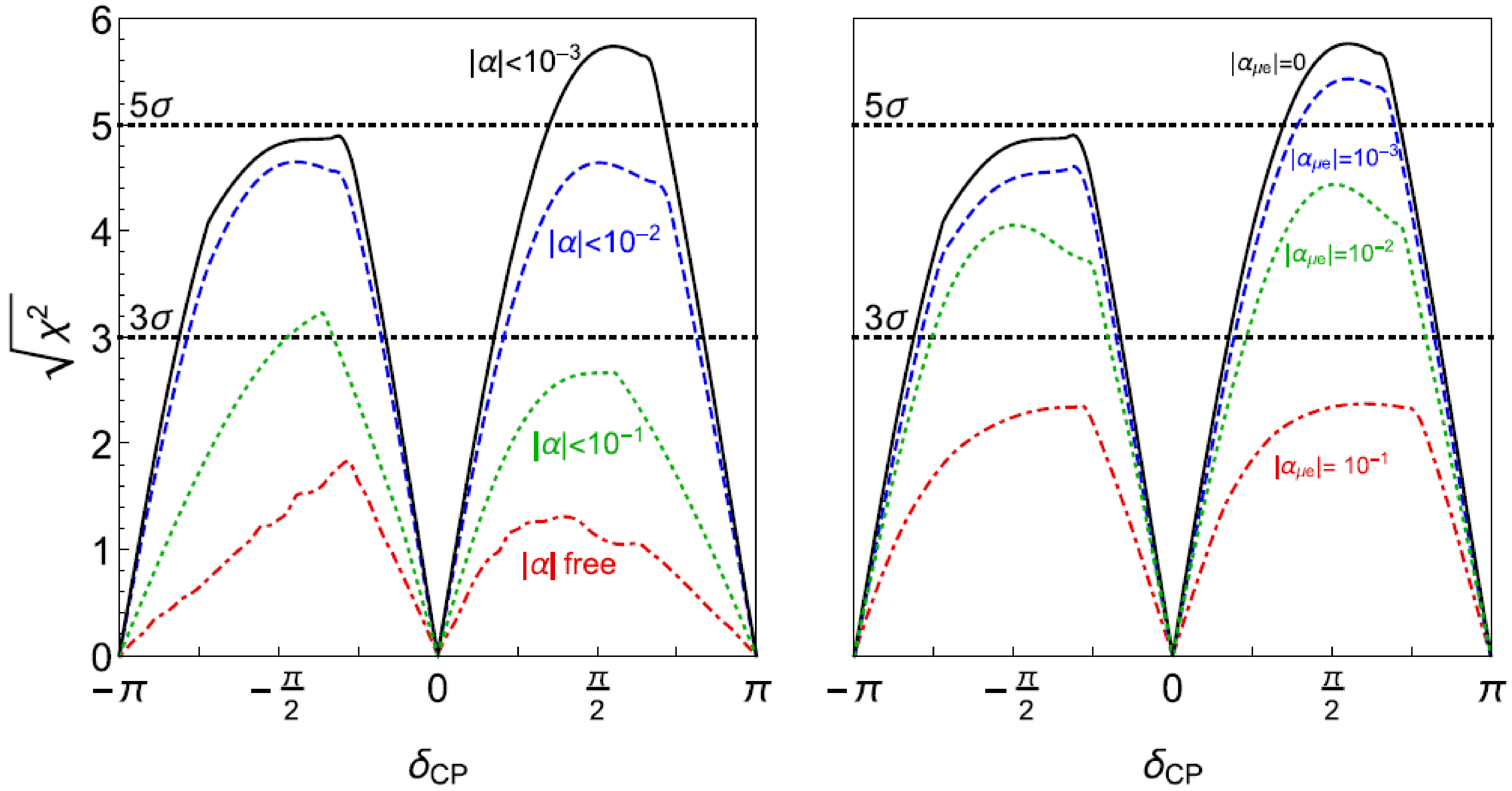
⇨ **On-axis beam:** wide range of neutrino energies


Neutrino Energy (GeV)
Neutrino Energy (GeV)
ND
FD
Probability
L/E (km/GeV)
Δm^2_{41} = 0.50 eV^2
Std. Osc. P($\nu_\mu \rightarrow \nu_\mu$)
P($\nu_\mu \rightarrow \nu_e$)
P($\nu_\mu \rightarrow \nu_\mu$)
P($\nu_\mu \rightarrow \nu_\tau$)
1-P($\nu_\mu \rightarrow \nu_s$)
Δm^2_{41} = 0.05 eV^2
Std. Osc. P($\nu_\mu \rightarrow \nu_\mu$)
P($\nu_\mu \rightarrow \nu_e$)
P($\nu_\mu \rightarrow \nu_\mu$)
P($\nu_\mu \rightarrow \nu_\tau$)
1-P($\nu_\mu \rightarrow \nu_s$)
(km/GeV)
Δm^2_{41} = 50.00 eV^2
Std. Osc. P($\nu_\mu \rightarrow \nu_\mu$)
P($\nu_\mu \rightarrow \nu_e$)
P($\nu_\mu \rightarrow \nu_\mu$)
P($\nu_\mu \rightarrow \nu_\tau$)
1-P($\nu_\mu \rightarrow \nu_s$)



DUNE
Simulation
DUNE ND+FD 90% C.L.
DUNE FD-Only 90% C.L.
Daya Bay/Bugey-3 95% C.L.
Δm^2_{41} (eV^2)
$\sin^2(\theta_{14})$
DUNE
Simulation
DUNE ND+FD 90% C.L.
DUNE FD-Only 90% C.L.
MINOS & MINOS+ 90% C.L.
IceCube 90% C.L.
Super-K 90% C.L.
CDHS 90% C.L.
CCFR 90% C.L.
SciBooNE + MiniBooNE 90% C.L.
Gariazzo et al. (2016) 90% C.L.
Δm^2_{41} (eV^2)
$\sin^2(\theta_{24})$

Non unitarity



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

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

We are left "only" with neutral current NSNI

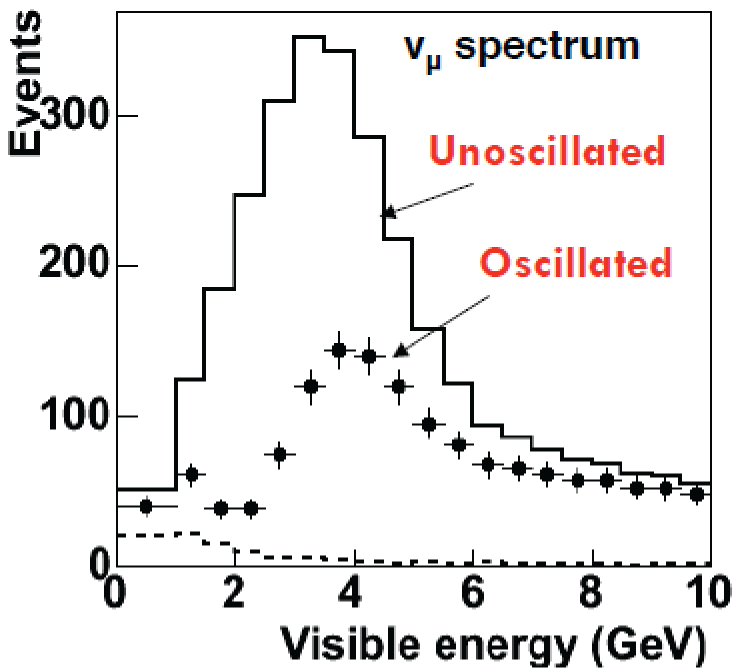
$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$$

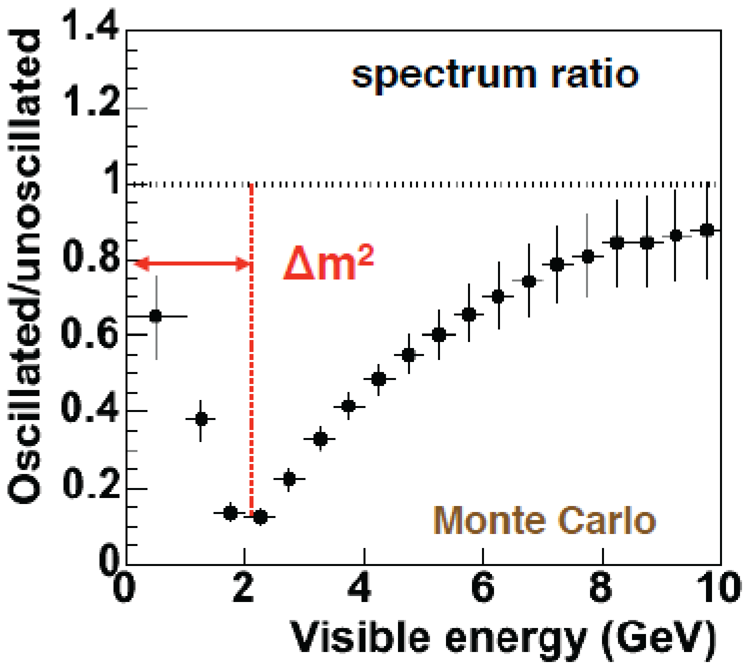
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu}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

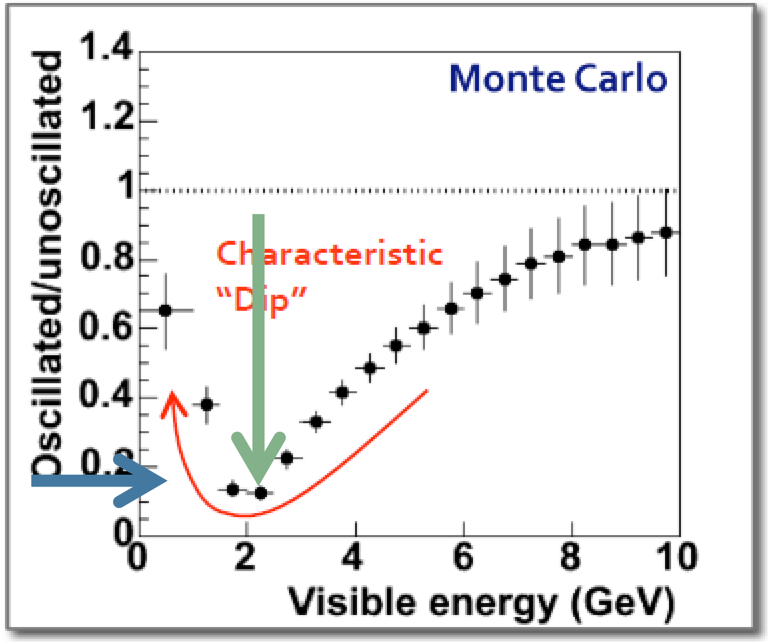
$$a \equiv 2\sqrt{2}G_F n_e E$$

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

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







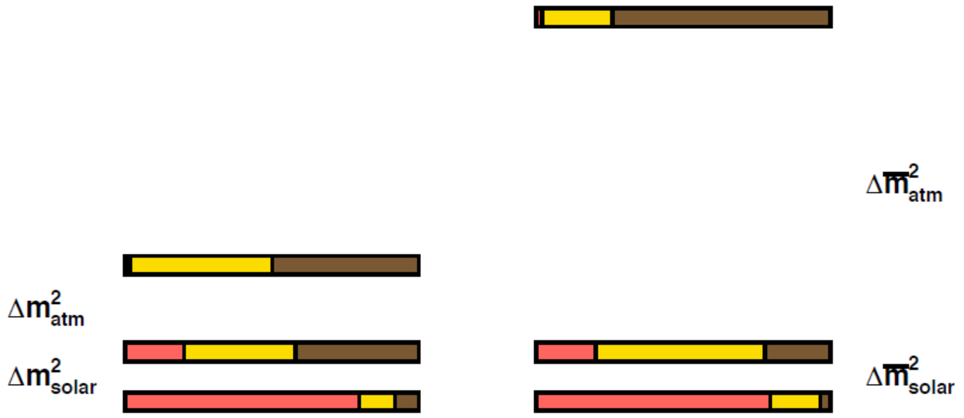
$\varepsilon_{\mu\tau}$ changes the disspearence probability at large energies shifts the position of the minimum in energy

$$\Delta m^2$$

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

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

CPT violation



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

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

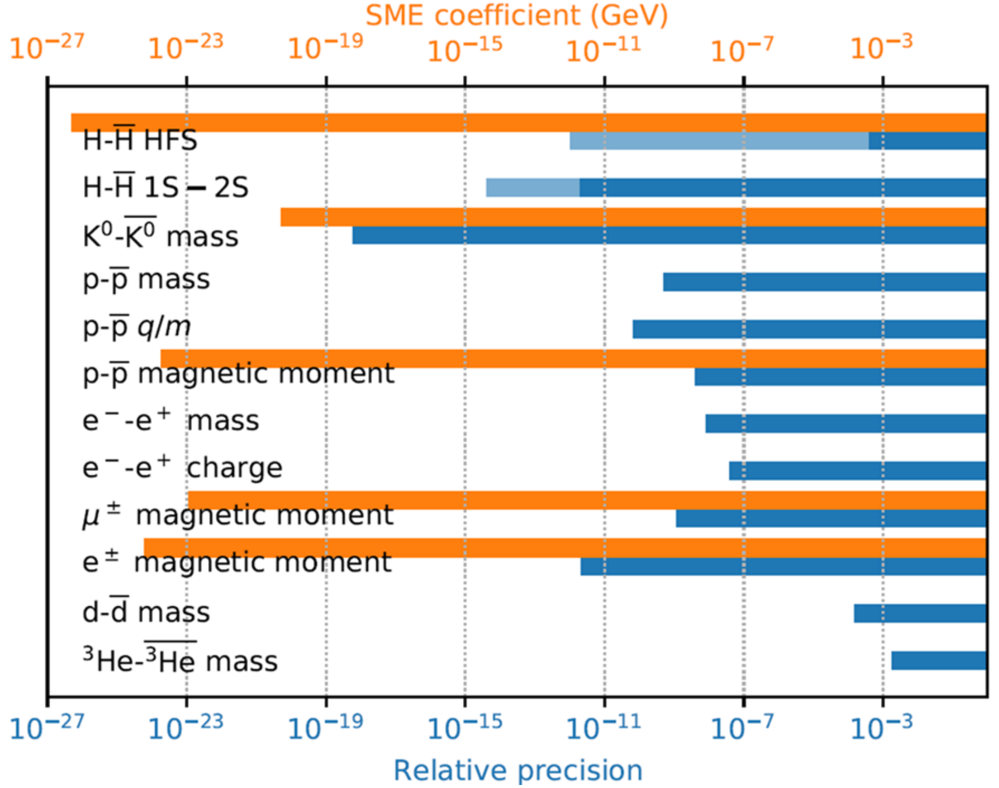
$$(m(K_0) - m\left(\overline{K_0}\ \right)\ )(m(K_0) + m(\overline{K_0\ })) < 2\ \ 10^{-18} m_{K-av}{}^2$$

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

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	-

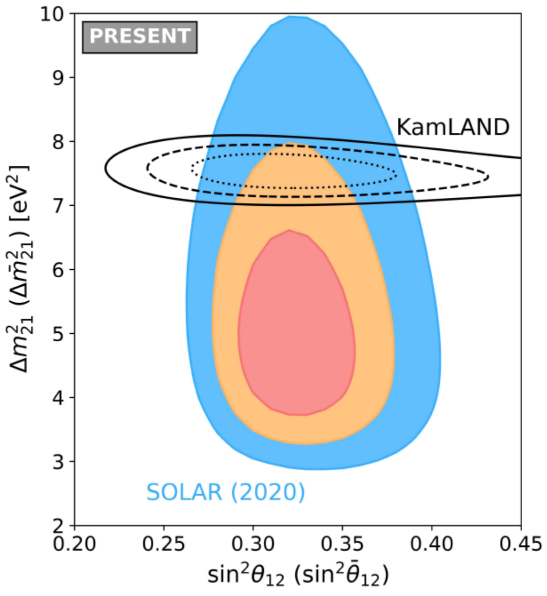
SOL: Solar
ATM: Amtopsheric neutrinos

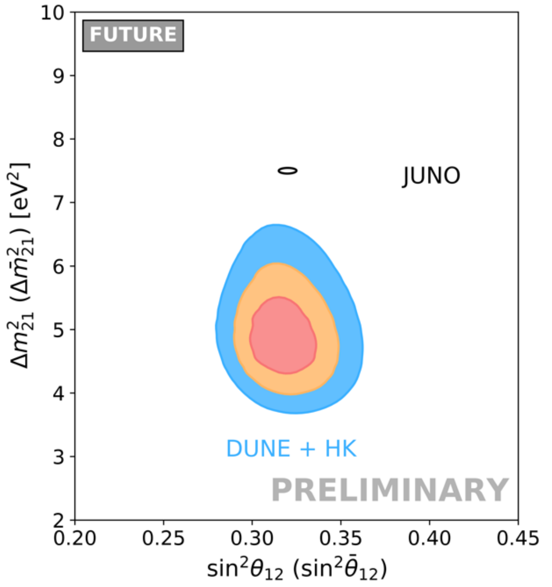
LBL: Long baseline accelerator experiments
REAC: Short-baseline reactor experiments

Current bounds

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

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





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

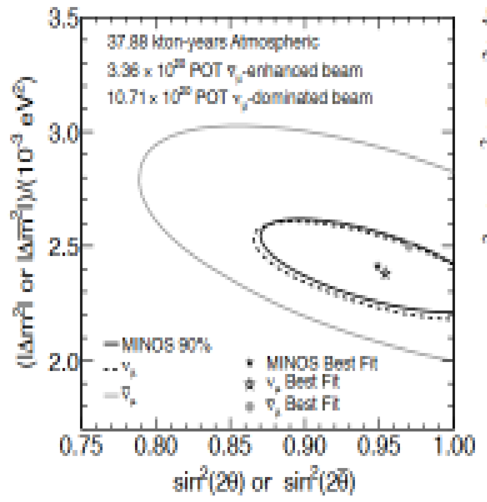
T2K results, a hint ?

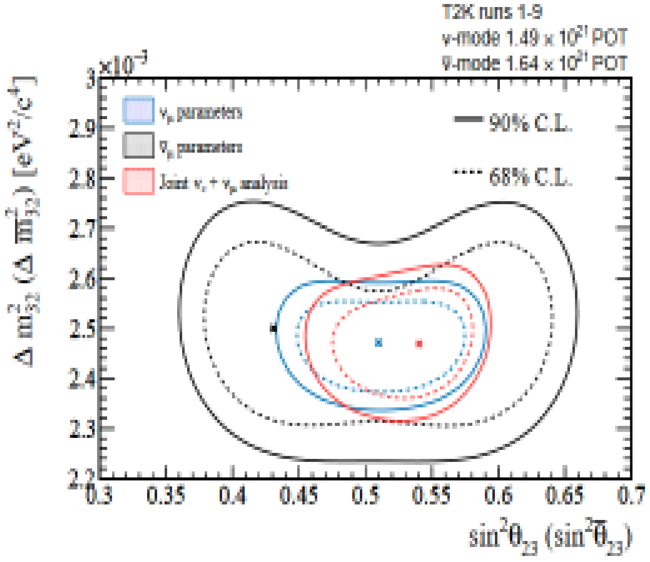
- T2K studied neutrino and anti-neutrino oscillations separated

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

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

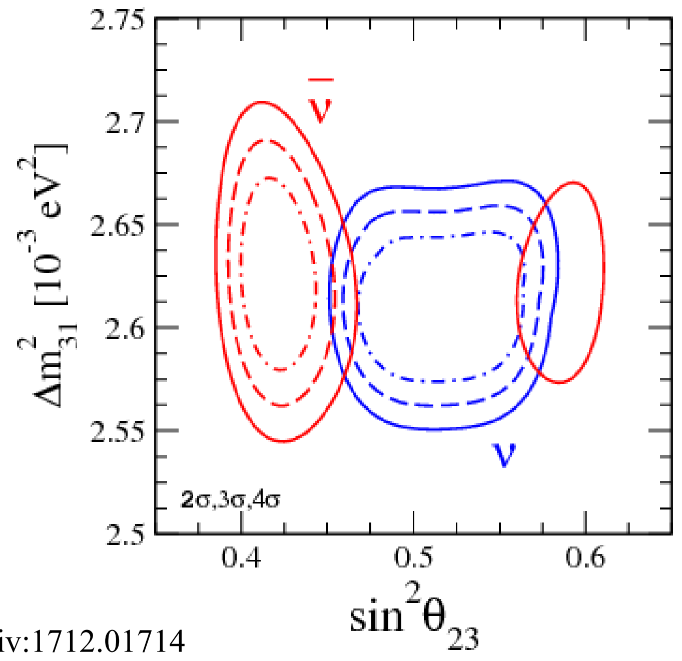
- Results are consistent with
- CPT-conservation

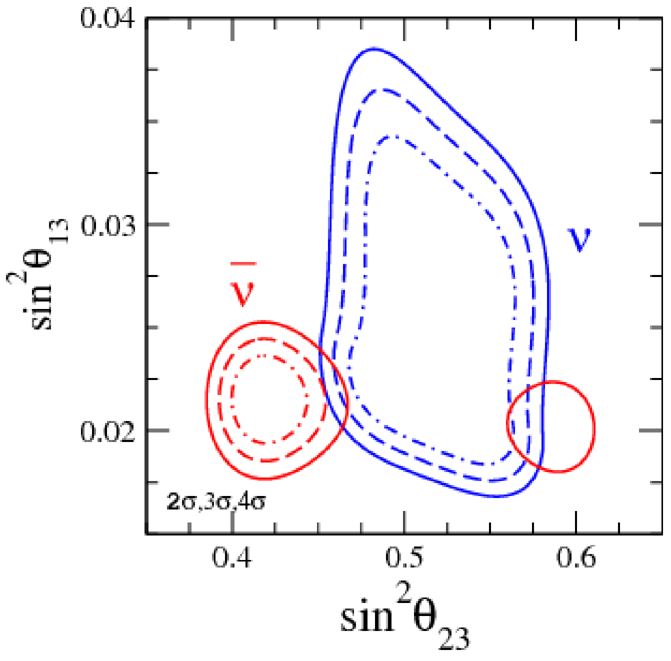




DUNE about T2K

- 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

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

and then minimize this function

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

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

$$x = y$$

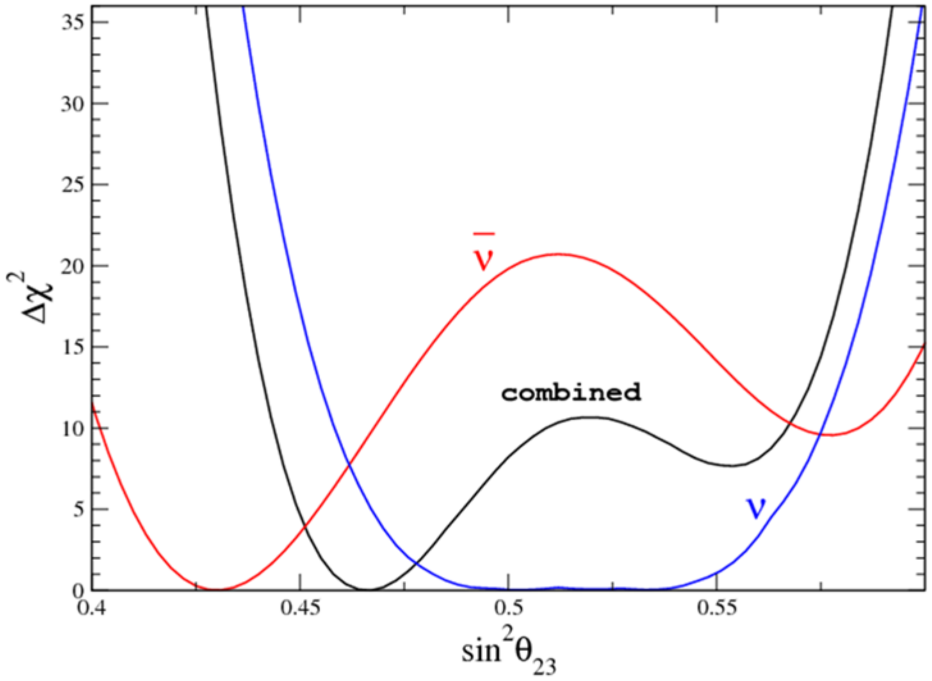
$$h(x) = f(x) + g(x)$$

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

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

Obtaining impostor solutions

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



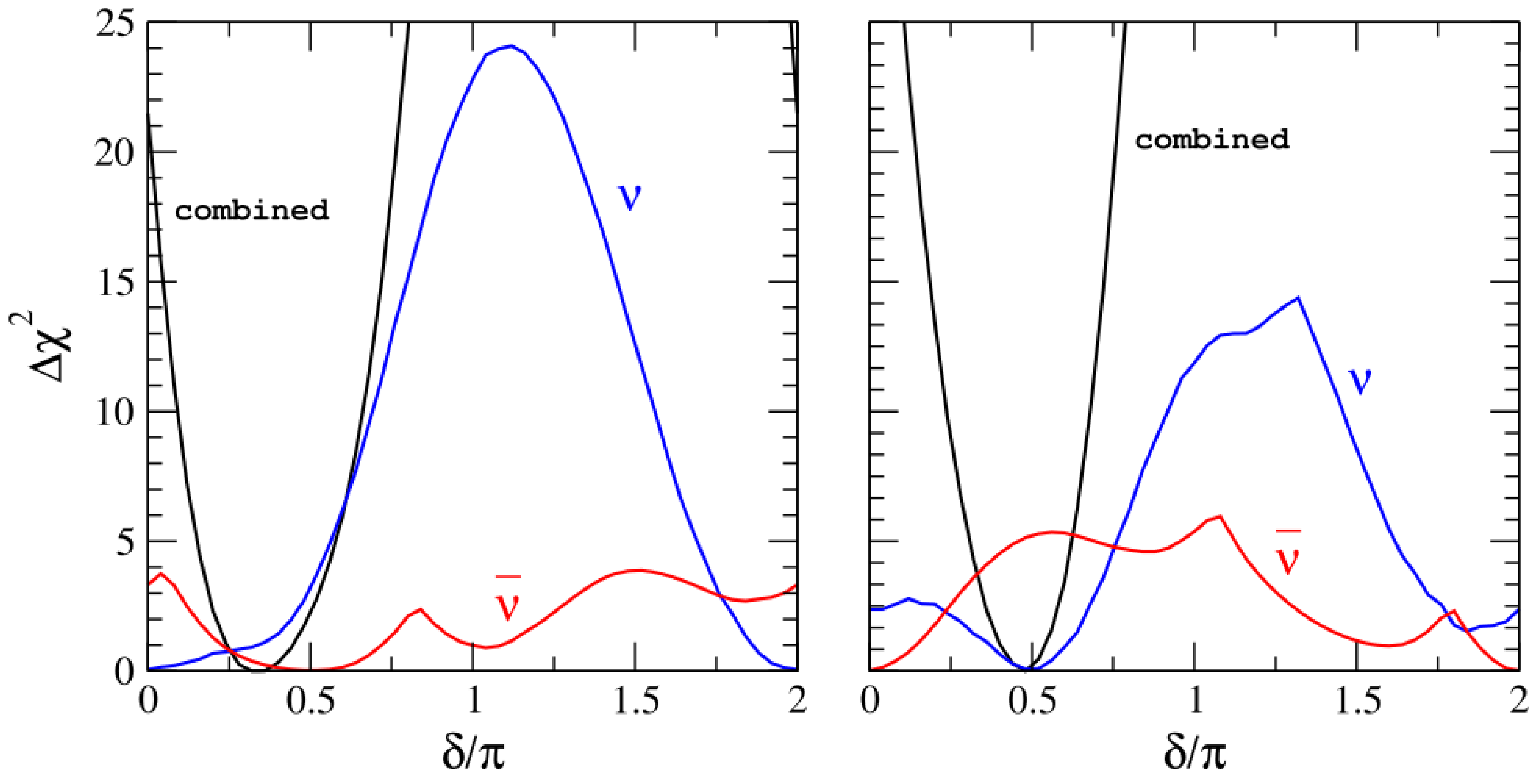
Combined best fit value is now

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

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

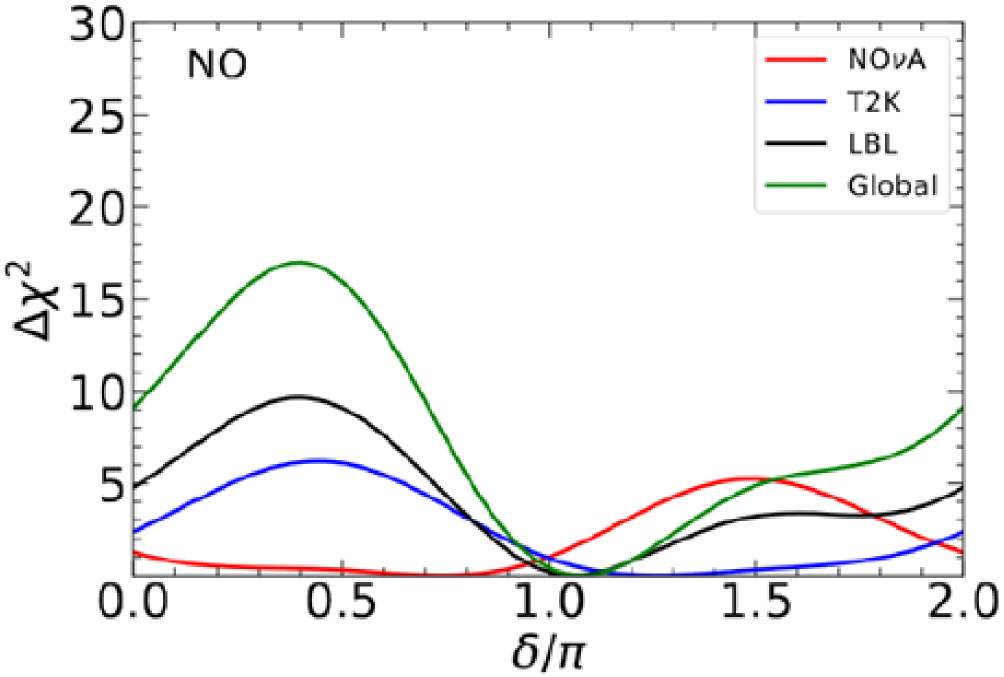
This can also happen

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



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 $\Delta\chi2 = 4.9$

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

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

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

in matter

$\Delta m_\nu^2 \cos 2$ $\qquad$ $- \epsilon_{\tau\tau} A ,$

$\Delta m_\nu^2 \sin 2$ $\qquad$ $- 2\epsilon_{\mu\tau} A .$

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

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

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

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

Violations of Lorentz invariance

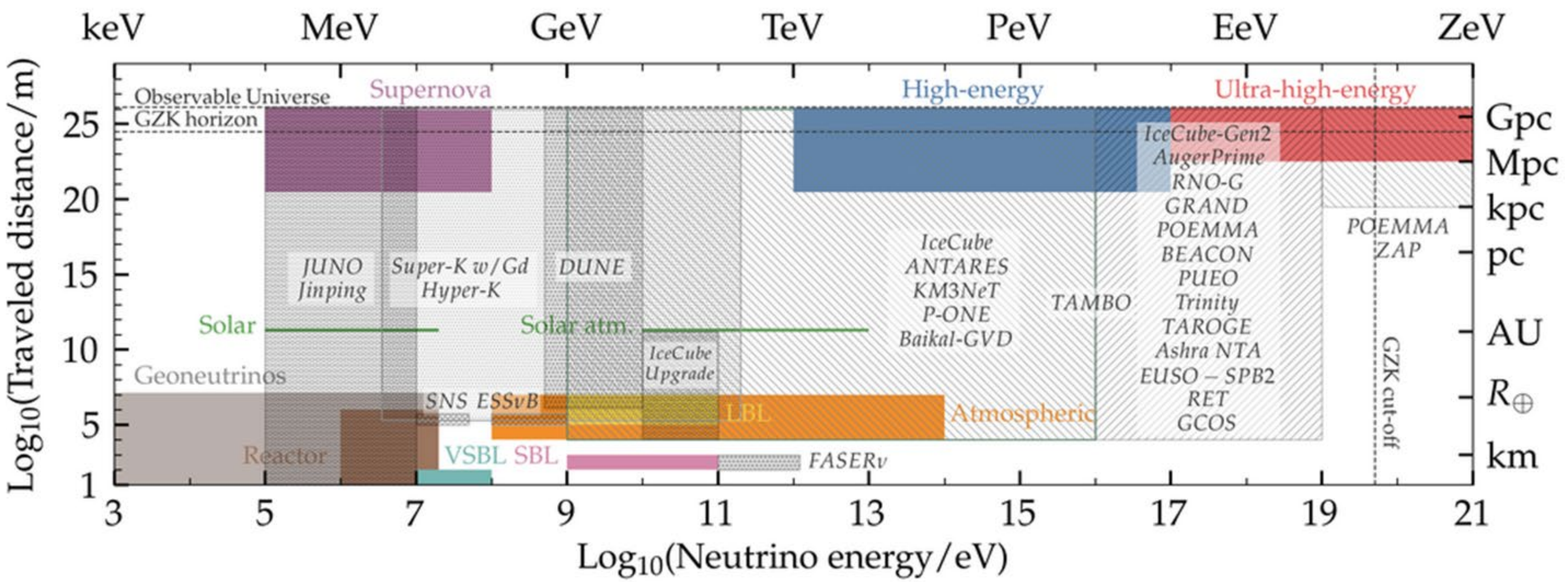
Lorentz violation

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

standard Lorentz covariant term

violates both CPT and Lorentz invariance

Conclusions: Neutrino physics will continue delivering results



Extraordinary ~~claims~~ precision requires extraordinary ~~evidence~~ caution

Mariam Tortola

Christoph Ternes

Pablo Martinez-Mirave