Búsqueda de nueva física en futuros experimentos de neutrinos

Omar Miranda

Cinvestav

Feb 12, 2025

Outline

December 4th 1930

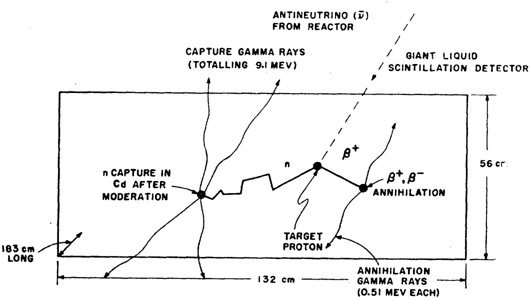
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei **electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.** *The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...*

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant, W. Pauli

Introduction and motivation

$$\nu + p \to n + e^+$$



Reines, Cowan, Nature 1956, Phys. Rev. **113** p 273 (1959)

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}{}^+)$ and the $\tau^+(\equiv K_{\pi 3}{}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

The existence of parity selection rules which work

Nuclear Physics **3** (1957) 127—131; *North-Holland Publishing Co., Amsterdam*

ON THE CONSERVATION LAWS FOR WEAK INTERACTIONS

L. LANDAU

Institute for Physical Problems, USSR Academy of Sciences, Moscow

Received 9 January 1957

Abstract: A variant of the theory is proposed in which non-conservation of parity can be introduced without assuming asymmetry of space with respect to inversion.

Various possible consequences of non-conservation of parity are considered which pertain to the properties of the neutrino and in this connection some processes involving neutrinos are examined on the assumption that the neutrino mass is exactly zero.

Introduction and motivation

Pontecorvo (1957,1967), Maki, Nakagawa, Sakata (1962)

Massive ν's:
the neutrino mass states ν_i (i=1,2,3) are different from the flavor states (weak interaction) ν_α (e, μ, τ)

$$|\nu_\alpha\rangle = \sum_i U_{ai} |\nu_i\rangle$$

$$\text{Tme: } t = 0 \quad |\nu_\alpha(x, t = 0)\rangle = \sum_i U_{\alpha i} e^{ip_i x} |\nu_i\rangle$$

$$\text{Time: } t > 0 \quad |\nu_\alpha(x, t)\rangle = \sum_i U_{\alpha i} e^{ip_i x - iE_i t} |\nu_i\rangle$$

$$\text{Ultrarelativistic } \nu\text{-s } m_i \ll p_i \qquad E_i = \sqrt{m_i^2 + p_i^2} \approx p_i + \frac{m_i^2}{2p_i}$$

$$\text{and } x \approx t \quad |\nu_\alpha(x, t)\rangle = \sum_i U_{\alpha i} e^{-i\frac{m_i^2}{2p_i}t} |\nu_i\rangle$$

Introduction and motivation

Survival probability $\nu_e \to \nu_e$

$$P_{\nu_e \to \nu_e}(x) = 1 - 1 \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2_{21}}{4E} L\right)$$

Conversion probability $\nu_e \to \nu_\mu$

$$P_{\nu_e \to \nu_\mu}(x) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2_{21}}{4E} L\right)$$

Wolfenstein 1978, Mikheev & Smirnov 1985

- Neutral currents (NC): Z_0
- Charged currents (CC): $W_\pm$

$$V_e = \sqrt{2}\, G_F \left(N_e - \frac{N_n}{2} \right) , \qquad V_\mu = V_\tau = \sqrt{2}\, G_F \left(- \frac{N_n}{2} \right) .$$

Evolution ecuation

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}\, G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} .$$

Conversion probability $\nu_e \leftrightarrow \nu_\mu$:

$$P(\nu_e \to \nu_\mu;\, L) = \sin^2 2\theta_m \, \sin^2\left(\pi \frac{L}{l_m}\right) \, ,$$

Matter mixing angle

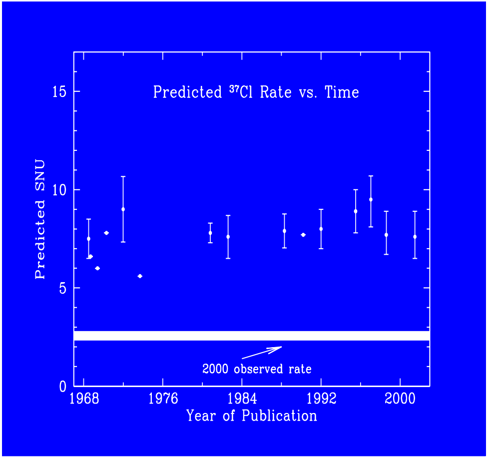
$$\sin^2 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}{\left(\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\, G_F\, N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}$$

Resonance $\sqrt{2}\, G_F\, N_e = \frac{\Delta m^2}{2E}\cos 2\theta$

Wolfenstein 1978, Mikheev & Smirnov 1985

Sola neutrinos

$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ *Pontecorvo'46*



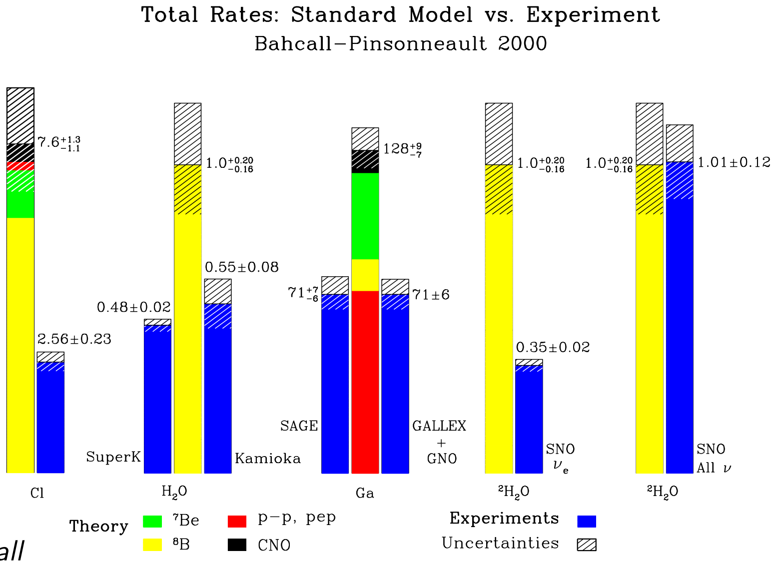
SNO Solar neutrinos

PRL **89** 011301 '02

$$\begin{array}{llll} \nu_e + \mathrm{d} & \rightarrow & \mathrm{p} + \mathrm{p} + \mathrm{e}^- & \text{(CC)}, \\ \nu_x + \mathrm{d} & \rightarrow & \mathrm{p} + \mathrm{n} + \nu_x & \text{(NC)}, \\ \nu_x + \mathrm{e}^- & \rightarrow & \nu_x + e^- & \text{(ES)}. \end{array}$$

$$\begin{aligned} \phi_e &= 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.}) \\ \phi_{\mu\tau} &= 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.}) \end{aligned}$$

$$\phi_{\mathrm{NC}}^{\mathrm{SNO}} = 6.42^{+1.57}_{-1.57}(\text{stat.})^{+0.55}_{-0.58}\ (\text{syst.})$$



Total Rates: Standard Model vs. Experiment
Bahcall−Pinsonneault 2000
7.6$^{+1.3}_{-1.1}$
2.56±0.23
1.0$^{+0.20}_{-0.16}$
0.55±0.08
0.48±0.02
SuperK
Kamioka
128$^{+9}_{-7}$
71$^{+7}_{-6}$
71±6
SAGE
GALLEX
+
GNO
1.0$^{+0.20}_{-0.16}$
0.35±0.02
SNO
ν_e
1.0$^{+0.20}_{-0.16}$
1.01±0.12
SNO
All ν
Cl
H_2O
Ga
^2H_2O
^2H_2O
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments
Uncertainties

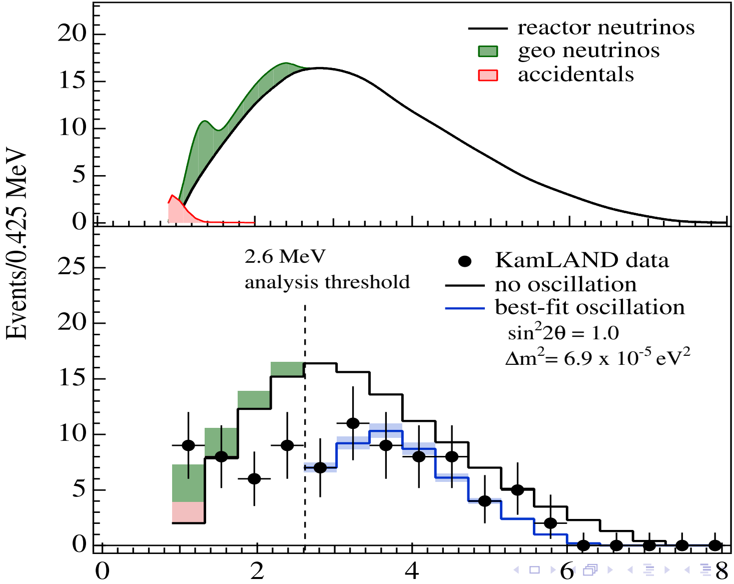
Bahcall

KamLAND

$$\bar{\nu}_e + p \to n + e^+ : \quad P_{\bar{\nu}_e \to \bar{\nu}_\mu}(x) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}x\right)$$

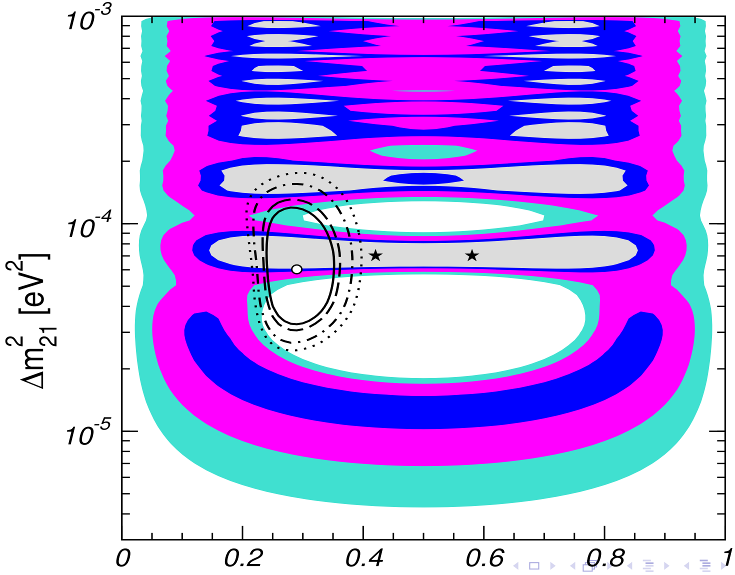
KamLAND neutrinos

PRL **90** 021802 '03

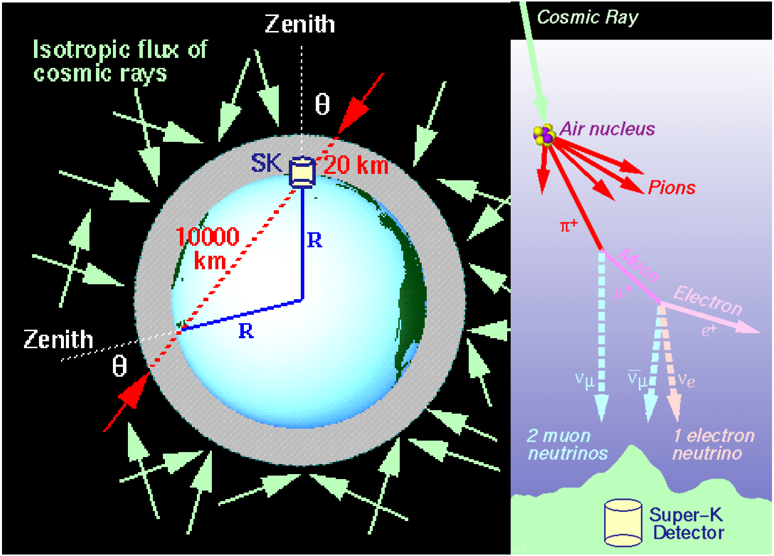


Solar neutrino problem solved

Maltoni, Schwetz, Tortola, Valle NJP **6** 122 (2004)

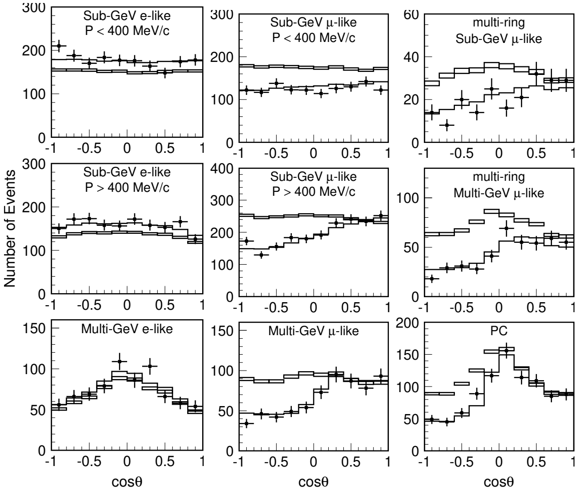


Atmospheric neutrinos



Super-Kamiokande atmospheric neutrino detection

Atmospheric neutrinos



Neutrino experiments

Nobel prize 2015 "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Three families

$$U = R_{23}(\theta_{23}; 0)\, R_{13}(\theta_{13}; \delta)\, R_{12}(\theta_{12}; 0)\, P\,,$$

$$R_{13}(\theta_{13}; \delta) = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}.$$

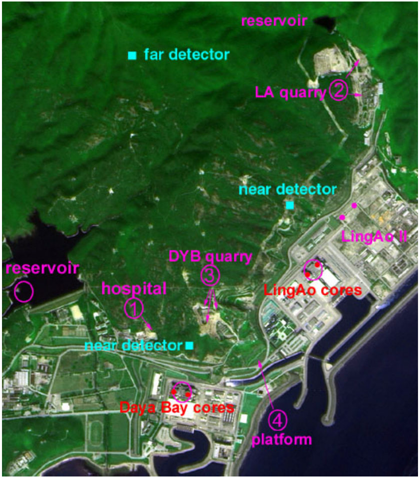
$P = \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$

Three families

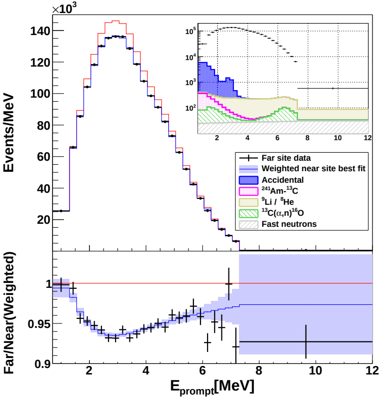
$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\,e^{-i\delta} \\ -(s_{12}c_{23}+c_{12}s_{23}s_{13}\,e^{i\delta}) & (c_{12}c_{23}-s_{12}s_{23}s_{13}\,e^{i\delta}) & s_{23}c_{13} \\ (s_{12}s_{23}-c_{12}c_{23}s_{13}\,e^{i\delta}) & -(c_{12}s_{23}+s_{12}c_{23}s_{13}\,e^{i\delta}) & c_{23}c_{13} \end{pmatrix}$$

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= \left|\sum_j U^*_{\alpha j} U_{\beta j}\, e^{-i\frac{m_j^2}{2E}L}\right|^2 = \\ \delta_{\alpha\beta} &- 4\sum_{i>j} \Re\left\{U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right\}\sin^2\left(\frac{\Delta m^2_{ij}}{4E}L\right) \\ &+ 2\sum_{i>j} \Im\left\{U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right\}\sin\left(\frac{\Delta m^2_{ij}}{2E}L\right) \end{aligned}$$

Daya Bay

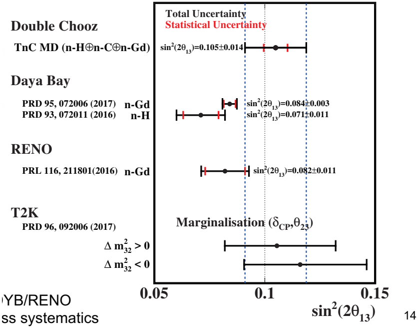

reservoir
far detector
LA quarry ②
near detector
LingAo II
DYB quarry
③
reservoir
hospital
①
LingAo cores
near detector
Daya Bay cores
④
platform

Daya Bay



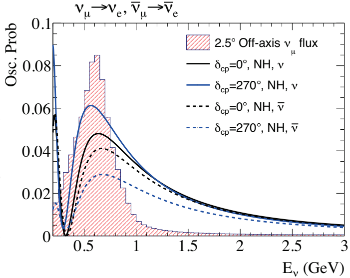
Daya Bay ArXiv:1809.04660

Daya Bay, Double Chooz, Reno



C. Buck Talk at the XXVIII International Conference on Neutrino Physics and Astrophysics DOI: 10.5281/zenodo.1286843

T2K



M. Waskcko Talk at the XXVIII International Conference on Neutrino Physics and Astrophysics DOI: 10.5281/zenodo.1286751

NOvA

NOvA Far Detector
MINOS Far Detector
Ontario
Wisconsin
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Chicago
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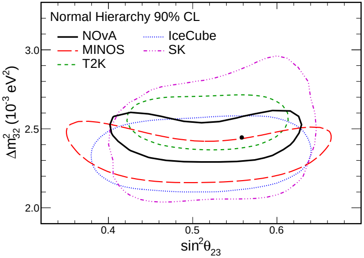
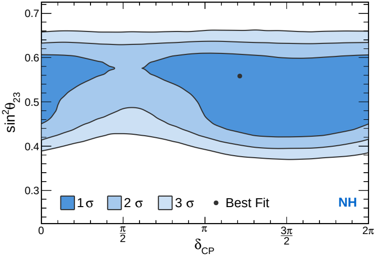
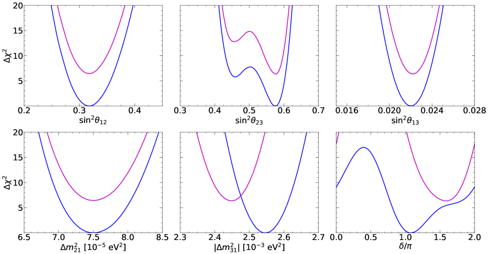
NOvA

Phys. Rev. **D98** (2018) 032012





The current global picture

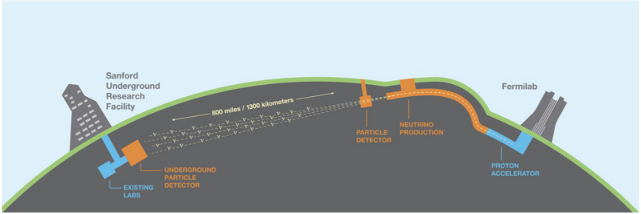


de Salas, **D.V. Forero**, C.A. Ternes, Tortola, Valle Phys. Lett. **B782** (2018) 633
https://globalfit.astroparticles.es/

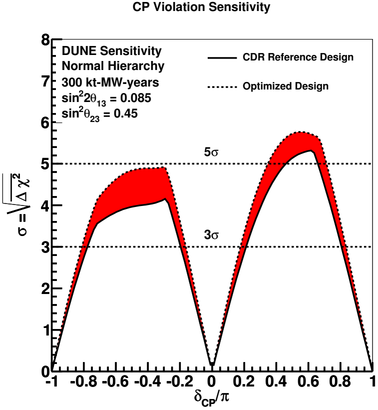
Future neutrino experiments: (Standard roads)

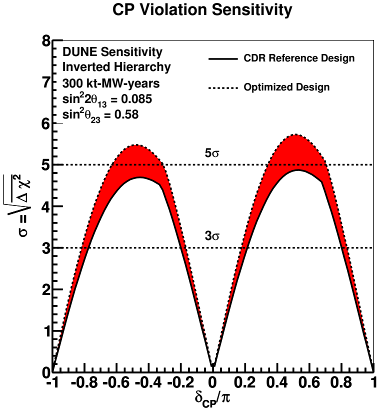
future neutrino experiments

DUNE ArXiv:1807.1033

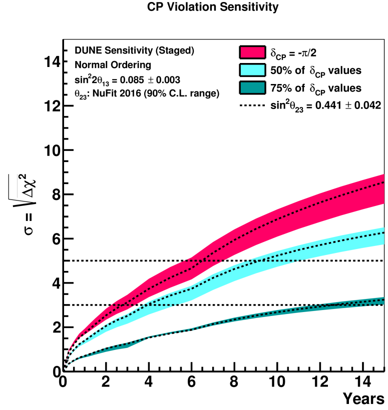


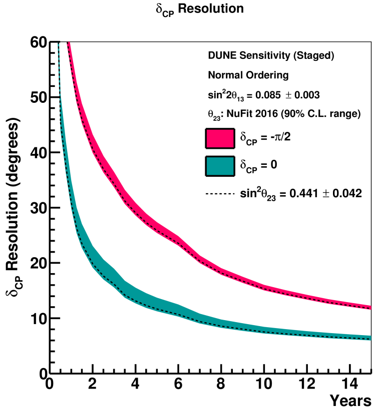
DUNE ArXiv:1512.06148



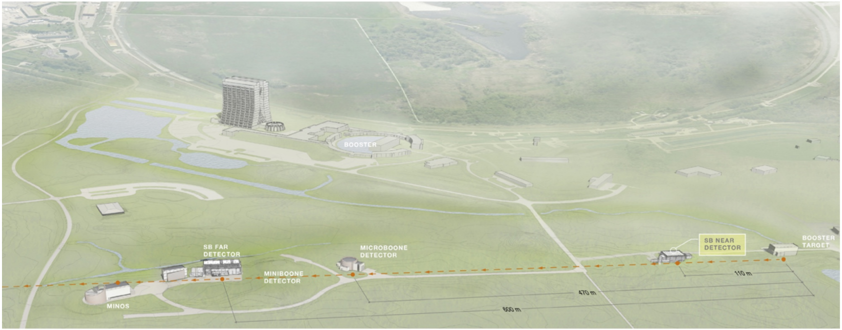


DUNE ArXiv:1807.1033



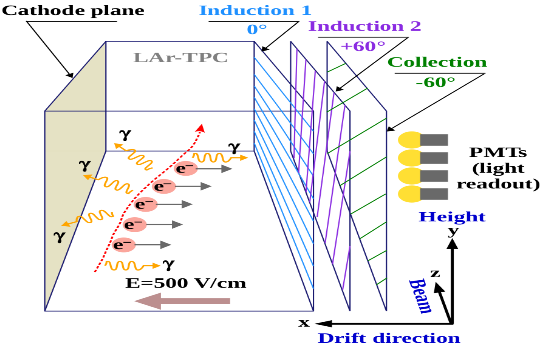


Short Baseline Neutrino Experiment SBNE



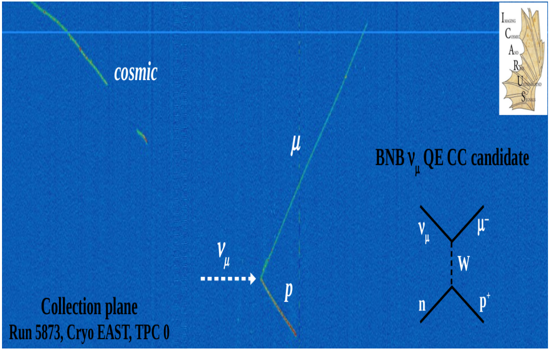
ArXiv:1503.01520

The ICARUS detector



Guadalupe Moreno-Granados, Ph. D. Thesis

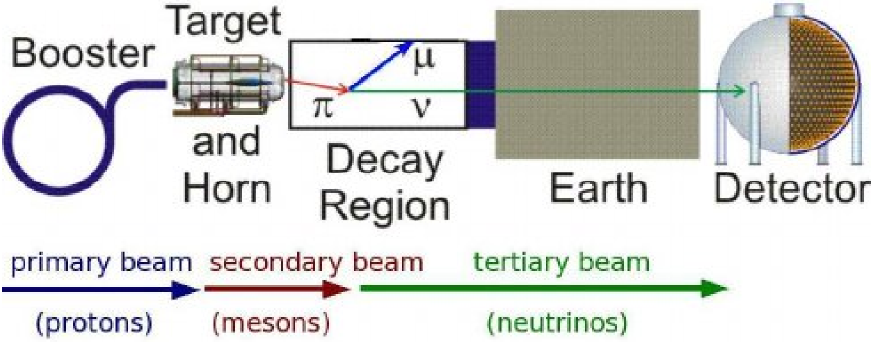
The ICARUS detector



Guadalupe Moreno-Granados, Ph. D. Thesis

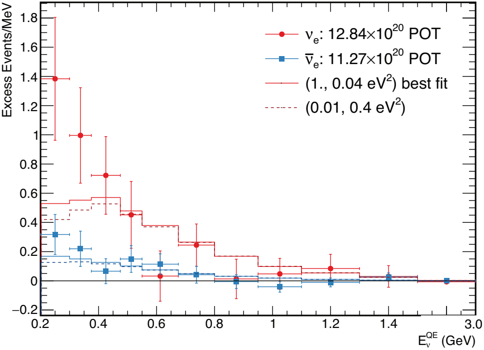
Sterile neutrinos

LSND-MiniBooNE anomaly



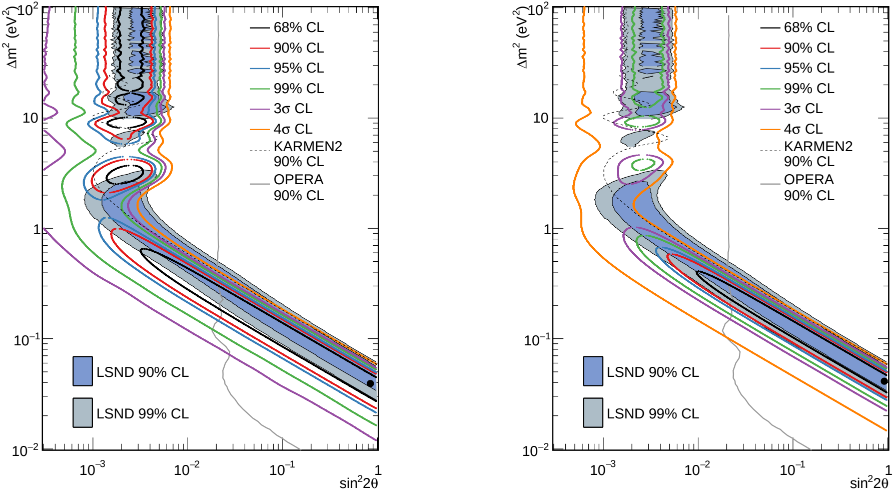
A. Aguilar-Arevalo et al. Phys.Rev. D81 (2010) 092005

LSND-MiniBooNE anomaly



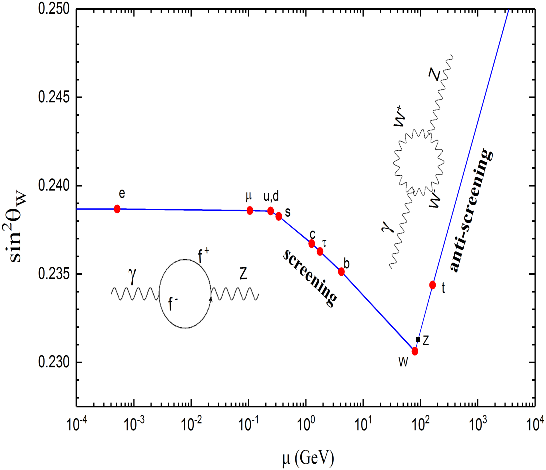
E.C. Huang Talk at the XXVIII International Conference on Neutrino Physics and Astrophysics DOI: 10.5281/zenodo.1287003

LSND-MiniBooNE anomaly



A. Aguilar-Arevalo et al. Phys. Rev. Lett. **121** (2018) 221801

The Weak Mixing Angle at low energies



J. Erler, R. Ferro-Hernández, JHEP 2018 196

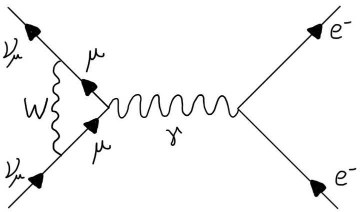
$$\frac{d\sigma}{dT} = \frac{2m_e G_F^2}{\pi} \left\{ g_L^2(T) \left[1 + \frac{\alpha}{\pi} f_-(z)\right] + g_R^2(T) \left(1 - \frac{T}{E_\nu}\right)^2 \left[1 + \frac{\alpha}{\pi} f_+(z)\right] \right.$$
$$\left. - g_R(T) g_L(T) m_e \frac{T}{E_\nu^2} \left[1 + \frac{\alpha}{\pi} f_{+-}(z)\right] \right\},$$

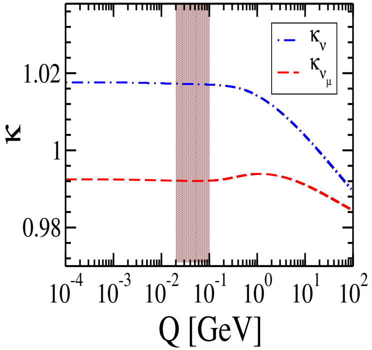
$$g_L'(T) = \rho_{\mathrm{NC}} \left[\frac{1}{2} - \kappa_{\nu_l}(T) \sin^2 \theta_W^{(m_Z)}\right]$$

and

$$g_R'(T) = -\rho_{\mathrm{NC}} \kappa_{\nu_l}(T) \sin^2 \theta_W^{(m_Z)},$$

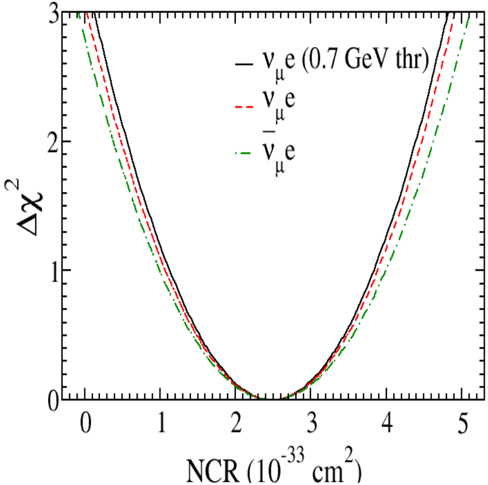
ν charge radius and DUNE





OGM, G. Moreno-Granados, C. A. Moura Phys.Rev.D 104 (2021) 013007

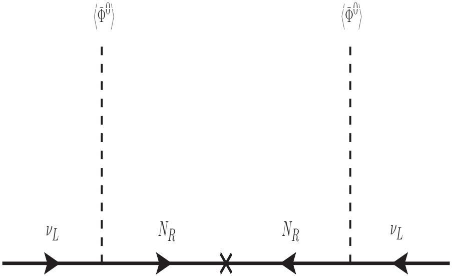
ν charge radius and DUNE



OGM, G. Moreno-Granados, C. A. Moura Phys.Rev.D 104 (2021) 013007

A BSM example: Non-Unitarity

Neutral heavy leptons and seesaw schemes



Minkowski 1977, Gell-Mann Ramond Slanski 1979, Yanagida 1979, Mohapatra Senjanovic 80, Schechter Valle 1980.

Seesaw schemes

$$\begin{bmatrix} M_L & D \\ D^T & M_R \end{bmatrix}$$

$$\begin{bmatrix} 0 & D & 0 \\ D^T & 0 & M \\ 0 & M^T & \mu \end{bmatrix}$$

$\frac{n(n-1)}{2}$ mixing angles

$\frac{(n-1)(n-2)}{2}$ phases

Minkowski 1977, Gell-Mann Ramond Slanski 1979, Yanagida 1979, Mohapatra Senjanovic 80, Schechter Valle 1980.

$$U^{NP} = \omega_{n-1\,n}\omega_{n-2\,n}\dots\omega_{2\,n}\omega_{1\,n}\omega_{n-2\,n-1}\dots\omega_{2\,n-1}\omega_{1\,n-1}\dots\omega_{3\,4}\,\omega_{2\,4}\omega_{1\,4}\,,$$

$$U^{3\times 3} = \omega_{2\,3}\,\omega_{1\,3}\,\omega_{1\,2}\,.$$

$$\omega_{13} = \begin{pmatrix} c_{13} & 0 & e^{-i\phi_{13}}s_{13} & \\ 0 & 1 & 0 & \vdots \\ -e^{i\phi_{13}}s_{13} & 0 & c_{13} & \\ & \dots & & 1 \end{pmatrix}$$

with $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, $\eta_{ij} = e^{-i\phi_{ij}}\,\sin\theta_{ij}$, and $\bar{\eta}_{ij} = -e^{i\phi_{ij}}\,\sin\theta_{ij}$

Mixing matrix

$$U_{\alpha i}^{n\times n} = \begin{pmatrix} N & S \\ V & T \end{pmatrix}$$

$$NN^\dagger + SS^\dagger = I,$$

$$N^\dagger N + V^\dagger V = I.$$

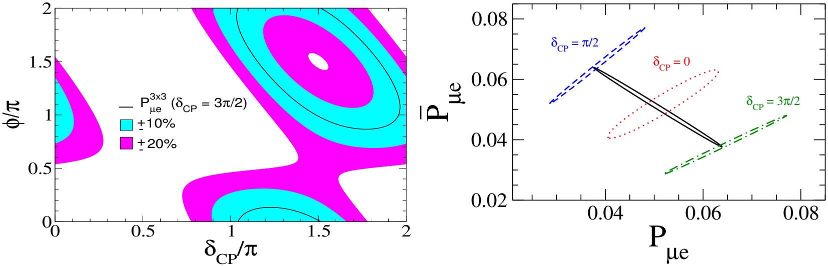
Mixing matrix

$$N = N^{NP}\, U^{3\times3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times3}$$

$$\begin{aligned} \alpha_{11} &= c_{1\,n}\, c_{1n-1} c_{1\,n-2} \dots c_{14}, \\ \alpha_{22} &= c_{2\,n}\, c_{2n-1} c_{2\,n-2} \dots c_{24}, \\ \alpha_{33} &= c_{3\,n}\, c_{3n-1} c_{3\,n-2} \dots c_{34}, \end{aligned}$$

Escrihuela, Forero, OGM, Tortola, Valle **PRD 93** 053009 (2015)

NSI and CP violation



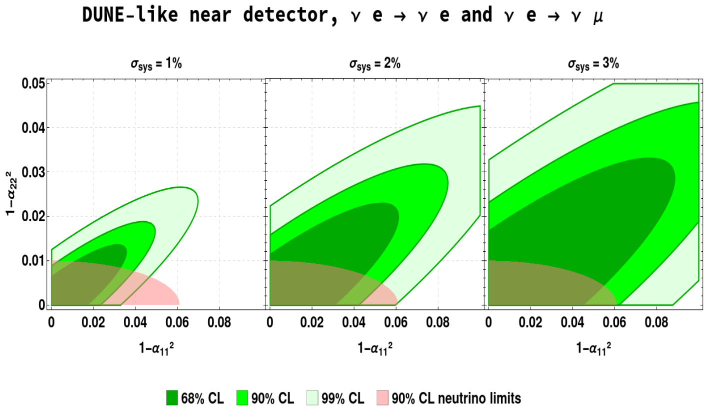
M. A. Tortola, OGM, J W F Valle, Phys.Rev.Lett. **117** (2016) 061804

$$\left(\frac{d\sigma}{dT}\right)^{\text{NU}} = \frac{\mathcal{P}_{\mu e}^{\text{NC}}}{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}\left(\frac{d\sigma}{dT}\right)^{\text{SM}} + \frac{2m_e G_\mu^2}{\pi}\frac{\mathcal{R}e\left[\mathcal{P}_{\mu e}^{\text{int}}\right]}{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}\left\{\frac{\mathcal{P}_{\mu e}^{\text{CC}}}{\mathcal{R}e\left[\mathcal{P}_{\mu e}^{\text{int}}\right]} + 2g_L - g_R\frac{m_e T}{E_\nu^2}\right\},$$

$$\mathcal{P}_{\mu e}^{\text{NC}} = (NN^\dagger NN^\dagger NN^\dagger)_{\mu\mu}$$
$$\mathcal{P}_{\mu e}^{\text{CC}} = (NN^\dagger)_{\mu e}(NN^\dagger)_{e\mu}(NN^\dagger)_{ee}$$
$$\mathcal{P}_{\mu e}^{\text{int}} = (NN^\dagger NN^\dagger)_{e\mu}(NN^\dagger)_{\mu e}.$$

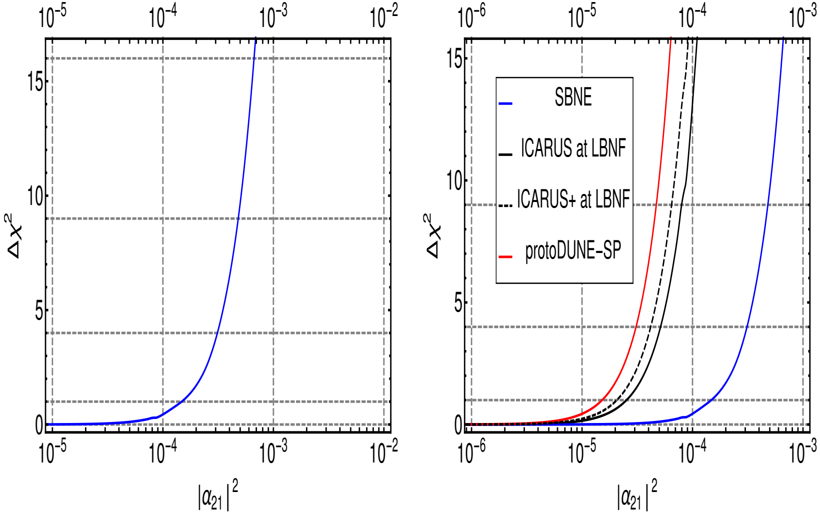
S. Centelles-Chuliá, OGM, J. W. F. Valle **PRD 109** 115007 (2024)

Non-Unitarity in the DUNE near-detector



S. Centelles-Chuliá, OGM, J. W. F. Valle **PRD 109** 115007 (2024)

ICARUS and DUNE near detector



OGM, Pasquini, Tortola, Valle Phys. Rev. **D97** (2018) 095026

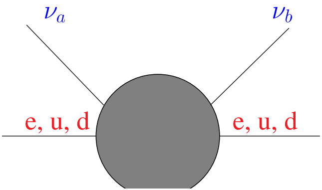
Non-standard interactions (NSI).

Non-standard interactions NSI

Most extensions of the SM predict neutral current non-standard interactions (NSI) of neutrinos which can be either flavor preserving (FD or NU) or flavor-changing (FC).

NSI effective Lagragian form:

$$\mathcal{L}_{eff}^{NSI} = -\sum_{\alpha\beta fP} \varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f}\gamma^\rho P f)$$



Here $\alpha, \beta = e, \mu, \tau$; $f = e, u, d$; $P = L, R$; $L = (1-\gamma_5)/2$; $R = (1+\gamma_5)/2$

Oscillations in matter

- Neutral currents (NC): exchange of Z_0
- Charge currents (CC): exchange of $W_\pm$

$$V_e = \sqrt{2}\, G_F \left(N_e - \frac{N_n}{2} \right), \qquad V_\mu = V_\tau = \sqrt{2}\, G_F \left(-\frac{N_n}{2} \right).$$

Evolution equation

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}\, G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}.$$

NSI degeneracy I

$$H_{\rm NSI} = \sqrt{2} G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix} .$$

Mixing angle in matter + NSI

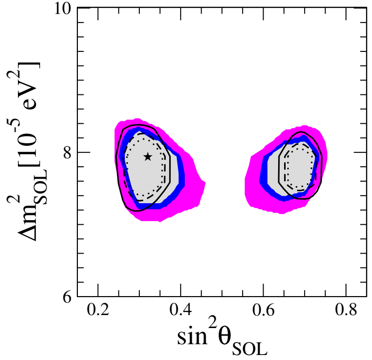
$$\tan 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right) \sin 2\theta + 2\sqrt{2} G_F \varepsilon N_d}{\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F \varepsilon'\, N_d} .$$

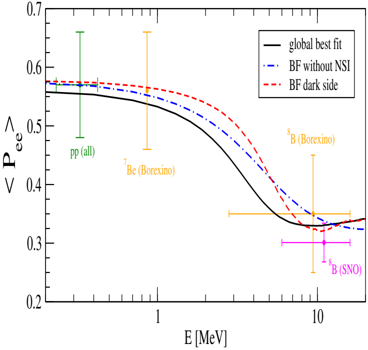
Resonance $\quad \frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F\, \varepsilon'\, N_d = 0 .$

$$\varepsilon' > \frac{N_e}{N_d}$$

OGM, M. Tortola, J. W. F. Valle, JHEP 0610:008 (2006) hep-ph/0406280

NSI degeneracy I





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M. C. Gonzalez-Garcia, M. Maltoni, JHEP **1309** 152 (2013)

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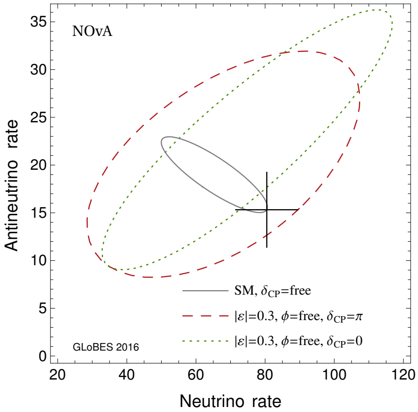
NSI degeneracy II

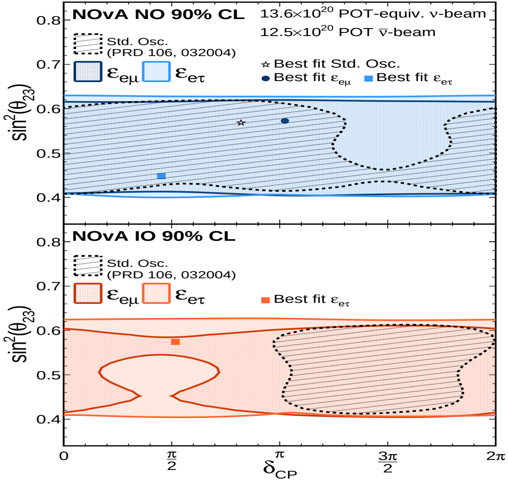


P. Huber, **D. V. Forero** Phys.Rev.Lett. 117 (2016) no.3, 031801

see OGM, Tortola, Valle PRL 117 061804 for the case of non-unitarity

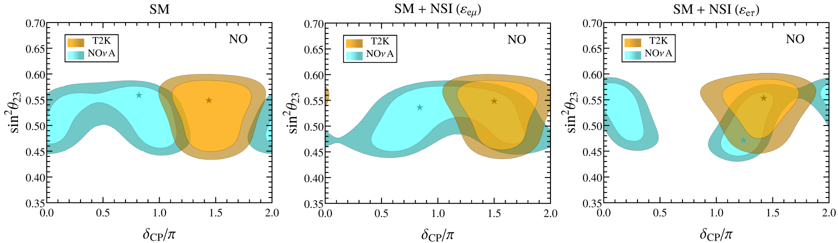
F.J. Escrihuela, **D.V. Forero**, O.G. Miranda, M. Tortola, J.W.F. Valle

NSI and the NOVA-T2K tension



M. A. Acero, NOvA Coll. Phys.Rev.Lett. 133 (2024) 201802

NSI and the NOVA-T2K tension

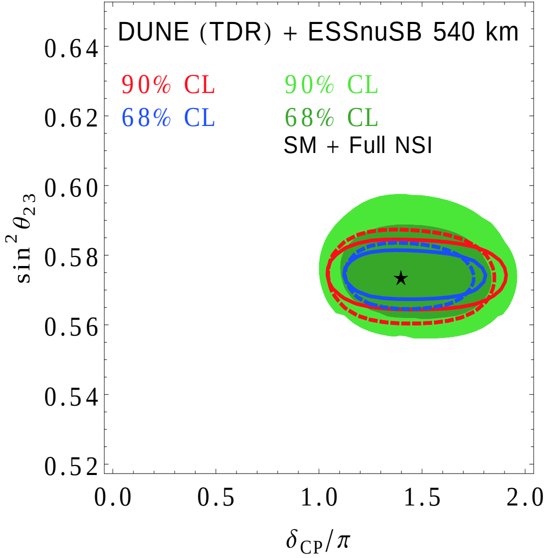


S. Chatterjee and A. Palazzo, ArXiv: 2409.10599 and PRL 126 (2021) 051802

The ESSnuSB

E. Baussan, et al ESSnuSB Coll. Nucl.Phys.B 885 (2014) 127-149

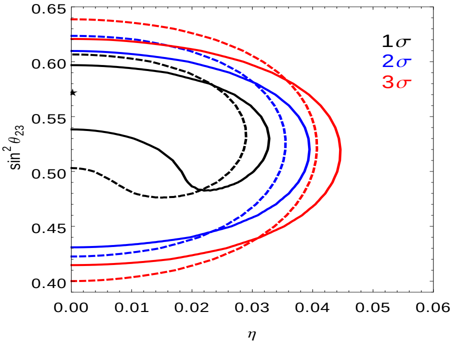
The ESSnuSB



L. A. Delgadillo, OGM Phys.Rev.D 108 (2023) 095024

The ESSnuSB

$$\mathcal{L}_{m_\nu} \supset \frac{\lambda^{\alpha\beta} v^2}{2\Lambda}(\nu_\alpha)^T \nu_\beta + \frac{y^{\alpha\beta} v^2}{2\Lambda^2}\phi(\nu_\alpha)^T \nu_\beta.$$

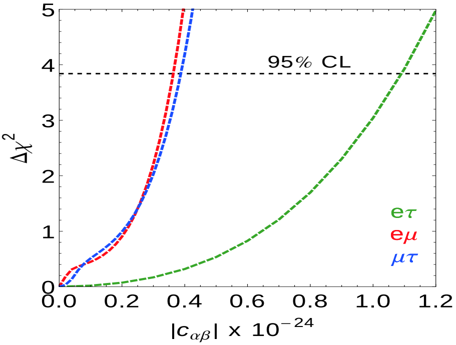


R. Cordero, L. A. Delgadillo, OGM Phys.Rev.D 107 (2023) 075023

DUNE and LIV

$$-\mathcal{L}_{\text{eff}} = -i\frac{\lambda_{\alpha\beta}}{M_*^4} T_\varphi^{\mu\nu} \bar{\nu}_\alpha \gamma_\mu (1-\gamma_5) \partial_\nu \nu_\beta,$$

$$c_{\alpha\beta}^{\mu\nu} \to \frac{\lambda_{\alpha\beta}}{M_*^4} T_\varphi^{\mu\nu}.$$



R. Cordero, L. A. Delgadillo, OGM Eur.Phys.J.C 85 (2025) 6

Conclusions

- ✓ Neutrino physics is currently in the precision era and we expect to have the complete standard picture in the next few years
- ✓ It will be possible to search for different types of physics beyond the Standard Model
- ✓ The interplay between different experiments will be crucial

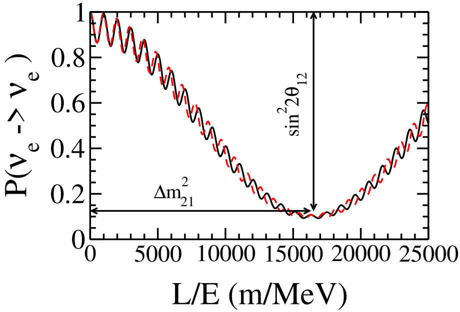
Thanks

future neutrino experiments

JUNO Reactor antineutrino experiment J. Phys. **G43** (2016) 030401

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)\right]$$

$$\Delta m_{32}^2 = \Delta m_{31}^2 (1 - \frac{\Delta m_{21}^2}{\Delta m_{31}^2})$$



Non-standard interactions

Non-standard neutrino-electron and neutrino quark interactions:

$$\mathcal{L} = \lambda_{ijk} \tilde{e}_R^{k*} (\bar{\nu}_L^i)^c e_L^j + \lambda'_{ijk} \tilde{d}_L^j \bar{d}_R^k \nu_L^i + \dots$$

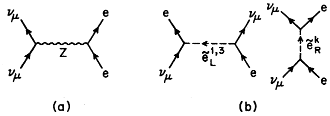
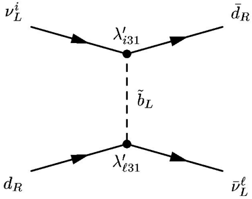
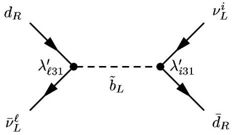


FIG. 2. Feynman diagrams for $\nu_\mu e$ scattering from (a) the standard model, and (b) the R-breaking interactions.

Barger, Giudice & Han'89





See e.g. Roulet'91, Amanik et al'05