Searching for non standard decoherence effects in neutrino oscillations

Christoph Andreas Ternes

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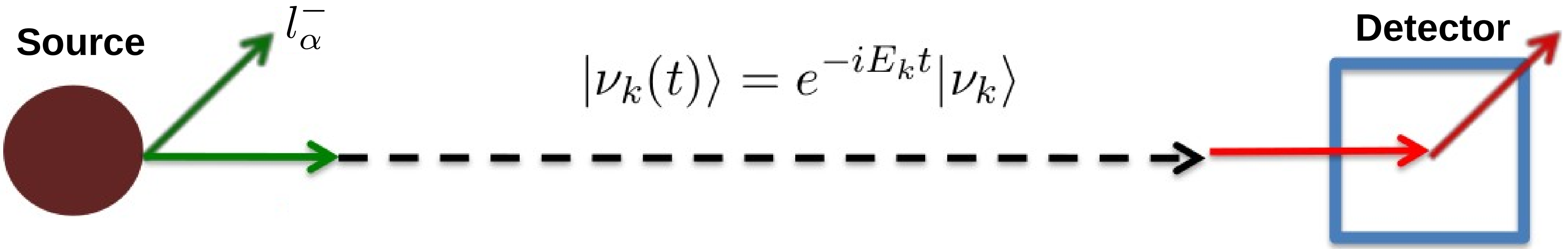
Neutrino oscillations



$$l_\alpha^-$$

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

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

$$\langle \nu_\beta | \nu_\alpha(t)\rangle = \sum_k U_{\alpha k}^* U_{\beta k} e^{-iE_k t}$$

$$P_{\nu_\alpha \to \nu_\beta}(t) = \left| A_{\nu_\alpha \to \nu_\beta}(t) \right|^2 = \sum_{k,j} U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^* \, e^{-i(E_k - E_j)t}$$

Three-neutrino oscillations

Neutrino mixing matrix

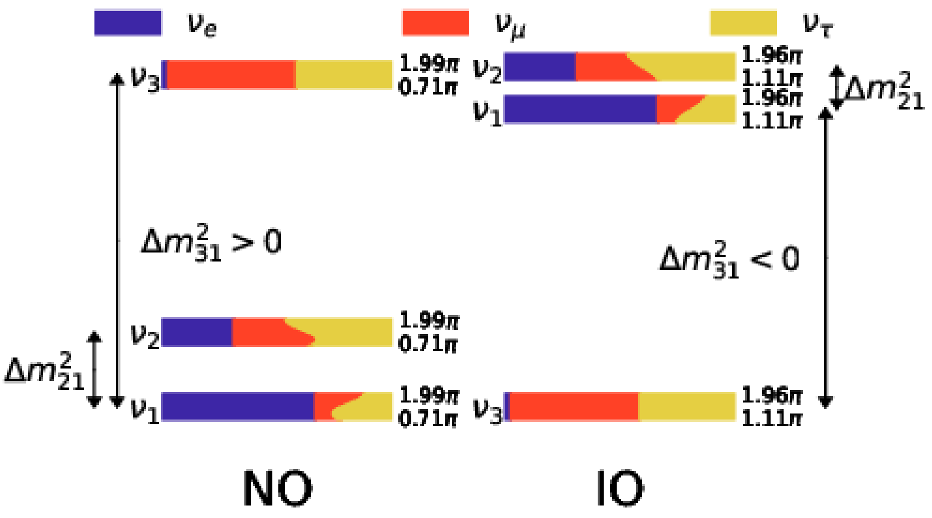
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$

1 Dirac + 2 Majorana CP-phases

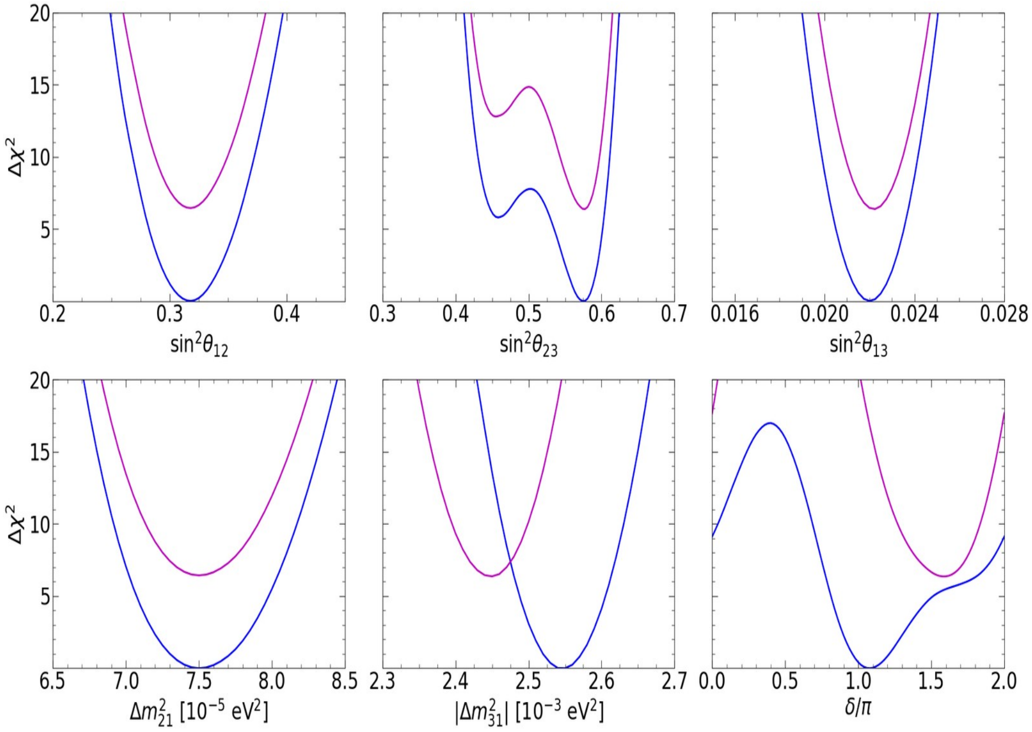
Three masses m_1, m_2, m_3 for which two orderings are possible

Oscillations are only sensitive to mass splittings



Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



parameter	best fit $\pm 1\sigma$	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
$\|\Delta m^2_{31}\| [10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\|\Delta m^2_{31}\| [10^{-3}\text{eV}^2]$ (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
$\sin^2\theta_{23}/10^{-1}$ (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

See also:
Bari – 2107.00532, PRD 2021

See also:
NuFit - 2111.03086 , Universe 2021

Neutrino quantum decoherence

Neutrino quantum decoherence

Treat neutrinos as a subsystem which is weakly interacting with its environment

Neutrino oscillations can be described by the Lindblad Master equation

$$\frac{\partial \rho(t)}{\partial t} = -i[H, \rho(t)] + \mathcal{D}[\rho(t)]$$

Lindblad, Commun. Math. Phys. 1976
Gorini, Kossakowski, Sudarshan, J. Math. Phys. 1976

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Dissipator encoding the decoherence effect

Lindblad, Commun. Math. Phys. 1976
Gorini, Kossakowski, Sudarshan, J. Math. Phys. 1976

Neutrino quantum decoherence

In general the dissipator has a very complicated form:

$$\mathcal{D}[\rho_\nu(t)] = \frac{1}{2}\sum_{j=1}^{N^2-1}\left([\mathcal{O}_j, \rho_\nu(t)\mathcal{O}_j^\dagger] + [\mathcal{O}_j\rho_\nu(t), \mathcal{O}_j^\dagger]\right)$$

Benatti, Floreanini, hep-ph/0002221, JHEP 2000

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Operators describing the coupling of the neutrinos subsystem with the environment

Benatti, Floreanini, hep-ph/0002221, JHEP 2000

Neutrino quantum decoherence

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Expand everything in terms of Gell-Mann matrices

$$\mathcal{D}[\rho_\nu(t)] = c_k\lambda^k \ \left(\text{with } \rho_\nu = \sum \rho_\nu^k\lambda^k \text{and } \mathcal{O}_j = \sum \mathcal{O}_k^j\lambda^k\right)$$

$$\mathcal{D}[\rho_\nu(t)] \ = \ (\mathbf{D}_{k\ell} \ \rho_\nu^\ell)\lambda^k$$

Neutrino quantum decoherence

For 3 neutrinos the dissipator is given by:

$$\mathbf{D} = \begin{pmatrix} -\Gamma_0 & \beta_{01} & \beta_{02} & \beta_{03} & \beta_{04} & \beta_{05} & \beta_{06} & \beta_{07} & \beta_{08} \\ \beta_{01} & -\Gamma_1 & \beta_{12} & \beta_{13} & \beta_{14} & \beta_{15} & \beta_{16} & \beta_{17} & \beta_{18} \\ \beta_{02} & \beta_{12} & -\Gamma_2 & \beta_{23} & \beta_{24} & \beta_{25} & \beta_{26} & \beta_{27} & \beta_{28} \\ \beta_{03} & \beta_{13} & \beta_{23} & -\Gamma_3 & \beta_{34} & \beta_{35} & \beta_{36} & \beta_{37} & \beta_{38} \\ \beta_{04} & \beta_{14} & \beta_{24} & \beta_{34} & -\Gamma_4 & \beta_{45} & \beta_{46} & \beta_{47} & \beta_{48} \\ \beta_{05} & \beta_{15} & \beta_{25} & \beta_{35} & \beta_{45} & -\Gamma_5 & \beta_{56} & \beta_{57} & \beta_{58} \\ \beta_{06} & \beta_{16} & \beta_{26} & \beta_{36} & \beta_{46} & \beta_{56} & -\Gamma_6 & \beta_{67} & \beta_{68} \\ \beta_{07} & \beta_{17} & \beta_{27} & \beta_{37} & \beta_{47} & \beta_{57} & \beta_{67} & -\Gamma_7 & \beta_{78} \\ \beta_{08} & \beta_{18} & \beta_{28} & \beta_{38} & \beta_{48} & \beta_{58} & \beta_{68} & \beta_{78} & -\Gamma_8 \end{pmatrix}$$

Neutrino quantum decoherence

- *Unitarity of the system.* Probability conservation implies $\mathbf{D}_{k0} = \mathbf{D}_{0\ell} = 0$ [42], given that $f_{ab0} = 0$.

- *Complete positivity* of the time-evolution ρ_ν place conditions on the diagonal elements, thus making them not completely independent.

- *Entropy increase.* The condition $\mathcal{O}_j = \mathcal{O}_j^\dagger$ implies that the Von Neumann entropy $S = -\mathrm{Tr}(\rho_\nu \ln \rho_\nu)$ increases with time [77].

- *Energy conservation* of the neutrino subsystem is satisfied through the commutation relation $[H, \mathcal{O}_j] = 0$. This bound includes the decoherence effect in the evolution.

$$\mathbf{D} = -\mathrm{diag}(\Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0)$$

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Set to 0 due to strong bounds from solar neutrinos

$$\mathbf{D} = -\mathrm{diag}(\Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0)$$

de Holanda, 1909.09504, JCAP 2020

Neutrino oscillations with decoherence

For this scenario the neutrino oscillation probability is very similar to the standard case

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 2\sum_{k>j} \Re\left[\tilde{U}^*_{\alpha k}\tilde{U}_{\beta k}\tilde{U}_{\beta j}\tilde{U}^*_{\beta j}\right] \left[1 - \cos\left(\frac{\Delta\tilde{m}^2_{kj} L}{2E}\right) e^{-\Gamma_{kj}(E)L}\right]$$

$$+ 2\sum_{k>j} \Im\left[\tilde{U}^*_{\alpha k}\tilde{U}_{\beta k}\tilde{U}_{\beta j}\tilde{U}^*_{\beta j}\right] \sin\left(\frac{\Delta\tilde{m}^2_{kj} L}{2E}\right) e^{-\Gamma_{kj}(E)L},$$

Neutrino oscillations with decoherence

We assume different energy dependencies

$$\Gamma_{ij}(E) = \Gamma_{ij}(E_0)\left(\frac{E}{E_0}\right)^n \qquad E_0 = 1\ \mathrm{GeV}$$

Christoph Ternes

Neutrino oscillations with decoherence

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$$\Gamma_{ij}(E) = \Gamma_{ij}(E_0)\left(\frac{E}{E_0}\right)^n \qquad E_0 = 1\,\text{GeV}$$

and different "models" of decoherence

Model A	We vary $\Gamma_{21} = \Gamma_{31} = \Gamma_{32}$
Model B	We vary $\Gamma_{21} = \Gamma_{31}$ and keep $\Gamma_{32} = 0$
Model C	We vary $\Gamma_{21} = \Gamma_{32}$ and keep $\Gamma_{31} = 0$
Model D	We vary $\Gamma_{31} = \Gamma_{32}$ and keep $\Gamma_{21} = 0$
Model E	We vary Γ_{21} and keep $\Gamma_{31} = \Gamma_{32} = 0$
Model F	We vary Γ_{31} and keep $\Gamma_{21} = \Gamma_{32} = 0$
Model G	We vary Γ_{32} and keep $\Gamma_{21} = \Gamma_{31} = 0$

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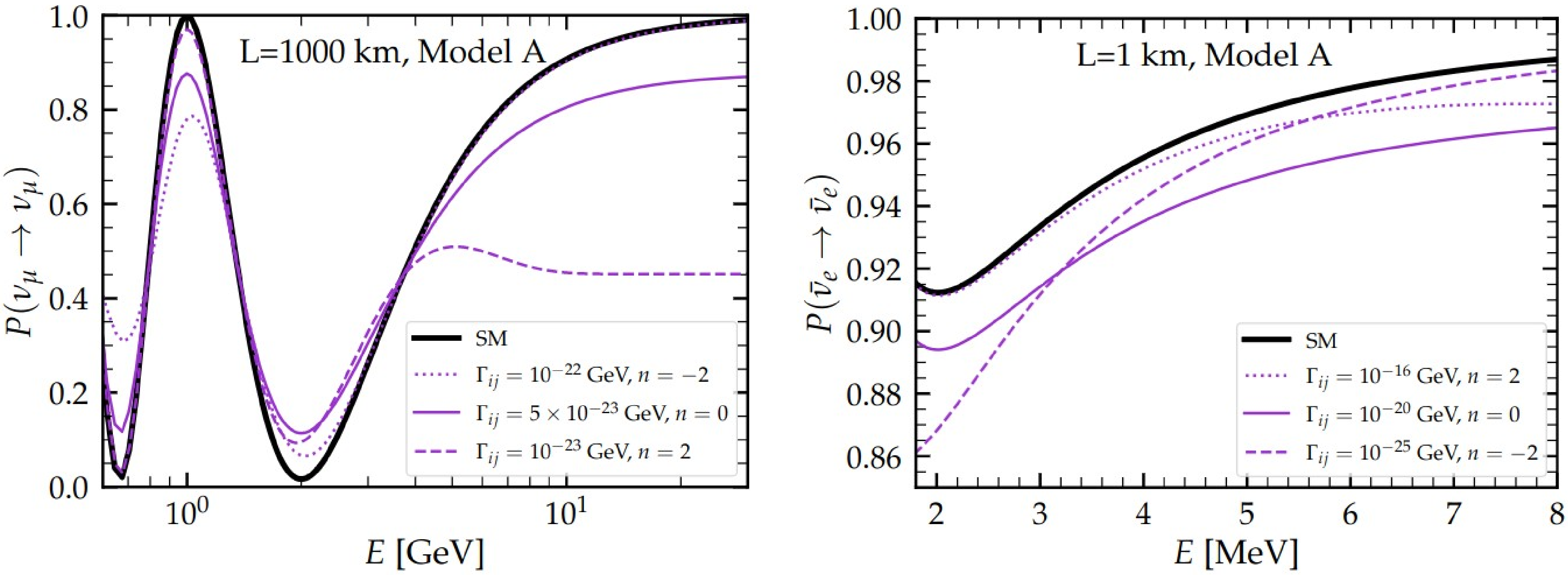
Neutrino oscillations with decoherence

Many accelerator and reactor experiments have been considered

Experiment	Baseline	Energy range	Main oscillation channel
KamLAND [57]	$\mathcal{O}(100) - \mathcal{O}(1000)$ km	1.8 – 8.0 MeV	$\overline{\nu}_e \to \overline{\nu}_e$
Daya Bay [56] and RENO [55]	$\mathcal{O}(100) - \mathcal{O}(1000)$ m	1.8 – 8.0 MeV	$\overline{\nu}_e \to \overline{\nu}_e$
T2K [62]	295 km	0.2 – 2.0 GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$ and $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$
NOvA [61]	812 km	0.8 – 5.0 GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$ and $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$
MINOS/MINOS+ [59]	735 km	0 – 40.0 GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$
JUNO [64]	~ 53 km	1.8 – 8.0 MeV	$\overline{\nu}_e \to \overline{\nu}_e$
DUNE [95]	1285 km	0.5 – 20 GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$ and $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$
DUNE HE [96]	1285 km	0.5 – 20 GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$ and $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$

De Romeri, Giunti, Ternes, Stuttard, 2306.14699

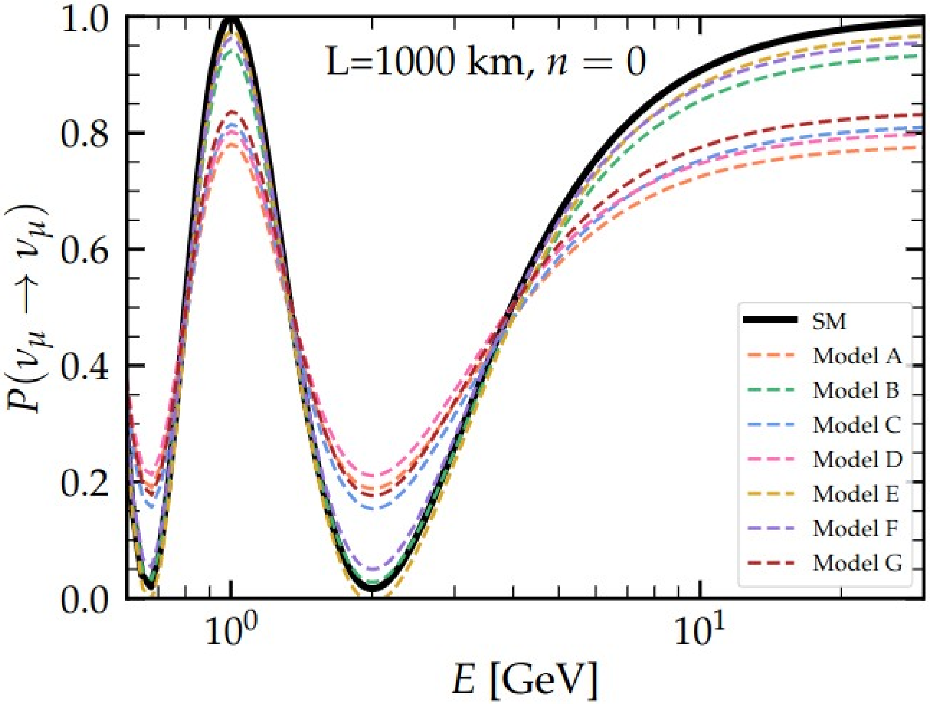
Neutrino oscillations with decoherence

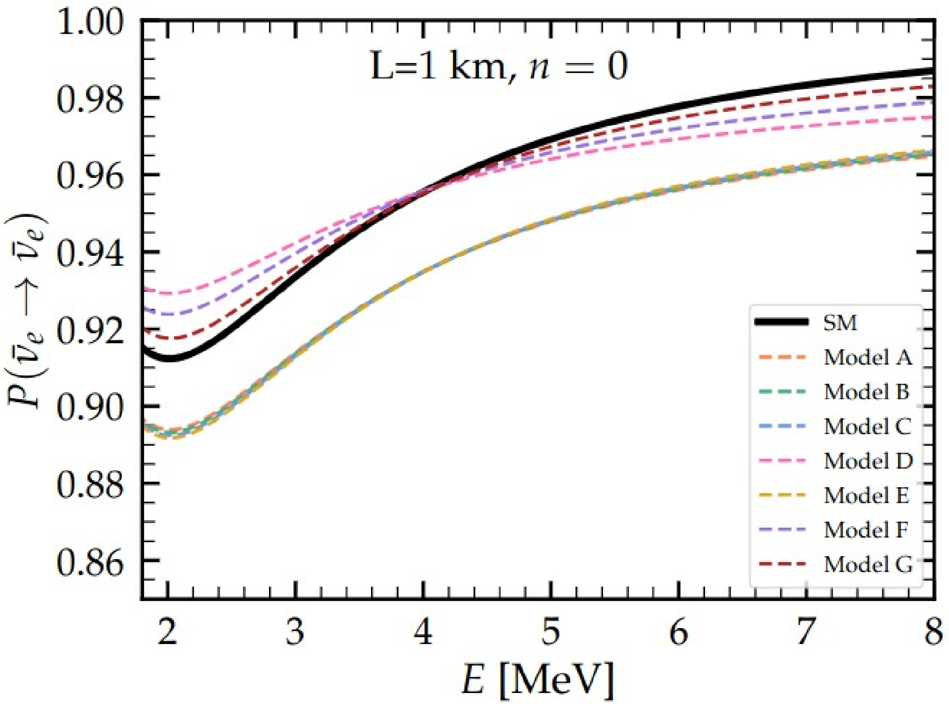


Negative (positive) exponents affect smaller (larger) energies

De Romeri, Giunti, Ternes, Stuttard, 2306.14699

Neutrino oscillations with decoherence

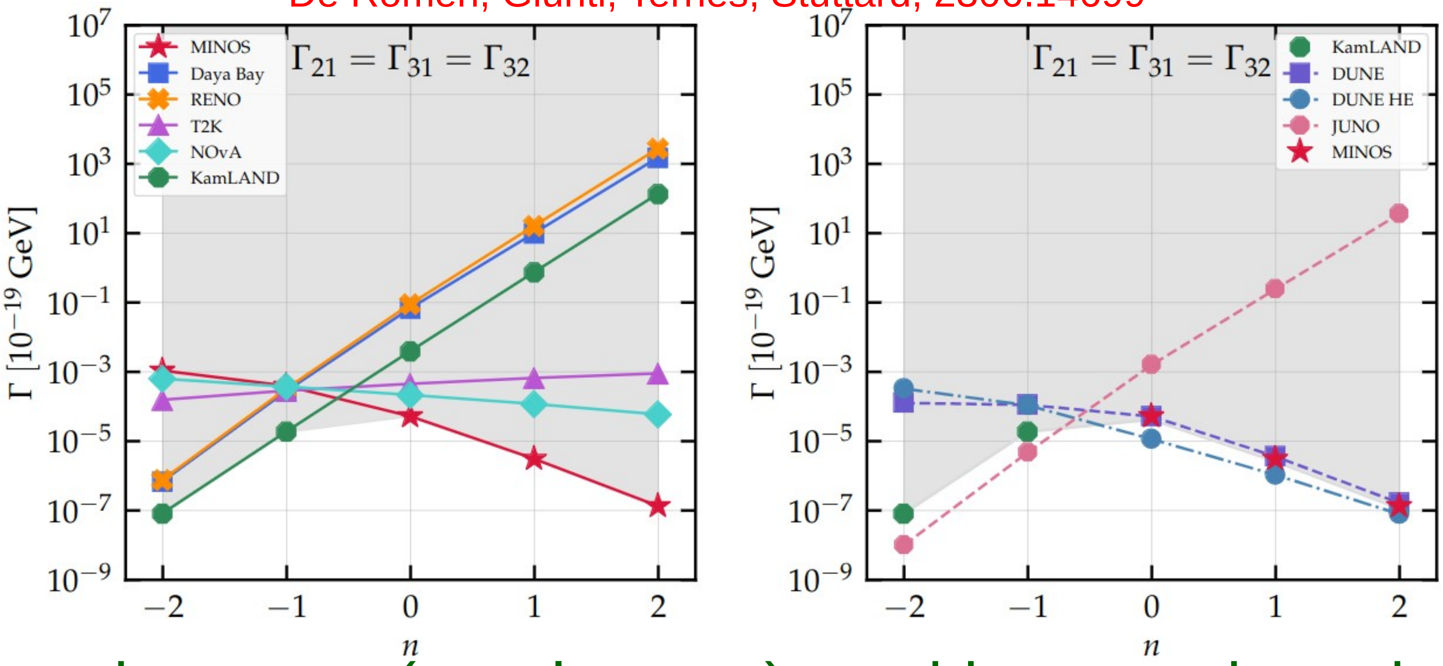




Accelerators are particularly sensitive to models with $\Gamma_{32} \neq 0$
Reactor experiments to Γ_{21} plus one other term

Results, Model A

De Romeri, Giunti, Ternes, Stuttard, 2306.14699

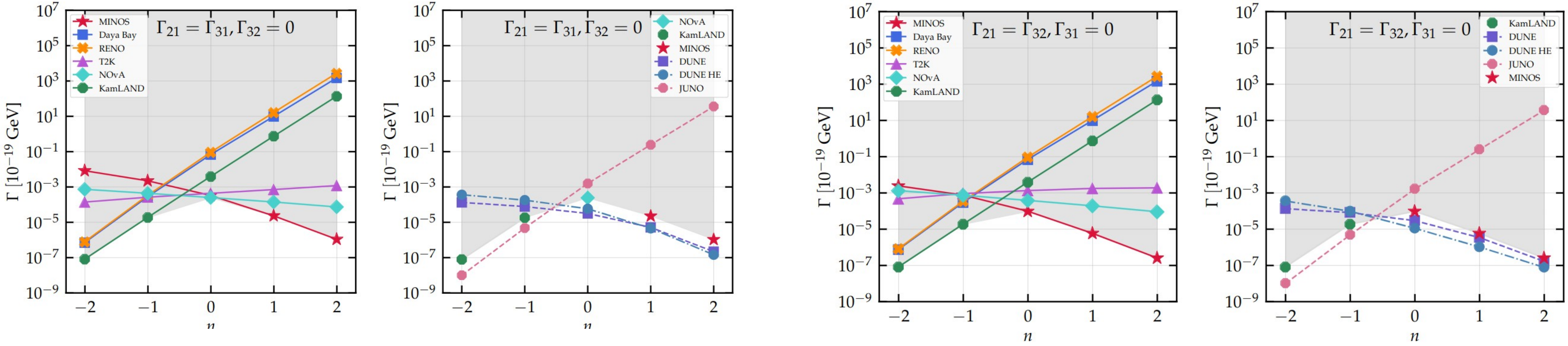


As anticipated reactors (accelerators) provide strong bounds for negative (positive) n

The slope of the curves is due to the energies used in the experiments

Results, Models B and C

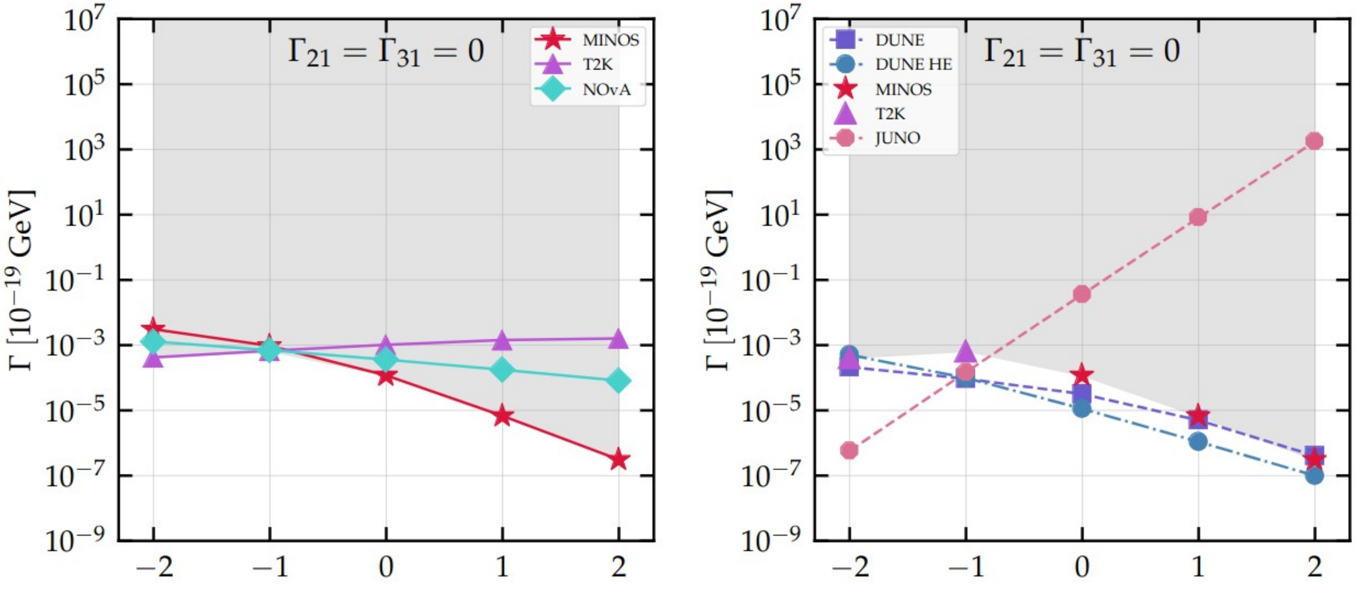
De Romeri, Giunti, Ternes, Stuttard, 2306.14699



As expected bounds on Model B and C are nearly the same for reactors, while accelerators provide slightly better bounds for model C

Results, Model G

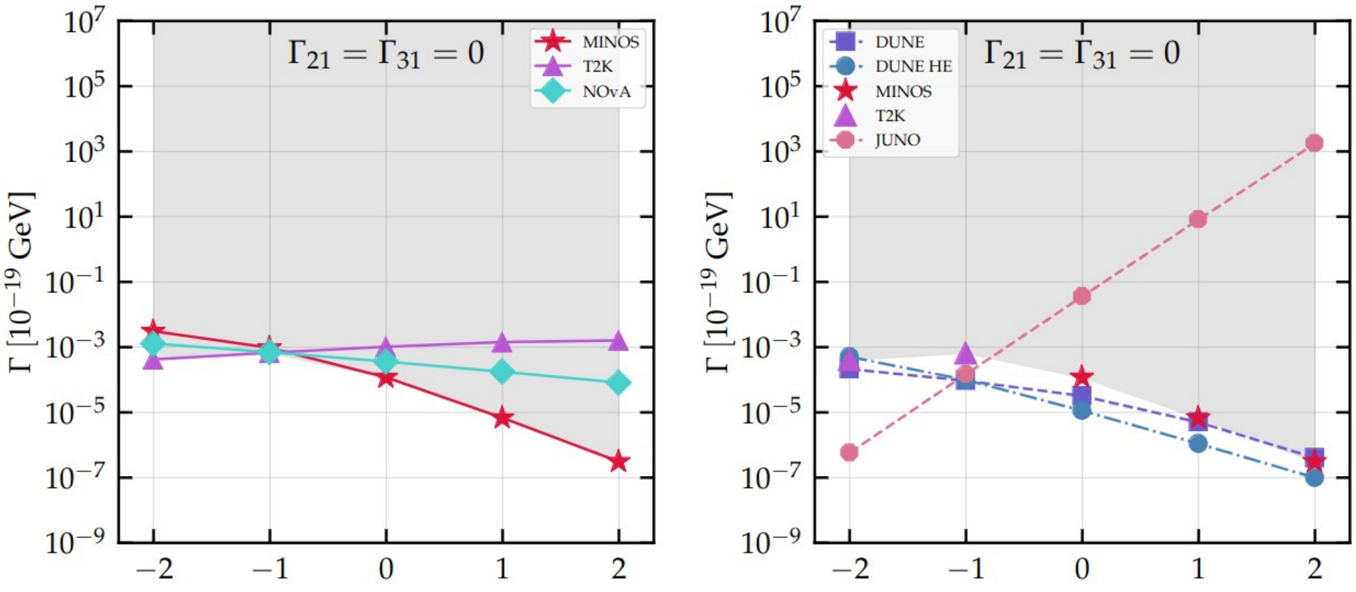
De Romeri, Giunti, Ternes, Stuttard, 2306.14699



Current reactor experiments are not capable of bounding model G

Results, Model G

De Romeri, Giunti, Ternes, Stuttard, 2306.14699

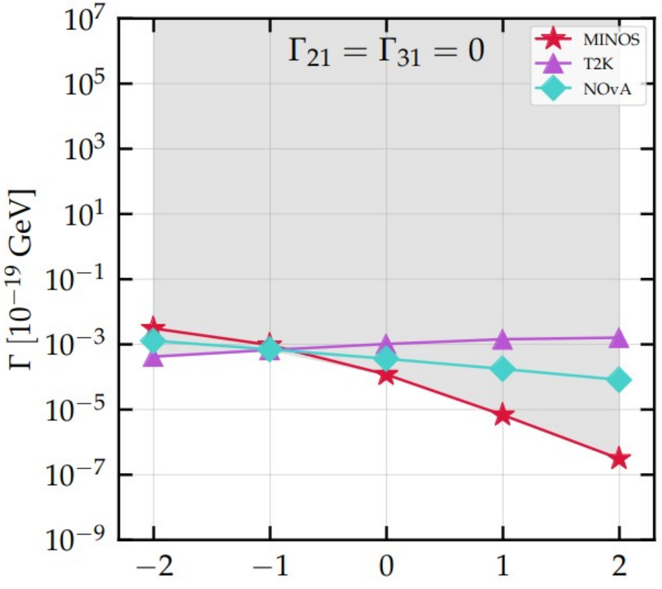


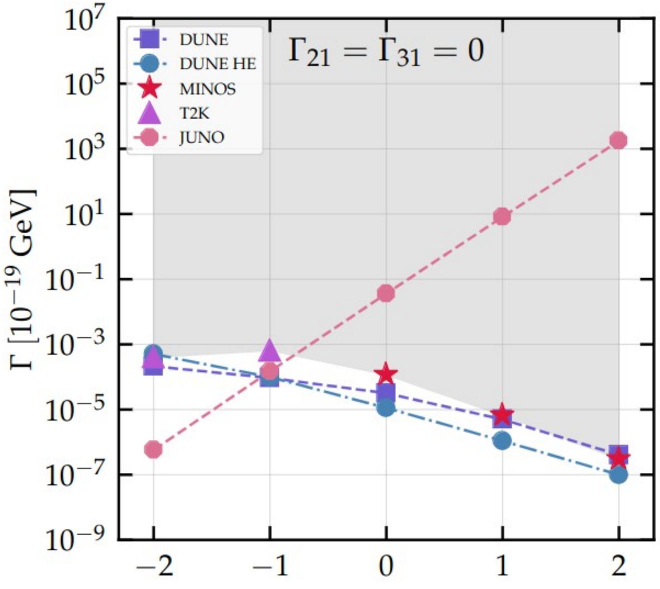
Current reactor experiments are not capable of bounding model G

$$P_{ee}^{\mathrm{KL}} = c_{13}^4 \left(1 - \frac{1}{2}\sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)\right) + s_{13}^4$$

Results, Model G

De Romeri, Giunti, Ternes, Stuttard, 2306.14699





Current reactor experiments are not capable of bounding model G

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}] - P_{\odot}$$

Results

Decoherence Model	$n = -2$	$n = -1$	$n = 0$	$n = +1$	$n = +2$
A: $\Gamma_{21} = \Gamma_{31} = \Gamma_{32}$	7.8×10^{-27} (KL)	1.8×10^{-24} (KL)	5.1×10^{-24} (M)	3.0×10^{-25} (M)	1.3×10^{-26} (M)
B: $\Gamma_{21} = \Gamma_{31}, \Gamma_{32} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	2.4×10^{-23} (N)	2.3×10^{-24} (M)	1.0×10^{-25} (M)
C: $\Gamma_{21} = \Gamma_{32}, \Gamma_{31} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	9.4×10^{-24} (M)	5.7×10^{-25} (M)	2.5×10^{-26} (M)
D: $\Gamma_{31} = \Gamma_{32}, \Gamma_{21} = 0$	6.9×10^{-25} (R)	2.1×10^{-23} (T2K)	5.6×10^{-24} (M)	3.3×10^{-25} (M)	1.5×10^{-26} (M)
E: $\Gamma_{21}, \Gamma_{31} = \Gamma_{32} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	3.2×10^{-23} (M)	2.2×10^{-24} (M)	1.0×10^{-25} (M)
F: $\Gamma_{31}, \Gamma_{21} = \Gamma_{32} = 0$	1.0×10^{-24} (R)	1.9×10^{-23} (T2K)	2.3×10^{-23} (N)	2.2×10^{-24} (M)	1.0×10^{-25} (M)
G: $\Gamma_{32}, \Gamma_{21} = \Gamma_{31} = 0$	4.0×10^{-23} (T2K)	6.5×10^{-23} (T2K)	1.1×10^{-23} (M)	6.6×10^{-25} (M)	3.0×10^{-26} (M)

TABLE III: Summary of results: each column shows the most constraining upper limit on Γ_{ij}, in GeV, for each model (A to G) and value of n. We also clarify, within parenthesis, which experiment sets the bound (KL = KamLAND, R = RENO, M = MINOS/MINOS+, N = NOvA).

The sensitivity for most of the cases is dominated by KamLAND and MINOS/MINOS+

De Romeri, Giunti, Ternes, Stuttard, 2306.14699

Results

We update previous analyses of decoherence adding new data and new decoherence models:

KamLAND: Balieiro Gomes, et al, 1603.04126, PRD 2017

MINOS and T2K: Gomes, et al, 2001.09250

NOvA: Coelho, et al, 1702.04738, PRL 2017

DUNE: Balieiro Gomes, et al, 1805.09818, PRD 2019

Our analysis puts the strongest bounds to date for $n<0$

For positive n very strong bounds are obtained from atmospheric data: Coloma, et al, 1803.04438, EPJC 2018

Conclusions

The Lindblad formalism is a very powerful tool to study neutrino quantum decoherence in a model-independent way

We provide analyses for many reactor and accelerator experiments using different decoherence parameters and energy dependencies

We obtain the strongest bounds to data for negative values of n (many orders of magnitude stronger than bounds from atmospheric experiments)

We showed that these bounds will be further improved by DUNE and JUNO

Conclusions

The Lindblad formalism provides an extremely rich phenomenology and more work is under way and has already been performed

Papers by
Benatti, Floreanini,
Fogli, Lisi, et al
Anchordoqui, et al
Farzan, Schwetz, Smirnov,
Oliveira, Guzzo, Balieiro Gomes, de Holanda,
Coelho, et al
Gago, et al,
Buoninfante, Capolupo, Giampaolo, Lambiase,
Gomes, Peres,
Barenboim, Mavromatos

Thanks!