Searching for new physics with neutrino experiments

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Why do we study neutrinos?

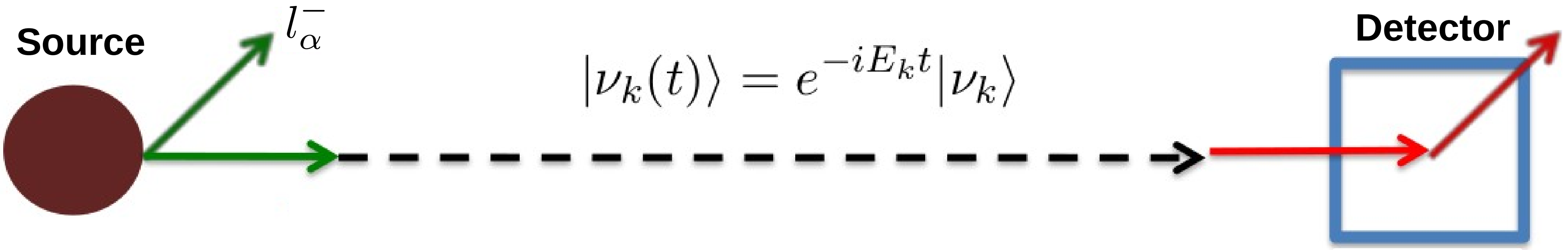
Due to the small interaction rate neutrinos can be used to study the interior of the Sun or also Supernova explosions

Neutrinos play a role in the evolution of the universe, in the formation of large scale structures, big bang nucleosynthesis, etc.

Neutrinos might help (sort of) to understand the matter-antimatter asymmetry of the Universe

Neutrinos are our only clear hint for physics beyond the standard model! Note that there is no particle detection of dark matter so far :(

Neutrino oscillations



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

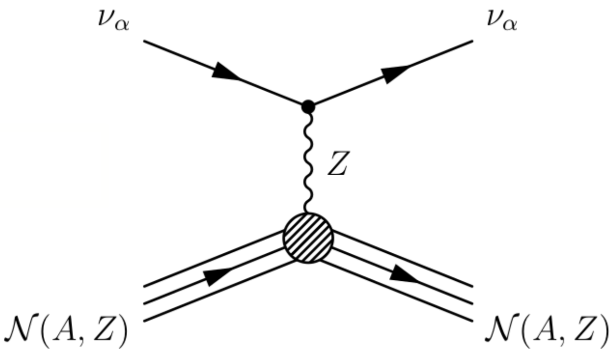
$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle$$

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

$$P(\alpha\to\beta;E,L) = \sum_{k,j} U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}e^{i\frac{\Delta m^2_{kj}}{2E}L}$$

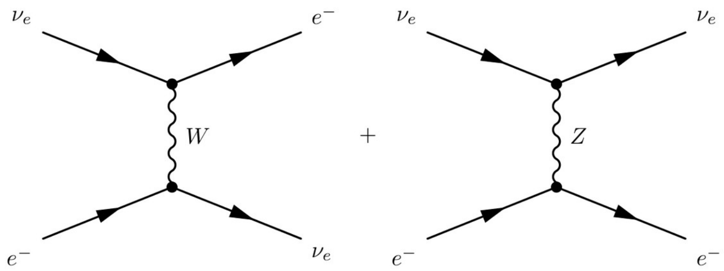
(Two selected) detection channels

Coherent elastic neutrino nucleus scattering



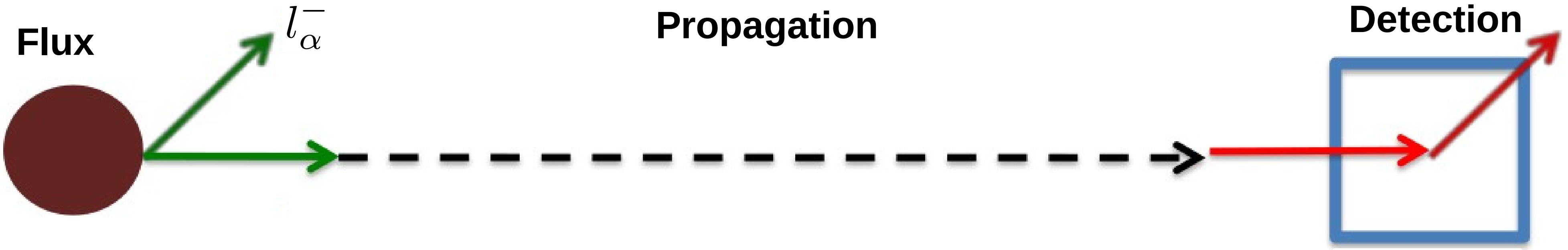
$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\rm nr}}(E,T_{\rm nr}) = \frac{G_{\rm F}^2 M}{\pi}\left(1-\frac{MT_{\rm nr}}{2E^2}\right)(Q^V_{\ell,{\rm SM}})^2$$

Elastic neutrino electron scattering

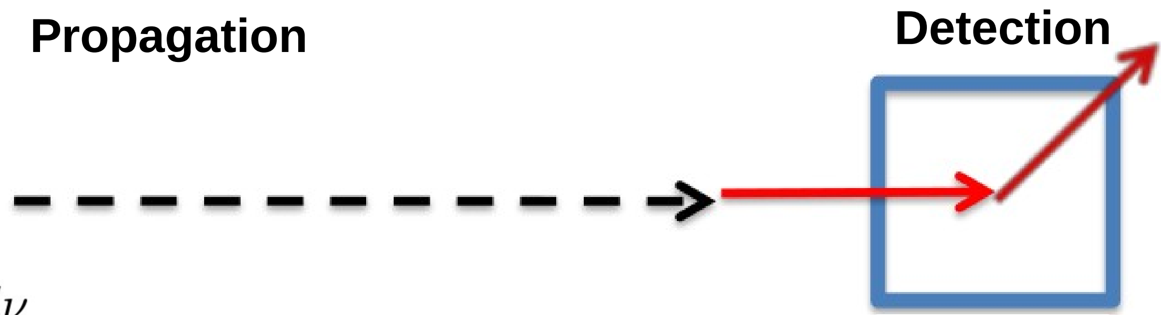


$$\frac{d\sigma^{\rm SM}_{\nu_\ell-{\rm Xe}}}{dT_{\rm e}}(E_\nu,T_{\rm e}) = Z^{\rm Xe}_{\rm eff}(T_e)\frac{G_{\rm F}^2 m_e}{2\pi}\Big[(g_V^{\nu_\ell}+g_A^{\nu_\ell})^2 + (g_V^{\nu_\ell}-g_A^{\nu_\ell})^2\left(1-\frac{T_e}{E_\nu}\right)^2 - ((g_V^{\nu_\ell})^2-(g_A^{\nu_\ell})^2)\frac{m_eT_e}{E_\nu^2}\Big]$$

A neutrino experiment



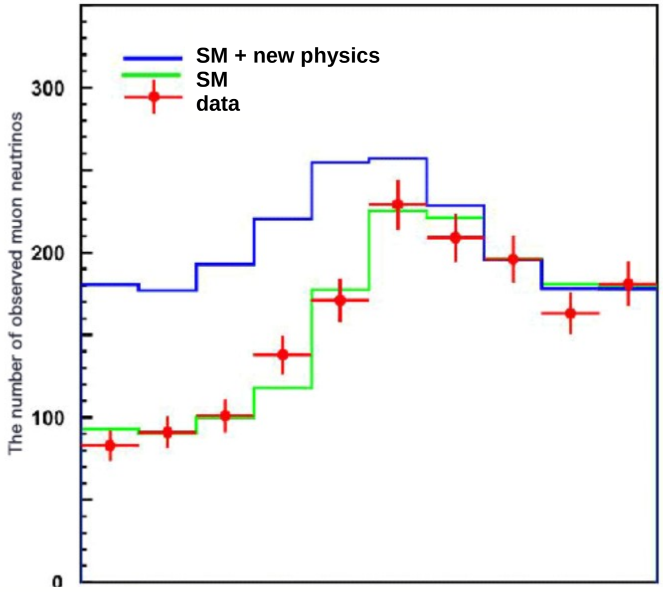
A neutrino experiment

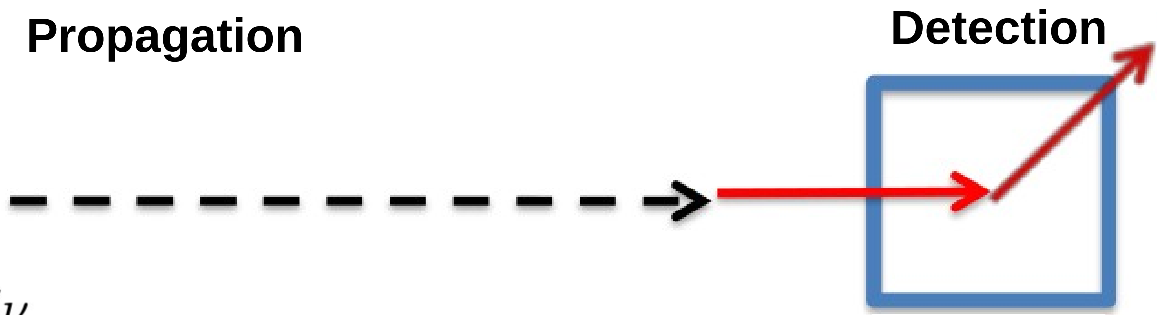


$$i\frac{d\nu}{dt} = \mathcal{H}\nu$$

$$\sigma(\nu\mathcal{X})$$

A neutrino experiment





$$i\frac{d\nu}{dt} = (\mathcal{H} + \mathcal{H}_{\rm NP})\nu$$

$$\sigma(\nu\mathcal{X}) = \sigma(\nu\mathcal{X})_{\rm SM} + \sigma(\nu\mathcal{X})_{\rm NP}$$

Possible scenarios

CPT violation

Altered dispersion relations

Quantum gravity effects

NSI

Neutrino decay

Lorentz violation

Neutrino wavepackets

active sterile transitions

Quasi-Dirac neutrinos

Light sterile neutrinos

New vector bosons

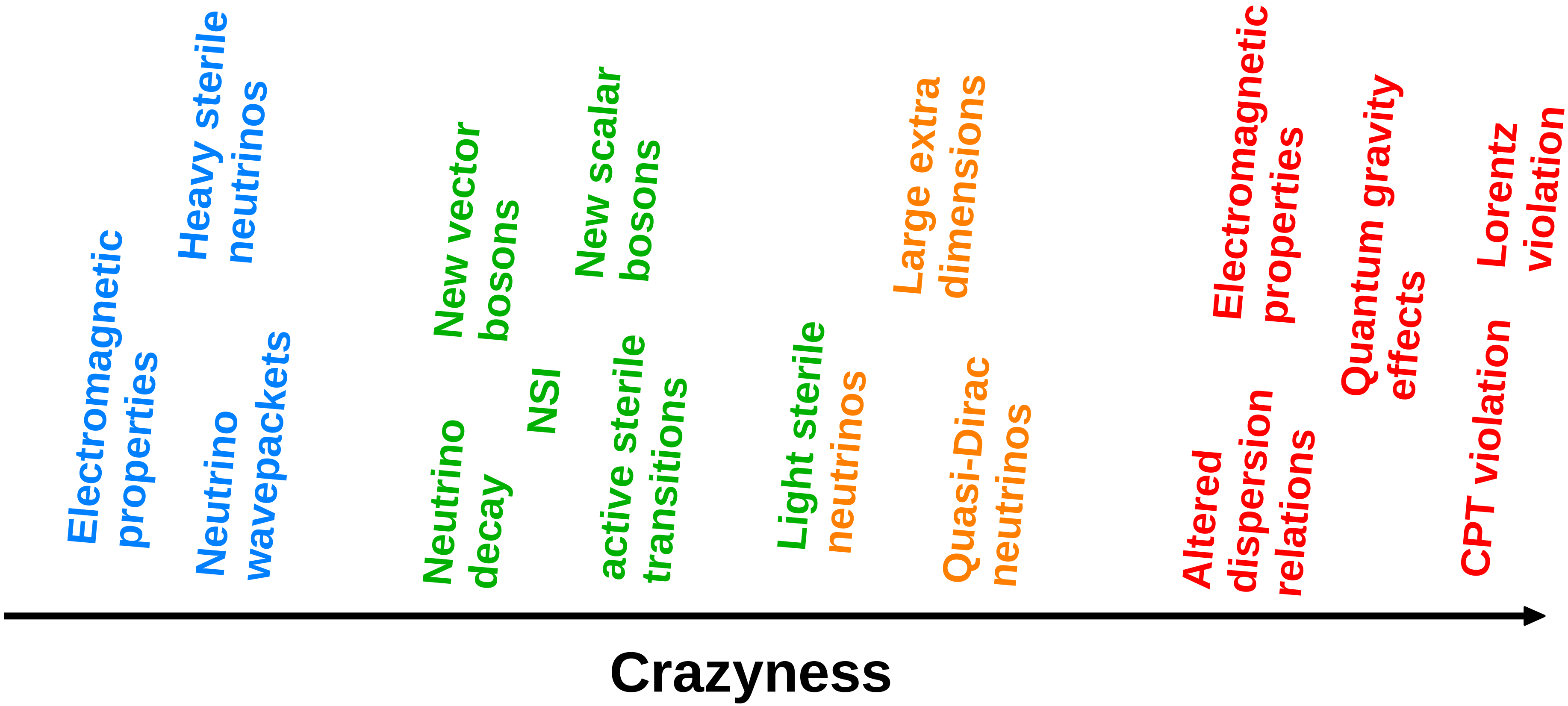
New scalar bosons

Large extra dimensions

Electromagnetic properties

Heavy sterile neutrinos

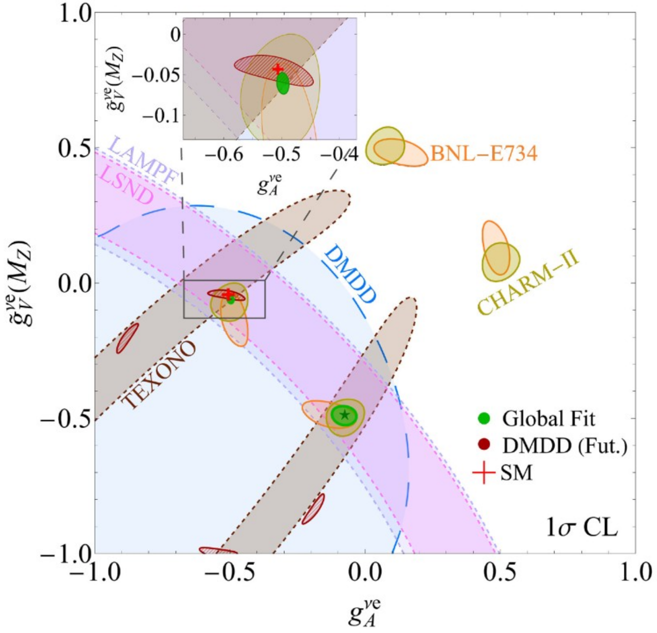
Possible scenarios



Examples

Standard model measurements

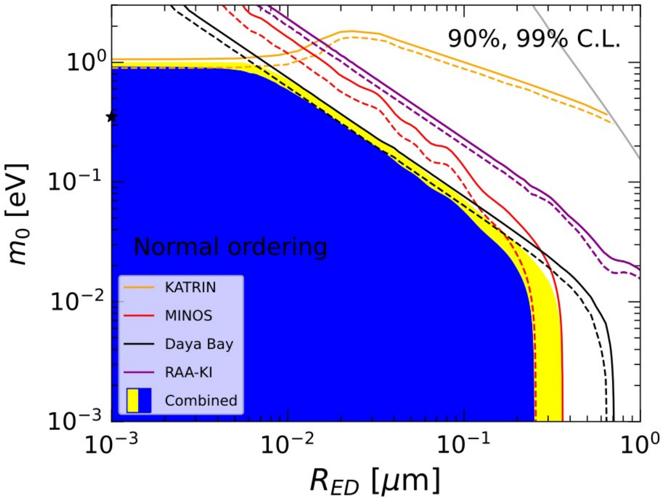
E.g.: Measuring the weak couplings with neutrino scattering



Ternes+, 2504.05272, PRL 2025

BSM searches with neutrino oscillations

E.g.: effects of Large Extra Dimensions on short baseline oscillations



Forero, Giunti, Ternes, Tyagi 2207.02790, PRD 2022

Astrophysical neutrinos

E.g.: Supernova neutrinos and Planck scale black hole interactions

TABLE I. Bounds on the decoherence parameter γ_0 in GeV at 90% CL obtained in this paper with the TI and the TD approach. For comparison we also show an order-of-magnitude estimate from the leading bounds from other experiments, Ref. [55] for $n < 0$, Ref. [50] for $n = 0$, and Ref. [54] for $n > 0$.

n	Previous bound	This work (TI)	This work (TD)
−2	$\mathcal{O}(10^{-27})$	3.1×10^{-41}	6.4×10^{-41}
−1	$\mathcal{O}(10^{-24})$	3.2×10^{-39}	5.5×10^{-39}
0	$\mathcal{O}(10^{-28})$	3.1×10^{-37}	5.0×10^{-37}
1	$\mathcal{O}(10^{-28})$	1.5×10^{-35}	1.8×10^{-35}
2	$\mathcal{O}(10^{-32})$	2.3×10^{-34}	3.2×10^{-34}

Ternes, Pagliaroli, Villante, 2503.04573, PRD 2025


Grazie!
electron-neutrino
muon neutrino
tau-neutrino

Three-neutrino oscillations

Neutrino mixing matrix

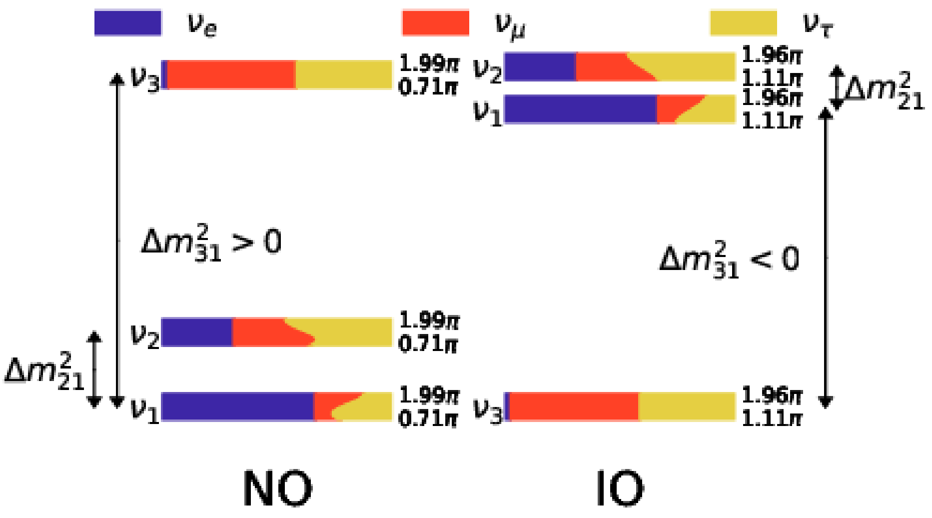
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Parameter	Main contribution from	Other contributions from
Δm^2_{21}	KamLAND	SOL
$\|\Delta m^2_{31}\|$	LBL+ATM+REAC	-
θ_{12}	SOL	KamLAND
θ_{23}	LBL+ATM	-
θ_{13}	REAC	(LBL+ATM) and (SOL+KamLAND)
δ	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

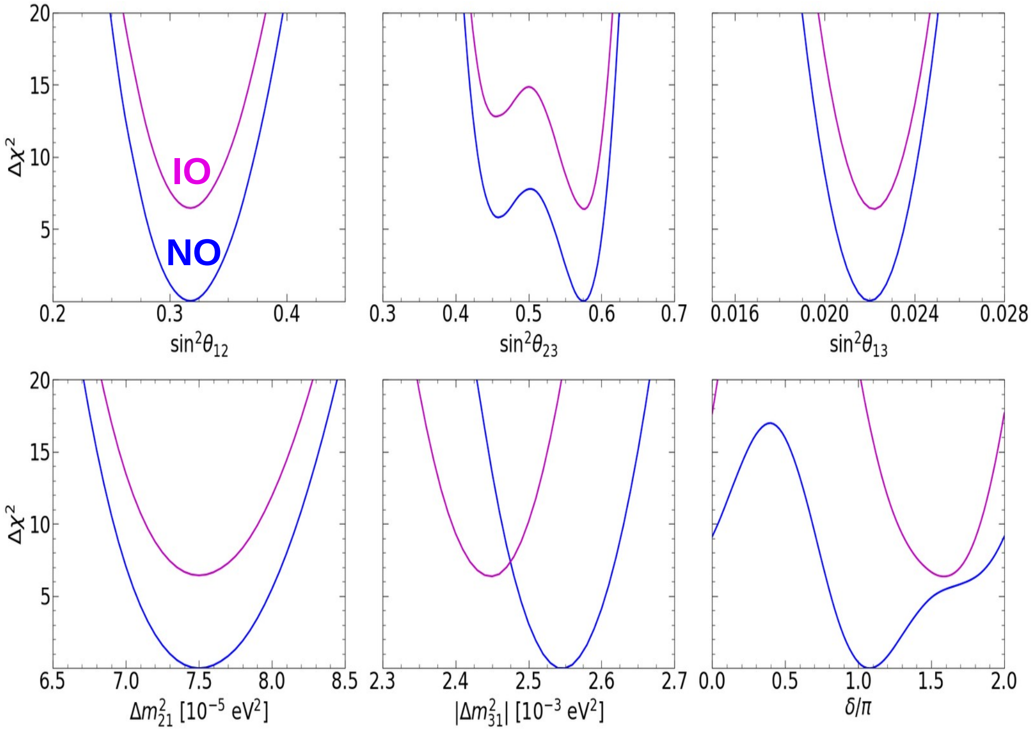
Common sensitivities from different types of experiments

Combination of data sets can enhance sensitivities to oscillation parameters

=> Perform a global fit to neutrino oscillation data!

Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



parameter	best fit ± 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
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (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