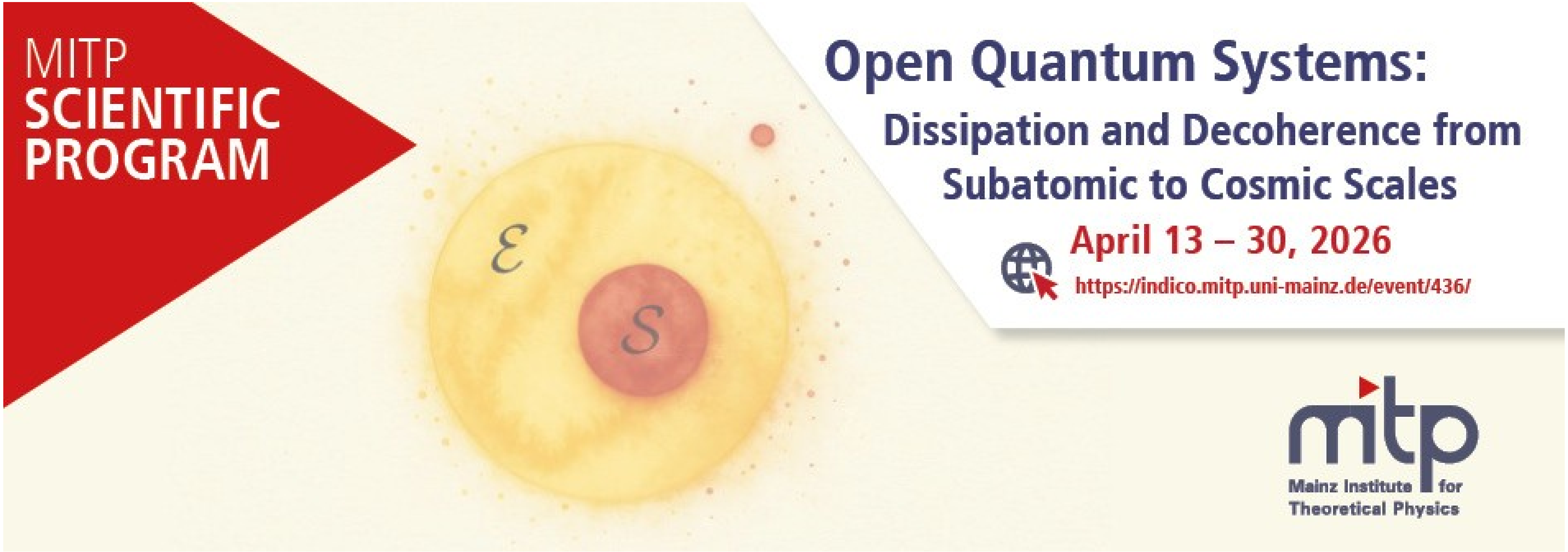
Decoherence in neutrino oscillations



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Outline

Status of standard 3-neutrino oscillations

Neutrino decoherence due to wave-packet separation

Neutrino decoherence due to an (unknown) environment

Neutrino oscillations

The standard formula is derived from projecting

$$|\nu(t,\vec{x})\rangle \;=\; \sum_i U^*_{\alpha i}\, e^{-ip_i x}|\nu_i^{\text{mass}}\rangle$$

onto the detected state

$$P(\nu_\alpha \to \nu_\beta; t, \vec{x}) \;=\; \left|\langle\nu_\beta|\nu(t,\vec{x})\rangle\right|^2$$

which will depend on the phase difference

$$\Delta\phi \;=\; \Delta E \cdot t - \Delta\vec{p}\cdot\vec{x}$$

Neutrino oscillations

and assuming either

$$\Delta\phi = \Delta E \cdot t - \Delta\vec{p}\cdot\vec{x}$$

Same momentum approach

$$E_i = \sqrt{\vec{p}^2 + m_i^2} \simeq p + \frac{m_i^2}{2p}$$

$$\Delta\phi = \Delta E \cdot t \simeq \frac{\Delta m^2}{2p} t \qquad L \simeq t$$

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

Neutrino oscillations

and assuming either

$$\Delta\phi = \cancel{\Delta E} \cdot t - \Delta\vec{p}\cdot\vec{x}$$

Same energy approach

$$\vec{x}||\vec{p} \quad p_i = \sqrt{E^2 - m_i^2} \simeq E - \frac{m_i^2}{2E}$$

$$\Delta\phi = -\Delta p \cdot L \simeq \frac{\Delta m^2}{2E} L$$

Same momentum approach

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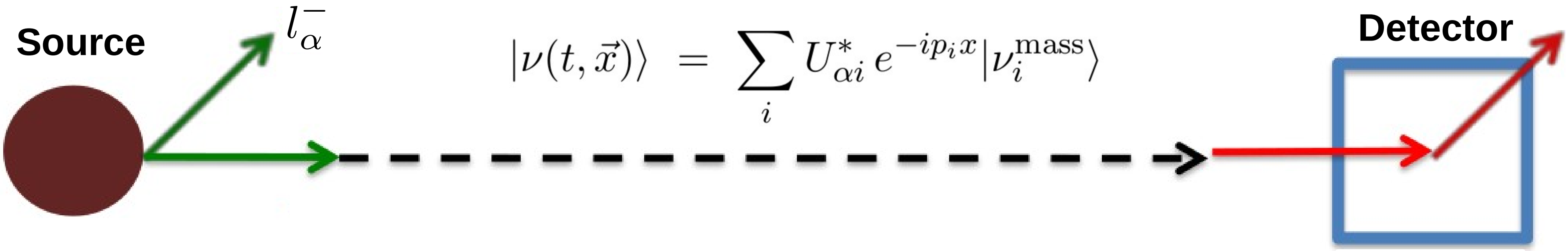
Neutrino oscillations



$$|\nu(t,\vec{x})\rangle \;=\; \sum_i U^*_{\alpha i}\, e^{-ip_i x} |\nu_i^{\text{mass}}\rangle$$

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

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\, \exp\left(-i\,\frac{\Delta m^2_{kj} L}{2E}\right)$$

Three-neutrino oscillations

Neutrino mixing matrix

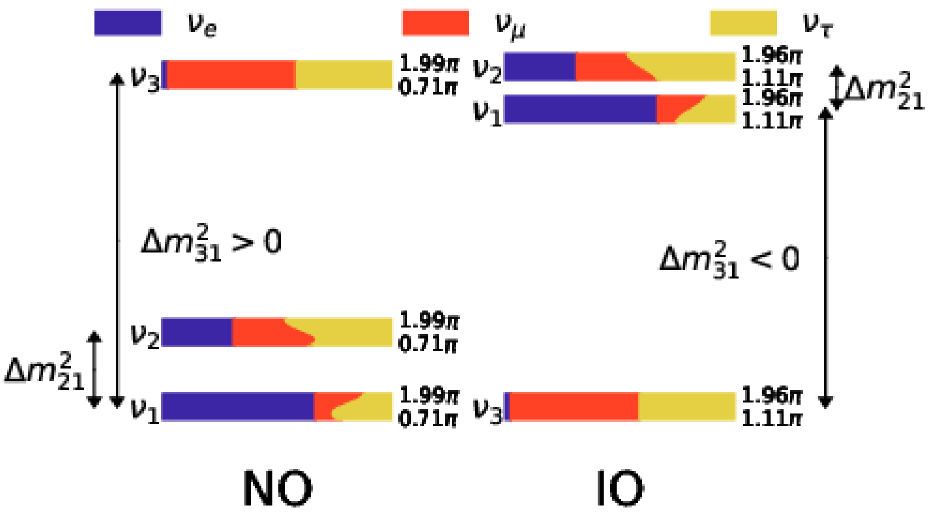
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

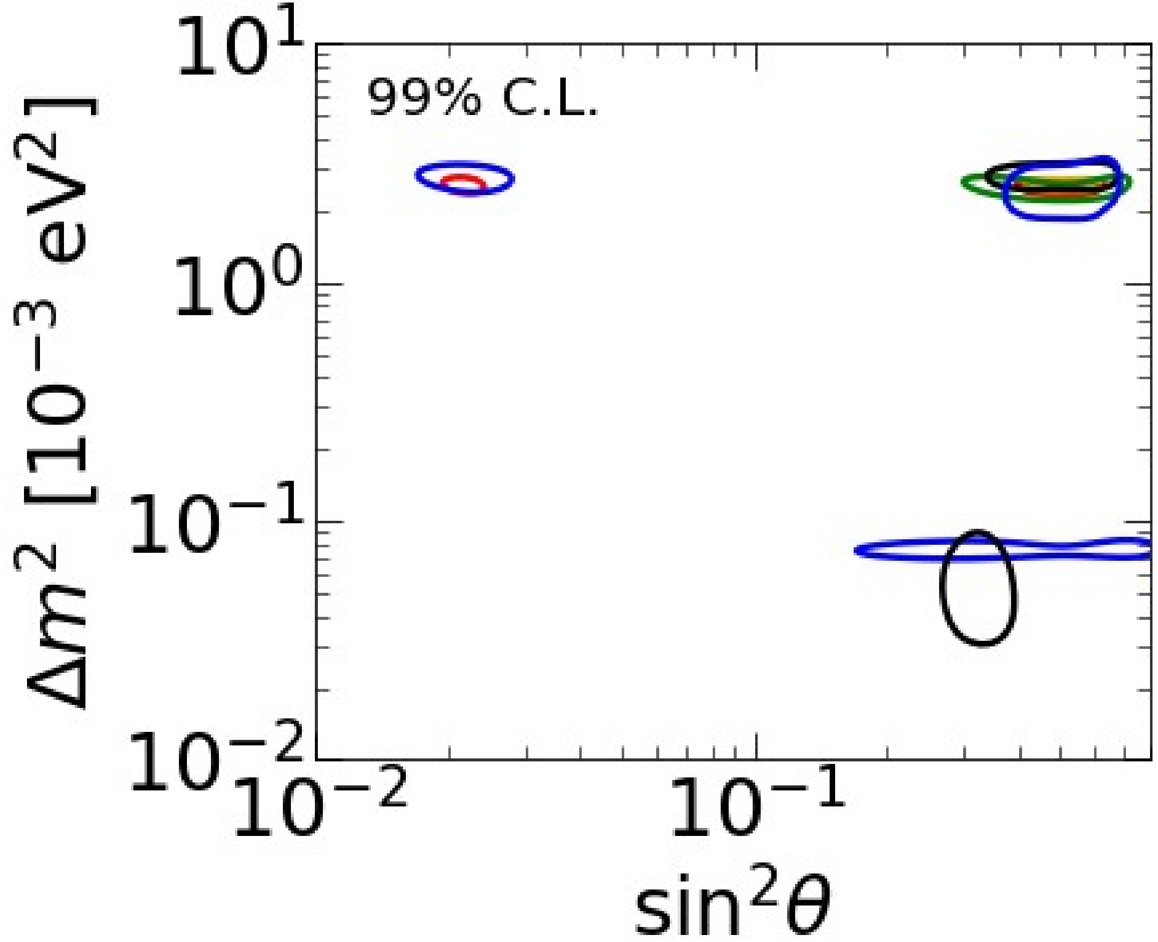
Parameter	Main contribution from	Other contributions from
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
θ_{12}	SOL	KamLAND
θ_{23}	LBL+ATM	-
θ_{13}	REAC	(LBL+ATM) and (SOL+KamLAND)
δ	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

Common sensitivities from different types of experiments

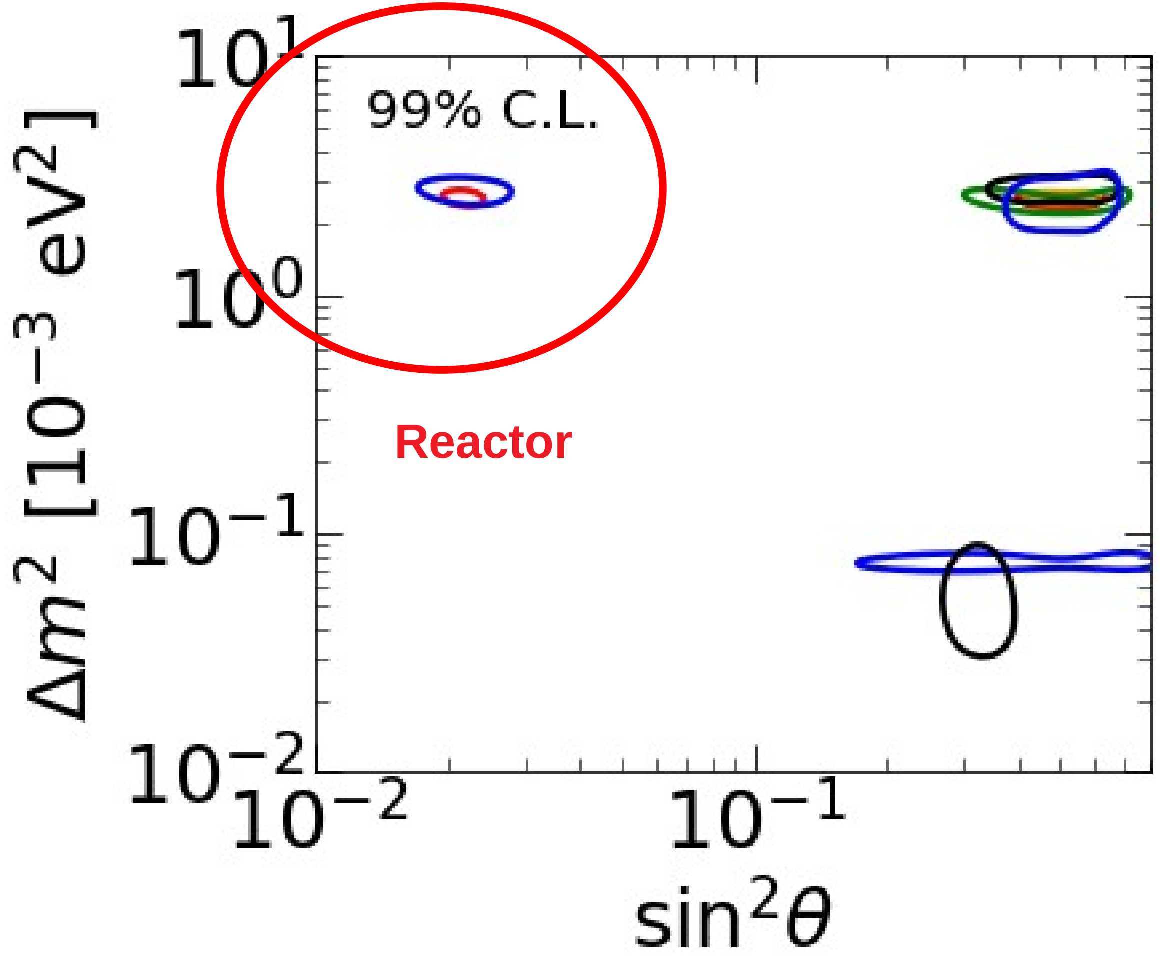
Combination of data sets can enhance sensitivities to oscillation parameters

=> Perform a global fit to neutrino oscillation data!

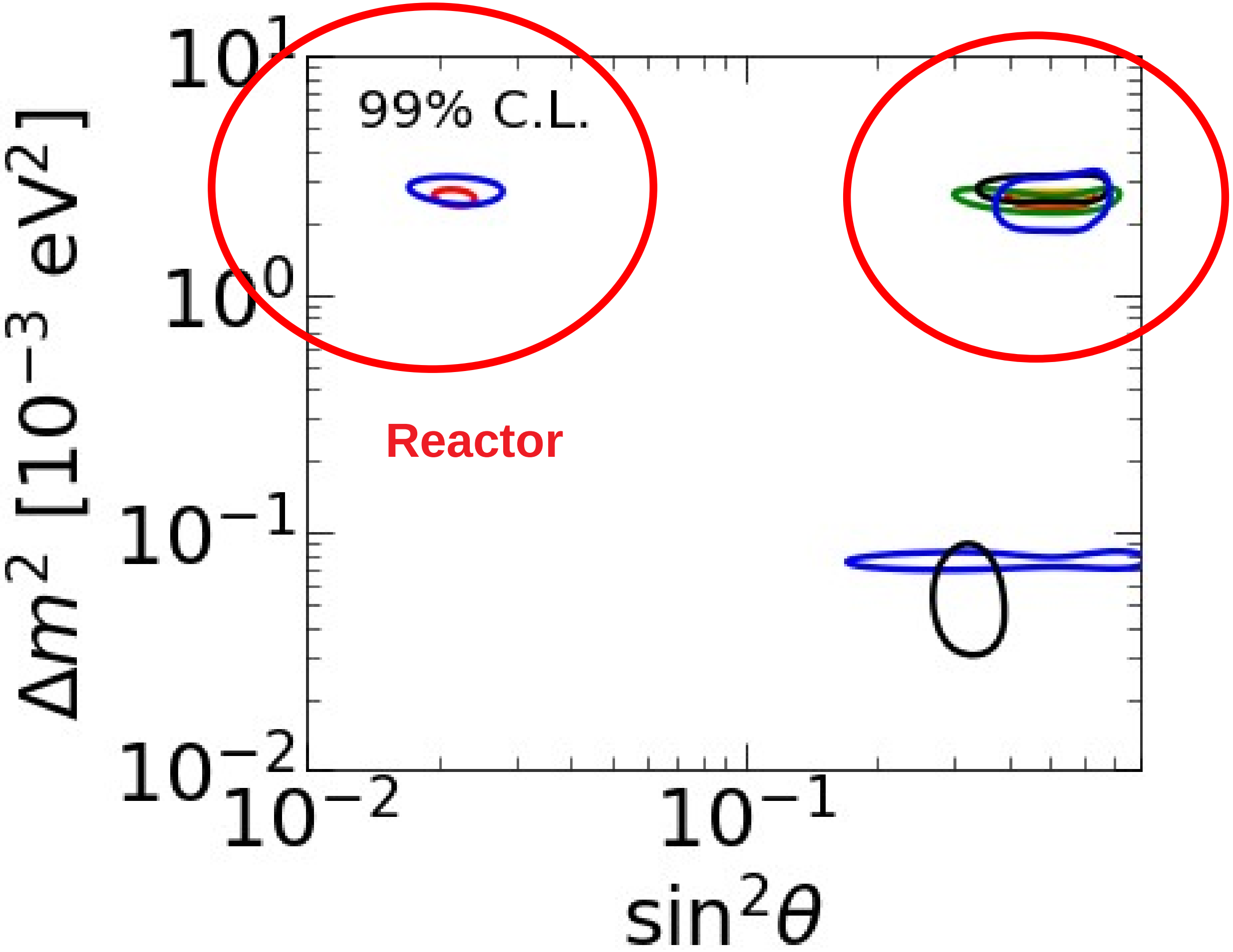
Three-neutrino oscillations



Three-neutrino oscillations

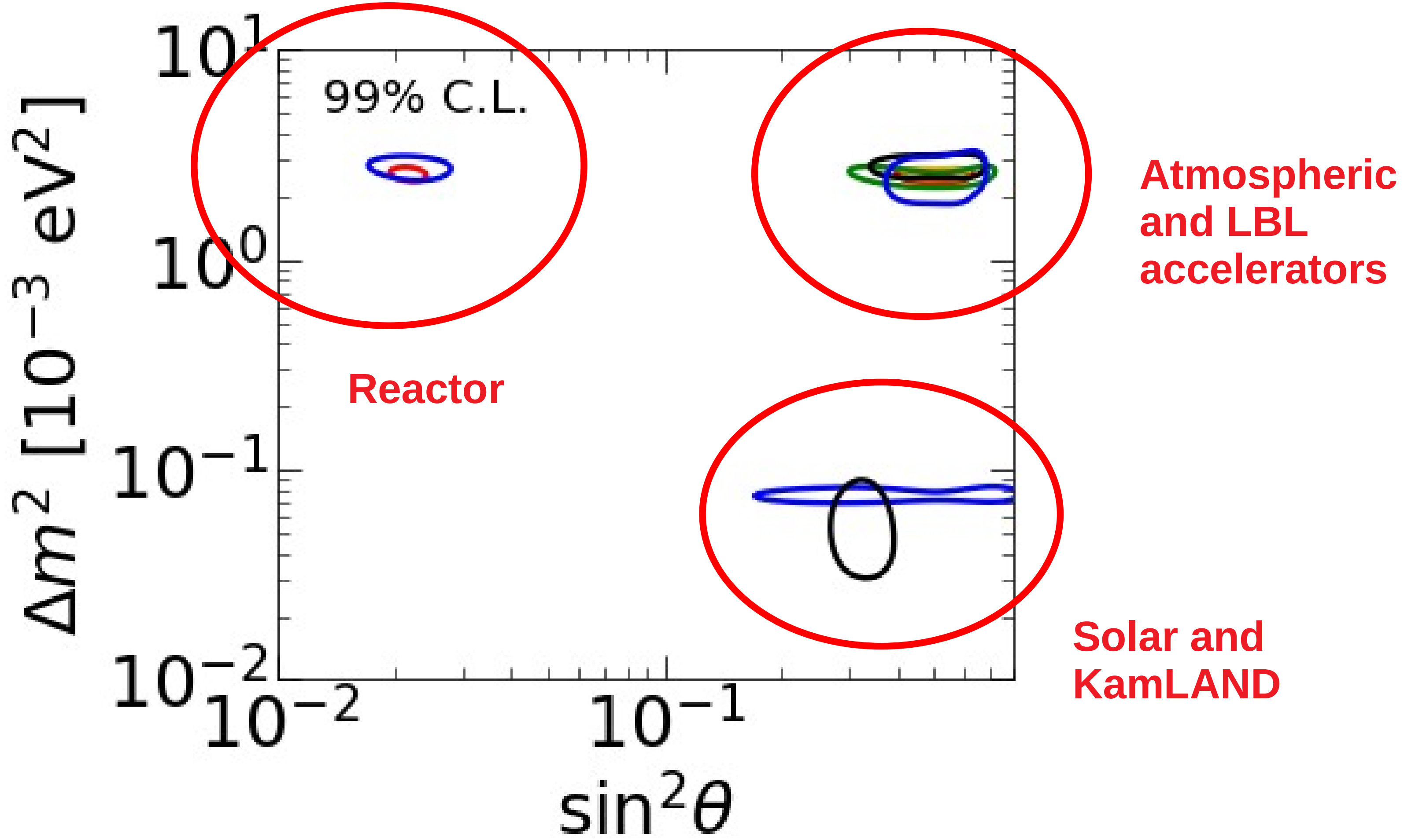


Three-neutrino oscillations

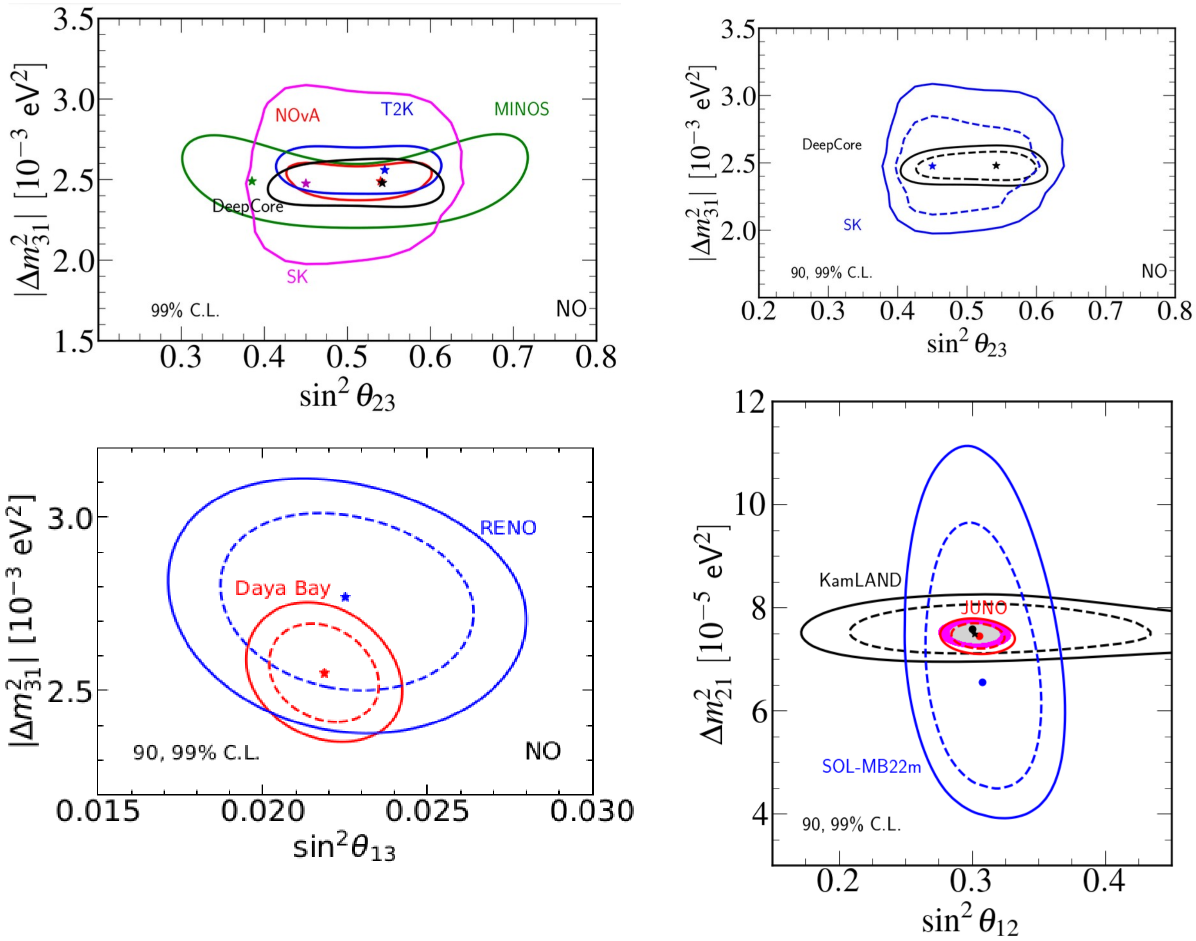


Atmospheric and LBL accelerators

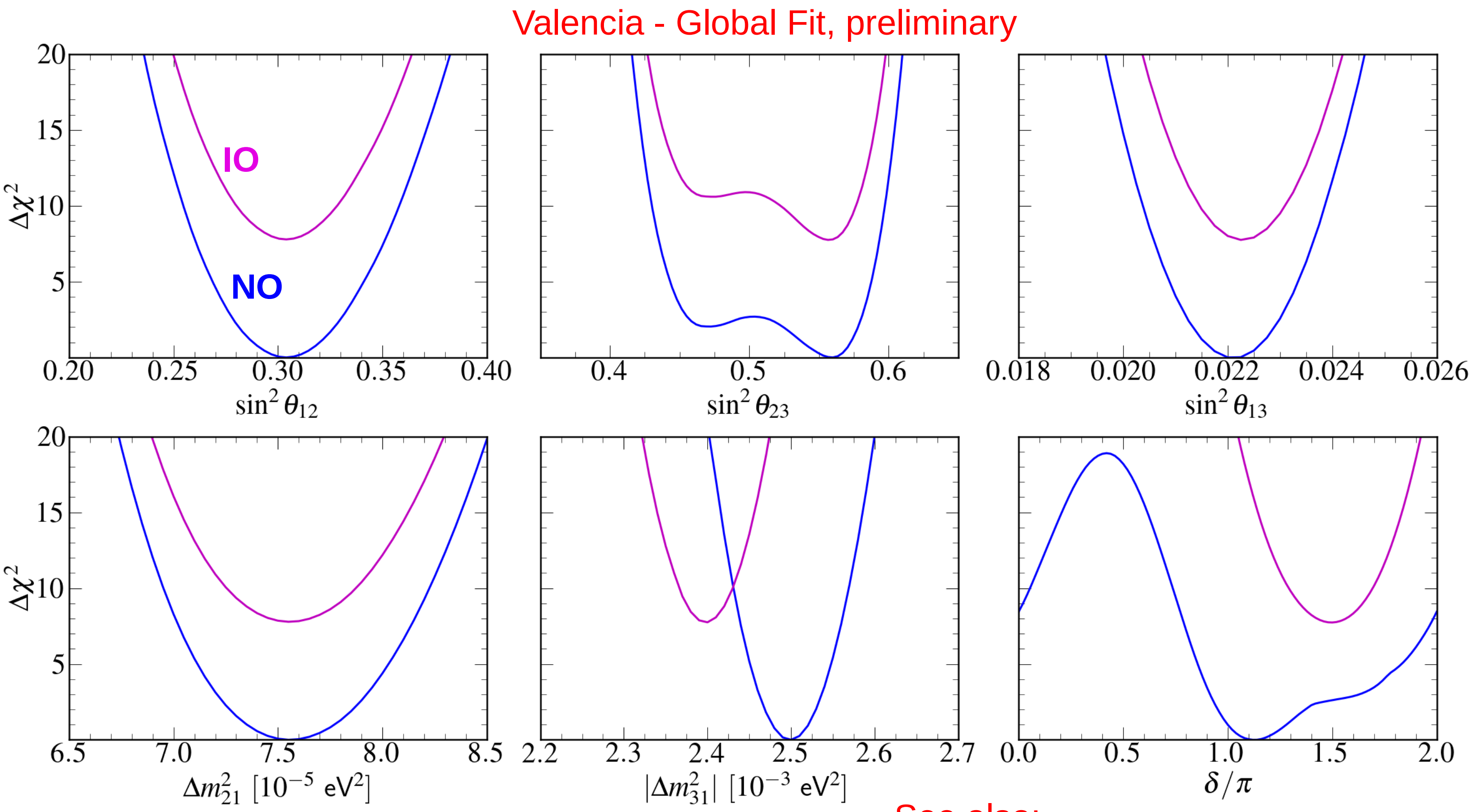
Three-neutrino oscillations



Three-neutrino oscillations



Three-neutrino oscillations



See also:
Bari - 2107.00532, PRD 2021

See also:
NuFit - 2111.03086, Universe 2021

Decoherence due to wave-packet separation

Back to neutrino oscillations

$$\Delta\phi = \Delta E \cdot t - \Delta\vec{p} \cdot \vec{x}$$

Same energy approach

$$\vec{x} || \vec{p} \quad p_i = \sqrt{E^2 - m_i^2} \simeq E - \frac{m_i^2}{2E}$$

$$\Delta\phi = -\Delta p \cdot L \simeq \frac{\Delta m^2}{2E} L$$

Same momentum approach

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Back to neutrino oscillations

But take as an example pion-decay $\pi \longrightarrow \mu\nu$

Energy-momentum conservation leads to

$$E_i^2 = \frac{m_\pi^2}{4}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2 + \frac{m_i^2}{2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right) + \frac{m_i^4}{4m_\pi^2}\,,$$

$$p_i^2 = \frac{m_\pi^2}{4}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2 - \frac{m_i^2}{2}\left(1+\frac{m_\mu^2}{m_\pi^2}\right) + \frac{m_i^4}{4m_\pi^2}\,.$$

and therefore

$$E_i \simeq E + \xi\frac{m_i^2}{2E}\,, \qquad p_i \simeq E - (1-\xi)\frac{m_i^2}{2p}\,,$$

$$E \simeq p \equiv \frac{m_\pi}{2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right) \simeq 30\ \mathrm{MeV}\,, \qquad \xi \equiv \frac{1}{2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right) \approx 0.2.$$

Akhmedov, 1901.05232

Back to neutrino oscillations

$$\Delta\phi = \Delta E \cdot t - \Delta\vec{p}\cdot\vec{x}$$

Same energy approach

$$\vec{x}||\vec{p} \quad p_i = \sqrt{E^2 - m_i^2} \simeq E - \frac{m_i^2}{2E}$$

WRONG!

$$\Delta\phi = -\Delta p \cdot L \simeq \frac{\Delta m^2}{2E} L$$

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Neutrino oscillations with decoherence

Neutrinos do not propagate as plane waves, but as wave-packets

$$\Psi_i(\vec{x},\, t) = e^{i\vec{p}_0\vec{x} - iE_i(p_0)t} \; \frac{1}{(2\pi\sigma_x^2)^{3/4}} \exp\left\{ -\frac{(\vec{x} - \vec{v}_{gi}t)^2}{4\sigma_x^2} \right\}$$

and the states are given by

$$|\nu(\vec{x},t)\rangle \; = \; \sum_i U^*_{\alpha i} |\nu_i(\vec{x},t)\rangle \; = \; \sum_i U^*_{\alpha i}\, \Psi_i(\vec{x},t)|\nu_i\rangle$$

Giunti, Kim, Lee, PLB 1992
M. Beuthe, PRD 2002
Kayser, Kopp, arXiv:1005.4081
Akhmedov, 1901.05232

Neutrino oscillations with decoherence

When treating neutrinos as wave-packets, there is a correction due to the wave packet size

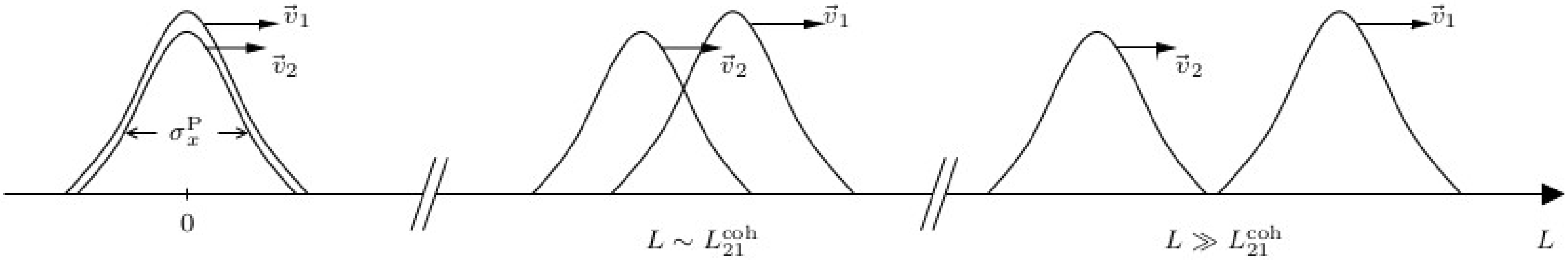
$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{k,j} U^*_{\alpha k} U_{\alpha j} U_{\beta k} U^*_{\beta j} \exp\left[-2\pi i \frac{L}{L^{\text{osc}}_{kj}} - \left(\frac{L}{L^{\text{coh}}_{kj}}\right)^2\right]$$

where the coherence length depends on the size of the wave-packet

$$L^{\text{coh}}_{jk} = \frac{4\sqrt{2}E^2}{|\Delta m^2_{jk}|}\sigma$$

Neutrino oscillations with decoherence

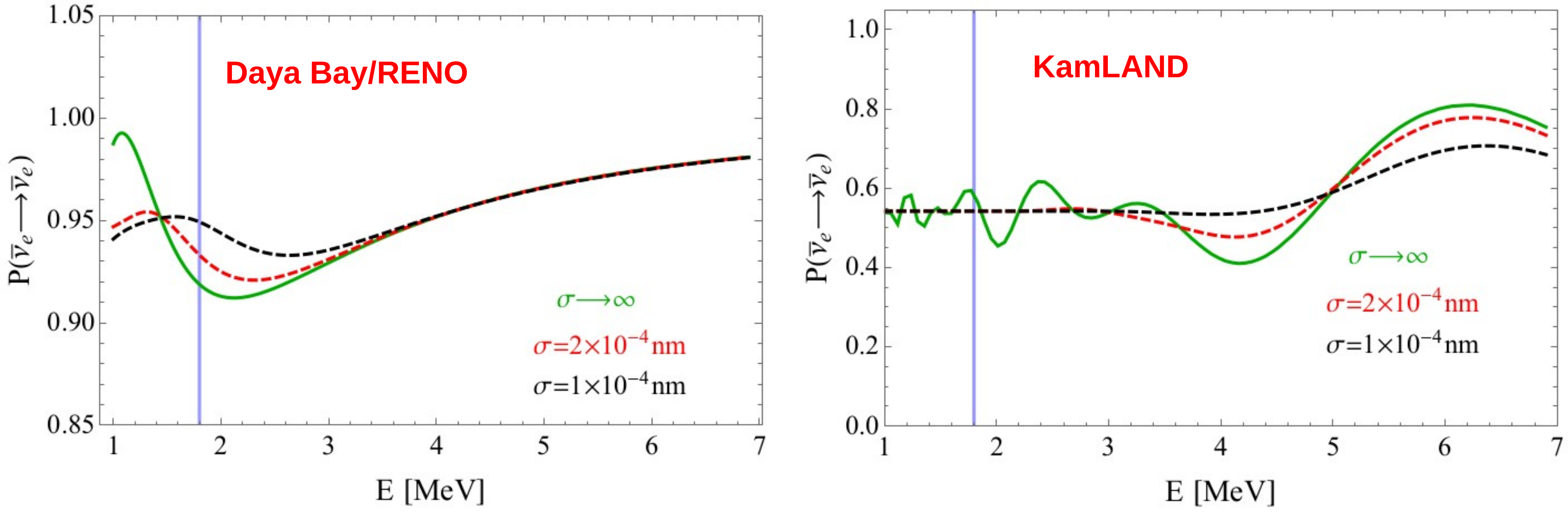
Neutrinos decohere due to different group velocities for different mass states



Giunti, Kim, Fundamentals of neutrino physics

Neutrino oscillations with decoherence

Oscillation probability for baselines relevant at reactor experiments



de Gouvêa, De Romeri, Ternes, 2104.05806, JHEP 2021

Neutrino oscillations with decoherence

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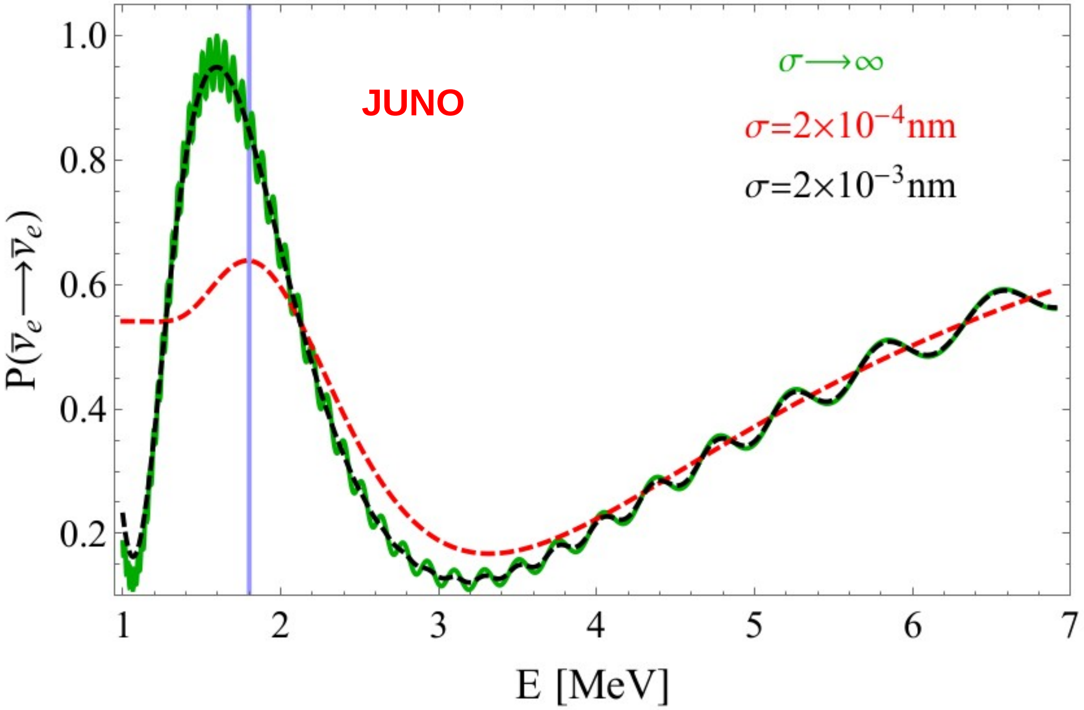
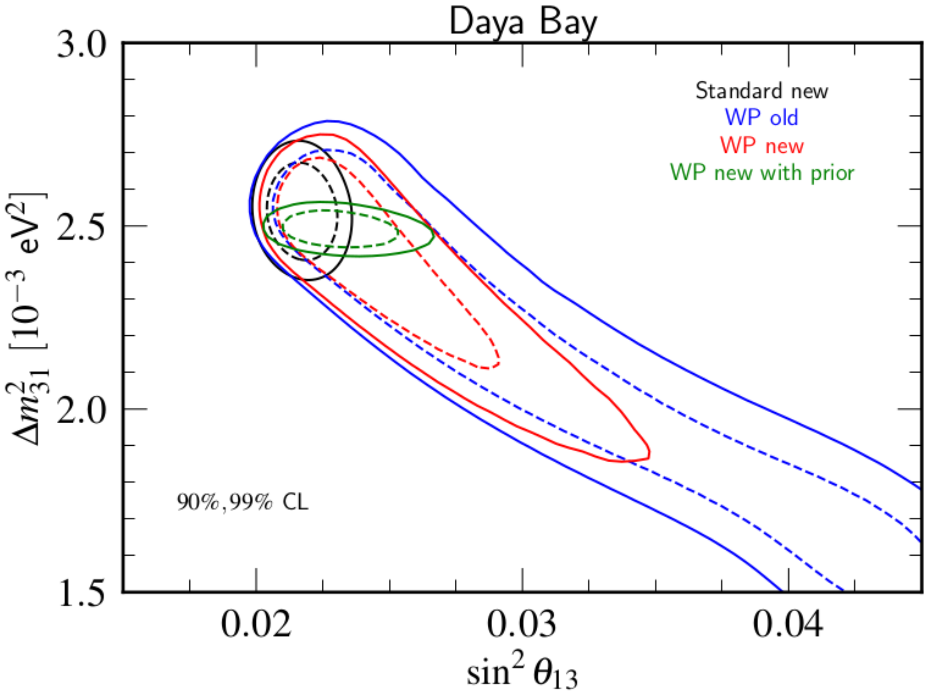
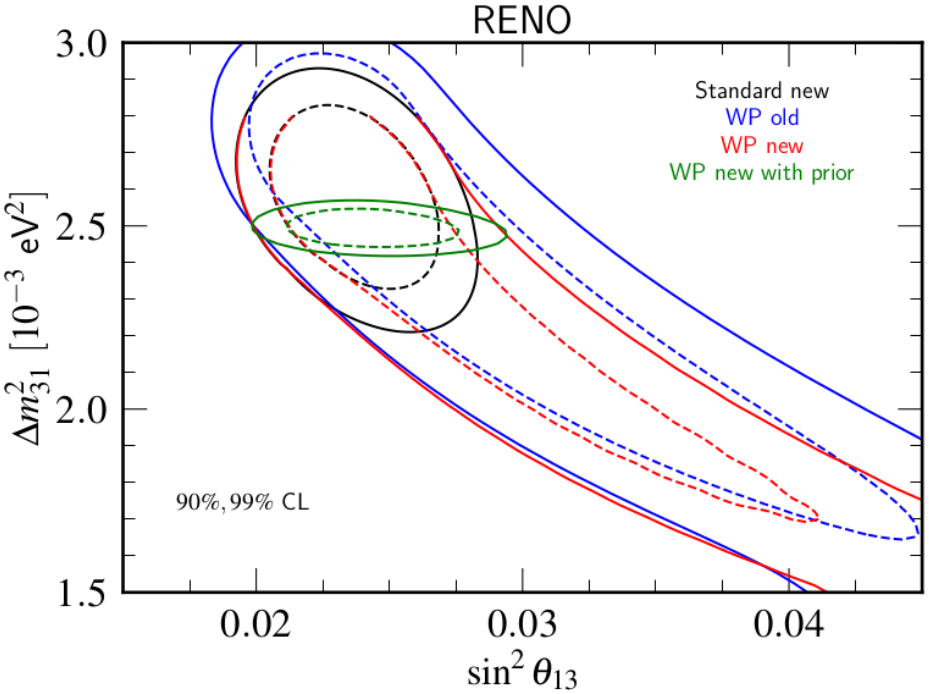


de Gouvêa, De Romeri, Ternes, 2005.03022, JHEP 2020

Bounding the wave-packet size

Include the wave-packet width as a parameter in analysis

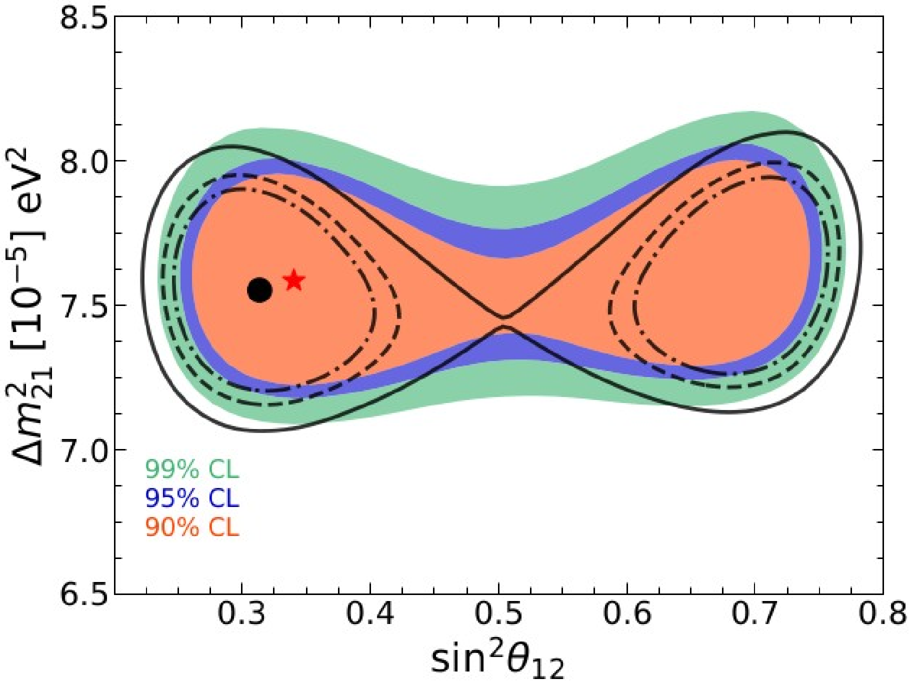


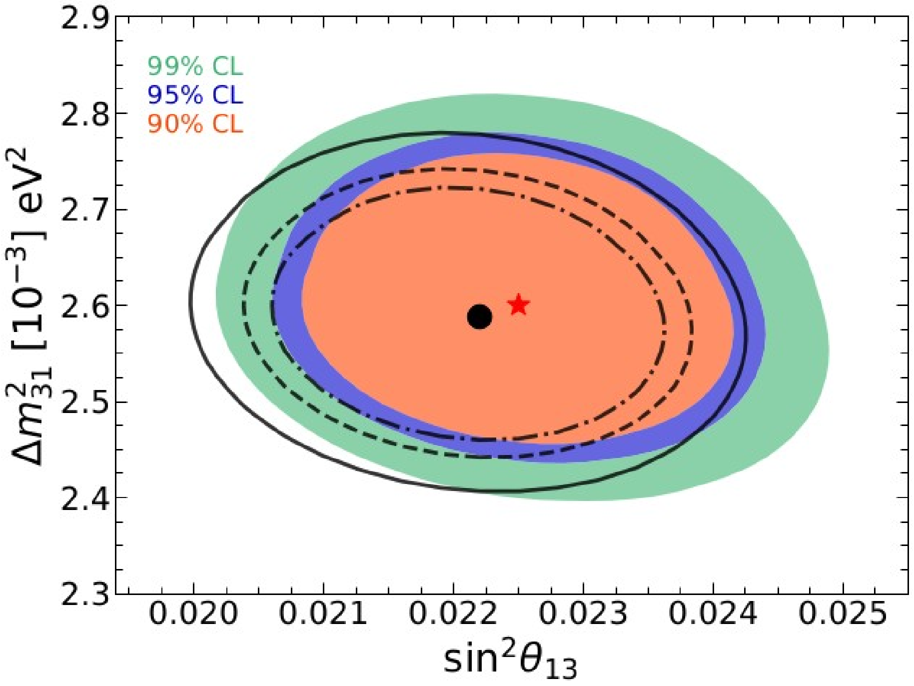


de Gouvêa, De Romeri, Ternes, 2410.01357, JHEP 2024
de Gouvêa, De Romeri, Ternes, 2005.03022, JHEP 2020

Bounding the wave-packet size

Degeneracies are broken when KamLAND is included in analysis





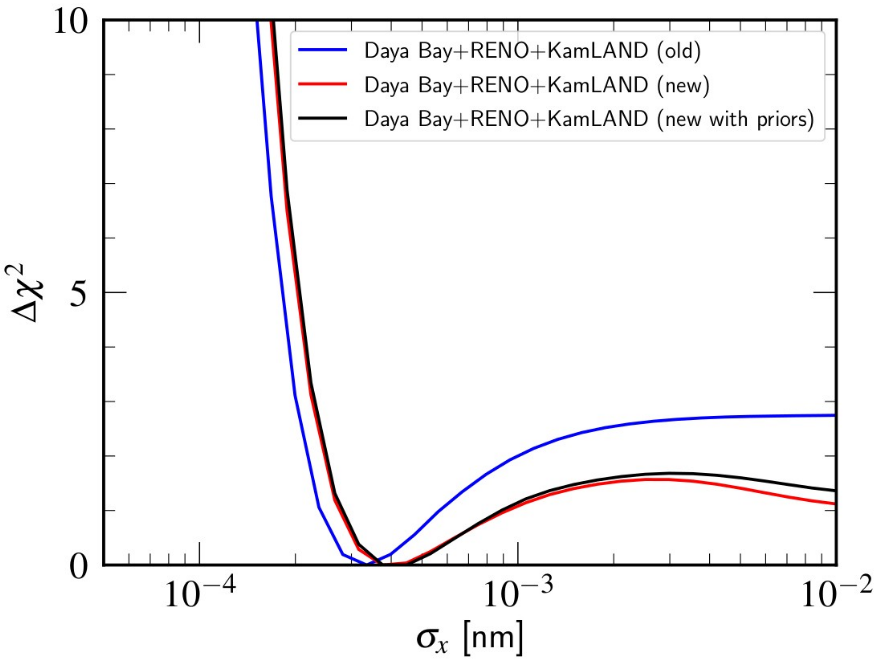
de Gouvêa, De Romeri, Ternes, 2104.05806, JHEP 2021

Bounding the wave-packet size

We can obtain the bounds

Experiment	90% CL	3σ
RENO [4]	1.4×10^{-4} nm	0.3×10^{-4} nm
Daya Bay [3]	0.9×10^{-4} nm	0.5×10^{-4} nm
RENO [4] (with Δm^2_{31} prior)	1.5×10^{-4} nm	1.0×10^{-4} nm
Daya Bay [3] (with Δm^2_{31} prior)	1.1×10^{-4} nm	0.8×10^{-4} nm
RENO [4] + Daya Bay [3]	1.5×10^{-4} nm	0.8×10^{-4} nm
RENO [4] + Daya Bay [3] (with Δm^2_{31} prior)	1.4×10^{-4} nm	1.0×10^{-4} nm
KamLAND [10]	2.2×10^{-4} nm	1.6×10^{-4} nm
Global	2.3×10^{-4} nm	1.7×10^{-4} nm
Global (with Δm^2_{31} and $\sin^2\theta_{12}$ priors)	2.4×10^{-4} nm	1.8×10^{-4} nm

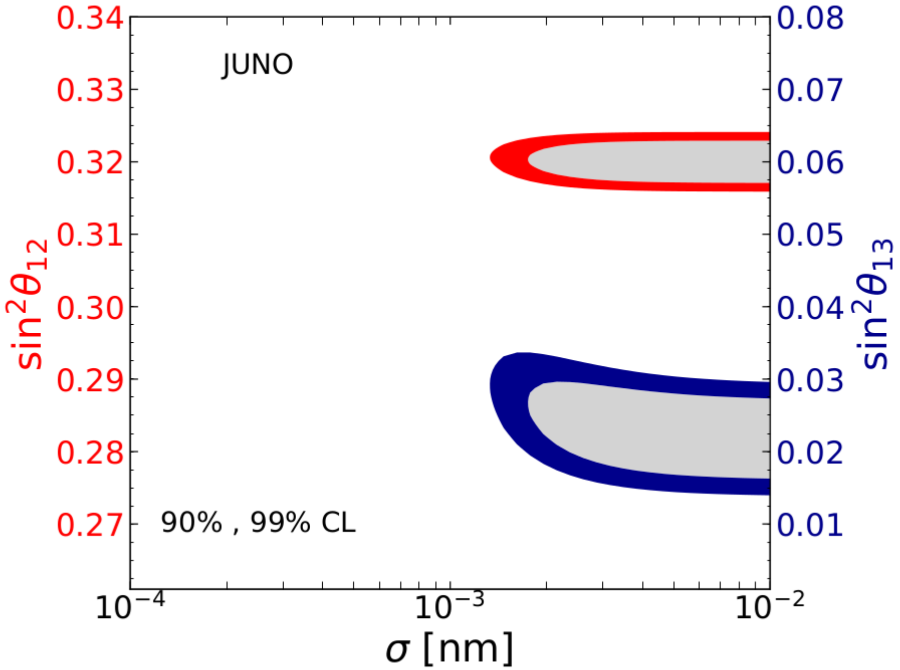
Table 1. Bounds on the size of the neutrino wave-packet width obtained from the analyses of reactor antineutrino data.

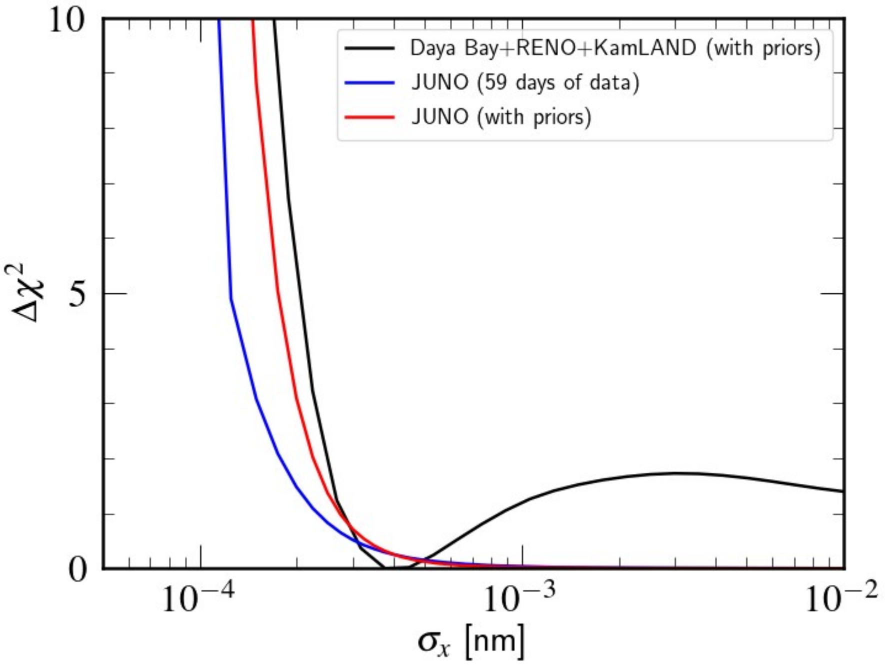


de Gouvêa, De Romeri, Ternes, 2410.01357, JHEP 2024

Bounding the wave-packet size

Current JUNO data sets a bound of similar strength, to be improved significantly in the future





de Gouvêa, De Romeri, Ternes, 2005.03022, JHEP 2020

Bounding the wave-packet size

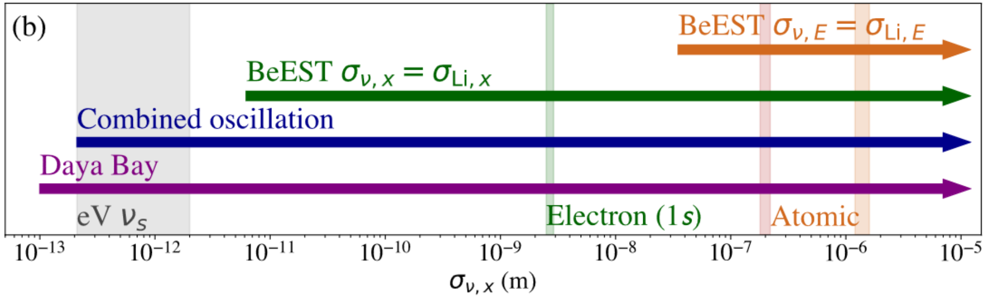
Bounds from BeEST

Indirect measurement

They study electron capture and not beta-decay

It is not the same wave-packet

Smolsky et al, 2404.03102, Nature 2024



Calculating the wave-packet size

Two estimations have been performed recently for the size of the wave-packet

Akhmedov and Smirnov find that

$$\sigma_x = (2 \times 10^{-5} - 1.4 \times 10^{-4})\ \text{cm}$$

outside the range of all current and future experiments

Jones, Marzec and Spitz find that

$$\sigma_{\nu,x} \sim 10\text{—}400\ \text{pm}$$

only slightly above the sensitivity reach of JUNO

Akhmedov, Smirnov, 2208.03736, JHEP 2022
Jones, Marzec, Spitz, 2211.00026, PRD 2023

Decoherence due to interactions with the environment

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

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
Gago et al, hep-ph/0208166

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Operators describing the coupling of the neutrinos subsystem with the environment

Benatti, Floreanini, hep-ph/0002221, JHEP 2000
Gago et al, hep-ph/0208166

Neutrino quantum decoherence

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Unlike in previous topics: We do not know what the interactions or the environment are!

Expand everything in terms of Gell-Mann matrices

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

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

Benatti, Floreanini, hep-ph/0002221, JHEP 2000
Gago et al, hep-ph/0208166

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 $S = -\text{Tr}(\rho_\nu \ln \rho_\nu)$ 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.

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

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

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

Neutrino oscillations with decoherence

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Exponents motivated by different models

- n = -2 gravitationally induced decoherence Domi et al, 2403.03106, JCAP 2024
- n = -1 decay like decoherence See e.g. Stankevich et al, 2411.19303, PRD 2025
- n = 0 energy-independent model Many papers on decoherence
- n > 0 Quantum-gravity motivations E.g. Ellis et al, hep-th/9207103, PLB 1992

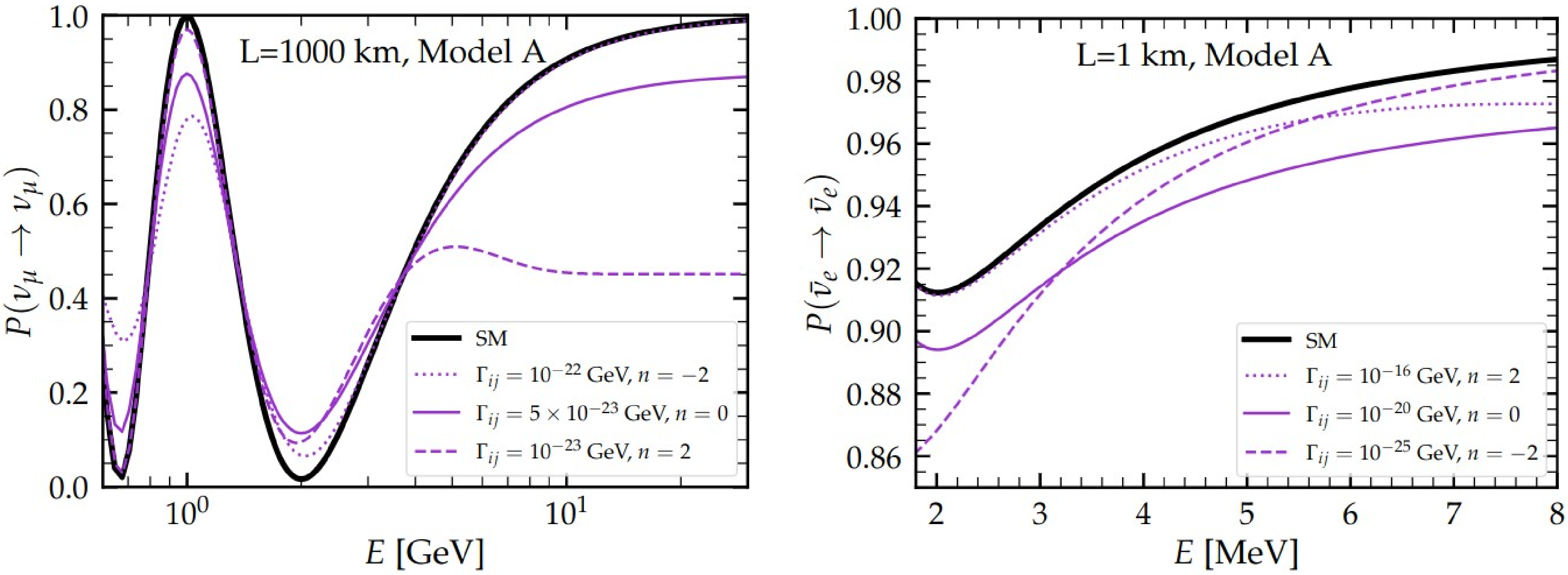
Neutrino oscillations with decoherence

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, JHEP 2023

Neutrino oscillations with decoherence



Negative (positive) exponents affect smaller (larger) energies

De Romeri, Giunti, Ternes, Stuttard, 2306.14699, JHEP 2023

Bounds on neutrino-loss

Allow for non-unitary evolution $\mathbf{D}_{\nu-\text{loss}} = \text{diag}(\Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma)$

Neutrinos are destroyed on their trajectory, e.g. due to interaction with quantum foam black holes Stuttard, Jensen, 2007.00068, PRD 2020

Set strong bounds on this scenario from SN1987A observation

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

Other interesting phenomenologies

Allowing certain non-diagonal elements to be non-zero can induce CPT violation in neutrino oscillations

$$\Delta P_{\not{CPT}} = P_{\nu_\alpha \to \nu_\alpha} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}$$

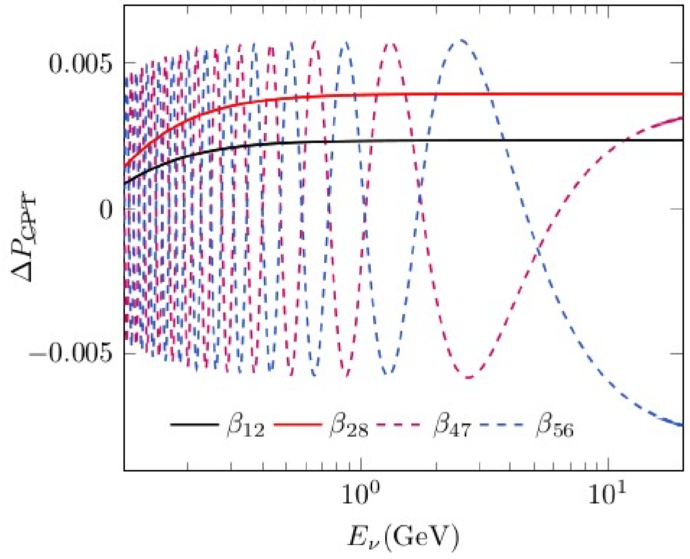


FIG. 1: $\Delta P_{\not{CPT}}$ versus E_ν, evaluated for $\Gamma = 10^{-23}$ GeV and $\delta_{CP} = 3\pi/2$. This is for $\beta_{28} = \Gamma/\sqrt{3}$, $\beta_{12} = \Gamma/3$, $\beta_{56} = \Gamma/\sqrt{3}$ and $\beta_{47} = \Gamma/\sqrt{3}$. The remaining parameters are given in Table III.

Carrasco, Diaz, Gago, 1811.04982, PRD 2019
Capolipo, Giampaolo, Lambiase, 1807.07823, PLB 2019

Conclusions

We use neutrino oscillations to test various manifestations of decoherence in neutrino oscillations

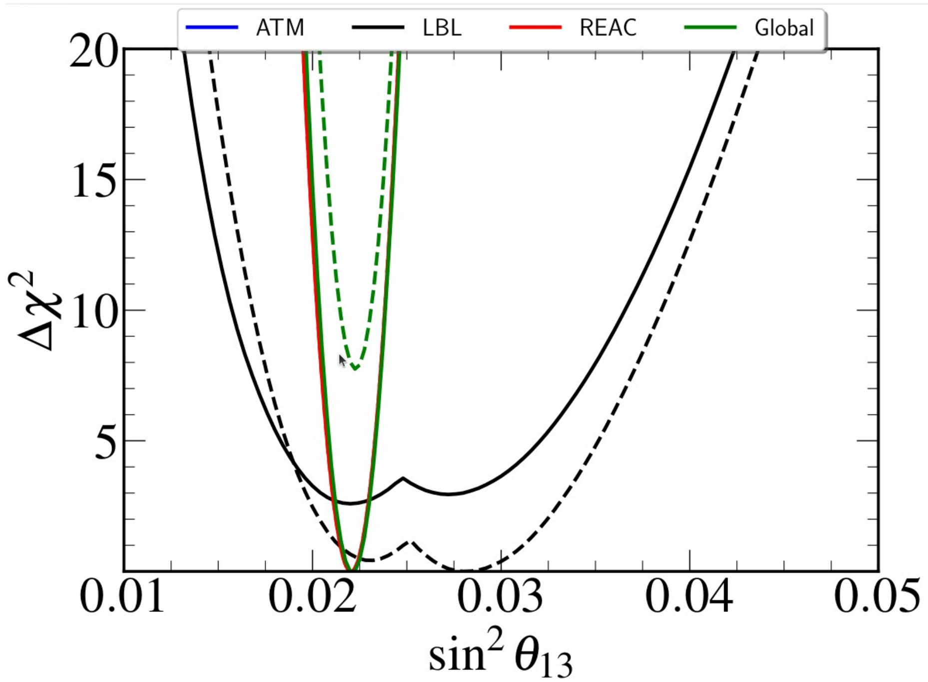
We provide analyses for many reactor and accelerator experiments using different decoherence parameters and energy dependencies

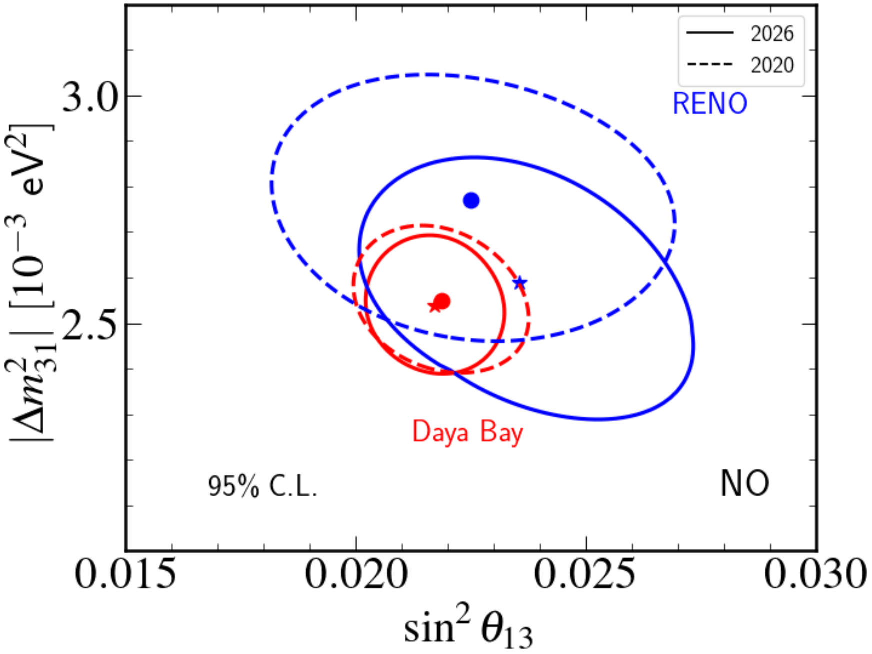
We obtain the strongest bounds to data for negative values of n (many orders of magnitude stronger than bounds from atmospheric experiments)

We showed that the the sensitivity range will be further improved by DUNE and JUNO

Thanks!

Reactor angle





Global fit: Better than 3% precision on reactor angle

Better agreement in new data!

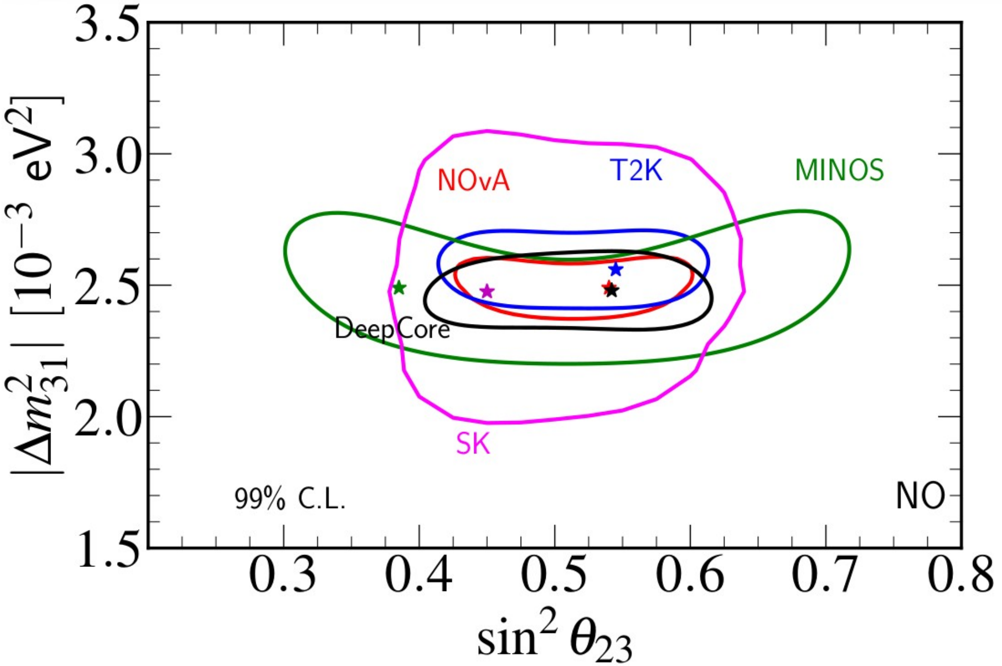
$$P_{ee}^{\mathrm{REAC}} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

Atmospheric octant

Good agreement among all experiments!

LBL data on their own do not distinguish atmospheric octants

Atmospheric data are now as competitive as accelerators

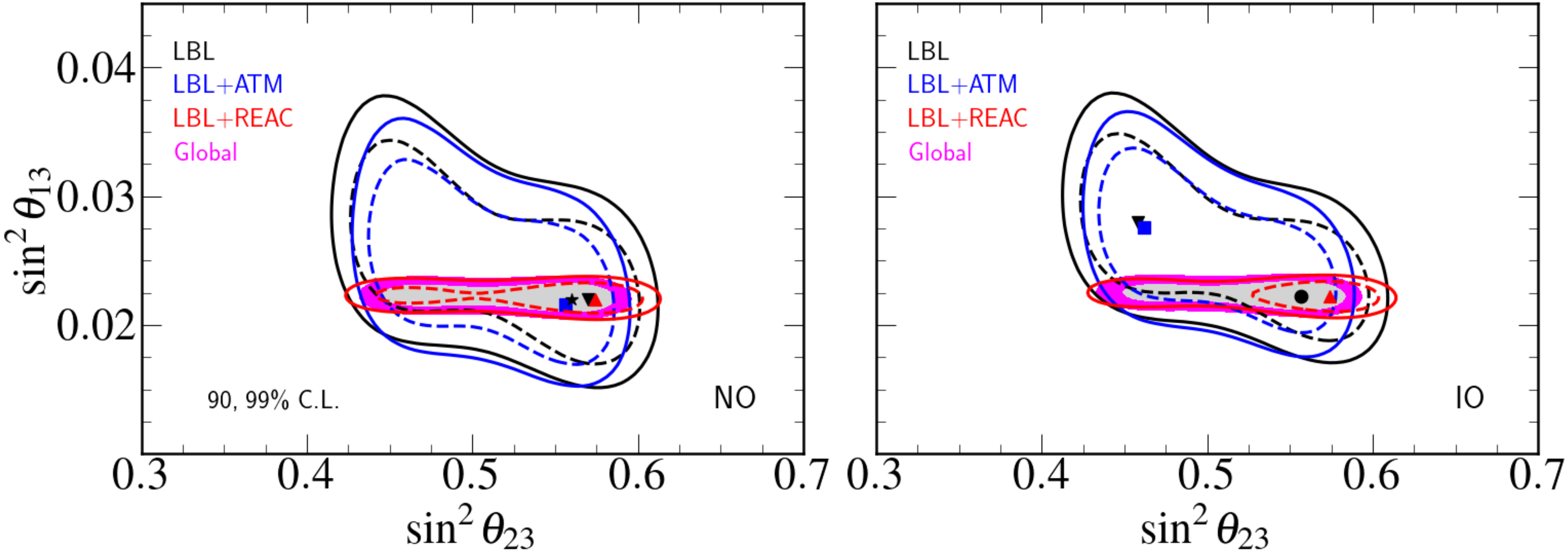


$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

$$P_{\mu\mu}^{\mathrm{LBL}} = 1 - \sin^2 2\theta_{\mu\mu}\sin^2\left(\frac{\Delta m^2_{\mu\mu}L}{4E}\right)$$

Atmospheric octant

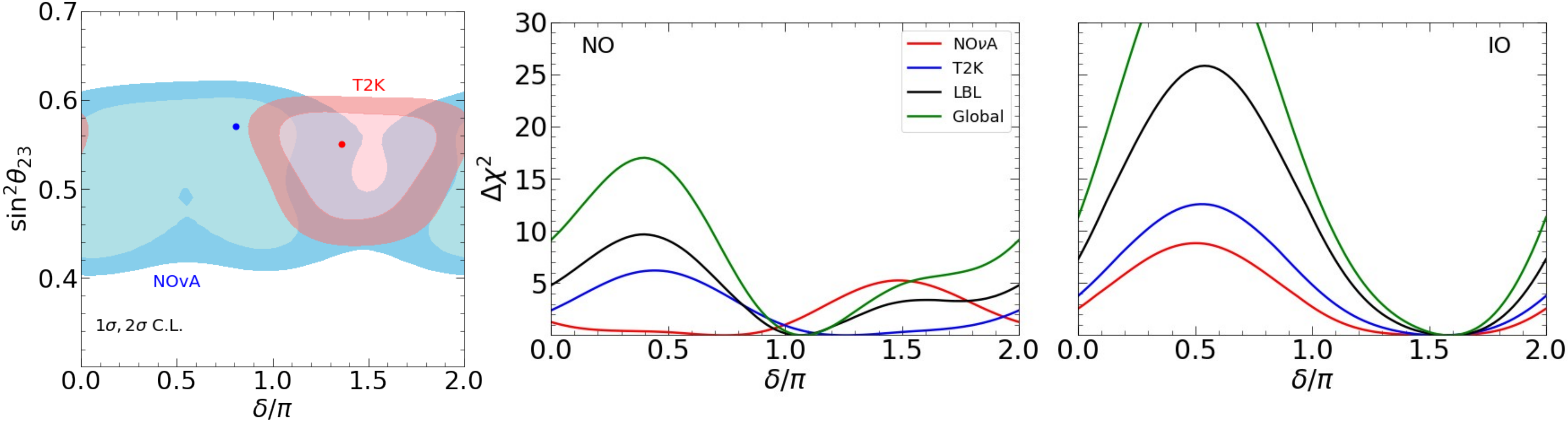
Adding reactor constraints breaks degeneracies



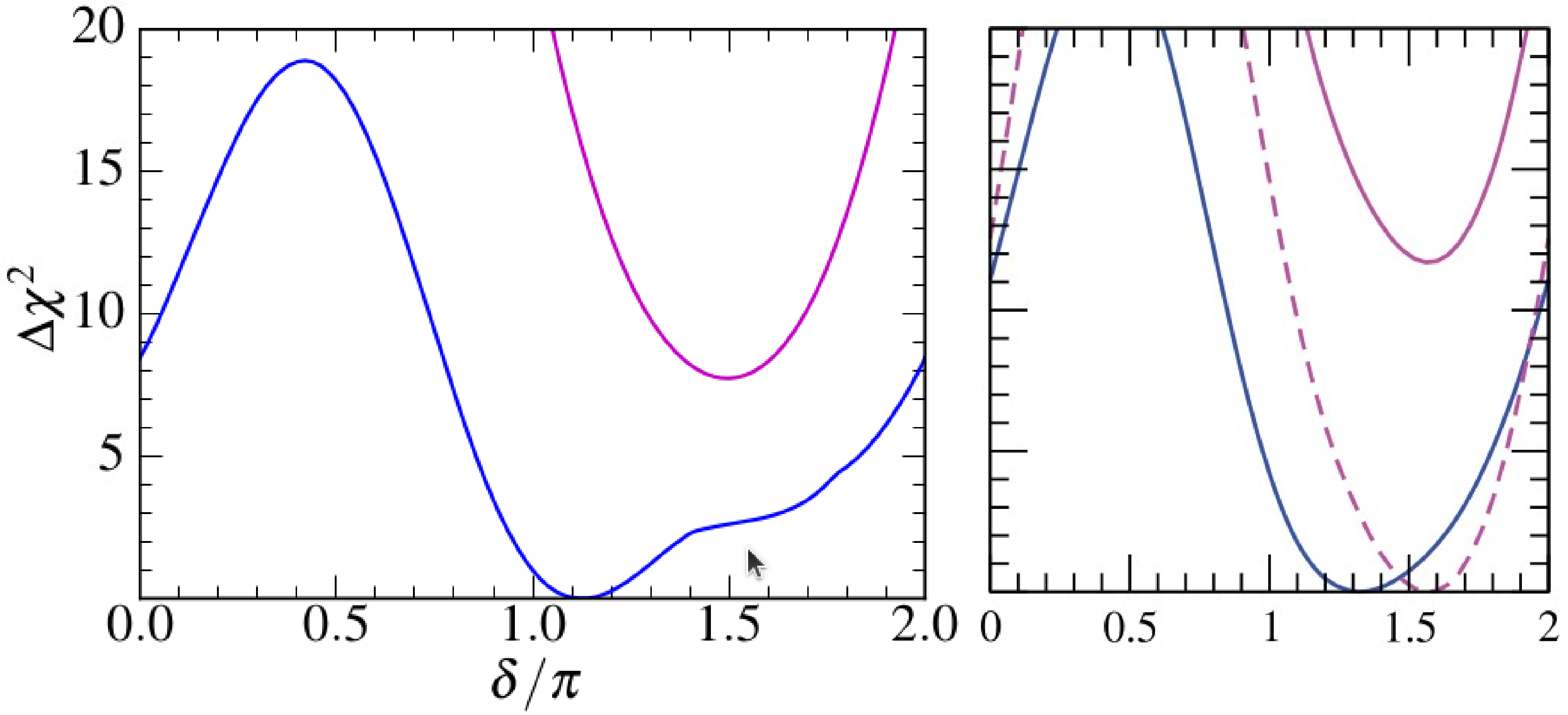
CP violation

Disagreement in the measurement of the CP phase in current data

Data from 2020, update under preparation (the result will not change significantly)



CP violation

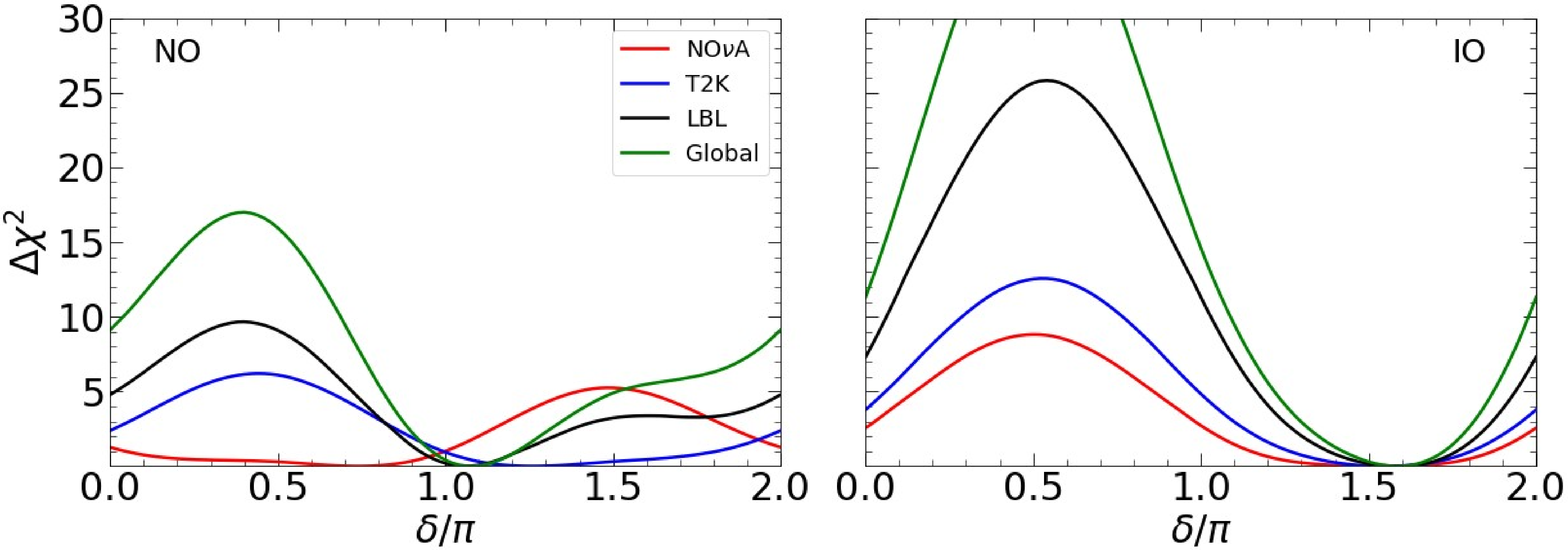


The measurement of delta is now worse than it was before

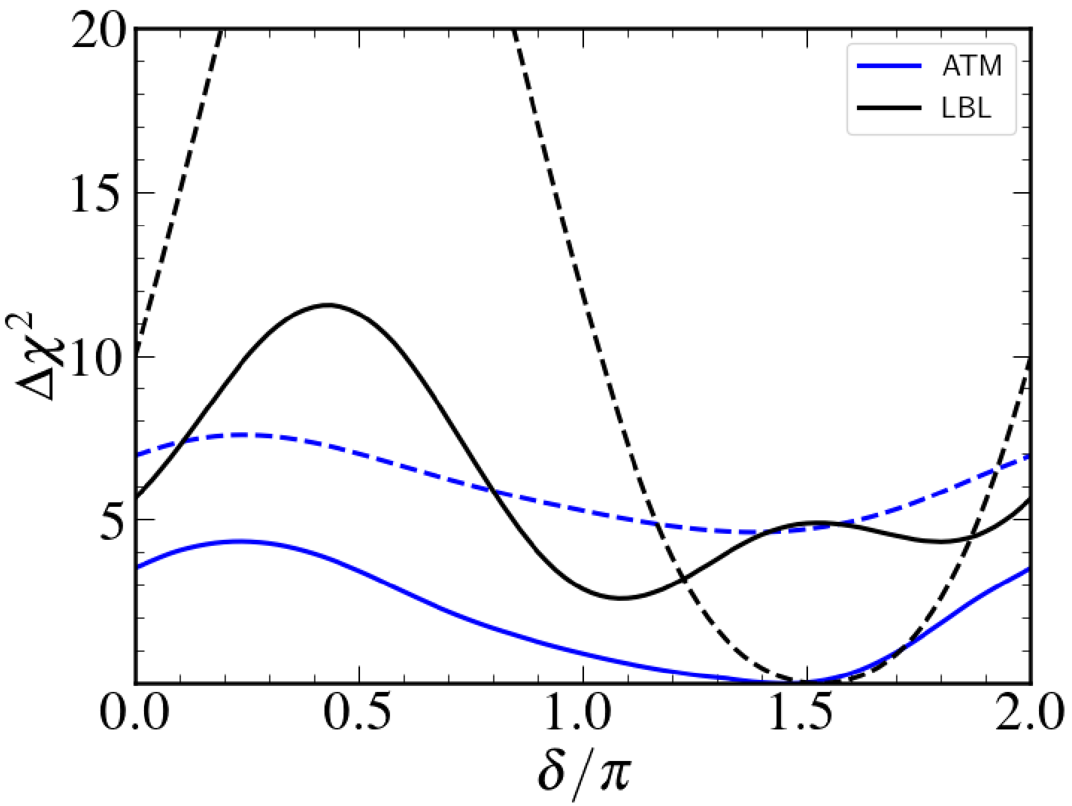
Valencia - Global Fit 2024, preliminary
Valencia - Global Fit 2018, 1708.01186, PLB 2018

Neutrino mass ordering

The disagreement between T2K and NOvA in the measurement of the CP phase appears only for normal ordering



Neutrino mass ordering

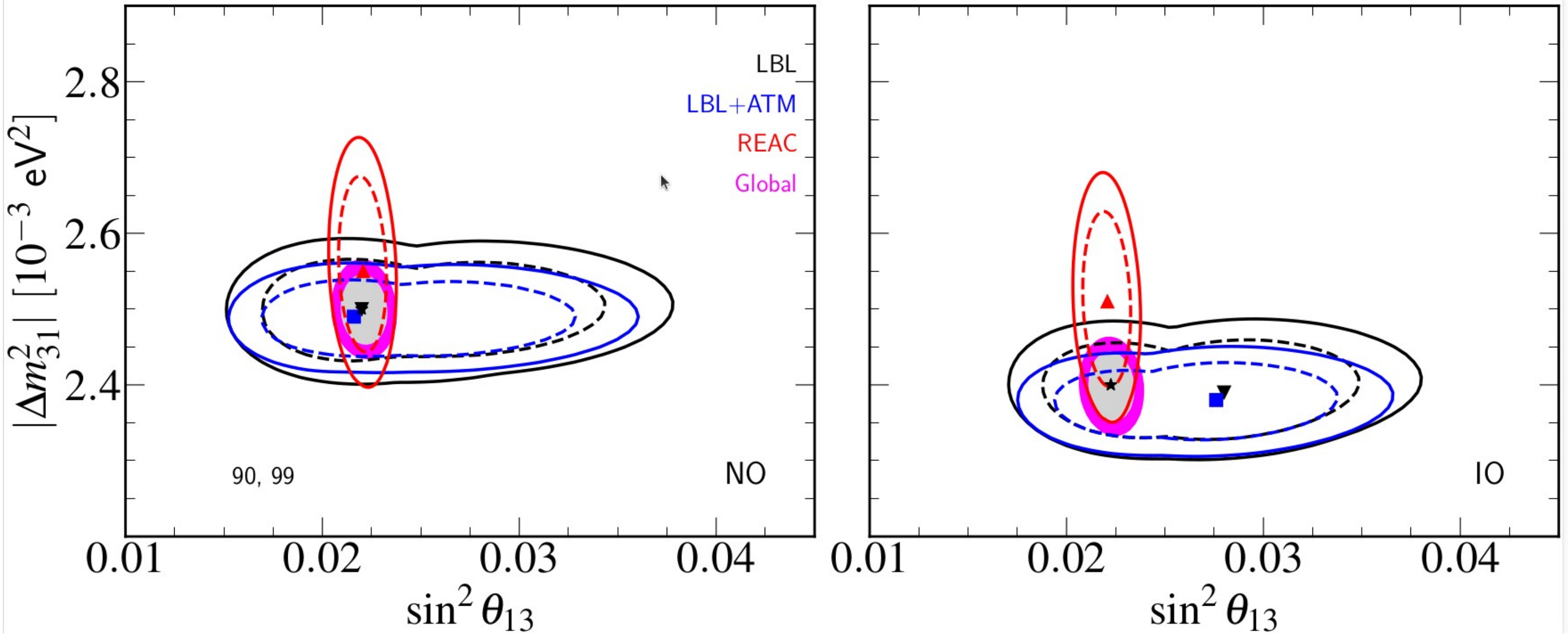


Although none of the experiments has a preference on its own, the combined analysis of all LBL data prefers IO!

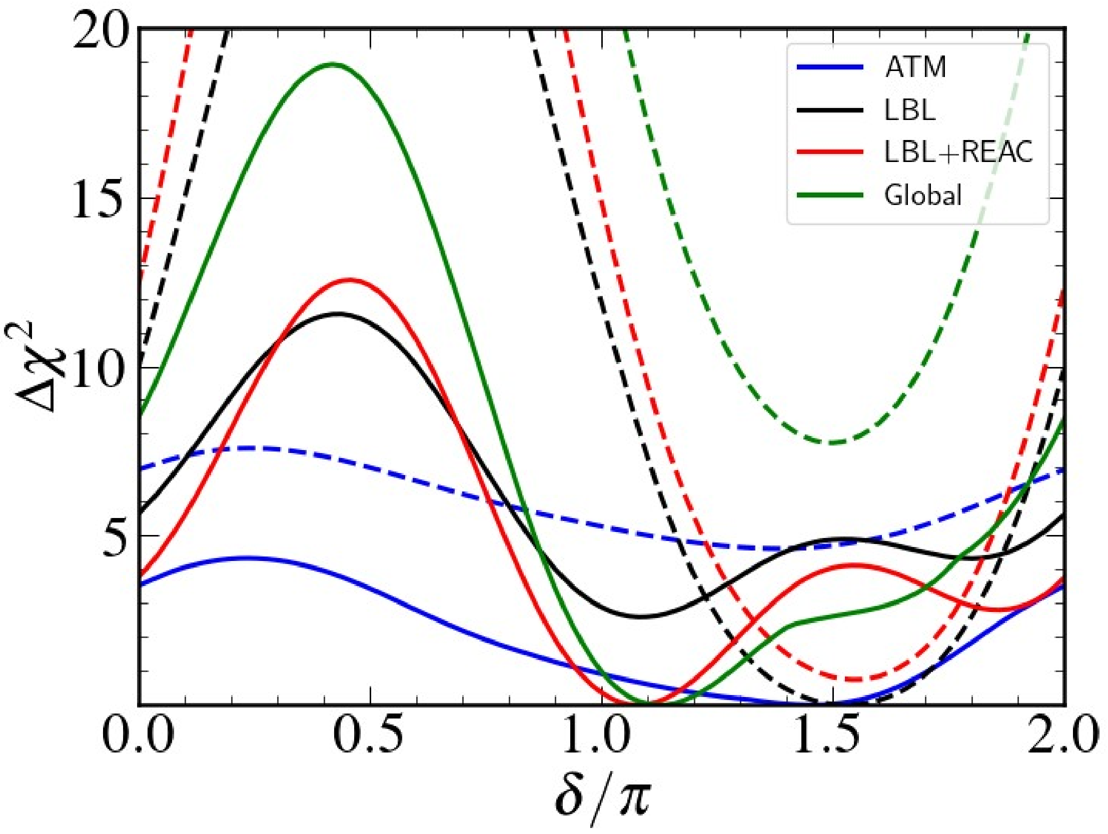
At the same time there is slight preference for NO from atmospheric experiments

Neutrino mass ordering

When combining LBL with REAC, NO is again preferred at 1σ level, due to a better agreement in the measurement of the mass splitting among accelerators and reactor for normal ordering



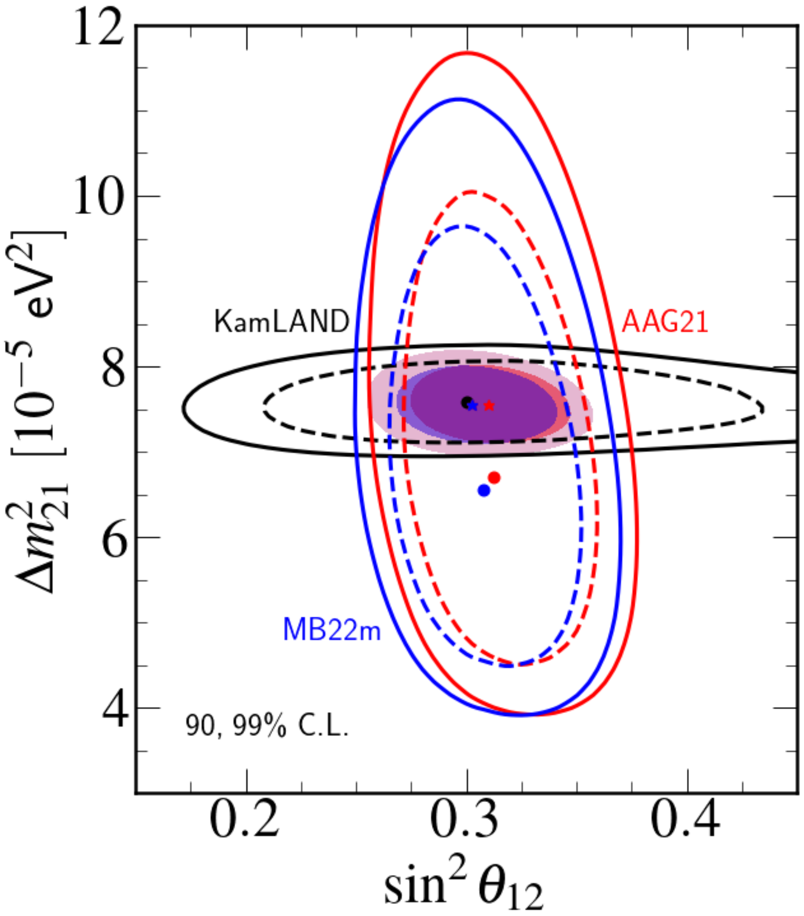
Neutrino mass ordering



When combining LBL with REAC, NO is again preferred at 1σ level, due to a better agreement in the measurement of the mass splitting among accelerators and reactor for normal ordering

After combing everything we get 2.8σ

Solar sector



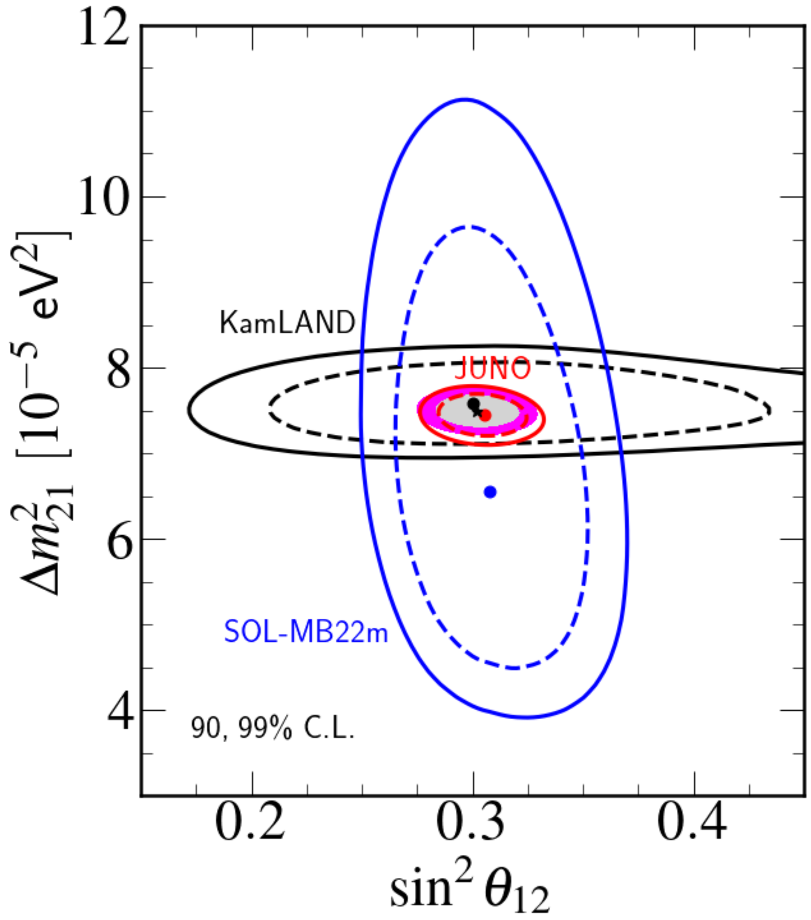
Better determination of mass splitting / mixing angle at KamLAND / solar experiments

The tension in the measurement of the mass splitting is relaxed

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

$$P_{ee}^{\rm SOL} = \frac{1}{2}c_{13}^2(c_{13}^m)^2(1+c_{12}c_{12}^m)+s_{13}^2(s_{13}^m)^2$$

Solar sector



We also use newest data from JUNO

The measurement becomes dominated by JUNO already with 59 days of data!

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

$$P_{ee}^{\rm SOL} = \frac{1}{2}c_{13}^2(c_{13}^m)^2(1 + c_{12}c_{12}^m) + s_{13}^2(s_{13}^m)^2$$