Global fits of neutrino oscillation data with 3 and 3+1 neutrinos

Christoph Andreas Ternes

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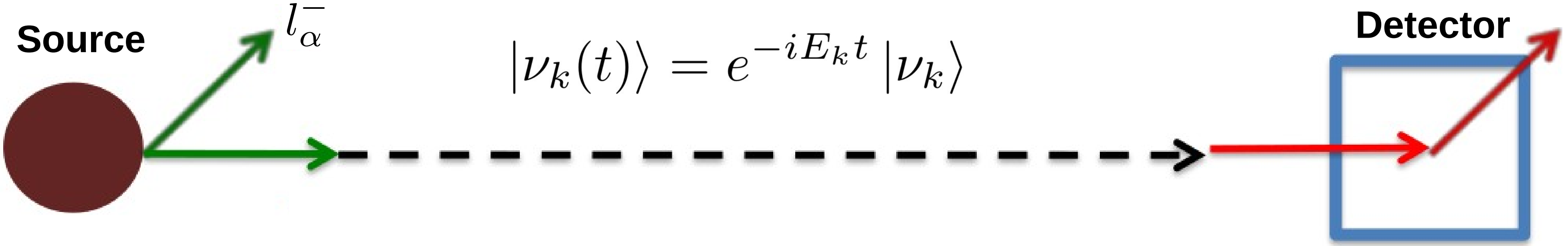
INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Neutrino oscillations



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

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

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

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

Three-neutrino oscillations

Neutrino mixing matrix

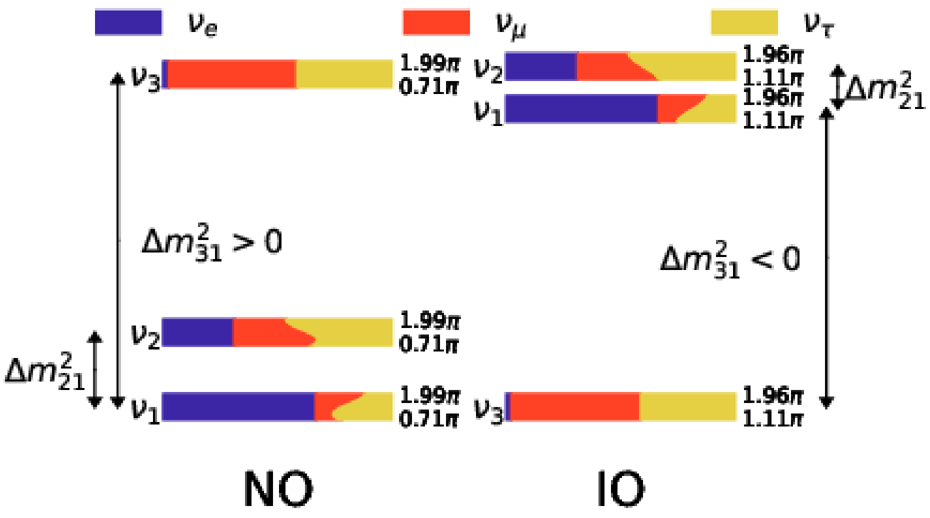
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

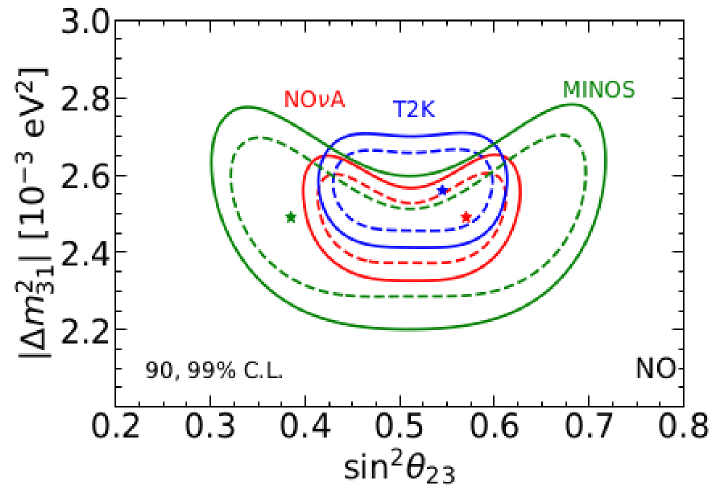
Neutrino oscillation probability in vacuum is given by

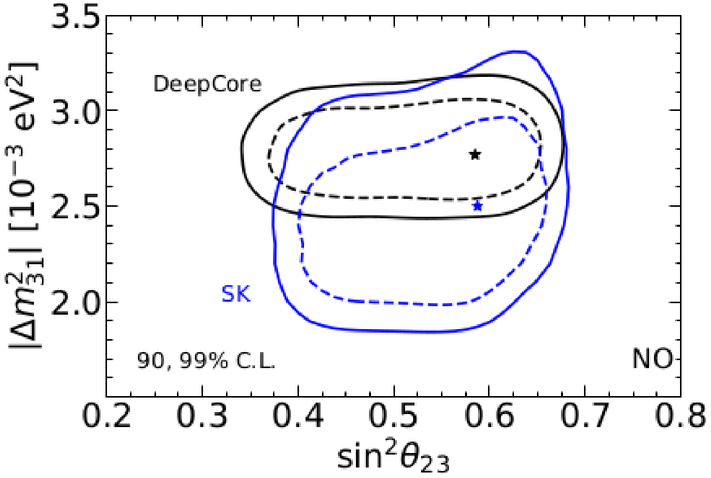
$$P_{\alpha\beta}(E,L) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{i\frac{\Delta m^2_{kj}}{2E}L}$$

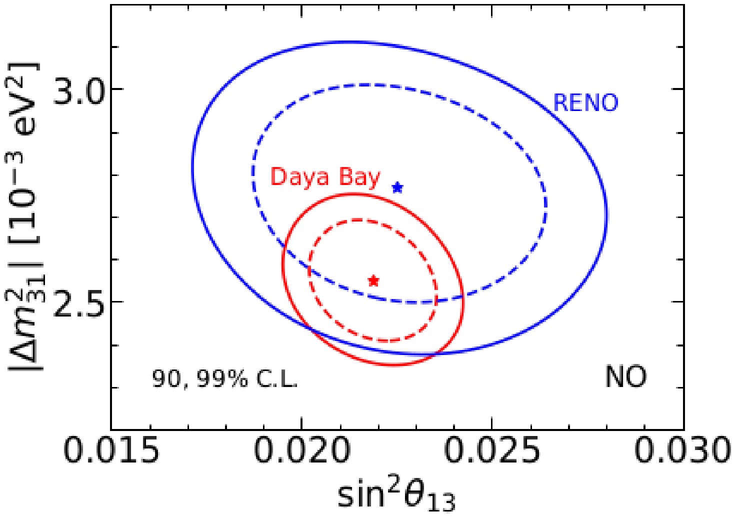
From the interplay of the mass splittings with energy and distance we see that different types of experiments are sensitive to different parameters

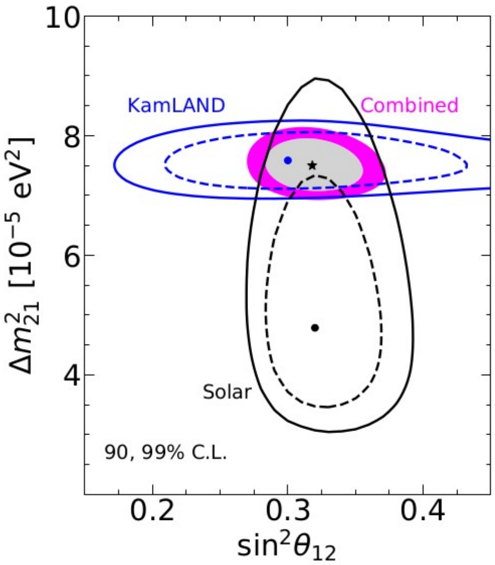
Parameter	Main contribution from	Other contributions from
Δm^2_{21}	KamLAND	SOL
$\|\Delta m^2_{31}\|$	LBL+ATM+REAC	-
θ_{12}	SOL	KamLAND
θ_{23}	LBL+ATM	-
θ_{13}	REAC	(LBL+ATM) and (SOL+KamLAND)
δ	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

Valencia - Global Fit, 2006.11237, JHEP 2021



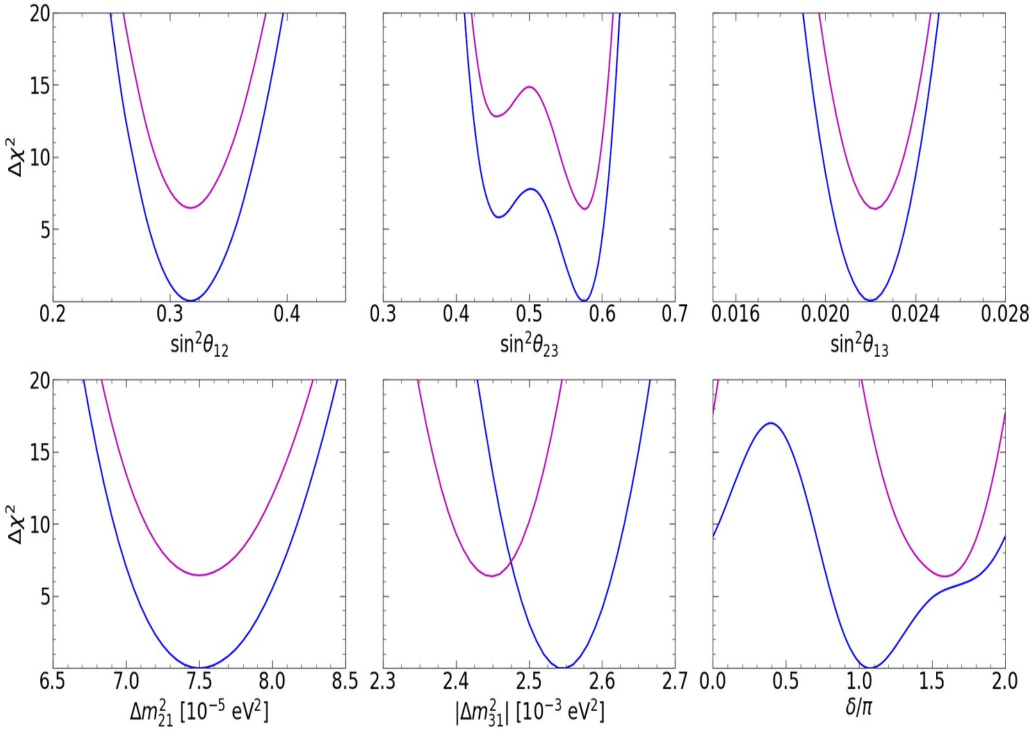






Global fit

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

See also:
NuFit - 2007.14792, JHEP 2020

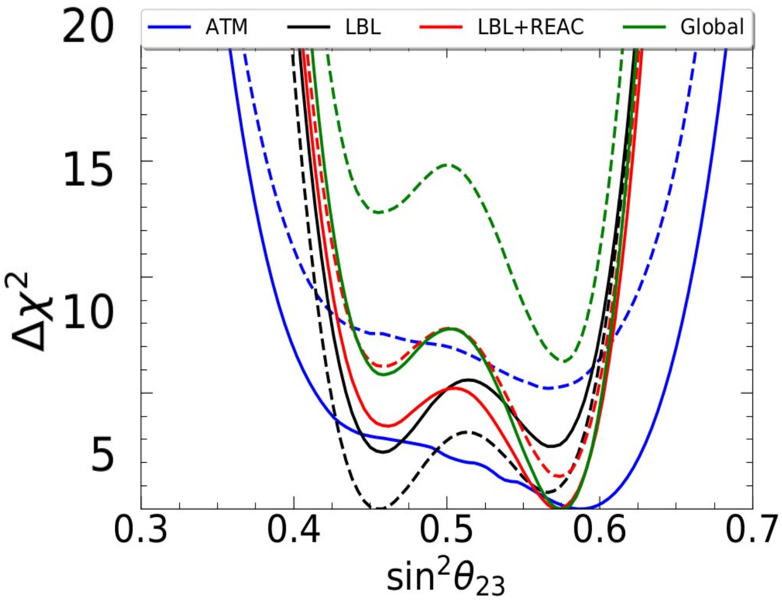
Atmospheric octant

LBL data on their own do not distinguish octants

Adding ATM and REAC breaks degeneracies

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

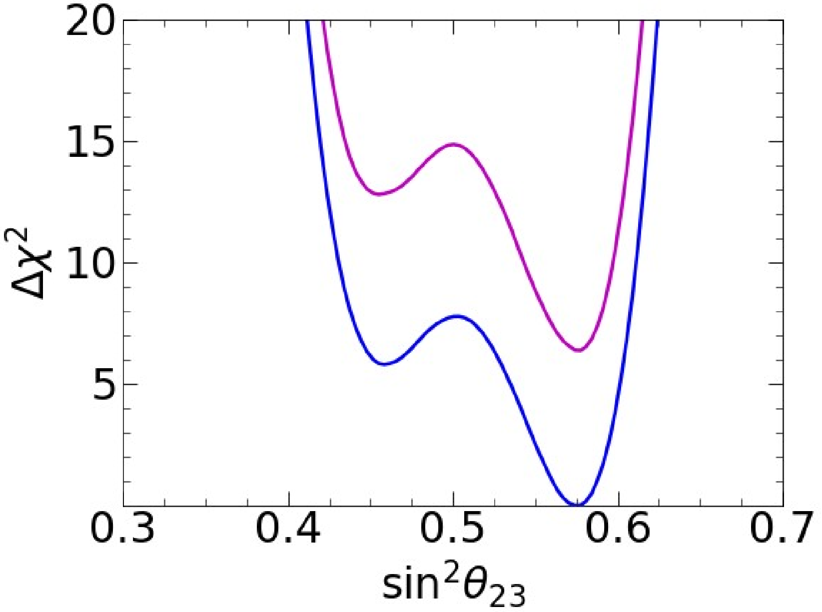
$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\ & + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\rm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



Valencia - Global Fit, 2006.11237, JHEP 2021

Atmospheric octant

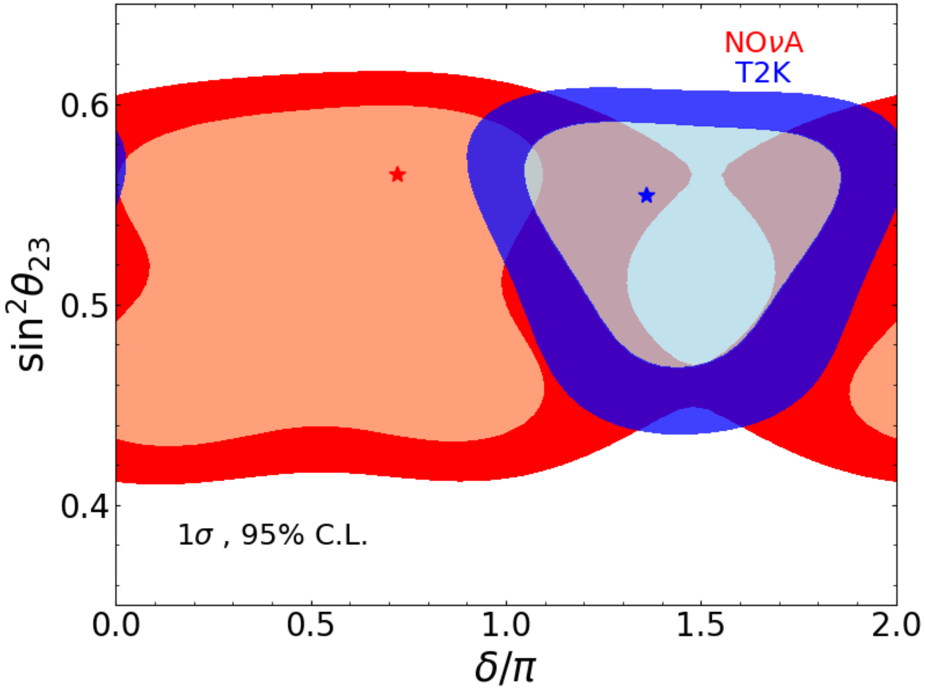
Current global fit prefers second octant



Valencia - Global Fit, 2006.11237, JHEP 2021

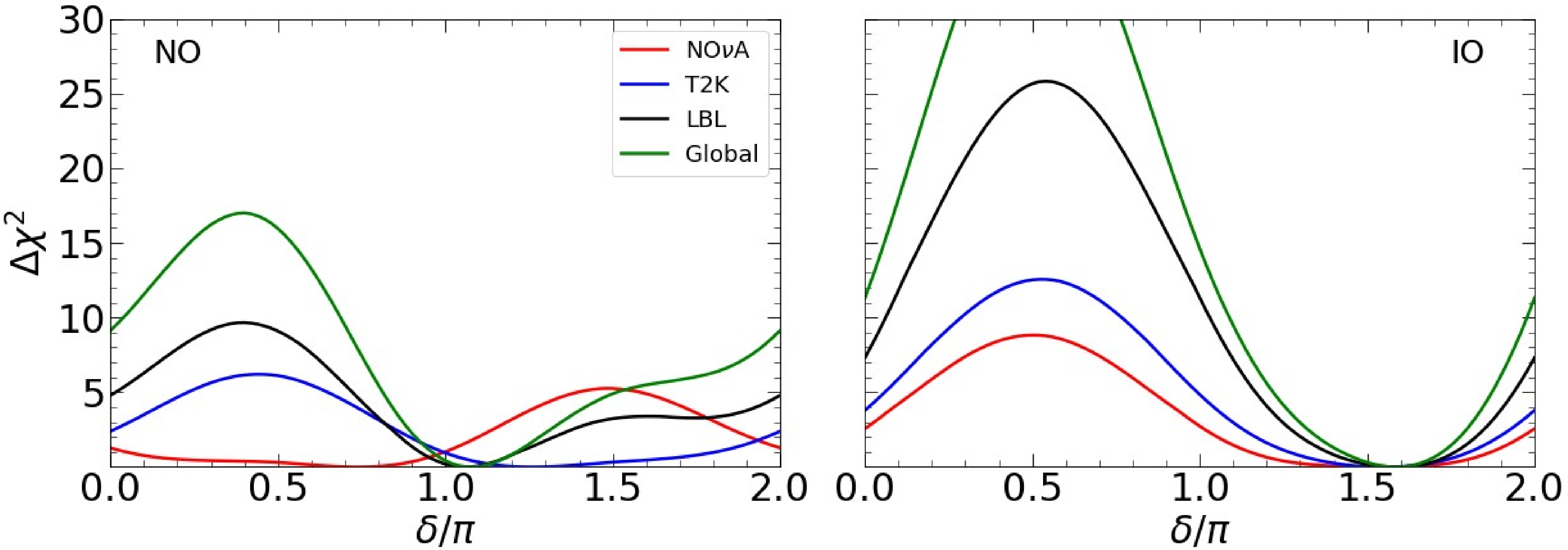
CP violation

Disagreement in the measurement of the CP phase in current data



CP violation

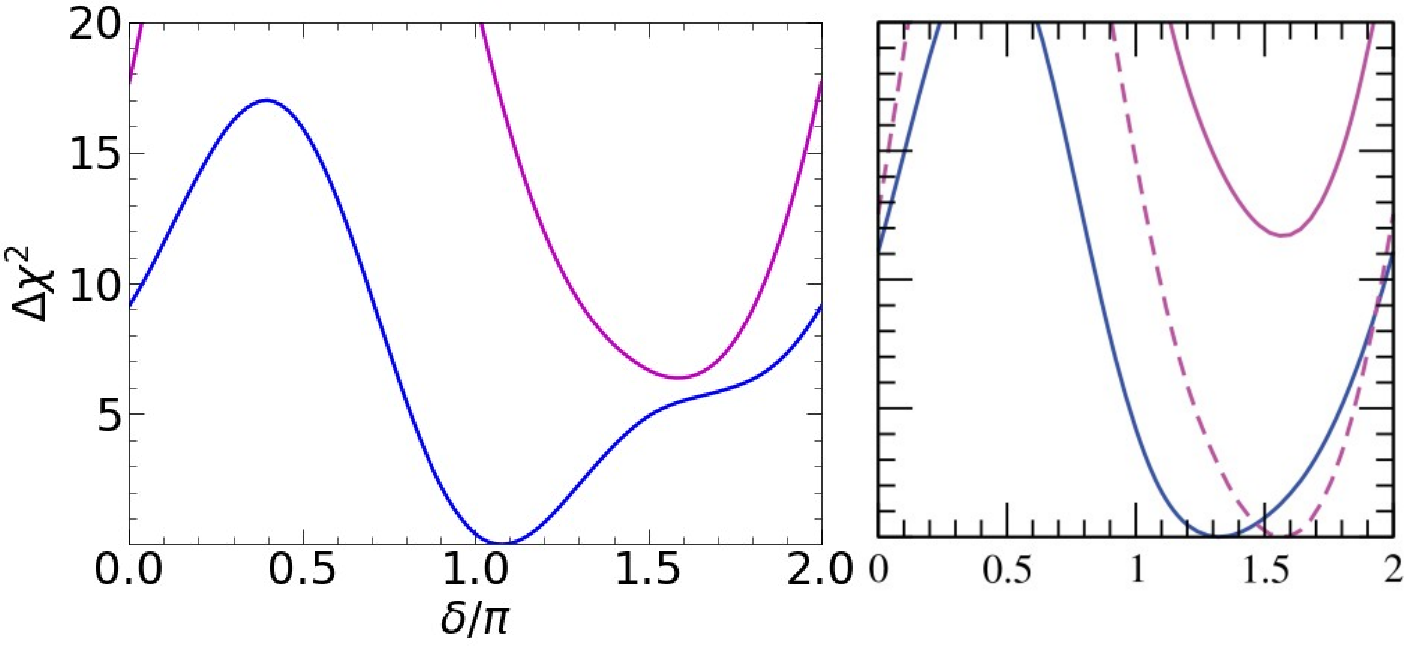
T2K and NOνA profiles disagree for NO



Valencia - Global Fit, 2006.11237, JHEP 2021

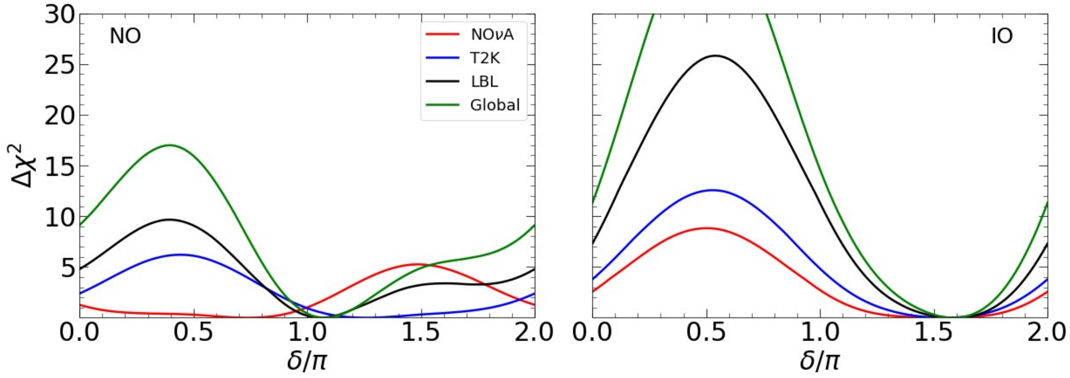
CP violation

The measurement of delta is now worse than it was before

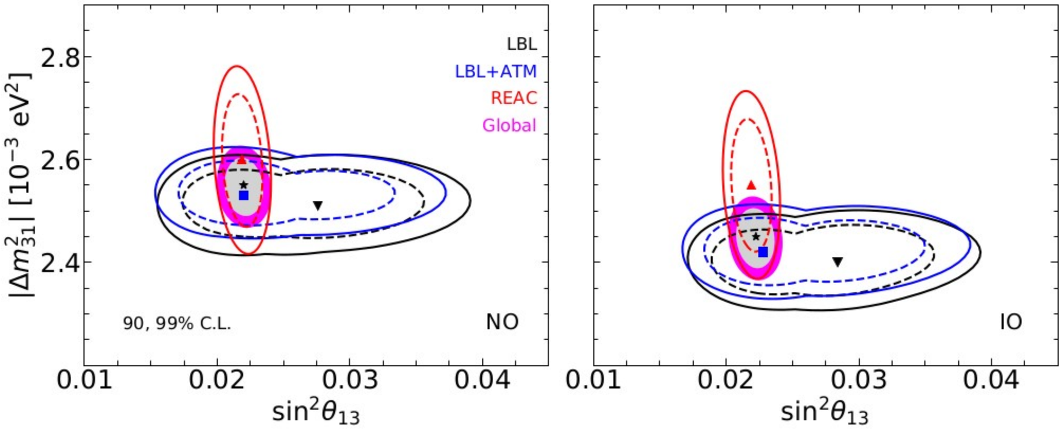


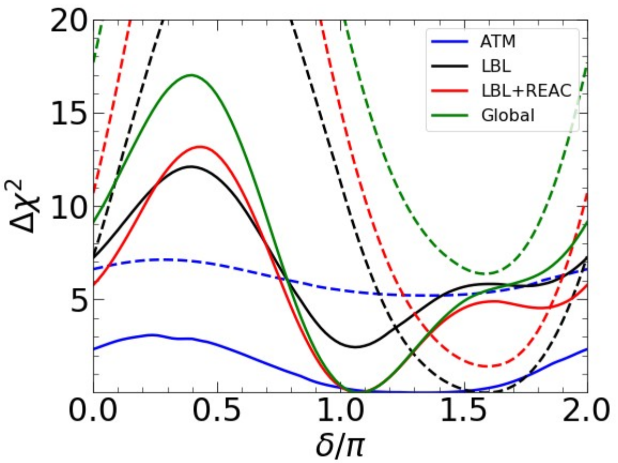
Valencia – Global Fit (current), 2006.1123, JHEP 2021
Valencia – 2018 Global Fit, 1708.01186, PLB 2018

Mass ordering



Preference in current global fits comes from several small tensions/disagreements in the data

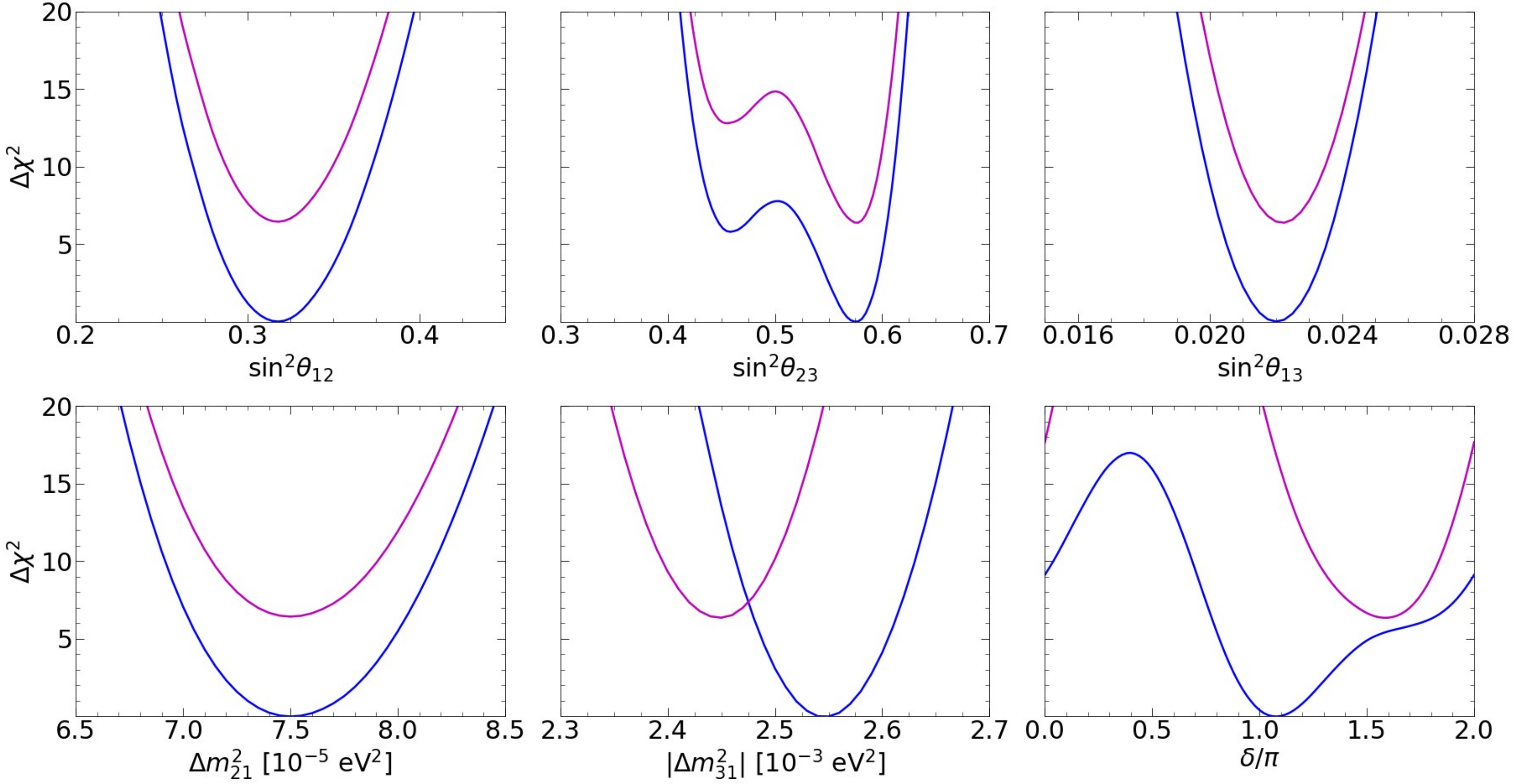




Valencia - Global Fit, 2006.11237, JHEP 2021

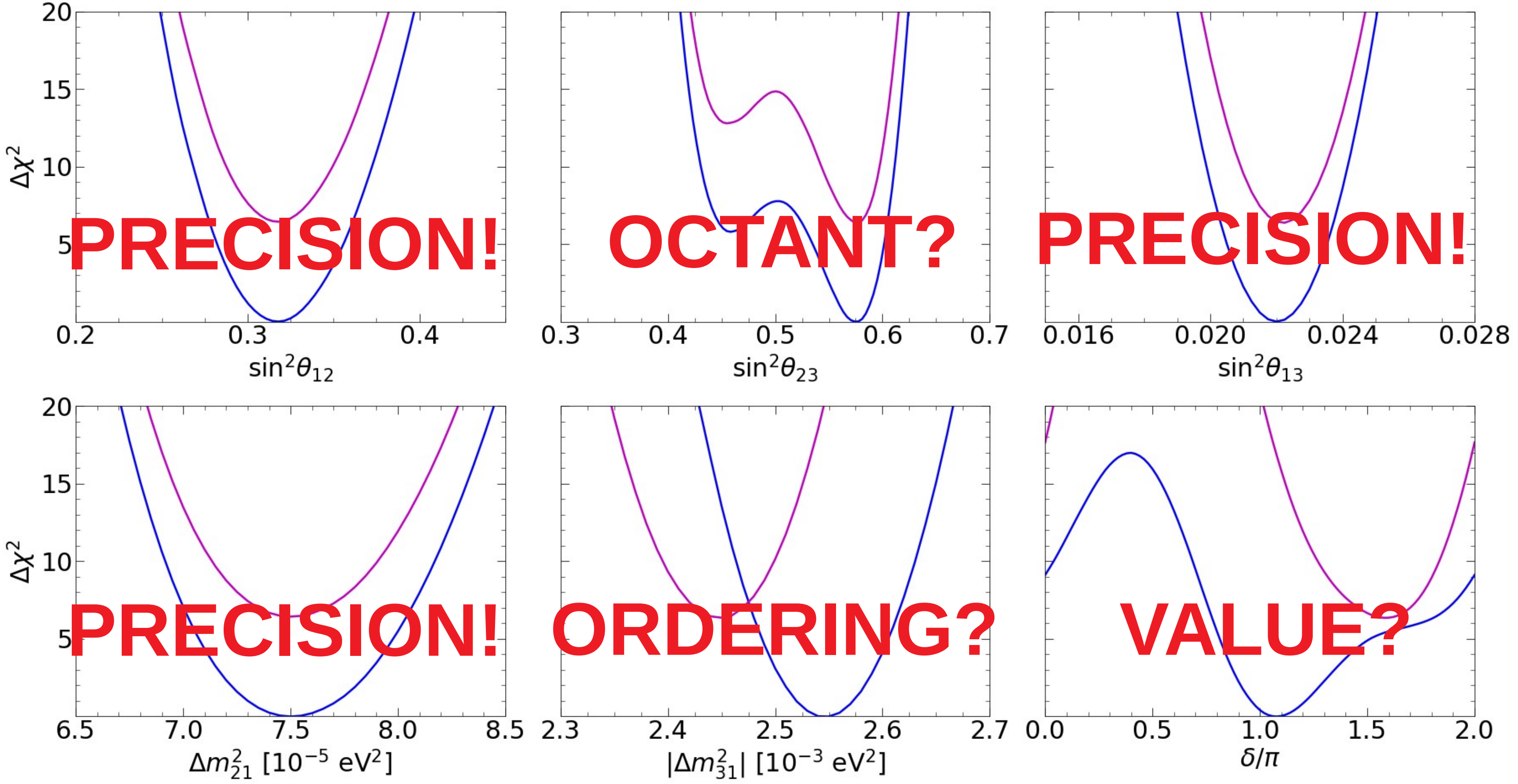
Global fit

Valencia - Global Fit, 2006.11237, JHEP 2021
https://globalfit.astroparticles.es/



Global fit

Valencia - Global Fit, 2006.11237, JHEP 2021
https://globalfit.astroparticles.es/



Global fit

Valencia - Global Fit, 2006.11237, JHEP 2021
https://globalfit.astroparticles.es/

parameter	best fit ± 1σ		2σ range	3σ range
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$\lvert\Delta m^2_{31}\rvert [10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	**1.2%**	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert [10^{-3}\text{eV}^2]$ (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	**5.0%**	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	**2.5%**	5.41–5.99	4.34–6.10
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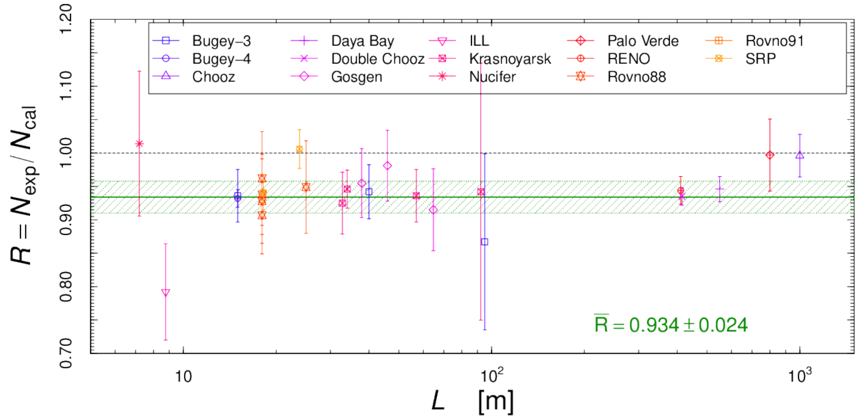
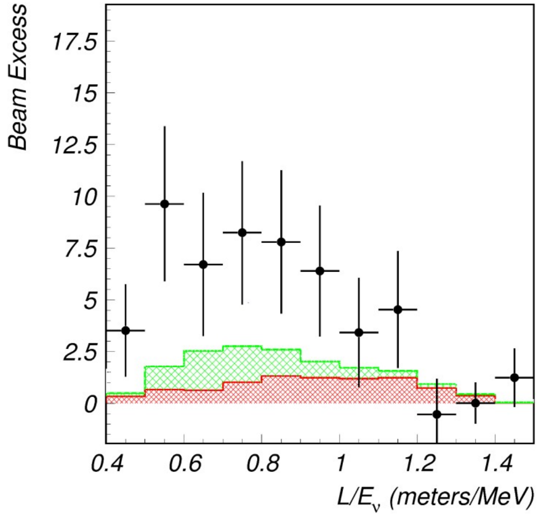
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$		2.086–2.356	2.018–2.424
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	**12%**	0.84–1.42	0.71–1.99
δ/π (IO)	$1.58^{+0.15}_{-0.16}$		1.26–1.85	1.11–1.96

Anomalies

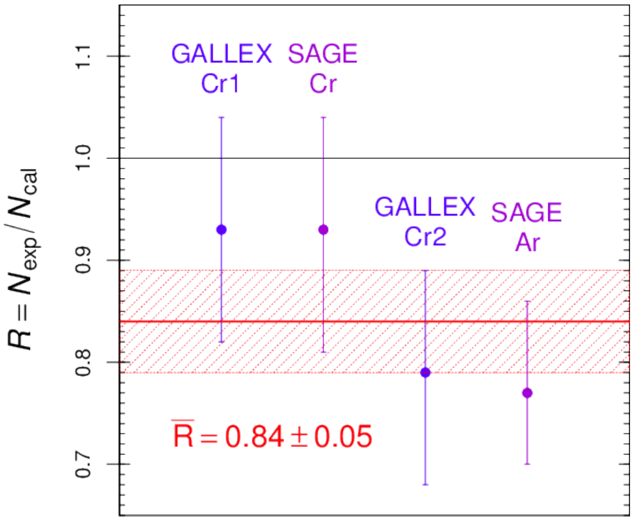
Deficit of events in reactor rates -> ~3σ



Excess of events in LSND -> ~4σ



Deficit of events in Gallium -> ~3σ



Anomalies

Three neutrino oscillations can not account for short baseline anomalies

$$L_{kj}^{\text{osc}} = \frac{4\pi E}{\Delta m_{kj}^2}$$

$$L_{21}^{\text{osc}} \gtrsim 50\ \text{km}\ \frac{E}{\text{MeV}}$$

$$L_{31}^{\text{osc}} \gtrsim 1\ \text{km}\ \frac{E}{\text{MeV}}$$

Short baseline oscillations require:

$$\frac{L}{E} \lesssim 10\,\text{m}/\text{MeV} \quad \Longrightarrow \quad \Delta m^2 \gtrsim 0.1\,\text{eV}^2$$

3+1 neutrino oscillations

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \Rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Appearance

$$P_{\alpha\beta}^{\rm SBL} \approx \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

@LSND, Karmen, MiniBooNE, Opera

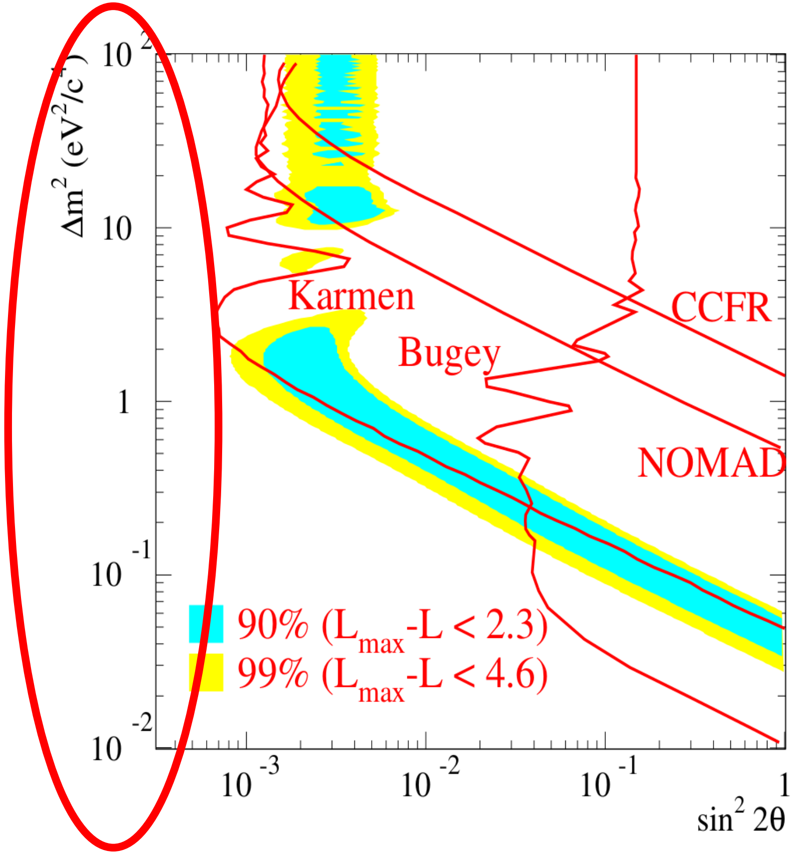
Disappearance

$$P_{\alpha\alpha}^{\rm SBL} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

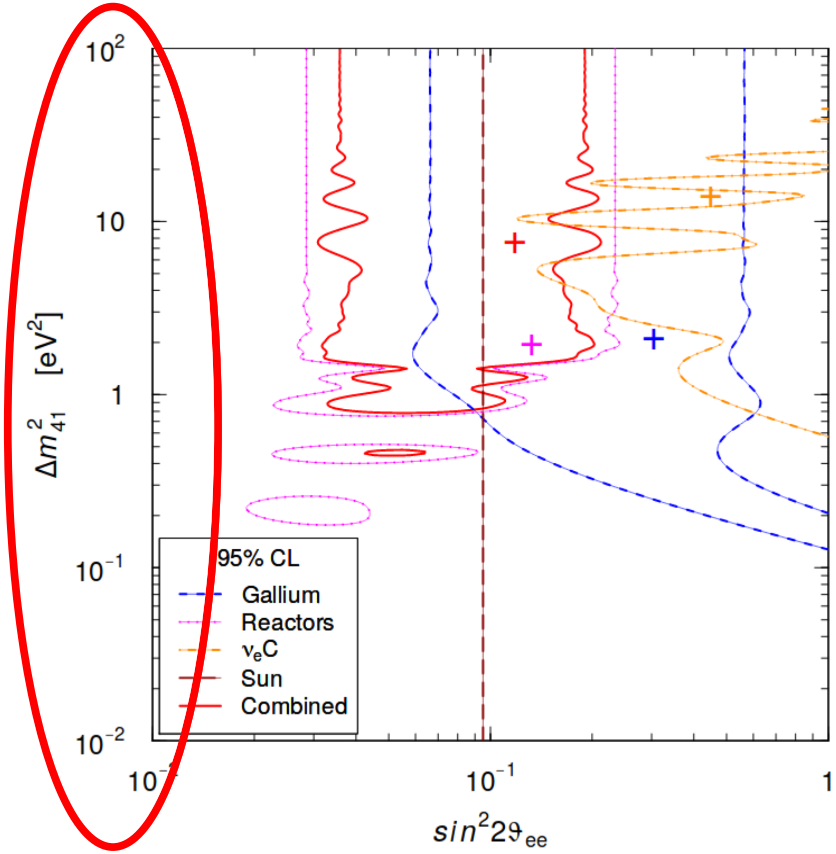
$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2)$$

@Reactors and Gallium
@atmospherics and accelerators

3+1 neutrino oscillations

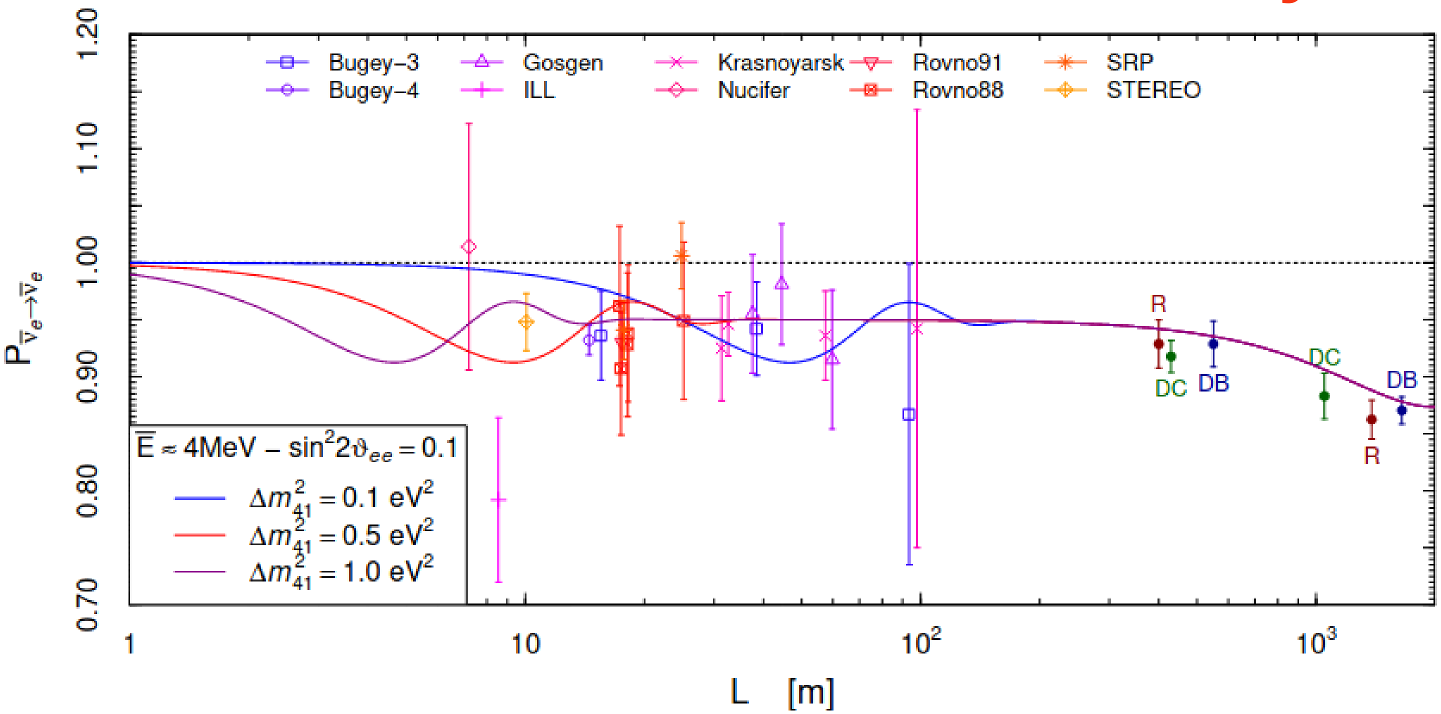


LSND collaboration
hep-ex/0104049, PRD 2001



Giunti, Laveder, Li, Liu, Long
1210.5715, PRD 2012

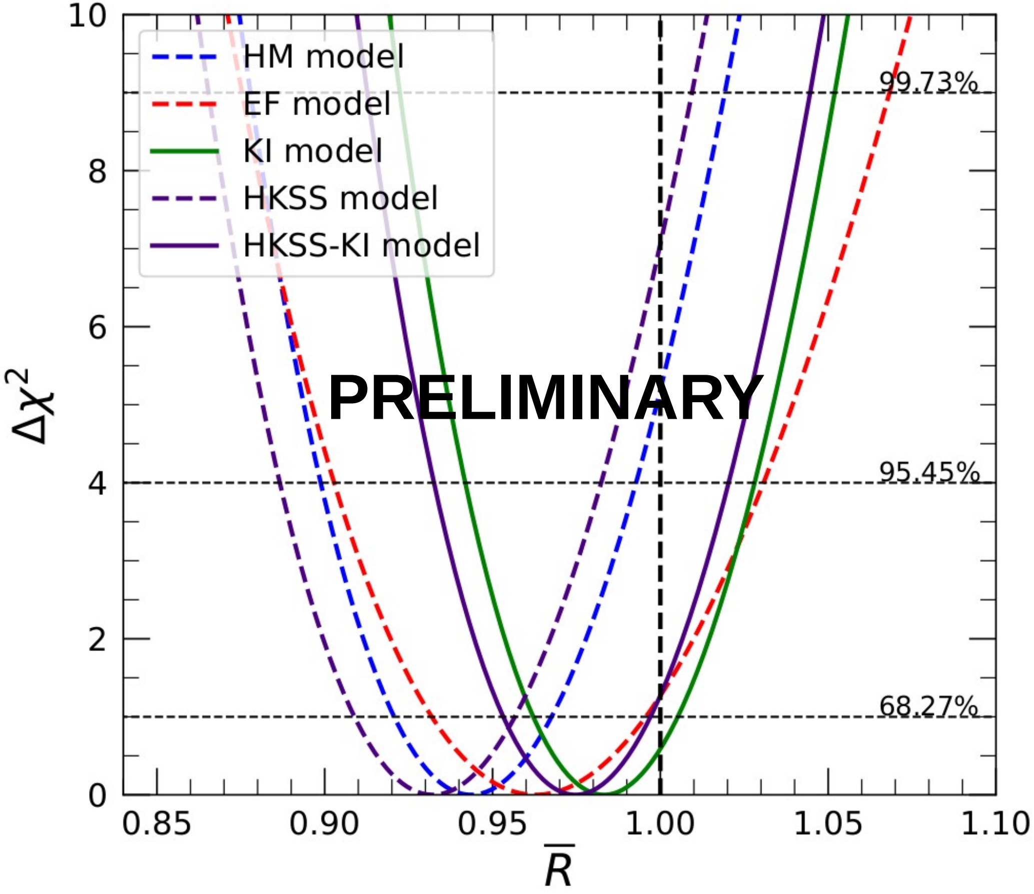
The reactor antineutrino anomaly



Sterile oscillations are averaged out at larger distances

The reactor anomaly is model dependent

The reactor antineutrino anomaly



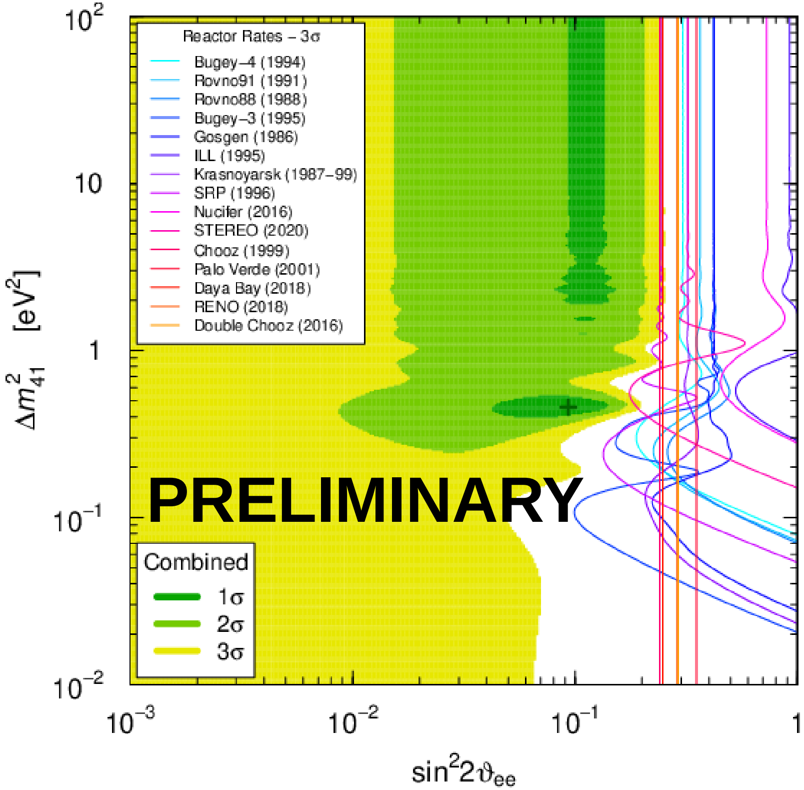
Giunti, Li, Ternes, Xin, Preliminary

Good agreement between measured and predicted IBD yields for KI, KI-HKSS and EF models!

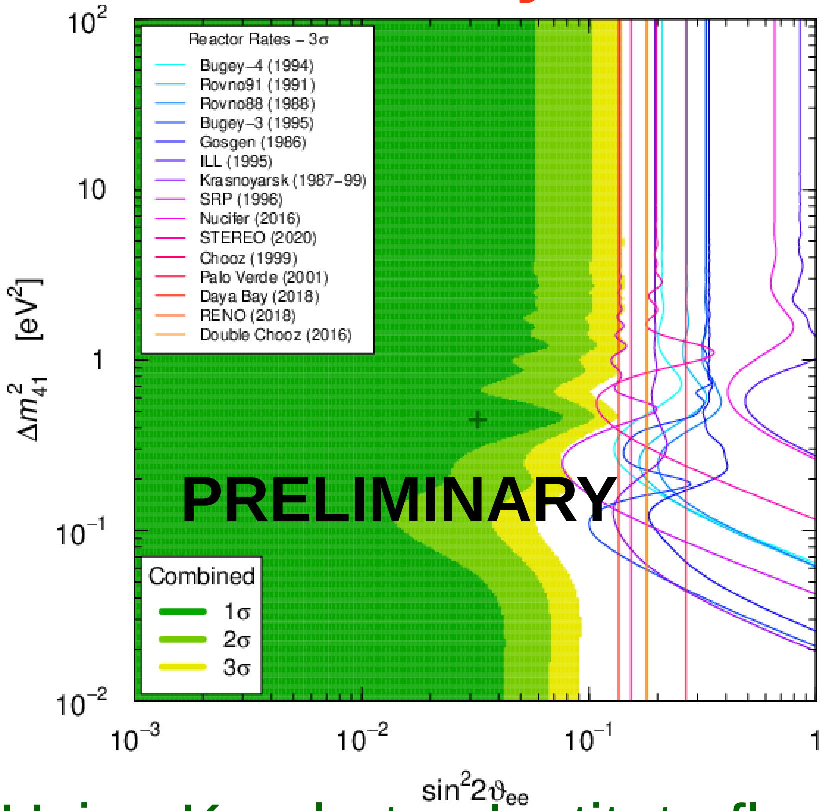
There is NO (!) reactor antineutrino anomaly using the latest flux calculations!

P. Huber, 1106.0687, PRC 2011
T. Mueller, et al, 1101.2663, PRC 2011
M. Estienne, et al, 1904.09358, PRL 2020
V. Kopeikin, et al, 2103.01684
L. Hayen, et al, 1908.08302, PRC 2019

The reactor antineutrino anomaly



Using Huber Mueller flux model

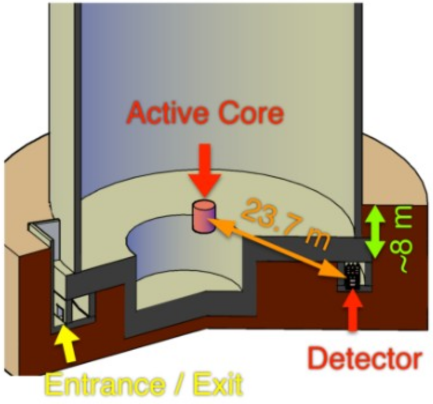


Using Kurchatov Institute flux model

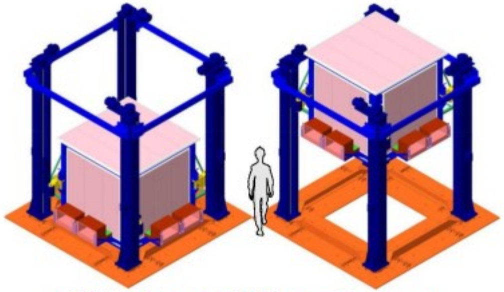
Giunti, Li, Ternes, Xin, Preliminary

Ratio analysis

NEOS

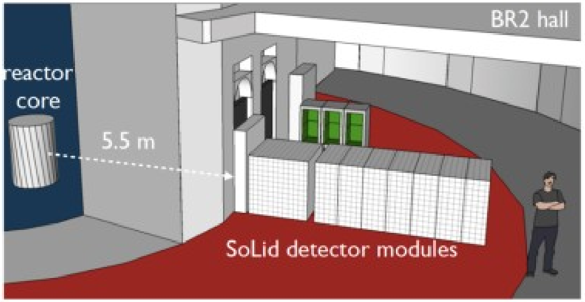


DANSS

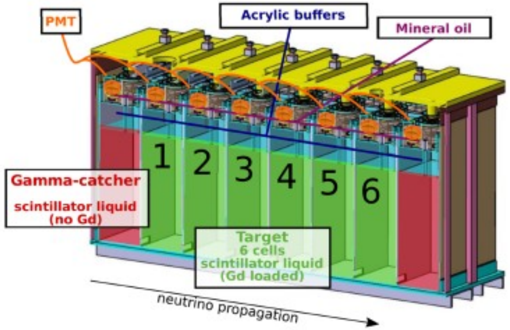


DANSS on a lifting platform

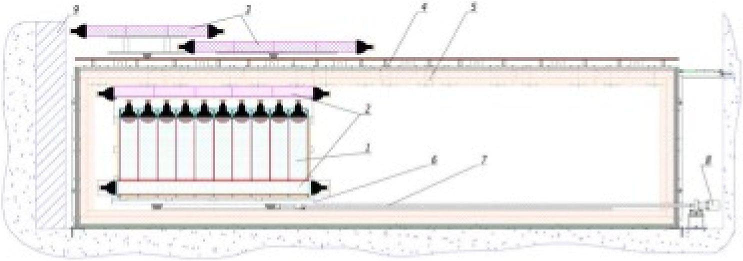
SoLid



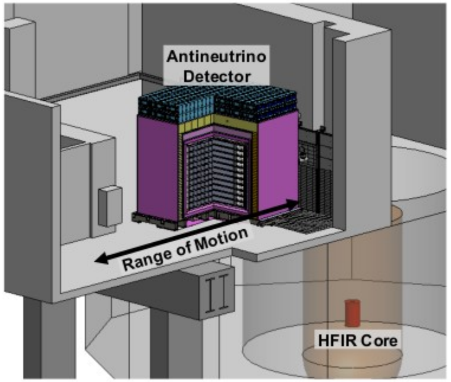
STEREO



Neutrino-4

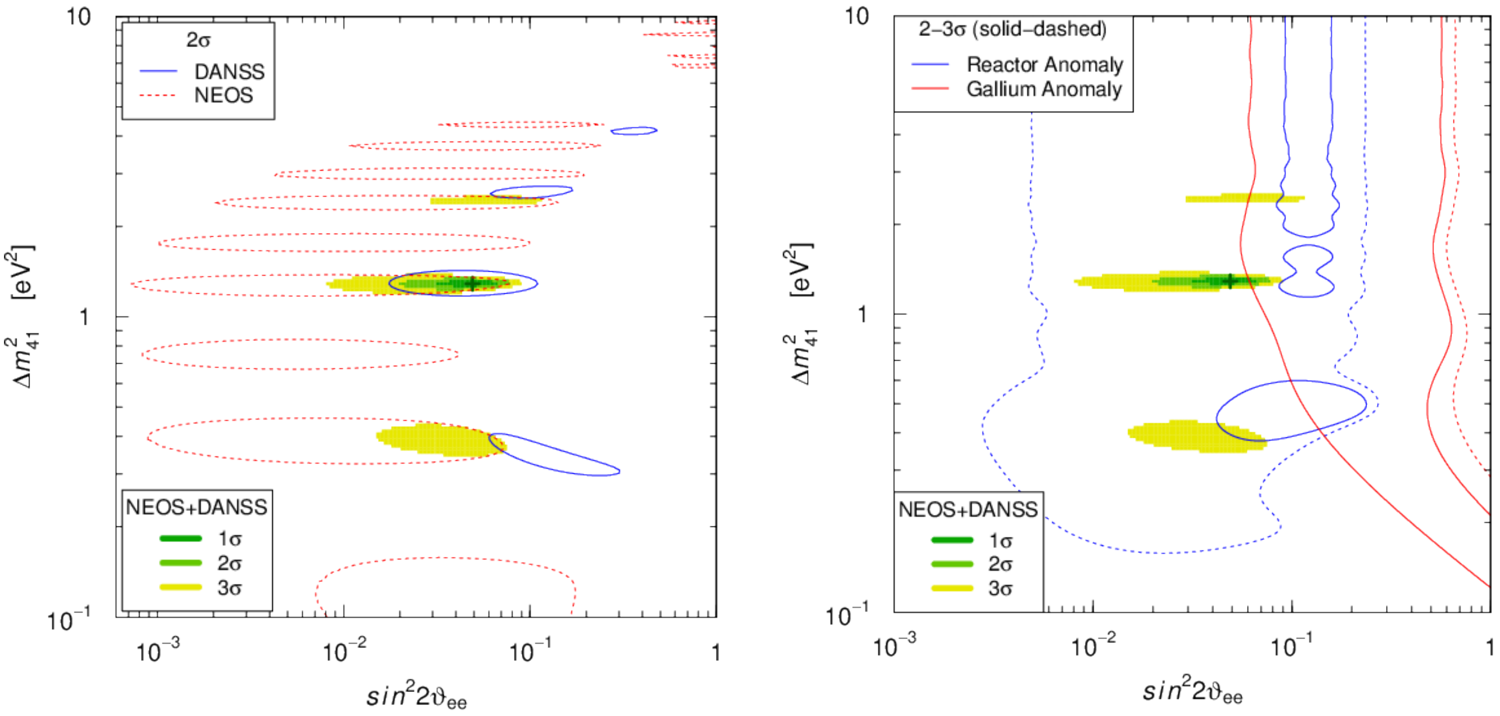


PROSPECT



Ratio analysis 2018

Gariazzo, Giunti, Laveder, Li, 1801.06467, PLB 2018

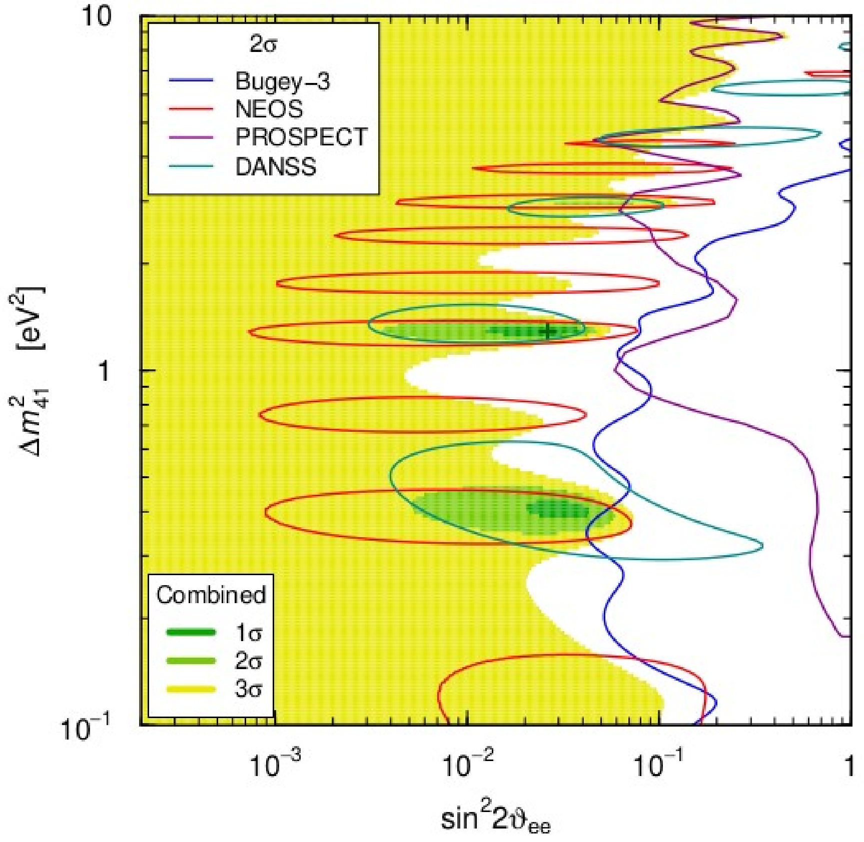


~2σ individual preference from DANSS and NEOS

>3σ combined preference

Ratio analysis 2019/2020

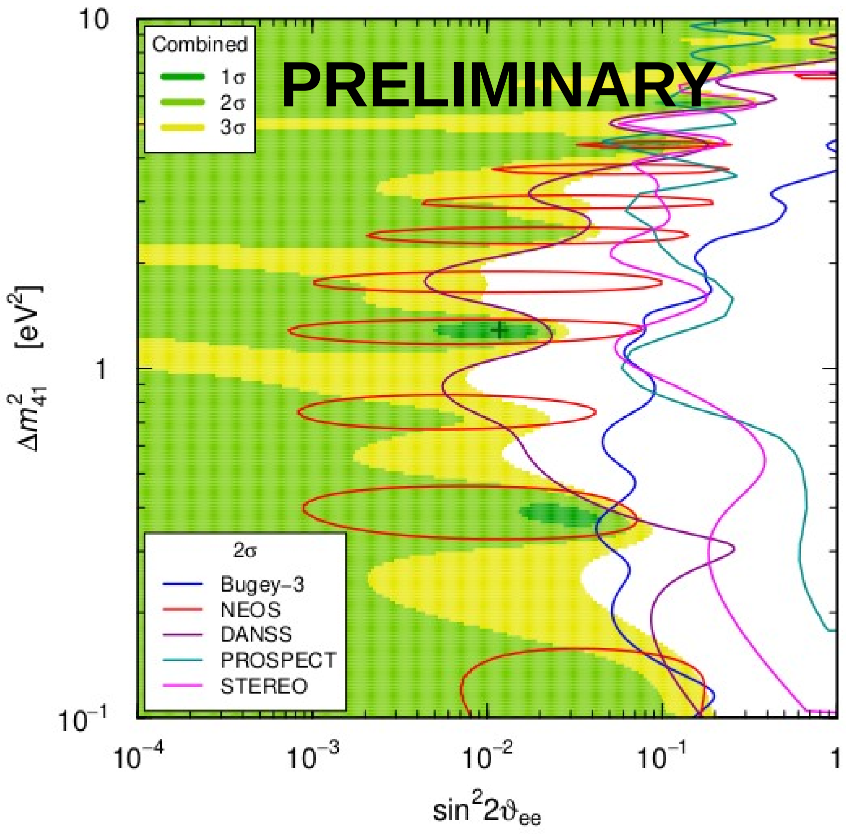
Giunti, Li, Zhang, 1912.12956, JHEP 2020



Less agreement between DANSS and NEOS

still >2σ combined preference

Ratio analysis 2021

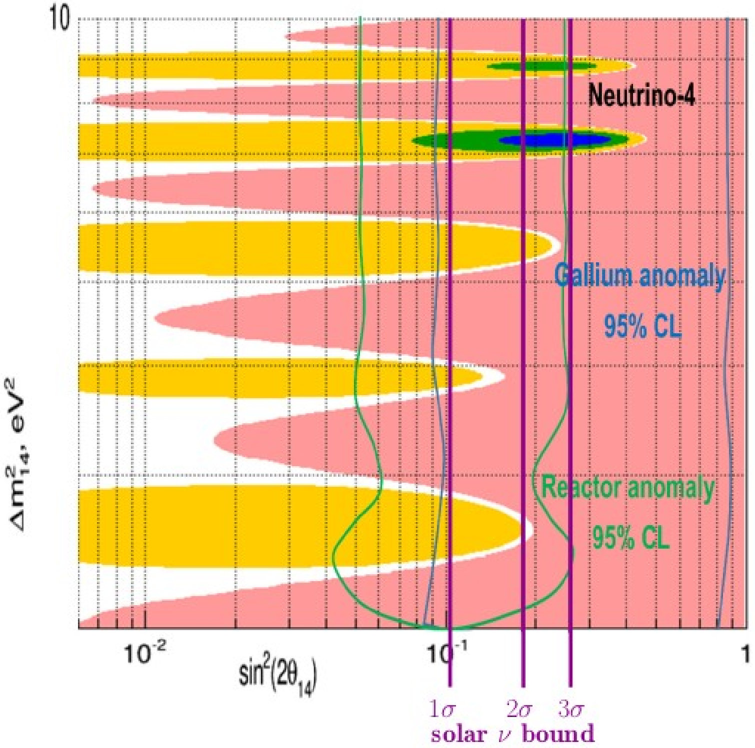


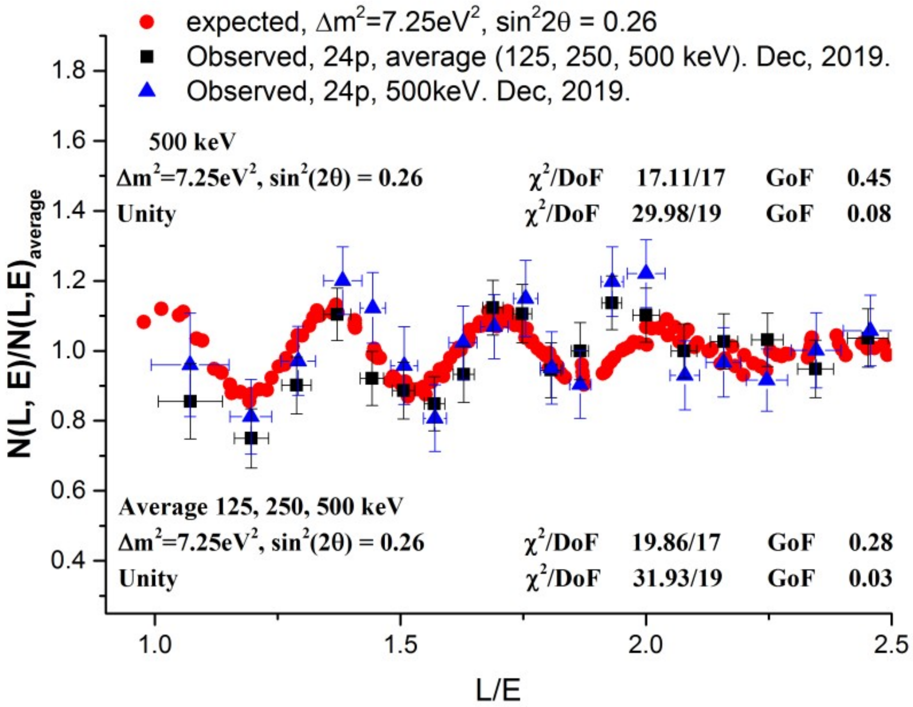
No preference at all for oscillations in DANSS data

no closed contours at 2σ

we can only set upper limits on $|U_{e4}|^2 = \sin^2\theta_{14}$

Neutrino-4





Neutrino-4 observes sterile oscillations at ~3σ

Very large mixing In tension with solar data

Neutrino-4

$$R_{ik}^{\mathrm{the}} = \frac{1 - \sin^2 2\vartheta_{ee} \left\langle \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)\right\rangle_{ik}}{1 - \sin^2 2\vartheta_{ee}\, n_L^{-1} \sum_{k'=1}^{n_L} \left\langle \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)\right\rangle_{ik'}}$$

For the predicted number of events one needs to average over the oscillation term

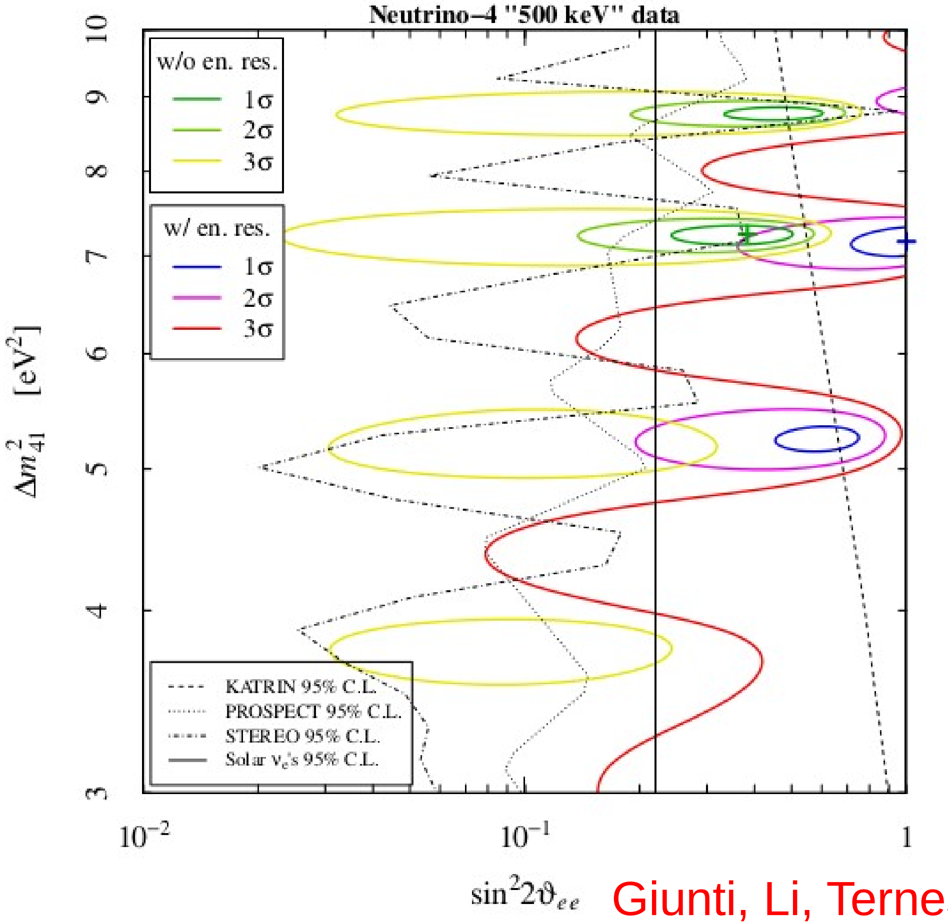
Averaging contains integration over flux, distance, detector resolution

$$\left\langle \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)\right\rangle_{ik} = \frac{\int_{L_k^{\min}}^{L_k^{\max}} dL\, L^{-2} \int_{E_i^{\min}}^{E_i^{\max}} dE'_{\mathrm{p}} \int dE_{\mathrm{p}}\, R(E_{\mathrm{p}}, E'_{\mathrm{p}}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \phi_{\bar{\nu}_e}(E)\, \sigma_{\bar{\nu}_e p}(E)}{\int_{L_k^{\min}}^{L_k^{\max}} dL\, L^{-2} \int_{E_i^{\min}}^{E_i^{\max}} dE'_{\mathrm{p}} \int dE_{\mathrm{p}}\, R(E_{\mathrm{p}}, E'_{\mathrm{p}})\, \phi_{\bar{\nu}_e}(E)\, \sigma_{\bar{\nu}_e p}(E)}$$

Using energy calibration information from 2005.05301 we extract the approximate energy resolution function

$$R(E_{\mathrm{p}}, E'_{\mathrm{p}}) = \frac{1}{\sqrt{2\pi}\sigma_{E_p}} \exp\left(-\frac{(E_{\mathrm{p}} - E'_{\mathrm{p}})^2}{2\sigma_{E_p}^2}\right) \qquad \sigma_{E_p} = 0.19\sqrt{\frac{E_p}{\mathrm{MeV}}}\,\mathrm{MeV}.$$

Neutrino-4



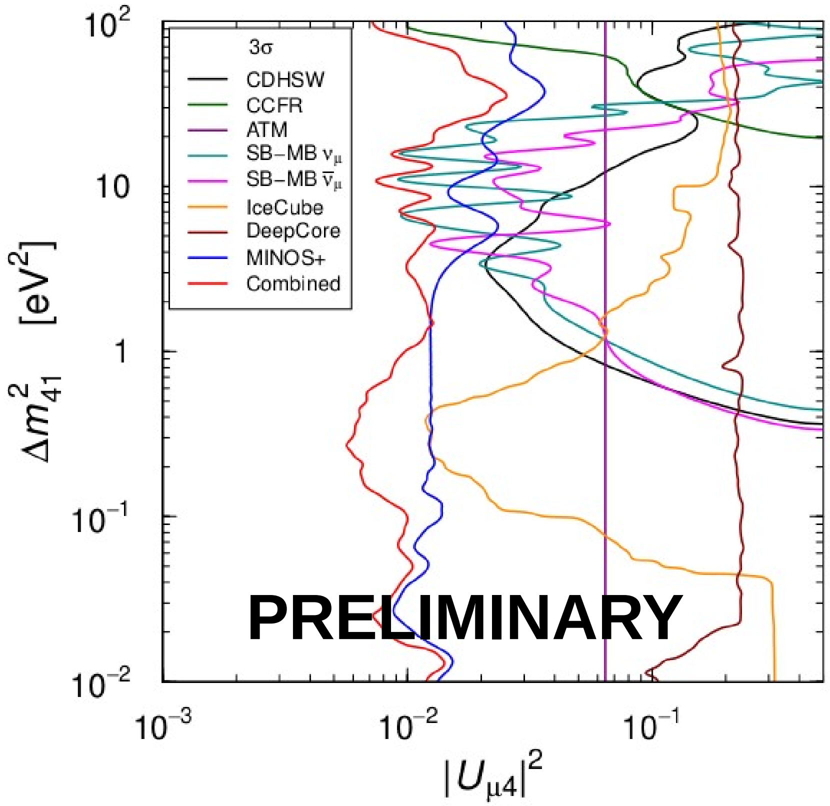
We can only reproduce Neutrino-4 confidence regions when not including energy resolution

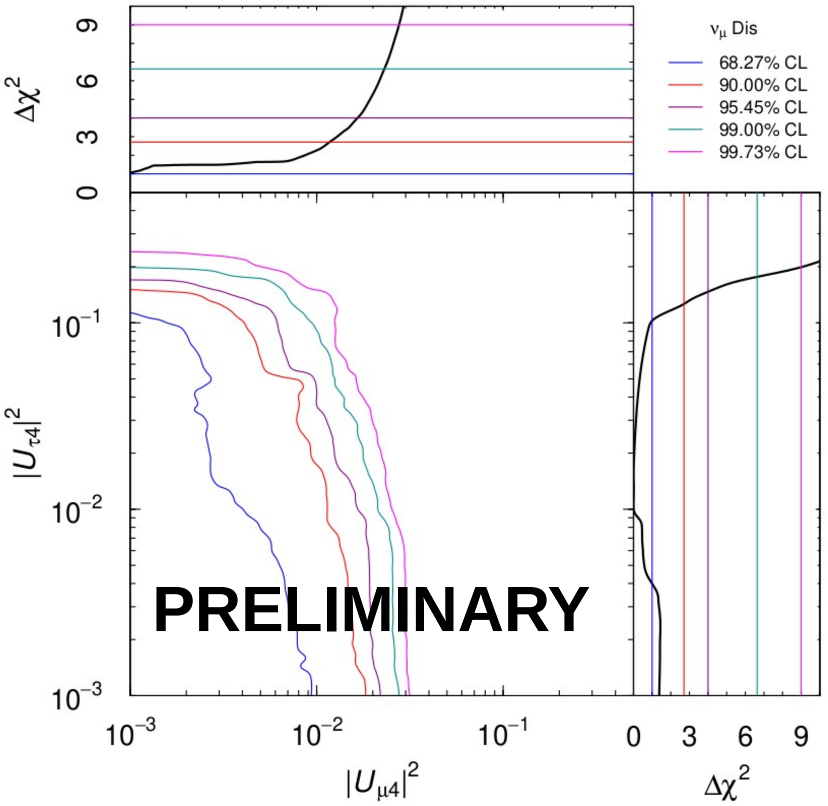
Inclusion shifts the best fit to even larger values, but reduces the preference for sterile oscillations

Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

Other channels

No evidence in muon disappearance

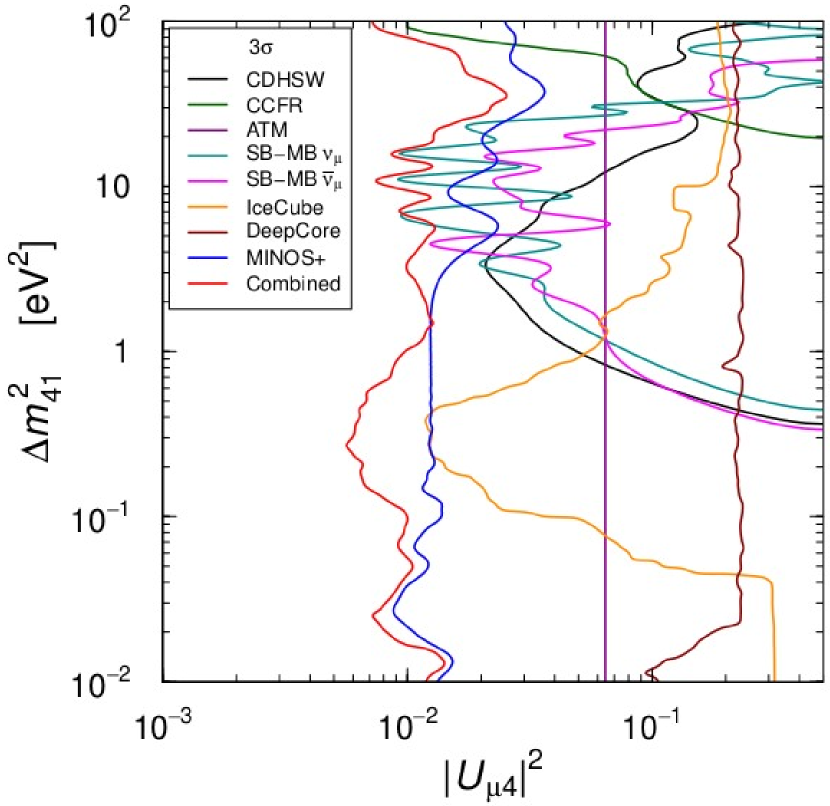


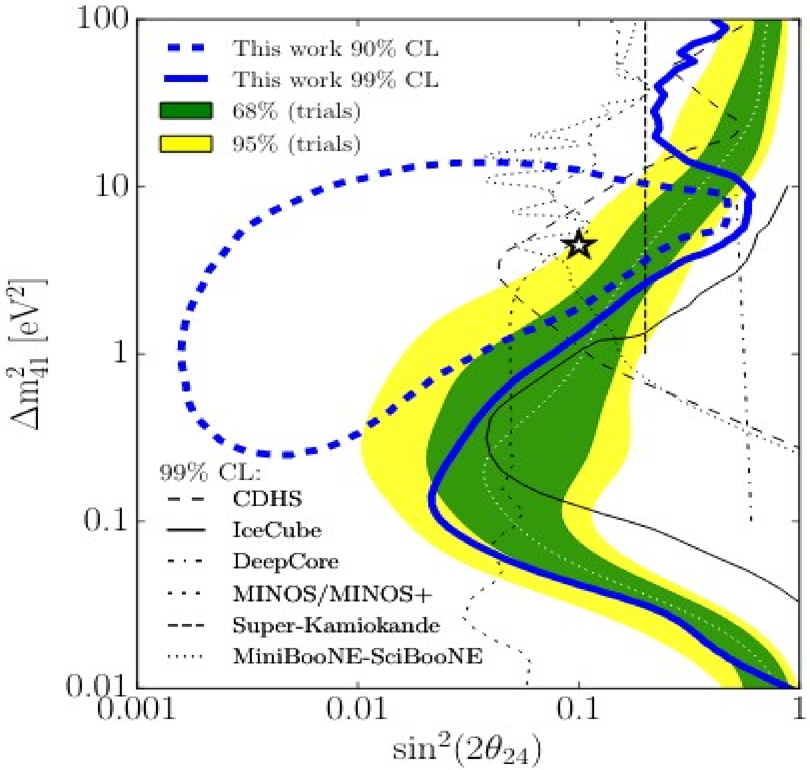


Other channels

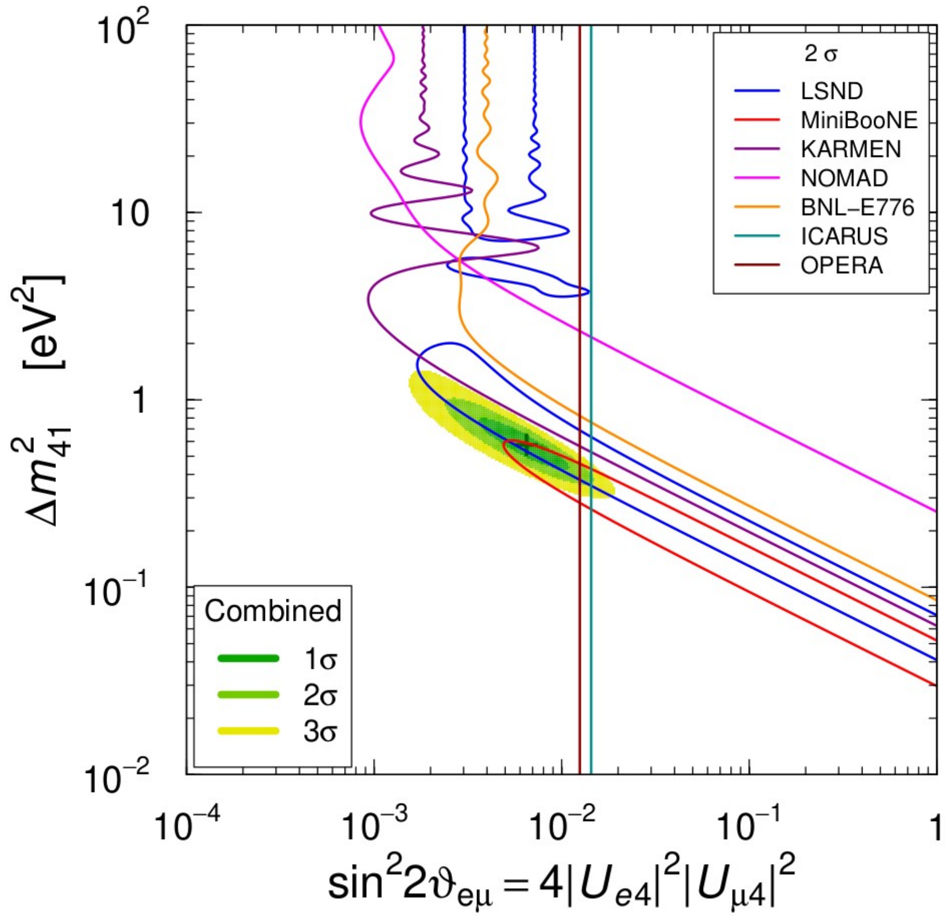
No evidence in muon disappearance

IceCube, 2005.12942, PRL 2020





Other channels

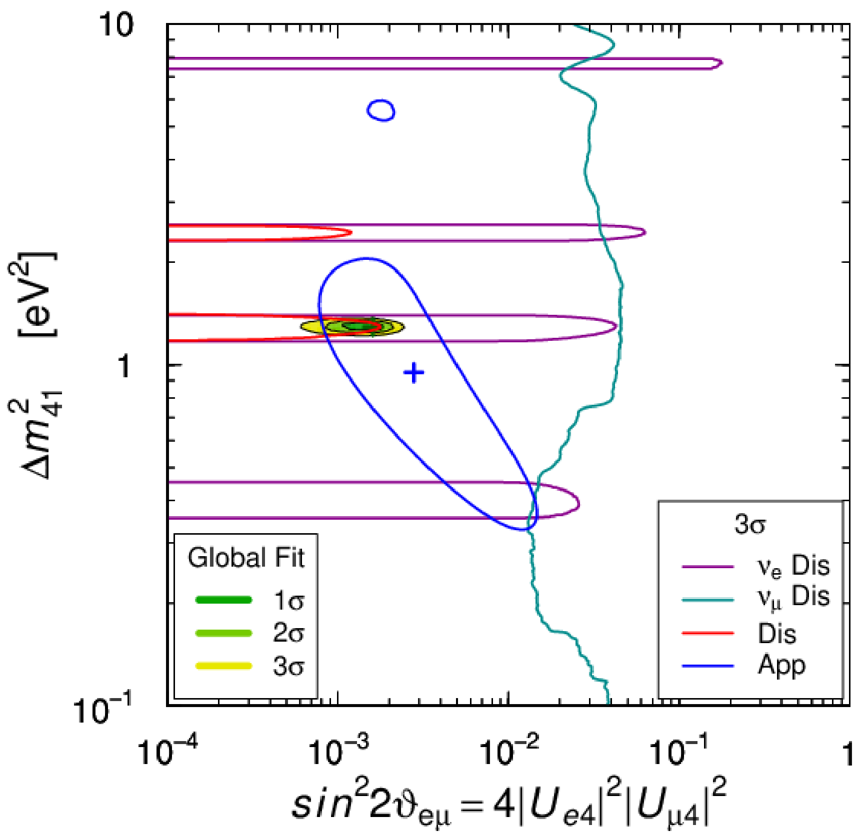


Strong preference in appearance channel

The best fit value of MiniBooNE is excluded by Icarus and Opera

LSND and MiniBooNE only partially agree

Global fit?



$$\nu_e \to \nu_e : |U_{e4}|^2 = \sin^2\theta_{14}$$

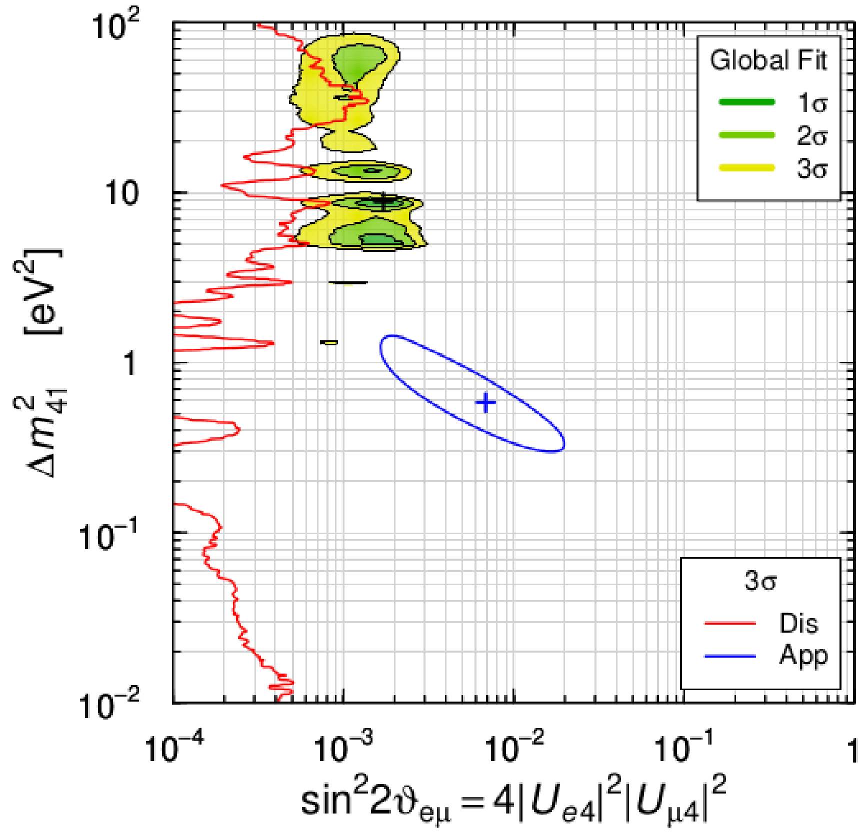
$$\nu_\mu \to \nu_\mu : |U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

$$\nu_\mu \to \nu_e : \sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2|U_{\mu 4}|^2$$

Gariazzo, Giunti, Laveder, Li, 1703.00860, JHEP 2017

See also: Dentler, et al, 1803.10661, JHEP 1808

Global fit?



No overlap anymore!

GoF_{PG}= 7 x 10^{-11}

Global 3+1 fit is unacceptable!

NOT most up-to-date data included in this figure!

Conclusions

Short baseline anomalies can not be explained with 3-neutrino oscillations

There is no reactor antineutrino anomaly using the newest flux calculations

The preference for 3+1 mixing from ratio experiments is fading away, the Neutrino-4 result is doubtful

No significant preference for sterile neutrinos from disappearance experiments!

A global 3+1 fit is statistically unacceptable

What were LSND and MiniBooNE observing?


Thanks!
electron-neutrino
muon neutrino
tau-neutrino