Global fit to ν_μ disappearance data with sterile neutrinos

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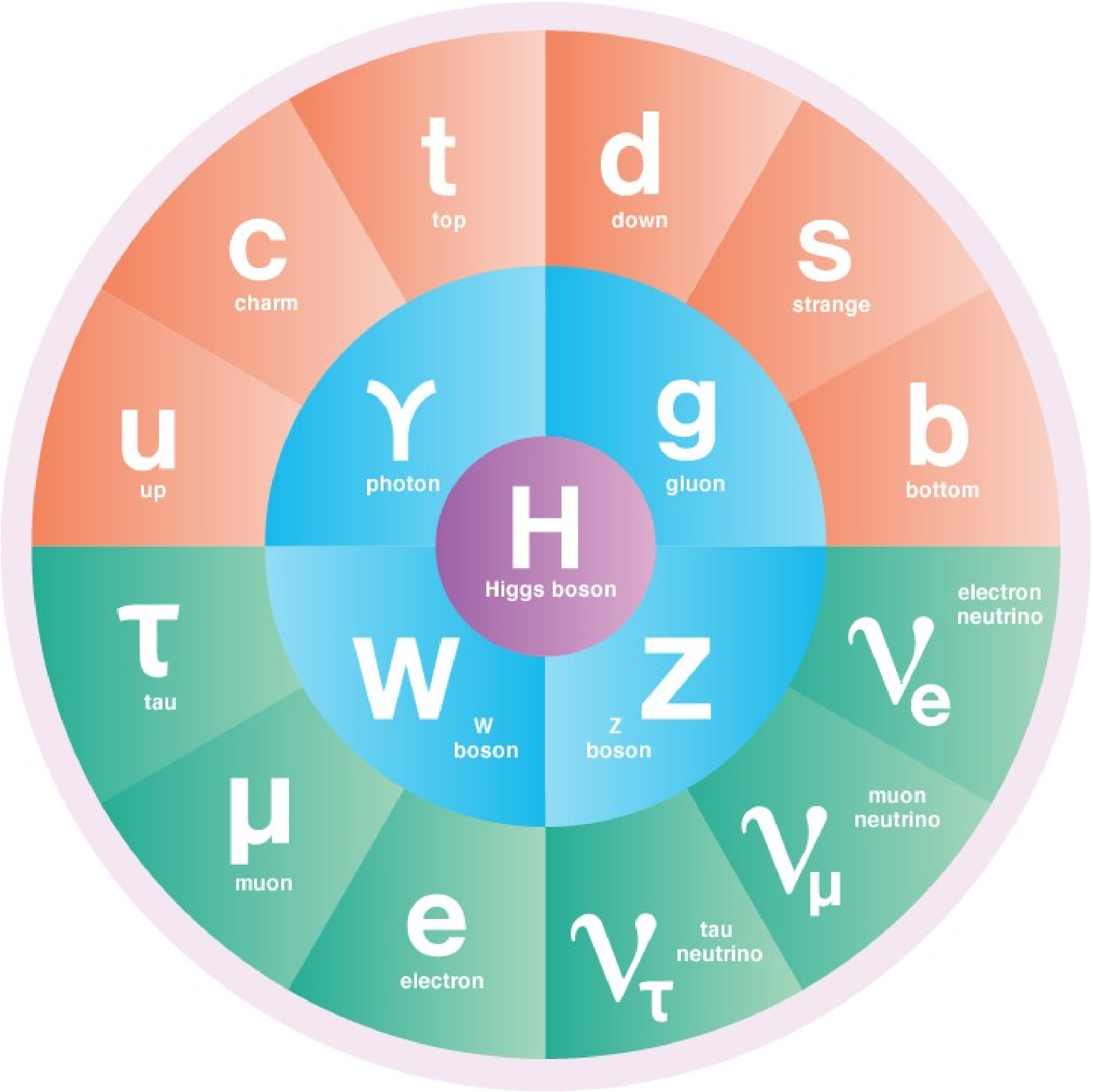
IFIC, Universitat de València/CSIC

The 27th International Workshop on Weak Interactions and Neutrinos

Bari, June 5th, 2019

Standard model of particle physics



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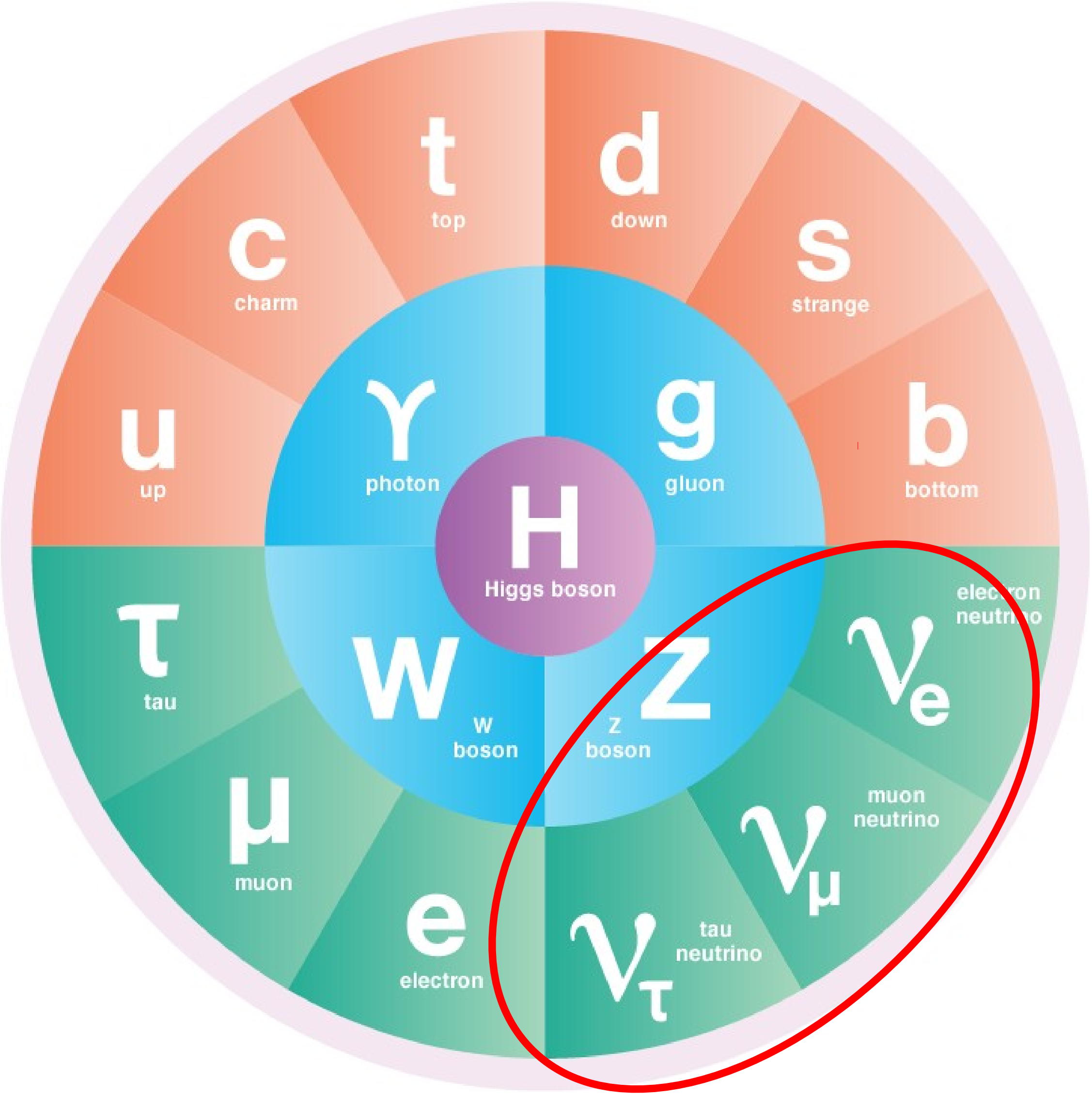
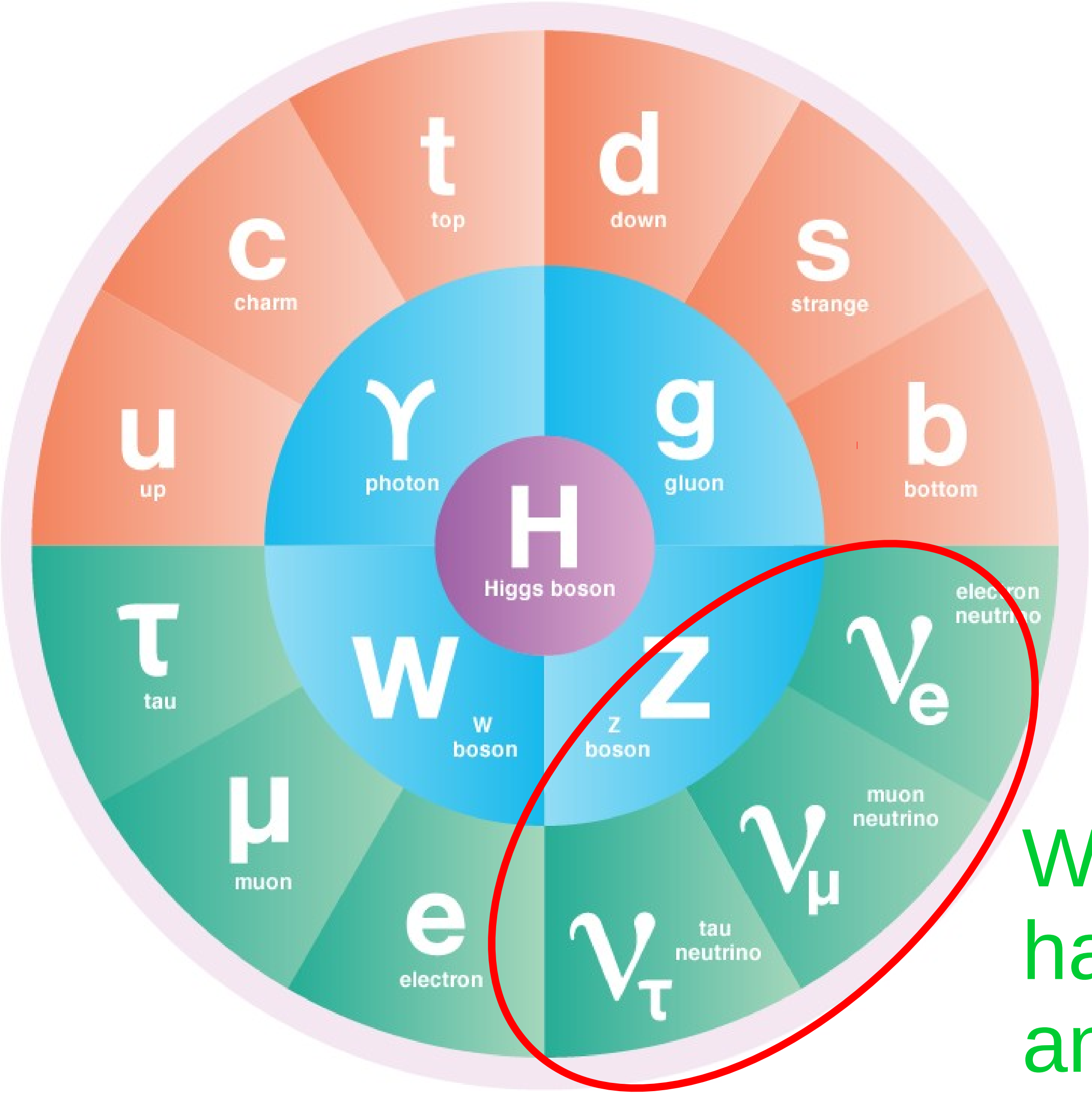


3ν in SM

Standard model of particle physics*

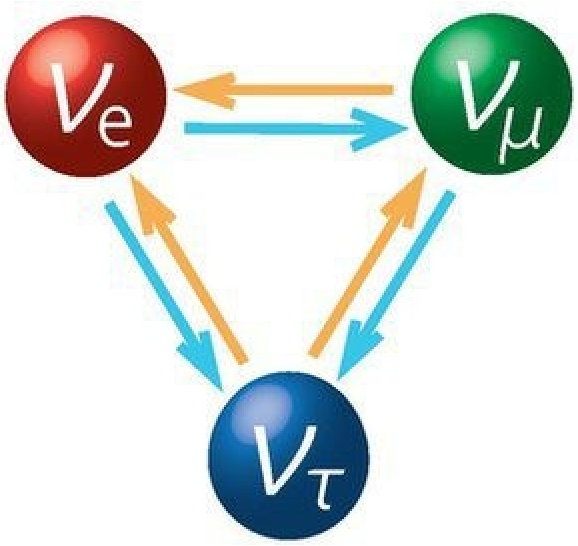


3ν in SM

We know they have masses and they mix

*with massive neutrinos

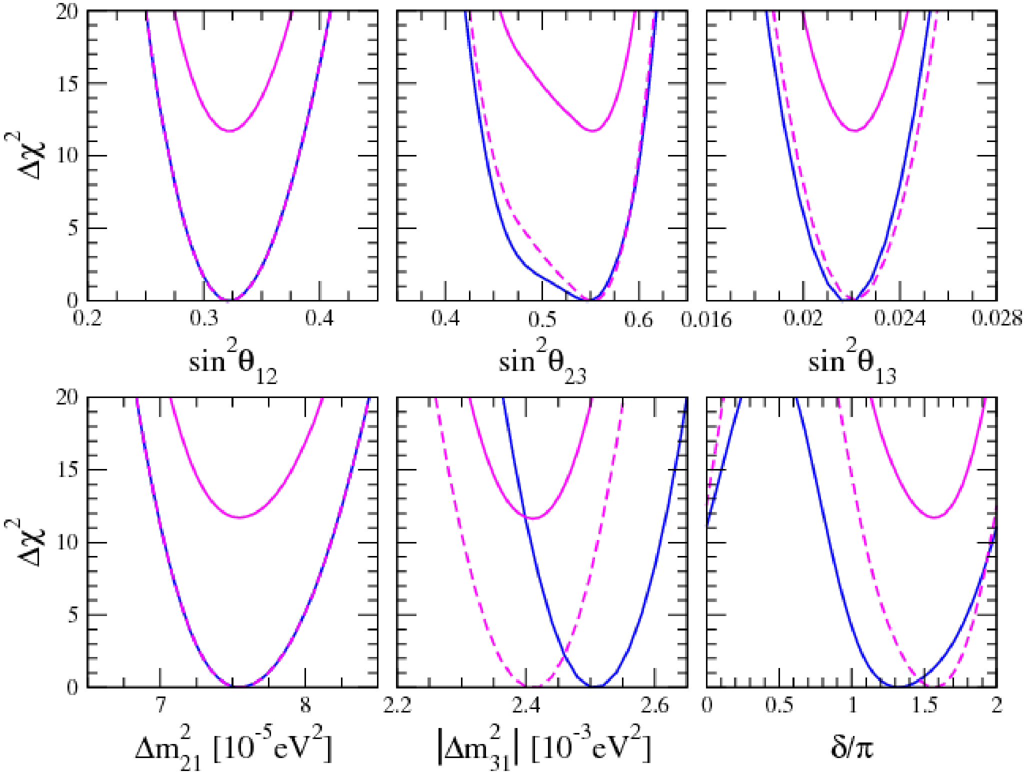
Three-neutrino oscillations



Three-neutrino oscillations

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

parameter	best fit $\pm 1\sigma$	3σ range
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

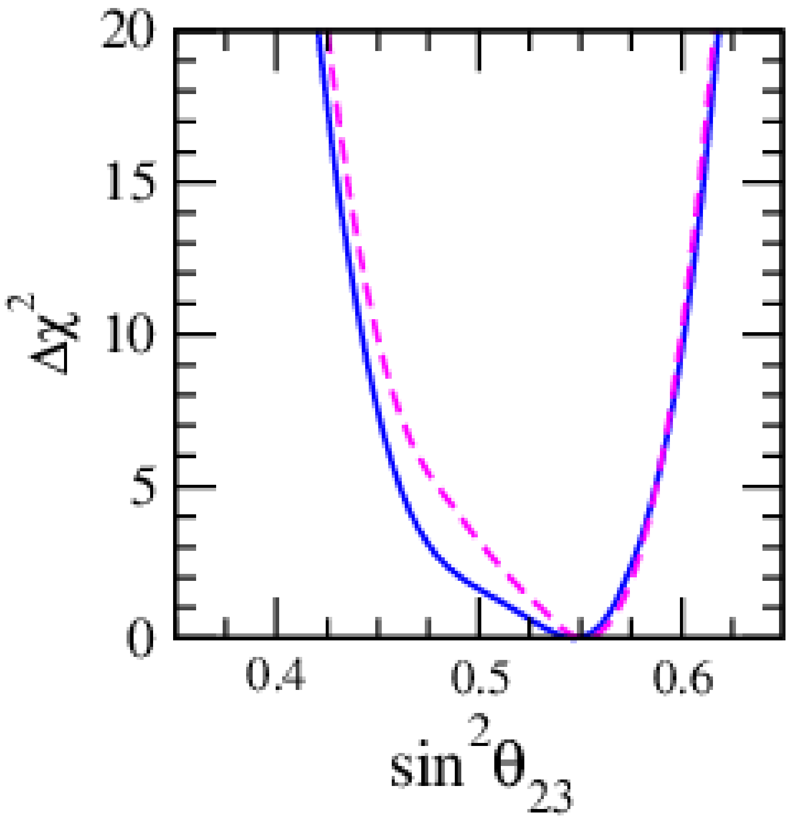


Phys.Lett. B782 (2018) 633-640, P.F. de Salas, D.V. Forero, CAT, M. Tórtola, J.W.F. Valle
https://globalfit.astroparticles.es/

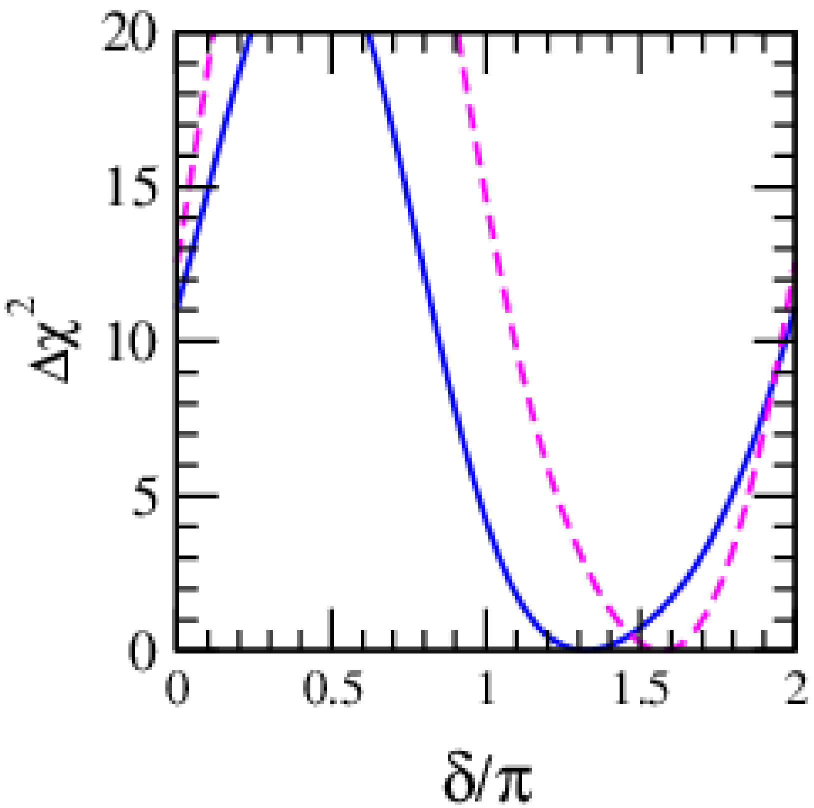
See also: -Bari-group (Prog.Part.Nucl.Phys. 102 (2018) 48-72)
-Nu-fit (JHEP 1901 (2019) 106)

Three-neutrino oscillations

Remaining unknowns are



Atmospheric octant

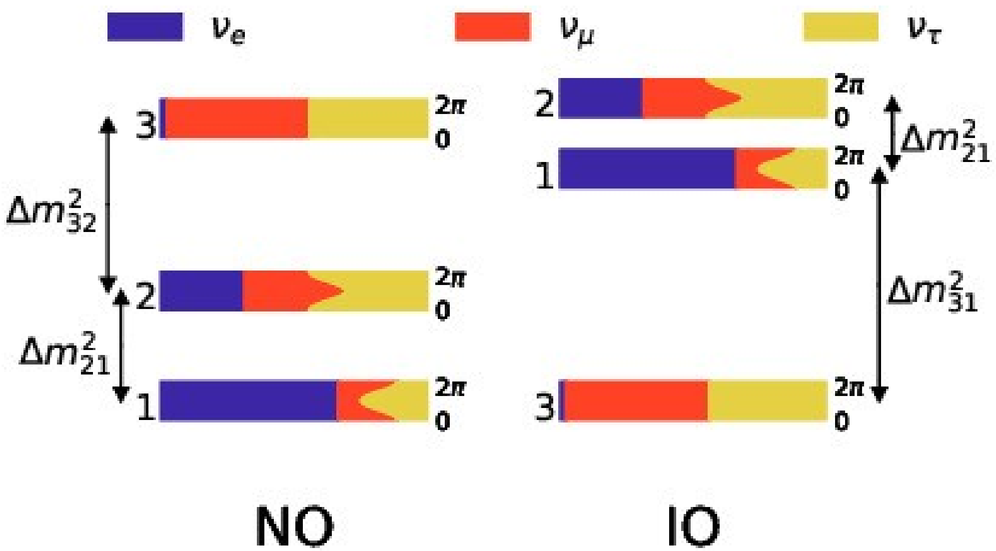


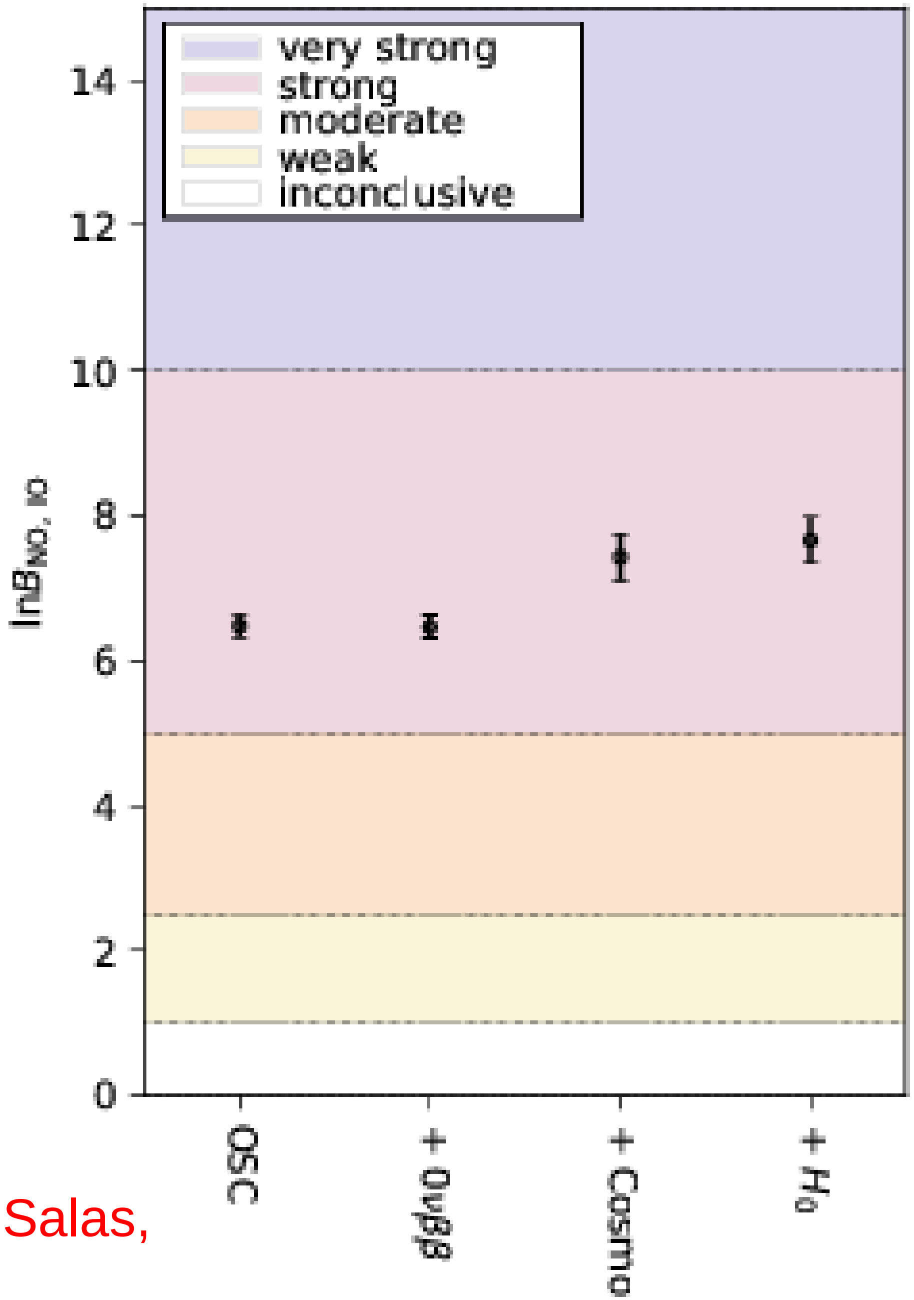
Value of CP-phase

Phys.Lett. B782 (2018) 633-640, P.F. de Salas, D.V. Forero, CAT, M. Tórtola, J.W.F. Valle

Three-neutrino oscillations

Neutrino mass ordering





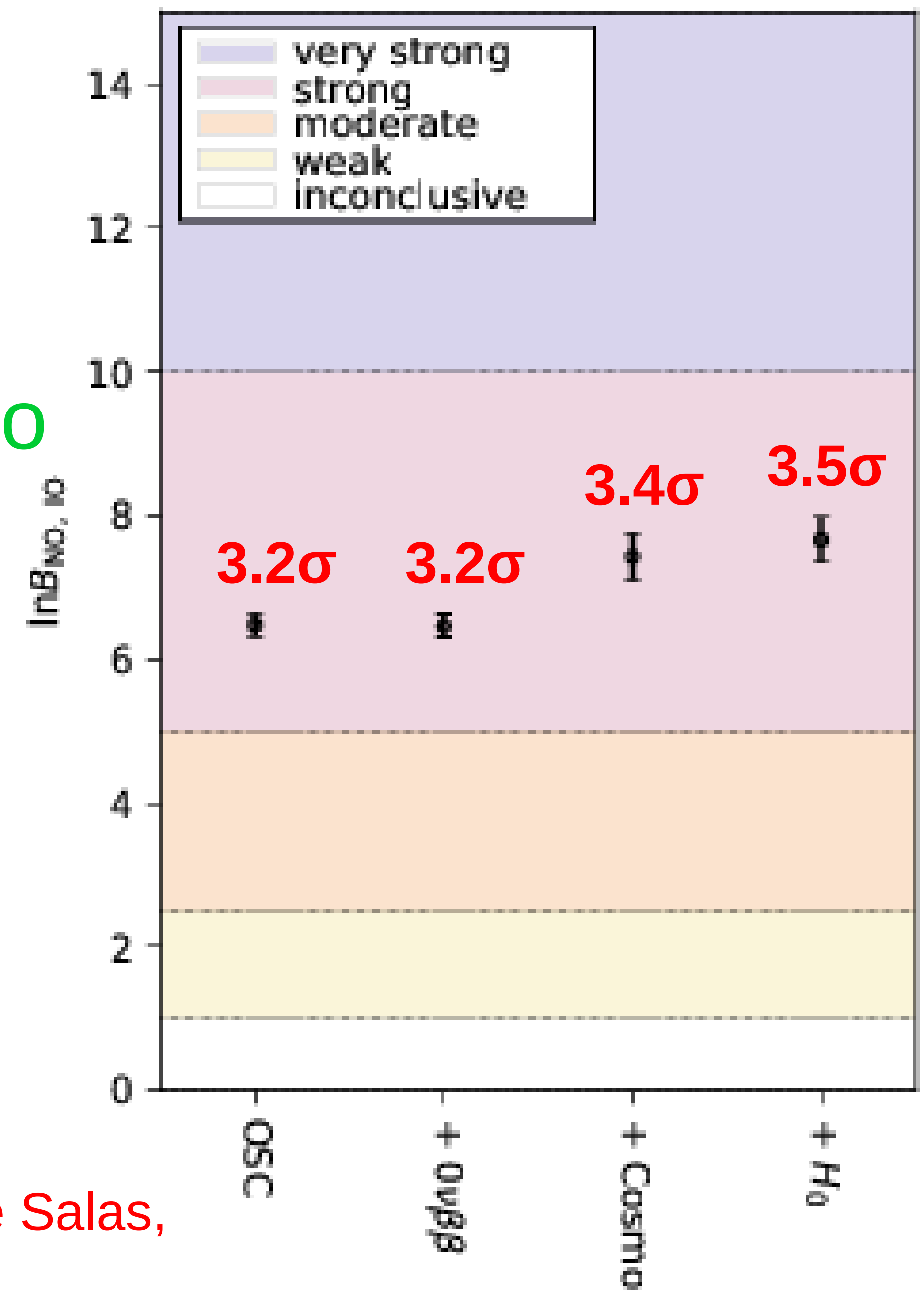
JCAP 1803 (2018) no.03, 011, S. Gariazzo, M. Archidiacono, P.F. de Salas, O. Mena, CAT, M. Tórtola

Front. Astron. Space Sci. 5 (2018) 36, P.F. de Salas, S. Gariazzo, O. Mena, CAT, M. Tórtola

Three-neutrino oscillations

Neutrino mass ordering

Combine with data from decay experiments and cosmological observation using conservative priors to obtain 3.5σ preference for normal ordering



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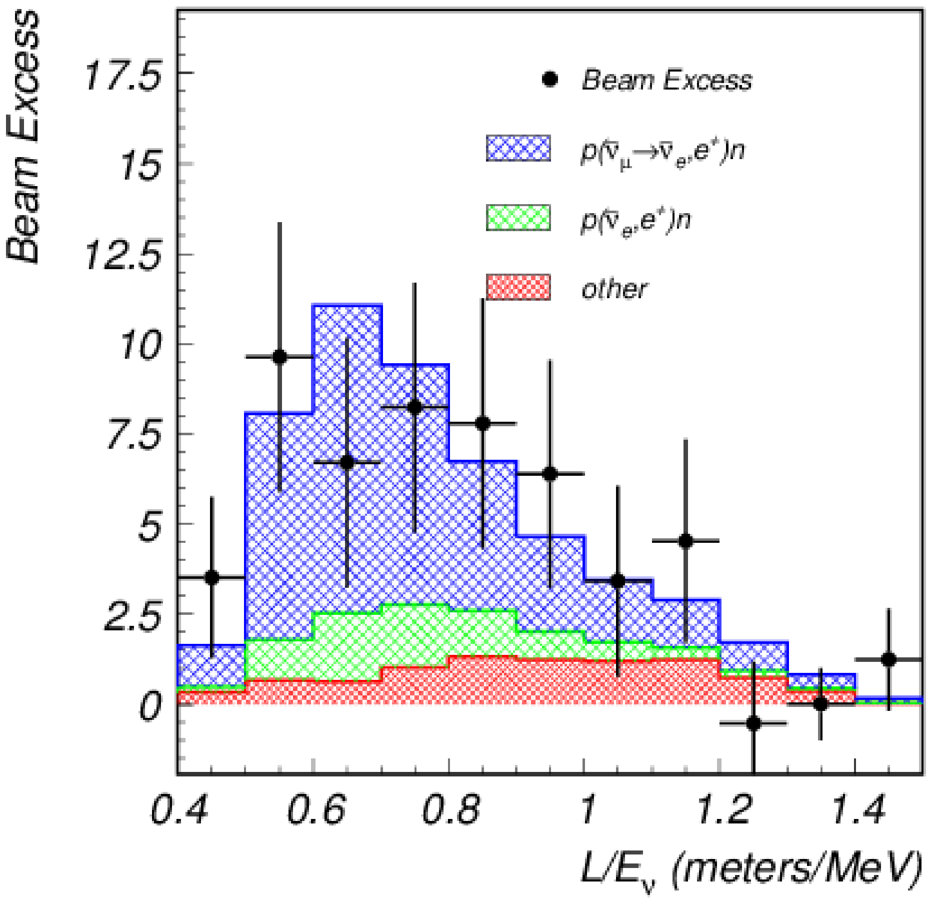
Anomalies in oscillations

LSND

Appearance of electron antineutrinos from a pure source of muon antineutrinos $\overline{\nu}_\mu \to \overline{\nu}_e$ for energies 20 MeV < E < 52.8 MeV over 30m



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PRL 75 (1995) 2650
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PRL 77 (1996) 3082
PRD 64 (2001) 112007

Karmen
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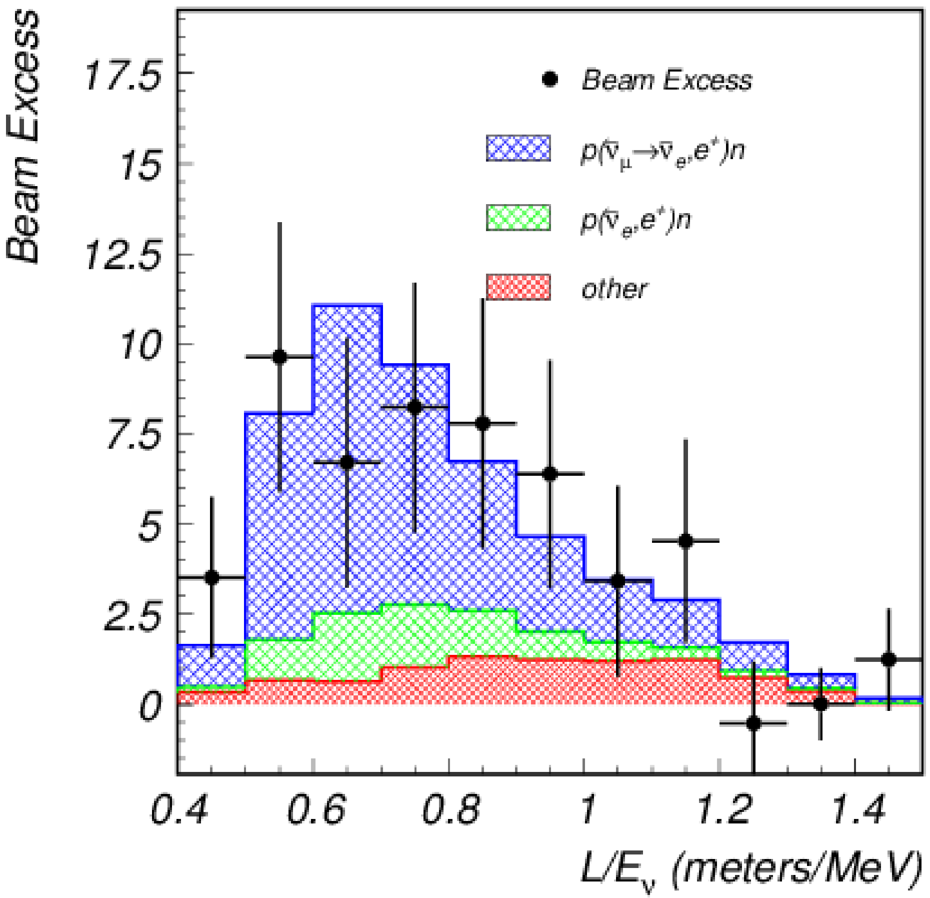
LSND saw a 3.8σ excess



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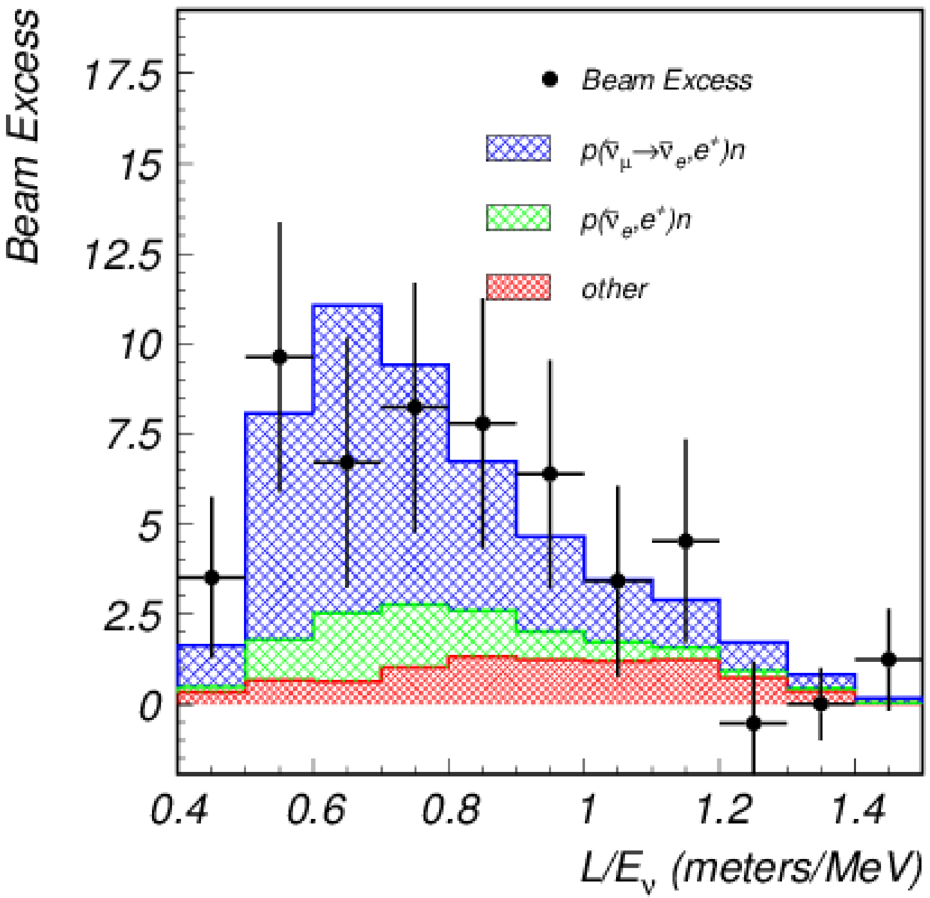
No signal seen by **Karmen** at 18m (same technique)



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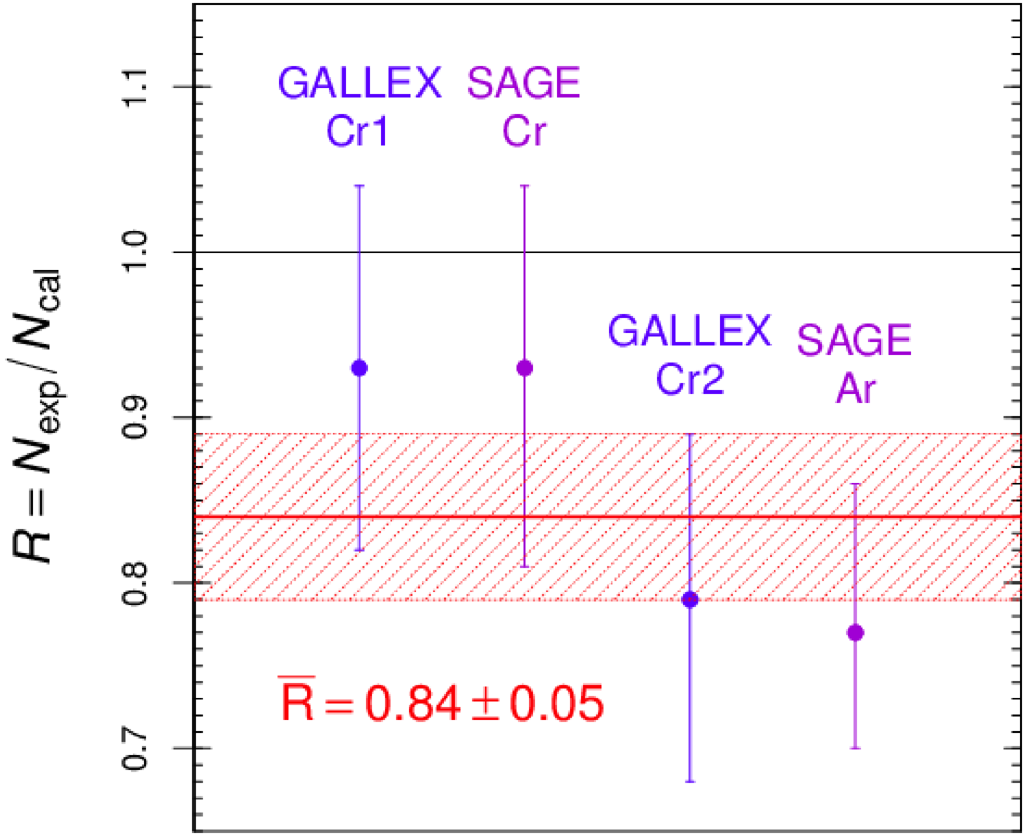
Gallium anomaly

Gallium Radioactive Source Experiments **Gallex** and **Sage**



PRC 73 (2006) 045805, **SAGE**
PRC 80 (2009) 015807, **SAGE**
Nucl.Phys.Proc.Suppl. 168 (2007) 344, Laveder et al
PRD 78 (2008) 073009 and PRC 83 (2011) 065504, C. Giunti et al

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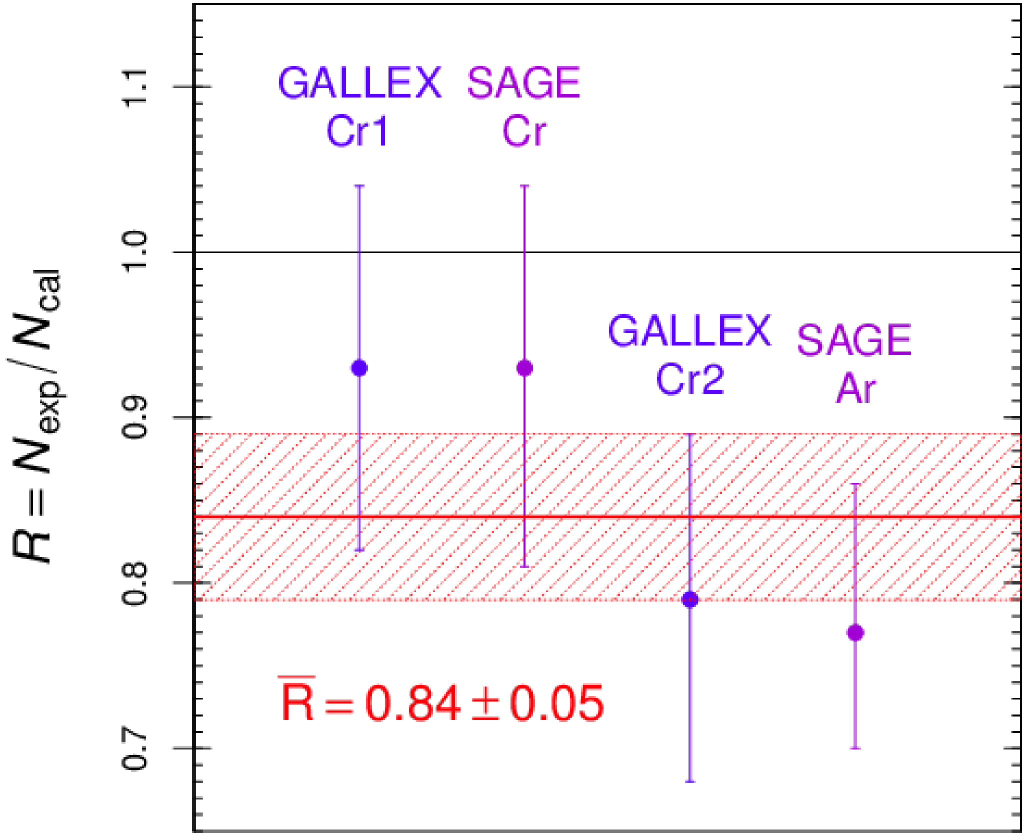
Measure electron neutrinos $\nu_e \to \nu_e$



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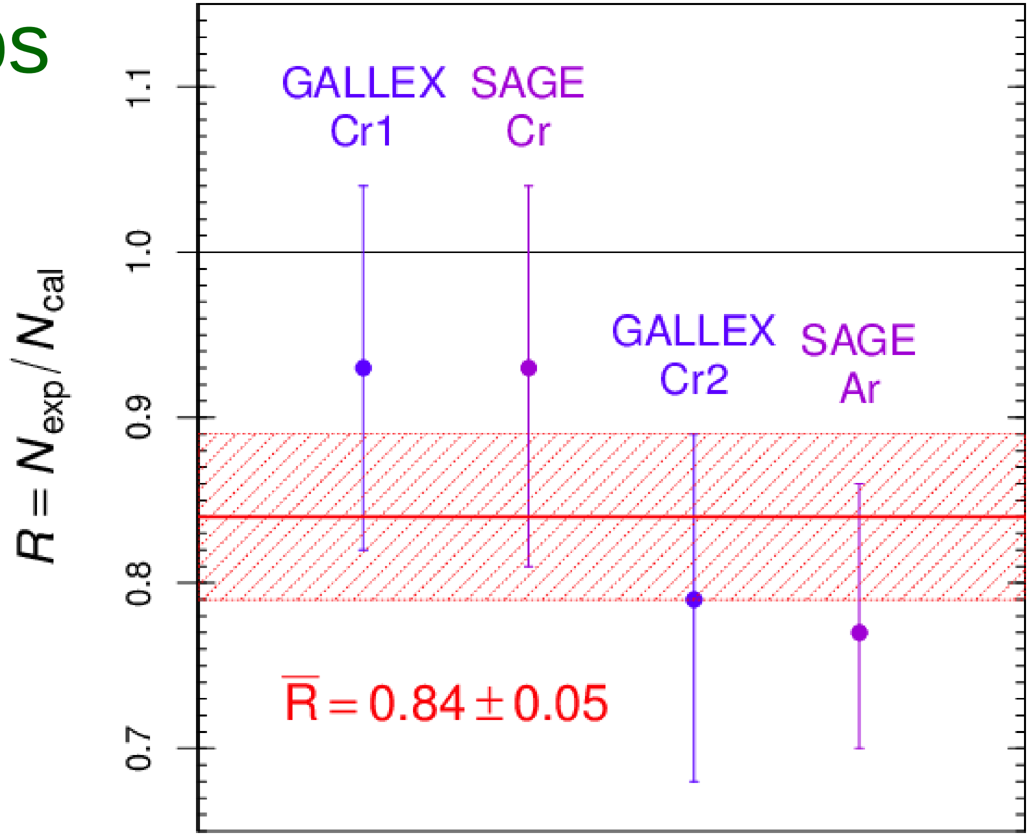
~3σ deficit of neutrinos



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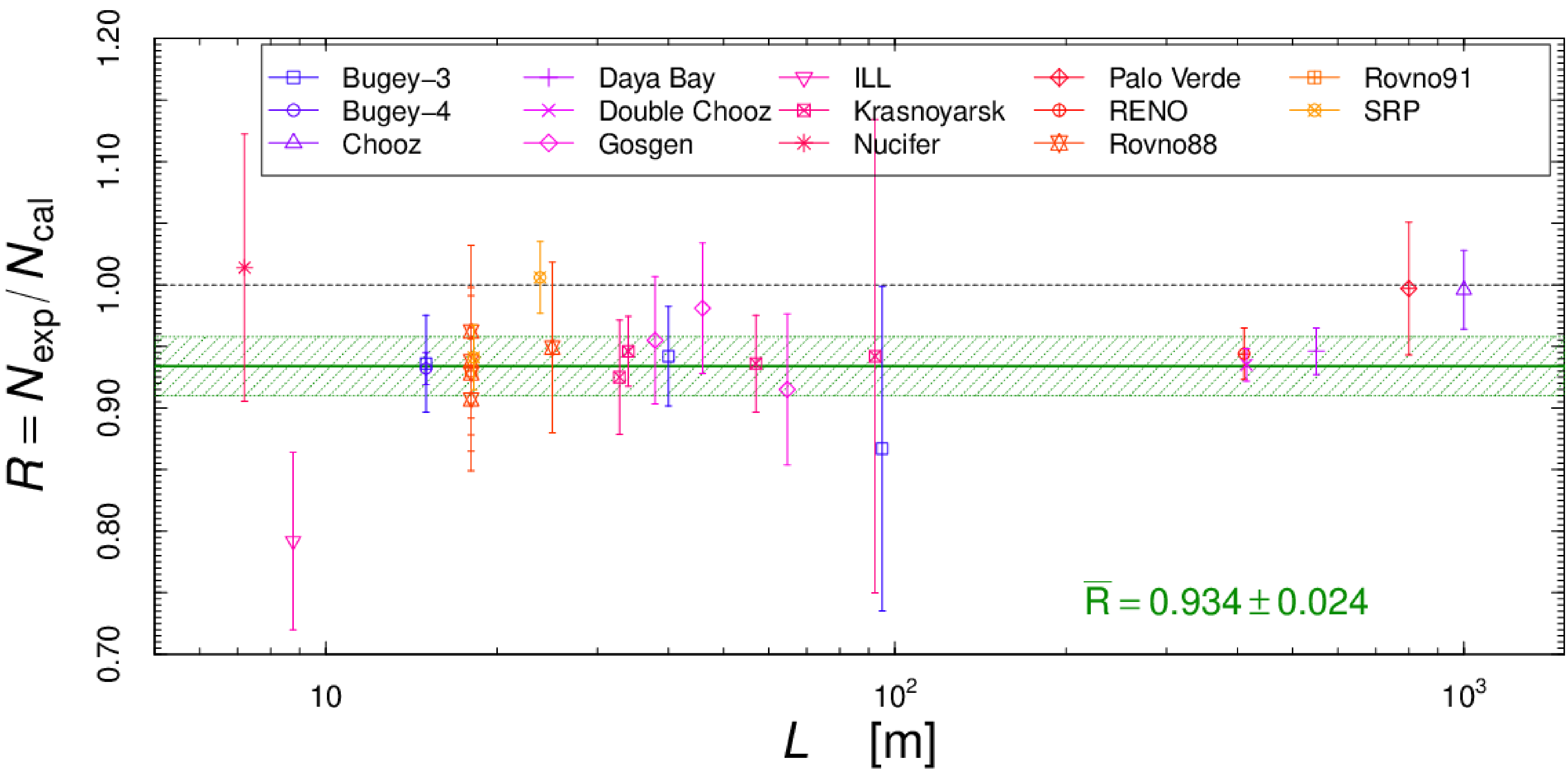
PRD 78 (2008) 073009 and PRC 83 (2011) 065504, C. Giunti et al

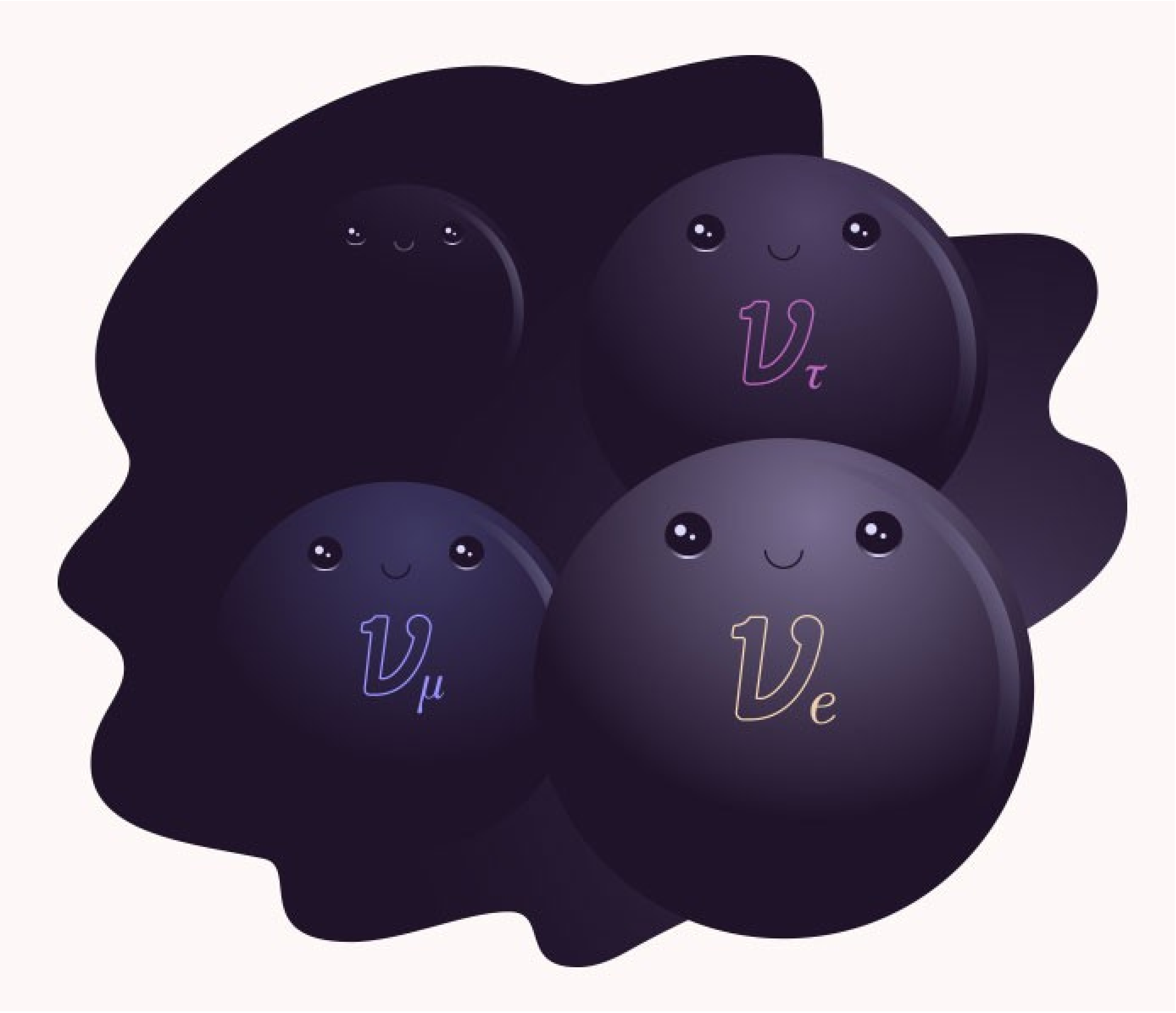
Reactor Antineutrino Anomaly

New reactor antineutrino fluxes, again ~3σ deficit



PRD 83 (2011) 073006, Mention et al
PRC 83 (2011) 054615, Mueller et al
PRC 84 (2011) 024617, Huber

Beyond three-neutrino oscillations



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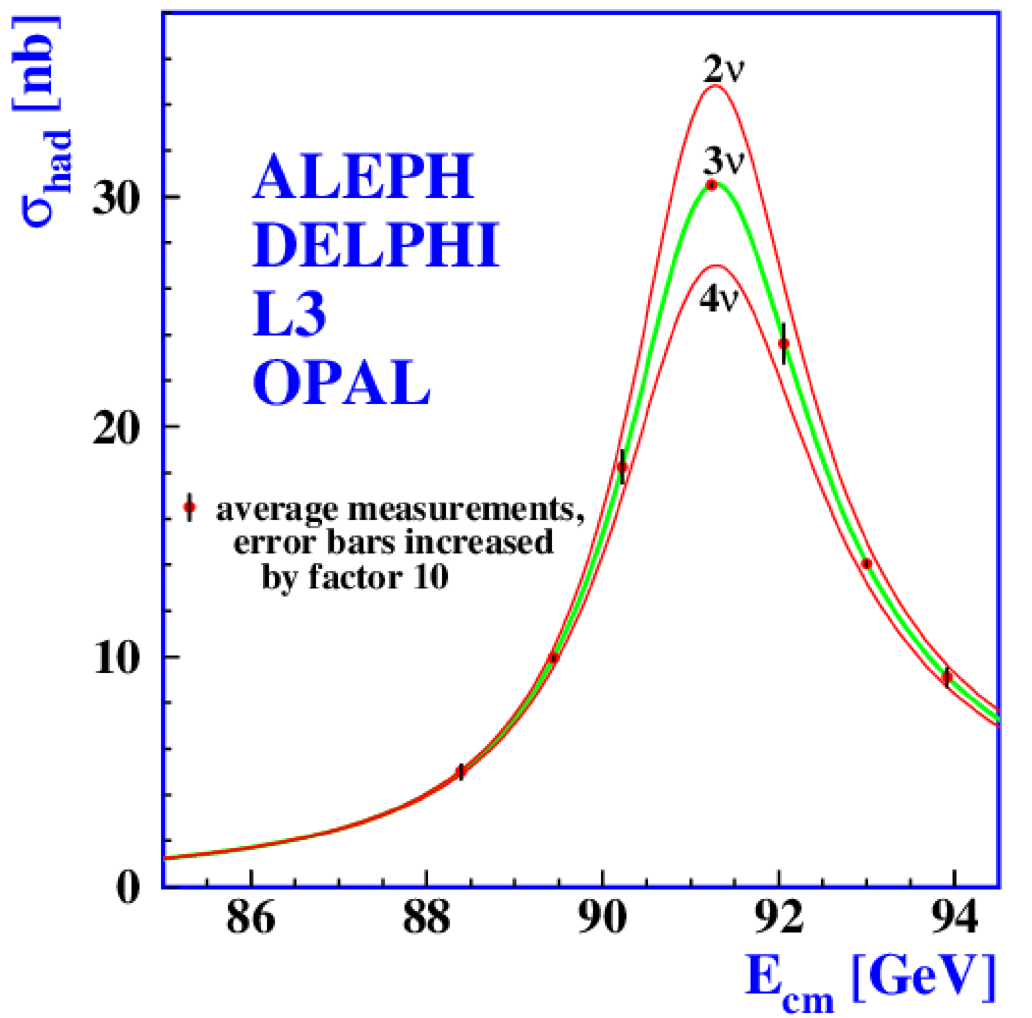
A forth active neutrino is excluded by observations of invisible Z-decays

$$e^+e^- \to Z \to \sum_{j=e,\mu,\tau} \nu_j$$



Phys. Rept. 427 (2006) 257, LEP

3+1 neutrino oscillations

We extend the mixing matrix

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \Rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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DISappearance

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

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@Reactors and **Gallium**

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@Reactors and **Gallium**

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@atmospherics and **accelerators**

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@LSND, **Karmen**, **MiniBooNE**, **Opera**

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@LSND, **Karmen**, **MiniBoone**, **Opera**

Quadratically suppressed

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3+1 neutrino oscillations

In LBL experiments matter effects are important!

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$$\begin{pmatrix} V_{\mathrm{CC}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow \begin{pmatrix} V_{\mathrm{CC}} + V_{\mathrm{NC}} & 0 & 0 & 0 \\ 0 & V_{\mathrm{NC}} & 0 & 0 \\ 0 & 0 & V_{\mathrm{NC}} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

3+1 neutrino oscillations

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Neutral current potential becomes important

3+1 neutrino oscillations

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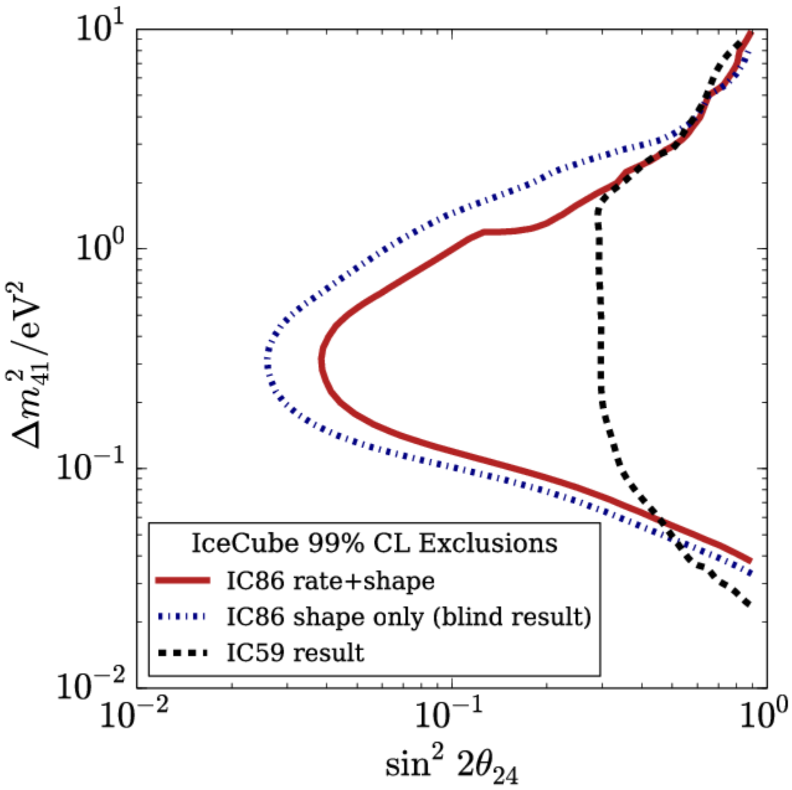
Neutral current potential becomes important

We have to take it into account when diagonalizing the Hamiltonian

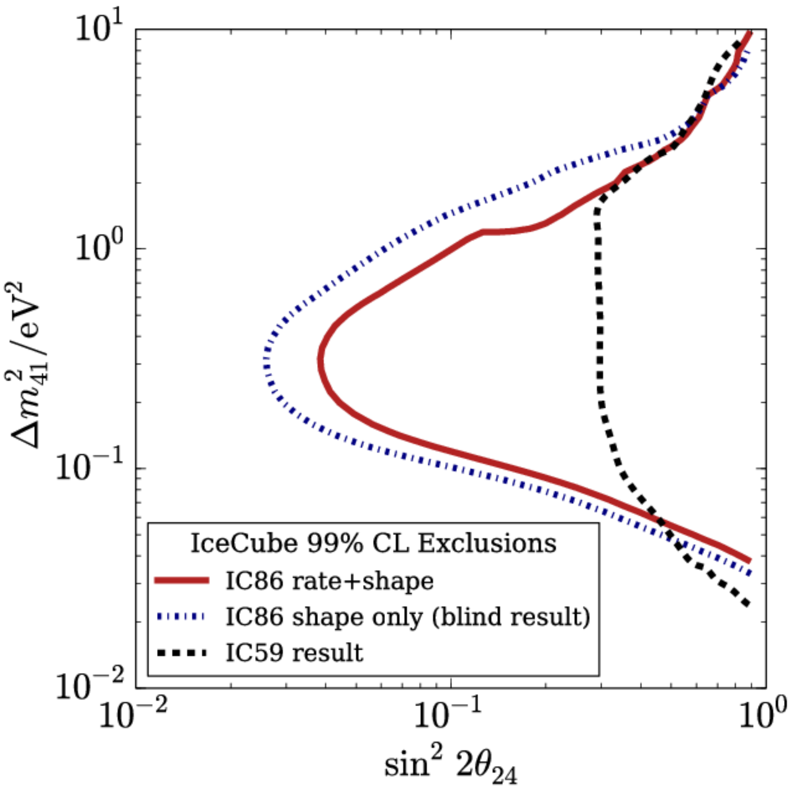
ν_μ disappearance experiments

IceCube and DeepCore



PRL 117 (2016) 071801

IceCube and DeepCore



High-energy regime

0.3 TeV – 20 TeV

PRL 117 (2016) 071801

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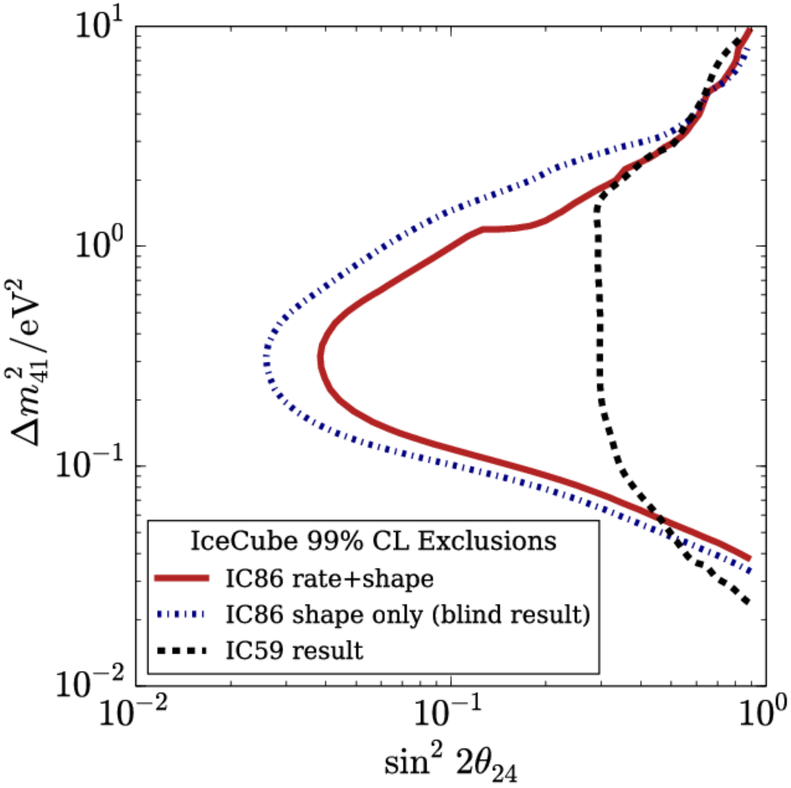

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Waiting for 7 yr update!

PRL 117 (2016) 071801

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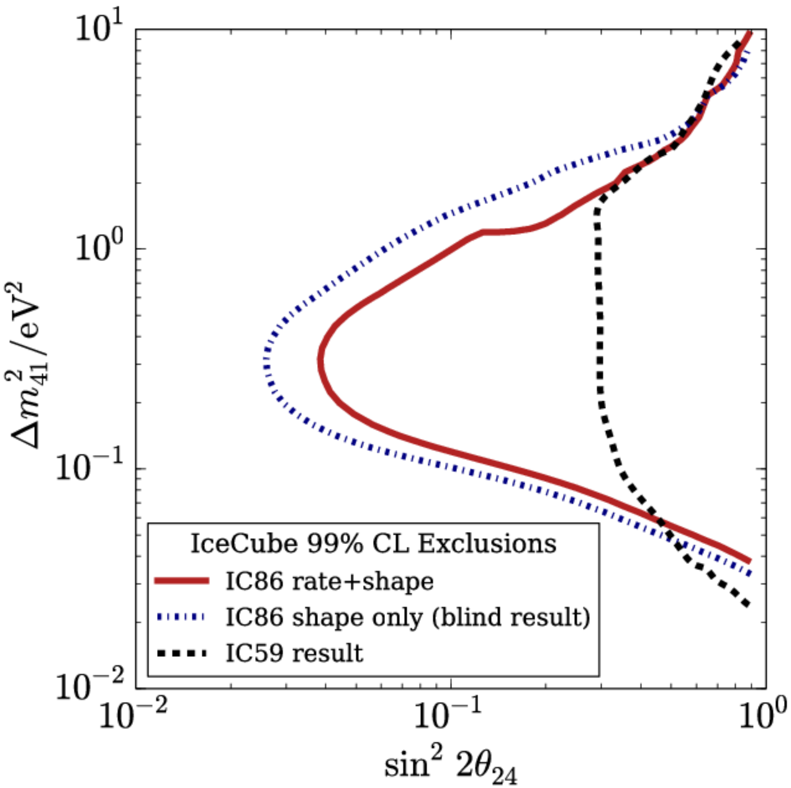

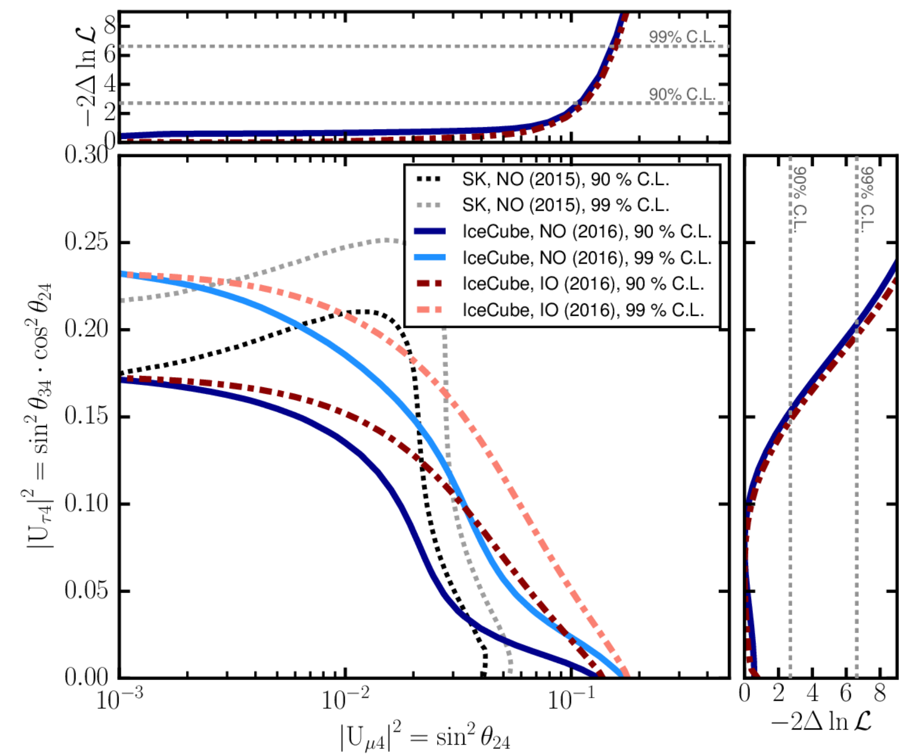

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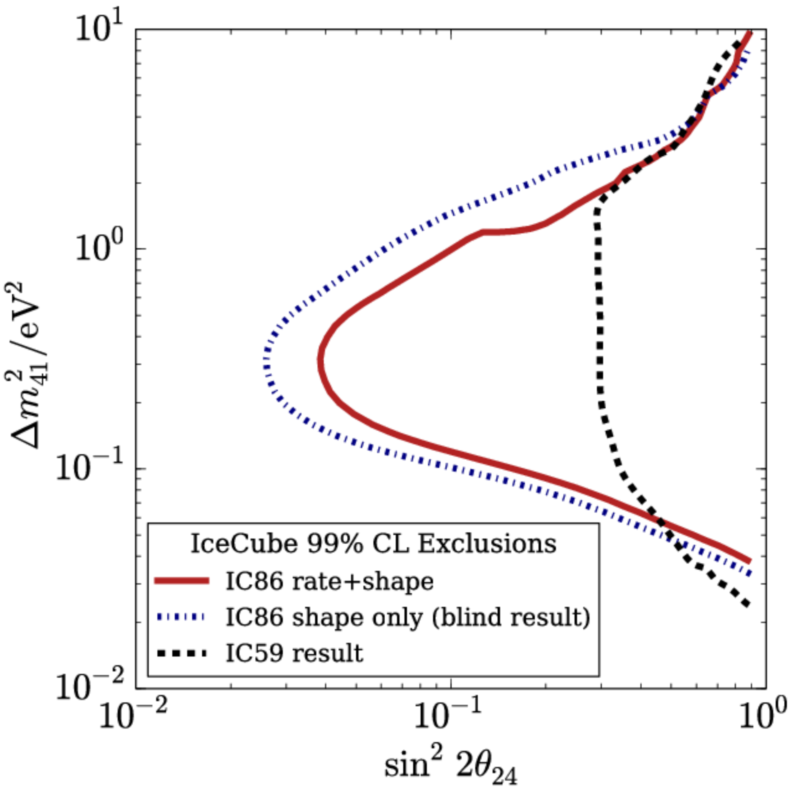
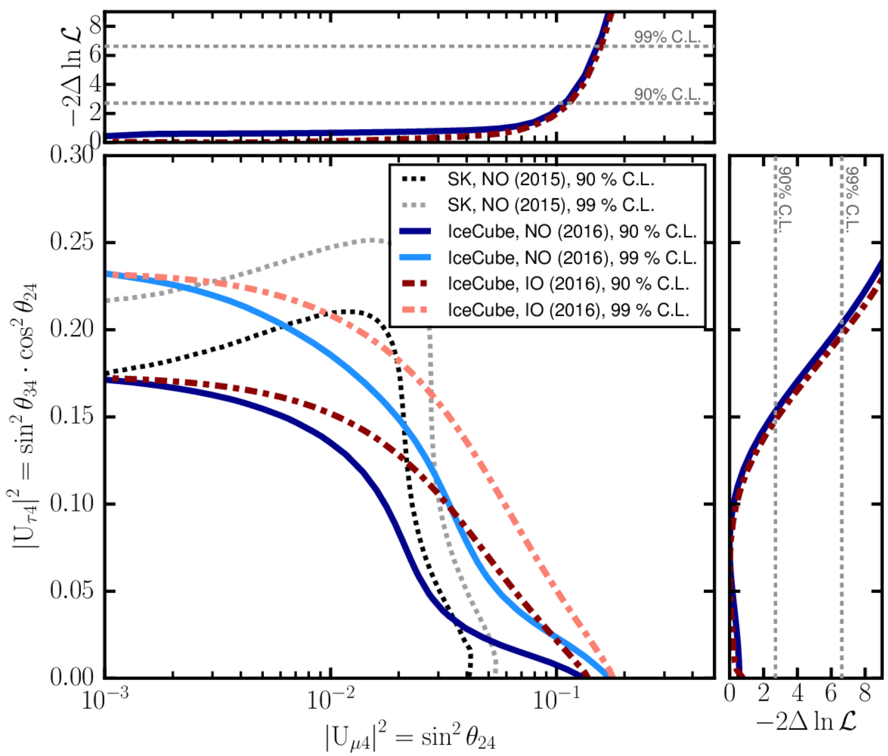
PRL 117 (2016) 071801

PRD 95 (2017) 112002

IceCube and DeepCore





High-energy regime

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Low-energy regime

6 GeV – 56 GeV

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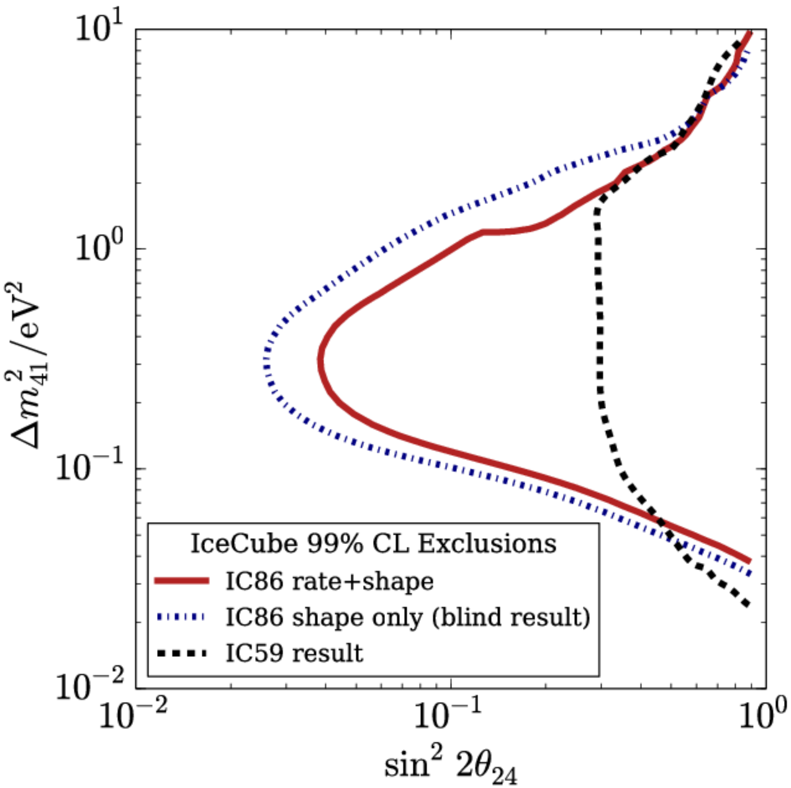
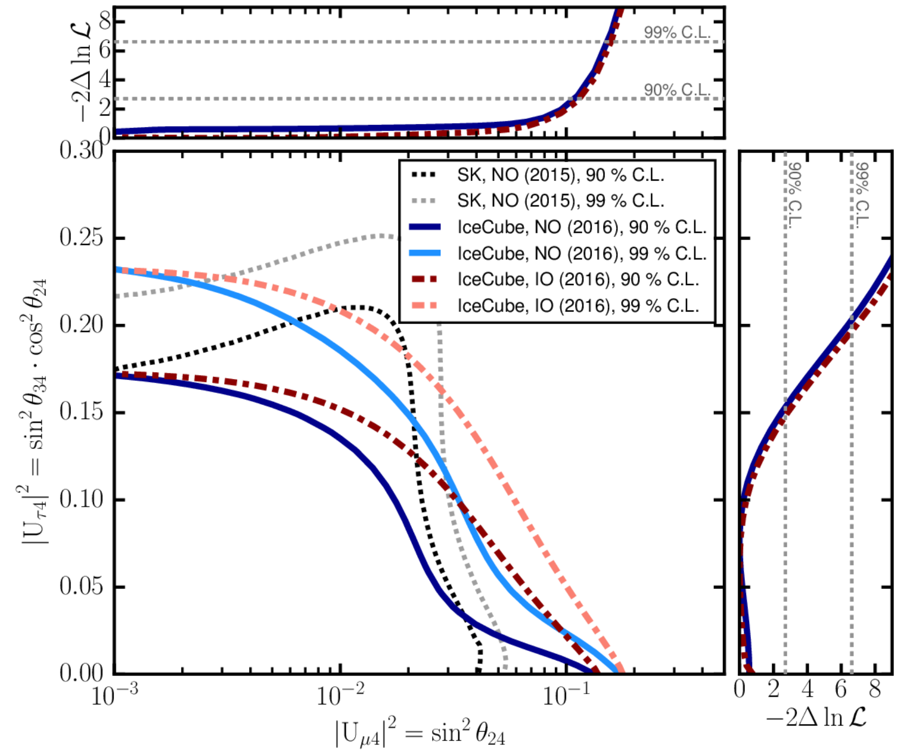
IceCube and DeepCore





High-energy regime

0.3 TeV – 20 TeV

Waiting for 7 yr update!

PRL 117 (2016) 071801

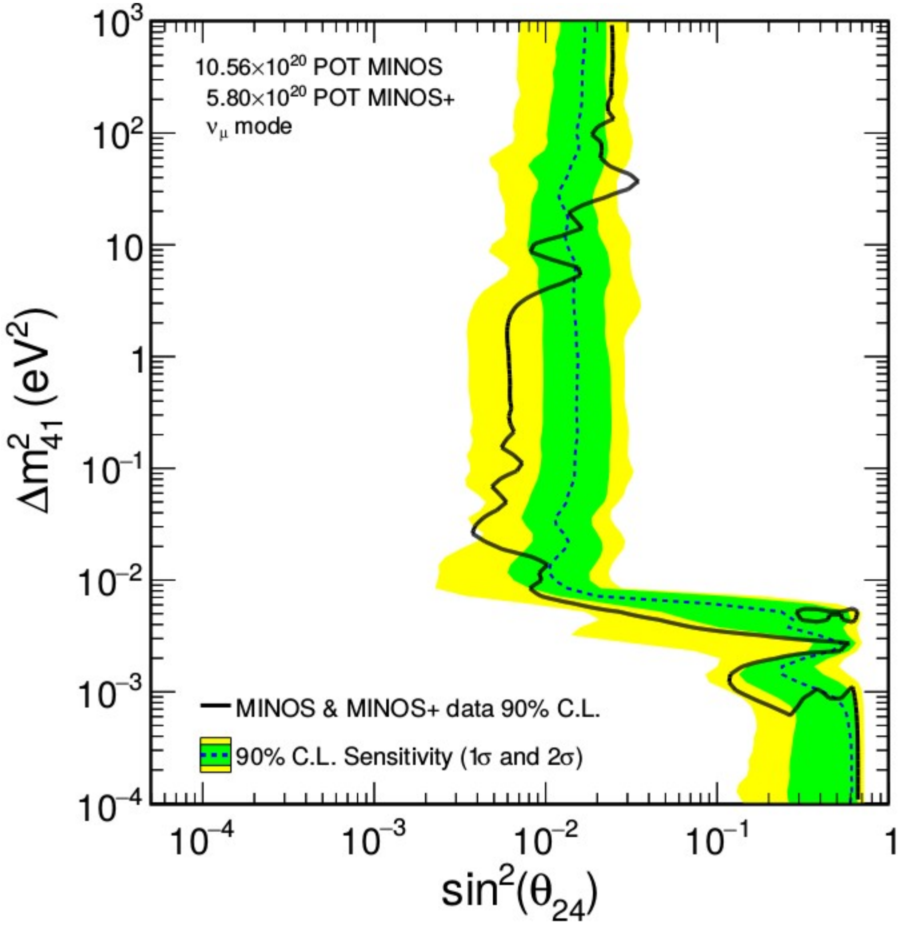
Low-energy regime

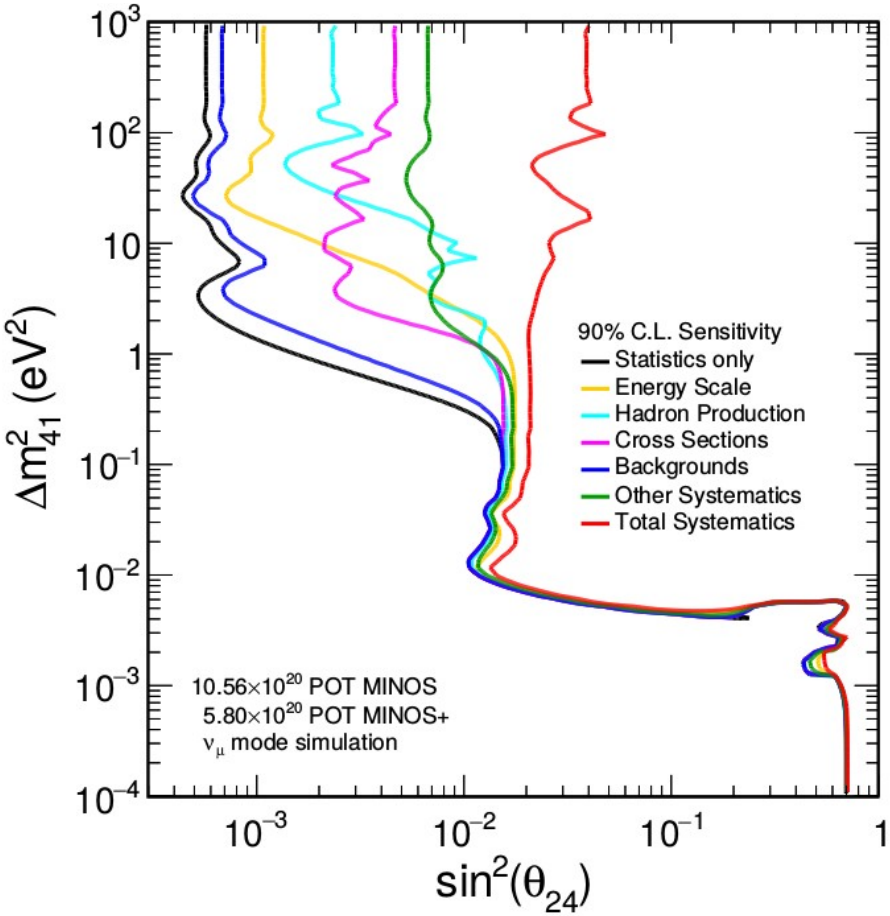
6 GeV – 56 GeV

Also constraining θ_{34}

PRD 95 (2017) 112002

MINOS/MINOS+

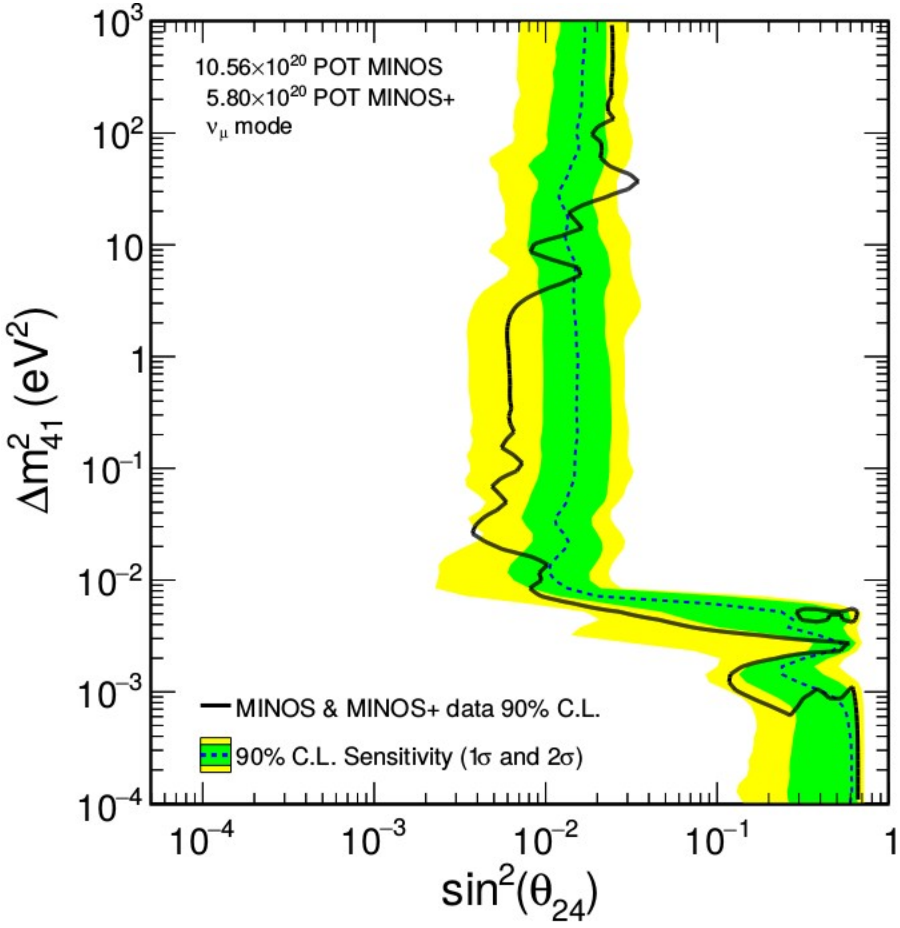


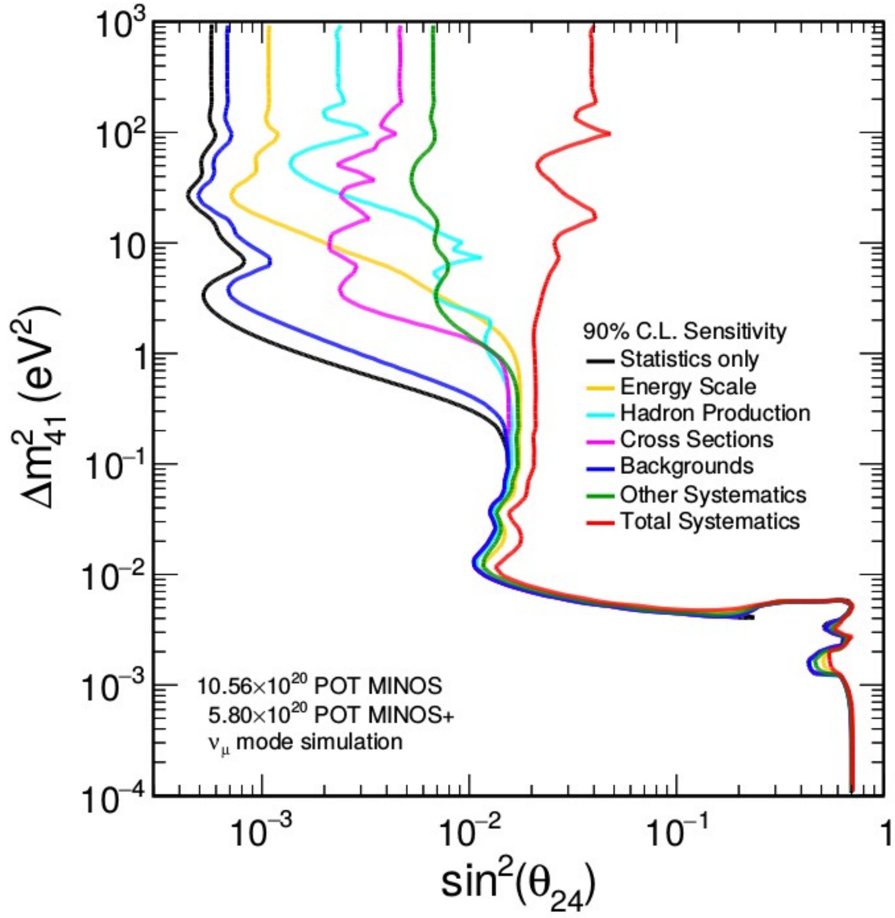


Two analyses: far-over-near ratio, and two-detector fit

PRL 117 (2016) 151803
PRL 122 (2019) 091803

MINOS/MINOS+



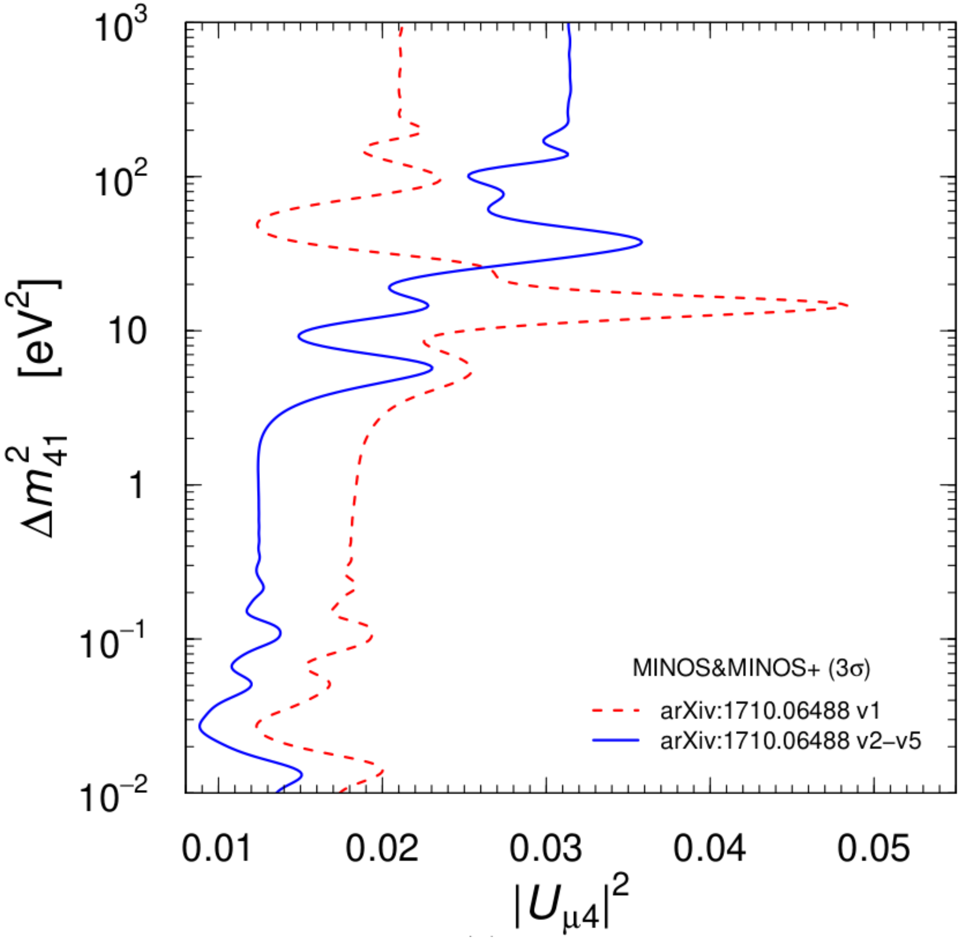


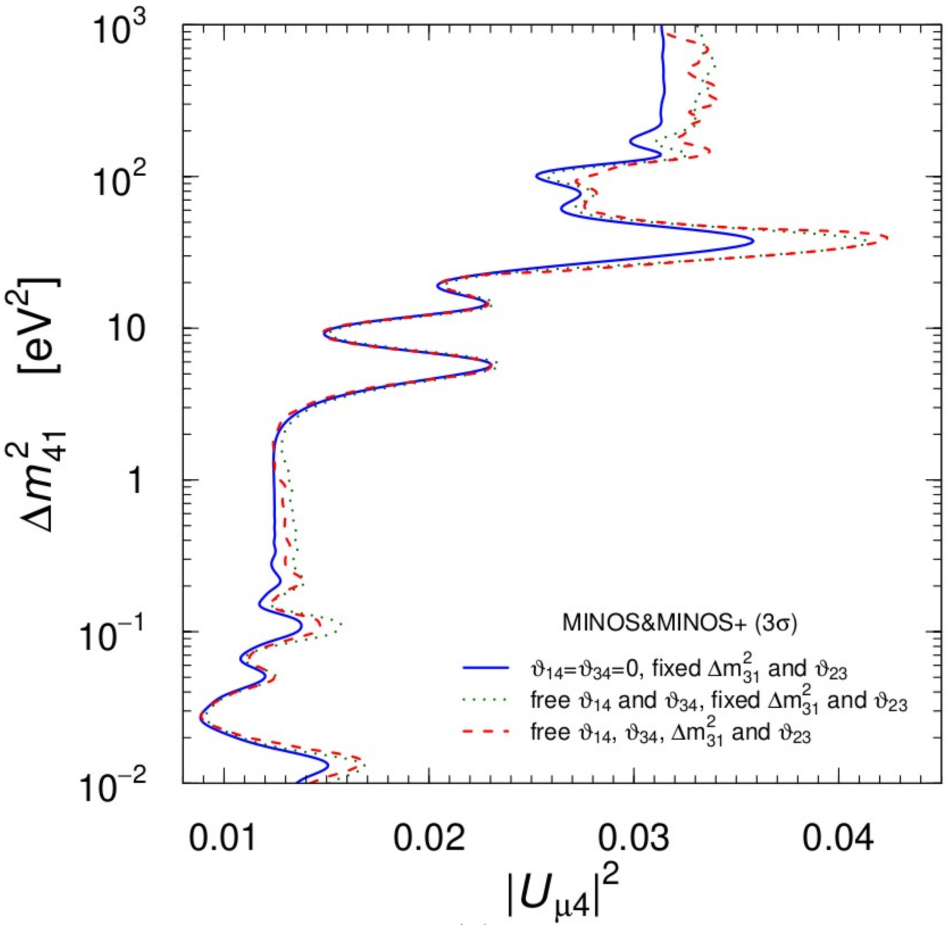
Two analyses: far-over-near ratio, and two-detector fit

For large mass splittings: systematic dominated

PRL 117 (2016) 151803
PRL 122 (2019) 091803

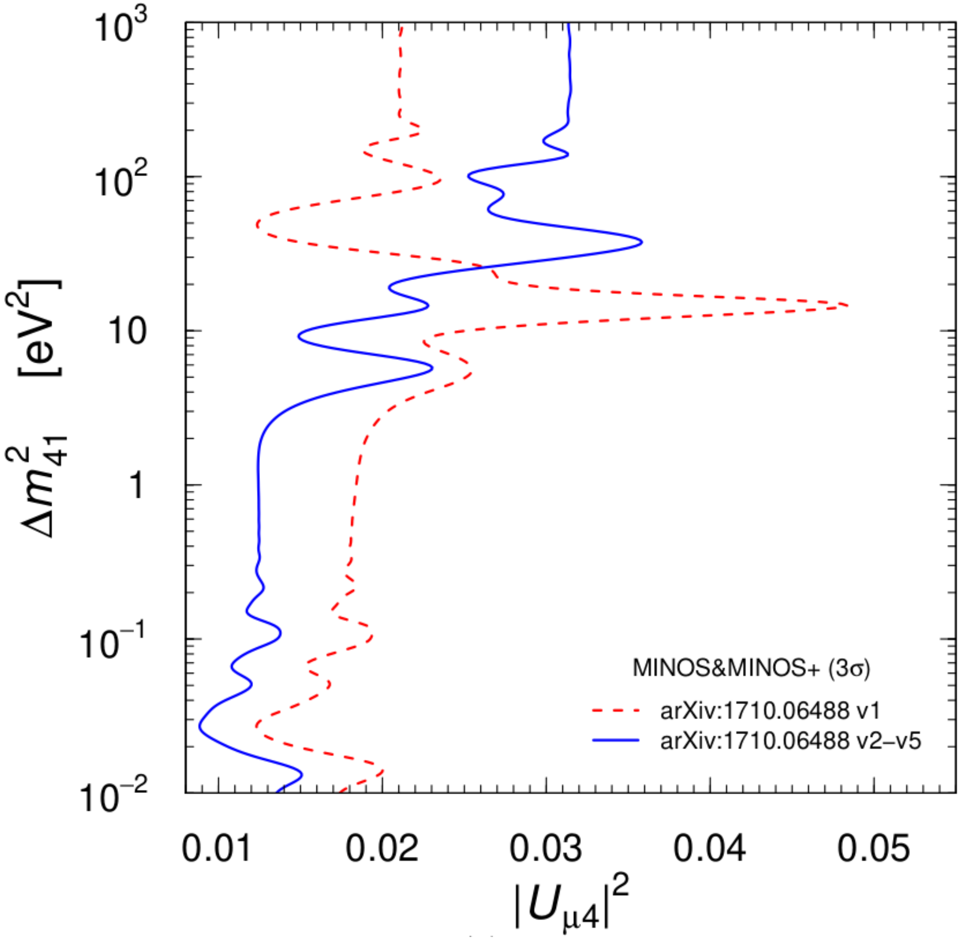
MINOS/MINOS+

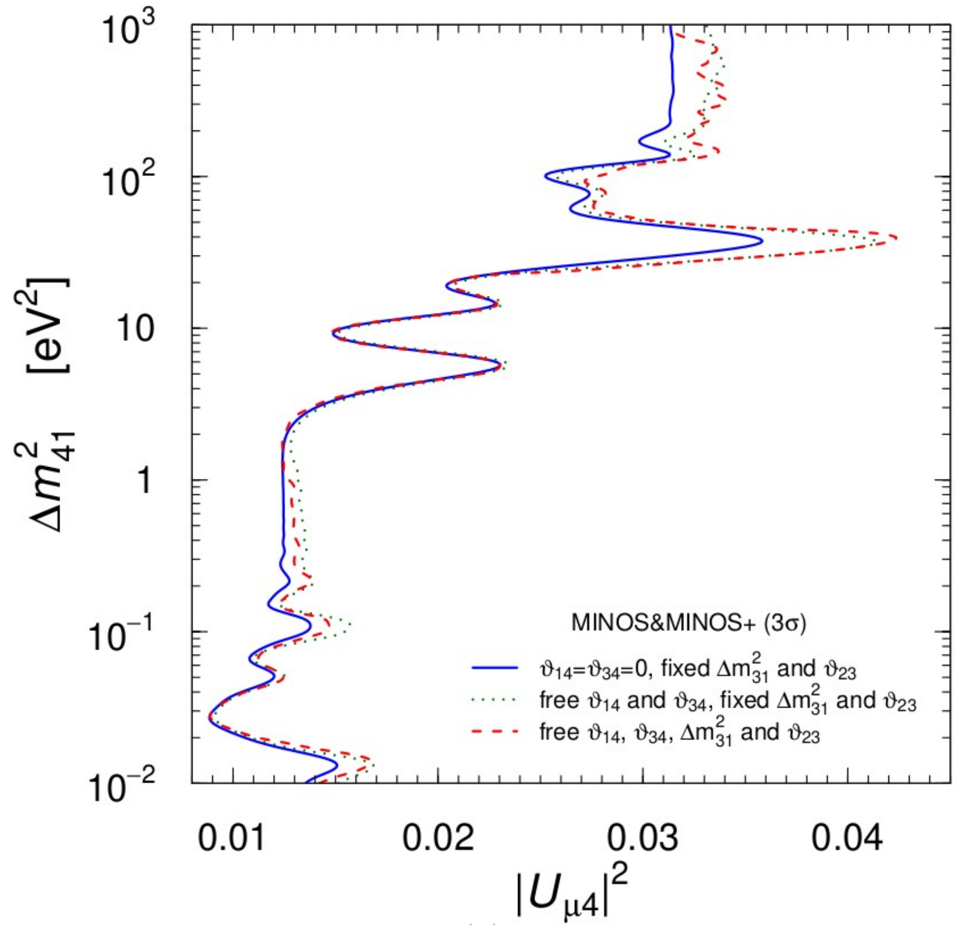




For mass splittings below 20 eV² the bound gets stronger after updating the analysis

MINOS/MINOS+



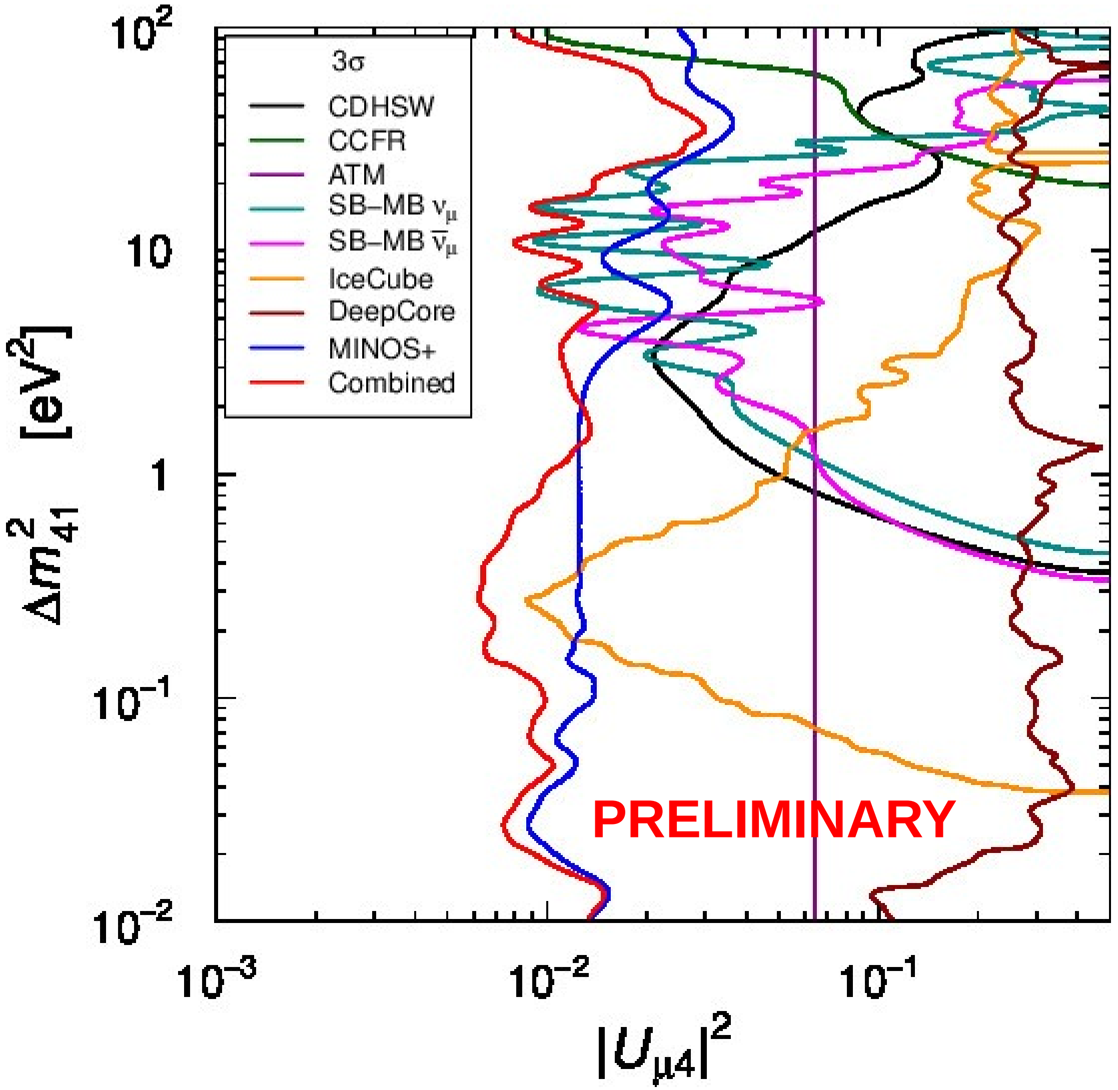


For mass splittings below 20 eV² the bound gets stronger after updating the analysis

The effect of the other oscillation parameters is very small in this region

Fit of $\nu_\mu/\overline{\nu}_\mu$ disappearance data

All data:



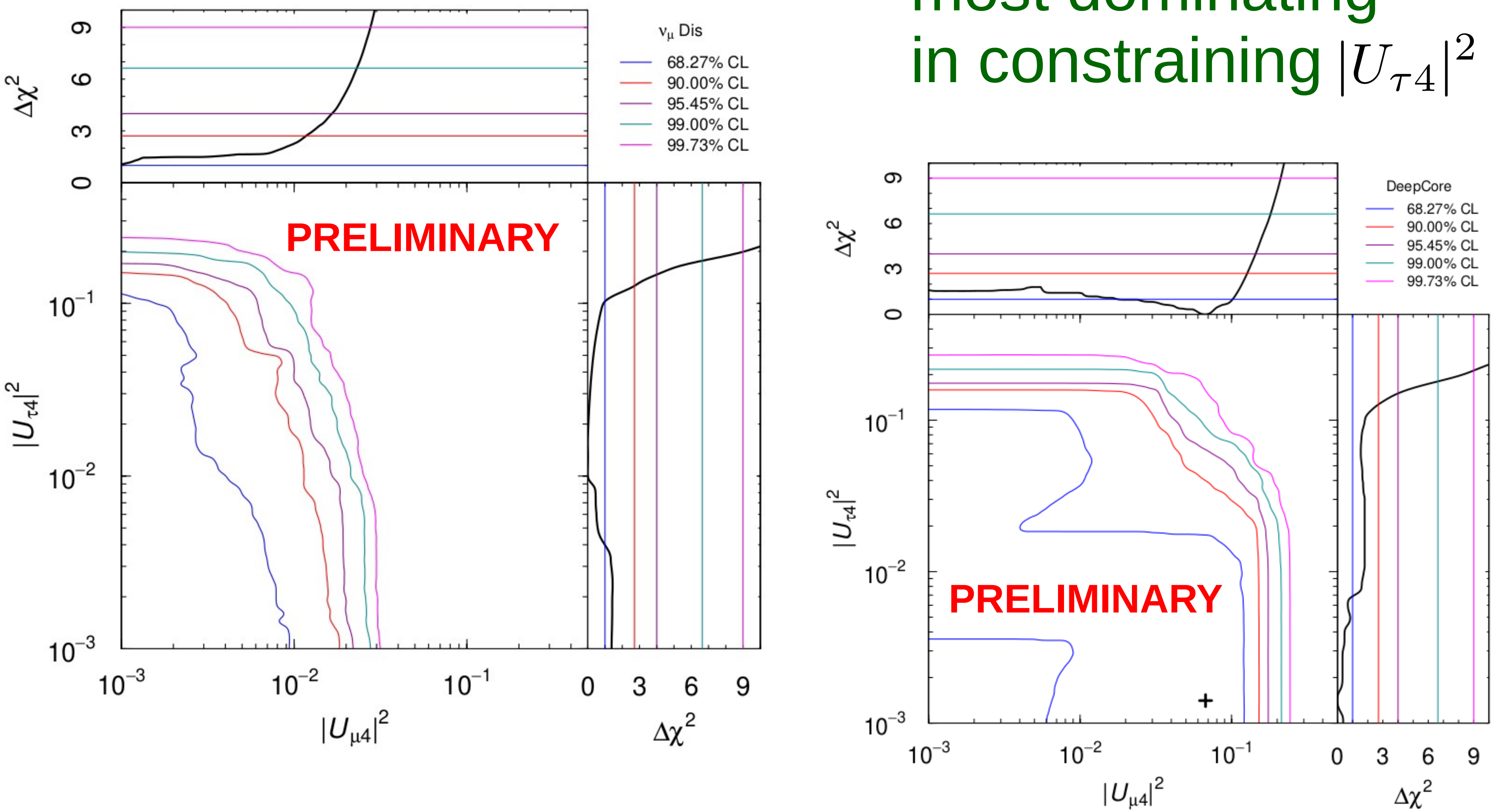
MINOS/MINOS+ is the most dominating experiment in the fit

In preparation, S. Gariazzo, C. Giunti, CAT

Fit of $\nu_\mu/\overline{\nu}_\mu$ disappearance data

All data:

DeepCore is the most dominating in constraining $|U_{\tau 4}|^2$



In preparation, S. Gariazzo, C. Giunti, CAT

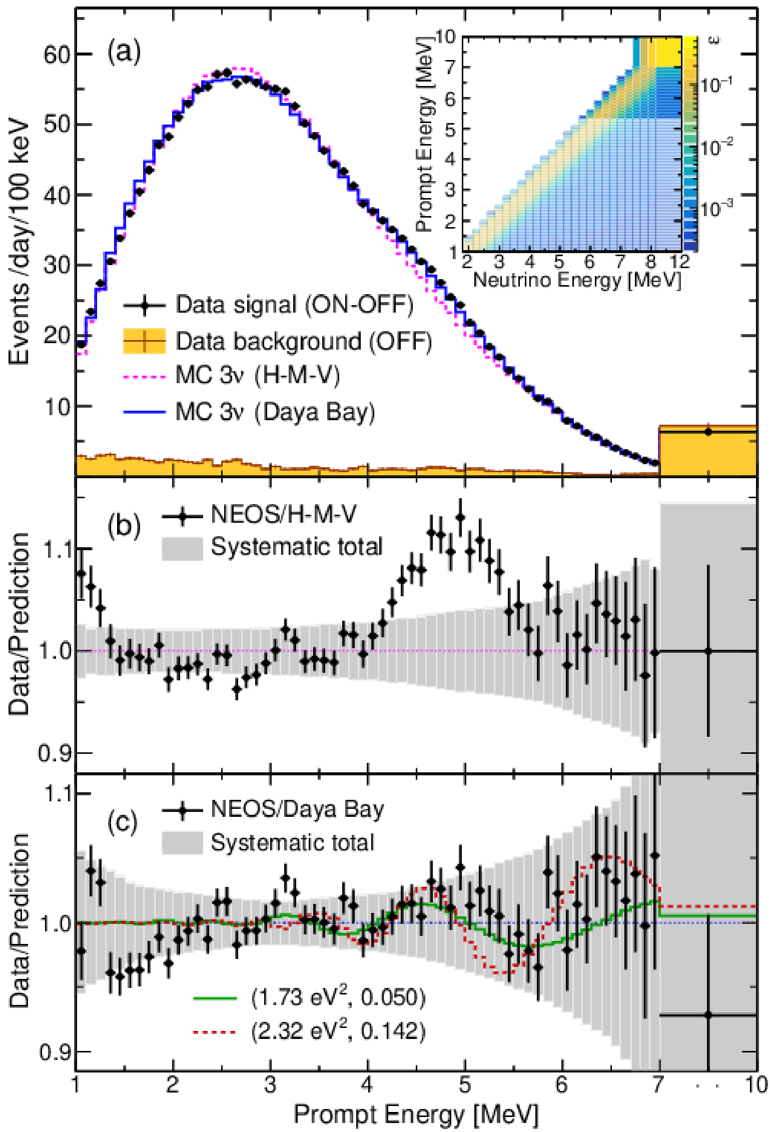
What is the impact on the 3+1 picture?

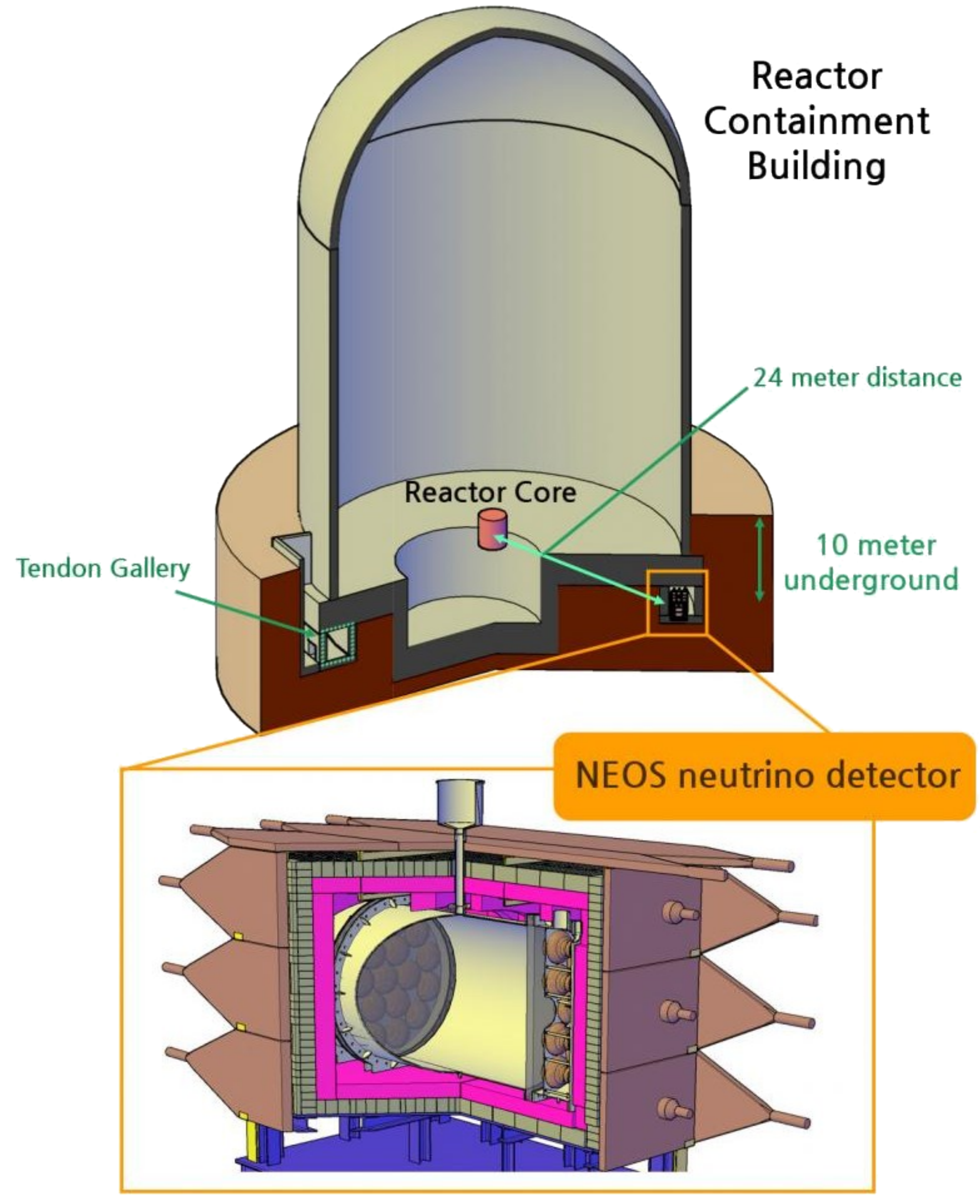
In preparation, S. Gariazzo, C. Giunti, CAT

ν_e disappearance experiments

NEOS

Single detector, taking ratio to **Daya Bay**

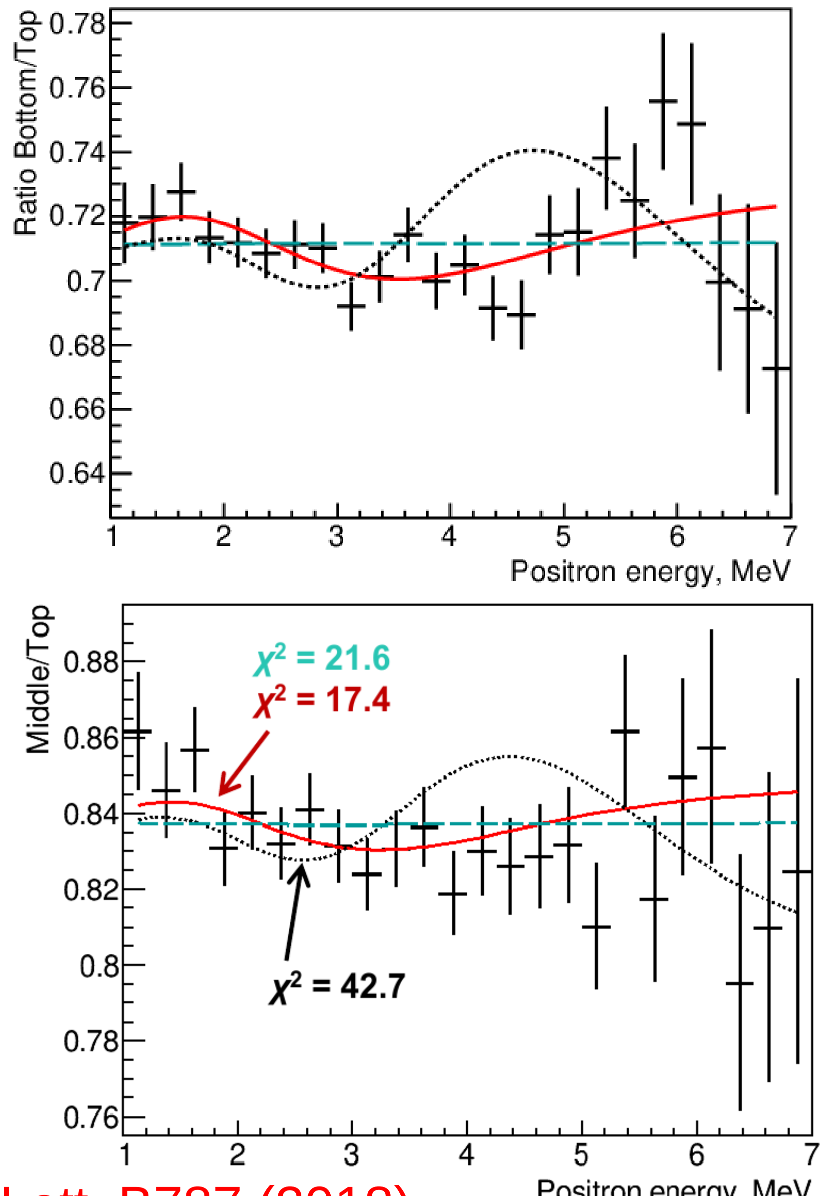




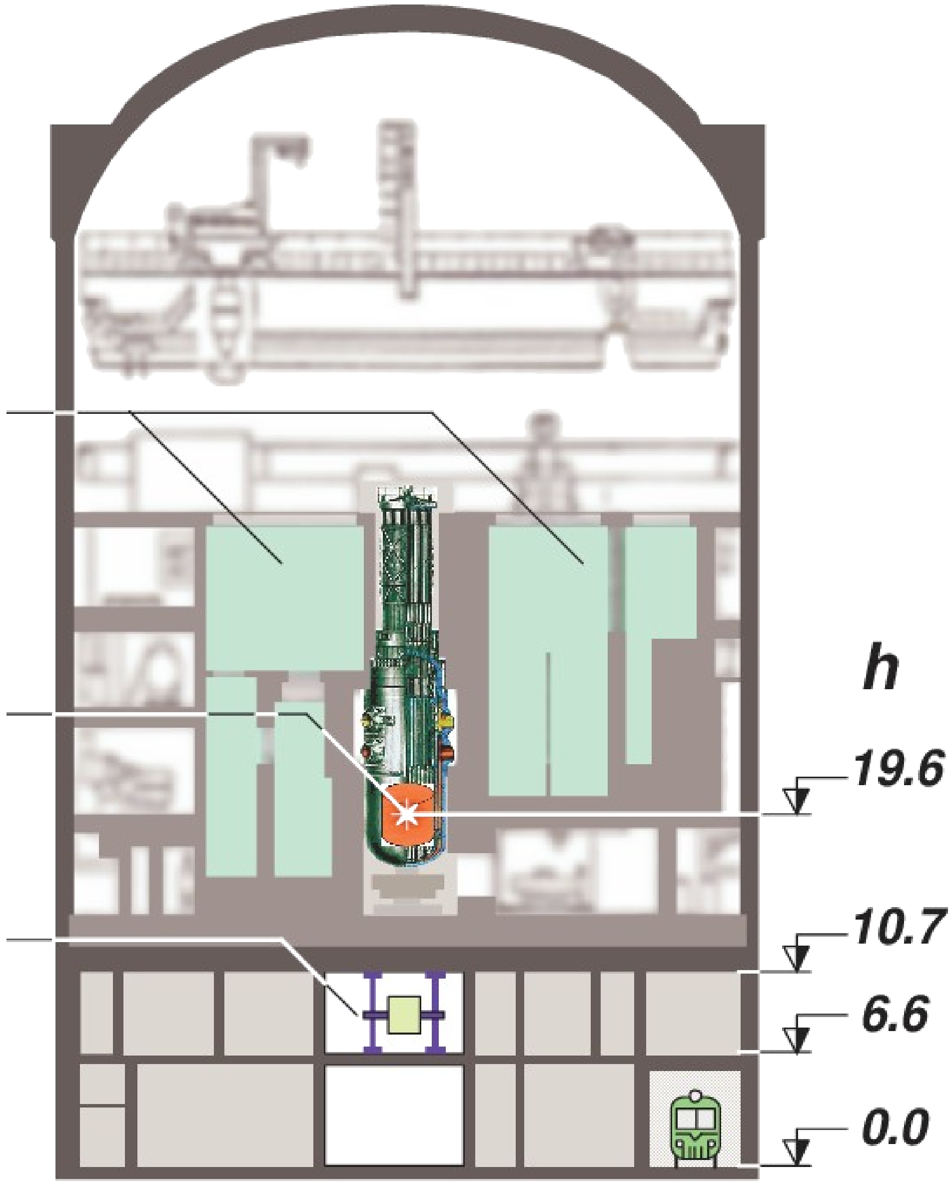
PRL 118 (2017) 121802

DANSS

Single movable detector, ~3σ preference for 3+1



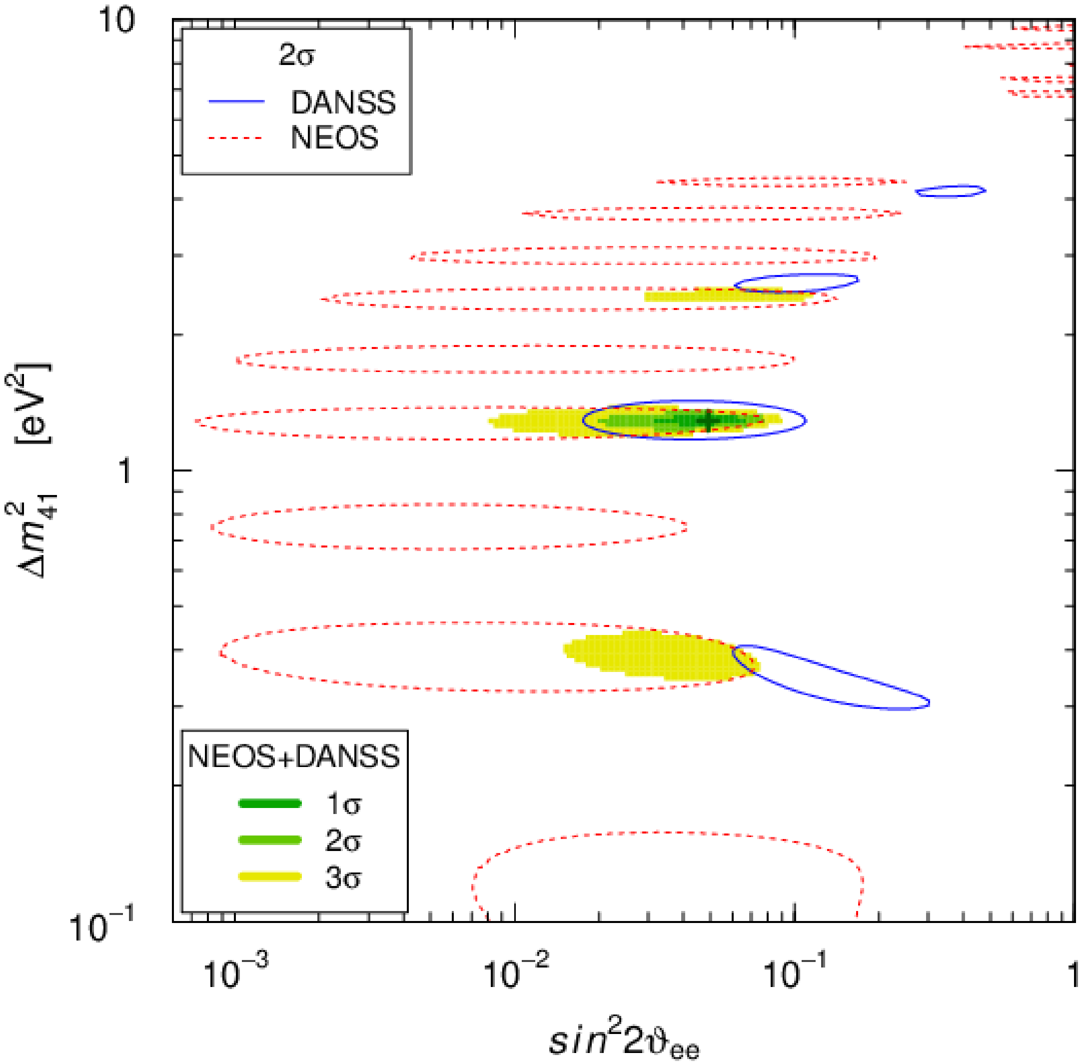
Phys.Lett. B787 (2018)



Fit of $\nu_e/\overline{\nu}_e$ disappearance data

DANSS / NEOS

Phys.Lett. B782 (2018) 13-21



Perfect agreement at

$$\Delta m^2_{41} = 1.3 \text{ eV}^2$$

$$\sin^2(2\theta_{ee}) = 0.05$$

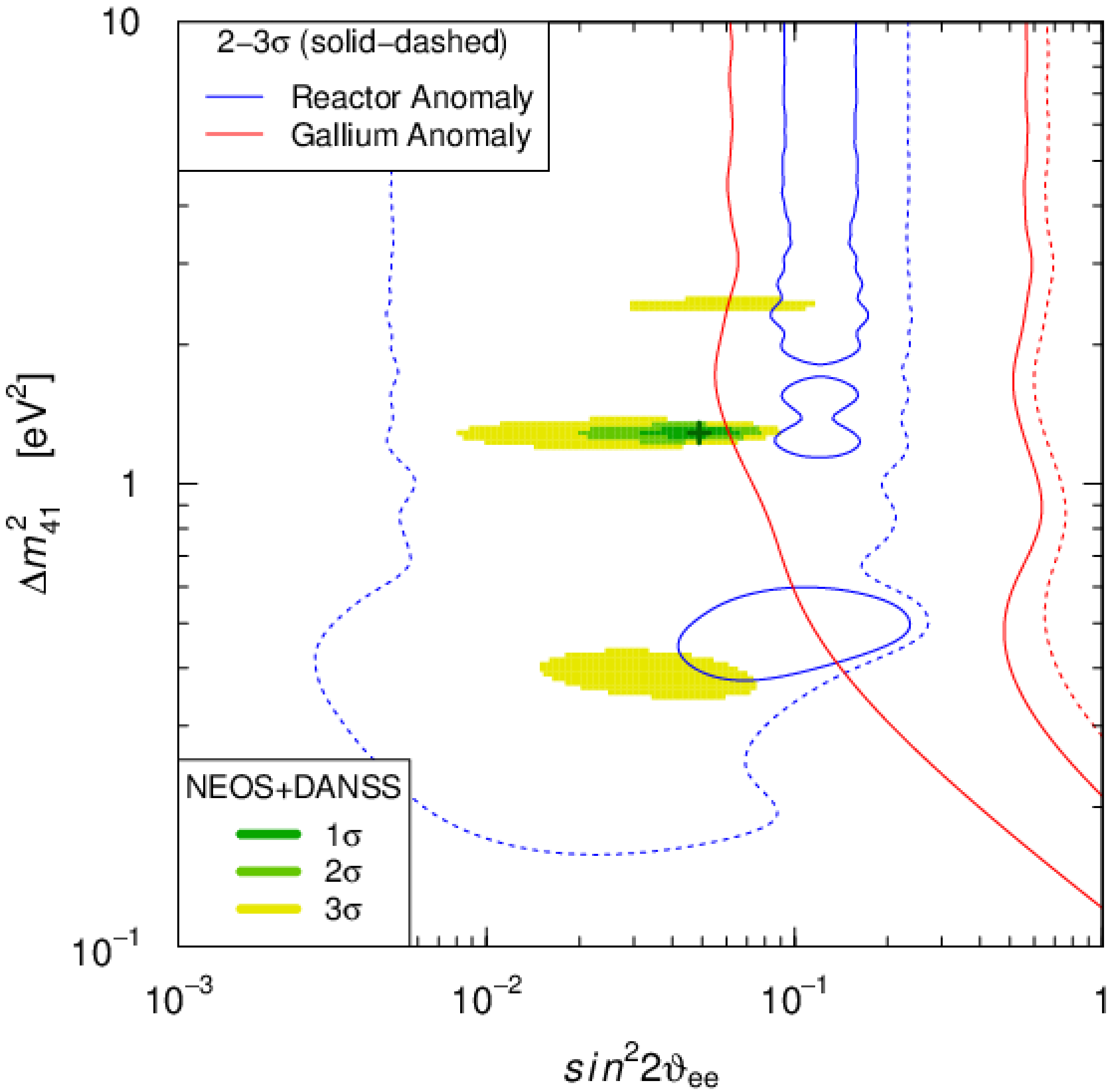
$$\sin^2\theta_{14} = 0.01$$

See also: JHEP 1711 (2017) 099, Dentler, M. et al

Fit of $\nu_e/\overline{\nu}_e$ disappearance data

DANSS / NEOS + Gallium + RAA

Phys.Lett. B782 (2018) 13-21

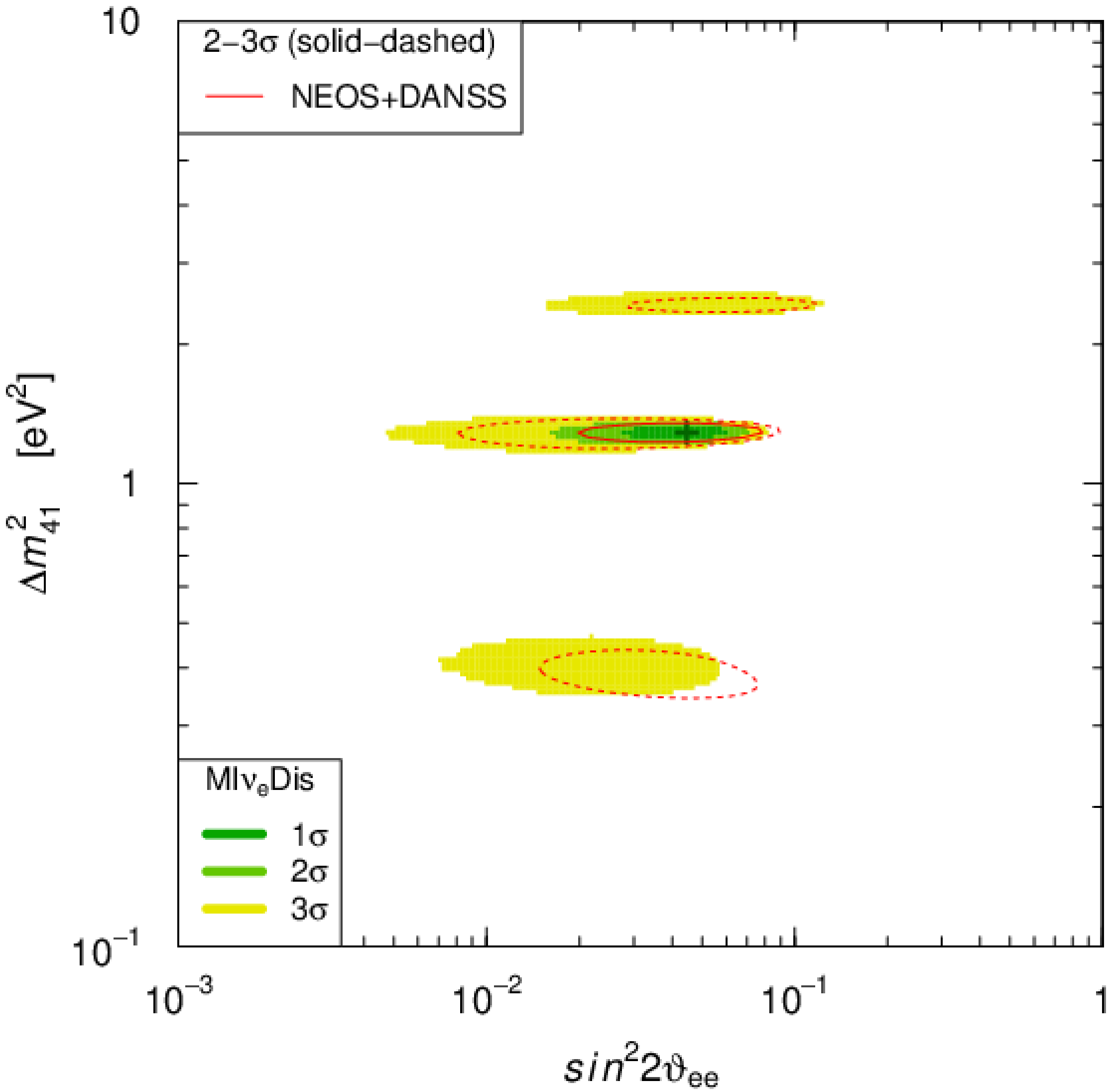


Small tension between **NEOS/DANSS** and **Gallium** and **RAA**

Fit of $\nu_e/\overline{\nu}_e$ disappearance data

All data:

Phys.Lett. B782 (2018) 13-21

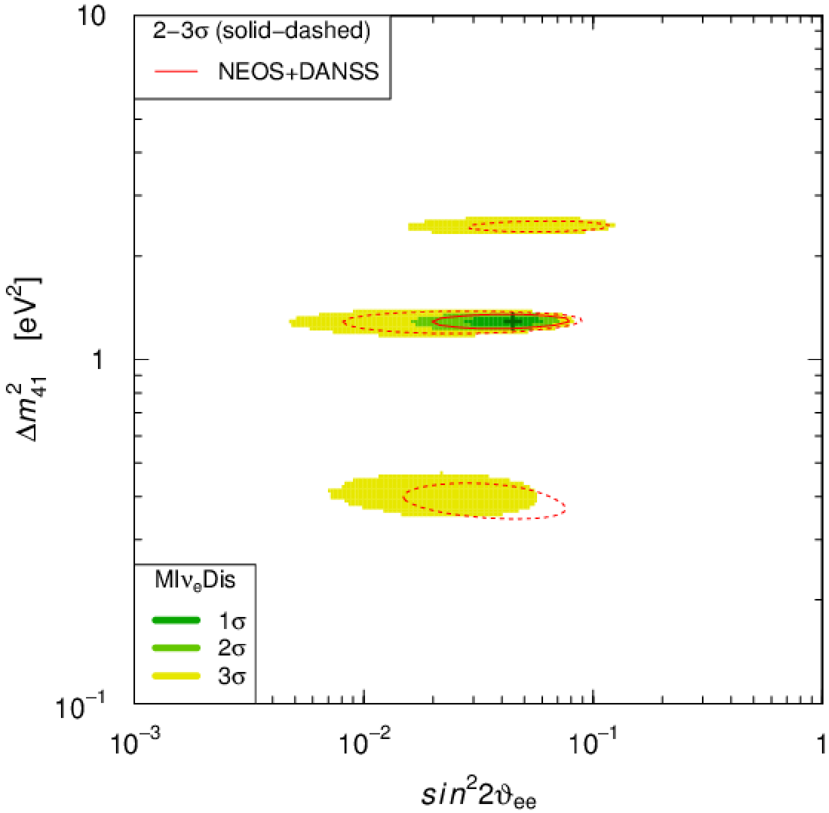


Fit is dominated by **NEOS/DANSS**

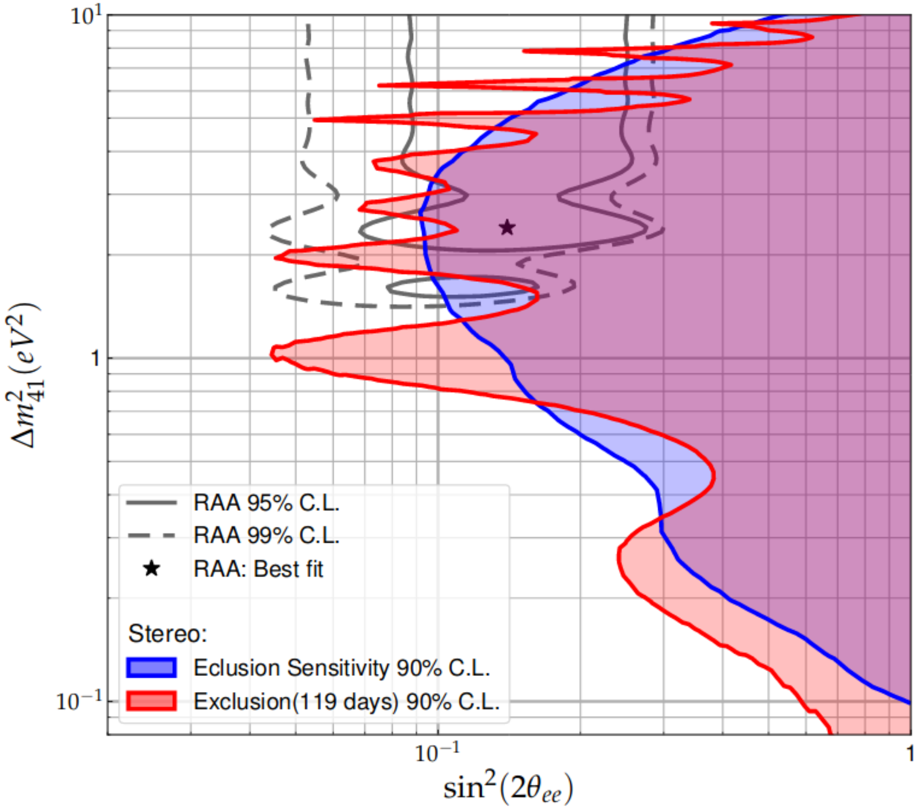
Fit of $\nu_e/\overline{\nu}_e$ disappearance data

New Stereo data:

Phys.Lett. B782 (2018) 13-21



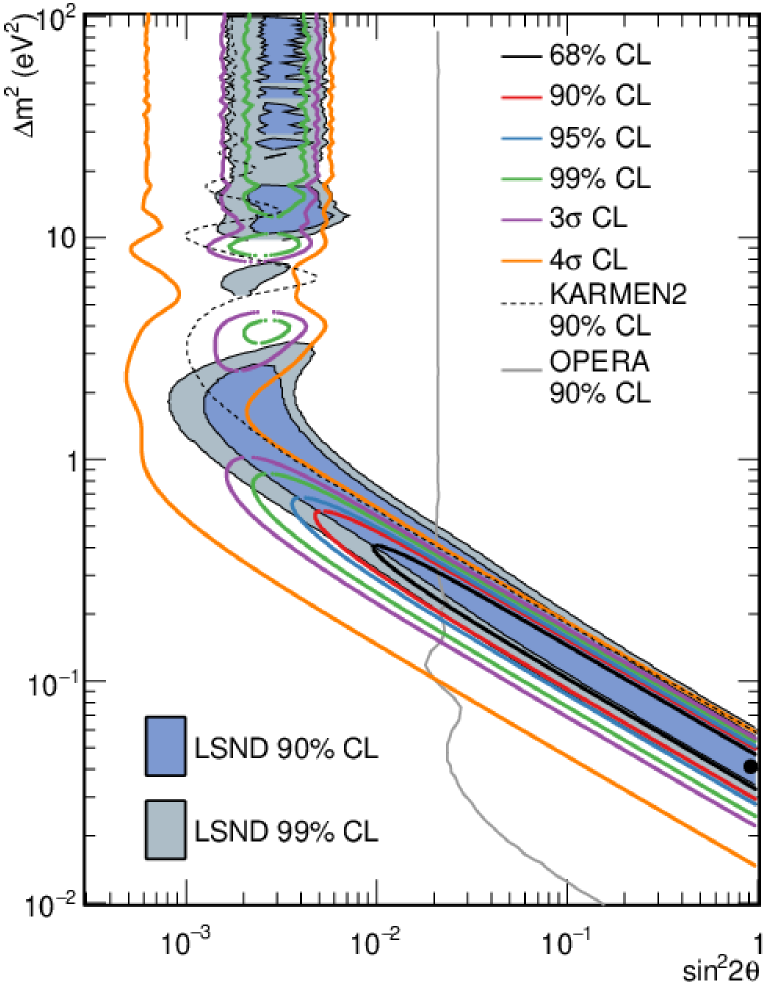
Talk by Christian Roca



ν_e appearance experiments

MiniBooNE

MiniBooNE was built to check the **LSND** results with a different baseline, but similar L/E



PRL 121 (2018) 221801

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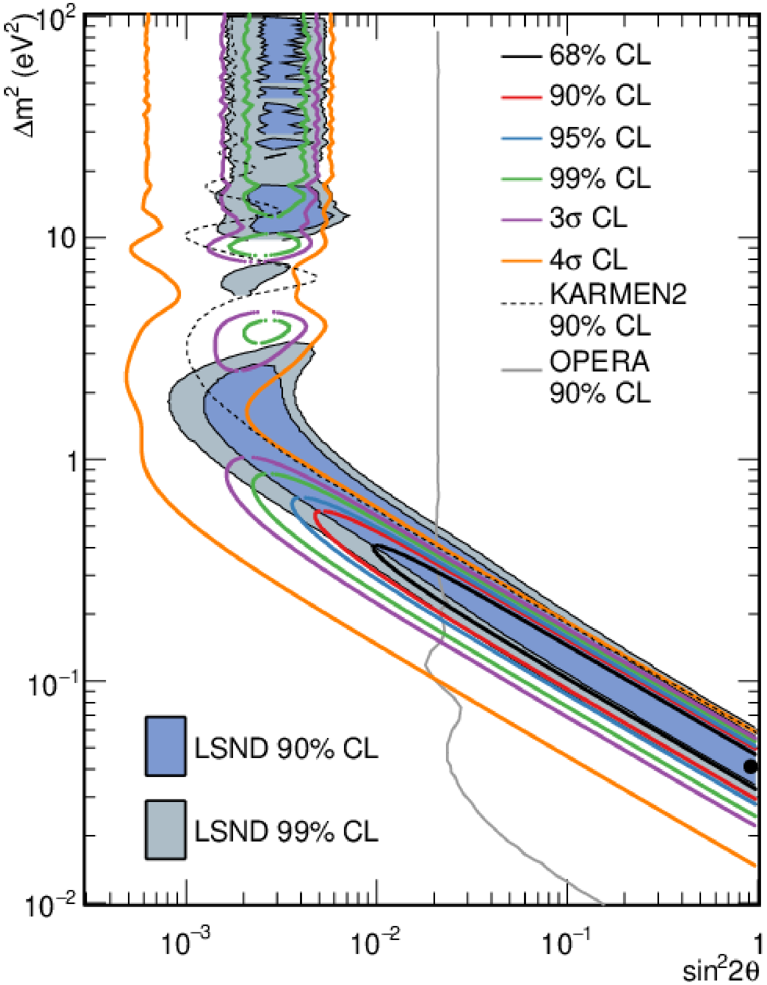
MiniBooNE has no near detector



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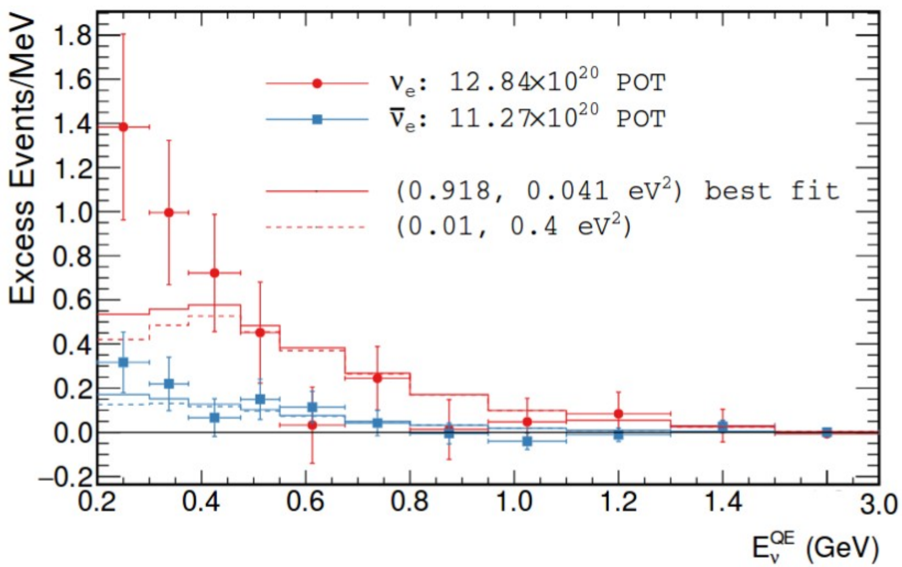
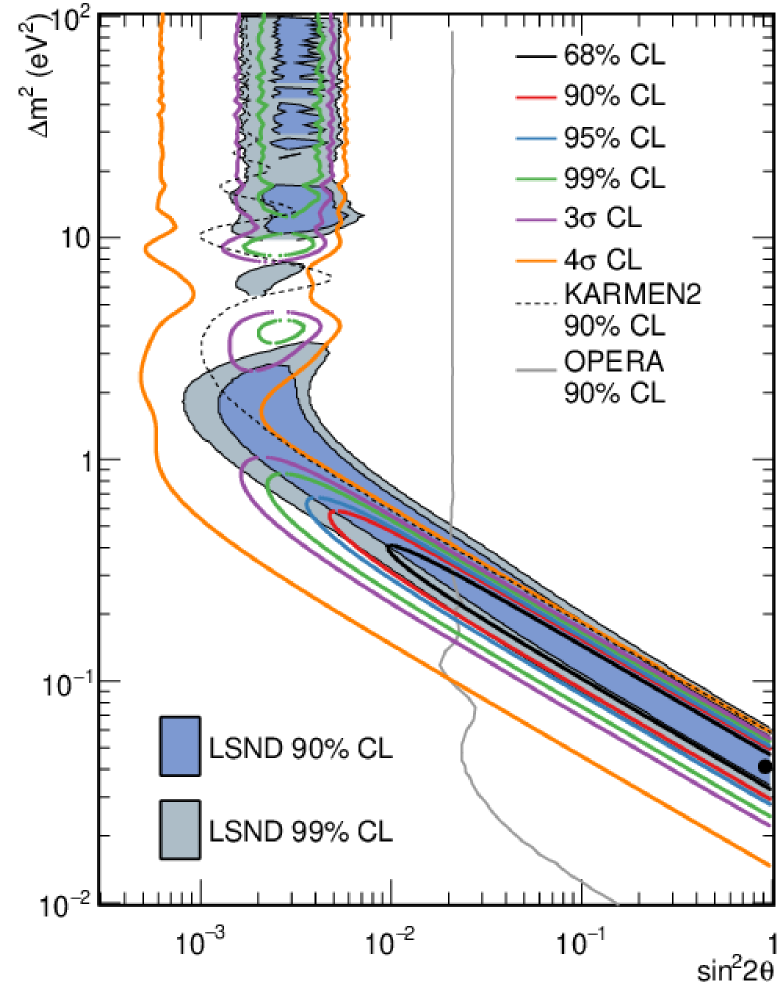


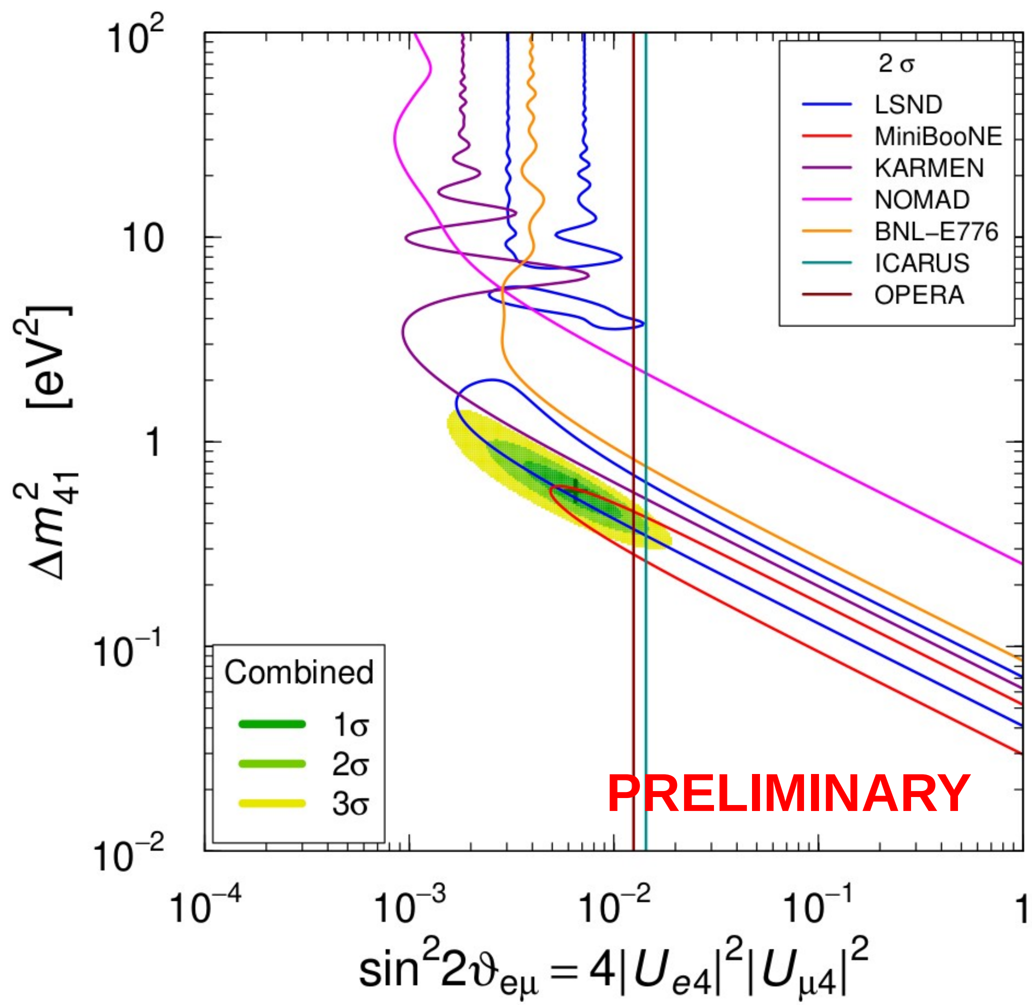


MiniBooNE sees an excess at ~5σ at low energies

PRL 121 (2018) 221801

Fit of $\nu_e/\overline{\nu}_e$ appearance data

All data:

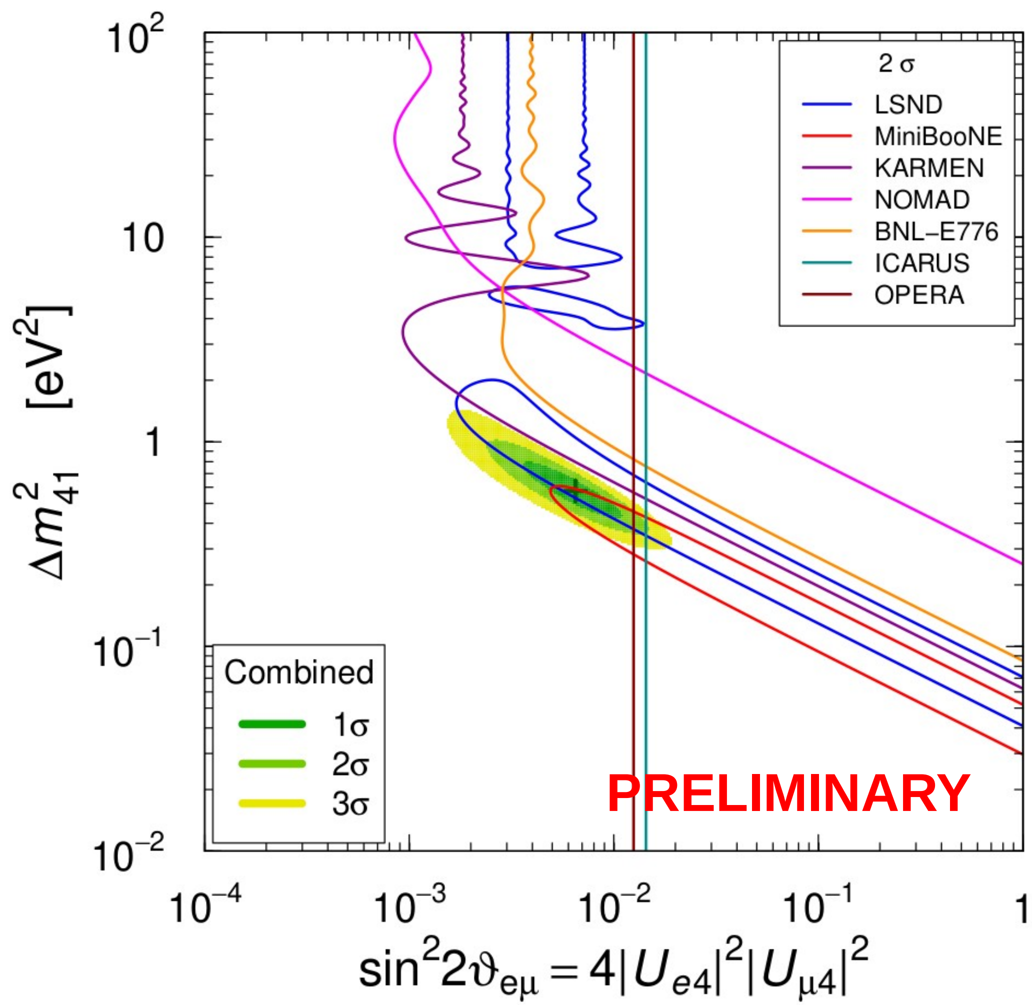


The best fit value of **MiniBooNE** is excluded by **Icarus** and **Opera**

In preparation, S. Gariazzo, C. Giunti, CAT

Fit of $\nu_e/\overline{\nu}_e$ appearance data

All data:



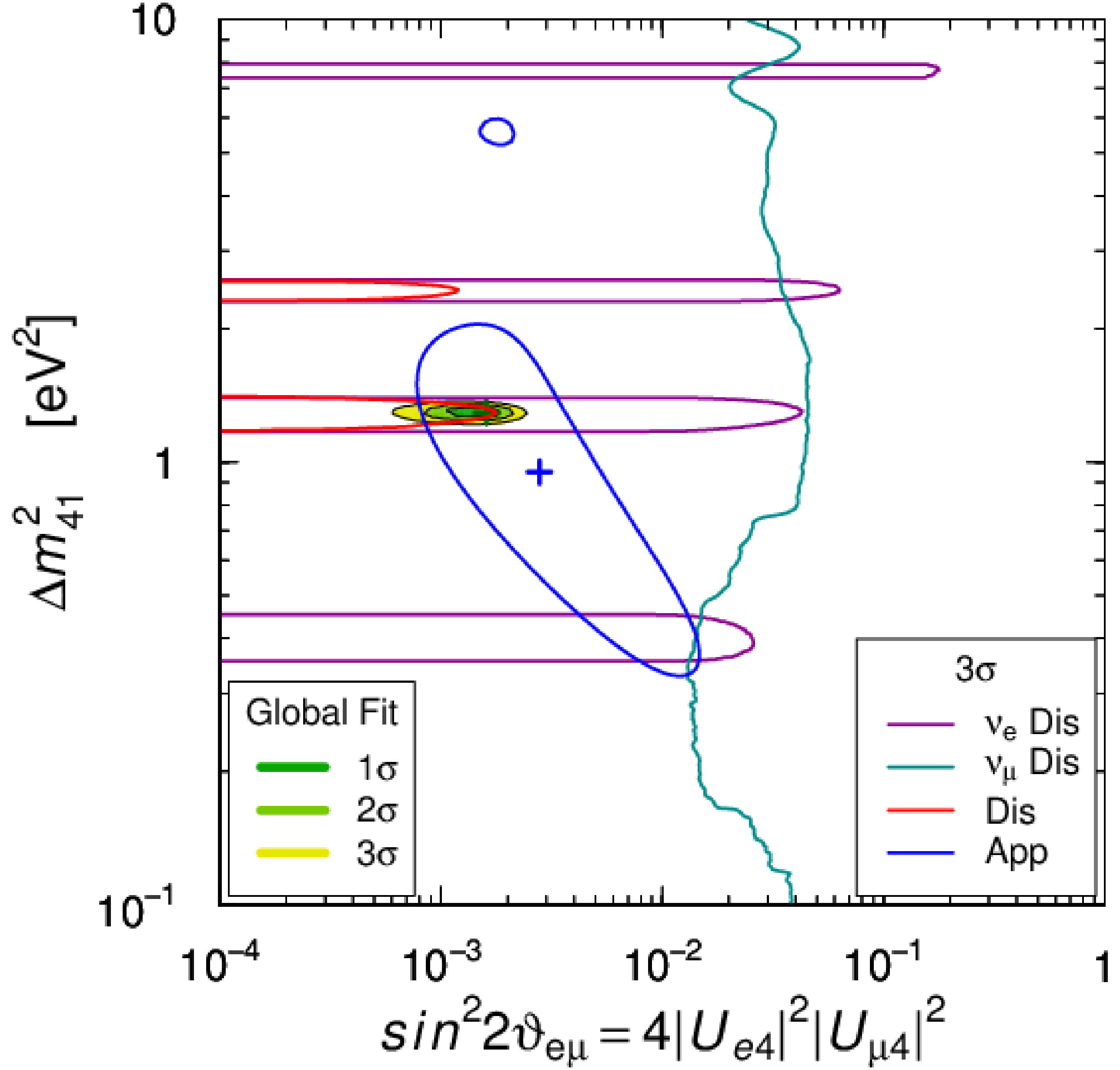
The best fit value of **MiniBooNE** is excluded by **Icarus** and **Opera**

LSND and **MiniBooNE** only partially agree

In preparation, S. Gariazzo, C. Giunti, CAT

Tension in APP vs DIS data

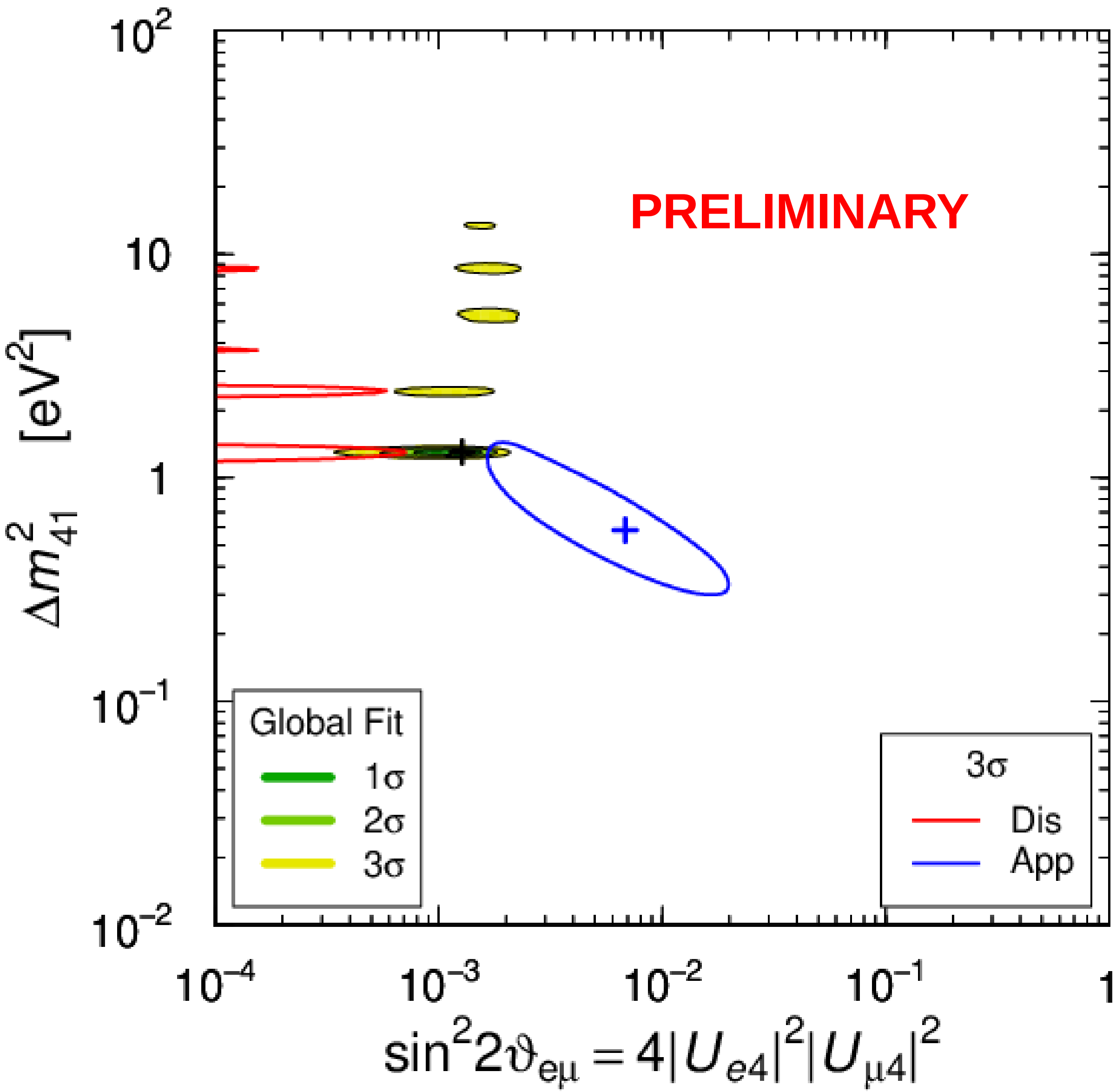
- Data end of 2017



JHEP 1706 (2017) 135, S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li

Tension in APP vs DIS data

Data June 2019

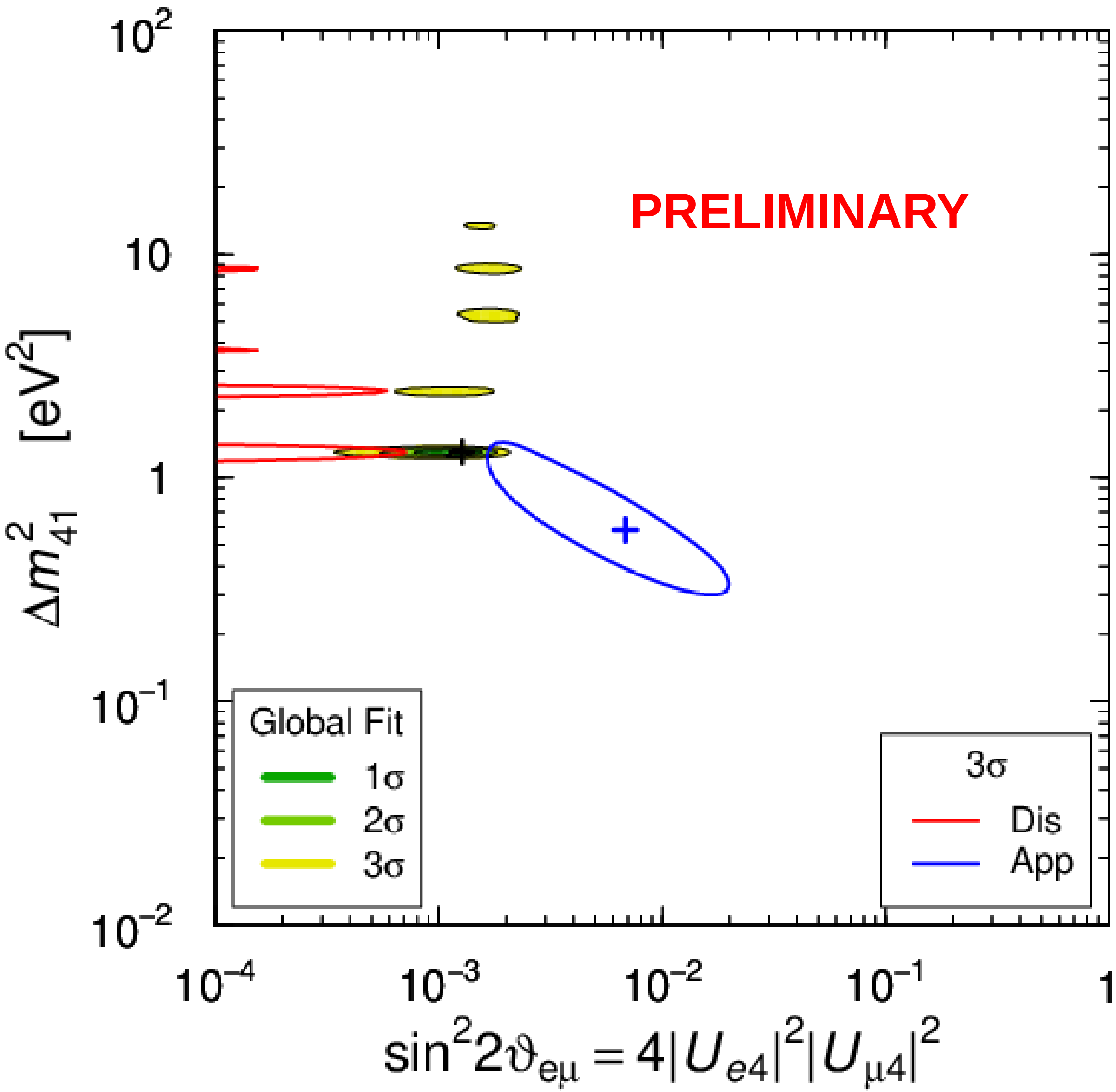


In preparation, S. Gariazzo, C. Giunti, CAT

Tension in APP vs DIS data

Data June 2019

No overlap anymore!



In preparation, S. Gariazzo, C. Giunti, CAT

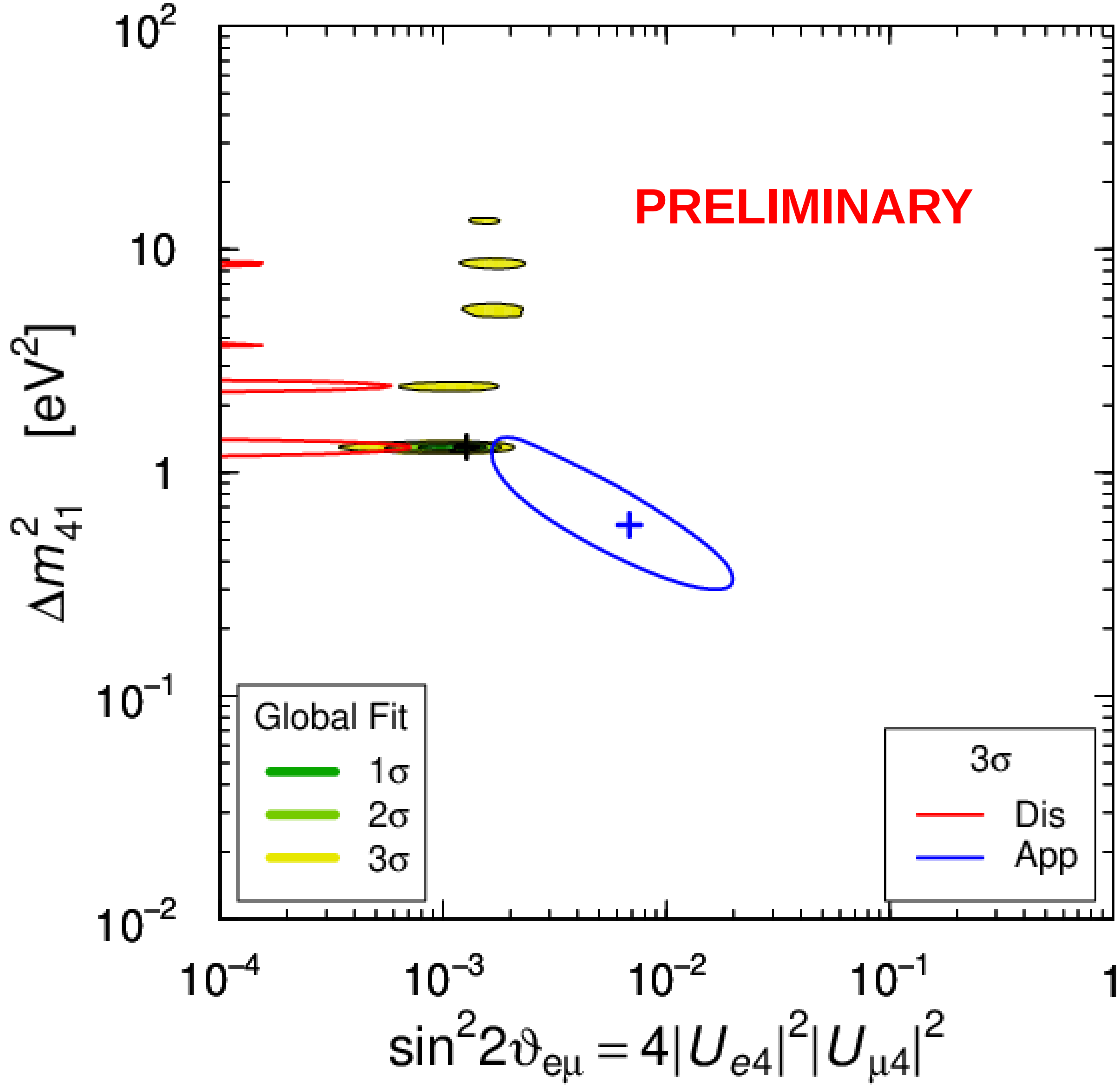
Tension in APP vs DIS data

Data June 2019

No overlap anymore!

We obtain:

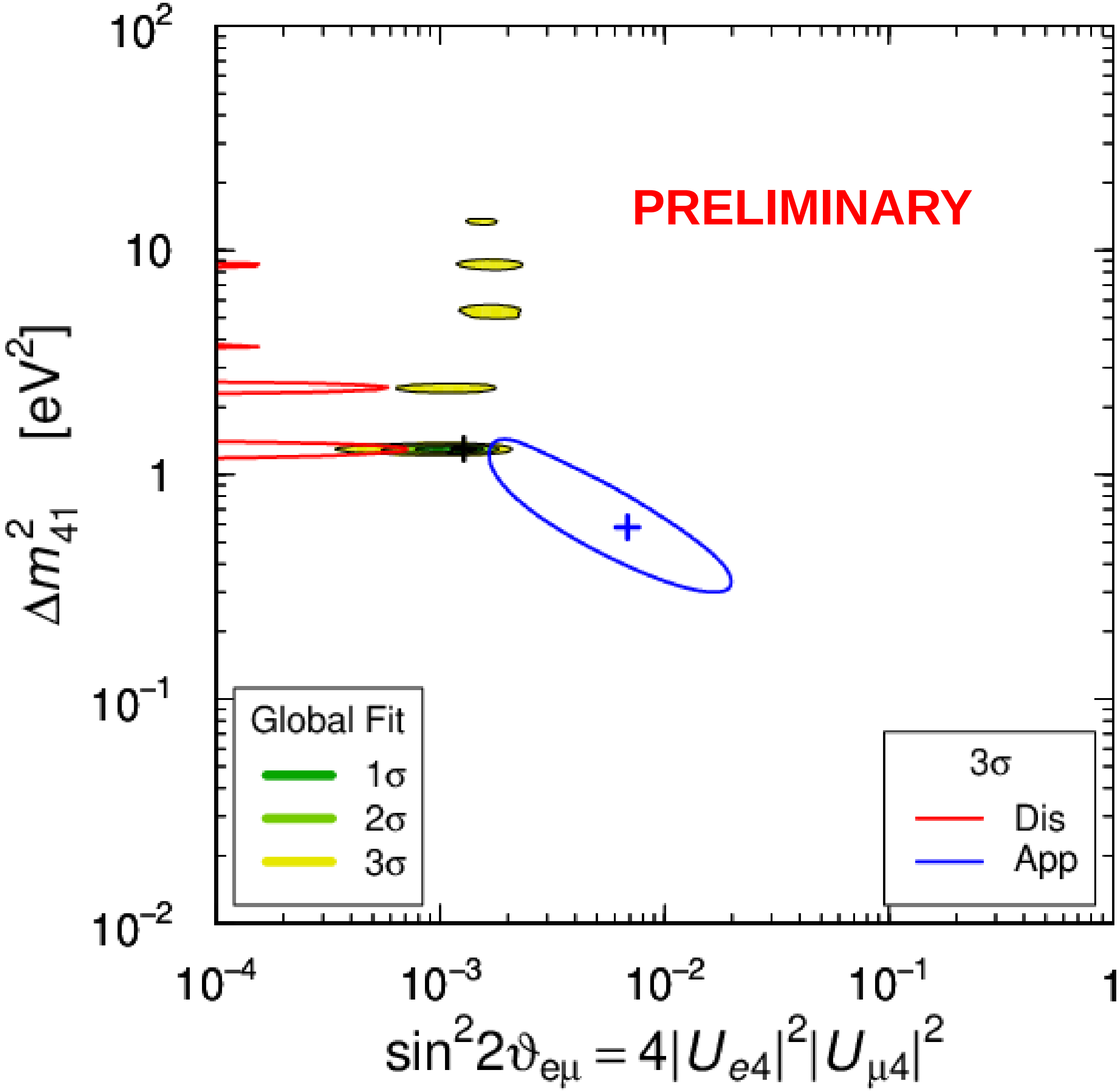
$GoF_{PG} = 3 \times 10^{-9}$



In preparation, S. Gariazzo, C. Giunti, CAT

Tension in APP vs DIS data

Data June 2019



No overlap anymore!

We obtain:

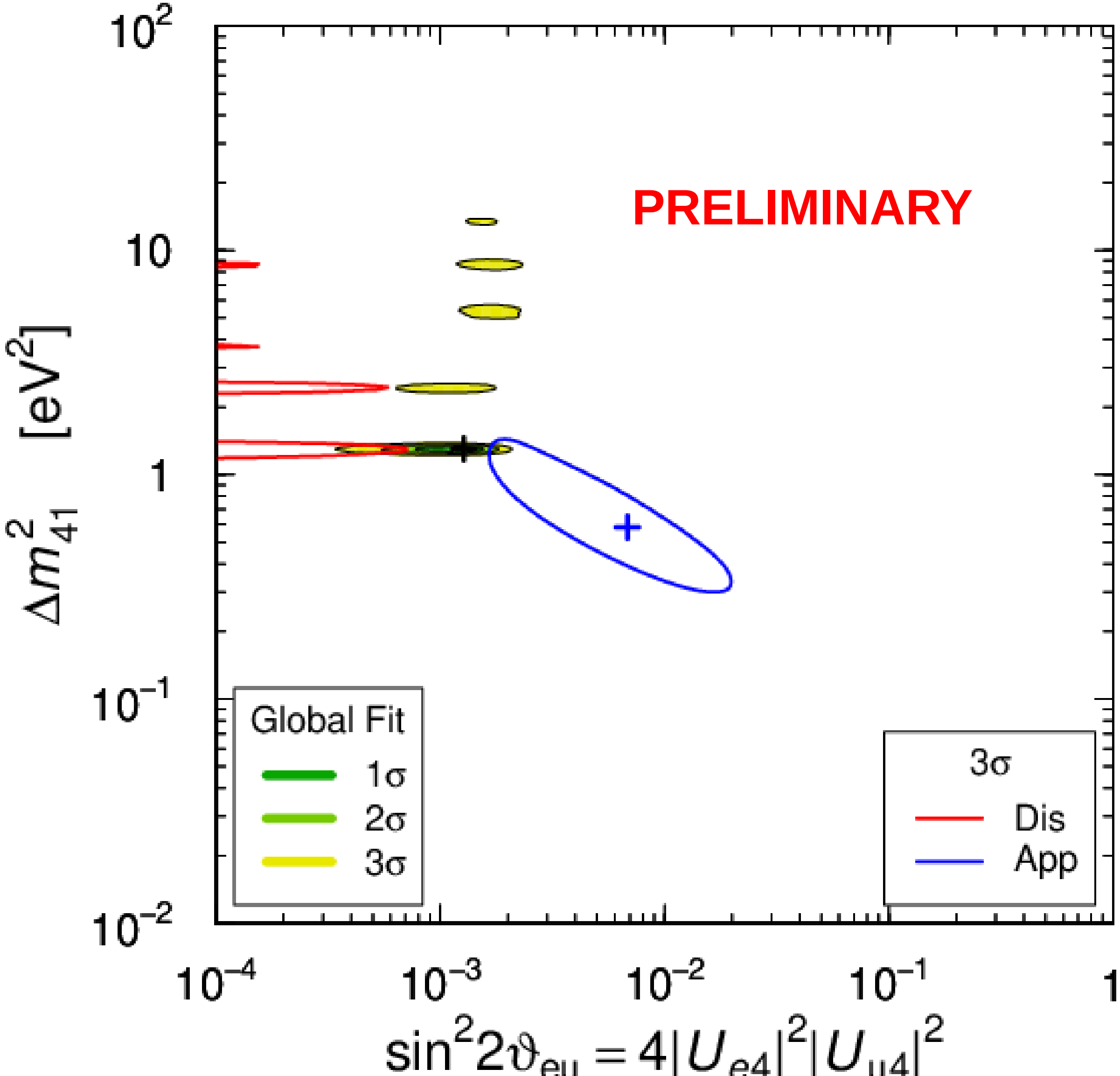
$GoF_{PG} = 3 \times 10^{-9}$

Global 3+1 fit more unaccaptable than ever before

In preparation, S. Gariazzo, C. Giunti, CAT

Tension in APP vs DIS data

Data June 2019



No overlap anymore!

We obtain:

$GoF_{PG} = 3 \times 10^{-9}$

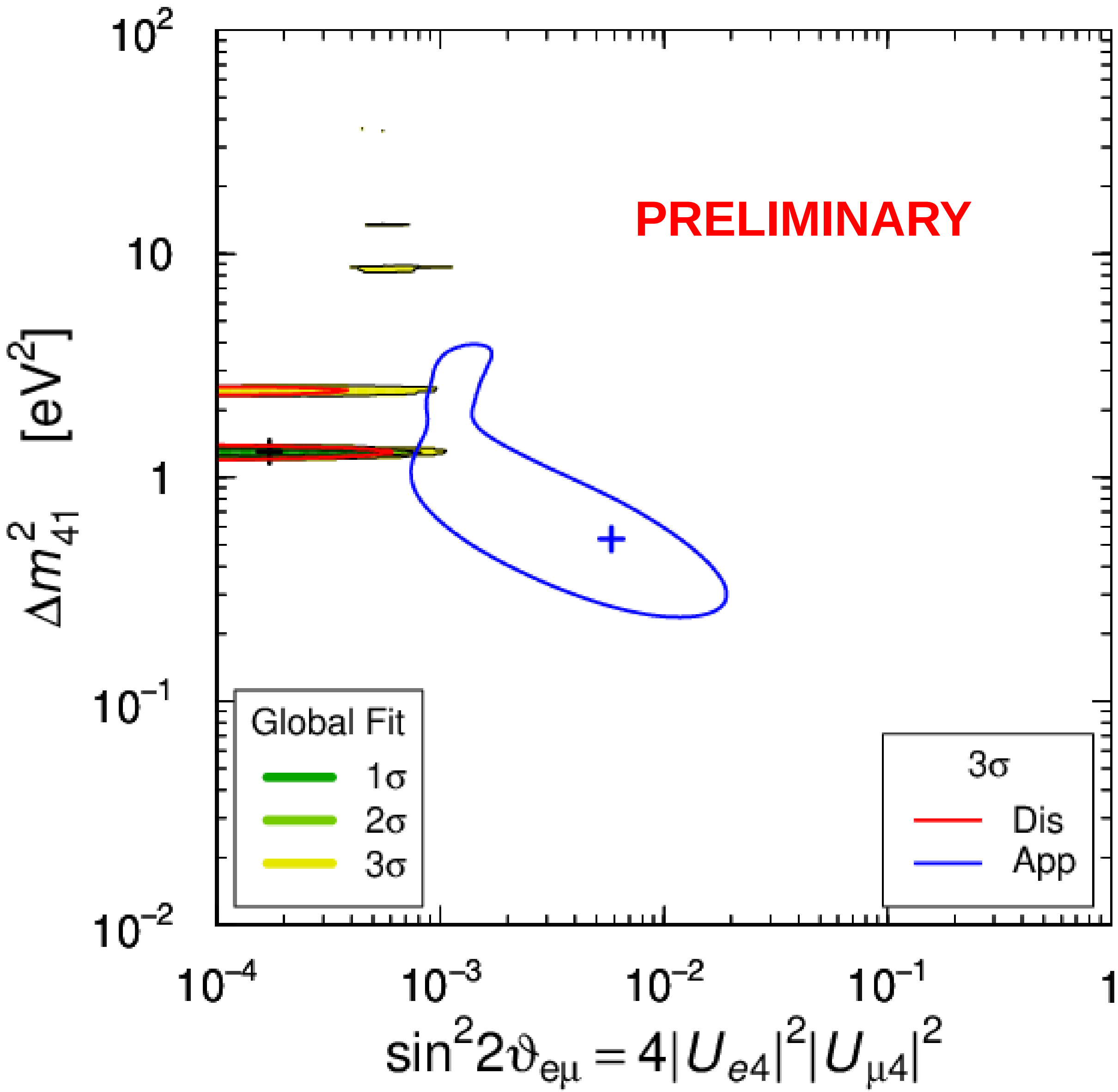
Global 3+1 fit more unaccaptable than ever before

This happens because of the lower bounds on $\theta_{\mu e}$ obtained by LSND and MiniBooNE

In preparation, S. Gariazzo, C. Giunti, CAT

Tension in APP vs DIS data

Data June 2019



Excluding LSND gives

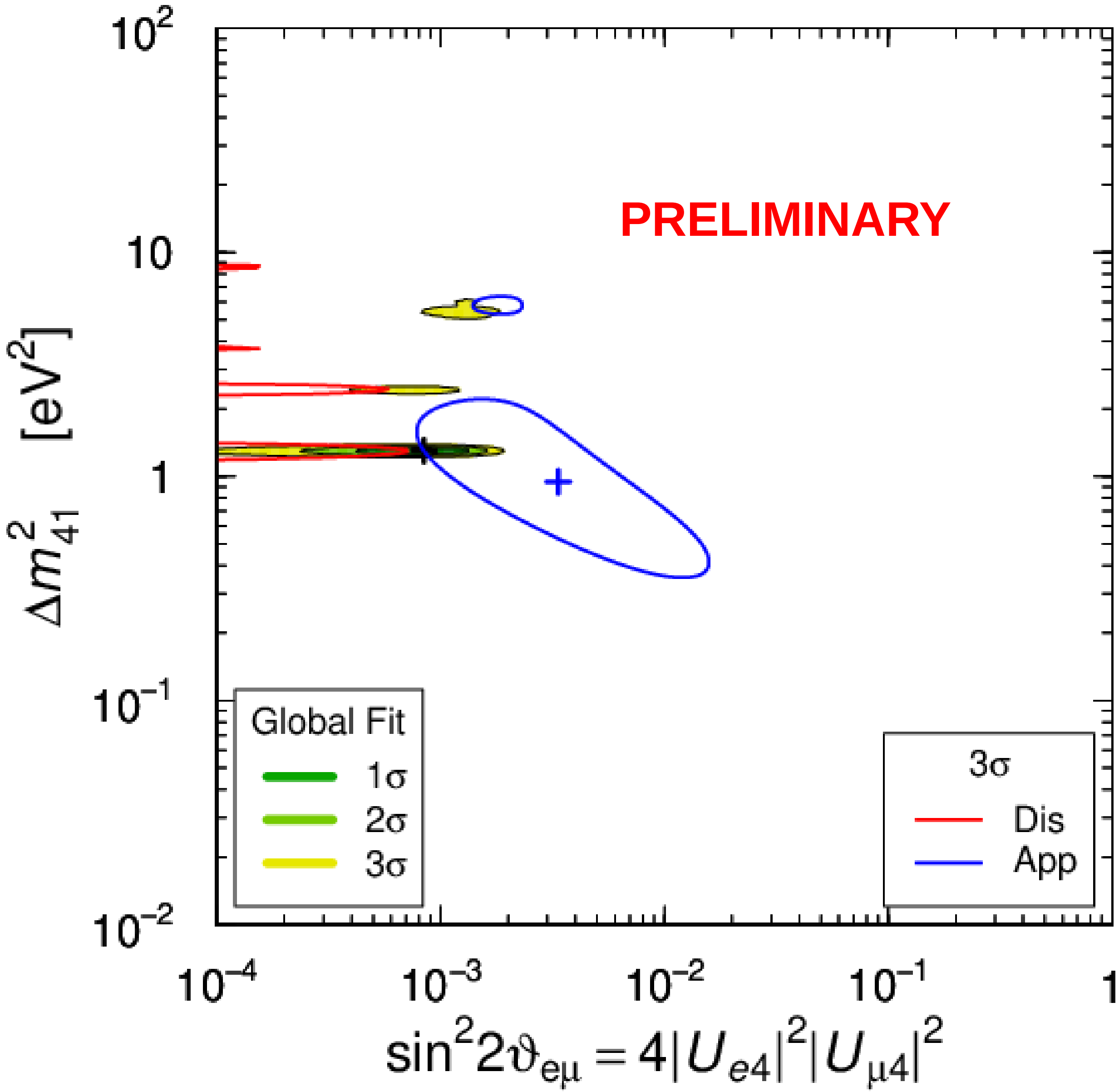
GoF_{PG}= 1 x 10^{-5}

Problem remains!

In preparation, S. Gariazzo, C. Giunti, CAT

Tension in APP vs DIS data

Data June 2019



Excluding MB gives

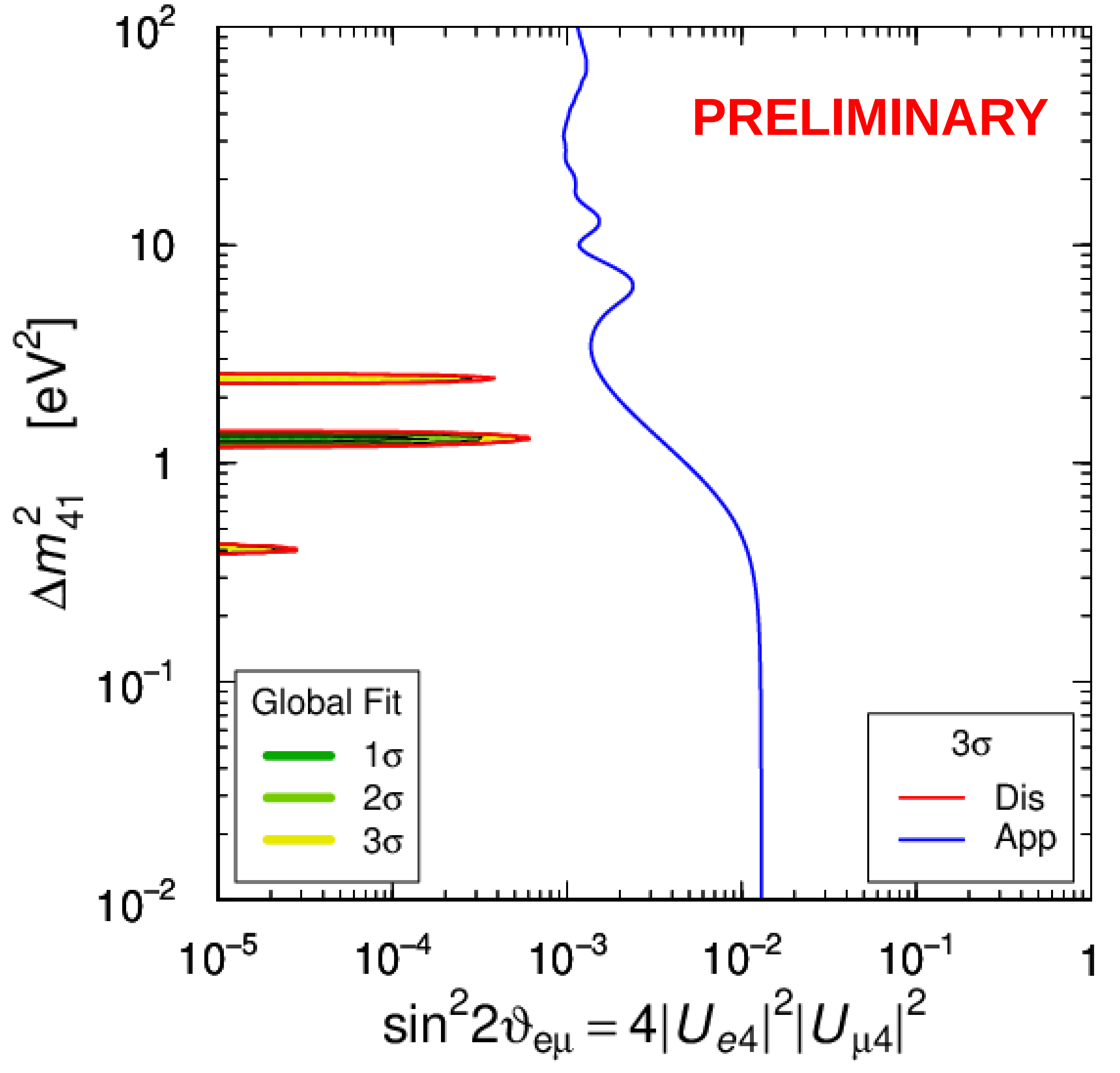
GoF$_{PG}$= 2 x 10^{-6}

Problem remains!

In preparation, S. Gariazzo, C. Giunti, CAT

Tension in APP vs DIS data

Only excluding LSND and MB solves the problem



No surprise, because now there is no lower bound

Conclusions

Conclusions

If one insists that all of the LSND and MB excesses comes from sterile mixing, then:

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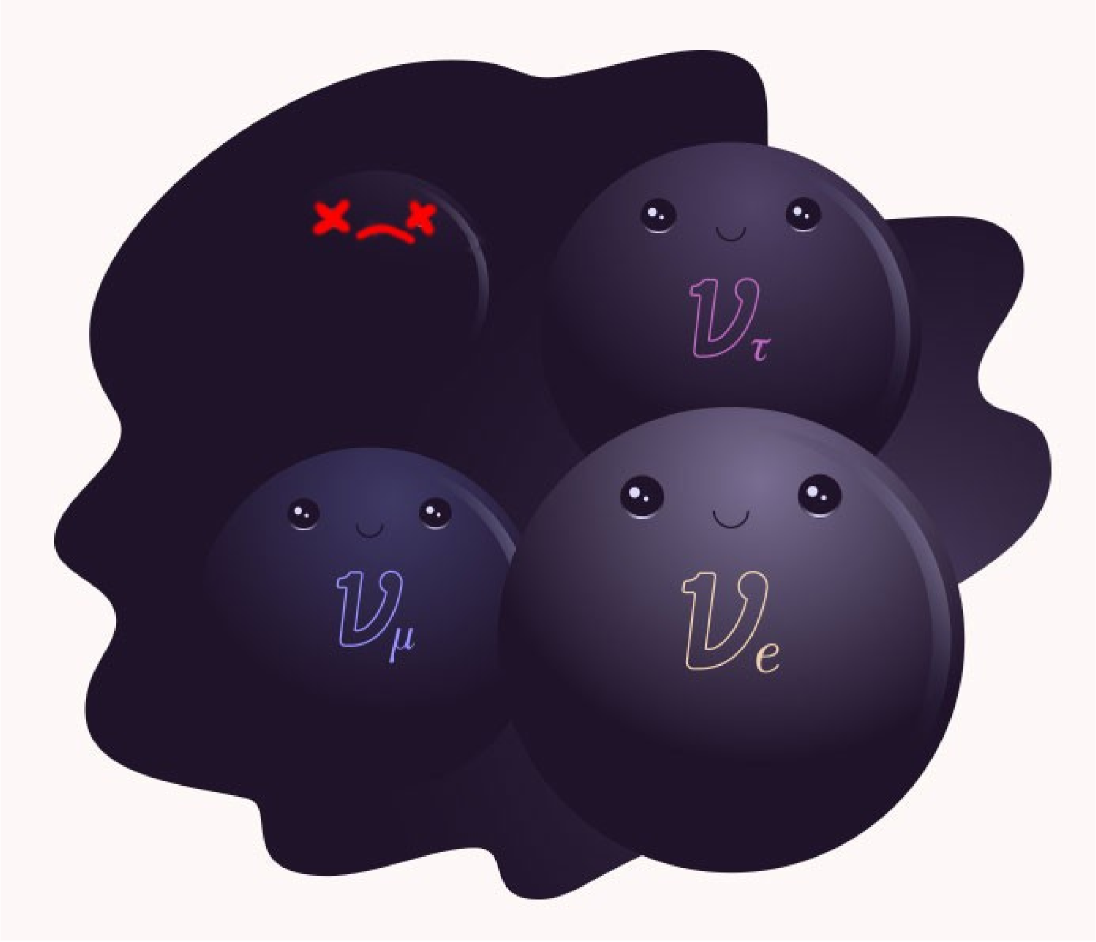
APP-DIS tension makes the 3+1 global fit unacceptable



Conclusions

If one assumes that (at least part of) the LSND and MB excesses could come from different physics:

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Model-independent indication of light sterile neutrino oscillations in very short-baseline reactor experiments

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But no such thing seen in muon neutrino disappearance experiments

Conclusions

If one assumes that (at least part of) the LSND and MB excesses could come from different physics:

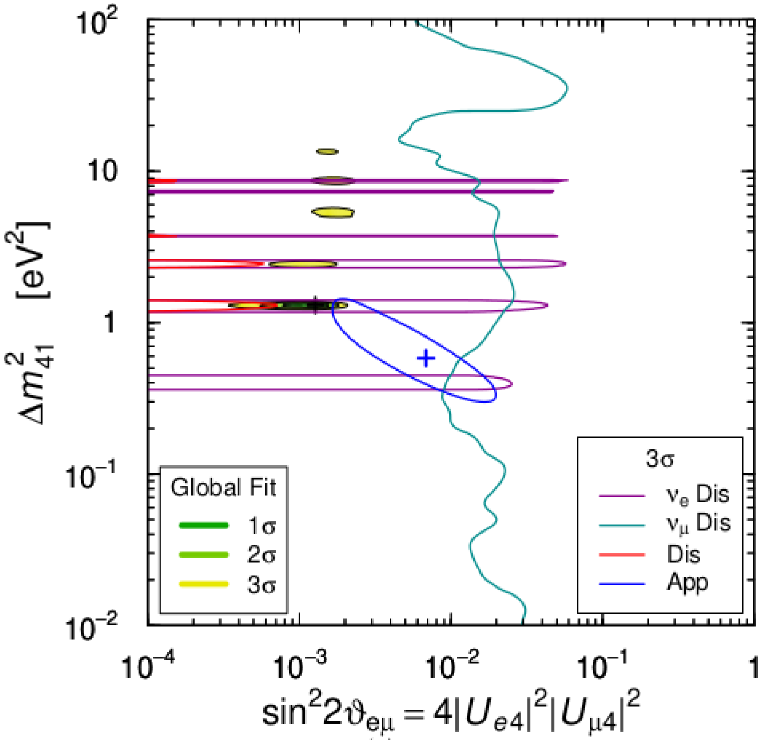
Model-independent indication of light sterile neutrino oscillations in very short-baseline reactor experiments

But no such thing seen in muon neutrino disappearance experiments

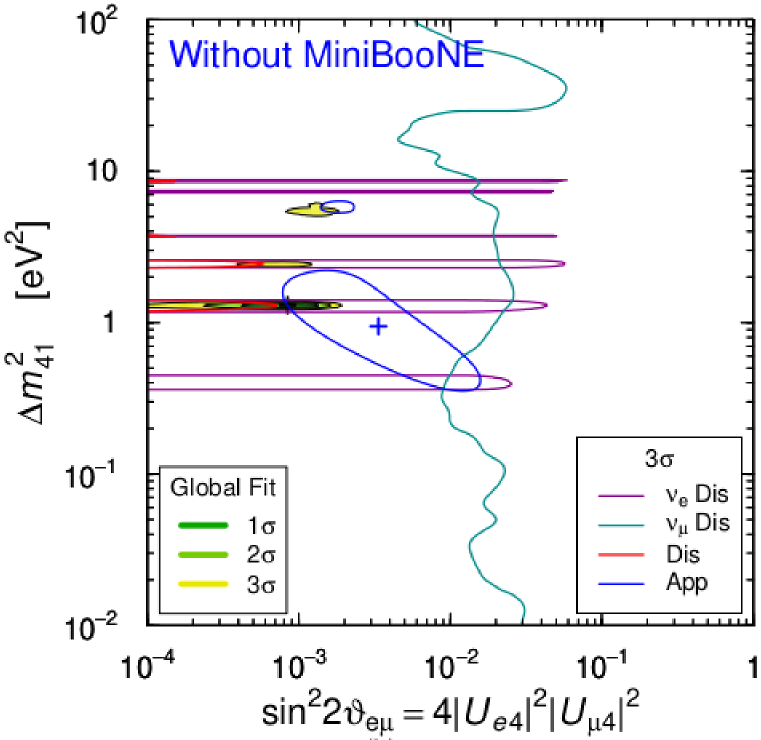
This raises the question: What are **LSND** and **MiniBoone** observing?

Grazie!

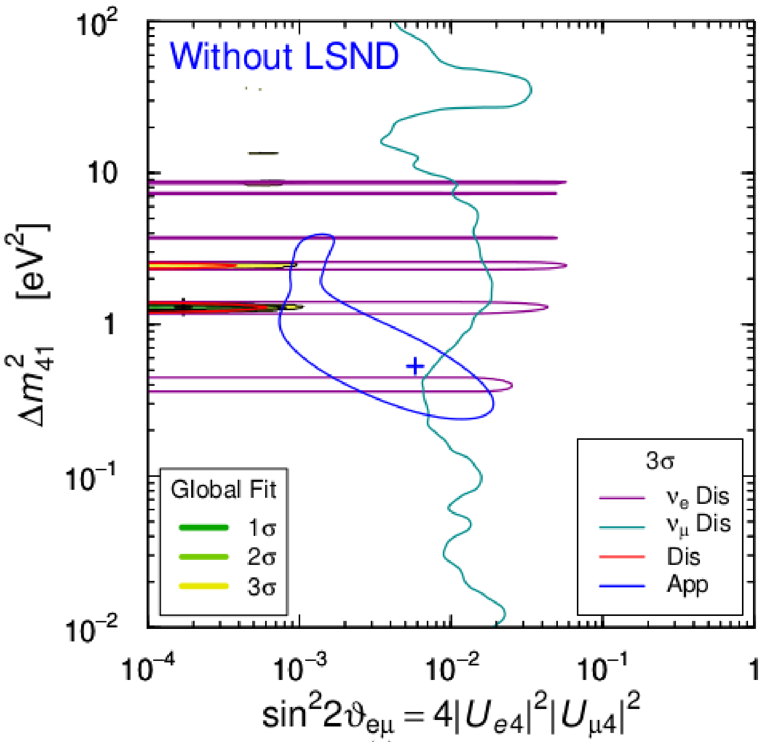
Backup


Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$
Global Fit
1σ
2σ
3σ
3σ
ν_e Dis
ν_μ Dis
Dis
App

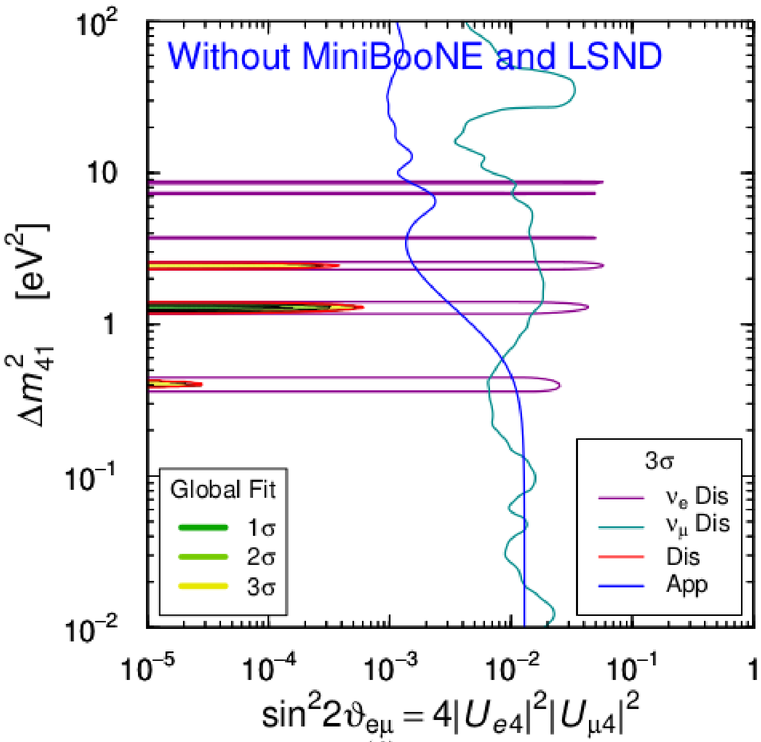
(a)


Without MiniBooNE
Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$
Global Fit
1σ
2σ
3σ
3σ
ν_e Dis
ν_μ Dis
Dis
App

(b)

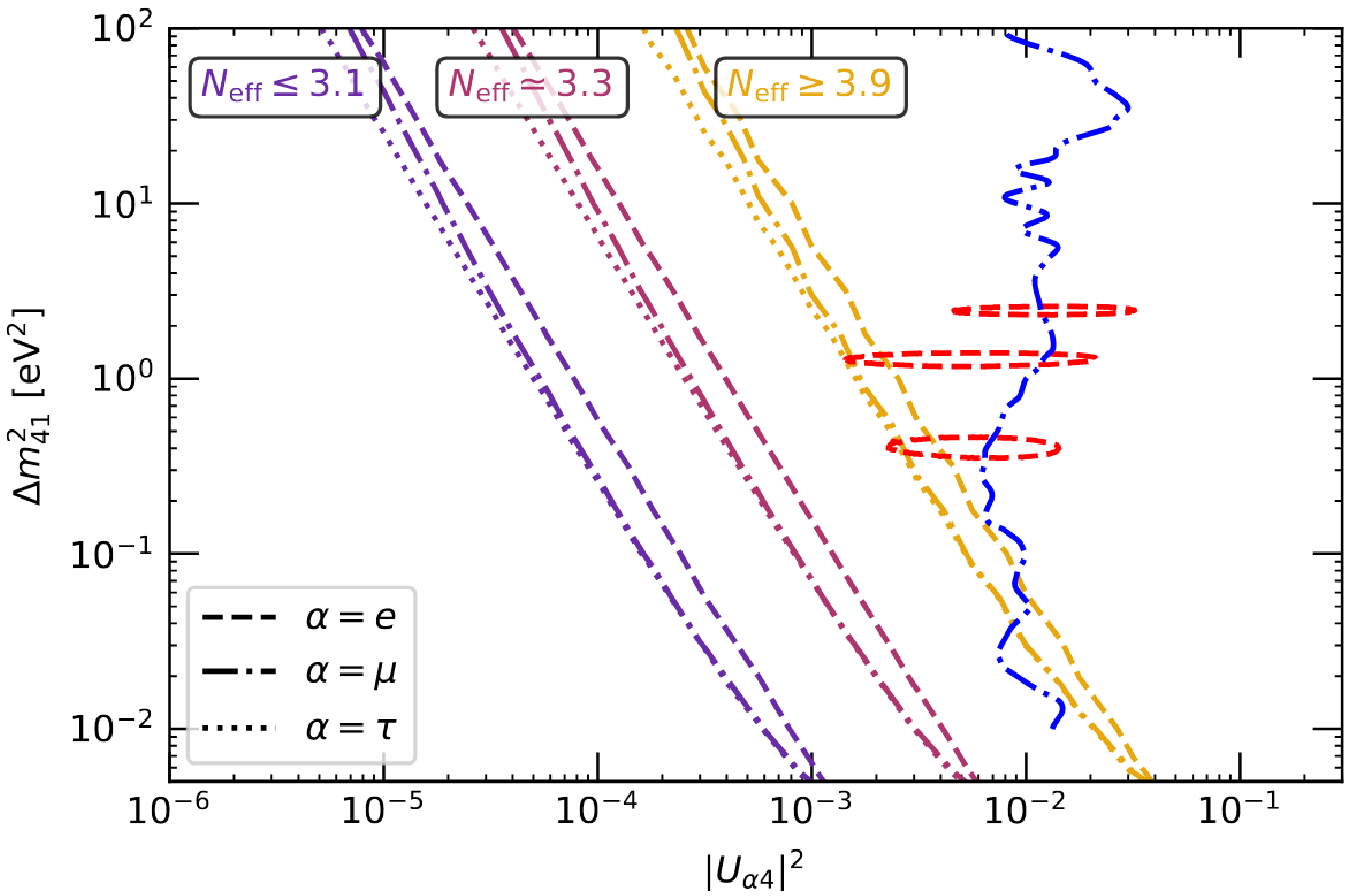

Without LSND
Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$
Global Fit
1σ
2σ
3σ
3σ
ν_e Dis
ν_μ Dis
Dis
App

(c)


Without MiniBooNE and LSND
Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$
Global Fit
1σ
2σ
3σ
3σ
ν_e Dis
ν_μ Dis
Dis
App

(d)

	All	~~MB~~	~~LSND~~	~~MB&LSND~~
$\chi^2_{\rm min}$	827.4	765.8	802.2	726.9
NDF	760	726	756	722
GoF	4.5%	15%	12%	44%
Δm^2_{41}	1.3	1.3	1.3	1.3
$\lvert U_{e4}\rvert^2$	0.017	0.016	0.012	0.012
$\lvert U_{\mu 4}\rvert^2$	0.019	0.013	0.0037	0
$\sin^2 2\vartheta_{e\mu}$	0.0013	0.00084	0.00017	0
$\sin^2 2\vartheta_{ee}$	0.068	0.064	0.046	0.047
$\sin^2 2\vartheta_{\mu\mu}$	0.073	0.052	0.015	0
$\Delta\chi^2_{\rm NO}$	43.5	31.3	16.2	17.7
$\mathrm{NDF}_{\rm NO}$	4	4	4	4
$n\sigma_{\rm NO}$	5.8	4.7	3.0	3.2
$(\chi^2_{\rm min})_{\rm App}$	98.4	49.8	90.3	37.4
$\mathrm{NDF}_{\rm App}$	80	46	76	42
$\mathrm{GoF}_{\rm App}$	7.9%	33%	13%	67%
Δm^2_{41}	0.58	0.93	0.52	0
$\sin^2 2\vartheta_{e\mu}$	0.0068	0.0033	0.0058	0
$(\chi^2_{\rm min})_{\rm Dis}$	690.0	$\leftarrow$	$\leftarrow$	$\leftarrow$
$\mathrm{NDF}_{\rm Dis}$	678	$\leftarrow$	$\leftarrow$	$\leftarrow$
$\mathrm{GoF}_{\rm Dis}$	37%	$\leftarrow$	$\leftarrow$	$\leftarrow$
Δm^2_{41}	1.3	$\leftarrow$	$\leftarrow$	$\leftarrow$
$\lvert U_{e4}\rvert^2$	0.012	$\leftarrow$	$\leftarrow$	$\leftarrow$
$\lvert U_{\mu 4}\rvert^2$	0	$\leftarrow$	$\leftarrow$	$\leftarrow$
$\sin^2 2\vartheta_{e\mu}$	0	$\leftarrow$	$\leftarrow$	$\leftarrow$
$\sin^2 2\vartheta_{ee}$	0.047	$\leftarrow$	$\leftarrow$	$\leftarrow$
$\sin^2 2\vartheta_{\mu\mu}$	0	$\leftarrow$	$\leftarrow$	$\leftarrow$
$\Delta\chi^2_{\rm PG}$	39.0	26.0	22.4	-0.008
$\mathrm{NDF}_{\rm PG}$	2	2	2	2
$\mathrm{GoF}_{\rm PG}$	3×10^{-9}	2×10^{-6}	1×10^{-5}	100%



1905.11290, S. Gariazzo, P.F. de Salas. S. Pastor