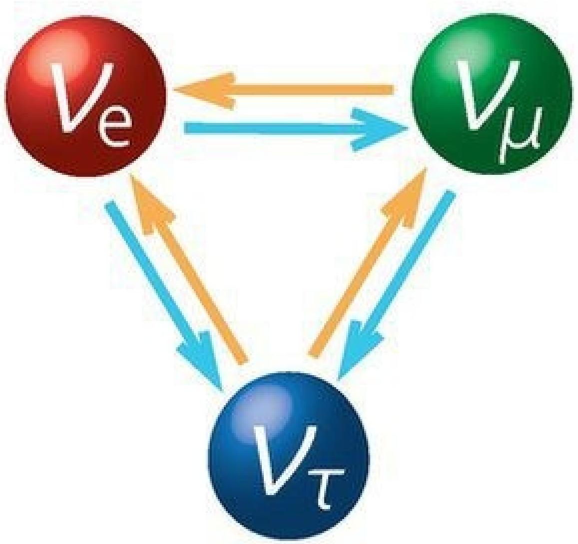
Current status of 3+1 neutrino mixing

Christoph Andreas Ternes
IFIC, Universitat de València - CSIC

Neutrino Platform Week 2019: Hot Topics in Neutrino Physics
CERN, Switzerland, October 7th 2019

Three-neutrino oscillations



Three-neutrino oscillations

Neutrino mixing matrix

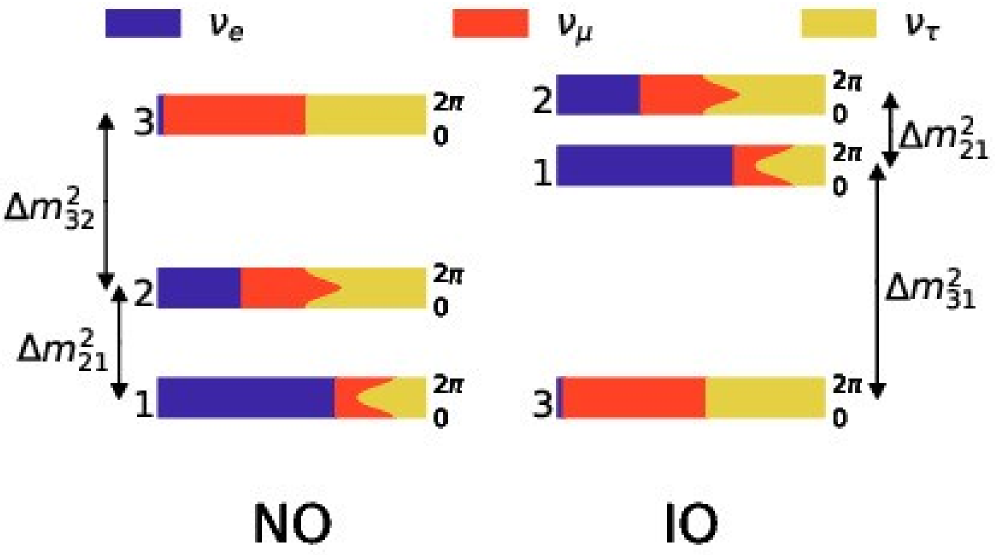
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

1 Dirac + 2 Majorana CP-phases

Three masses m_1, m_2, m_3

Oscillations are only sensitive to mass splittings, for which two possible orderings are possible



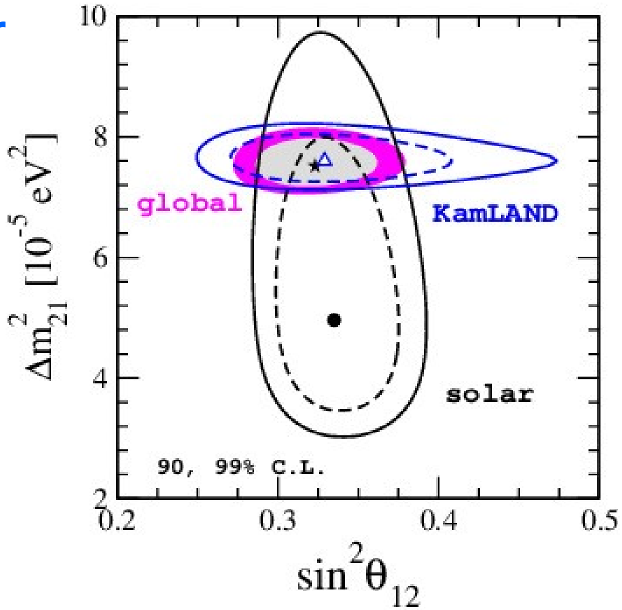
Three-neutrino oscillations

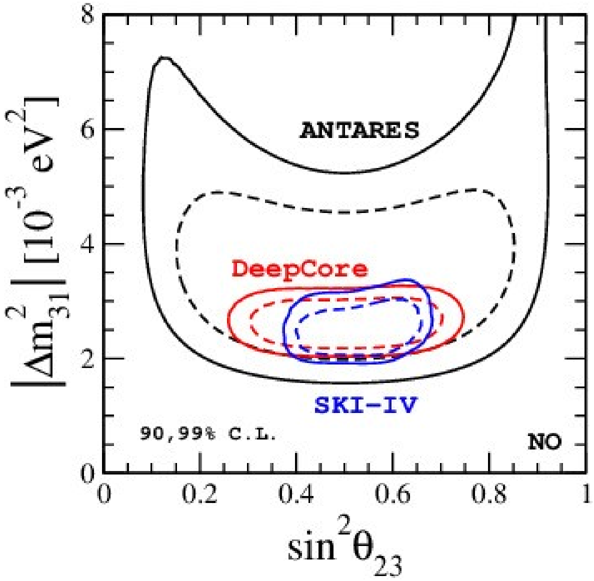
Solar sector

CL,Ga,SK

SNO, Borexino

KamLAND





Atmospherics

SK

DeepCore

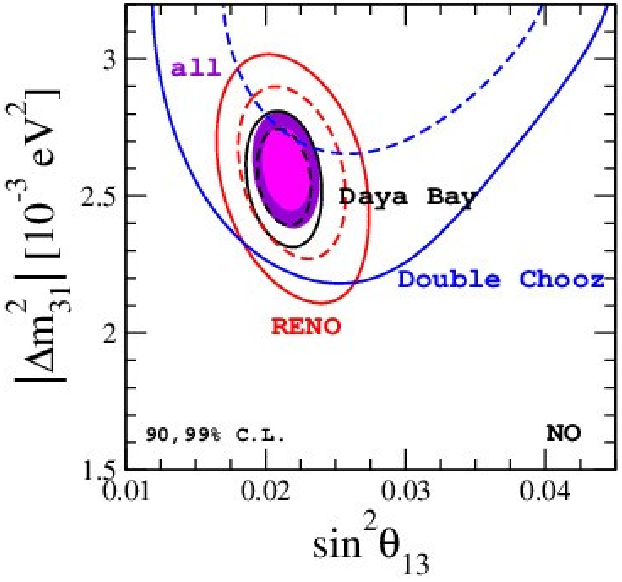
ANTARES

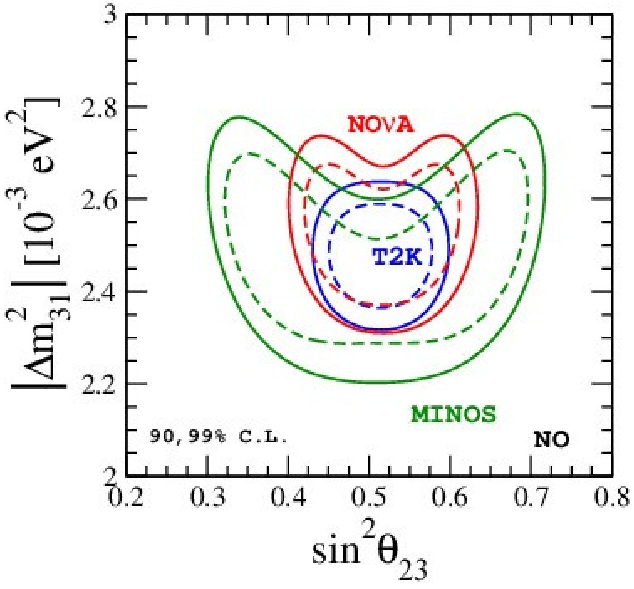
Reactors

Daya Bay

RENO

Double Chooz





Accelerators

MINOS

T2K

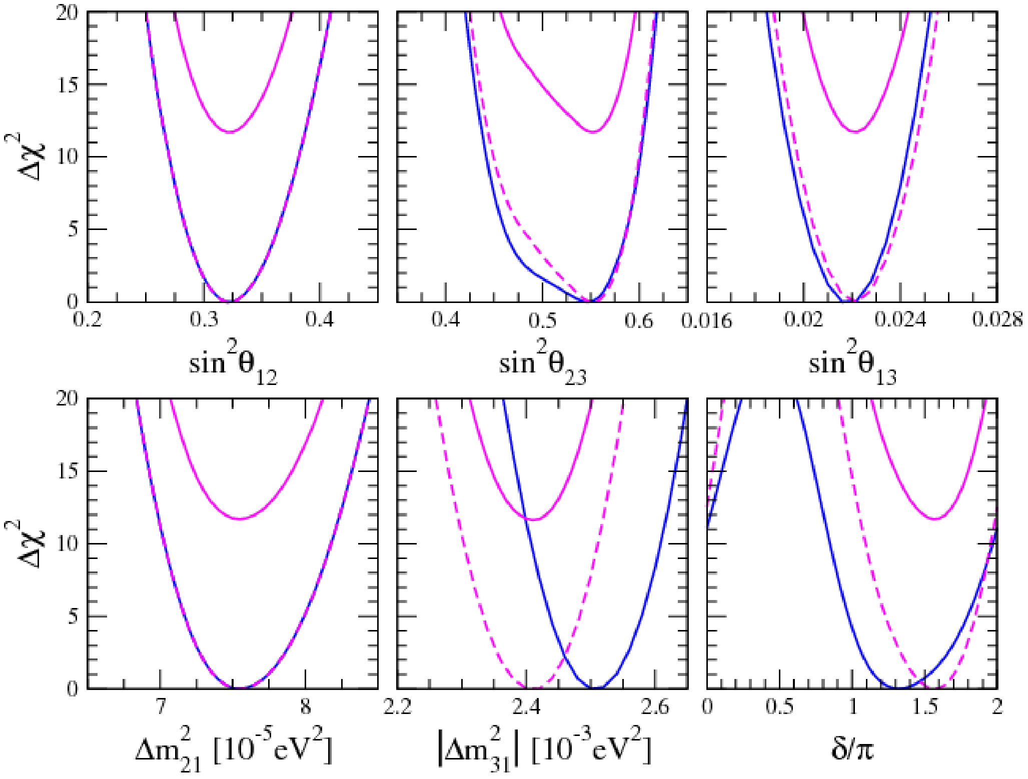
NOνA

PLB 782 (2018), de Salas, Forero, Ternes, Tórtola, Valle

Three-neutrino oscillations

Results of global combination:

parameter	best fit ± 1σ	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



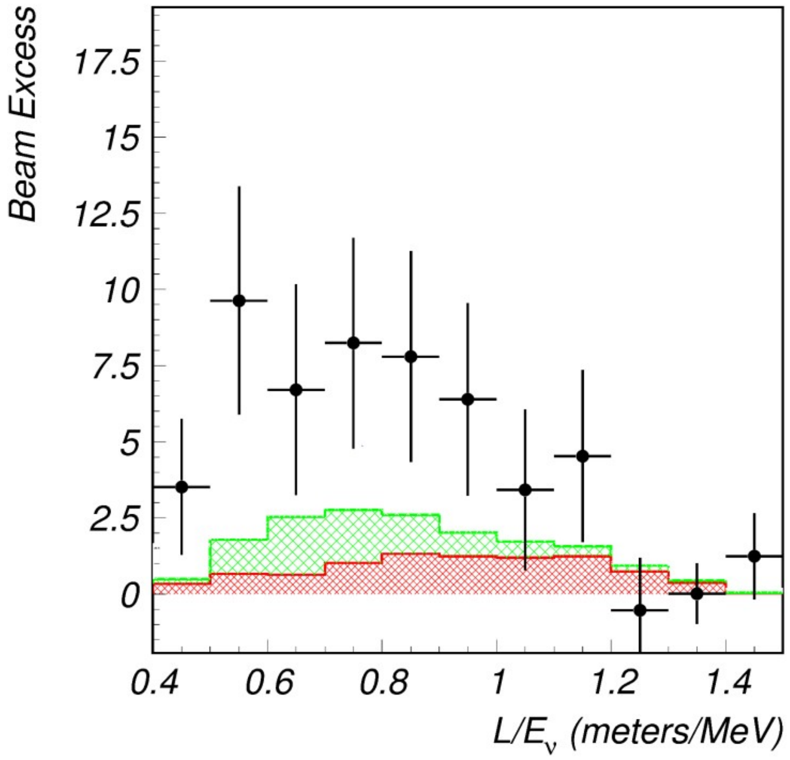
PLB 782 (2018), de Salas, Forero, Ternes, Tórtola, Valle

See also: -Bari-group, PPNP 102 (2018)
-Nu-fit, JHEP 1901 (2019)

Anomalies in oscillations

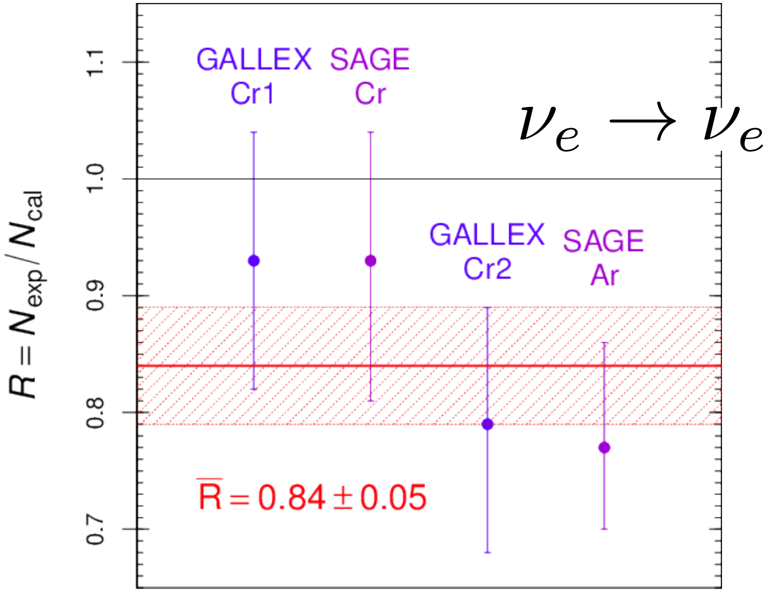
Anomalies in oscillations

3.8σ excess in **LSND**



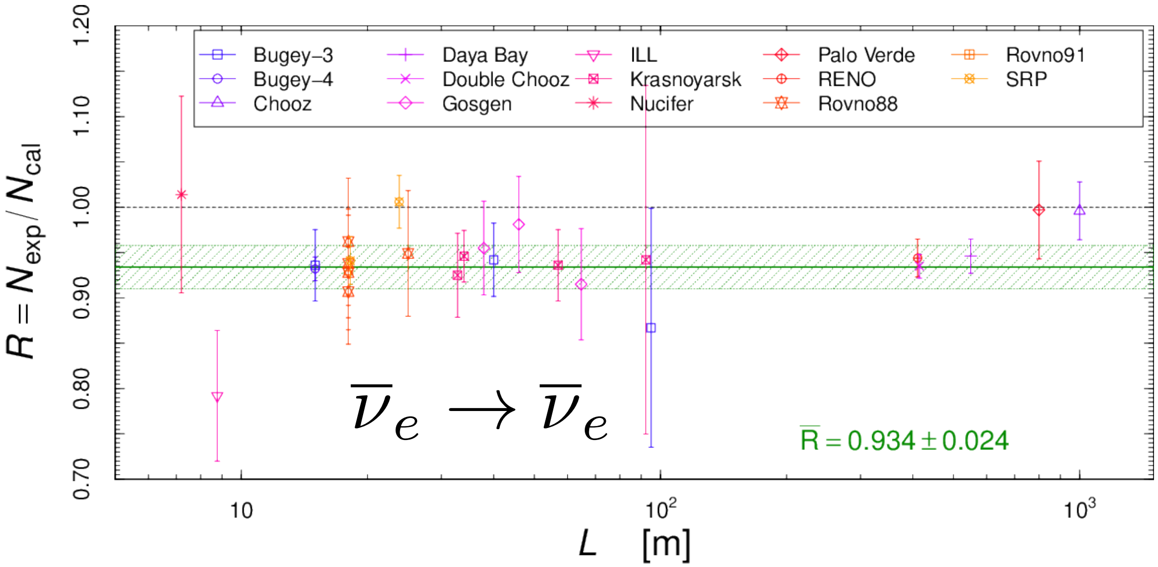
$$\overline{\nu}_\mu \to \overline{\nu}_e$$

~3σ deficit in **Gallium**



$$\nu_e \to \nu_e$$

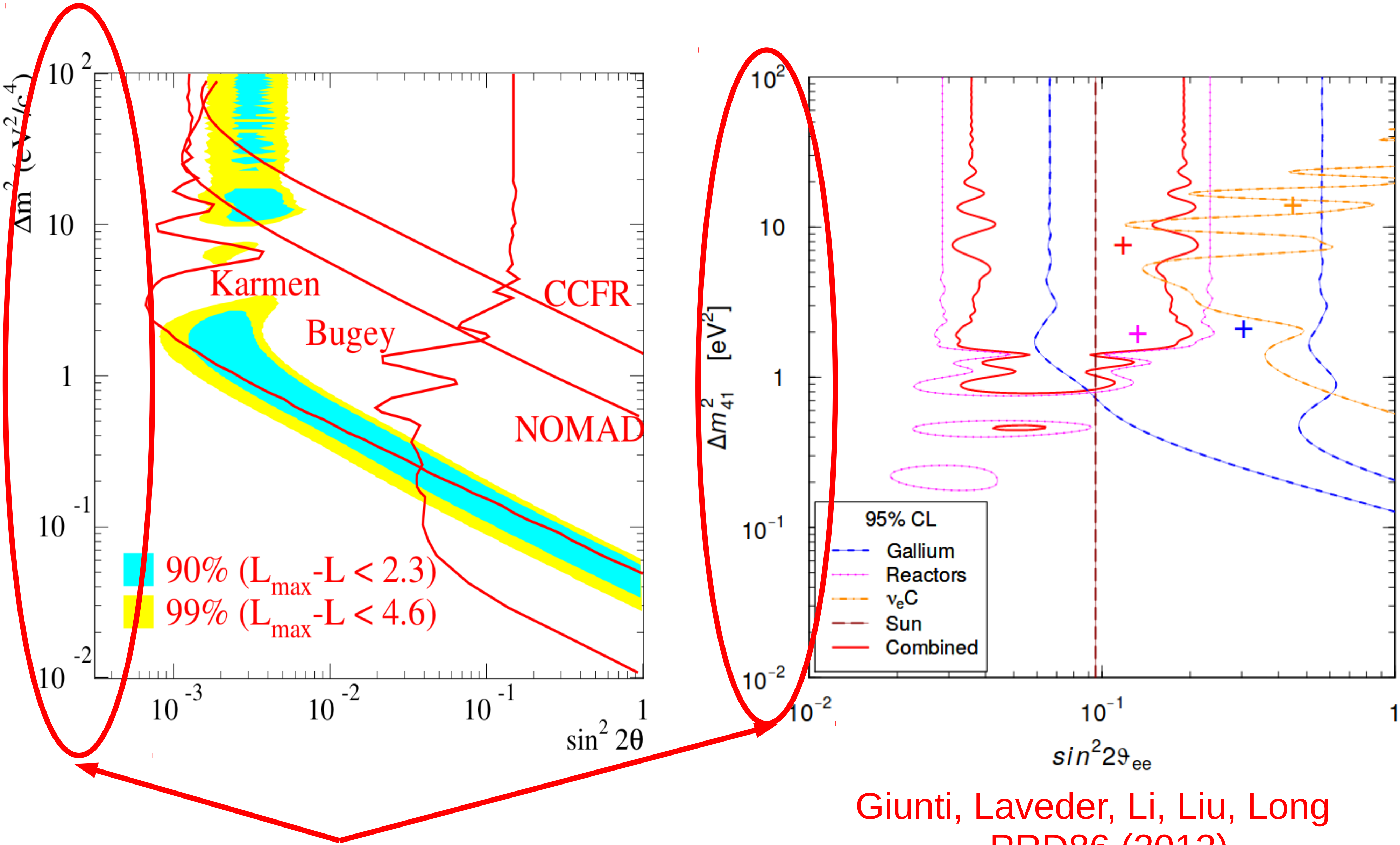
~3σ deficit in **reactors**



$$\overline{\nu}_e \to \overline{\nu}_e$$

LSND: PRL 75 (1995), PRC 54 (1996), PRL 77 (1996), PRD 64 (2001)
Karmen: PRD 65 (2002),
Gallium: PRC 80 (2009), **SAGE,** NPPS 168 (2007), Laveder et al, PRD 78 (2008) and PRC 83 (2011), C. Giunti et al
Reactor: PRD 83 (2011), Mention et al, PRC 83 (2011), Mueller et al, PRC 84 (2011), Huber

Anomalies in oscillations



Giunti, Laveder, Li, Liu, Long
PRD86 (2012)

Mass splittings much larger than the ones obtained by other experiments

Beyond three-neutrino oscillations

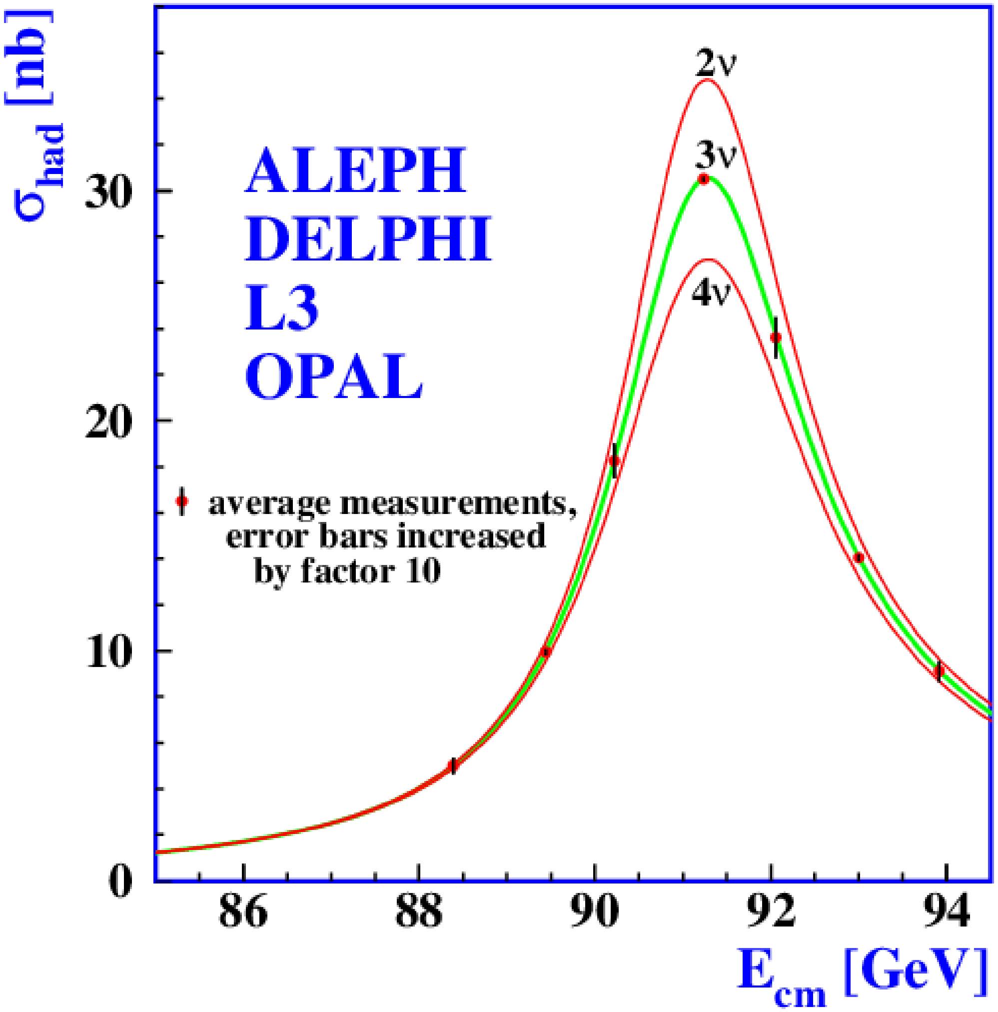
Beyond three-neutrino oscillations

We can add a forth neutrino

This neutrino must be sterile, which means it is a singlet under all standard model gauge groups

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), 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

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

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

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

@Reactors and **Gallium**

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

@atmospherics and **accelerators**

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

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

Quadratically suppressed

DISappearance

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@Reactors and **Gallium**

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

@atmospherics and **accelerators**

3+1 neutrino oscillations

Gallium anomaly, RAA, and LSND can be explained with new a mass splitting and new mixing anlges

$$\Delta m^2_{41}, \sin^2\theta_{ee}, \sin^2\theta_{\mu e}$$

How well does this explanation hold today?

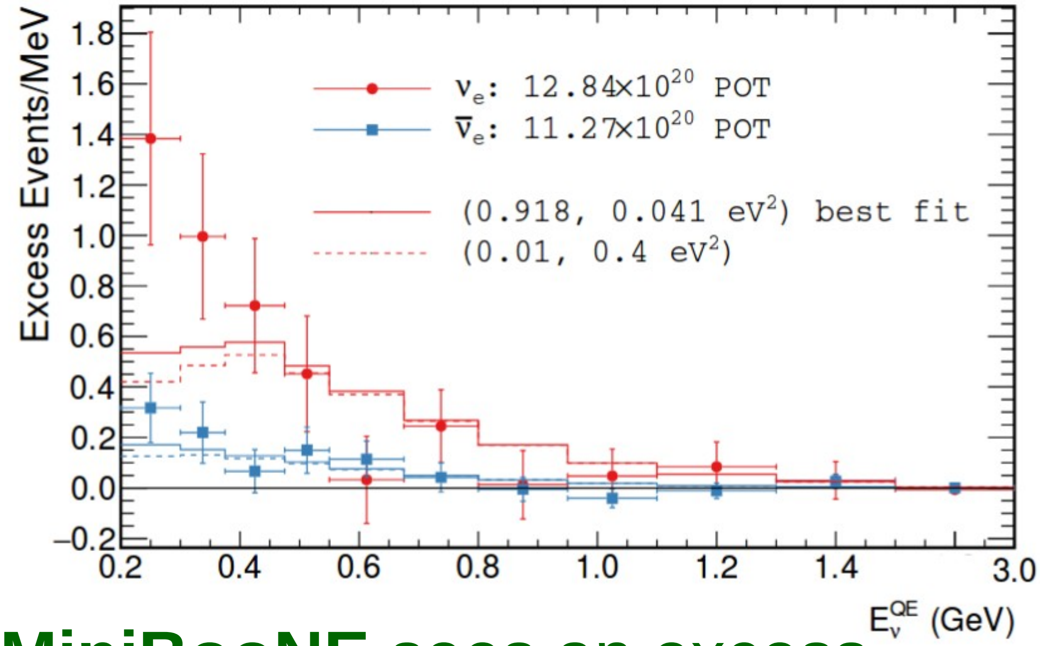
New experiments have been constructed in all sectors

ν_e appearance experiments

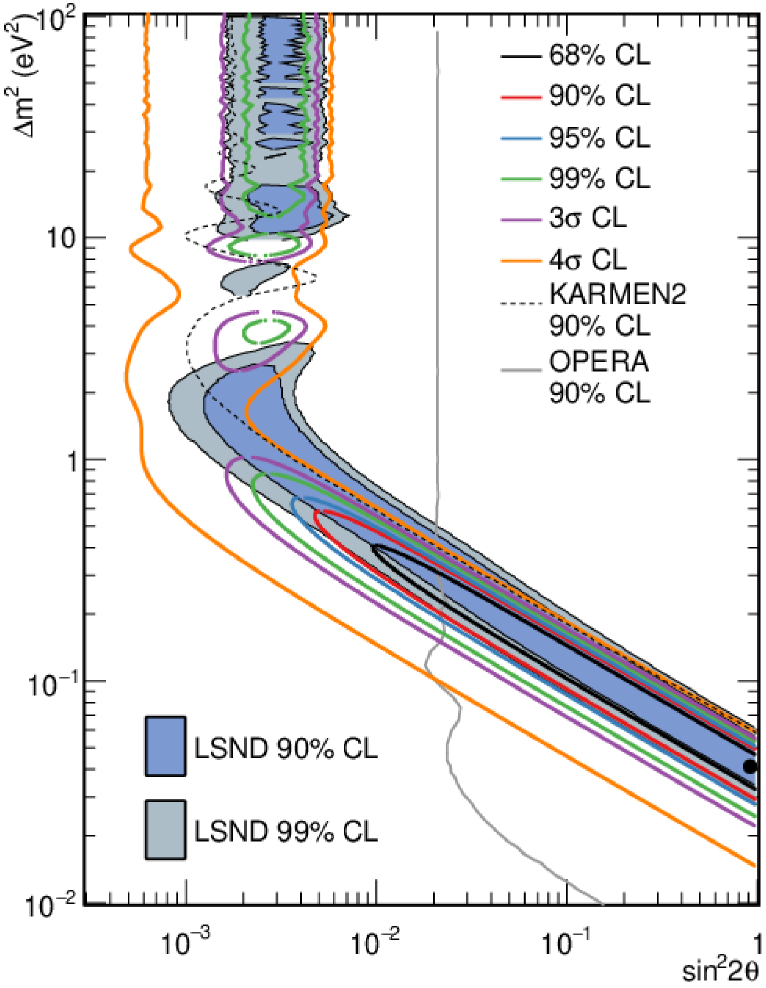
MiniBooNE

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

MiniBooNE has no near detector



MiniBooNE sees an excess at ~5σ at low energies



PRL 121 (2018)

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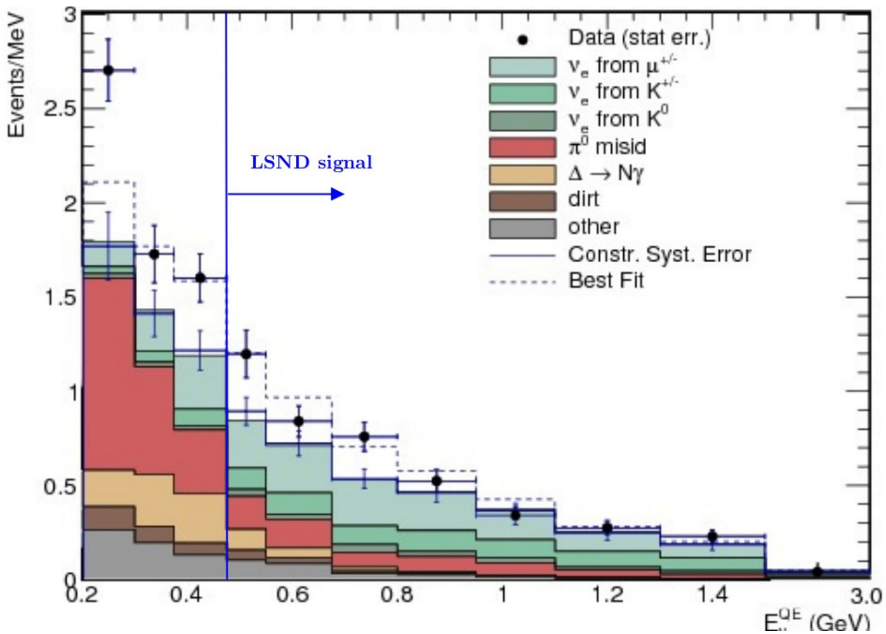
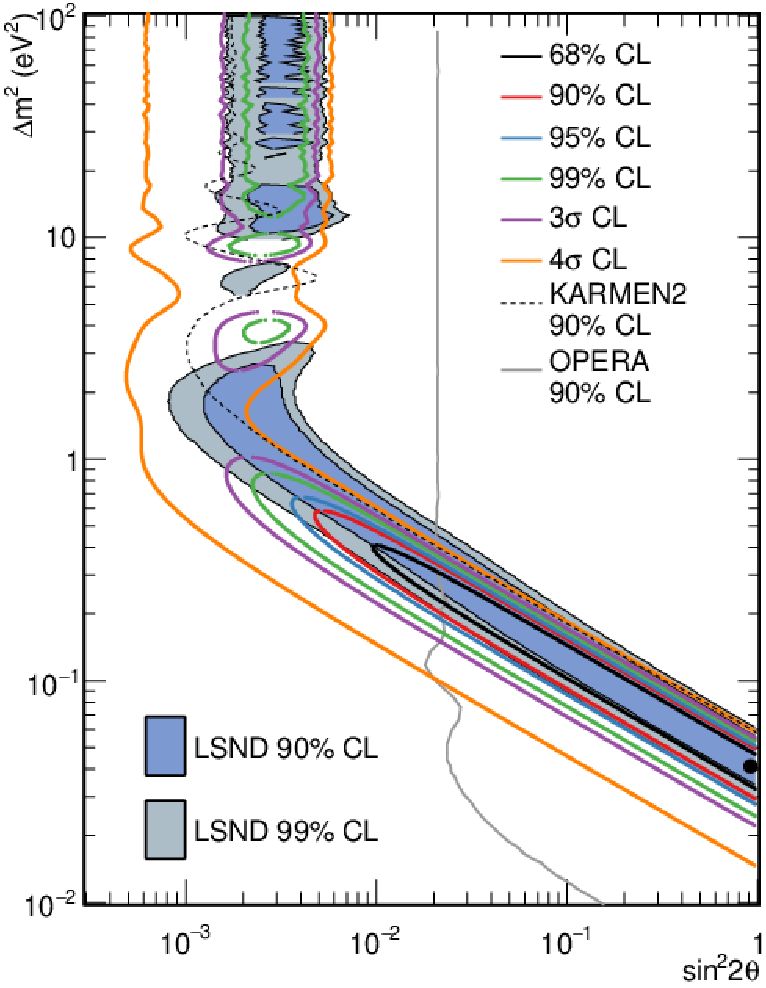


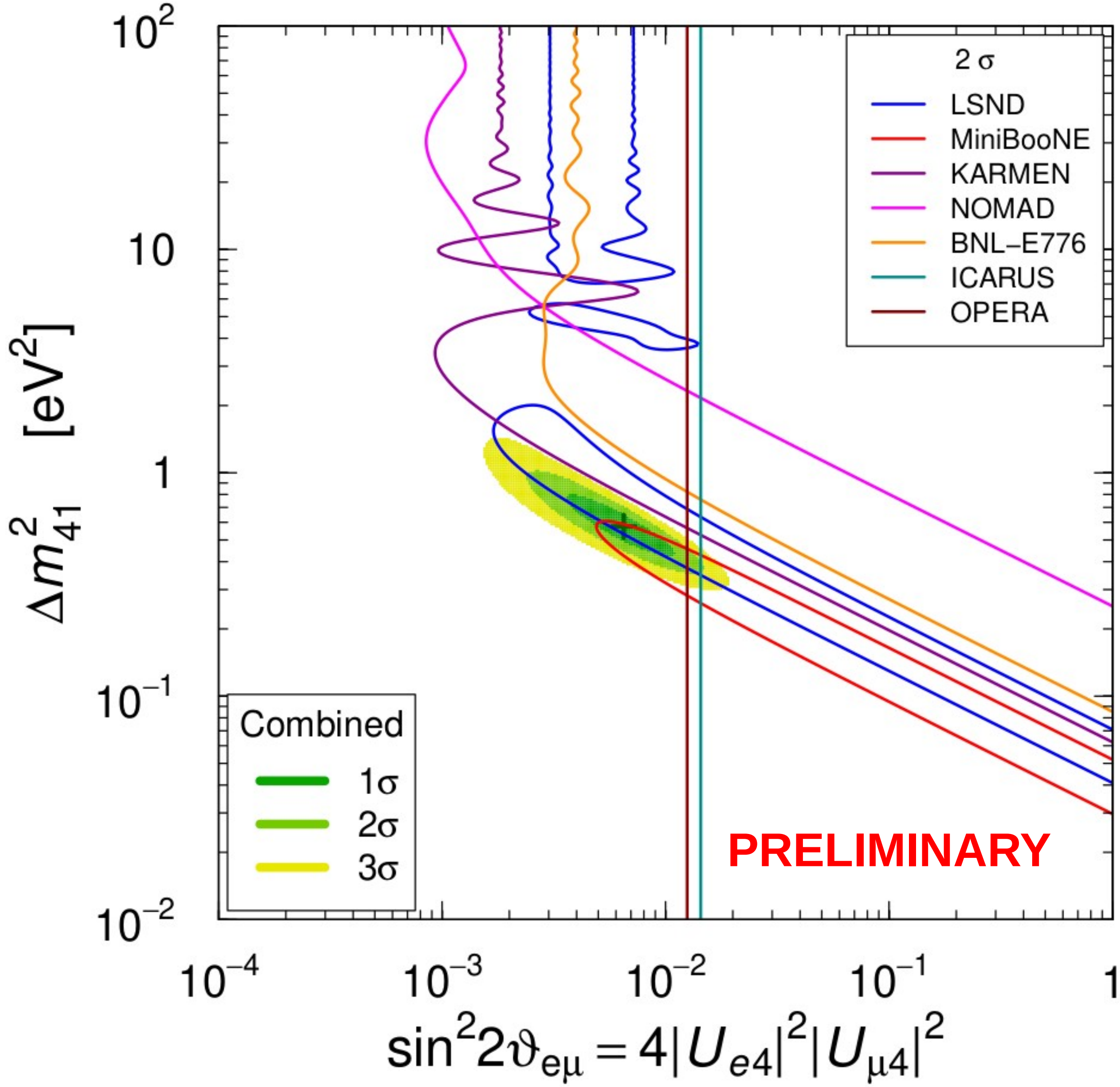
MiniBooNE sees an excess at ~5σ at low energies

However, not exactly where it should…



PRL 121 (2018)

Fit of ν_e appearance data



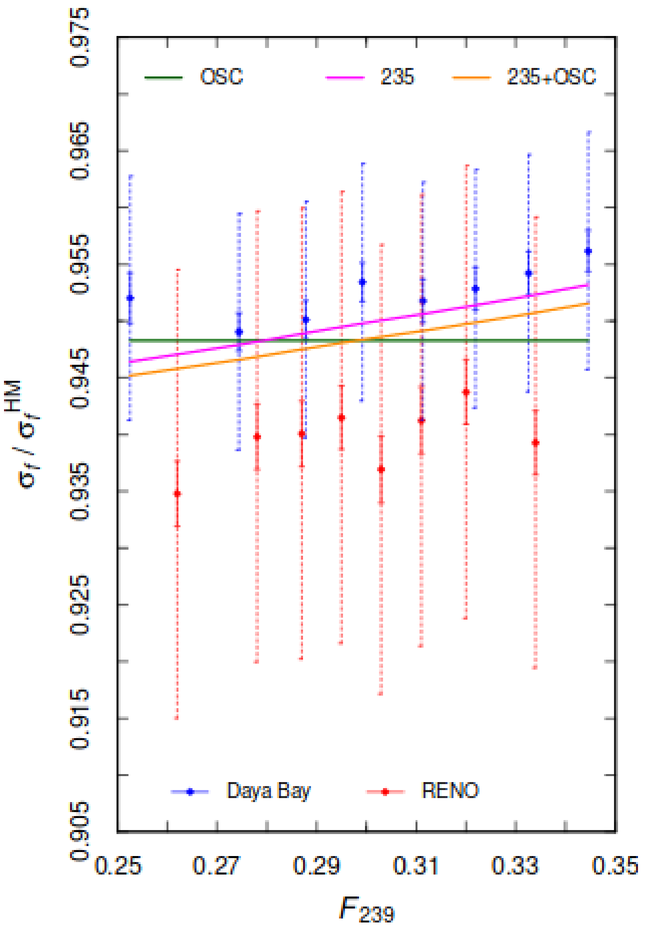
Gariazzo, Giunti, Ternes, in preparation

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

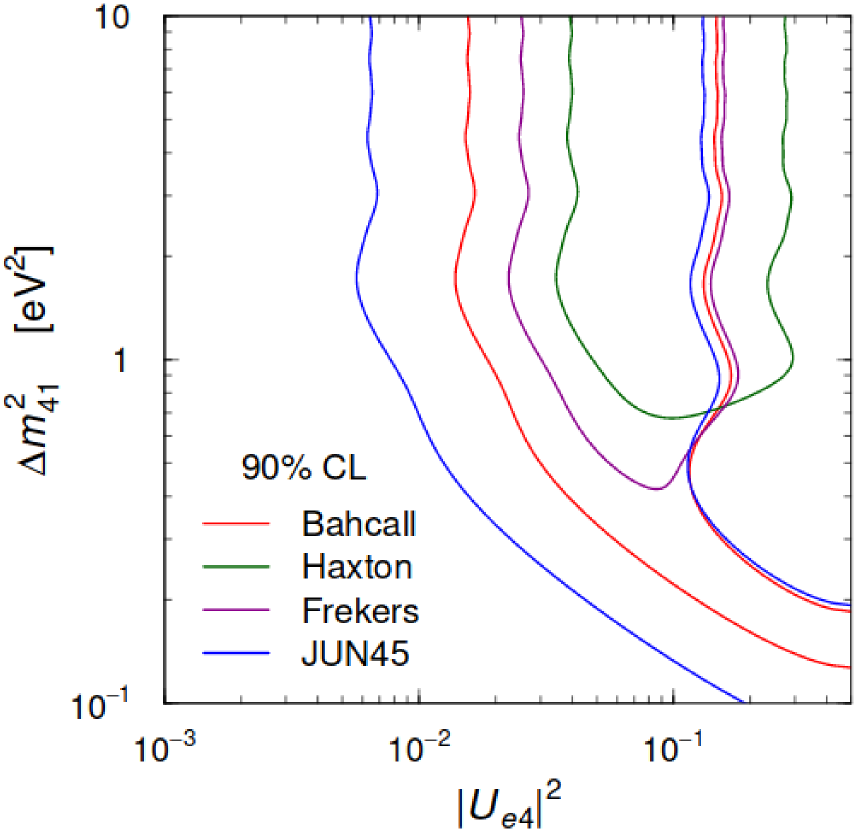
LSND and **MiniBooNE** only partially agree

ν_e disappearance experiments

Revisiting old results



Daya Bay and Reno prefer a suppression of ^{235}U flux over oscillations



Re-evaluation of Ga cross sections reduces the statistical significance of the Gallium anomaly to ~2σ

Giunti, Li, Littlejohn, Surukuchi
PRD 99 (2019)

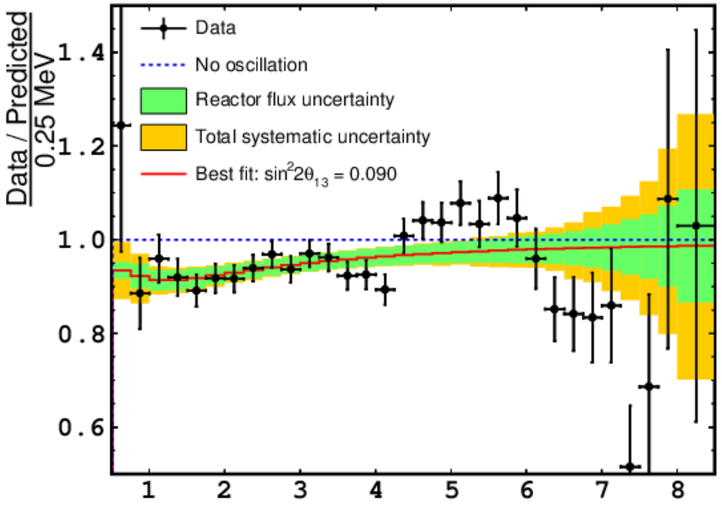
Kostensalo, Suhonen, Giunti, Srivastava
PLB795 (2019)

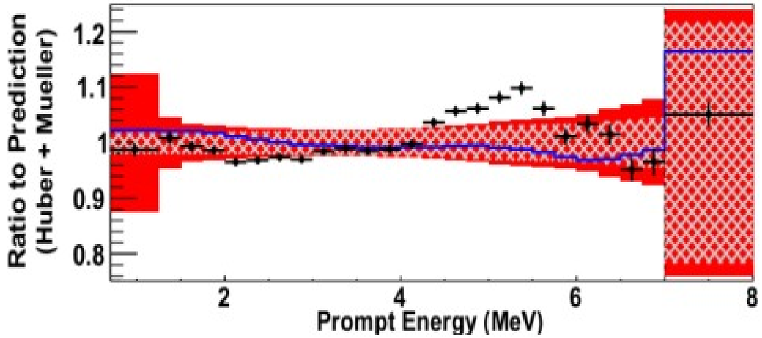
Reactor fluxes

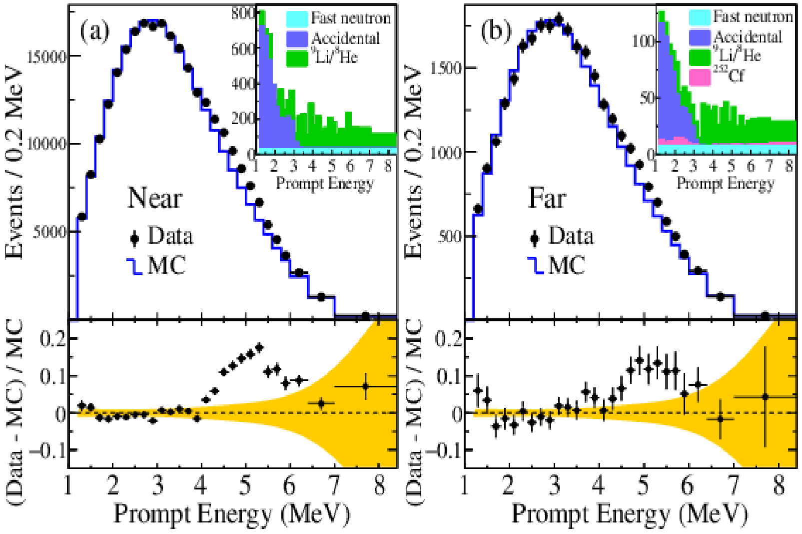
Huber-Mueller-fluxes do not predict the “bump”

The “bump” cannot be explained by sterile neutrino oscillations, because they should be washed out at these distances

We need a model-independent procedure, taking only ratios of fluxes at different distances into account



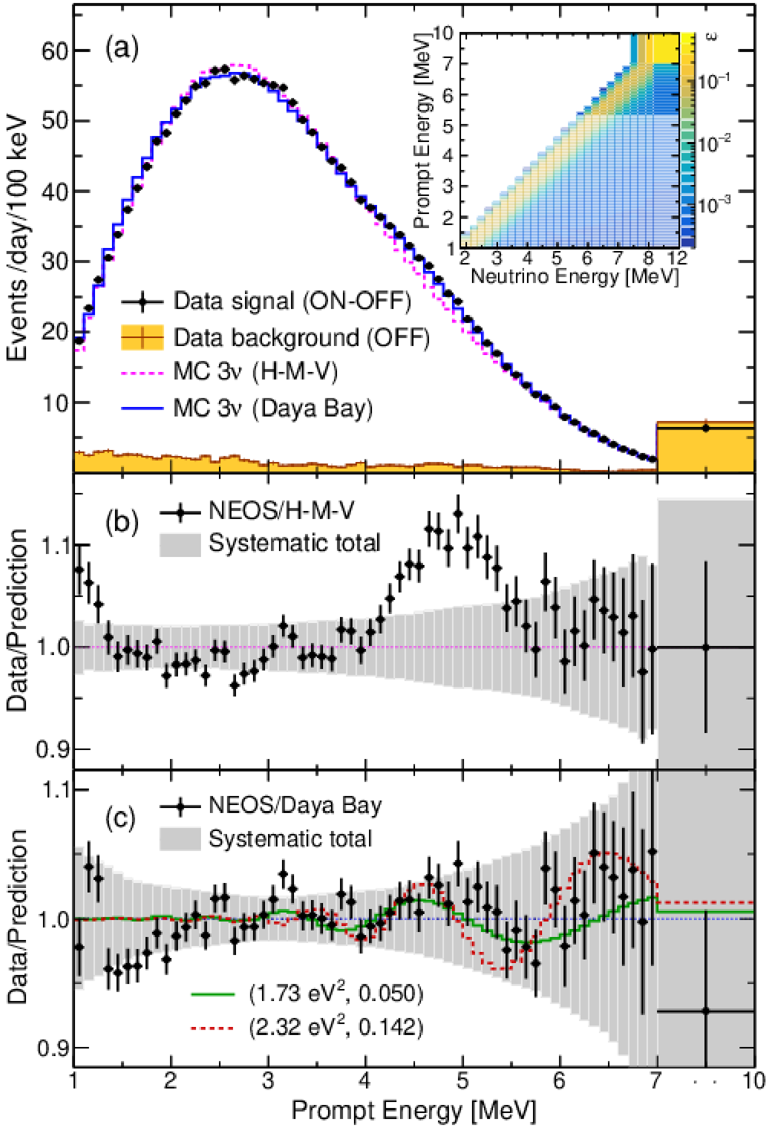


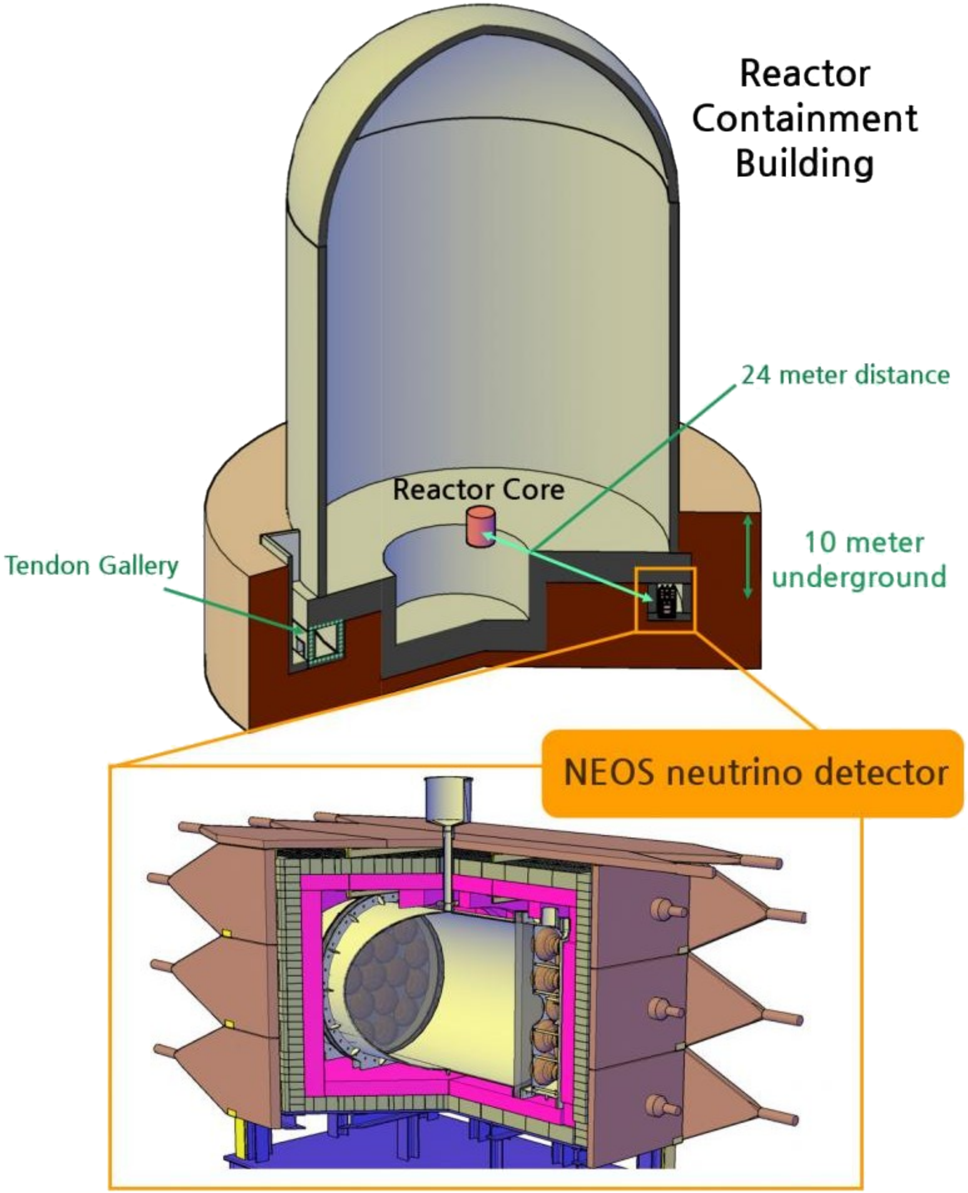


Double Chooz, JHEP 1410 (2014)
Daya Bay, PRL 116 (2016) no.6
RENO, PRL 116 (2016) no.21

NEOS

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

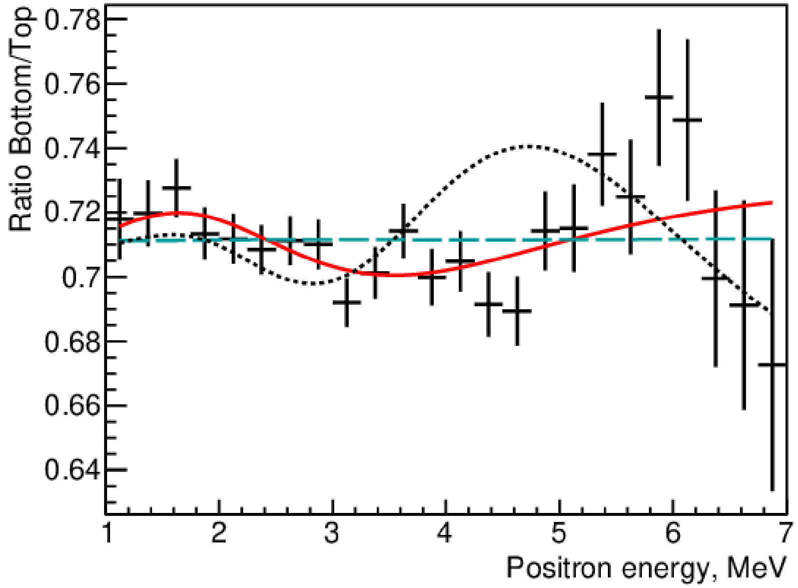


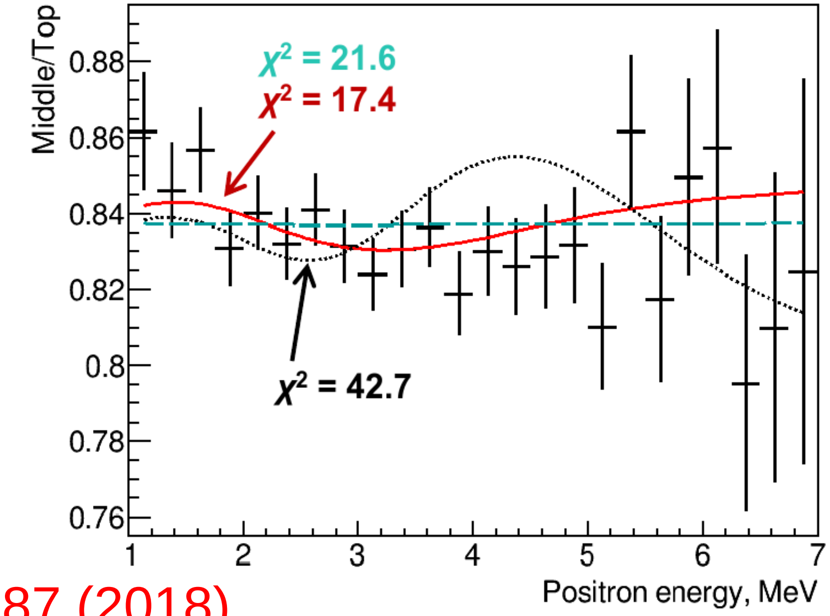


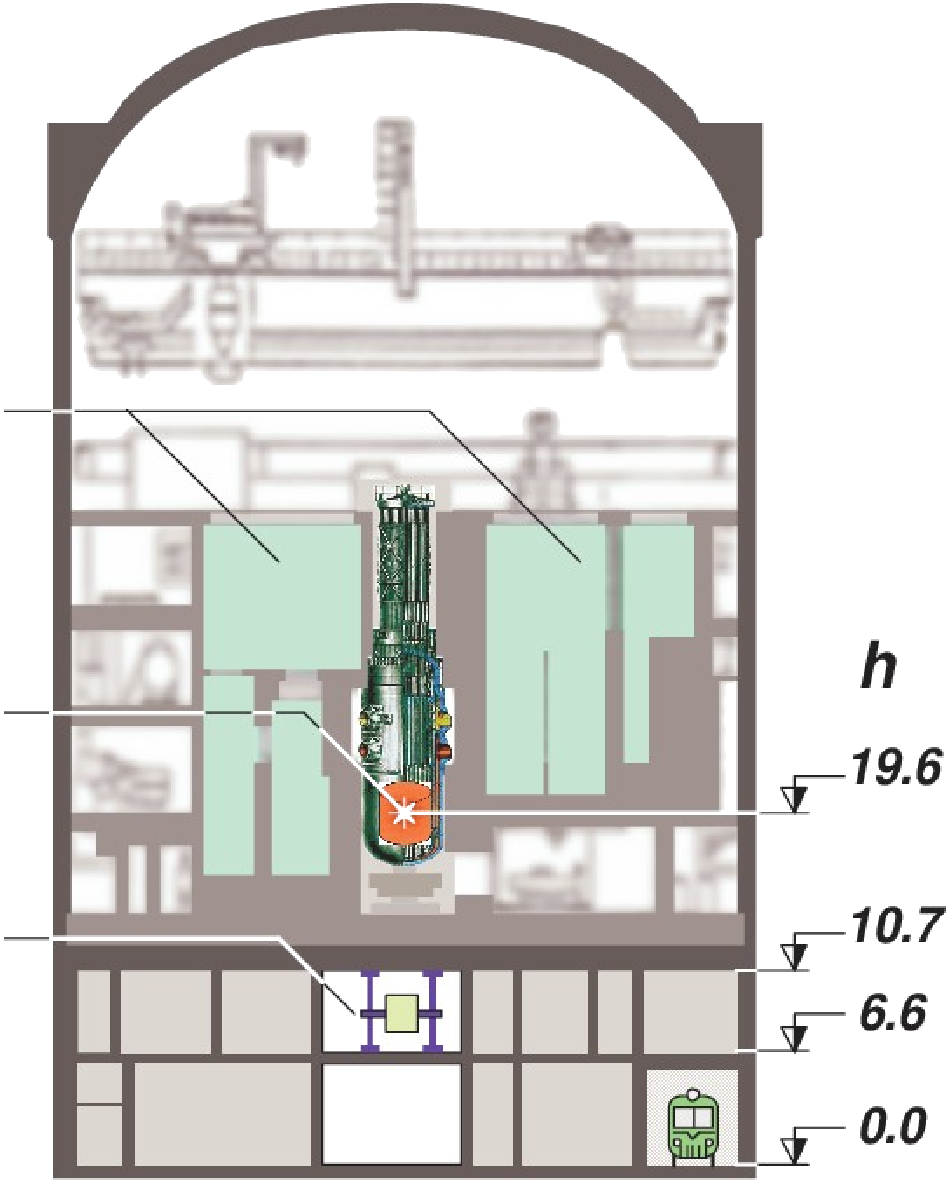
PRL 118 (2017)

DANSS

Single movable detector, ~3σ preference for 3+1 **in 2018**





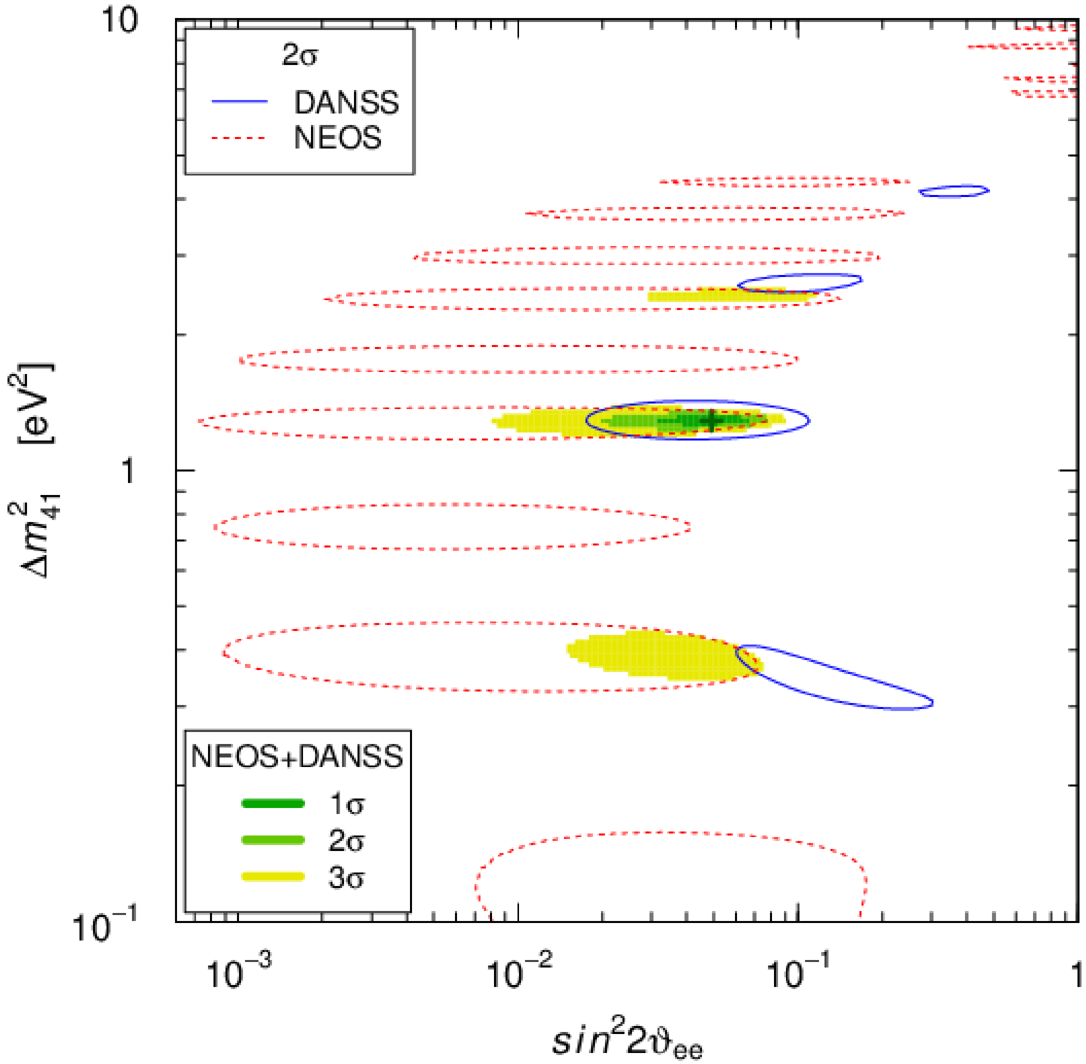


PLB787 (2018)

Fit of ν_e disappearance data

DANSS / **NEOS**

PLB782 (2018), Gariazzo, Giunti, Laveder, Li



Perfect agreement at

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

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

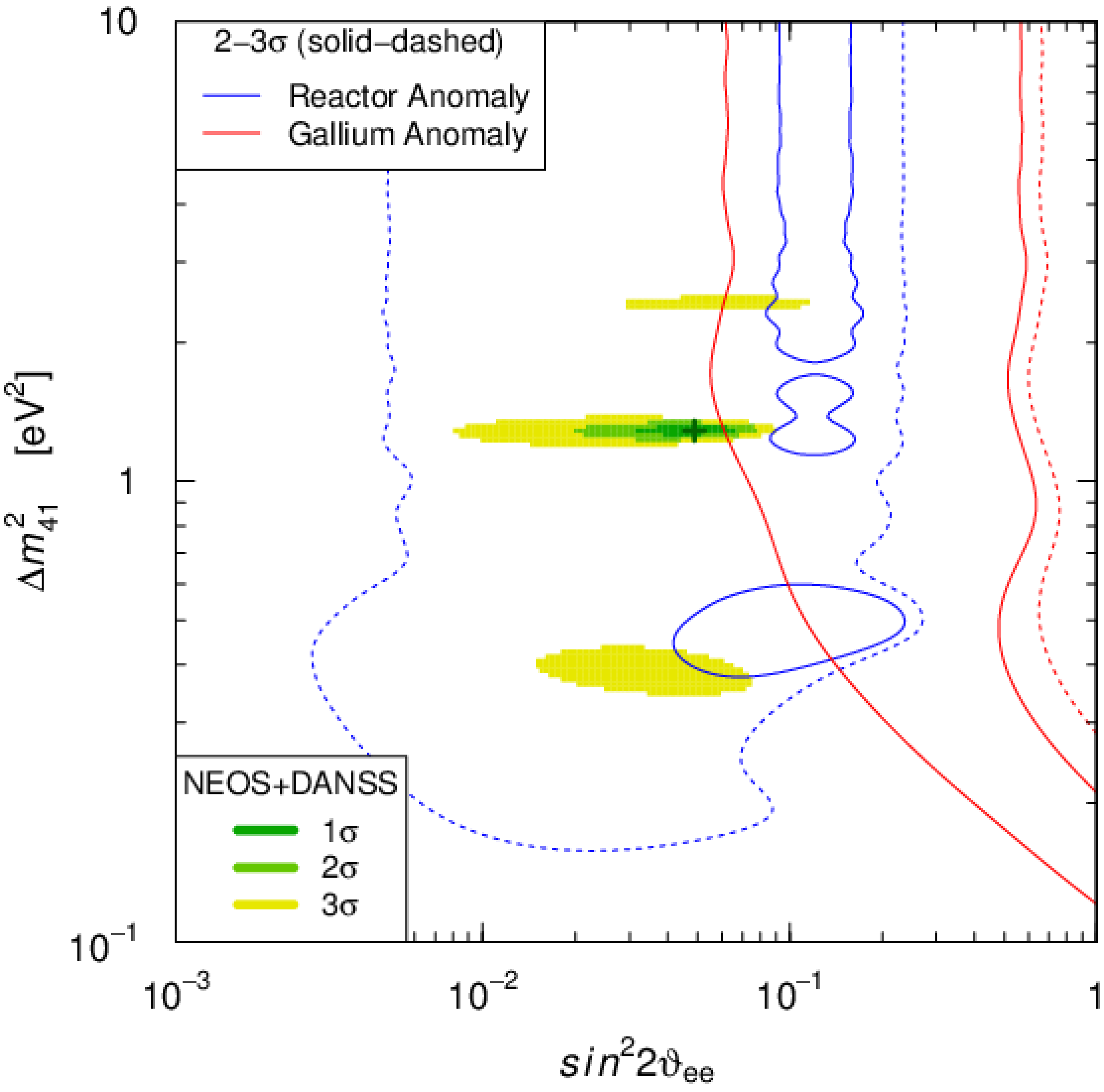
$$\sin^2 \theta_{14} = 0.01$$

See also:
Dentler, Hernández-Cabezudo,
Kopp, Maltoni, Schwetz,
JHEP 1711 (2017)

Fit of ν_e disappearance data

DANSS / NEOS + Gallium + RAA

PLB782 (2018), Gariazzo, Giunti, Laveder, Li

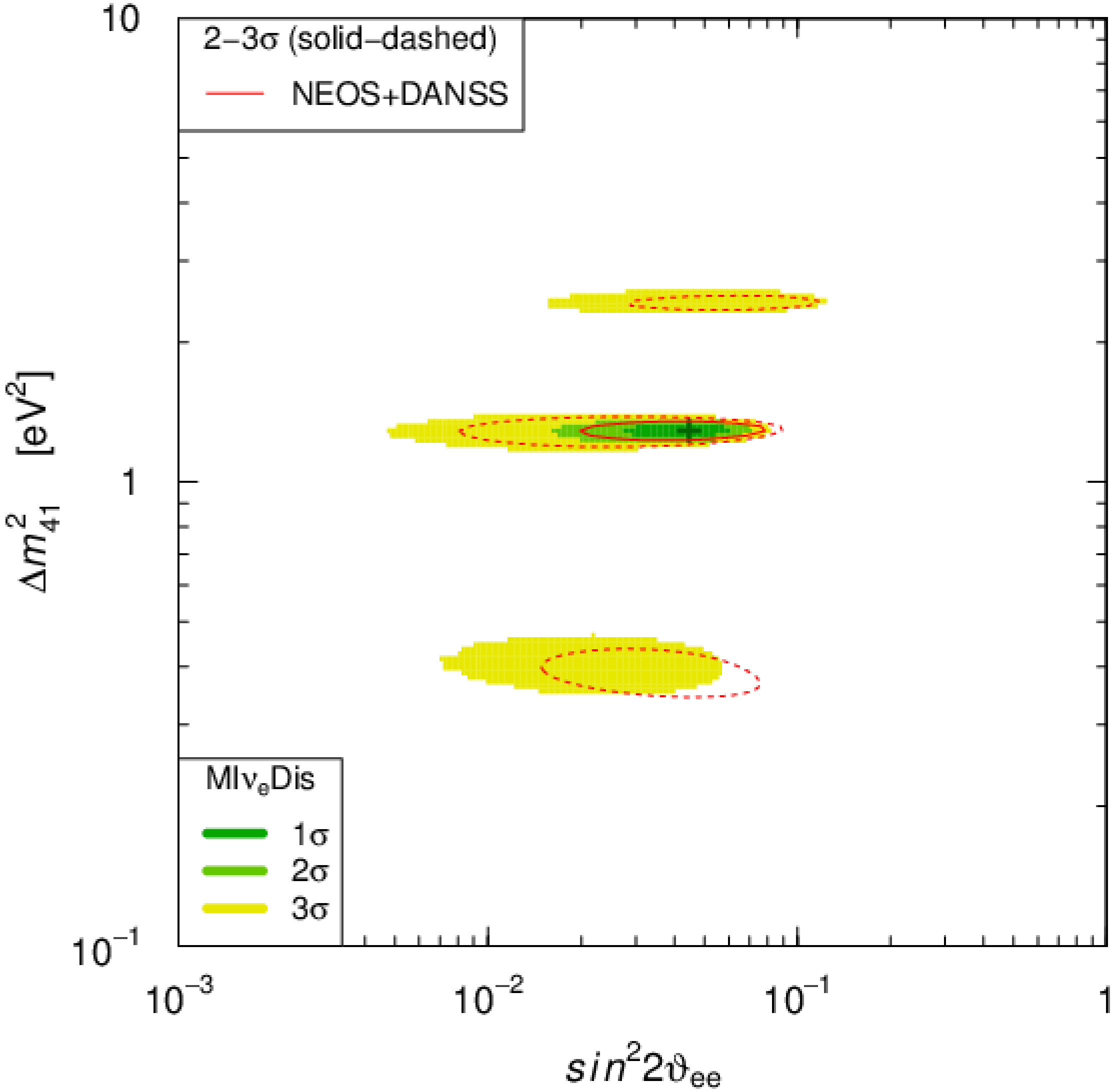


Small tension between **NEOS/DANSS** and **Gallium** and **RAA**

Fit of ν_e disappearance data

All data:

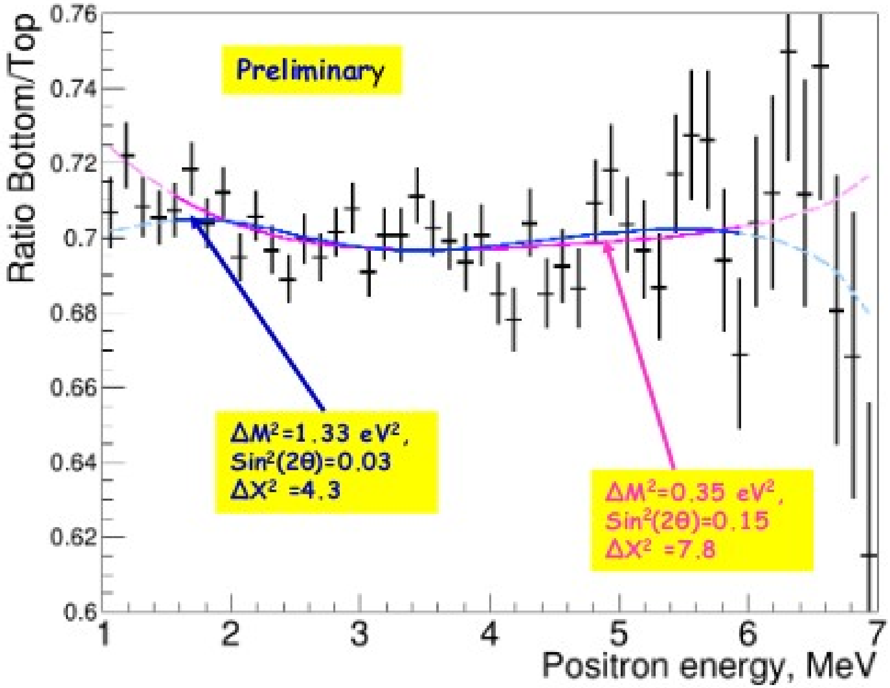
PLB782 (2018), Gariazzo, Giunti, Laveder, Li



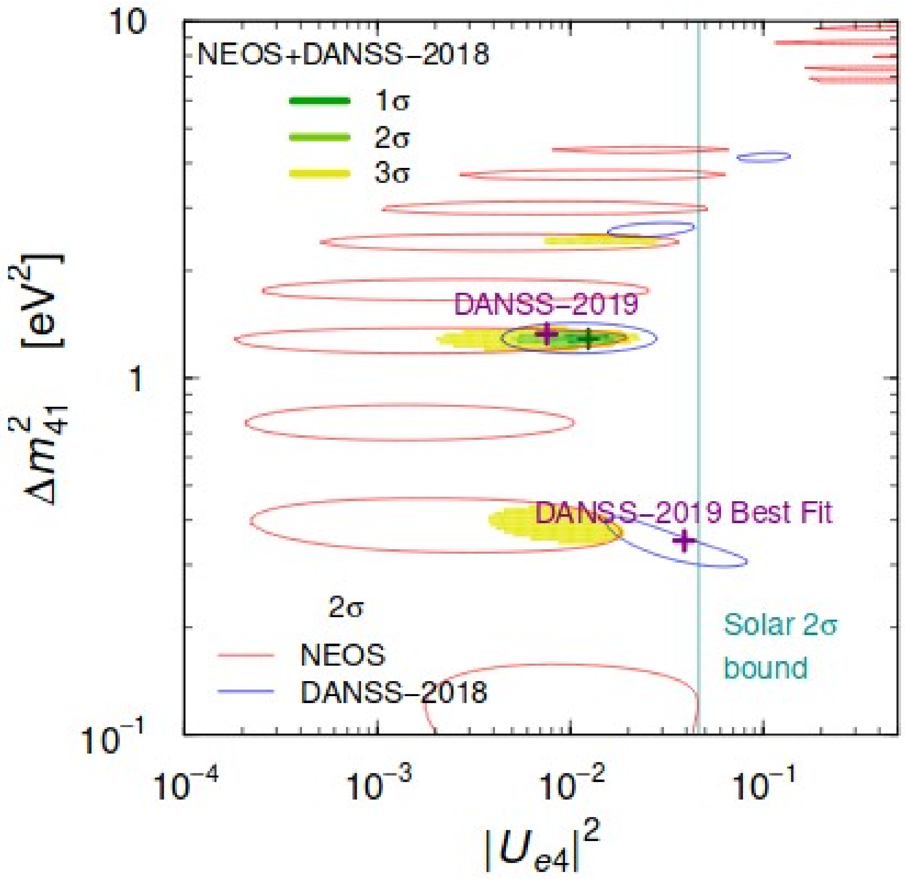
Fit is dominated by
NEOS/DANSS

But….

Fit of ν_e disappearance data



[Danilov @ EPS-HEP 2019]

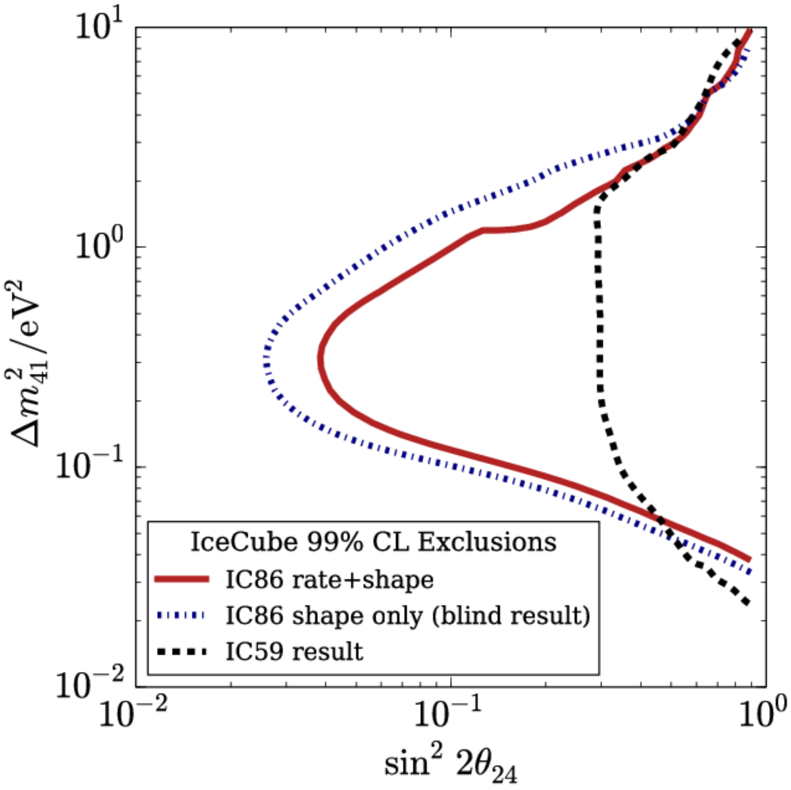


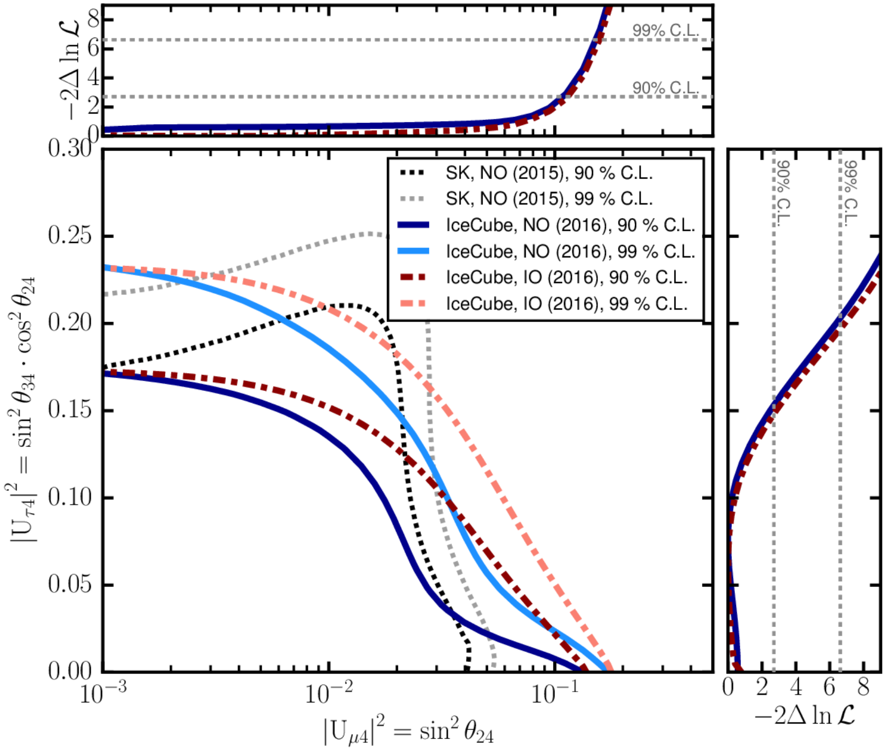
Less agreement between **Neos** and **DANSS**

Indications in favor of SBL oscillations fading away?

ν_μ disappearance experiments

IceCube and DeepCore





High-energy regime

0.3 TeV – 20 TeV

Waiting for 7 yr update!

Low-energy regime

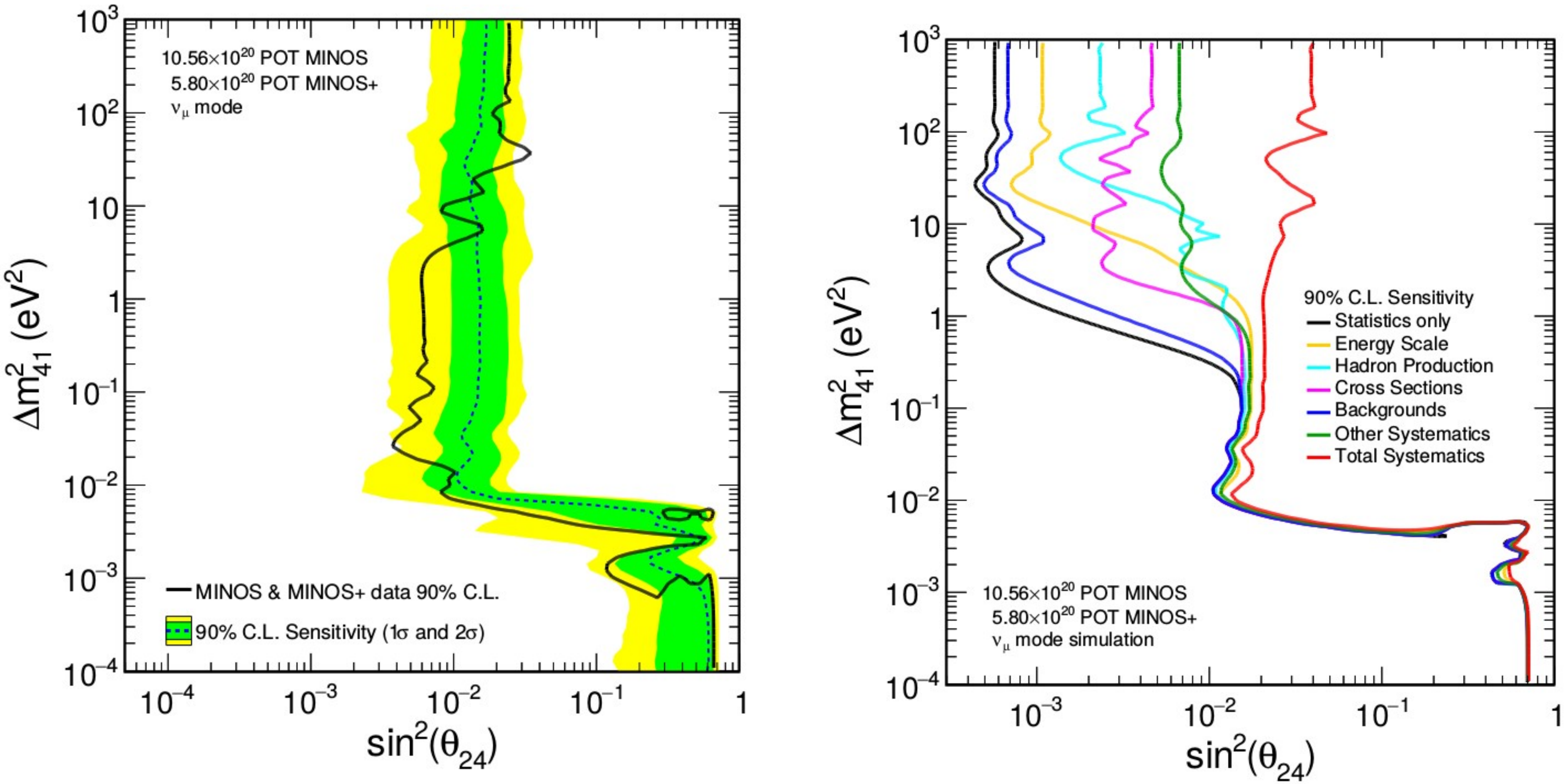
6 GeV – 56 GeV

Also constraining θ_{34}

PRL 117 (2016) 071801

PRD 95 (2017) 112002

MINOS/MINOS+

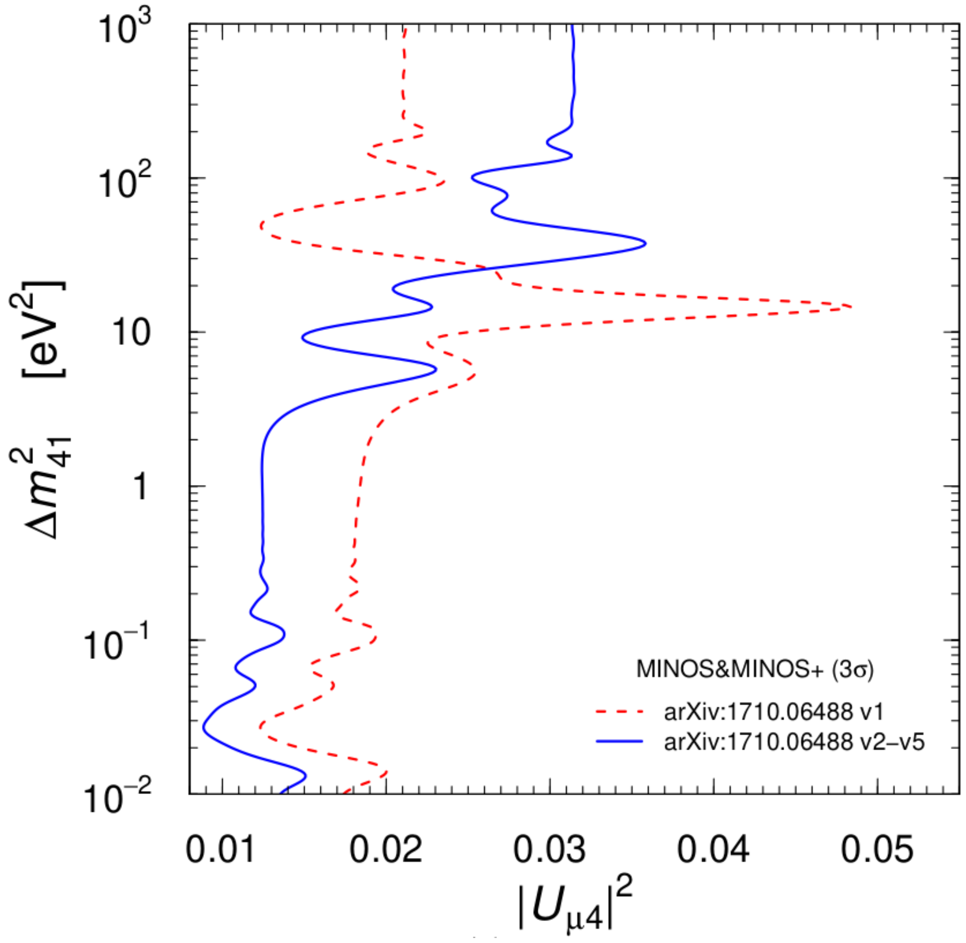


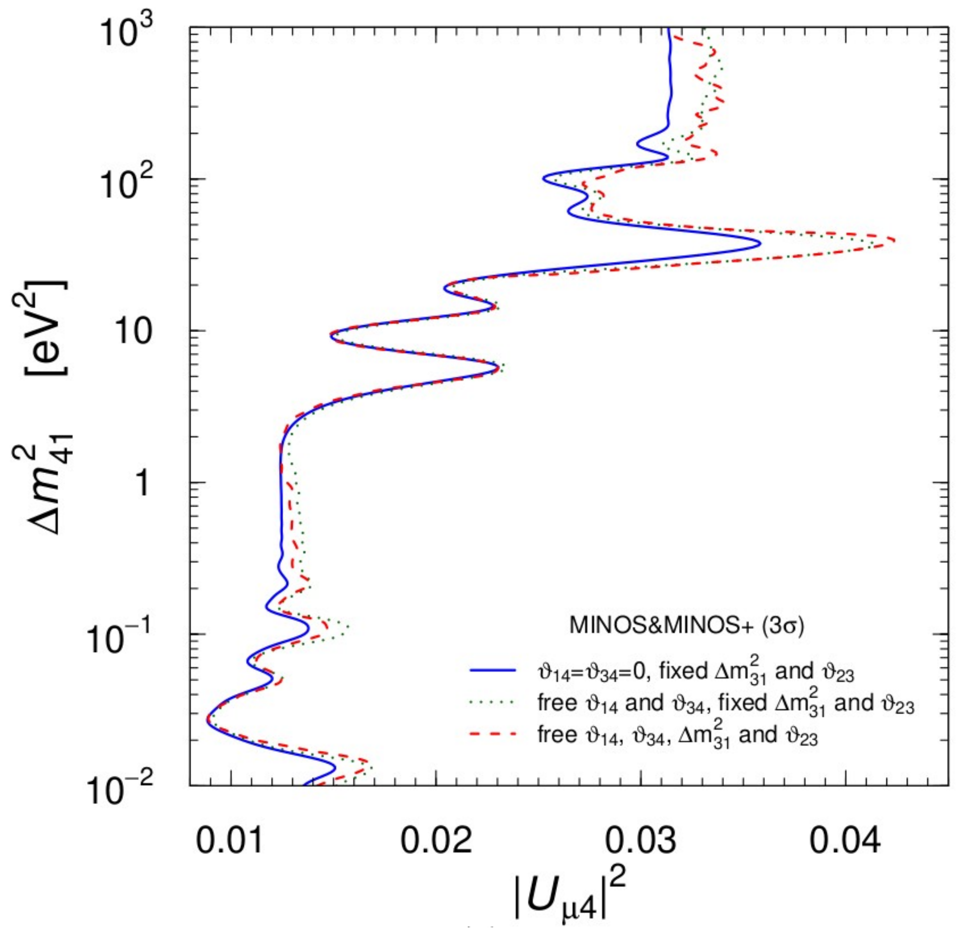
Two analyses: far-over-near ratio, and two-detector fit

For large mass splittings: systematic dominated

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

MINOS/MINOS+

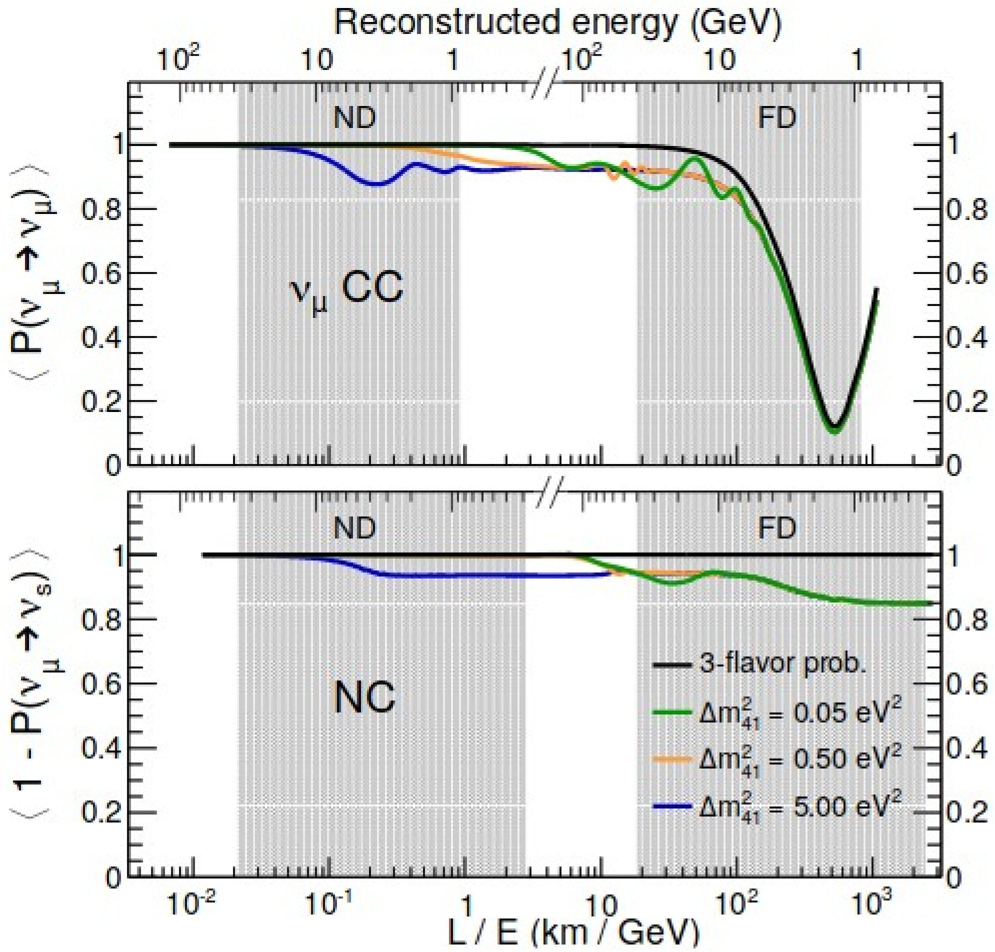


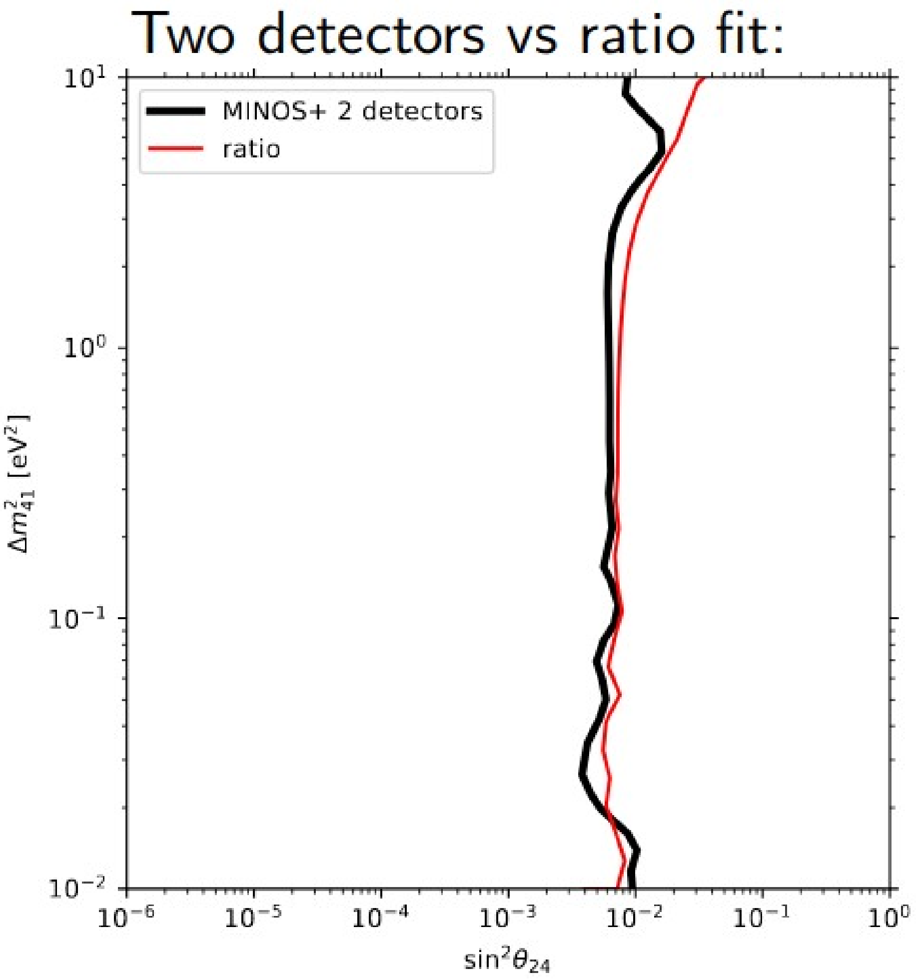


For mass splittings below 20 eV² the bound gets stronger after updating the analysis

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

MINOS/MINOS+





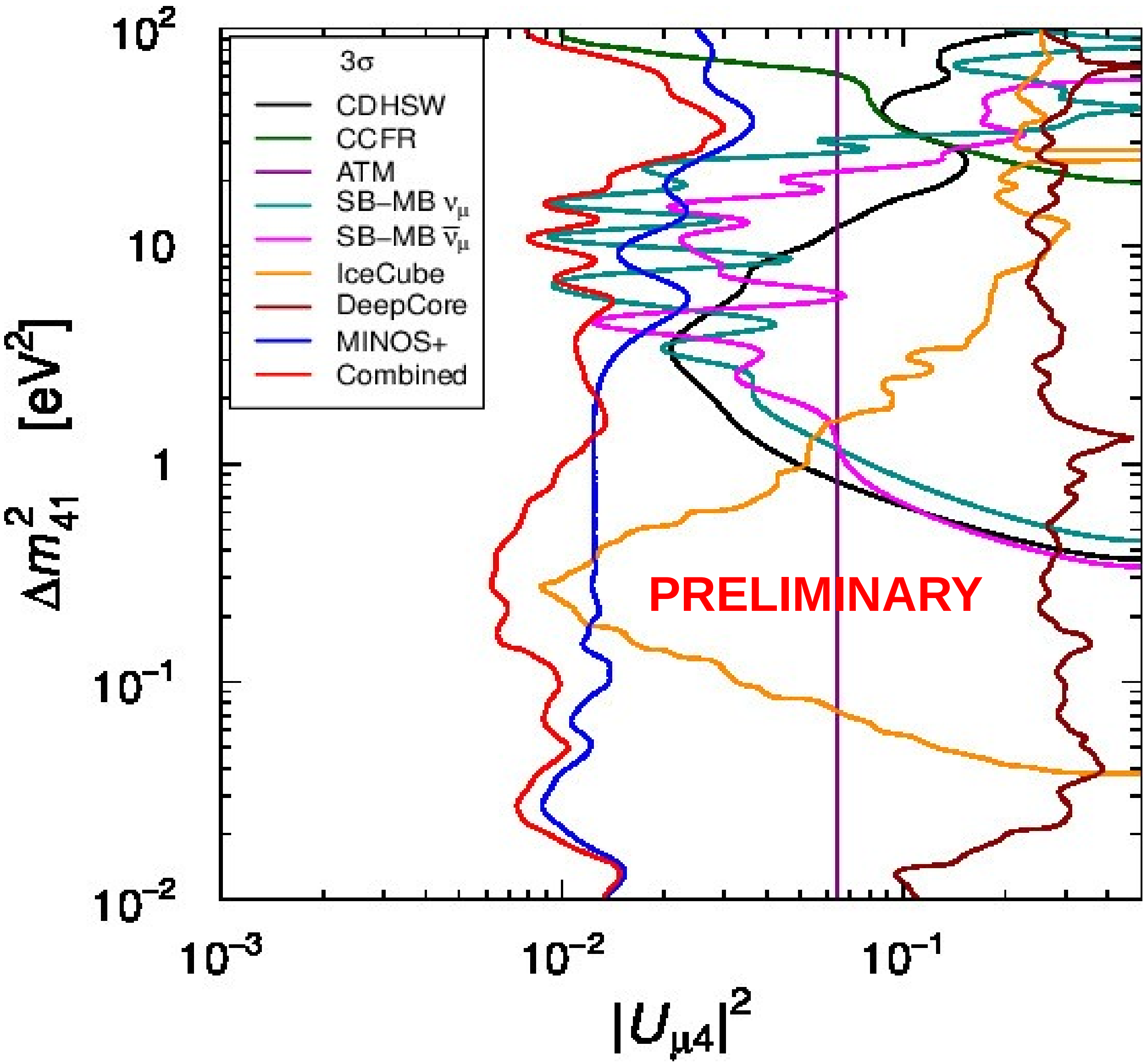
Results barely change in the important region

Far over near ratio;
PRL 117 (2016) 151803
Two detector fit:
PRL 122 (2019) 091803

Gariazzo, Giunti, Ternes,
in preparation

Fit of ν_μ disappearance data

All data:



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

Gariazzo, Giunti, Ternes, in preparation

Reminder

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

APPearance

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

DISappearance

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

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

Reminder

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

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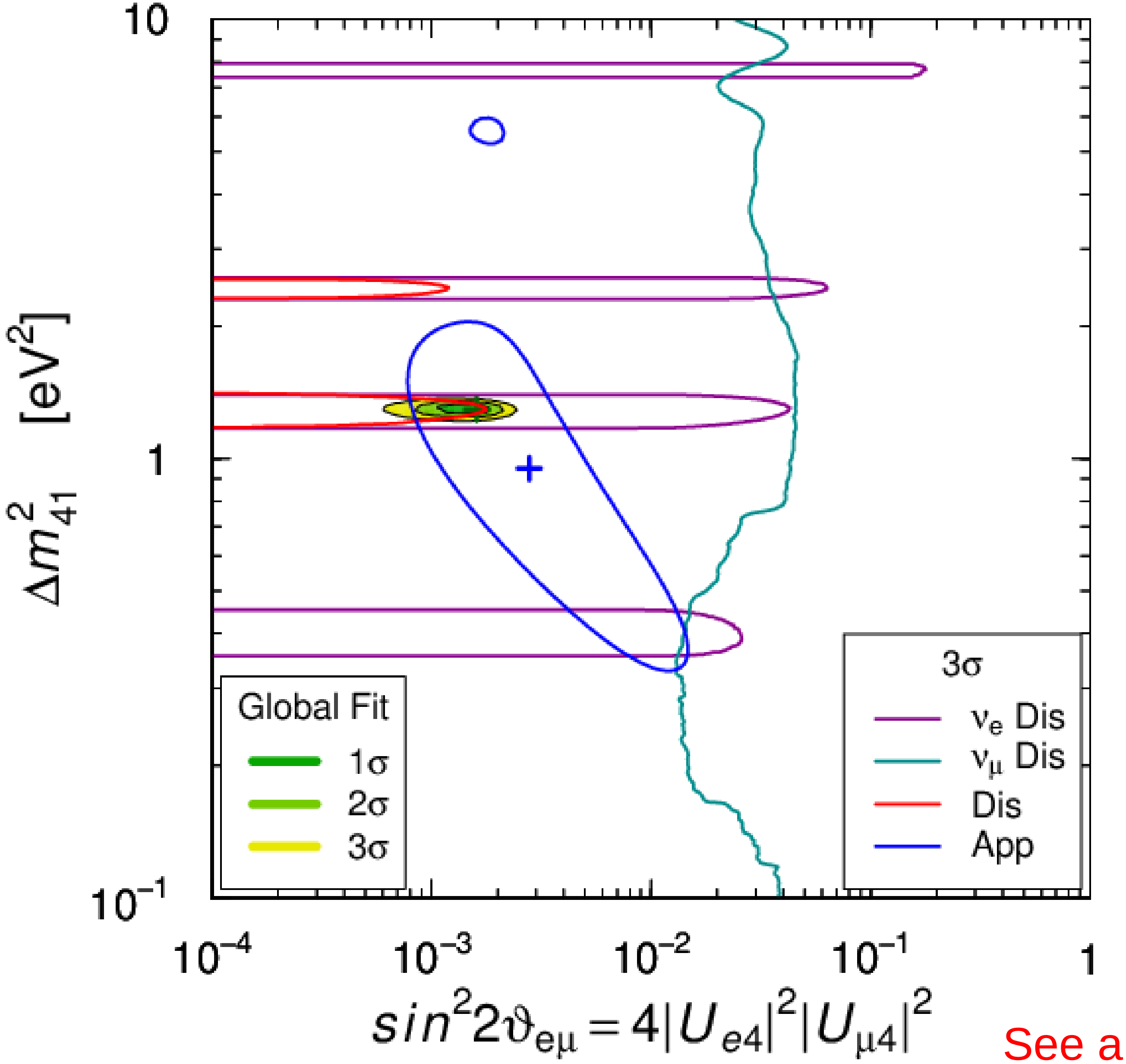
Tension here!

Global Fit: Tension in APP vs DIS data

Data end of 2017

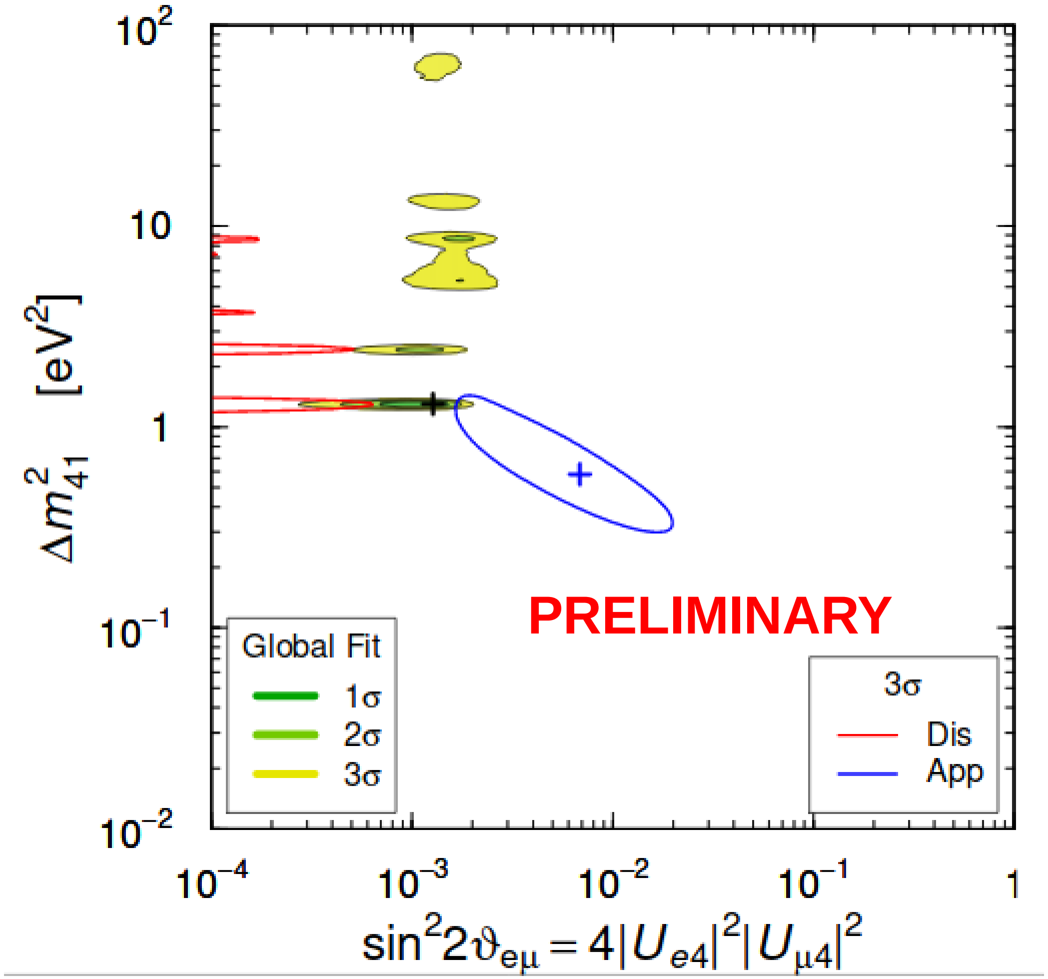


JHEP 1706 (2017), Gariazzo, Giunti, Laveder, Li

See also: Dentler, et al
JHEP 1808 (2018)

Global Fit: Tension in APP vs DIS data

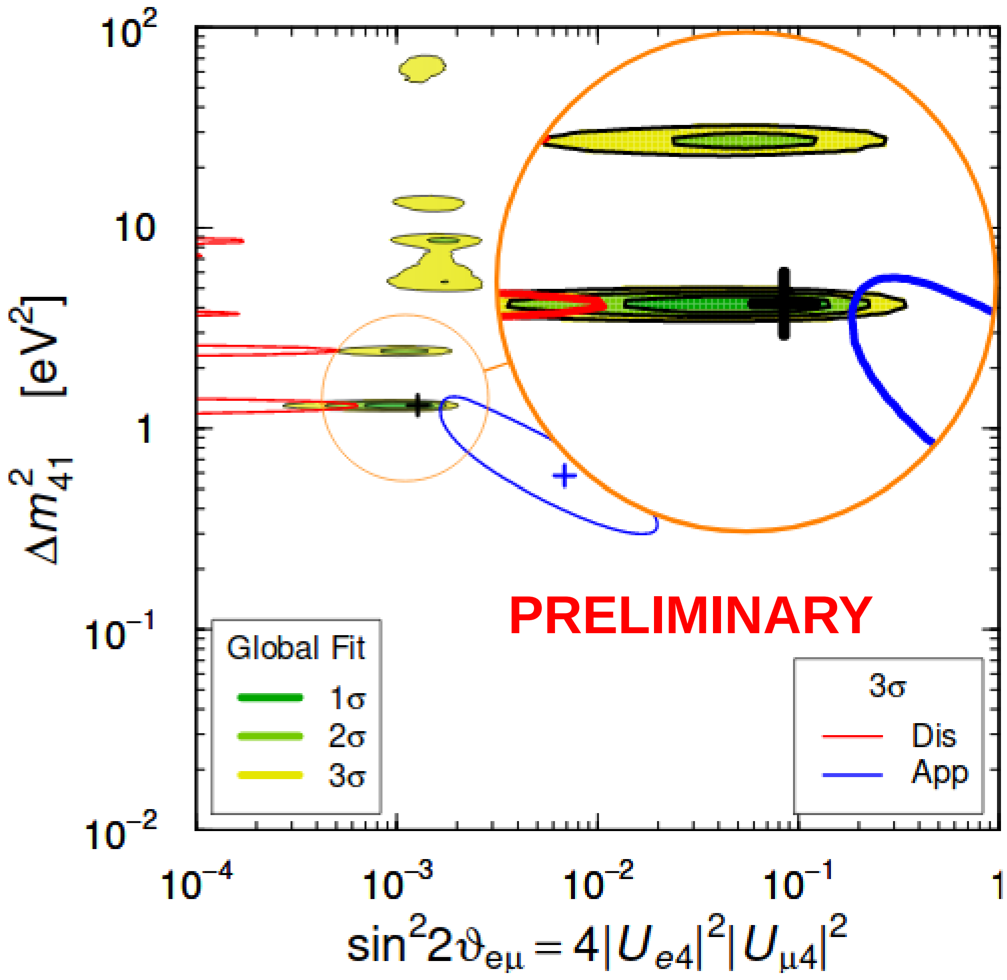
Data October 2019 (without new DANSS)



Gariazzo, Giunti, Ternes, in preparation

Global Fit: Tension in APP vs DIS data

Data October 2019 (without new DANSS)



No overlap anymore!

We obtain:

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

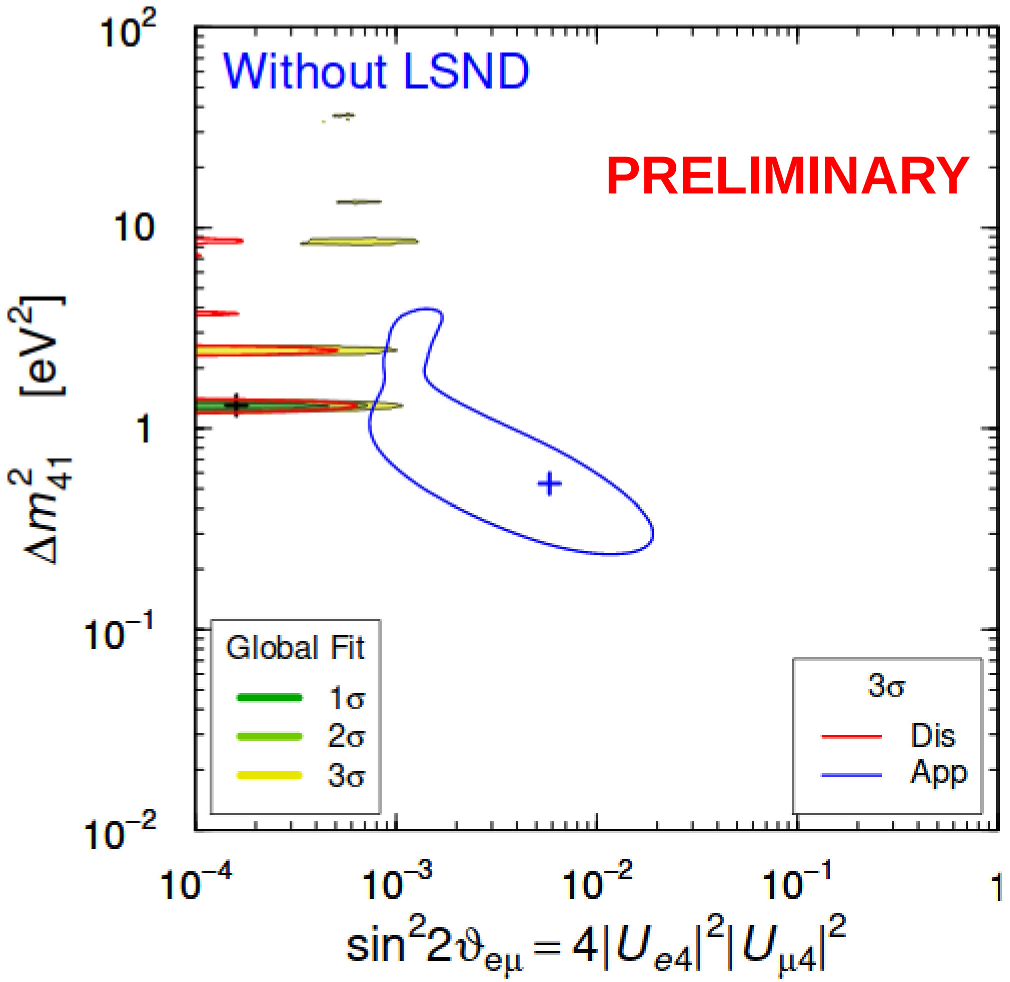
Global 3+1 fit is unaccaptable!

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

Gariazzo, Giunti, Ternes, in preparation

Global Fit: Tension in APP vs DIS data

Data October 2019 (without new DANSS)



Excluding LSND gives

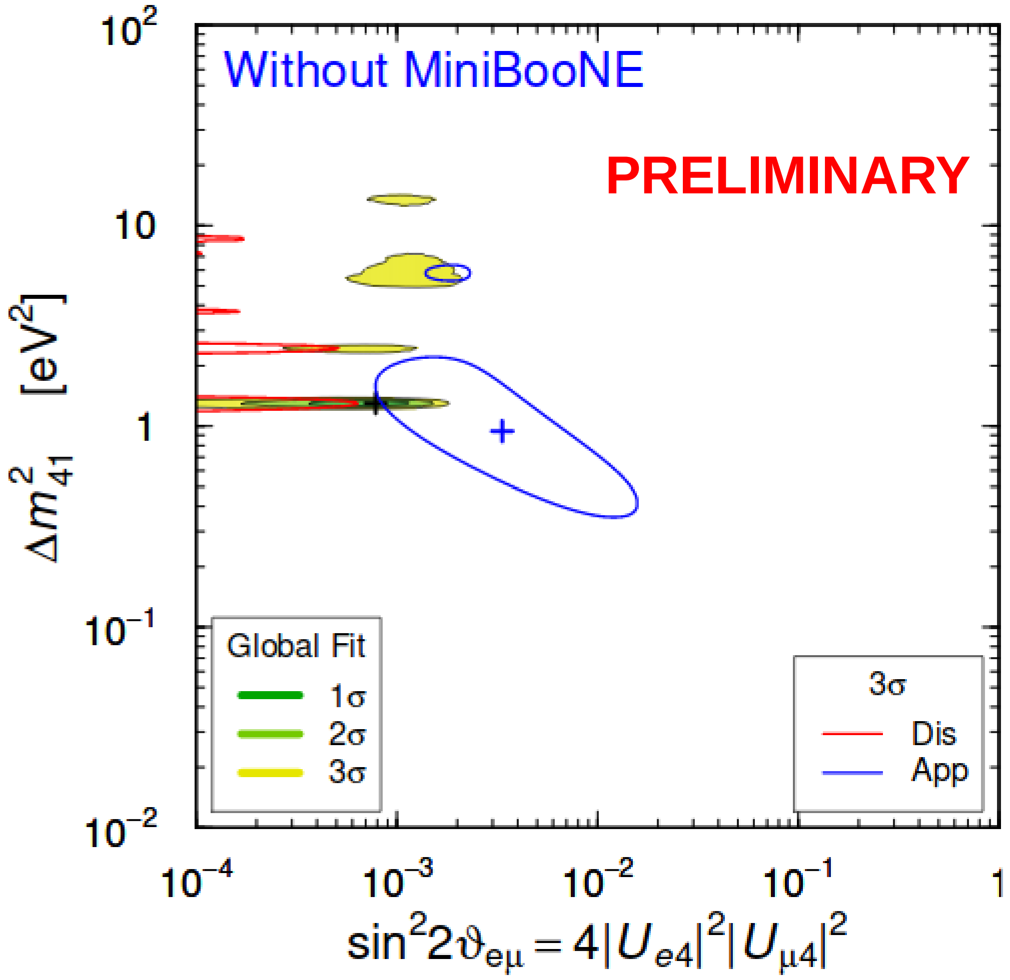
$\mathrm{GoF}_{\mathrm{PG}} = 2 \times 10^{-5}$

Problem remains!

Gariazzo, Giunti, Ternes, in preparation

Global Fit: Tension in APP vs DIS data

Data October 2019 (without new DANSS)



Excluding MB gives

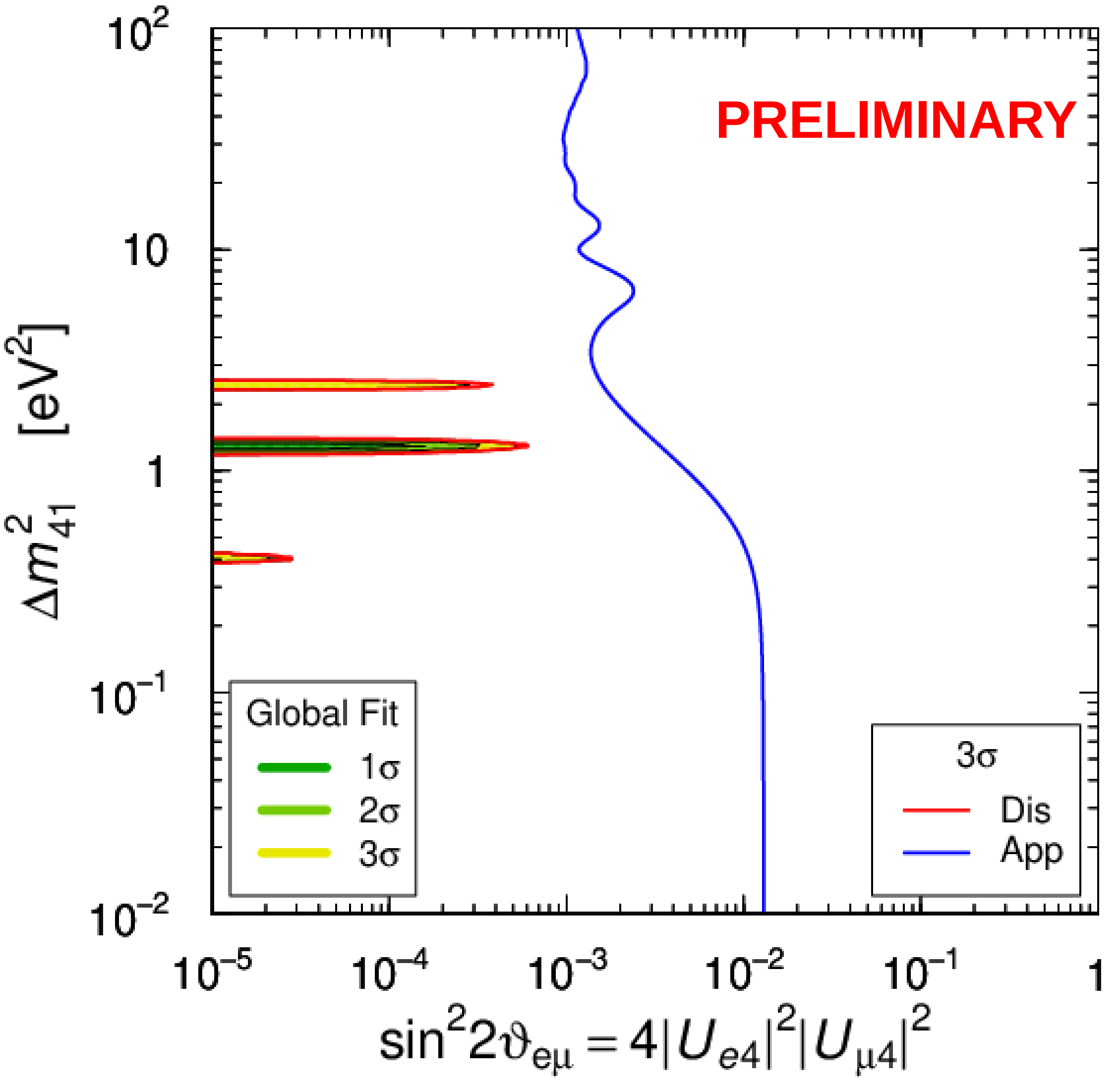
$\mathrm{GoF}_{\mathrm{PG}} = 6 \times 10^{-7}$

Problem remains!

Gariazzo, Giunti, Ternes, in preparation

Global Fit: Tension in APP vs DIS data

Only excluding LSND and MB solves the problem



No surprise, because now there is no lower bound

Conclusions

The RAA might be explained with updated reactor fluxes

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Conclusions

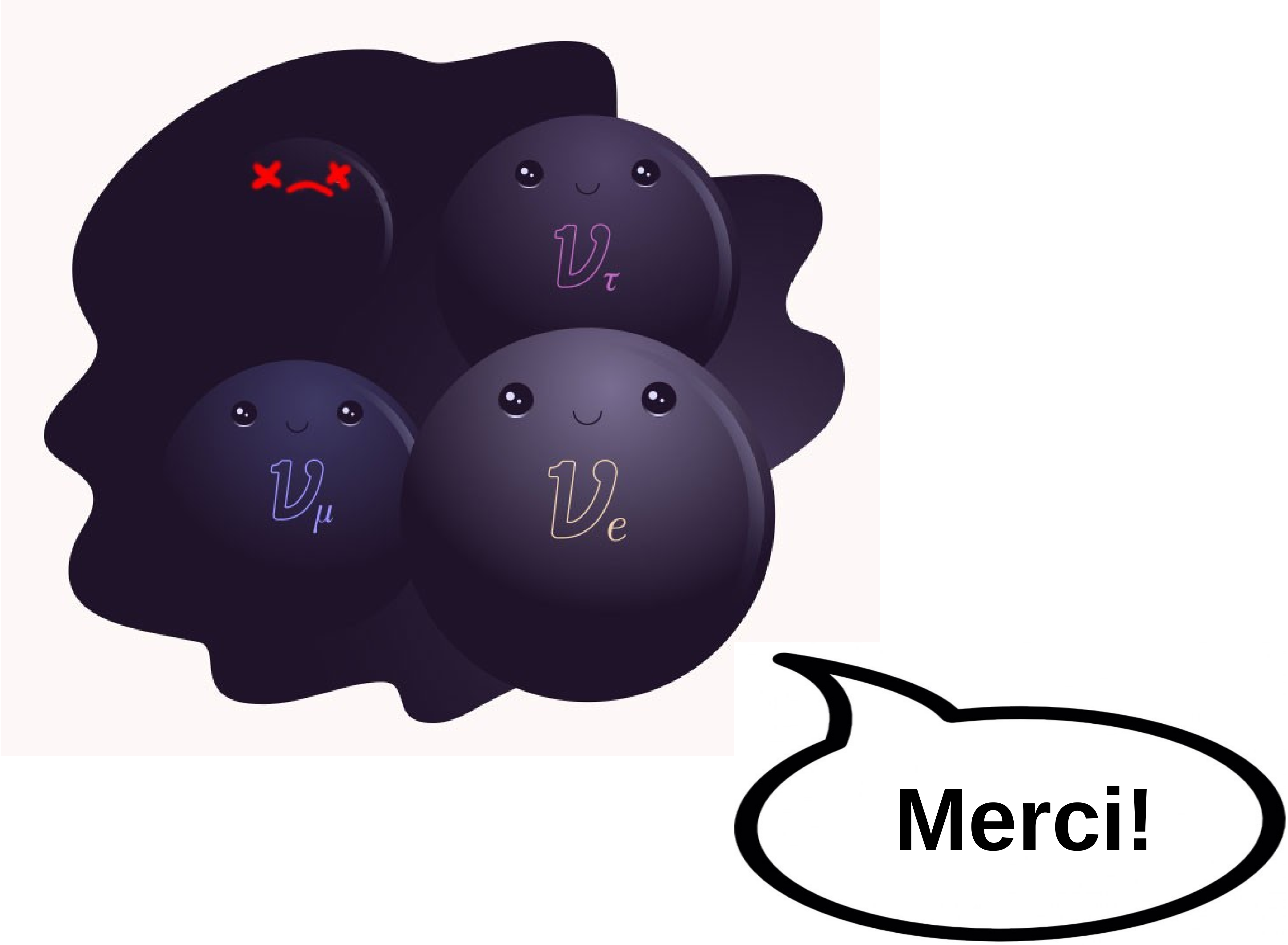
The RAA might be explained with updated reactor fluxes

The significance of the Gallium anomaly is reduced

The indication of SBL oscillations seen last year might be fading away due to new DANSS results

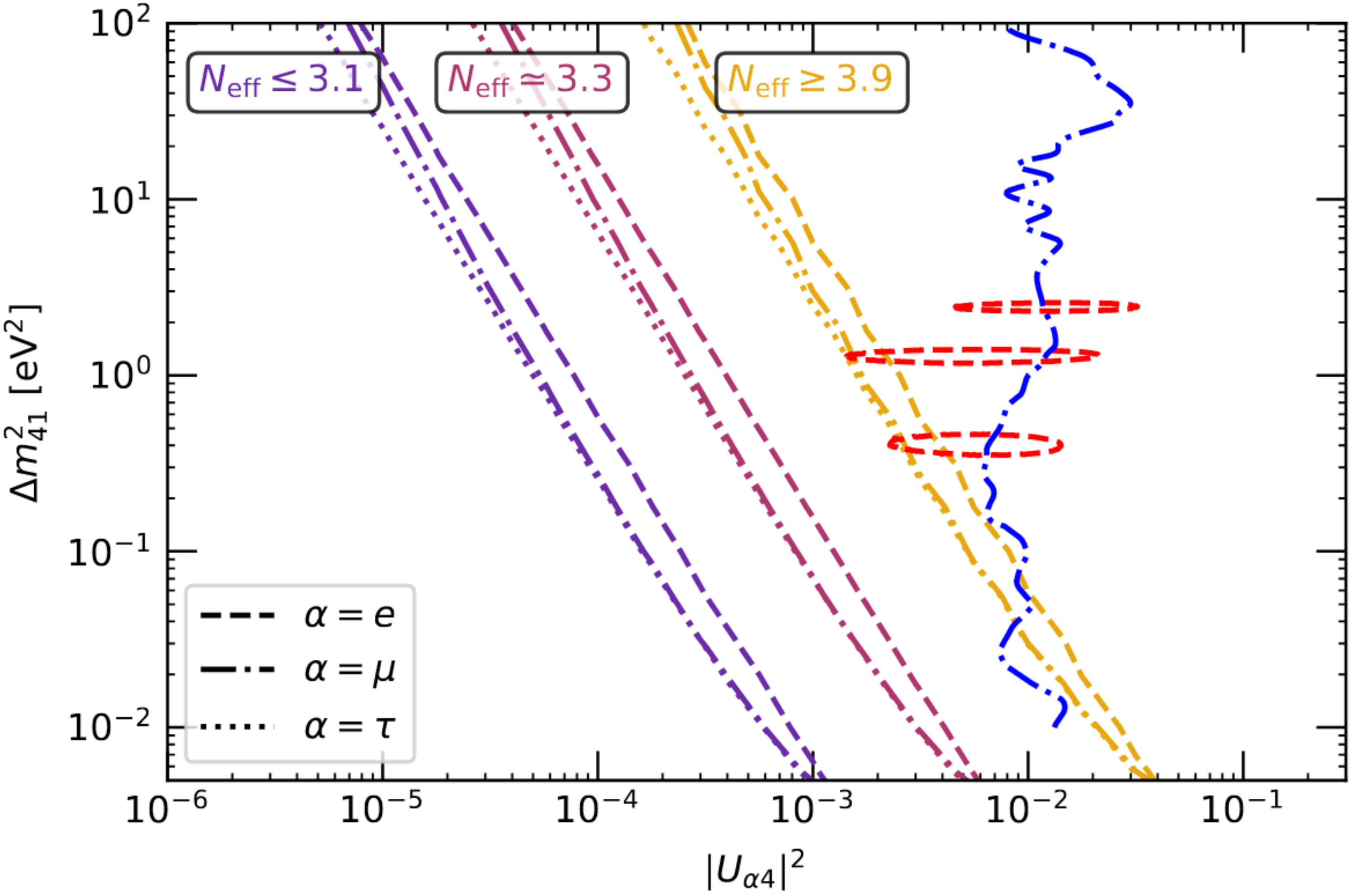
The tension between APP and DIS data makes a global 3+1 fit unacceptable

The current status: **It is pretty bad!**


ν_τ
ν_μ
ν_e
Merci!

Backup

Current regions are completely incompatible with cosmological observations!



Gariazzo, de Salas, Pastor, JCAP 1907 (2019)