Global Fits with Sterile Neutrinos and NSI

Christoph Andreas Ternes
IFIC, Universitat de València/CSIC

POND² Workshop
Fermilab, December 6th, 2018

Status of (3+1) mixing

(plus a few slides on NSI)

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ASTROPARTICLES
Astroparticles and High Energy Physics Group
IFIC
INSTITUT DE FÍSICA CORPUSCULAR
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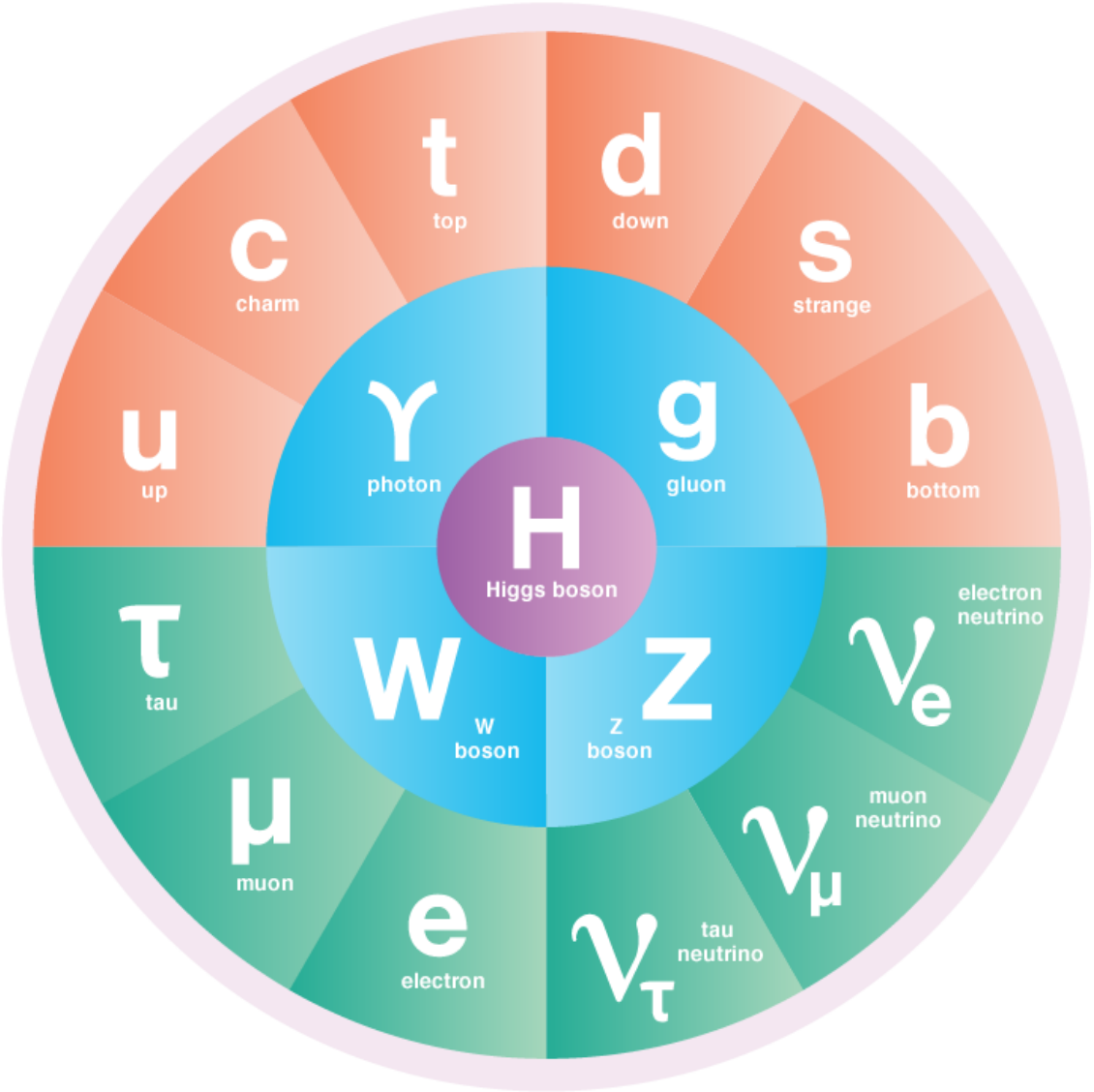
EXCELENCIA SEVERO OCHOA
GENERALITAT VALENCIANA

Standard model of particle physics



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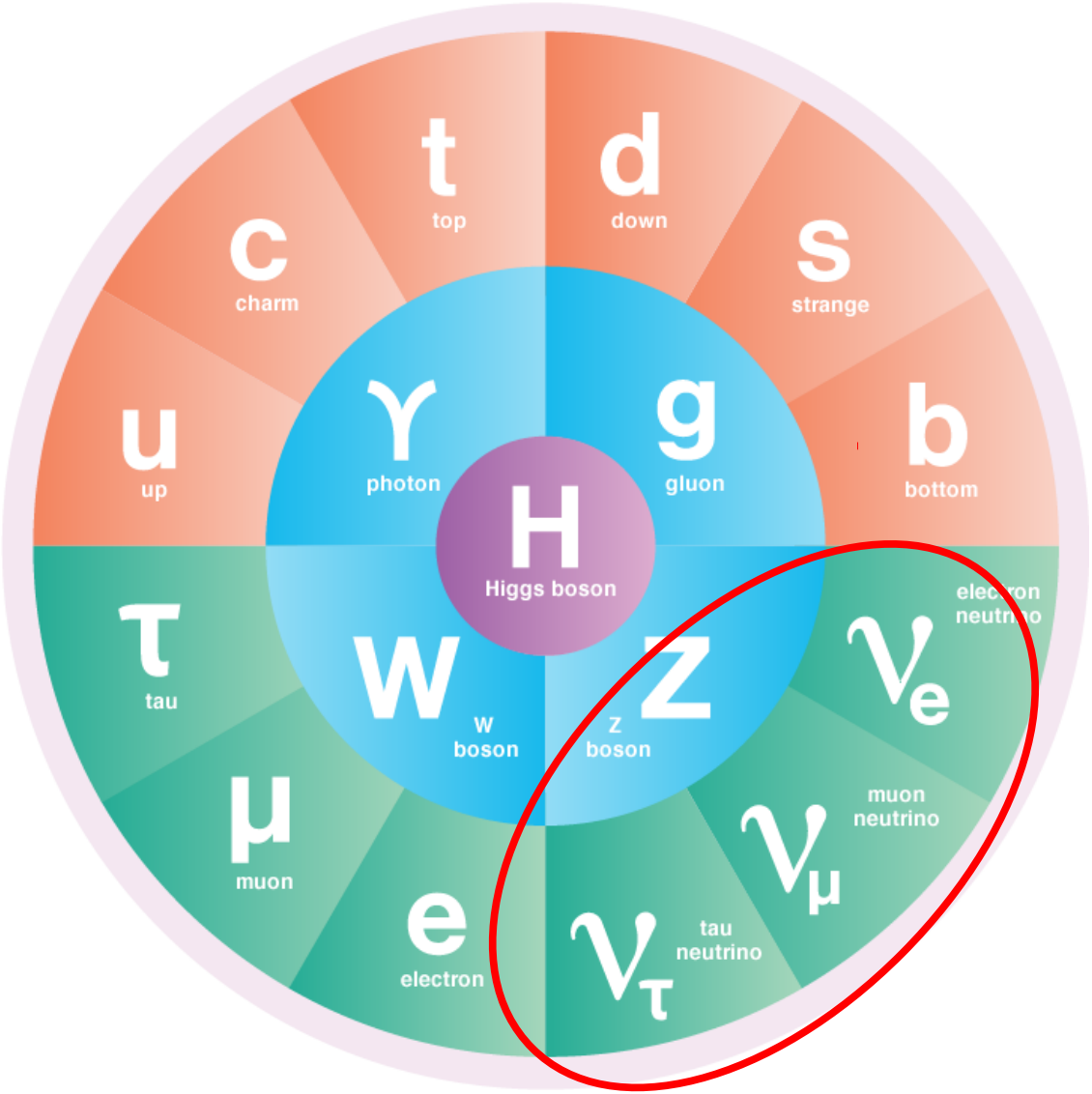
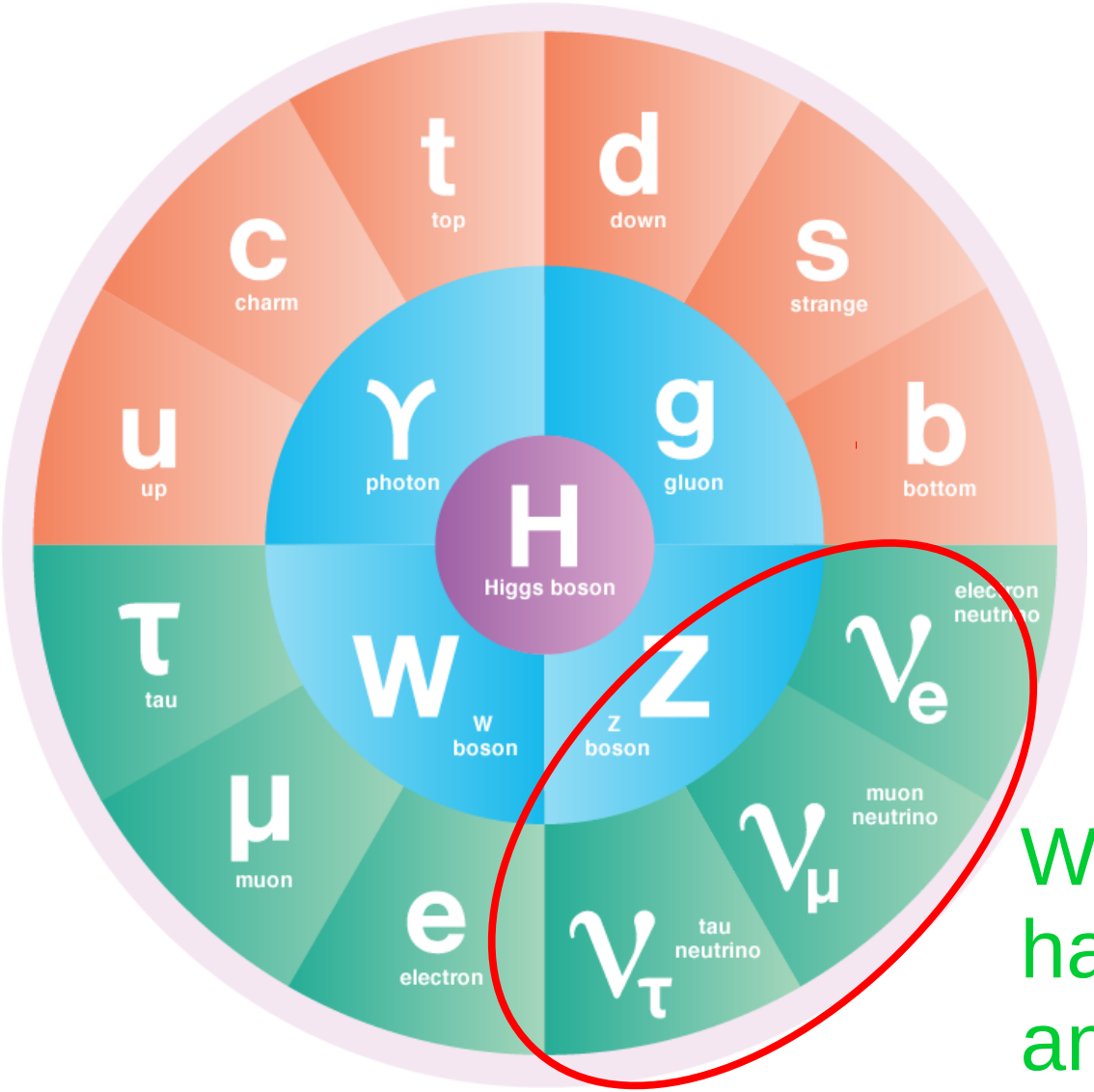


3ν in SM

Standard model of particle physics*

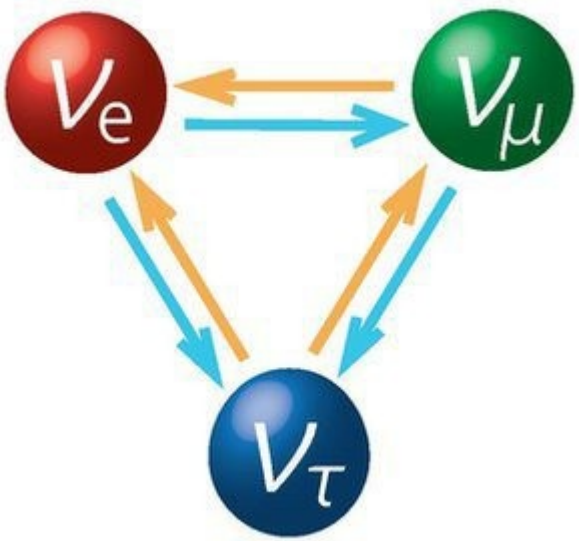


3ν in SM

We know they have masses and they mix

*with massive neutrinos

Three-neutrino oscillations

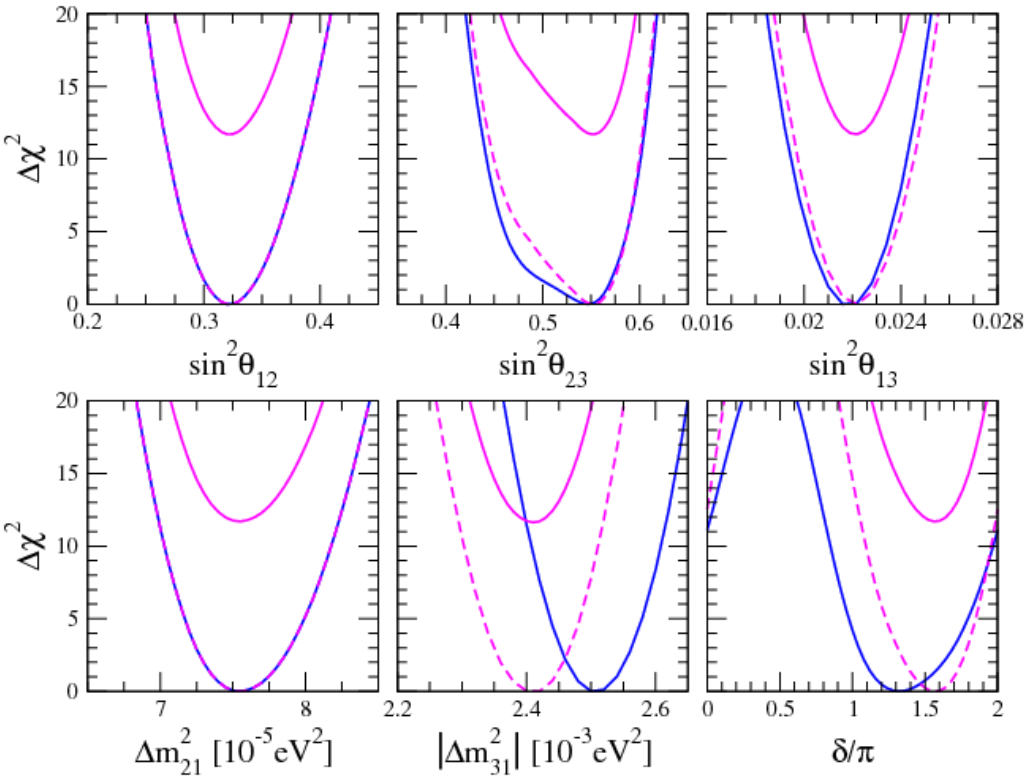


Talk by Ivan Martinez-Soler

Three-neutrino oscillations

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

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

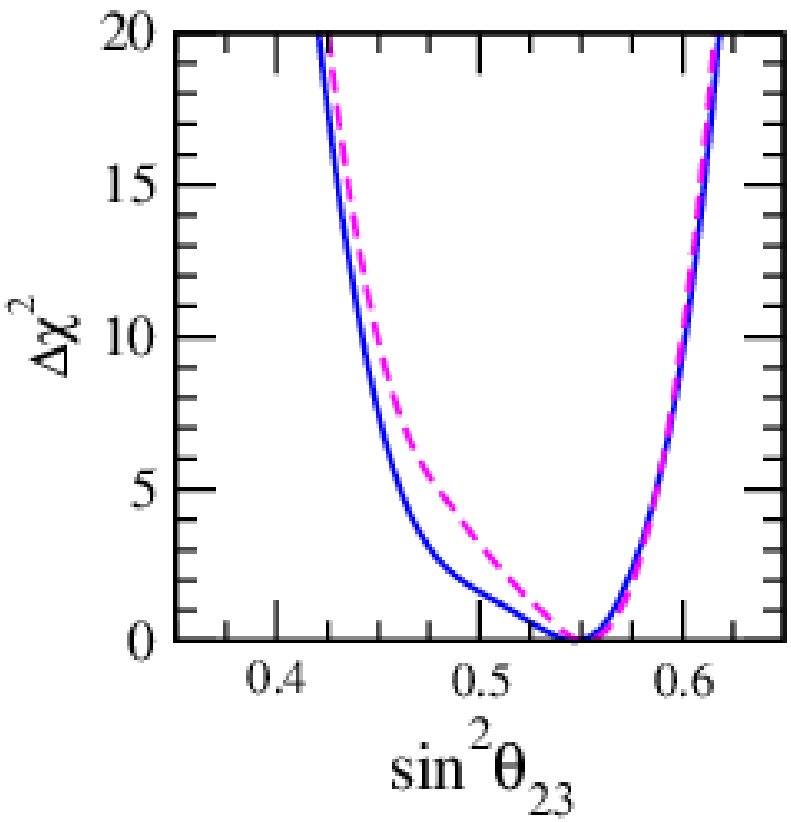


Phys.Lett. B782 (2018) 633-640, P.F. de Salas, D.V. Forero, CAT, M. Tórtola, J.W.F. Valle
https://globalfit.astroparticles.es/

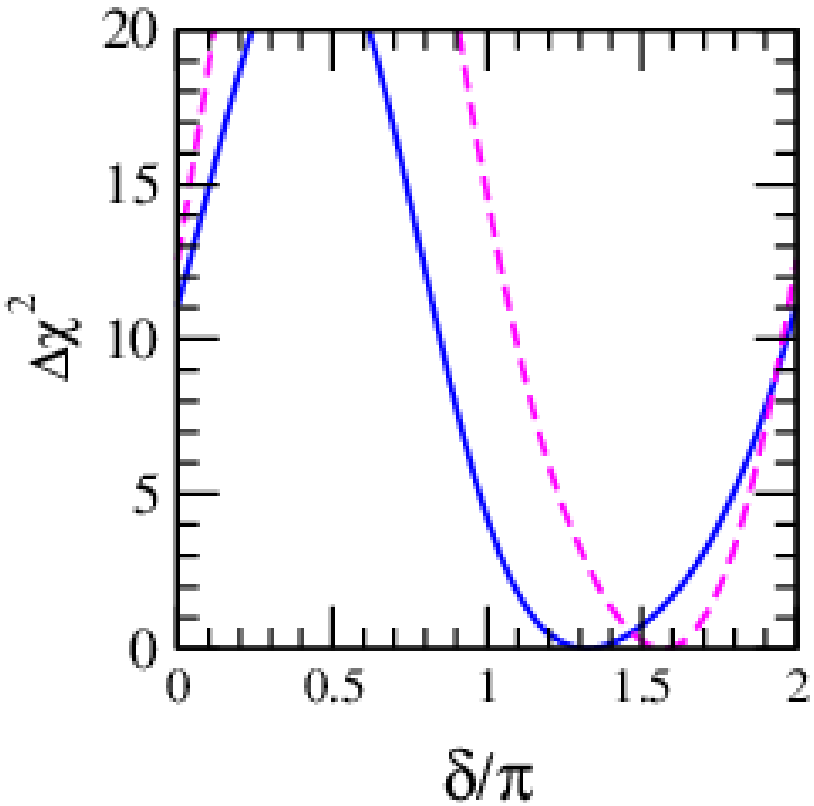
See also: -Bari-group (Prog.Part.Nucl.Phys. 102 (2018) 48-72)
-Nu-fit (1811.05487, talk by Ivan)

Three-neutrino oscillations

- Remaining unknowns are



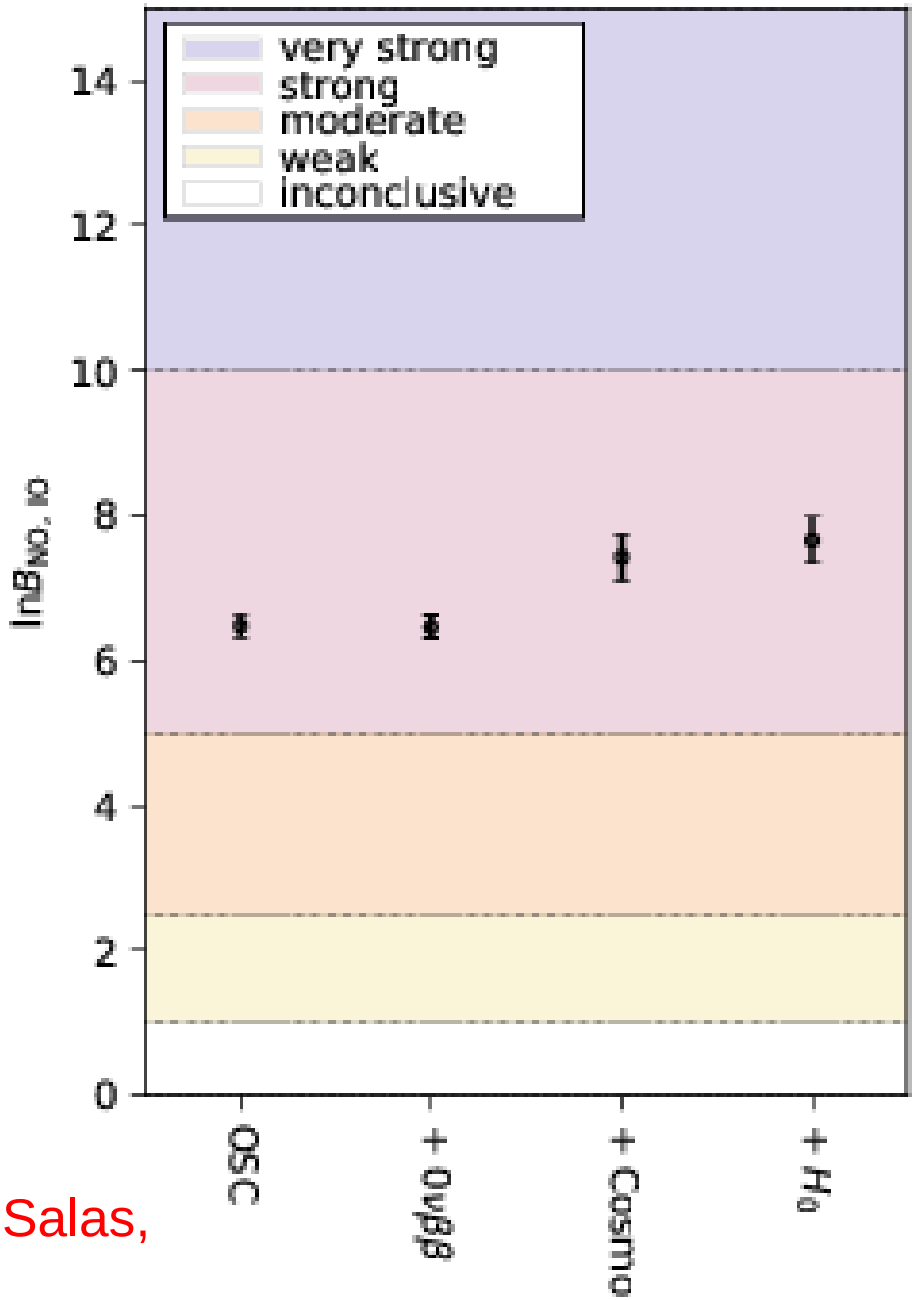
Atmospheric octant



Value of CP-phase

Three-neutrino oscillations

- Neutrino mass ordering

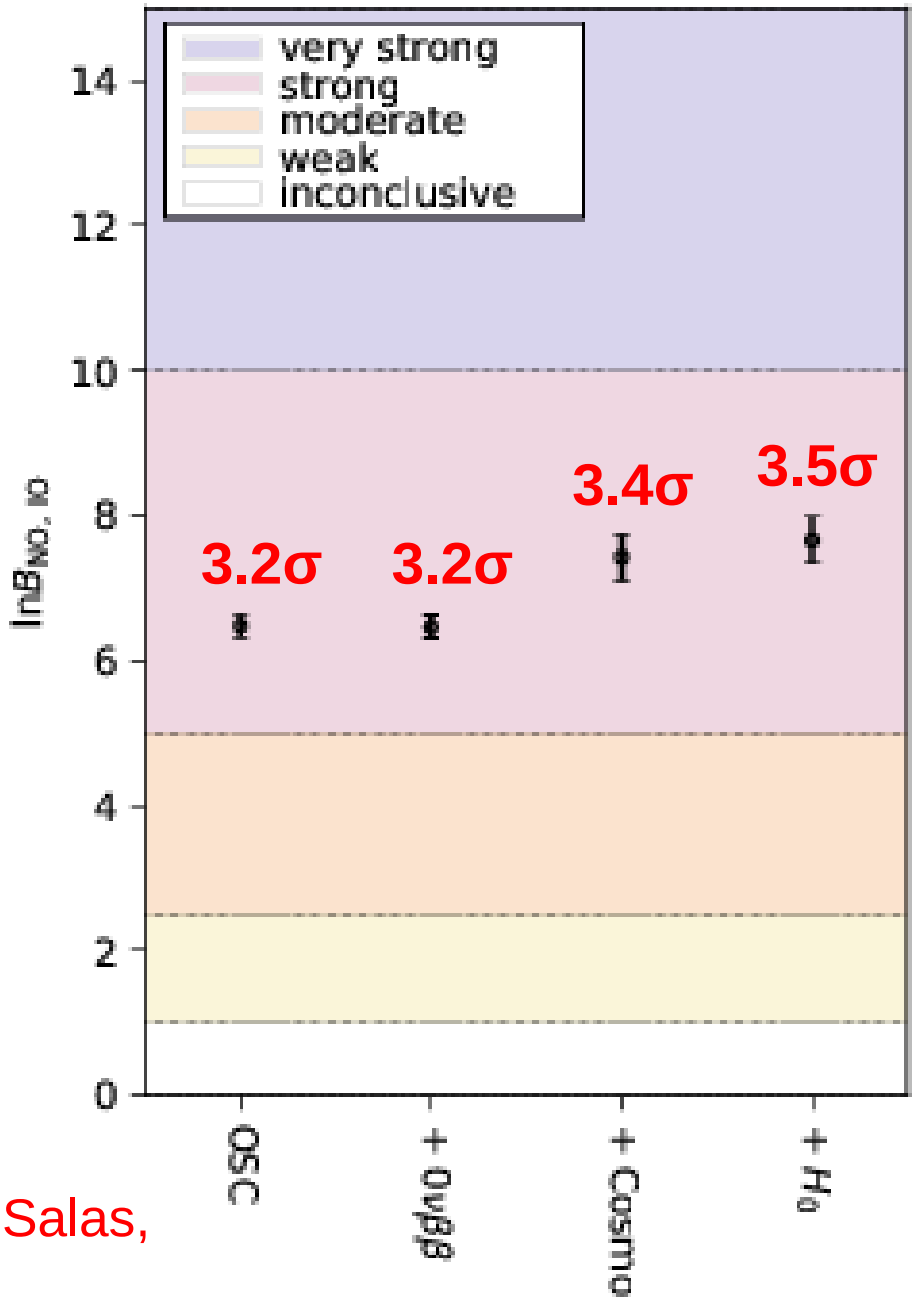


JCAP 1803 (2018) no.03, 011, S. Gariazzo, M. Archidiacono, P.F. de Salas, O. Mena, CAT, M. Tórtola

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



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

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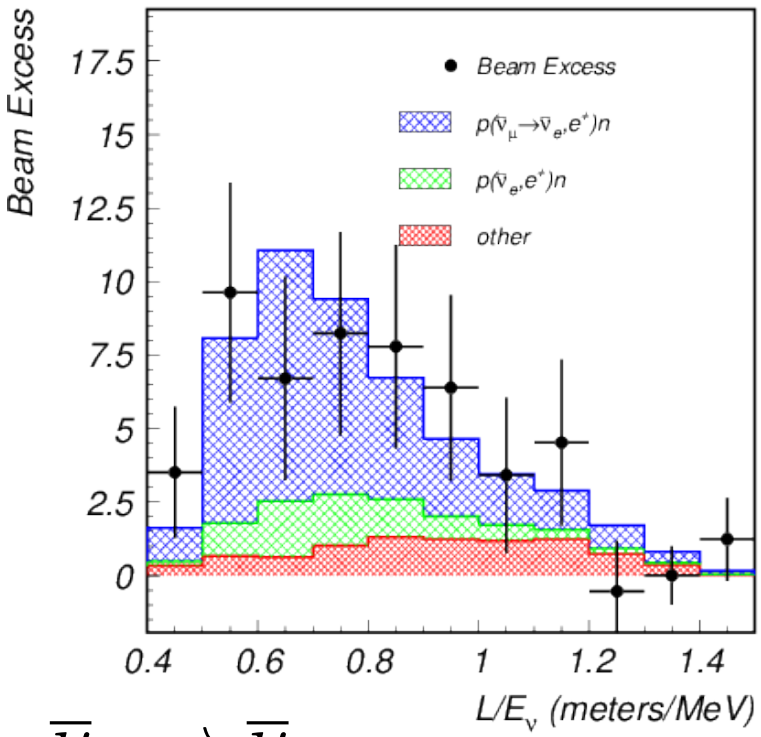
Anomalies in oscillations

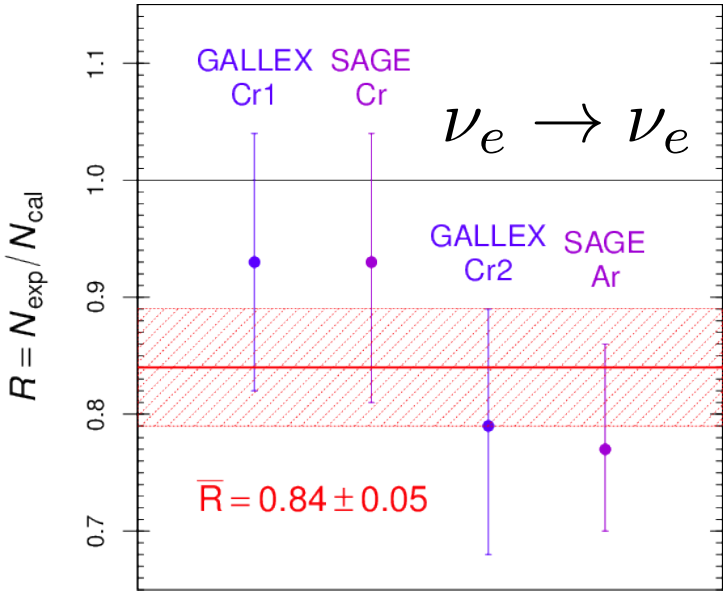
Anomalies in oscillations

- 3.8σ excess in **LSND**

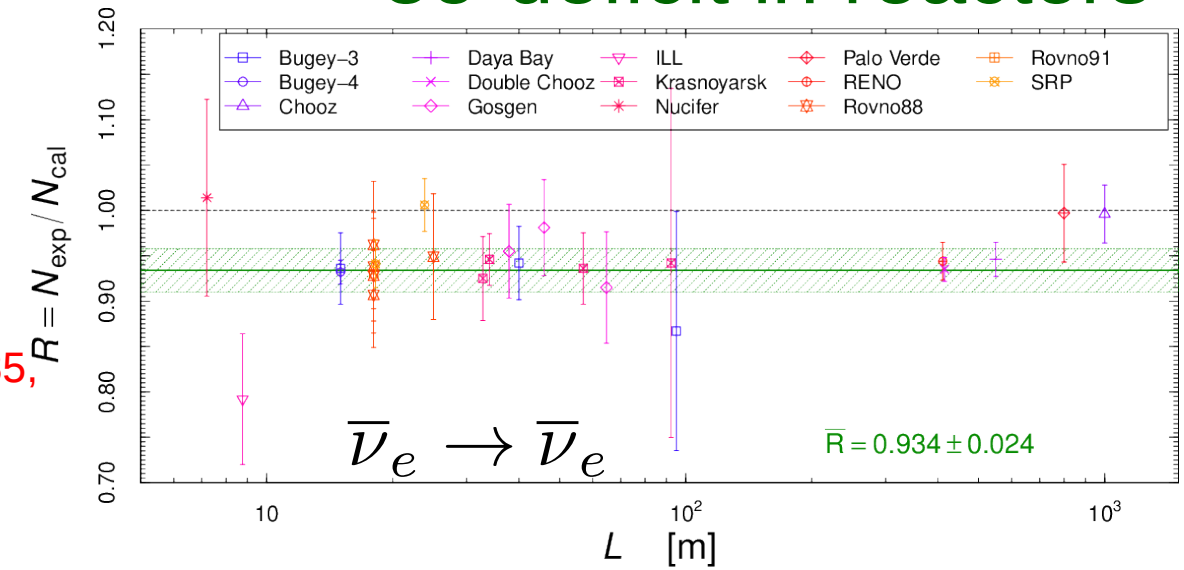


$\overline{\nu}_\mu \to \overline{\nu}_e$

- ~3σ deficit in **Gallium**



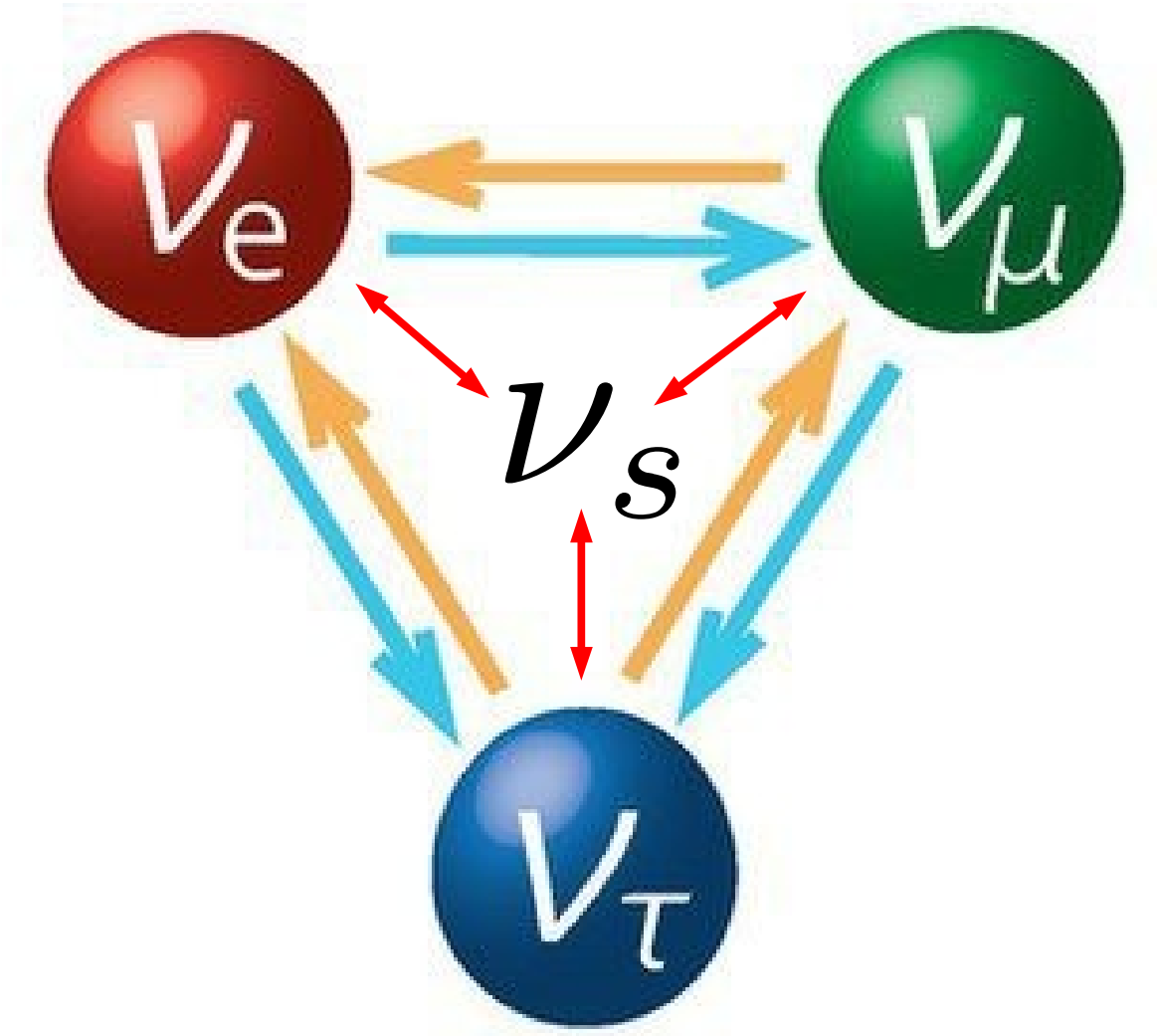
- ~3σ deficit in reactors



- No signal @**Karmen**

LSND: PRL 75 (1995) 2650, PRC 54 (1996) 2685, PRL 77 (1996) 3082, PRD 64 (2001) 112007
Karmen: PRD 65 (2002) 112001
Gallium: 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
Reactor: PRD 83 (2011) 073006, Mention et al, PRC 83 (2011) 054615, Mueller et al, PRC 84 (2011) 024617, Huber

Beyond three-neutrino oscillations



Beyond three-neutrino oscillations

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

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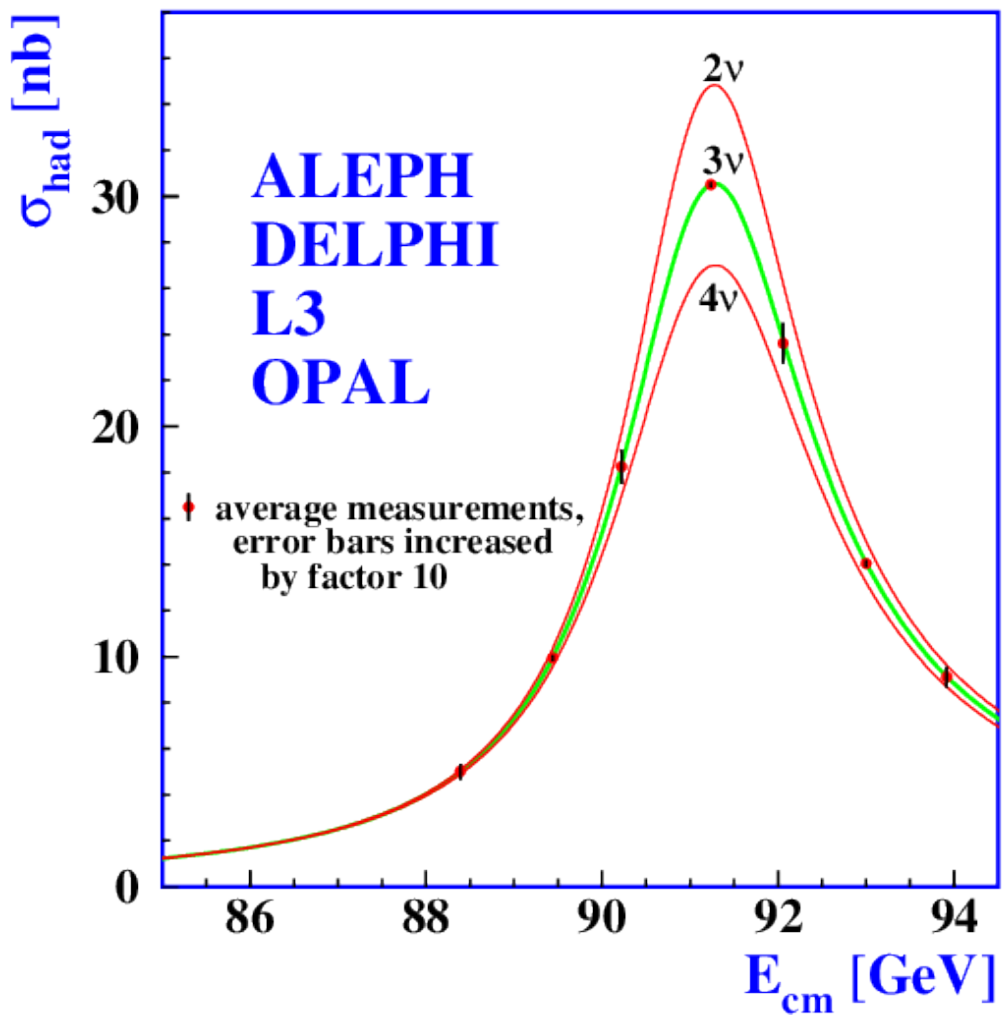
- We can add a forth neutrino
- This neutrino must be sterile, which means it is a singlet under all standard model gauge groups
- A forth active neutrino is excluded by observations of invisible Z-decays

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



Phys. Rept. 427 (2006) 257, LEP

Effective 3+1 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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@**Reactors** and **Gallium**

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@**atmospherics** and **accelerators**

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

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@atmospherics and **accelerators**

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

Quadratically suppressed

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@Reactors and **Gallium**

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@atmospherics and **accelerators**

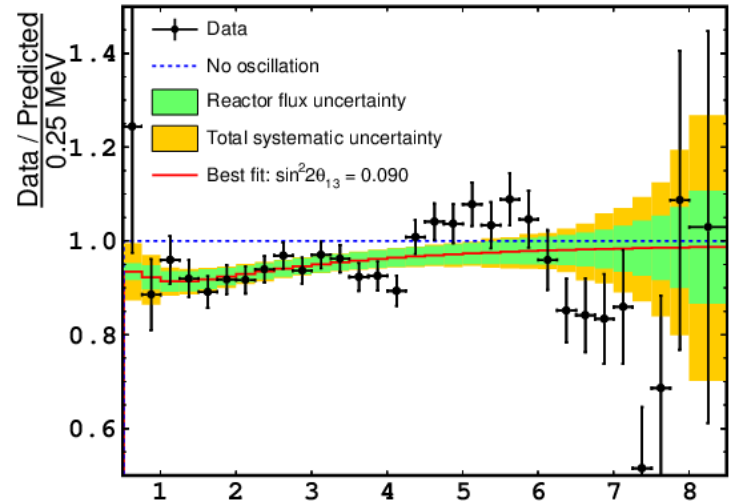
Current status of 3+1 oscillations

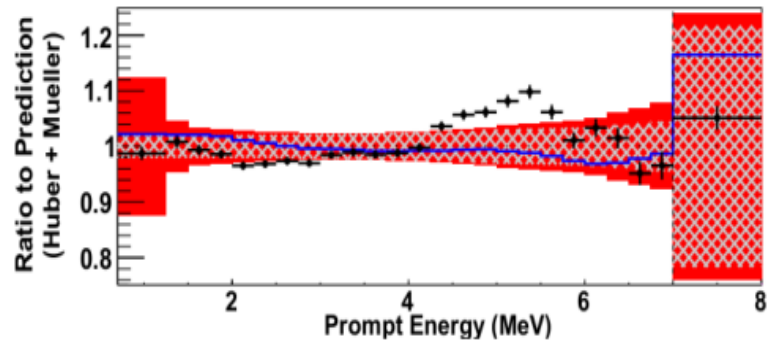
JHEP 1706 (2017) 135, S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li

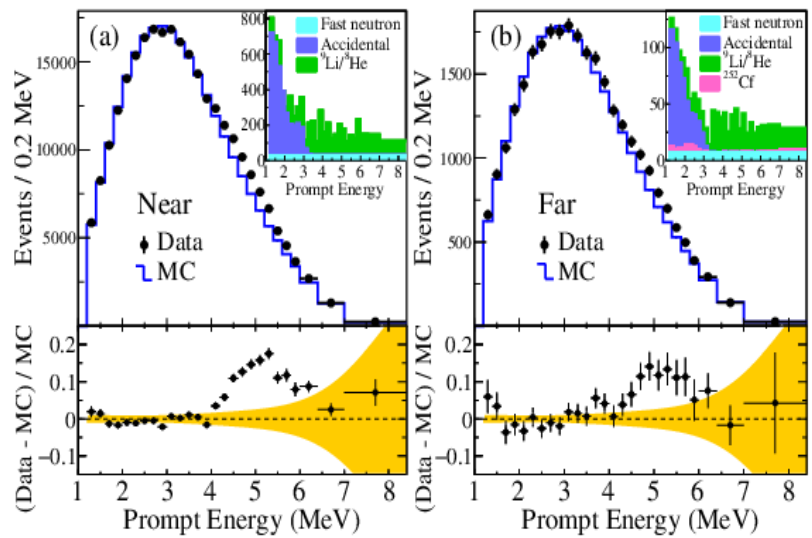
Phys.Lett. B782 (2018) 13-21, S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li

PRELIMINARY, S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, CAT

Reactor fluxes



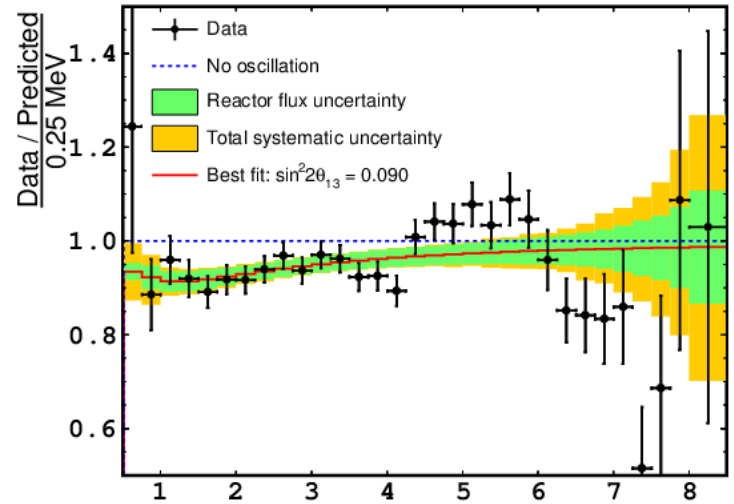


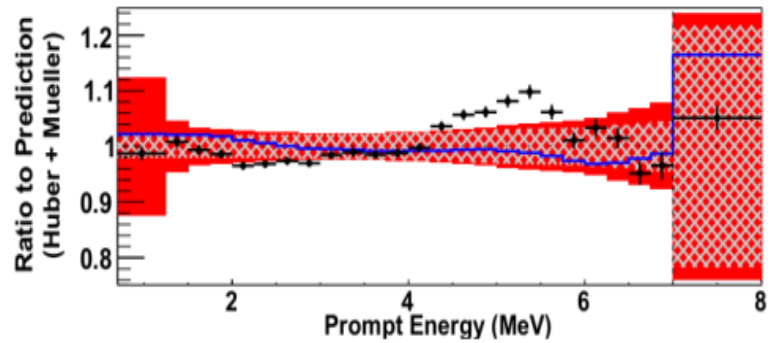


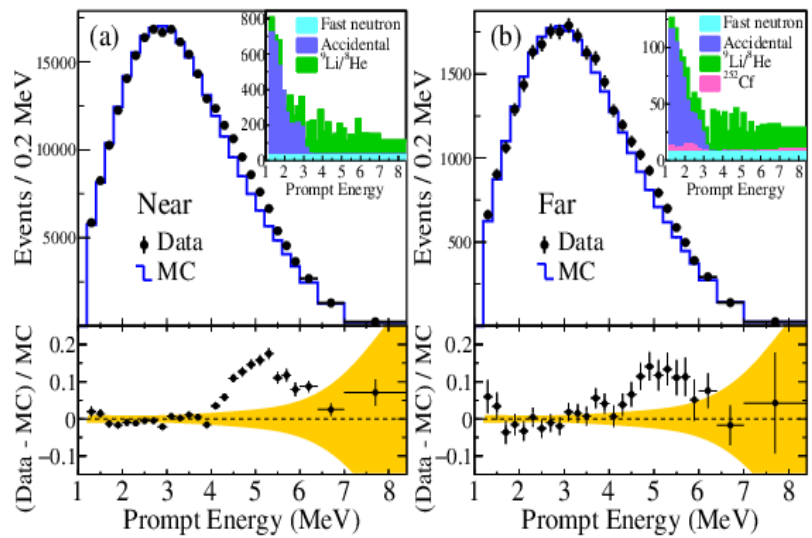
Double Chooz, arxiv:1406.7763
Daya Bay, arxiv:1508.04233
RENO, arxiv:1511.05849

Reactor fluxes

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







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Reactor fluxes

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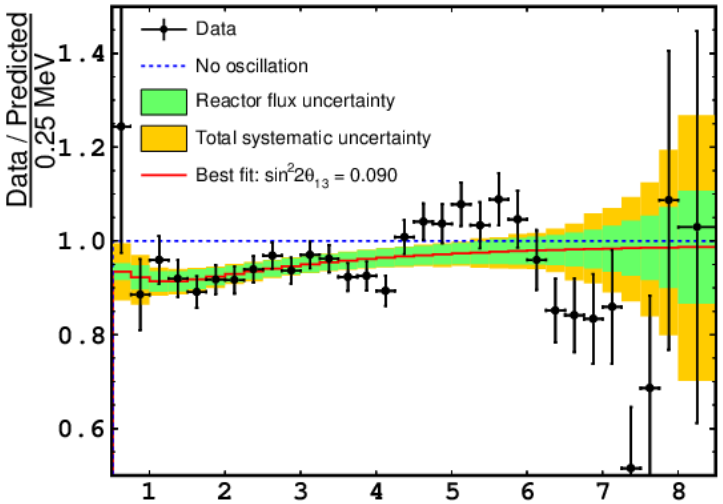
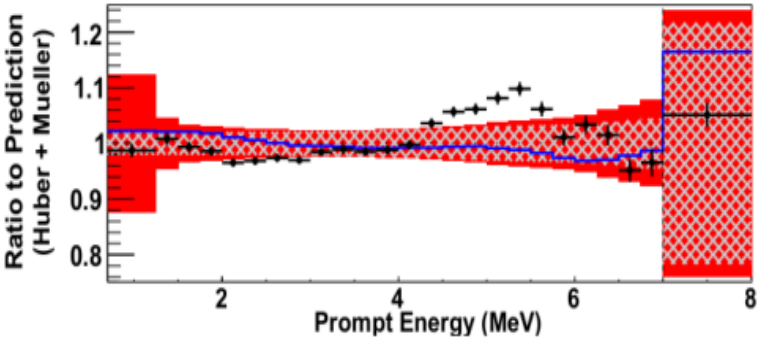
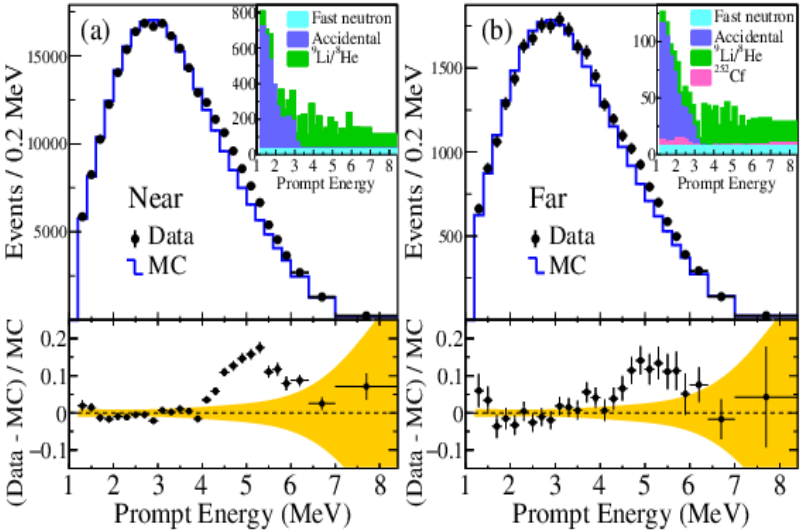
- The “bump” cannot be explained by sterile neutrino oscillations, because they should be washed out at these distances



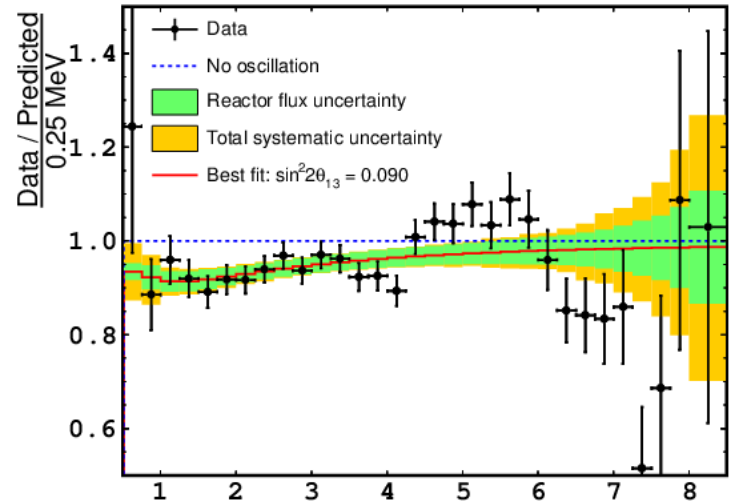


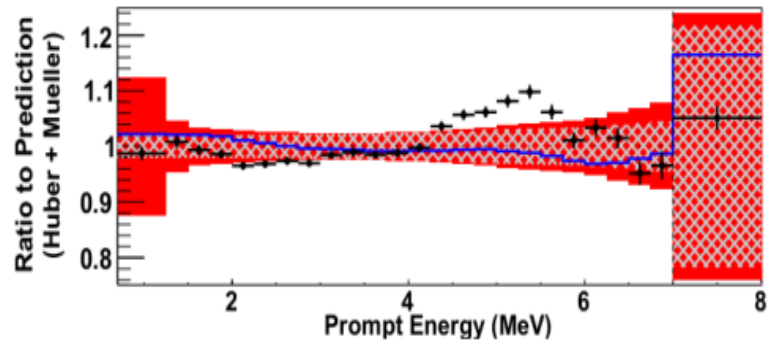


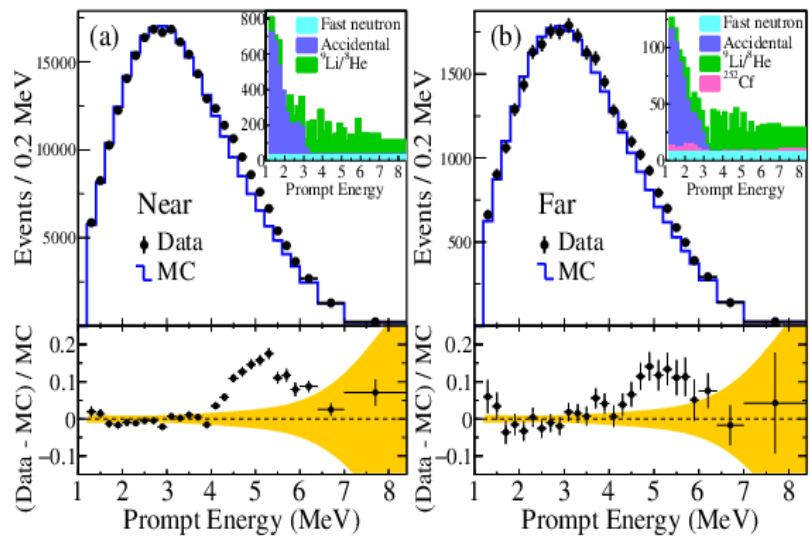
Double Chooz, arxiv:1406.7763
Daya Bay, arxiv:1508.04233
RENO, arxiv:1511.05849

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, arxiv:1406.7763
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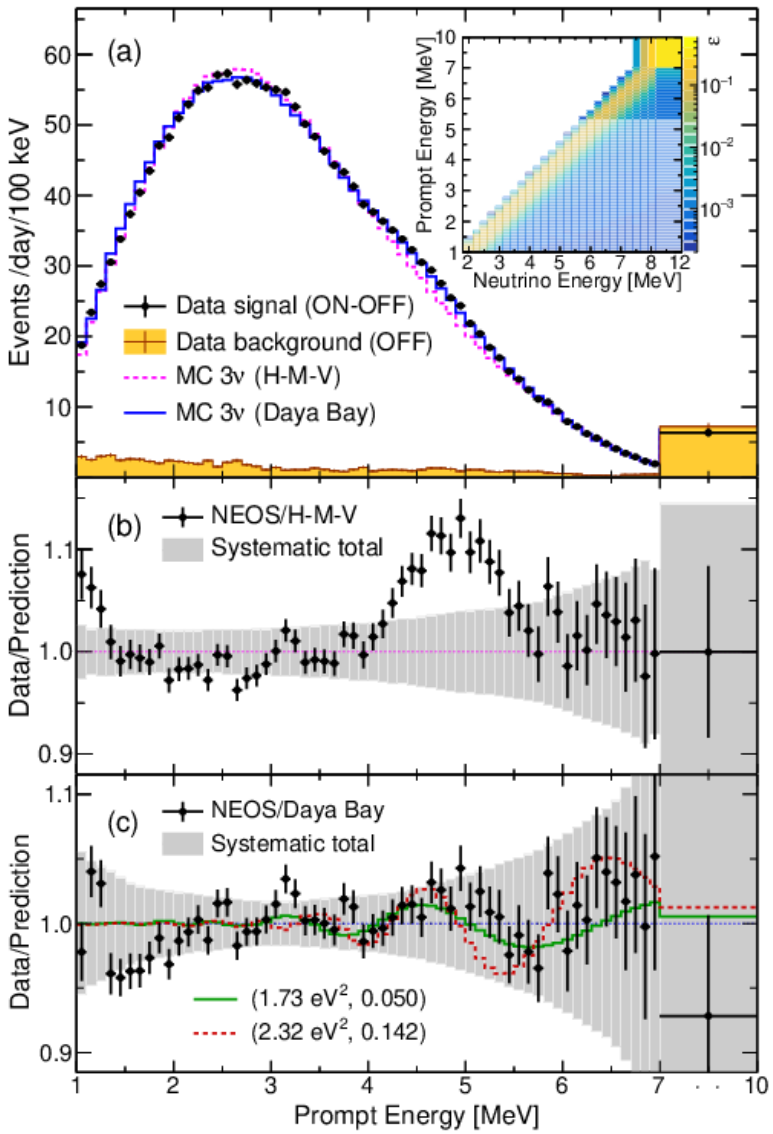
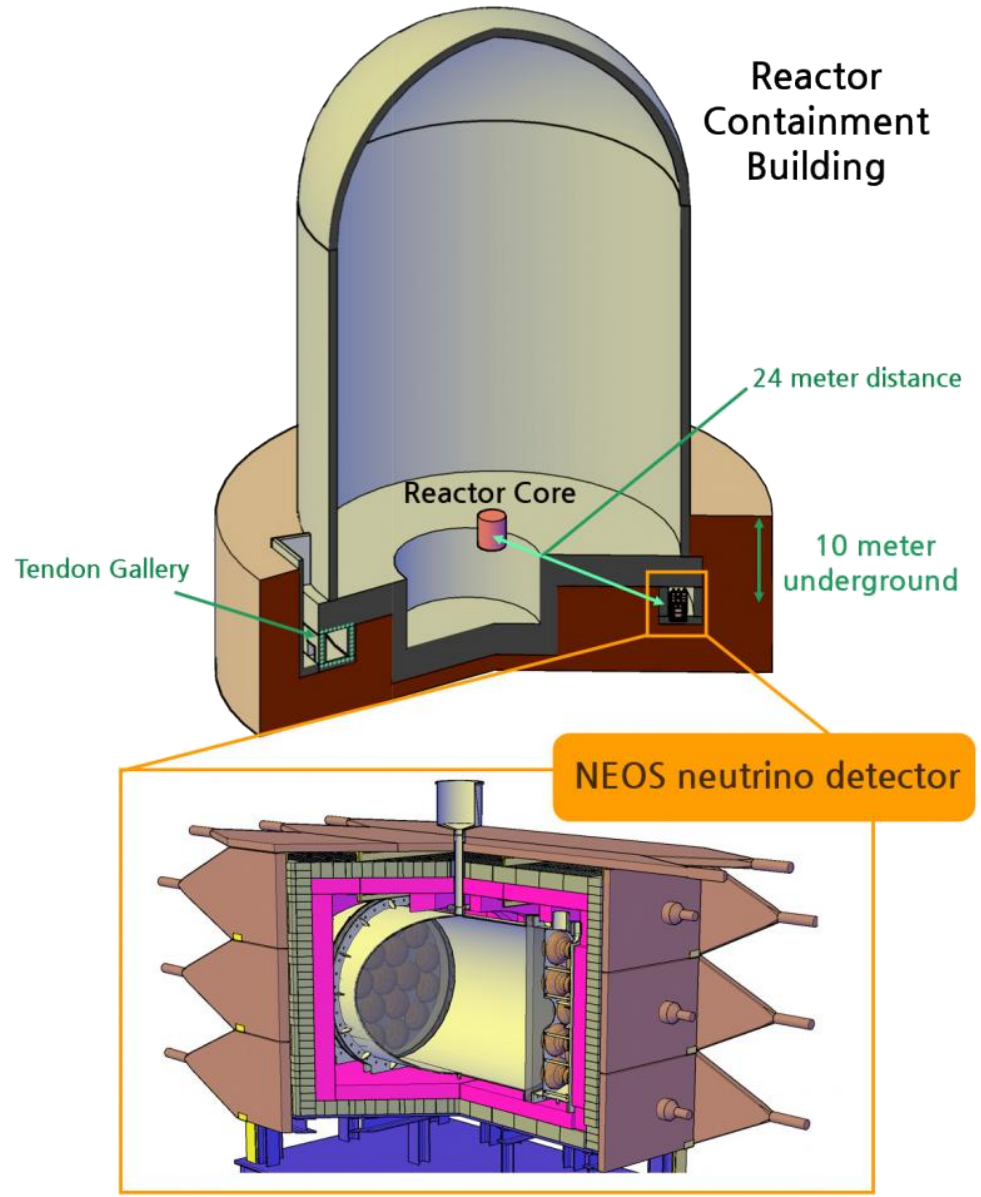
Electron (anti)neutrino disappearance

NEOS

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

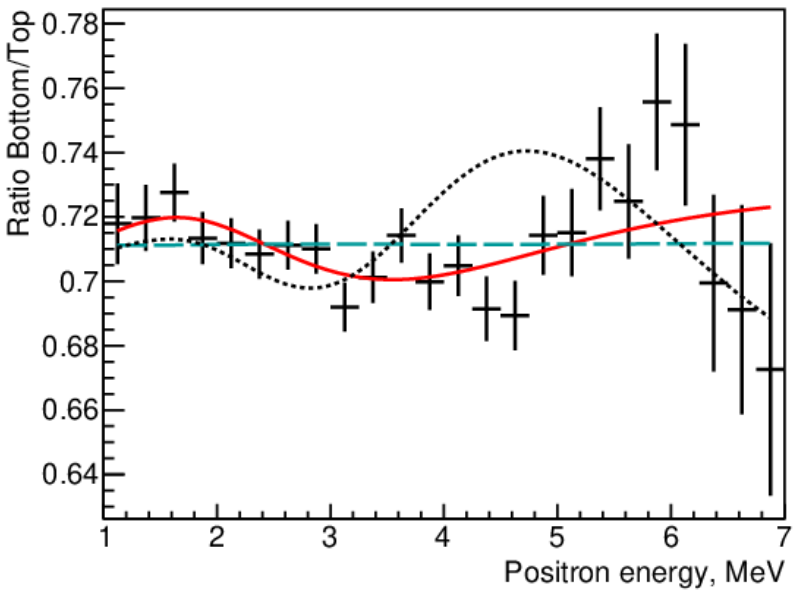


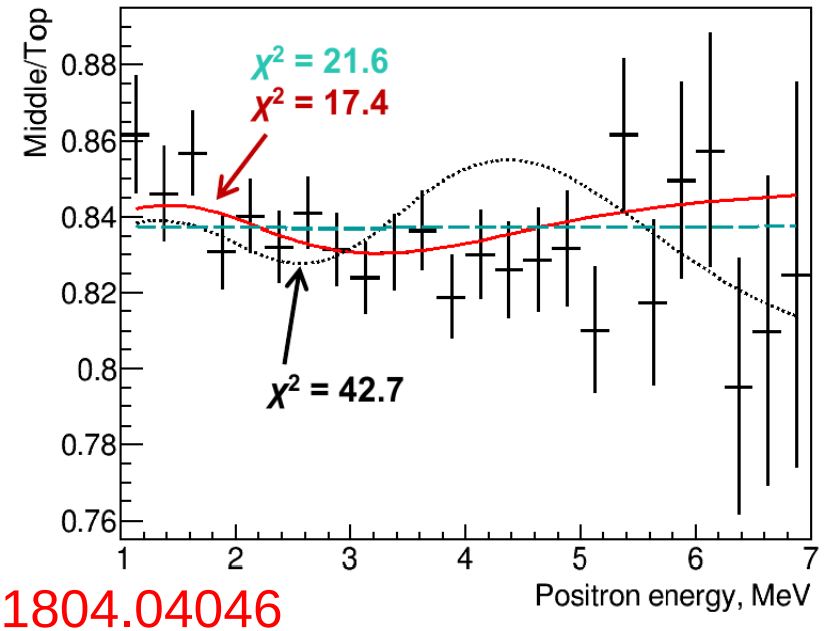


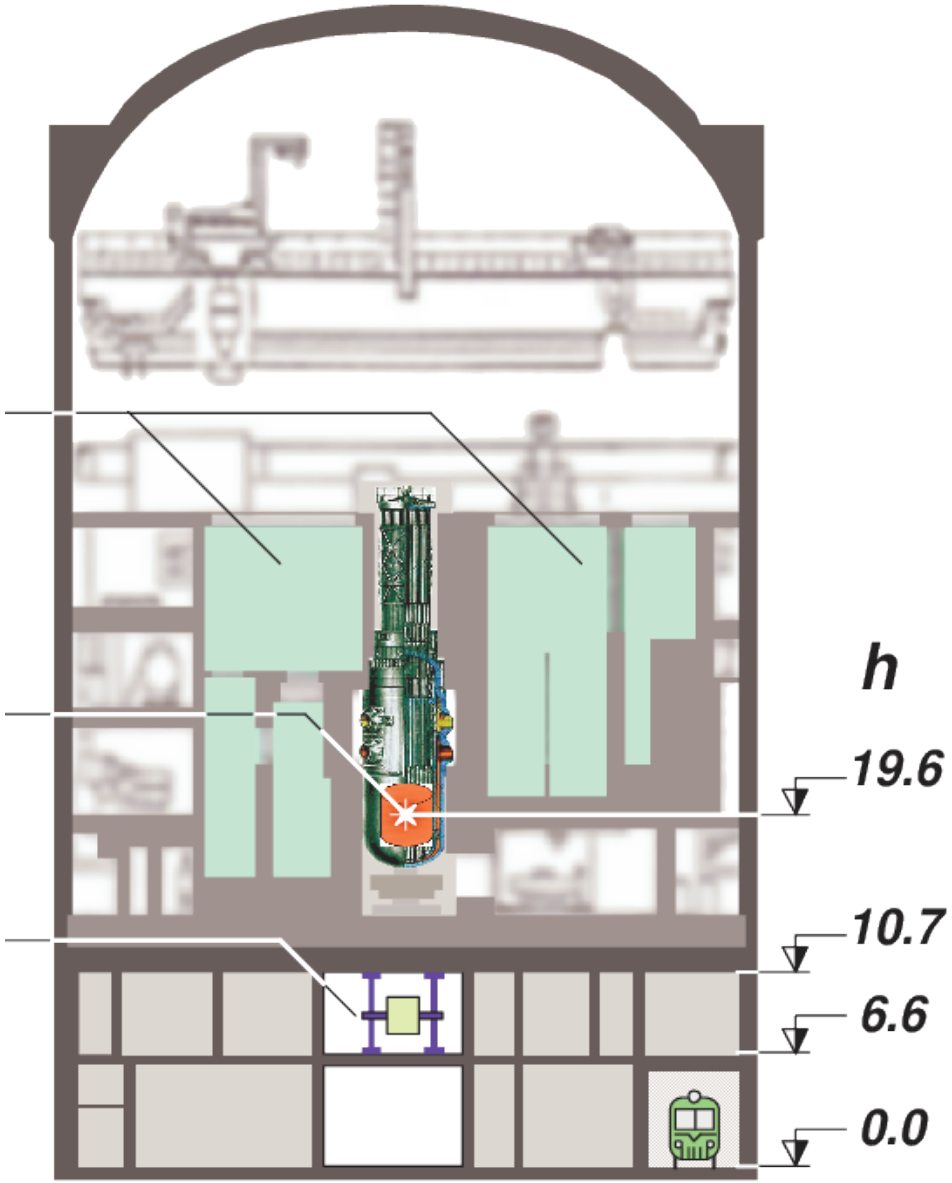
PRL 118 (2017) 121802

DANSS

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





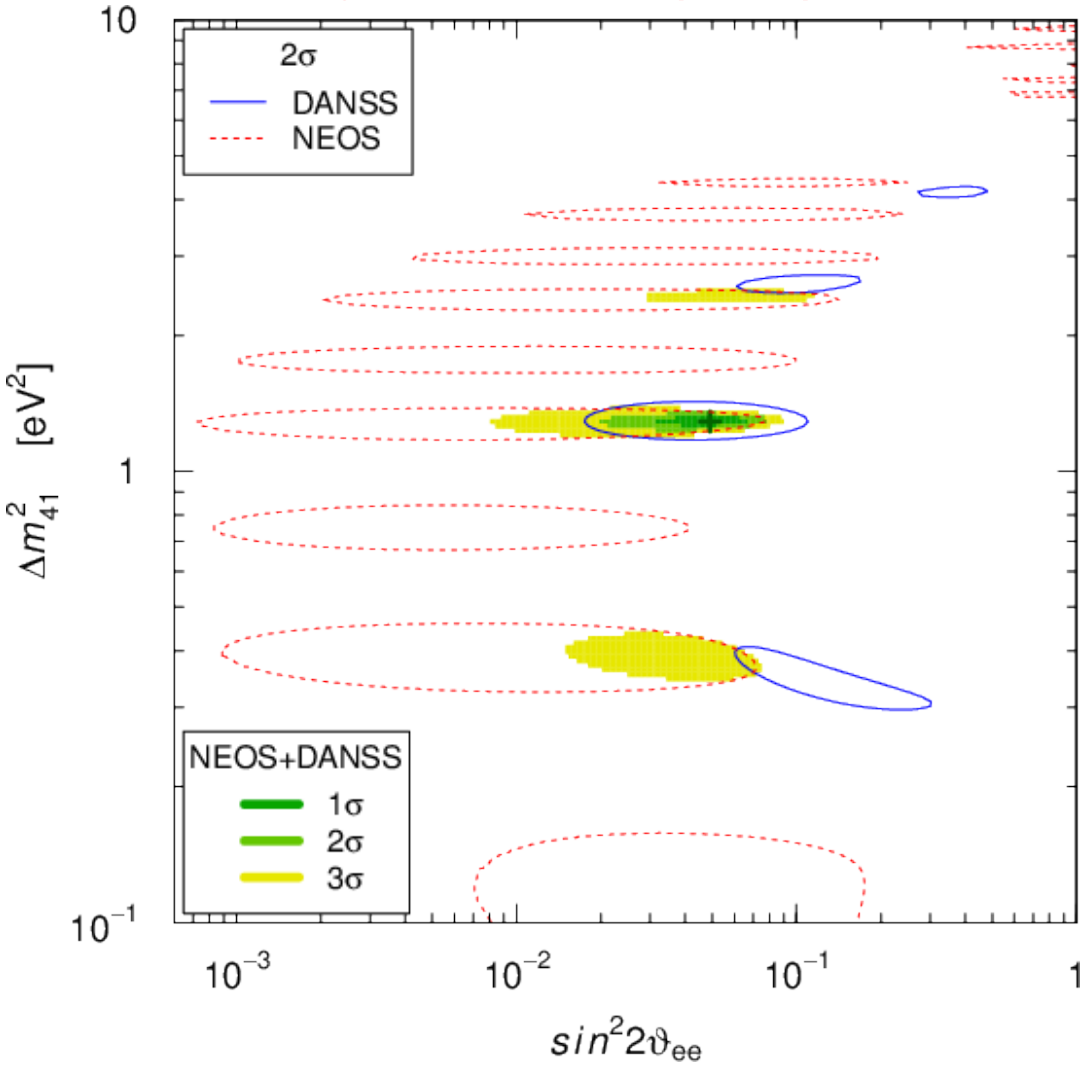


arXiv:1804.04046

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

- **DANSS / NEOS**

Phys.Lett. B782 (2018) 13-21



- Perfect agreement at

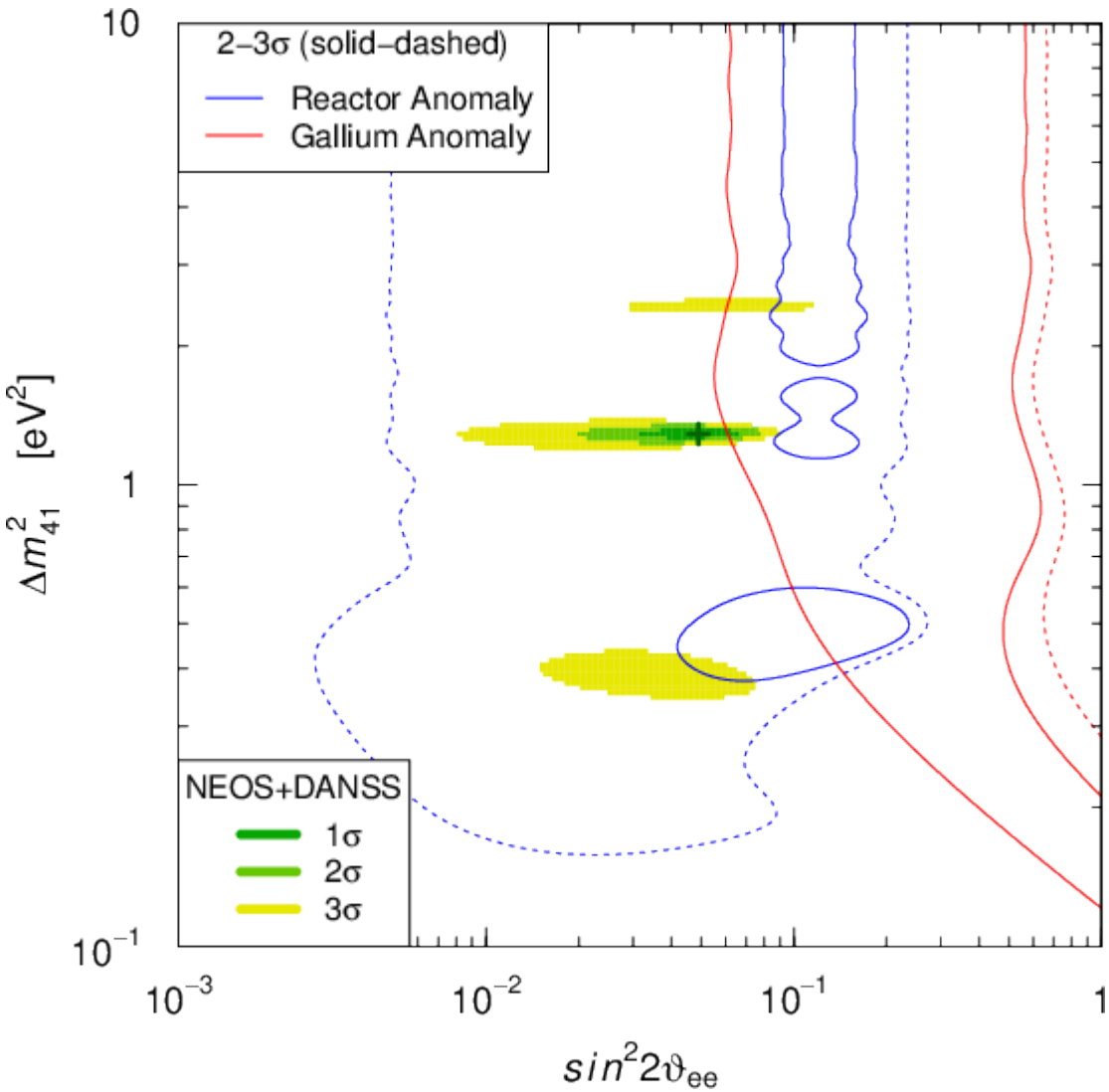
$$\Delta m^2_{41} = 1.3 \text{ eV}^2$$
$$\sin^2(2\theta_{ee}) = 0.05$$
$$\sin^2\theta_{14} = 0.01$$

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

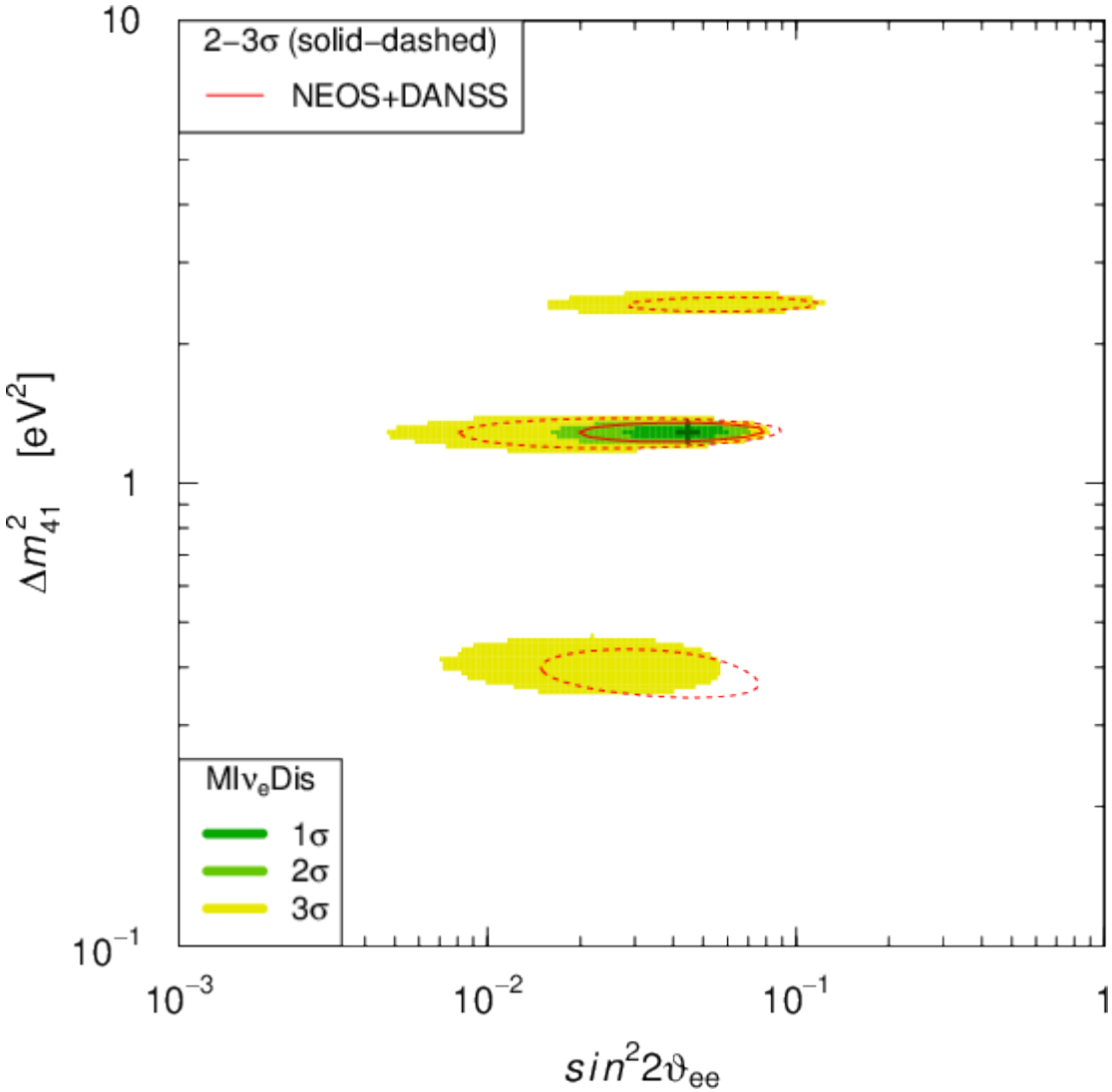


Small tension between NEOS/DANSS and Gallium and RAA

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

- All data:

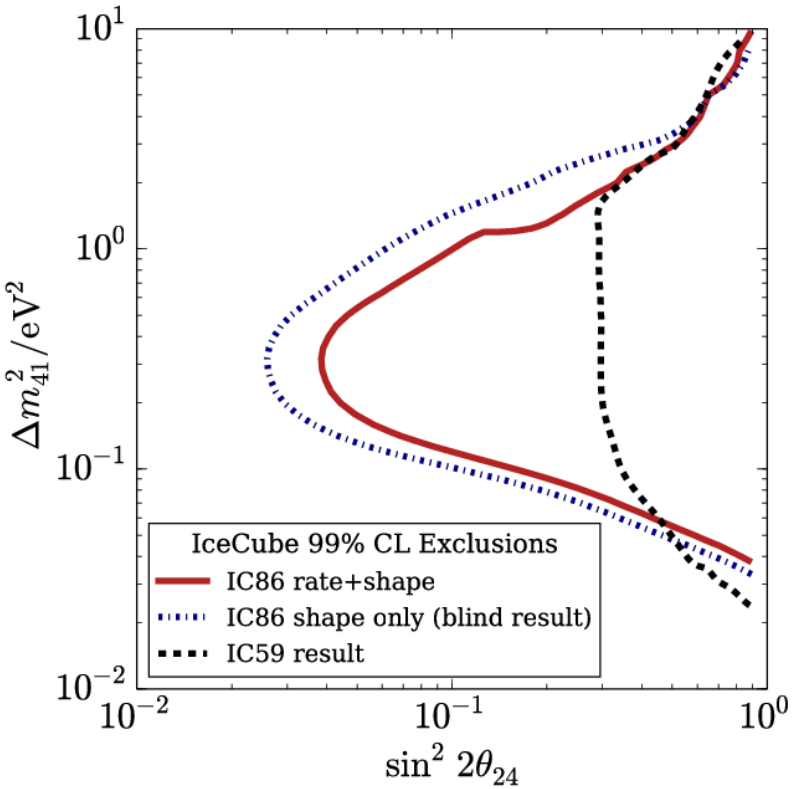
Phys.Lett. B782 (2018) 13-21



Fit is dominated by **NEOS/DANSS**

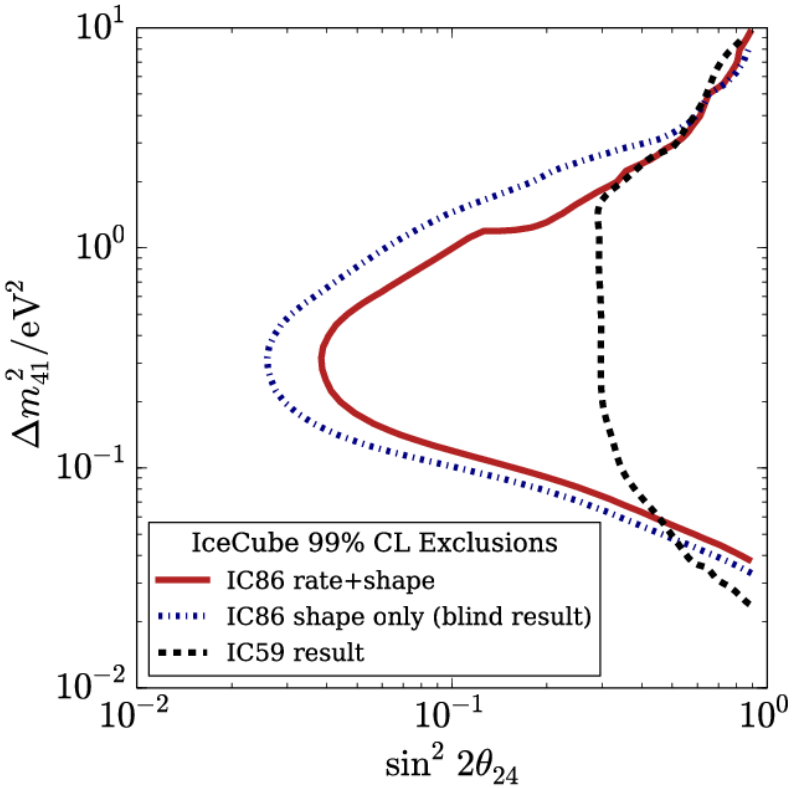
Muon (anti)neutrino disappearance

IceCube and DeepCore



PRL 117 (2016) 071801

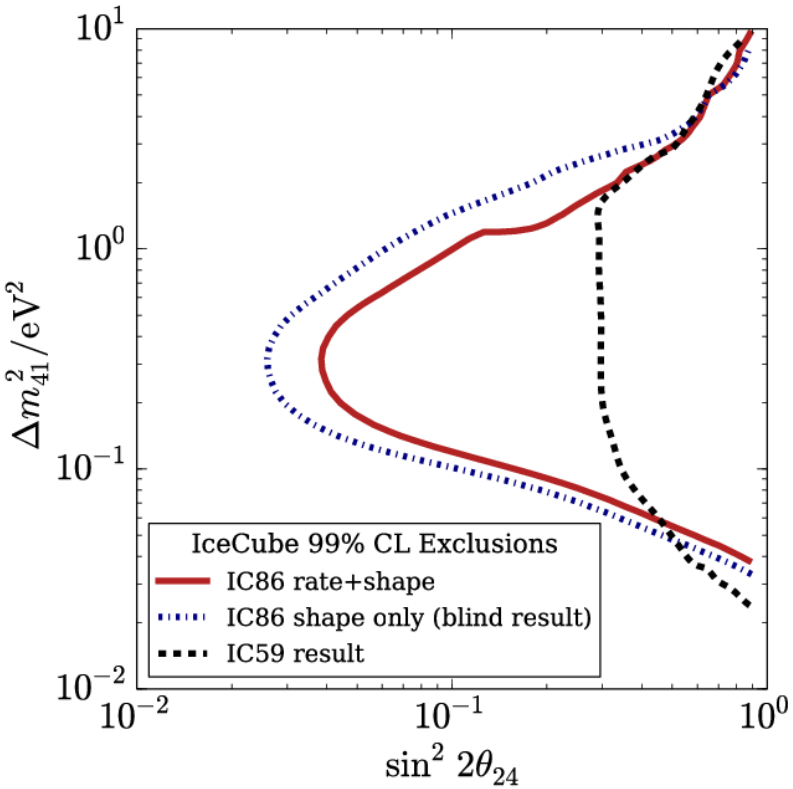
IceCube and DeepCore



- High-energy regime
- 0.3 TeV – 20 TeV

PRL 117 (2016) 071801

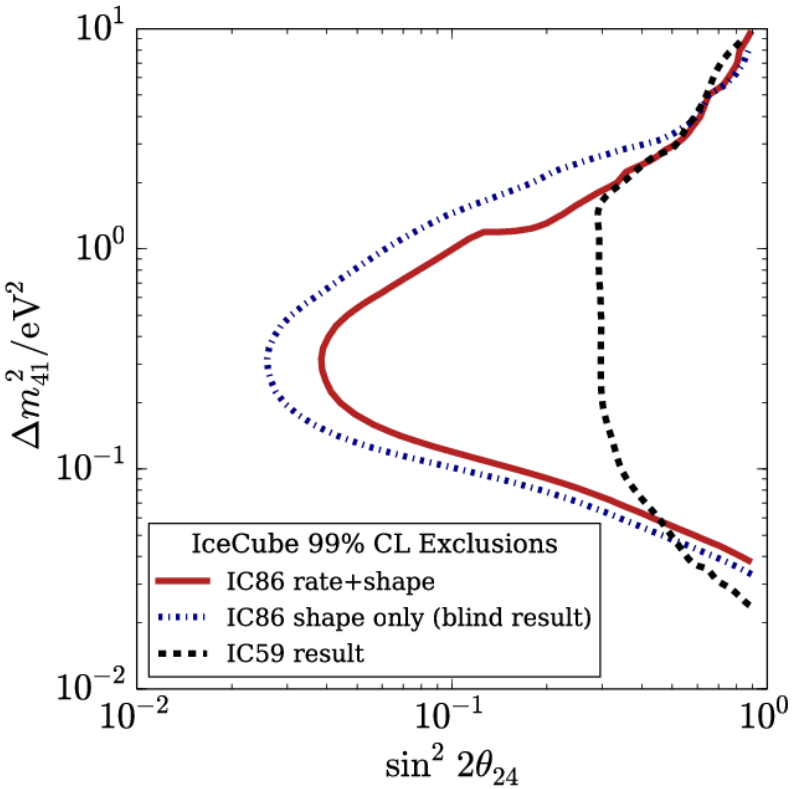
IceCube and DeepCore

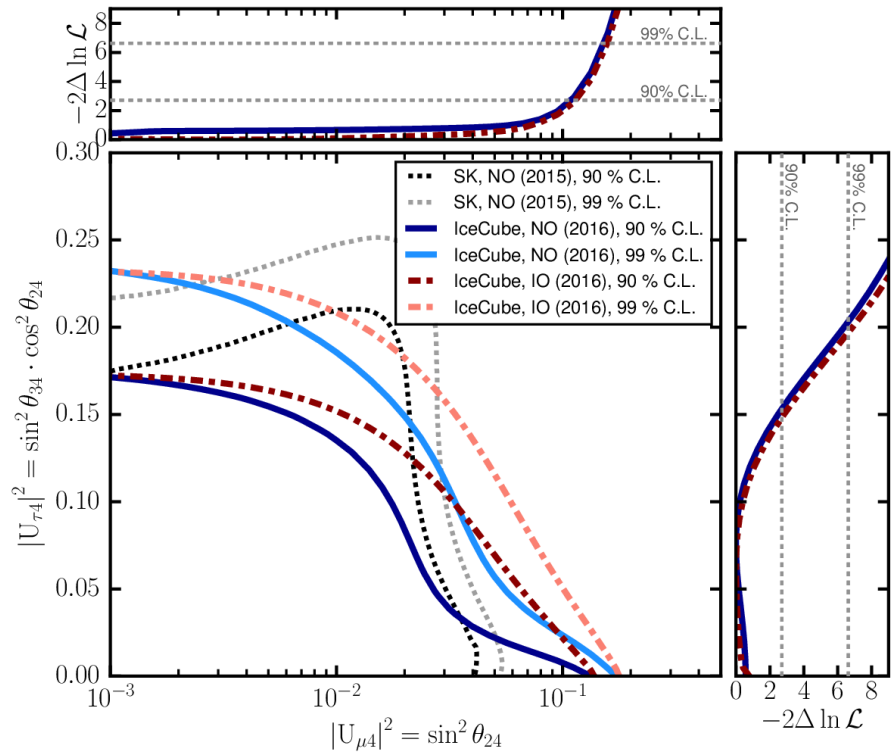


- High-energy regime
- 0.3 TeV – 20 TeV
- Waiting for 7 yr update!

PRL 117 (2016) 071801

IceCube and DeepCore





- High-energy regime
- 0.3 TeV – 20 TeV
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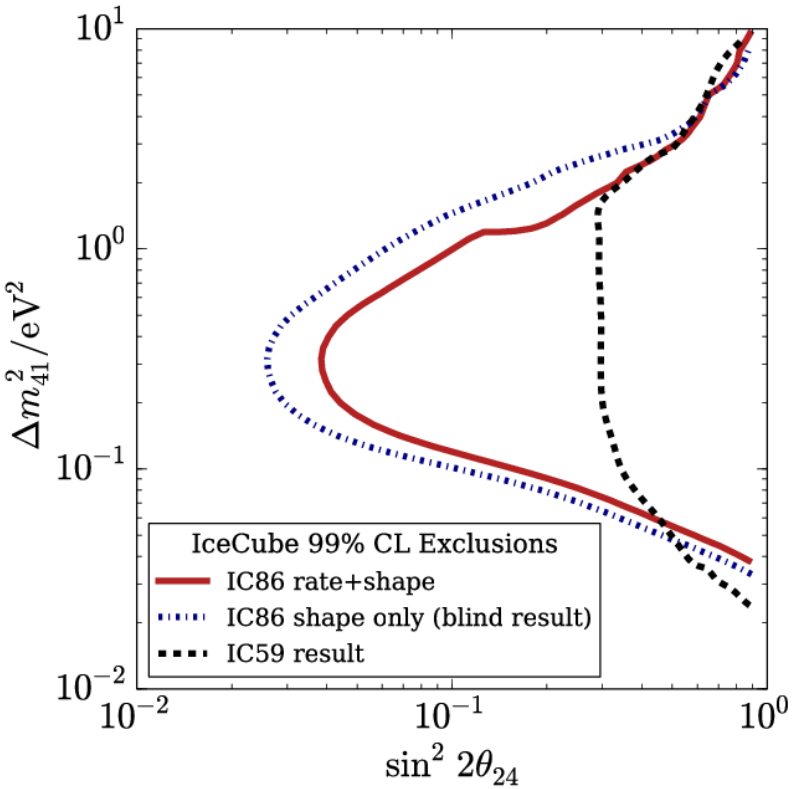
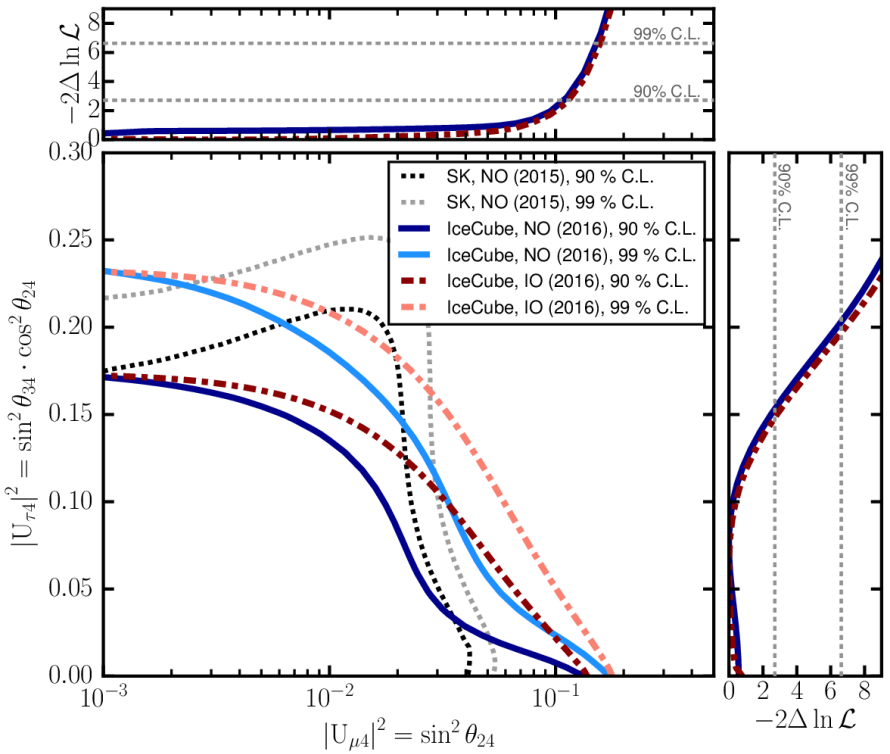
PRL 117 (2016) 071801

PRD 95 (2017) 112002

IceCube and DeepCore





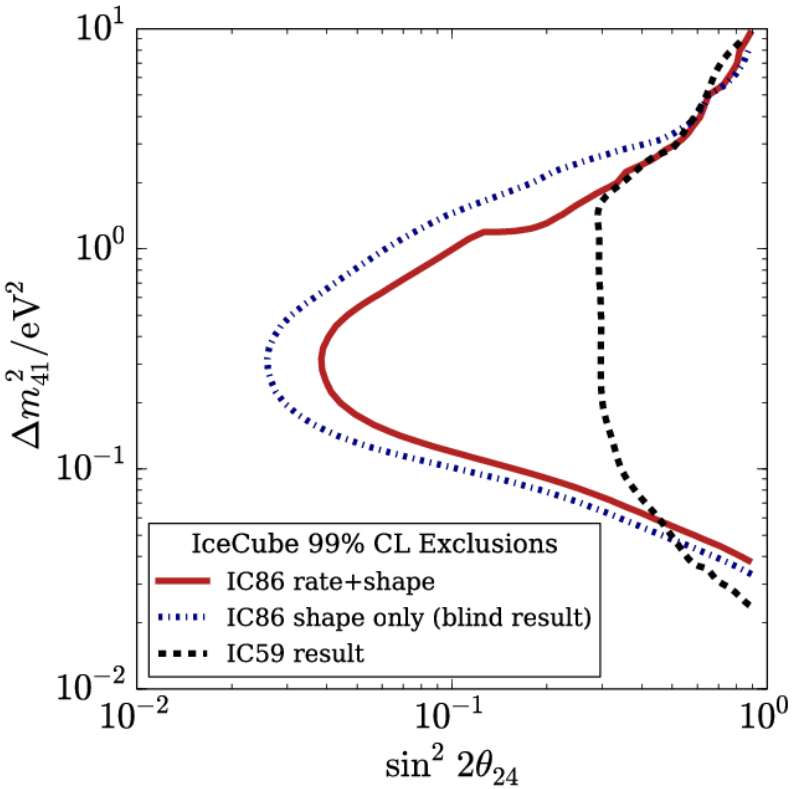
- High-energy regime
- 0.3 TeV – 20 TeV
- Waiting for 7 yr update!

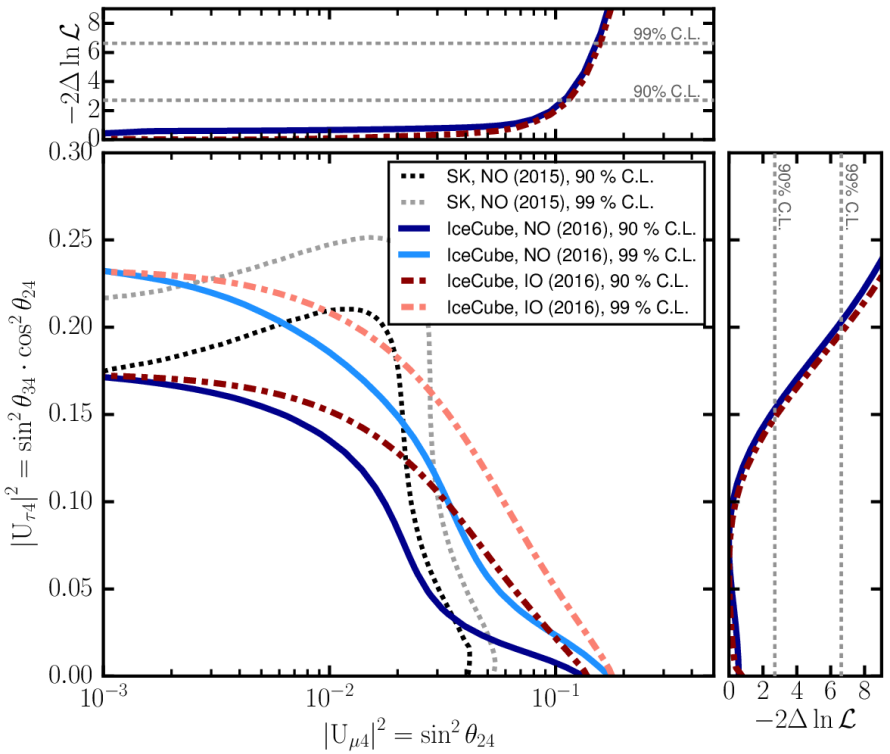
- Low-energy regime
- 6 GeV – 56 GeV

PRL 117 (2016) 071801

PRD 95 (2017) 112002

IceCube and DeepCore





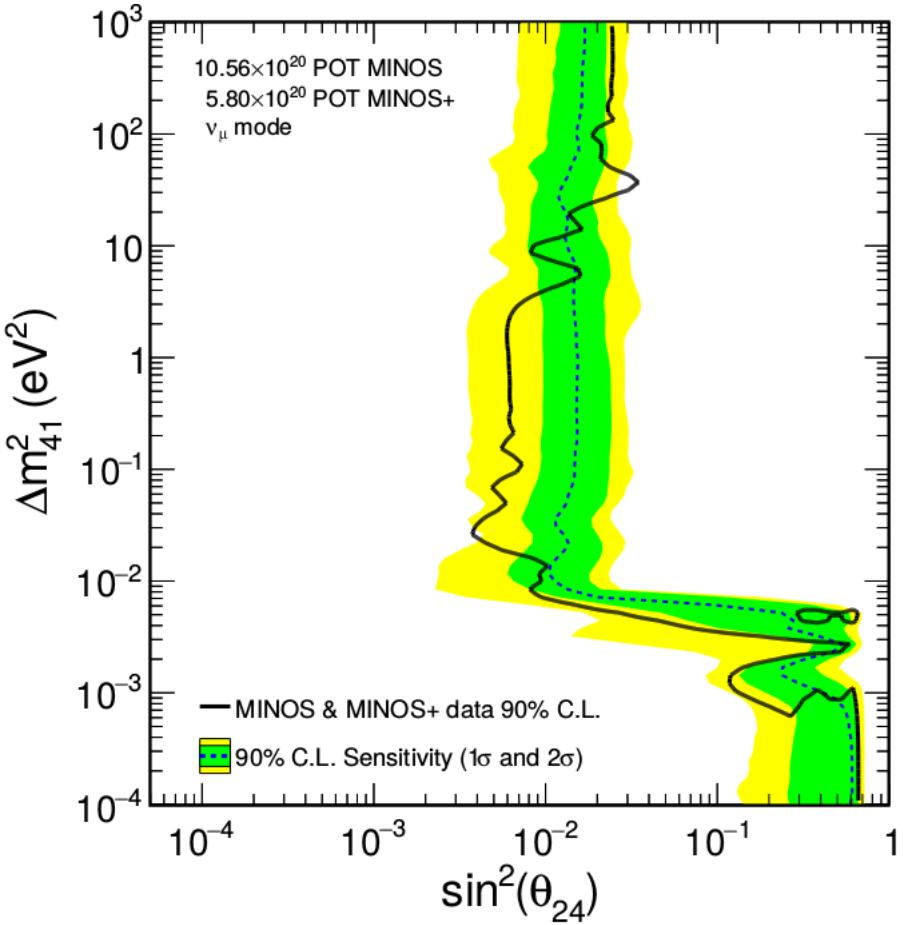
- High-energy regime
- 0.3 TeV – 20 TeV
- Waiting for 7 yr update!

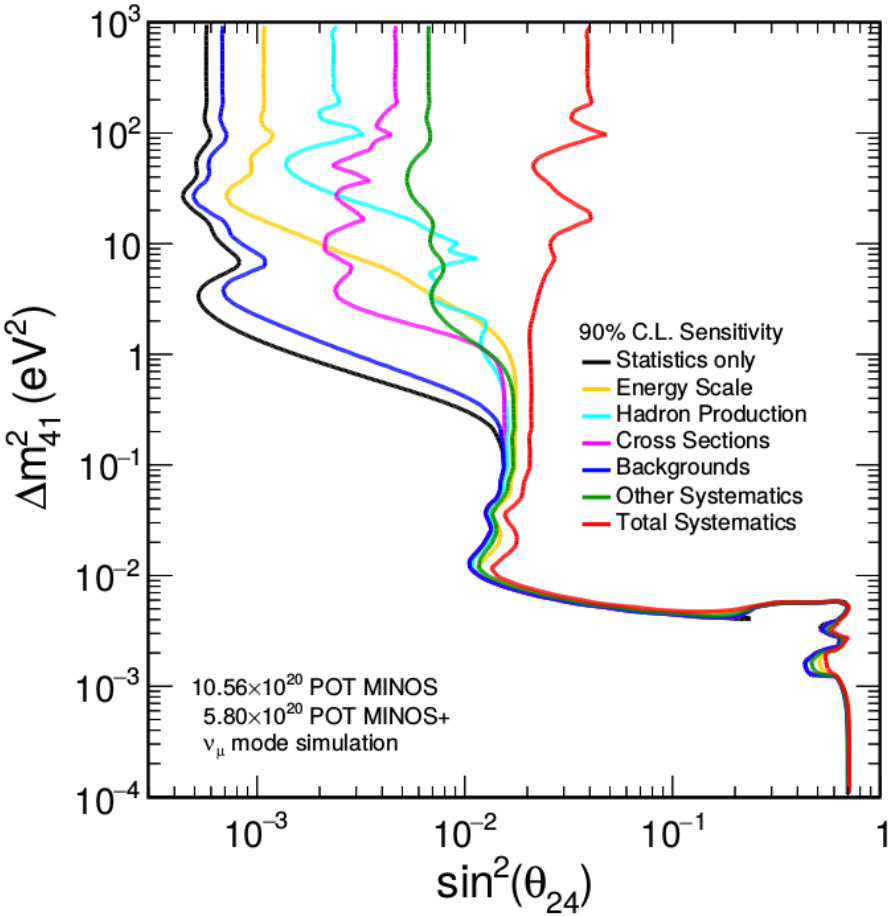
- Low-energy regime
- 6 GeV – 56 GeV
- Also constraining θ_{34}

PRL 117 (2016) 071801

PRD 95 (2017) 112002

MINOS/MINOS+

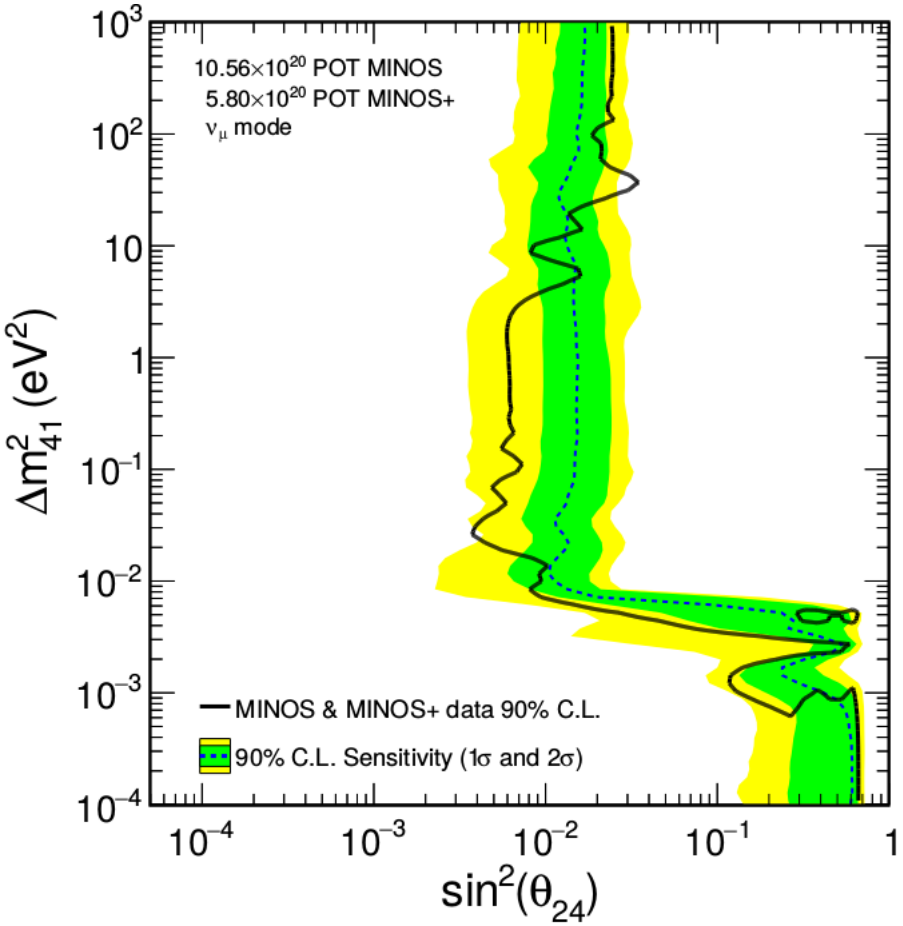


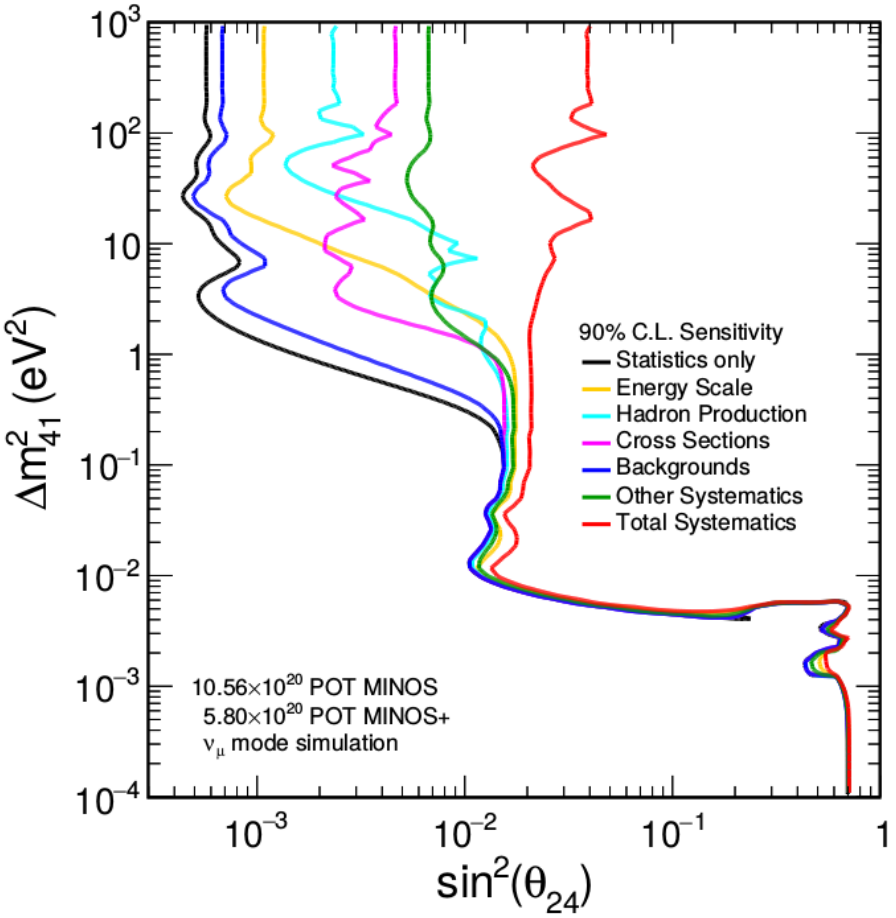


- Two analyses: far-over-near ratio, and two-detector fit

PRL 117 (2016) 151803
arxiv:1710.06488

MINOS/MINOS+



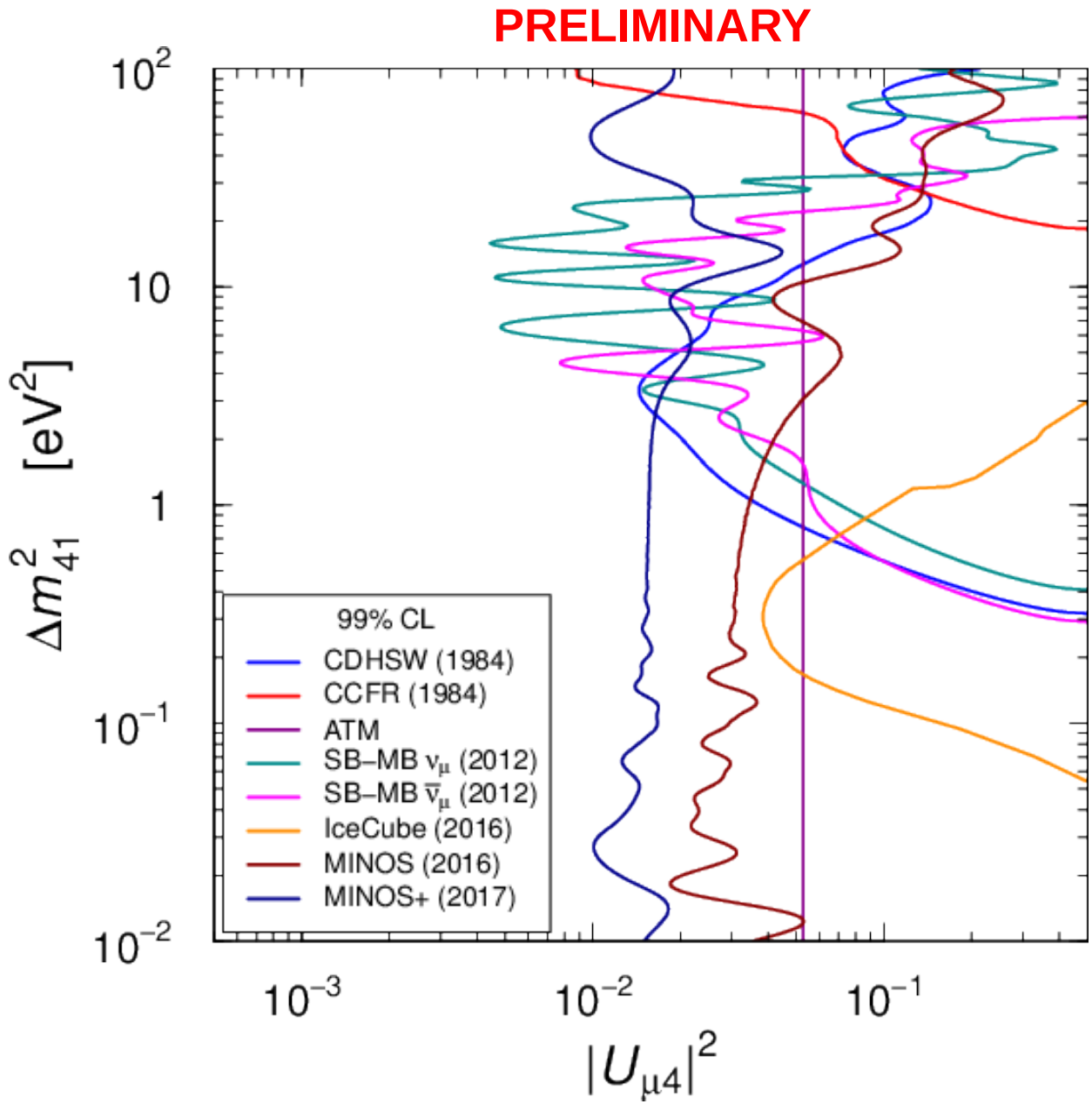


- Two analyses: far-over-near ratio, and two-detector fit
- For large mass splittings: systematic dominated

PRL 117 (2016) 151803
arxiv:1710.06488

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

- All data:

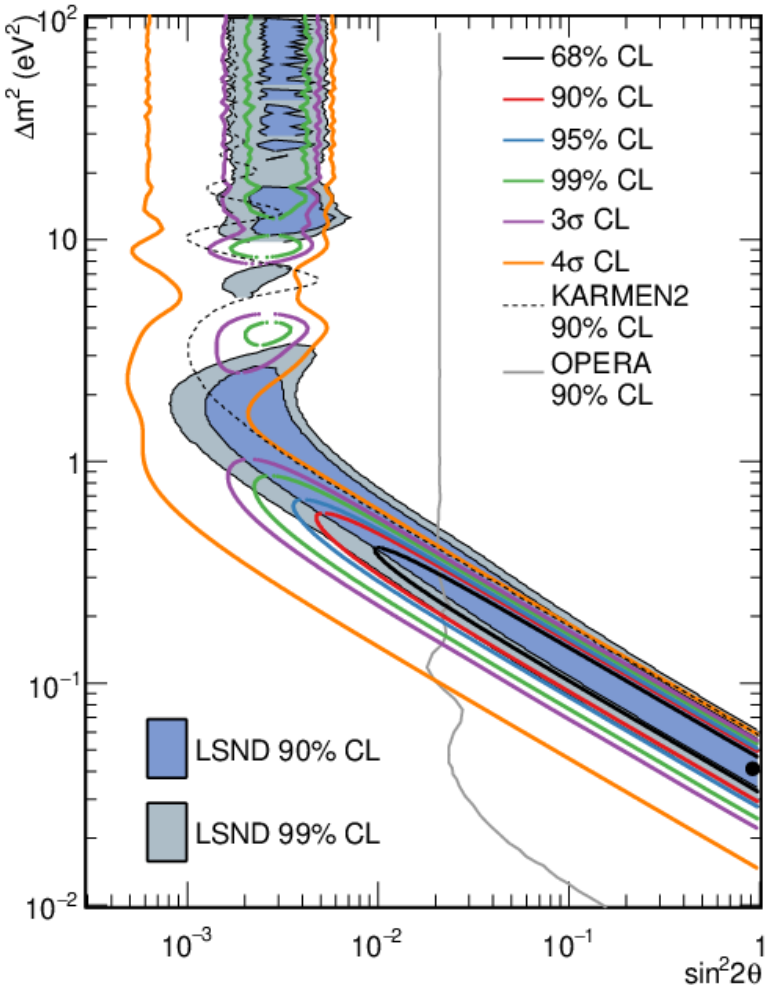


MINOS/MINOS+ dominates at small mass splittings

Electron (anti)neutrino appearance

MiniBooNE

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



PRL 121 (2018) 221801

MiniBooNE

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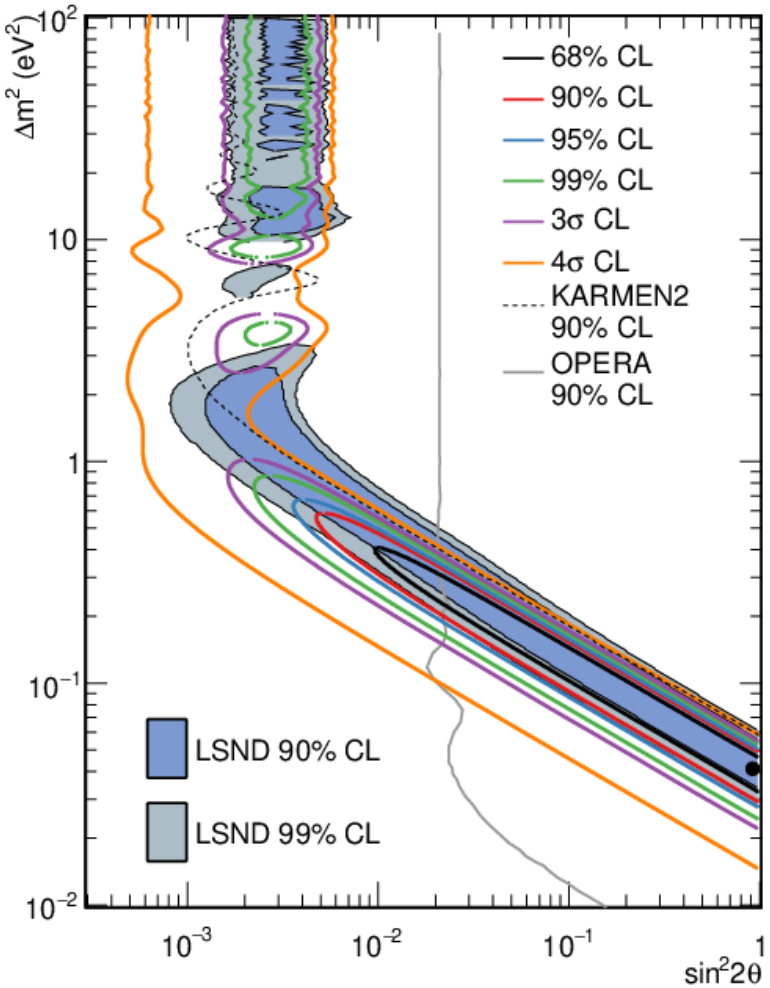
- **MiniBooNE** has no near detector



PRL 121 (2018) 221801

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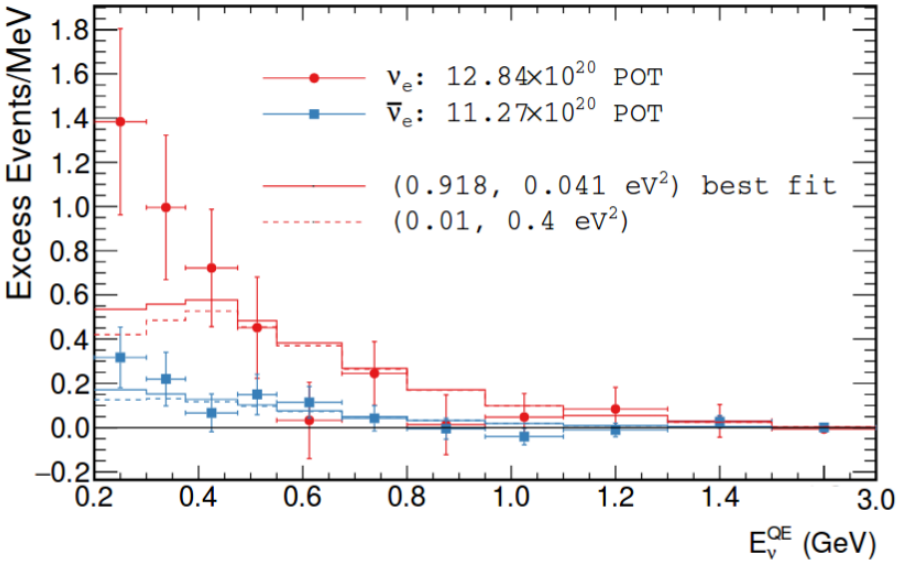
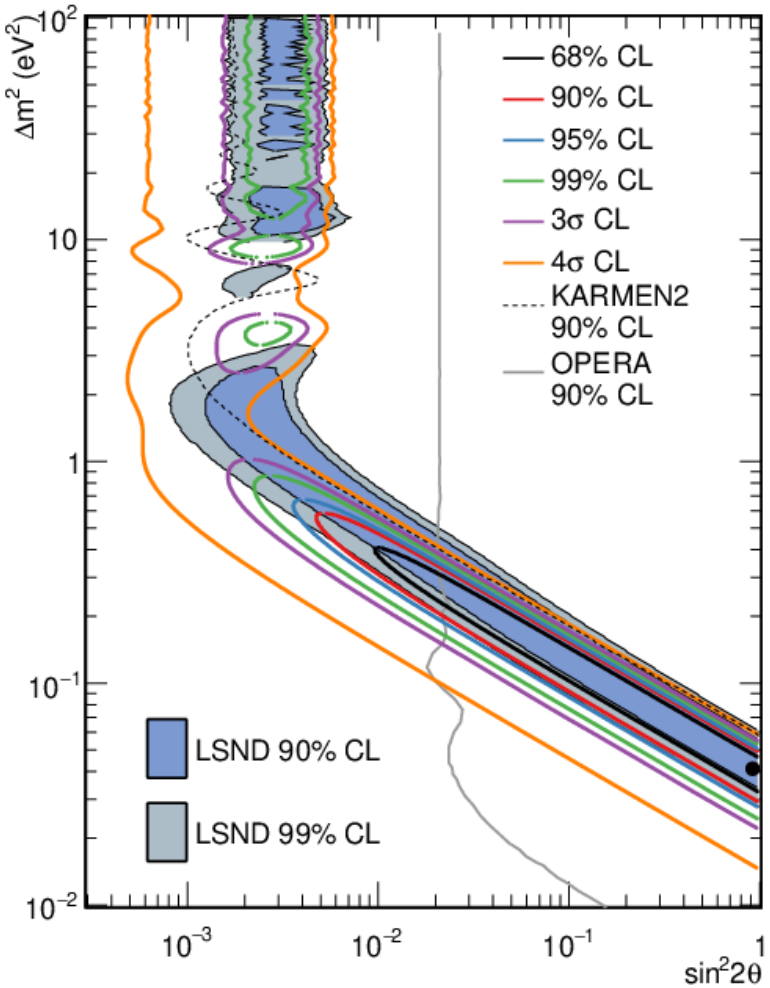


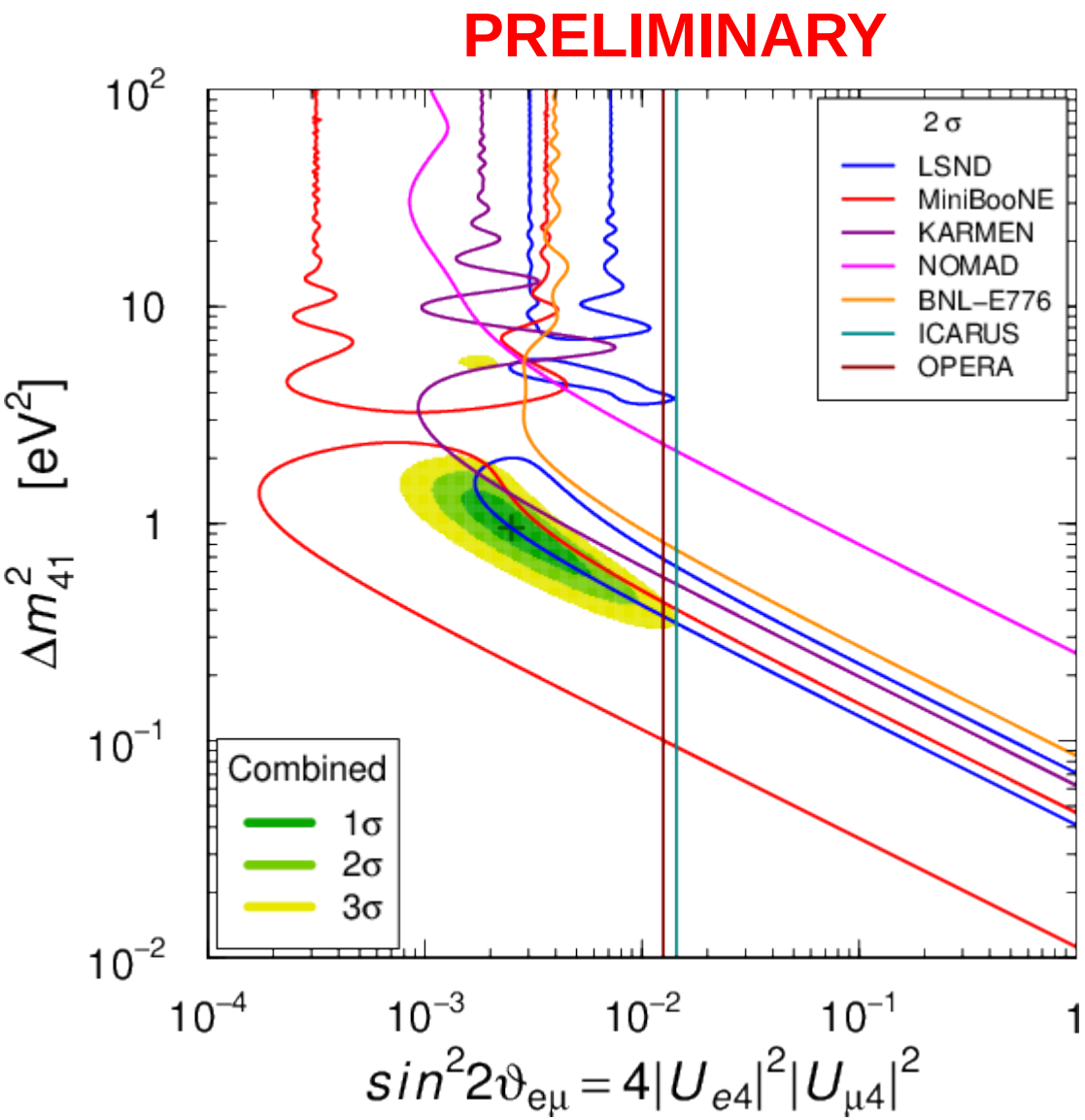


- **MiniBooNE** sees an excess, which cannot be explained with sterile oscillations

PRL 121 (2018) 221801

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

- All data:



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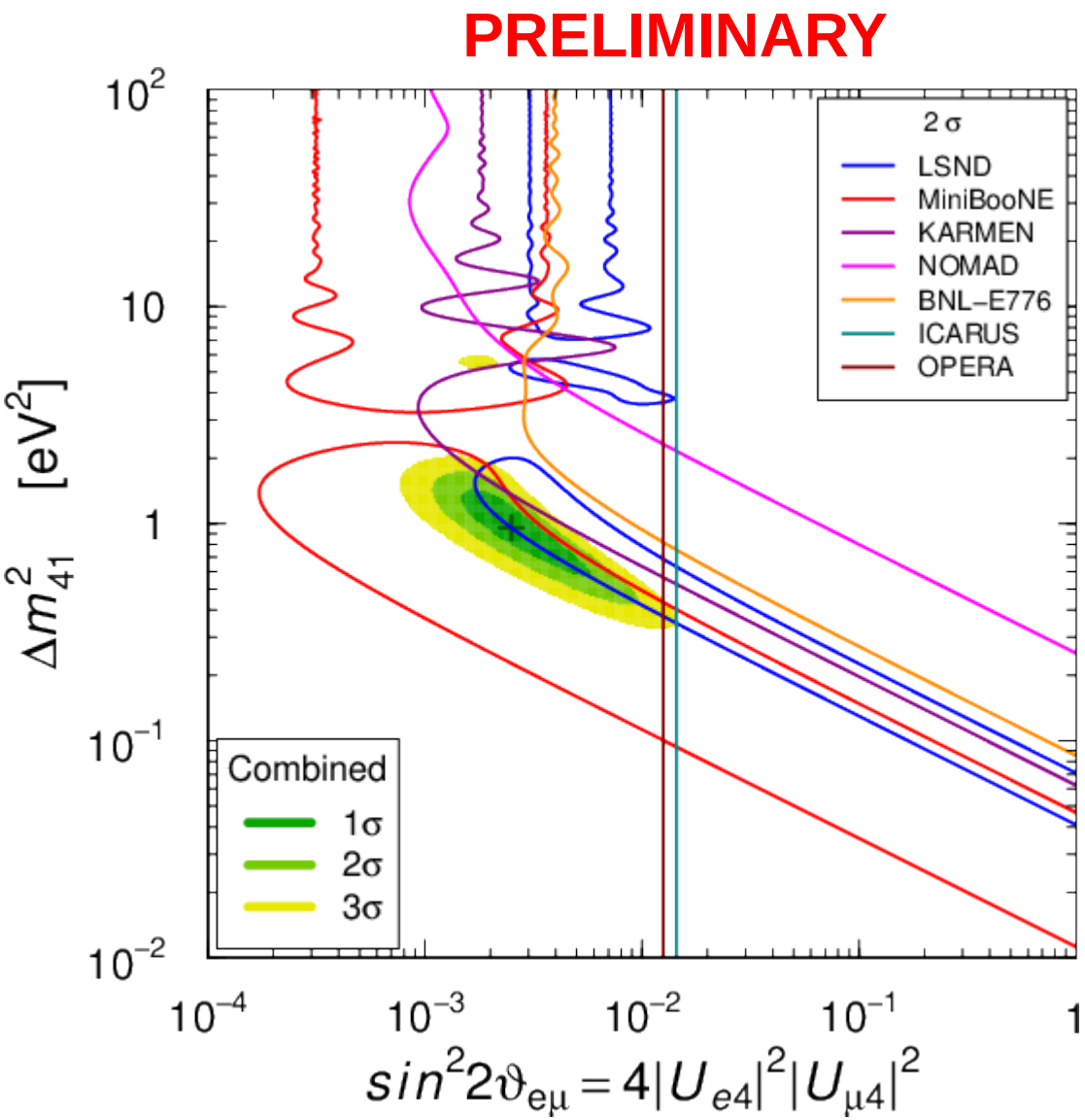
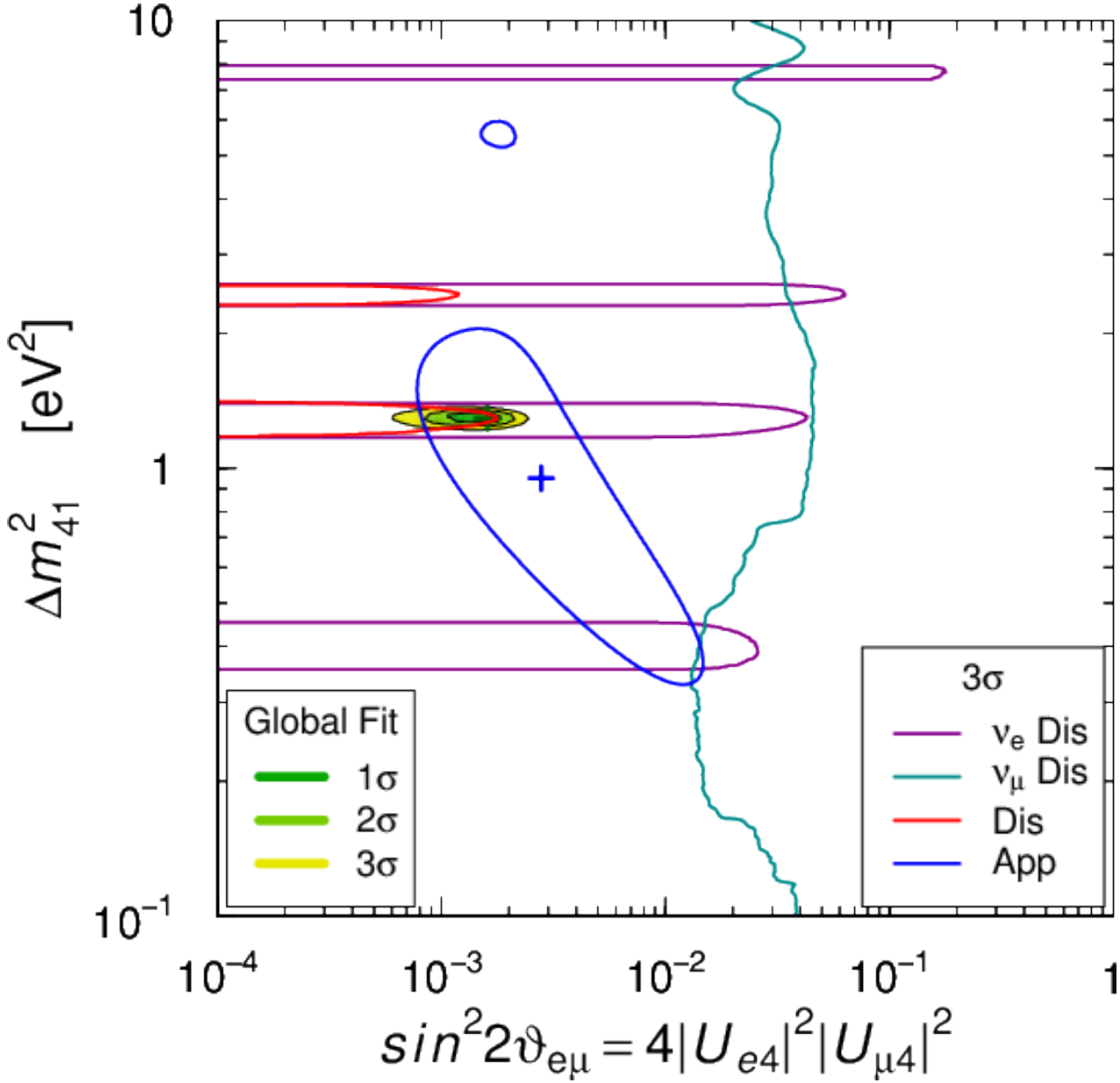


- The best fit value of **MiniBooNE** is excluded by **Icarus** and **Opera**
- **LSND** and **MiniBooNE** only partially agree

Tension in APP vs DIS data

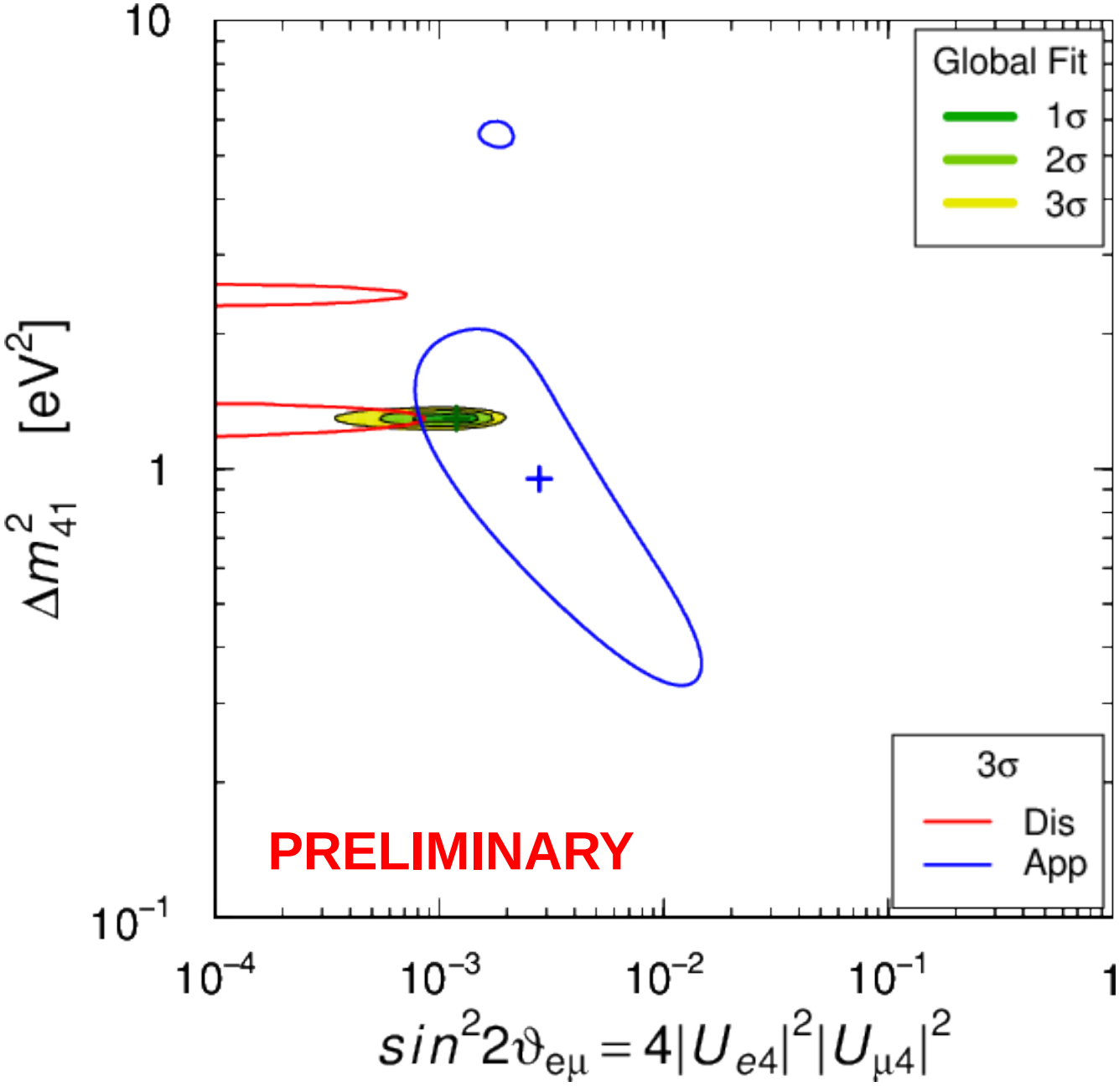
- Data before 2018



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

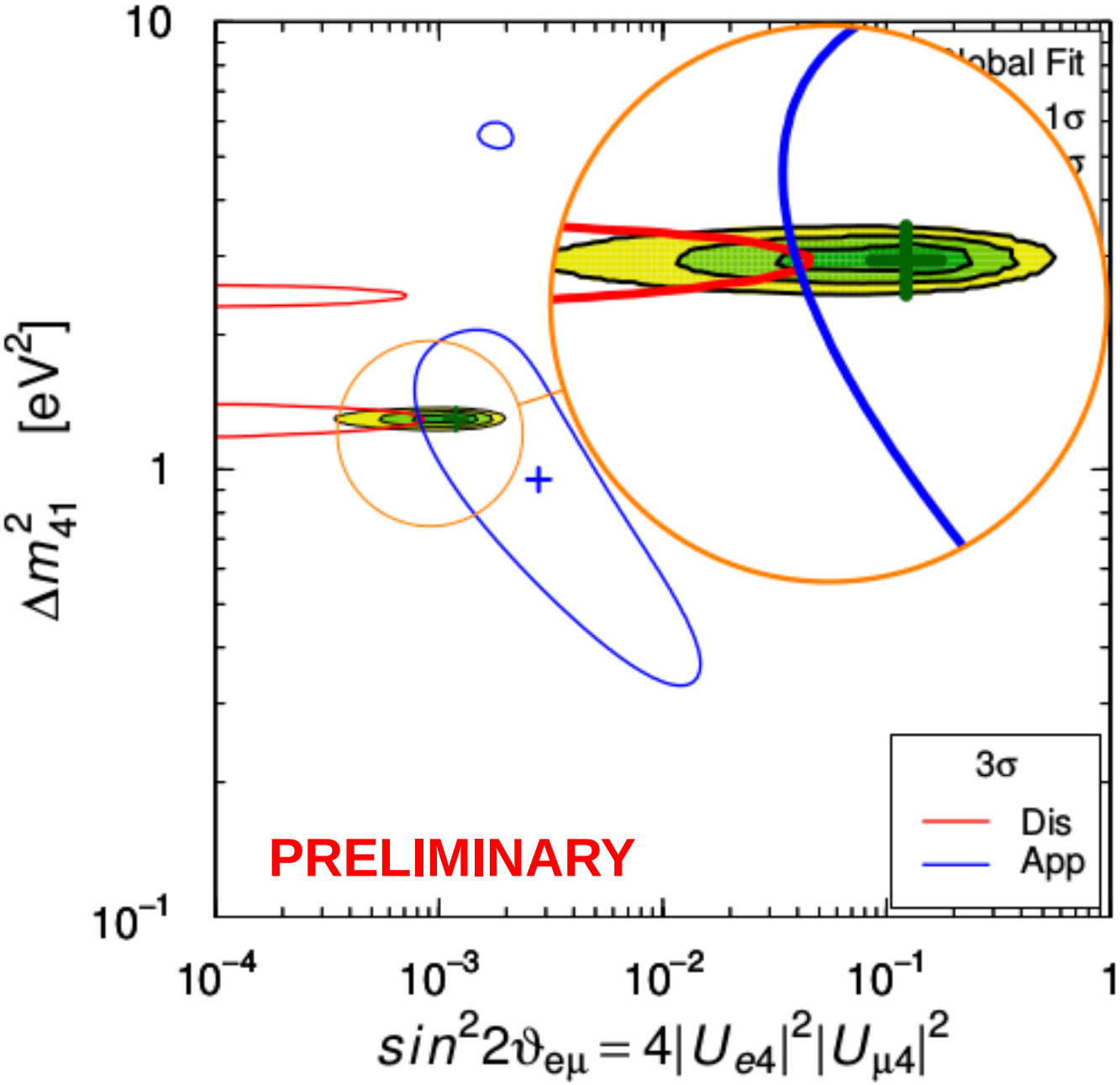
Tension in APP vs DIS data

- Data 2018



Tension in APP vs DIS data

- Data 2018



Tension in APP vs DIS data

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	$\chi^2_{\text{PG}}/\text{dof}$	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

JHEP 08 (2018) 010, Dentler, M. et al

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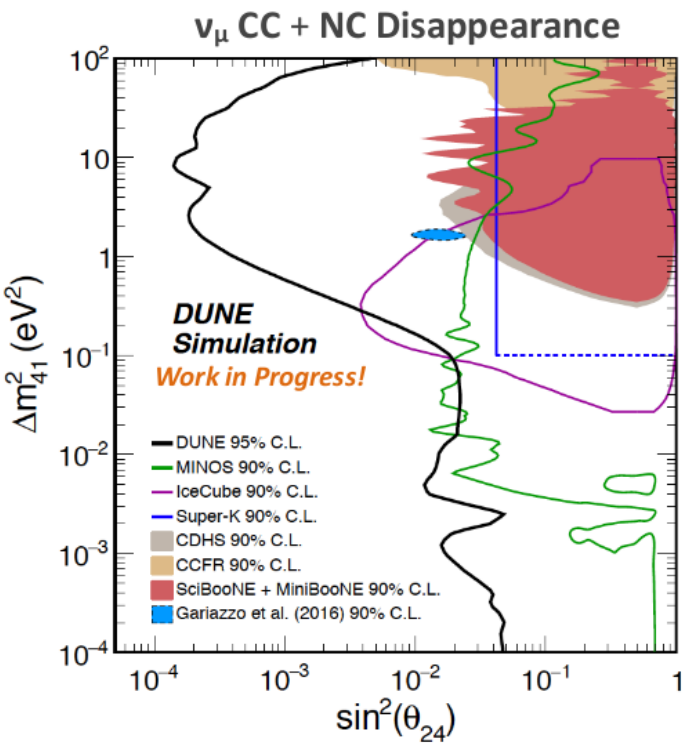
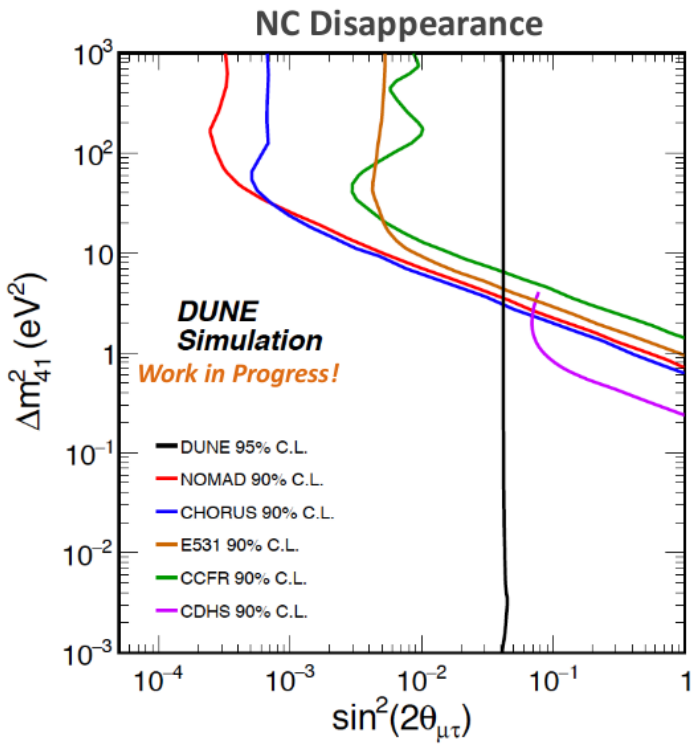
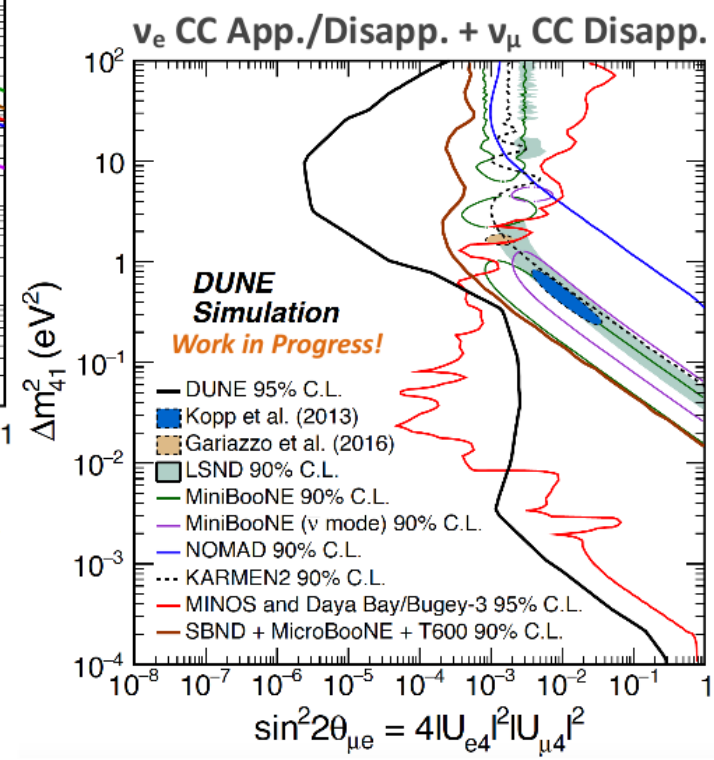
Future prospects at DUNE

PRELIMINARY,
sterile sub-group of DUNE-BSM group





$$\sin^2 2\theta_{\mu\tau} \equiv 4|U_{\tau 4}|^2|U_{\mu 4}|^2 = \cos^4\theta_{14}\sin^2 2\theta_{24}\sin^2\theta_{34}$$



Thanks to Alex Sousa!

See also: JHEP 1807 (2018) 079, Coloma, P. et al

Non-standard interactions (NSI)

Non-standard interactions

- NSI appear in many models of neutrino masses

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- They can affect the oscillation probabilities

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- Two types of NSI:
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  - NC: $\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fX}(\overline{\nu}_\alpha\gamma^\mu P_L \nu_\beta)(\overline{f}\gamma_\mu P^X f)$ affecting neutrino propagation in matter

Non-standard interactions

- For NSI in propagation the Hamiltonian is modified to

$$\mathcal{H}_F = \frac{1}{2E}\left\{ U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + A_{CC} \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix} \right\}$$

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- Non-universal couplings
- Flavor-changing neutral currents
- Total of 9 new parameters (3 real and 3 complex couplings)

LMA-D

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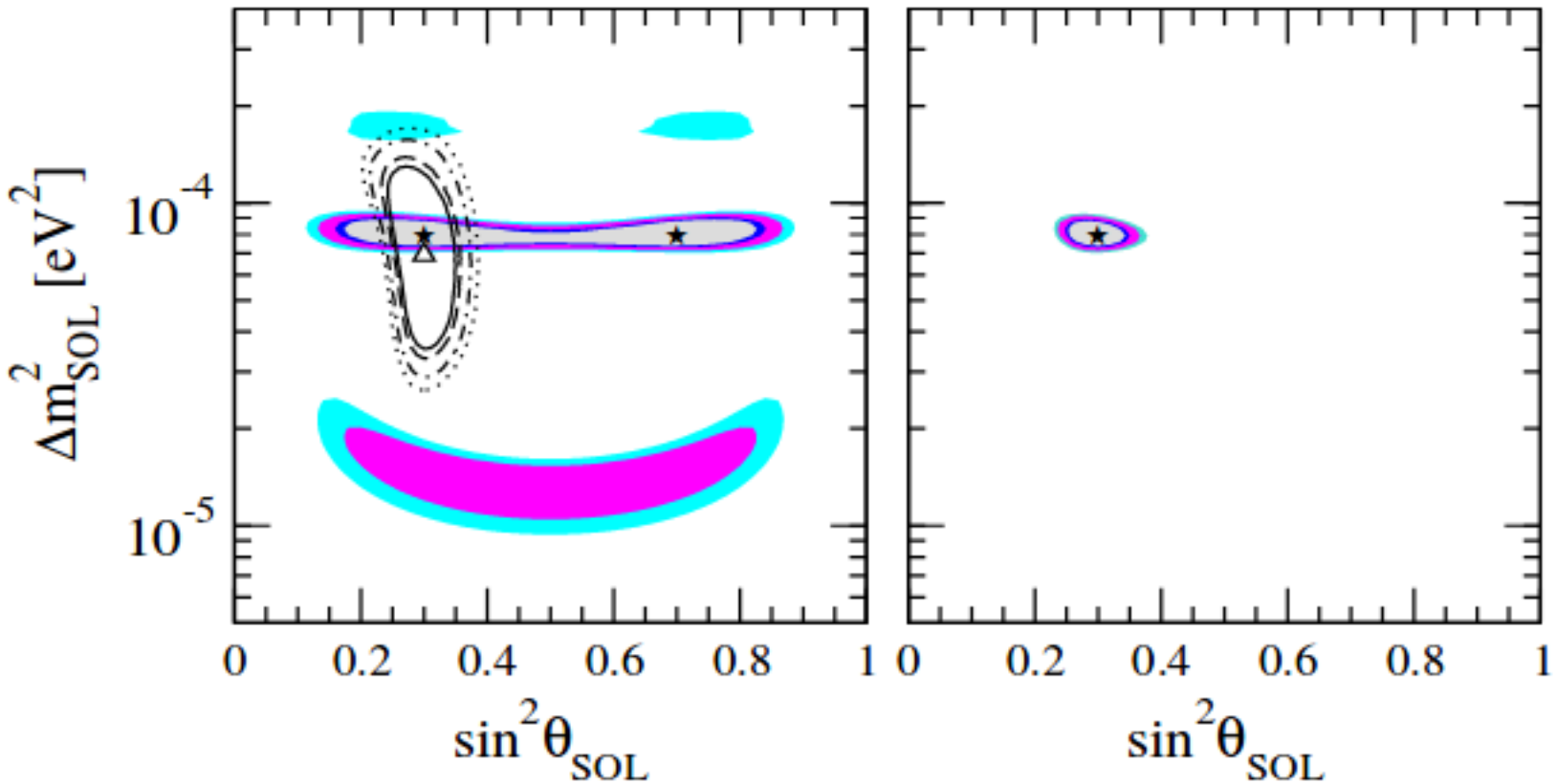
- Standard analysis:



JHEP 0610 (2006) 008, Miranda, O. et al

LMA-D

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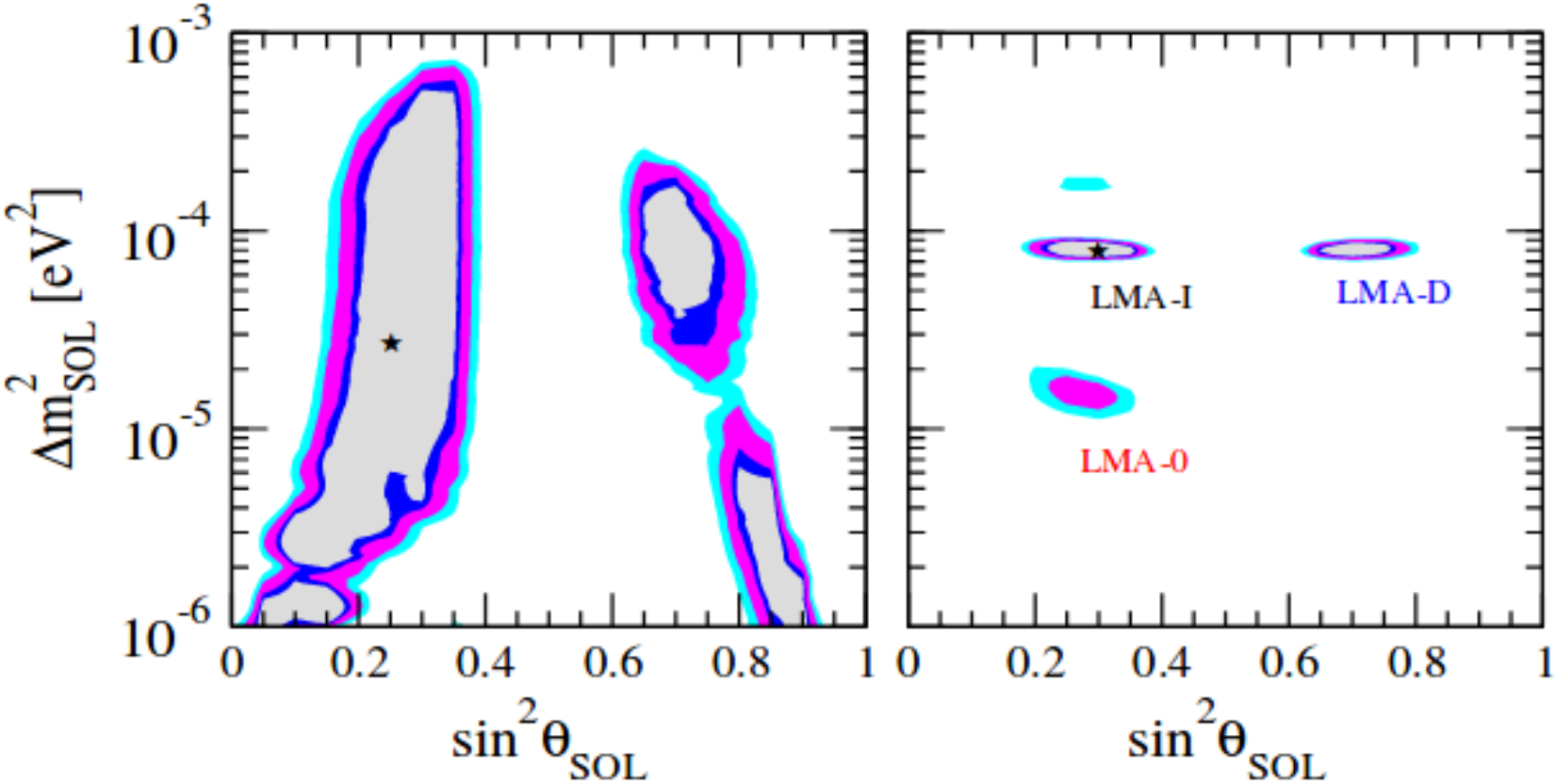
- Example: Determination of solar parameters
- NSI analysis:



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LMA-D

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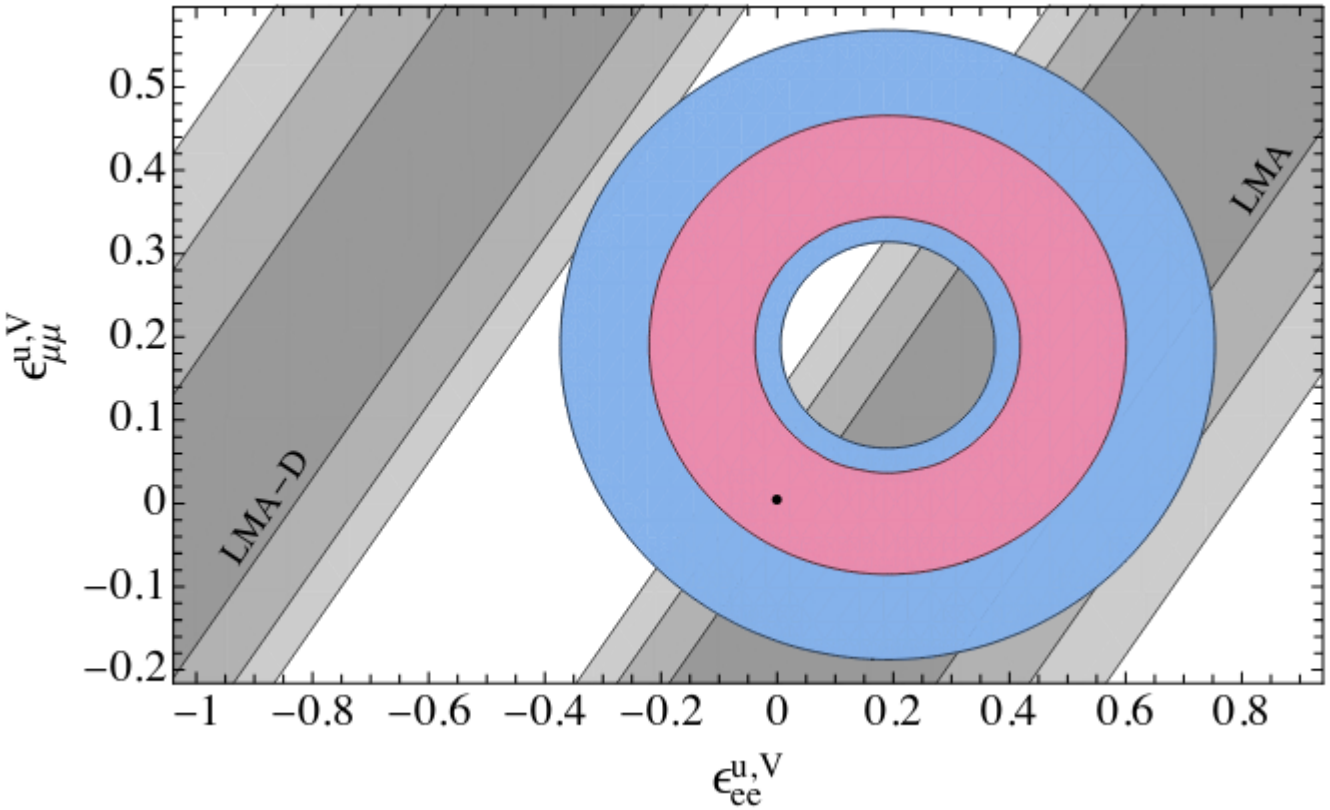

Phys.Rev. D96 (2017) no.11, 115007, Coloma, P. et al

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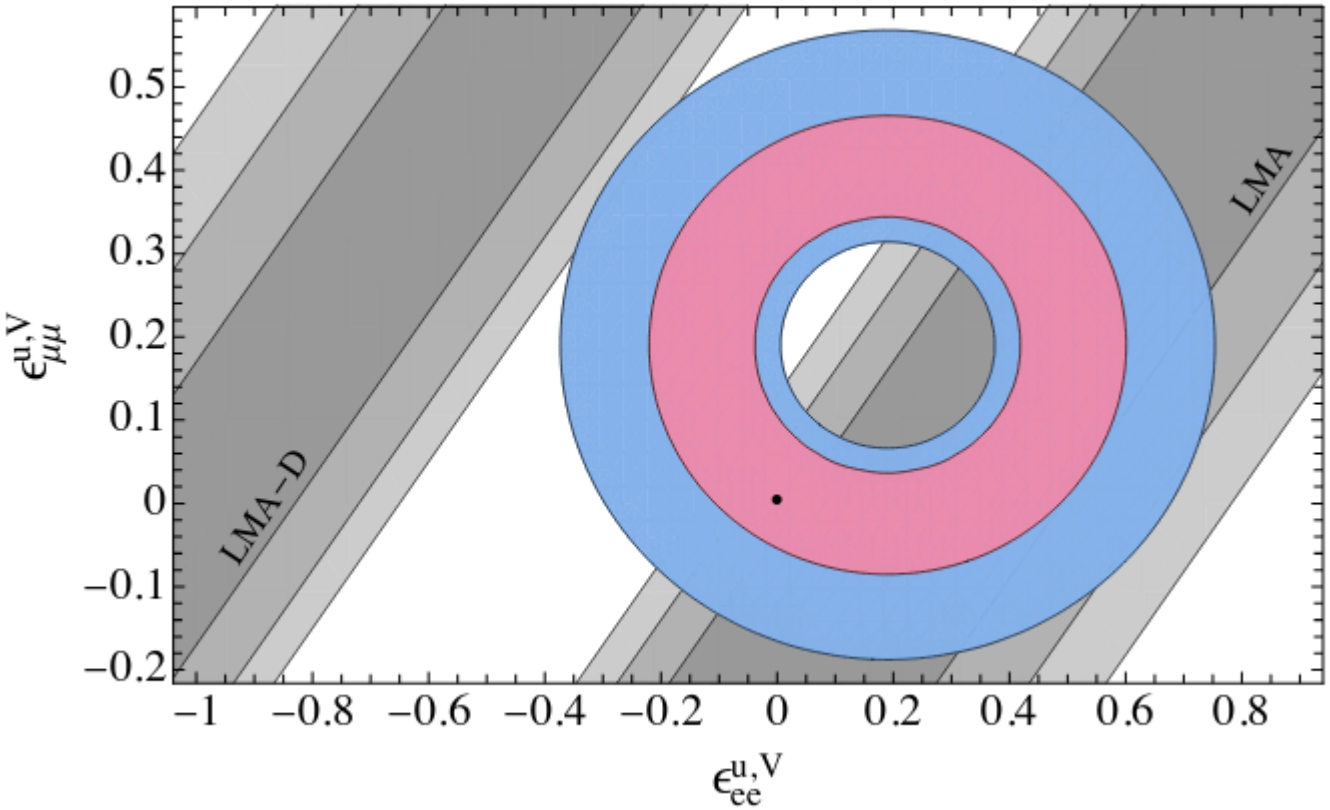
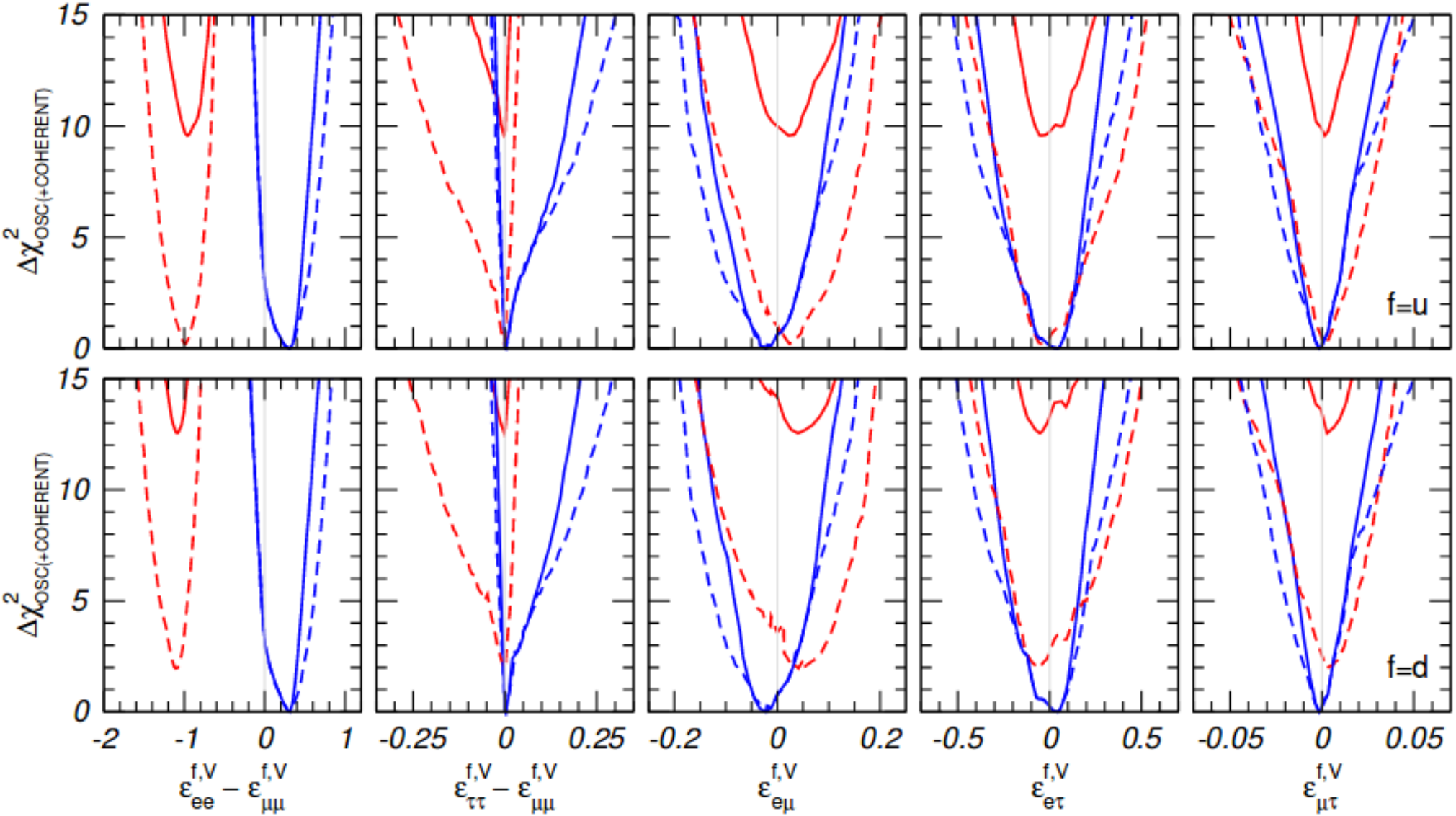


- These results do not apply for mediators of mass < 10 MeV

Phys.Rev. D96 (2017) no.11, 115007, Coloma, P. et al

LMA-D

- Combining OSC with COHERENT yields



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NSI-parameters from global fit

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JHEP 1808 (2018) 180, Esteban, I. et al

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JHEP 1808 (2018) 180, Esteban, I. et al

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- However, one can allow for NSI with up AND down quarks at the same time
- Marginalizing also over the relative strength between the two relaxes the disfavoring of LMA-D
- Combine oscillation data from solar experiments, KamLAND, atmospheric experiments, disappearance data from long-baseline experiments, reactors and data from COHERENT

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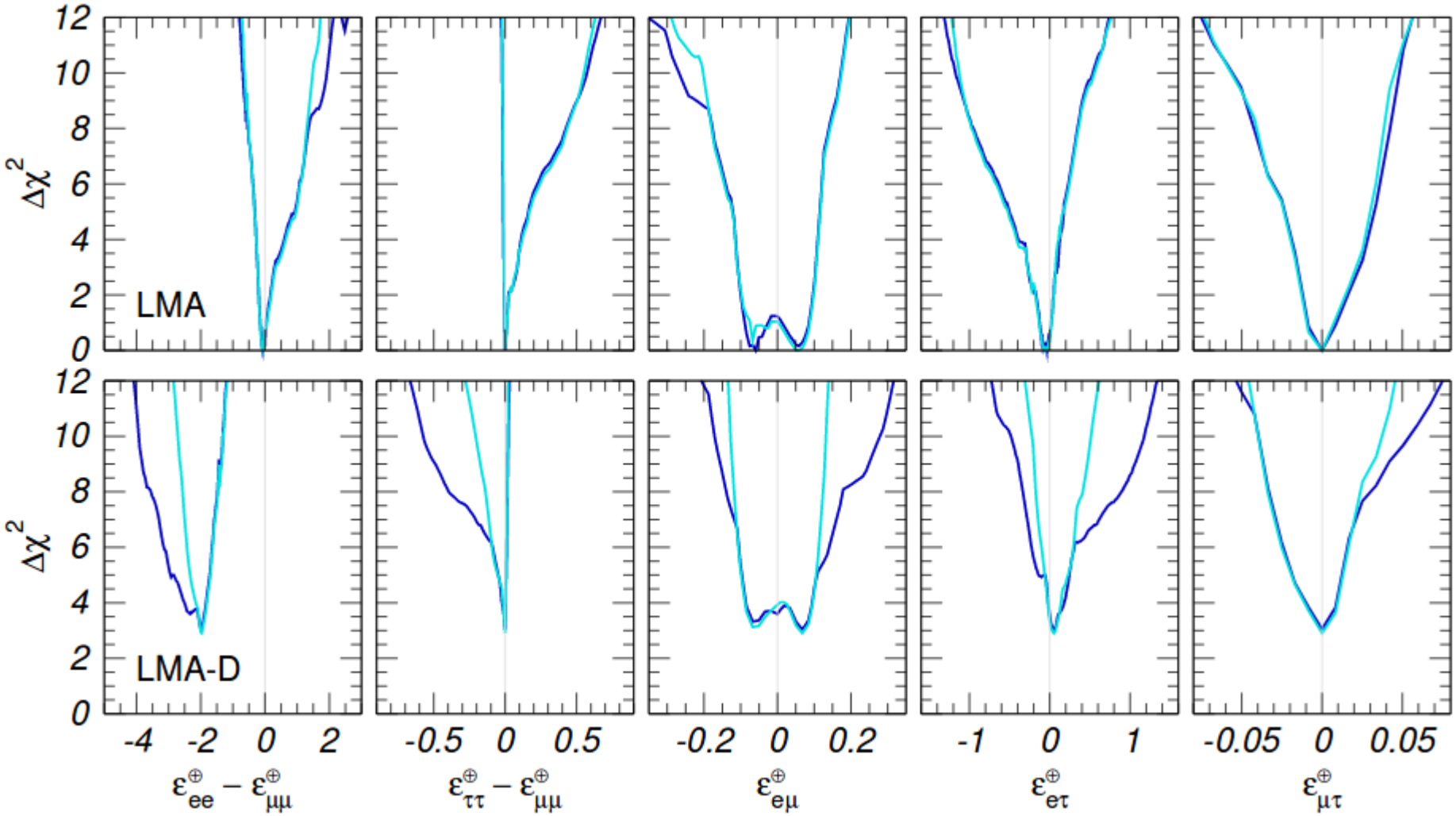
NSI-parameters from global fit

- Blue: OSC, CYAN: OSC+COHERENT



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- What are **LSND** and **MiniBooNE** observing? Systematics or new physics?

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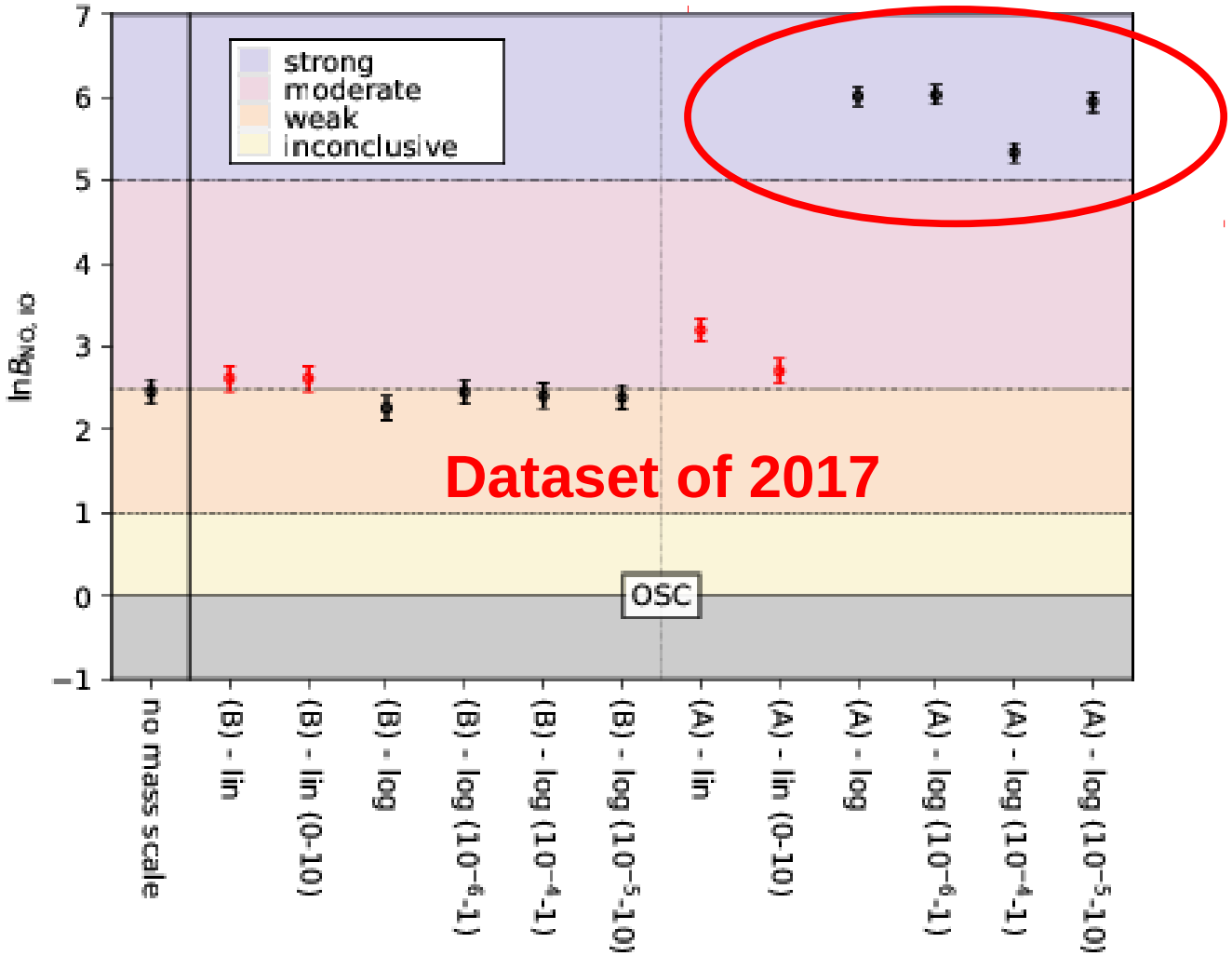
- NSI can affect the oscillation probabilities
- New degeneracies make precision measurements more difficult
- To obtain strong bounds we need to combine with data from oscillation and scattering experiments
- LMA-D revives after allowing for NSI with up AND down quarks
- Bounds from NSI with up AND down quarks are weaker than the ones for NSI with up OR down quarks

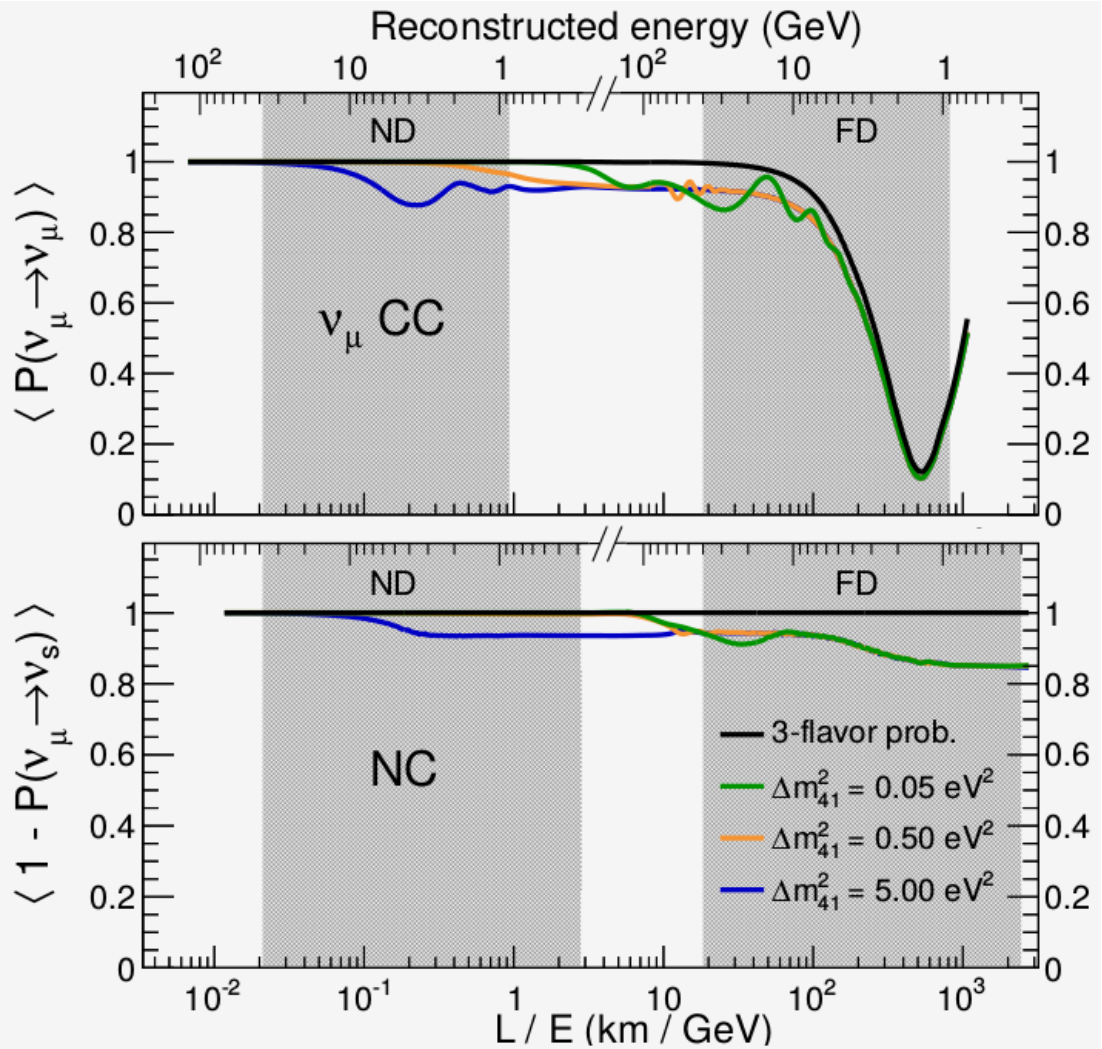
Thank you!
muon
neutrino

Parameterization and data



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

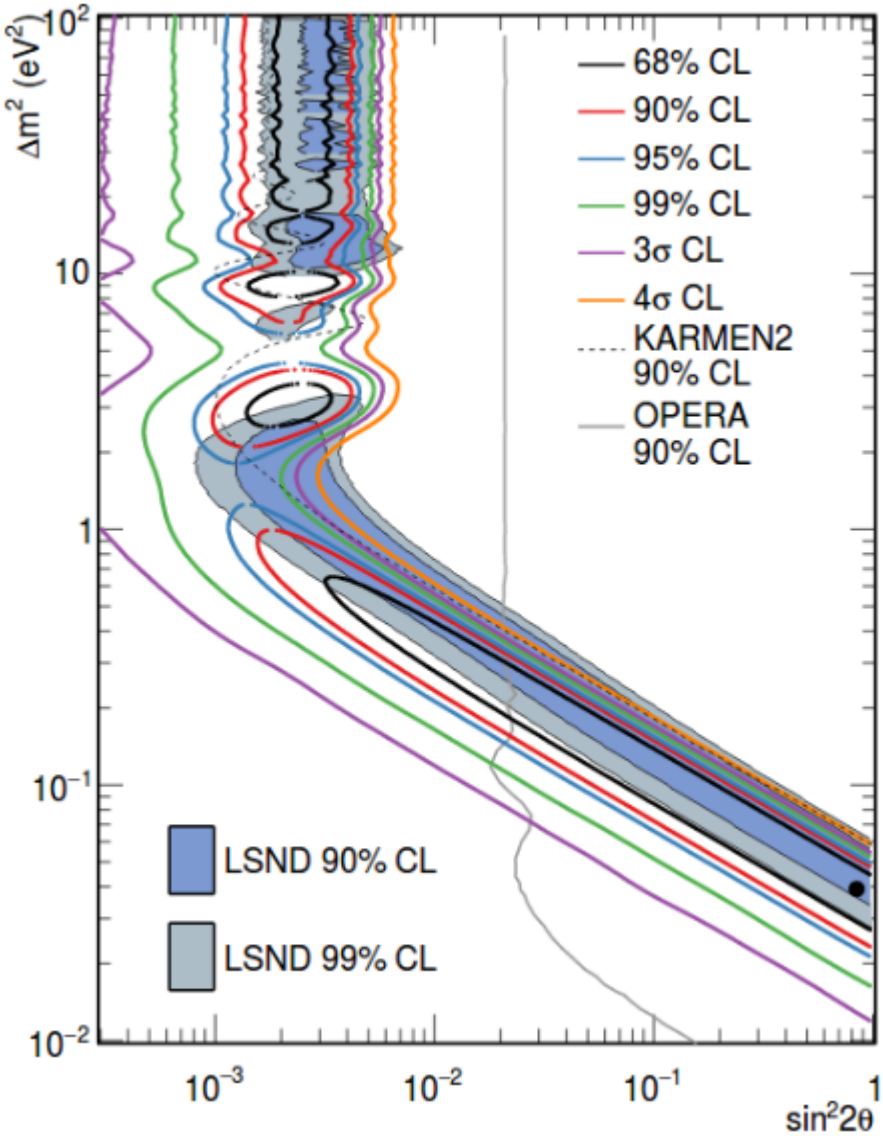
MINOS, oscillations at near detector



Arxiv:1710.06488
Ancillary PDF

$$\sin^2\theta_{14} = 0.02, \sin^2\theta_{24} = 0.04, \sin^2\theta_{34} = 0.2$$

MiniBooNE, neutrino only



PRL 121 (2018) 221801

Best fit values and confidence intervals

CL	$\lvert U_{e4}\rvert^2$	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
68.27% (1σ)	$0.016 - 0.024$	$0.011 - 0.018$	$\lesssim 0.0032$
95.45% (2σ)	$0.013 - 0.028$	$0.0083 - 0.022$	$\lesssim 0.018$
99.73% (3σ)	$0.0098 - 0.031$	$0.0060 - 0.026$	$\lesssim 0.039$

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

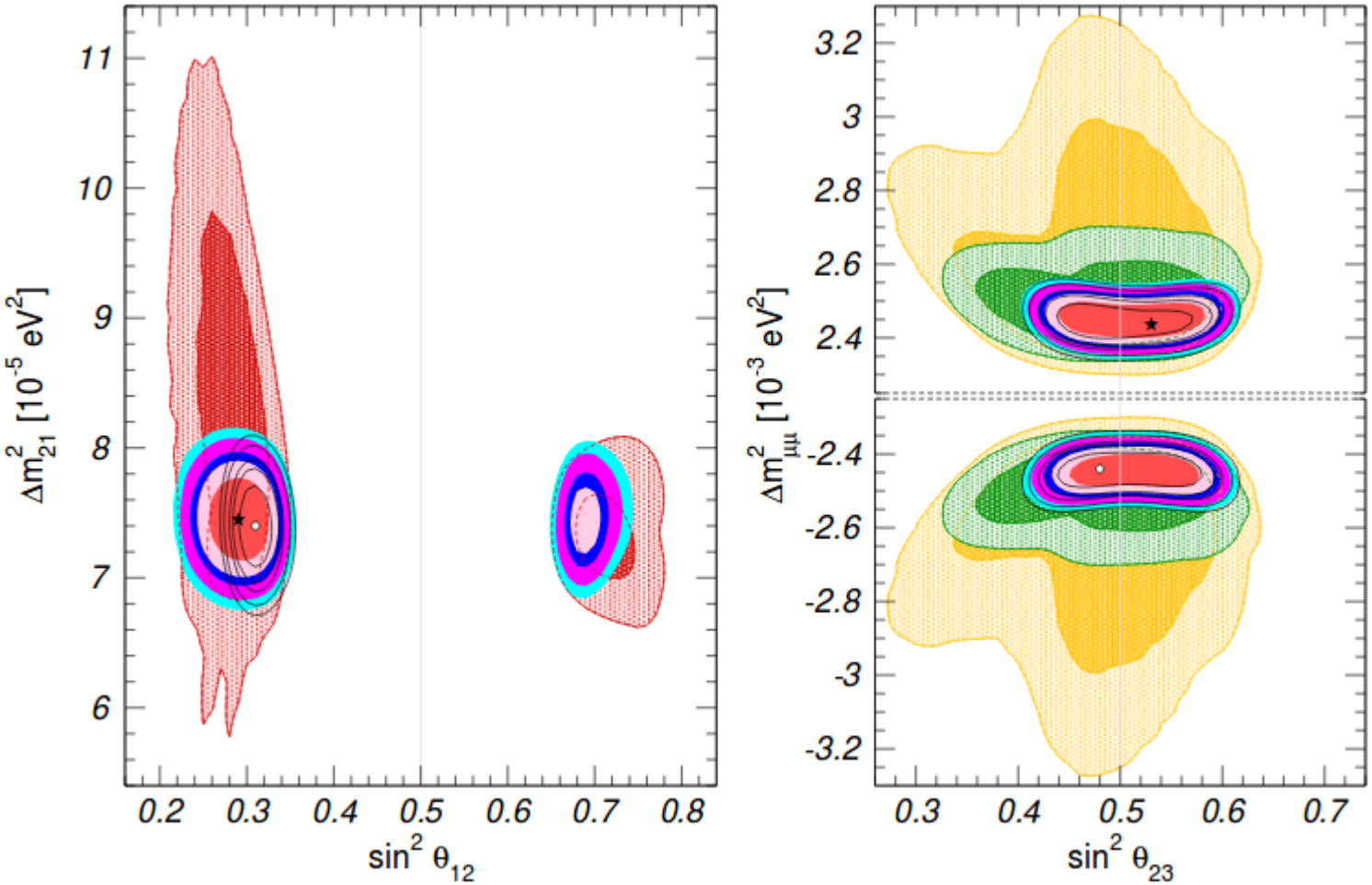
More than one sterile neutrino:

3+2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	ϕ_{54}
All	0.475	0.861	0.120	0.177	0.141	0.111	0.0662π

More information at:

Nucl.Phys. B908 (2016) 354-365, Collin, G.H. , et al

NSI-2dim regions



JHEP 1808 (2018) 180, Esteban, I. et al

Current bounds on CC-NSI

	90% C.L. range	origin	Ref.
		semileptonic NSI	
ϵ_{ee}^{udP}	$[-0.015, 0.015]$	Daya Bay	[13]
$\epsilon_{e\mu}^{udL}$	$[-0.026, 0.026]$	NOMAD	[33]
$\epsilon_{e\mu}^{udR}$	$[-0.037, 0.037]$	NOMAD	[33]
$\epsilon_{\tau e}^{udL}$	$[-0.087, 0.087]$	NOMAD	[33]
$\epsilon_{\tau e}^{udR}$	$[-0.12, 0.12]$	NOMAD	[33]
$\epsilon_{\tau\mu}^{udL}$	$[-0.013, 0.013]$	NOMAD	[33]
$\epsilon_{\tau\mu}^{udR}$	$[-0.018, 0.018]$	NOMAD	[33]
		purely leptonic NSI	
$\epsilon_{\alpha e}^{\mu eL}$, $\epsilon_{\alpha e}^{\mu eR}$	$[-0.025, 0.025]$	KARMEN	[33]
$\epsilon_{\alpha\beta}^{\mu eL}$, $\epsilon_{\alpha\beta}^{\mu eR}$	$[-0.030, 0.030]$	kinematic G_F	[33]

Front.in Phys. 6 (2018) 10, Farzan, Y. et al