COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Global Neutrino Oscillation Fits {with focus on short baselines}

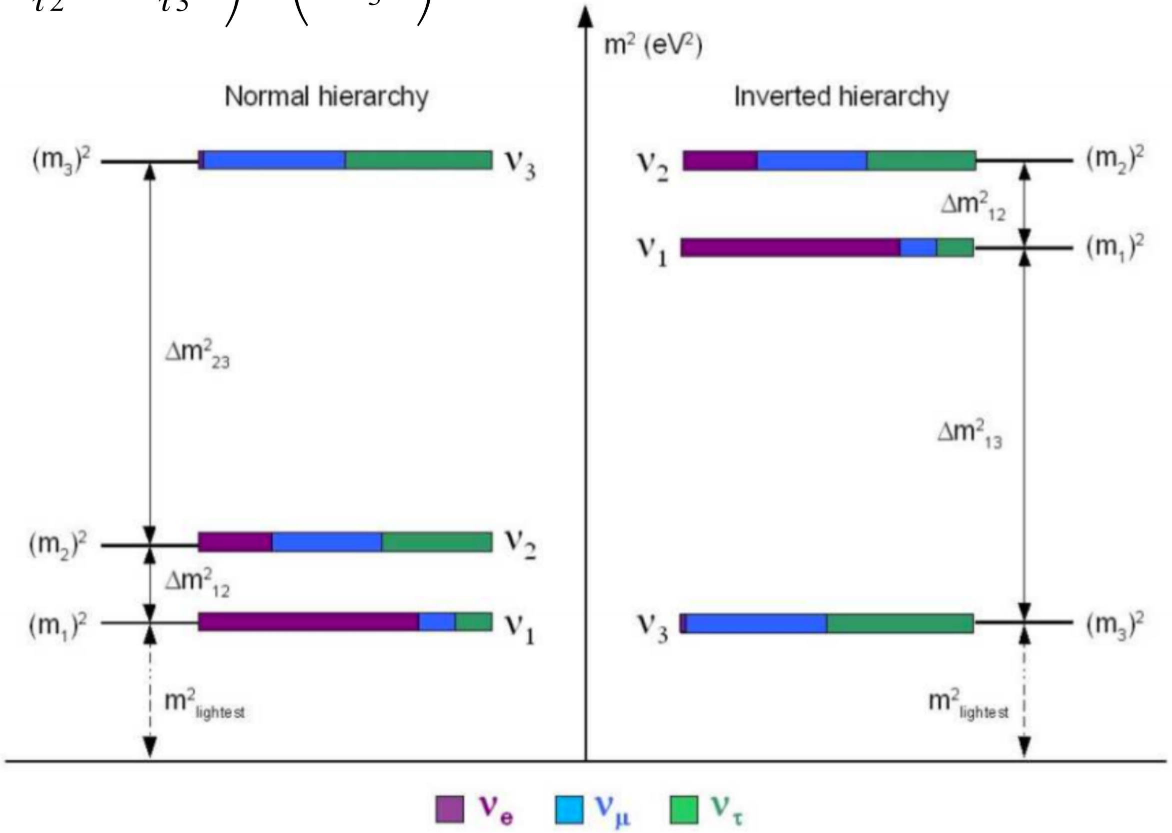
Georgia Karagiorgi, Columbia University

NuFact'2018 at Virginia Tech, Blacksburg, VA
August 17, 2018

Fit numero-phenomeno-logy

- **3-neutrino**, 3+1, 3+2, 3+3, 3+N

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

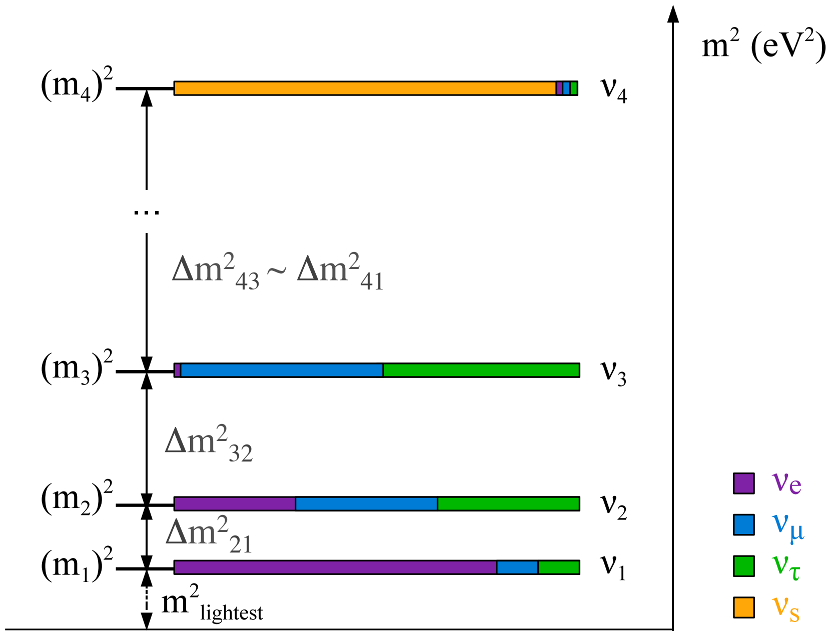
[3σ range]	Parameter	best-fit	3σ
~7%	Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
~5%	$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
~18%	$\sin^2\theta_{12}$	0.297	0.250 – 0.354
28%	$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
21%	$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
12%	$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
12%	$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
33%	δ/π	1.38 (1.31)	2σ: (1.0 - 1.9)
37%			(2σ: (0.92-1.88))

[PDG 2018]

Fit numero-phenomeno-logy

- 3-neutrino, **3+1**, 3+2, 3+3, 3+N

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

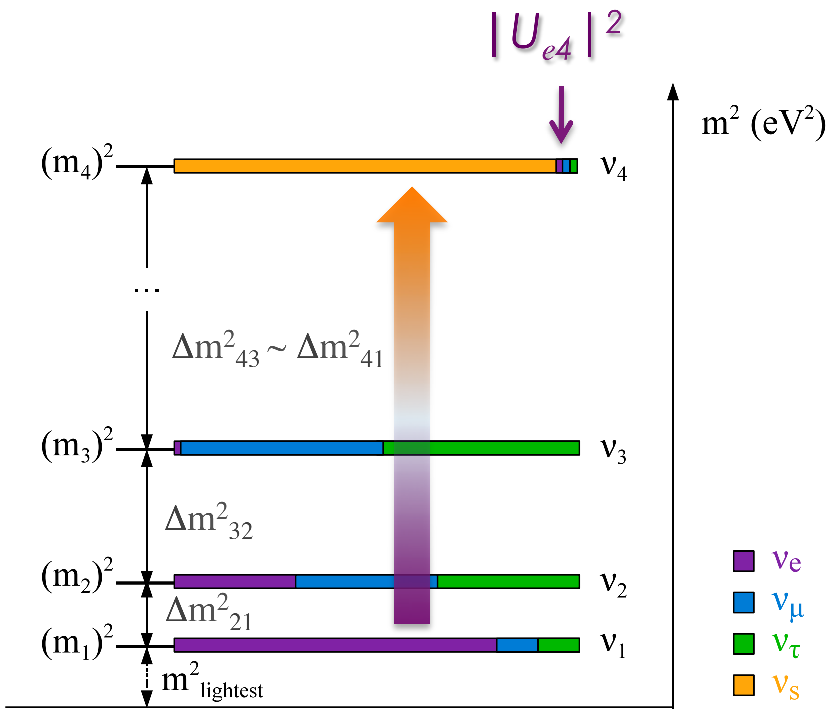


(Normal or inverted.)
To first order assumed degenerate,
with $m_1 \sim m_2 \sim m_3 \sim 0$ eV.

Effectively a two-neutrino oscillation approximation:
1 mass splitting, 3 mixing matrix parameters, no CP phases.

Fit numero-phenomeno-logy

- 3-neutrino, **3+1**, 3+2, 3+3, 3+N



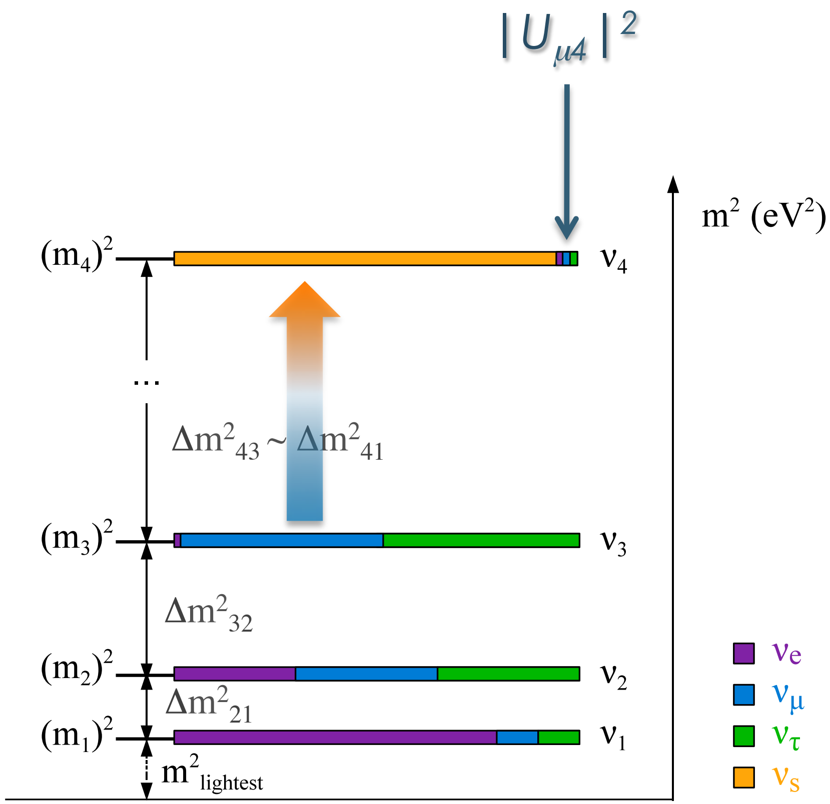
ν_e disappearance:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L / E)$$

$$\hookrightarrow 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right)$$

Fit numero-phenomeno-logy

- 3-neutrino, **3+1**, 3+2, 3+3, 3+N



ν_e disappearance:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27 \Delta m^2 L / E)$$

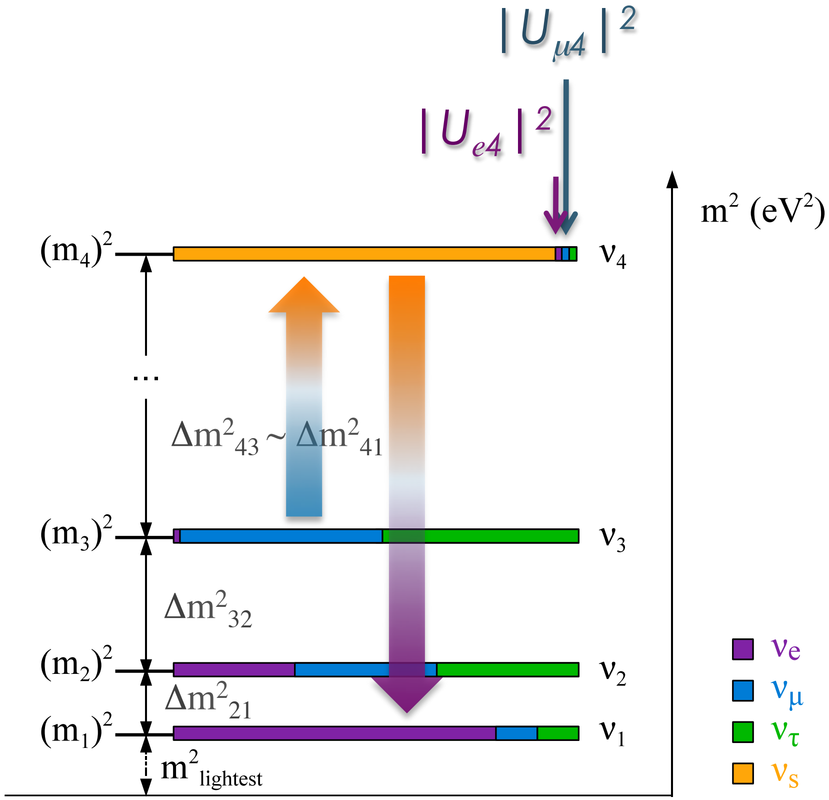
ν_μ disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27 \Delta m^2 L / E)$$

$$\hookrightarrow 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right)$$

Fit numero-phenomeno-logy

- 3-neutrino, **3+1**, 3+2, 3+3, 3+N



ν_e disappearance:

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

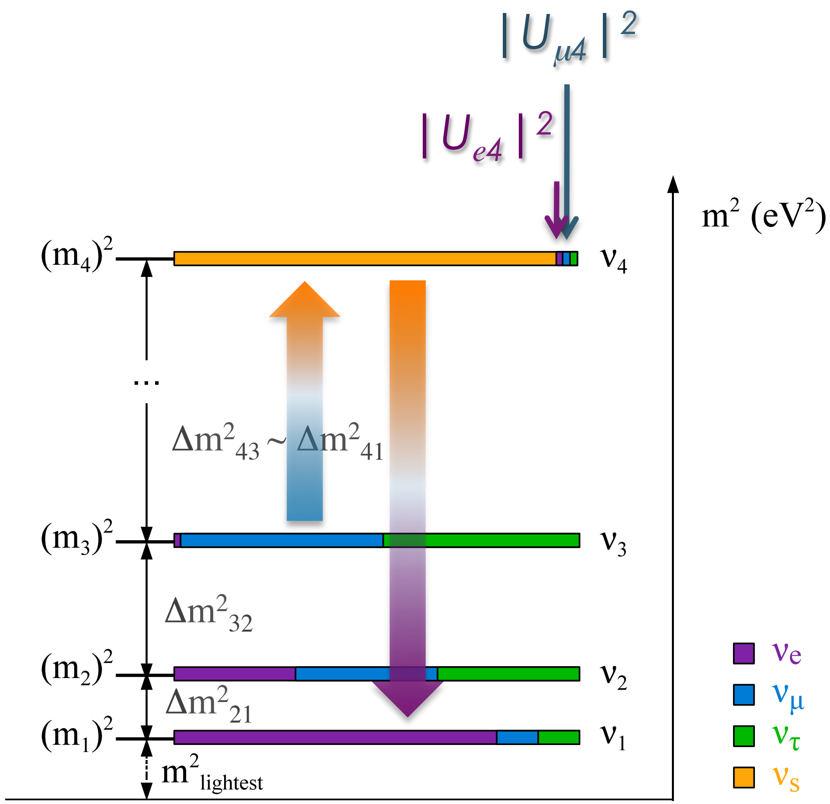
$\nu_\mu \to \nu_e$ appearance:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

$$\sin^2 2\vartheta_{\mu e} \to 4|U_{e4}|^2|U_{\mu 4}|^2$$

Fit numero-phenomeno-logy

- 3-neutrino, **3+1**, 3+2, 3+3, 3+N



ν_e disappearance:

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

$\nu_\mu \to \nu_e$ appearance:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

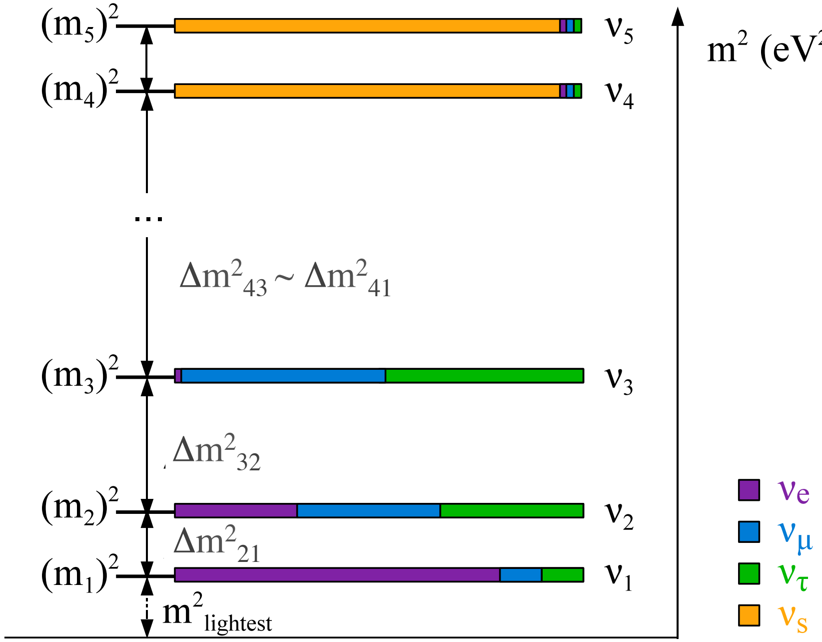
$\hookrightarrow 4|U_{e4}|^2|U_{\mu 4}|^2$

<u>Note</u>: $\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee}$

Fit numero-phenomeno-logy

- 3-neutrino, 3+1, **3+2**, 3+3, 3+N

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \end{pmatrix}$$

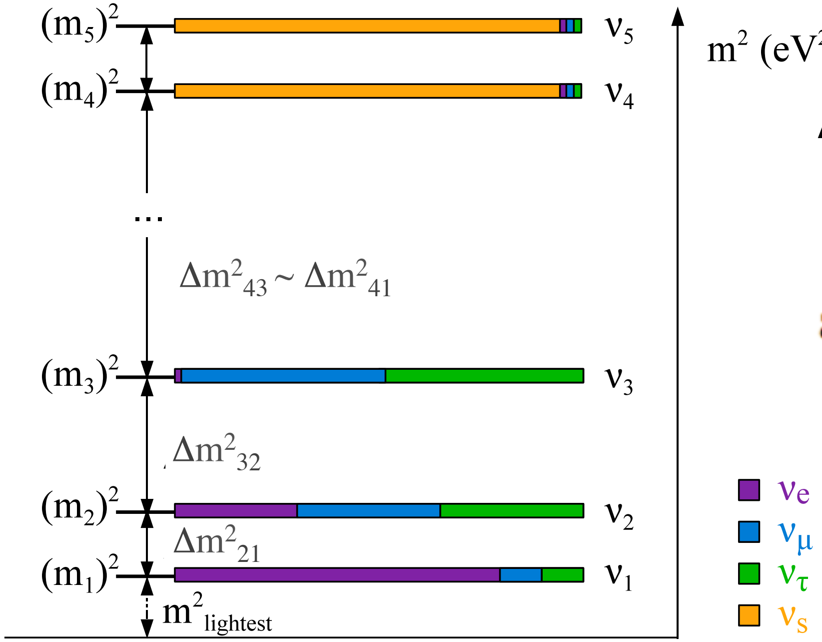


(Normal or inverted.)
To first order assumed degenerate, with $m_1 \sim m_2 \sim m_3 \sim 0$ eV.

Effectively a three-neutrino oscillation approximation:
2 independent mass splittings, 6 mixing matrix parameters, 1 CP violating phase.

Fit numero-phenomeno-logy

- 3-neutrino, 3+1, **3+2**, 3+3, 3+N



Disappearance:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 x_{54}]$$

Appearance:

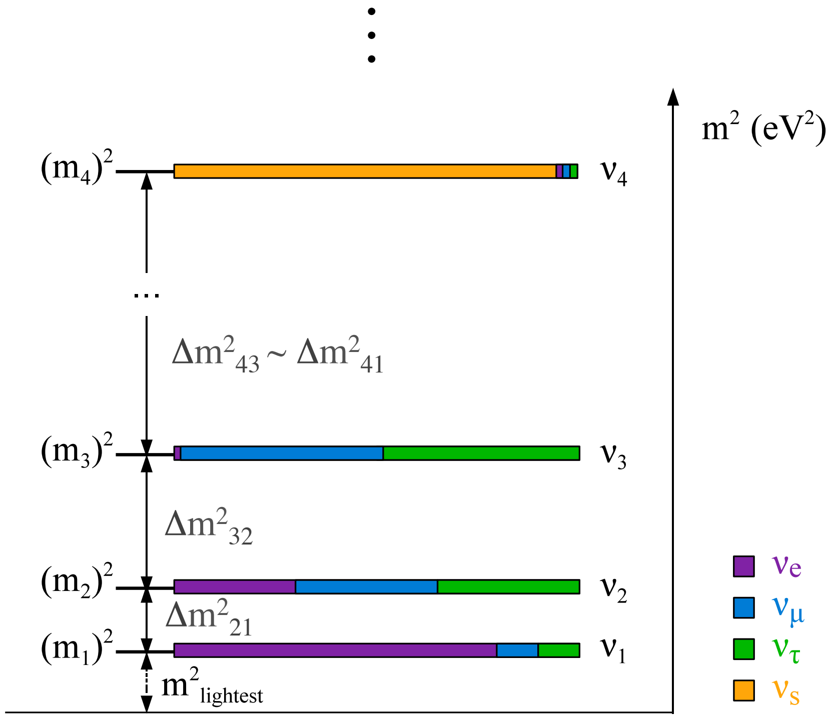
$$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

$$x_{ji} \equiv 1.27 \Delta m^2_{ji} L/E$$

CPV phase

Fit numero-phenomeno-logy

- 3-neutrino, 3+1, 3+2, 3+3, **3+N**



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s1} & U_{s2} & U_{s3} & \cdots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix}$$

(Normal or inverted.)
To first order assumed degenerate,
with $m_1 \sim m_2 \sim m_3 \sim 0$ eV.

Effectively an (N+1)-neutrino oscillation approximation:
N independent mass splittings, 3N mixing matrix parameters, N(N-1)/2 CP-violating phases.

Fit numero-phenomeno-logy

- 3-neutrino, 3+1, 3+2, 3+3, **3+N**

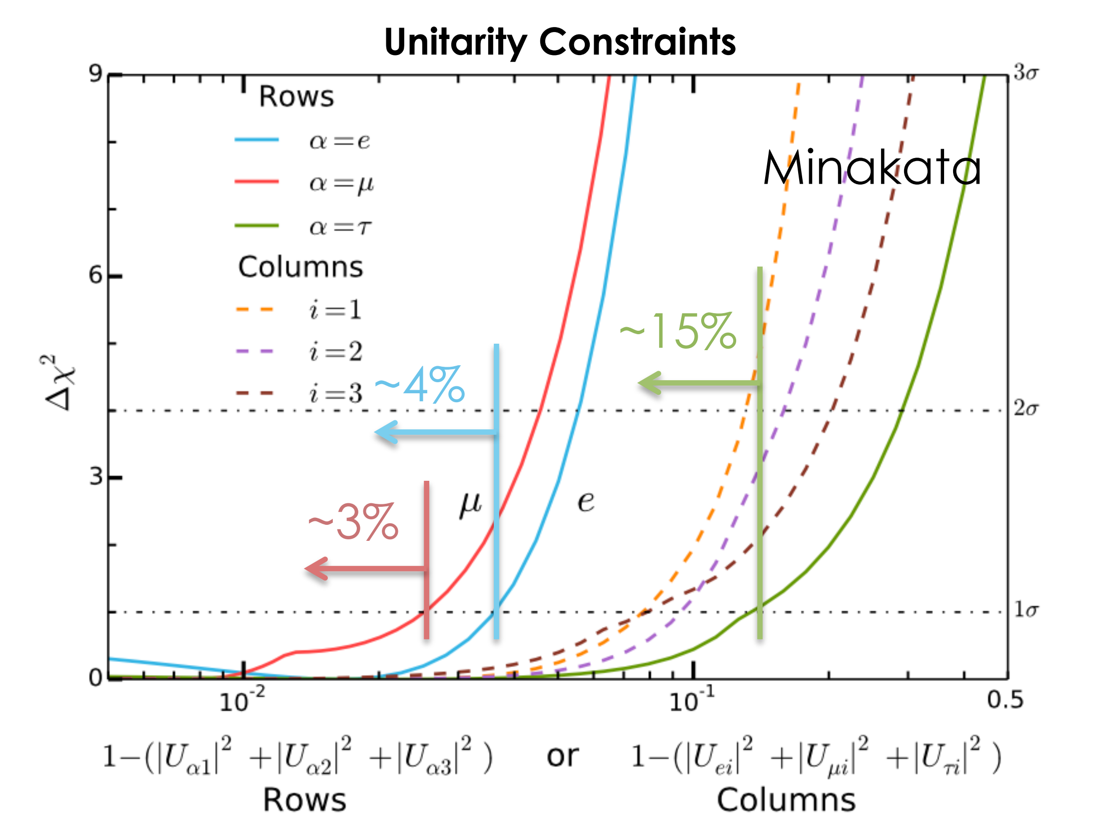
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s1} & U_{s2} & U_{s3} & \cdots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix}$$

Perfectly allowed, as long as:
(1) only 3 weakly interacting neutrinos that are light ($m_i < m_Z/2$).
(2) the sum over all neutrino masses does not become significantly larger than ~1 eV.
(3) the overall (3+N)x(3+N) mixing matrix is unitary.

Fit numero-phenomeno-logy

- 3-neutrino, 3+1, 3+2, 3+3, **3+N**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \dots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \dots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \dots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s1} & U_{s2} & U_{s3} & \dots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix}$$



[S. Parke, M. Ross-Lonergan, hep-ph/1508.05095]

Combined with unitarity constraints on the 3x3 sub-block, this requires that any additional neutrinos are mostly "sterile", and that they mix very little with active neutrinos.

See talk by H. Minakata

3-neutrino global fits

Some examples from literature:

- F. Capozzi et al., Phys. Rev. D95, 096014 (2017).
- M.C. Gonzalez-Garcia, Nucl. Phys. B908 (2016) 199-217.
- I. Esteban et al., JHEP 1701, 087 (2017).
- P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)
- S. Gariazzo, et al., JCAP 1803 (2018) no.03, 011.
- P. F. de Salas, et al., arXiv:1806.11051.

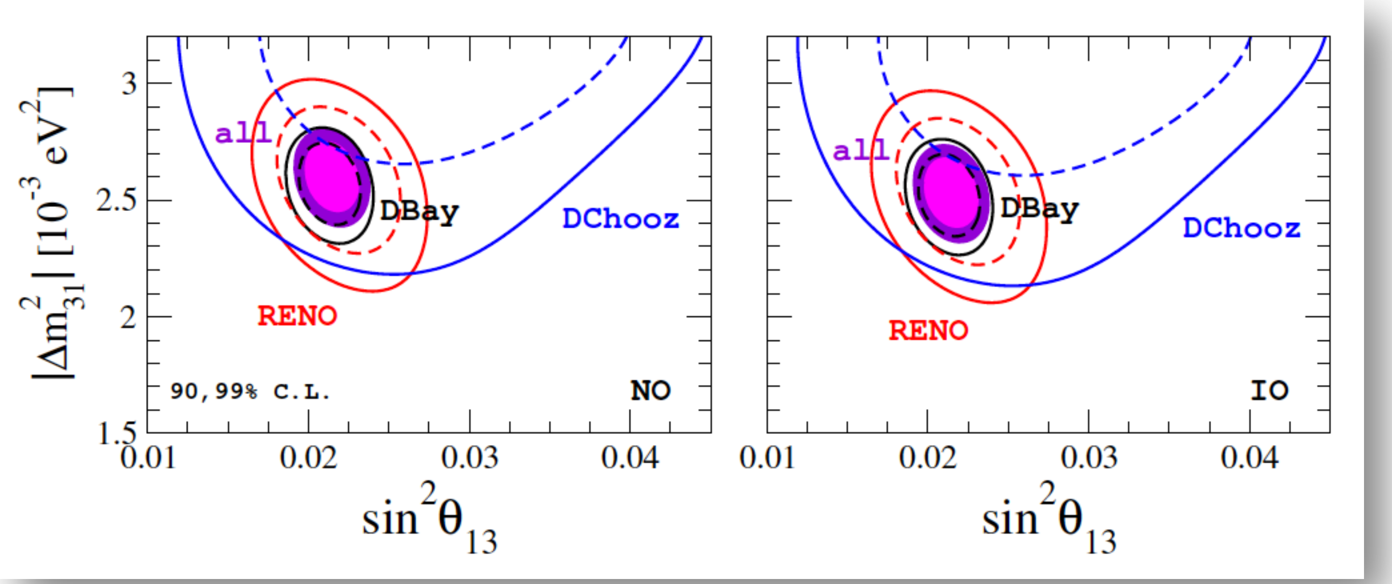
See talk by C. Ternes

3-neutrino global fits

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

Datasets:

- Reactor LBL
  Daya Bay, RENO, Double Chooz



3-neutrino global fits

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

Datasets:

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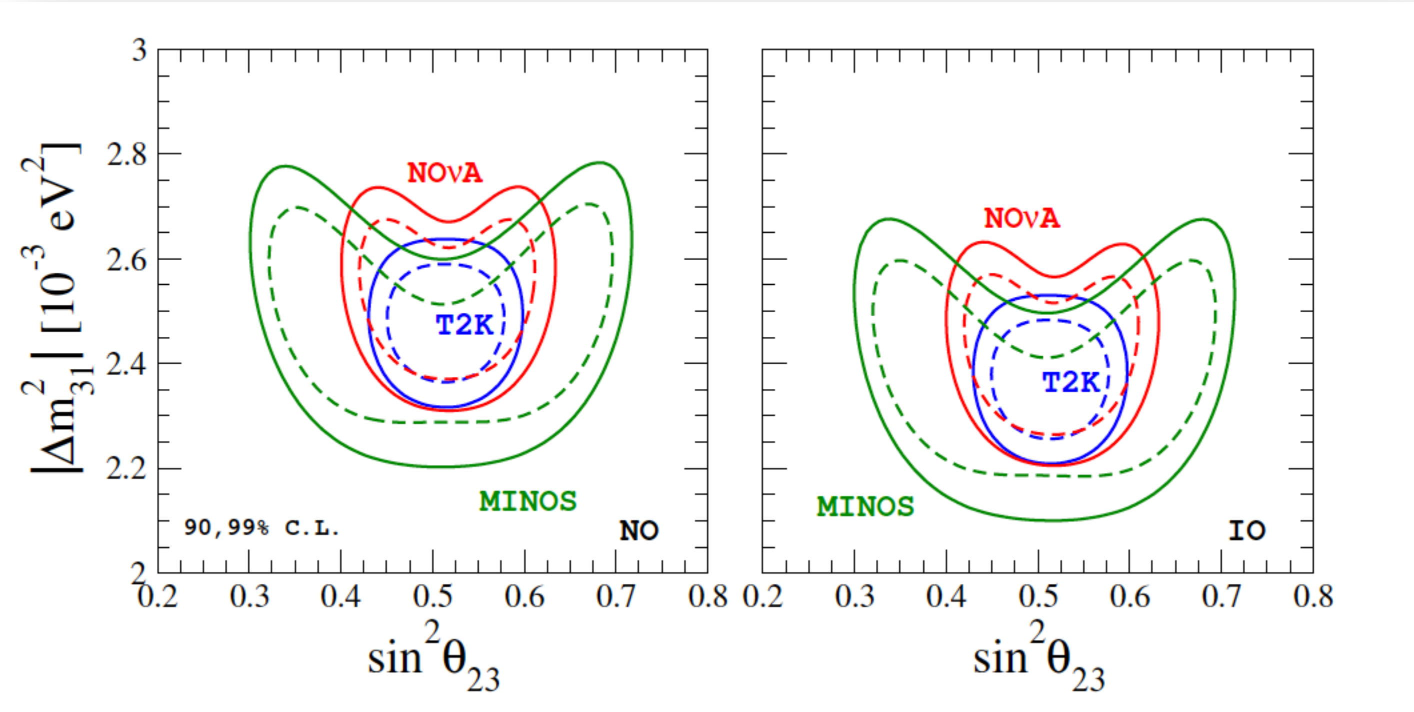
  NOvA, T2K neutrino and antineutrino, MINOS



3-neutrino global fits

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

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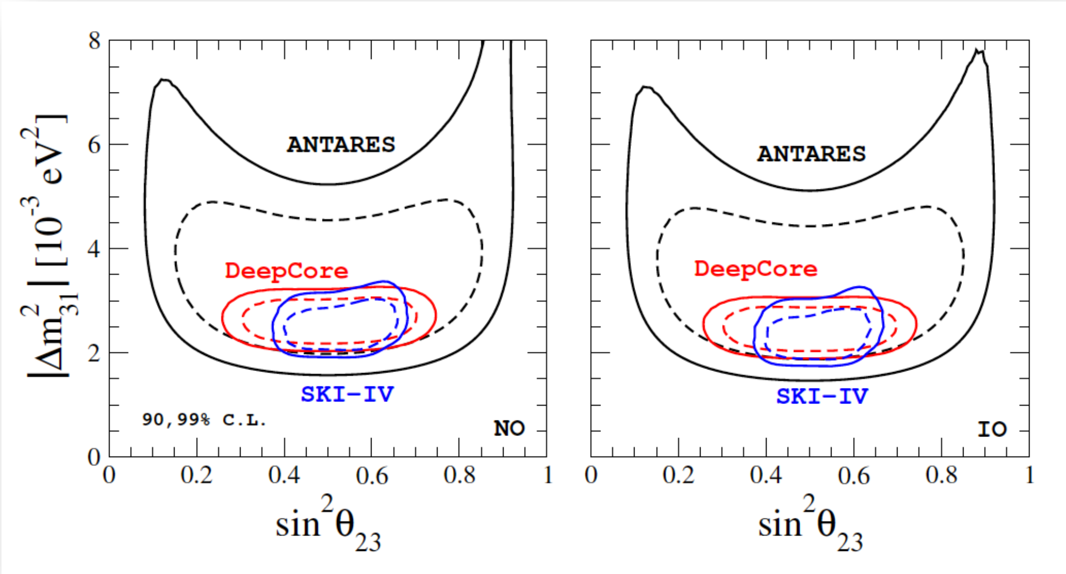
  IceCube/DeepCore, ANTARES, Super-K I-IV



3-neutrino global fits

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

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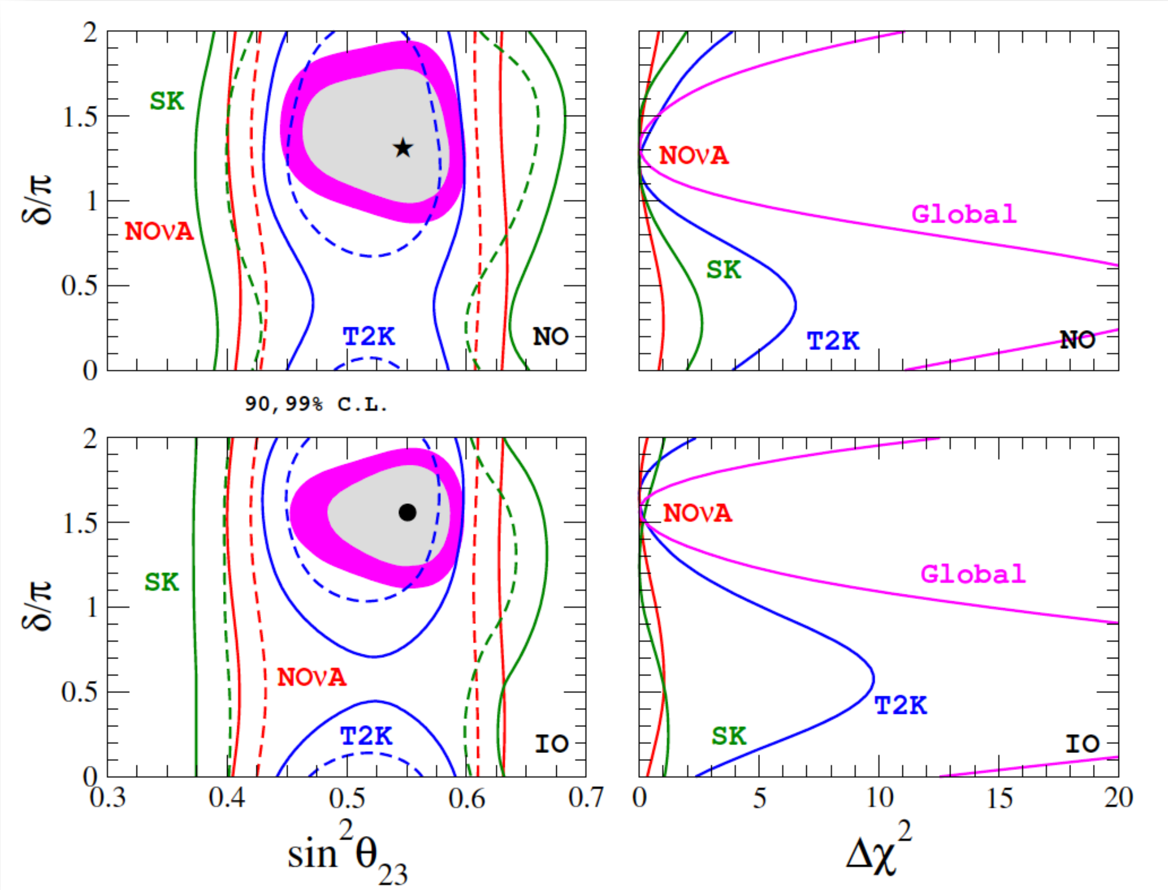
- Accelerator Long-Baseline (LBL)
  NOvA, T2K neutrino and antineutrino, MINOS

- Atmospheric
  IceCube/DeepCore, ANTARES, Super-K I-IV

- Solar
  Super-K D/N

3-neutrino global fits

CPV sensitivity, dominated by T2K



- Improved sensitivity to δ_{cp}
- $(\pi,2\pi)$ range strongly preferred and $\pi/2$ disfavored at $>4\sigma$

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

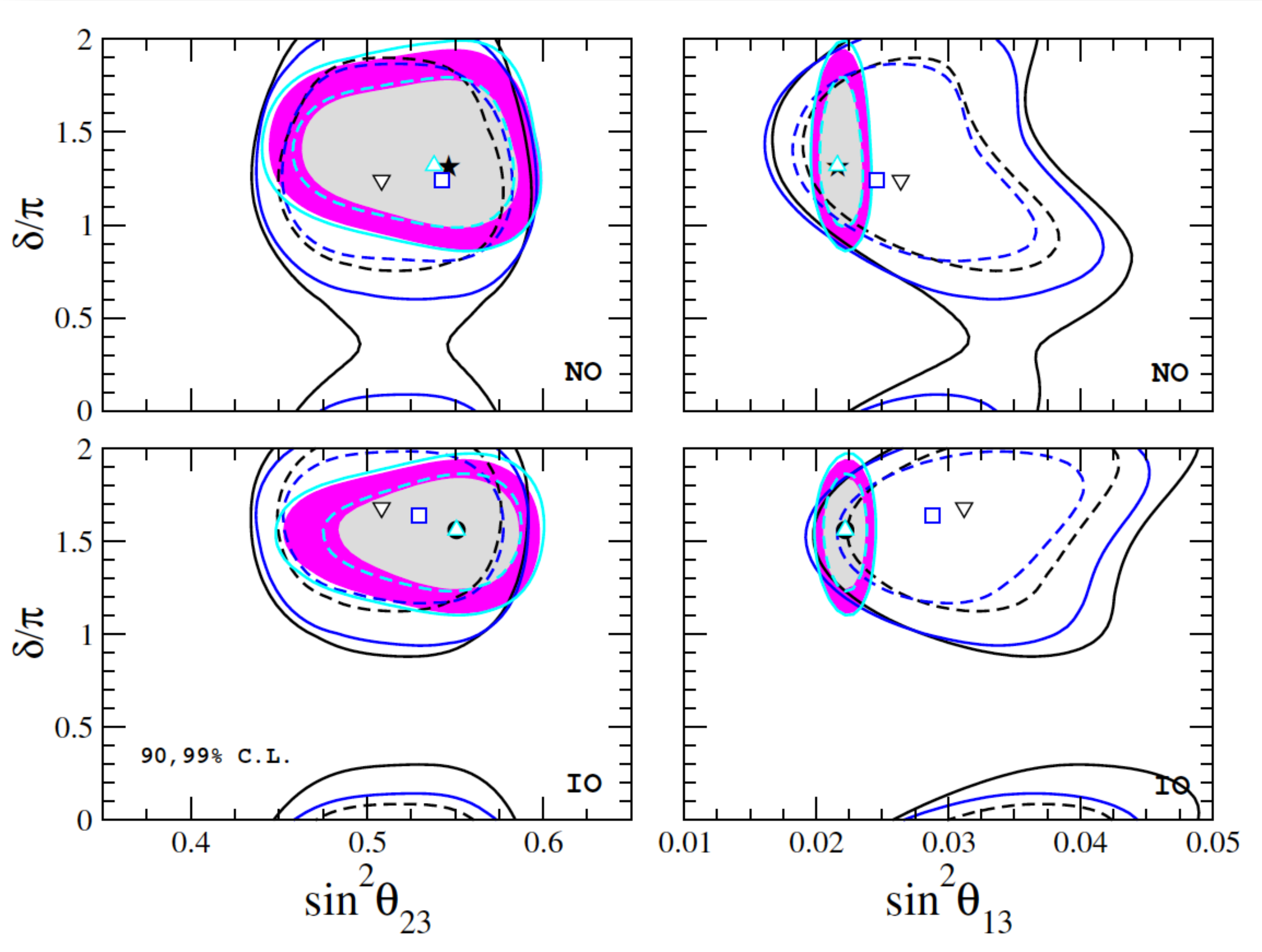
3-neutrino global fits

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

Comparing NO and IO global best fits:

Hint in favor of NO, with IO disfavored with $\Delta\chi^2$ = 11.7 (3.4 σ)

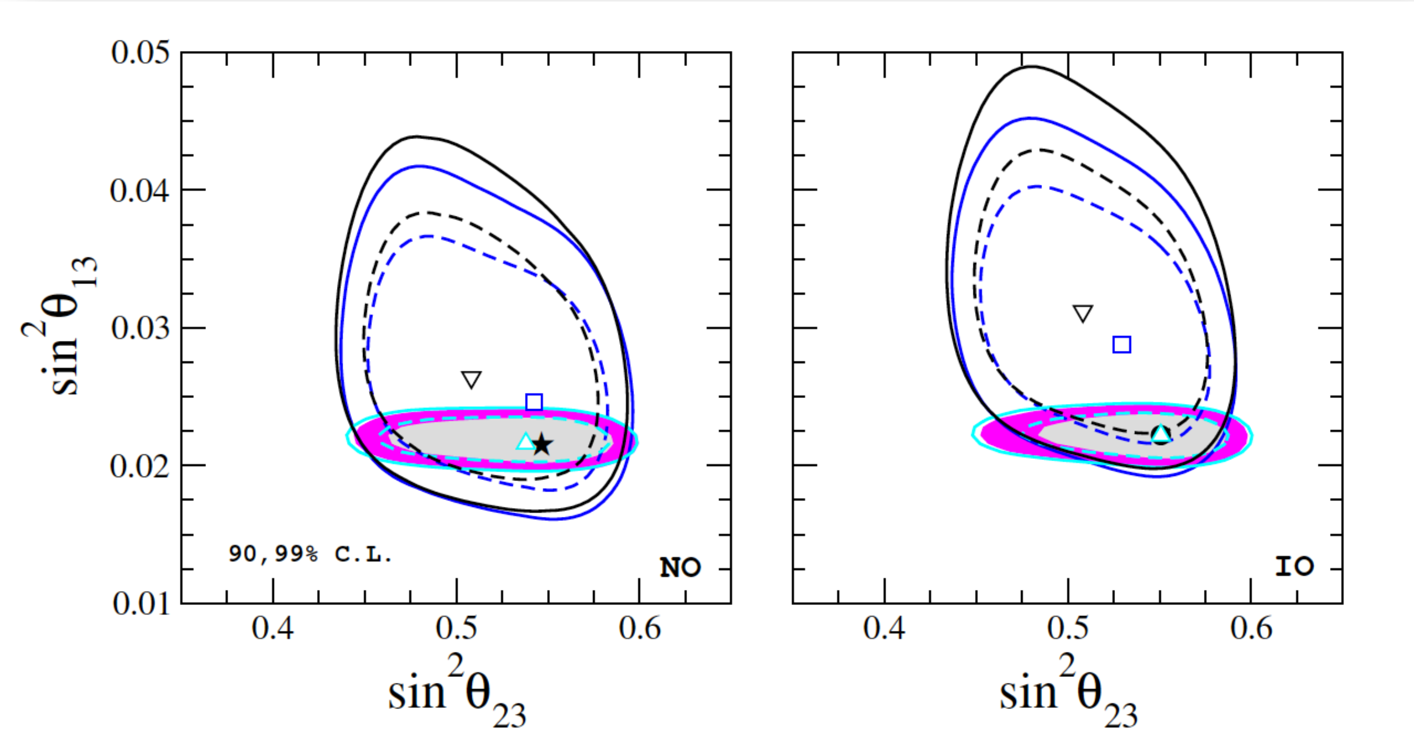
!



3-neutrino global fits

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

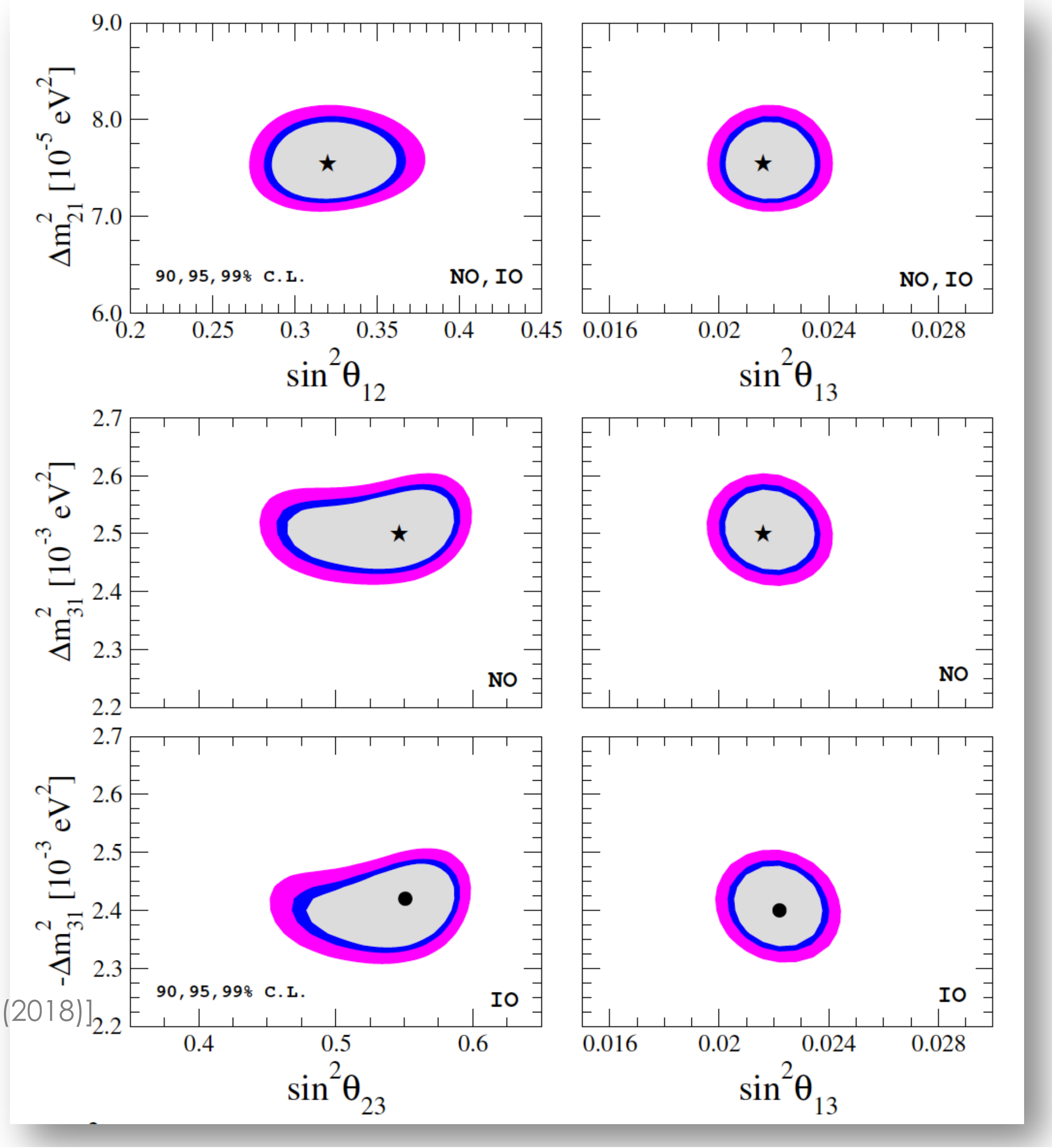
Octant determination: Slight preference for second octant, but not yet clear



3-neutrino global fits

90, 95 and 99% C.L. (2 d.o.f.)

Assuming unitarity,
no NSI, no new physics
beyond PMNS.



Reactor LBL:
Improved precision in θ_{13}

T2K nu+nubar:
$\delta_{cp}=(\pi,2\pi)$ strongly preferred and $\pi/2$ disfavored at >4δ

θ_{13} mismach in LBL experiments and SK I-IV:
Boost mass ordering preference to >3σ

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

3-neutrino global fits

Assuming unitarity,
no NSI, no new physics
beyond PMNS.

[P. F. de Salas et al., Phys. Lett. B 782, 633 (2018)]

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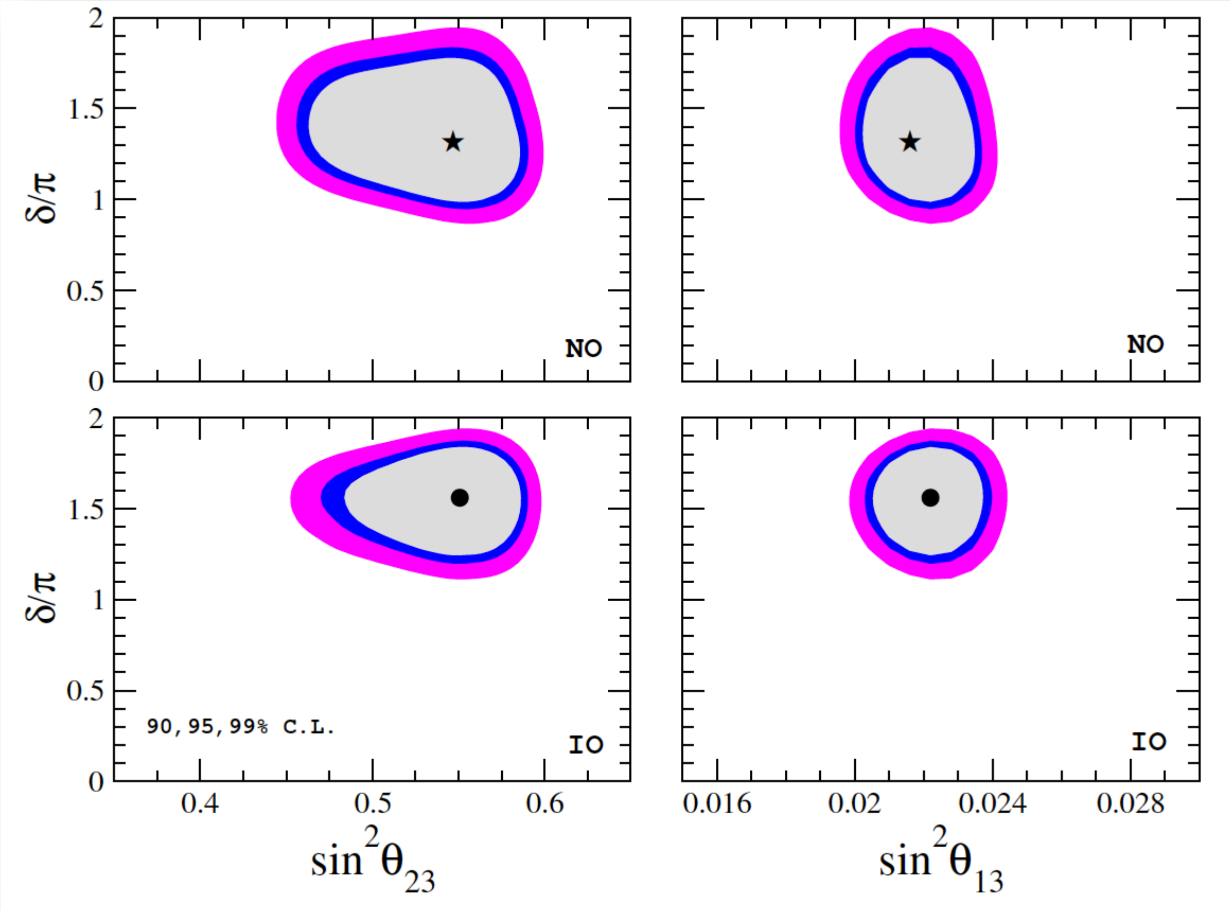
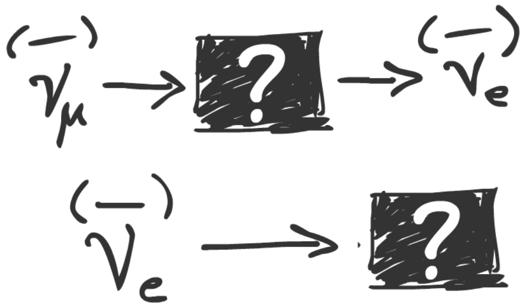


What if N ≠ 0?

- **Multiple anomalous signatures at L/E ~ 0.1 – 10 m/MeV**

See talk by
Z. Pavlovic

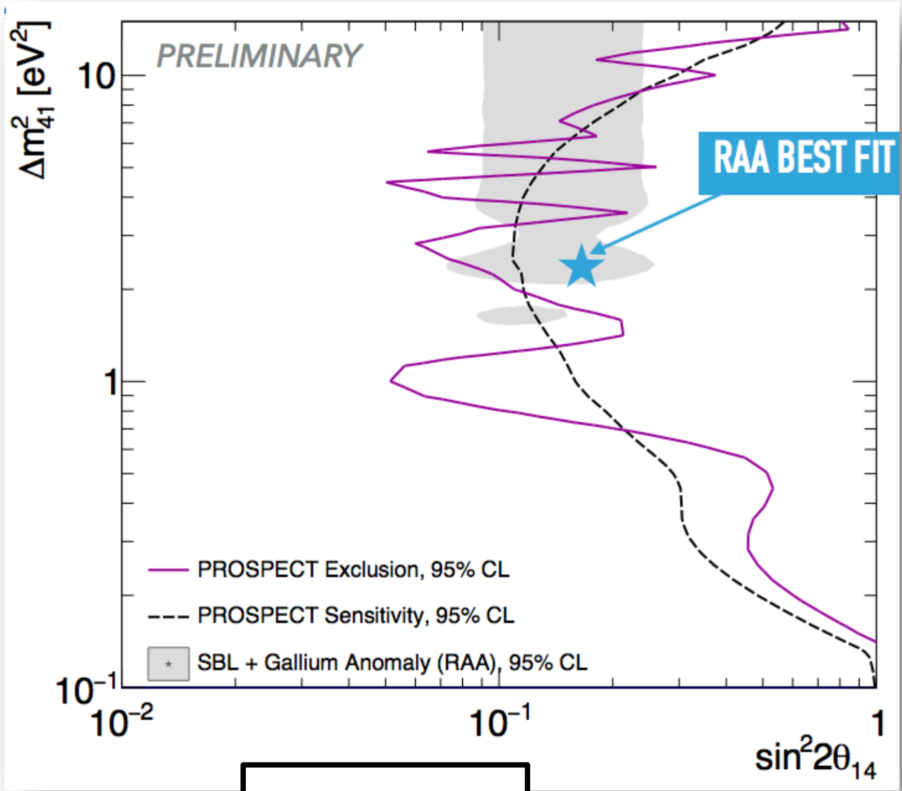
  - LSND (antineutrino)
  - MiniBooNE (neutrino and antineutrino)
  - Reactor Antineutrino Anomaly (Chooz, Bugey, ...)
  - Gallium (GALLEX and SAGE)



- Serve as **motivation for "light sterile neutrino oscillations"** (or beyond-PMNS physics)

New results from SBL reactor experiments pouring in as of recently...

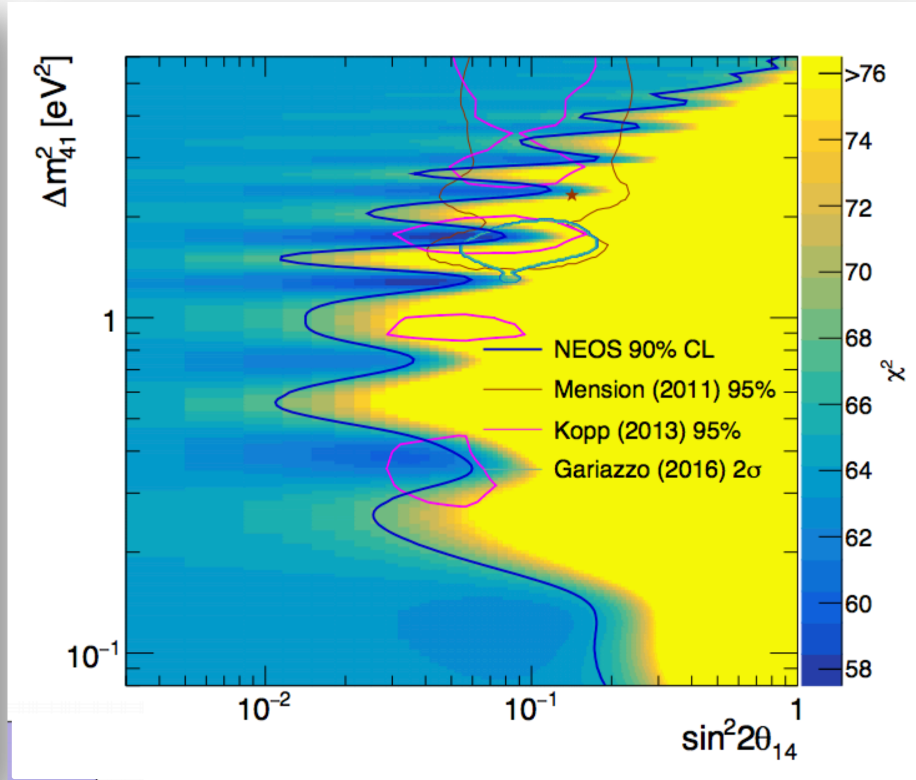
PROSPECT at High Flux Isotope Reactor:



See talk by N. Bowden

[Neutrino 2018]

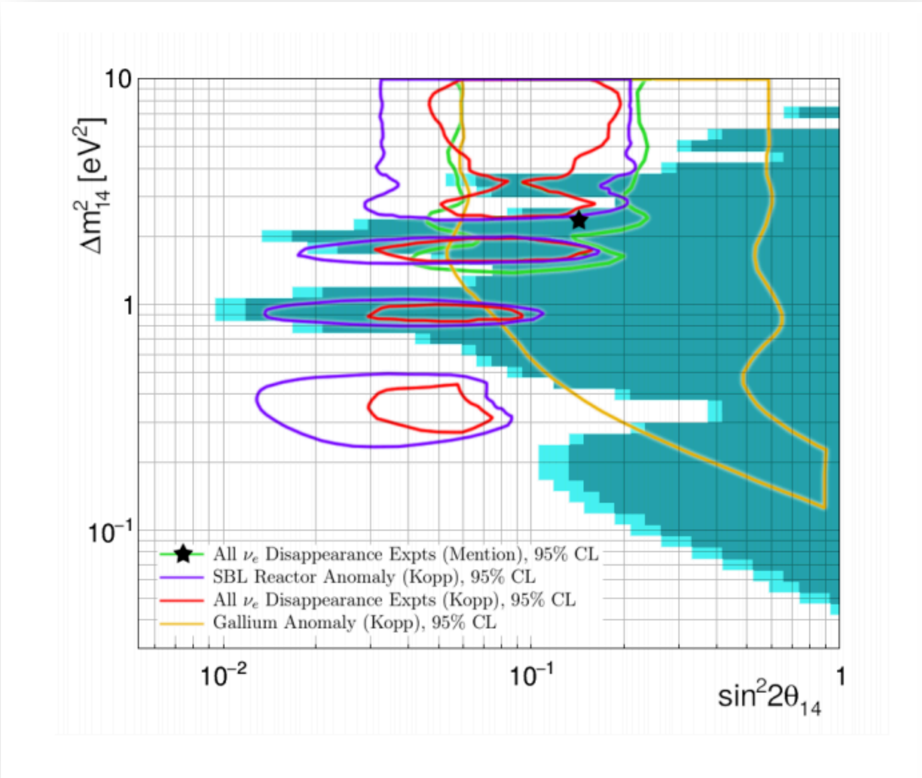
NEOS at Hanbit-5 Nuclear Reactor in Korea:



[Neutrino 2018]

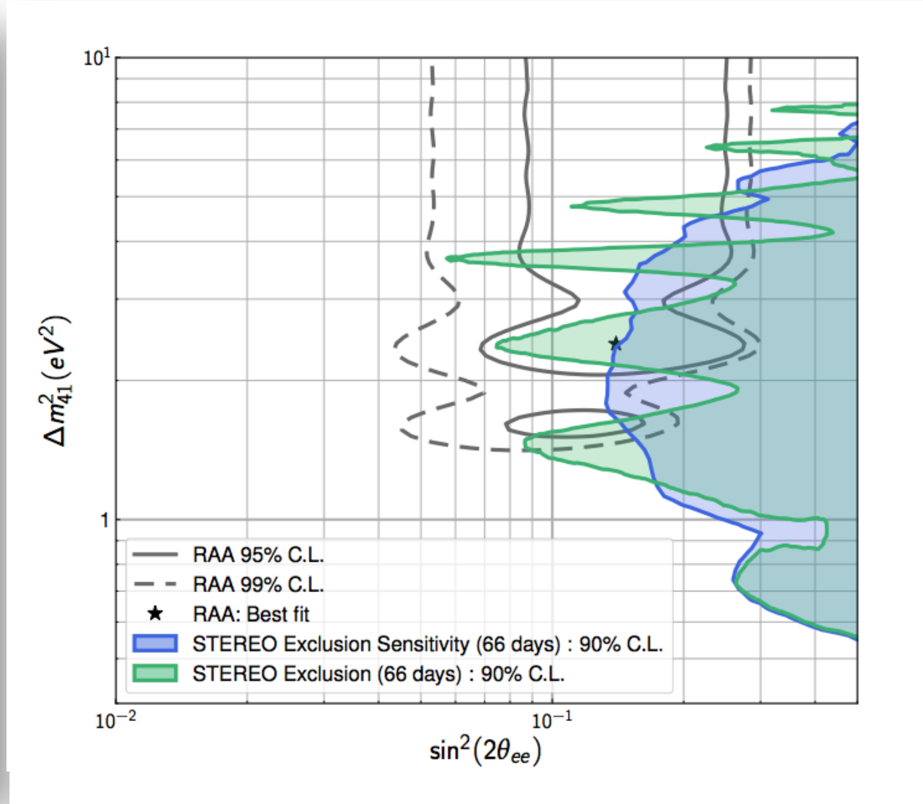
New results from SBL reactor experiments pouring in as of recently…

DANSS at Kalinin Nuclear Power Plant:



[https://arxiv.org/pdf/1804.04046.pdf]

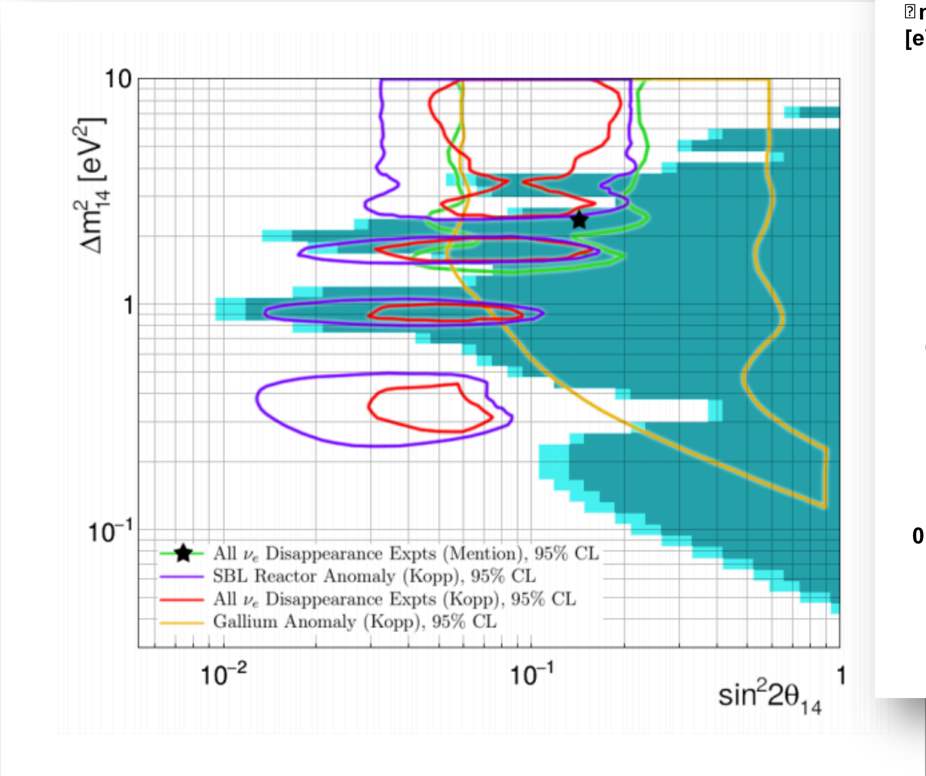
STEREO at ILL:



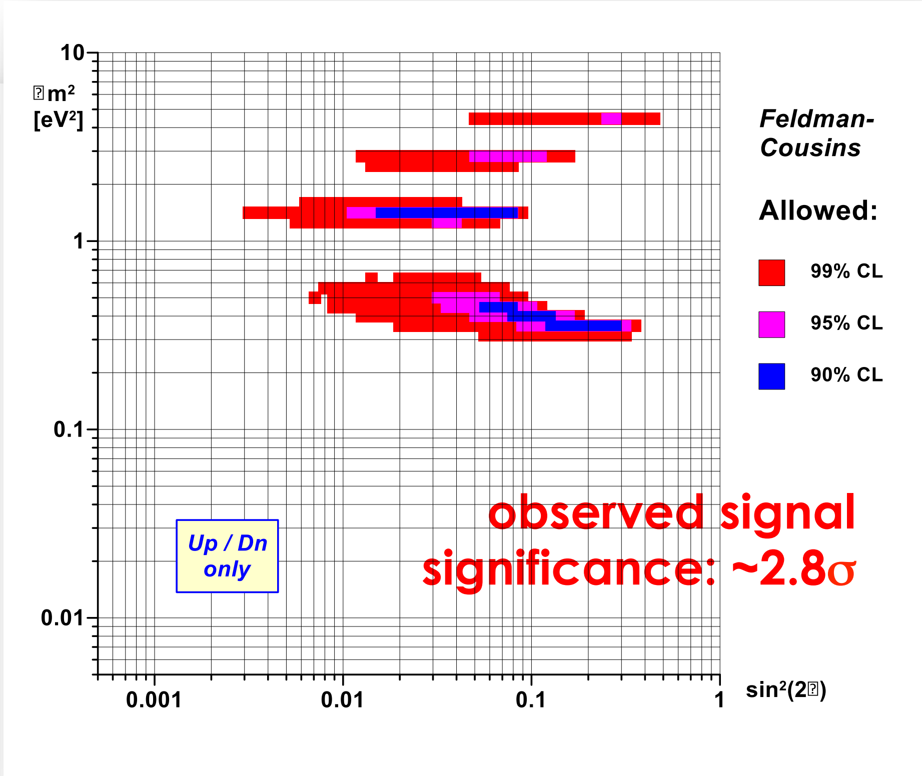
[https://arxiv.org/pdf/1806.02096.pdf]

New results from SBL reactor experiments pouring in as of recently…

DANSS at Kalinin Nuclear Power Plant:



[https://arxiv.org/pdf/1804.04046.pdf]



[Neutrino 2018]

3+1 global fits

Example past works (but not incorporating new results from MiniBooNE):

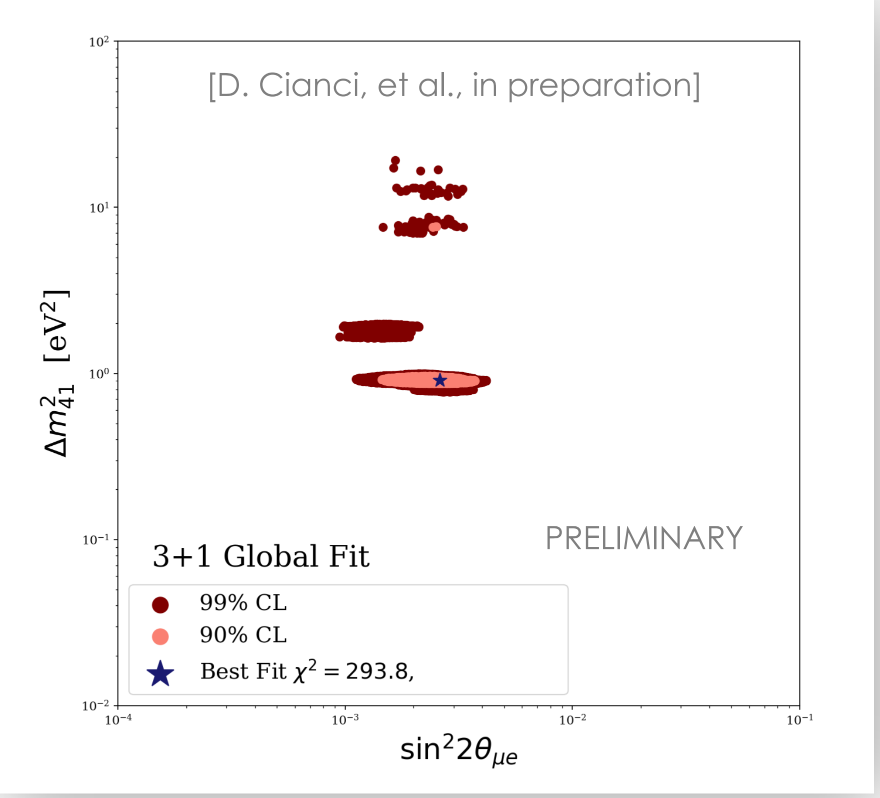
- M. Dentler, et al., JHEP 1808 (2018) 010.
- M. Dentler, et al., JHEP 1711 (2017) 099.
- S. Gariazzo, et al., JHEP 1706 (2017) 135.
- G. Collin, et al., PRL 117, 221801 (2016).
- D. Cianci et al., Phys. Rev. D 96, 055001 (2017).
- J. Conrad, et al., Adv. High Energy Phys. 2013 (2013) 163897.

Recent analyses **incorporating new results from MiniBooNE, MINOS/MINOS+** (but not IceCube/DeepCore and recent reactor SBL results)...

- D. Cianci, Y. Jwa, GK, M. Ross-Lonergan, in preparation.
- A. Diaz, J. Conrad, M. Shaevitz, ICHEP 2018.

3+1 global fits

When combined with all other available experimental constraints, MiniBooNE, LSND and Reactor SBL data **seem to indicate a preference for a (3+1) signal**

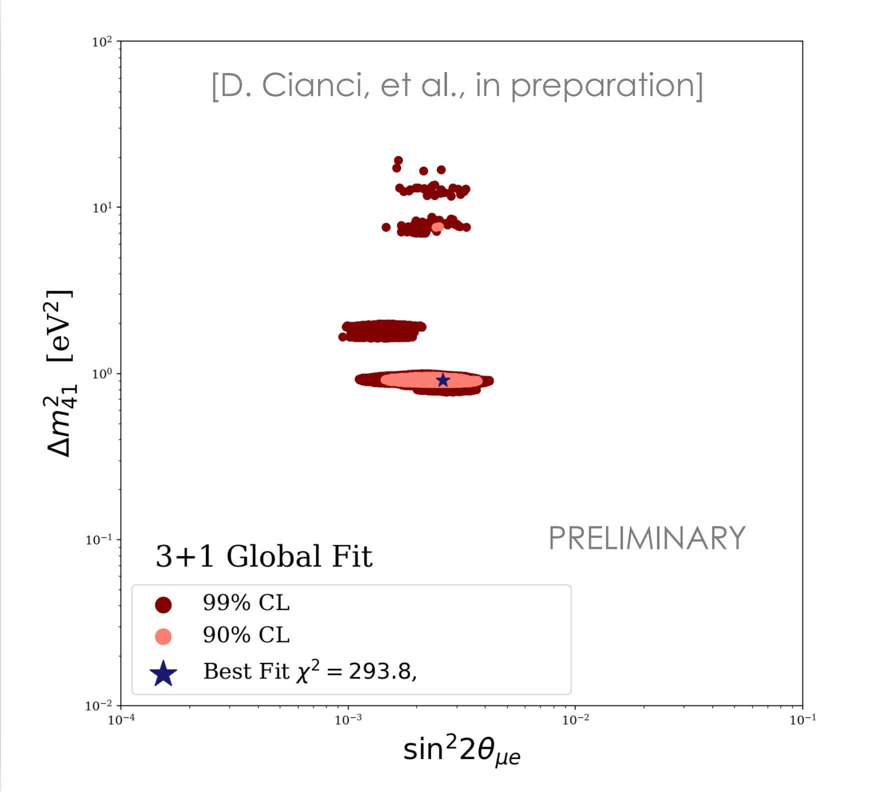


Data sets include:

- ν_e app: KARMEN, LSND, **MiniBooNE (NEW ν and old $\bar{\nu}$)**, NOMAD, NuMI/MiniBooNE
- ν_μ dis: CCFR84, CDHS, ATM, **MINOS/MINOS+ (NEW)**, SciBooNE/MiniBooNE
- ν_e dis: KARMEN/LSND xsec, Bugey, GALLEX/SAGE
- Reactor SBL not yet included

3+1 global fits

When combined with all other available experimental constraints, MiniBooNE, LSND and Reactor SBL data **seem to indicate a preference for a (3+1) signal**



Global best fit parameters:

Δm^2_{41} = 0.91 eV^2

U_{e4} = 0.149

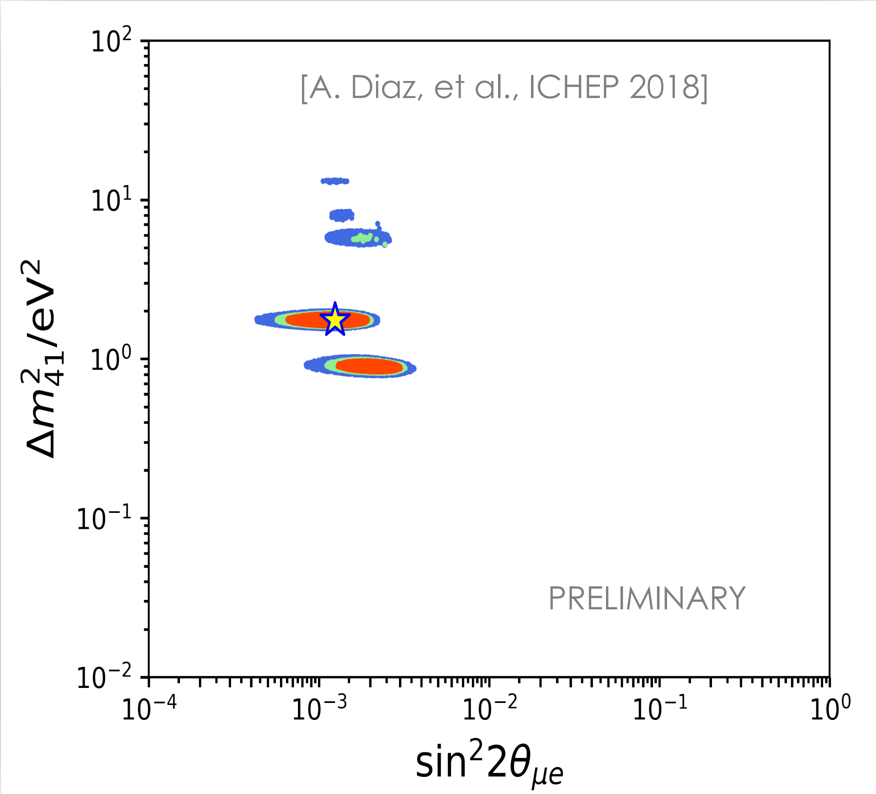
$U_{\mu 4}$ = 0.171

χ^2 bf = 293.8 (368 dof)

χ^2 probability = 99.8%

3+1 global fits

When combined with all other available experimental constraints, MiniBooNE, LSND and Reactor SBL data **seem to indicate a preference for a (3+1) signal**

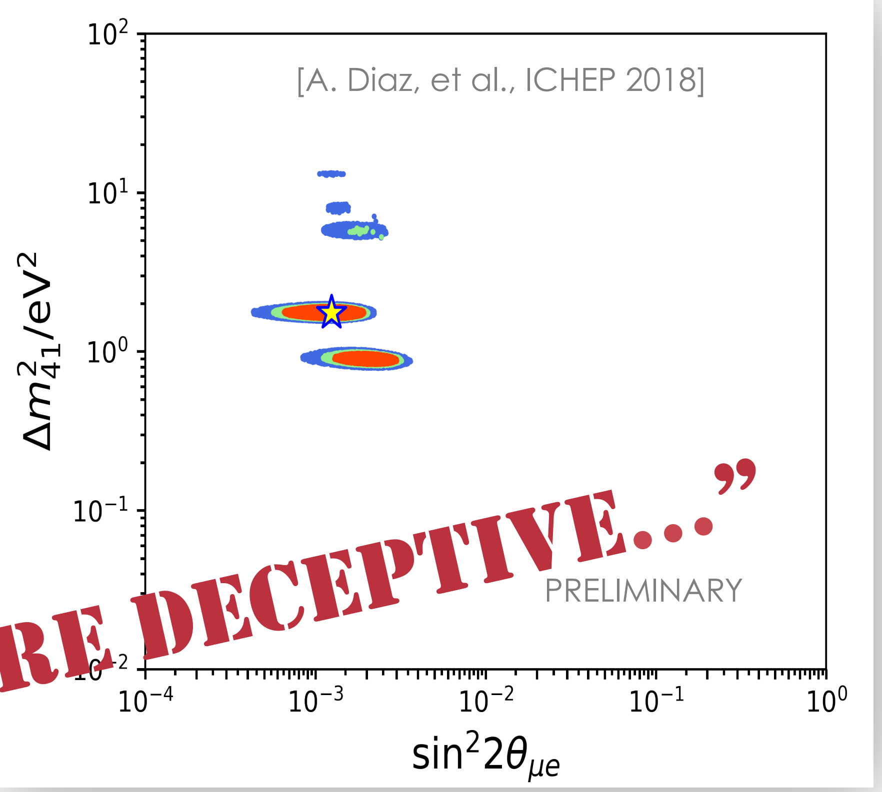


Data sets include:

- ν_e app: KARMEN, LSND, **MiniBooNE (NEW ν and old $\overline{\nu}$)**, NOMAD, NuMI/MiniBooNE
- ν_μ dis: CCFR84, CDHS, ATM, MINOS, SciBooNE/MiniBooNE
- ν_e dis: KARMEN/LSND xsec, Bugey, GALLEX/SAGE
- Reactor SBL not yet included

3+1 global fits

When combined with all other available experimental constraints, MiniBooNE, LSND and Reactor SBL data **seem to indicate a preference for a (3+1) signal**



Global best fit parameters:
Δm^2_{41} = 1.75 eV^2
U_{e4} = 0.159
$U_{\mu 4}$ = 0.110

χ^2 bf = 297 (318 dof)
χ^2 null = 329 (315 dof)

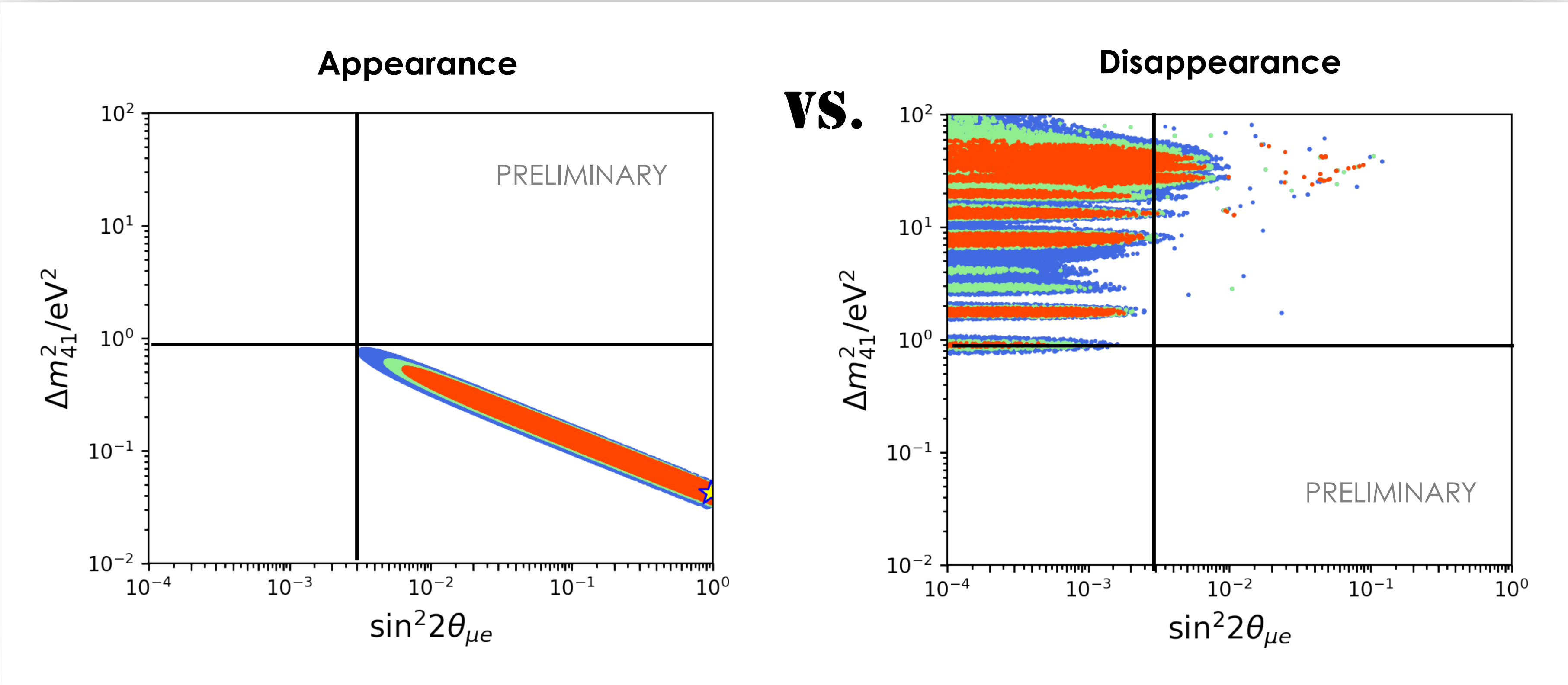
$\Delta\chi^2$ = 32 (3 dof)

"APPEARANCES ARE DECEPTIVE…"

3+1 global fits

Goodness-of-fit of global (3+1) fits can be deceptive...

A closer examination reveals **tension between datasets**:

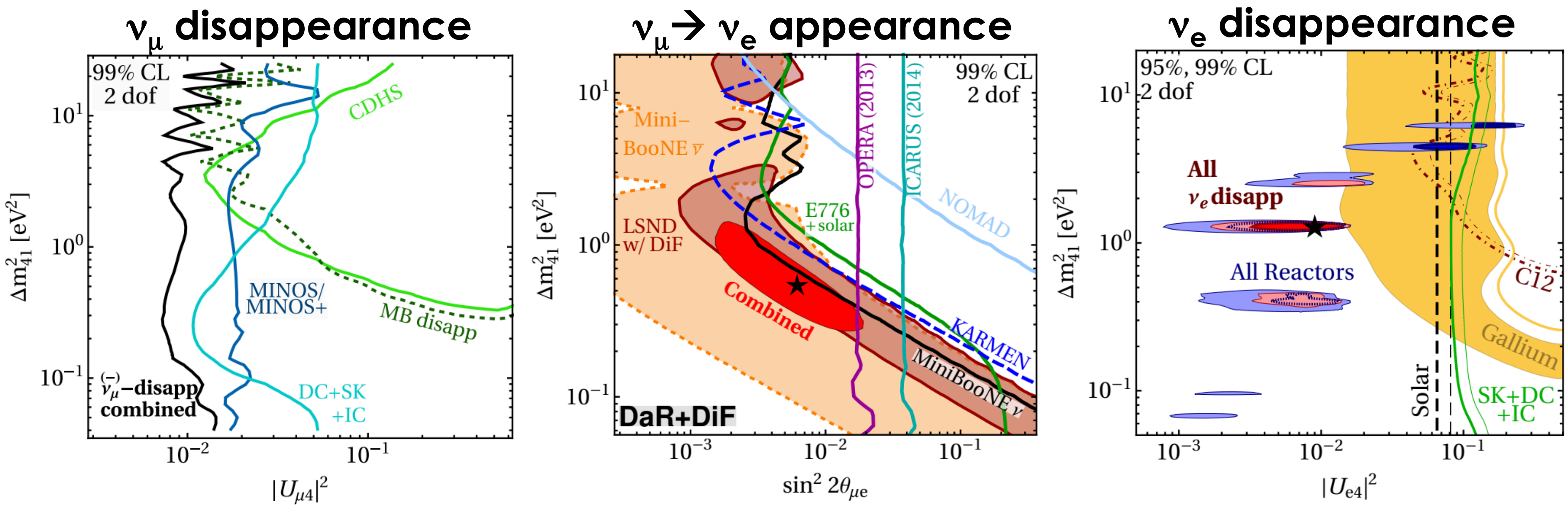


[A. Diaz, et al., ICHEP 2018]

Tension also exists among neutrino and antineutrino datasets.

3+1 global fits

[M. Dentler, et al., JHEP 1808 (2018) 010]

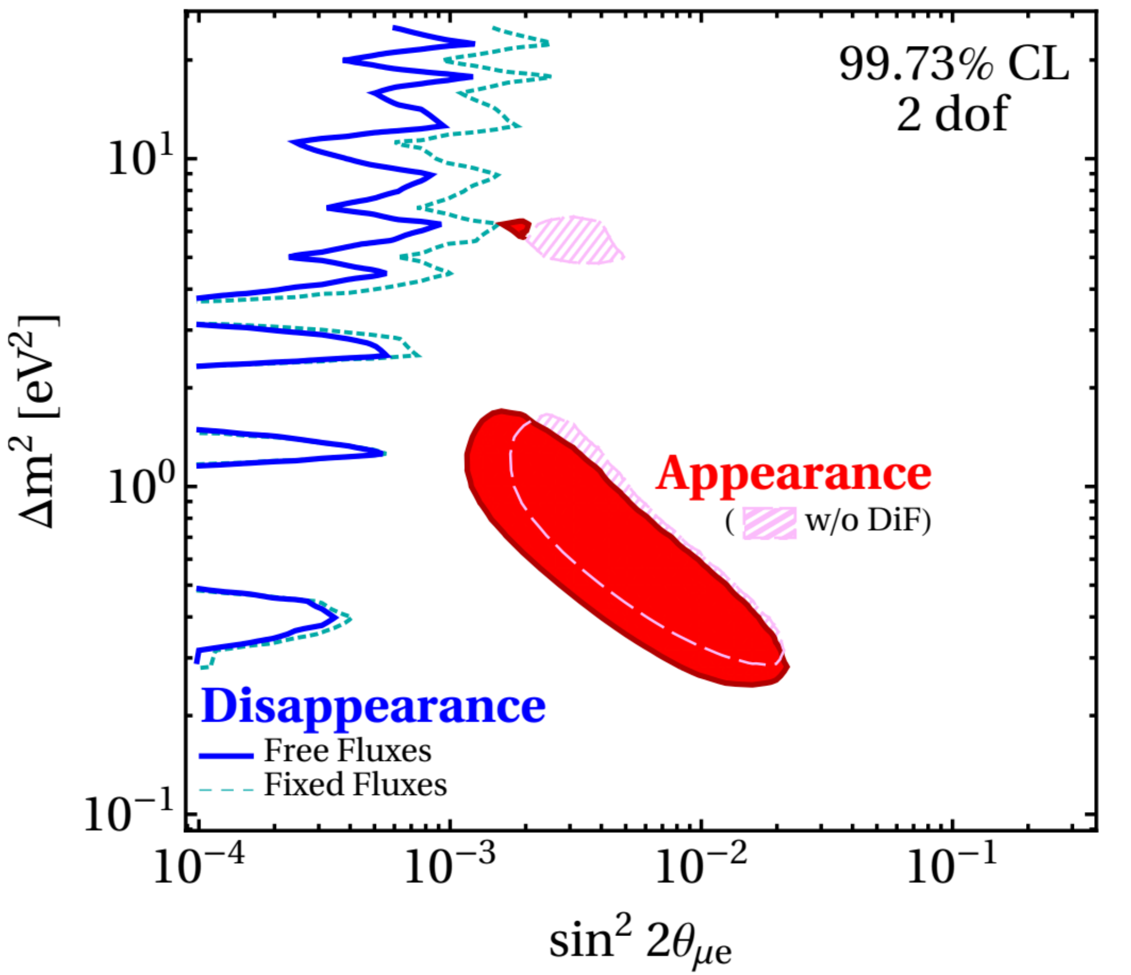


If one accepts (ν_e appearance and ν_e disappearance) signals as real,
source of tension is ν_μ disappearance searches:

$\sin^2 2\theta_{\mu e} \sim \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$ → Implies non-zero ν_μ disappearance.

But no ν_μ disappearance has been observed!

3+1 global fits



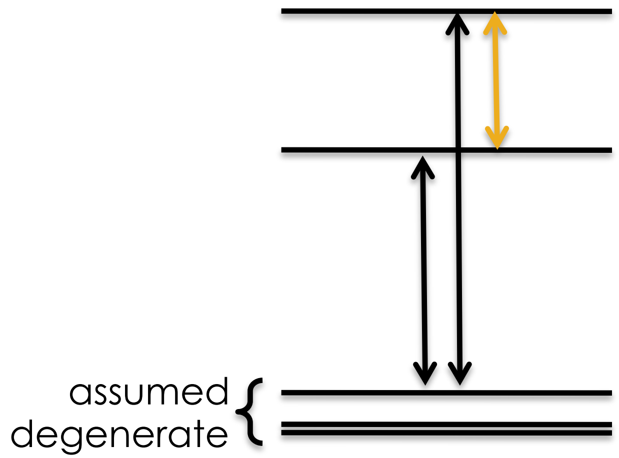
[M. Dentler, et al., JHEP 1808 (2018) 010]

3+2, 3+3 global fits

- Can CP violation allowed within 3+2 help?

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = 4|U_{\alpha4}|^2|U_{\beta4}|^2 \sin^2 x_{41} + 4|U_{\alpha5}|^2|U_{\beta5}|^2 \sin^2 x_{51} + 8|U_{\alpha5}||U_{\beta5}||U_{\alpha4}||U_{\beta4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

$$x_{ji} \equiv 1.27\Delta m^2_{ji} L/E$$



→ two effective Δm^2

- What about more fit parameters, CP phases, in 3+3?

3+2, 3+3 global fits

[D. Cianci, et al., in preparation]

With new MiniBooNE result:

3+2

m_4	$\|U_{e4}\|$	$\|U_{\mu 4}\|$	m_5	$\|U_{e5}\|$	$\|U_{\mu 5}\|$	ϕ_{45}
0.68 eV	0.116	0.187	0.95 eV	0.159	0.103	5.71 rad

χ^2 bf (dof) = 244.8 (236)
χ^2 probability = 33%

(Compare, previously, χ^2 (dof) = 238.2 (236))

PRELIMINARY

3+3

m_4	$\|U_{e4}\|$	$\|U_{\mu 4}\|$	m_5	$\|U_{e5}\|$	$\|U_{\mu 5}\|$	m_6	$\|U_{e6}\|$	$\|U_{\mu 6}\|$
0.68 eV	0.119	0.080	0.88 eV	0.139	0.086	0.97 eV	0.105	0.106

ϕ_{45}	ϕ_{46}	ϕ_{56}
5.26 rad	5.75 rad	6.03 rad

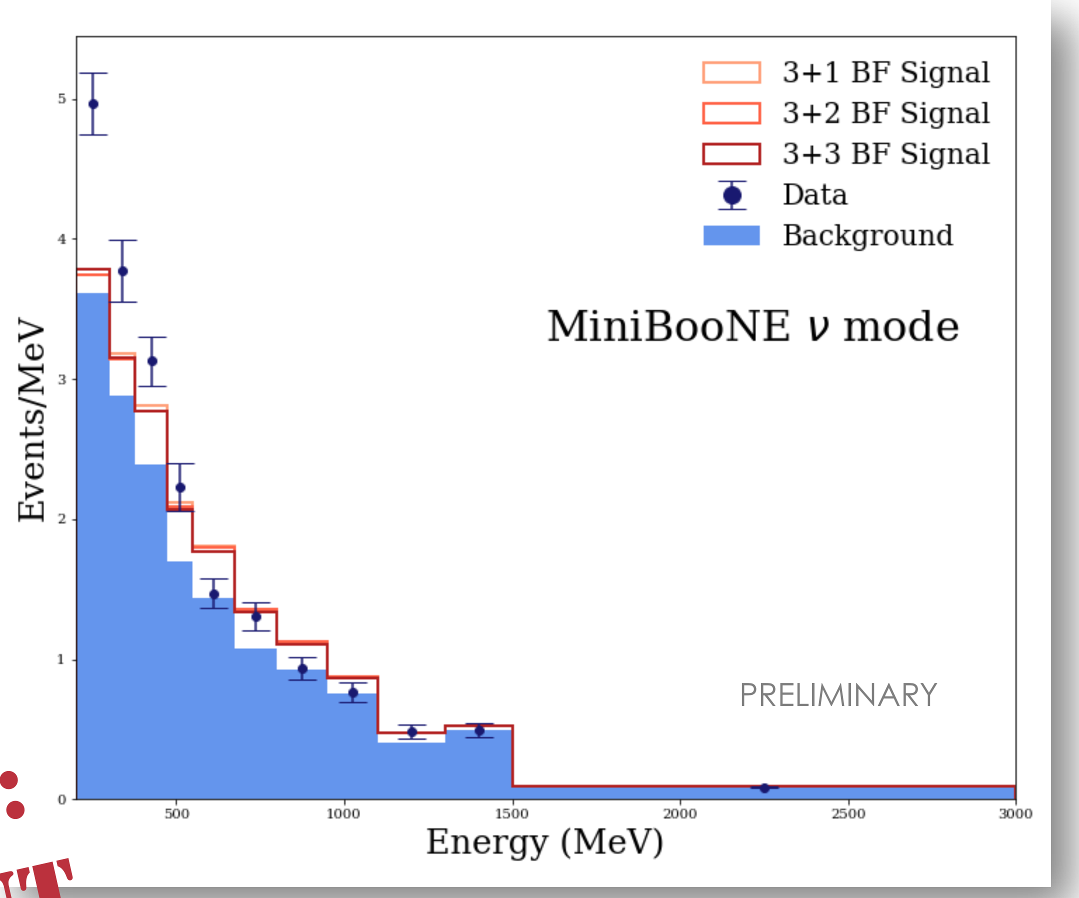
χ^2 bf (dof) = 240.5 (231)
χ^2 probability = 32%

(Compare, previously, χ^2 (dof) = 232.5 (231))

PRELIMINARY

3+N global fits

Yet another shortcoming:
Failure to accommodate MiniBooNE low-energy excess



"3+N STANDARD STERILE NEUTRINOS": INSUFFICIENT

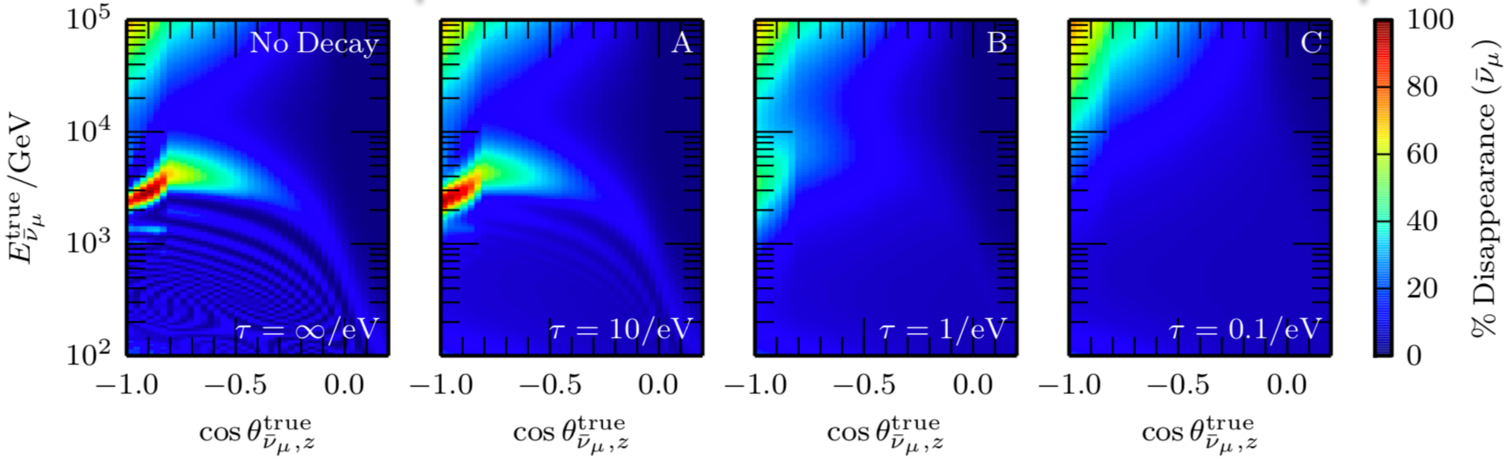
[D. Cianci, et al., in preparation]

A shift in focus?

The inability of 3+N global fits to provide a satisfactory, coherent explanation to all SBL anomalies has prompted the **exploration of new (physics) ideas**:

1. **Sterile neutrino + decay** [A. Diaz et al., ICHEP 2018]

4th (mostly sterile) neutrino mass eigenstate has finite lifetime, resulting in decoherence in neutrino propagation and no resonant matter effects --> Evades IceCube limits from ν_μ disappearance



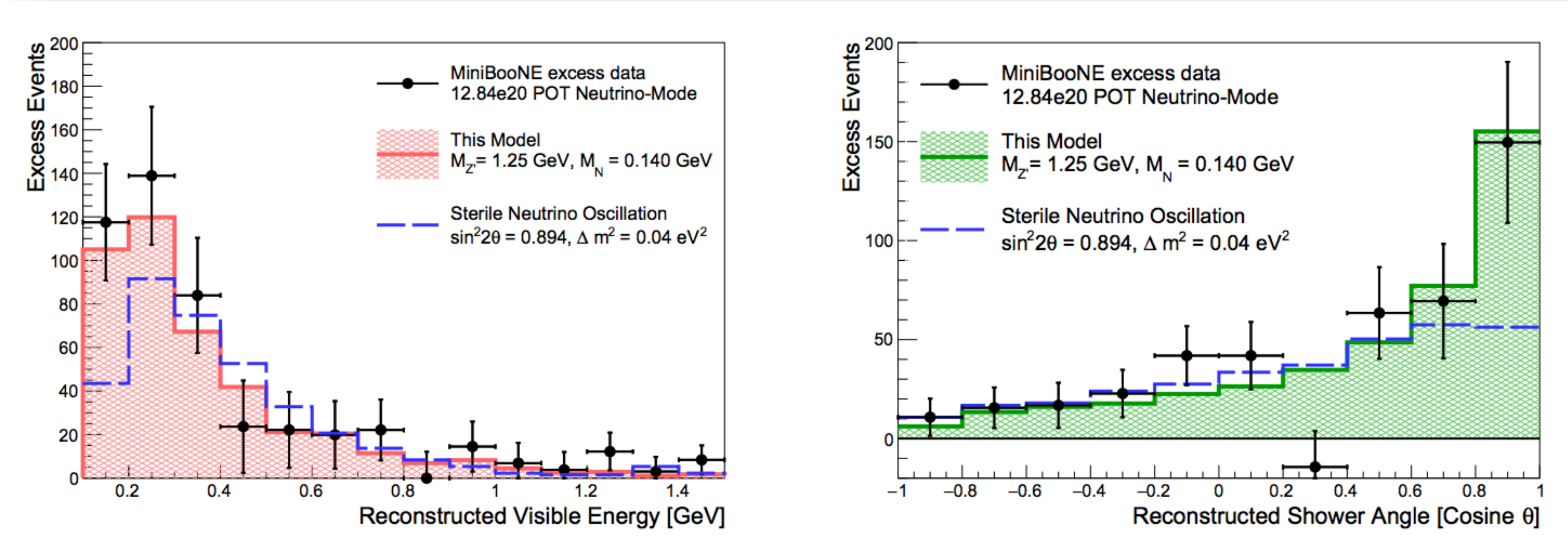
This model modestly relieves tension.

A shift in focus?

The inability of 3+N global fits to provide a satisfactory, coherent explanation to all SBL anomalies has prompted the **exploration of new (physics) ideas**:

2. Sterile neutrino + decay through Z' [P. Ballet, et al., arXiv:1808.02915]

$$\nu_\mu + \mathcal{N} \rightarrow \nu_4 + \mathcal{N} \qquad \nu_4 \rightarrow \nu_\alpha \, e^+ \, e^-$$



Best fit: m_4 = 0.14 GeV, $|U_{\mu 4}|$ = 1.5E-6, $m_{Z'}$ = 1.25 GeV, $|U_{\tau 4}|$ = 7.8E-4, χ^2 = 5E-6

Where do we go from here?

- Better statistical treatment of data in global fits
- Alternate models: non-standard interactions, sterile neutrino decay, …
- Follow-up high-sensitivity, direct experimental tests (ongoing, planned and proposed sterile neutrino oscillation searches):
  - Accelerator-based: **SBN, IsoDAR**
  - Reactor-based: **SoLiD, DANSS, NEOS, STEREO, PROSPECT,** …
  - Radioactive source: **BEST**
  - Also searches at long-baseline experiment near detectrs and (high-energy) atmospheric neutrino experiments (**MINOS/MINOS+, NOvA**, **T2K**, **IceCube/DeepCore, Super-K,** …)
  - And neutral-current based searches with coherent scattering (e.g. **COHERENT, CEvNS**)

See talks by
A. Fava, J. Zennamo,
L. Yates, Y.-T. Tsai,
S. Axani. J. Smolsky

See talk by
C. Zhang

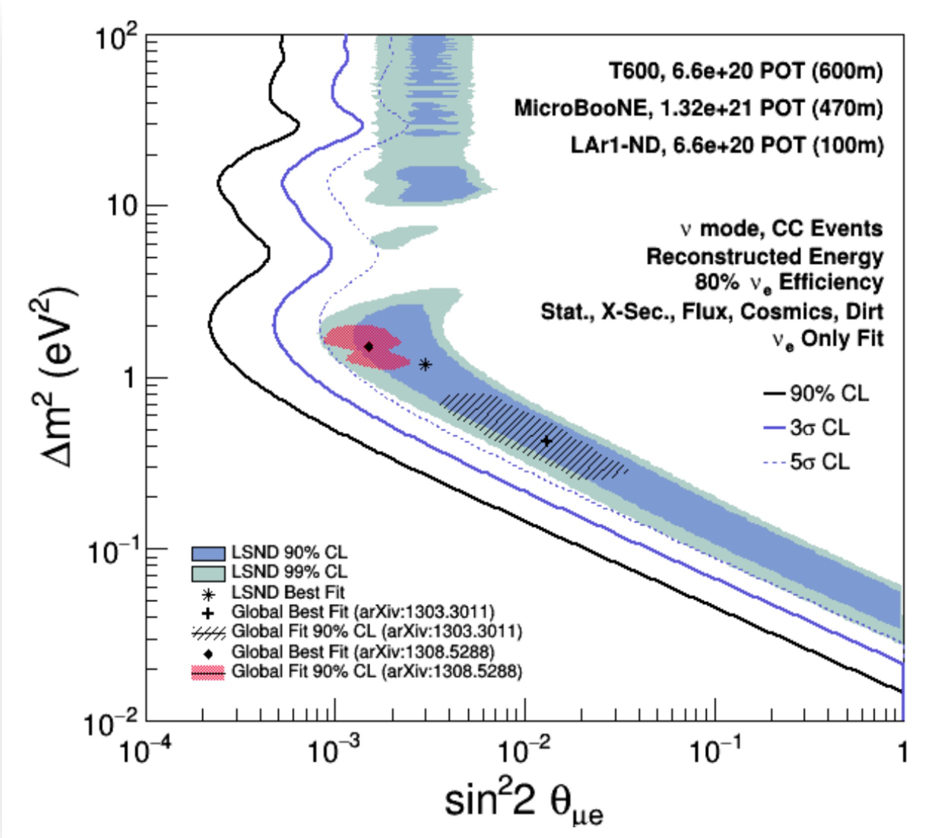
See talks by
J. Hernandez-Garcia,
M. Wallbank, J. Todd

See talk by
P. Barbeau

How can we do better? (E.g.: SBN at Fermilab)

SBN ν_e appearance channel search: (3+1)

[SBN Proposal 2015]

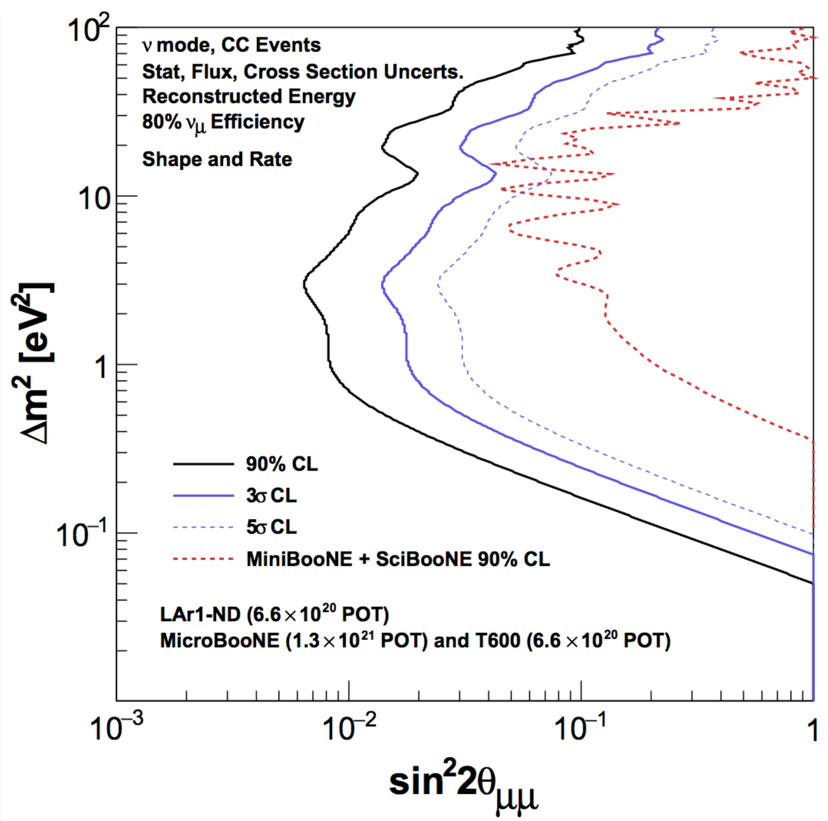


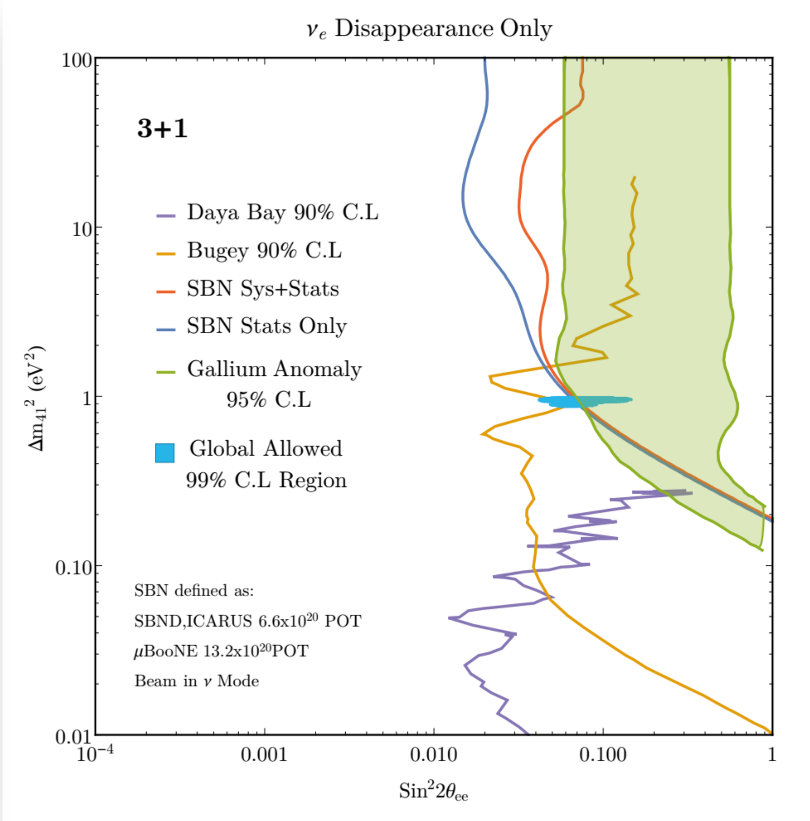
SBN will be able to test existing indications for ν_e appearance at 5σ level

How can we do better? (E.g.: SBN at Fermilab)

Also, SBN ν_e ν_μ and disappearance channel searches: (3+1)

[SBN Proposal 2015]



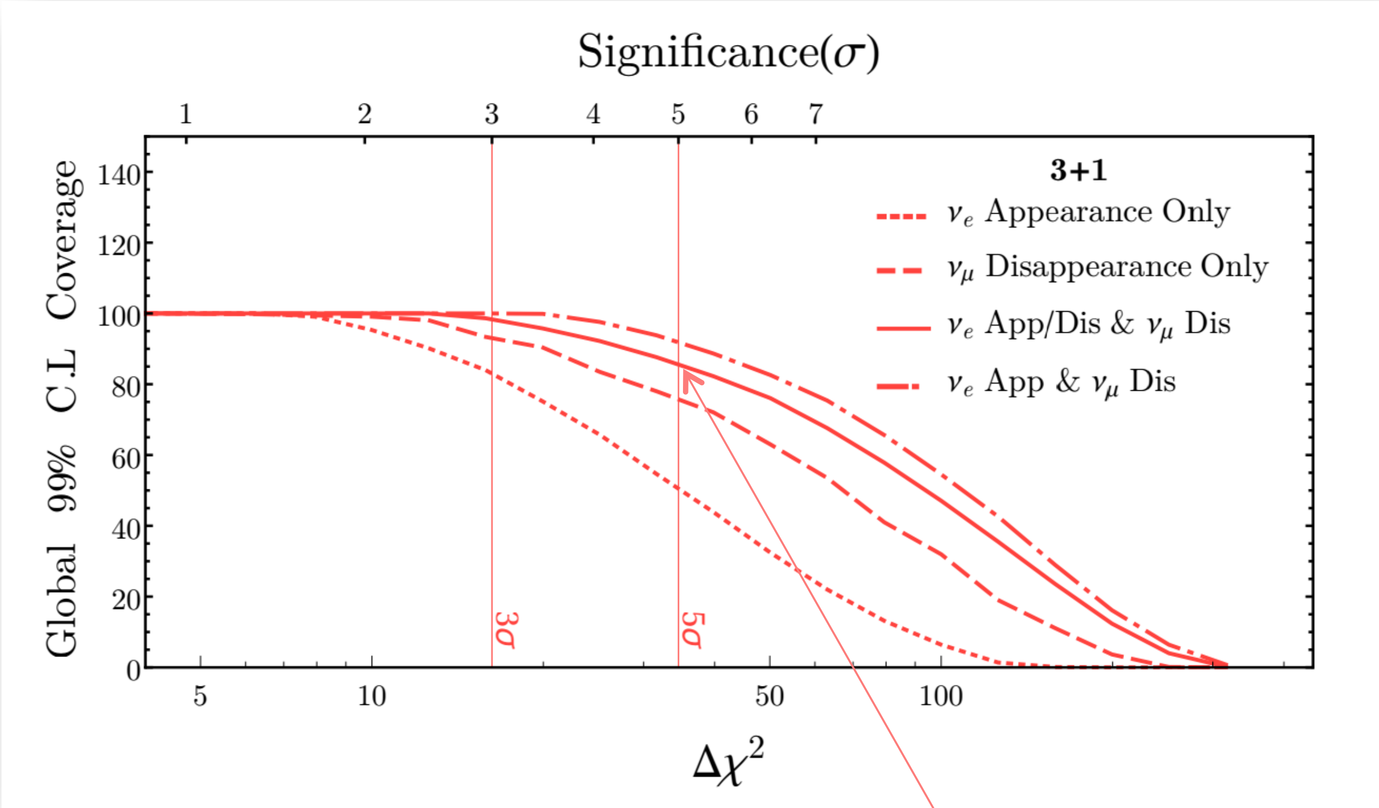


[D. Cianci, et al., Phys. Rev. D 96, 055001 (2017)]

SBN can probe multiple independent channels simultaneously...

How can we do better? (E.g.: SBN at Fermilab)

3+1 multi-channel SBN sensitivity:



[D. Cianci, et al., Phys. Rev. D 96, 055001 (2017)]

- ν_e app/dis and ν_μ disap search: 85% coverage of 99%CL allowed phase-space at 5σ

- Overall sensitivity to 3+1 greatly enhanced when combining multiple oscillation channels in the fit
- Simultaneous search for ν_e and ν_μ disappearance without consideration of ν_e disappearance overestimates sensitivity (case for model-independent assumptions!)

How can we do better? (E.g.: SBN at Fermilab)

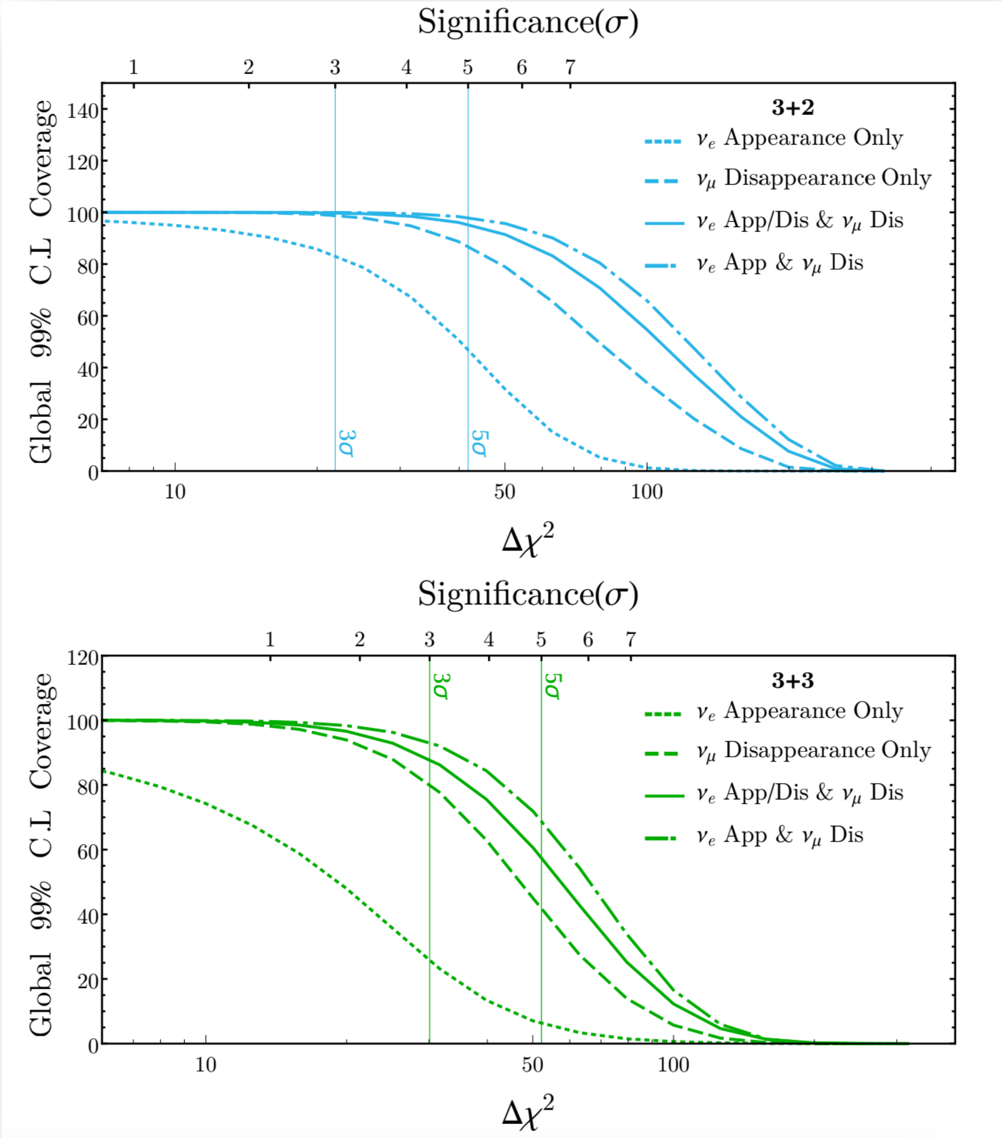
3+2 and 3+3 multi-channel SBN sensitivities:

- Improvement in sensitivity is significant even in extended scenarios with multiple sterile neutrinos

- ν_e app/dis and ν_μ dis search:

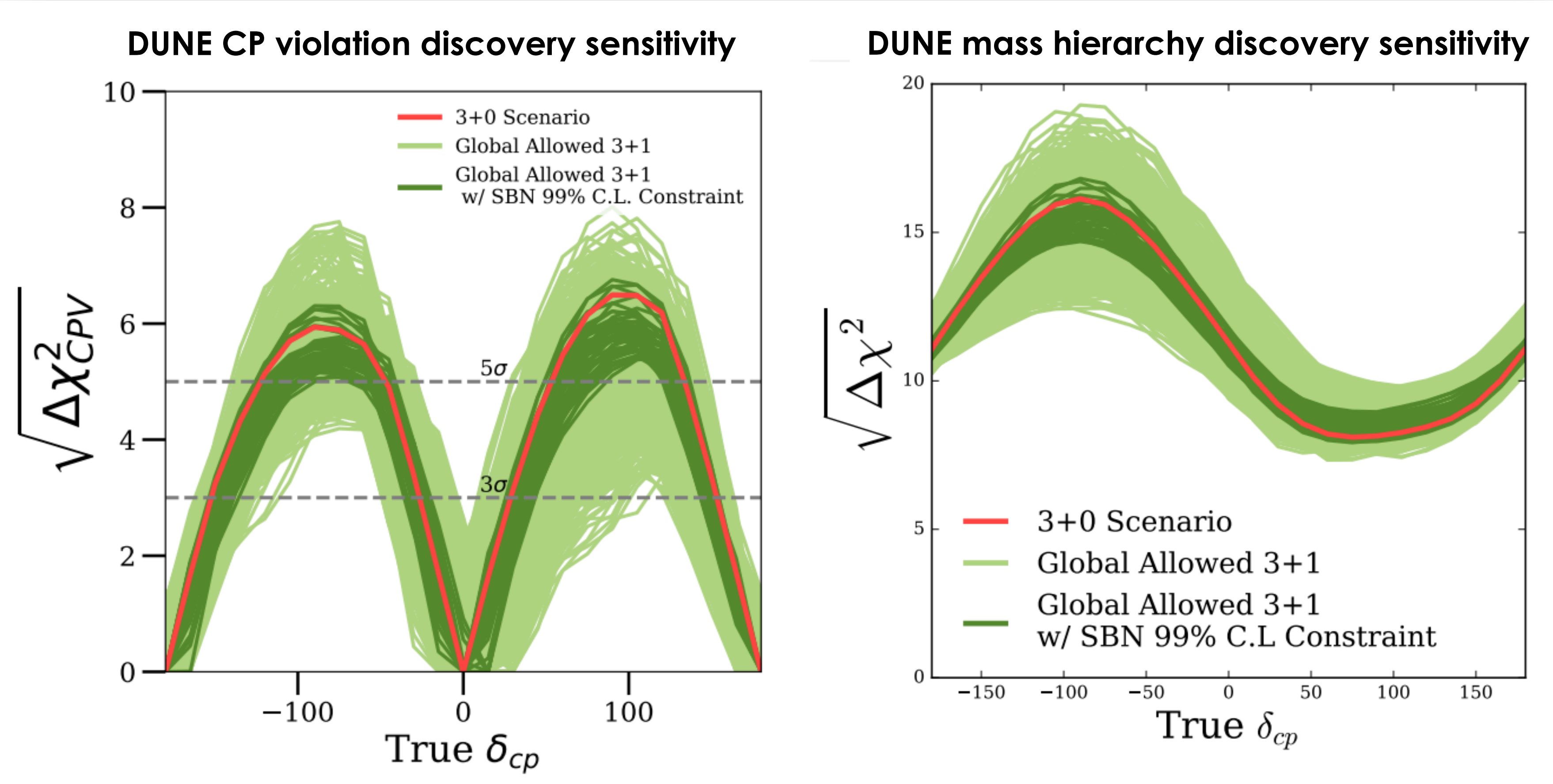
  95% coverage of 99%CL allowed phase-space at 5σ

  55% coverage of 99%CL allowed phase-space at 5σ



[D. Cianci, et al., Phys. Rev. D 96, 055001 (2017)]

How much better? (E.g.: SBN at Fermilab)

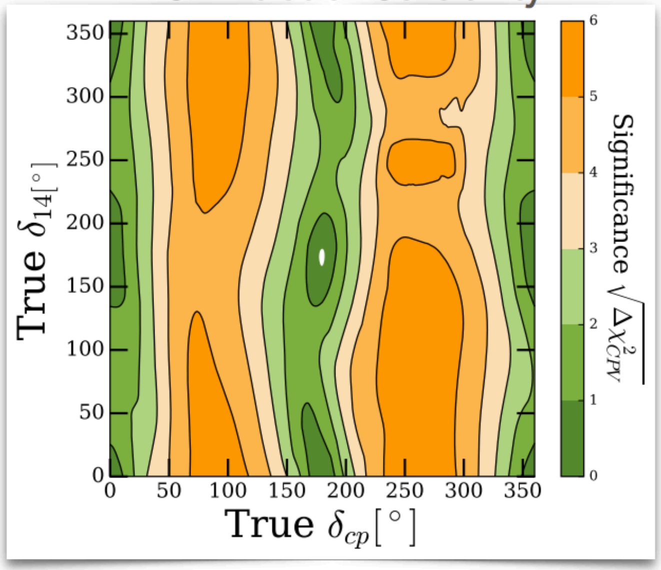


DUNE sensitivity degradation due to uncertainties in **sterile neutrino** parameters
(Δm^2_{41} = 1.7 eV^2 and varying mixing, additional CP phases),
without and **with SBN constraints (SBN consistent with null).**

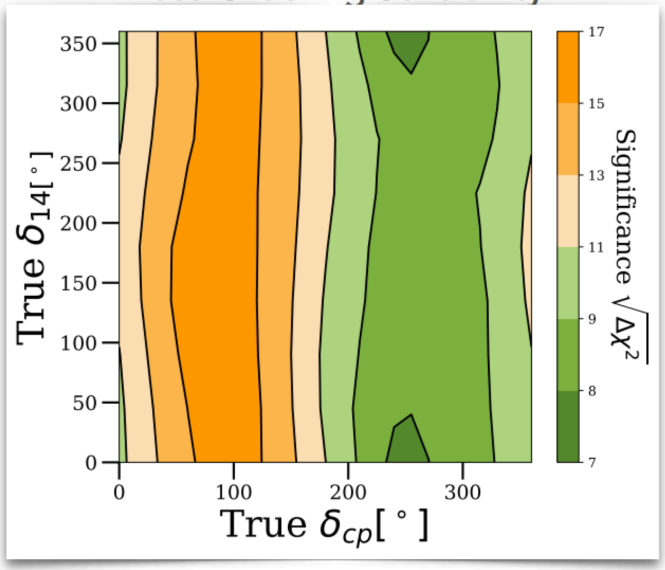
[Y. Jwa et al., ICHEP 2018]

How much better? (E.g.: SBN at Fermilab)

CP Violation Sensitivity



Mass Ordering Sensitivity



$\Delta m_{41}^2 = 1.7\text{eV}^2$,
$\delta_{14} = [-\pi, \pi]$,
$\delta_{34} = 0$,
$\theta_{23} = [38°, 53°]$,
$\theta_{14} = 8.3°$,
$\theta_{24} = 6.9°$,
$\theta_{34} = 10°$

At the global (3+1) best-fit point, for a **combined SBN+DUNE fit**,
CP violation sensitivity is over 5σ for a subset of (δ_{cp}, δ_{14}) pairs (assuming δ_{34}=0).
Mass ordering sensitivity is over 5σ throughout the entire (δ_{cp}, δ_{14}) plane.

[Y. Jwa et al., ICHEP 2018]

Summary

See talk by N. McCauley

Key Questions for WG1

Q1 What can we say about CP violation, the mass ordering and the octant? How well can we map the PMNS matrix?

- What do current experiments tell us?
- What is the pathway to the ultimate measurements with the required precision?

Q2 What are the current and future systematic limitations on these measurements and what can we do to address them?

Q3 Is there physics beyond the standard PMNS mixing model?

- Most free parameters of the three-neutrino (PMNS) picture have been determined to a few% or better (1σ)
- Thanks to T2K (nu and nubar running) and the interplay of accelerator LBL, reactor LBL, and atmospheric experiments, we now have
  - 3σ hints for normal ordering
  - Improved δ_{CP} sensitivity
- Will need future experiments for octant determination

- Many informative talks/discussions during conference!
- *With respect to global fits:*
  - *Multiple independent group analyses, in agreement, yield a consistent picture.*
  - *In a precision oscillometry era, a heavy burden rests on experiments to provide data sets as devoid of model-dependent assumptions as possible, and full transparency in approximations.*

- There are certainly experimental hints which do not fit within our three-neutrino picture.
- It's not clear yet what underlying physics is the source of it (3+N global fits with sterile neutrinos fall short of interpreting all SBL data simultaneously).
- It would be a (scientific) crime not to continue to explore these signals. Luckily a plethora of dedicated tests is ramping up. Stay tuned!

Thank you!