14.11.2026 DISCRETE 2026



Pseudo-Sterile States: A common origin of neutrino oscillation anomalies

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Outline

Introduction

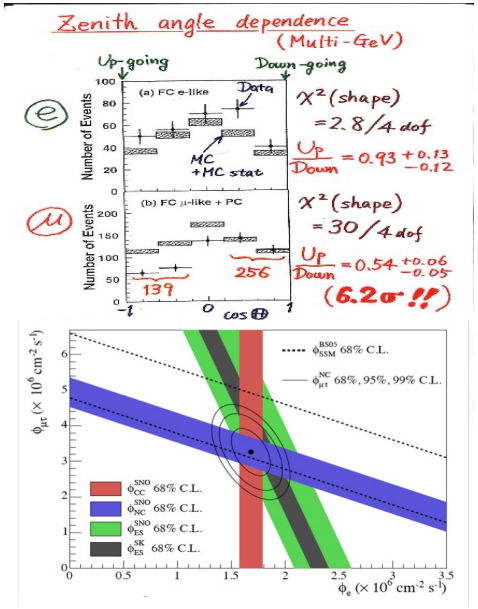
Neutrino osc. discrepancies across energies

A possible solution: pseudo-sterile states

Conclusions

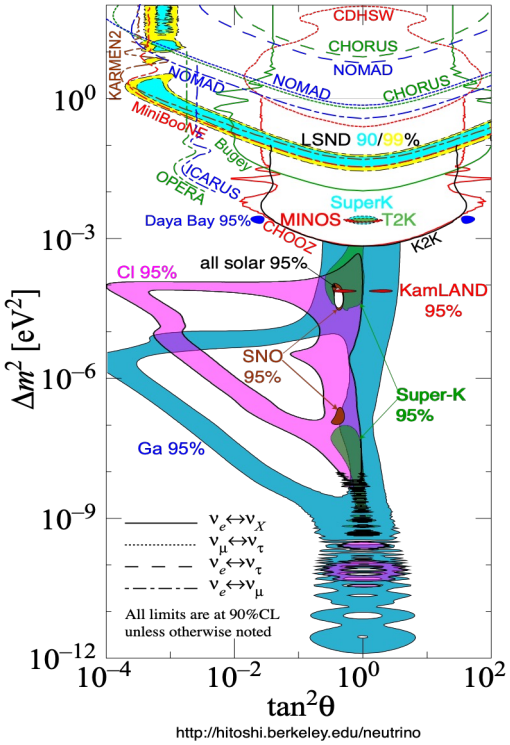
Outstanding progress in ν physics in ~ 30 years

Discoveries



+ many other ones:
solar, KamLAND,
θ_{13} at reactors & T2K
…

Interpretation



known knowns

$\delta m^2/eV^2 \sim 7.34 \times 10^{-5} \pm 0.9\%$
$\Delta m^2/eV^2 \sim 2.48 \times 10^{-3} \pm 0.8\%$
$\sin^2\theta_{12} \sim 0.303 \quad \pm 1.9\%$
$\sin^2\theta_{13} \sim 0.0225 \quad \pm 2.4\%$
$\sin^2\theta_{23} \sim 0.545 \quad \pm 5.0\%$

known unknowns

δ(CP)
sign(Δm^2)
octant(θ_{23})
absolute ν mass
Dirac/Majorana

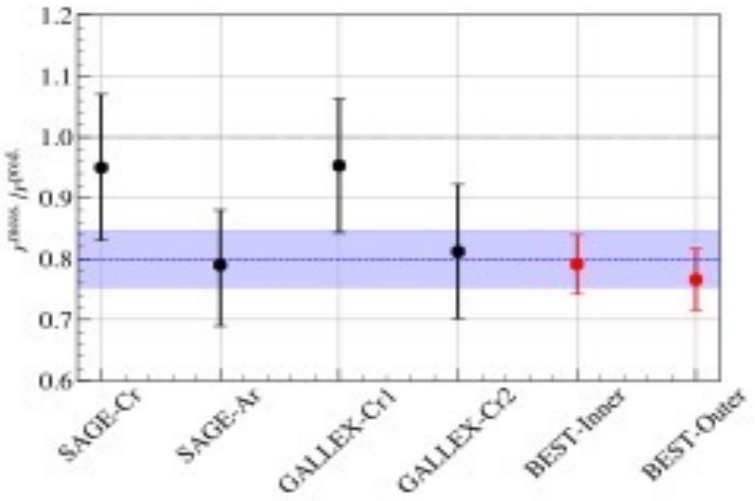
unkown unknowns

NSI, sterile states,
PMNS non-unitarity, …?

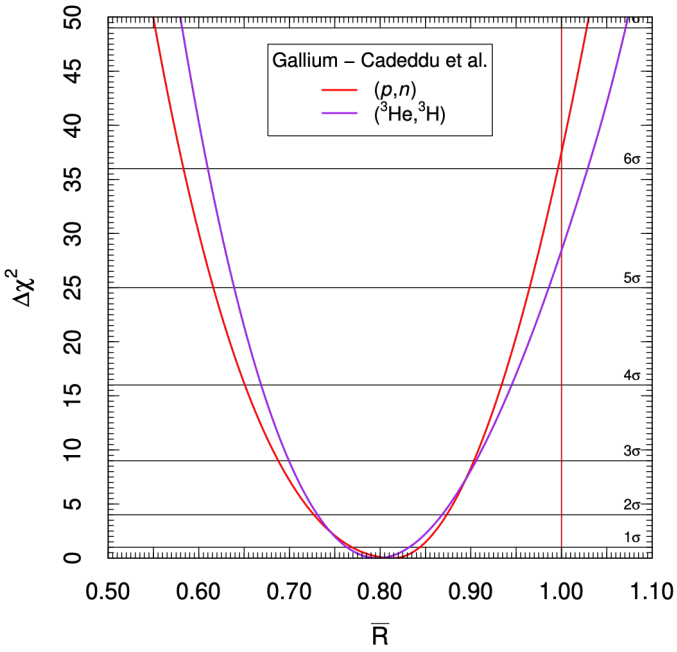
The right moment to look for cracks in the standard framework…

Anomalies across energies (and baselines)

The Gallium anomaly (sub-MeV)



SAGE coll., PRC 73 (2006) 045805



Cadeddu et al. 2507.13103

Statistical significance depends on CS calculations

Unknown systematics may contribute

The reactor anomaly (few MeV)

Mention et al. arXiv:1101:2755 [hep-ex] (**2.5** σ)

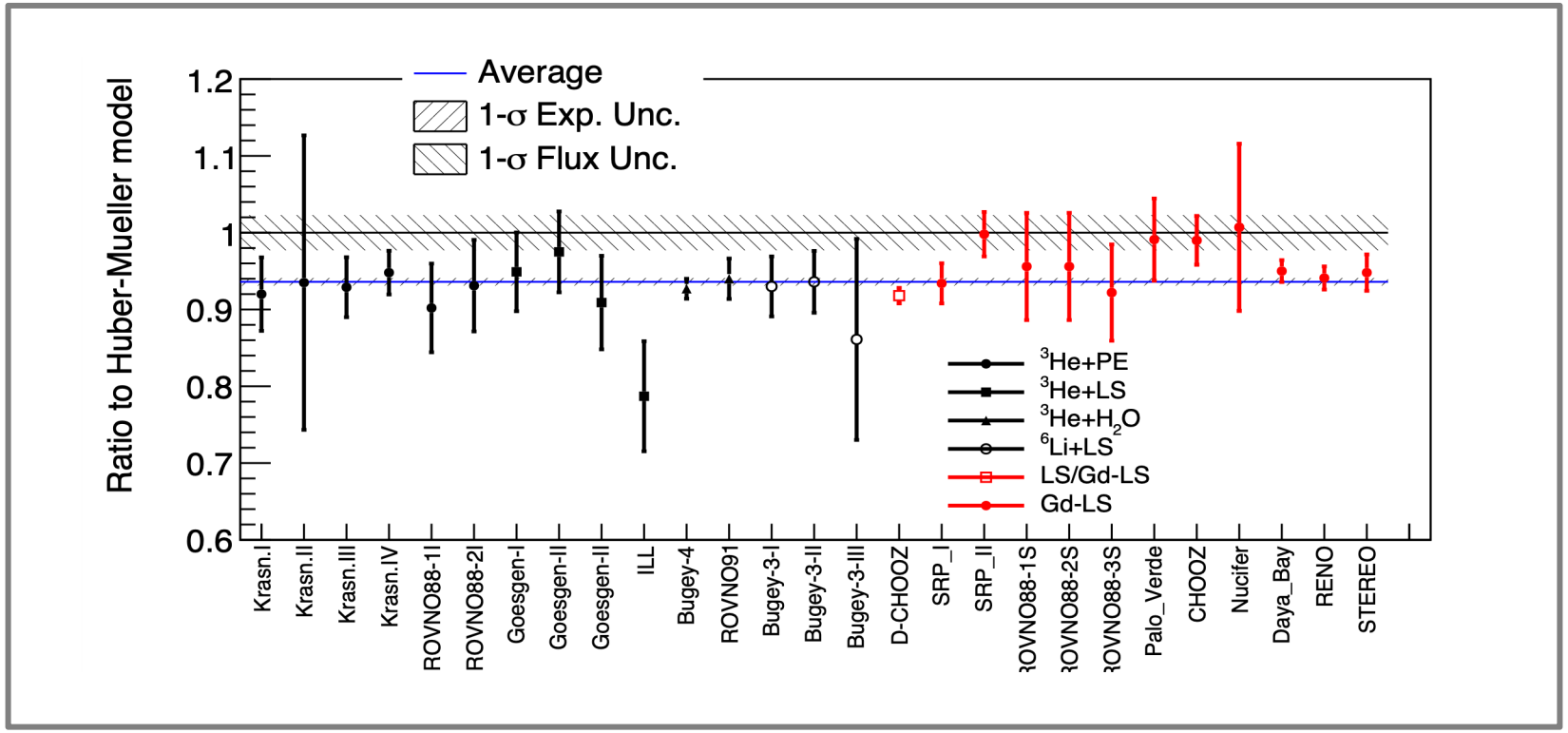
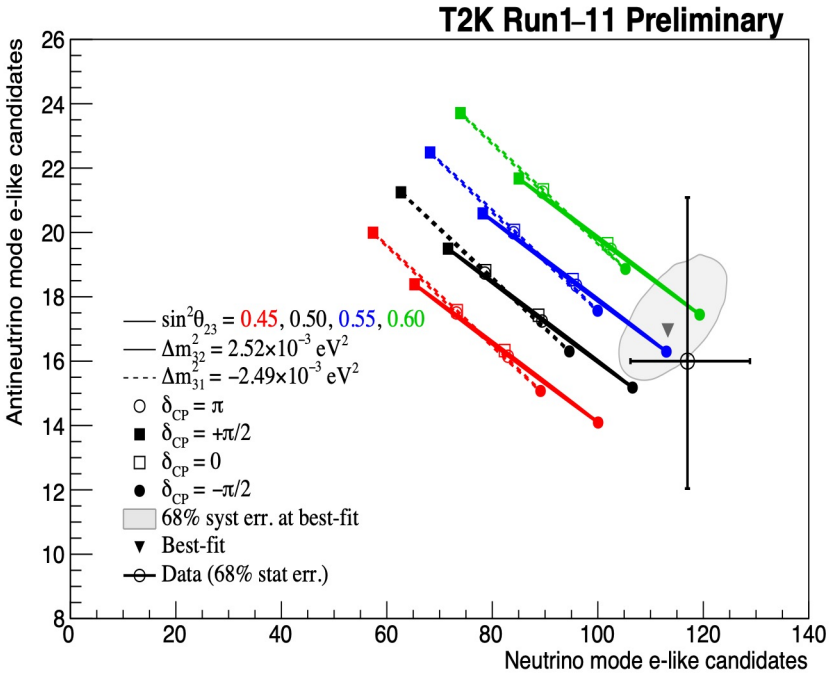
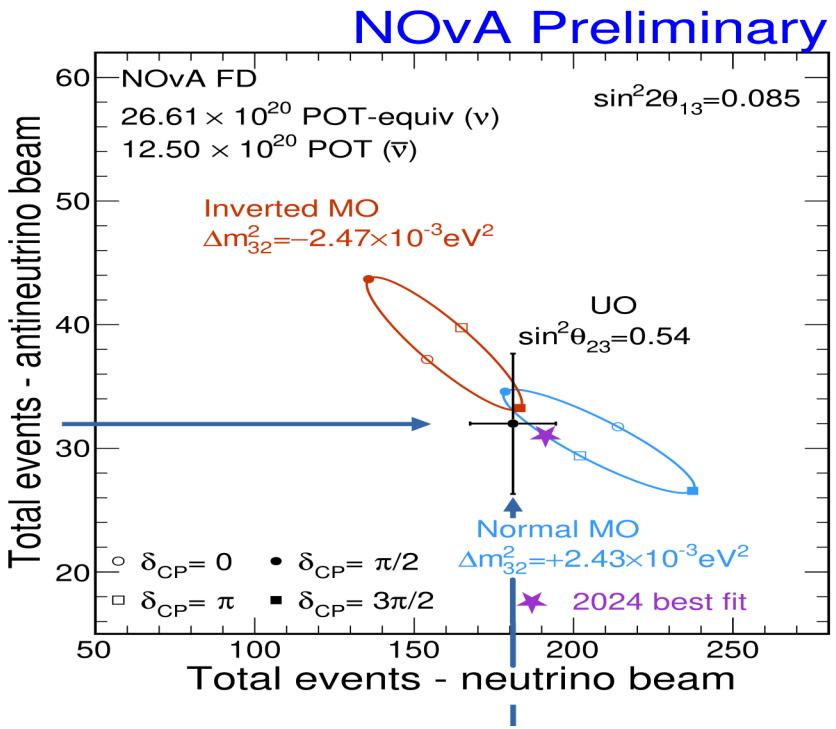


FIGURE from Zhang et al. arXiv:2310.13070[hep-ph] PPNP 136, 104106 (2024)

Giunti et al. arXiv:2605.10353 [hep-ph] (Latest update **2.2** σ)

Tension between NOvA & T2K (GeV)





Nomal Ordering:

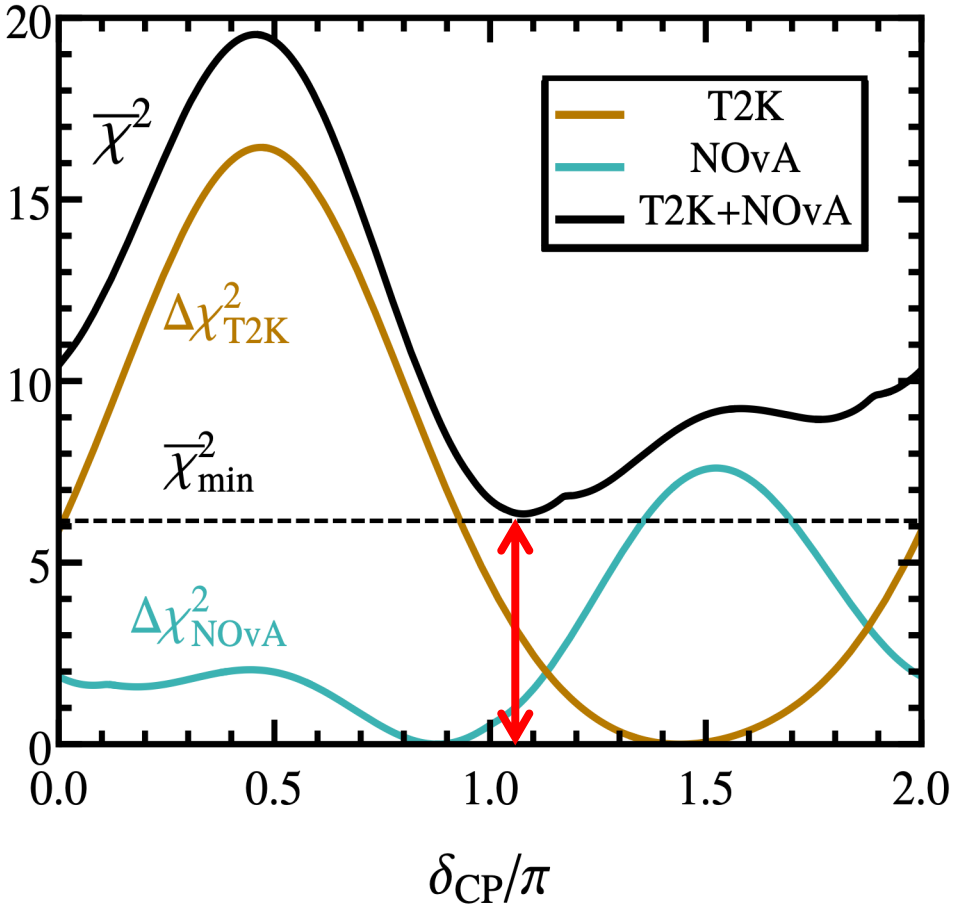
- **T2K prefers $\delta_{CP} \sim 1.5\pi$**
- **NOνA prefers $\delta_{CP} \sim 0.9\pi$**

Inverted ordering almost excluded (> 3σ)

Quantification of Tension

Chatterjee & Palazzo arXiv:2409.10599 PRD 11 113002 (2024)

$$\bar{\chi}^2(\delta_{\rm CP}) = \chi^2_{\rm T2K+NOvA}(\delta_{\rm CP}) - (\chi^2_{\rm T2K,min} + \chi^2_{\rm NOvA,min})$$

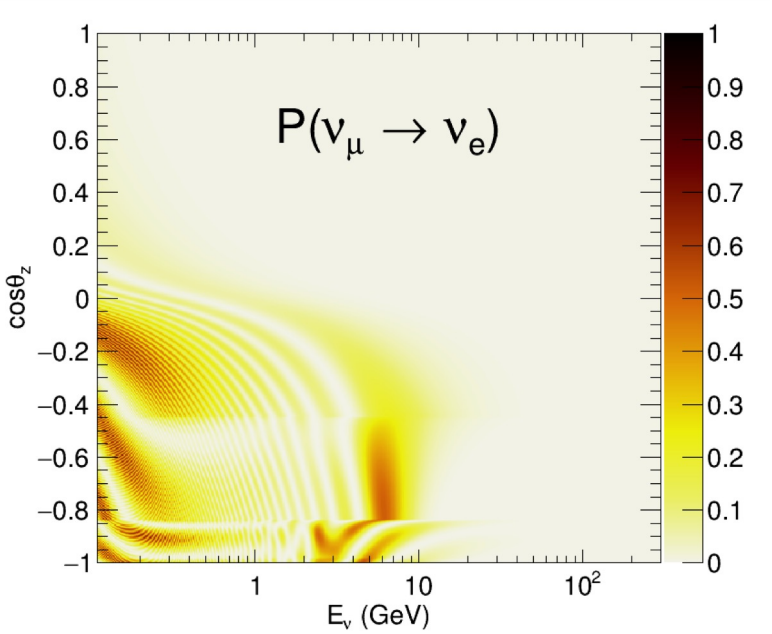


Maltoni & Schwetz Criterion
hep-ph/0304176 PRD (2003)

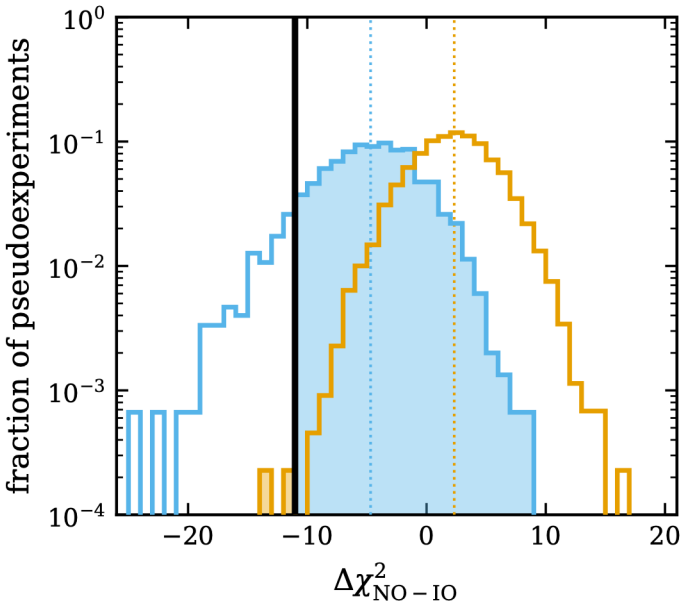
$$\bar{\chi}^2_{min} = 6.3$$

$$\text{GoF} = 1.4 \times 10^{-2}$$

A discrepancy in atmospheric ν's (multi-GeV)



Super-Kamiokande
arXiv: 2311.05105 [hep-ex]
PRD 109, 072014 (2024)

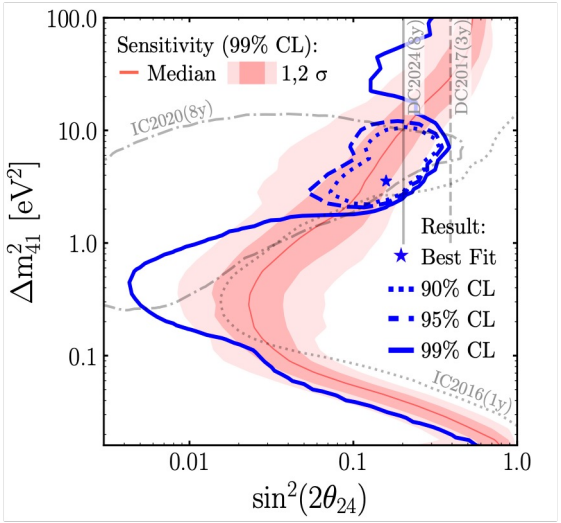


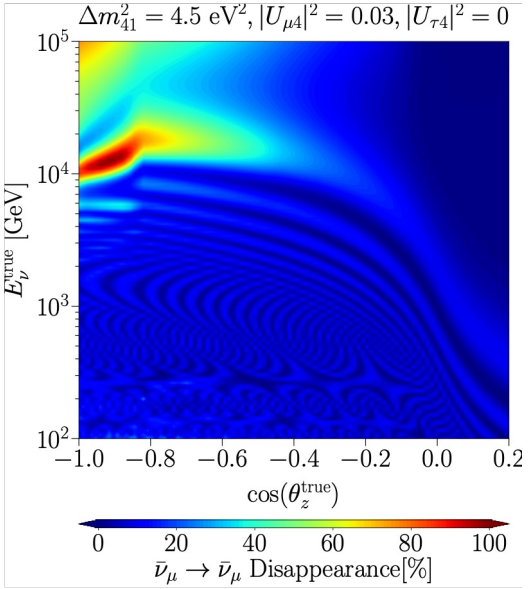
Jin, Arguelles,
Fernandez-Menendez, Martinez-Soler
arXiv: 2610.12208 [hep-ex]

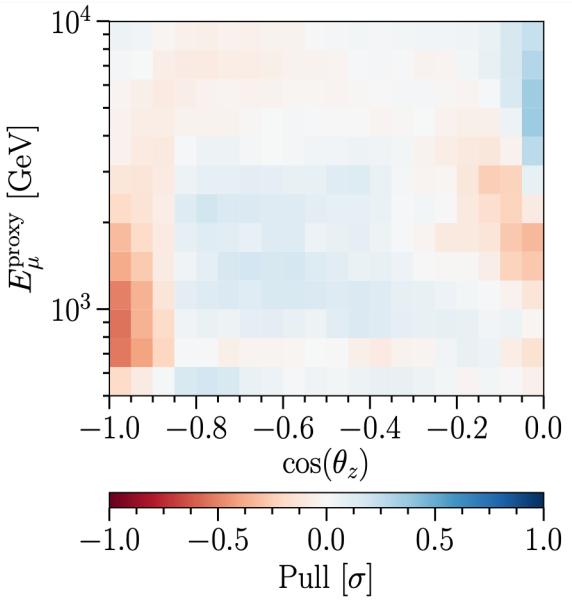
See also
Eller, 2606.09714 [hep-ex]

Preference for NO appreciably larger than sensitivity

Hint of a resonance in IceCube (multi-TeV)





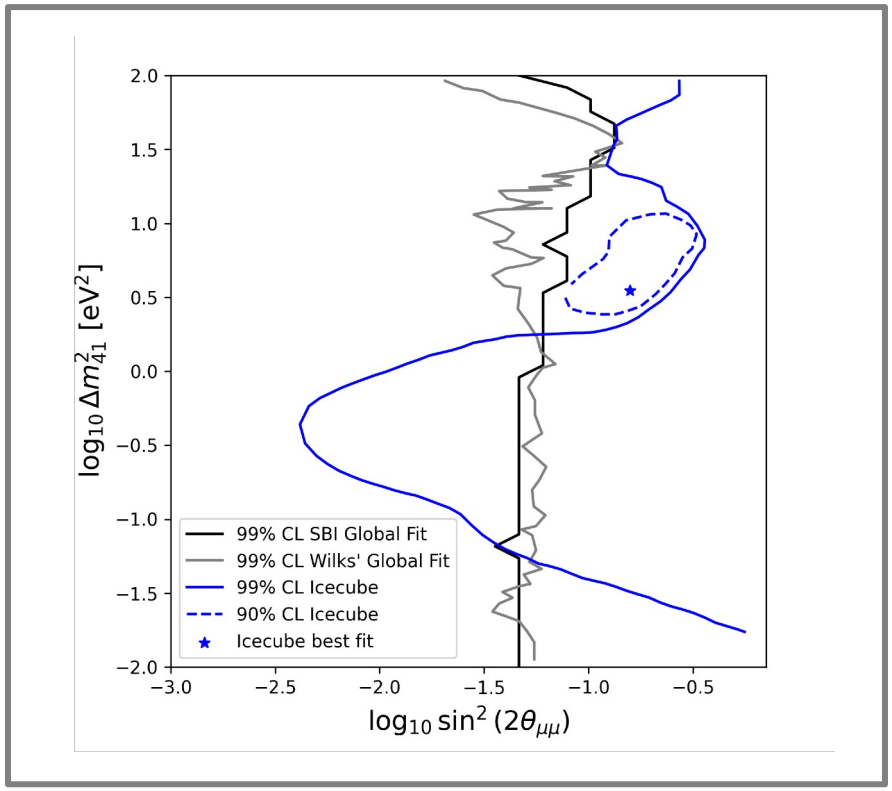


IceCube
arXiv: 2405.08070 [hep-ex]
PRL 133, 201804 (2024)

IceCube
arXiv: 2406.00905 [hep-ex]
PLB 858, 139077 (2024)

A consolidating trend

In 3+1 scheme resonance is in strong tension with other ν_μ disappearance searches



Villareal et al.
arXiv: 2507.01153 [hep-ph]
Mach. Learn. Sci. Tech. 6, 035053 (2025)

Note: Incompatibility at 3σ level

Inadequacy of the ordinary 3+1 scheme

ν_e disappearance in Gallium	→	$\|U_{e4}\|^2 \simeq 0.1$
ν_e disappearance in RAA & solar	→	$\|U_{e4}\|^2 \lesssim 0.03$
ν_μ disappearance at SBL-LBL	→	$\|U_{\mu 4}\|^2 \ll 0.01$
ν_μ dis. IceCube (resonance?)	→	$\|U_{\mu 4}\|^2 \simeq 0.04$
ν_e appearance in SBL (?) (disconfirmed by MicroBooNE)	→	$4\,\|U_{e4}\|^2\|U_{\mu 4}\|^2 \simeq 10^{-3}$

Several indications in mutual tension

In addition, severe problems with cosmology

Our attempt to address the problem:

Pseudo-Sterile neutrinos

Chatterjee & Palazzo,
arXiv: 2605.15146 [hep-ph]
PRD 114 (2026) 7, 075008

Definition of the new matter potential

$$H = U\,K\,U^\dagger + V \qquad U = \tilde{R}_{34} R_{24} \tilde{R}_{14} R_{23} \tilde{R}_{13} R_{12}$$

$$K = \mathrm{diag}\,(0, k_{21}, k_{31}, k_{41})$$

$$V = \mathrm{diag}\,(V_{CC}, 0, 0, V_S - V_{NC})$$

$$V = V_{CC} \times \mathrm{diag}\,(1, 0, 0, \bar{f})$$

$$\bar{f} = r(1+f) \qquad r = |V_{NC}|/|V_{CC}|$$

$$\begin{cases} V_{CC} = \sqrt{2} G_F N_e \\ V_{NC} = -\frac{1}{2}\sqrt{2} G_F N_n \\ V_S = -f \times V_{NC} \end{cases}$$

Resonance condition in the Earth $-\bar{f} V_{CC} \simeq f V_{NC} = k_{41}$

3+1 $\longrightarrow \Delta m^2_{41}$ **≃ 3 eV²**

New 3+1 $\longrightarrow |f| \times \Delta m^2_{41}$ **≃ 60 eV²**

We identified three distinct regimes

1) Vacuum

Identical to conventional 3+1 scheme

Relevant for kinematical beta-decay and SBL

2) Matter Low-Energy ($E \lesssim 1$ TeV)

Effective NSI-like behavior with specific rank-1 structure

Relevant for Solar, LBL, sub-TeV atmospheric neutrinos

3) Matter High-Energy ($E \simeq 10$ TeV)

Resonant behavior with dynamical mixing angles



a) Irreducible 3-level dynamics

b) Effective 2-level dynamics

Relevant for multi-TeV Atmospheric neutrinos

Effective NSI-like low-energy behavior (E < TeV)

change of basis

$$\bar{\nu} = \bar{U}^\dagger \nu$$

$$\bar{U} = \tilde{R}_{34} R_{24} \tilde{R}_{14}$$

$$\bar{H}^{\rm mat}_{3\nu} \approx V_{\rm CC} \begin{bmatrix} 1+\bar{f}_\oplus s^2_{14} & \bar{f}_\oplus \tilde{s}_{14} s_{24} & \bar{f}_\oplus \tilde{s}_{14} \tilde{s}^*_{34} \\ \dagger & \bar{f}_\oplus s^2_{24} & \bar{f}_\oplus s_{24} \tilde{s}^*_{34} \\ \dagger & \dagger & \bar{f}_\oplus s^2_{34} \end{bmatrix} = \bar{H}^{\rm SM}_{3\nu} + \bar{H}^{\rm NSI}_{3\nu}$$ *

$$\bar{H}^{\rm NSI}_{3\nu} = V_{CC} \bar{f}_\oplus u u^\dagger = ({\rm sgn}\, \bar{f}_\oplus) V_{\rm CC} \begin{bmatrix} |\varepsilon^\oplus_{ee}| & \sqrt{|\varepsilon^\oplus_{ee}||\varepsilon^\oplus_{\mu\mu}|} e^{i\phi_{e\mu}} & \sqrt{|\varepsilon^\oplus_{ee}||\varepsilon^\oplus_{\tau\tau}|} e^{i\phi_{e\tau}} \\ \dagger & |\varepsilon^\oplus_{\mu\mu}| & \sqrt{|\varepsilon^\oplus_{\mu\mu}||\varepsilon^\oplus_{\tau\tau}|} e^{i\phi_{\mu\tau}} \\ \dagger & \dagger & |\varepsilon^\oplus_{\tau\tau}| \end{bmatrix}$$

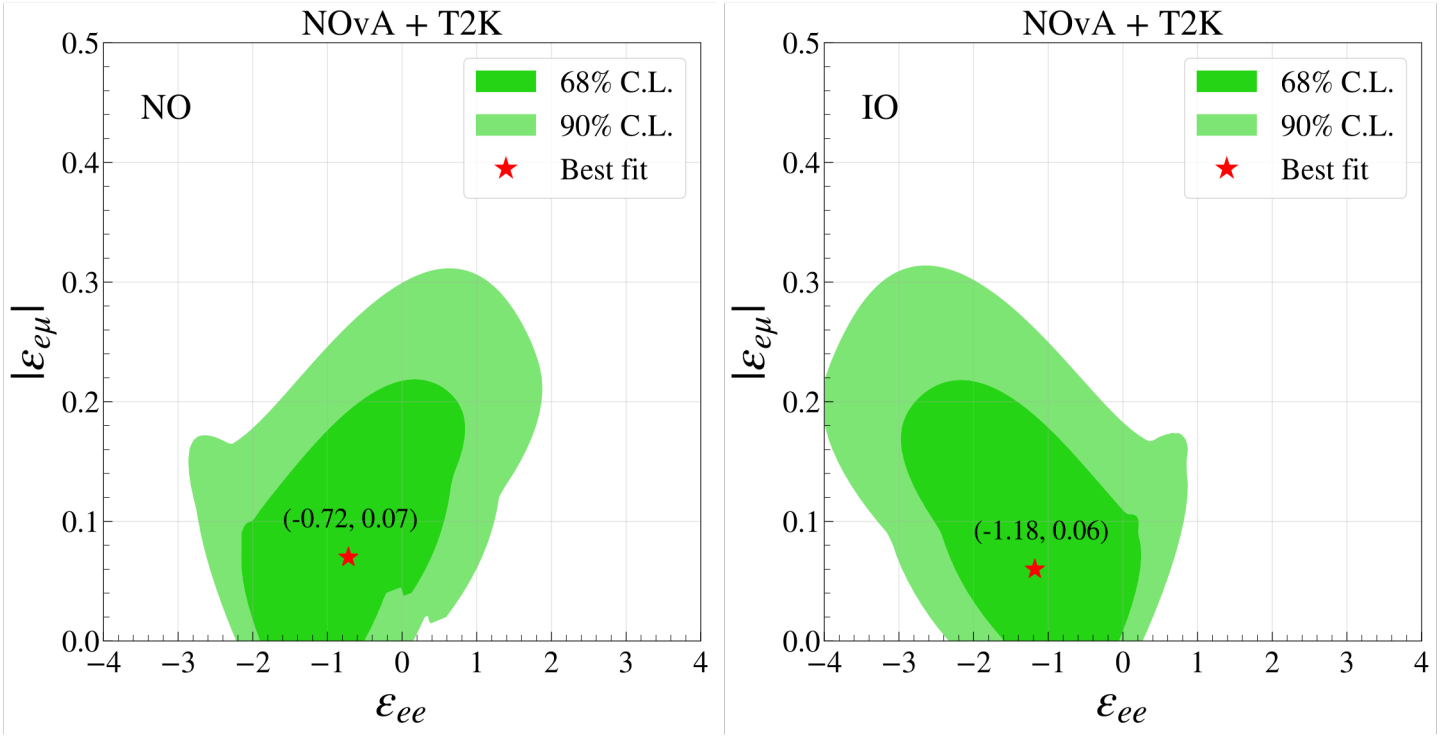
$$u = [\tilde{s}_{14}, s_{24}, \tilde{s}_{34}]^T$$

Distinctive non-generic NSI-like rank-1 Hamiltonian

NSI-like couplings are immune to bounds from charged leptons (via gauge-invariance) because they arise via mixing with a SU(2) singlet

* **Klop and Palazzo,** arXiv: 1412.7524 PRD 91, 073017 (2015)

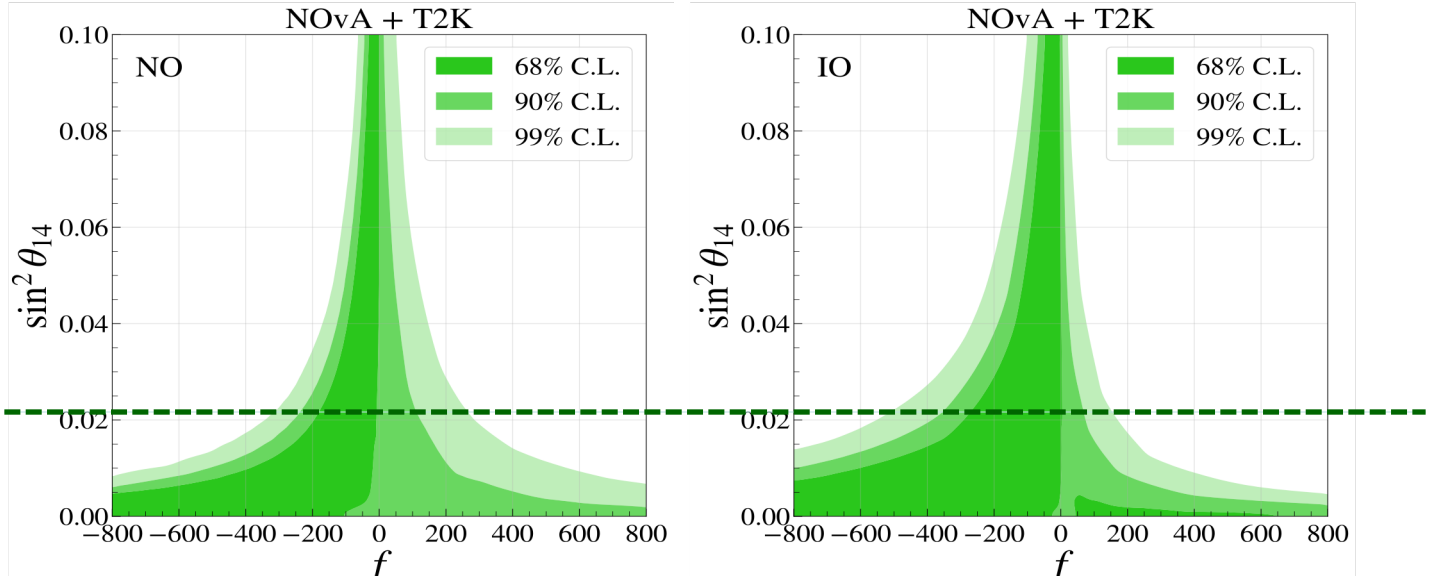
NOvA-T2K Tension suggests large NSI



However:

Ordinary NSI are problematic because of gauge-invariance

Interpretation of NOvA-T2K in the 3+1 scheme with new potential

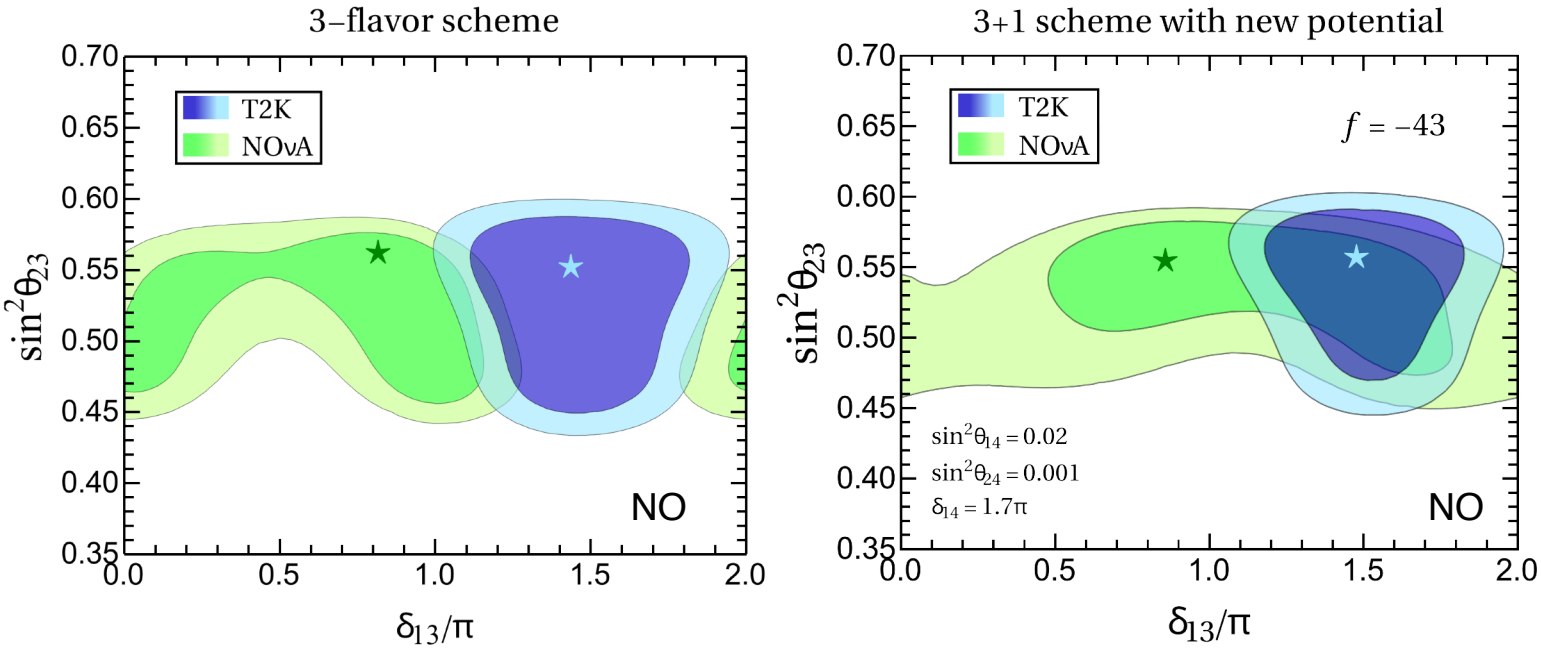


Regions follow contour lines of iso $\varepsilon_{ee} = f\, s^2_{14}$

Fixing a value of s^2_{14} determines a range for f

NOvA and T2K prefer negative values of f

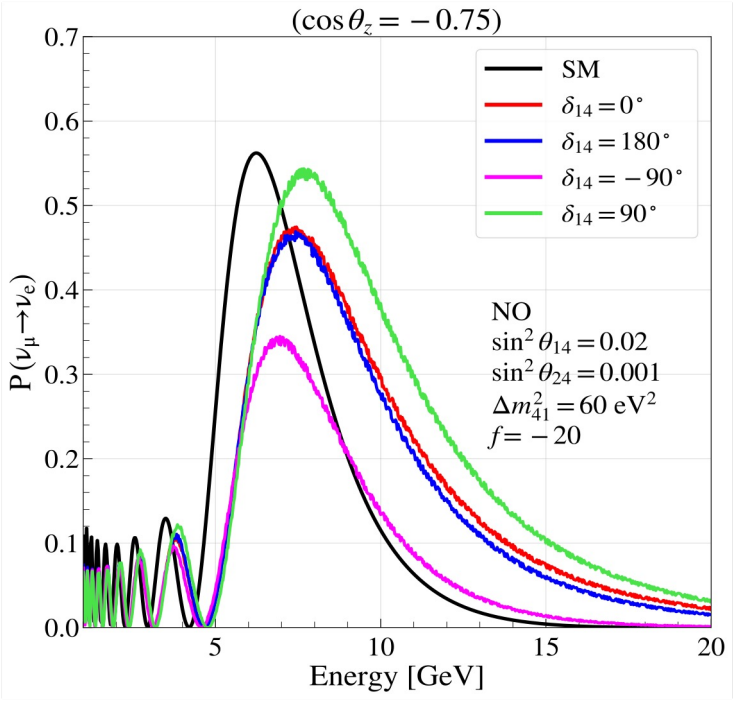
Resolution of the Tension between NOvA and T2K

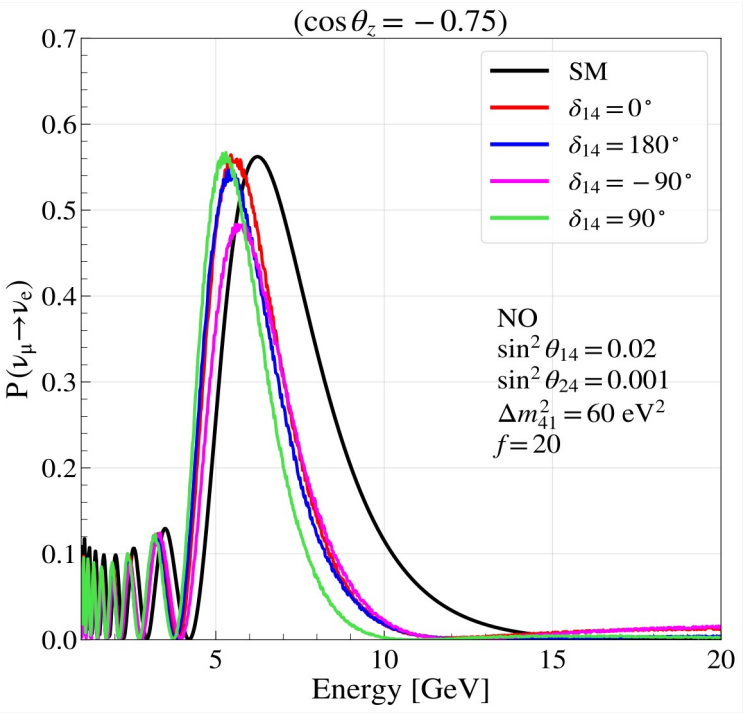


T2K regions almost unaltered: quasi-vacuum

NOνA regions strongly modified: matter-sensitive

NSI-like couplings modify the 6 GeV resonance in atm. νs





ν_e-like excess only in the case of negative potential (f<0)

This goes in the same direction of NOvA-T2K tension

High-energy unconventional (ν_μ-ν_e) resonance

Let's perform the previous change of basis

$$\bar{H}_{3\nu}^{(e\mu s)} = V_{\rm CC} \begin{bmatrix} 1+\bar{f}_\oplus s_{14}^2 & \bar{f}_\oplus \tilde{s}_{14} s_{24} & (1-\bar{f}_\oplus)\tilde{s}_{14} \\ \dagger & \bar{f}_\oplus s_{24}^2 & -\bar{f}_\oplus s_{24} \\ \dagger & \dagger & \bar{f}_\oplus + \frac{k_{41}}{V_{\rm CC}} \end{bmatrix} = V_{\rm CC} \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{es} \\ \dagger & \varepsilon_{\mu\mu} & \varepsilon_{\mu s} \\ \dagger & \dagger & \delta(E) \end{bmatrix}$$

Supposing $\theta_{34} = 0$ (no ν_τ)

Let's enucleate the toy Hamiltonian

$$\bar{H}_{3\nu}^{\prime(e\mu s)} = V_{\rm CC} \begin{bmatrix} 1 & 0 & \varepsilon_{es} \\ 0 & 0 & \varepsilon_{\mu s} \\ \dagger & \dagger & \delta(E) \end{bmatrix}$$

Two resonances (δ=0, δ=1)

ν_μ - ν_e conversion will be generated by amplified second order couplings

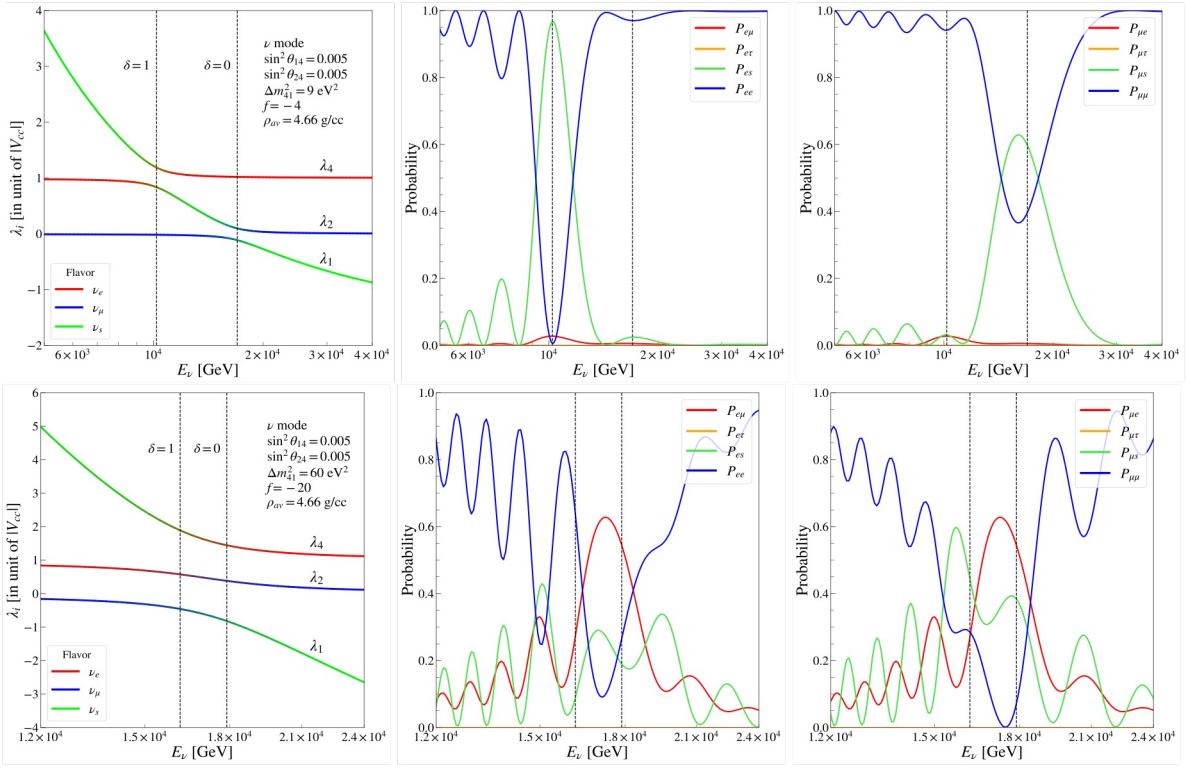
with

$$\varepsilon_{e\mu}^{eff} = \frac{\varepsilon_{es}\varepsilon_{\mu s}}{\delta} \qquad \varepsilon_{e\mu}^{eff} = \frac{\varepsilon_{es}\varepsilon_{\mu s}}{1-\delta} \qquad \varepsilon_{es}\varepsilon_{\mu s} \propto \bar{f}_\oplus^2 \tilde{s}_{14} s_{24}$$

ν_μ-ν_e resonance is driven by an underlying unconventional 3-level dynamics

|f| = 4

|f| = 20

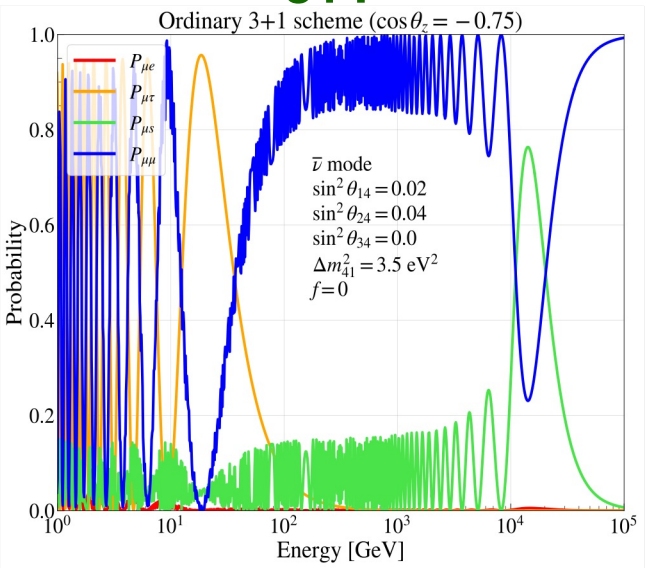


At large f, transition from 2-level to 3-level dynamics

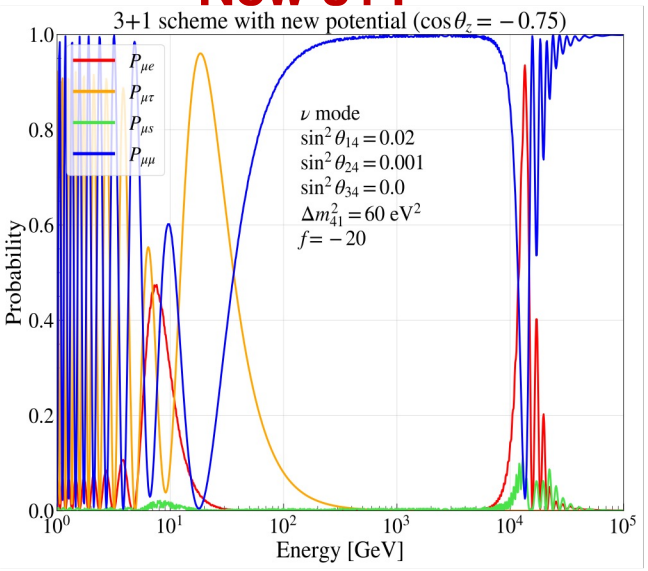
Emergence of a triple avoided crossing

IceCube Resonance (Mantle Crossing)

3+1



New 3+1



3+1: ν_μ -> ν_s conversion due to conventional 2-level dynamics

Large **$U^2_{\mu 4}$ = 0.04** involving (**in tension** with MINOS+/NOvA)

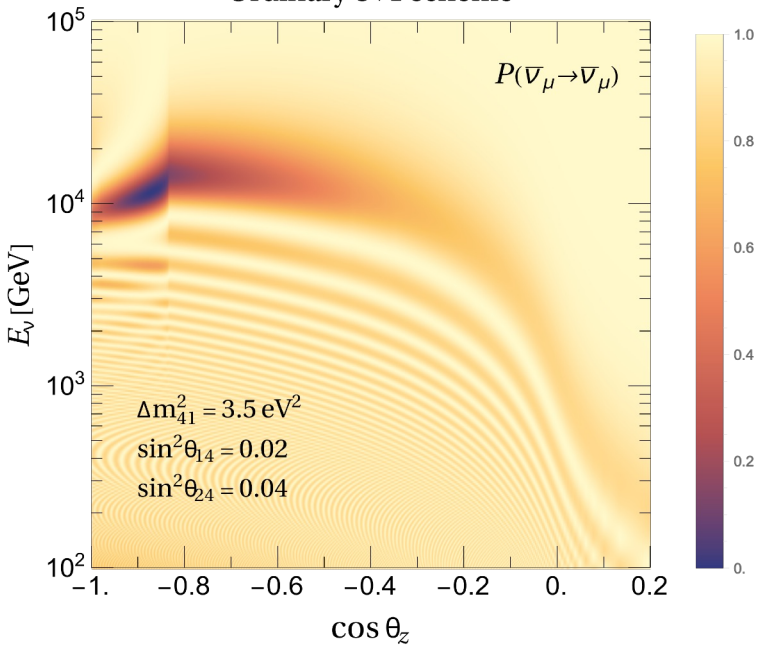
New 3+1: mostly ν_μ -> ν_e conversion due to unconventional 3-level dynamics

Small **$U^2_{\mu 4} = 10^{-3}$** involving (**No tension** with MINOS+/NOvA)

The oscillogram is different wrt ordinary 3+1

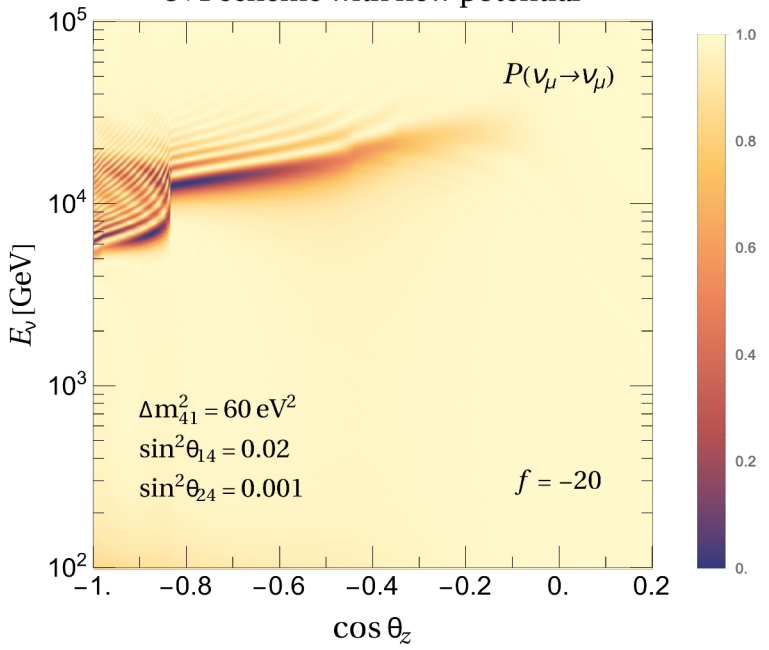
3+1

Ordinary 3+1 scheme



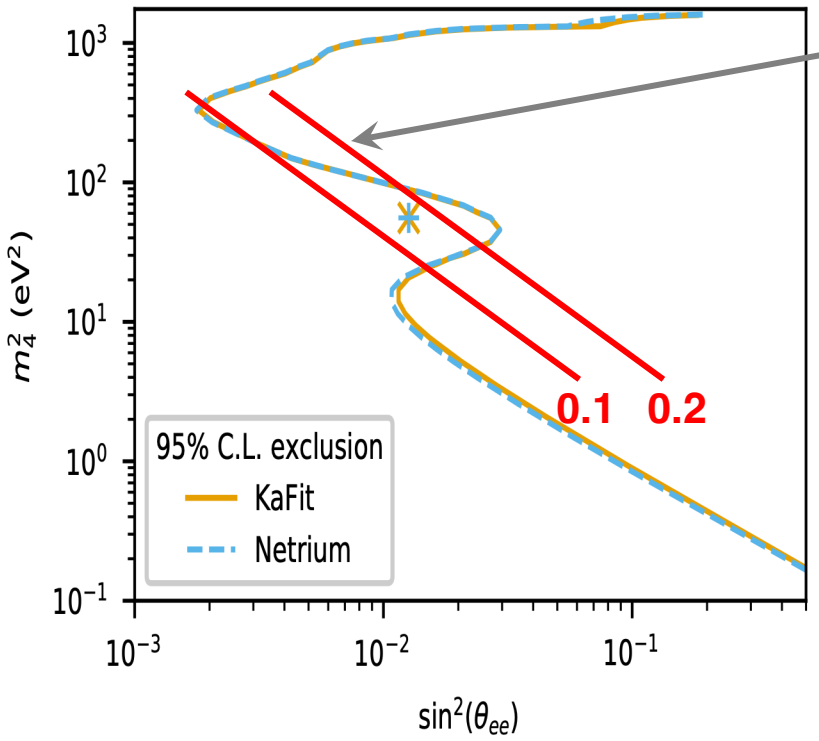
New 3+1

3+1 scheme with new potential



Also, differently from the conventional 3+1 scheme, the new scenario predicts cascades (ν_e)

KATRIN can directly probe the kinematical parameters ($\Delta m^2_{41}, \theta_{14}$)



Curves of iso $|\varepsilon_{ee}|$

Benchmark parameters

$$\varepsilon_{ee} = \bar{f} s^2_{14} = -\frac{\Delta m^2_{41}}{E_{Res}} \frac{s^2_{14}}{V_{cc}}$$

-0.2

-10

0.02

60 eV^2

15 TeV

Mantle

KATRIN is also indirectly sensitive to the new matter potential

Conclusions

The anomalies in neutrino oscillation experiments span a vast range of baselines and energies

Pseudo-Sterile neutrinos can provide a coherent picture of the anomalies, avoiding key tensions of the conventional 3+1 scheme

At low energies, new effective NSI-like couplings emerge with a non-generic rank-1 structure

The new effective NSI are immune to gauge-invariance bounds

At high energies, a new class of resonant phenomena, previously unidentified, emerge involving an irreducible multilevel dynamics

The proposed framework can be probed through complementary tests at KATRIN, Hyper-Kamiokande, DUNE, and neutrino telescopes

Thank you for your attention!

Back up slides

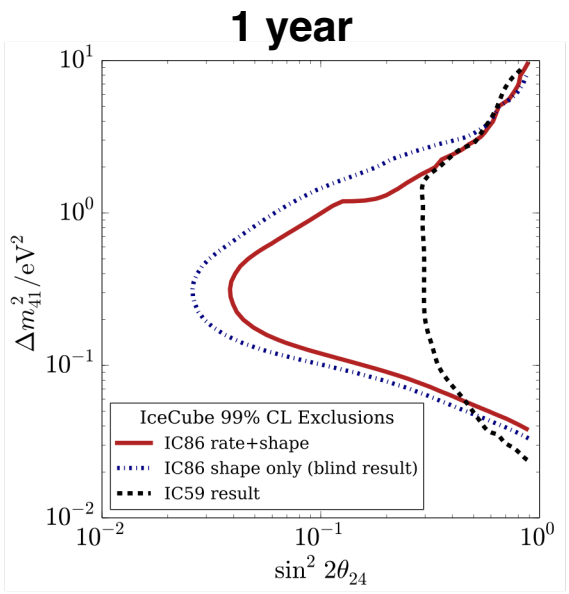
Previous works on interacting "sterile" ν *

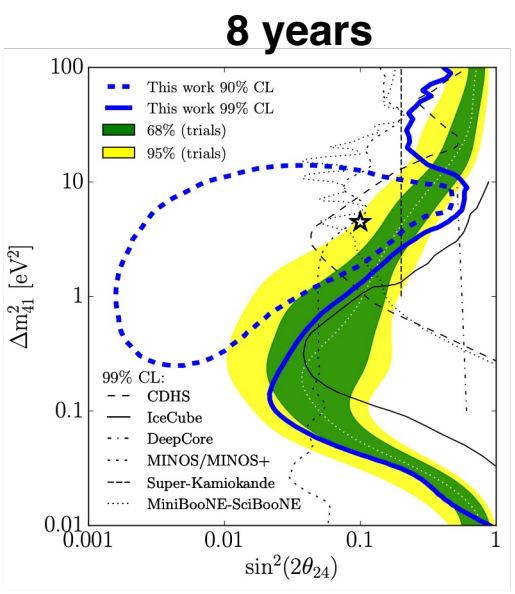
[1] Belotsky, Sudarikov, Khlopov, Phys. Atom. Nucl. 64 (2001) 1637.
[2] Nelson, Walsh, PRD 77 (2008) 033001, arXiv:0711.1363 [hep-ph].
[3] Engelhardt, Nelson, Walsh, PRD 81 (2010) 113001, arXiv:1002.4452 [hep-ph].
[4] Pospelov, PRD 84 (2011) 085008, arXiv:1103.3261 [hep-ph].
[5] Karagiorgi, Shaevitz, Conrad, arXiv:1202.1024 [hep-ph].
[6] Kopp, Welter, JHEP 12 (2014) 104, arXiv:1408.0289 [hep-ph].
[7] Berryman, Brdar, Huber, PRD 99 no. 5, (2019) 055045, arXiv:1803.08506 [hep-ph].
[8] Liao, Marfatia, Whisnant, PRD 99 no. 1, (2019) 015016, arXiv:1810.01000 [hep-ph].
[9] Esmaili, Nunokawa, EPJ. C 79 no. 1, (2019) 70, arXiv:1810.11940 [hep-ph].
[10] Denton, Farzan, Shoemaker, PRD 99 no. 3, (2019) 035003, arXiv:1811.01310 [hep-ph].
[11] Alves, Louis, deNiverville, JHEP 08 (2022) 034, arXiv:2201.00876 [hep-ph].
[12] Sponsler, Hostert, Martinez-Soler, Arguelles, arXiv:2405.12140 [hep-ph].
[13] Brdar, Chattopadhyay, PRL 136, 081001, arXiv:2502.21299 [hep-ph].

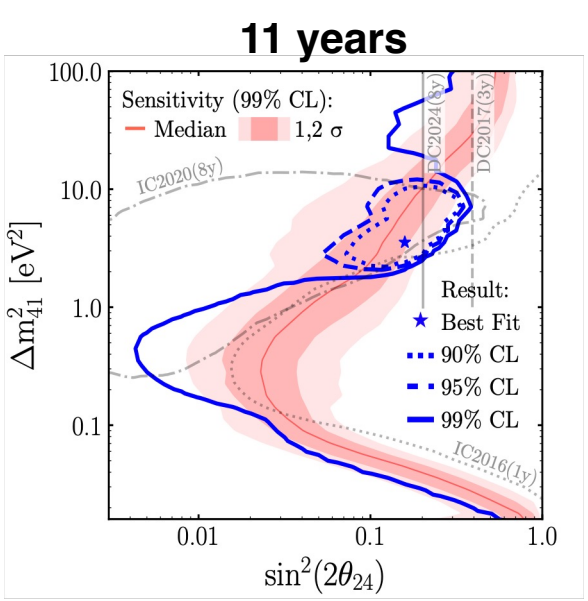
However, no conclusion reached so far on their concrete role in the anomalies

*** In addition, several related works on "secret interactions" in cosmology**

Hint of a resonance in IceCube





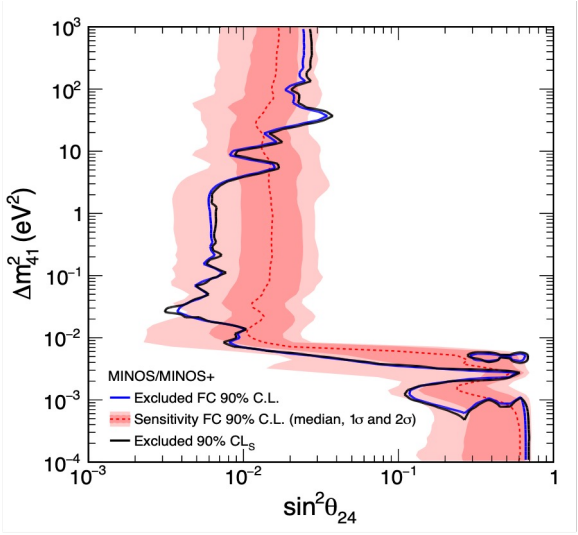


IceCube
arXiv: 1605.01990 [hep-ex]
PRL 117, 071801 (2020)

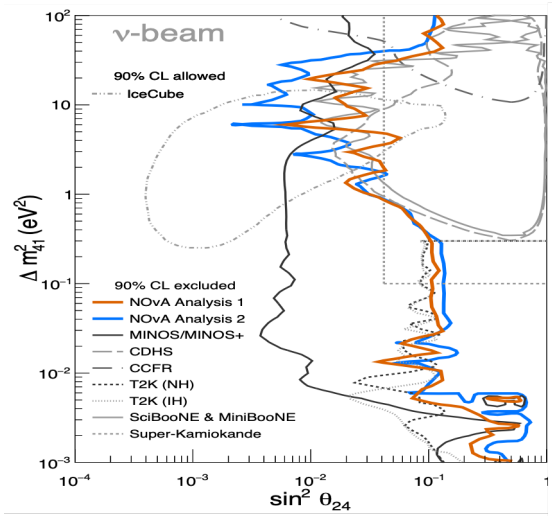
IceCube
arXiv: 2005.12942 [hep-ex]
PRL 125, 141801 (2020)

IceCube
arXiv: 2405.08070 [hep-ex]
PRL 133, 201804 (2024)

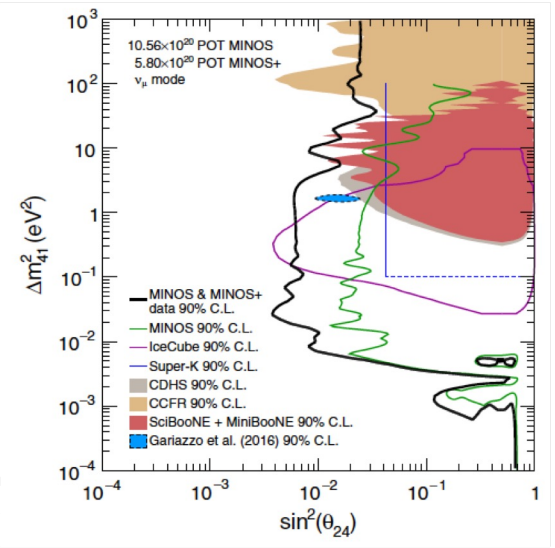
No ν_μ disappearance in SBL/LBL



MINOS/MINOS+
arXiv: 2002.00301 [hep-ex]
PRL 125, 071801 (2020)



NOvA
arXiv: 2409.04553 [hep-ex]
PRL 134, 081804 (2025)



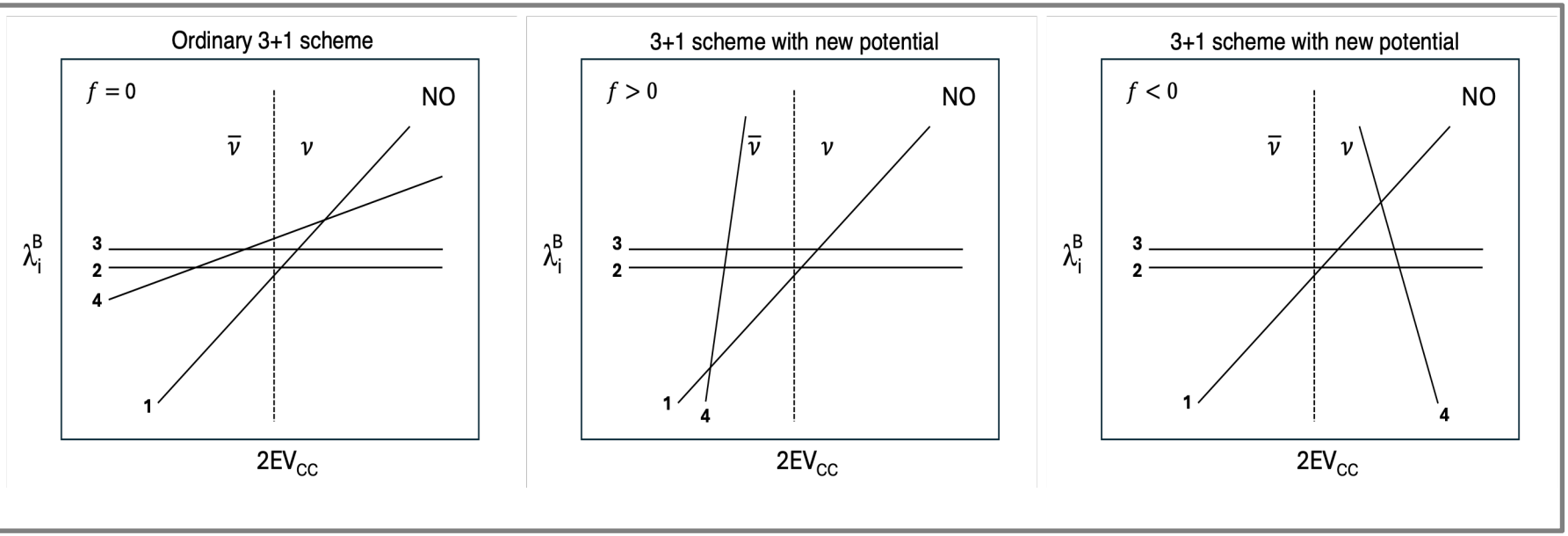
CCFR and CDHS
SciBooNE+MiniBooNE

3σ tension with IceCube Resonance in 3+1 scheme

Villareal et al.
arXiv: 2507.01153 [hep-ph]

Understanding the conventional resonances

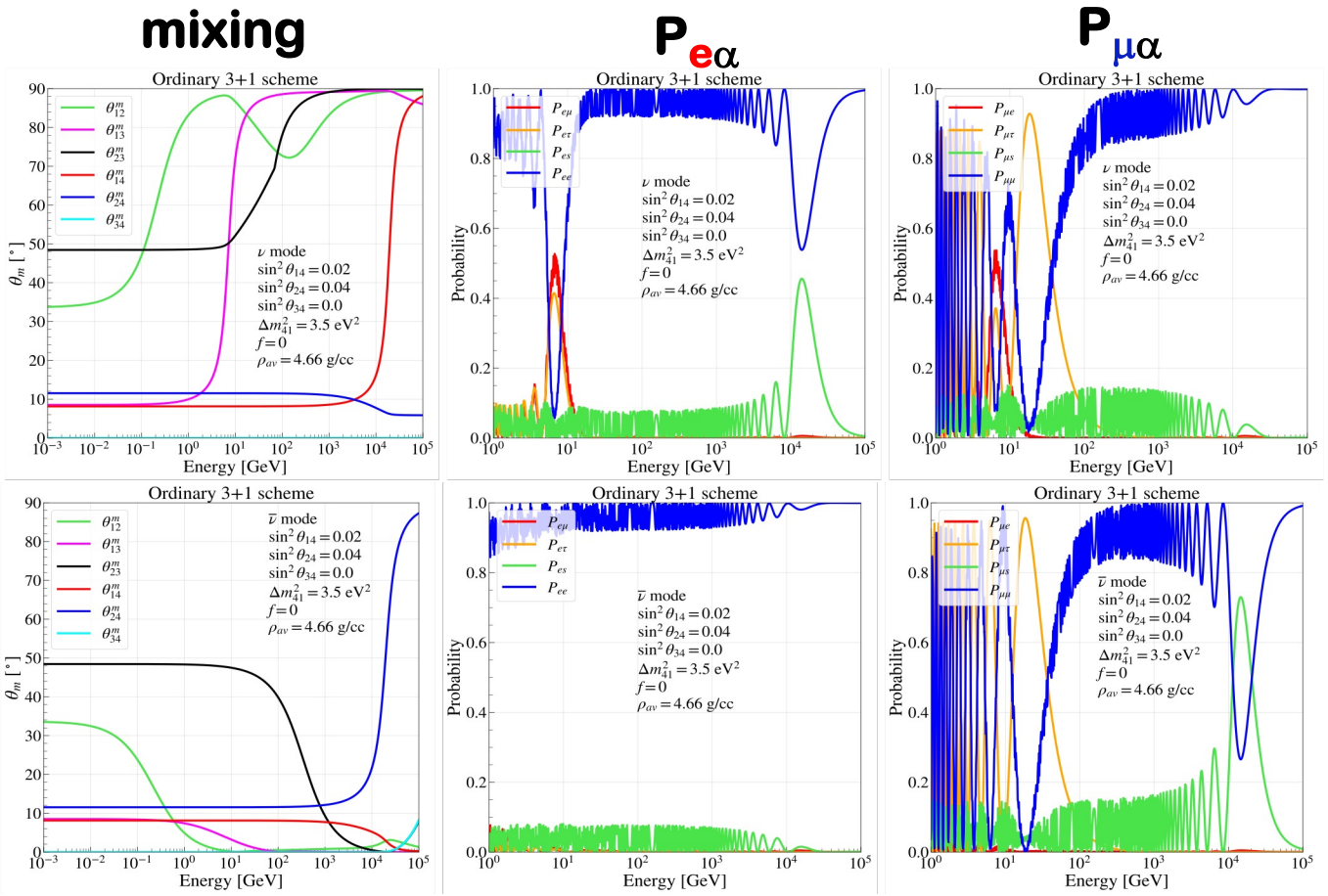
The "bare level crossing diagram" *



$$H_{4\nu}^{\text{bare}} = K + V = \frac{1}{2E}\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 & 0 \\ 0 & 0 & \Delta m^2_{31} & 0 \\ 0 & 0 & 0 & \Delta m^2_{41} \end{bmatrix} + \begin{bmatrix} V_{\text{CC}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \bar{f} V_{CC} \end{bmatrix}$$

* See also Brettell, Martinez-Soler, Minakata JHEP 04 (2025) 011

Resonances in the ordinary 3+1 scheme



Only conventional resonances develop

Resonances in the New 3+1 scheme (large f < 0 case)

ν

θ_{14}^m ν_e-ν_s

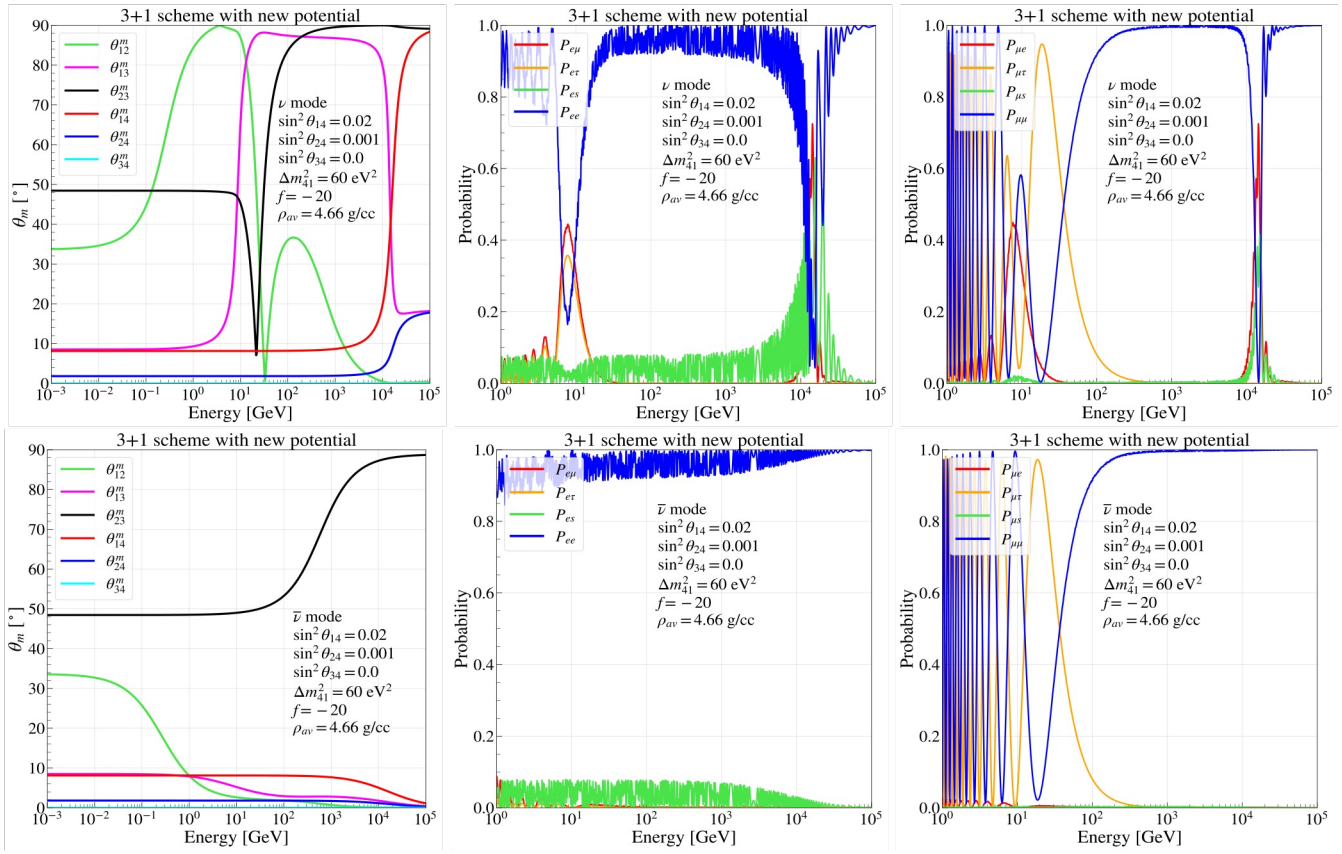
θ_{24}^m ν_μ-ν_s

θ_{13}^m ν_μ-ν_e

$\overline{\nu}$

No Resonance

mixing | **$P_{e\alpha}$** | **$P_{\mu\alpha}$**



An unconventional resonance develops (ν_μ-ν_e)

How the effective non-zero θ_{12}^m originates*

$$H_{3\nu}^{(e\mu s)} = R_{24} R_{14} K' R_{14}^T R_{24}^T + V' \simeq \begin{bmatrix} V_{\rm CC} + k s_{14}^2 & k s_{14} s_{24} & k s_{14} \\ \dagger & k s_{24}^2 & k s_{24} \\ \dagger & \dagger & \bar{f} V_{CC} + k \end{bmatrix}$$

Supposing $\theta_{34} = 0$ (no ν_τ)

$$U_{3\nu}^m = R_{24}^m R_{14}^m R_{12}^m$$

Diagonalizing mixing matrix

1) $\theta_{14} = 0, \ \theta_{24} \neq 0 \longrightarrow U_{3\nu}^m = R_{24}^m$

2) $\theta_{14} \neq 0, \ \theta_{24} = 0 \longrightarrow U_{3\nu}^m = R_{14}^m$

3) $\theta_{14} \neq 0, \ \theta_{24} \neq 0 \longrightarrow U_{3\nu}^m = R_{24}^m R_{14}^m R_{12}^m$

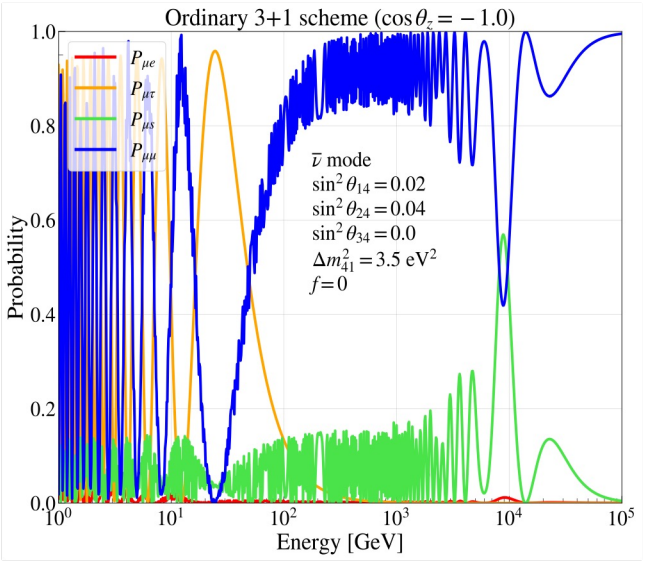
θ_{12}^m will depend on (θ_{14}, θ_{24}, f, k): one needs to solve a cubic

θ_{12}^m is unrelated to its vacuum value θ_{12}

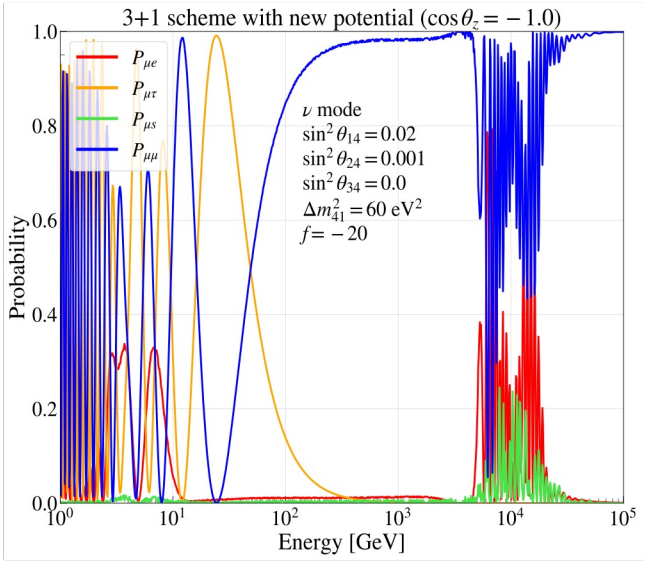
*In the full 4-flavor treatment θ_{12}^m is replaced by θ_{13}^m

IceCube Resonance (Core Crossing)

3+1



New 3+1



strong parametric effects

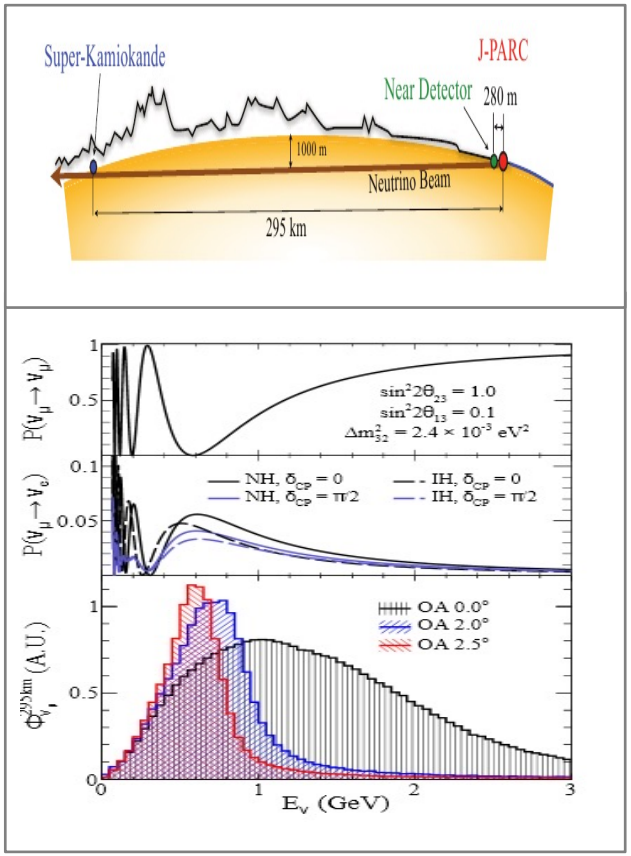
3+1: ν_μ -> ν_s conversion due to conventional 2-level dynamics

Large $U^2_{\mu 4}$ **= 0.04** involved (**in tension** with MINOS+/NOvA)

New 3+1: ν_μ -> ν_e conversion due to unconventional 3-level dynamics (**mostly**)

Small $U^2_{\mu 4}$ **= 10^{-3}** involved (**No tension** with MINOS+/NOvA)

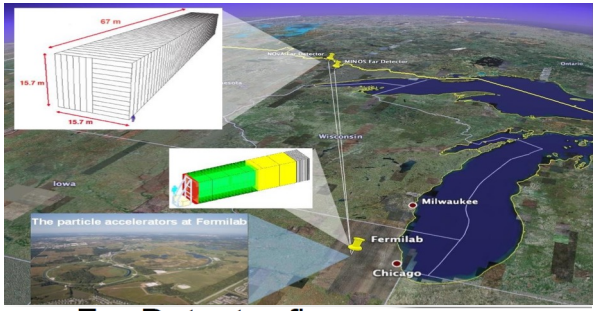
T2K & NOvA: similar but different

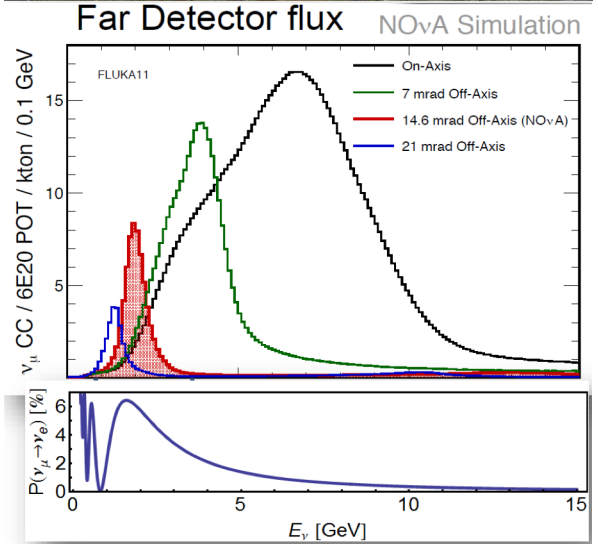


off-axis beam

$$\Delta = \frac{\Delta m^2_{13} L}{4E} \simeq \frac{\pi}{2}$$

First oscillation maximum





E = 0.6 GeV
L = 295 km

E = 2 GeV
L = 810 km

Why to consider non-standard interactions

Chatterjee and Palazzo, arXiv: 2008:0416, PRL 126 051801 (2021)

T2K and NOvA have different baselines and peak energies (L/E = costant)

Matter effects depend on the ratio $v = \frac{2V_{CC}E}{\Delta m^2_{31}} = 0.18\left[\frac{E}{2.0\,\mathrm{GeV}}\right]$

T2K $v \sim 0.05$

NOvA $v \sim 0.17$

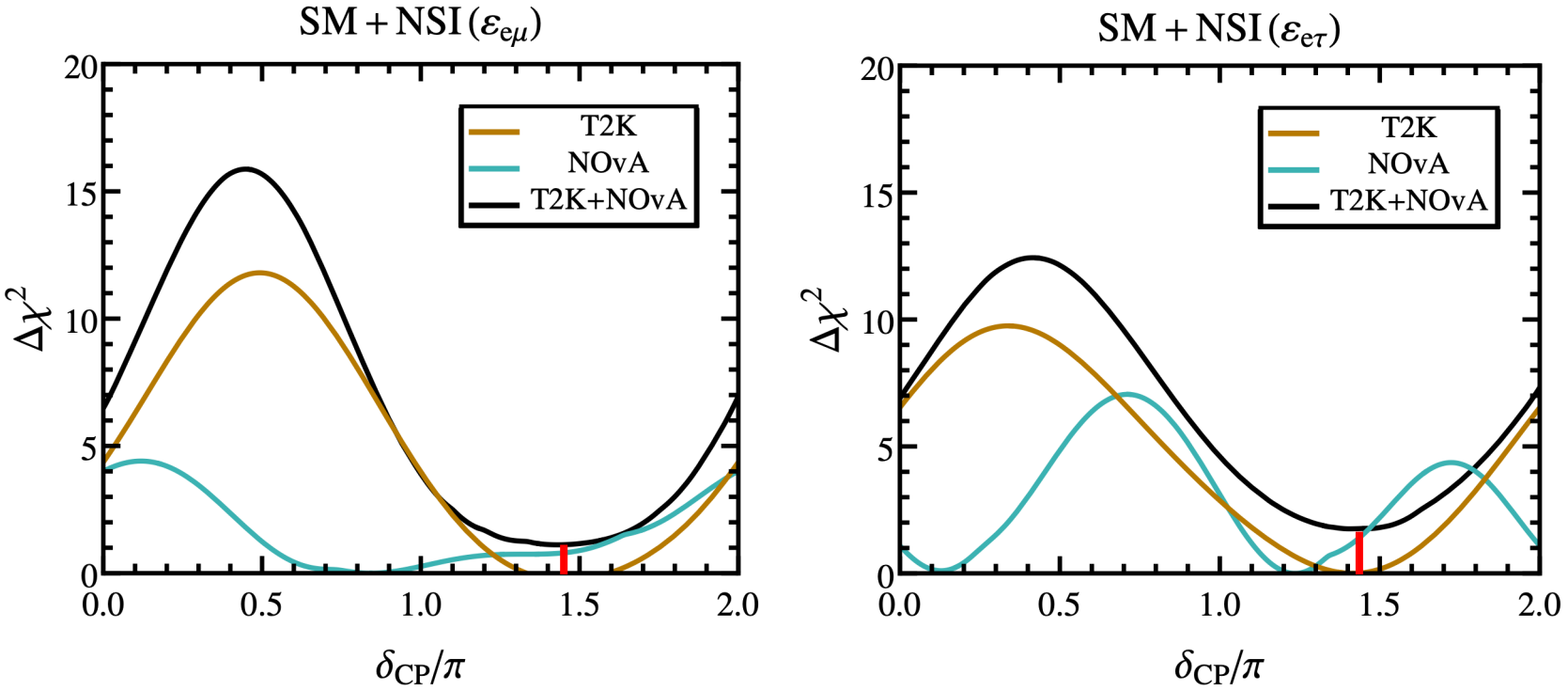
New matter effects encoded by NSI are also proportional to v

Basic Idea: suppose NSI exist, then:

T2K is a "quasivacuum" experiment. Its estimate of δ_{CP} is independent of NSI.

NOvA is a "matter dominated" experiment. The extracted value of δ_{CP} is affected by NSI. If NSI are taken into account, the estimate of δ_{CP} should return in agreement with that of T2K.

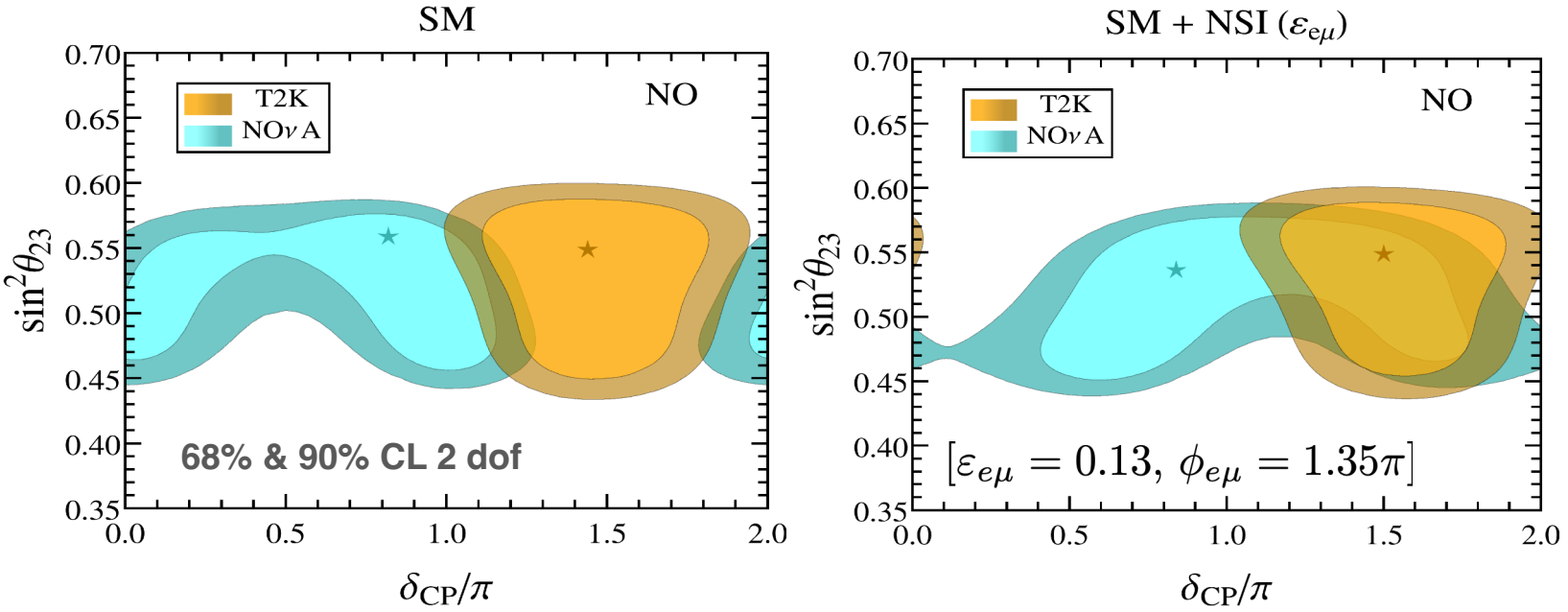
NSI substantially reduce the tension



Single $\Delta\chi^2$ obtained for the best fit of T2K + NOνA:

$$\begin{cases} [\varepsilon_{e\mu} = 0.13,\ \phi_{e\mu} = 1.35\pi] \\ [\varepsilon_{e\tau} = 0] \end{cases} \qquad \begin{cases} [\varepsilon_{e\mu} = 0] \\ [\varepsilon_{e\tau} = 0.22,\ \phi_{e\tau} = 1.70\pi] \end{cases}$$

NSI bring the estimates of δ_{CP} in agreement



T2K regions almost unaltered **NOνA regions strongly modified**

See also Denton, Gehrlein & Pestes, PRL 126 051801 (2021)

The Matter-Vacuum Synergy

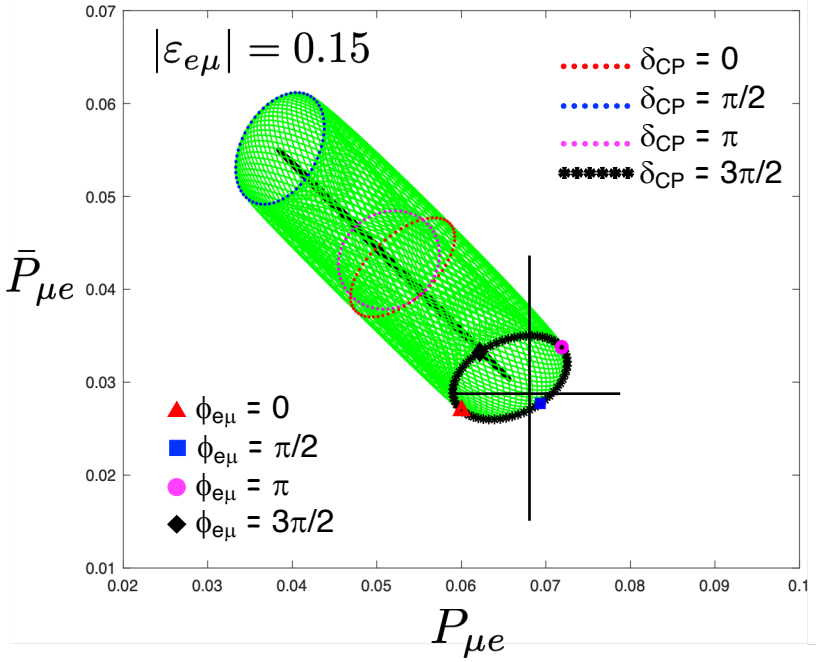
Use T2K as an anchor for NOvA

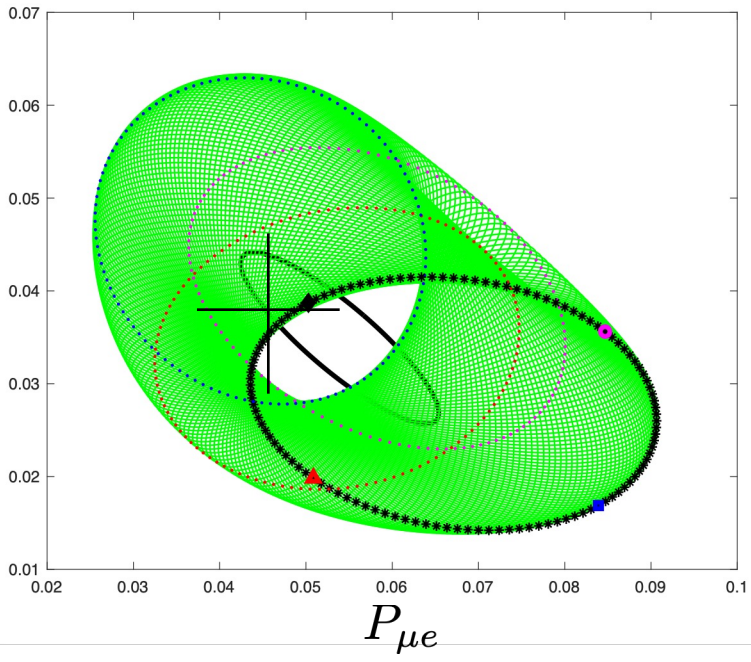
T2K

Strongly favors $\delta_{CP} \sim 3\pi/2$ ellipse
(almost no sensitivity to $\phi_{e\mu}$)

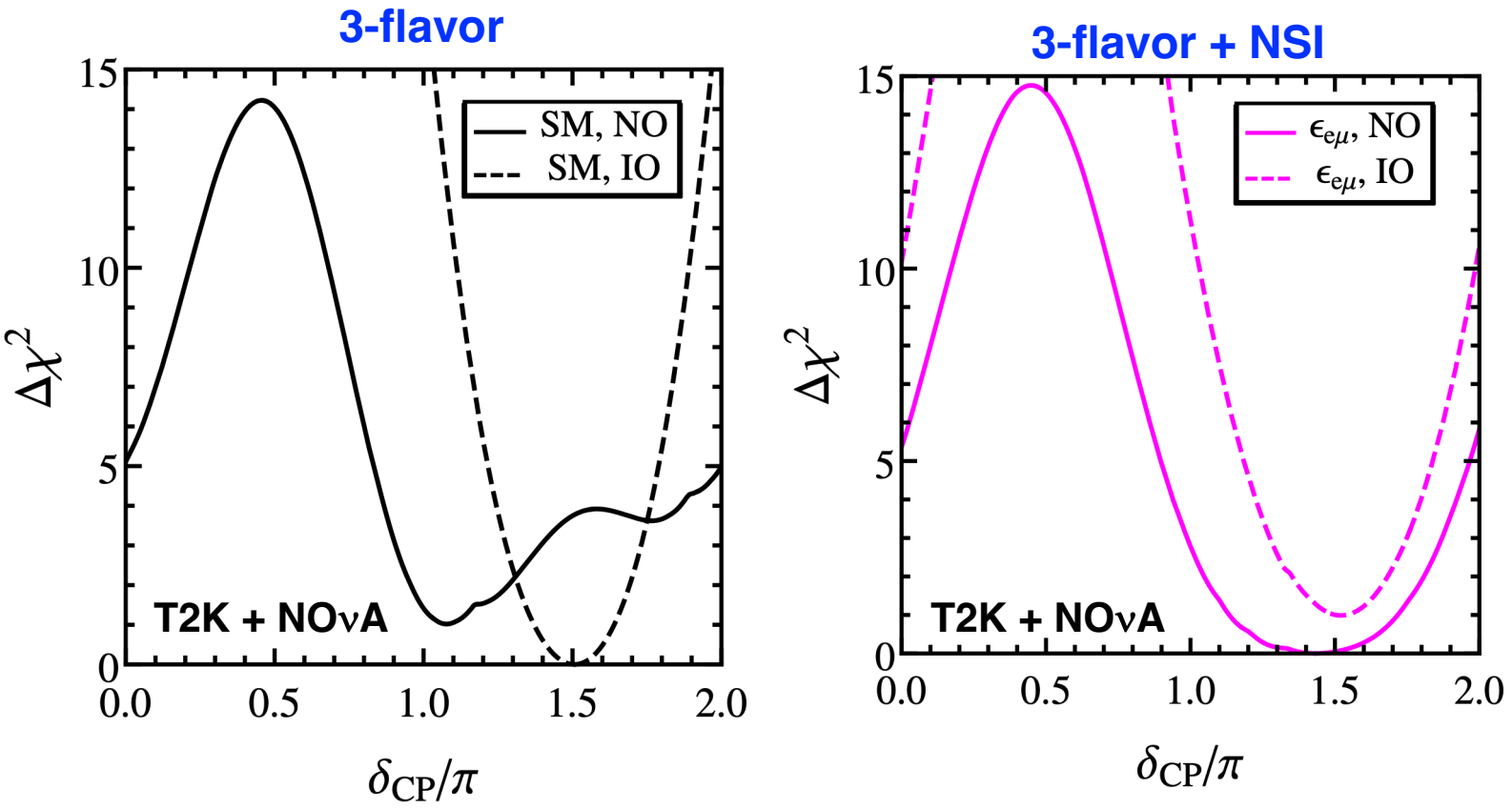
NOνA

In agreement with $\delta_{CP} \sim 3\pi/2$ ellipse.
On this ellipse it pins down $\phi_{e\mu} \sim 3\pi/2$



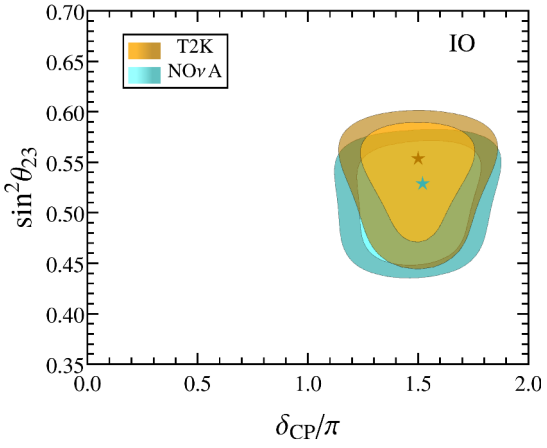


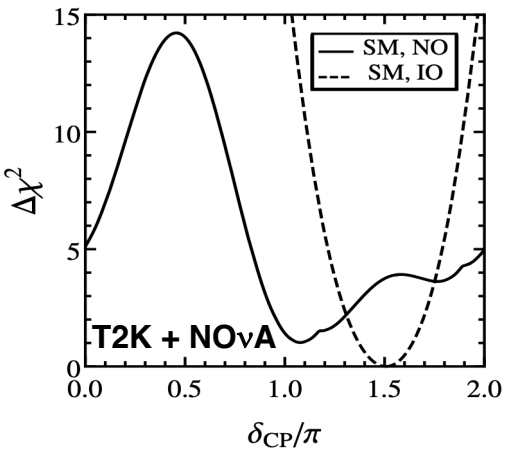
NSI restore the preference for NO

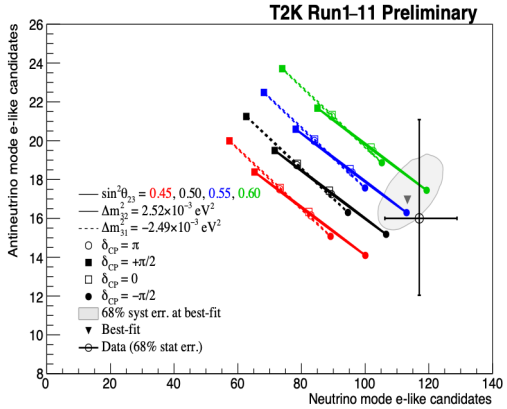


Better agreement with all the other data

Can the tension be resolved assuming IO?







For IO the best fit of δ_{CP} is the same in T2K and NOvA (left panel).

However, IO gains only $\chi^2_{IO} - \chi^2_{NO} \sim -1$ in T2K + NOvA combination (middle panel).

The reason is that T2K disfavors IO (dotted ellipses) (right panel).

T2K and NOνA disappearance channel + JUNO prefer NO ($\chi^2_{IO} - \chi^2_{NO} \sim 5$).

SK atmospheric data prefer NO ($\chi^2_{IO} - \chi^2_{NO} \sim 11$).

Therefore, IO seems strongly disfavored

Four ways of looking at the NOvA-T2K tension

1) In NO they prefer "orthogonal" values of δ_{CP} (T2K $\delta_{CP} = 1.5\ \pi$, NOvA $\delta_{CP} = \pi$)

2) Taken alone they prefer NO but jointly prefer IO

3) They jointly prefer IO while all other data prefer NO

4) They prefer zero MSW effect as if they were operating in vacuum ($\varepsilon_{ee} = -1$ preferred)

What theory says about (ordinary) NSI?

T2K and NOνA point to effective couplings of about 0.2. These can be obtained with fundamental couplings on electrons, u and d quarks of a few %. This is still a large number from a theoretical perspective.

Neutrinos are components of an $SU(2)_L$ doublet. Gauge invariance at high energies implies that NSI operators come together with operators involving charged leptons, on which there are strong constraints from CLFV.

So, it is very difficult to build models with large NSI [Gavela et al. 0809.3451]

Some possibilities:

Heavy mediators
- **Tree-level see-saw** [Forero & Huang 1608.04719]
- **Radiative see-saw** [Babu et al. 1907.09498]

Light mediators are an appealing alternative
Farzan, Heeck 1607.07616 Farzan 1912.09408

Note that forward scattering probes $q^2 = 0$ and a light mediator is felt as an heavy one. Hence, also in this case it is legitimate to describe NSI by an effective dim-6 operator.