T2K-NOvA Tension and Physics BSM

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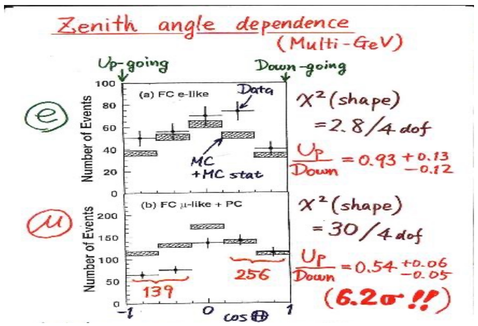
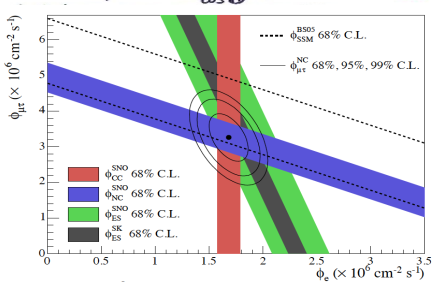
Outstanding progress in ν physics in ~ 25 years

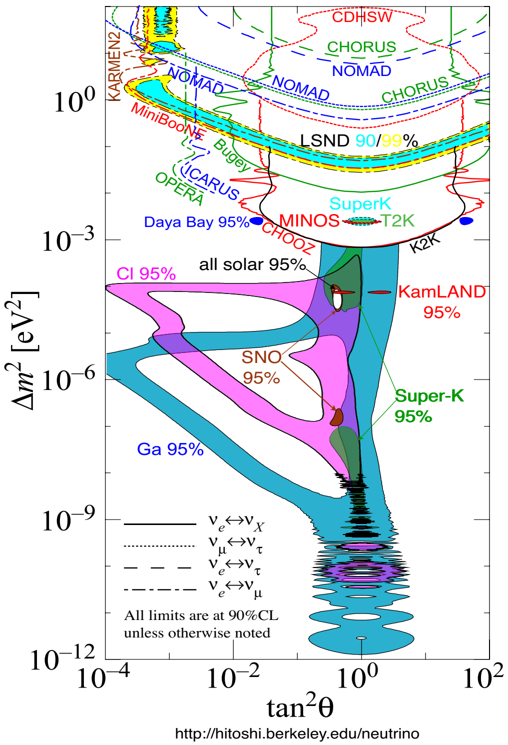
Discoveries





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

Interpretation



known knowns

$\delta m^2/eV^2$ ~ 7.34 x 10^{-5} ±2.2%
$\Delta m^2/eV^2$ ~ 2.48 x 10^{-3} ±1.3%
$\sin^2\theta_{12}$ ~ 0.303 ±4.4%
$\sin^2\theta_{13}$ ~ 0.0225 ±3.8%
$\sin^2\theta_{23}$ ~ 0.545 ±5.0%

known unknowns

δ(CP)
sign(Δm^2)
octant(θ_{23})
absolute ν mass
Dirac/Majorana
NSI, sterile states,
non-unitarity, …

unkown unknowns

3-flavor scheme now established as the standard framework…

The 3ν mixing matrix

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \qquad U = O_{23}\Gamma_\delta O_{13}\Gamma^\dagger_\delta O_{12}$$

$$\Gamma_\delta = \mathrm{diag}(1, 1, e^{+i\delta})$$

$$\delta \in [0, 2\pi]$$

Dirac CP-violating phase δ

U is non-real if $\delta \neq (0, \pi)$

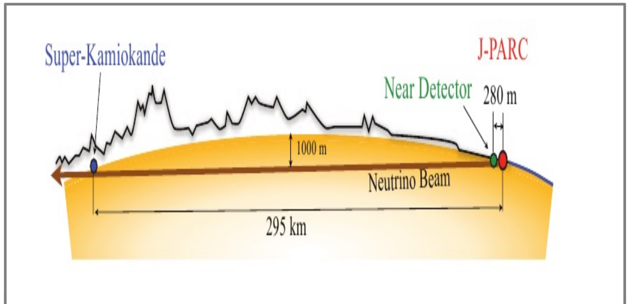
Explicit form

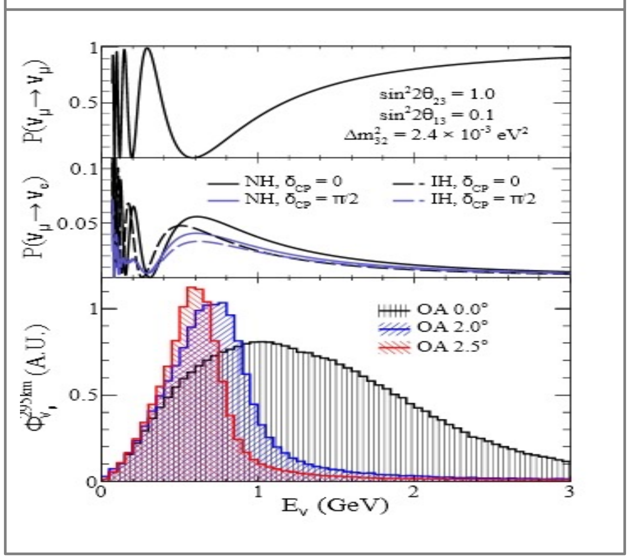
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45^\circ$ **$\theta_{13} \sim 9^\circ$** **$\theta_{12} \sim 34^\circ$**

Three non-zero θ_{ij}: Way open to CPV searches…

Two main actors: T2K & NOνA

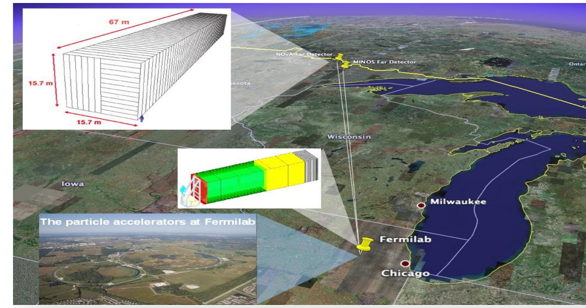


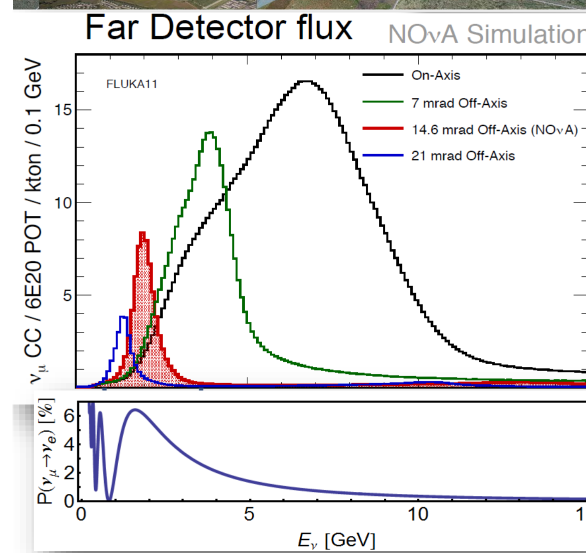


off-axis beam

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

First oscillation maximum

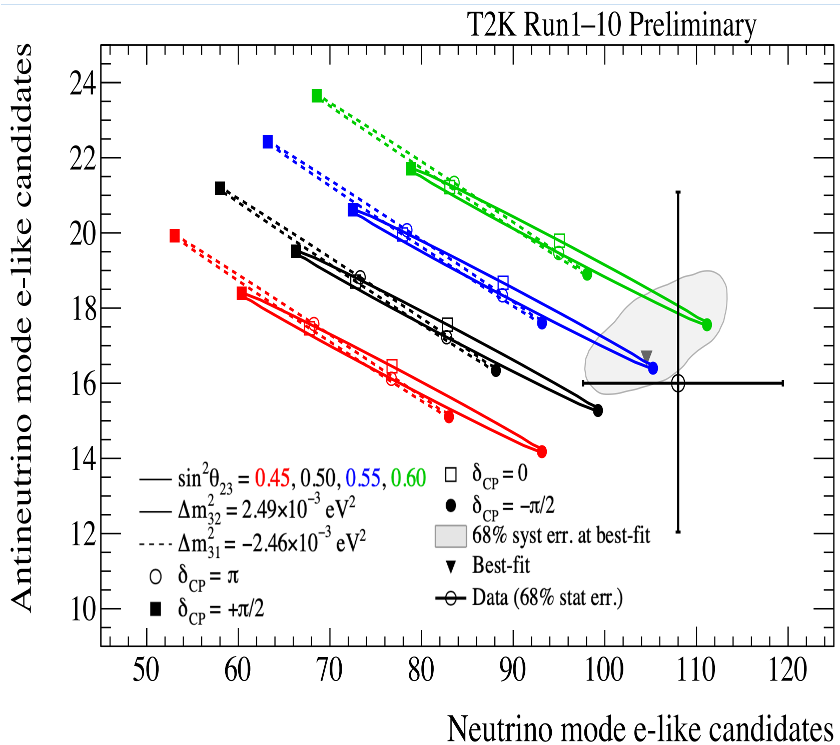


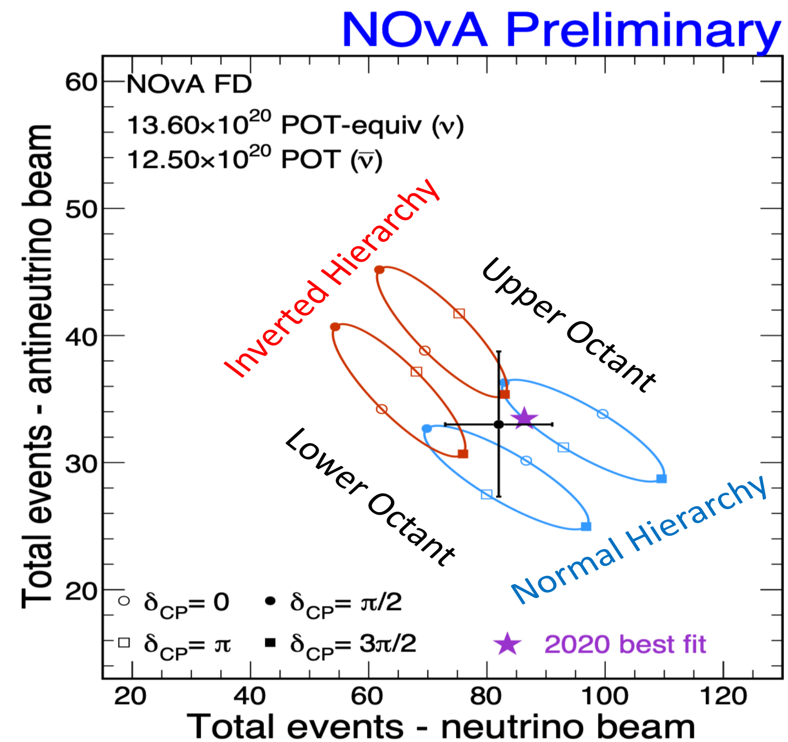


E = 0.6 GeV
L = 295 km

E = 2 GeV
L = 810 km

Bird's-eye view: 2020

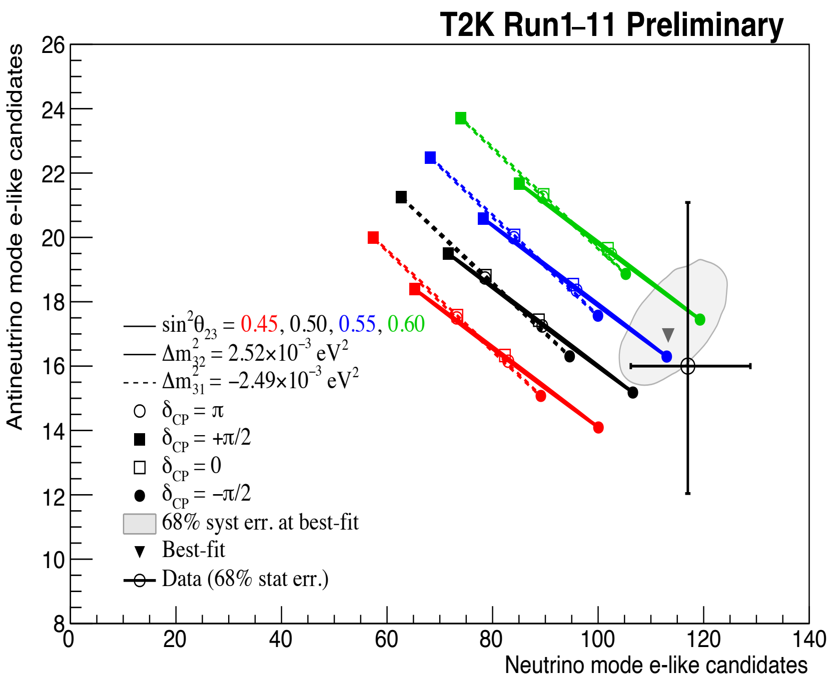




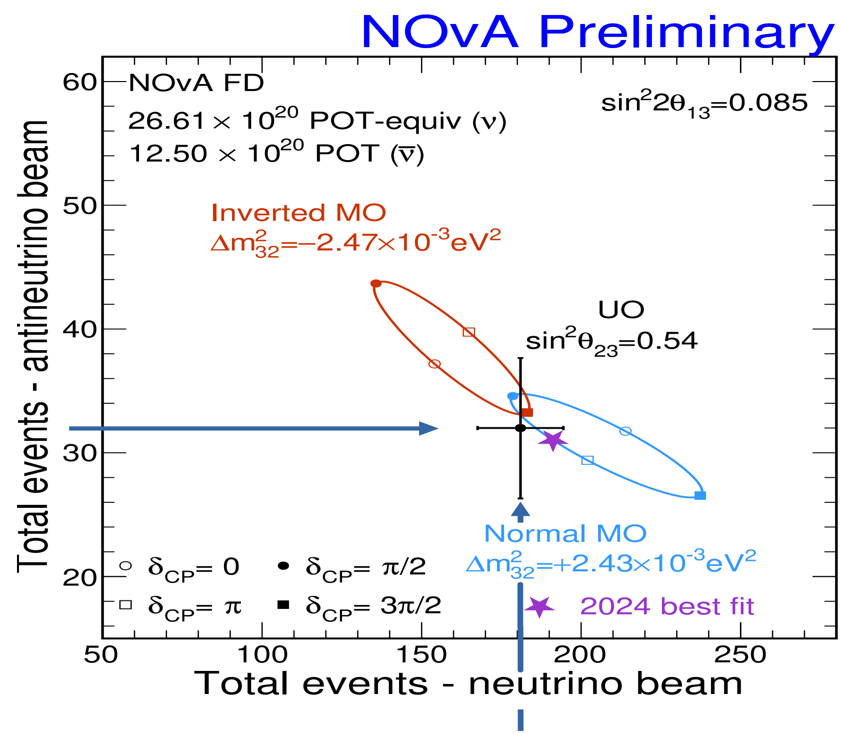
TENSION for Nomal Ordering:

- **T2K prefers $\delta_{CP} \sim 1.5\pi$**
- **NOνA prefers $\delta_{CP} \sim 0.8\pi$**

Bird's-eye view: 2024



T2K almost unaltered statistics



NOvA doubled ν statistics

TENSION INCREASED for Nomal Ordering:

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

Almost unchanged

Soon after Neutrino 2020

PHYSICAL REVIEW LETTERS **126,** 051802 (2021)

Nonstandard Neutrino Interactions as a Solution to the NOνA and T2K Discrepancy

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(Received 17 August 2020; accepted 3 December 2020; published 4 February 2021)

The latest data of the two long-baseline accelerator experiments NOνA and T2K, interpreted in the standard three-flavor scenario, display a discrepancy. A mismatch in the determination of the standard *CP* phase δ_{CP} extracted by the two experiments is evident in the normal neutrino mass ordering. While NOνA prefers values close to $\delta_{\mathrm{CP}} \sim 0.8\pi$, T2K identifies values of $\delta_{\mathrm{CP}} \sim 1.4\pi$. Such two estimates are in disagreement at more than 90% C.L. for 2 degrees of freedom. We show that such a tension can be resolved if one hypothesizes the existence of complex neutral-current nonstandard interactions (NSIs) of the flavor changing type involving the $e-\mu$ or the $e-\tau$ sectors with couplings $|\varepsilon_{e\mu}| \sim |\varepsilon_{e\tau}| \sim 0.2$. Remarkably, in the presence of such NSIs, both experiments point towards the same common value of the standard *CP* phase $\delta_{\mathrm{CP}} \sim 3\pi/2$. Our analysis also highlights an intriguing preference for maximal *CP* violation in the nonstandard sector with the NSI *CP* phases having best fit close to $\phi_{e\mu} \sim \phi_{e\tau} \sim 3\pi/2$, hence pointing towards imaginary NSI couplings.

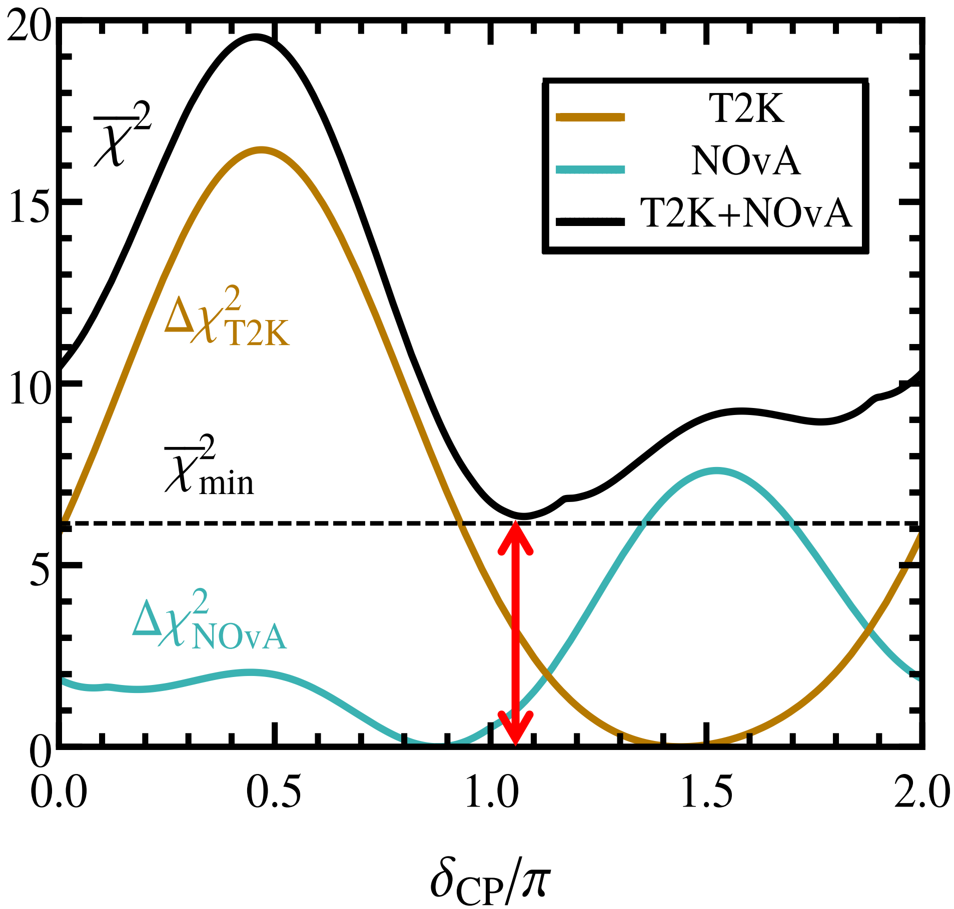
DOI: 10.1103/PhysRevLett.126.051802

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

After Neutrino 2024

Chatterjee & Palazzo arXiv:2409.XXXXX

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



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

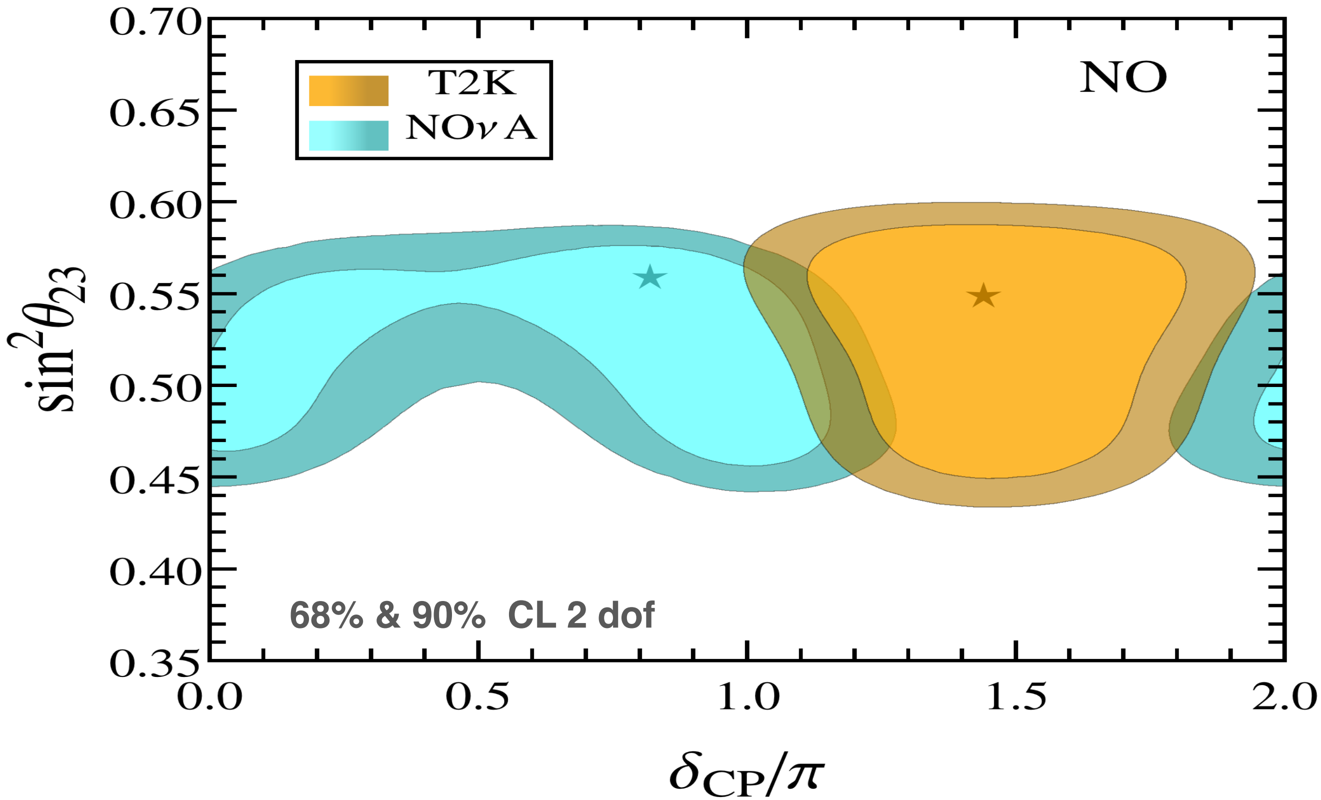
$$\bar{\chi}^2_{min} = 6.3$$

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

Alert for:

- Experimentalists
- Phenomenologists
- Theorists

View in two-paramer space (2024)



Maybe a statistical fluctuation or a systematic error

But interesting to consider alternative explanations…

Why to consider non-standard interactions

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

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

T2K $v \sim 0.05$

NOvA $v \sim 0.17$

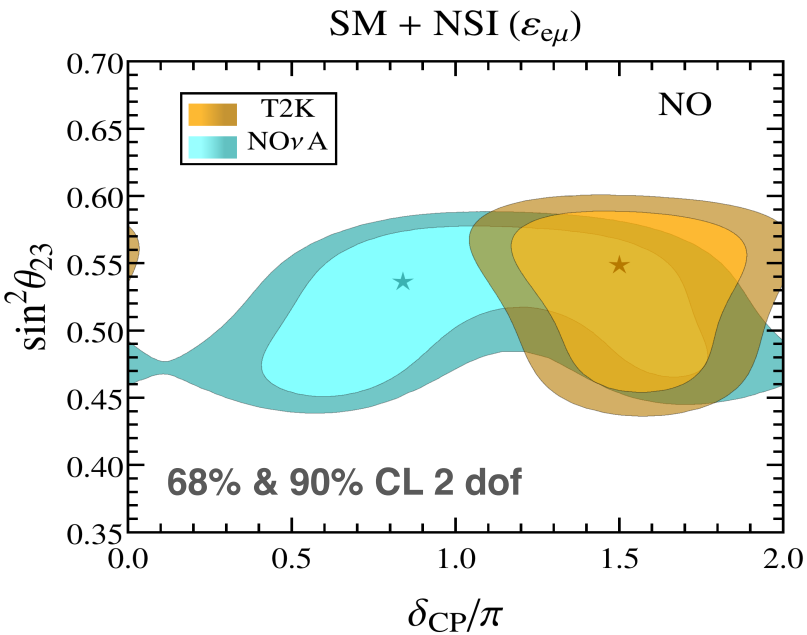
New matter effects encoded by NSI are also proportional to v

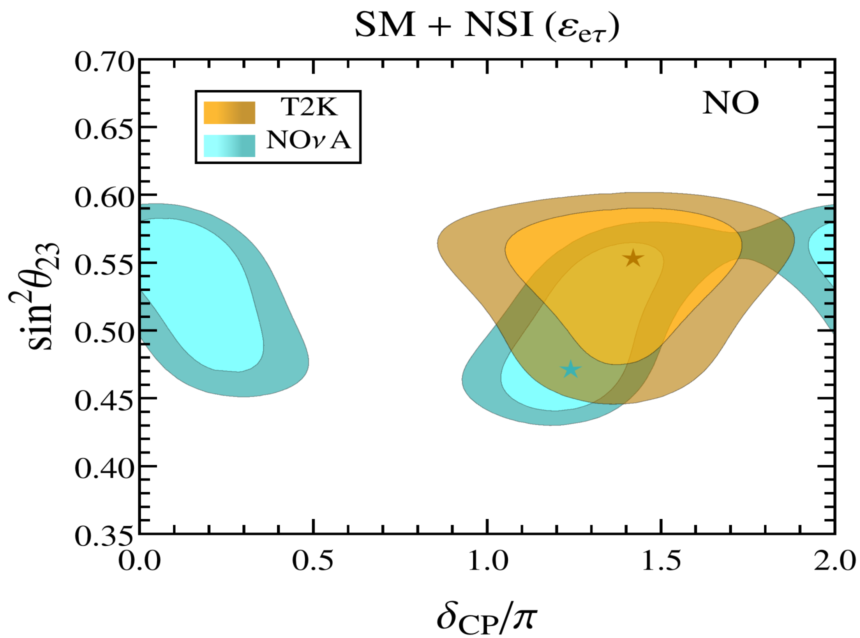
Basic Idea: suppose NSI exist, then:

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 bring the estimates of δ_{CP} in agreement



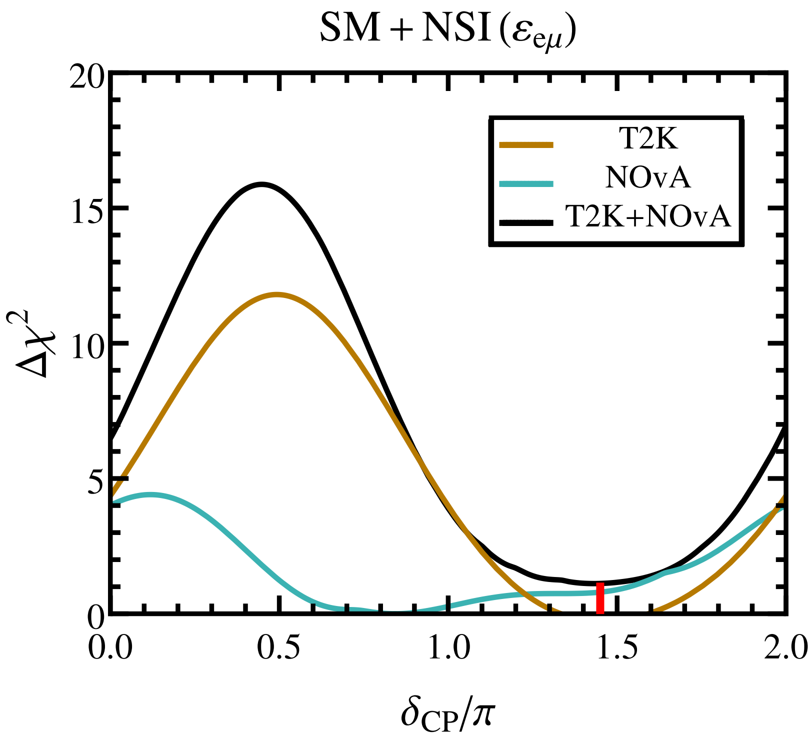


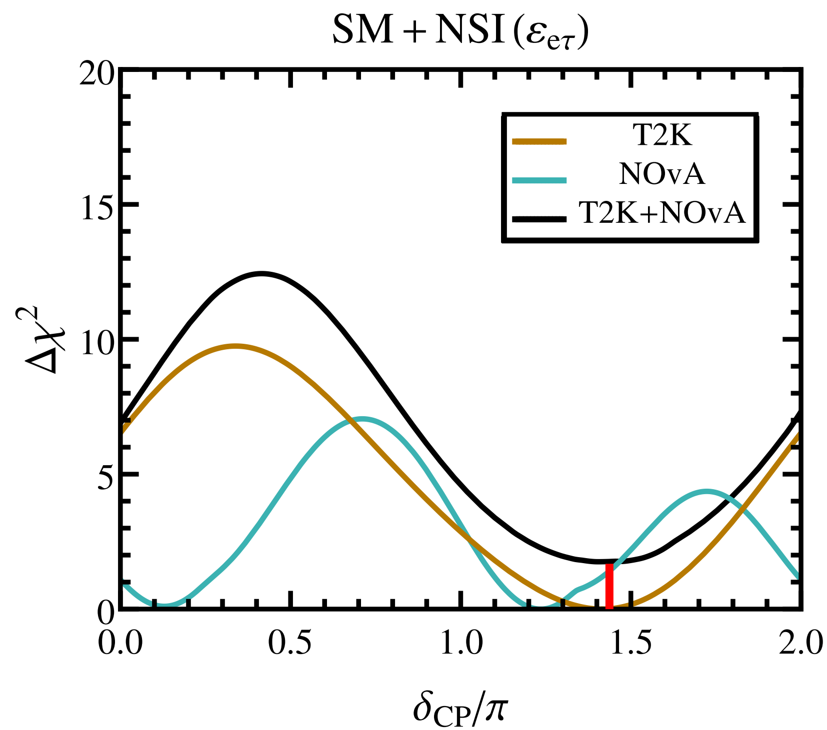
Contours obtained for the best fit of T2K + NOνA:

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

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

NSI substantially reduce the tension

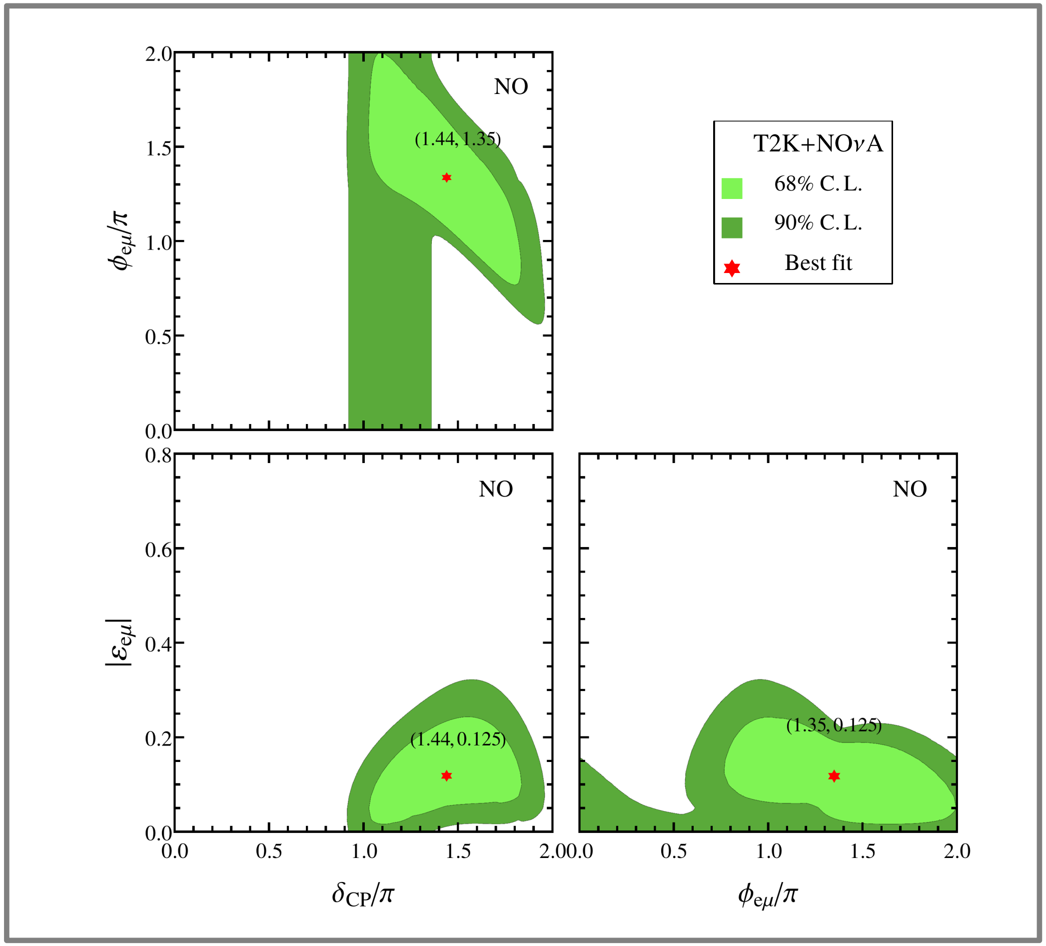




Single $\Delta\chi^2$ obtained for the best fit of T2K + NOvA:

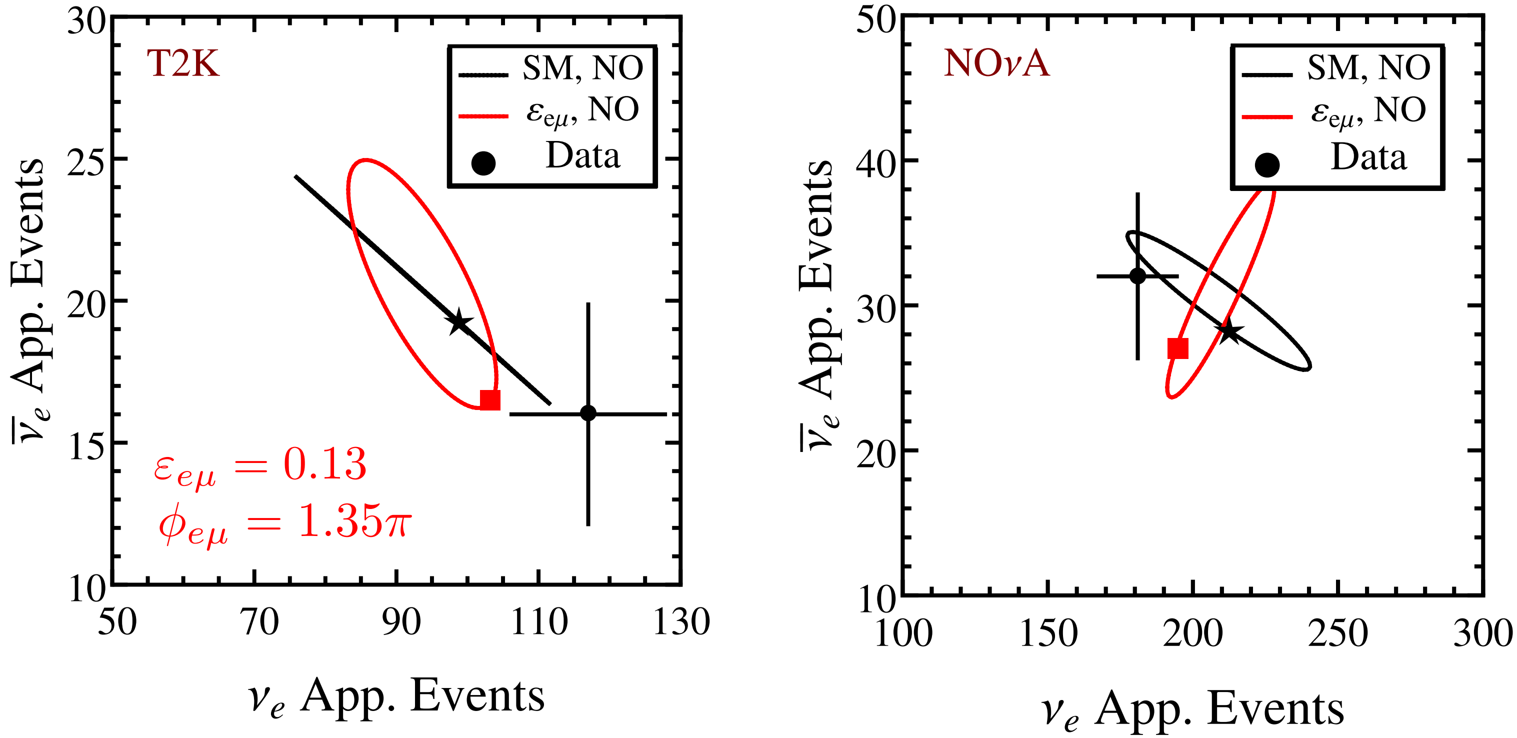
$$\begin{cases} [\varepsilon_{e\mu} = 0.13,\ \phi_{e\mu} = 1.35\pi] \\ [\varepsilon_{e\tau} = 0] \end{cases} \qquad \begin{cases} [\varepsilon_{e\mu} = 0] \\ [\varepsilon_{e\tau} = 0.22,\ \phi_{e\tau} = 1.70\pi] \end{cases}$$

Hint of non-zero $\varepsilon_{e\mu}$ from T2K + NOνA



~1.8 sigma preference for NSI

Bievents plots in the presence of NSI

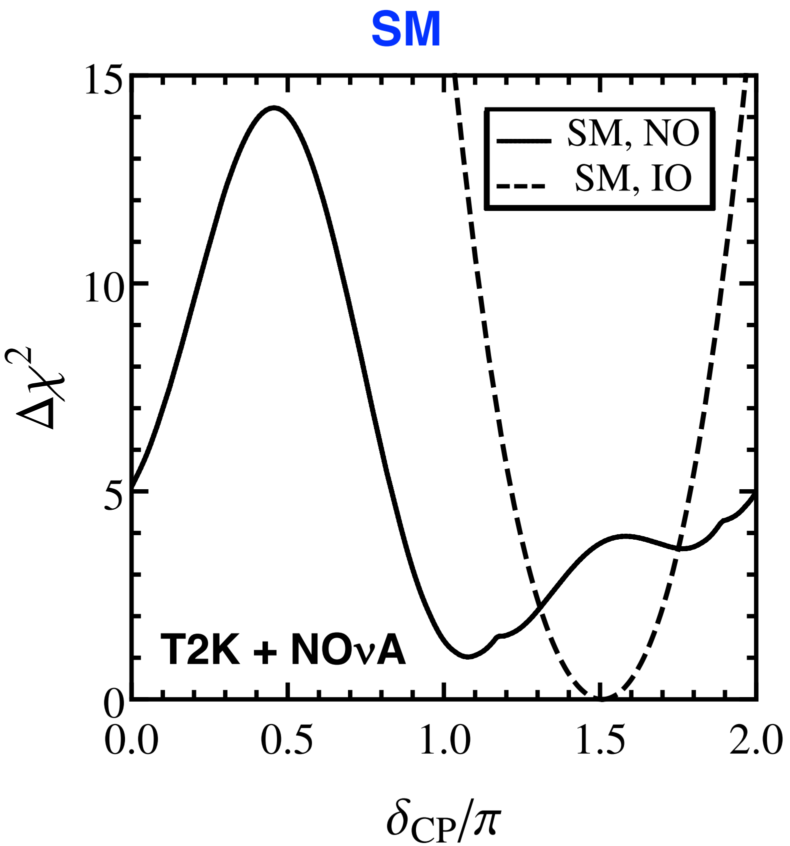


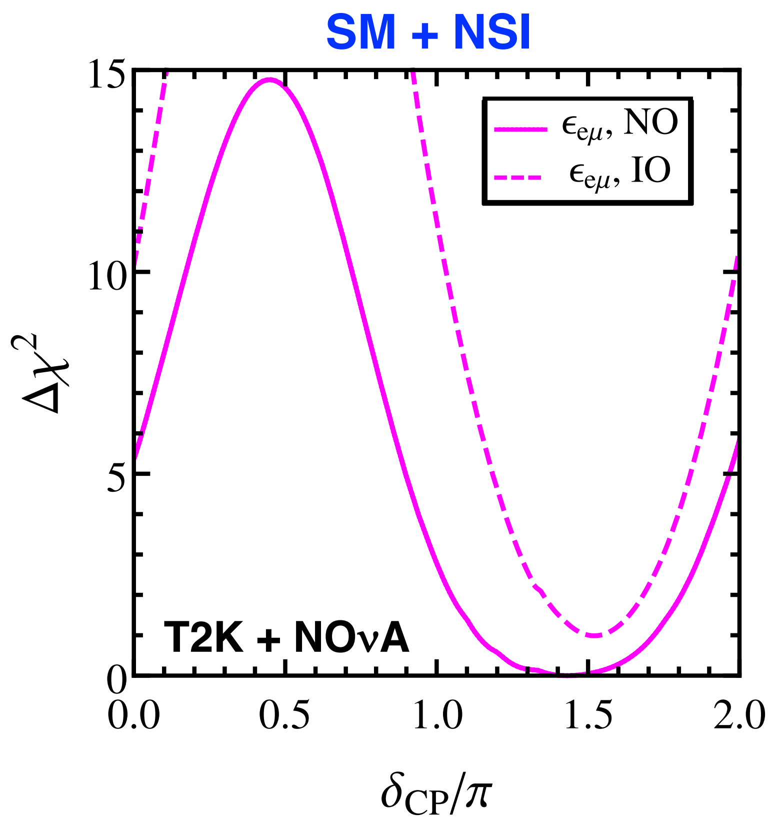
Best fit of [δ_{CP}, $\phi_{e\mu}$, $\varepsilon_{e\mu}$] of **combination** of T2K **+** NOVA

★ $\delta_{\mathrm{CP}} = 1.1\pi$ compromise between 1.5π and 0.9π

■ $\delta_{\mathrm{CP}} = 1.44\pi$ almost no need of compromise

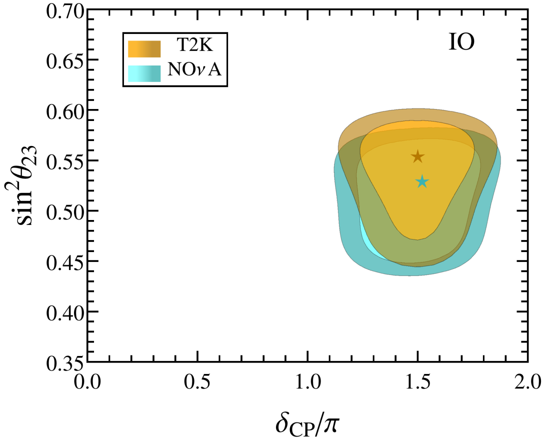
NSI restore the preference for NO

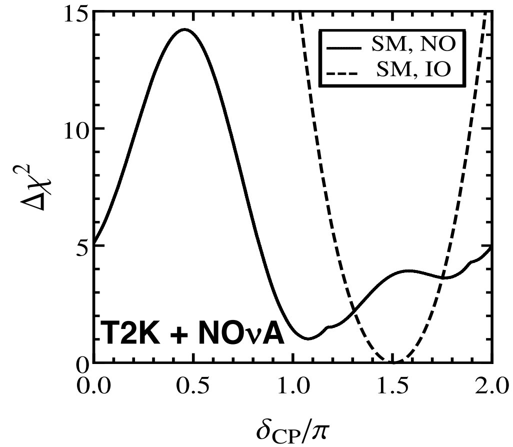


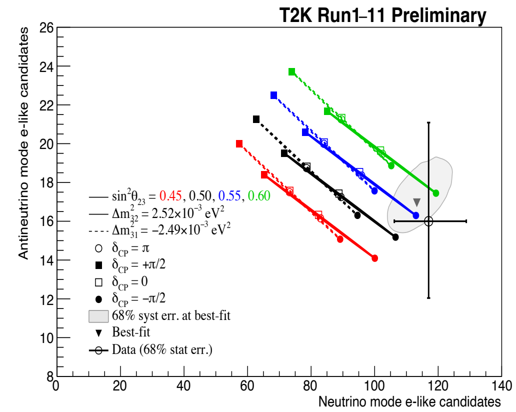


Better agreement with all the other data

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 + Reactors prefer NO ($\chi^2_{IO} - \chi^2_{NO} \sim 4$).

SK atmospheric data (ν 2020) prefer NO ($\chi^2_{IO} - \chi^2_{NO} \sim 3$).

Therefore, IO seems not to be the favored solution
but I think it is still premature do discard it

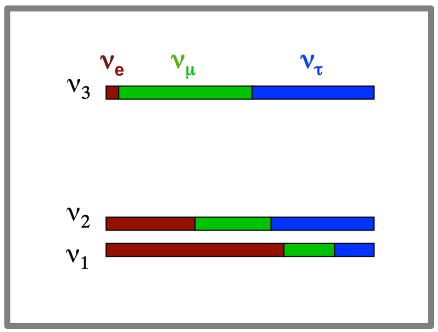
Can sterile neutrinos resolve the tension?

Chattejee & Palazzo arXiv:2005.10338

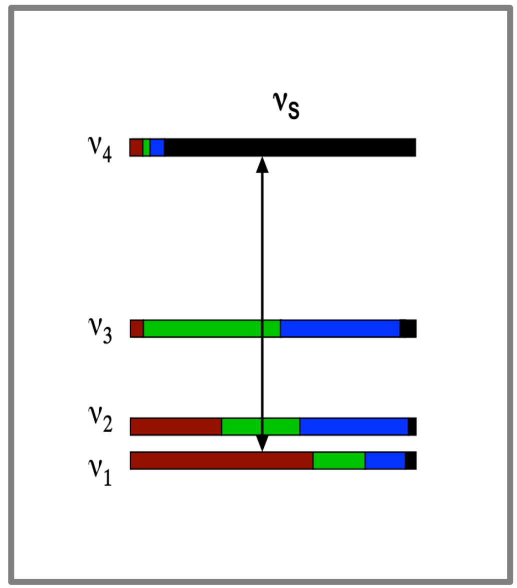
3ν scheme

Δm^2_{atm}

Δm^2_{sol}



3+1 scheme



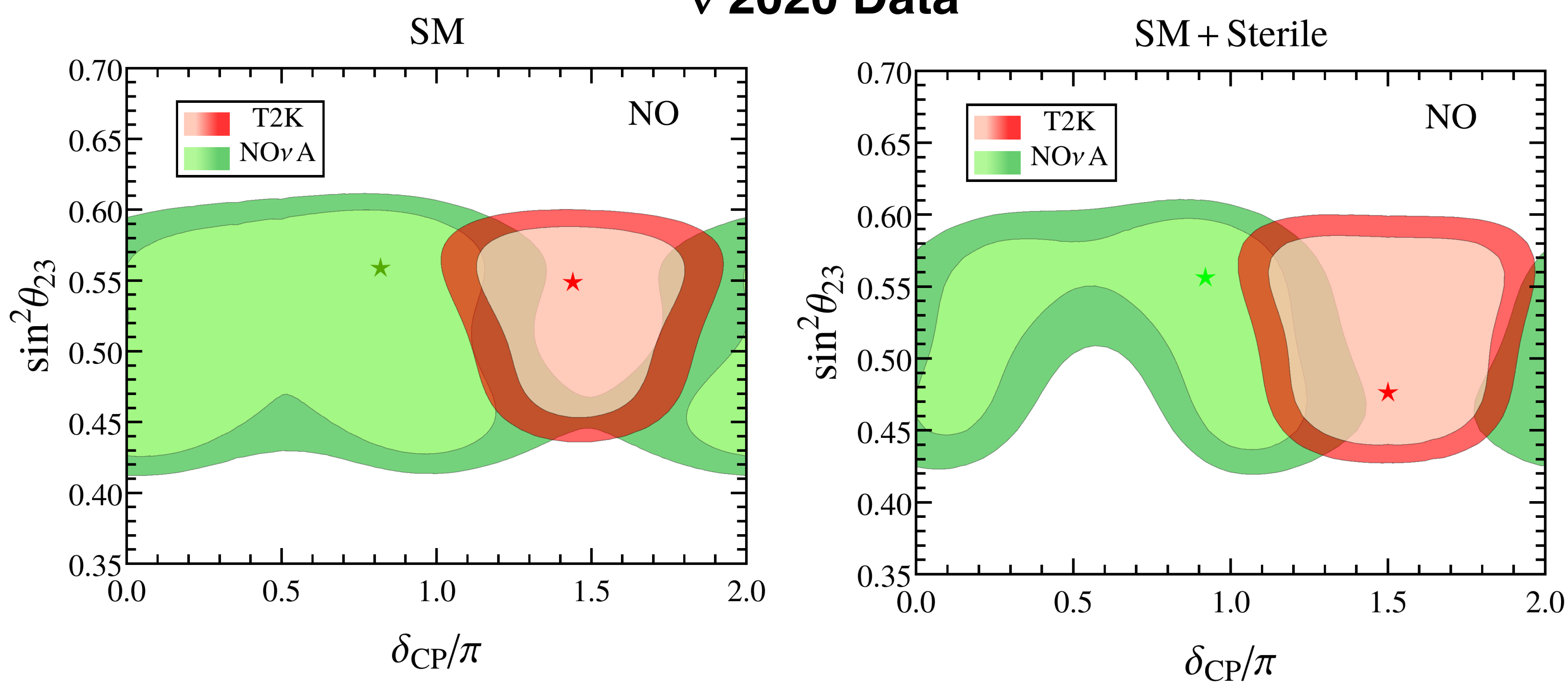
$|U_{s4}| \sim 1$

$\Delta m^2_{14} \sim 1\ \text{eV}^2$

At LBL the effective 2-flavor SBL description is no more valid and calculations should be done in the 3+1 (or 3+N_s) scheme

Sterile don't work: tension is still there!

ν 2020 Data



Why?

Sterile νs NSI: Two different kinds of interference

Sterile

Kinematical

Same amplitude in NOνA / T2K

$$\begin{cases} P^{\mathrm{ATM}} \simeq 4 s_{23}^2 s_{13}^2 \sin^2 \Delta \\ P_{\mathrm{I}}^{\mathrm{INT}} \simeq 8 s_{13} s_{23} c_{23} s_{12} c_{12} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) \\ P_{\mathrm{II}}^{\mathrm{INT}} \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) \end{cases}$$

NSI

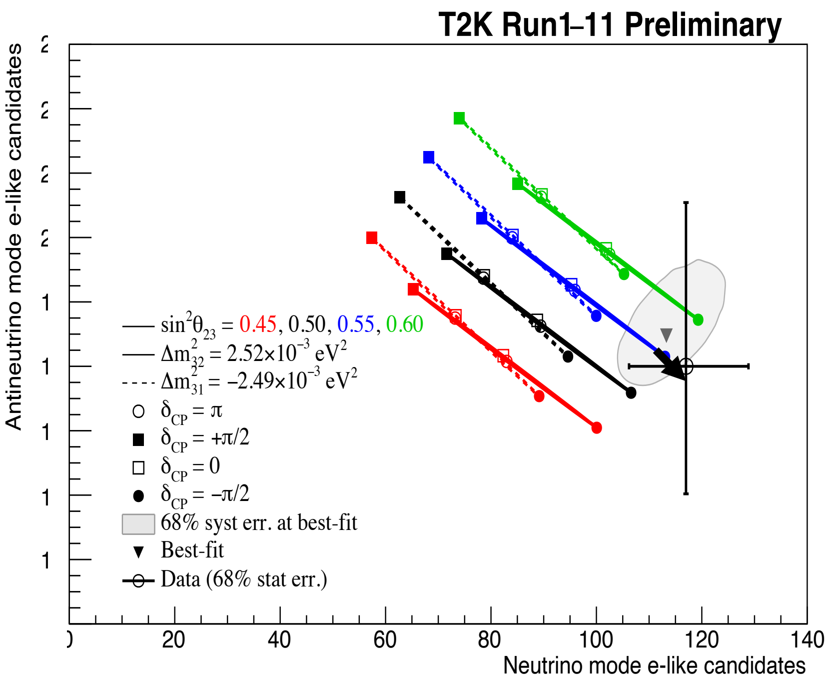
Dynamical

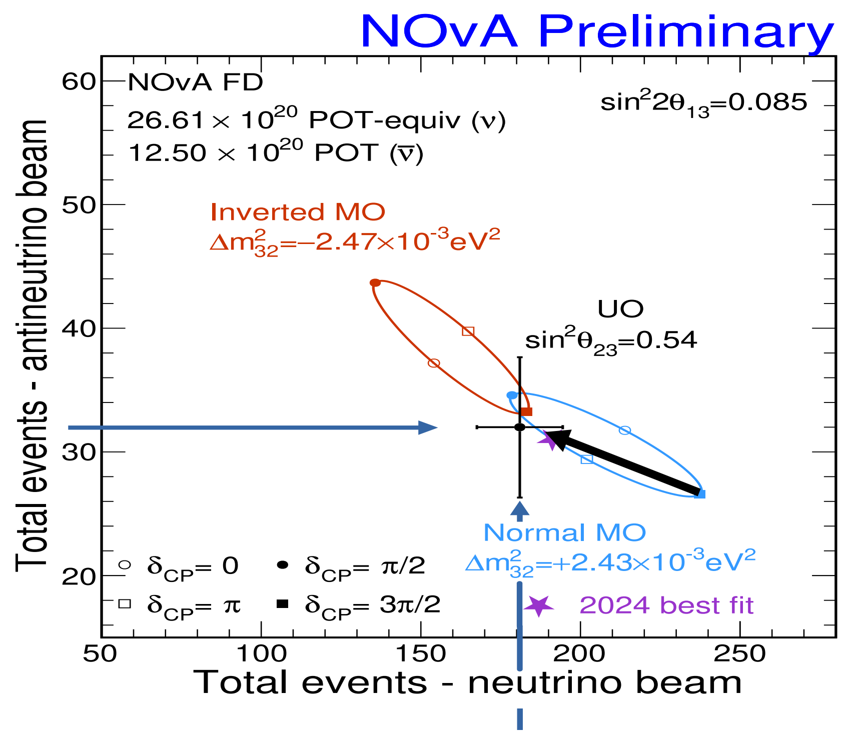
Different amplitude in NOνA / T2K

$$\begin{cases} P_0 \simeq 4 s_{13}^2 s_{23}^2 f^2 \\ P_1 \simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta_{\mathrm{CP}}) \\ P_2 \simeq 8 s_{13} s_{23} v |\varepsilon_{\alpha\beta}| [a f^2 \cos(\delta_{\mathrm{CP}} + \phi_{\alpha\beta}) + b f g \cos(\Delta + \delta_{\mathrm{CP}} + \phi_{\alpha\beta})] \end{cases}$$

$$v = \frac{2 V_{\mathrm{CC}} E}{\Delta m_{31}^2} = 0.18 \left[\frac{E}{2.0\,\mathrm{GeV}} \right]$$

Gaining insight with bievents plots





We need a noticeable displacement in NOvA

while no displacement is needed in T2K

This is possible only with NSI (different values of ν)

Conclusions

T2K and NOνA display a tension at ~2.5 sigma level

Complex flavor-changing NSI can solve the tension for $\varepsilon \sim 0.1$

Sterile neutrinos are not able to do the same job

Dynamical (NSI) vs kinematical (sterile) mechanism

Various other mechanisms have been investigated (non-unitarity, LV, ultra-light DM, …) none satisfactory

New information may come in a few years from T2K, NOνA, ANTARES and Icecube

If the NSI indication persists, DUNE and HK will definitely confirm/disconfirm it.

Back up slides

Thank you for your attention

Analytical expectations with NSI

$P_{\mu e}$ involves 4 small quantities

$s_{13} = 0.15$	ϵ	$v = \dfrac{2V_{CC}E}{\Delta m^2_{31}} = 0.18\left[\dfrac{E}{2.0\,\mathrm{GeV}}\right]$	ϵ
$\alpha = 0.03$	ϵ^2	$\lvert\varepsilon_{\alpha\beta}\rvert \sim 0.2$	ϵ

$P_{\mu e}$ is the sum of three terms

$$P_{\mu e} \simeq \underbrace{P_0 + P_1}_{\text{SM}} + \underbrace{P_2}_{\text{NSI}}$$

T2K $v \sim 0.05$

NOvA $v \sim 0.18$

$$P_0 \simeq 4 s_{13}^2 s_{23}^2 f^2 \qquad \epsilon^2$$

$$P_1 \simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta_{CP}) \qquad \epsilon^3$$

$$P_2 \simeq 8 s_{13} s_{23} v |\varepsilon_{\alpha\beta}| [a f^2 \cos(\delta_{CP} + \phi_{\alpha\beta}) + b f g \cos(\Delta + \delta_{CP} + \phi_{\alpha\beta})] \qquad \epsilon^3$$

$$f \equiv \frac{\sin[(1-v)\Delta]}{1-v}, \qquad g \equiv \frac{\sin v\Delta}{v}$$

$$a = s_{23}^2, \quad b = c_{23}^2 \quad \text{if} \quad \alpha\beta = e\mu$$

$$a = s_{23}c_{23}, \quad b = -s_{23}c_{23} \quad \text{if} \quad \alpha\beta = e\tau$$

$$\nu \to \bar{\nu} \quad [v, \delta_{CP}, \phi_{\alpha\beta}] \to [-v, -\delta_{CP}, -\phi_{\alpha\beta}]$$

P_2 brings one additional CP-phase $\phi_{\alpha\beta}$

Parametric curve in biprobability plot:

$[x, y] = [P_{\mu e}, \bar{P}_{\mu e}]$

- **For fixed $\phi_{\alpha\beta}$ → ellipse for varying δ_{CP}**
- **For fixed δ_{CP} → ellipse for varying $\phi_{\alpha\beta}$**

What theory says about 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:

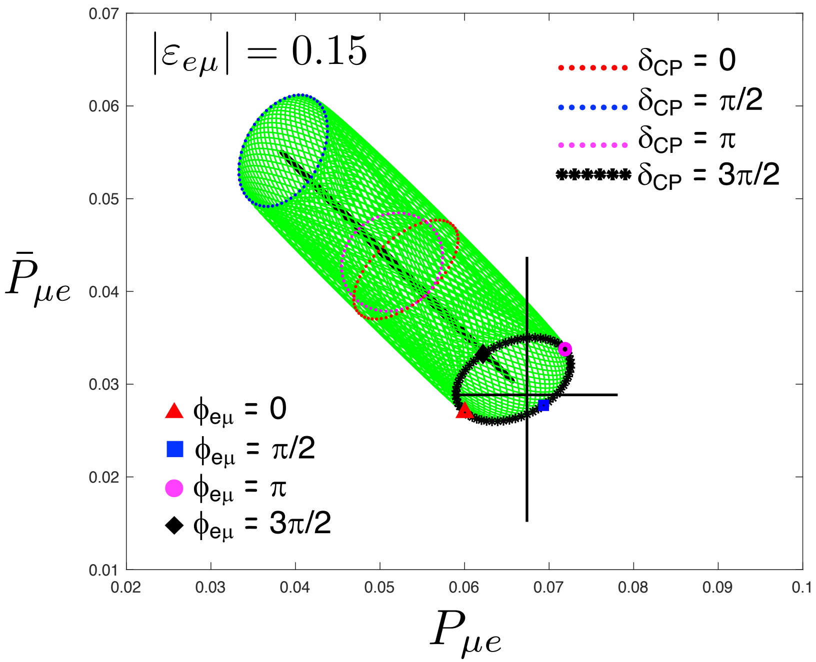
Heavy mediators
- **Tree-level see-saw** [Forero & Huang 1608.04719]
- **Radiative see-saw** [Babu et al. 1907.09498]

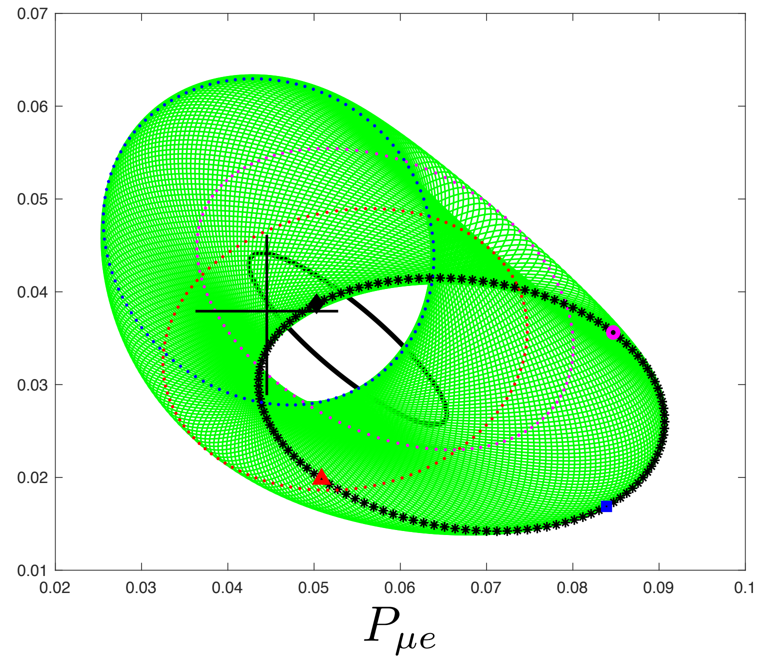
Light mediators are an appealing alternative
Farzan, Heeck 1607.07616 Farzan 1912.09408

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.

Biprobability plots in the presence of NSI

T2K	**NOνA**
Strongly favors $\delta_{CP} \sim 3\pi/2$ ellipse (almost no sensitivity to $\phi_{e\mu}$)	In agreement with $\delta_{CP} \sim 3\pi/2$ ellipse. On this ellipse it pins down $\phi_{e\mu} \sim 3\pi/2$





Mixing Matrix in the 3+1 scheme

$$U = \tilde{R}_{34} R_{24} \tilde{R}_{14} \underbrace{R_{23} \tilde{R}_{13} R_{12}}_{3\nu}$$

$$R_{ij} = \begin{bmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{bmatrix}$$

$$\tilde{R}_{ij} = \begin{bmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}^*_{ij} & c_{ij} \end{bmatrix}$$

$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$
$$\tilde{s}_{ij} = s_{ij} e^{-i\delta_{ij}}$$

3ν { 3 mixing angles, 1 Dirac phase, 2 Majorana phases }

3+1 { 6, 3, 3 }

3+N { 3+3N, 1+2N, 2+N }

In general, we have additional sources of CPV

LBL transition probability in 3-flavor

$$P^{3\nu}_{\nu_\mu \to \nu_e} = P^{\mathrm{ATM}} + P^{\mathrm{SOL}} + P^{\mathrm{INT}}$$

In vacuum:

$$P^{\mathrm{ATM}} = 4 s_{23}^2 s_{13}^2 \sin^2 \Delta$$
$$P^{\mathrm{SOL}} = 4 c_{12}^2 c_{23}^2 s_{12}^2 (\alpha\Delta)^2$$
$$P^{\mathrm{INT}} = 8 s_{23} s_{13} c_{12} c_{23} s_{12} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{CP})$$

$$\Delta = \frac{\Delta m_{31}^2 L}{4E}, \qquad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

$\Delta \sim \pi/2$

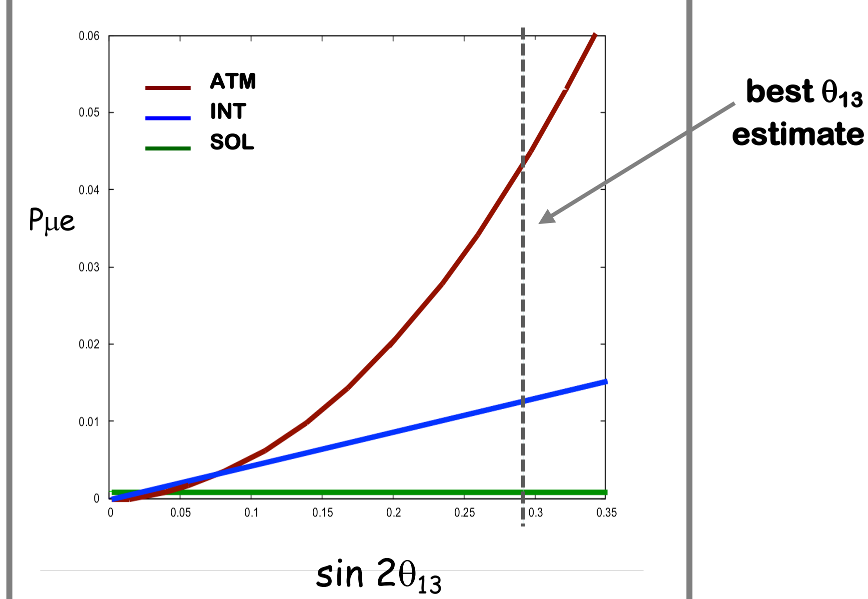
$\alpha \sim 0.03$

P^{ATM} leading → $\theta_{13} > 0$

P^{INT} subleading → dependency on δ

P^{SOL} negligible

T2K osc. maximum E = 0.6 GeV



A new interference term in the 3+1 scheme

N. Klop & A.P., PRD (2015)

- Δ_{14} >> 1 : fast oscillations are averaged out

- But interference of Δ_{14} & Δ_{13} survives and is observable

$$P^{4\nu}_{\mu e} \simeq P^{\rm ATM} + P^{\rm INT}_{\rm I} + P^{\rm INT}_{\rm II}$$

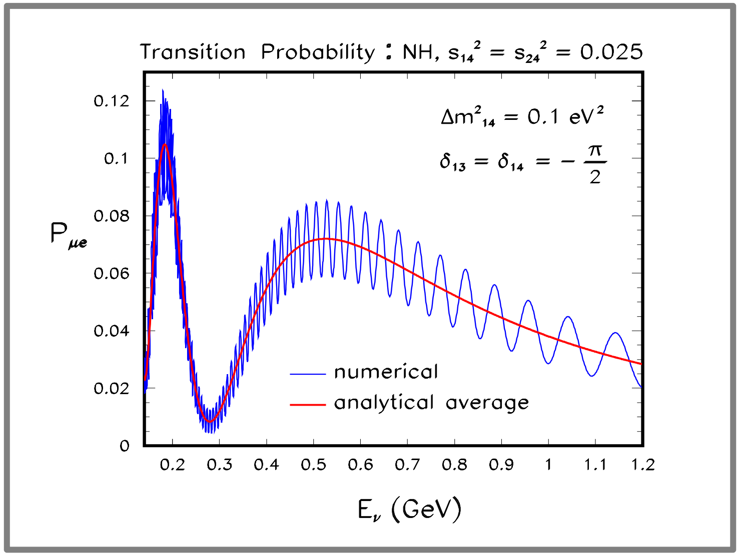
$s_{13} \sim s_{14} \sim s_{24} \sim 0.15 \sim \varepsilon$

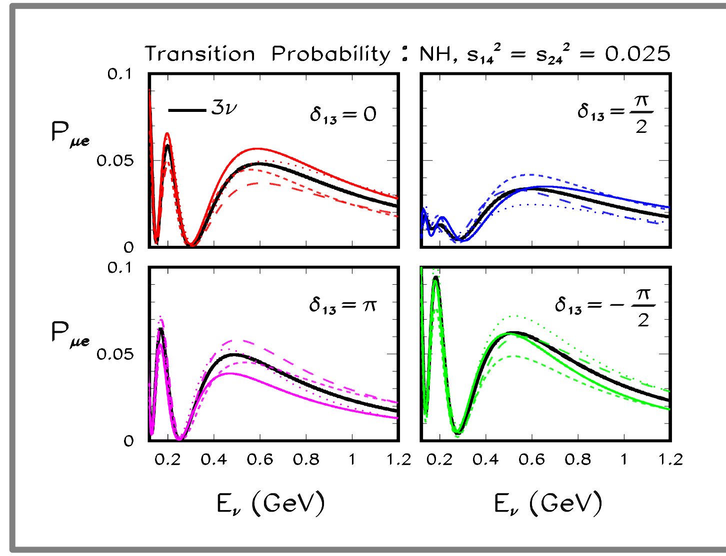
$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

$$\begin{cases} P^{\rm ATM} \simeq 4 s_{23}^2 s_{13}^2 \sin^2\Delta & \sim \varepsilon^2 \\ P^{\rm INT}_{\rm I} \simeq 8 s_{13} s_{23} c_{23} s_{12} c_{12} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) & \sim \varepsilon^3 \\ P^{\rm INT}_{\rm II} \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) & \sim \varepsilon^3 \end{cases}$$

Sensitivity to the new CP-phase δ_{14}

Numerical examples of 4ν probability





The fast oscillations get averaged out due to the finite energy resolution

Different line styles ⇔ Different values of δ_{14}

The modifications induced by δ_{14} are almost as large as those induced by the standard CP-phase δ_{13}

In principle we can try to explain the tension with 4ν