25/10/2023

NeuTel 2023

Confronting sterile νs with NSIs in T2K and NOvA

Antonio Palazzo

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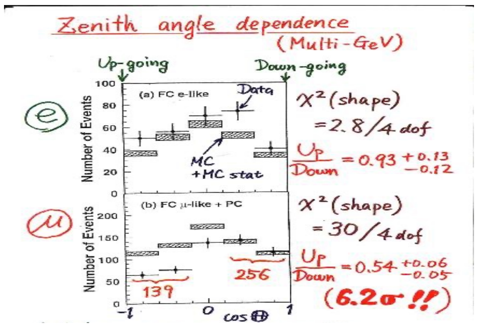
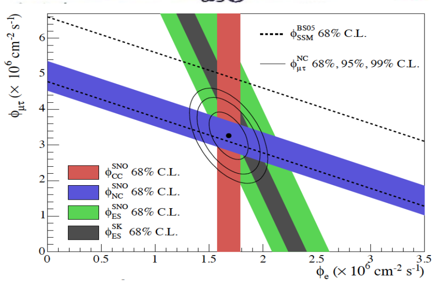
Outstanding progress in ν physics in ~ 25 years

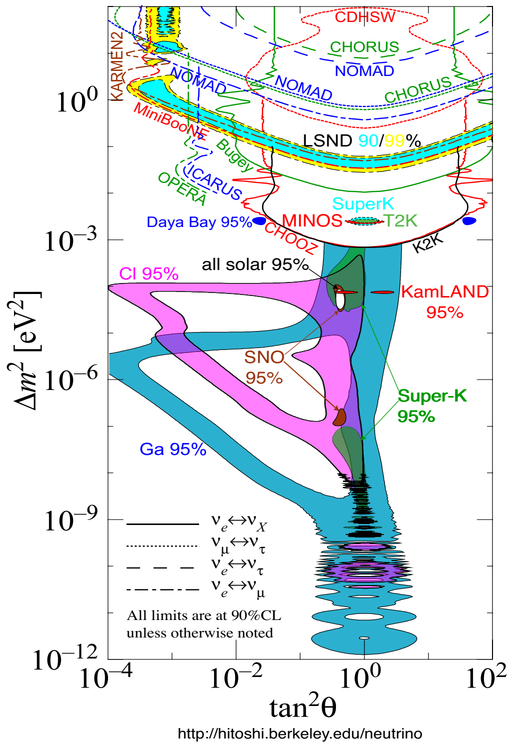
Discoveries





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

Interpretation



known knowns

$\delta m^2/eV^2 \sim 7.34 \times 10^{-5}$ ±2.2%
$\Delta m^2/eV^2 \sim 2.48 \times 10^{-3}$ ±1.3%
$\sin^2\theta_{12} \sim 0.303$ ±4.4%
$\sin^2\theta_{13} \sim 0.0225$ ±3.8%
$\sin^2\theta_{23} \sim 0.545$ ±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, ...?

3-flavor scheme now established as the standard framework…

The 3ν mixing matrix

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

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

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

Dirac CP-violating phase δ

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

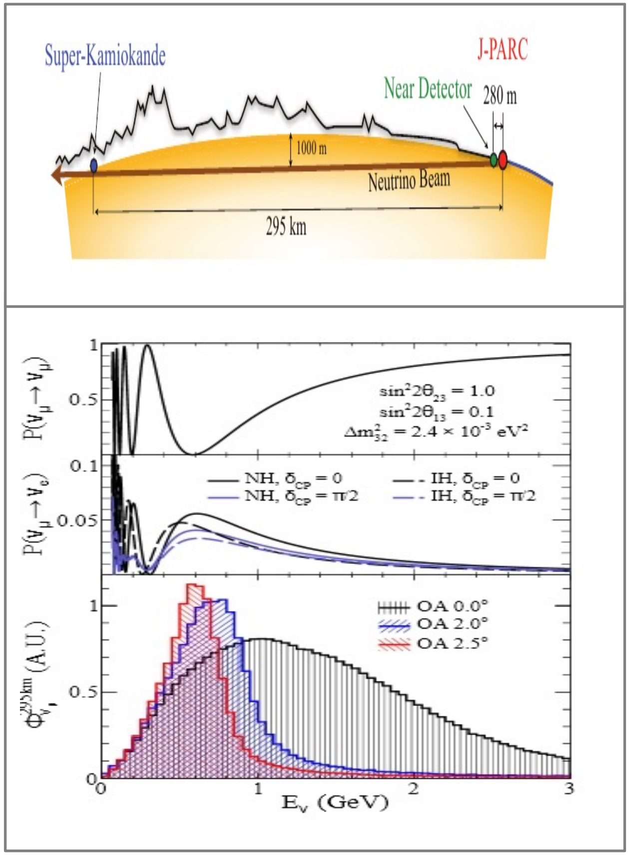
Explicit form

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

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

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

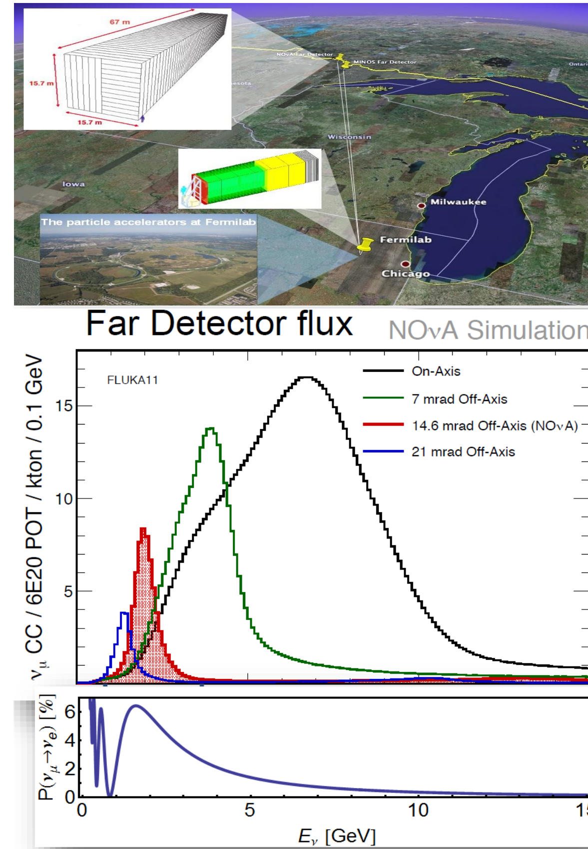
Two main actors: T2K & NOνA



off-axis beam

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

First oscillation maximum



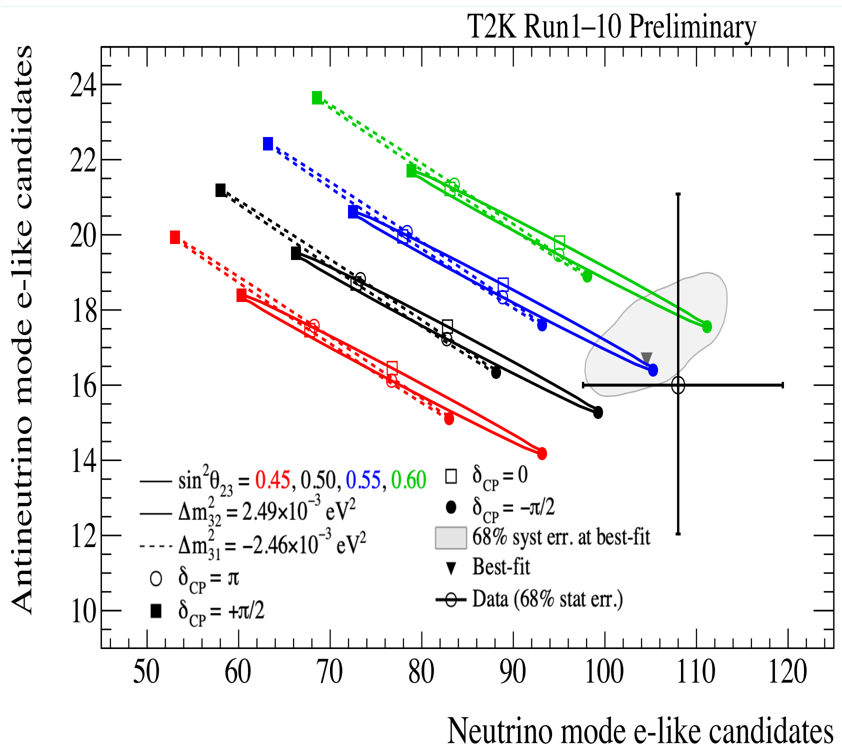
E = 0.6 GeV

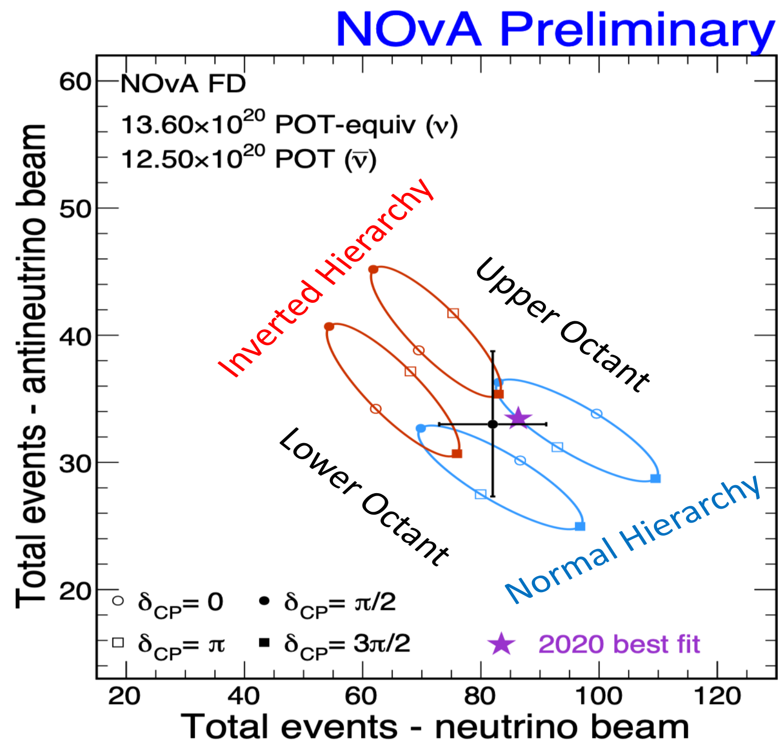
L = 295 km

E = 2 GeV

L = 810 km

Bird's-eye view: bievents plots

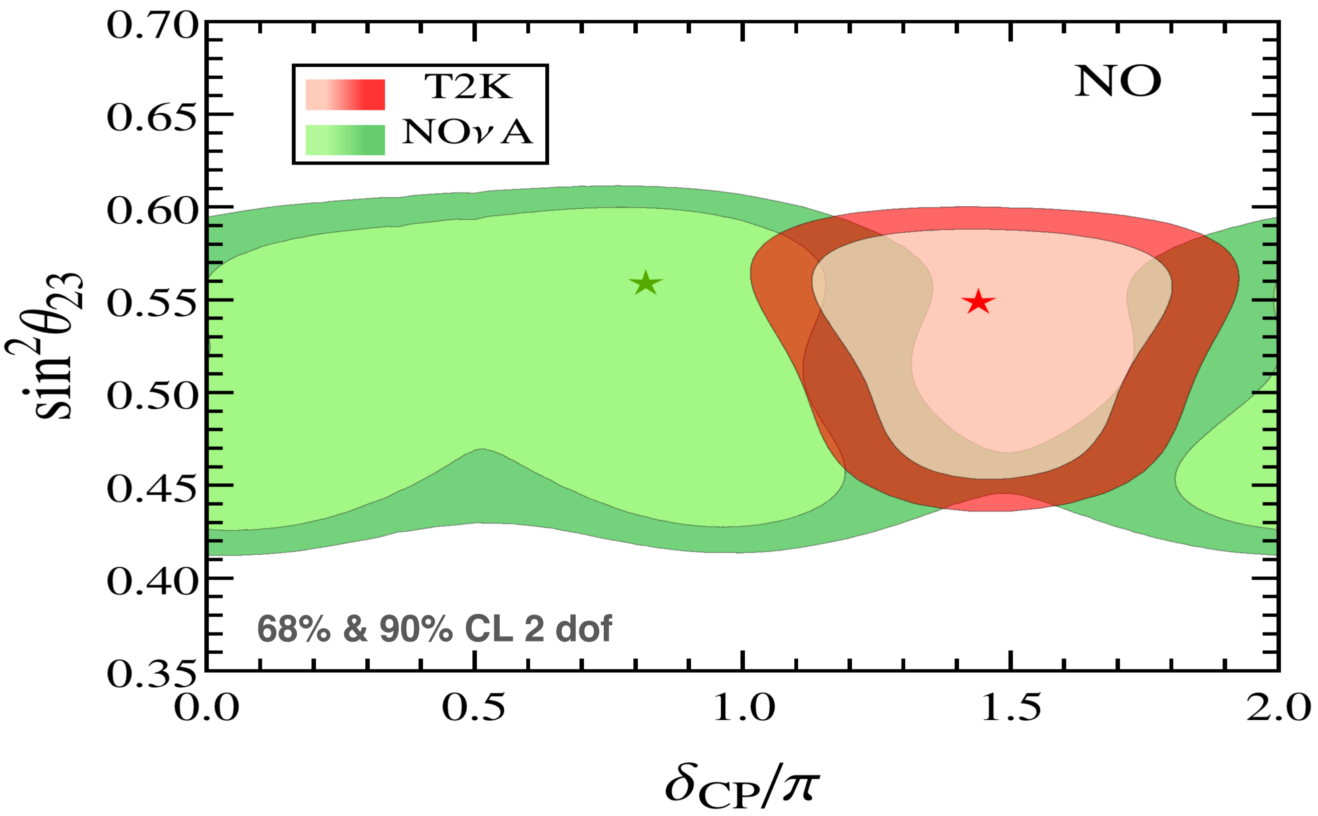




for Normal Ordering:

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

In NO, tension in the determination of δ_{CP}



Maybe a statistical fluctuation or a systematic error

But interesting to consider alternative explanations…

At NeuTel 2021

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 $\delta_{\rm CP}$ extracted by the two experiments is evident in the normal neutrino mass ordering. While NOνA prefers values close to $\delta_{\rm CP} \sim 0.8\pi$, T2K identifies values of $\delta_{\rm CP} \sim 1.4\pi$. 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 $\delta_{\rm CP} \sim 3\pi/2$. 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

19/02/2021 Neutel 2021

Possible indication of NSI from NOνA & T2K

Mostly based on
S.S. Chatterjee & A.P.,
PRL 126 051802 (2021) arXiv:2008.04161

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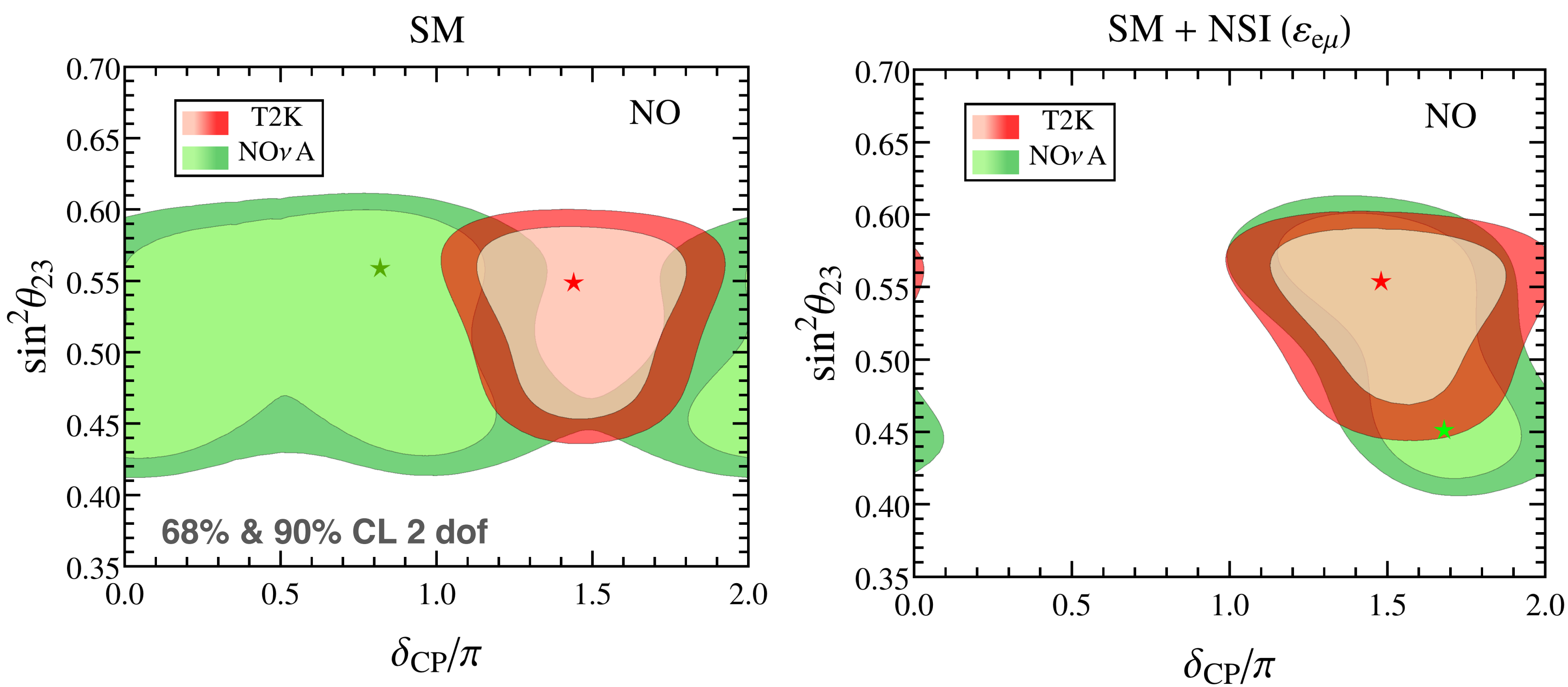
I showed that NSI can solve the tension

NSI bring the estimates of δ_{CP} in agreement



Contours obtained for the best fit of T2K + NOνA: $[\varepsilon_{e\mu} = 0.15,\ \phi_{e\mu} = 1.38\pi]$

T2K region almost unaltered

NOνA region strongly modified

Can sterile neutrinos resolve the tension?

Interpretation of NOνA and T2K data in the presence of a light sterile neutrino

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We study in detail the impact of a light sterile neutrino in the interpretation of the latest data of the long baseline experiments NOνA and T2K, assessing the robustness/fragility of the estimates of the standard 3-flavor parameters with respect to the perturbations induced in the 3+1 scheme. We find that all the basic features of the 3-flavor analysis, including the weak indication ($\sim$1.4σ) in favor of the inverted neutrino mass ordering, the preference for values of the CP-phase $\delta_{13} \sim 1.2\pi$, and the substantial degeneracy of the two octants of θ_{23}, all remain basically unaltered in the 4-flavor scheme. Our analysis also demonstrates that it is possible to attain some constraints on the new CP-phase δ_{14}. Finally, we point out that, differently from non-standard neutrino interactions, light sterile neutrinos are not capable to alleviate the tension recently emerged between NOνA and T2K in the appearance channel.

Submitted to New Journal of Physics

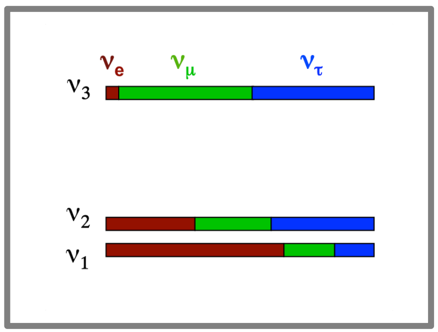
Enlarging the 3-flavor scheme

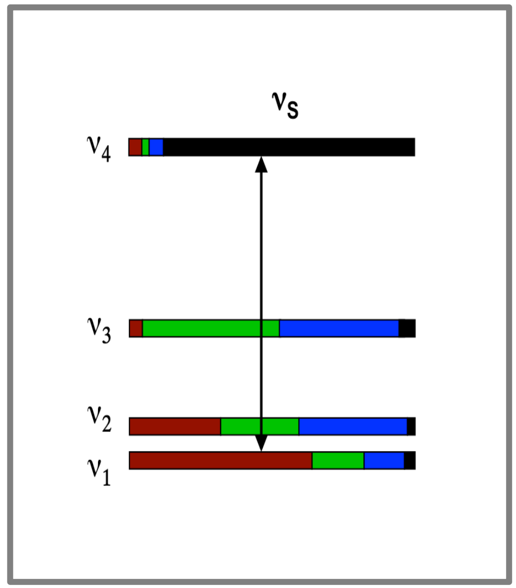
3+1 scheme

3ν scheme

Δm^2_{atm}

Δm^2_{sol}





$|U_{s4}| \sim 1$

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

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

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

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

In vacuum:

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

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

$\Delta \sim \pi/2$

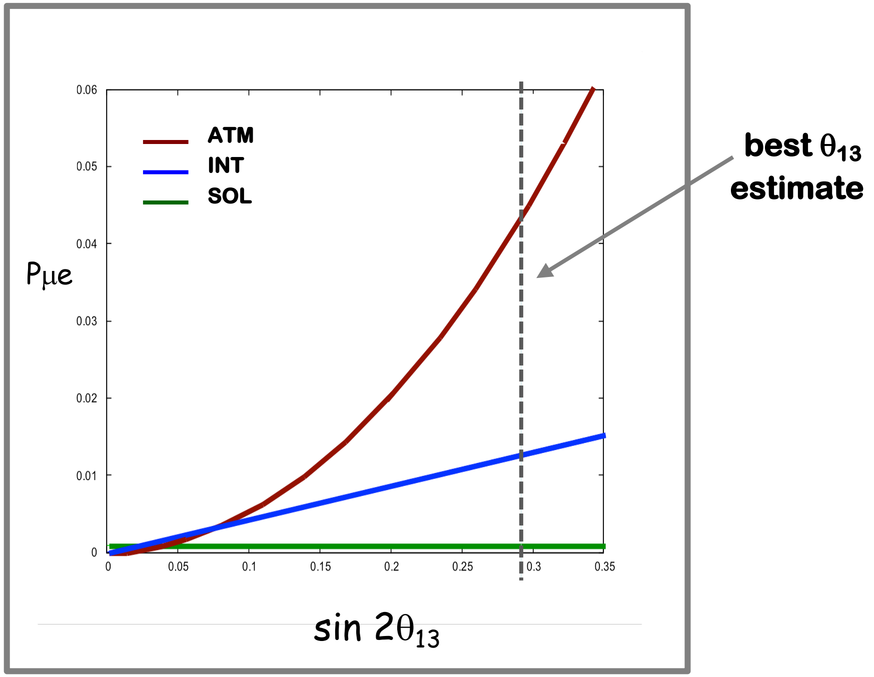
$\alpha \sim 0.03$

$P^{\rm ATM}$ leading → $\theta_{13} > 0$

$P^{\rm INT}$ subleading → dependency on δ

$P^{\rm SOL}$ 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

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

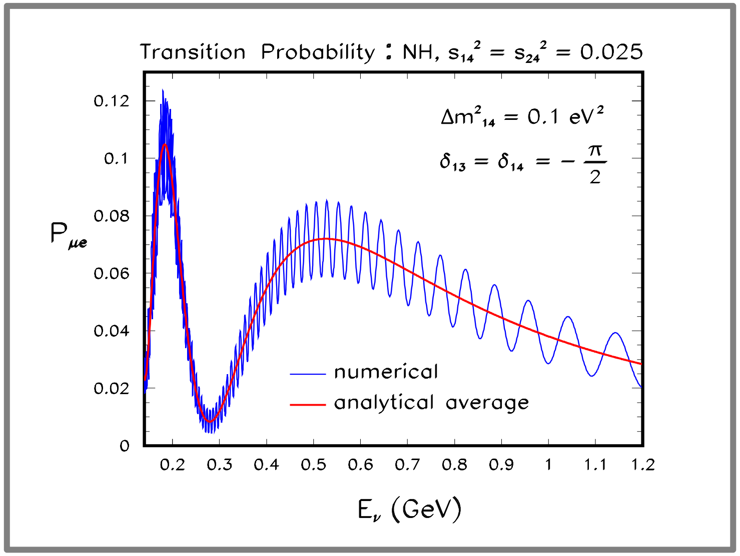
$s_{13} \sim s_{14} \sim s_{24} \sim 0.15 \sim \varepsilon$

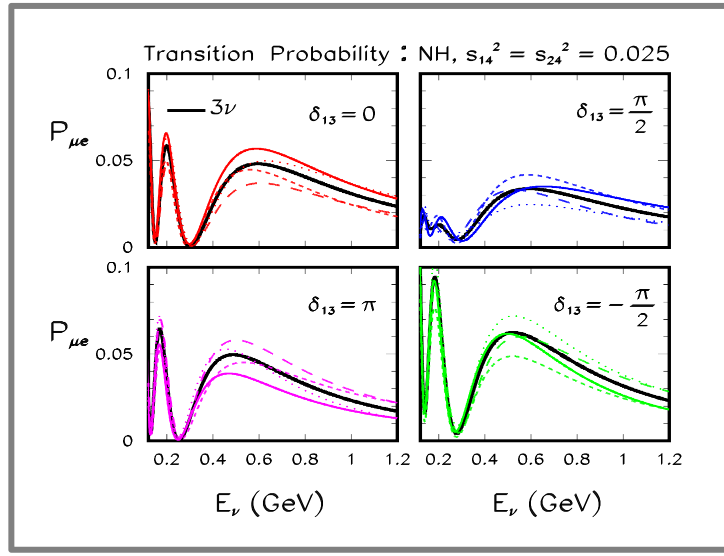
$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

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

Sensitivity to the new CP-phase δ_{14}

Numerical examples of 4ν probability





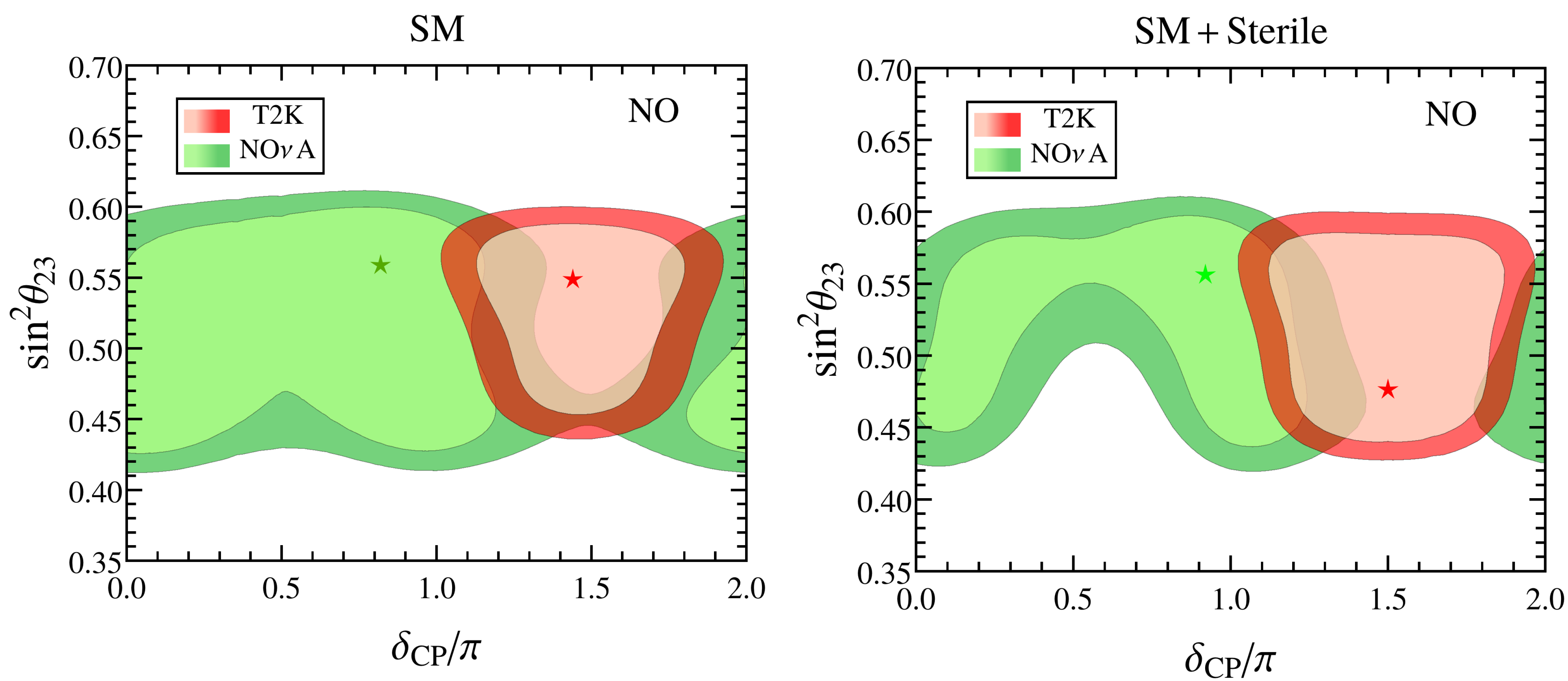
The fast oscillations get averaged out due to the finite energy resolution

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

However, it doesn't work: tension is still there!



Why?

Sterile νs NSI:
Two different kinds of interference

Sterile

Kinematical

Same amplitude in NOvA / T2K

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

NSI

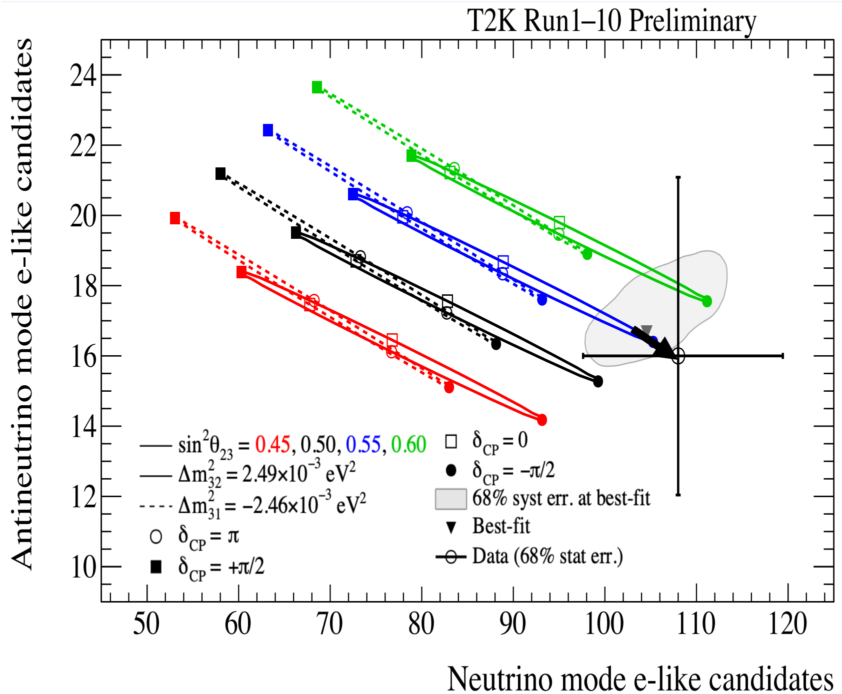
Dynamical

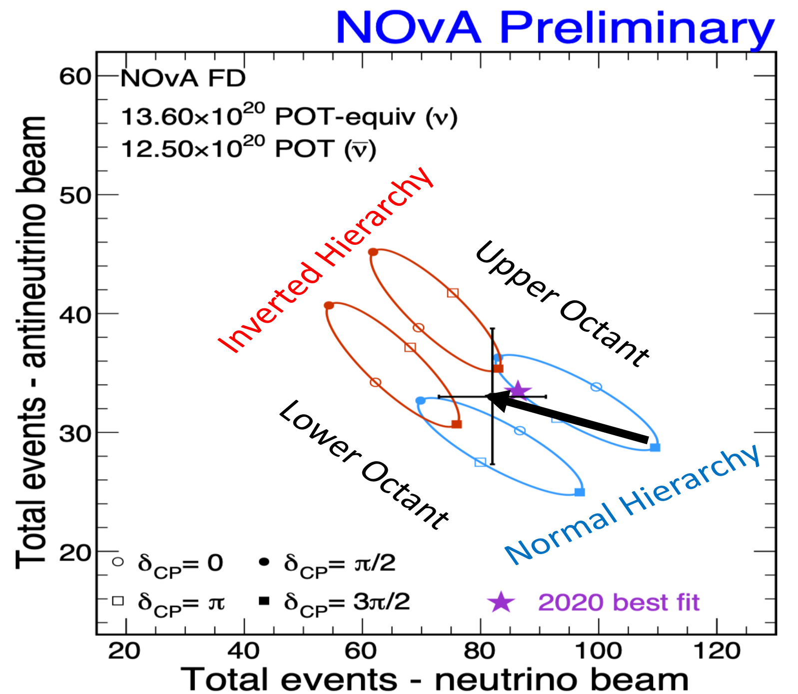
Different amplitude in NOvA / T2K

$$\begin{cases} P_0 \simeq 4s^2_{13}s^2_{23}f^2 \\ P_1 \simeq 8s_{13}s_{12}c_{12}s_{23}c_{23}\underline{\alpha} fg\cos(\Delta+\delta_{\rm CP}) \\ P_2 \simeq 8\underline{s_{13}}s_{23}\underline{v}|\underline{\varepsilon_{\alpha\beta}}|[af^2\cos(\delta_{\rm CP}+\phi_{\alpha\beta})+bfg\cos(\Delta+\delta_{\rm CP}+\phi_{\alpha\beta})] \end{cases}$$

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

Gaining insight with bievents plots





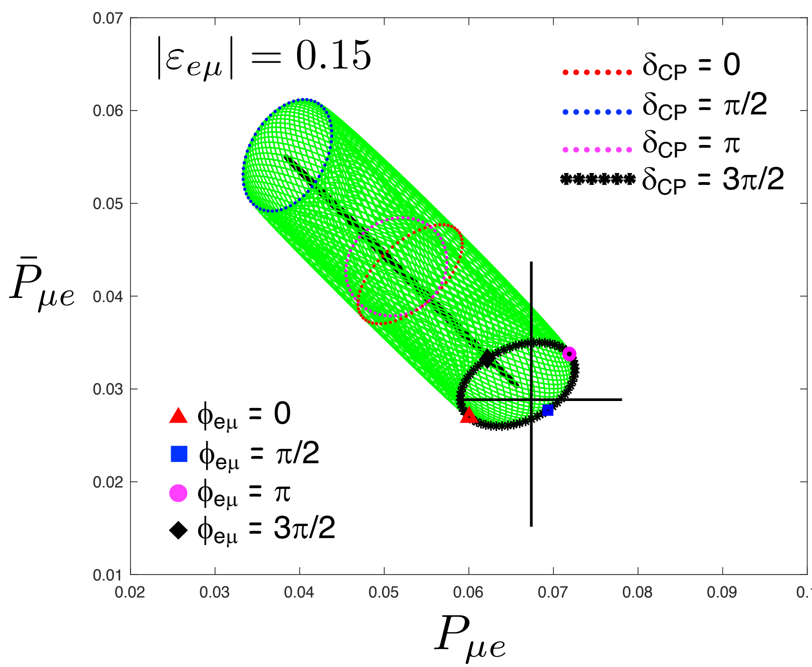
We need a noticeable displacement in NOvA

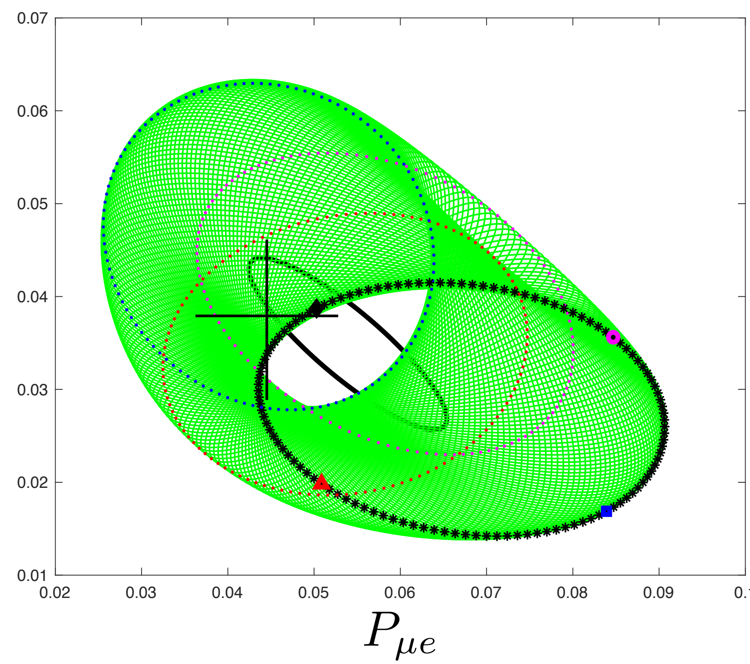
while no displacement is needed in T2K

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

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 $\phi_{e\mu} \sim 3\pi/2$





Conclusions

T2K and NOνA display a tension at ~2 sigma level

Complex flavor-changing NSI can solve the tension for $\varepsilon \sim 0.2$

Sterile neutrinos are not able to do the same job

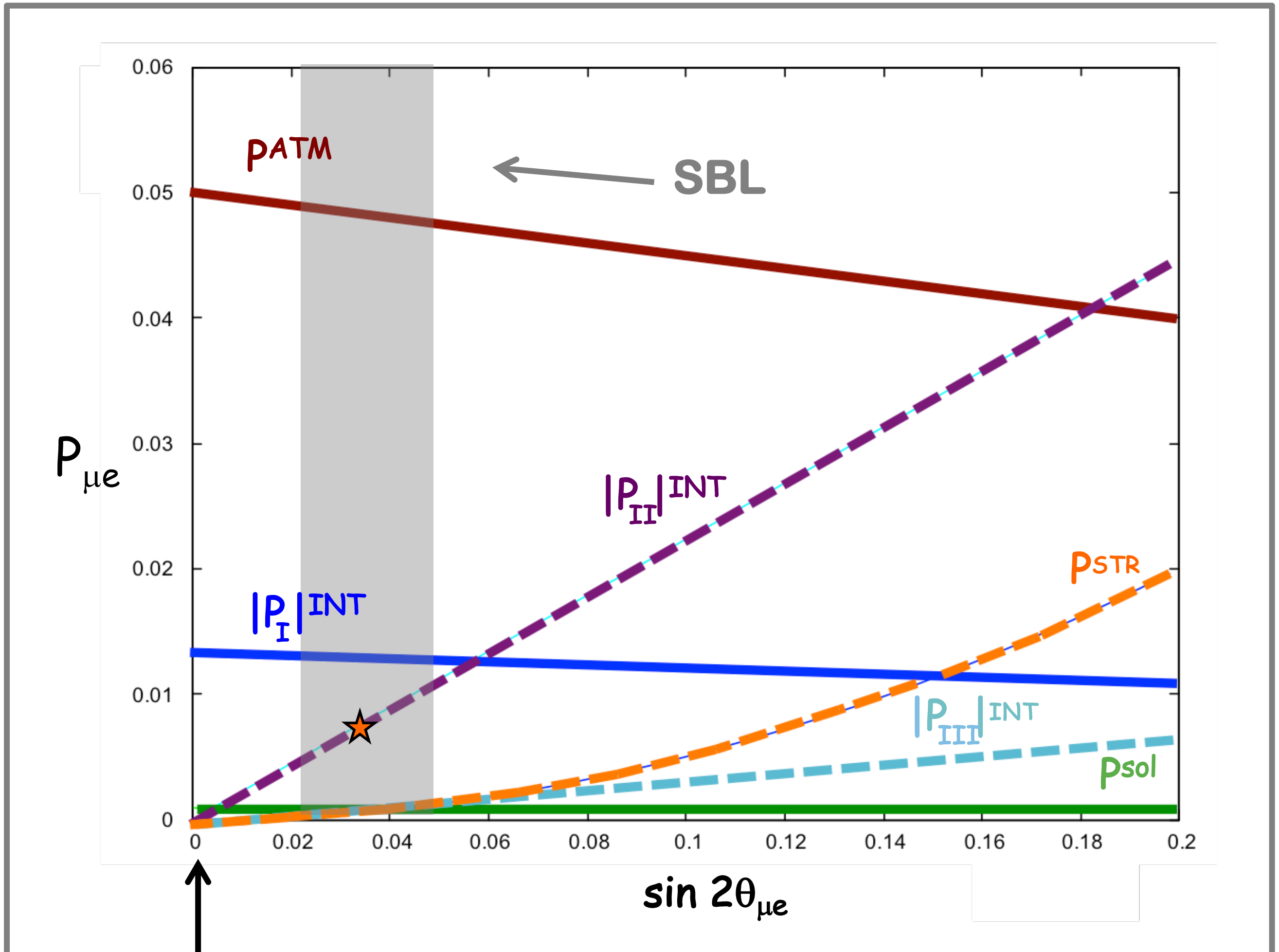
Dynamical (NSI) vs Kinematical (sterile) mechanism

If the NSI indication persists, Hyper-Kamiokande T2HK and DUNE will definitely confirm/disconfirm it.

Back up slides

Amplitude of the new interference term

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



3ν limit

T2K
θ_{13} = 9°
E = 0.6 GeV

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

CPV and averaged oscillations

$$A^{\rm CP}_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar\nu_\alpha \to \bar\nu_\beta)$$

$$A^{\rm CP}_{\alpha\beta} = -16 J^{12}_{\alpha\beta} \sin\Delta_{21} \underbrace{\sin\Delta_{13} \sin\Delta_{32}}$$

if $\Delta \equiv \Delta_{13} \simeq \Delta_{23} \gg 1$ $\longrightarrow$ $\langle \sin^2\Delta \rangle = 1/2$

osc. averaged out by finite E resol.

It can be: $A^{\rm CP}_{\alpha\beta} \neq 0$ **(if sin δ = Ø)**

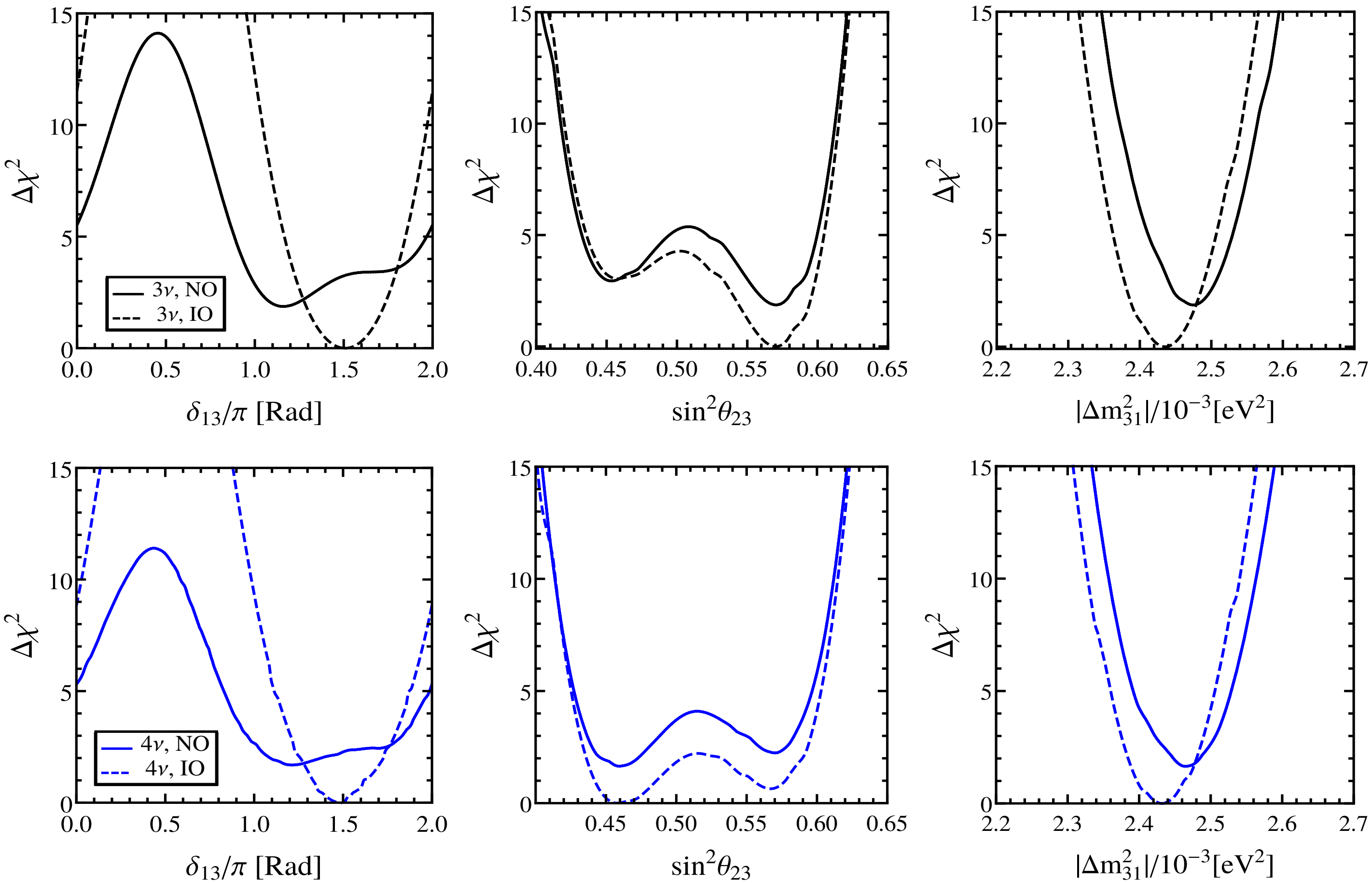
The bottom line is that if one of the three ν_i is ∞ far from the other two ones this does not erase CPV

(relevant for the 4ν case)

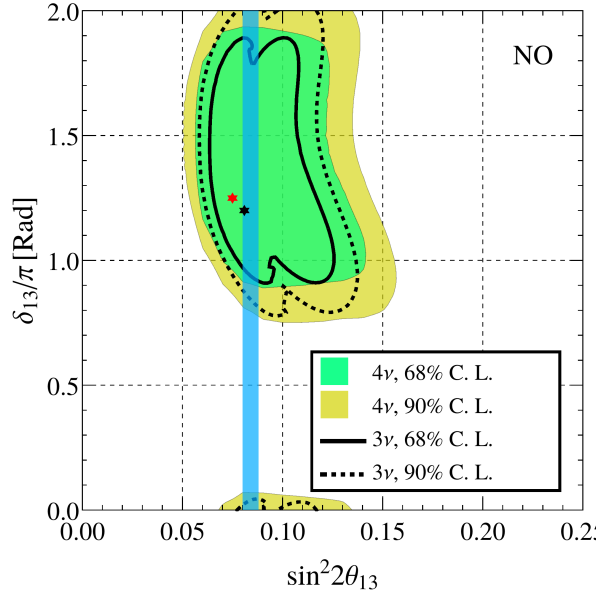
Estimates of standard oscillation parameters

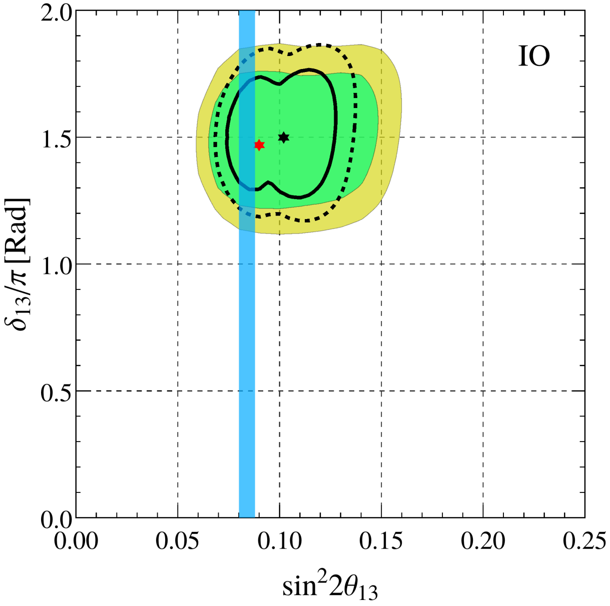
3ν

4ν



Estimates of standard oscillation parameters





Analytical expectations with NSI

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

$s_{13} = 0.15$	ϵ	$v = \frac{2V_{CC}E}{\Delta m^2_{31}} = 0.18\left[\frac{E}{2.0\,\mathrm{GeV}}\right]$	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	$v \sim 0.18$

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

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

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

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

$$a = s^2_{23}, \quad b = c^2_{23} \quad \text{if} \quad \alpha\beta = e\mu$$

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

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

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

Parametric curve in biprobability plot:

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

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

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.

Summary of the results of the fit (NOνA + T2K)

NMO	NSI	$\lvert\varepsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	$\delta_{\rm CP}/\pi$	$\Delta\chi^2$
NO	$\varepsilon_{e\mu}$	0.15	1.38	1.48	4.50
	$\varepsilon_{e\tau}$	0.27	1.62	1.46	3.75
IO	$\varepsilon_{e\mu}$	0.02	0.96	1.50	0.07
	$\varepsilon_{e\tau}$	0.15	1.58	1.52	1.01

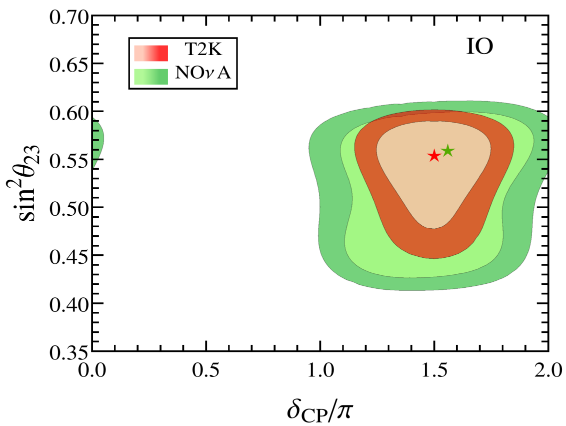
$$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{SM+NSI}$$

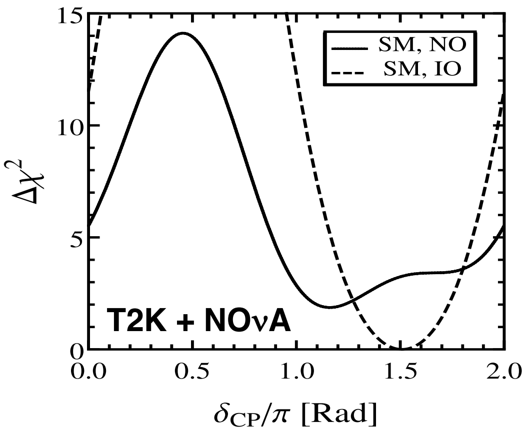
NO
- **$\Delta\chi^2 \sim 4$ signals a satisfactory resolution of the discrepancy**
- **Best fits of both CP phases δ_{CP} and $\phi_{\alpha\beta}$ are close to $3\pi/2$**
- **The coupling $\varepsilon_{e\mu}$ is slightly favored over $\varepsilon_{e\tau}$**

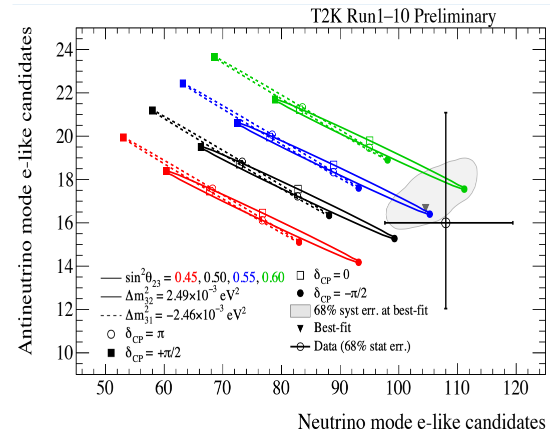
IO
- **No significant preference for non-zero NSI**

Similar results found by Denton, Gehrlein & Pestes, PRL 126 051801 (2021)

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

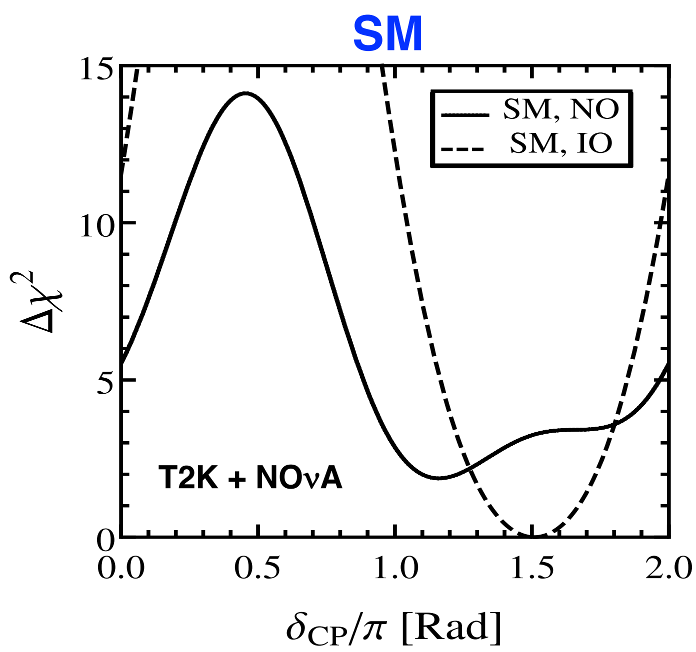
The reason is that T2K disfavors IO (dotted ellipses) (right panel).

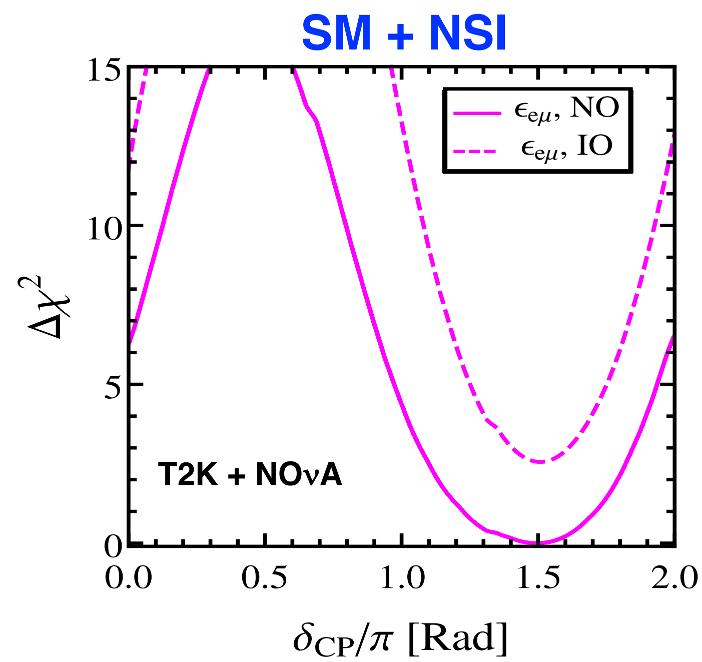
T2K and NOνA disappearance channel + Reactors prefer NO ($\chi^2_{IO} - \chi^2_{NO} \sim 4$).

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

Therefore, IO seems not to be the favored solution

NSI restore the preference for NO





Better agreement with all the other data

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:

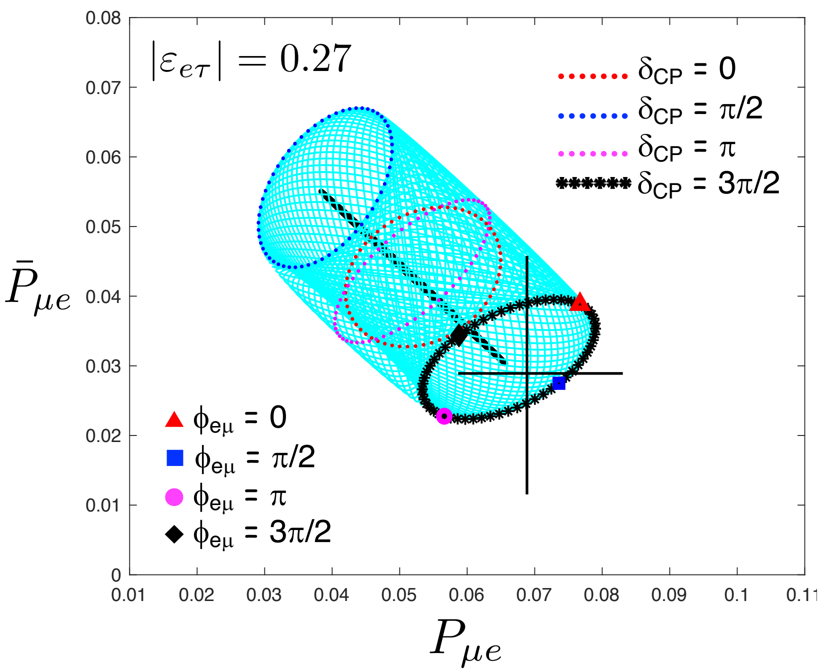
Heavy mediators
- **Tree-level see-saw** [Forero & Huang 1608.04719]
- **Radiative see-saw** [Babu et al. 1907.09498]

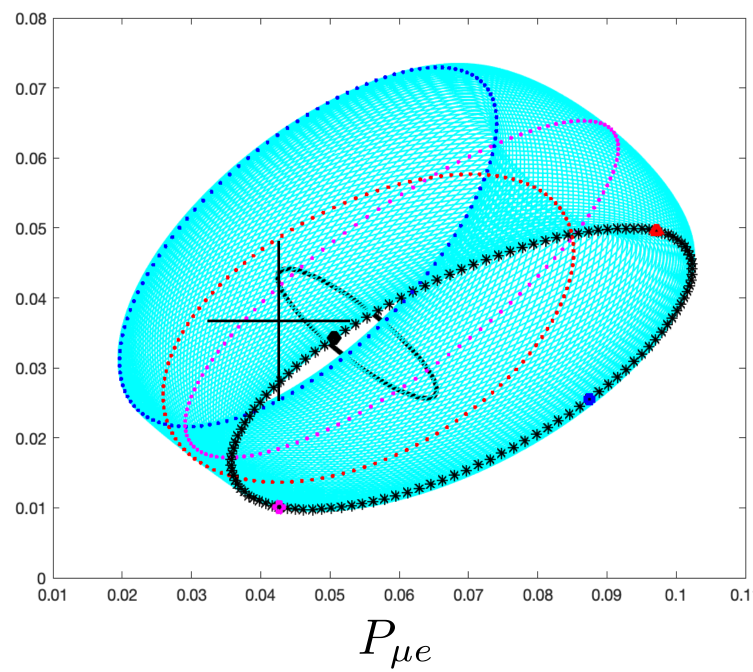
Light mediators are an appealing alternative
Farzan, Heeck 1607.07616 Farzan 1912.09408

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.

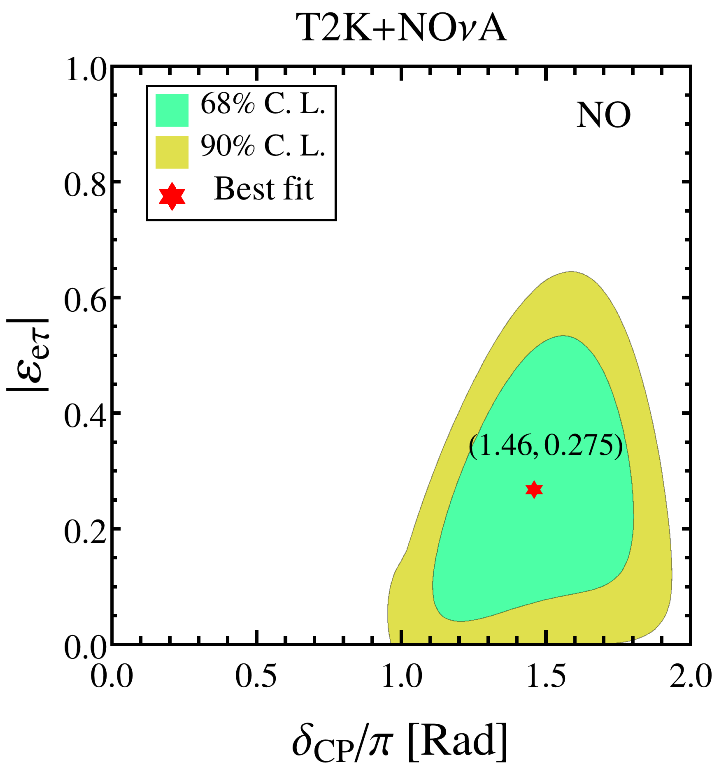
Biprobability plots in the presence of NSI

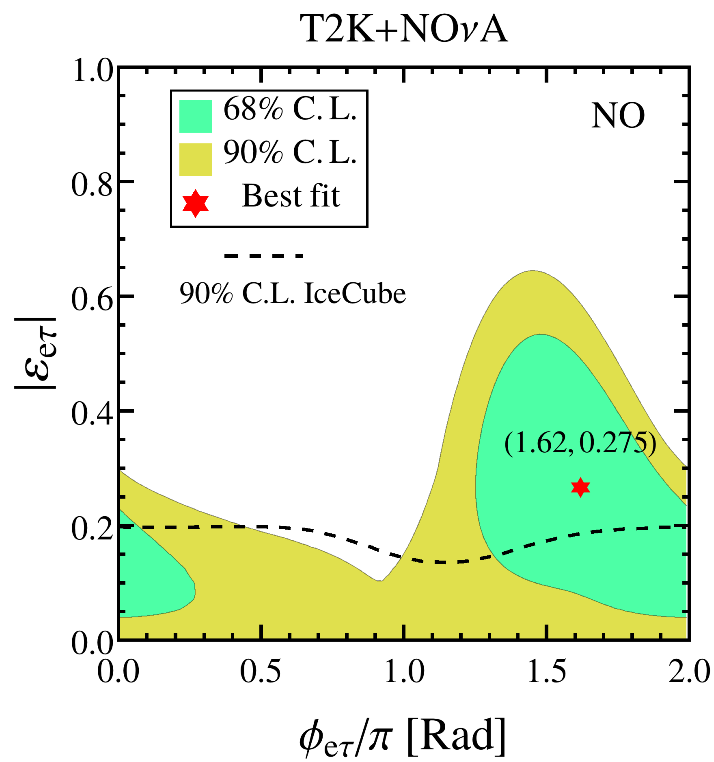
T2K	**NOνA**
Strongly favors $\delta_{CP} \sim 3\pi/2$ ellipse (almost no sensitivity to $\phi_{e\mu}$)	In agreement with $\delta_{CP} \sim 3\pi/2$ ellipse. On this ellipse it pins down $\phi_{e\mu} \sim 3\pi/2$





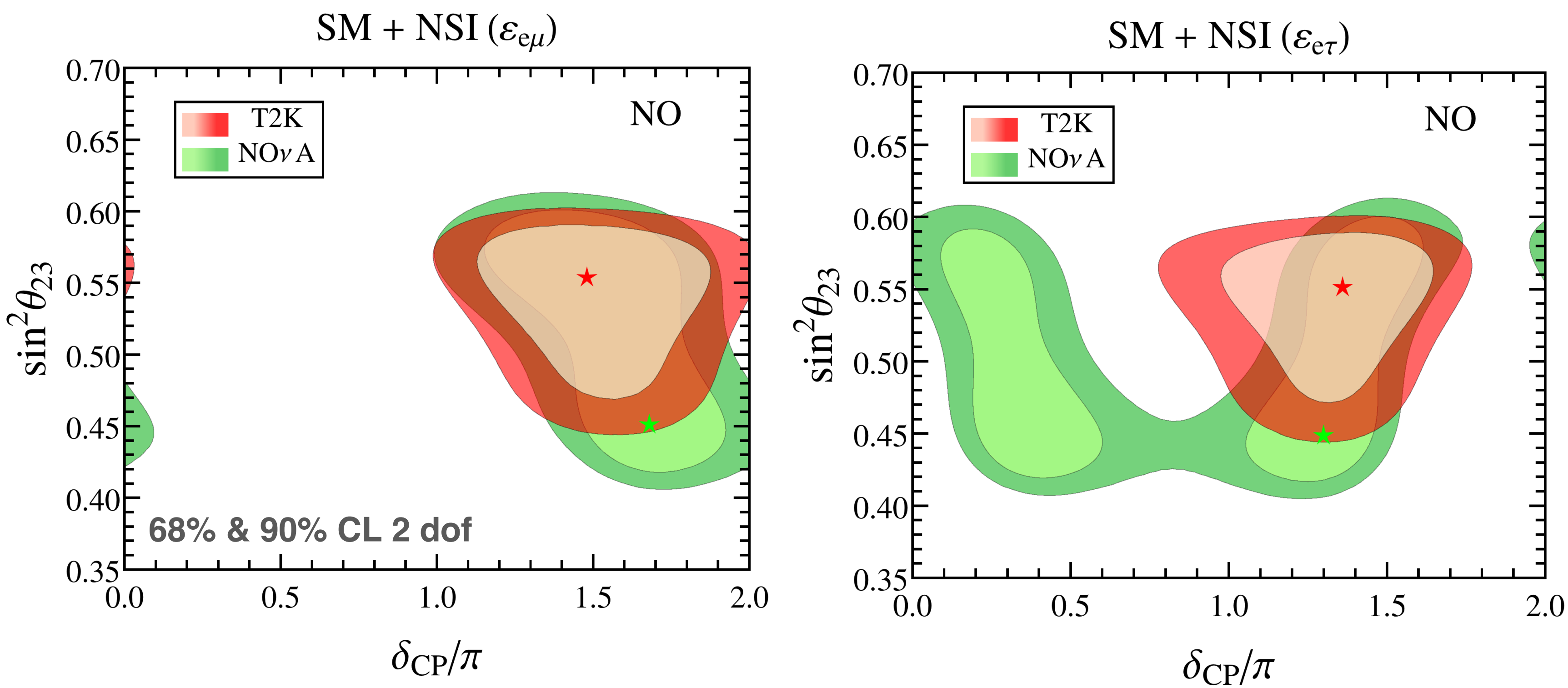
Indication of non-zero $\varepsilon_{e\tau}$ from T2K + NOνA





~2 sigma preference for NSI

Confronting $\varepsilon_{e\mu}$ with $\varepsilon_{e\tau}$



NOνA allowed region is different because $P_{\mu e}$ has different analytical form in the two cases (the relative sign of the coefficients a and b is opposite)

Confronting sterile νs with NSIs in T2K and NOvA

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*** Speaker**

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