Possible indication of NSI from NOνA & T2K

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*** Speaker**

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

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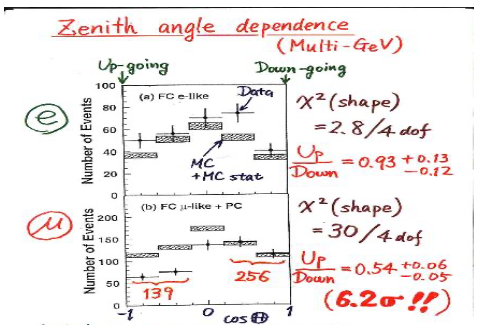
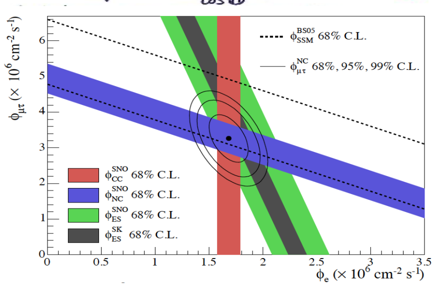
Outstanding progress in ν physics in ~ 20 years

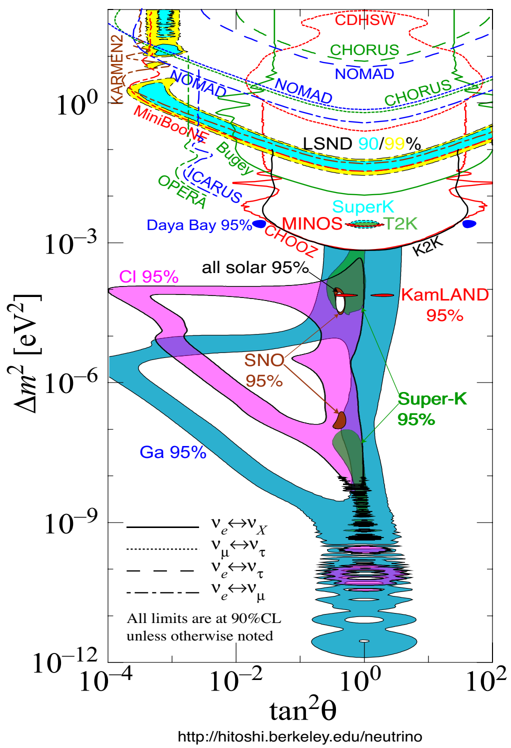
Discoveries





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

Interpretation



known knowns

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

known unknowns

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

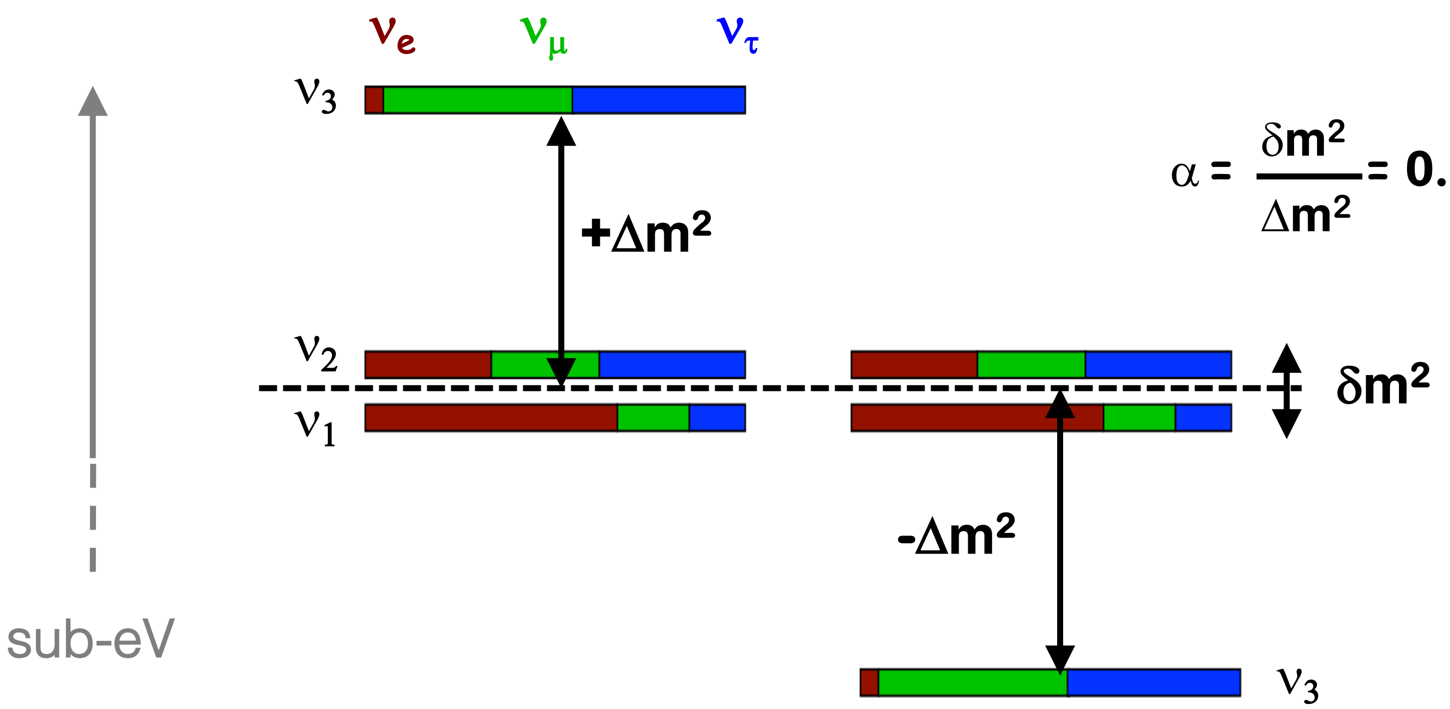
unkown unknowns

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

3-flavor scheme now established as the standard framework…

The 3ν mass spectrum

NO or IO ? NO favored at > 2σ



$$\alpha = \frac{\delta m^2}{\Delta m^2} = 0.03$$

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 $\delta \neq (0, \pi)$

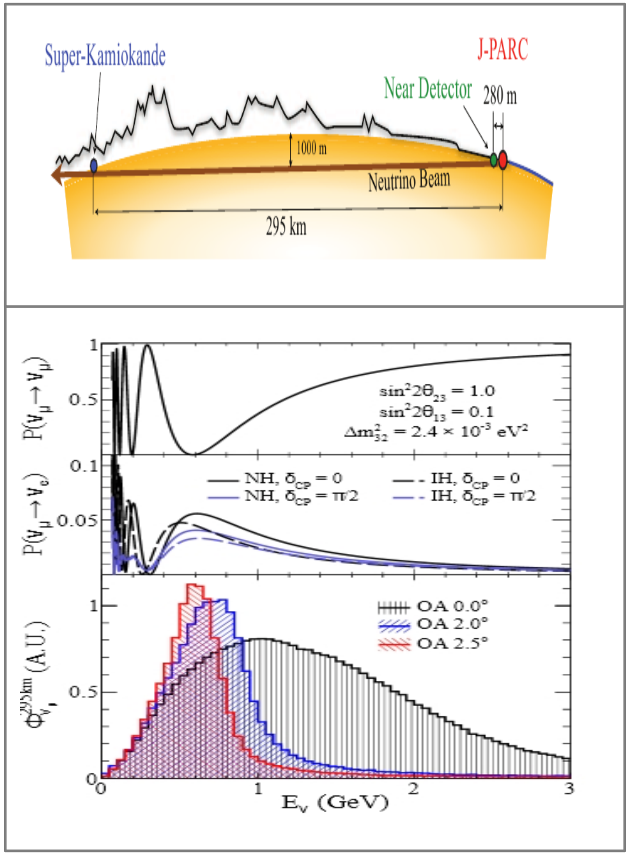
Explicit form

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

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

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

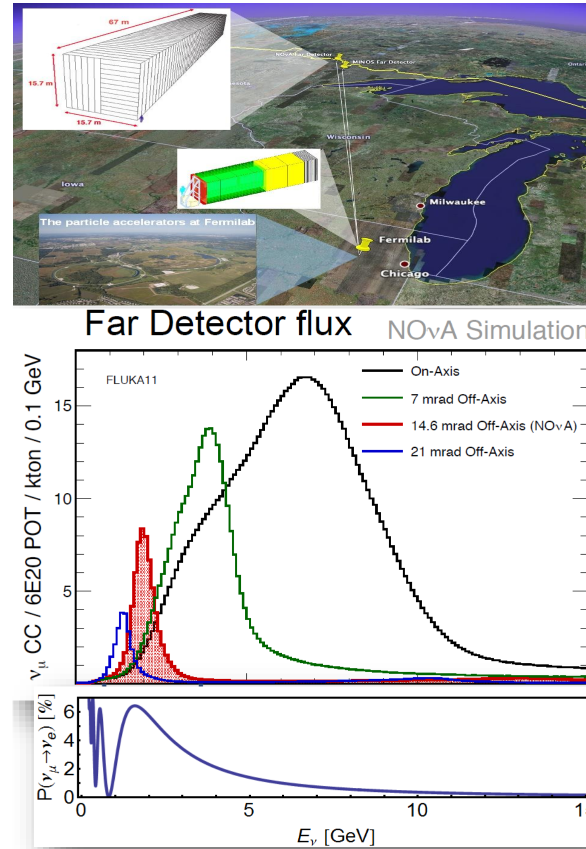
Two main actors: T2K & NOνA



off-axis beam

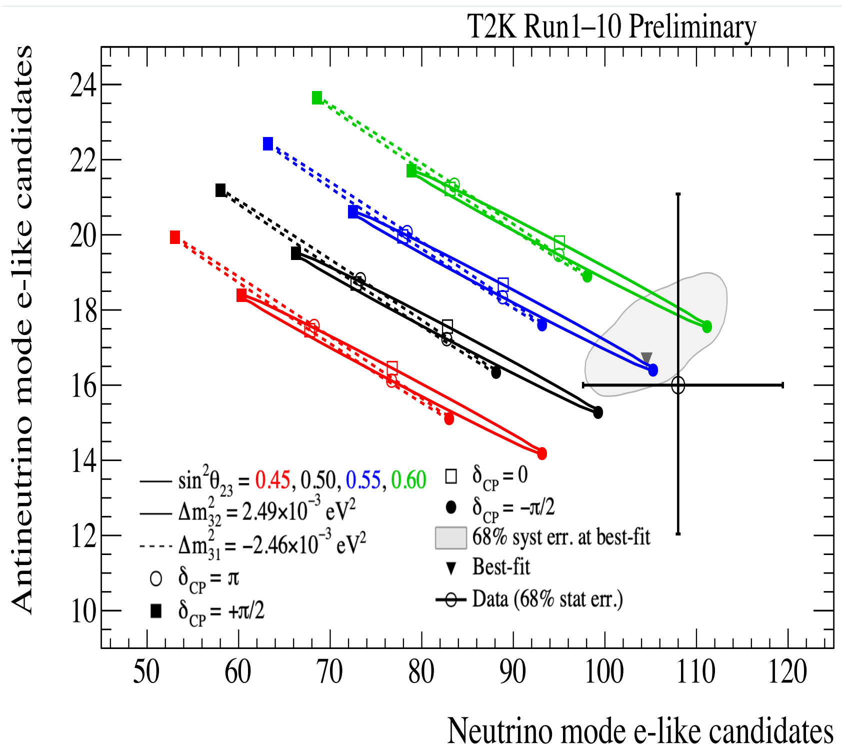
$$\Delta = \frac{\Delta m_{13}^2 L}{4E} \simeq \frac{\pi}{2}$$

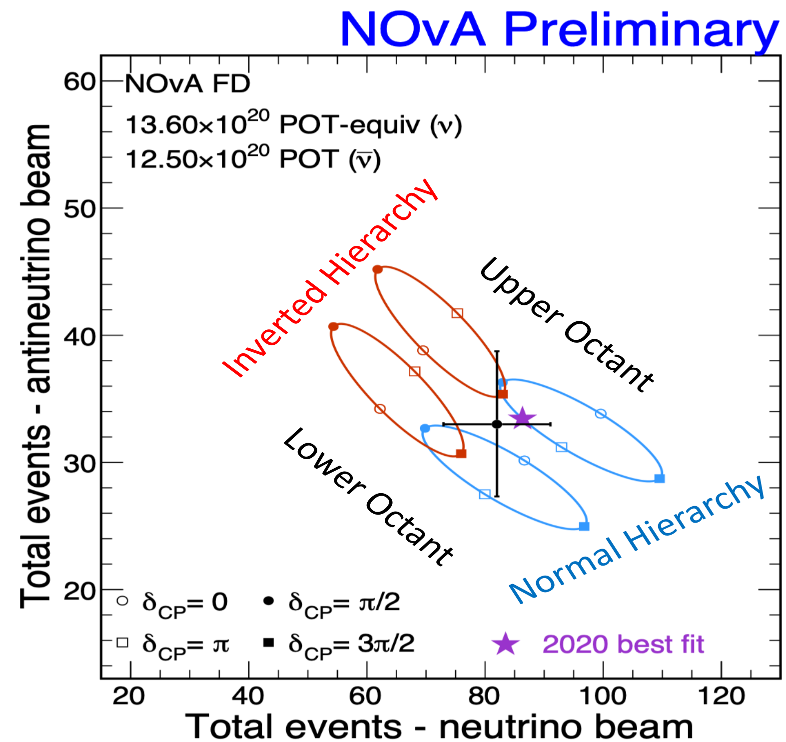
First oscillation maximum



T2K	NOνA
E = 0.6 GeV	**E = 2 GeV**
L = 295 km	**L = 810 km**

Bird's-eye view: bievents plots of ν 2020

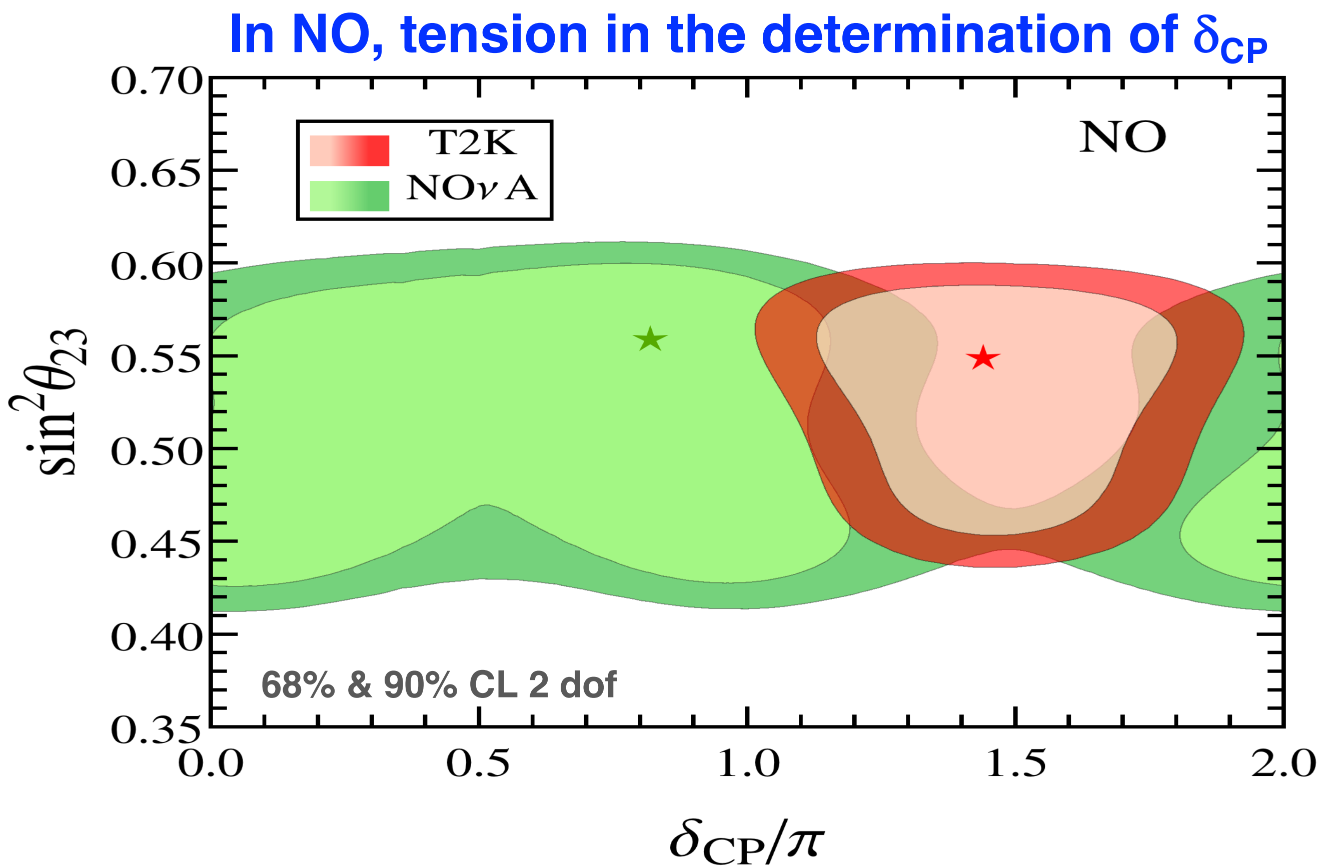




for Normal Ordering:

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

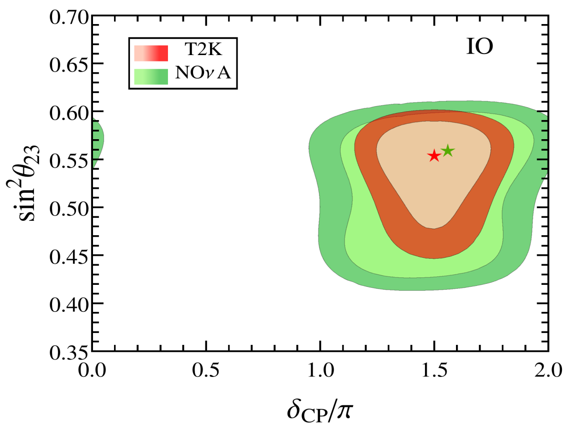
Our analysis of ν 2020 preliminary data

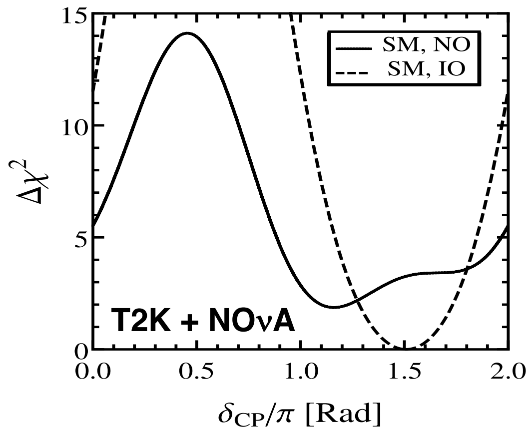


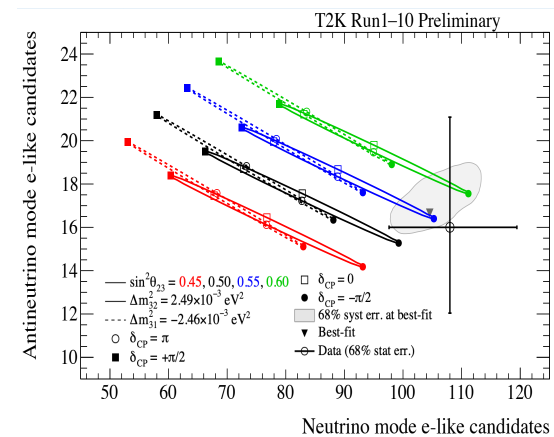
Maybe a statistical fluctuation or a systematic error

But interesting to consider alternative explanations…

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

Why to consider non-standard interactions

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

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

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.

Theoretical Framework

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \dots$$

← **NSI**

$$\delta\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F \sum_{f,P} \epsilon_{\alpha\beta}^{fP} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P f\right)$$

$$f = e, u, d$$

$$P = (P_L, P_R)$$

Only vectorial couplings are relevant for matter effects

$$\varepsilon_{\alpha\beta}^{f} = \varepsilon_{\alpha\beta}^{f,L} + \varepsilon_{\alpha\beta}^{f,R}$$

Effective couplings in the Earth's crust ($N_n \cong N_p$)

$$\varepsilon_{\alpha\beta} \simeq \varepsilon_{\alpha\beta}^{e} + 3\varepsilon_{\alpha\beta}^{u} + 3\varepsilon_{\alpha\beta}^{d}$$

$$H = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & k_{21} & 0 \\ 0 & 0 & k_{31} \end{bmatrix} U^\dagger + V_{\rm CC} \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{bmatrix}$$

$$k_{ij} = \frac{\Delta m_{ij}^2}{2E}$$

$$V_{\rm CC} = \sqrt{2} G_F N_e$$

Off-diagonal $\varepsilon_{\alpha\beta}$ are complex and bring a CP phase

$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| e^{i\phi_{\alpha\beta}}$$

We focus on $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ ($\varepsilon_{\mu\tau}$: small effect on ν_e apperance and strong bounds)

Analytical expectations

$P_{\mu e}$ 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	$v \sim 0.18$

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

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

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

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

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

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

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

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

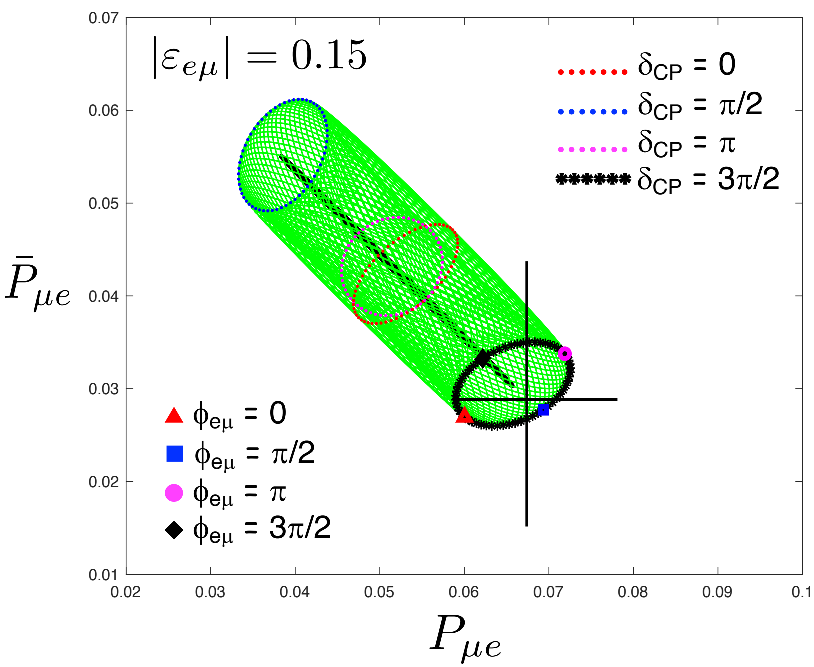
Parametric curve in biprobability plot:

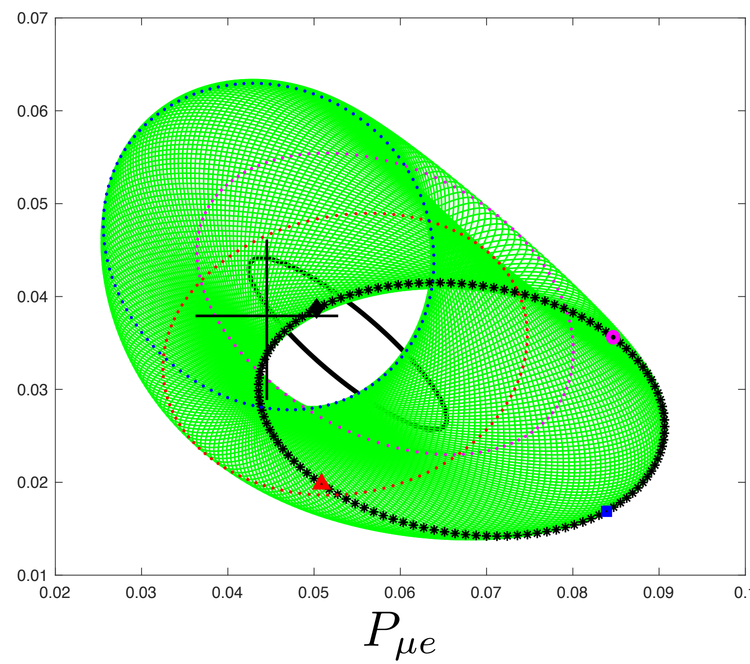
$[x, y] = [P_{\mu e}, \bar{P}_{\mu e}]$

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

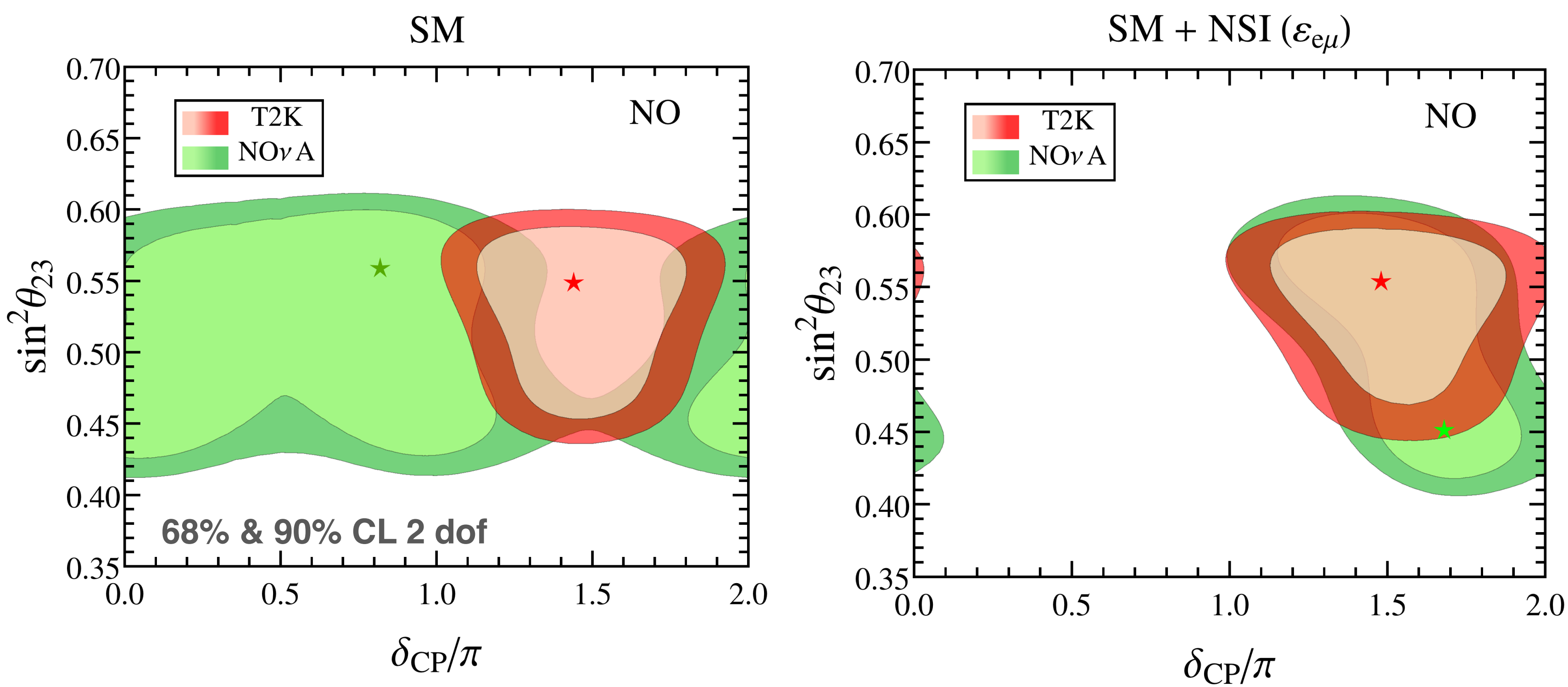
Biprobability plots in the presence of NSI

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





NSI bring the estimates of δ_{CP} in agreement

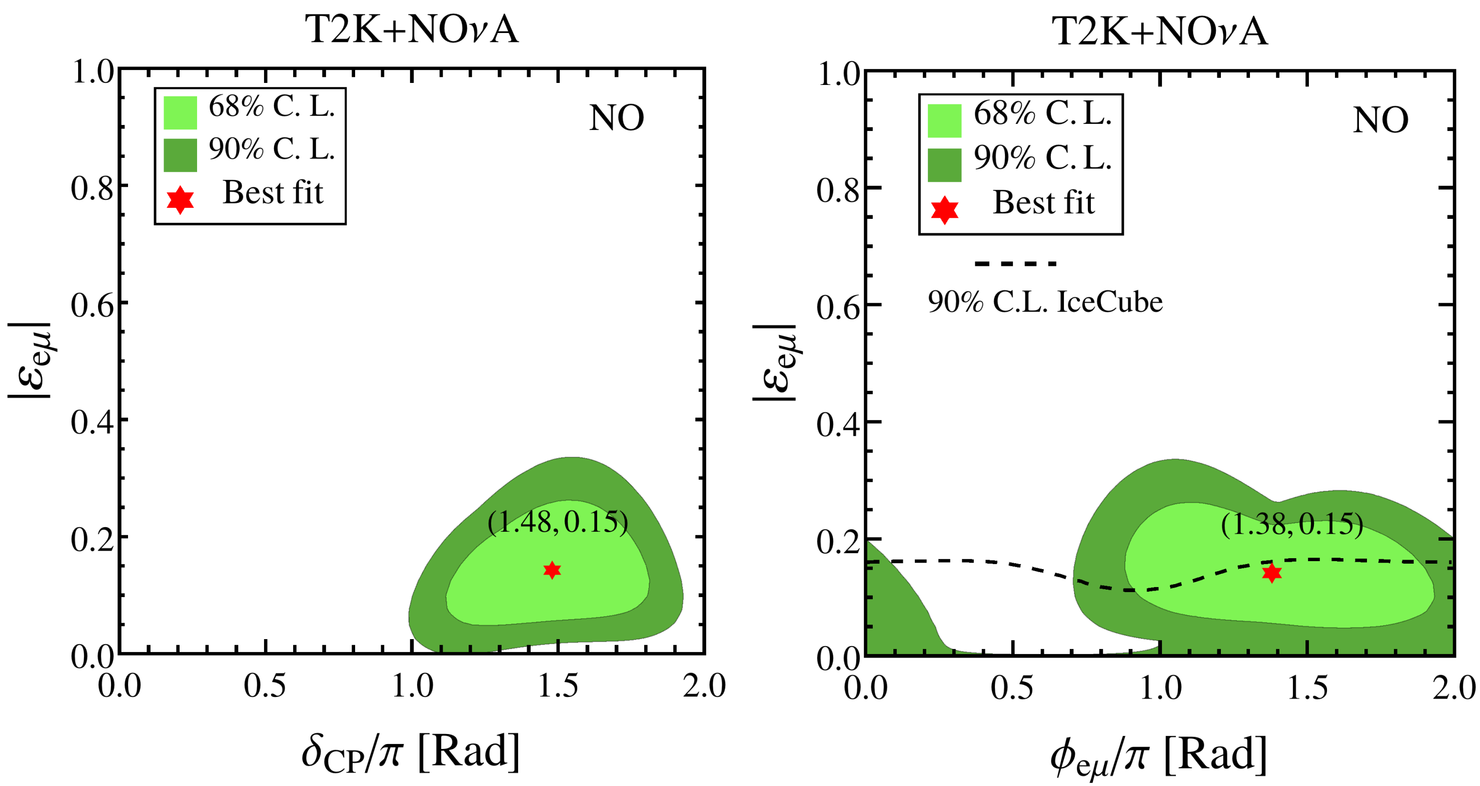


Contours obtained for the best fit of T2K + NOνA: $[\varepsilon_{e\mu} = 0.15,\ \phi_{e\mu} = 1.38\pi]$

T2K region almost unaltered

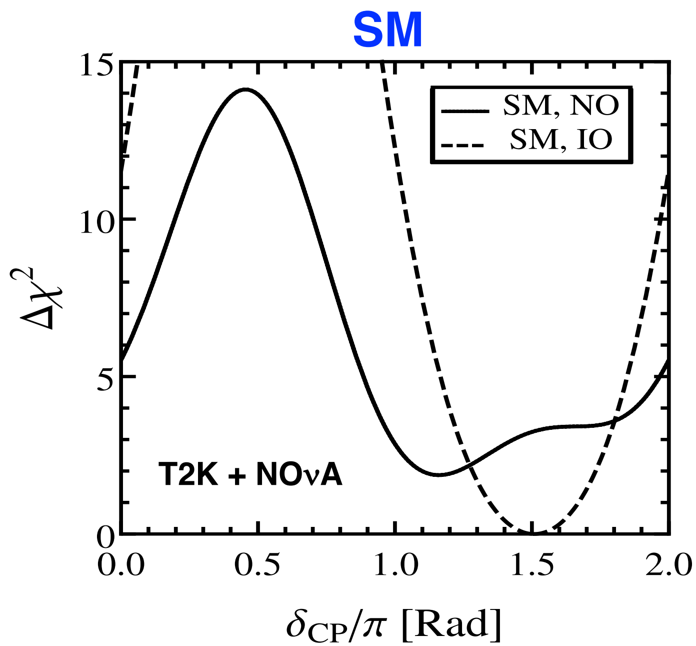
NOνA region strongly modified

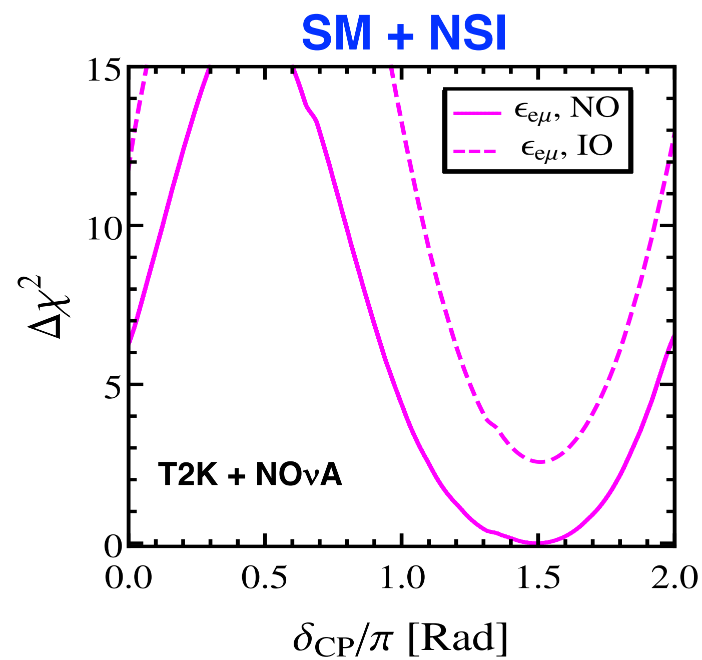
Indication of non-zero $\varepsilon_{e\mu}$ from T2K + NOνA



~2 sigma preference for NSI

NSI restore the preference for NO





Better agreement with all the other data

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 $\varepsilon_{e\tau}$**

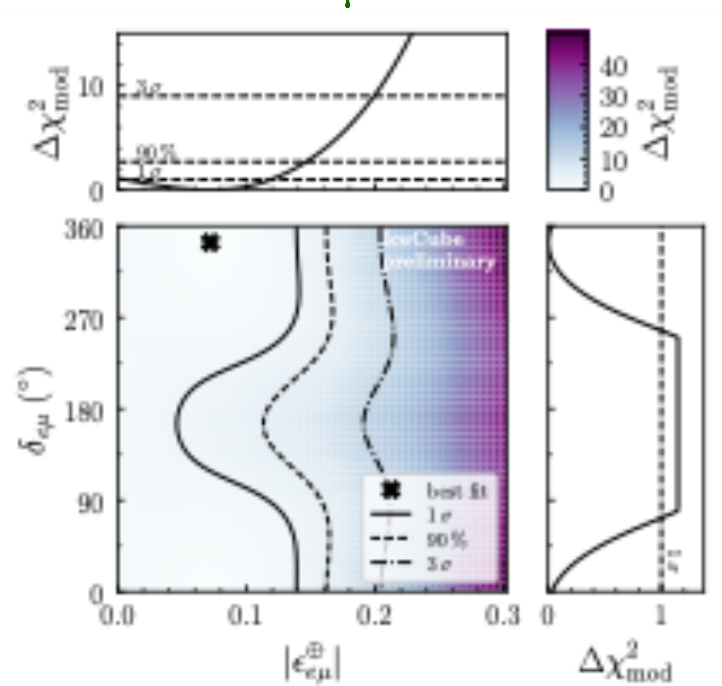
IO
- **No significant preference for non-zero NSI**

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

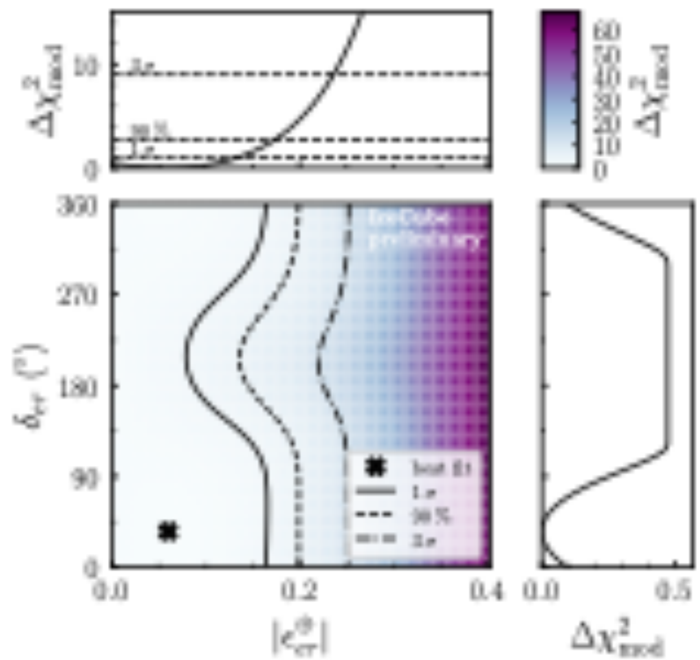
Current bounds from IceCube

DeepCore
3-years sample

$\varepsilon_{e\mu}$



$\varepsilon_{e\tau}$



Thomas Ehrhardt, PPNT 2019

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.

Conclusions

In NO, T2K and NOνA display a tension at ~2 sigma level

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

Hard to generate such couplings with heavy mediators but easier with light mediators

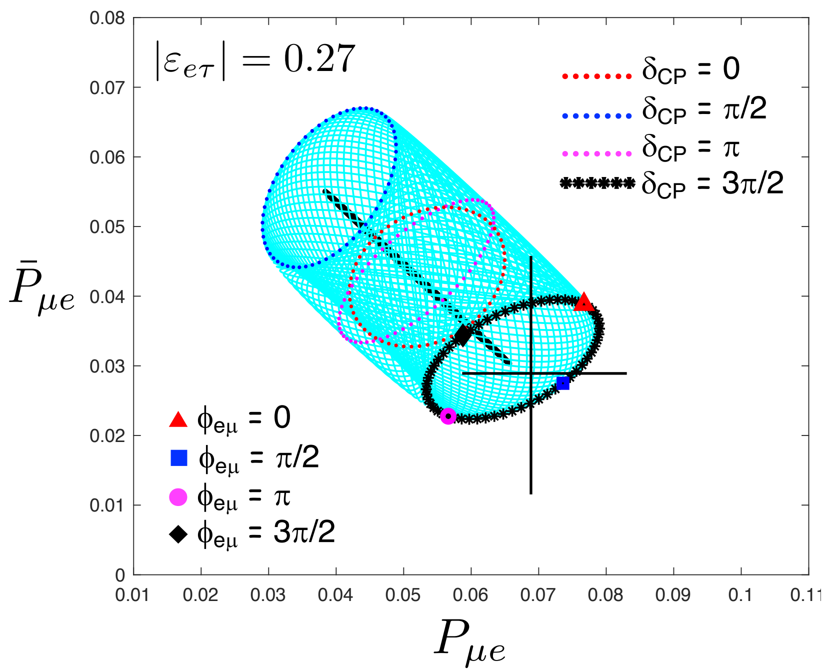
New IceCube data with higher statistics should be able to probe these couplings

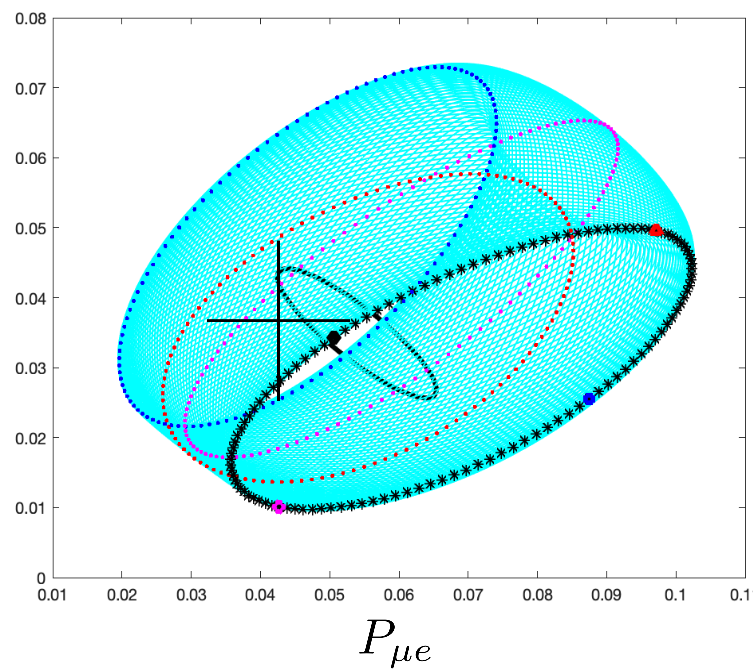
If the NSI indication persists, T2HK and DUNE will definitely confirm/disconfirm it.

Backup slides

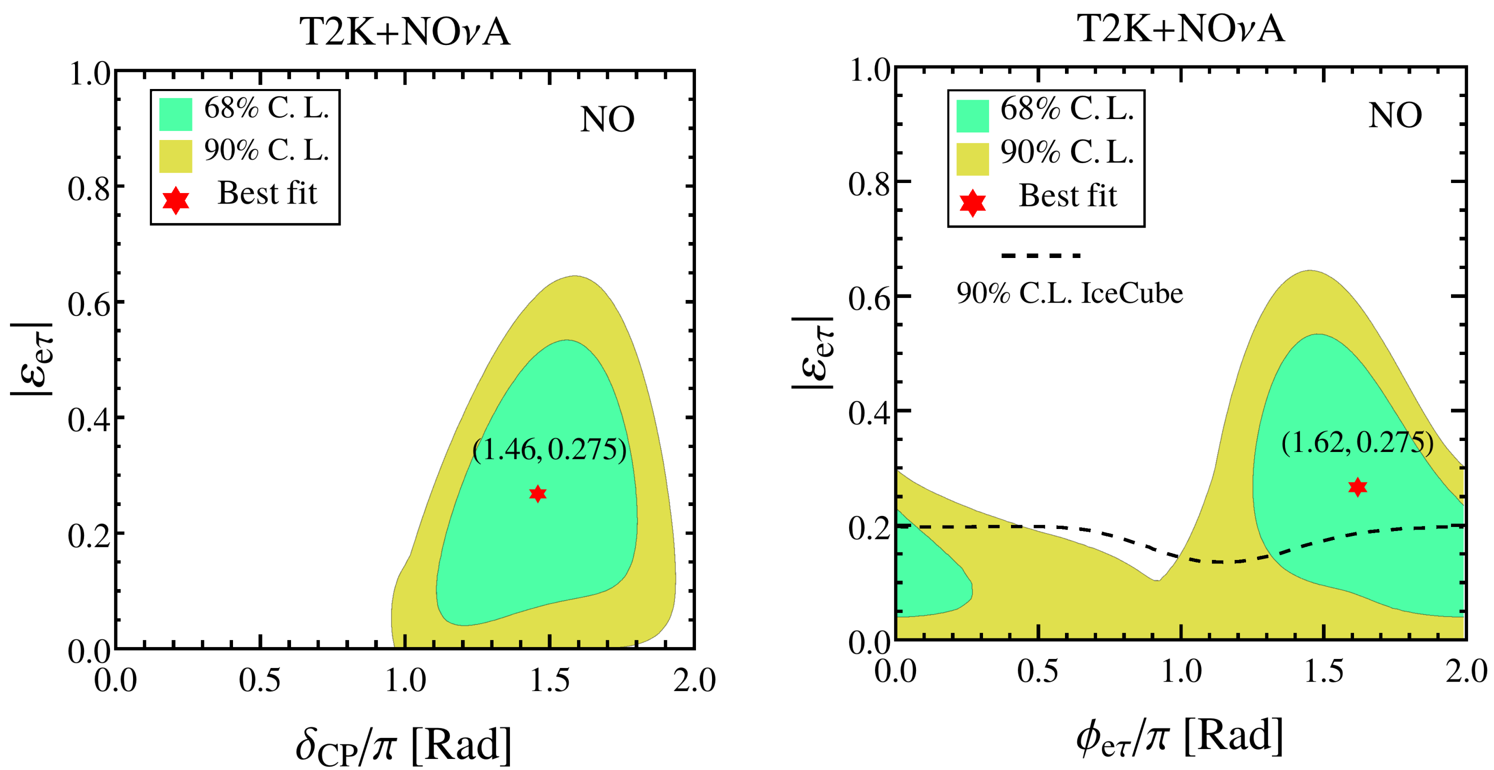
Biprobability plots in the presence of NSI

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



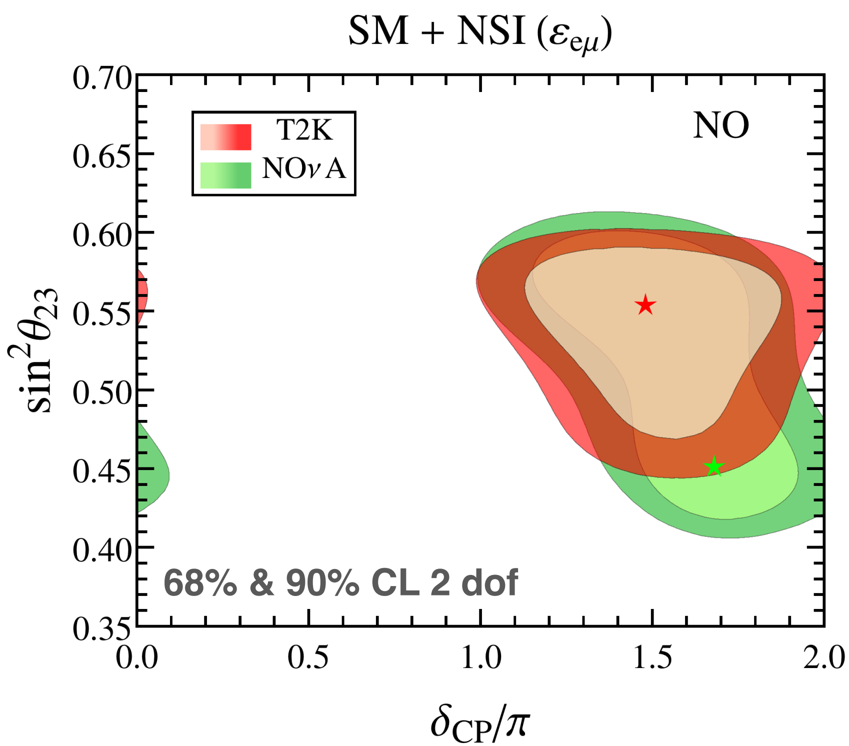


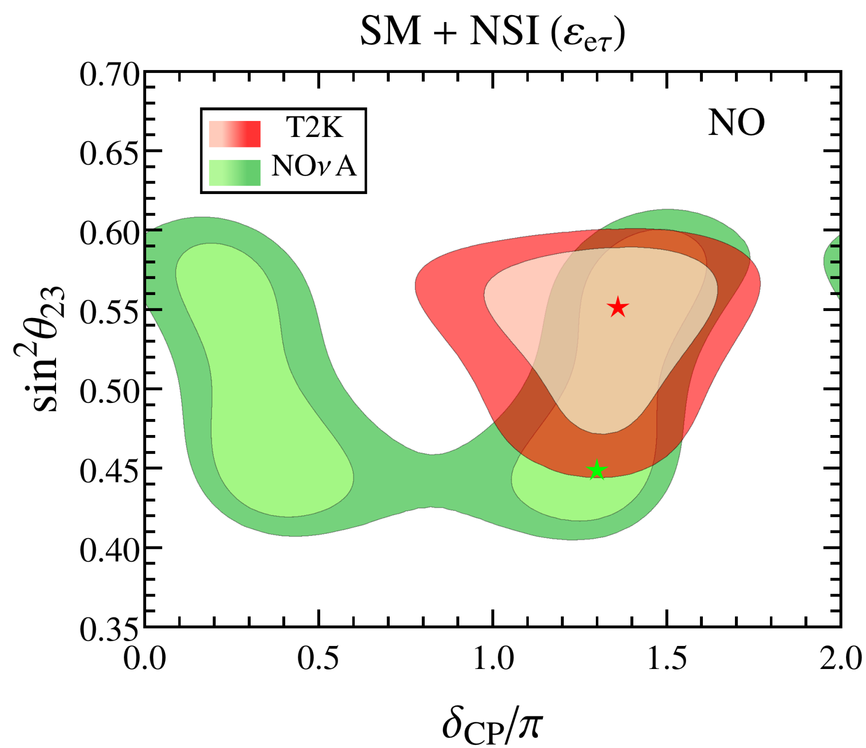
Indication of non-zero $\varepsilon_{e\tau}$ from T2K + NOνA



~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)