CP-Violating Neutrino Non-Standard Interactions in Long-Baseline-Accelerator Data

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WIN 2021

June 2021

Based on 2008.01110, Phys. Rev. Lett. 126 (2021) no.5, 051801
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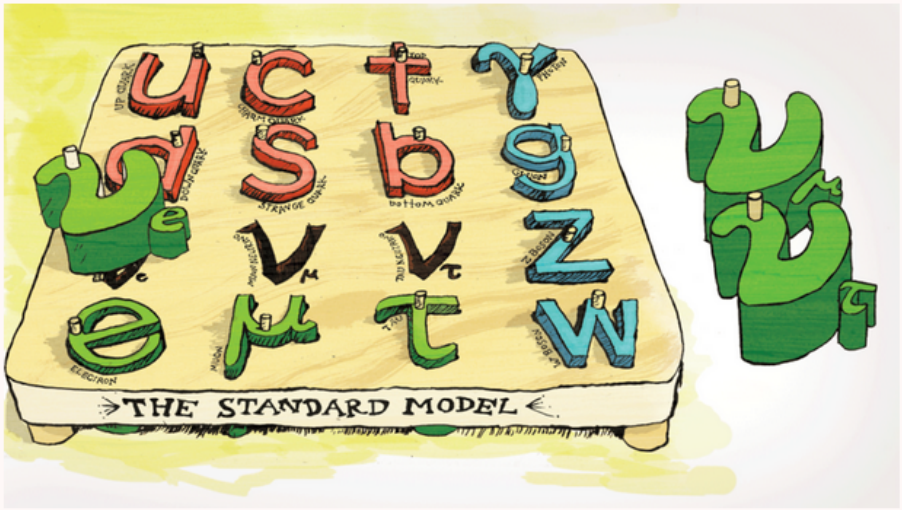
Neutrino oscillations

- Neutrino oscillations: **strong** evidence for BSM physics



Neutrino oscillations

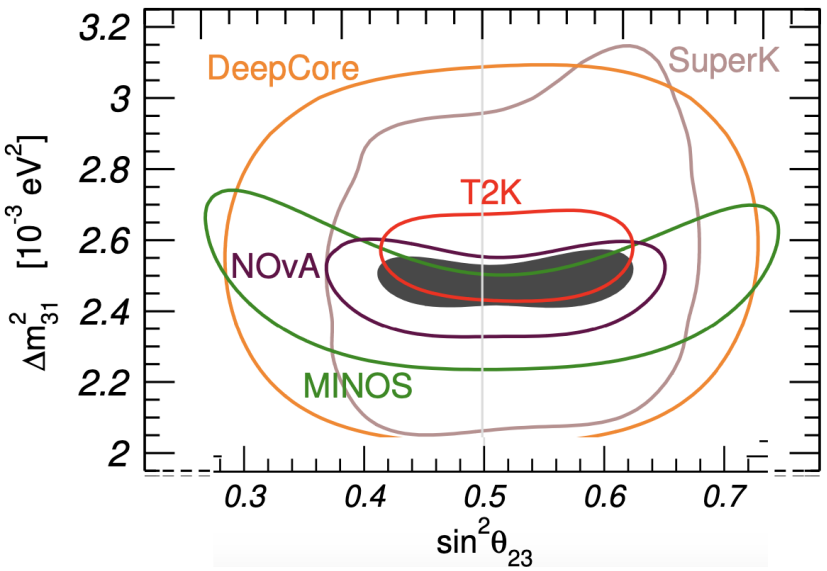
- flavor eigenstates (of weak interaction) and mass eigenstates (of free particle Hamiltonian) not aligned for neutrinos $\rightarrow$ related by mixing matrix
- standard parametrization for PMNS matrix as a series of three rotations

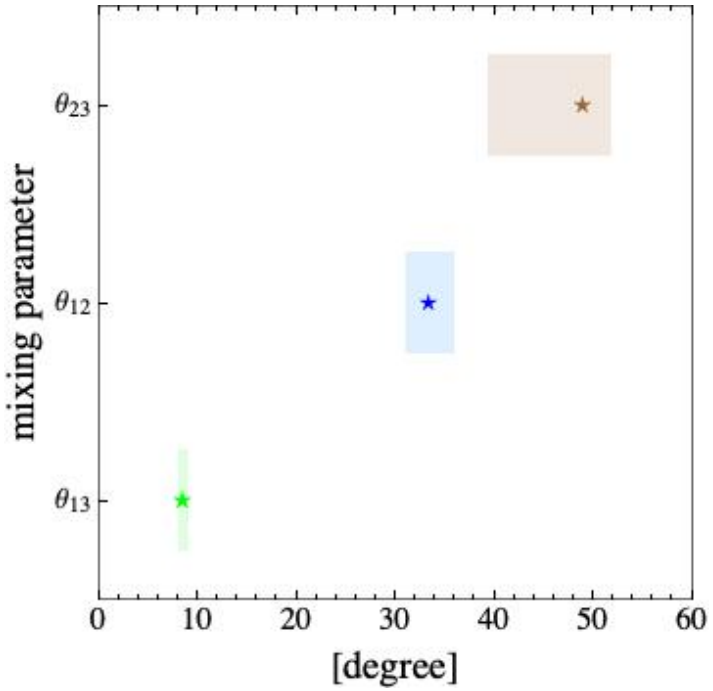
$$U_{PMNS} = U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta)U_{12}(\theta_{12})$$

$\Rightarrow$ **want to measure these new parameters!**

Neutrino oscillations

- many experiments have measured the angles and mass splittings
  $\rightarrow$ impressive agreement between experiments

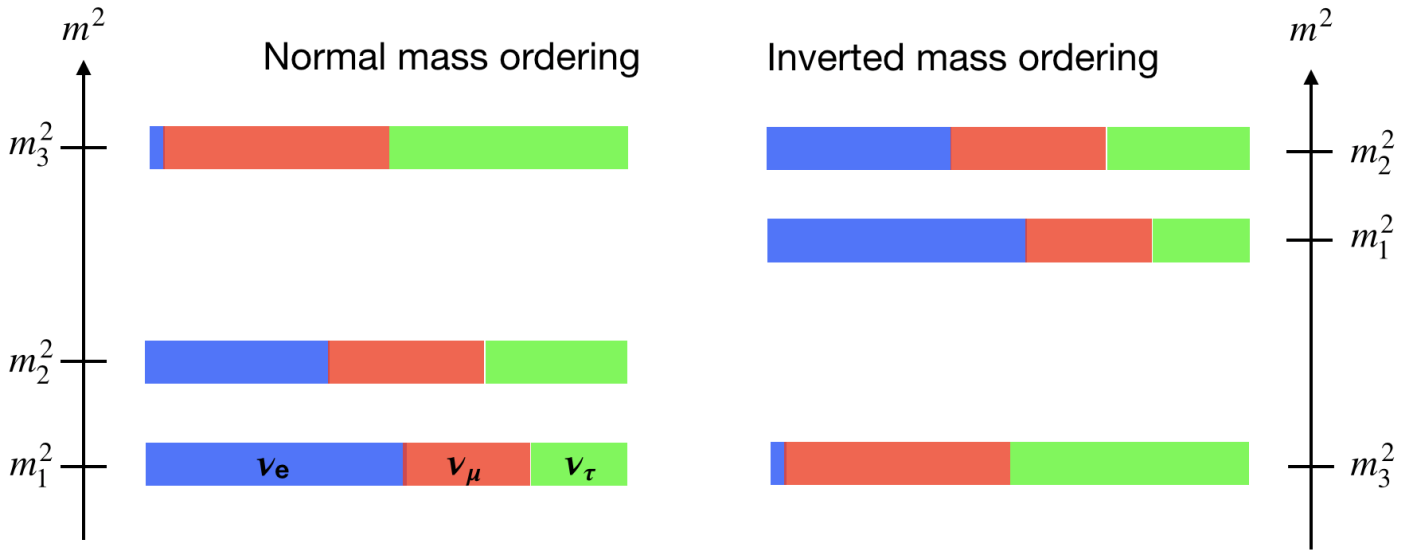




[nuFit v5.0]

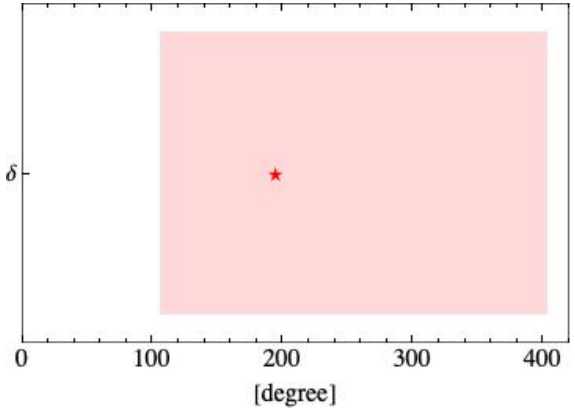
Neutrino oscillations

- mass splittings: $|\Delta m^2_{32}| = 2.5 \cdot 10^{-3}$ eV^2, $\Delta m^2_{21} = 7.4 \cdot 10^{-5}$ eV^2
- mass ordering unknown



CP violation

- all three mixing angles are non-zero $\rightarrow$ possibility for CPV
- currently least known parameter is δ which governs CPV in lepton sector
- want to measure δ!



[nuFit v5.0]

CPV in the SM

- CPV in mass matrices quantified via basis invariant

$$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta$$

$J_{CP}^{max} = 1/(6\sqrt{3}) \approx 0.096$ [Jarlskog '85]

- quark mixing matrix: non-zero δ_{CKM} but CPV is small
  $|J_{CKM}|/J_{CP}^{max} = 3 \cdot 10^{-4}$

- **Is CP violated in the lepton sector? By how much?**
  $|J_{PMNS}|/J_{CP}^{max} < 0.34$

CPV in the lepton sector

How to measure CPV?

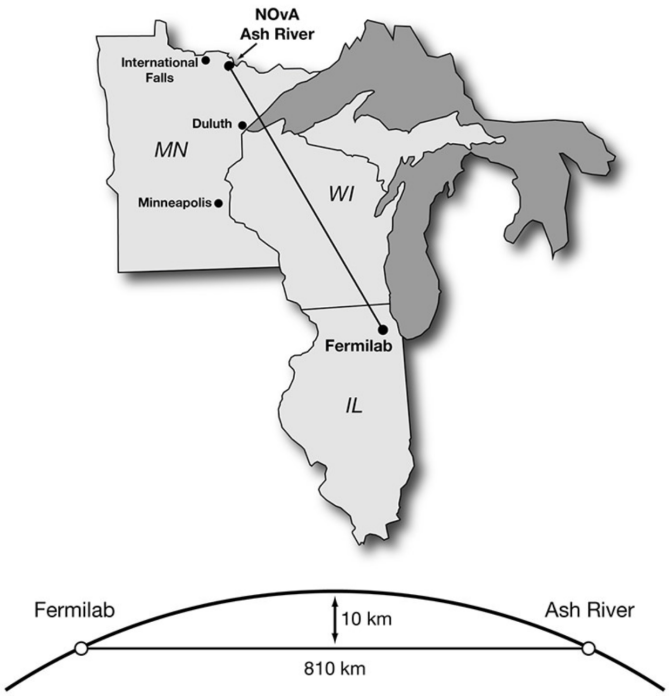
- measure CPV in appearance experiments $P(\nu_\alpha \to \nu_\beta)$
- compare neutrino with anti neutrino oscillation probability

use $P(\nu_\mu \to \nu_e)$ as oscillation channel!

due to matter effects this channel is also sensitive to the MO

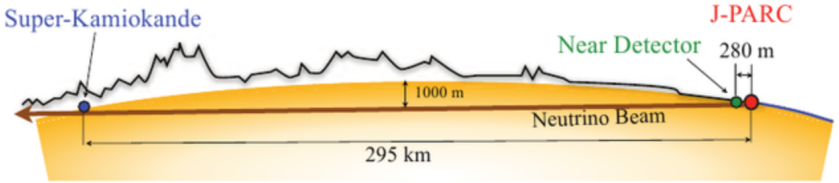
Long baseline experiments: NOvA

- neutrinos from NUMI beam at Fermilab
- $E \sim 1.9$ GeV, L=810 km
- matter density $\rho = 2.84$ g/cc
- Near (far) detector 0.3 (14) kT liquid scintillator

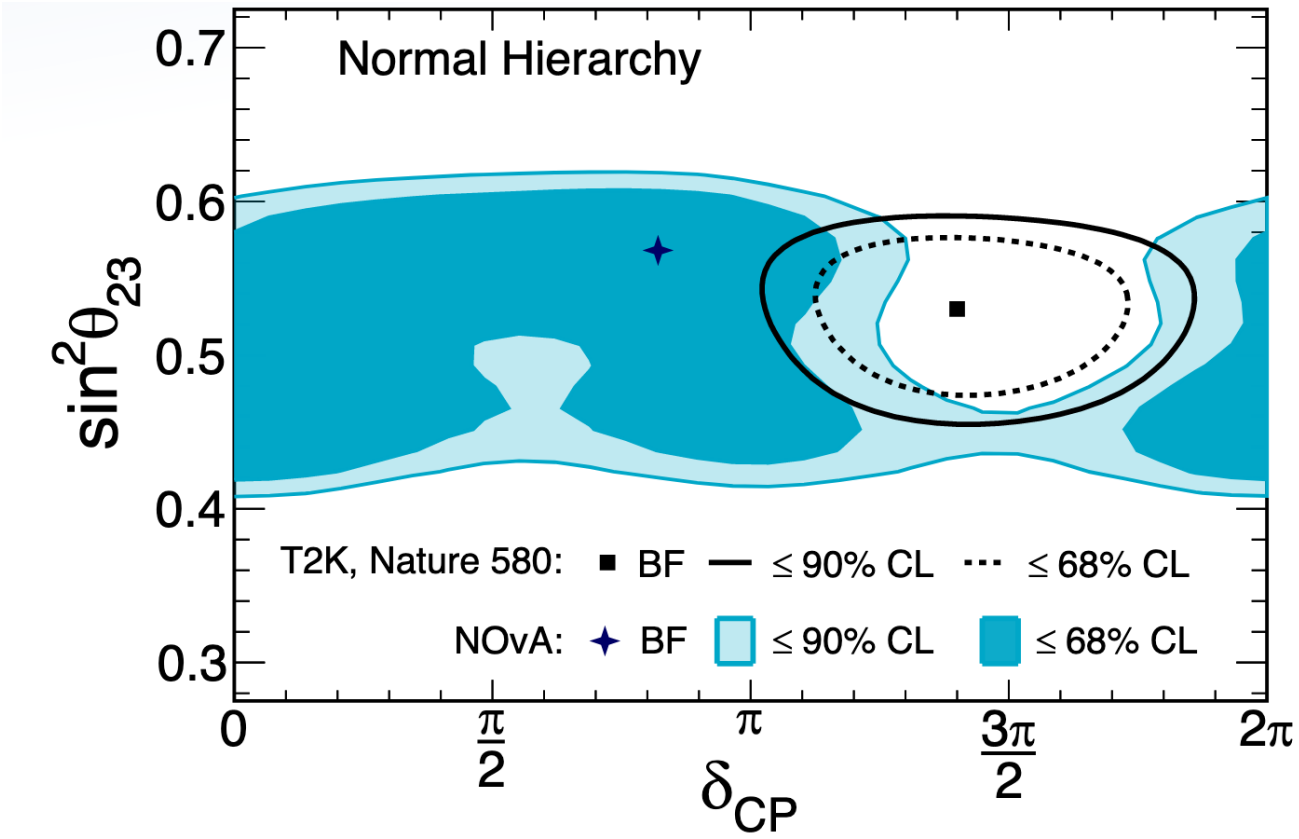


Long baseline experiments: T2K

- neutrinos from JPARC beam
- $E \sim 0.6$ GeV, L=295 km
- matter density $\rho = 2.3$ g/cc
- near detector: scintillator, far detector is SuperK

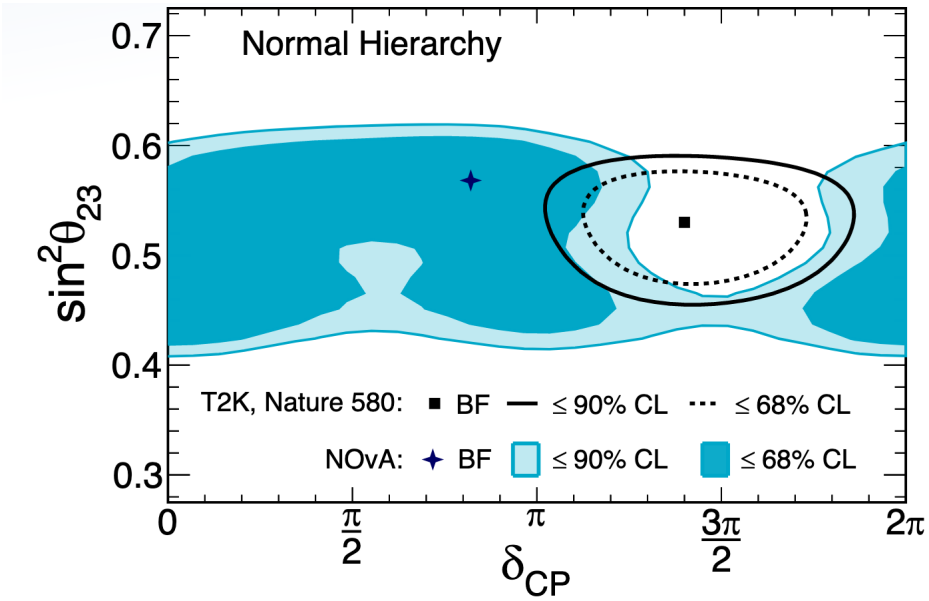


Excitement at Neutrino2020!



[Himmel '20]

Neutrino2020

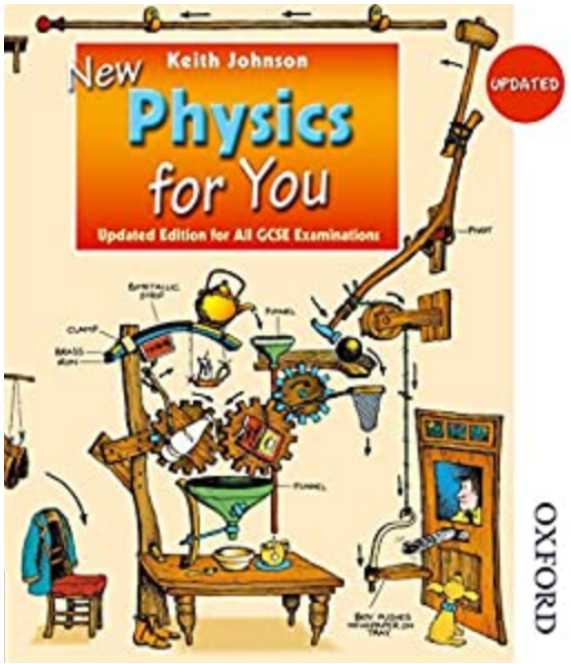


[Himmel '20]

- both experiments prefer NO
- T2K prefers $\delta = 3\pi/2$
- no strong preference for NOvA, generally around $\delta \sim \pi$
- slight disagreement at $\sim 2\sigma$

New physics solutions

Can new physics alleviate this slight discrepancy?



New physics

difference between NOvA and T2K is the baselines and the matter density

$\rightarrow$ neutrinos at NOvA experience stronger matter effects

new physics solution could be related to this difference

introduce new matter interactions for neutrinos

$\Rightarrow$ **neutrino non-standard interactions**

Non-standard interactions [Dev et al '19]

- framework

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon^{f,P}_{\alpha\beta}(\overline{\nu}_\alpha\gamma^\mu\nu_\beta)(\overline{f}\gamma_\mu f)$$

- affect oscillations via new matter effect

$$H = \frac{1}{2E}\left[U^\dagger M^2 U + a\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right]$$

matter potential $a \propto G_F \rho E$

Non-standard interactions

focus on vectorial NSI (for propagation), flavor changing parameters

6 real parameters:

$$|\epsilon_{e\mu}|e^{i\phi_{e\mu}},\ |\epsilon_{e\tau}|e^{i\phi_{e\tau}},\ |\epsilon_{\mu\tau}|e^{i\phi_{\mu\tau}}$$

consider only one complex parameter at a time

NSI: analytical results [Denton, JG, Pestes '20]

estimate for magnitude of NSI parameter

$$|\epsilon_{e\beta}| \approx \frac{s_{12}c_{12}c_{23}\pi\Delta m^2_{21}}{2s_{23}w_\beta}\left|\frac{\sin\delta_{\text{T2K}} - \sin\delta_{\text{NOvA}}}{a_{\text{NOvA}} - a_{\text{T2K}}}\right| \approx \begin{cases} 0.22 & \text{for } \beta = \mu \\ 0.24 & \text{for } \beta = \tau \end{cases},$$

with $w_\beta = \sin\theta_{23}(\cos\theta_{23})$

- if $\sin\delta_{\text{T2K}} = \sin\delta_{\text{NOvA}} \Rightarrow |\epsilon| = 0$
- if $\sin\delta_{\text{T2K}} \neq \sin\delta_{\text{NOvA}}$ & $a_{\text{T2K}} = a_{\text{NOvA}} \Rightarrow |\epsilon| \to \infty$

NSI: analytical results [Denton, JG, Pestes '20]

estimate for phase of NSI parameter

with $\delta_{\text{NOvA}} \neq \delta_{\text{T2K}}$

we find that $\sin(\delta_{\text{true}} + \phi_{e\beta}) \approx 0$

with $a_{\text{NOvA}} > a_{\text{T2K}}$ and $\sin\delta_{\text{T2K}} < \sin\delta_{\text{NOvA}}$:

$$\cos(\delta_{\text{true}} + \phi_{e\beta}) \approx -1$$

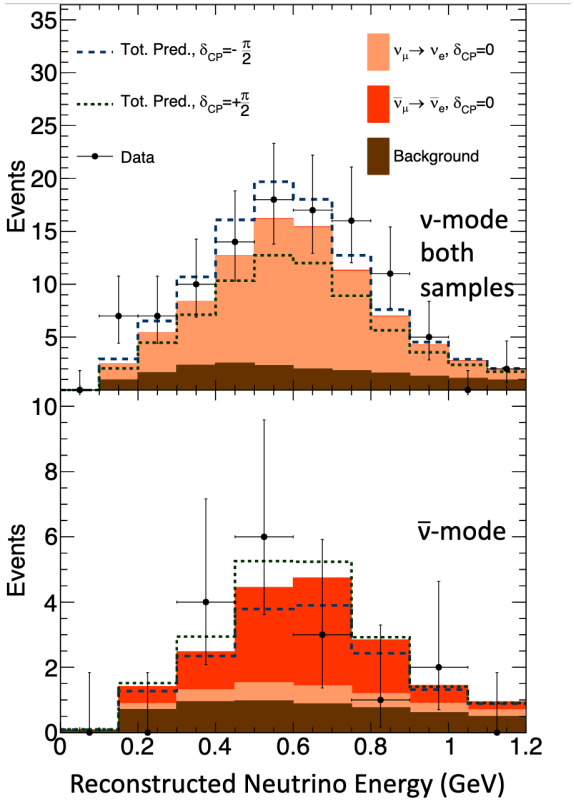
$$\delta_{\text{true}} \approx \delta_{\text{T2K}} \rightarrow \phi_{e\beta} \approx \frac{3}{2}\pi$$

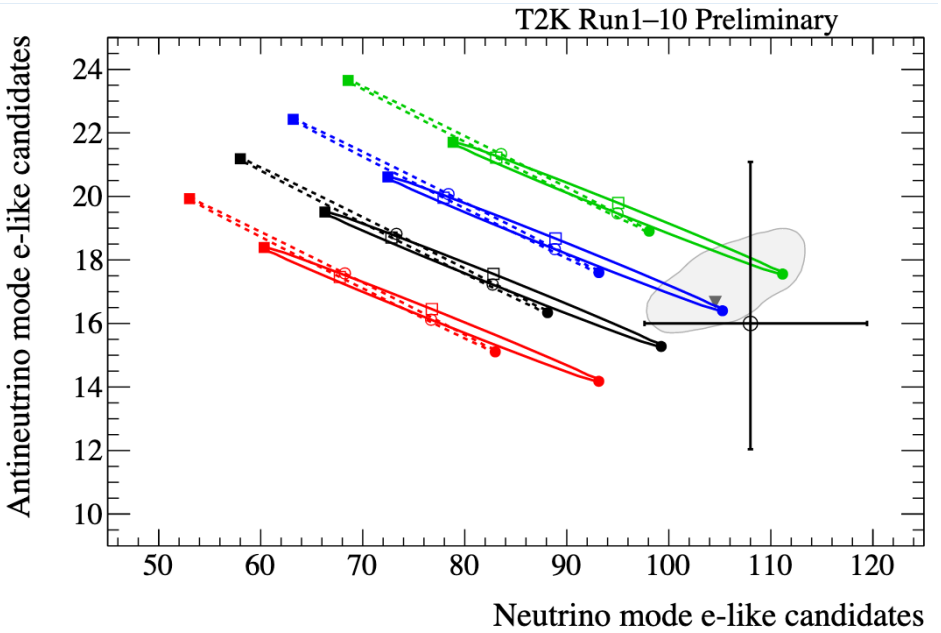
NSI: numerical results [Denton, JG, Pestes '20]

- Appearance data:

$$n(\nu_e) = xP(\nu_\mu \to \nu_e) + yP(\bar{\nu}_\mu \to \bar{\nu}_e) + z\,,$$

include wrong sign leptons, fit to points on biprobability plot





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include wrong sign leptons, fit to points on biprobability plot

- Disappearance data:

NOvA: use fit results from [Kelly et al '20]
$|\Delta m^2_{32}| = (2.41 \pm 0.07) \times 10^{-3}$ eV^2,
$4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) = 0.99 \pm 0.02$

T2K: use provided likelihoods for $\theta_{23},\ \Delta m^2_{32}$

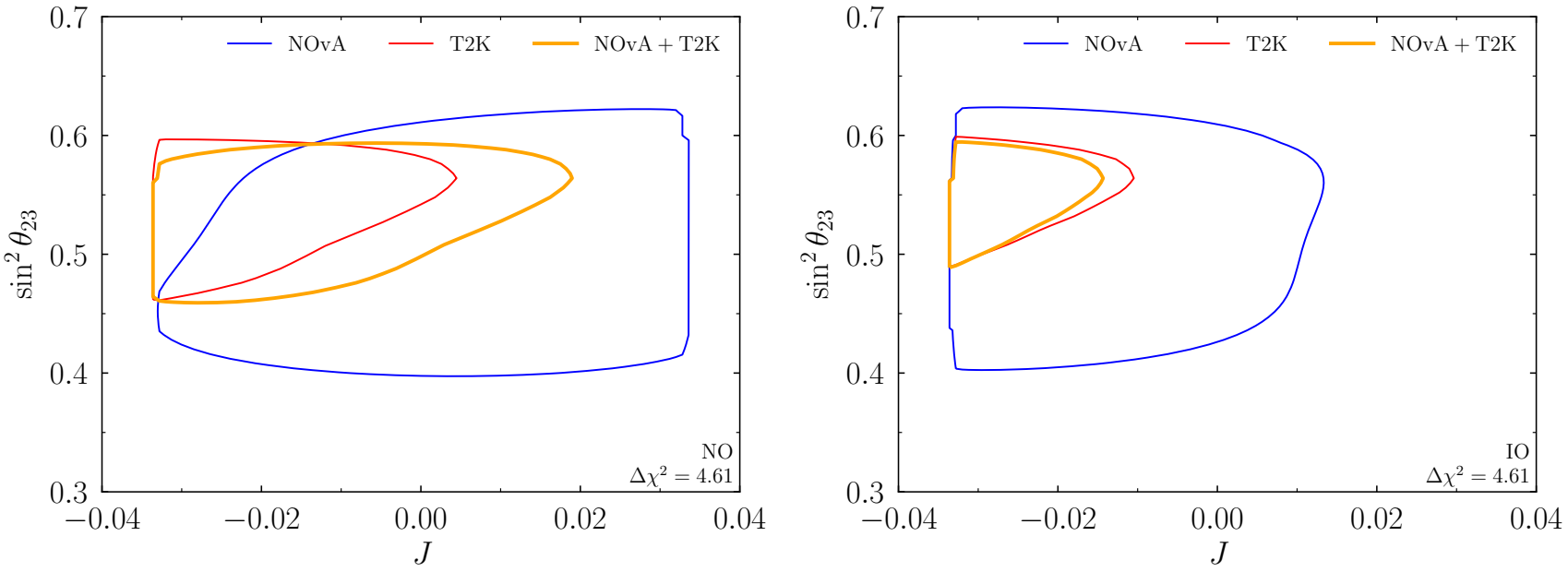
NSI: numerical results [Denton, JG, Pestes '20]

use information from vacuum experiments for remaining parameters

- Daya Bay: θ_{13}, $|\Delta m^2_{32}|$ [1809.02261]
- KamLAND: θ_{12}, $|\Delta m^2_{21}|$ [1303.4667]
- SNO: $\Delta m^2_{21} > 0$

conduct combined analysis of NOvA and T2K using a log likelihood ratio with Poisson statistics

Standard oscillation parameters [Denton, JG, Pestes '20]



combination is more compatible with IO, IO preferred over NO at $\Delta\chi^2 = 2.3$

[Kelly et al '20; Esteban et al '20; Denton, JG, Pestes '20]

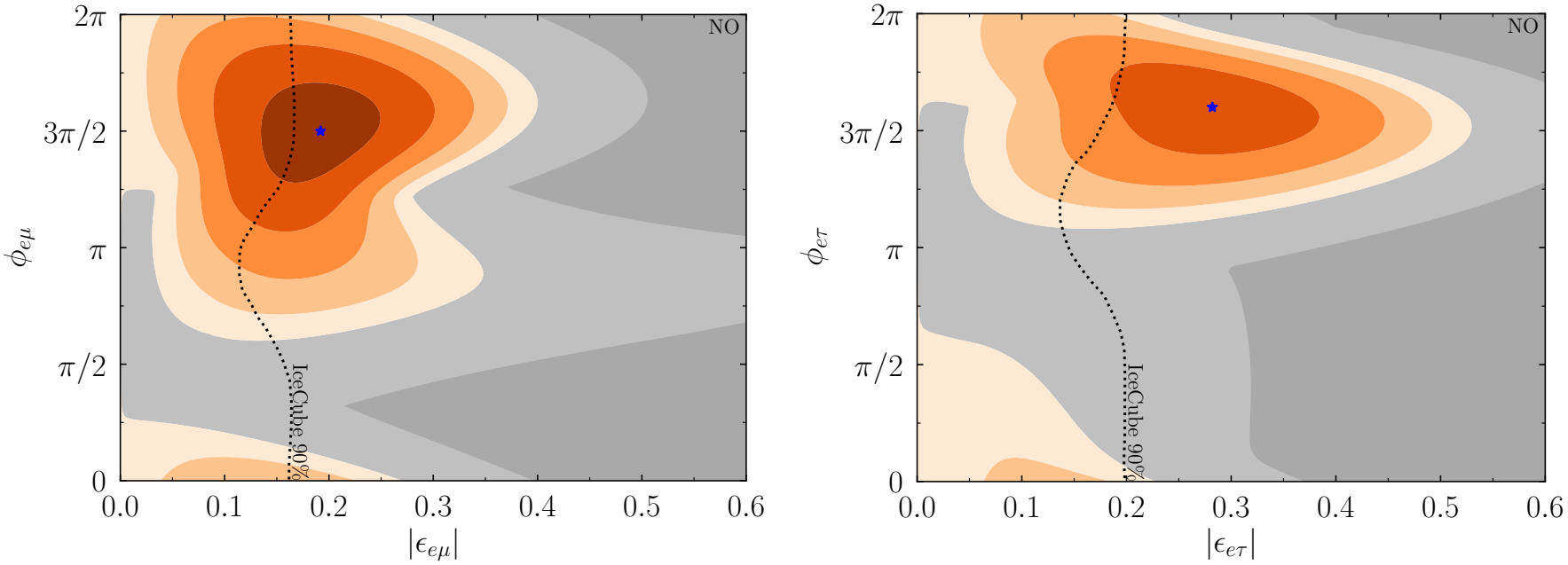
Swap mass ordering

discrepancy slightly resolved by swapping the mass ordering

1. NOvA and T2K both prefer NO over IO
2. NOvA+T2K prefers IO over NO
3. SK still prefers NO over IO
4. NOvA+T2K+SK still prefers NO over IO
5. near future reactor experiments provide information in the future

[Kelly et al '20; Esteban et al '20; Denton, JG, Pestes '20]

NSI parameters [Denton, JG, Pestes '20]



orange preferred over SM at integer values of $\Delta\chi^2$, dark gray disfavored at $\Delta\chi^2 = 4.61$

[see also Chatterjee, Palazzo '20]

NSI parameters [Denton, JG, Pestes '20]

analytical estimates: $|\epsilon_{\alpha\beta}| \approx 0.2,\ \phi_{\alpha\beta} \approx 3\pi/2,\ \delta_{\text{true}} \approx 3\pi/2$

MO	NSI	$\lvert\epsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	δ/π	$\Delta\chi^2$
NO	$\epsilon_{e\mu}$	0.19	1.50	1.46	4.44
	$\epsilon_{e\tau}$	0.28	1.60	1.46	3.65
	$\epsilon_{\mu\tau}$	0.35	0.60	1.83	0.90
IO	$\epsilon_{e\mu}$	0.04	1.50	1.52	0.23
	$\epsilon_{e\tau}$	0.15	1.46	1.59	0.69
	$\epsilon_{\mu\tau}$	0.17	0.14	1.51	1.03

$\Delta\chi^2 = \chi^2_{\text{SM}} - \chi^2_{\text{NSI}}$ for a fixed MO, $\chi^2_{\text{NO}} - \chi^2_{\text{IO}} = 2.3$

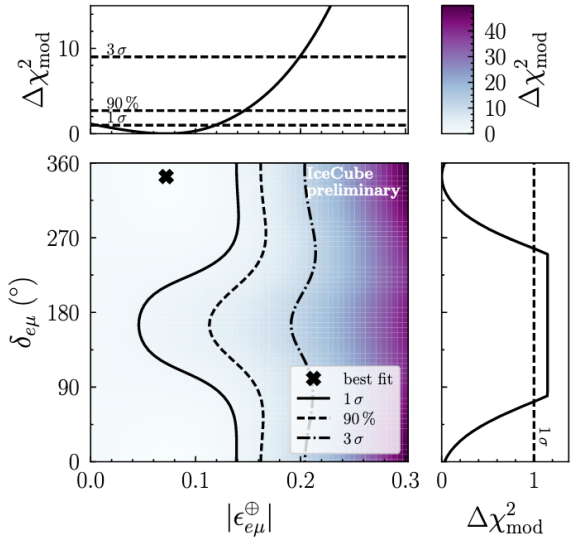
Constraints on NSI parameters

NSI effects grow with energy, distance and matter density

- $\epsilon_{\mu\tau}$ best probed with atmospheric neutrinos
- $\epsilon_{e\mu}$, $\epsilon_{e\tau}$ best probed with LBL appearance, atmospheric neutrinos

- IceCube: slightly disfavors LBL best fit points, prefers non-zero $|\epsilon_{e\mu}|$ at 1σ

- SuperK: only considered real NSI, comparable sensitivity to IceCube



[Ehrhardt '19]

- COHERENT: applies to $M_{Z'} > 10$ MeV, comparable constraints

[Denton, JG '20]

Summary & Conclusions

- open question of CPV in lepton sector
- slight tension between NOvA and T2K
- swap in mass ordering NO$\rightarrow$ IO can resolve this partially
- tension fully resolved with NSI!
- predict maximal CP violation in PMNS matrix and for new physics
- hint for NSI can be further probed with near-future experiments like T2HK and DUNE

End of the talk

Thank you for your attention!

[Art work by symmetry magazine]

Backup: NSI: analytical results [Denton, JG, Pestes '20]

assumption: NSI only affects δ, θ_{23}&Δm^2_{31} unaffected

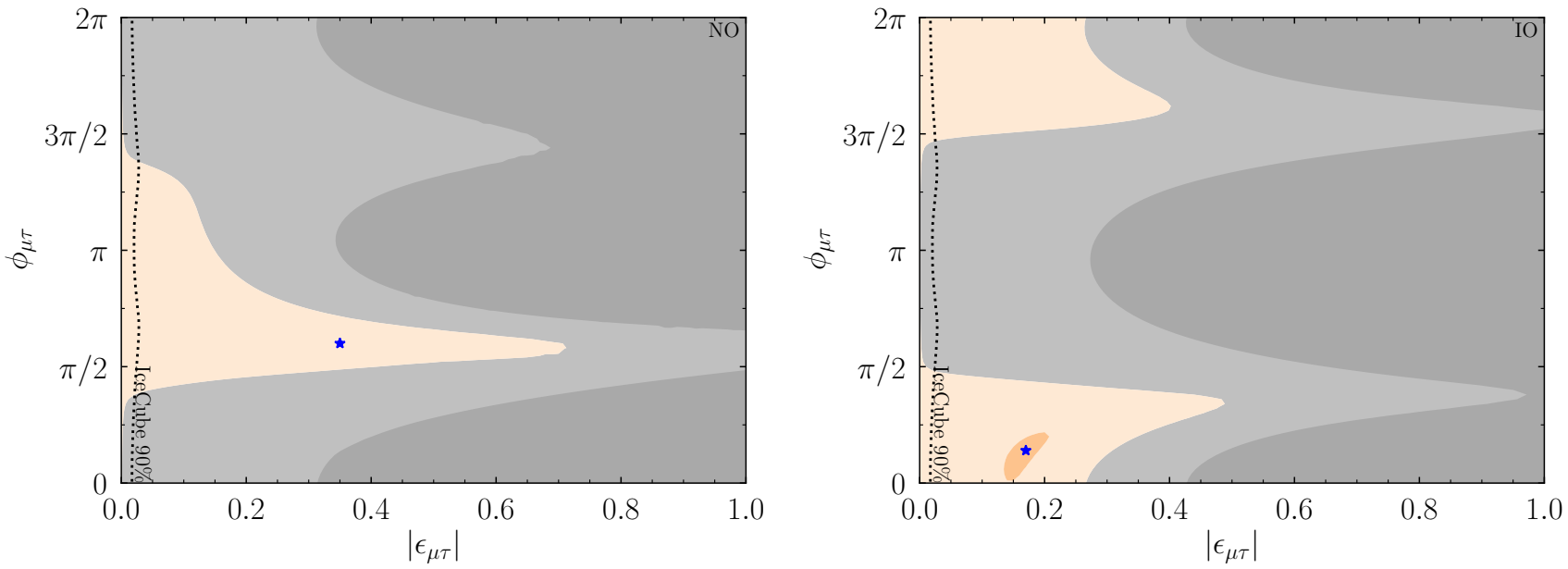
$$P(\epsilon = 0, \delta_{\text{meas}}) = P(\epsilon, \delta_{\text{true}}) \,,$$
$$\bar{P}(\epsilon = 0, \delta_{\text{meas}}) = \bar{P}(\epsilon, \delta_{\text{true}}) \,,$$

using approximate expressions for NSI in LBL from [Kikuchi '09]

$\rightarrow$ estimates for needed magnitude and phase of NSI parameter

Backup: NSI parameters [Denton, JG, Pestes '20]

in general no preference for IO with NSI parameters



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Backup: analytical results [Denton, JG, Pestes '20]

$$P(\epsilon = 0, \delta_{\text{meas}}) = P(\epsilon, \delta_{\text{true}}) \,,$$
$$\bar{P}(\epsilon = 0, \delta_{\text{meas}}) = \bar{P}(\epsilon, \delta_{\text{true}}) \,,$$

$$-s_{12}c_{12}c_{23}\frac{\pi}{2}\Delta m^2_{21}\sin\delta + a_{\rm NOvA}|\epsilon_{e\beta}|\left[w_\beta s_{23}\cos(\delta+\phi_{e\beta}) - v_\beta c_{23}\frac{\pi}{2}\sin(\delta+\phi_{e\beta})\right] \approx -s_{12}c_{12}c_{23}\frac{\pi}{2}\Delta m^2_{21}\sin\delta_{\rm NOvA}\,, \tag{A3}$$

$$s_{12}c_{12}c_{23}\frac{\pi}{2}\Delta m^2_{21}\sin\delta - a_{\rm NOvA}|\epsilon_{e\beta}|\left[w_\beta s_{23}\cos(\delta+\phi_{e\beta}) + v_\beta c_{23}\frac{\pi}{2}\sin(\delta+\phi_{e\beta})\right] \approx s_{12}c_{12}c_{23}\frac{\pi}{2}\Delta m^2_{21}\sin\delta_{\rm NOvA}\,, \tag{A4}$$