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

Julia Gehrlein

Brookhaven National Laboratory

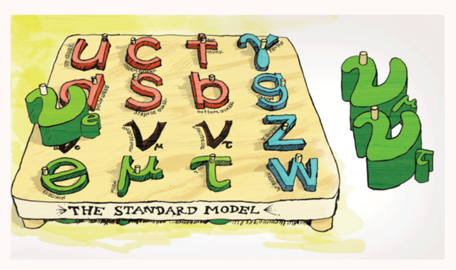
EPS 2021

27 July 2021

Based on 2008.01110, Phys. Rev. Lett. 126 (2021) no.5, 051801
in collaboration with Peter B. Denton and Rebekah Pestes

Neutrino oscillations

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



Neutrino oscillations

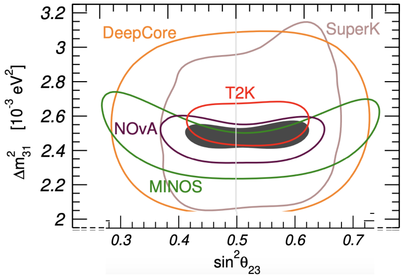
- flavor eigenstates (of weak interaction) and mass eigenstates (of free particle Hamiltonian) not aligned for neutrinos $\rightarrow$ related by mixing matrix
- standard parametrization for PMNS matrix as a series of three rotations

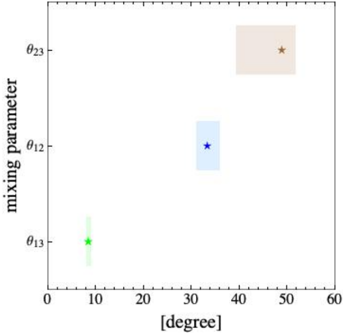
$$U_{PMNS} = U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta)U_{12}(\theta_{12})$$

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

Neutrino oscillations

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

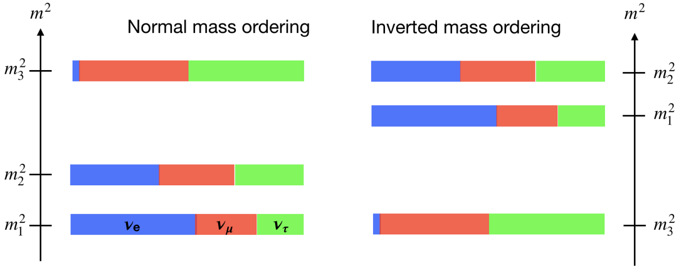




[nuFit v5.0]

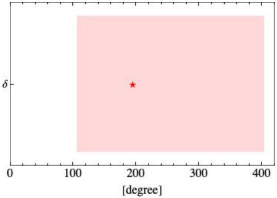
Neutrino oscillations

- 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 lepton sector

How to measure CPV?

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

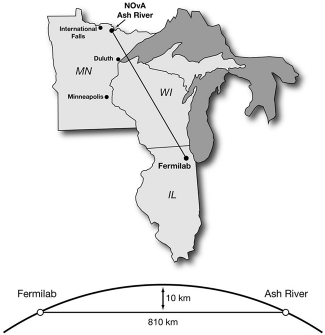
use $P(\nu_\mu \to \nu_e)$ as oscillation channel!

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

Long baseline experiments: NOvA

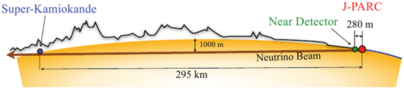
[see also S. Calvez's talk yesterday]

- 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



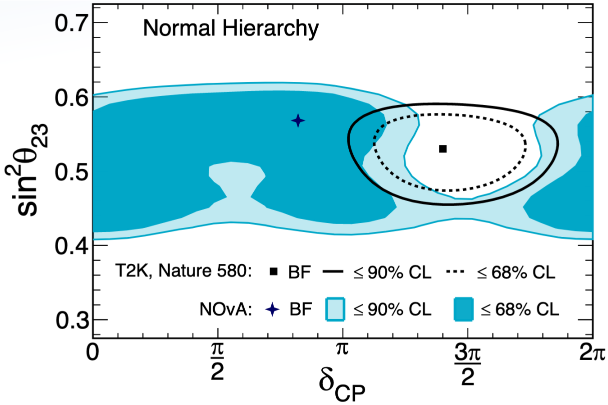
[see also S. Dolan's talk yesterday]

- 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



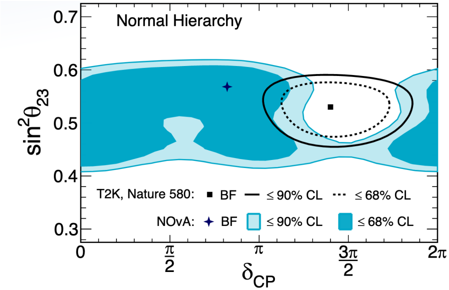
Neutrino2020

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

Can new physics alleviate this slight discrepancy?

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

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

- 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

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

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

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

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 $\sin\delta_{\text{T2K}} < \sin\delta_{\text{NOvA}}$:

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

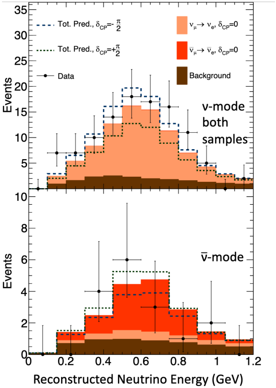
$$\delta_{\text{true}} \approx \delta_{\text{T2K}} \rightarrow \phi_{e\beta} \approx \frac{3}{2}\pi$$

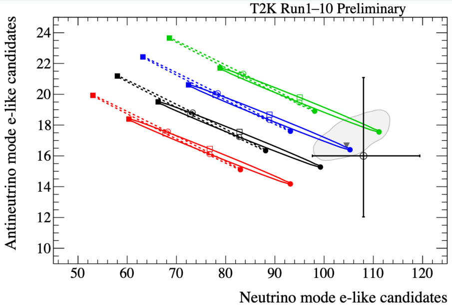
NSI: numerical results [Denton, JG, Pestes '20]

- 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





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

- Disappearance data:

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

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

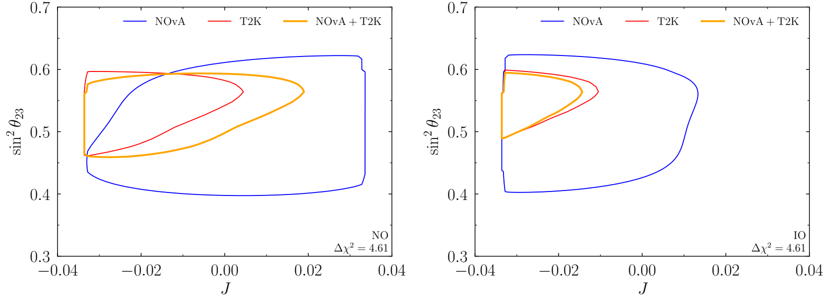
NSI: numerical results [Denton, JG, Pestes '20]

use information from vacuum experiments for remaining parameters

- Daya Bay: $\theta_{13},\ |\Delta m^2_{32}|$ [1809.02261]
- KamLAND: $\theta_{12},\ |\Delta m^2_{21}|$ [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]



$J = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta$ [Jarlskog '85]

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]

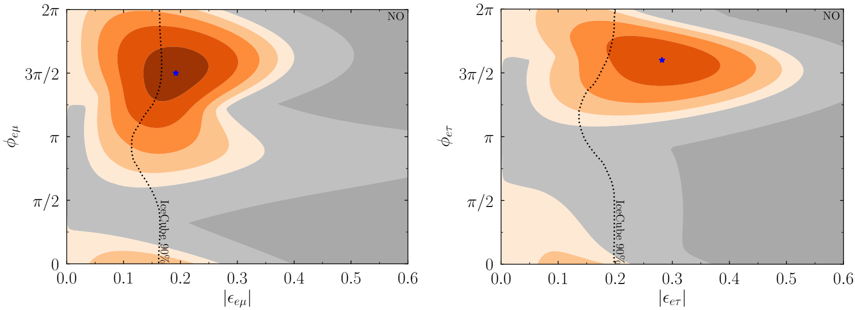
Swap mass ordering

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	$\|\epsilon_{\alpha\beta}\|$	$\phi_{\alpha\beta}/\pi$	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

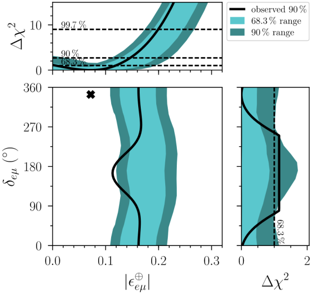
$\Delta\chi^2 = \chi^2_{\text{SM}} - \chi^2_{\text{NSI}}$ for a fixed MO, $\chi^2_{\text{NO}} - \chi^2_{\text{IO}} = 2.3$

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



[IceCube '21]

- 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

Thank you for your attention!

[Art work by symmetry magazine]

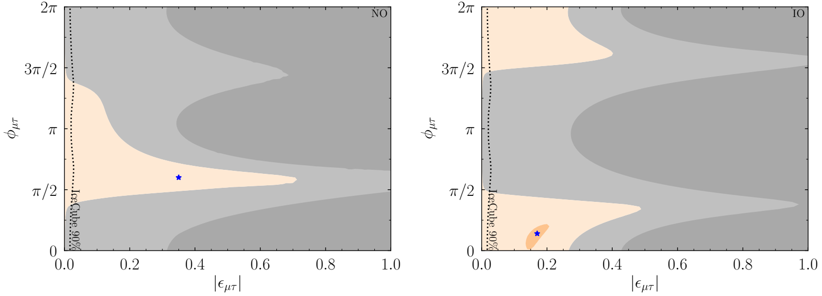
Backup: NSI: analytical results [Denton, JG, Pestes '20]

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 in general no preference for IO with NSI parameters



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

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

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

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

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

Backup: 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?**
  $|J_{PMNS}|/J_{CP}^{max} < 0.34$