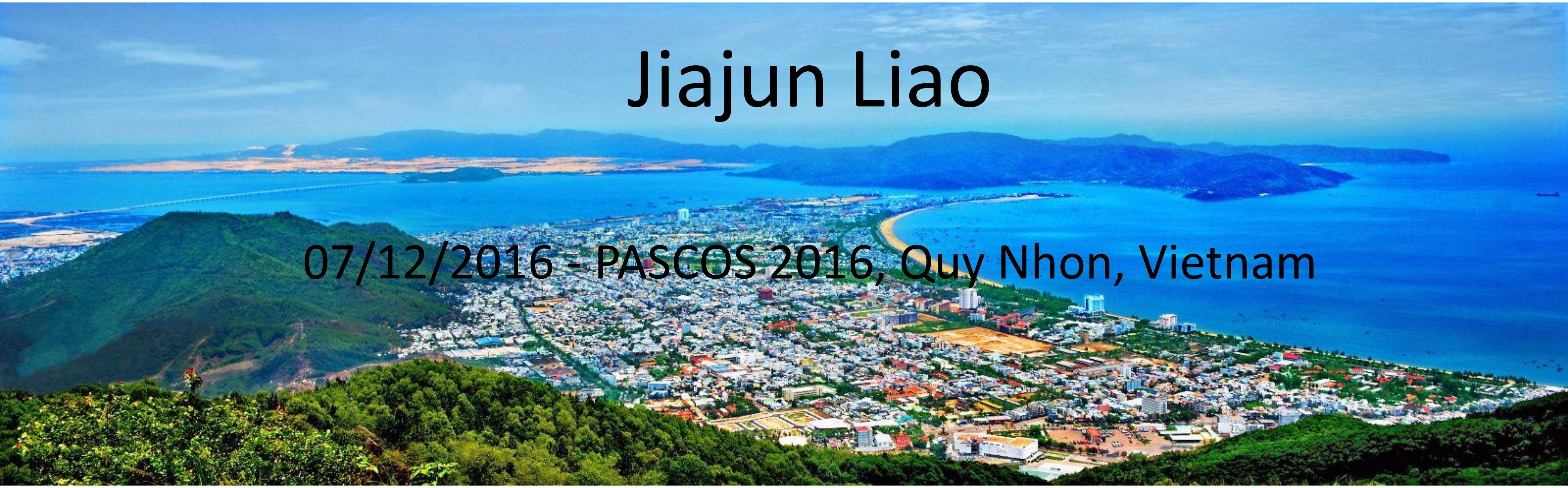
Degeneracies
in long-baseline neutrino experiments from
Non-Standard Interactions



Jiajun Liao

07/12/2016 - PASCOS 2016, Quy Nhon, Vietnam

with D. Marfatia and K. Whisnant

Based on work in

Phys. Rev. D93 (2016) no.9, 093016

[arXiv:1601.00927]

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Outline

- Introduction to NSI
- Degeneracies in long baseline experiments
- Summary

3ν Oscillation Parameters

Parameter	Central Value	Relative Uncertainty
θ_{12}	33.5°	2%
θ_{13}	8.5°	3%
θ_{23} (NH)	42.3°	6%
θ_{23} (IH)	49.5°	5%
δm_{21}^2	$7.50 \times 10^{-5}\ eV^2$	2%
$\lvert\delta m_{31}^2\rvert$	$2.45 \times 10^{-3}\ eV^2$	2%

Gonzalez-Garcia et al. [1409.5439]

Primary goals:

- CP violation by measuring δ_{cp}
- Mass Hierarchy, δm_{31}^2>0 or δm_{31}^2<0
- θ_{23} Octant, θ_{23}> 45° or θ_{23}<45°

Matter NSI

$$\mathcal{L}_{\rm NSI} = 2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fC}[\overline{\nu_\alpha}\gamma^\rho P_L\nu_\beta][\bar{f}\gamma_\rho P_C f] + {\rm h.c.}\,,$$

$\alpha,\beta = e,\mu,\tau,\ C = L,R,\ f = u,d,e$ [Wolfenstein, Phys. Rev. D 17, 2369 (1978)]

$$H = \frac{1}{2E}\left[U{\rm diag}(0,\delta m_{21}^2,\delta m_{31}^2)U^\dagger + V\right] \qquad A \equiv 2\sqrt{2}G_F N_e E$$

Modification of matter potential

$$V = A\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \to A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

Effective coefficient $\epsilon_{\alpha\beta}e^{i\phi_{\alpha\beta}} \equiv \sum_{f,C}\epsilon_{\alpha\beta}^{fC}\frac{N_f}{N_e}$ On earth $N_u = N_d = 3N_e$

The current neutrino-only bounds for earth matter at 90% CL

$$\begin{pmatrix} \epsilon_{ee} < 4.2 & \epsilon_{e\mu} < 0.33 & \epsilon_{e\tau} < 3.0 \\ & \epsilon_{\mu\mu} < 0.07 & \epsilon_{\mu\tau} < 0.33 \\ & & \epsilon_{\tau\tau} < 21 \end{pmatrix}$$

Ohlsson [1209.2710]

Oscillation probabilities

$$P(\nu_\mu \to \nu_e) = x^2 f^2 + 2xyfg\cos(\Delta+\delta) + y^2 g^2$$ ← Reduce to the SM when $\epsilon_{ee} = 0$

$$+ \quad 4\hat{A}\epsilon_{e\mu}\left\{xf[s_{23}^2 f\cos(\phi_{e\mu}+\delta) + c_{23}^2 g\cos(\Delta+\delta+\phi_{e\mu})]\right.$$ ← 1st order due to $\epsilon_{e\mu}$

r suppressed → $$\left. + yg[c_{23}^2 g\cos\phi_{e\mu} + s_{23}^2 f\cos(\Delta-\phi_{e\mu})]\right\}$$

$$+ \quad 4\hat{A}\epsilon_{e\tau}s_{23}c_{23}\left\{xf[f\cos(\phi_{e\tau}+\delta) - g\cos(\Delta+\delta+\phi_{e\tau})]\right.$$ ← 1st order due to $\epsilon_{e\tau}$

r suppressed → $$\left. - yg[g\cos\phi_{e\tau} - f\cos(\Delta-\phi_{e\tau})]\right\}$$

$$+ \quad 4\hat{A}^2\left(g^2c_{23}^2|c_{23}\epsilon_{e\mu} - s_{23}\epsilon_{e\tau}|^2 + f^2 s_{23}^2|s_{23}\epsilon_{e\mu} + c_{23}\epsilon_{e\tau}|^2\right)$$ ← 2nd order corrections

$$+ \quad 8\hat{A}^2 fgs_{23}c_{23}\left\{c_{23}\cos\Delta\left[s_{23}(\epsilon_{e\mu}^2 - \epsilon_{e\tau}^2) + 2c_{23}\epsilon_{e\mu}\epsilon_{e\tau}\cos(\phi_{e\mu}-\phi_{e\tau})\right]\right.$$

$$\left. - \epsilon_{e\mu}\epsilon_{e\tau}\cos(\Delta - \phi_{e\mu} + \phi_{e\tau})\right\} + \mathcal{O}(s_{13}^2\epsilon, s_{13}\epsilon^2, \epsilon^3),$$

$$x \equiv 2s_{13}s_{23}, \quad y \equiv 2rs_{12}c_{12}c_{23}, \quad r = |\delta m_{21}^2/\delta m_{31}^2|,$$

$$f, \bar{f} \equiv \frac{\sin[\Delta(1\mp\hat{A}(1+\epsilon_{ee}))]}{(1\mp\hat{A}(1+\epsilon_{ee}))}, \quad g \equiv \frac{\sin(\hat{A}(1+\epsilon_{ee})\Delta)}{\hat{A}(1+\epsilon_{ee})},$$

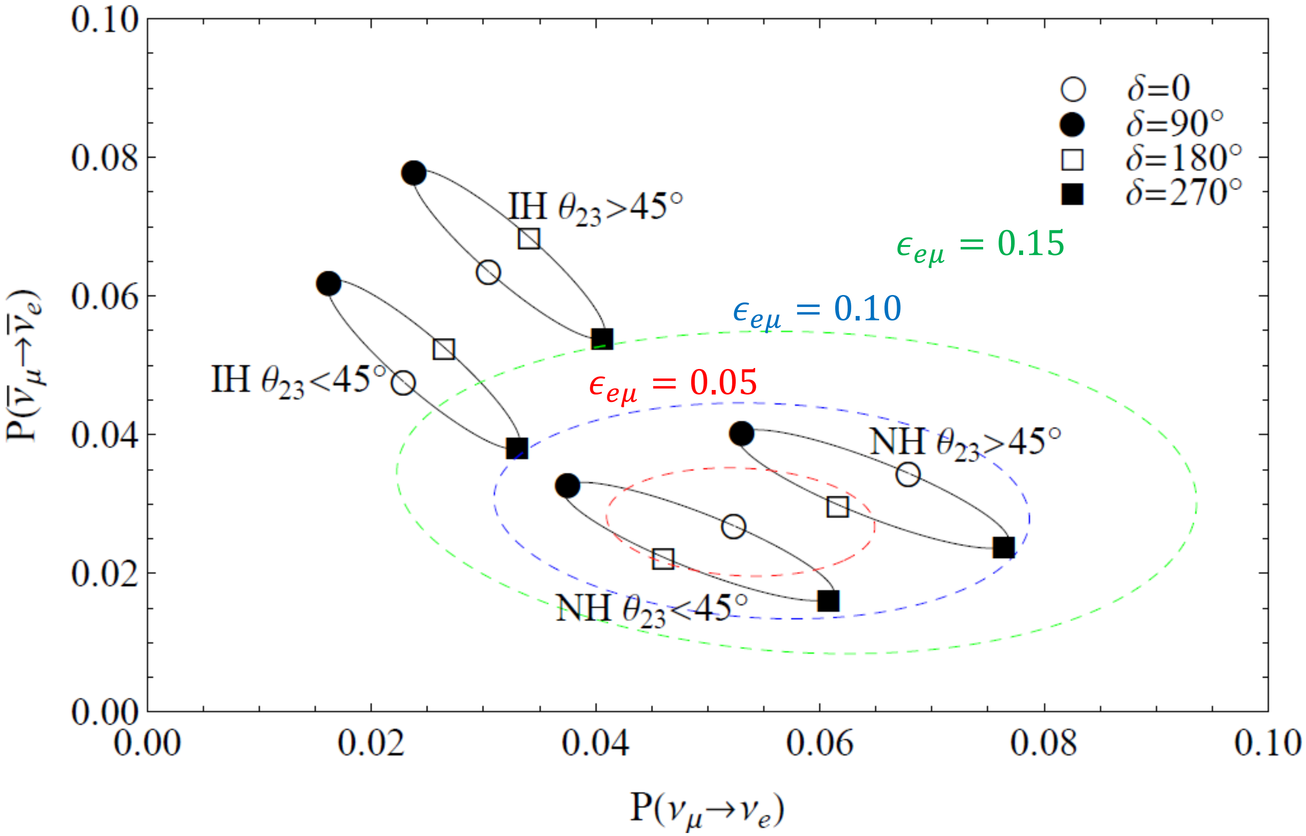
$$\Delta \equiv \left|\frac{\delta m_{31}^2 L}{4E}\right|, \quad \hat{A} \equiv \left|\frac{A}{\delta m_{31}^2}\right|$$

- $P_{\mu e} \to \bar{P}_{\mu e}$
  $\hat{A} \to -\hat{A}$ $(f \to \bar{f})$,
  $\delta \to -\delta$, $\phi_{\alpha\beta} \to -\phi_{\alpha\beta}$
- NH → IH
  $\Delta \to -\Delta$, $y \to -y$
  $\hat{A} \to -\hat{A}$ $(f \leftrightarrow -\bar{f}$, and $g \to -g)$

One off-diagonal NSI ($\epsilon_{e\mu}$ or $\epsilon_{e\tau}$)

degeneracy occur
for a single L and E

$$P^{SM}(\delta) = P^{NSI}(\delta', \epsilon, \phi)$$
$$\overline{P}^{SM}(\delta) = \overline{P}^{NSI}(\delta', \epsilon, \phi)$$

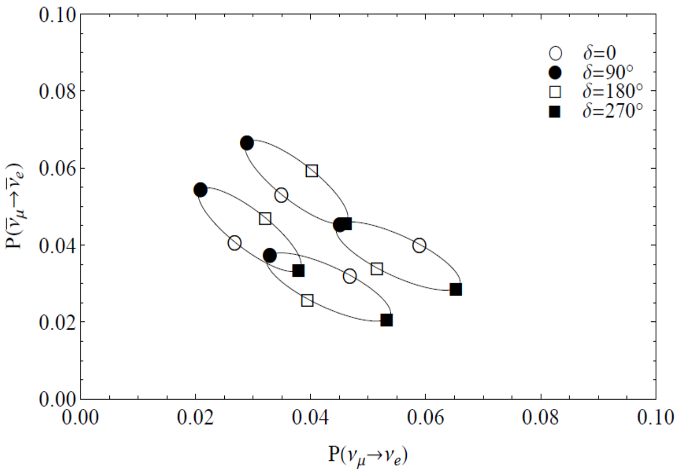


$L = 1300$ km and $E = 3$ GeV

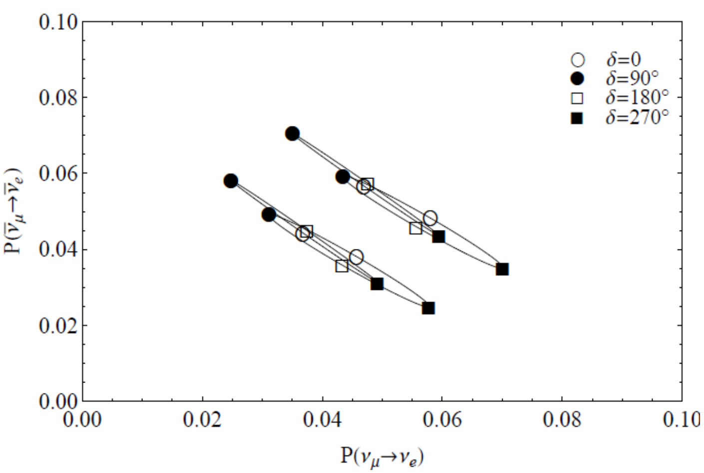
Continuous four-fold degeneracy

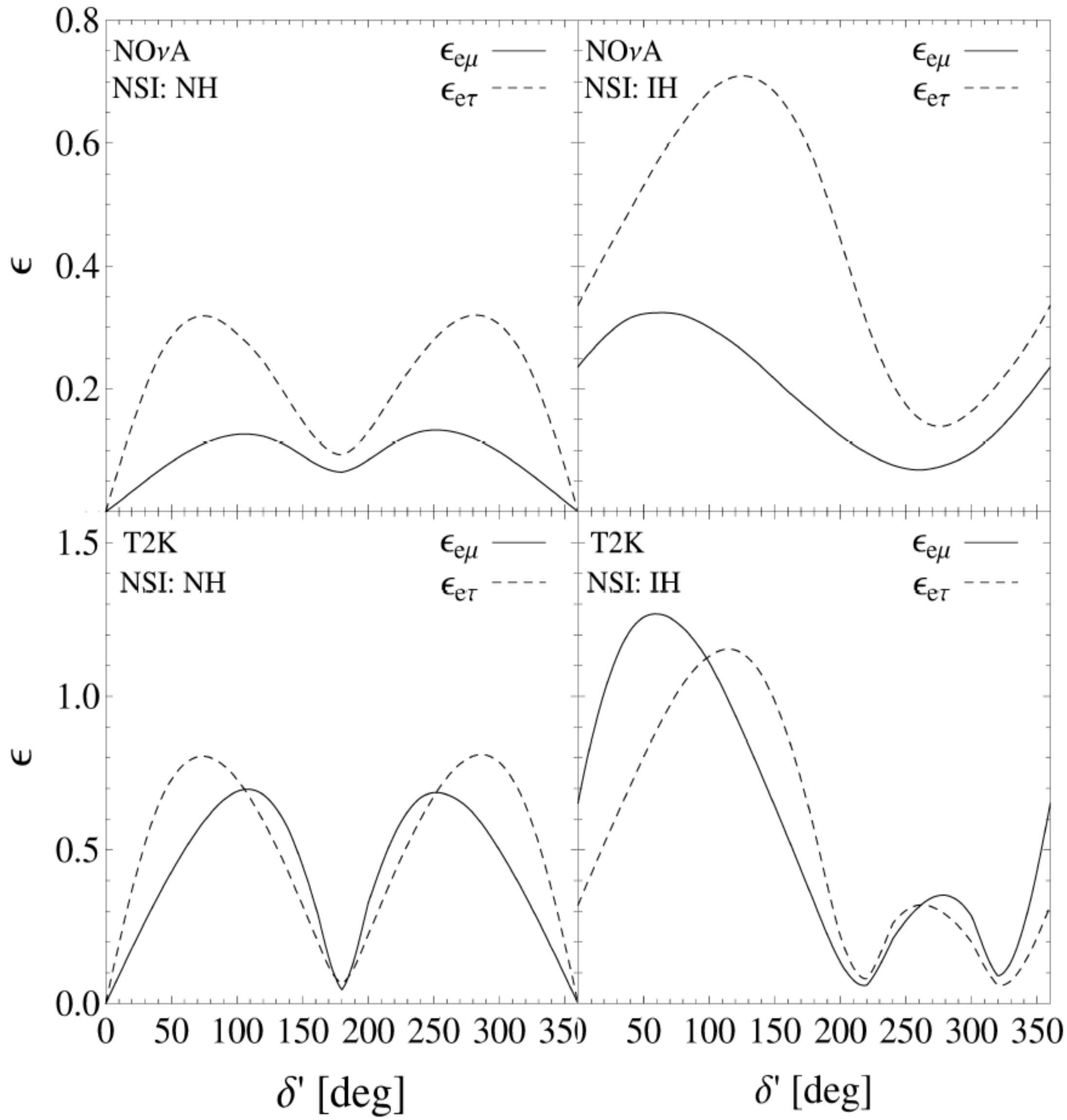
Narrow-band Beam experiments

- NOvA (L = 810 km, E = 2 GeV)

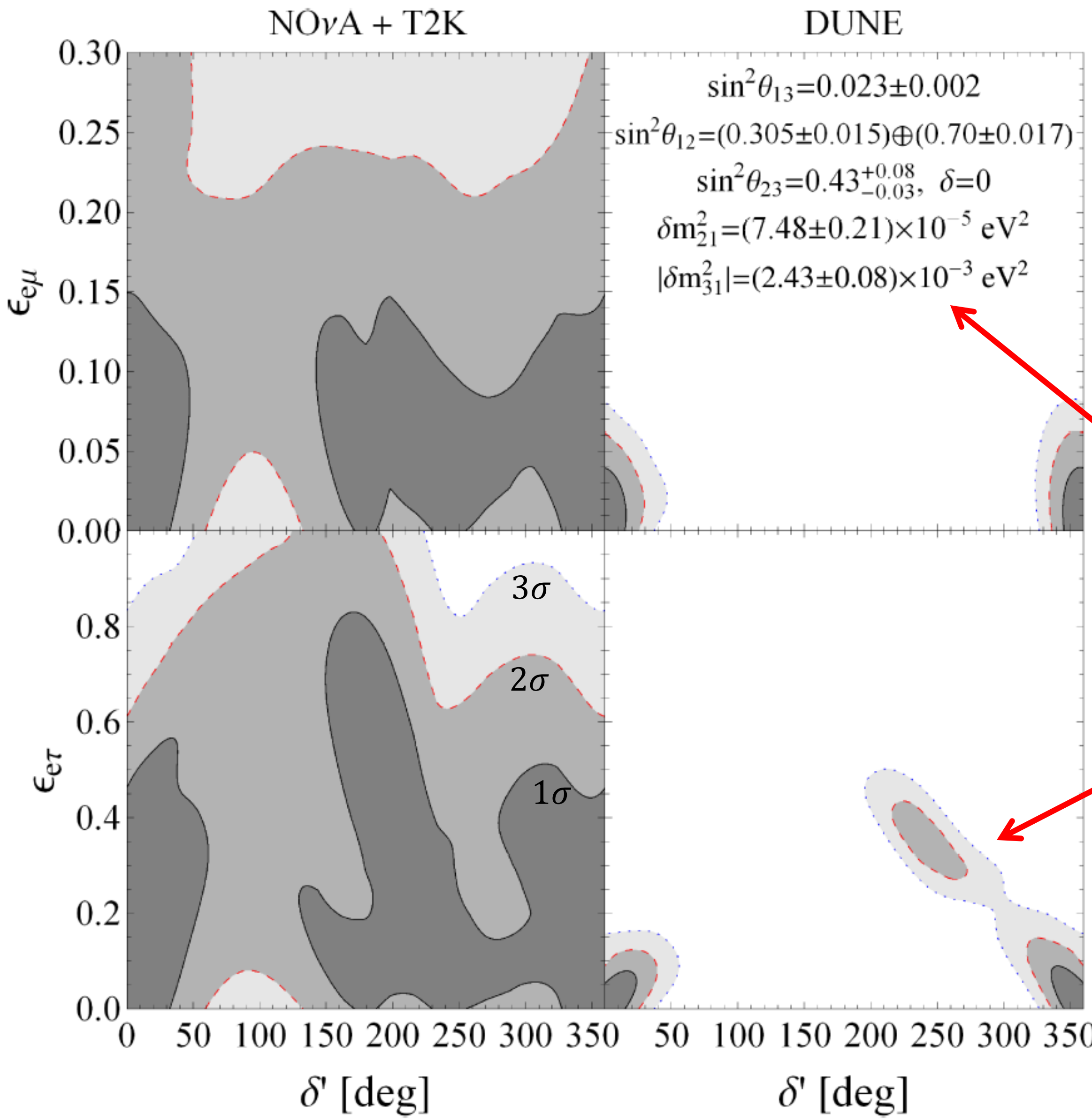


- T2K (L = 295 km, E = 0.6 GeV)





Simulations



The data are simulated with the SM with δ = 0, the NH and first octant. We scan over all octant and hierarchy combinations to obtain the allowed regions.

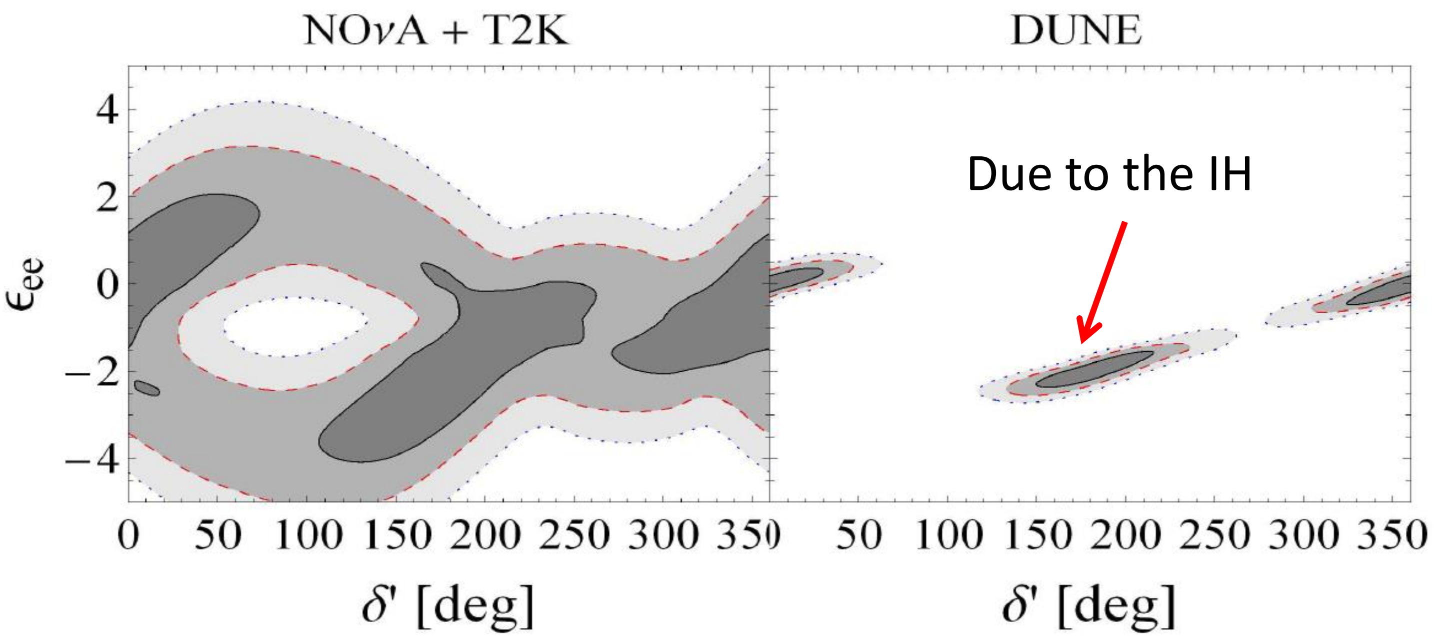
The central values and priors in our calculation are adopted from the global-fit with NSI.

Gonzalez-Garcia, Maltoni [1307.3092]

Due to the IH

θ_{23} lies in the second octant in parts of the allowed regions.

One diagonal NSI (ϵ_{ee})



$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21}$$
$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}\,,\ \delta \to \pi - \delta$$
$$\epsilon_{ee} \to -\epsilon_{ee} - 2$$

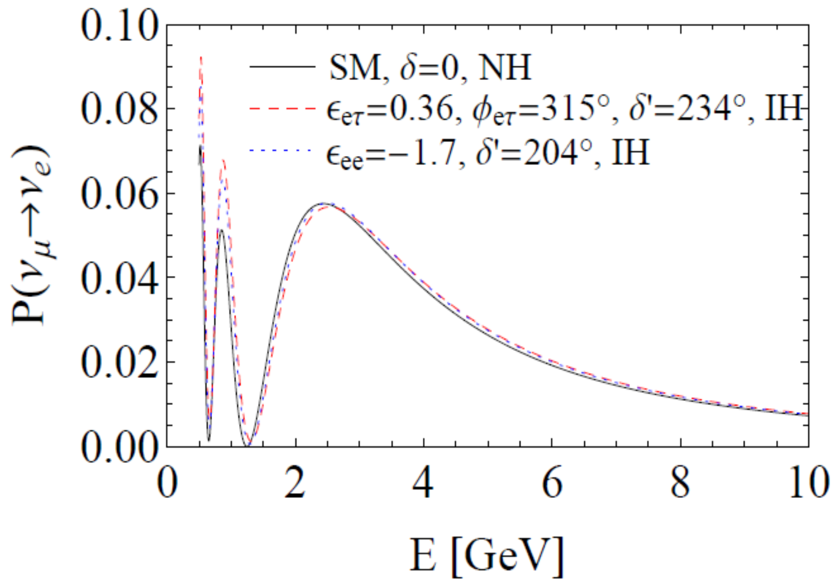
$\Rightarrow$

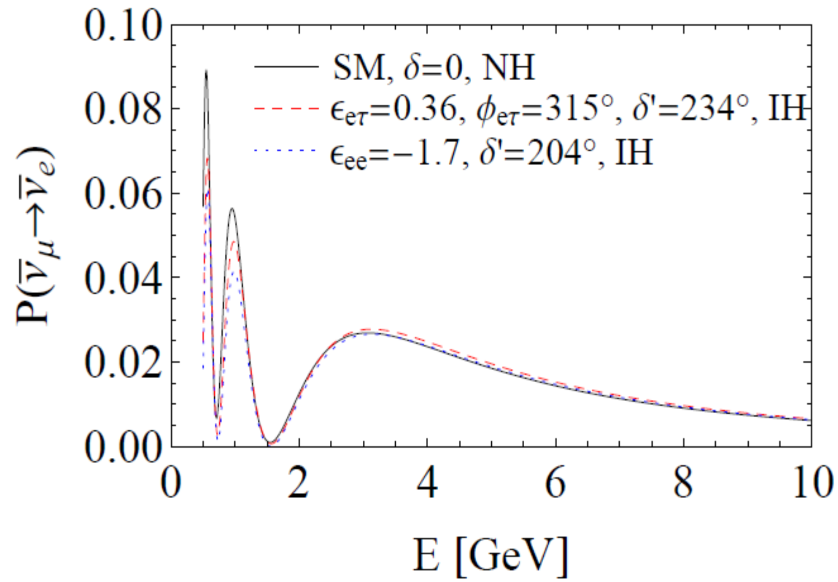
$$H \to -H^*$$

Same oscillation probabilities

Coloma, Schwetz [1604.05772]

Oscillation Probabilities





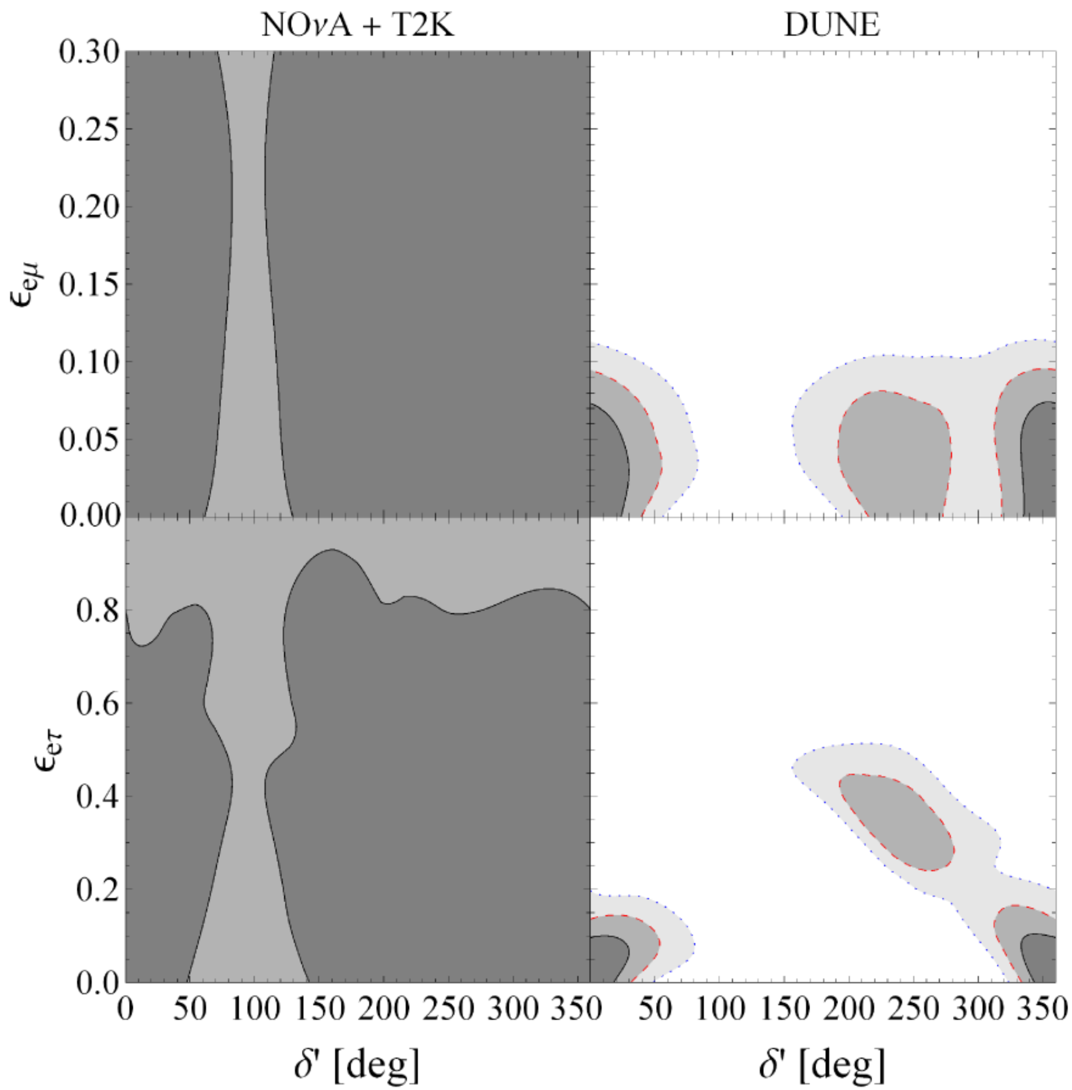
$\sin^2\theta_{13}=0.023,\ \sin^2\theta_{12}=0.305$

$\sin^2\theta_{23}=0.43,\ \delta=0$

$\delta m^2_{21}=7.48\times10^{-5}\ \mathrm{eV}^2$

$|\delta m^2_{31}|=2.43\times10^{-3}\ \mathrm{eV}^2$

Two off-diagonal NSI ($\epsilon_{e\mu}$ and $\epsilon_{e\tau}$)



Summary

- There is a continuous four-fold degeneracy for an off-diagonal NSI in NOνA or T2K.
- DUNE can resolve most of the degeneracies. However, for nonzero $\epsilon_{e\tau}$ or ϵ_{ee}, there are some parameter regions in which DUNE could lead to a wrong determination of the mass hierarchy, and of CP violation. Also, for nonzero $\epsilon_{e\tau}$, an incorrect conclusion of the octant of θ_{23} may be drawn.
- In conclusion, DUNE alone cannot resolve all the degeneracies arising from NSI.

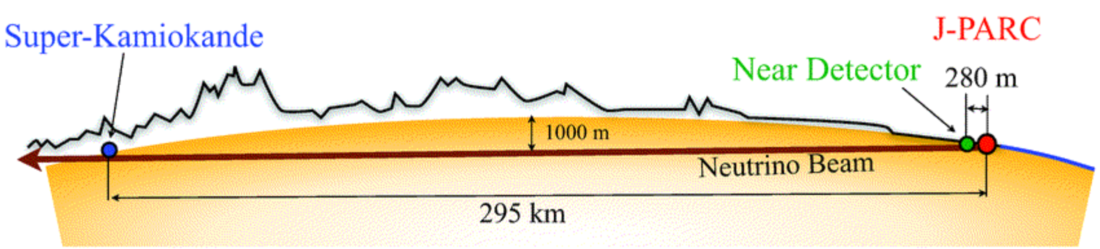
Thank you for your attention!

Any questions?

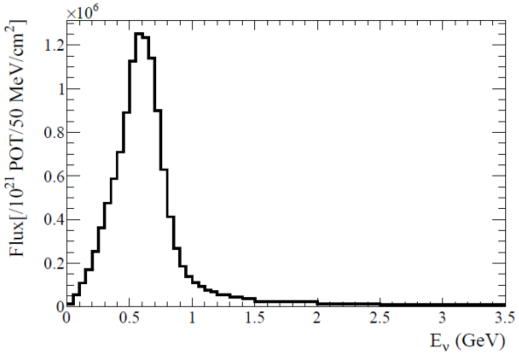
Backup slides

Current long-baseline experiments

The T2K experiment



off-axis angle is 2.5°

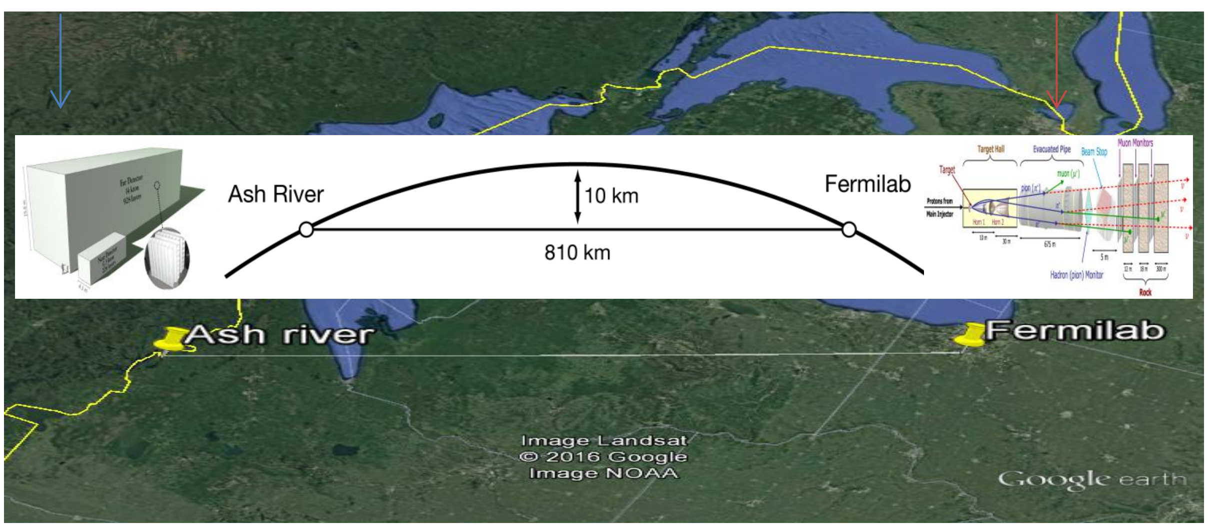


T2K Collaboration [1106.1238]

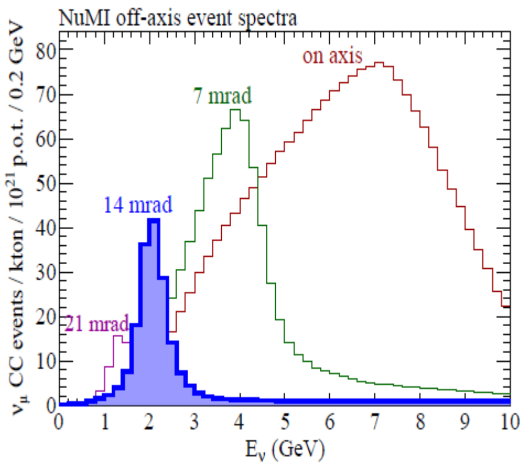
The NOνA experiment

NOνA FD

NuMI Beam



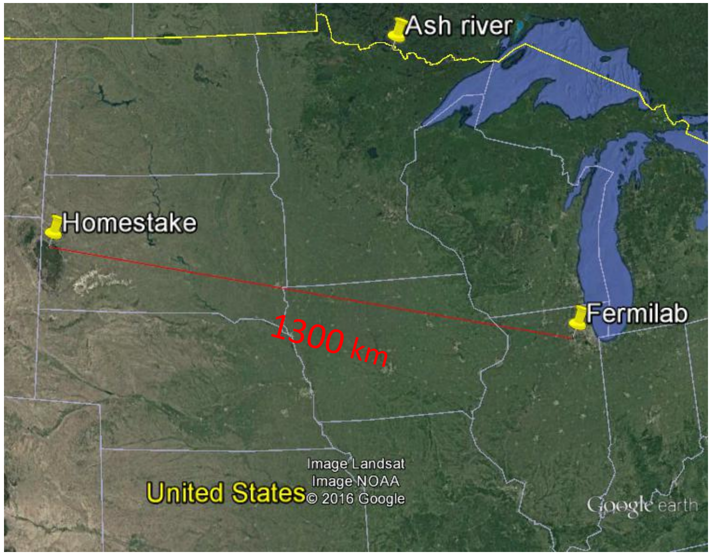
off-axis angle is 0.8°

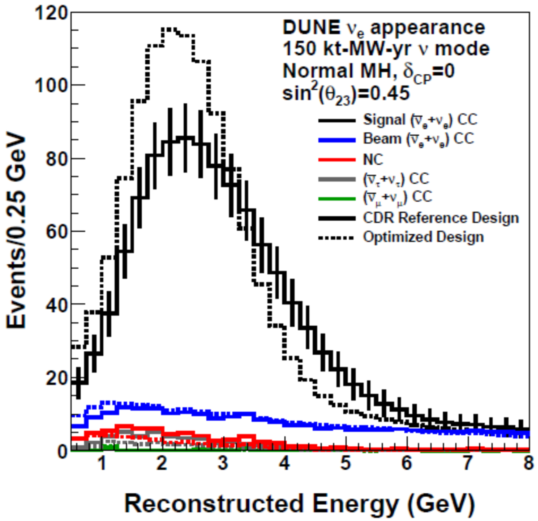


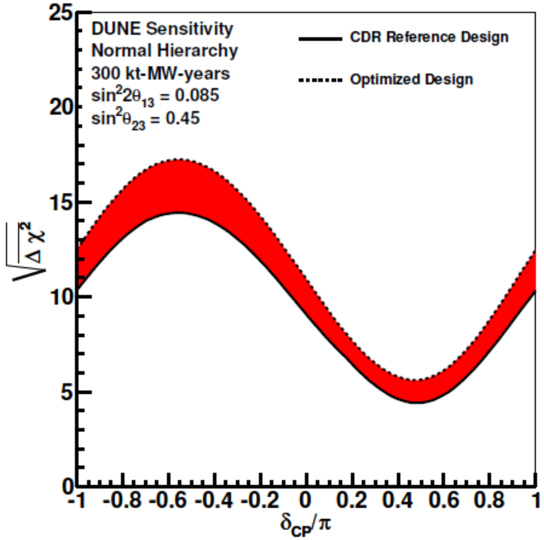
NOνA Collaboration [1209.0716]

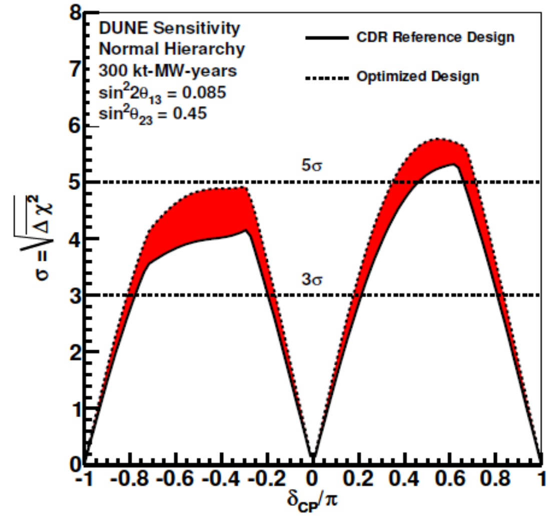
DUNE

- LArTPC on axis
- Wide-beam experiment
- Determine CP violation at 3σ for 75% of δ_{cp} values
- Determine mass hierarchy at 5σ for all values of δ_{cp}









The DUNE Collaboration [1512.06148]

Approximate Formulas

For NH with $\epsilon_{e\mu}$:

$$\tan(\phi_{e\mu} + \delta') = \frac{s_{23}^2(f - \bar{f})}{2c_{23}^2 g \sin\Delta} + \frac{\cos\Delta(\cos\delta - \cos\delta')[2c_{23}^2 g \cos\Delta + s_{23}^2(f + \bar{f})]}{2c_{23}^2 g \sin^2\Delta(\sin\delta - \sin\delta')},$$

$$\epsilon_{e\mu} = \frac{yg[\cos(\Delta + \delta) - \cos(\Delta + \delta')]}{2\hat{A}[c_{23}^2 g \cos(\Delta + \phi_{e\mu} + \delta') + s_{23}^2 f \cos(\phi_{e\mu} + \delta')]}$$

For NH with $\epsilon_{e\tau}$:

$$\tan(\phi_{e\tau} + \delta') = \frac{(\bar{f} - f)}{2g \sin\Delta} + \frac{\cos\Delta(\cos\delta - \cos\delta')[2g \cos\Delta - f - \bar{f}]}{2g \sin^2\Delta(\sin\delta - \sin\delta')},$$

$$\epsilon_{e\tau} = \frac{-yg[\cos(\Delta + \delta) - \cos(\Delta + \delta')]}{2\hat{A}s_{23}c_{23}[g \cos(\Delta + \phi_{e\tau} + \delta') - f \cos(\phi_{e\tau} + \delta')]}$$

Similar equations exist for each of the other possible hierarchy and octant

Simulation details

- The simulations are done using GLoBES software

Huber et al. [hep-ph/0407333, 0701187]

- NOνA: Liquid Scintillator with 15 kiloton fiducial mass, 3+3 years.
- T2K: Water Cherenkov with 22.5 kiloton fiducial mass, 5+5 years.

Huber et al. [0907.1896]

- DUNE: 34 kiloton liquid argon detector with a 1.2 MW beam, and running for 3+3 years.

Berryman et al. [1507.03986] ,
DUNE CDR [1512.06148]

- The central values and priors in our simulation adopted from the global-fit with NSI.

Gonzalez-Garcia, Maltoni [1307.3092]

$$\sin^2\theta_{13}=0.023\pm0.002$$
$$\sin^2\theta_{12}=(0.305\pm0.015)\oplus(0.70\pm0.017)$$
$$\sin^2\theta_{23}=0.43^{+0.08}_{-0.03},\ \delta=0$$

$$\delta m^2_{21}=(7.48\pm0.21)\times10^{-5}\ \mathrm{eV}^2$$
$$|\delta m^2_{31}|=(2.43\pm0.08)\times10^{-3}\ \mathrm{eV}^2$$