EXPLORING BSM MODELS AT LONG BASELINE NEUTRINO EXPERIMENTS

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FLASY2022, Lisbon, June 30th

NEUTRINO OSCILLATIONS AT LONG BASELINE EXPERIMENTS

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E_\nu}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A_{CC}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

- GeV neutrinos, ~10^3 Km baseline → Atmospheric oscillation maxima $\Delta m^2_{31} L/4E \sim (2n+1)\pi/2$
- Well known muon neutrino beam → Possibility of spectral analysis, small electronic neutrino contamination
- Possibility to look at different oscillation channels

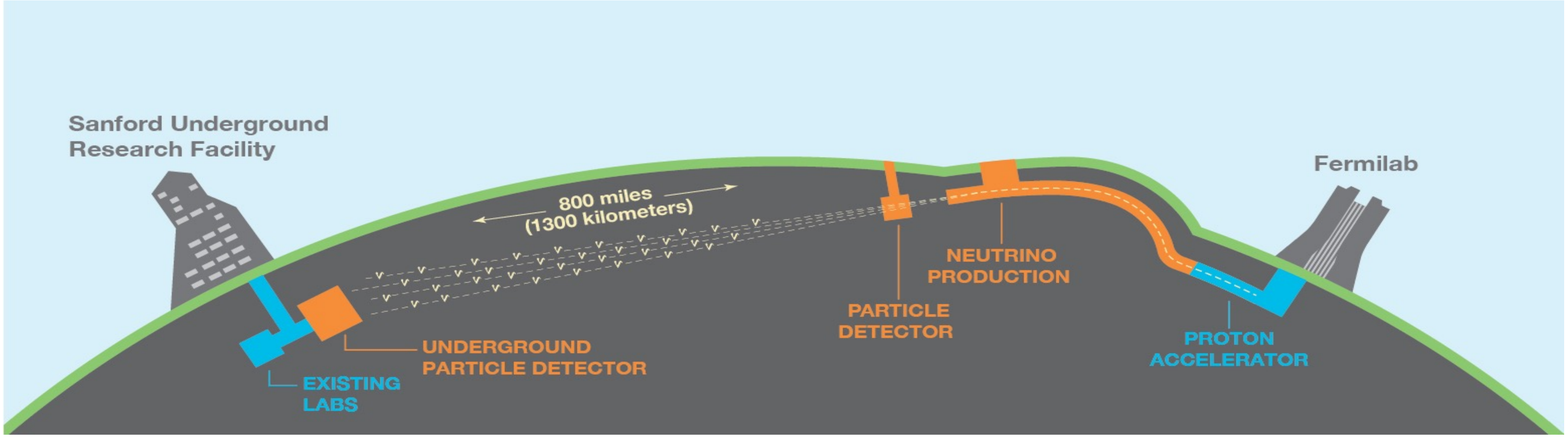
$\nu_\mu \rightarrow \nu_e$
$(\theta_{13}, \theta_{23}, \delta)$

$\nu_\mu \rightarrow \nu_\mu$
$(\theta_{23}, \Delta m^2_{31})$

$\nu_\mu \rightarrow \nu_\tau$
BSM

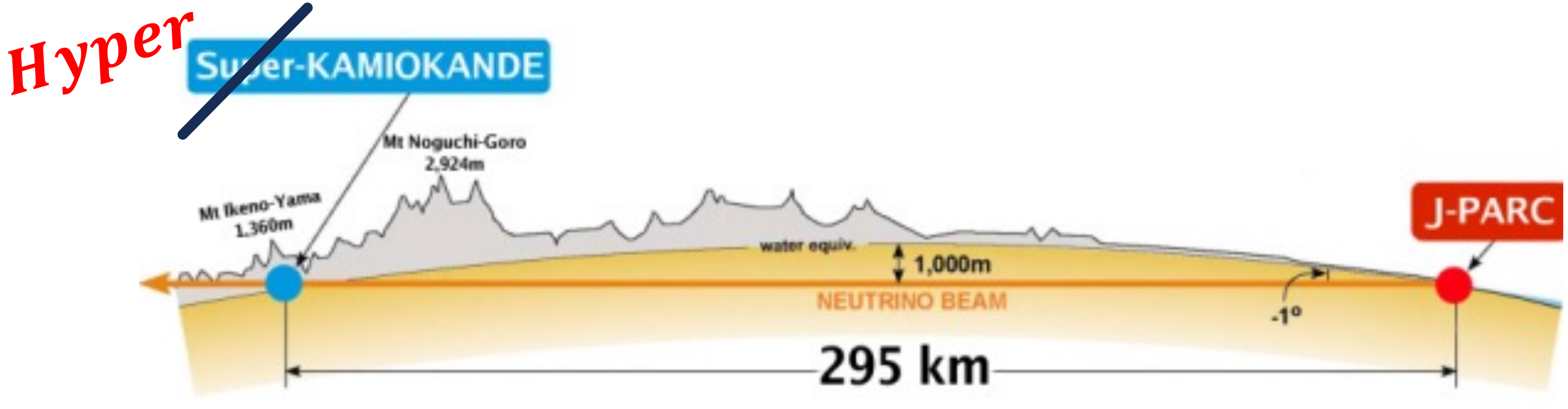
$E_\nu > 3$ GeV

FUTURE LBL EXPERIMENTS: DUNE



- 2.5 GeV peaked neutrinos, L=1200 km ***FIRST OSCILLATION MAXIMUM***
- On axis, broad band beam ***L/E SCAN***
- All channels accessible (also NC), LAr-TPC detectors ***GREAT PRECISION ON PARAMETERS AND MH***
- Matter effects ***FAKE CP VIOLATION, STILL 70% CP SENSITIVITY COVERAGE AT 3σ***

FUTURE LBL EXPERIMENTS: T2HK



- 0.6 GeV peaked neutrinos, L=295 km ***FIRST OSCILLATION MAXIMUM***
- Off-axis, narrow band beam ***PRECISION MEASUREMENTS AT THE FIRST MAXIMUM***
- Unprecedent statistics on electron appearance (Cherenkov detector) ***GREAT PRECISION ON PARAMETERS AND MH***
- Almost no matter effects ***GOOD SENSITIVITY TO CPV***

FUTURE LBL EXPERIMENTS: T2HKK

- Second proposed detector in Korea. ***SECOND OSCILLATION MAXIMUM***
- Same beam and same detector of the T2HK ***INCREASED STATISTICS***
- <u>Improvement of CPV sensitivity due to the clean enviroment provided by the second oscillation maximum</u>

STUDY OF BSM MODELS AT DUNE AND T2HKK

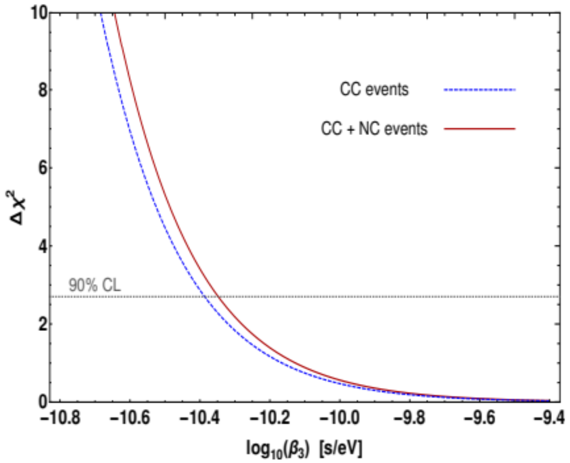
INVISIBLE DECAY MODEL AT DUNE (GIARNETTI, GHOSHAL, MELONI 2003.09012)

Invisible decay: one of the neutrinos decays into invisible particles, e.g. sterile neutrino states

$$H = U\left[\frac{1}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix} - i\frac{1}{2\beta_3 E}\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 1\end{pmatrix}\right]U^\dagger + \begin{pmatrix}A & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

- All the CC channels and the **NC channel** are sensitive to the decay parameter

$$\sum_{\alpha}^{e,\mu,\tau} P_{\mu\alpha} = 1 + (e^{-\frac{L}{\beta_3 E}} - 1)\cos^2\theta_{13}\sin^2\theta_{23} \neq 1$$



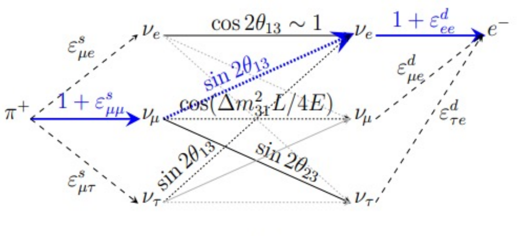
New constraint from DUNE 5.1×10−11 s/eV

NON STANDARD INTERACTIONS

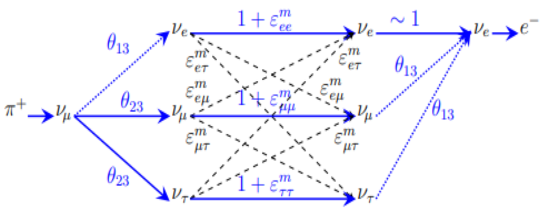
-Source NSI: occur when neutrinos are produced by hadrons decays at the accelerator level

-Propagation NSI: occur while neutrinos travel in the matter

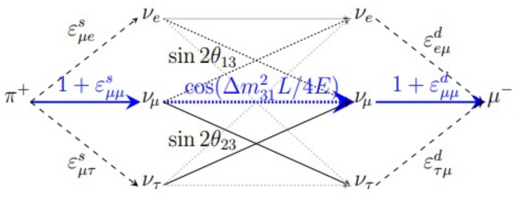
-Detector NSI: occur while neutrinos are detected



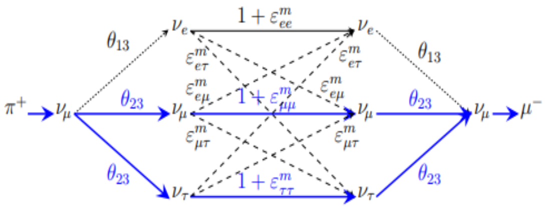
(a)



(a)



(b)

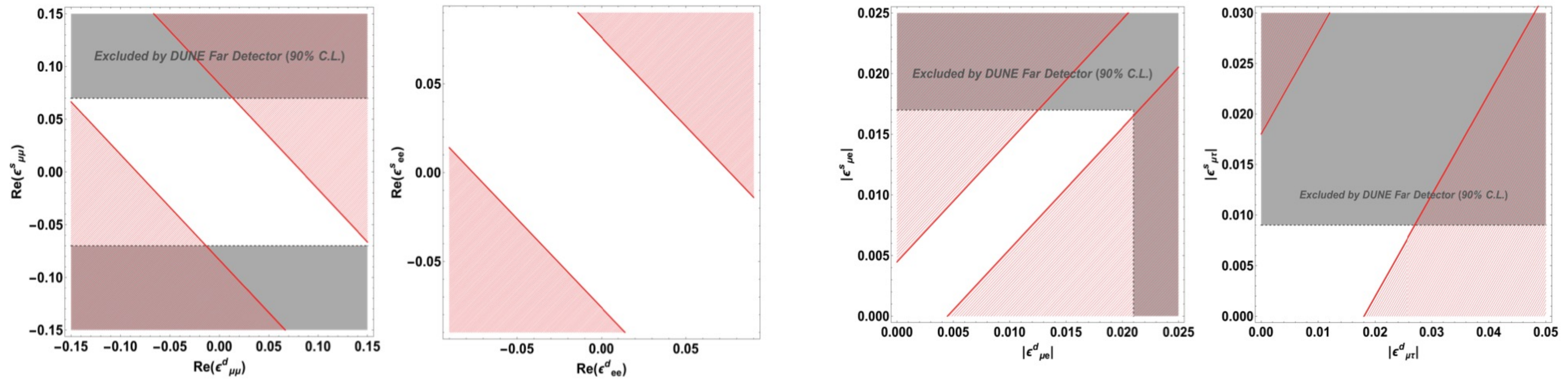


0708.0152 (Lindner, Kop, Ota, Sato)

SOURCE AND DETECTOR NSI AT DUNE ND (GIARNETTI, MELONI 2005.10272))

$$P_{\alpha\alpha} = 1 + 2|\varepsilon^s_{\alpha\alpha}|\cos\Phi^s_{\alpha\alpha} + 2|\varepsilon^d_{\alpha\alpha}|\cos\Phi^d_{\alpha\alpha}$$

$$P_{\alpha\beta} = |\varepsilon^s_{\alpha\beta}|^2 + |\varepsilon^d_{\alpha\beta}|^2 + 2|\varepsilon^s_{\alpha\beta}||\varepsilon^d_{\alpha\beta}|\cos(\Phi^s_{\alpha\beta} - \Phi^d_{\alpha\beta})$$

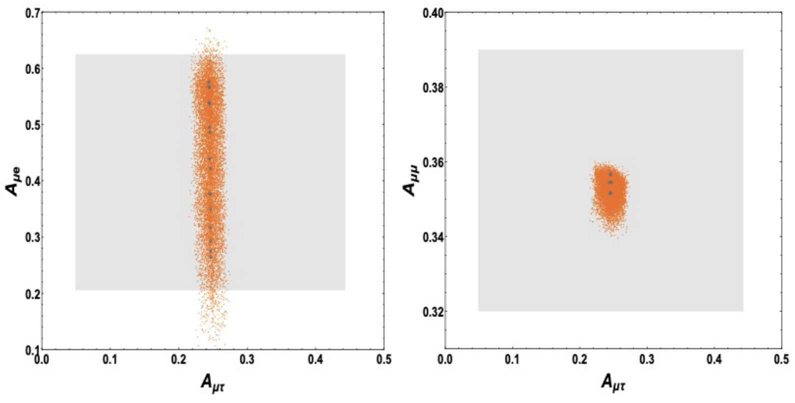


CP VIOLATION WITH NSI AT DUNE (GIARNETTI, MELONI **2106.00030**)

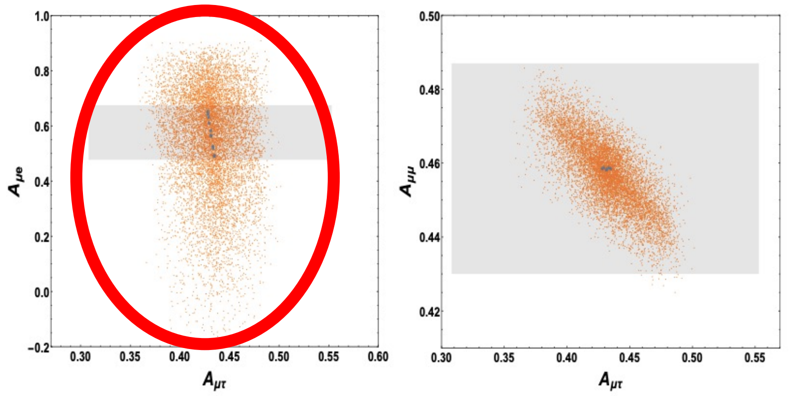
$$A_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$$

→ ***δ_{CP} induced***

→ ***Matter induced***



Standard 2.5 GeV flux



High energy flux

Search for hints of new physics:

-Compute the asymmetries in the standard model with their uncertainties

-Compute the asymmetries in NSI model with parameters in their allowed ranges

-Check whether some sets of new parameters generate anomalous asymmetires

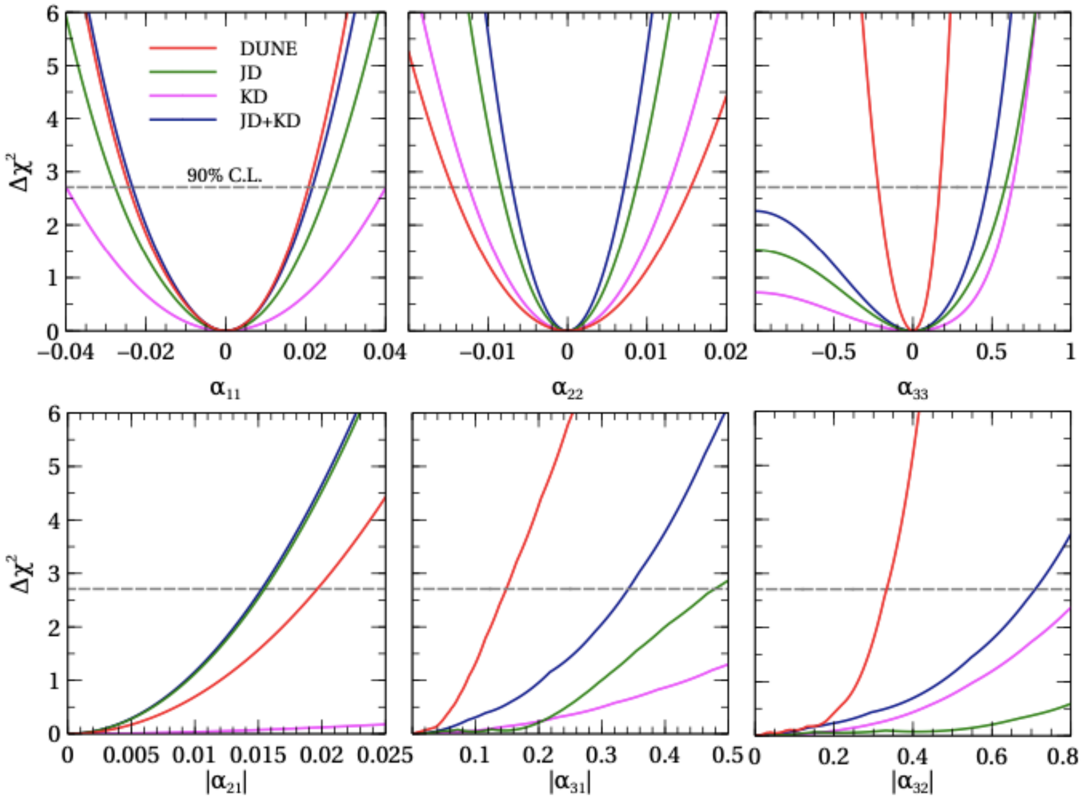
NON UNITARITY OF THE PMNS MATRIX

$$N = (1+\alpha)U_{PMNS}\,. \qquad \alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}|e^{i\phi_{21}} & \alpha_{22} & 0 \\ |\alpha_{31}|e^{i\phi_{31}} & |\alpha_{32}|e^{i\phi_{32}} & \alpha_{33} \end{pmatrix}$$

Different models which explain the introduce new particles in the standard model in the leptonic sector. In these cases, the neutrino mixing matrix is no longer 3x3.

Thus, the PMNS matrix that we observe is only a submatrix of the complete one, losing its unitarity property.

NU AT FUTURE DUNE, T2HK AND T2HKK (AGARWALLA, DAS, GIARNETTI, MELONI, 2111.00329)



-T2HKK has great limits on a22

-DUNE and T2HKK have comparable limits on a21 and a11

-Other parameters sensitivity dominated by DUNE due to bigger matter effects

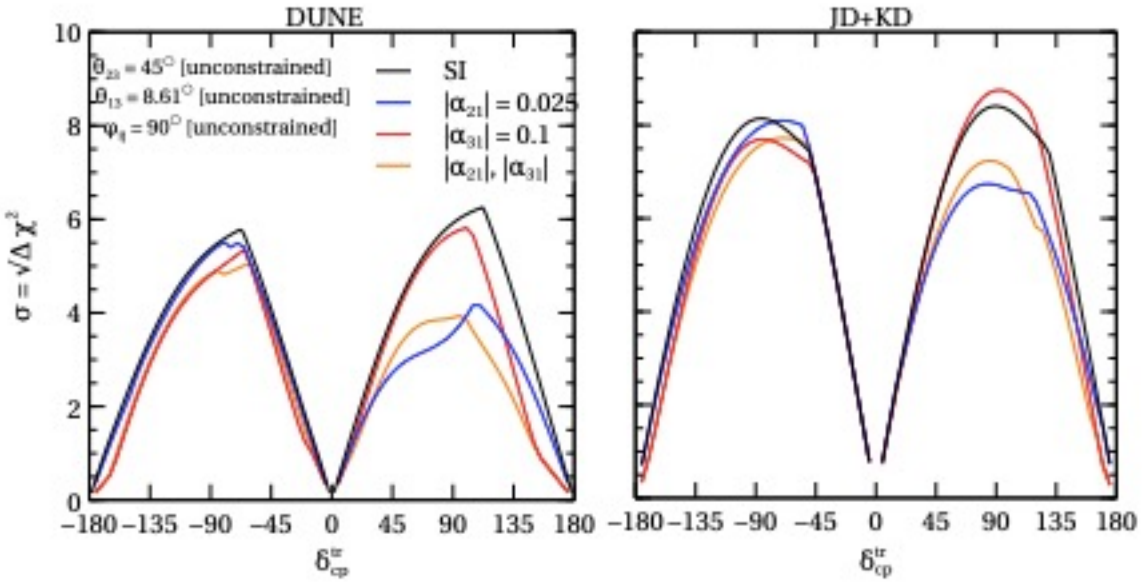
However, if the flux is measured at the ND, sensitivity to a22 is lost.

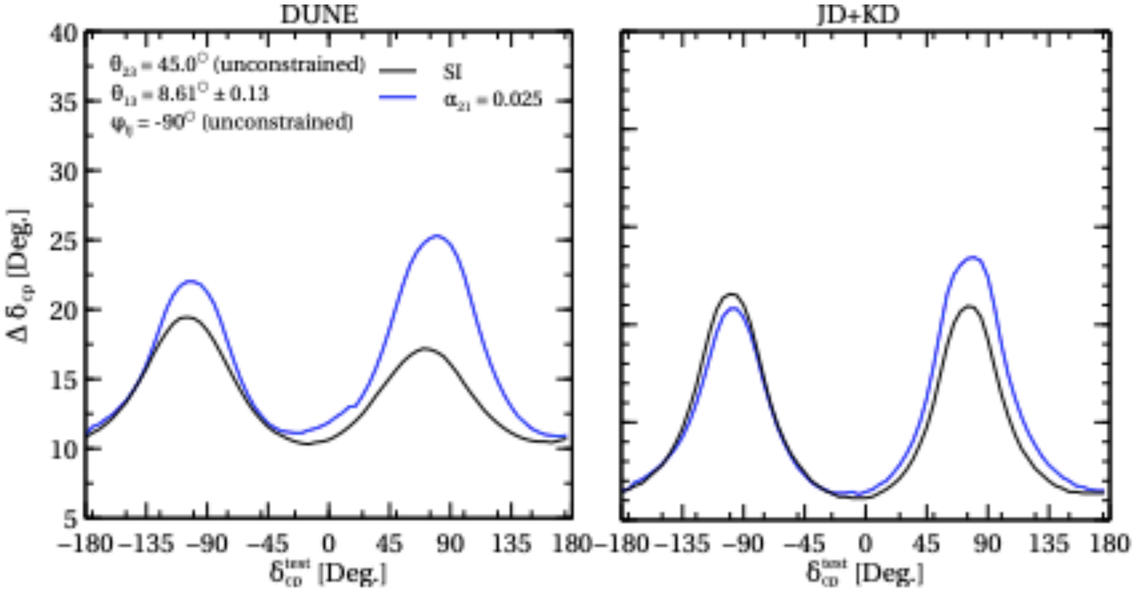
Improved limits with DUNE ν_τ sample and Near detectors

NU AND CPV

$$P_{\mu e} \subset -2|\alpha_{21}| r \sin\Delta_{31} \sin(\delta_{CP} - \phi_{21} + \Delta_{31}) + f(\alpha_{31}, A)$$

Effect of NU on CP phase determination!
(Future developments…)





PROPAGATION VECTOR NSI VS SCALAR NSI

$$\mathcal{L}_{\rm NSI}^{eff} = -2\sqrt{2}G_F \sum_{f,\alpha,\beta} \varepsilon_{\alpha\beta}^{f}(\bar{\nu}_\alpha \gamma_\rho \nu_\beta)(\bar{f}\gamma^\rho f) \longrightarrow H = \frac{1}{2E}\left[UM^2U^\dagger + A\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}\right]$$

Vector Propagation NSI: coupled to matter potential, limits from oscillation experiments

$$\mathcal{L}_{\rm scalar\ NSI}^{eff} = y_f Y_{\alpha\beta}(\bar{\nu}_\alpha \nu_\beta)(\bar{f}f) \longrightarrow \delta\tilde{M} = \sqrt{\Delta m_{31}^2}\begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{e\mu}^* & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{e\tau}^* & \eta_{\mu\tau}^* & \eta_{\tau\tau} \end{pmatrix}$$

LBL??

Scalar NSI: modification of the mass matrix, oscillations sensitive to absolute mass scale

CONCLUSIONS

- Oscillation measurements have now reached a good precision, bounds to new physics parameters are possible

- DUNE and T2HK (T2HKK) are two long baseline experiments which will be able to determine (hopefully) all the unkown oscillation observables

- Their great potential could be used to find bounds on new physics parameters which could be competitive with other non-oscillation bounds

- The complementarity between the two experiments is essential