

# PROBING BSM MODELS AT FUTURE HIGH-PRECISION LONG BASELINE EXPERIMENTS

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# NEUTRINO OSCILLATIONS AT LONG BASELINE EXPERIMENTS

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

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

$$\nu_\mu \rightarrow \nu_e$$

$(\theta_{13}, \theta_{23}, \delta)$

$$\nu_\mu \rightarrow \nu_\mu$$

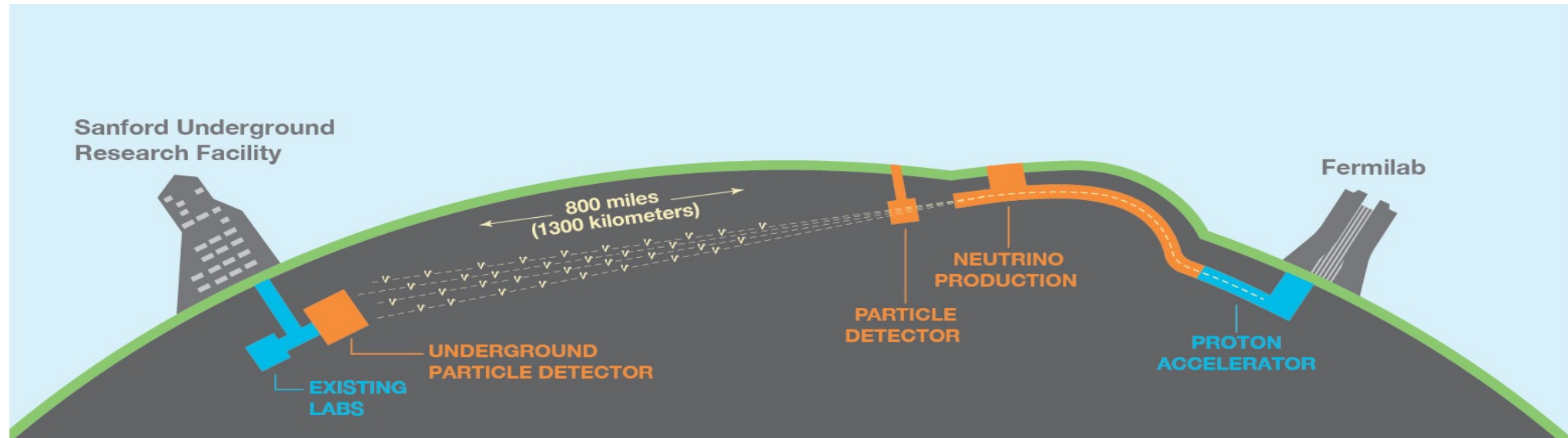
$(\theta_{23}, \Delta m_{31}^2)$

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

BSM

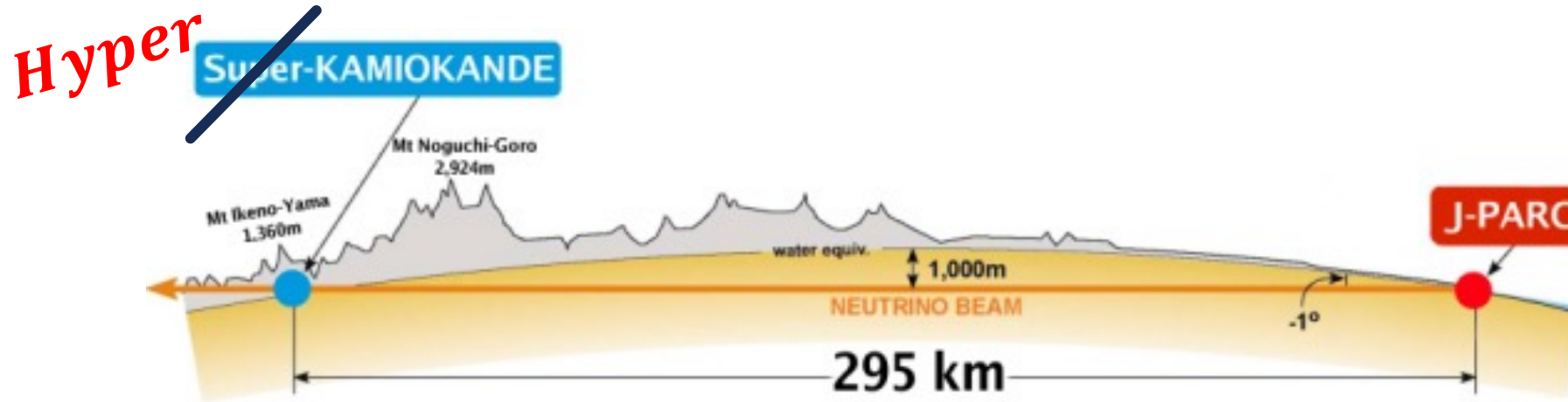
$E_\nu > 3 \text{ GeV}$

# 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  $3\sigma$**

# 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**
- Unprecedented statistics on electron appearance (Cherenkov detector) **GREAT PRECISION ON PARAMETERS AND  $M_H$**
- 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**
- Improvement of CPV sensitivity due to the clean environment provided by the second oscillation maximum



# STUDY OF BSM MODELS AT DUNE AND T2HKK





# **NEUTRINO INVISIBLE DECAY AT DUNE: A MULTI-CHANNEL ANALYSIS**

**(GHOSHAL, GIARNETTI, MELONI; 2003.09012)**

## INVISIBLE DECAY MODEL

In the standard model, all the three neutrino mass eigenstates are stable. However we can take into account the possibility of the neutrino decay mediated by scalar particles often called Majorons:

**-Visible decay:** the heaviest neutrino decays into the other active neutrinos

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



# INVISIBLE DECAY MODEL

Consider now only the invisible decay. The less constrained neutrino lifetime is the  $\nu_3$  one.

The neutrinos hamiltonian reads

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

PMNS matrix

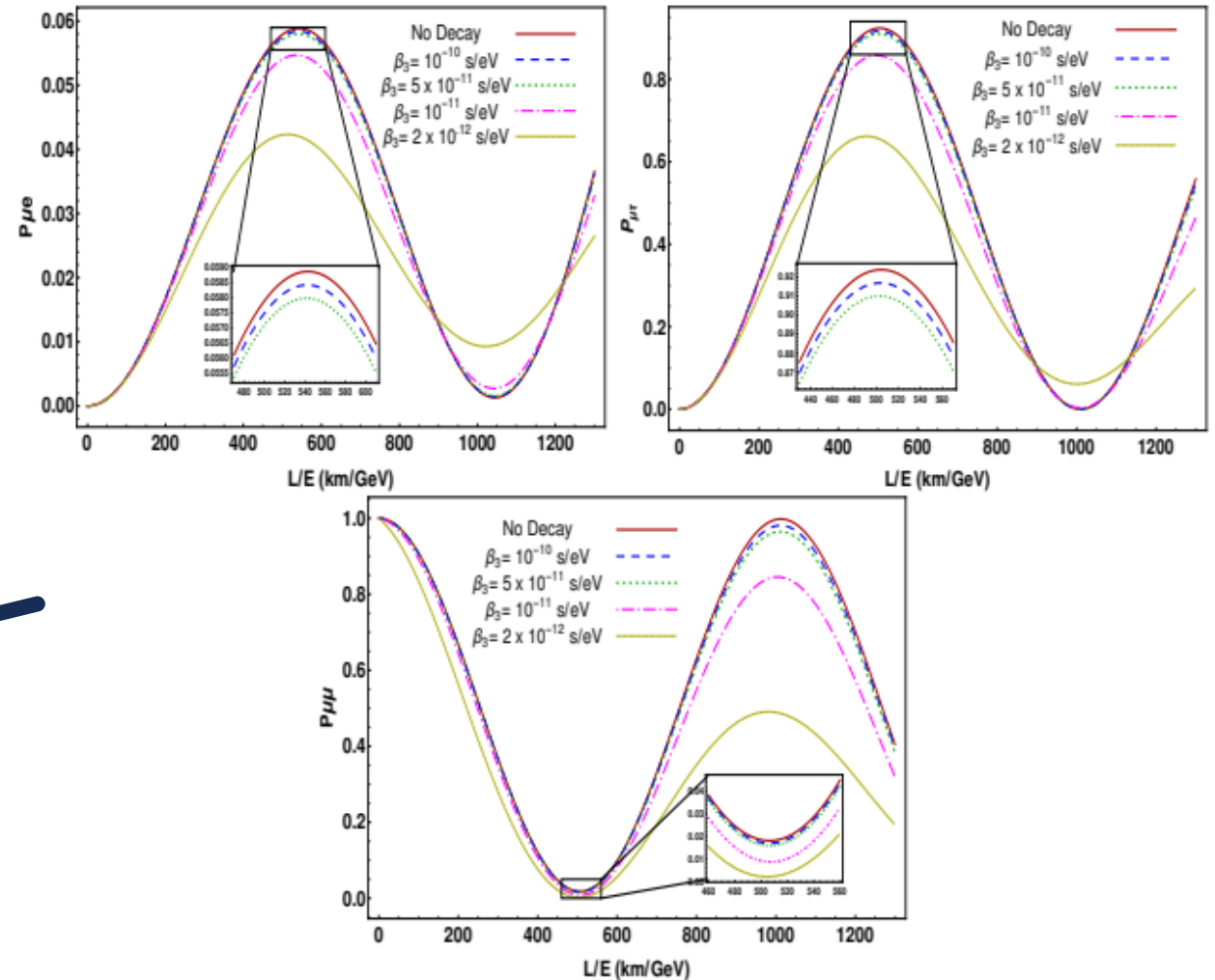
**Decay term**

Matter potential

# INVISIBLE DECAY MODEL

Computing the time evolution of a given flavor state, we obtain the oscillation probabilities.

The smaller is the decay parameter, the more oscillation probabilities are flattened, and tend to a value which do not depend to  $L/E$

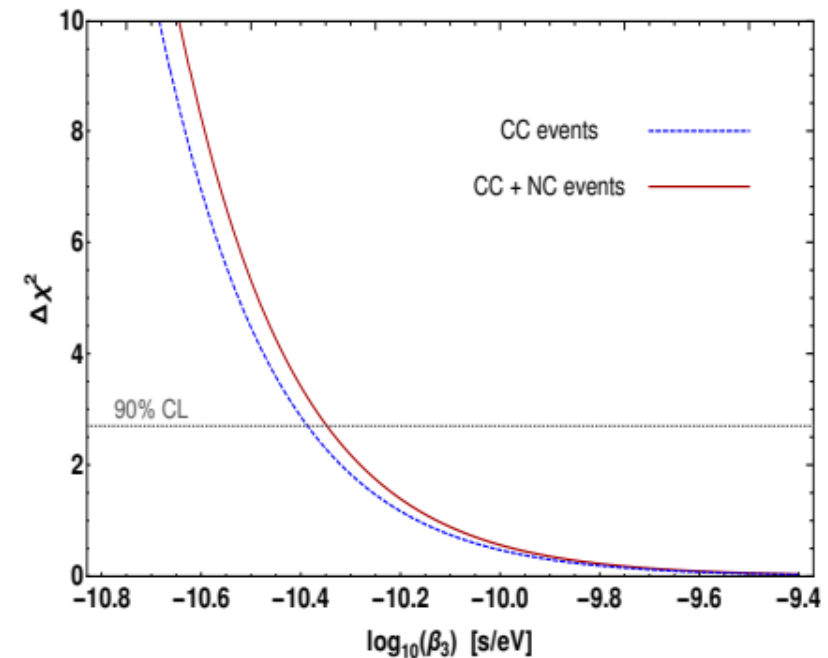


# INVISIBLE DECAY MODEL

Since one neutrino mass state decays during his lifetime, the total number of neutrinos at the Far Detector, is not the same as the number of neutrinos produced at the source! Indeed

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

- Being the number of Neutral Current events proportional to the total number of neutrinos (the NC interactions are flavor independent), we found out that this new channel would improve the DUNE sensitivity to the decay parameter!



**New constraint  $5.1 \times 10^{-11}$  s/eV**



# **PROBING SOURCE AND DETECTOR NSI PARAMETERS AT THE DUNE NEAR DETECTOR**

**(GIARNETTI, MELONI; 2005.10272)**

## NON STANDARD INTERACTIONS

We can consider the possibility of four-fermions effective operators in the lagrangian which couple each of the neutrinos to all the three leptons. We have three cases:

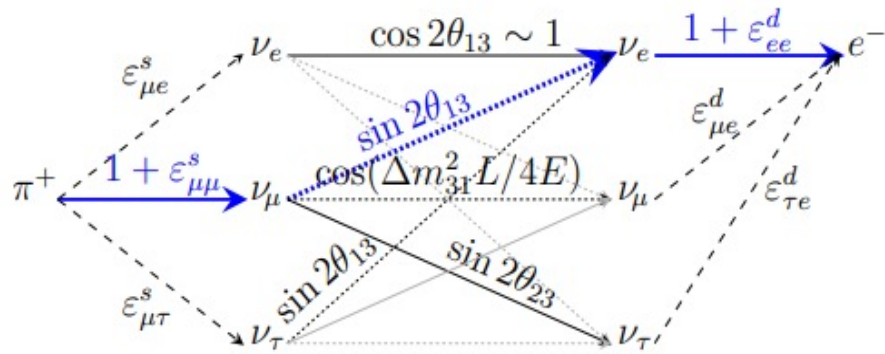
- Source NSI:** occur when neutrinos are produced by hadrons decays at the accelerator level
- Propagation NSI:** occur while neutrinos travel in the matter
- Detector NSI:** ons occur while neutrinos are detected

## NON STANDARD INTERACTIONS

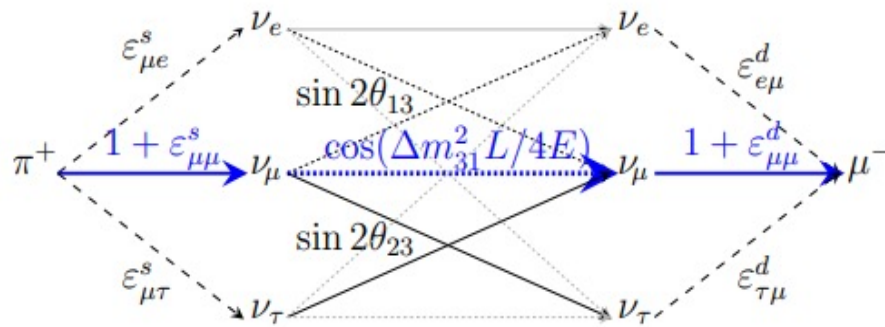
In the most general case, we have a plethora of effective NSI couplings to take into account. Indeed both source and detector NSI-s are described by a  $3 \times 3$  complex matrix, which has 18 real parameters. The propagation NSI, due to hermiticity relations, is described on the other hand by only 8 real parameter.

**In total we have 44 new real independent parameters appearing in the oscillation probabilities!**

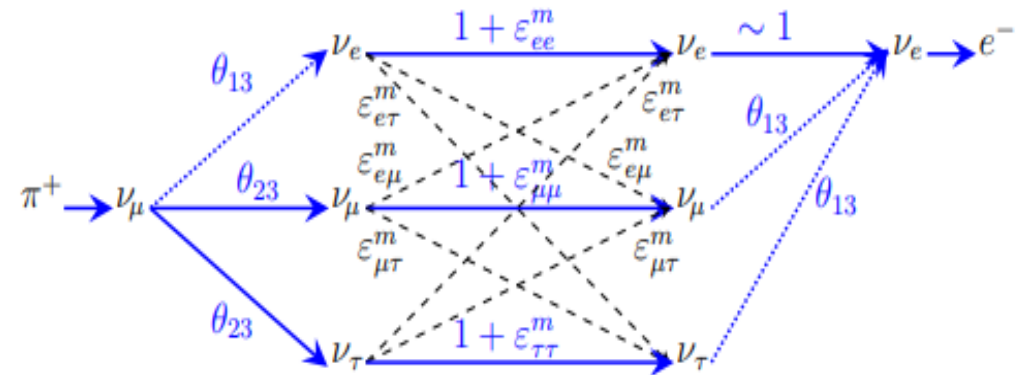
# NON STANDARD INTERACTIONS



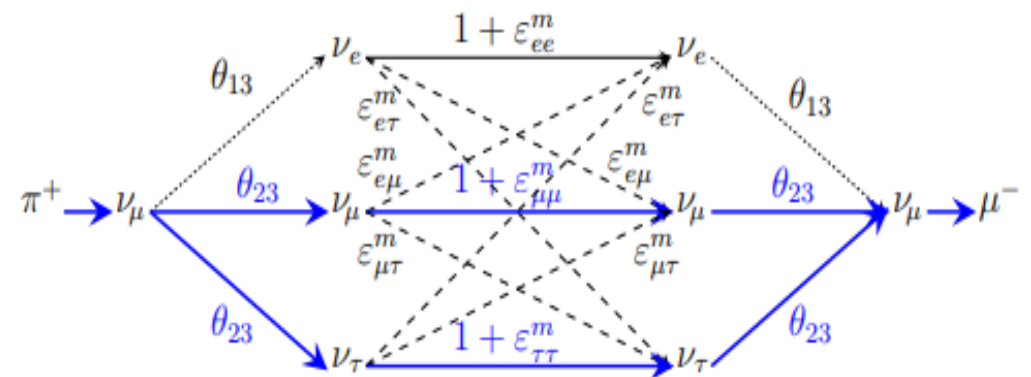
(a)



(b)



(a)



## NON STANDARD INTERACTIONS

If we want to study source and detector NSI-s, we can cancel the effect of the propagation ones, studying the Near Detector events, which are at almost zero baseline.

In presence of NSI, the transition probabilities at zero baseline are very simple!

$$P_{\alpha\alpha} = 1 + 2|\varepsilon_{\alpha\alpha}^s| \cos \Phi_{\alpha\alpha}^s + 2|\varepsilon_{\alpha\alpha}^d| \cos \Phi_{\alpha\alpha}^d$$

$$P_{\alpha\beta} = |\varepsilon_{\alpha\beta}^s|^2 + |\varepsilon_{\alpha\beta}^d|^2 + 2|\varepsilon_{\alpha\beta}^s||\varepsilon_{\alpha\beta}^d| \cos(\Phi_{\alpha\beta}^s - \Phi_{\alpha\beta}^d)$$



## NON STANDARD INTERACTIONS

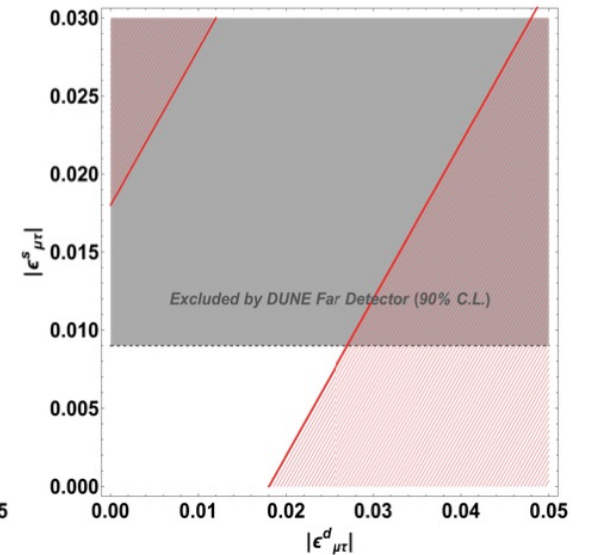
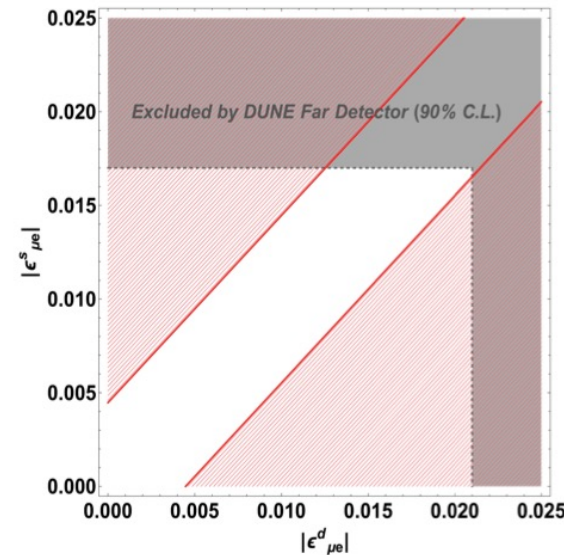
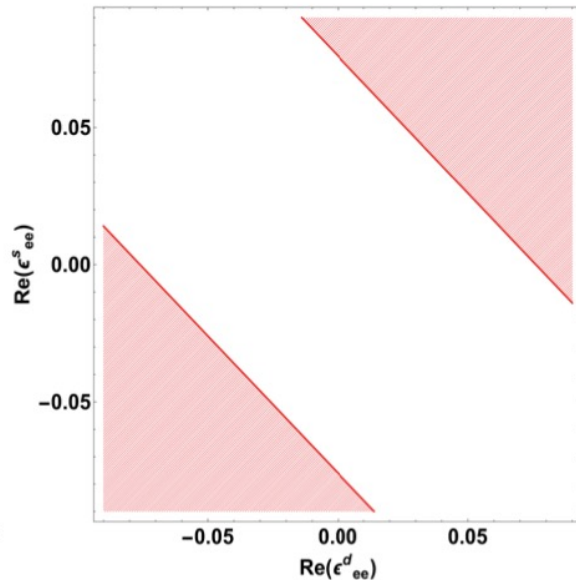
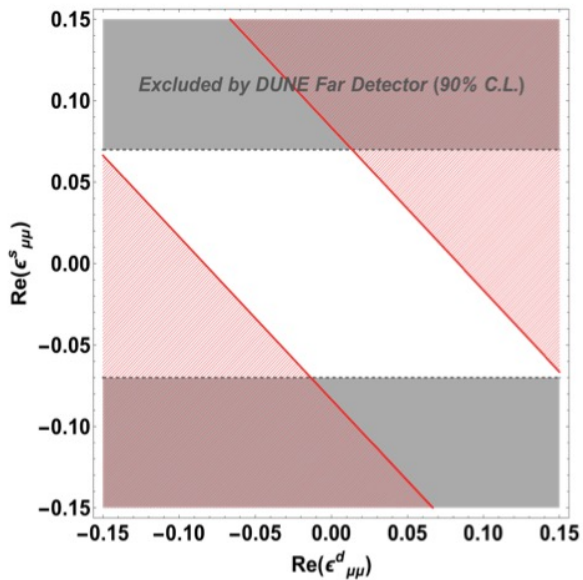
Thus, given a certain number events in each channel at the Near Detector, we can exclude the following parameters space regions at a given CL

$$||\varepsilon_{\alpha\beta}^s| - |\varepsilon_{\alpha\beta}^d|| > \sqrt[4]{\frac{\chi_{0,\alpha\beta}^2 \sigma^2}{N_0^2}}$$

$$|\Re(\varepsilon_{\alpha\alpha}^s) + \Re(\varepsilon_{\alpha\alpha}^d)| > \sqrt{\frac{\chi_{0,\alpha\alpha}^2 \sigma^2}{4N_0^2}}$$

# NON STANDARD INTERACTIONS

At the DUNE 50ton LAr-TPC Near detector, considering electron disappearance and appearance, tau appearance and muon disappearance, we excluded the following regions of the parameter spaces





# MODEL-INDEPENDENT CONSTRAINTS ON NON-UNITARY NEUTRINO MIXING FROM HIGH-PRECISION LONG-BASELINE EXPERIMENTS

**(AGARWALLA, DAS, GIARNETTI, MELONI; 2111.00329)**

# NON UNITARITY OF THE PMNS MATRIX

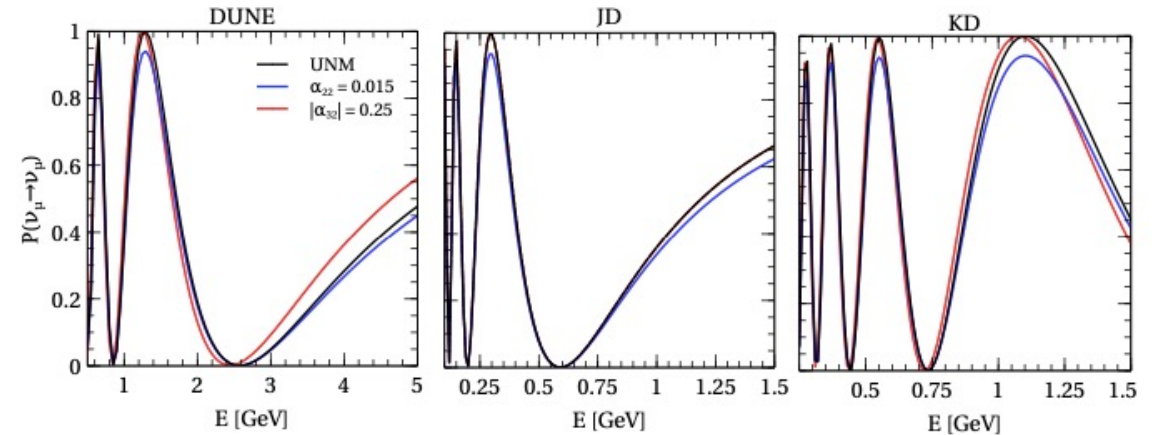
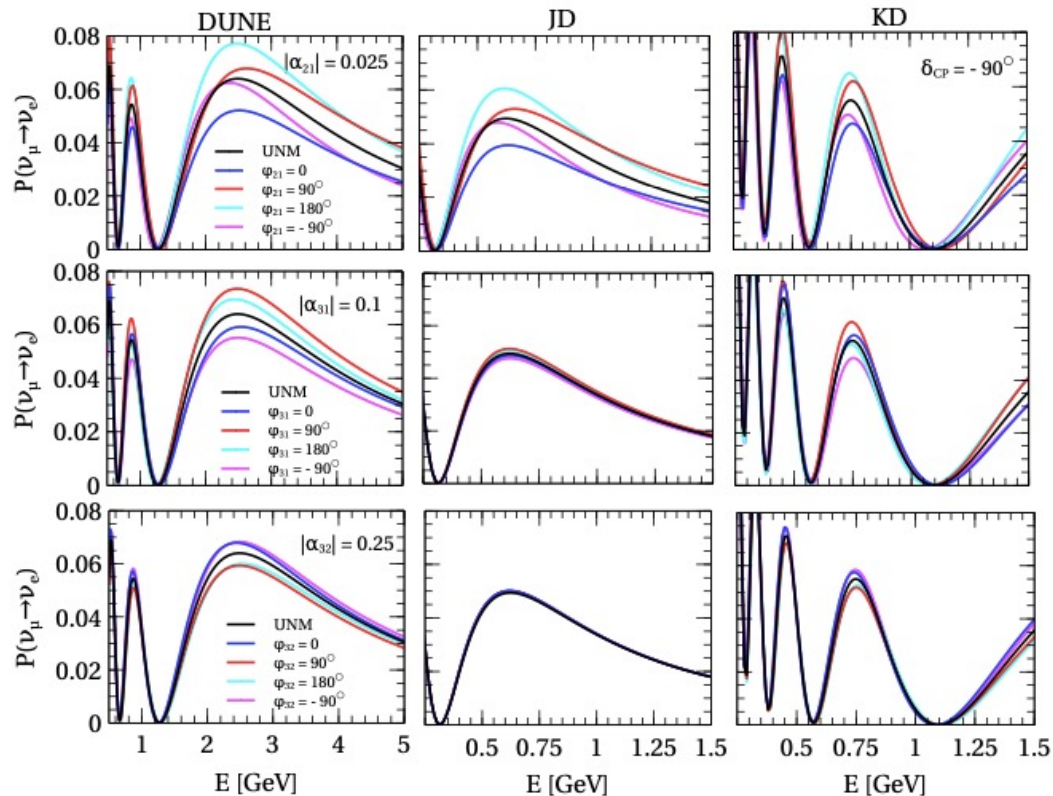
Different models which explain the introduce new particles in the standard model in the leptonic sector. In these cases, the neutrino mixing matrix is no longer 3x3.

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

In a complete model-independet way, the non-unitary 3x3 matrix can be parameterized with 6 more parameters (3 complex+3 real)

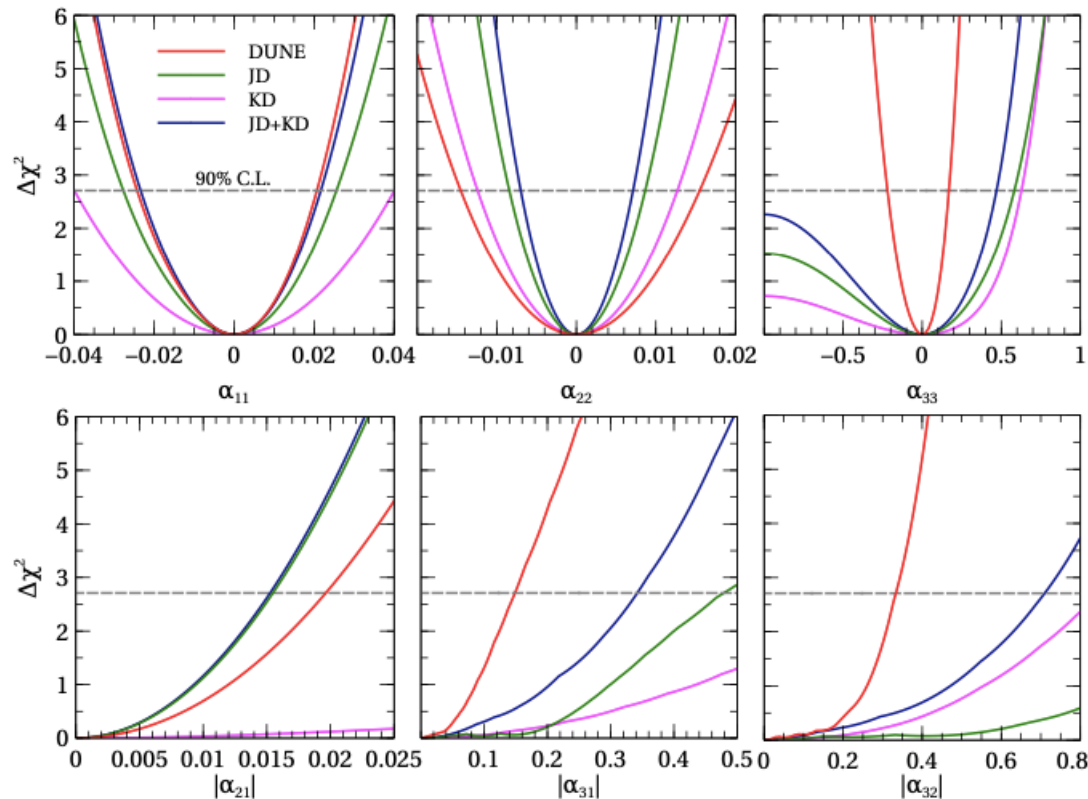
$$N = (1 + \alpha)U_{PMNS}.$$
$$\alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}|e^{i\phi_{21}} & \alpha_{22} & 0 \\ |\alpha_{31}|e^{i\phi_{31}} & |\alpha_{32}|e^{i\phi_{32}} & \alpha_{33} \end{pmatrix}$$

# NON UNITARITY OF THE PMNS MATRIX



- Appearance dominated by  $a_{21}$
- Appearance depends on  $a_{31}$  and  $a_{32}$  through matter (DUNE)
- Disappearance dominated by  $a_{22}$

# SENSITIVITY TO NON-UNITARITY PARAMETERS



	DUNE	JD	KD	JD+KD	JD+KD+DUNE
$\alpha_{11}$	[-0.020, 0.020]	[-0.025, 0.025]	[-0.040, 0.040]	[-0.022, 0.022]	[-0.017, 0.017]
$\alpha_{22}$	[-0.014, 0.014]	[-0.0087, 0.0087]	[-0.013, 0.013]	[-0.007, 0.007]	[-0.006, 0.006]
$\alpha_{33}$	[-0.2, 0.17]	< 0.6	< 0.63	< 0.476	[-0.17, 0.17]
$ \alpha_{21} $	< 0.022	< 0.015	< 0.10	< 0.016	< 0.012
$ \alpha_{31} $	< 0.15	< 0.48	< 0.70	< 0.34	< 0.11
$ \alpha_{32} $	< 0.33	< 1.2	< 0.85	< 0.71	< 0.27

-T2HKK has great limits on  $\alpha_{22}$

-DUNE and T2HKK have comparable limits on  $\alpha_{21}$  and  $\alpha_{11}$

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



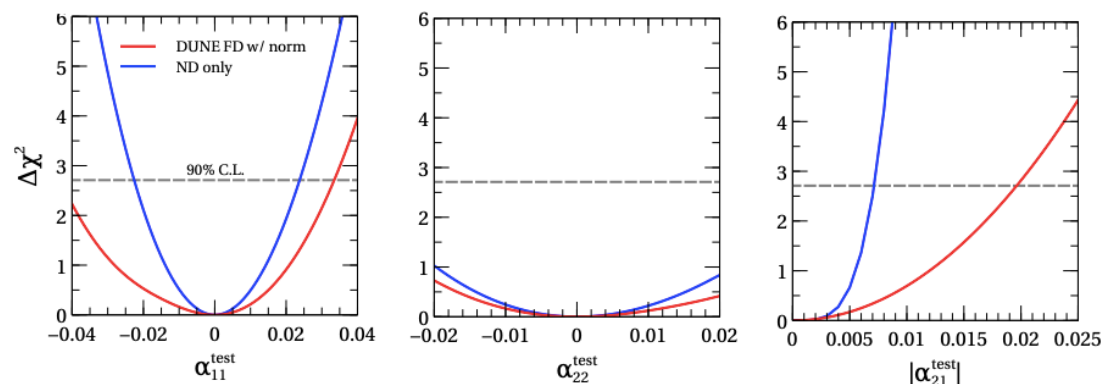
*However, if the flux is measured at the ND, sensitivity to  $\alpha_{22}$  is lost.*

# NEAR DETECTOR CONSTRAINTS

**Systematic dominated**

$$|\alpha_{22}| > \frac{\sqrt{\chi_0^2} \sigma_{sys}}{4}$$

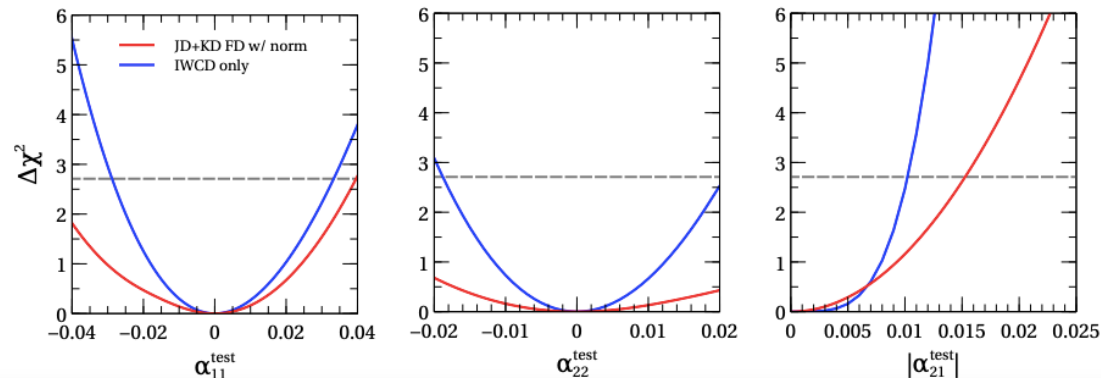
$$|\alpha_{11}| > \frac{\sqrt{\chi_0^2} \sigma_{sys}^{\nu_e}}{4}$$



**DUNE 50t LAr-TPC Near Detector  
(574 m)**

**Statistic dominated**

$$|\alpha_{21}| < \sqrt[4]{\frac{\chi_0^2 N_{obs}}{N_0^2}},$$



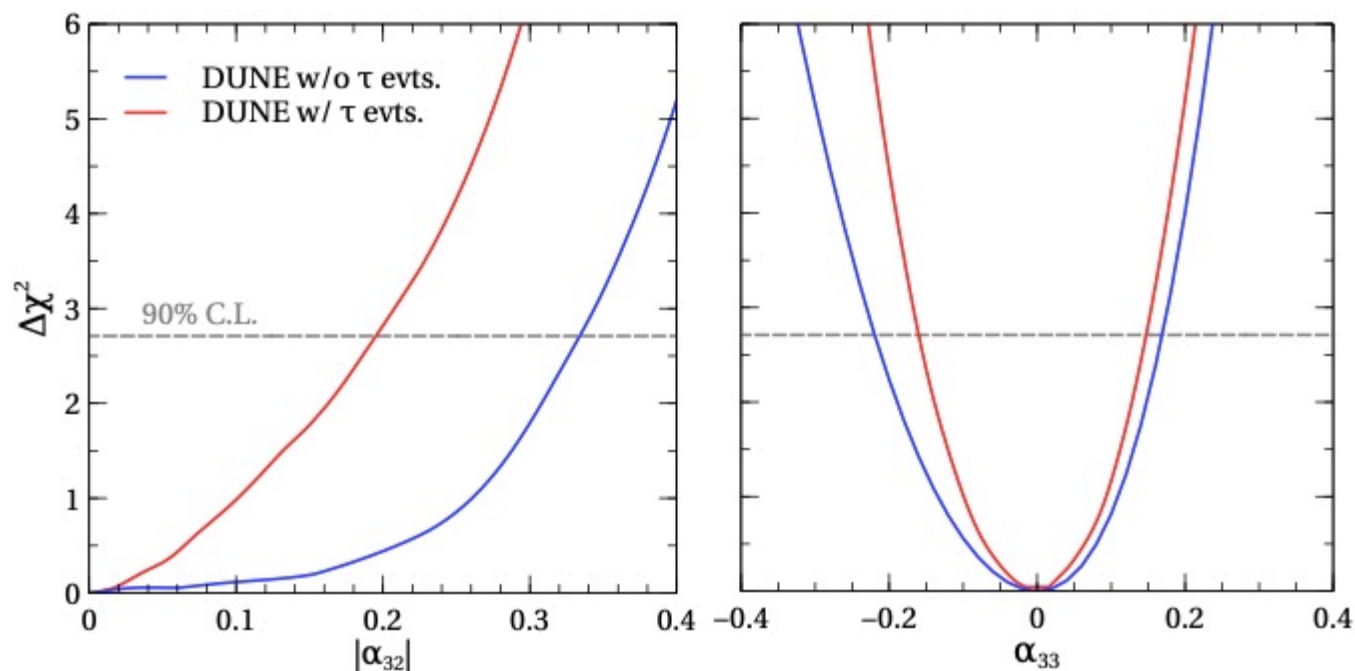
**T2HKK 1kt Cherenkov Near Detector  
(1 km)**



# TAU CONSTRAINTS

$$P_{\mu\tau} = \sin^2 \Delta_{31} (1 + 2\alpha_{22} + \underline{2\alpha_{33}} - 4a^2 + \alpha_{22}^2 + \underline{\alpha_{33}^2} + 4\underline{\alpha_{22}\alpha_{33}}) + \underline{|\alpha_{32}|} \sin 2\Delta_{13} [2\Delta_n \cos \phi_{32} - \sin \phi_{32}] +$$

**Enhanced constraints on  $a_{32}$  and  $a_{33}$  using the DUNE tau sample!**



Parameter	w/o $\nu_\tau$ appearance	w/ $\nu_\tau$ appearance
$\alpha_{33}$	$[-0.2, 0.17]$	$[-0.16, 0.15]$
$ \alpha_{32} $	$< 0.33$	$< 0.19$





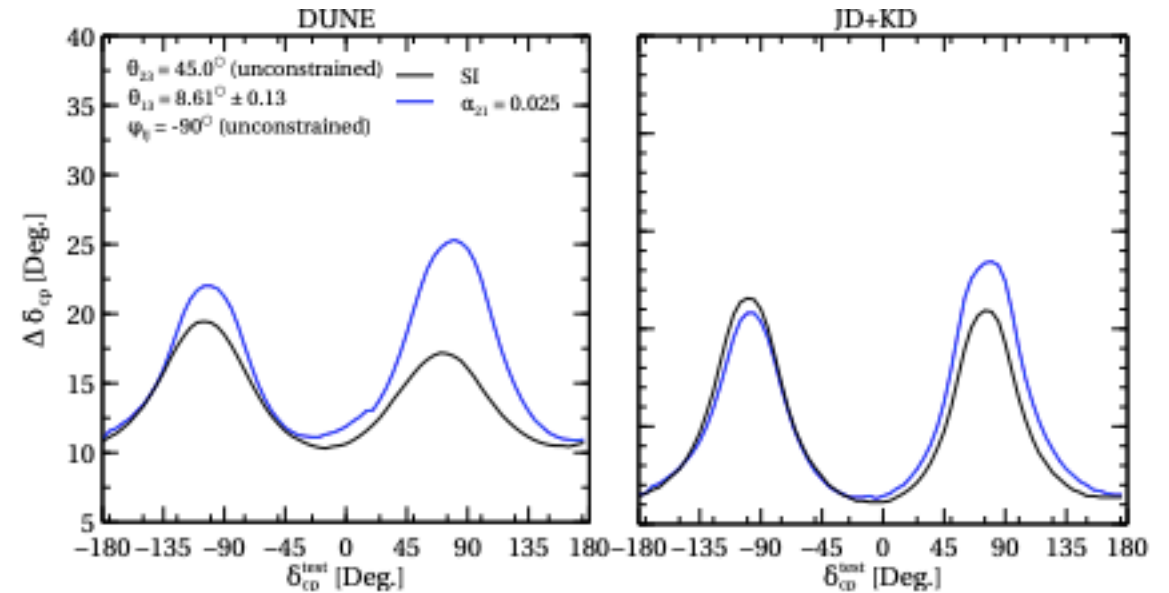
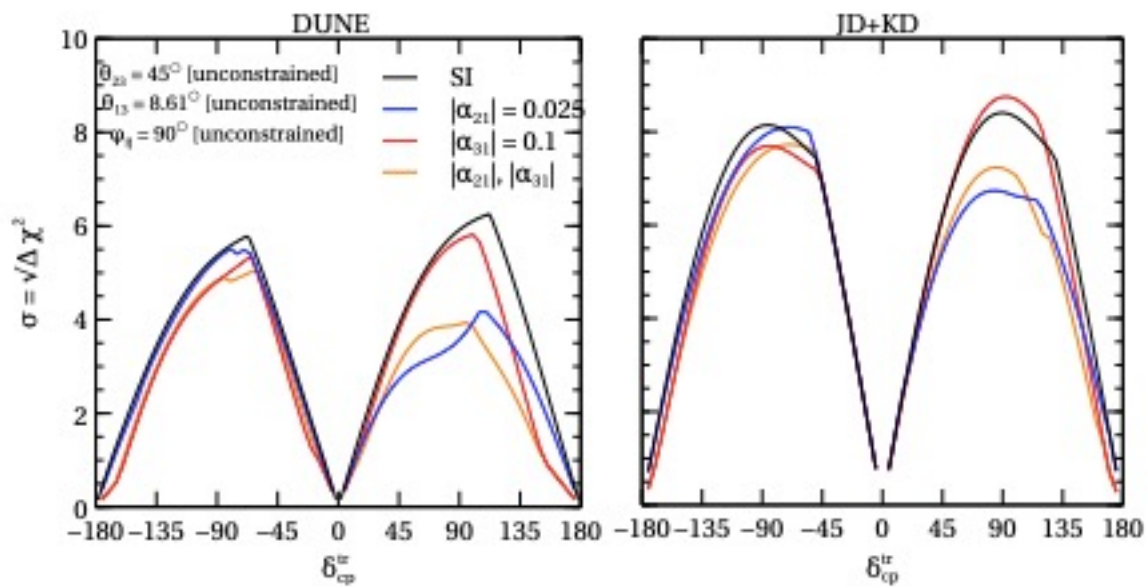
# FURTHER DEVELOPMENTS



# 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

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

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

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

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 unknown 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



THANK YOU FOR YOUR ATTENTION

