NEW APPROACHES TO THE STUDY OF BSM PHYSICS AT FUTURE LONG-BASELINE EXPERIMENTS

ALESSIO GIARNETTI

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NEUTRINO OSCILLATIONS AT LONG BASELINE EXPERIMENTS

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

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

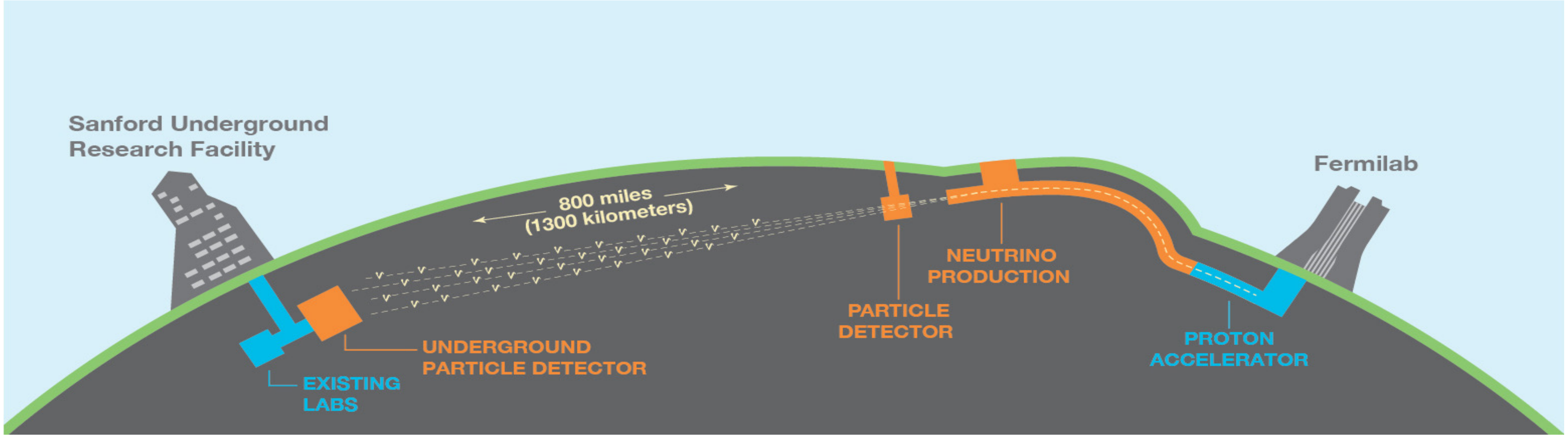
$\nu_\mu \to \nu_e$
$(\theta_{13}, \theta_{23}, \delta)$

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

$\nu_\mu \to \nu_\tau$
BSM

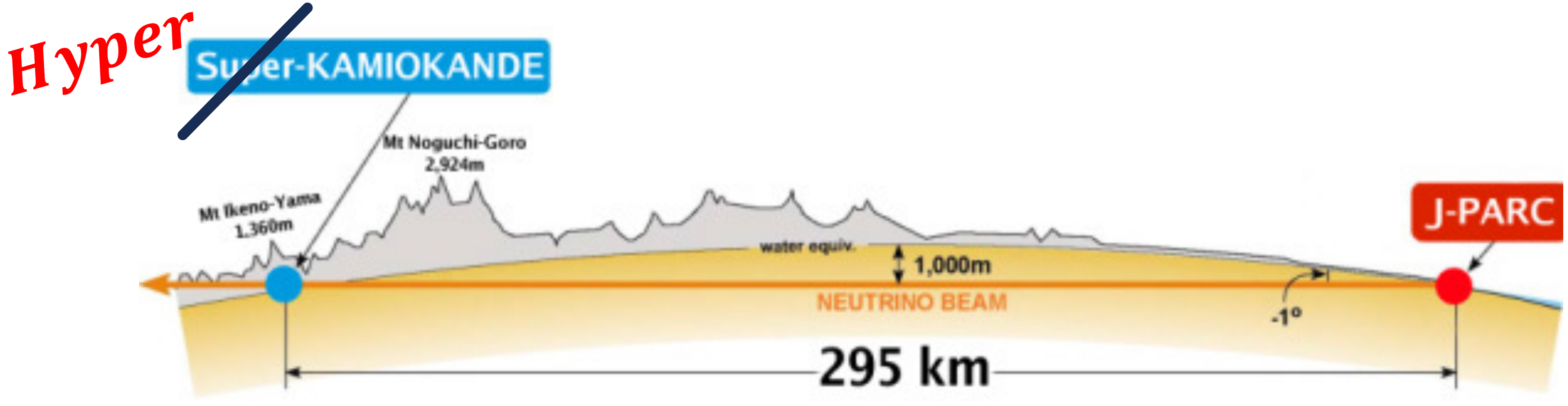
$E_\nu > 3$ GeV

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

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:

-**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 ν_3 one.

The neutrinos hamiltonian reads

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

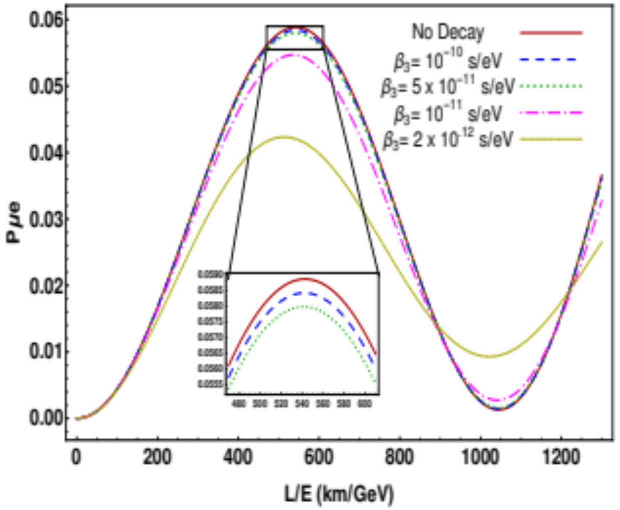
Decay term

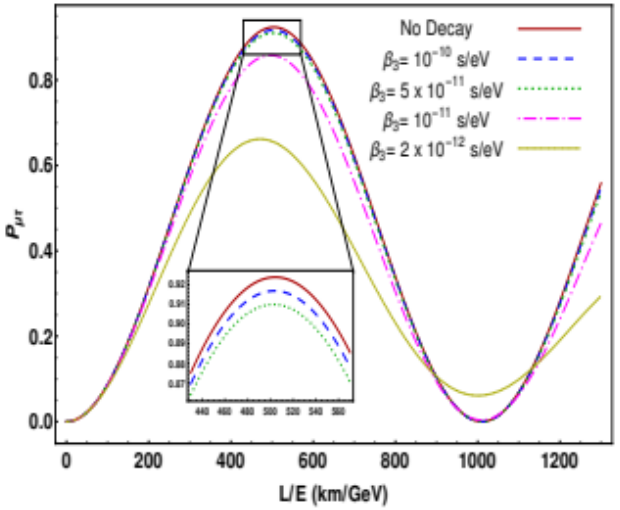
Matter potential

PMNS matrix

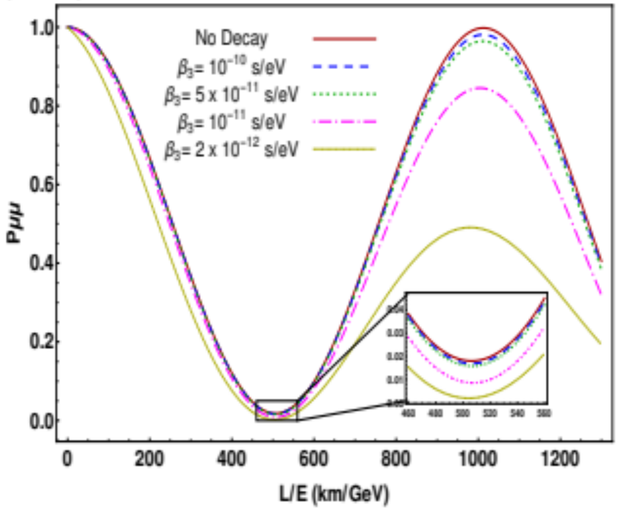
INVISIBLE DECAY MODEL

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

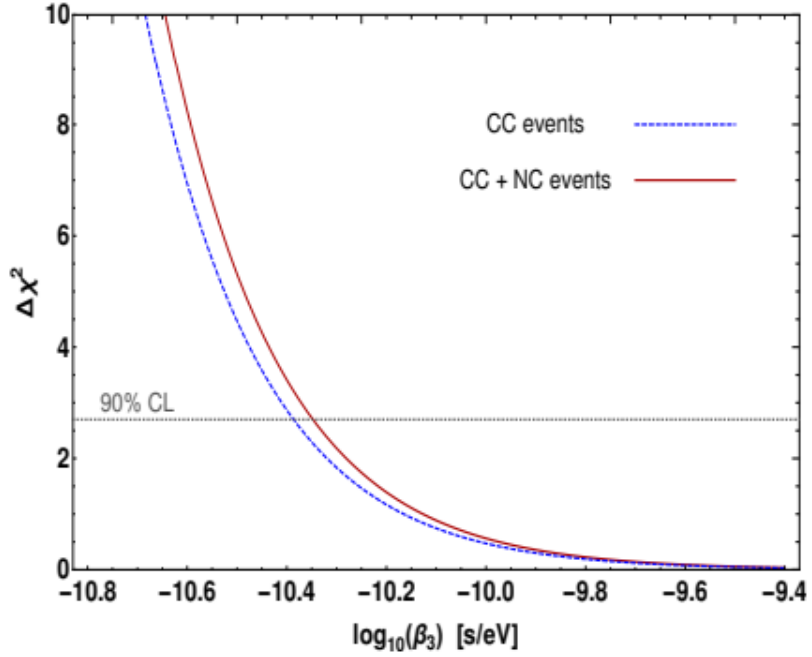


INVISIBLE DECAY MODEL

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 5.1×10−11 s/eV

NEW SOURCES OF CP VIOLATION AT DUNE

(GIARNETTI, MELONI, 2106.00030)

CP VIOLATION IN PRESENCE OF NON-STANDARD-INTERACTIONS

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

δ_{CP} ***induced***

Matter induced

+ BSM

$$A_{CC} \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$$\varepsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}| e^{i\underline{\delta_{\alpha\beta}}}$$

New terms in the asymmetries!

CP VIOLATION IN PRESENCE OF A LIGHT STERILE NEUTRINO

$$U = R(\theta_{34})R(\theta_{24})R(\theta_{23},\delta_3)R(\theta_{14})R(\theta_{13},\delta_2)R(\theta_{12},\delta_1)$$

New sources of CP violation!

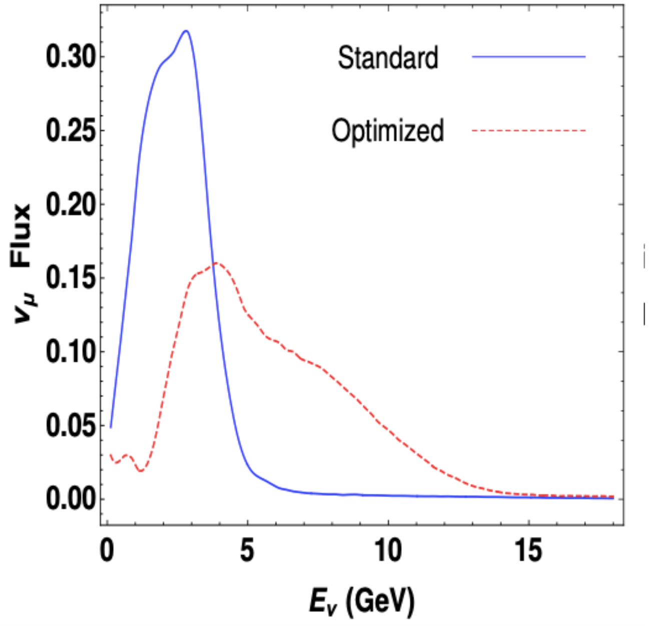
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[\frac{1}{2E_\nu}U\begin{pmatrix}0&0&0&0\\0&\Delta m^2_{21}&0&0\\0&0&\Delta m^2_{31}&0\\0&0&0&\Delta m^2_{41}\end{pmatrix}U^\dagger + \begin{pmatrix}A_{CC}+A_{NC}&0&0&0\\0&A_{NC}&0&0\\0&0&A_{NC}&0\\0&0&0&0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

A CASE STUDY: DUNE

We considered to options for the starting neutrino flux at DUNE:

-Standard flux peaked at 2.5 GeV (first atmospheric maximum)

-τ-optimized high energy flux



Integrated asymmetries

$$A_{\alpha\beta} = \frac{N_\beta - \bar{N}_\beta}{N_\beta + \bar{N}_\beta}$$

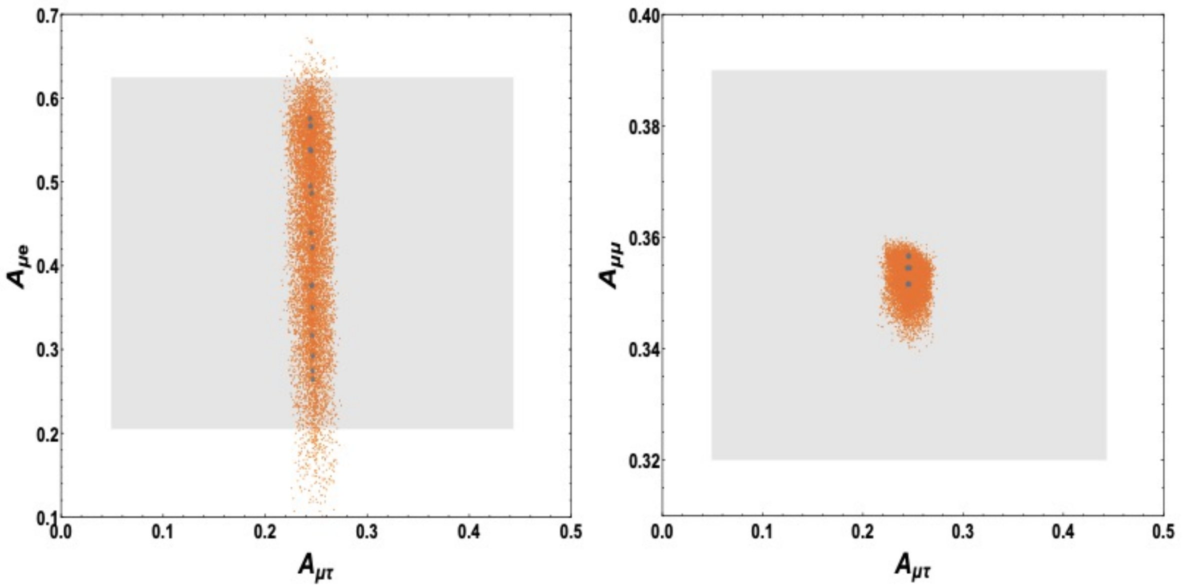
Search for hints of new physics:

-Compute the asymmetries in the standard model with their uncertainties

-Compute the asymmetries in 3+1 and NSI models with parameters in their allowed ranges

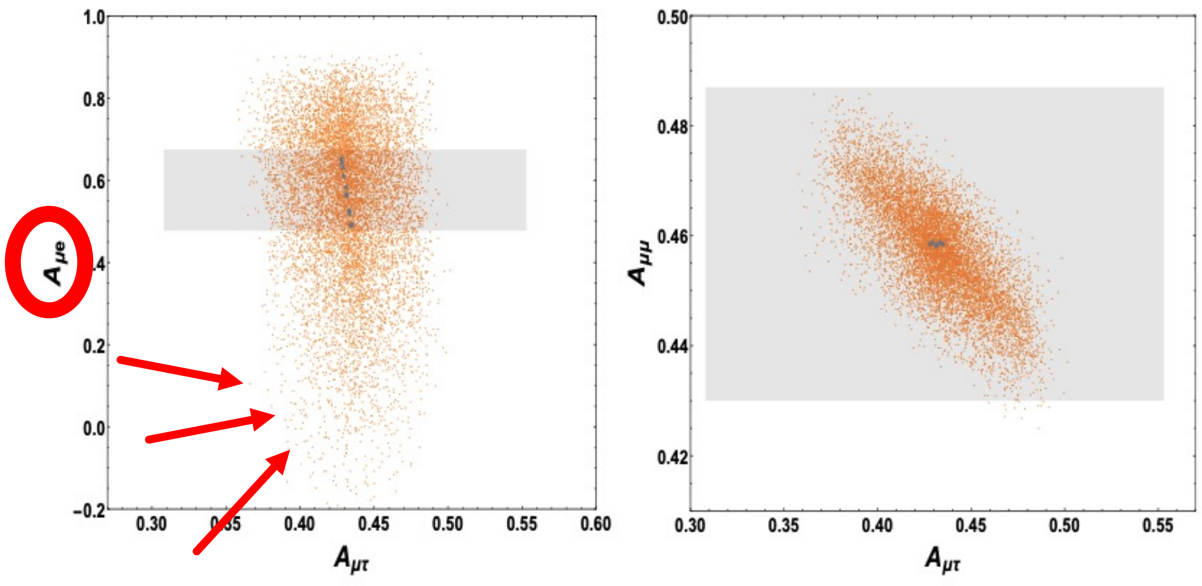
-Check whether some sets of new parameters generate anomalous asymmetires

ASYMMETRIES IN THE NSI MODEL



Standard flux

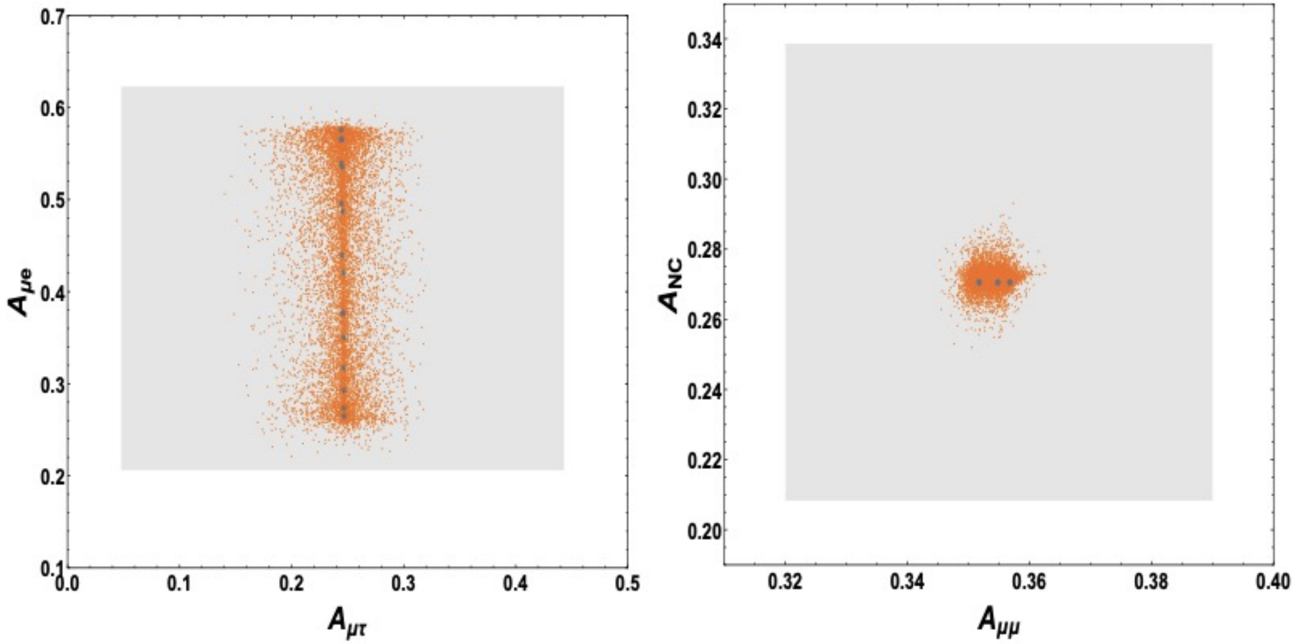
High energy flux



ASYMMETRIES IN THE 3+1 MODEL

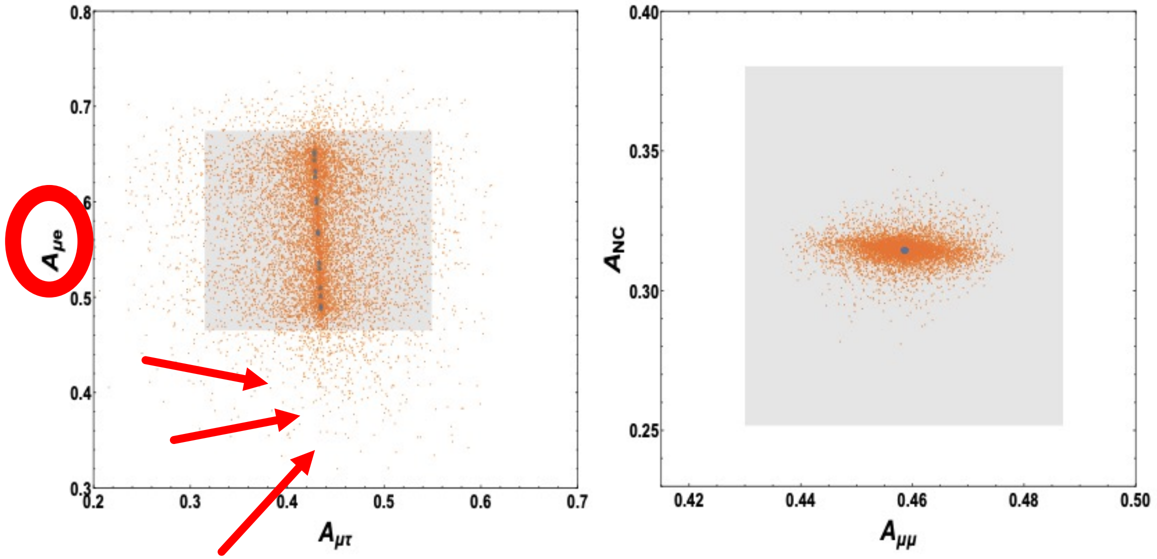
Inclusion of the NC sample $\longrightarrow$ $N_{NC} \propto P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau)$

$\longrightarrow 1 - P(\nu_\mu \to \nu_s)$



Standard flux

High energy flux



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.

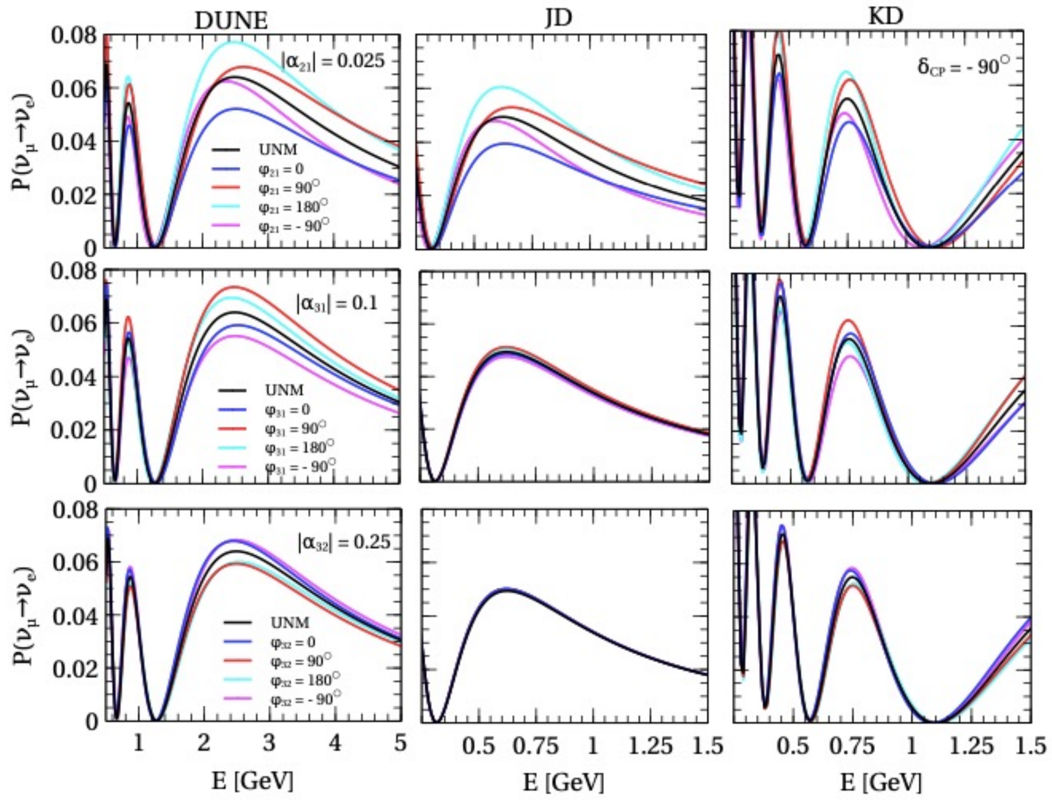
Thus, the PMNS matrix that we observe is only a submatrix of the complete one, losing its unitarity property.

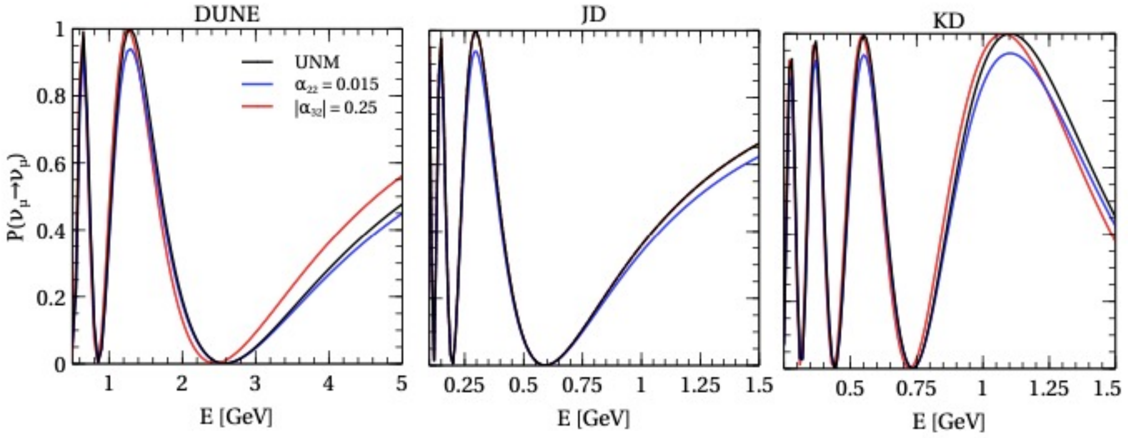
$$N = (1+\alpha)U_{PMNS} \cdot$$

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

$$\alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}|e^{i\phi_{21}} & \alpha_{22} & 0 \\ |\alpha_{31}|e^{i\phi_{31}} & |\alpha_{32}|e^{i\phi_{32}} & \alpha_{33} \end{pmatrix}$$

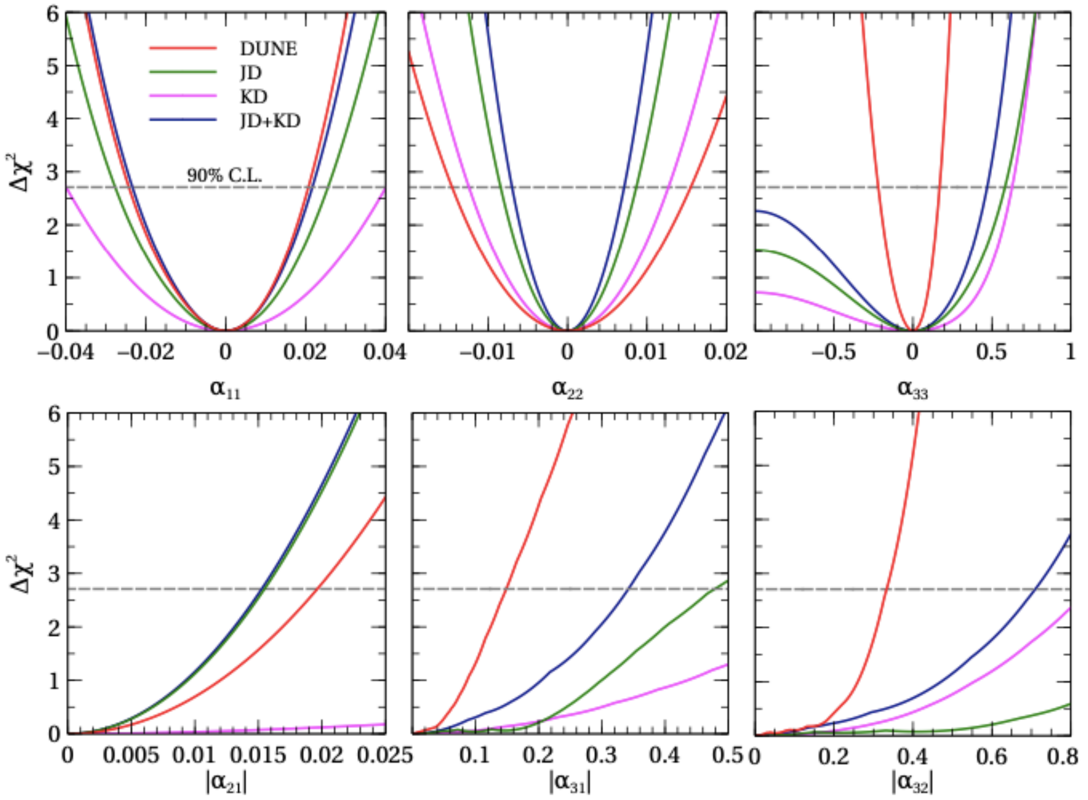
NON UNITARITY OF THE PMNS MATRIX





-Appearance dominated by a21
-Appearance depends on a31 and a32 through matter (DUNE)
-Disappearance dominated by a22

SENSITIVITY TO NON-UNITARITY PARAMETERS



	DUNE	JD	KD	JD+KD	JD+KD+DUNE
α_{11}	[-0.020, 0.020]	[-0.025, 0.025]	[-0.040, 0.040]	[-0.022, 0.022]	[-0.017, 0.017]
α_{22}	[-0.014, 0.014]	[-0.0087, 0.0087]	[-0.013, 0.013]	[-0.007, 0.007]	[-0.006, 0.006]
α_{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 a22

-DUNE and T2HKK have comparable limits on a21 and a11

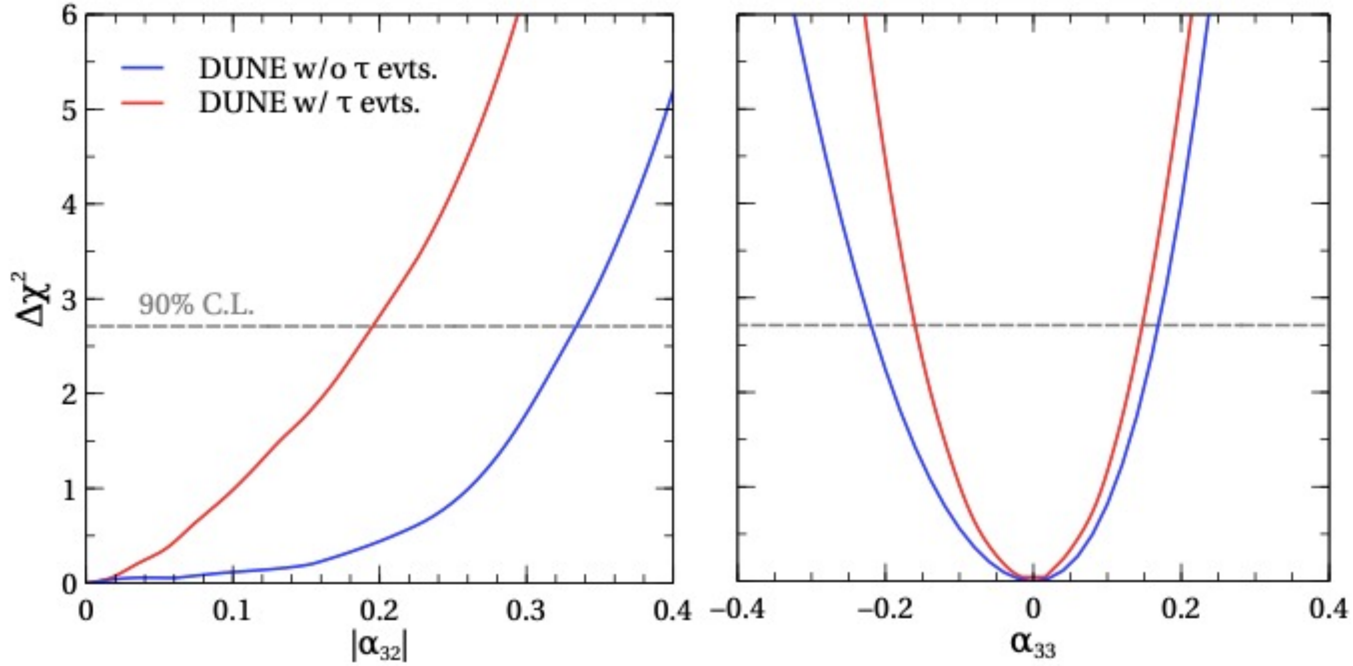
-Other parameters sensitivity dominated by DUNE due to bigger matter effects

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

TAU CONSTRAINTS

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

Enhanced constraints on a32 and a33 using the DUNE tau sample!



Parameter	w/o ν_τ appearance	w/ ν_τ appearance
α_{33}	[-0.2, 0.17]	[-0.16, 0.15]
$\lvert\alpha_{32}\rvert$	< 0.33	< 0.19

HOW TO IDENTIFY DIFFERENT NEW NEUTRINO OSCILLATION PHYSICS SCENARIOS AT DUNE

(DENTON, GIARNETTI, MELONI; 2210.00109**)**

PROPAGATION VECTOR NSI VS SCALAR NSI

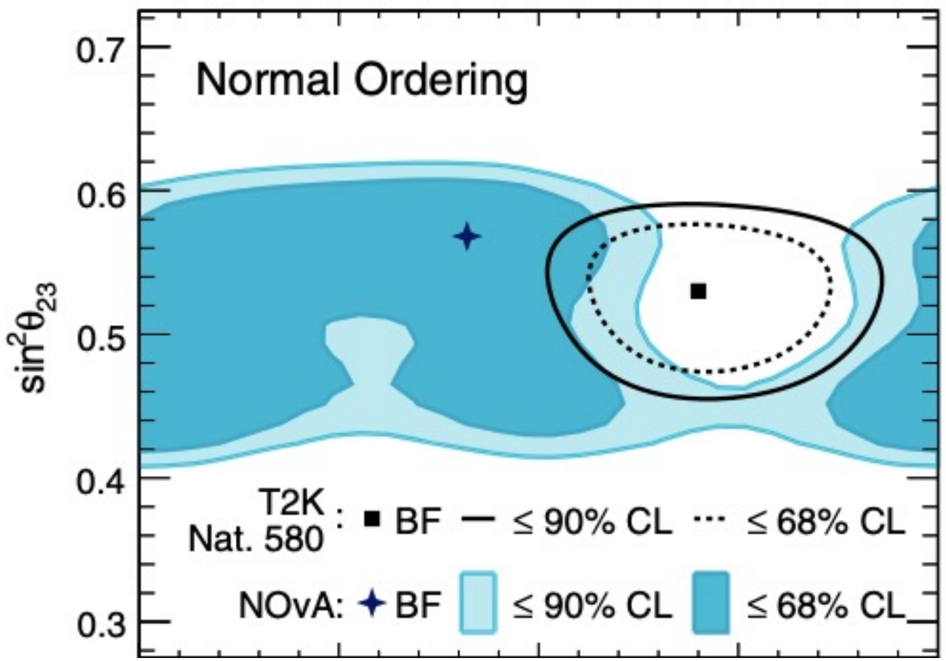
$$\mathcal{L}_{\text{NSI}}^{eff} = -2\sqrt{2}G_F \sum_{f,\alpha,\beta} \varepsilon_{\alpha\beta}^{f} (\bar{\nu}_\alpha \gamma_\rho \nu_\beta)(\bar{f}\gamma^\rho f) \longrightarrow H = \frac{1}{2E}\left[U M^2 U^\dagger + A \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\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

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

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

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

REDUCING THE T2K-NOVA TENSION WITH NSI



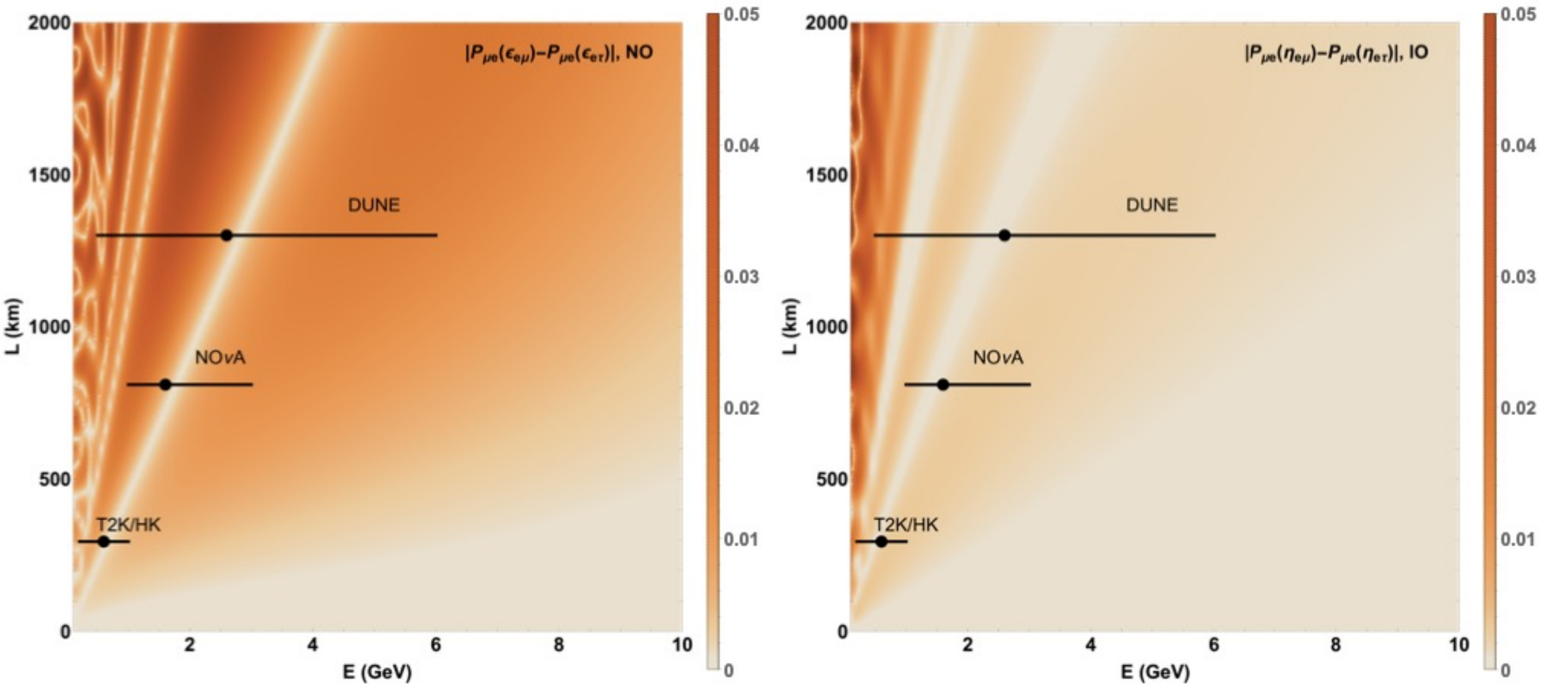
NOvA collab, PhysRevD.106.032004

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

2008.01110

MO	NSI	$\lvert\eta_{\alpha\beta}(3)\rvert$	$\phi_{\alpha\beta}/\pi$	δ/π	$\Delta\chi^2$
NO	$\eta_{e\mu}(3)$	0.009	1.40	1.17	0.04
	$\eta_{e\tau}(3)$	0.016	1.42	1.10	0.02
	$\eta_{\mu\tau}(3)$	0.006	1.22	1.11	0.08
IO	$\eta_{e\mu}(3)$	0.016	1.82	1.86	2.33
	$\eta_{e\tau}(3)$	0.013	0.66	1.89	2.20
	$\eta_{\mu\tau}(3)$	0.057	1.60	1.85	2.33

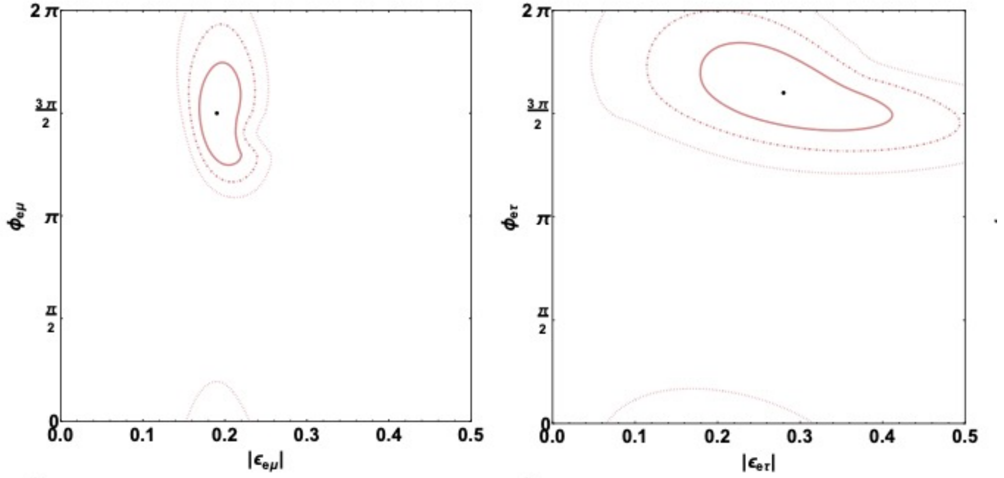
REDUCING THE T2K-NOVA TENSION WITH NSI



In DUNE conditions, at the probability level, the different benchmark models are different!

TESTING THE BEST FIT MODELS AT DUNE

Vector NSI in NO

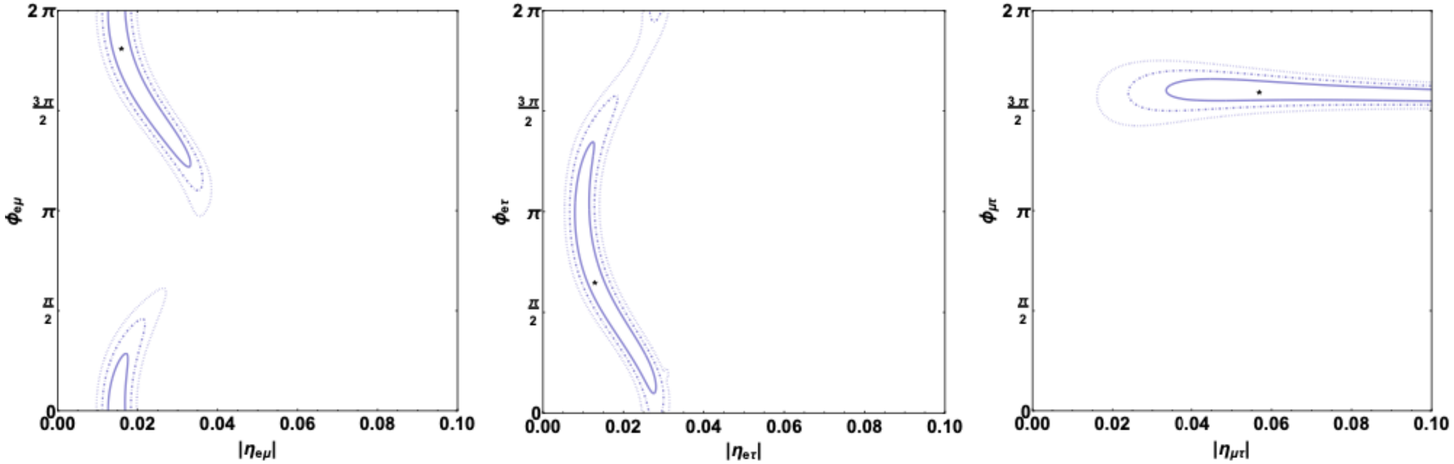


$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
$\varepsilon_{e\mu}$ NO	200	140	140	170	/	180	160	80
$\varepsilon_{e\tau}$ NO	60	48	50	45	50	/	50	40
$\varepsilon_{\mu\tau}$ NO	200	180	170	180	160	180	/	80
$\varepsilon_{e\mu}$ IO	170	80	75	90	/	10	13	3
$\varepsilon_{e\tau}$ IO	70	50	50	45	45	/	60	20
$\varepsilon_{\mu\tau}$ IO	500	400	400	400	300	350	/	160

Distinguishable at DUNE

Scalar NSI in IO

$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
$\eta_{e\mu}$ NO	0.14	/	0.005	0.088	0.071	0.033	0.055	0.02
$\eta_{e\tau}$ NO	0.08	0.003	/	0.041	SM	SM	SM	0.01
$\eta_{\mu\tau}$ NO	0.60	0.48	0.48	/	SM	SM	SM	0.02
$\eta_{e\mu}$ IO	100	/	4.7	6.3	80	70	90	21
$\eta_{e\tau}$ IO	60	1.0	/	1.5	44	38	50	11
$\eta_{\mu\tau}$ IO	30	4.6	4.8	/	23	20	29	12



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

THANK YOU FOR YOUR ATTENTION