NEW APPROACHES TO THE STUDY OF STANDARD AND BESM NEUTRINO OSCILLATIONS AT FUTURE LBL EXPERIMENTS

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NEUTRINO OSCILLATIONS AT LONG BASELINE EXPERIMENTS

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

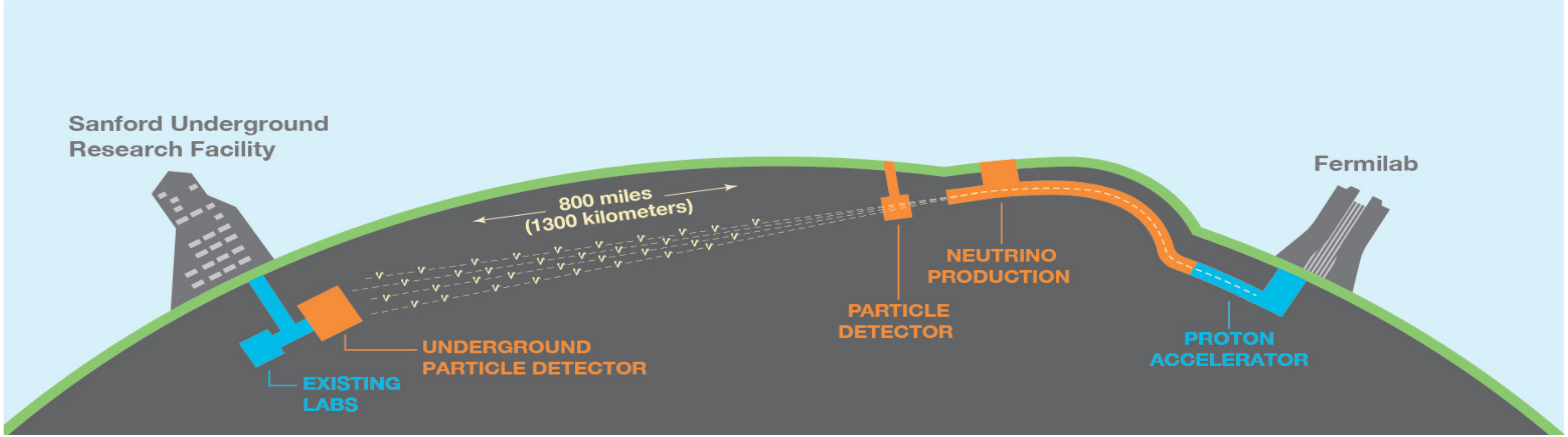
- GeV neutrinos, ~10^3 Km baseline → Atmospheric oscillation maxima $\Delta m^2_{31} L/4E \sim (2n+1)\pi/2$
- Well known muon neutrino beam → Possibility of spectral analysis, small electronic neutrino contamination
- Possibility to look at different oscillation channels

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

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

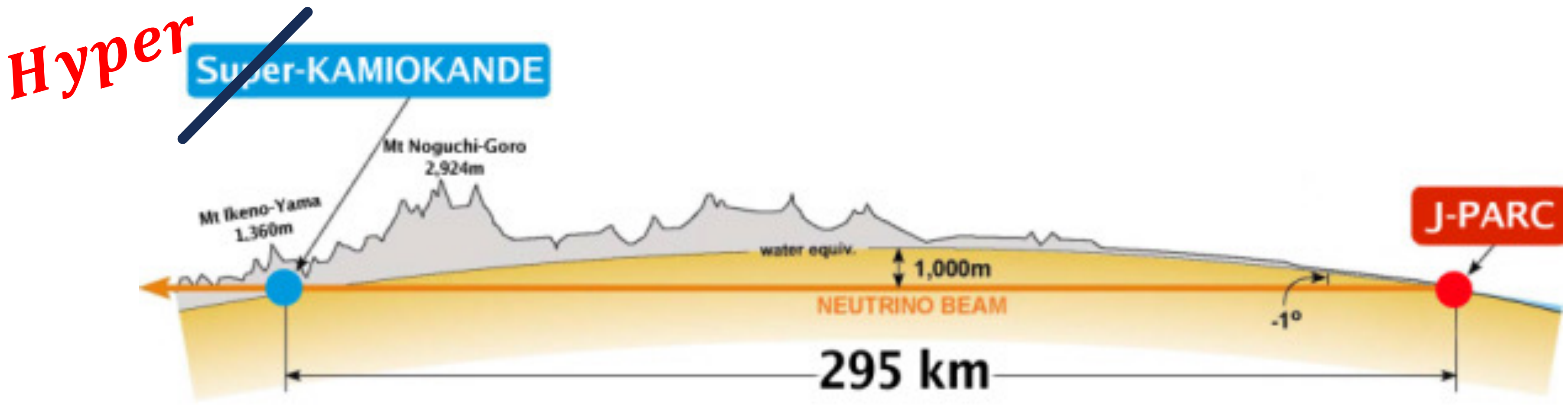
$\nu_\mu \to \nu_\tau$
BSM
$E_\nu > 3$ GeV

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>

HOW TO IDENTIFY DIFFERENT NEW NEUTRINO OSCILLATION PHYSICS SCENARIOS AT DUNE

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

PROPAGATION VECTOR NSI VS SCALAR NSI

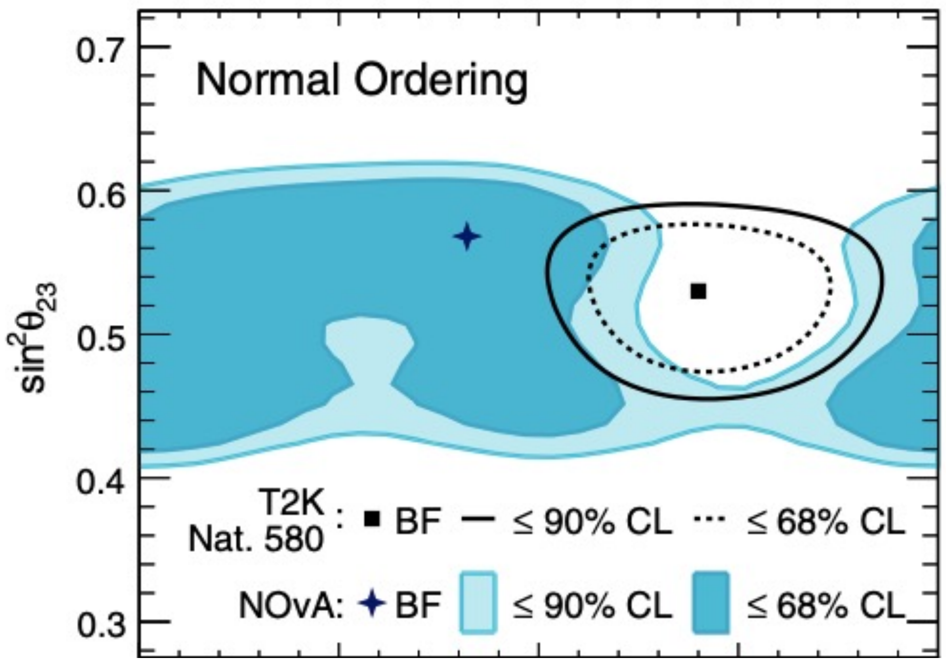
$$\mathcal{L}^{eff}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,\alpha,\beta} \varepsilon^f_{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\bar{f}\gamma^\rho f) \longrightarrow H = \frac{1}{2E}\left[UM^2U^\dagger + A\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu}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

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

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

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

REDUCING THE T2K-NOVA TENSION WITH NSI



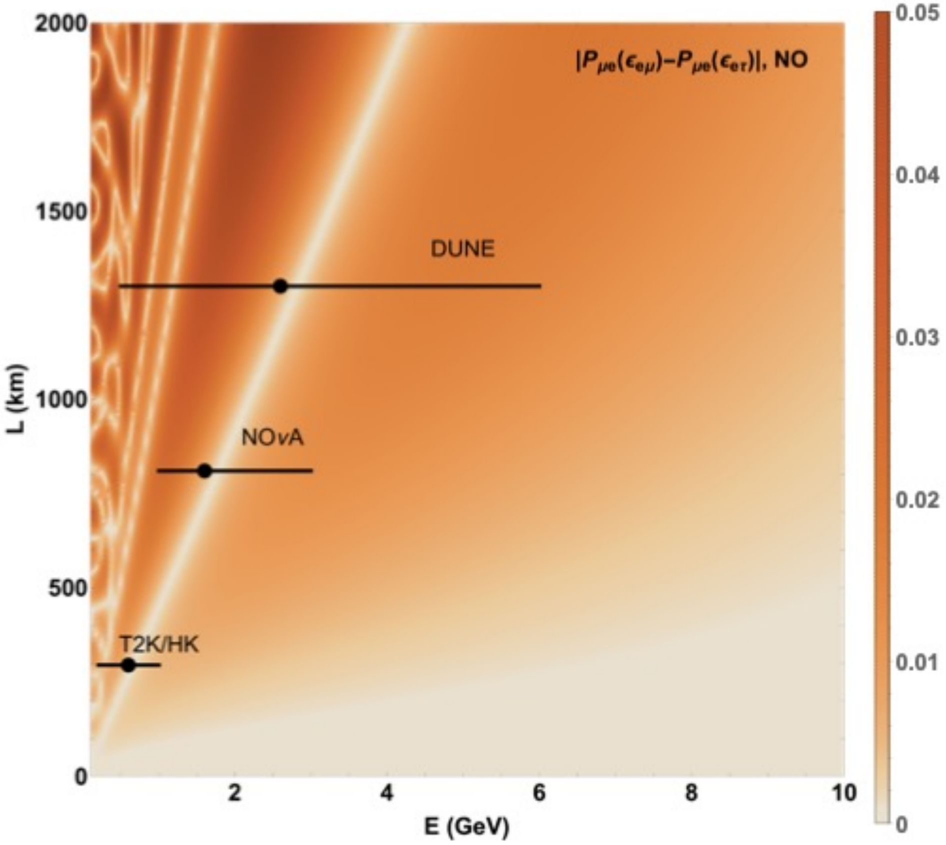
NOvA collab, PhysRevD.106.032004

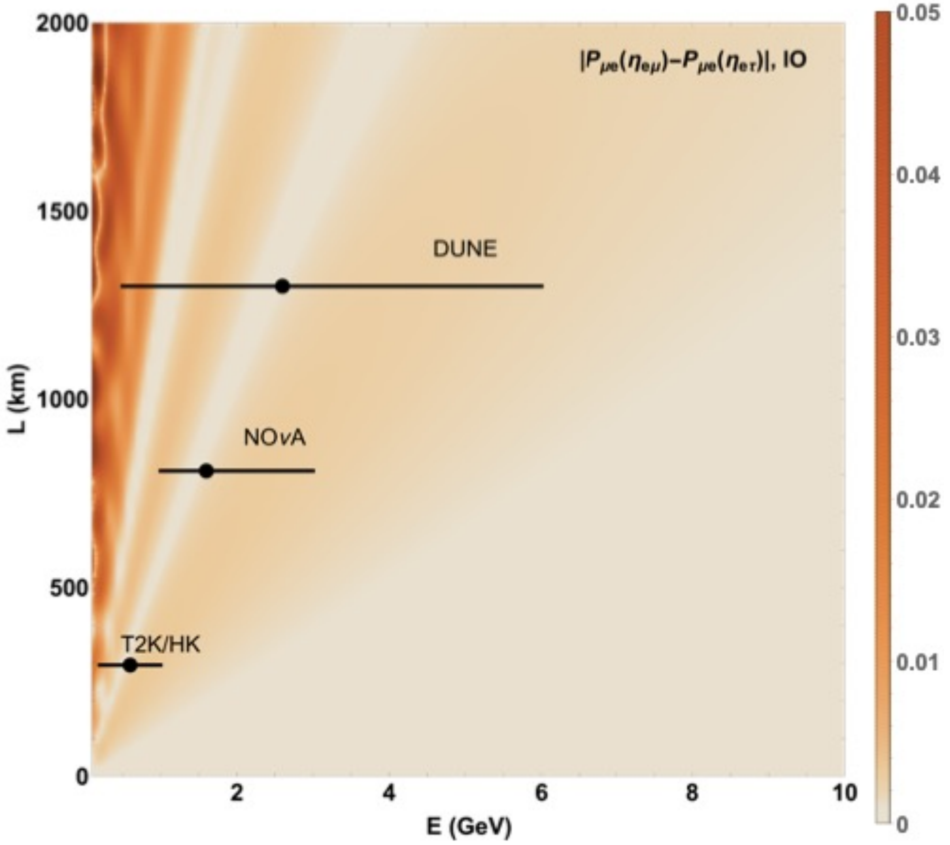
MO	NSI	$\lvert\varepsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	δ/π	$\Delta\chi^2$
NO	$\varepsilon_{e\mu}$	0.19	1.50	1.46	4.44
	$\varepsilon_{e\tau}$	0.28	1.60	1.46	3.65
	$\varepsilon_{\mu\tau}$	0.35	0.60	1.83	0.90
IO	$\varepsilon_{e\mu}$	0.04	1.50	1.52	0.23
	$\varepsilon_{e\tau}$	0.15	1.46	1.59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

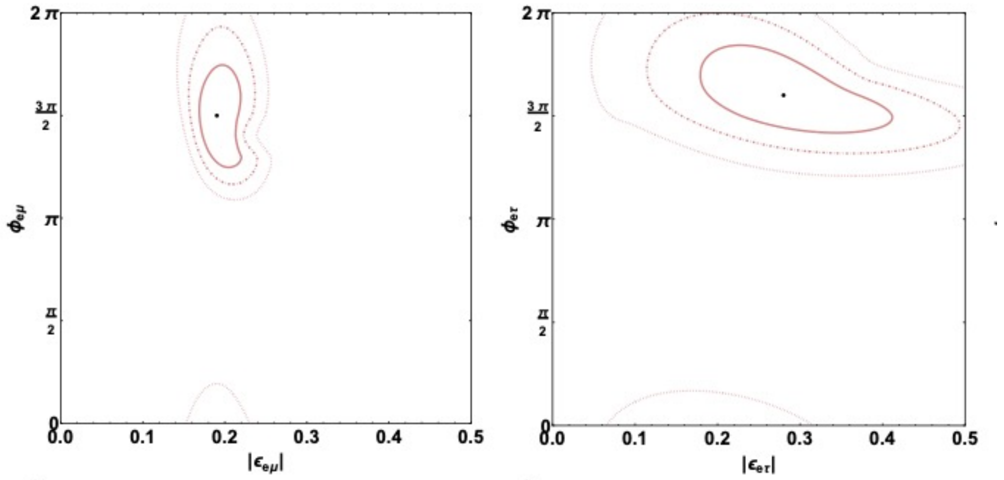




In DUNE conditions, at the probability level, the different benchmark models are different!

TESTING THE BEST FIT MODELS AT DUNE

Vector NSI in NO

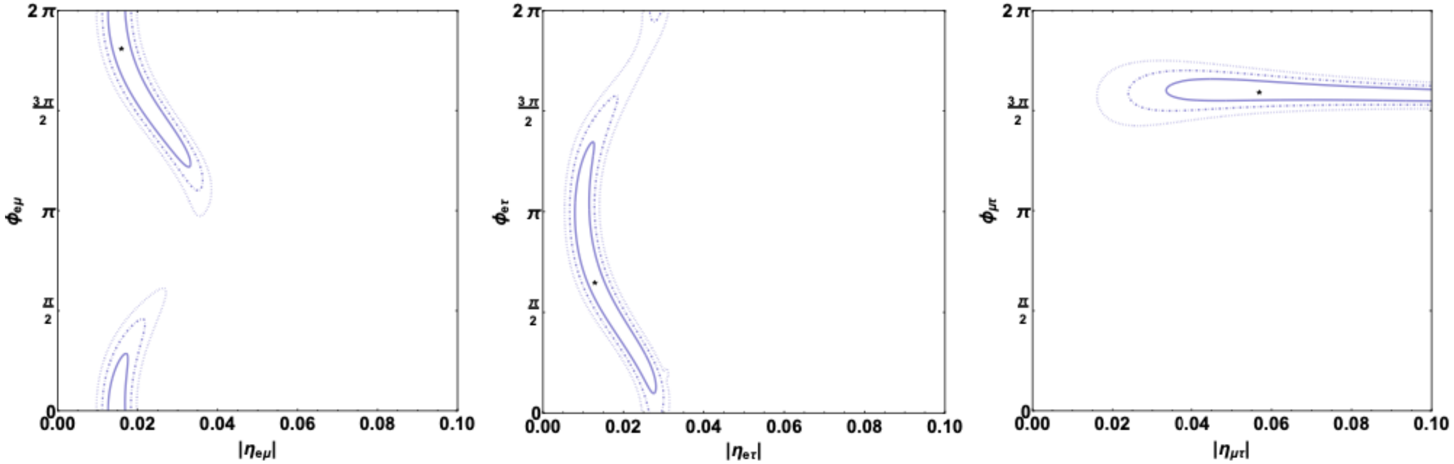


$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
$\varepsilon_{e\mu}$ NO	200	140	140	170	/	180	160	80
$\varepsilon_{e\tau}$ NO	60	48	50	45	50	/	50	40
$\varepsilon_{\mu\tau}$ NO	200	180	170	180	160	180	/	80
$\varepsilon_{e\mu}$ 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



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.

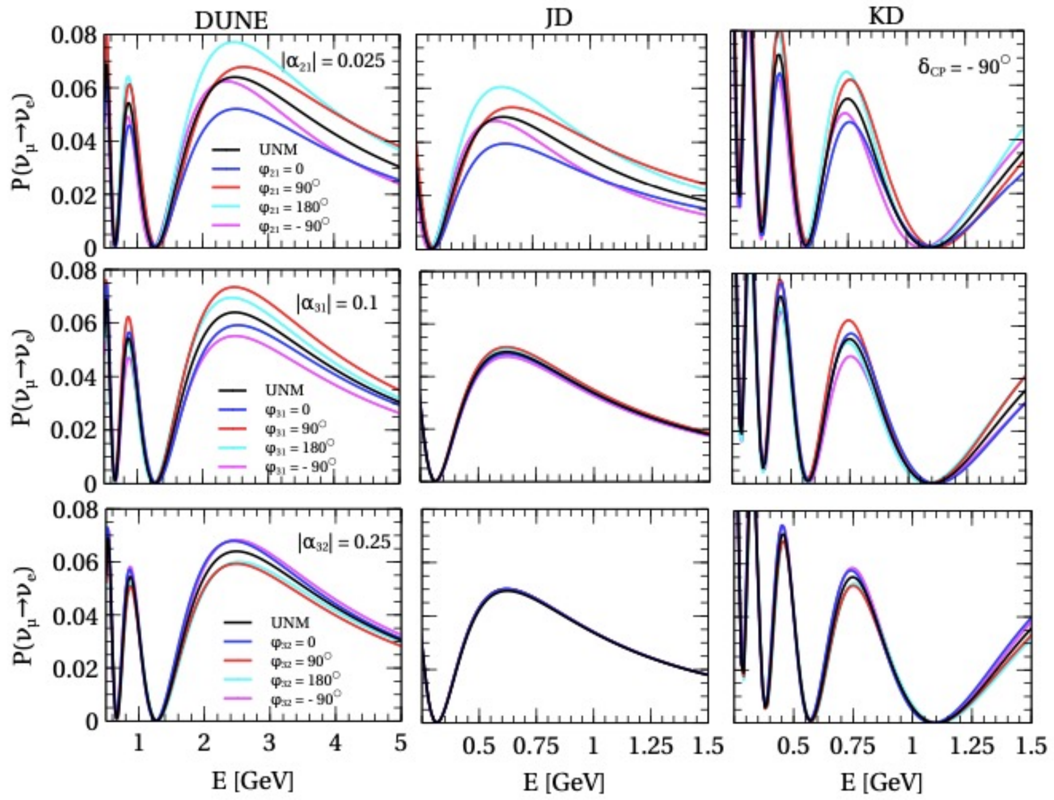
Thus, the PMNS matrix that we observe is only a submatrix of the complete one, losing its unitarity property.

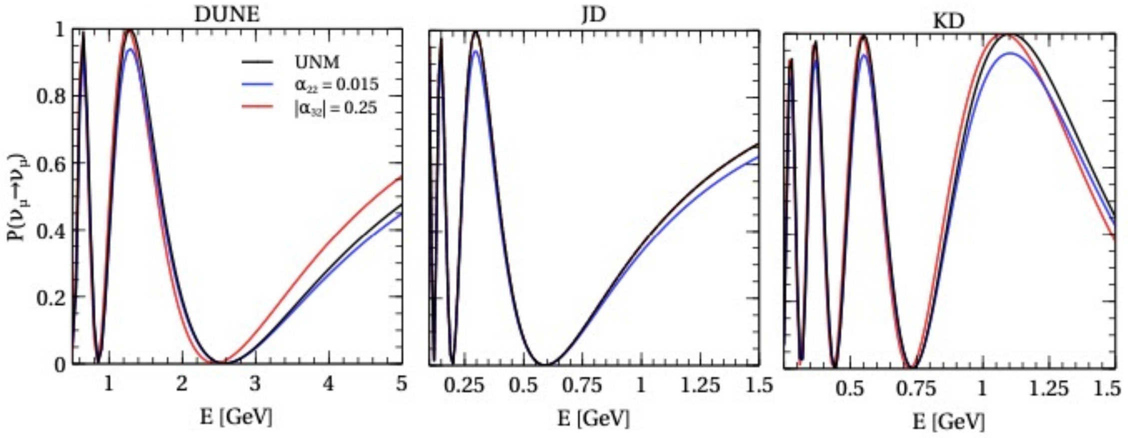
$$N = (1+\alpha)U_{PMNS}\,.$$

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

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

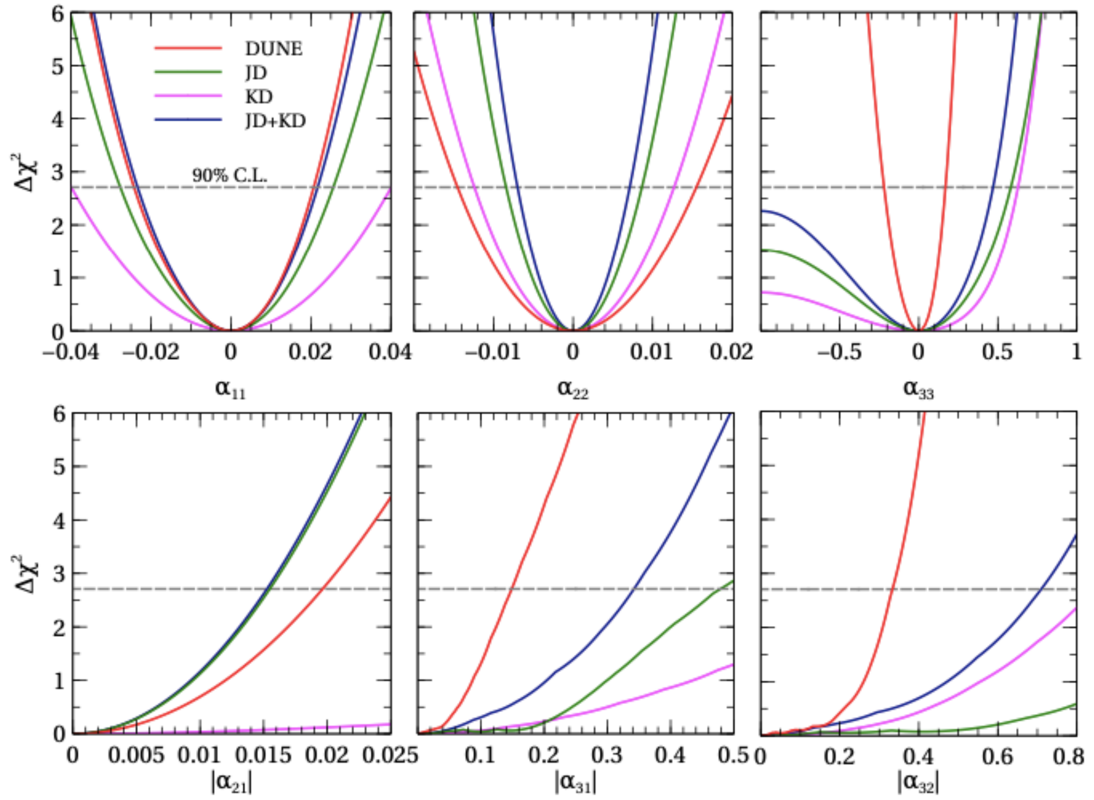
NON UNITARITY OF THE PMNS MATRIX





-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****.*

NEAR DETECTOR CONSTRAINTS

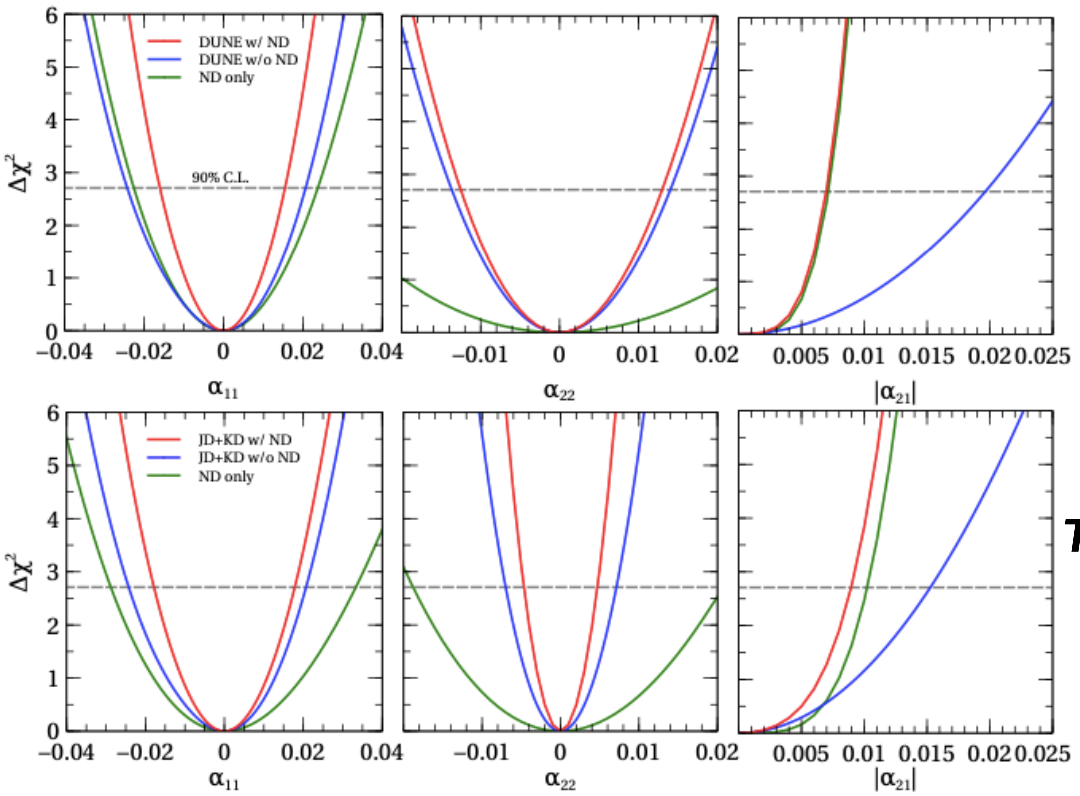
Systematic dominated

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

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

Statistic dominated

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



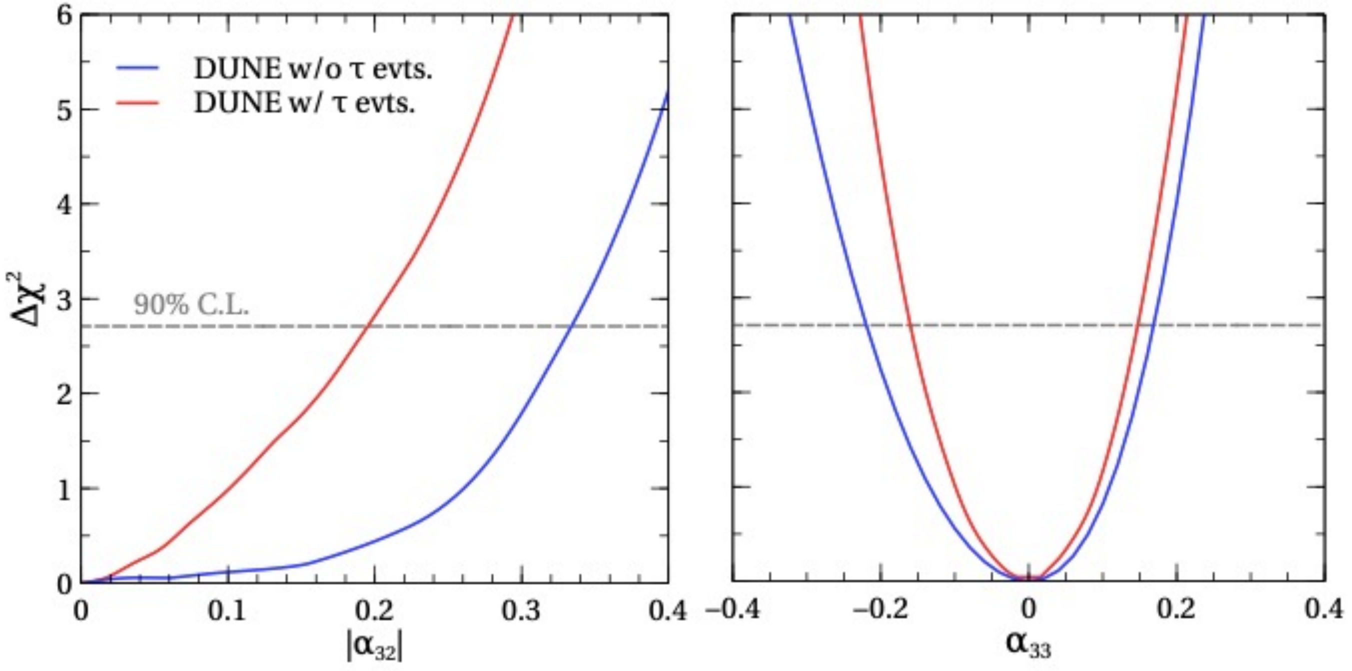
DUNE 50t LAr-TPC Near Detector (574 m)

T2HKK 1kt Cherenkov Near Detector (1 km)

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]
$\|\alpha_{32}\|$	< 0.33	< 0.19

ENHANCING SENSITIVITY TO LEPTONIC CP VIOLATION USING COMPLEMENTARITY AMONG DUNE, T2HK, AND T2HKK

AGARWALLA, DAS, GIARNETTI, MELONI, SINGH (2211.10620)

THE DISCOVERY OF THE PMNS MATRIX PHASE

The most unknown oscillation parameter so far is the CP-violating phase in the PMNS matrix.

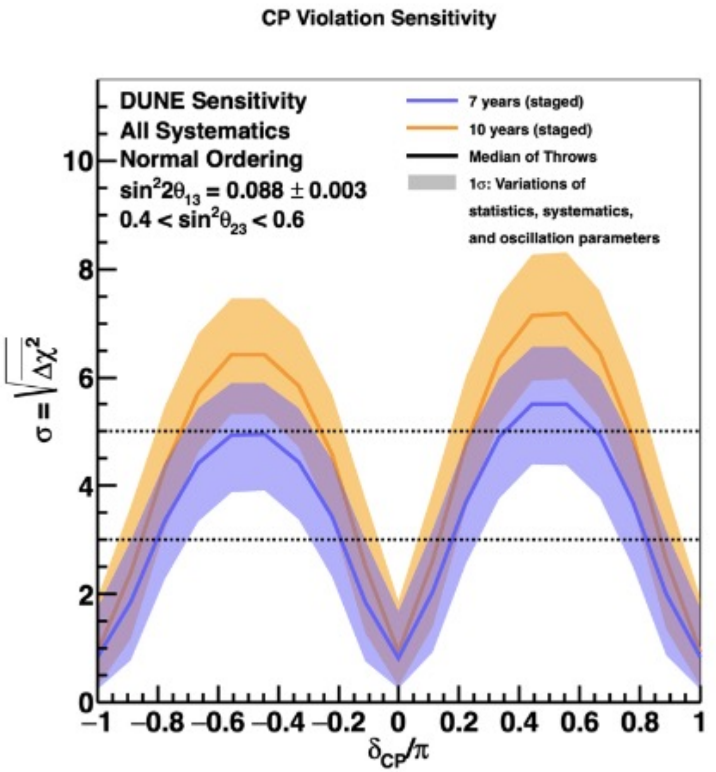
In the oscillation regimes available at neutrino experiments its effect is subleading.

It can be observed at high precision LBL experiments via electron-neutrino appearance, in which the leading term is rather small

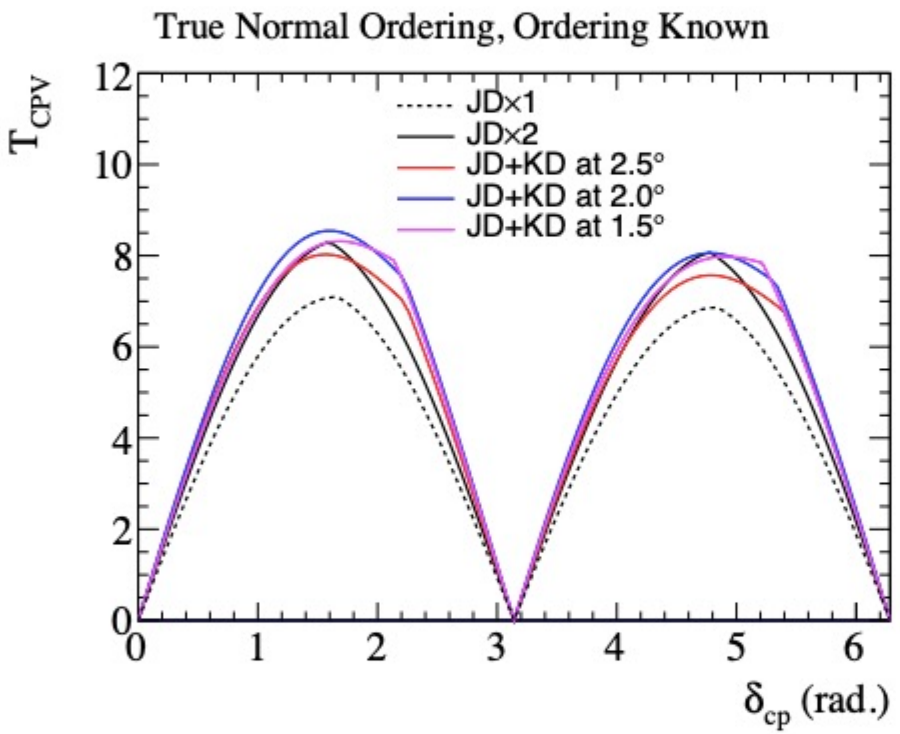
$$P_{\mu e} \sim \sin^2(2\theta_{13})\sin^2\theta_{23}\frac{\sin^2[(1-\hat{V})\Delta]}{(1-\hat{V})^2} + \\ -\alpha \underline{\sin\delta} \sin^2(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\sin\Delta\frac{\sin(\hat{V}\Delta)}{\hat{V}}\frac{\sin[(1-\hat{V})\Delta)}{1-\hat{V}} + \\ +\alpha \underline{\cos\delta} \sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\cos\Delta\frac{\sin(\hat{V}\Delta)}{\hat{V}}\frac{\sin[(1-\hat{V})\Delta)}{1-\hat{V}}$$

EXPECTED SENSITIVITY AT DUNE AND TH2K

DUNE



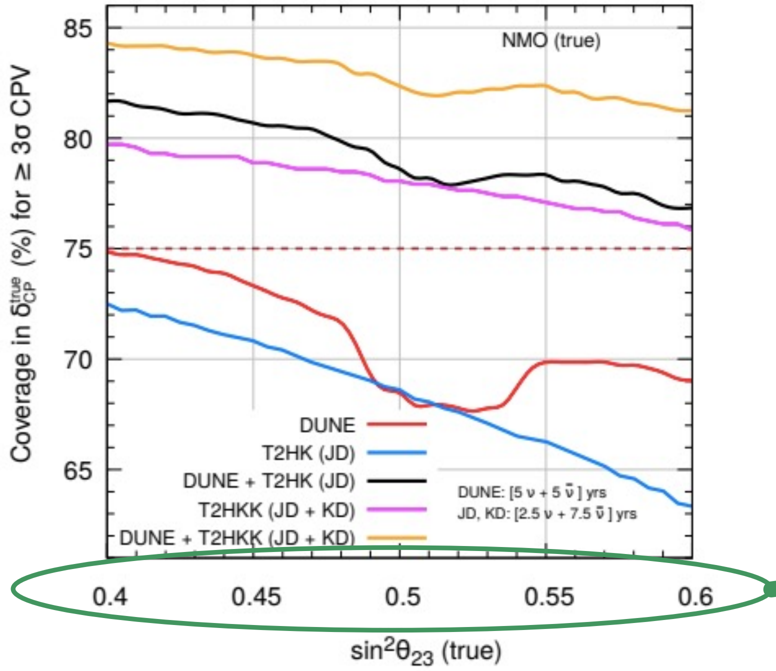
T2HK



THE 3σ COVERAGE

The 3σ coverage is defined as the fraction of true values of the CP-violating phase for which an experiment can reach at least 3σ sensitivity.

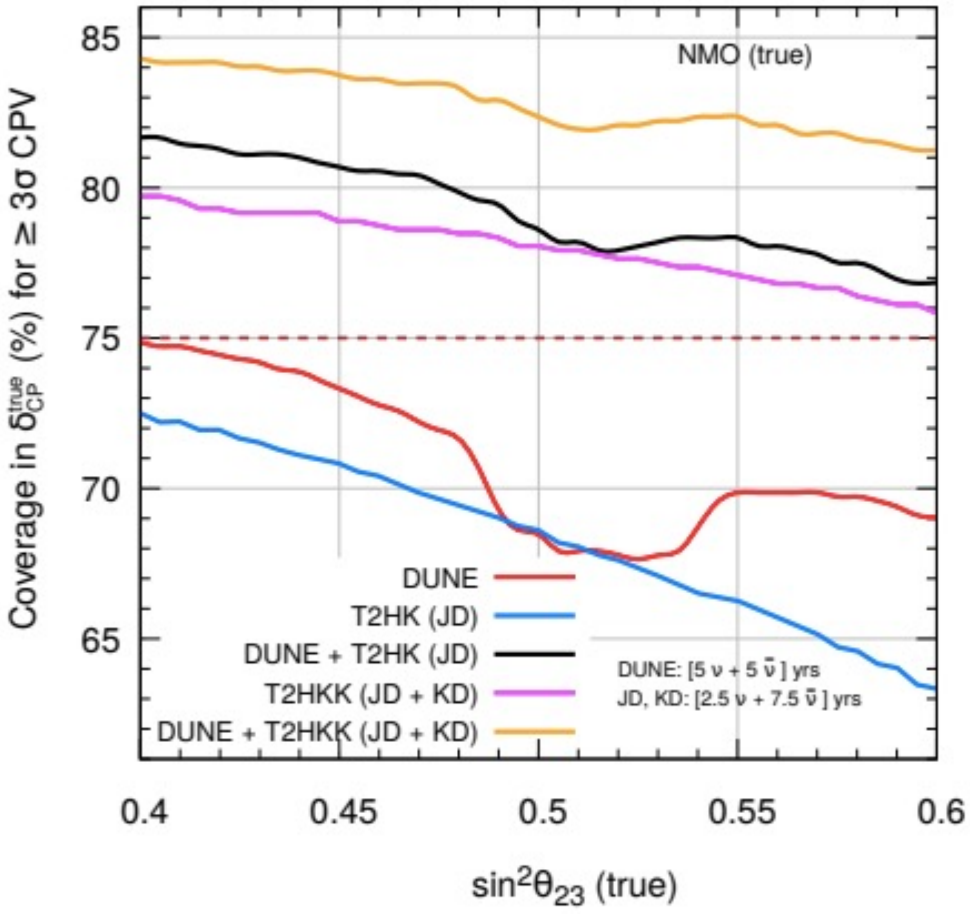
-PHYSICS GOAL FOR FUTURE LBL EXPERIMENTS: 75% COVERAGE



Large allowed range!

We study the impact of the atmospheric mixing angle on the CP coverage at DUNE, T2HK, T2HKK and their combination.

THE 3σ COVERAGE



Main results:

-Neither DUNE nor T2HK alone can reach 75%

-The combination of the two experiments is crucial

The coverage decreases for large mixing angles

Subleading effects are less visible at the electron neutrino appearance channel

The coverage decreases for DUNE around 45°

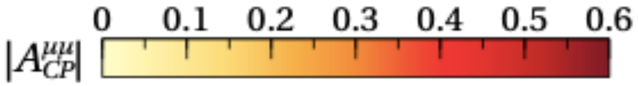
For these values the disappearance channel fails to measure the atmospheric mixing angle independently from the CP-phase

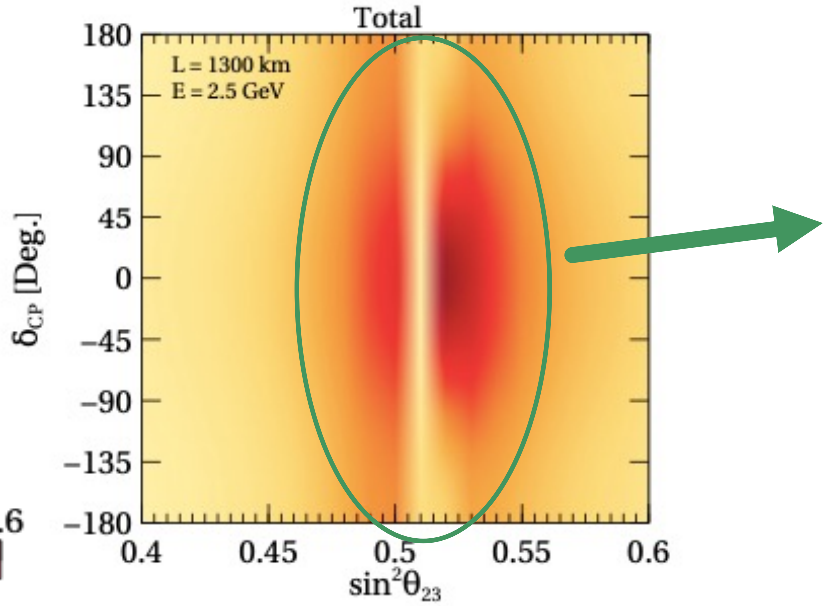
THE $\delta_{CP} - \theta_{23}$ DEGENERACY

It is well known that different couples of parameters $(\delta_{CP}, \theta_{23})$ can lead to the same oscillation probabilities in the electron neutrino and antineutrino appearance channel.

One way to break the degeneracy is to look also at the muon disappearance channel, from which the atmospheric mixing angle can be measured with a very good precision.

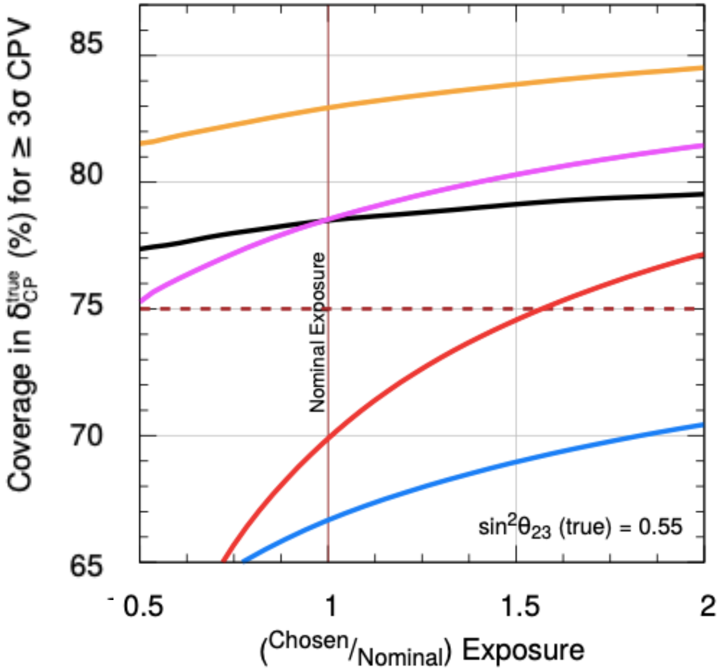
- However, in presence of matter effects:



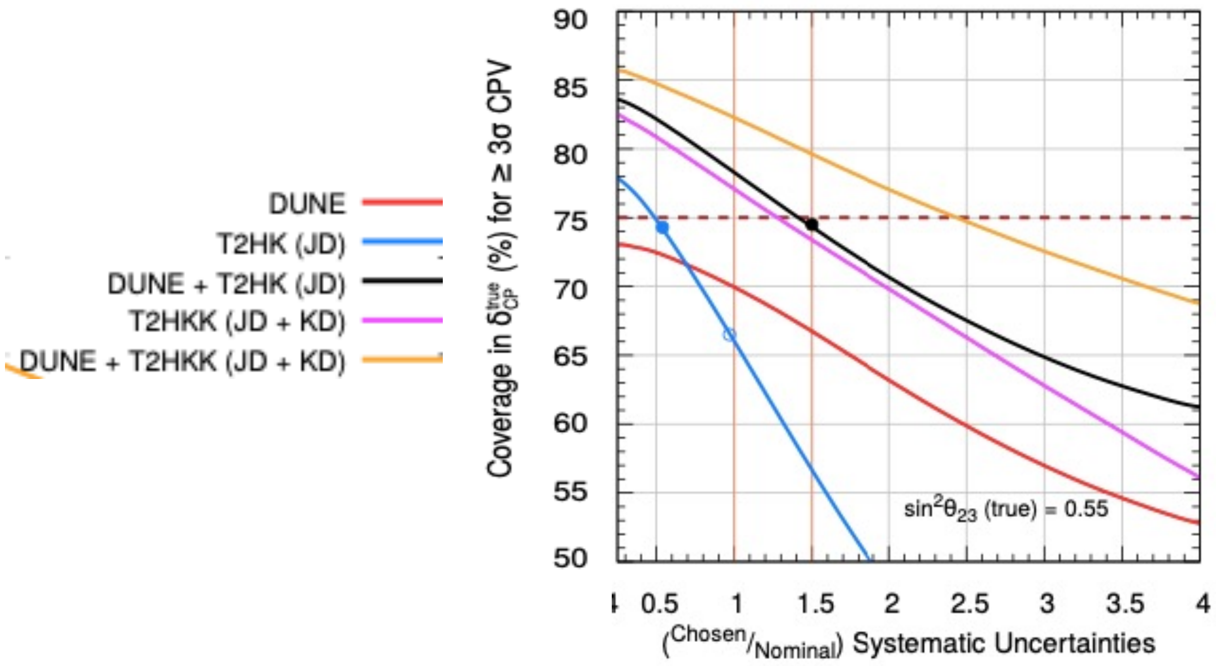


Around 45° the matter potential introduce a δ_{CP}-like effect which do not allow to measure θ_{23} with the required accuracy

THE POWER OF THE COMPLEMENTARITY



DUNE+T2HK can reach 75% coverage also with half exposure



DUNE+T2HK can reach 75% coverage also with increased systematic uncertainties

CONCLUSIONS

- We are now in the precision era for the measurements of neutrino oscillation parameters
- Future Long Baseline accelerator experiments will play the leading role in determining the last unknowns in the neutrino oscillation sector
- The search for BSM effects on the neutrino oscillation at future experiments is promising
- The development of new strategies to get the most from the future experiments datasets is extremely important

THANK YOU FOR YOUR ATTENTION

ESSENTIAL EXPERIMENTAL FEATURES

Characteristics	DUNE	JD/KD
Baseline (km)	1285	295 (1100)
ρ_{avg} (g/cm^3)	2.848	2.7 (2.8)
Beam	LBNF	J-PARC
Beam Type	wide-band, on-axis	narrow-band, 2.5° off-axis
Beam Power	1.2 MW	1.3 MW
Proton Energy	120 GeV	30 GeV
P.O.T./year	1.1×10^{21}	2.7×10^{22}
Flux peaks at (GeV)	2.5	0.6
1st (2nd) oscillation maxima for appearance channel (GeV)	2.6 (0.87)	0.6 (0.2) / 1.8 (0.6)
Detector mass (kt)	40, LArTPC	187 each, water Cherenkov
Runtime ($\nu + \bar{\nu}$) yrs	5 + 5	2.5 + 7.5
Exposure (kt·MW·yrs)	480	2431
Signal Norm. Error (App.)	2%	5%
Signal Norm. Error (Disapp.)	5%	3.5%