Prospects for Beyond the νStandard Model Physics in Long Baseline Neutrino Experiments

Brookhaven Forum 2021 (BF2021), Nov 3-5, 2021, virtual

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November 4, 2021

Outline

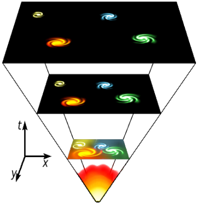
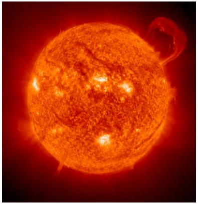
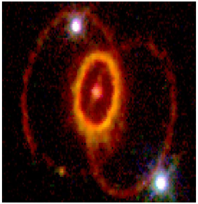
Introduction to Long Baseline Neutrino Experiments

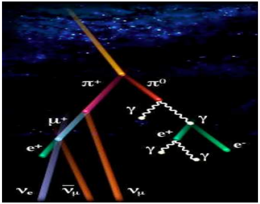
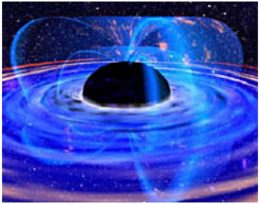
BSM and Neutrino Oscillations

Due to the very small masses and large mixing of neutrinos, their oscillations over a long distance act as an *exquisitely precise interferometer with high sensitivity to very small perturbations caused by new physics phenomena*, **for e.g.:**

- **Non-standard interactions in matter that manifest in long-baseline oscillations as deviations from the three-flavor mixing model**
- **Sterile neutrino states that mix with the three known active neutrino states**
- **New long-distance potentials arising from discrete symmetries that manifest as small perturbations on neutrino and antineutrino oscillations over a long baseline**
- **Large compactified extra dimensions from String Theory models that manifest through mixing between the Kaluza-Klein states and the three active neutrino states**
- **Non-unitarity of the 3-flavor mixing matrix due to BSM of unknown origin**

Sources of Neutrinos

Big Bang	Reactors	Sun	SuperNova
			
10^{-4} eV **56/cm^3**	**few MeV** 10^{21}/**GW$_{th}$/s**	**0.1-14 MeV** 10^{10}/**cm^2/s**	$\sim$ 10 **MeV** 10^9/**cm^2/s**

Atmosphere	Accelerators	Extragalactic
		
$\sim$ 1 **GeV** **few/cm^2/s**	**1-20 GeV** 10^6/**cm^2/s/MW (at 1km)**	**TeV-PeV** **varies**

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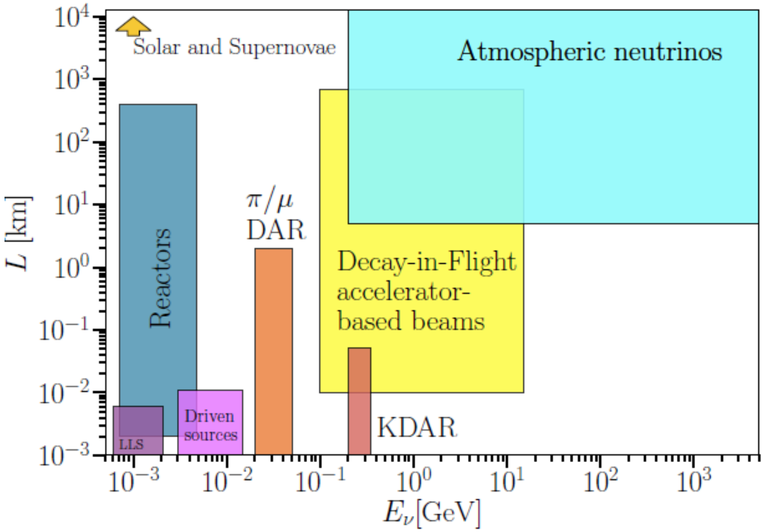
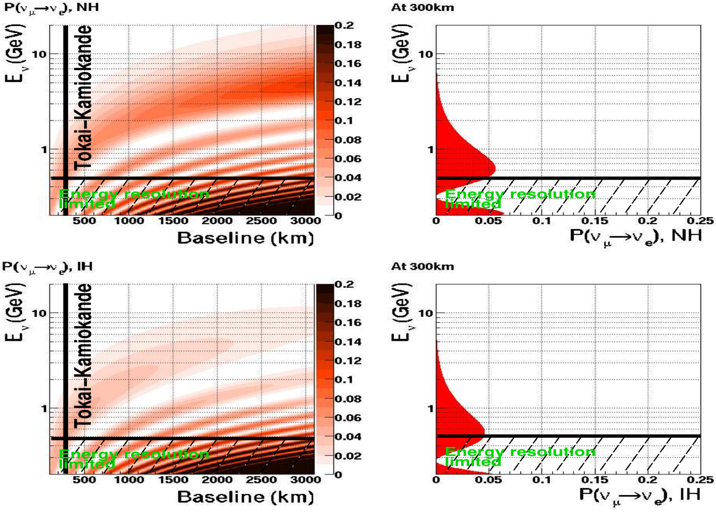
Sources of Neutrinos

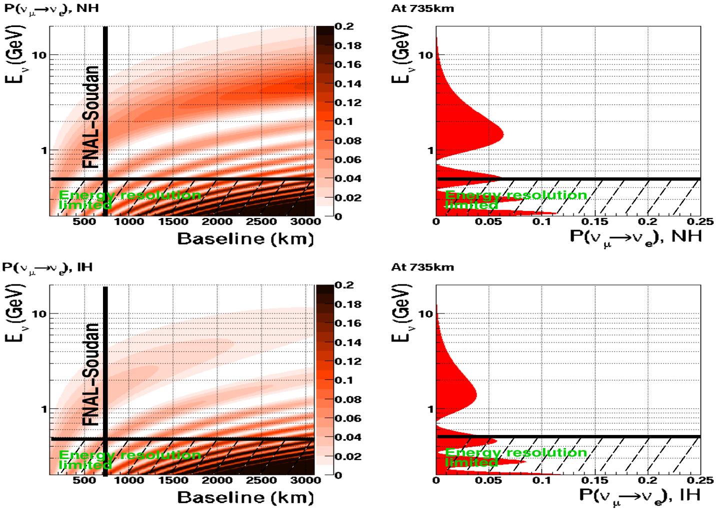


Oscillations of $\nu_\mu \to \nu_e$ at different baselines



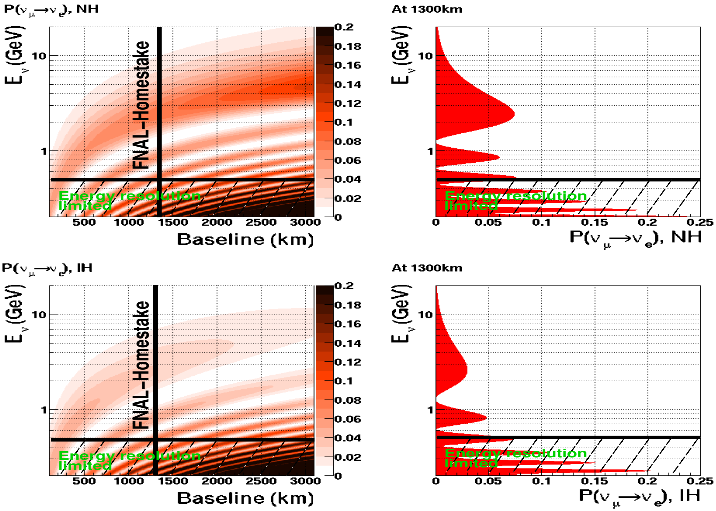
$P(\nu_\mu \to \nu_e)$ **maxima:** $E^n_\nu(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$ for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ **eV^2**

Oscillations of $\nu_\mu \rightarrow \nu_e$ at different baselines



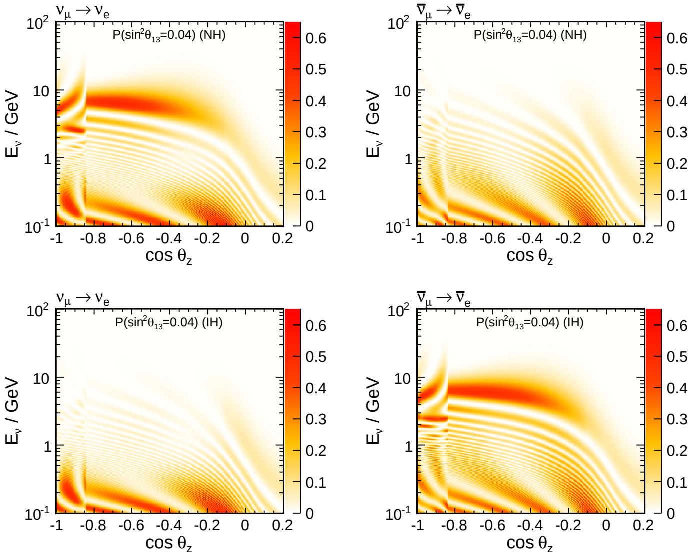
$P(\nu_\mu \rightarrow \nu_e)$ maxima: $E^n_\nu(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$ for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

Oscillations of $\nu_\mu \to \nu_e$ at different baselines



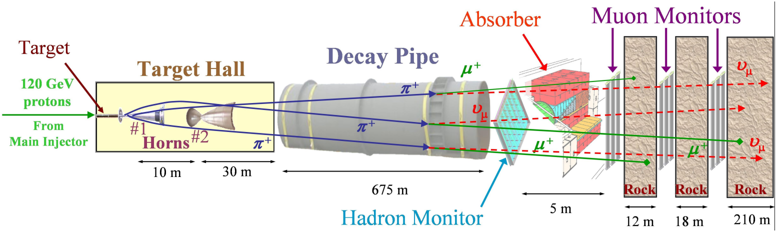
$P(\nu_\mu \to \nu_e)$ maxima: $E^n_\nu(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$ for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ **eV^2**

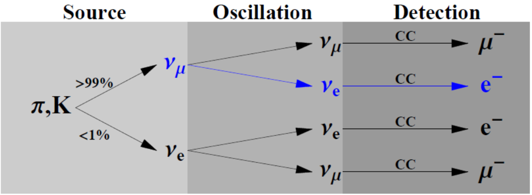
Atmospheric Neutrino Oscillations



Neutrinos from High Power Proton Sources

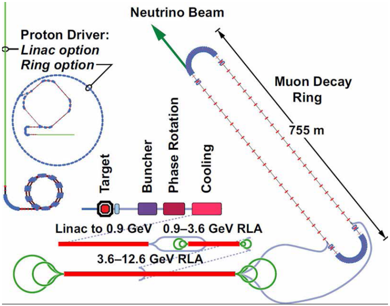
Conventional horn-focused neutrino beams (decay-in-flight):

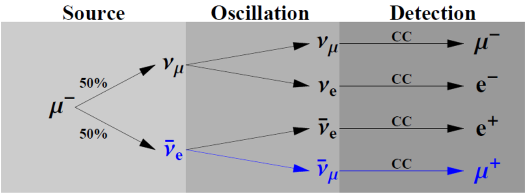




Neutrinos from High Power Proton Sources

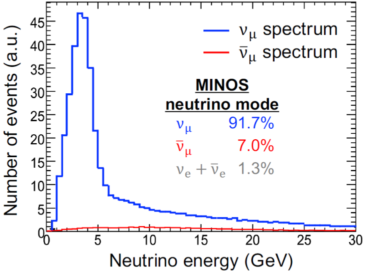
Muon Storage Rings:

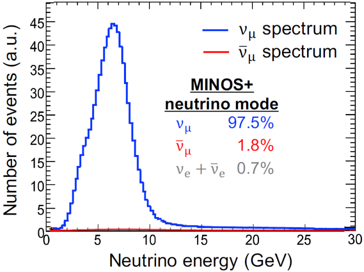




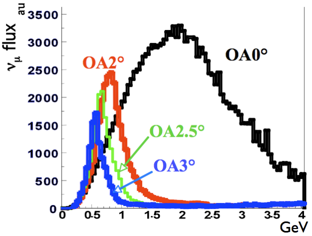
Accelerator Neutrino Beam Spectra/Fluxes

Broad-band beams: MINOS/MINOS+:





To get below 1 GeV from an π DIF accelerator source, go off-axis to a high energy proton beam - the JPARC beam for T2K (295 km baseline). This produces a narrow-band beam:



Neutrino CC Event Rates - Various Experiments

From arXiv:1307.7335, for 50 kton.years* of exposure:

Super Beams				
Experiment	**Baseline**	$\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$
T2K **30 GeV, 750 kW** 9×10^{20} **POT/year**	**295km (off-axis)**	**900**	< 1	**40 - 70**
MINOS LE **120 GeV, 700 kW** 6×10^{20} **POT/year**	**735km**	**11,000**	**115**	**230-340**
NOνA **120 GeV, 700 kW** 6×10^{20} **POT/year**	**810km (off-axis)**	**1500**	**10**	**120 - 200**
LBNE (LBNF) LE **80 GeV, 1.1MW** 1.5×10^{21} **POT/year**	**1,300km**	**4300**	**160**	**350 - 600**
LBNE (LBNF) ME **120 GeV, 1.2MW** 1.1×10^{21} **POT/year**	**1,300km**	**12,000**	**690**	**290 - 430**

ν Factory at Fermilab				
Experiment	**Baseline**	$\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_\mu$
NuMAX I **3 GeV, 1MW** 0.94×10^{20} μ**/year** **(no μ cooling)**	**1,300km**	**340**	**30**	**70 - 120**
NuMAX II **3 GeV, 3MW** 5.6×10^{20} μ**/year**	**1,300km**	**2000**	**300**	**420 - 700**

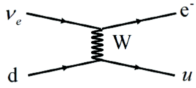
* **Facility duty factor taken into consideration**

Probing new physics beyond 3-flavor oscillations: Non Standard Interactions

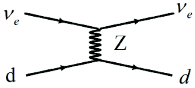
NSI in Long-Baseline Oscillations

see talk by I. Mocioiu

- In the Standard Model,



$$\mathcal{L}_{CC} = (\overline{\ell}_\alpha \gamma^\mu P_L \nu_\alpha)(\overline{f}\gamma_\mu P_L f')$$



$$\mathcal{L}_{NC} = (\overline{\nu}_\alpha \gamma^\mu P_L \nu_\alpha)(\overline{f}\gamma_\mu P_L f')$$

- With new physics, we could have

$$\mathcal{L}_{CC} = (\overline{\ell}_\alpha \gamma^\mu P_L \nu_\beta)(\overline{f}\gamma_\mu P_{L,R} f')$$

CC NSI
production, detection

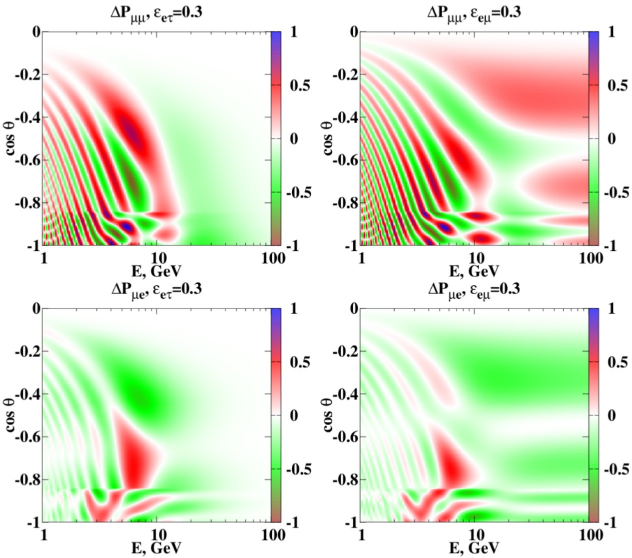
$$\mathcal{L}_{NC} = (\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\overline{f}\gamma_\mu P_{L,R} f')$$

NC NSI
propagation

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}$$

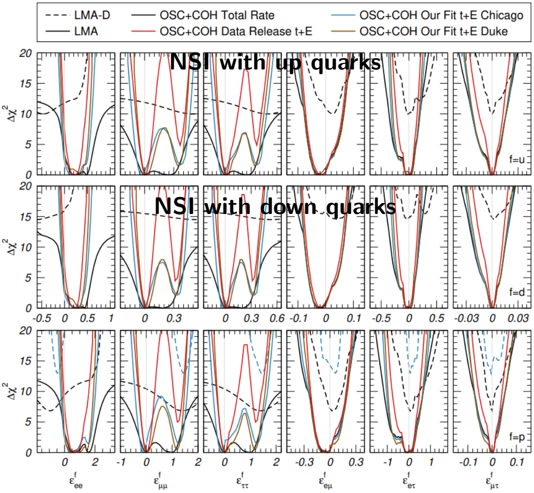
$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

NSI impact on Atmospheric Long Baseline



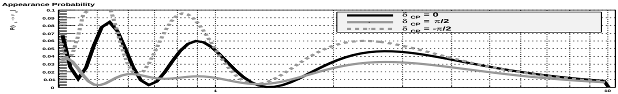
NSI limits from Current Experiments

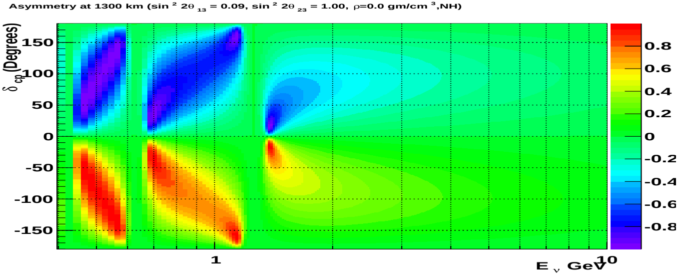
P. Coloma *et. al.* **JHEP 02 (2020) 023:**



CP Asymmetry vs E_ν and δ_{cp}

$$\mathcal{A} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

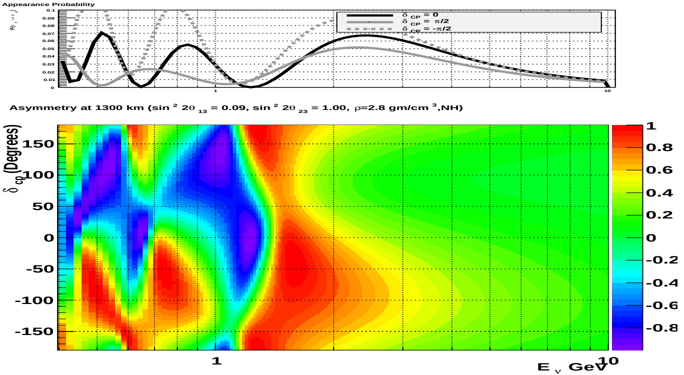




Asymmetries caused by CPV and matter are a complex phenomena

CP Asymmetry vs E_ν and δ_{cp}

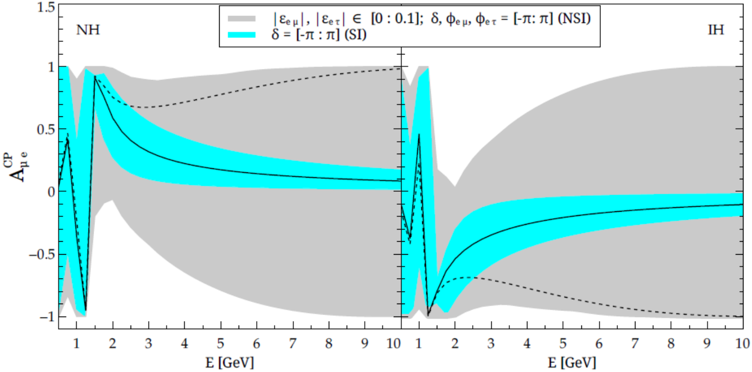
$$\mathcal{A} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$



Asymmetries caused by CPV and matter are a complex phenomena

Extricating NSI from 3-flavor Oscillations

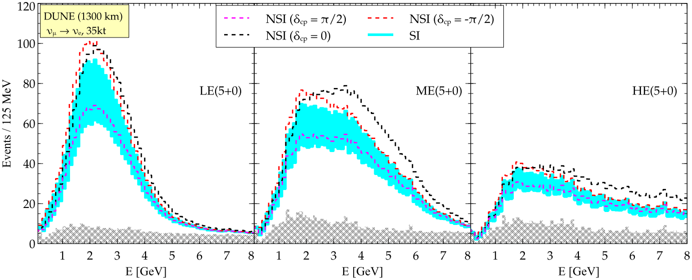
NSI could also impact interpretation of observed CP asymmetries in long-baseline:



(M. Masud, A. Chatterjee, P. Mehta arXiv:1510.08261)

Extricating NSI from 3-flavor Oscillations

Study NSI sensitivity with GLoBeS using $\nu_\mu \rightarrow \nu_{\mu,e}$ and 3 sample LBNF-like beam tunes : LE, ME and HE*.
NSI parameters used: $|\epsilon_{e\mu}| = 0.04$, $|\epsilon_{e\tau}| = 0.04$, $\epsilon_{ee} = 0.4$, $\phi_{e\mu=0}$, $\phi_{e\tau}$



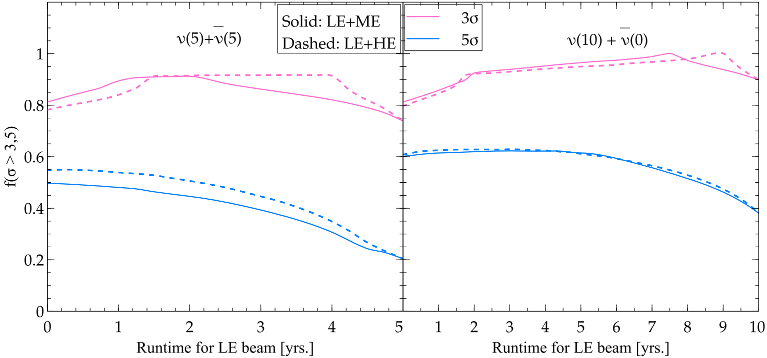
NSI effects in $\nu_\mu \rightarrow \nu_e$ are larger at higher energy

* **2 NuMI horns, 230kA, 6.6m apart and horns were not moved for higher energy beam tunes (non-optimal beams). Decay pipe was assumed to be 250m.**

M. Masud, M. Bishai and P. Mehta. Sci. Rep. 9 (2019) no.1, 352

Extricating NSI from 3-flavor Oscillations

Fraction of SI δ_{cp} for which SI/NSI can be separated at the $3/5\sigma$ level:



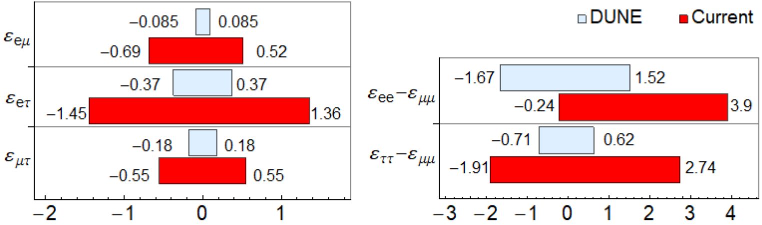
Can achieve 3σ separation for $> 80\%$ of true δ_{cp}

No beam optimization attempted yet!

M. Masud, M. Bishai and P. Mehta. Sci. Rep. 9 (2019) no.1, 352

Future NSI Constraints from LBL: DUNE

P. Abi *et. al.* **Eur. Phys. J. C (81) (2021):**

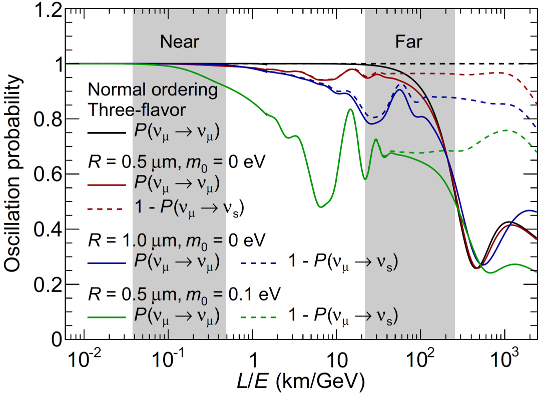


In LBL expts DUNE (default) has the best senstivity to NSI and T2HKK (with 2nd detector in Korea) has best sensitivity to CP phase in the presence of NSI. For comparison between DUNE, T2HK, T2HKK - check out JHEP 1701:071 (2017)

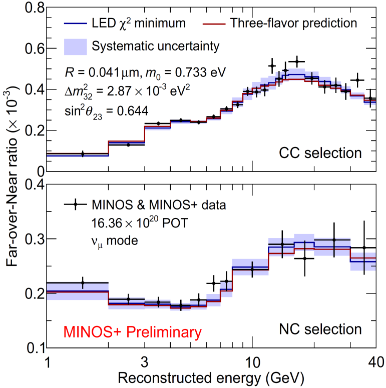
Search for Large Extra Dimensions with MINOS/MINOS+

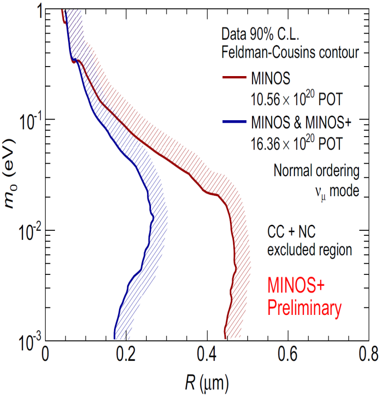
Large Extra Dimensions (LED) and ν_μ Disappearance

In some models of LED, sterile neutrinos arise as Kaluza-Klein states in an extra dimension compactified on a circle with radius R. Using the MINOS detector energy resolution the impact on the $\mathrm{P}(\nu_\mu \to \nu_\mu)$ oscillation probability for a given R and m_0 the mass of the lightest neutrino state:



Results from MINOS/MINOS+ search for LED



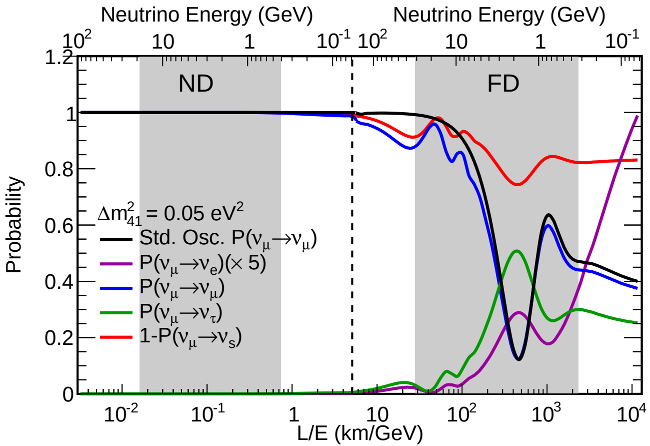


Wide-band beams, long baselines, high efficiency/purity ν_μ selection and combination of CC and NC channels start to constrain LED models.

Phys.Rev. D94 (2016) no.11, 111101

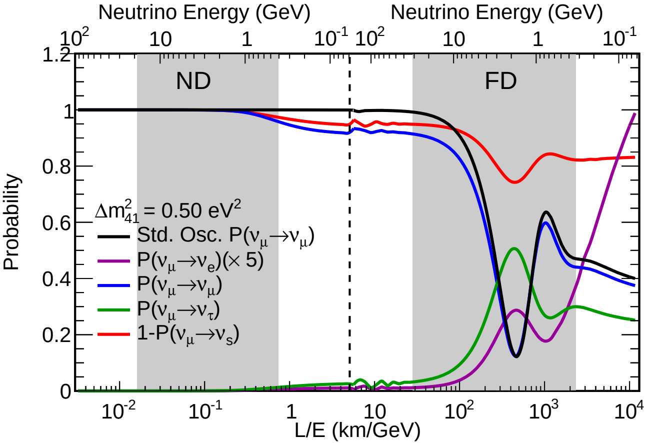
Probing new physics beyond 3-flavor oscillations: Sterile neutrinos

Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



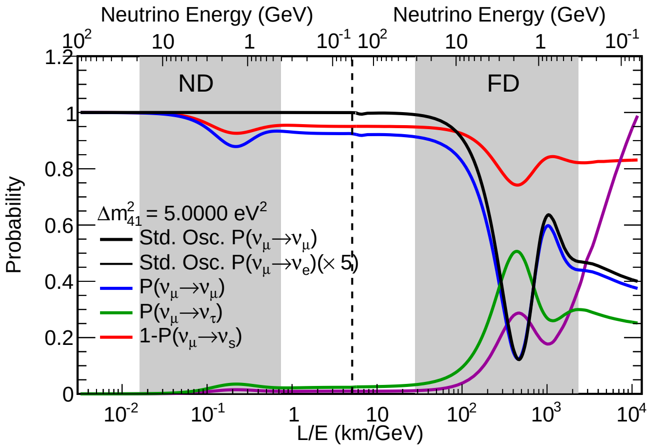
A. Sousa, U. Cinncinati

Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



A. Sousa, U. Cinncinati

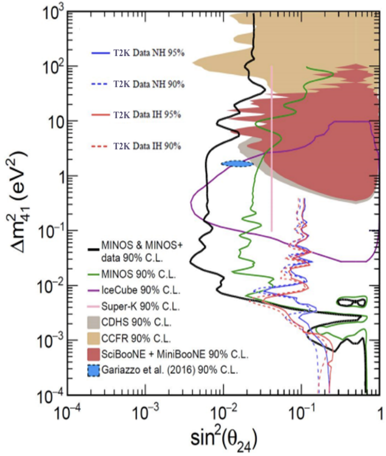
Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



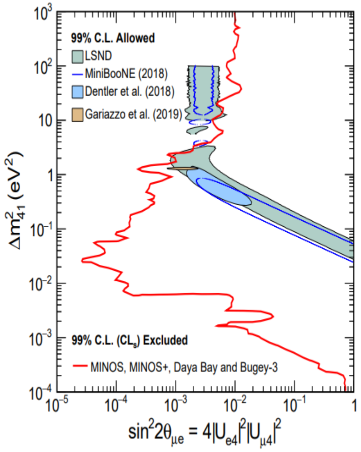
A. Sousa, U. Cinncinati

Sensitivities to 3+1 from SBL/LBL Appearance and Disappearance

Disappearance



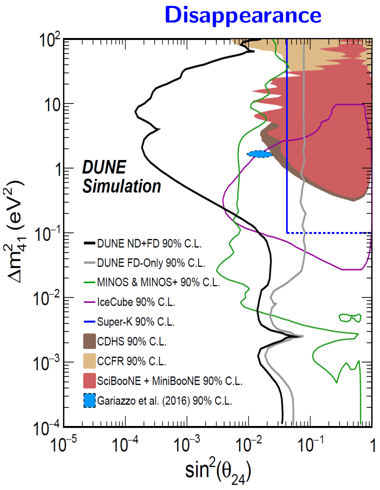
Appearance

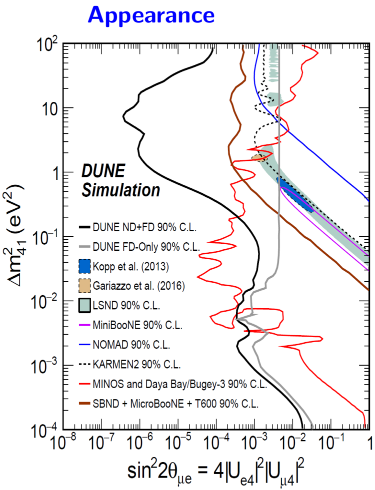


MicroBooNE result Oct 27,2021: MiniBooNE is not ν_e appearance

(see B. Fleming's talk)

Sensitivities to 3+1 from SBL/LBL Appearance and Disappearance





DUNE with CP optimized beam only

Probing new physics beyond 3-flavor oscillations: Lortentz and CPT Violation

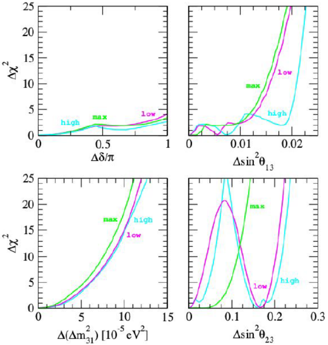
Probing CPT Violation ν_μ Disappareance

- $\mathrm{P}(\nu_\mu \to \nu_e) \neq \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow$ **CP Violation**
- $\mathrm{P}(\nu_\mu \to \nu_\mu) \neq \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu) \Rightarrow$ **CPT Violation**

DUNE sensitivity to neutrino-antineutrino parameters difference

$$\begin{aligned}
|\Delta m_{21}^2 - \Delta \overline{m}_{21}^2| &< 4.7 \times 10^{-5}\,\mathrm{eV}^2,\\
|\Delta m_{31}^2 - \Delta \overline{m}_{31}^2| &< 3.7 \times 10^{-4}\,\mathrm{eV}^2,\\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14,\\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.03,\\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.32.
\end{aligned}$$

parameter	value
Δm_{21}^2	$7.56 \times 10^{-5}\mathrm{eV}^2$
Δm_{31}^2	$2.55 \times 10^{-3}\mathrm{eV}^2$
$\sin^2\theta_{12}$	0.321
$\sin^2\theta_{23}$	0.43, 0.50, 0.60
$\sin^2\theta_{13}$	0.02155
δ	1.50π

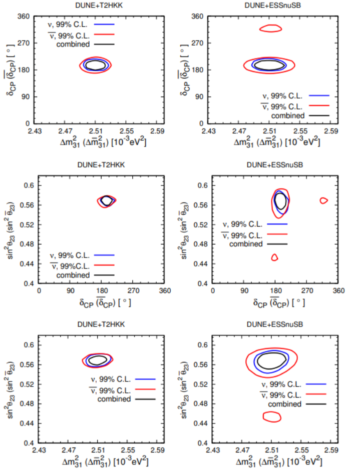


Combined Limits on Oscillation Parameters with Future LBL Experiments

Future LBL expt *including* upgrades

Experiment	T2HK	T2HKK	ESSnuSB	DUNE
Baseline	295 km	295 km; 1100 km	540 km	1300 km
Fiducial Volume	374 kt	187 kt (@ 295 km) + 187 kt (@ 1100km)	500 kt	40 kt
Normalisation uncertainty				
ν_e signal (bkg)	3.2% (5%)	3.8% (5%)	3.2% (5%)	2% (5%)
$\bar{\nu}_e$ signal (bkg)	3.9% (5%)	4.1% (5%)	3.9% (5%)	2% (5%)
ν_μ signal (bkg)	3.6% (5%)	3.8% (5%)	3.6% (5%)	5% (5%)
$\bar{\nu}_\mu$ signal (bkg)	3.6% (5%)	3.8% (5%)	3.6% (5%)	5% (5%)

Can get to % level precision with accelerator based expts with upgrades to push statistical uncertainties to be comparable/less than systematics but difficult to get precision beyond that.



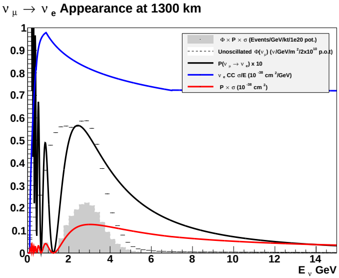
Phys.Rev.D 104 (2021) 5, 055002

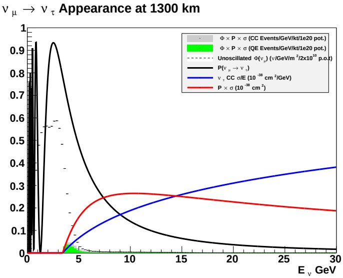
Probing new physics beyond 3-flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$

Higher ν Energy Beam Tunes with DUNE (M. Bishai proposal)

NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \to \nu_\tau$ with high statistics.

2015 two horn optimized design $E_p = 66$ GeV:



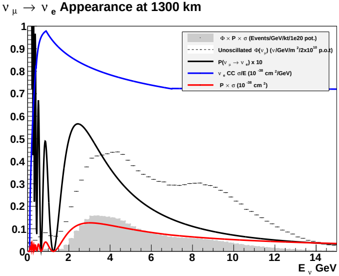


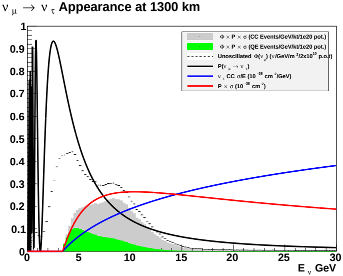
$\nu_\mu \to \nu_e$ **290 events** ν_μ rightarrowν_τ **60 events**
in 40 ktons, 1 year at 1.2 MW

Higher ν Energy Beam Tunes with DUNE (M. Bishai proposal)

NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \to \nu_\tau$ with high statistics.

LBNF target -2m from horn 1, NuMI focusing 230 kA, horns 17m apart





$\nu_\mu \to \nu_e$ 330 events   **$\nu_\mu \to \nu_\tau$ 700 events**

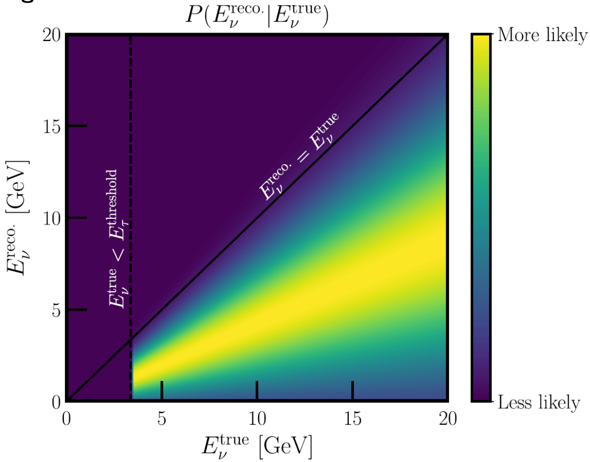
in 40 ktons, 1 year at 1.2 MW

Increase ν_τ appearance 10x!!!

Increase high energy ν_e appearance - good for NSI/Sterile searches

The Trouble with Taus

Using ν_τ appearance for precision oscillation measurements is difficult. For ν_τ CC interactions where the τ decays hadronically there is a lot of smearing:

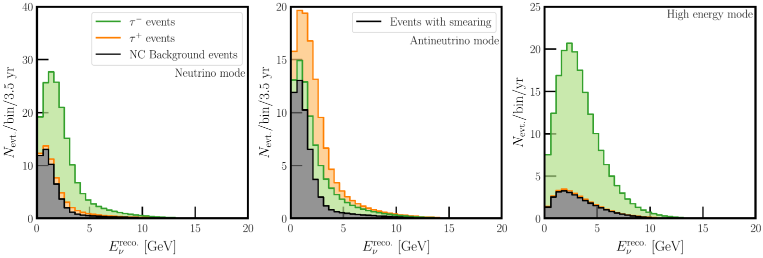


Phys. Rev. D. 100, 016004 (2019)

ν_τ Appearance Measurements in DUNE

Using some optimistic assumptions about ν_τ CC events in DUNE with τ hadronic decays a possible signal in 3.5 yrs running in CPV optimized beam and 1 yr in HE beam:

Appearance spectra



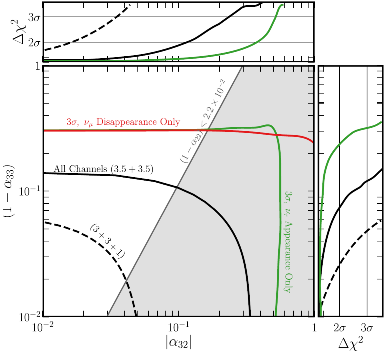
Phys. Rev. D. 100, 016004 (2019)

Simple Unitarity Tests with ν_τ Appearance in DUNE

Run in 3.5 (ν) +3.5 ($\bar{\nu}$) years with ν_μ disappearance, ν_e appearance and ν_τ appearance in the default low-energy beam or combine all 3 modes with 3+3 years in LE + 1 year in HE beam:

U: Unitary matrix, N: non-unitary matrix

$$U \rightarrow NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$



Phys. Rev. D. 100, 016004 (2019)

See also talk by Julia Gehrlein: Wed Nov 3 1:30pm

Summary

Summary

- **Long-baseline experiments are entering an era of precision oscillation measurements with most 3-flavor oscillation parameters - like the mixing angles and mass differences - now measured at the few % level of precision.**
- **This opens up a new frontier of using precision oscillation measurements to search for physics beyond the Standard Model and beyond the 3-flavor ν model.**
- **Long-baseline oscillation experiments using high purity well known neutrino sources from accelerators are particularly sensitive to NC NSI, new interactions in matter, compactified large extra dimensions and low mass sterile neutrinos.**
- **Future LBL experiments like DUNE are also opening up a new frontier of new physics searches using ν_τ appearance. This promises tighter constraints on unitarity tests.**