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

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Outline

Introduction to Long Baseline Neutrino Experiments

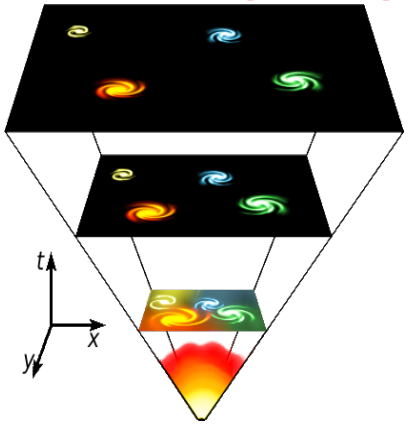
BSM and Neutrino Oscillations

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

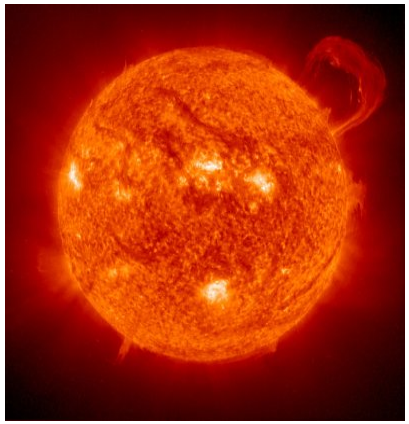


10^{-4} eV
$56/\mathrm{cm}^3$

Reactors

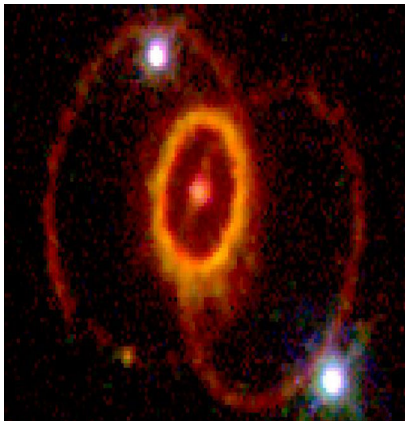
few MeV
$10^{21}/\mathrm{GW_{th}}/\mathrm{s}$

Sun



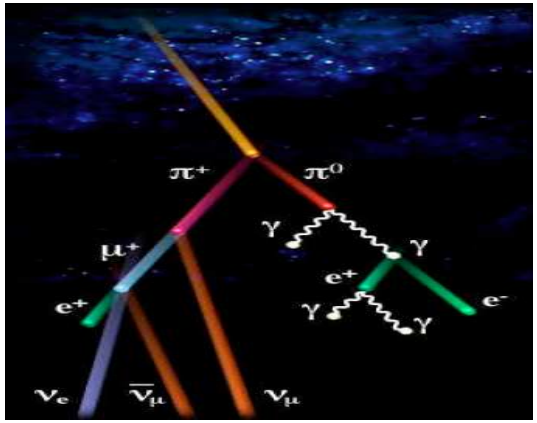
0.1-14 MeV
$10^{10}/\mathrm{cm}^2/\mathrm{s}$

SuperNova



$\sim$ 10 MeV
$10^9/\mathrm{cm}^2/\mathrm{s}$

Atmosphere



$\sim$ 1 GeV
few/cm^2/s

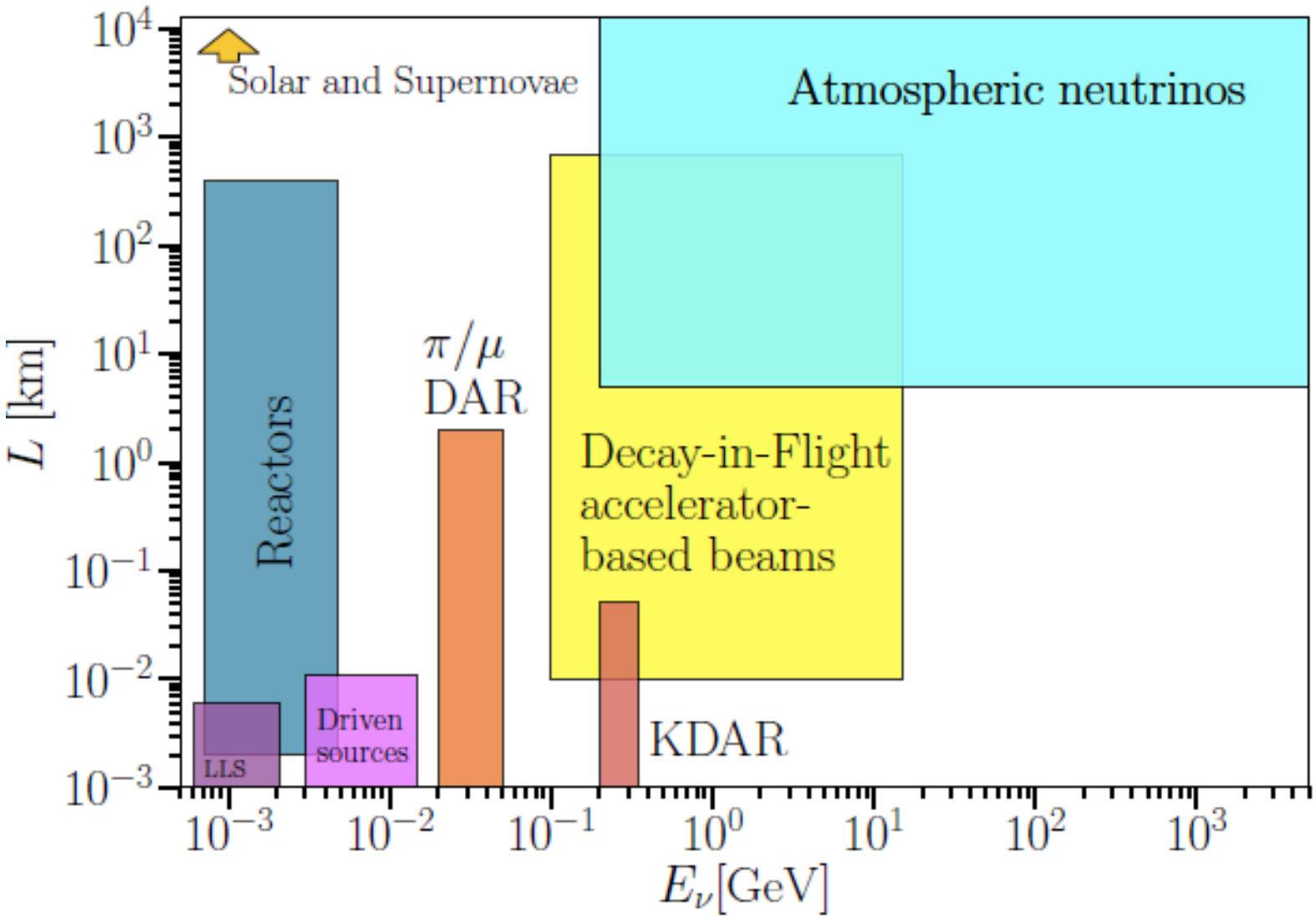
Accelerators

1-20 GeV
$10^6/\mathrm{cm}^2/\mathrm{s}/\mathrm{MW}$ (at 1km)

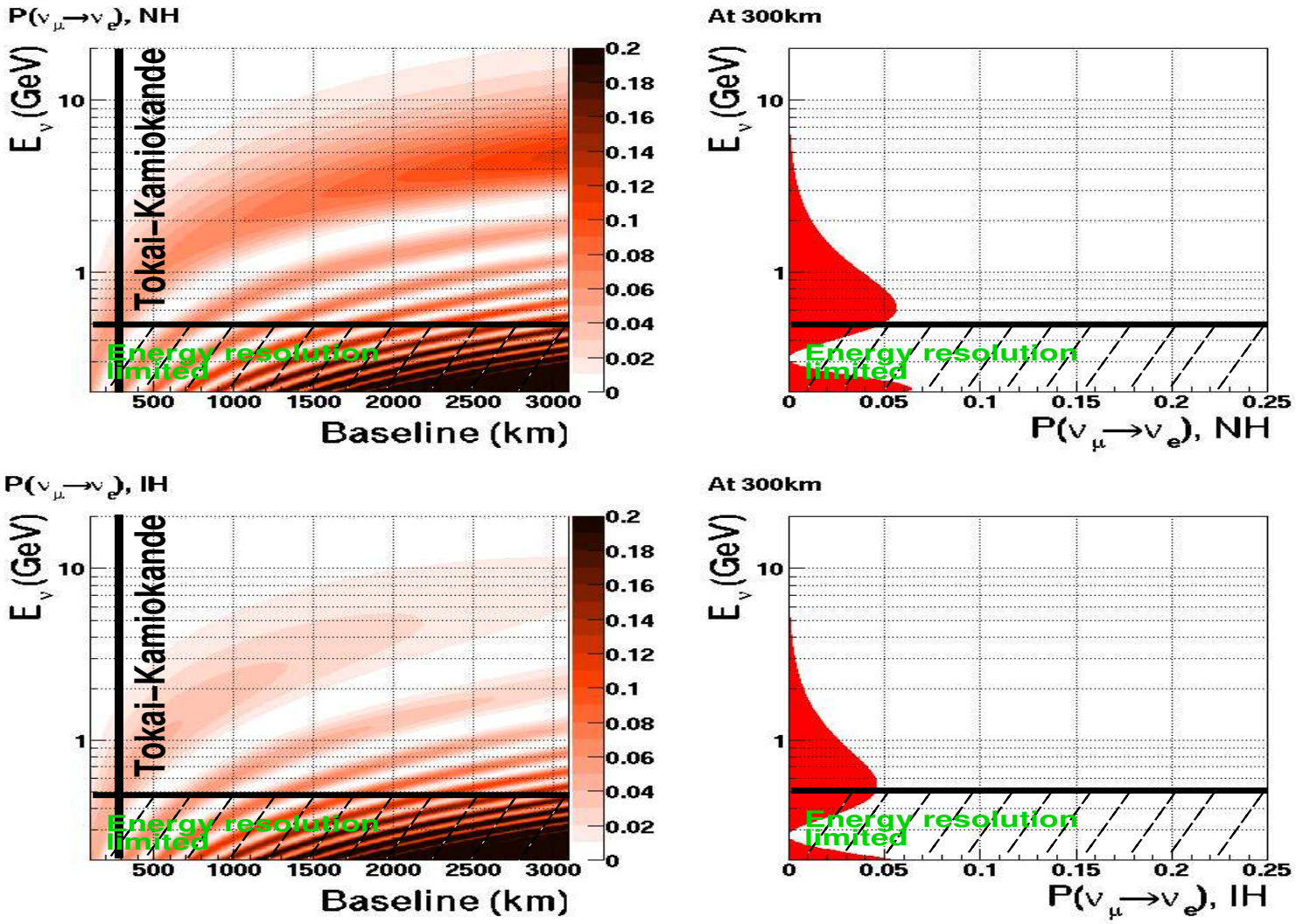
Extragalactic

TeV-PeV
varies

Sources of Neutrinos



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



$P(\nu_\mu \rightarrow \nu_e)$ maxima: $E_\nu^n(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$

for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

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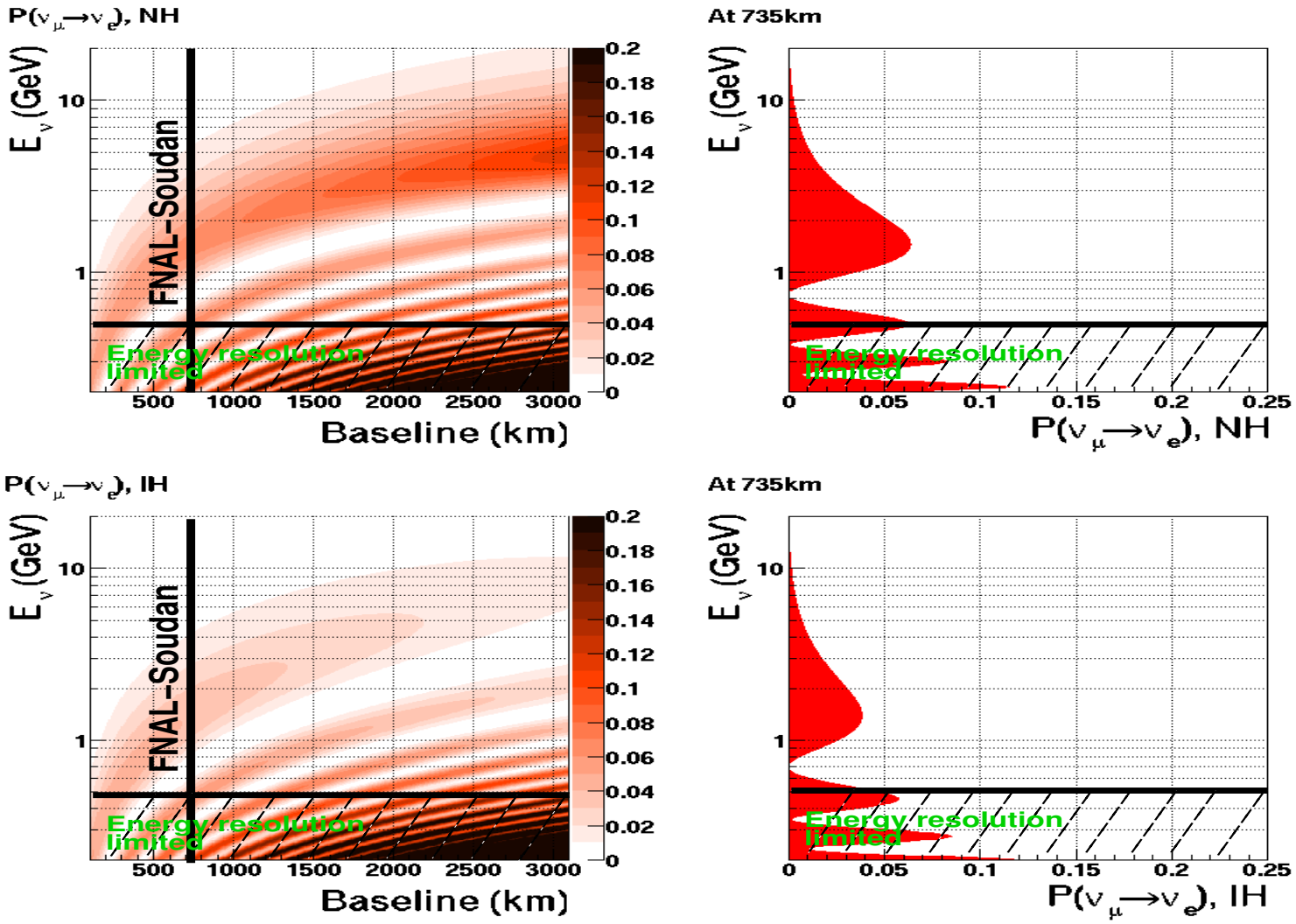
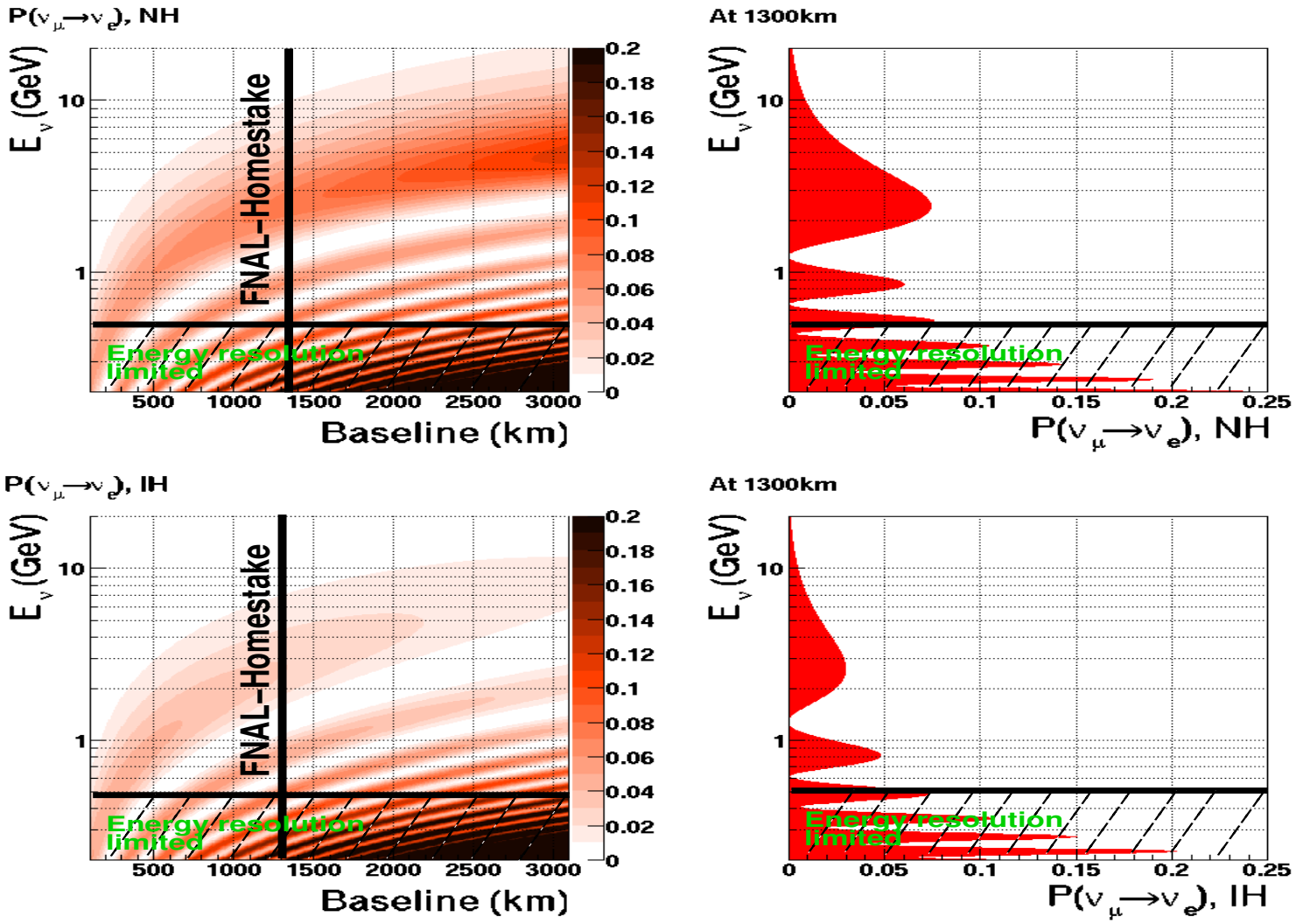


$\mathbf{P(\nu_\mu \rightarrow \nu_e)}$ **maxima:** $\mathbf{E^n_\nu(GeV) \sim Baseline(km)/(515 \times (2n-1))}$

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: $E^n_\nu(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$

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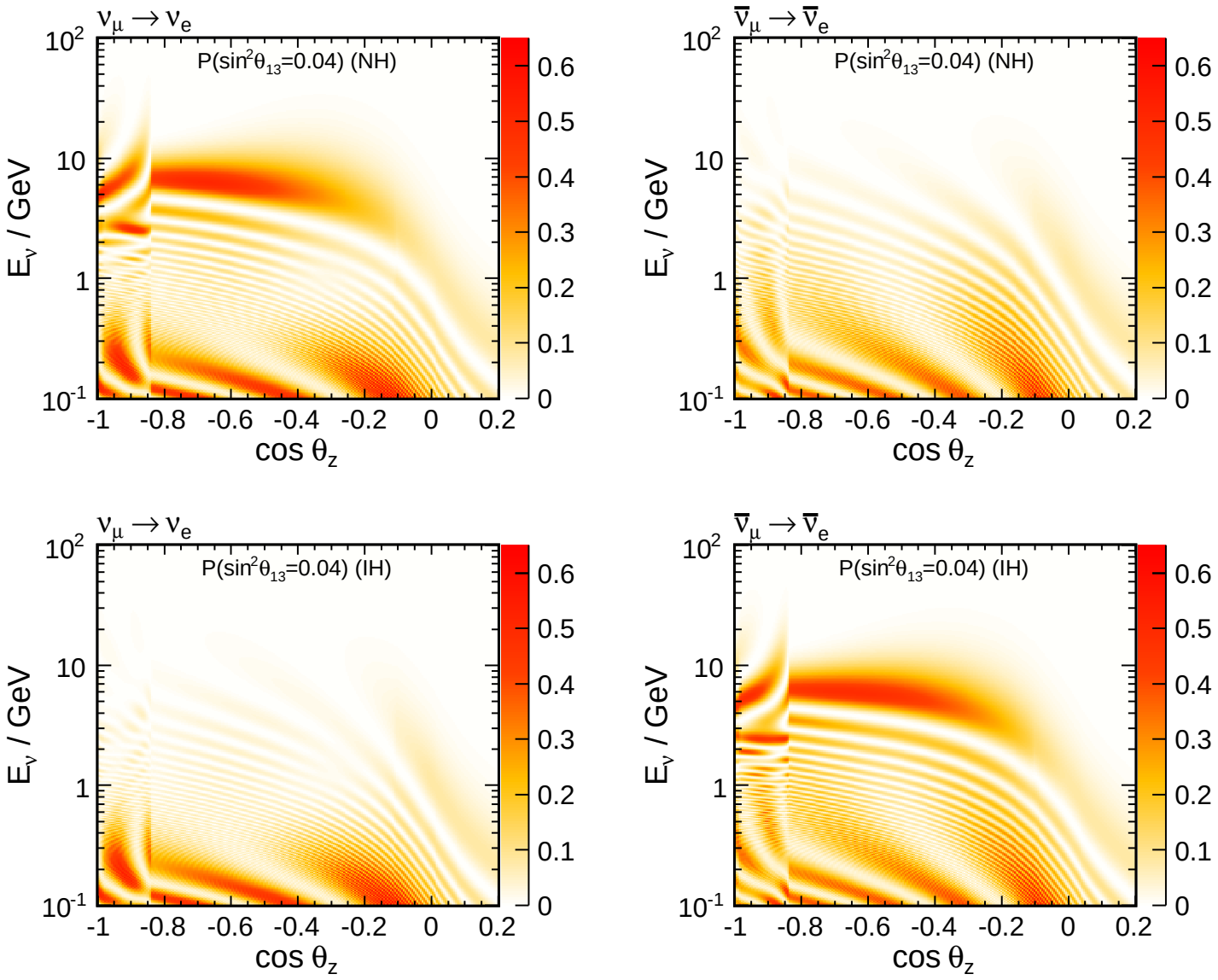
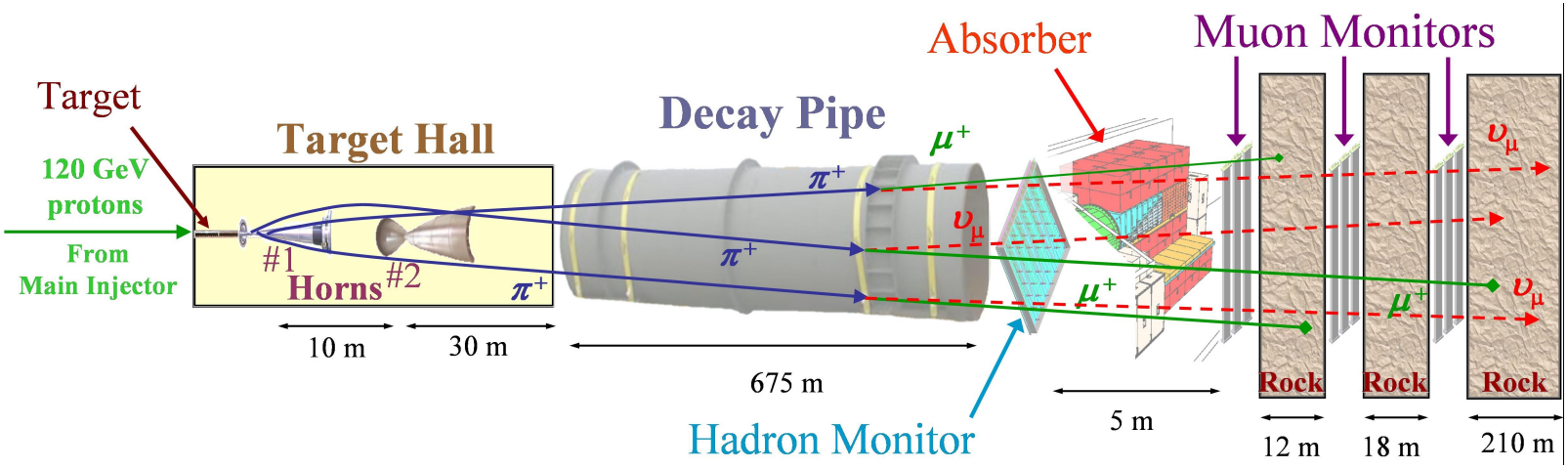
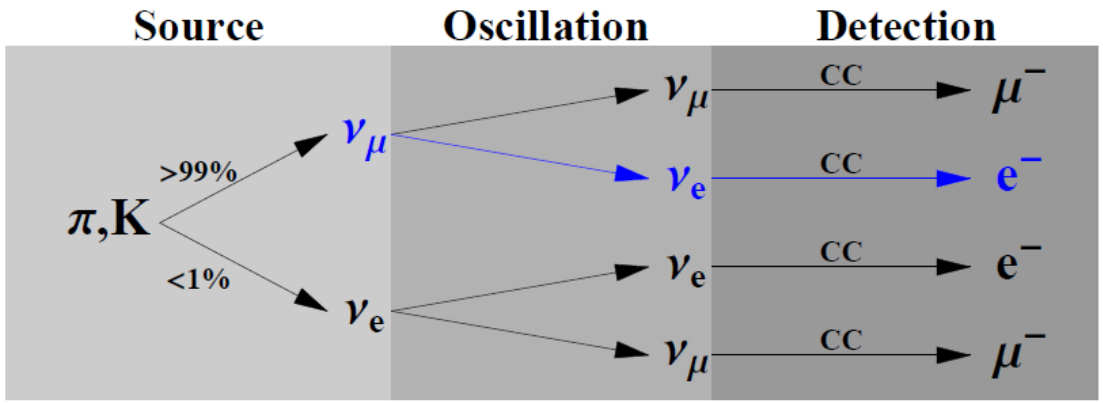
Atmospheric Neutrino Oscillations



Neutrinos from High Power Proton Sources

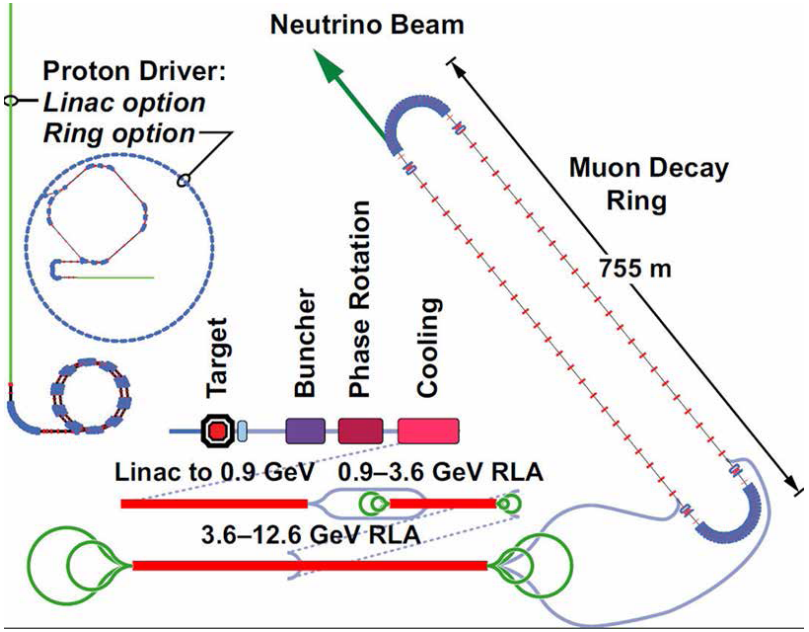
Conventional horn-focused neutrino beams (decay-in-flight):

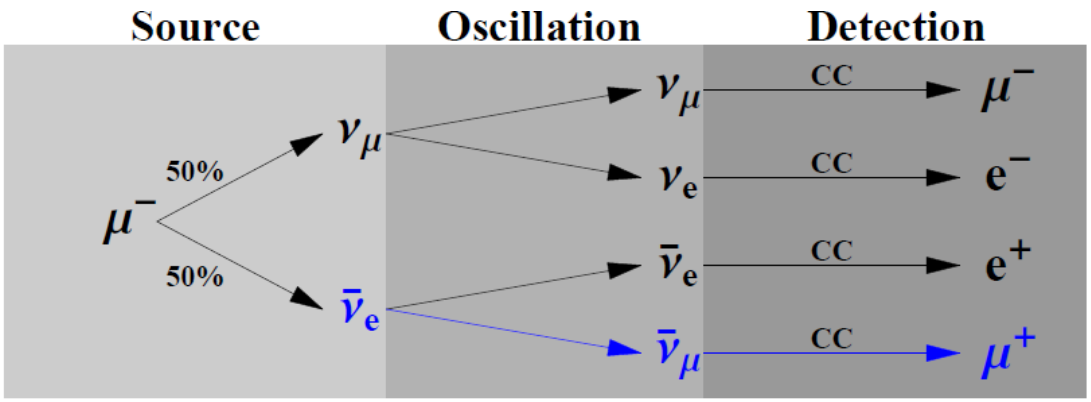




Neutrinos from High Power Proton Sources

Muon Storage Rings:

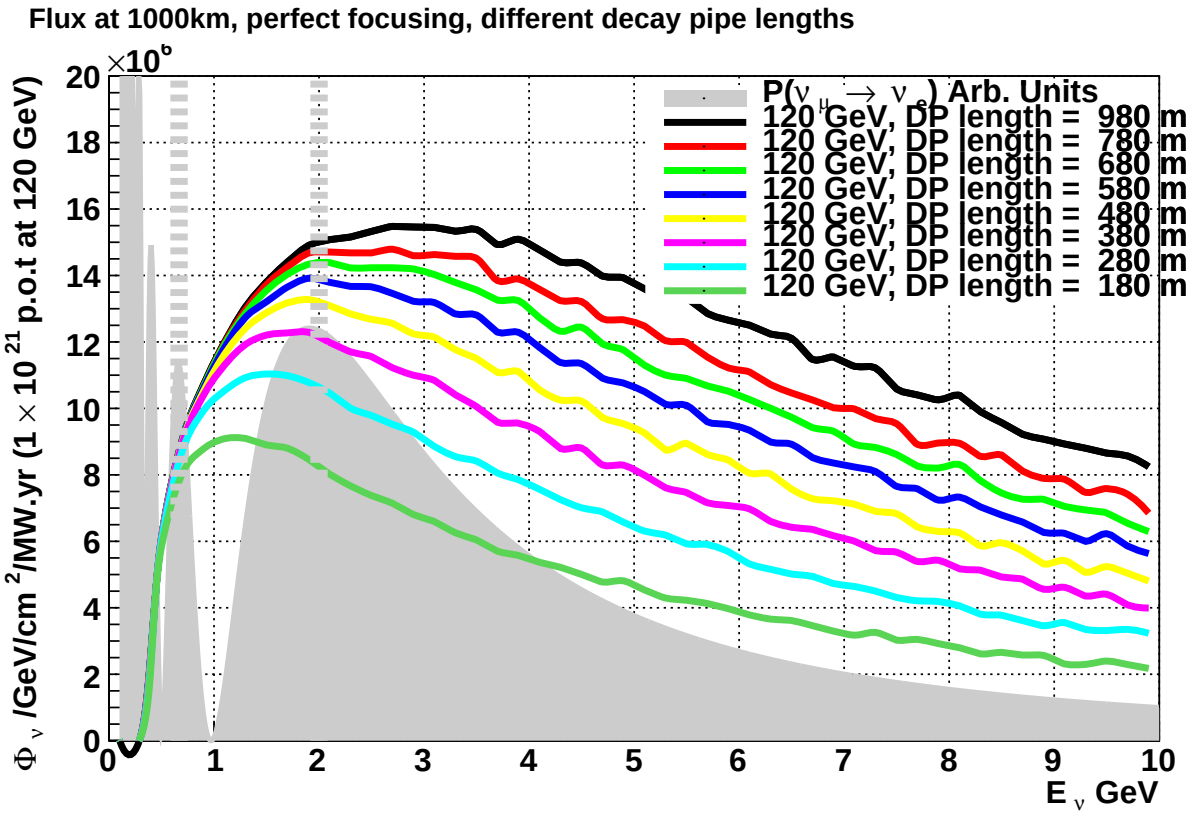




Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams assuming perfect focusing and charge selection:

120 GeV, decay channel lengths from 200m to 1km



Gain with longer decay channels, BUT excavation is challenging/expensive

Expected Appearance Signal Event Rates

The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N_{\nu_e}^{appear}(L) = N_{target} \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \to \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

Assume the neutrino beam source produces a wide coverage that is flat in energy in the oscillation region and approximate the probability with the dominant term for $P(\nu_\mu \to \nu_e)$

$$\Phi^{\nu_\mu}(E_\nu, L) \approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/m^2/GeV//MW/yr \text{ at 1 km}$$

$$P^{\nu_\mu \to \nu_e}(E_\nu, L) \approx \underbrace{\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{31}^2 L/E_\nu)}_{P_0}$$

$$\sigma^{\nu_e}(E_\nu) = 0.7 \times 10^{-42} (m^2/GeV/N) \times E_\nu, \quad E_\nu > 1 \text{ GeV}$$

$$N_{target} = 6.022 \times 10^{32} N/kt$$

Assuming constant flux: $C \approx 1.2 \times 10^{17}\ \nu_\mu/m^2/GeV/(MW/yr)$ at 1 km:

$$N_{\nu_e}^{appear}(L) \approx (2 \times 10^6 \text{events}/(kt/MW/yr))(km/GeV)^2 \times \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx,$$

$$x \equiv L/E_\nu, \quad a \equiv 1.27\Delta m_{31}^2.$$

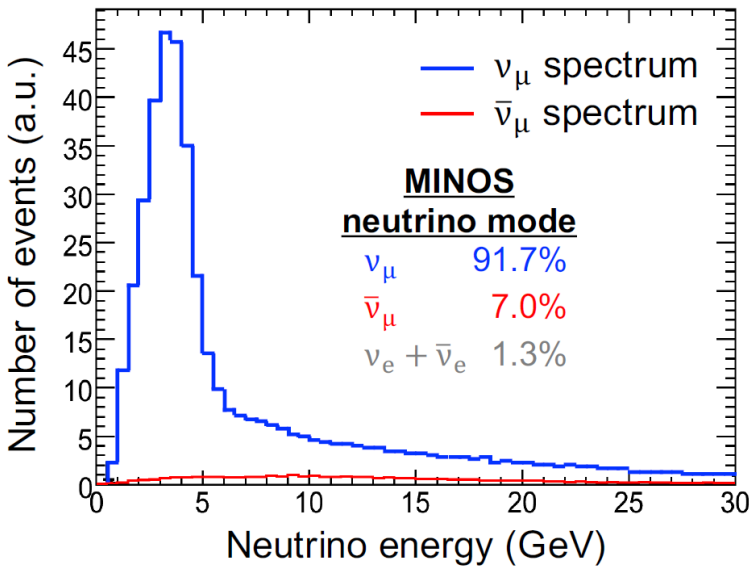
For $x_0 = 100$ km/GeV and $x_1 = 2000$ km/GeV (1st and 2nd oscillation maxima)

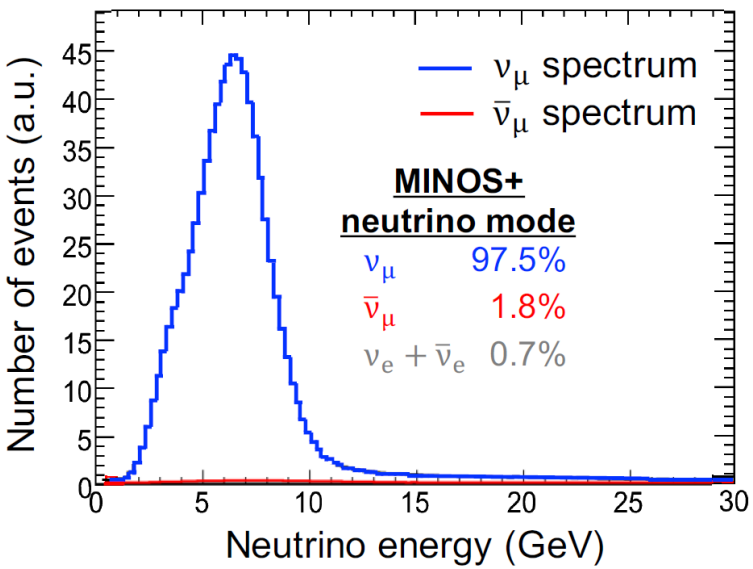
$$N_{\nu_e}^{appear}(L) \sim \mathcal{O}(20) \text{ events}/(kt/MW/yr)$$

constant for $L \geq 300$ km in vacuum!

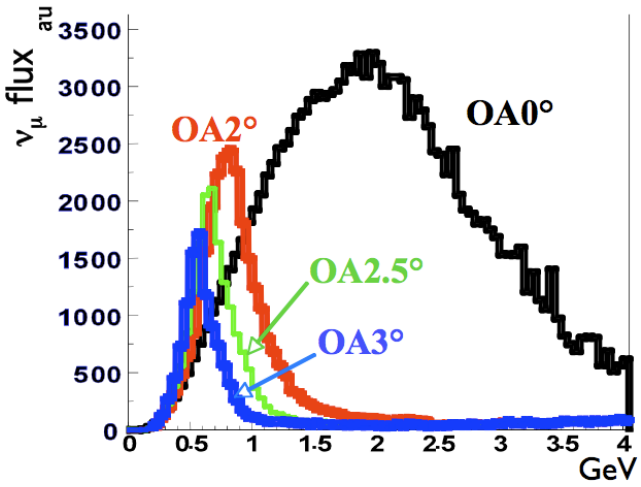
Accelerator Neutrino Beam Spectra/Fluxes

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:

Experiment	Baseline	Super Beams $\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$
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

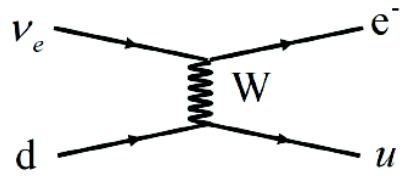
Experiment	Baseline	ν Factory at Fermilab $\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_\mu$
NuMAX I 3 GeV, 1MW 0.94×10^{20} μ/year (no μ cooling)	1,300km	340	30	70 - 120
NuMAX II 3 GeV, 3MW 5.6×10^{20} μ/year	1,300km	2000	300	420 - 700

* Facility duty factor taken into consideration

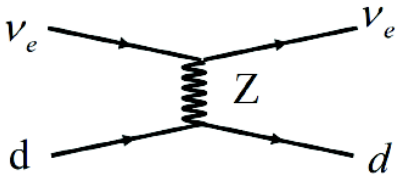
Probing new physics beyond 3-flavor oscillations: Non Standard Interactions

NSI in Long-Baseline Oscillations

- In the Standard Model,



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



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

- With new physics, we could have

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

CC NSI
production, detection

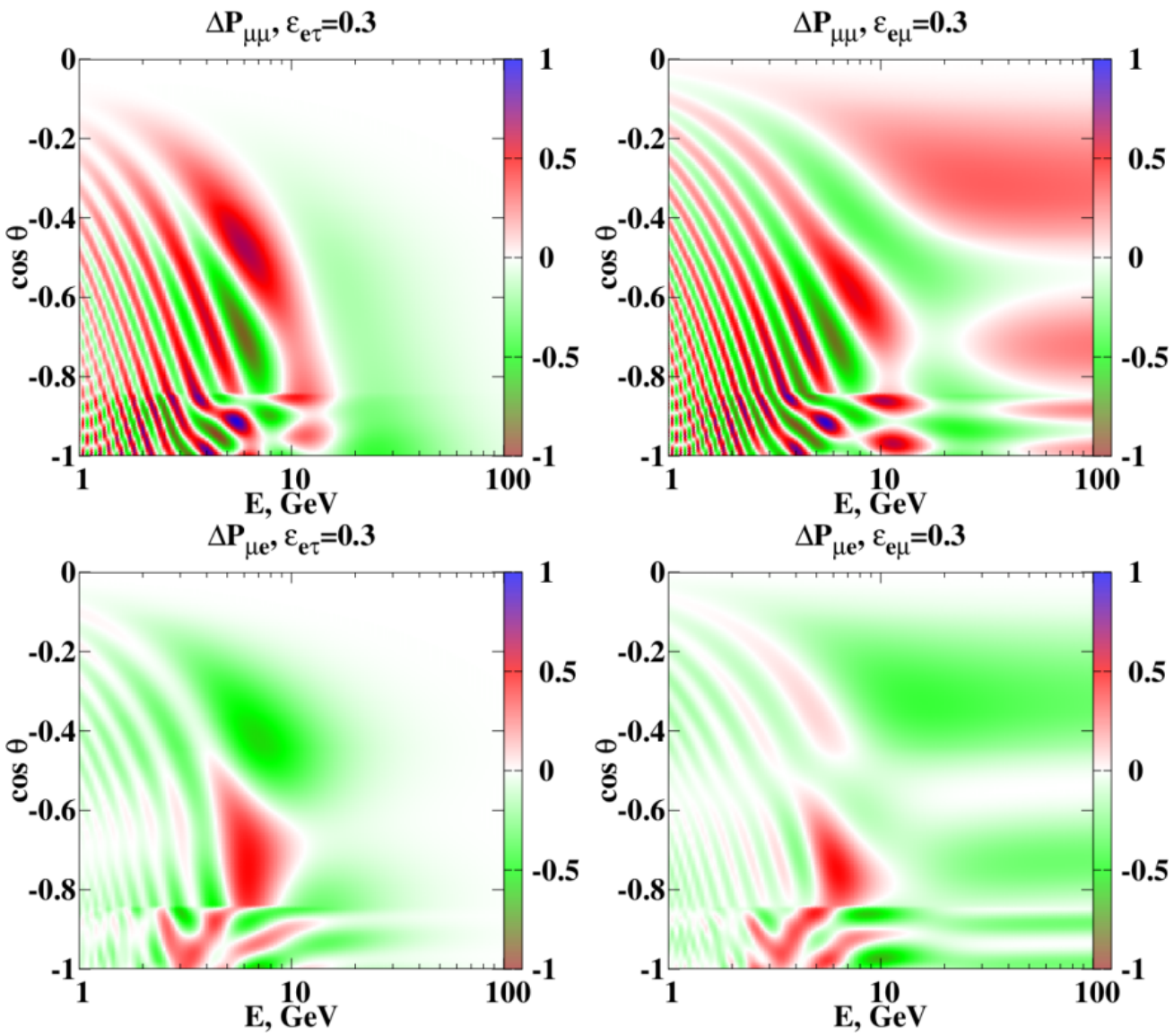
$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$

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

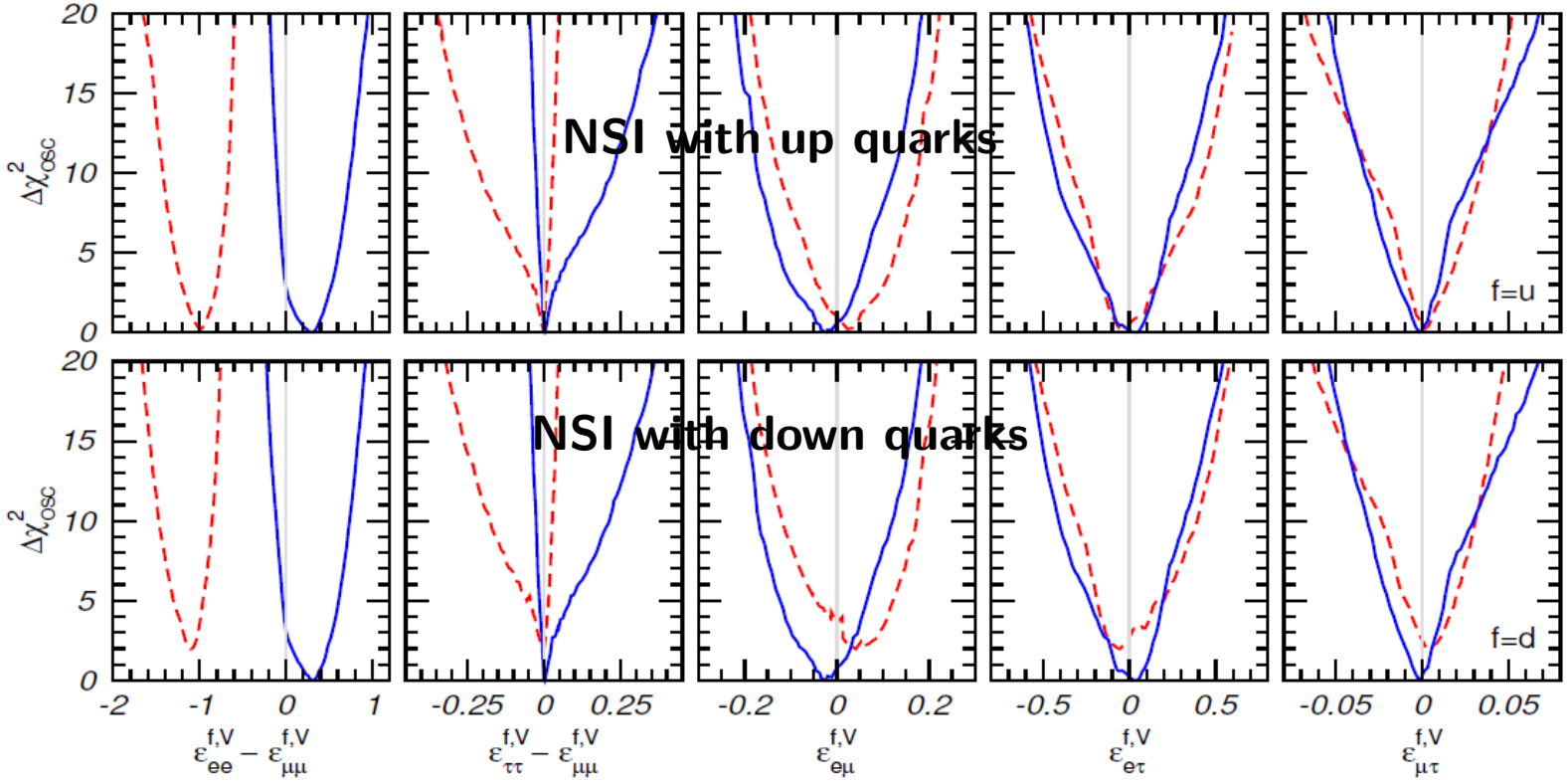


NSI limits from Current Experiments

P. Coloma *et. al.* **JHEP 04 (2017) 116:**

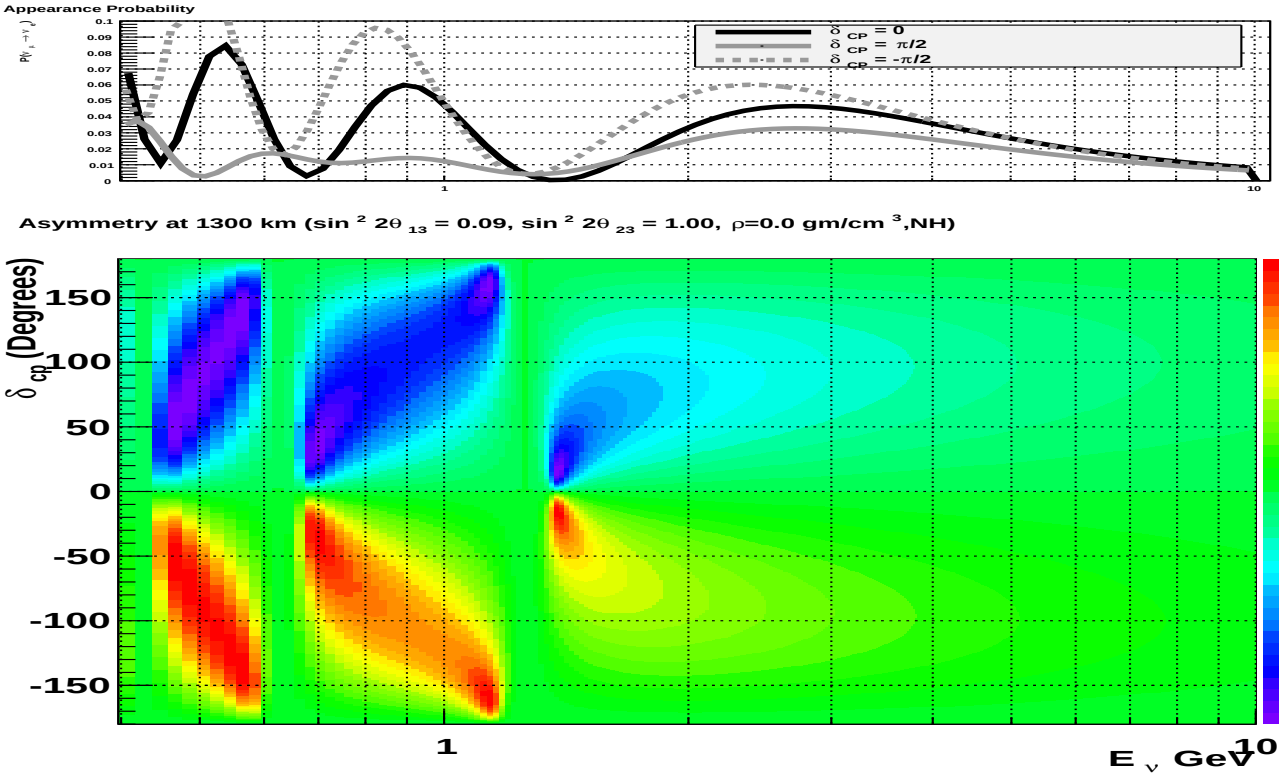
Standard solution with $\theta_{12} < 45°$

Degenerate solution with $\theta_{12} > 45°$ and large $|\epsilon_{ee}|$



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}

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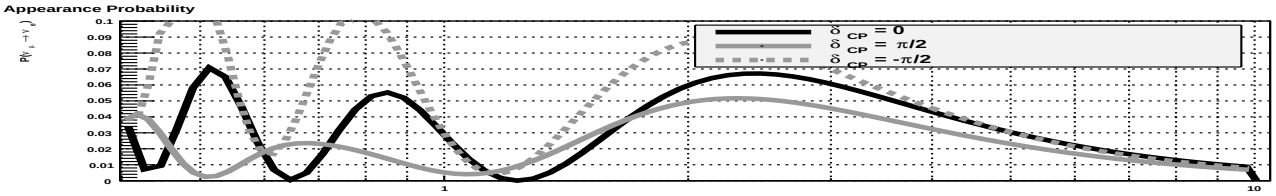
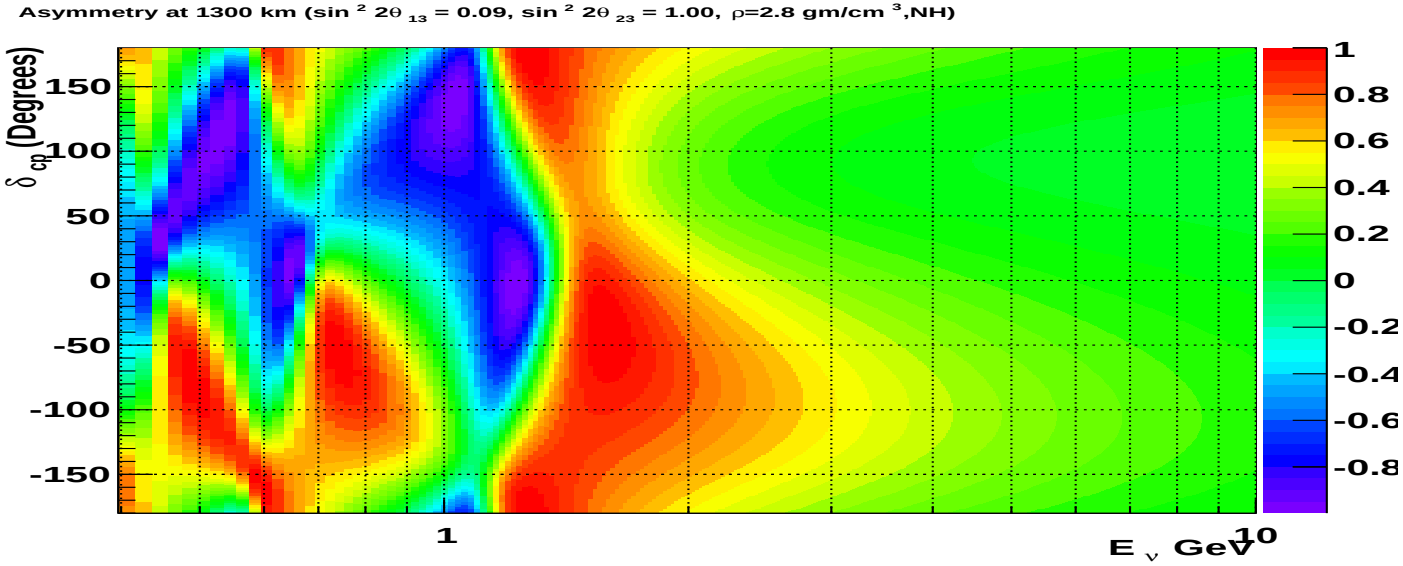
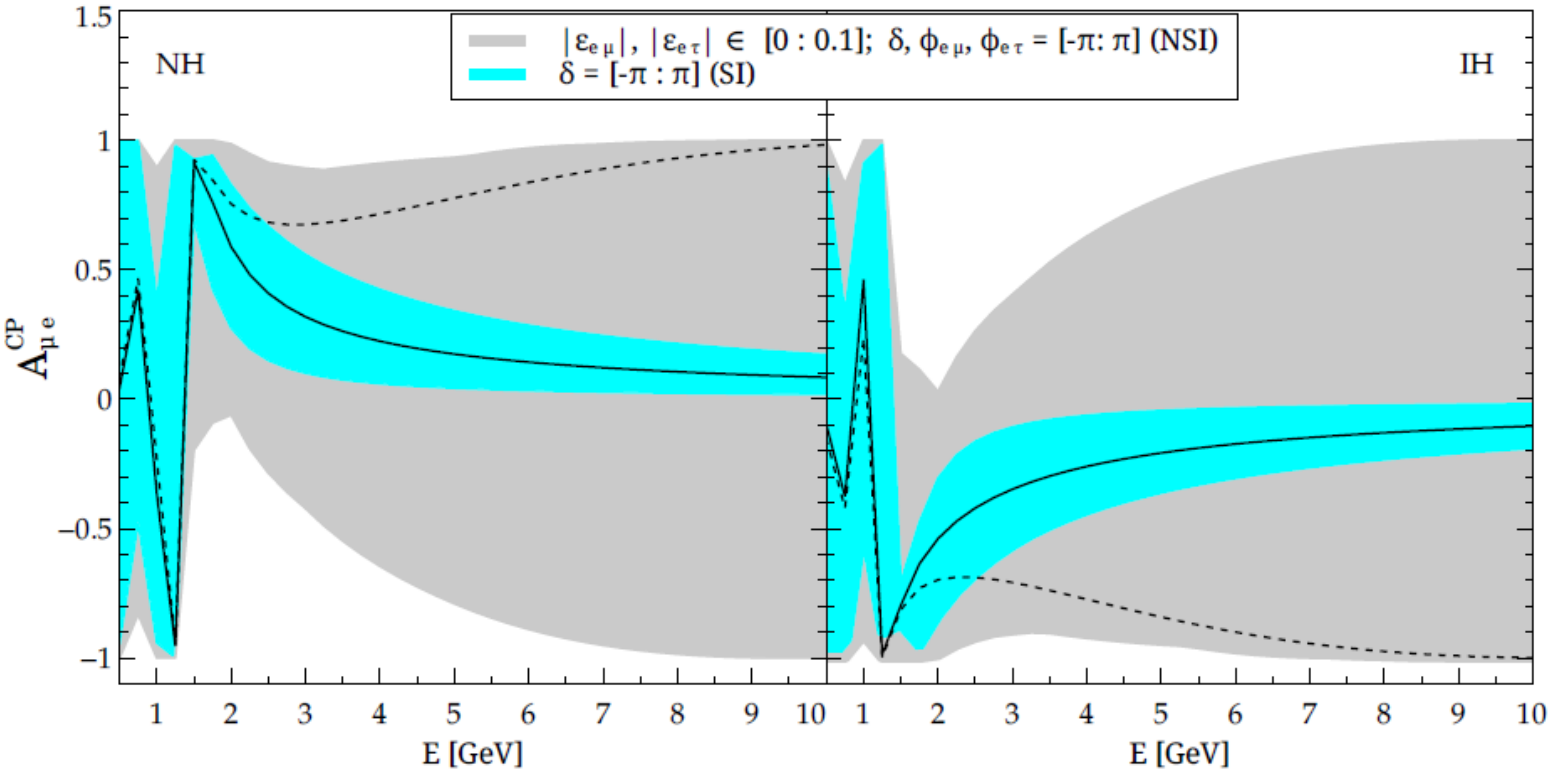




Asymmetries caused by CPV and matter are a complex phenomena

Extricating NSI from 3-flavor Oscillations

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



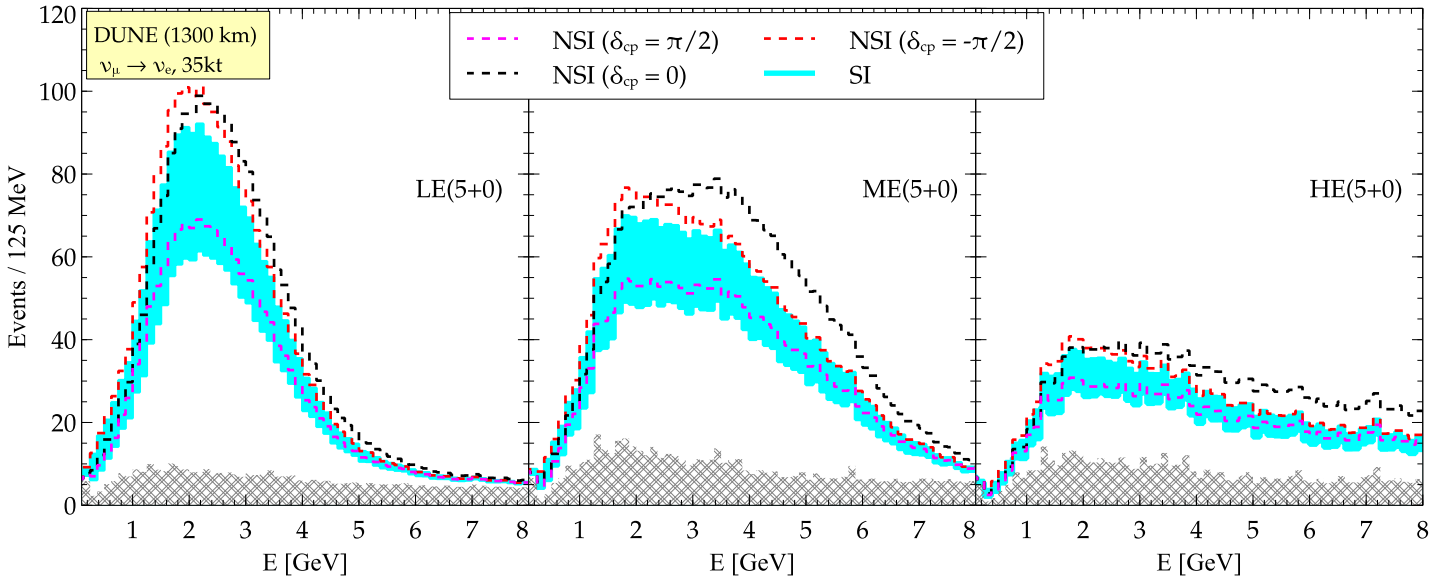
(M. Masud, A. Chatterjee, P. Mehta arXiv:1510.08261)

Extricating NSI from 3-flavor Oscillations

Study NSI sensitivity with GLoBeS using $\nu_\mu \to \nu_{\mu,e}$ and 3 sample LBNF-like beam tunes : LE, ME and HE*.

NSI parameters used:

$|\epsilon_{e\mu}| = 0.04,\ |\epsilon_{e\tau}| = 0.04,\ \epsilon_{ee} = 0.4,\ \phi_{e\mu=0},\ \phi_{e\tau}$



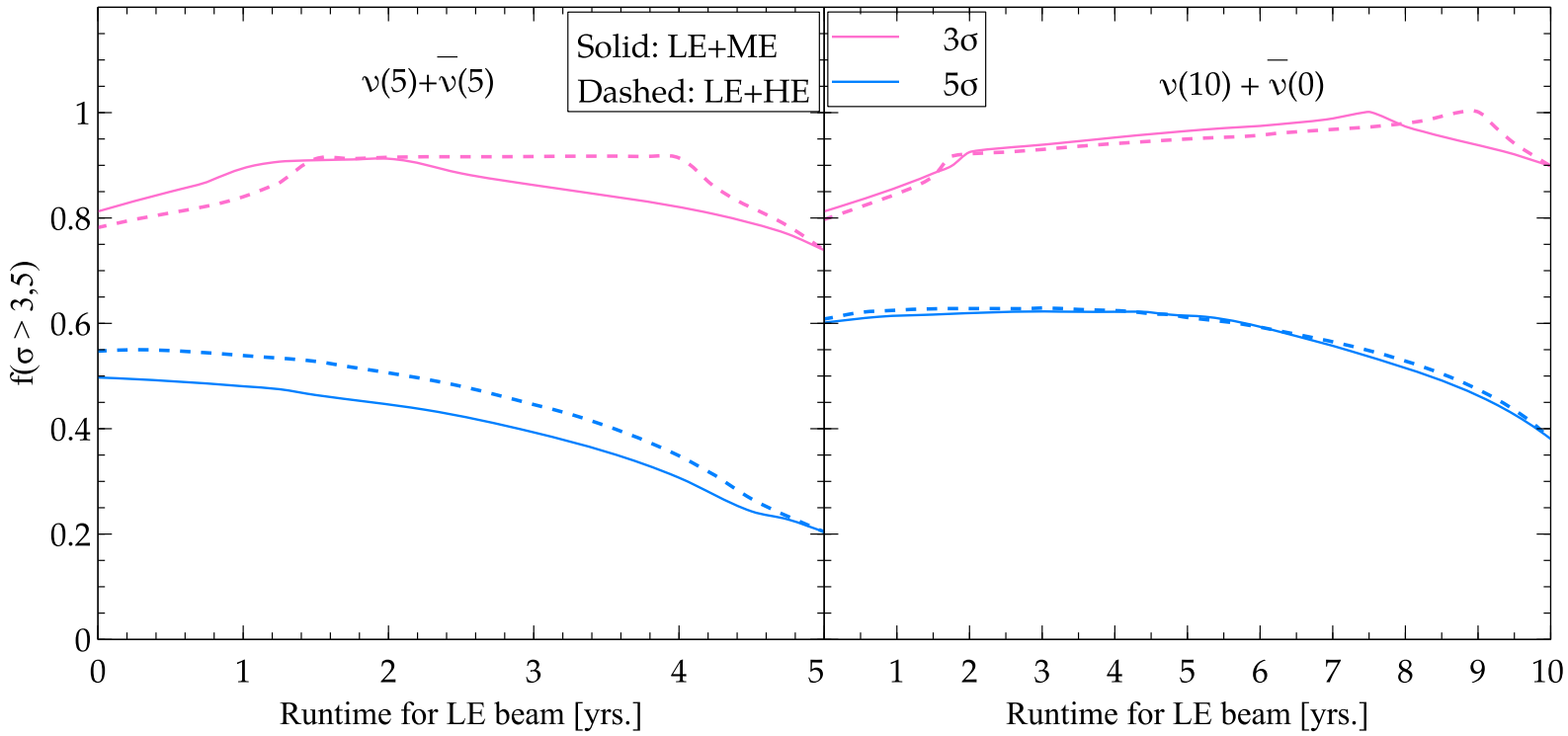
NSI effects in $\nu_\mu \to \nu_e$ are larger at higher energy

* 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 3/5σ level:



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

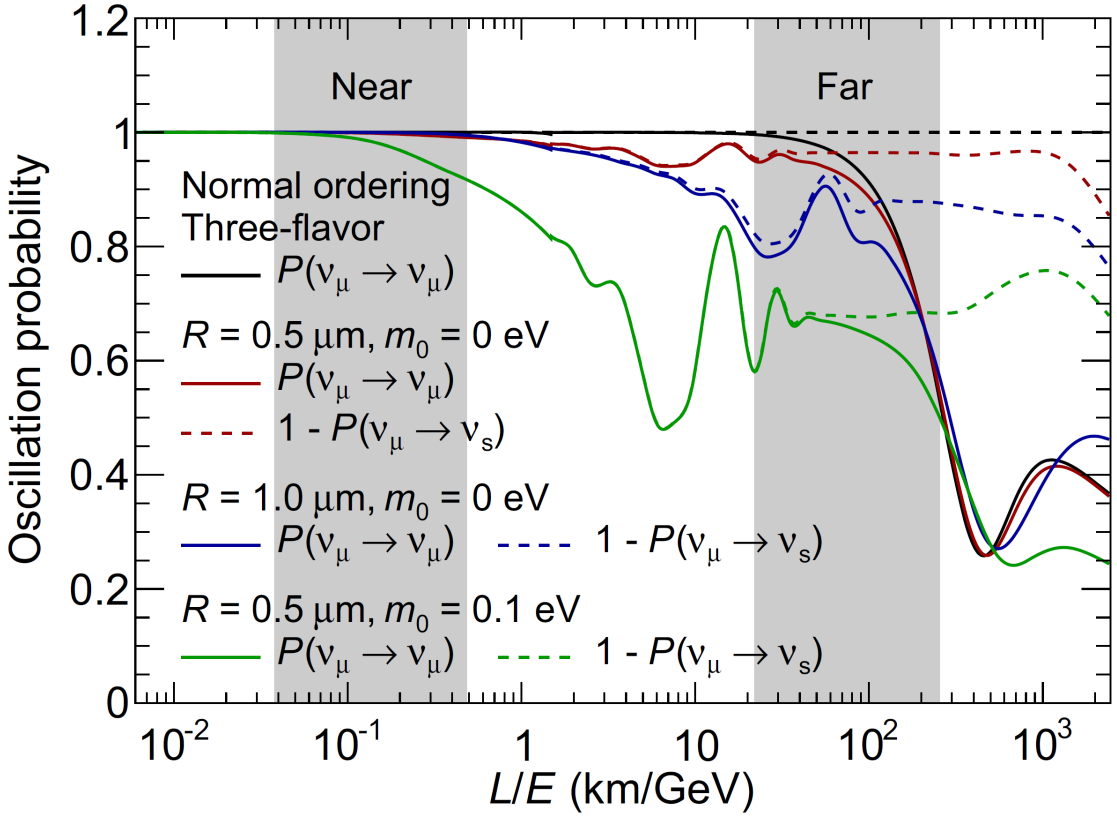
No beam optimization attempted yet!

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

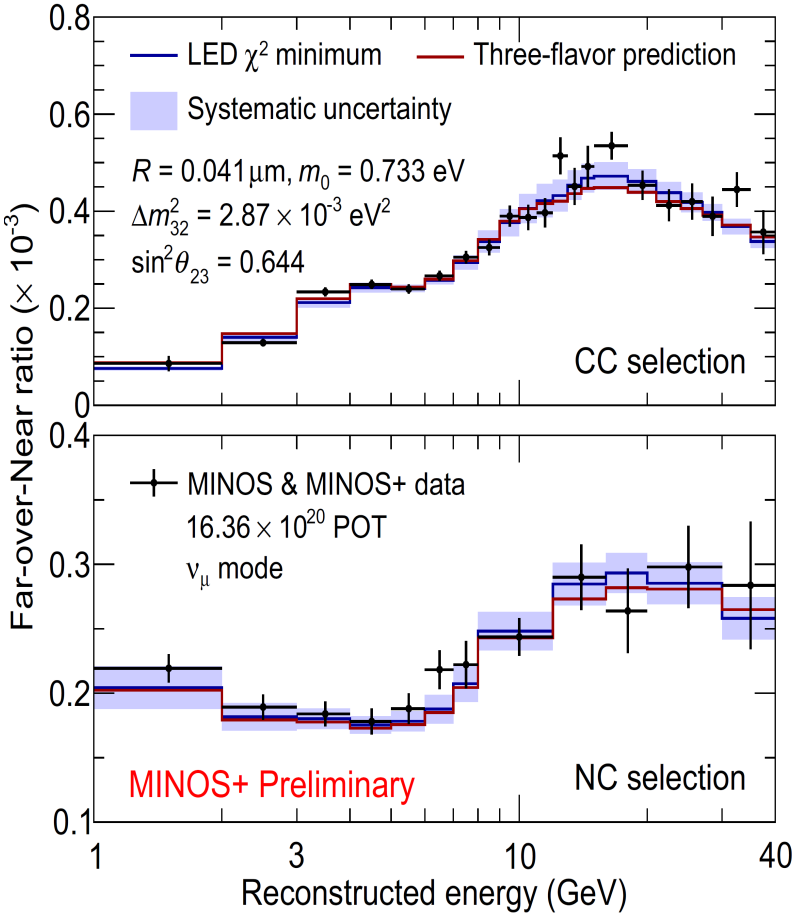
Search for Large Extra Dimensions with MINOS/MINOS+

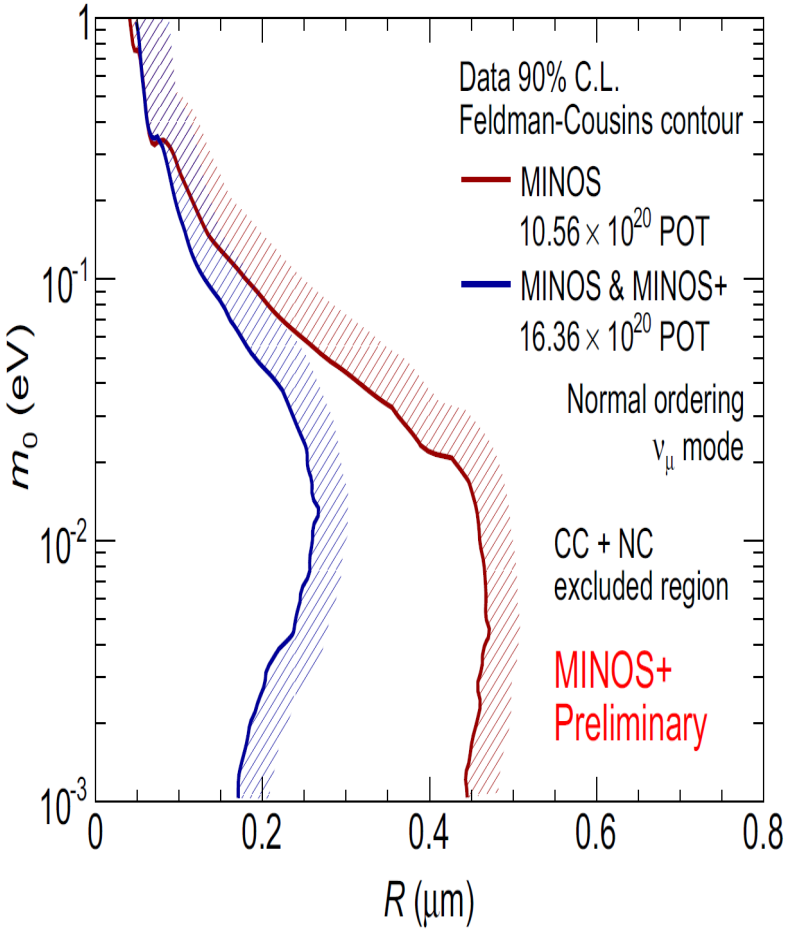
Large Extra Dimensions (LED) and ν_μ Disappearance

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 P($\nu_\mu \rightarrow \nu_\mu$ oscillation probability for a given R and m_0 the mass of the lightest neutrino state:



Results from MINOS/MINOS+ search for LED



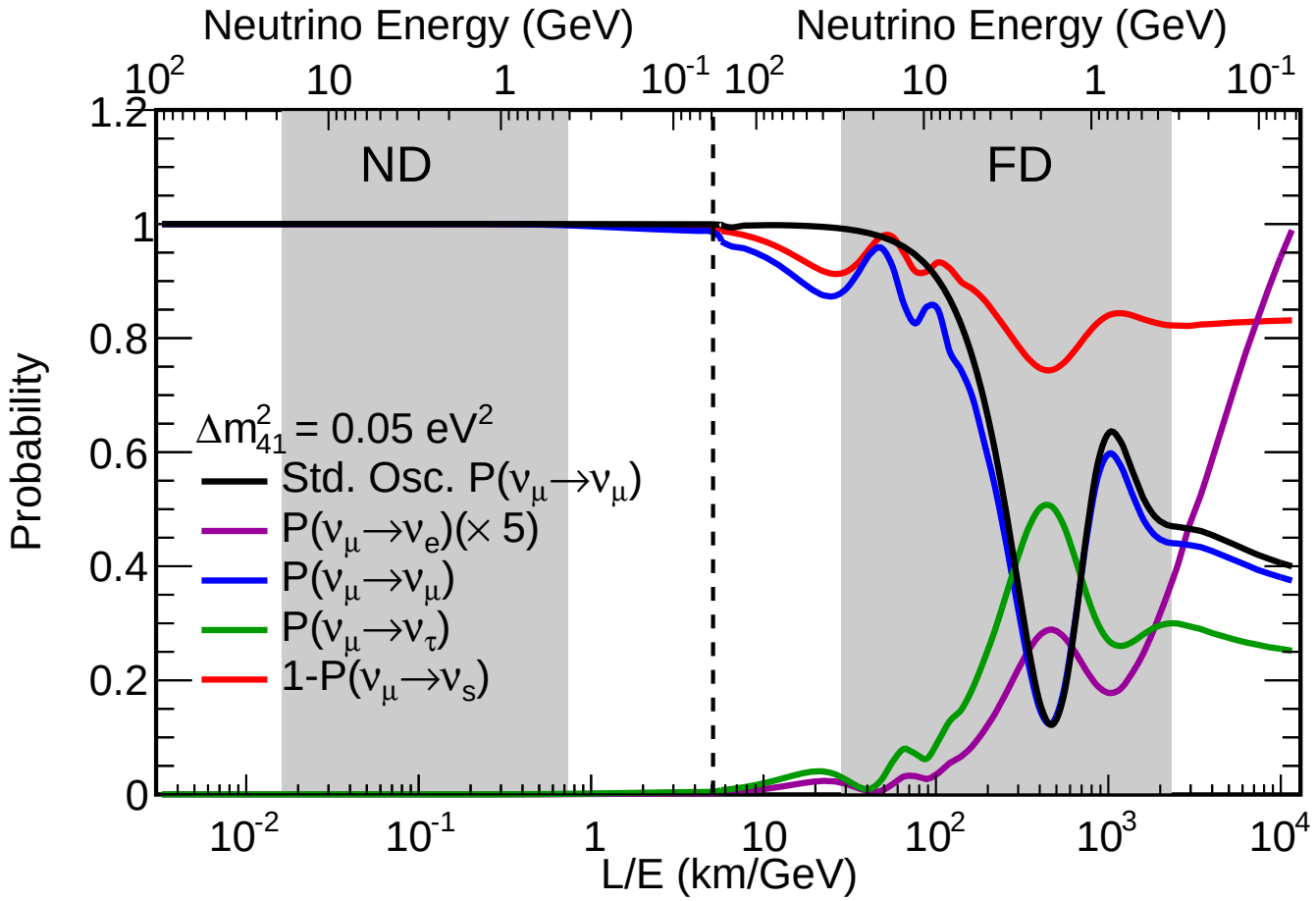


Wide-band beams, long baselines, high efficiency/purity ν_μ selection and combination of CC and NC channels start to constrain LED models.

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

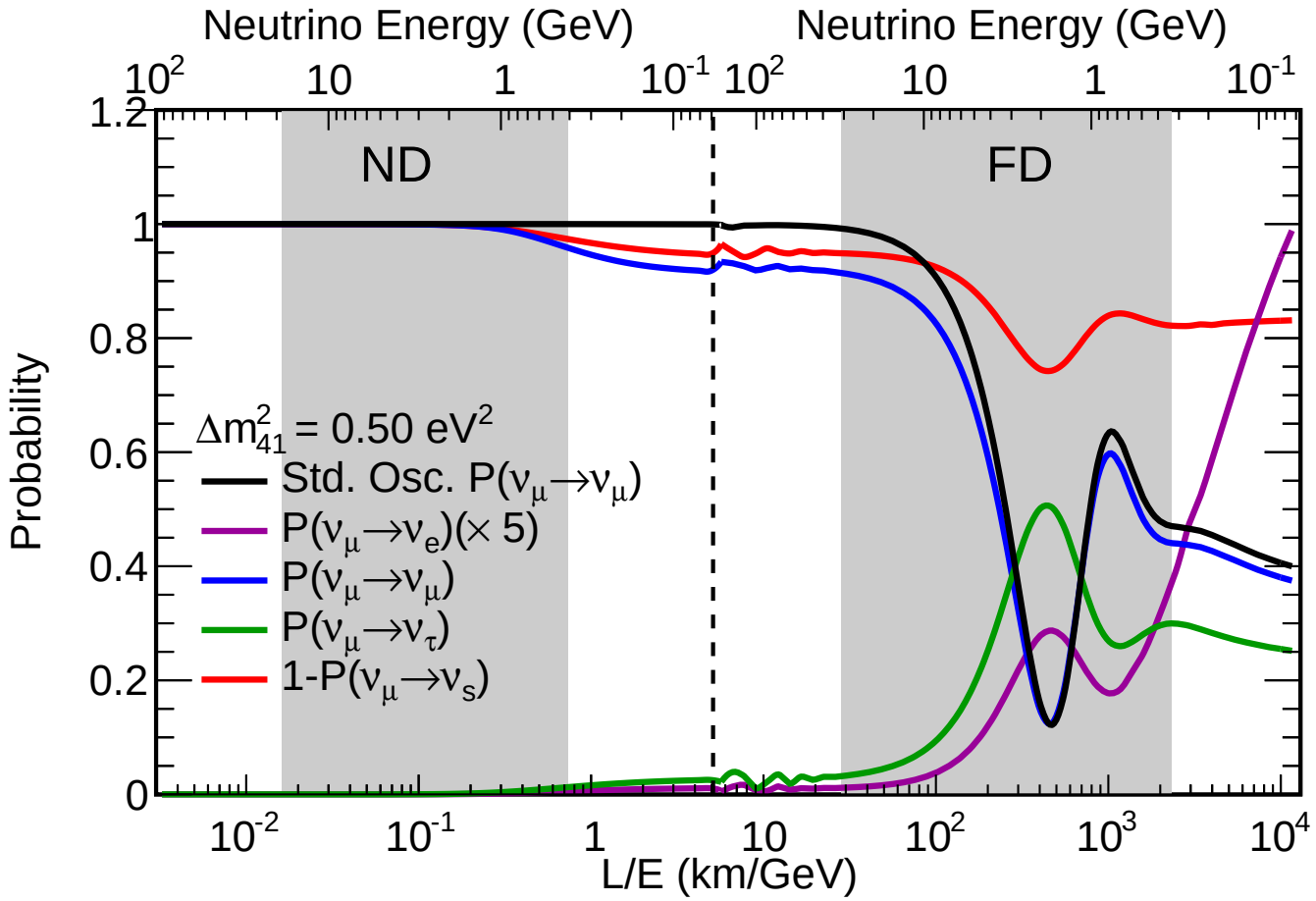
Probing new physics beyond 3-flavor oscillations: Sterile neutrinos

Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



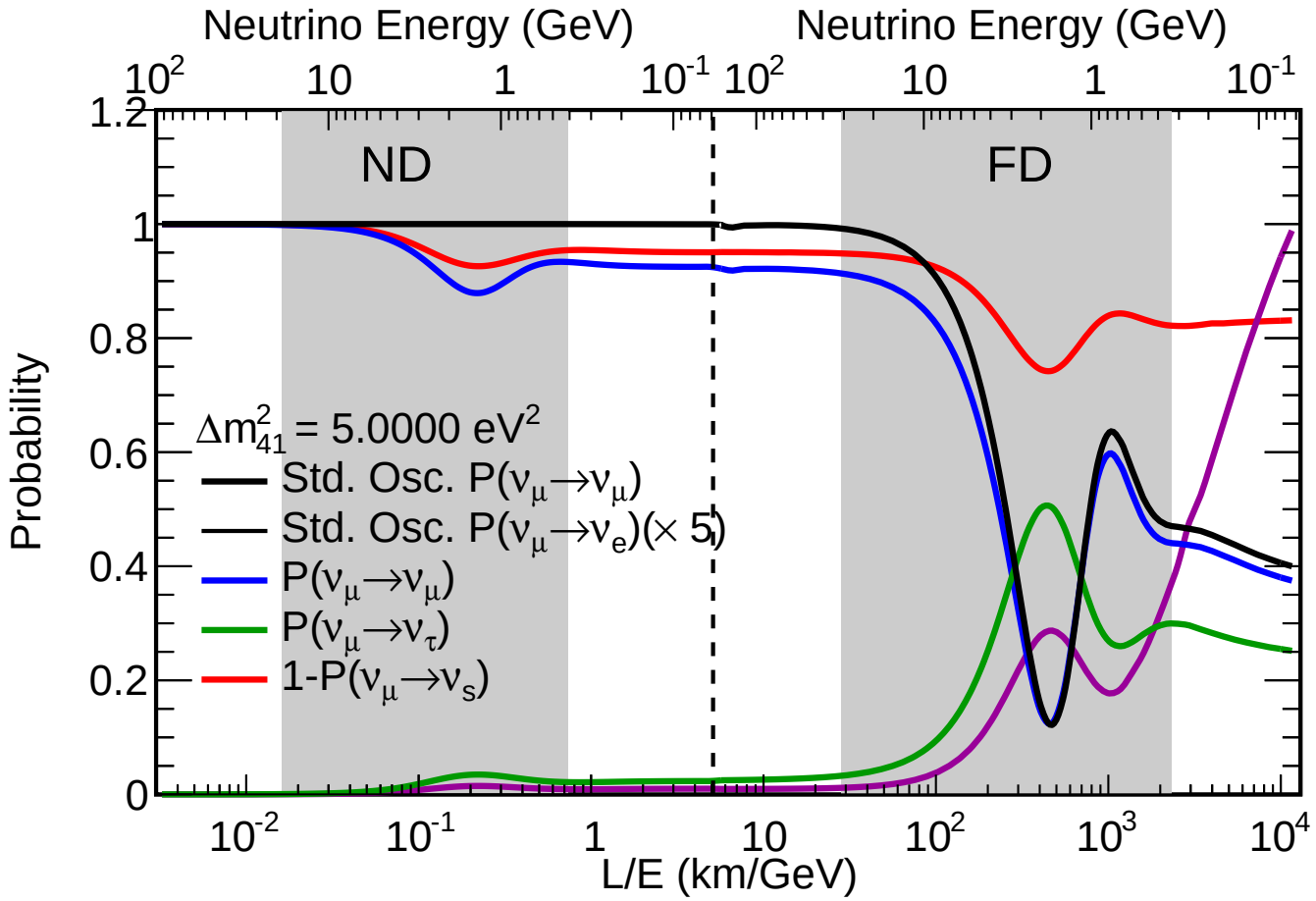
A. Sousa, U. Cinncinati

Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



A. Sousa, U. Cinncinati

Impact of Sterile Neutrinos on Long-Baseline ν Oscillations



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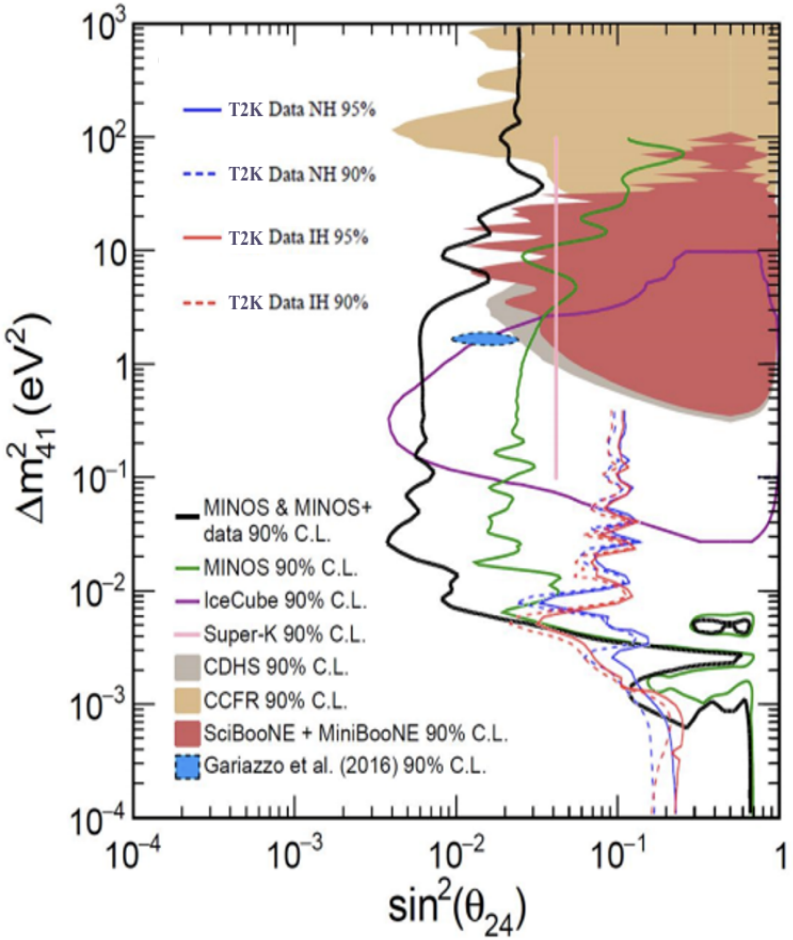
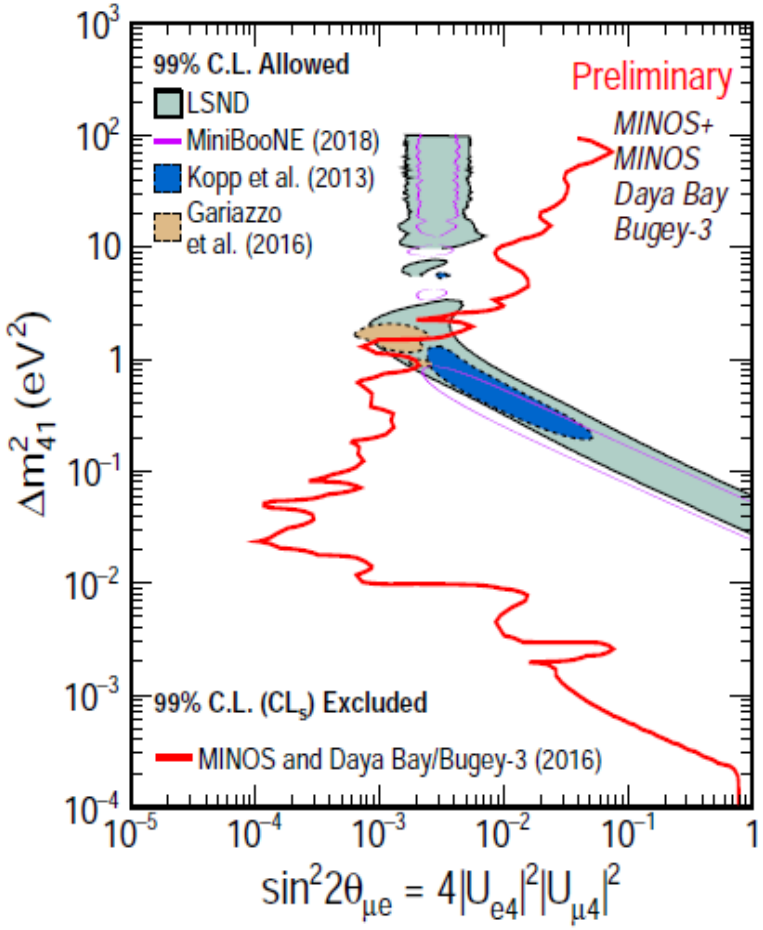
Sensitivities to 3+1 from SBL/LBL Appearance and Disappearance

Disappearance



Appearance



Tension between LBL ν_μ disappearance and SBL ν_e appearance

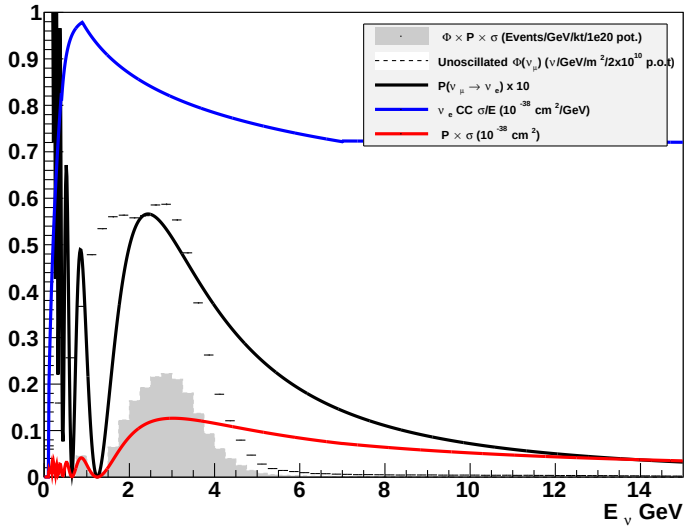
Probing new physics beyond 3-flavor oscillations: $\nu_\mu \to \nu_\tau$

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

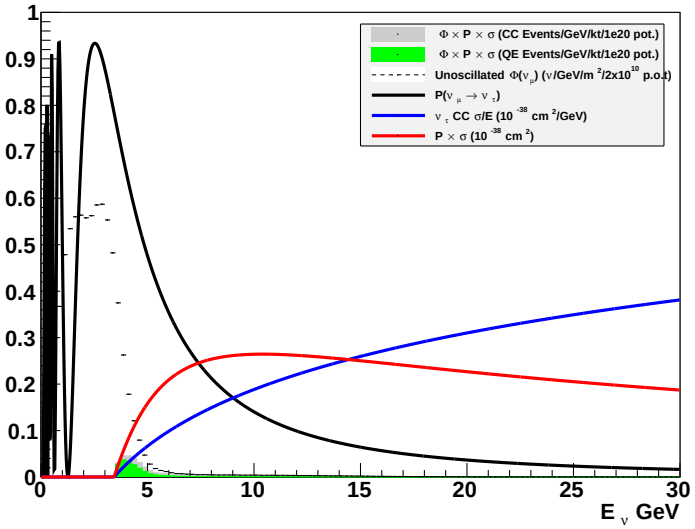
NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \rightarrow \nu_\tau$ with high statistics.

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

$\nu_\mu \rightarrow \nu_e$ Appearance at 1300 km



$\nu_\mu \rightarrow \nu_\tau$ Appearance at 1300 km

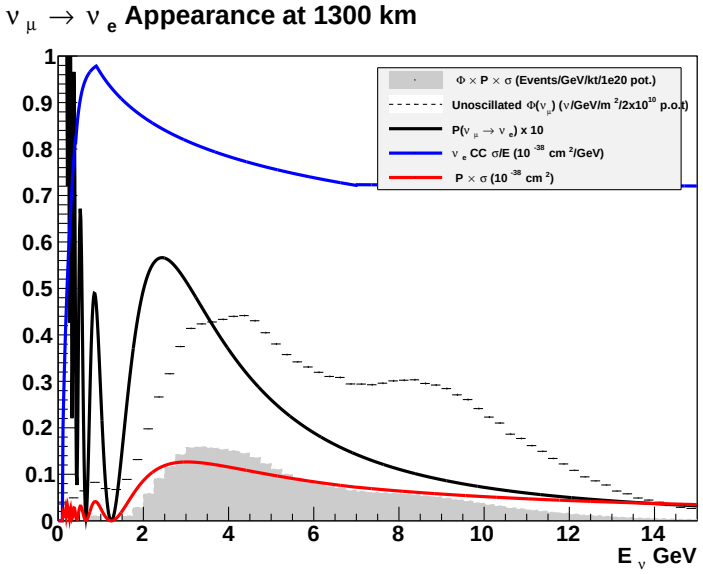


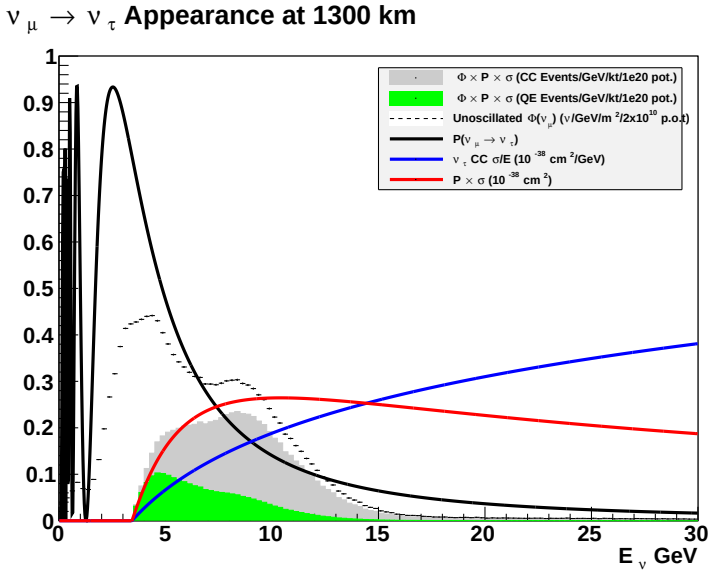
$\nu_\mu \rightarrow \nu_e$ 290 events $\quad$ ν_μ rightarrowν_τ 60 events
in 40 ktons, 1 year at 1.2 MW

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

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

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





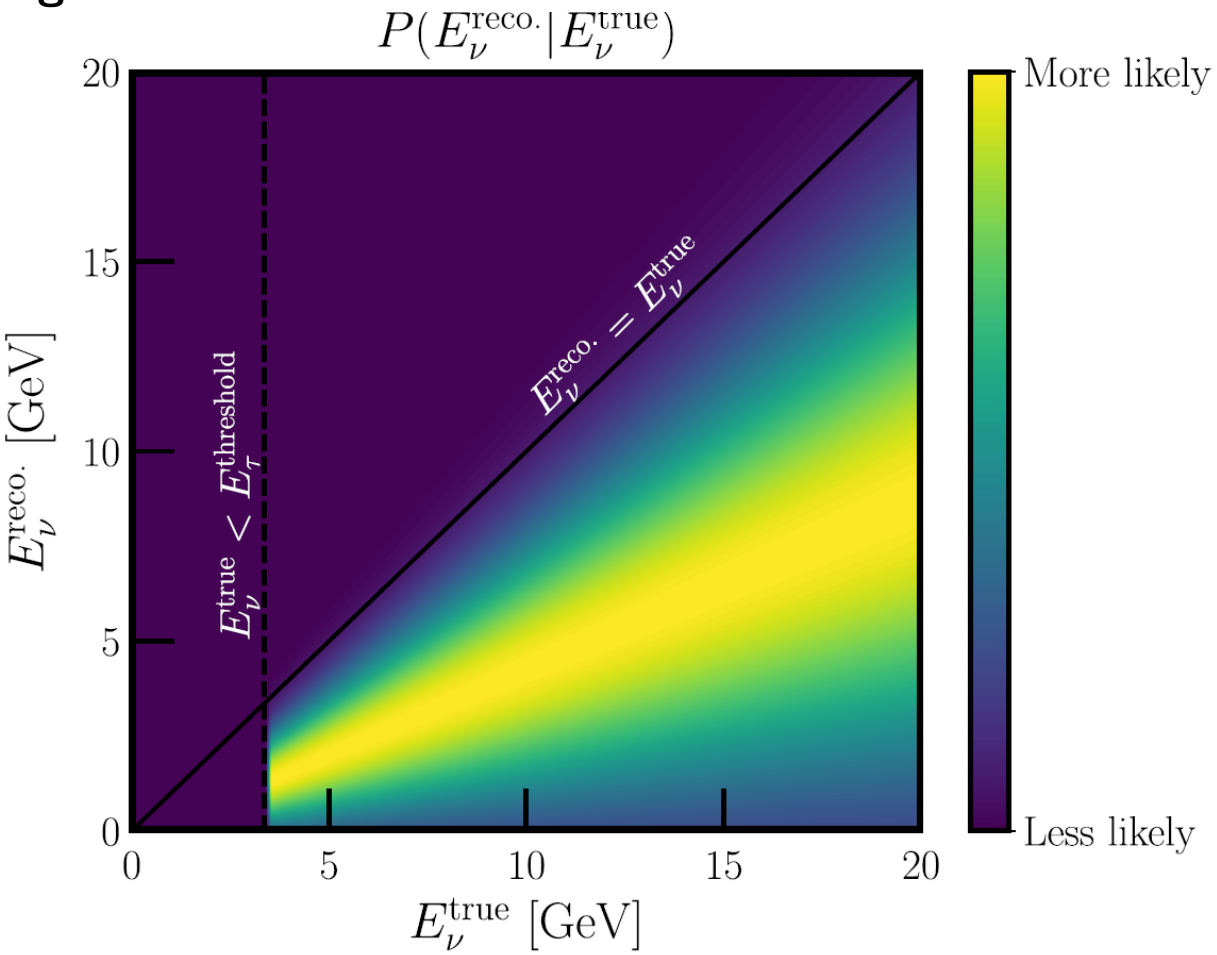
$\nu_\mu \rightarrow \nu_e$ **330 events** $\nu_\mu \rightarrow \nu_\tau$ **700 events**
in 40 ktons, 1 year at 1.2 MW

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:



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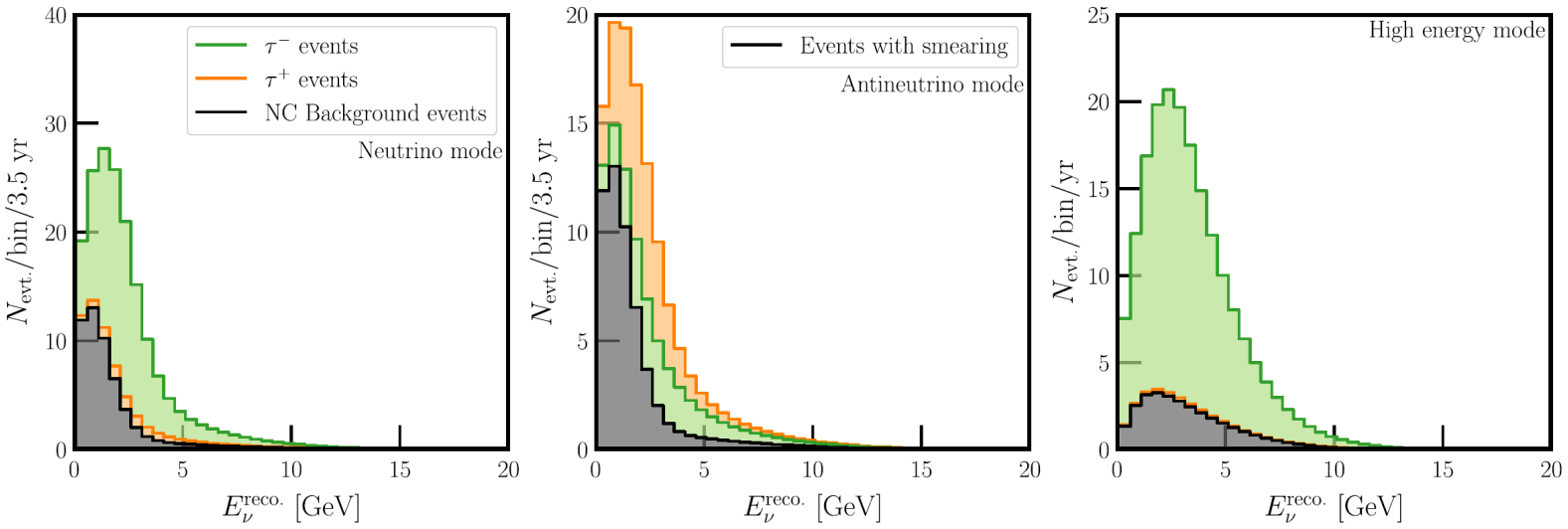
ν_τ Appearance Measurements in DUNE

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



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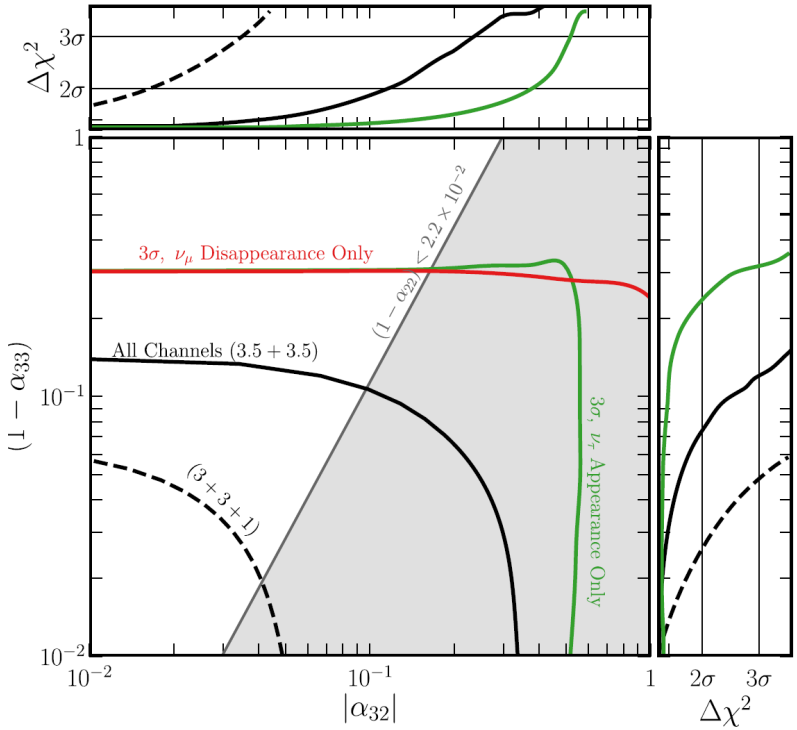
Simple Unitarity Tests with ν_τ Appearance in DUNE

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

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



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Summary and Next Steps

Followup talks on BSM in LBL Expts

- **Saturday 12:00:** Long Baseline Neutrino Oscillation Physics at DUNE. Speaker: Hanyu Wei
- **Sunday 10:30:** Neutrino Cross-sections. Speaker: Steve Dytman
- **Monday 12:10:** Experimental Overview of Reactor Experiments. Speaker: Xin Qian
- **Monday 15:00:** The many faces of non-standard neutrino interactions. Speaker: Danny Marfatia
- **Monday 16:00:** Non-Standard Interactions of Neutrinos and where to find them. Speaker: Tatsu Takeuchi
- **Tuesday 15:35:** Dark Matter and Physics Beyond the Standard Model at DUNE. Speaker: Valentina De Romeri

Next Steps in νBSM Studies

The Snowmass process has started in the US and the ν BSM community is planning a year long effort. Community activities so far:

- **Workshop on New Opportunities at the Next Generation Neutrino Experiments 12-13 April 2019 University of Texas, Arlington. Explored Dark Matter Searches at Neutrino Experiments and BSM Physics with Neutrinos.**
- **White Paper on New Opportunities at the Next-Generation Neutrino Experiments (Part 1: BSM Neutrino Physics and Dark Matter) C.A Arguelles (MIT)** *et al.* **ArXiv:0906.4114**
- **2nd workshop planned April 2-4, 2020 in Pittsburgh, PA**

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.**


NDM-2020
THANK YOU