BROOKHAVEN NATIONAL LABORATORY

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Beam Upgrades for LBNF/DUNE and Physics Potential

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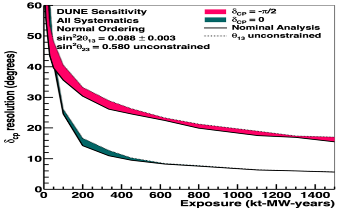
Physics Motivation

ν@Snowmass: Questions for experimental community:

- **What are the next next generation neutrino oscillation experiments? What is the physics motivation?**

- **How can we reach few degree resolution on δ_{cp} (and does it matter)?**

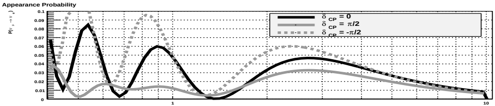
Theorists are requesting 3° resolution if near maximal

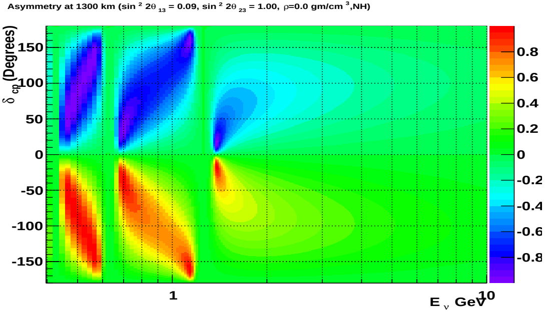


- **How can we best probe for new sources of ν CPV? Search for physics beyond the νBSM?**
- **How does the hunt for sterile neutrinos evolve beyond SBN and SBL reactor?**
- **Is the PMNS matrix unitary?**

LBL Physics Motivation

Precision measurement of neutrino oscillation parameters - including mass hierarchy (MH) and J_{cp} requires a detailed look at the $\nu_\mu \rightarrow \nu_e$ over a large L/E range. At a fixed L - study oscillation over a wide energy range:





LBL Physics Motivation

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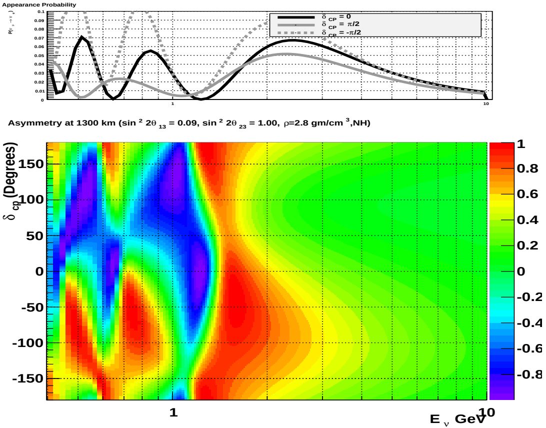

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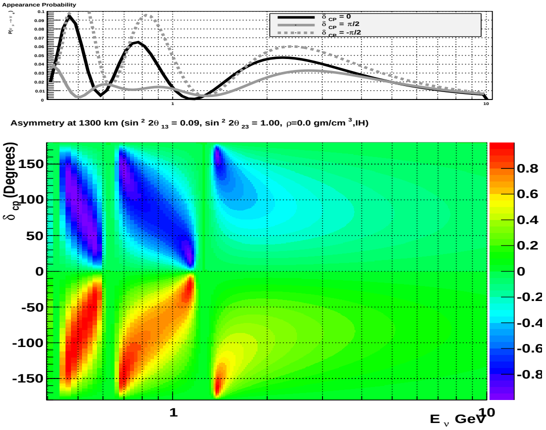

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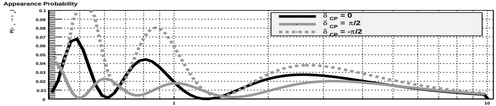

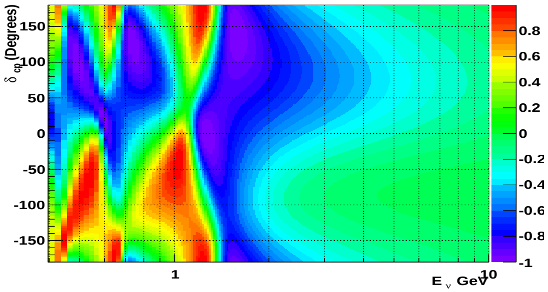

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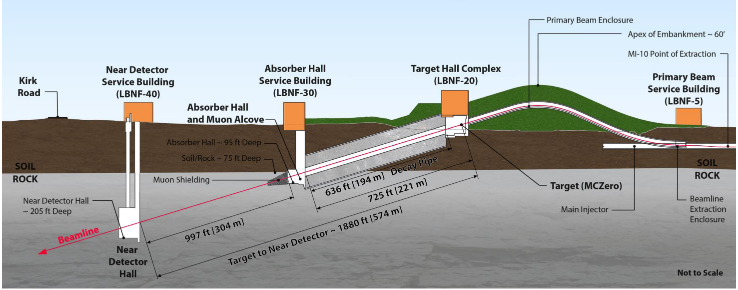
Design of the LBNF/DUNE Beamline

Overview of the LBNF Beamline

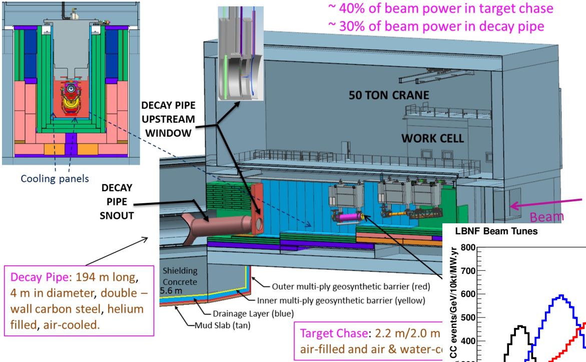


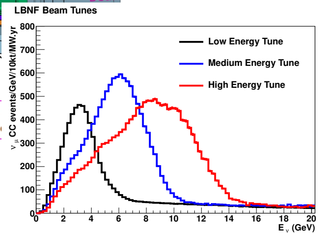
- **Primary proton beam 60-120 GeV**
- **Initial 1.2 MW beam power, upgradable to 2.4 MW**
- **Embankement allows target complex to be at grade**
- **Wide-band beam (on-axis) optimized for CP violation sensitivity**
- **Decay pipe: 194m x 4m diameter, He filled**

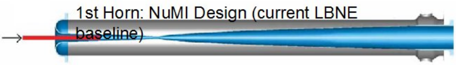
ND default: 574 m from target, FD: 1300 km

The LBNF Reference Design (up to 2015)

Initial conceptual design was of a *tunable wide-band* NuMI-style focusing:





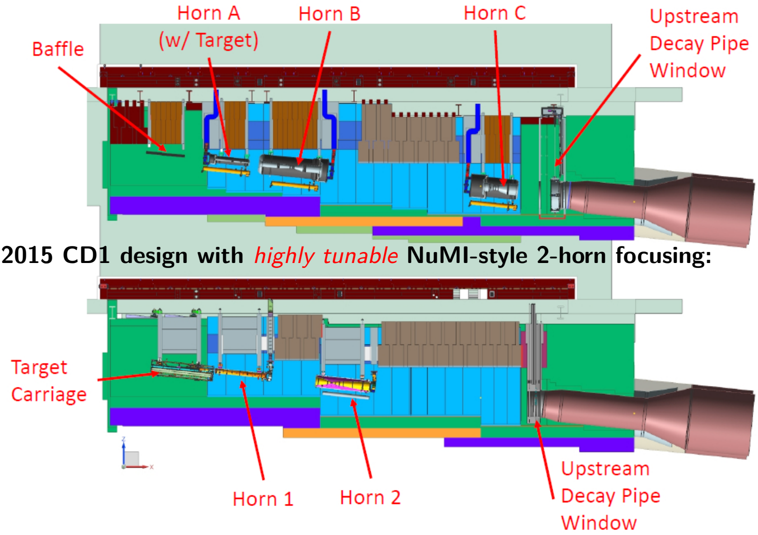


LBNF has switched to CPV optimized focusing design with 3 horns

CPV Optimized Design

2017 3-horn CPV genetic algorithim optimized design:

2015 CD1 design with *highly tunable* NuMI-style 2-horn focusing:



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Physics with High Energy Beam Upgrades

Optimization of CDR Design for $\nu_\mu \to \nu_\tau$

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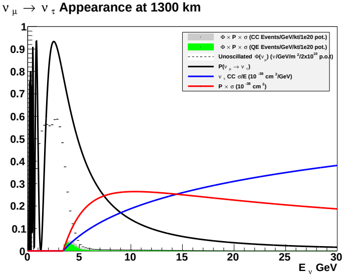
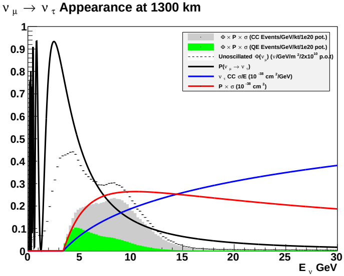
NuMI-like CD1 reference design could be tuned to higher energy to observe $\nu_\mu \to \nu_\tau$ with high statistics. In 40 ktons, 1yr at 1.2MW optimized to maximize ν_τ appearance:



CPV beam $\sim$ 60 ν_τ CC



ν_τ ME beam $\sim$ 700ν_τ CC

Increase ν_τ yield by $\sim 10\times$

Optimal ν_τ yield obtained with NuMI-style ME tune with Horn 1 and Horn 2 17m apart (in place of Horn A and C) and LBNF 2015 target design 2m upstream of Horn 1.

ν_τ Appearance Measurements in DUNE

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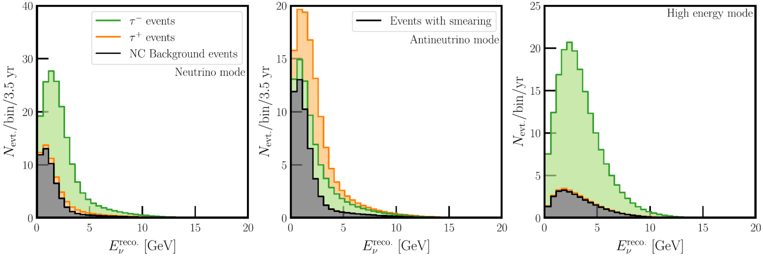
Using some optimistic assumptions about ν_τ CC events in DUNE with τ hadronic decays a possible signal in 3.5 yrs running in CPV optimized beam and 1 yr in a medium energy (ME) beam optimized to maximize ν_τ CC rates:

Appearance spectra



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

Simple Unitarity Tests with ν_τ Appearance in DUNE

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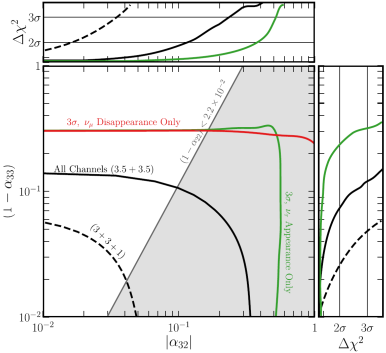
Run in 3.5 (ν) +3.5 ($\bar{\nu}$) years with ν_μ disappearance, ν_e appearance and ν_τ appearance in the default low-energy beam or combine all 3 modes with 3+3 years in LE + 1 year in ME beam:

U: Unitary matrix, N: non-unitary matrix

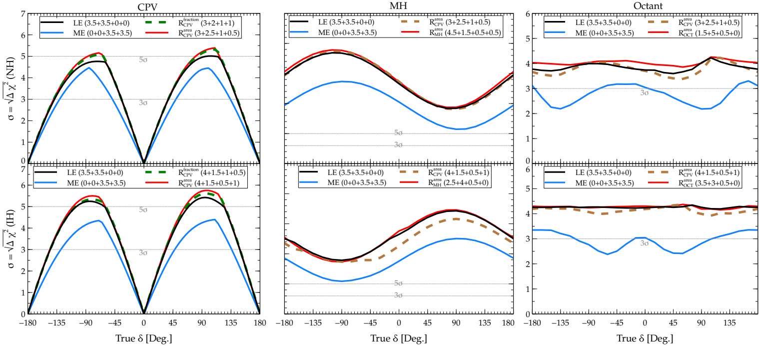
$$U \rightarrow NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$



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

LE and ME Runtime Optimization Study

Combine ν_e and ν_τ appearance signals and optimize runtime in CPV (LE) optimized beam and the ME beam optimized for ν_τ appearance to improve CPV/MH and octant sensitivity:



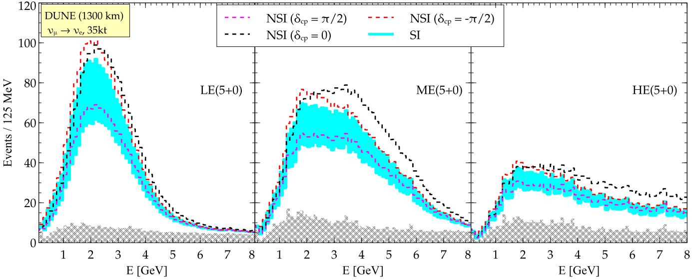
NEW: arXiv:2009.05061 (2020)

Running a small fraction of time in the ME tune for ν_τ studies can also improve other 3-flavor measurements when properly combined with LE running.

LBNF/DUNE Medium Energy Beams and NSI

P. Mehta, M. Masud, M. Bishai

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



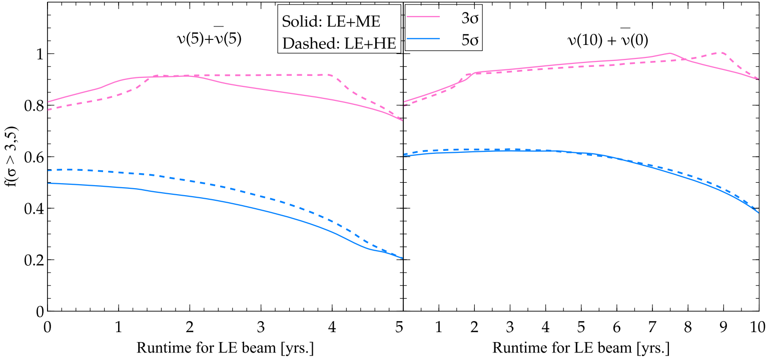
NSI effects in $\nu_\mu \rightarrow \nu_e$ are larger at higher energy

* **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.**

SI/NSI Separation with Different Beams

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

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



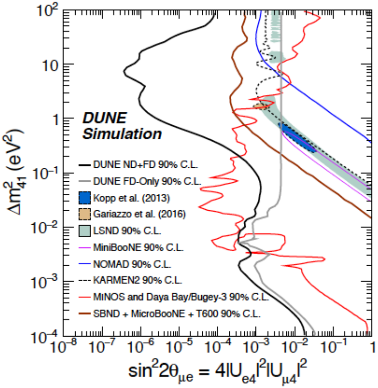
Can achieve 3σ separation for > 80% of true δ_{cp}

No beam optimization attempted yet!

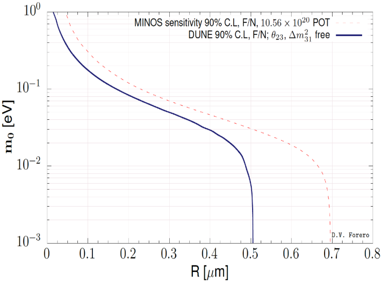
Sterile/LED Searches with LBNF/DUNE

From the TDR (running only in CPV optimized beam)

Sterile



Large Extra Dimensions



HE beam would greatly improve sensitivity

Study of CPV+HE running should be done for Snowmass

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Physics with Low Energy Beam Upgrades

DUNE+PIPIII SCLinac to improve δ_{cp} Resolution

Proposed for the last Snowmass by BNL team (preDUNE) for ProjectX:

arXiv:1307.0807v1 [hep-ex] 2 Jul 2013

Precision Neutrino Oscillation Measurements using Simultaneous High-Power, Low-Energy Project-X Beams

M.Bishai, M.Diwan, S.Kettell, J.Stewart, B.Viren, E.Worcester
Brookhaven National Laboratory

R.Tschirhart
Fermi National Accelerator Laboratory

L.Whitehead
University of Houston

Abstract

The first phase of the long-baseline neutrino experiment, LBNE10, will use a broadband, high-energy neutrino beam with a 10-kt liquid argon TPC at 1300 km to study neutrino oscillation. In this paper, we describe potential upgrades to LBNE10 that use Project X to produce high-intensity, low-energy neutrino beams. Simultaneous, high-power operation of 8- and 60-GeV beams with a 200-kt water Cerenkov detector would provide sensitivity to $\nu_\mu \to \nu_e$ oscillations at the second oscillation maximum. We find that with ten years of data, it would be possible to measure $\sin^2(2\theta_{13})$ with precision comparable to that expected from reactor antineutrino disappearance and to measure the value of the CP phase, δ_{CP}, with an uncertainty of $\pm(5-10)^\circ$. This document is submitted for inclusion in Snowmass 2013.

Study is being redone with DUNE setup for the PIPII SC Linac option.

V. PRELIMINARY: 8 GeV beam with CPV focusing

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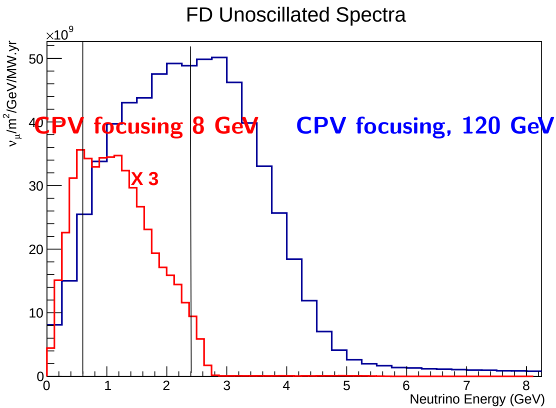

Assume a 4 MW SCLinac at 8 GeV with 3 MW for LBNF/DUNE

With PIPIII expect 2.4MW at 120 GeV from Main Injector

Assume we can interleave 8 GeV pulses with 120 GeV pulses

V. PRELIMINARY: Event Spectra

from P. Mehta, JNU

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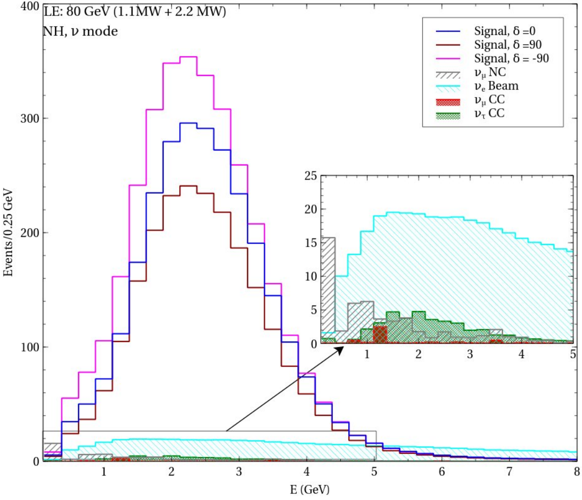
Neutrino mode: 120 GeV, 1.2 MW for 5 yrs + 120 GeV, 2.4MW for 5 yrs



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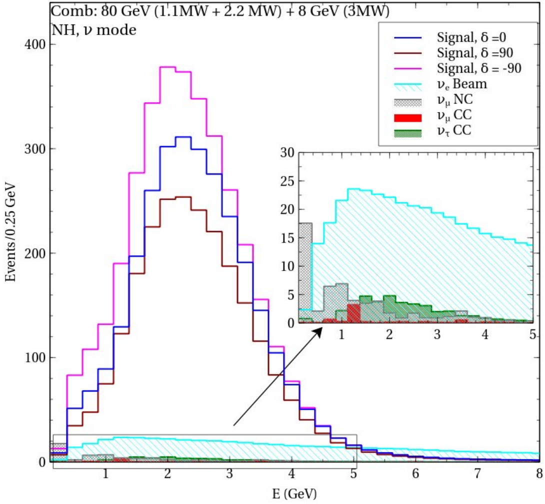
Neutrino mode: 120 GeV, 1.2 MW for 5 yrs + 120 GeV, 2.4MW for 5 yrs + 8 GeV, 3 MW for 5 yrs (simultaneous with 2.4MW)



V. PRELIMINARY: δ_{cp} Resolution

from P. Mehta, JNU

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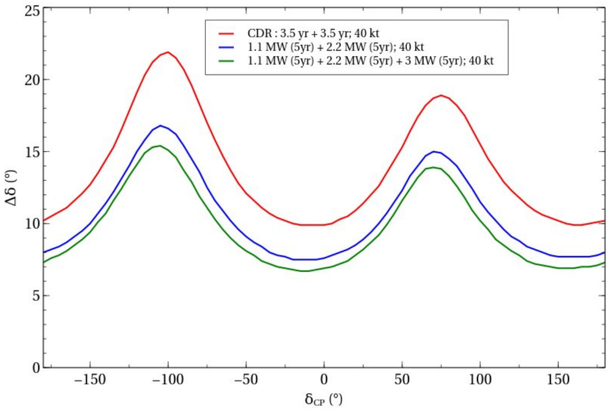
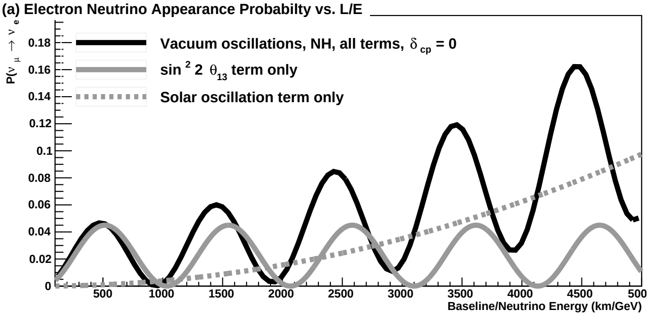


Some small improvement on δ_{cp} resolution. Need better detector resolution at 2nd maxima to fully study this option

How about the solar parameters?

If we can lower the energy of the neutrinos from PIPIII - can we start to access the solar parameters in $\nu_\mu \rightarrow \nu_e$ oscillations?



Need to explore ways of getting lower energy beams and higher power with PIPIII
Would need to be coupled with a high resolution FD!

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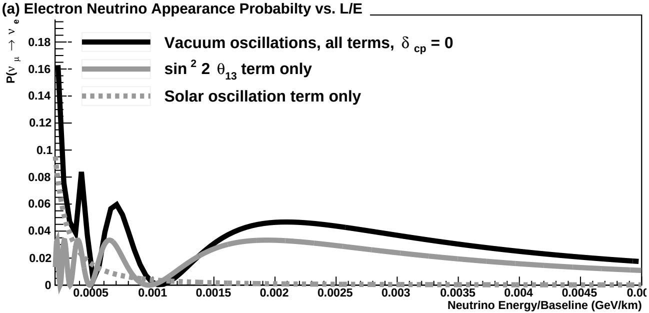

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Summary

Some parting thoughts...

DUNE is the only future long-baseline neutrino experiment with potential access to the full spectral information of $\nu_\mu \to \nu_x$ oscillation with $x = e, \mu, \tau$.

- **T2HK is 10x larger - it comes online earlier or at the same time and may reach desired CPV sensitivity first.**
- **The flexibility of the design and PIPIII offer unique opportunities for DUNE. There is interest in the international community to do physics at the 2nd maxima - T2KK and ESSνSB for example. DUNE already does this physics and can do even better with beam upgrades.**
- **Is it too early to consider upgrades and the expanded program? ABSOLUTELY NOT! You cannot retrofit a neutrino beamline to operate in multi-MW beams with new focusing designs if it hasnt been designed to be upgradable. After CD2 its too late to change the design.**