Physics Opportunities at DUNE with Future Beam Upgrade

Mary Bishai Brookhaven National Laboratory

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Brookhaven National Laboratory

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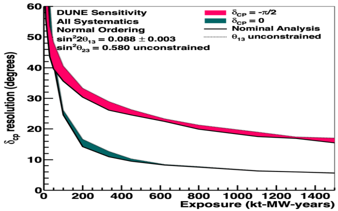
Recap of last meeting

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



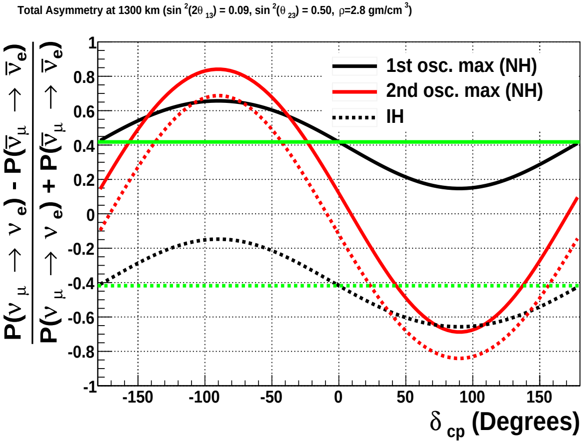
- **How can we best probe for new sources of ν CPV? Search for physics beyond the νBSM?**
- **How does the hunt for sterile neutrinos evolve beyond SBN and SBL reactor?**
- **Is the PMNS matrix unitary?**

BNL lead the community in defining the current program of ν oscillation experiments

Design of the LBNF/DUNE Beamline

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:



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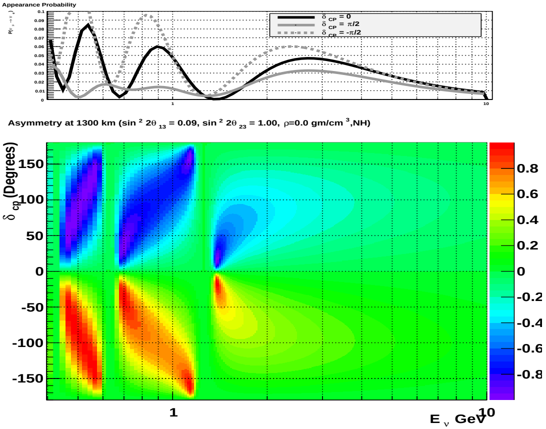

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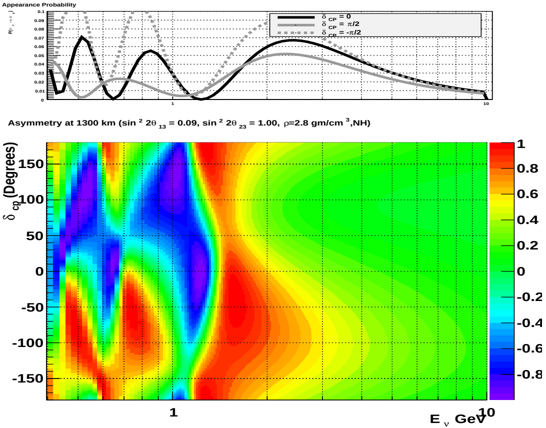

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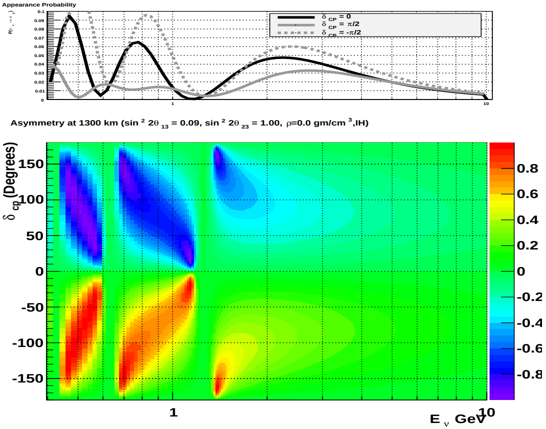

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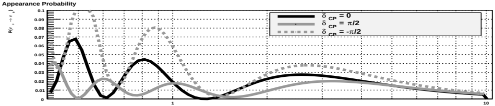
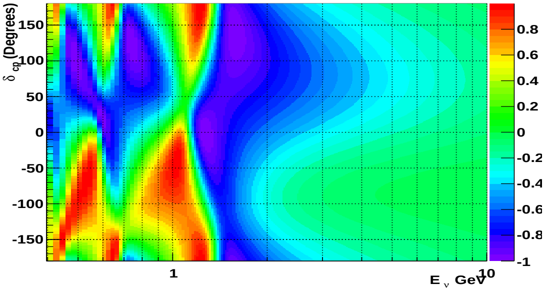


Asymmetry at 1300 km ($\sin^2 2\theta_{13} = 0.09$, $\sin^2 2\theta_{23} = 1.00$, ρ=2.8 gm/cm^3,IH)



Global Science Requirements of the Beam

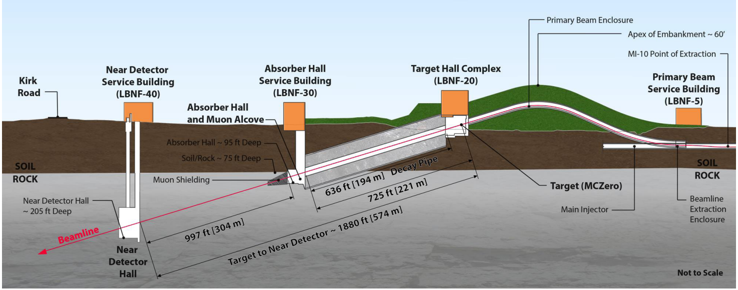
From DUNE/LBNF's formal requirement document:

Glo-Sci-13: The neutrino beam spectrum shall cover the energy region of the first two oscillation maxima affected by muon-neutrino conversion from the atmospheric parameters.

Glo-Sci-60: The neutrino beam spectrum shall extend beyond the first maximum to higher energies, while maintaining a high signal to background ratio to obtain the maximum number of charged current signal events.

Glo-Sci-14: The neutrino beam spectrum shall be tunable so that beam with both lower peak energy (below the first oscillation node) and higher peak energy (significantly higher than the first oscillation node) can be achieved without substantial downtime that reduces the overall exposure.

Overview of the LBNF Beamline

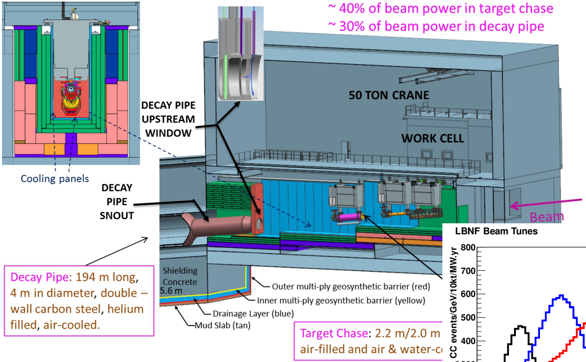


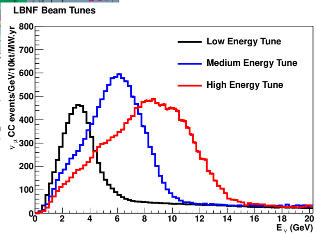
- **Primary proton beam 60-120 GeV**
- **Initial 1.2 MW beam power, upgradable to 2.4 MW**
- **Embankement allows target complex to be at grade**
- **Wide-band beam (on-axis) optimized for CP violation sensitivity**
- **Decay pipe: 194m x 4m diameter, He filled**

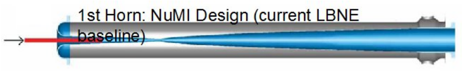
ND default: 574 m from target, FD: 1300 km

The LBNF Reference Design (up to 2015)

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



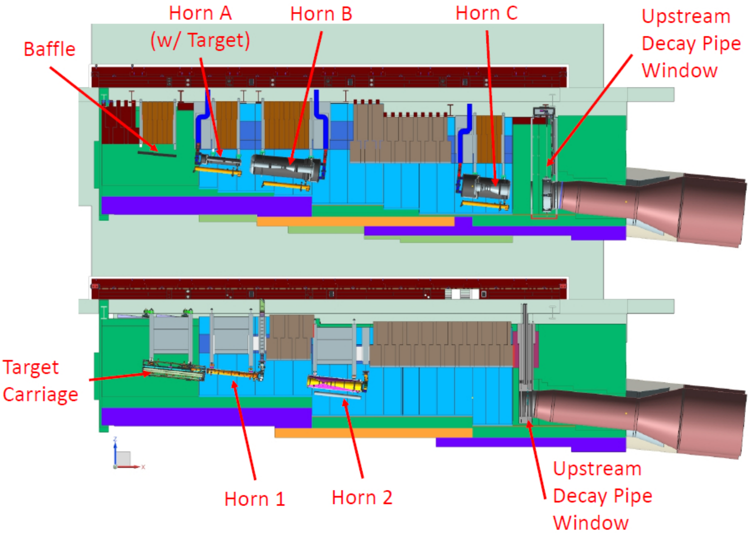




LBNF has switched to CPV optimized focusing design with 3 horns

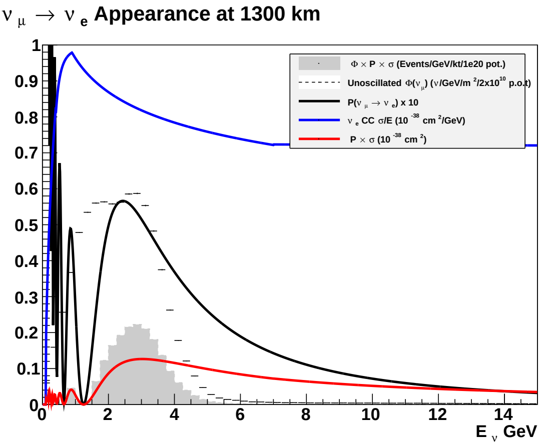
CPV Optimized Design

Target hall layout 3-horn optimized vs CD1R reference designs:



CPV Optimized Design

The CPV optimized focusing design:

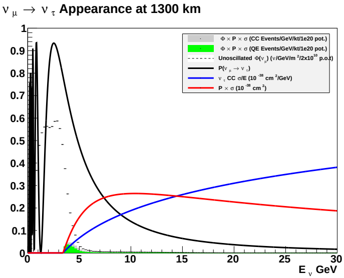


The 2015 CD1R *highly tunable* focusing design can be deployed as upgrade to provide higher energy beams

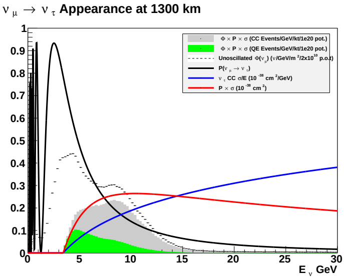
Physics with High Energy Beam Upgrades

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

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



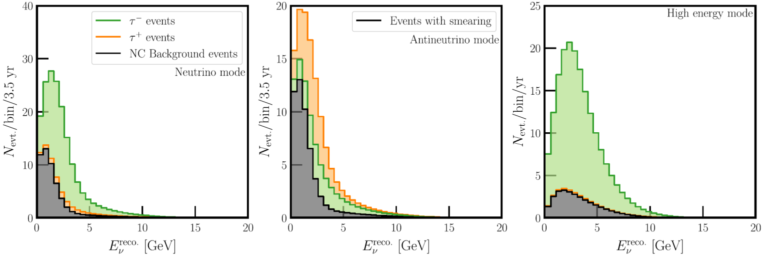
ν_τ HE beam $\sim$ 700ν_τ CC

Increase ν_τ yield by $\sim$ 10$\times$

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 a HE beam optimized to maximize ν_τ CC rates:

Appearance spectra



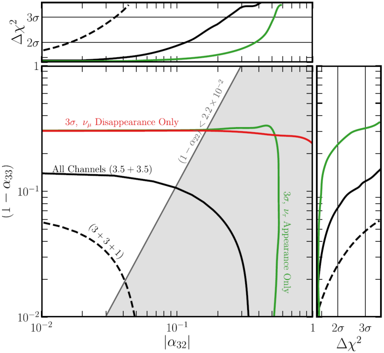
Phys. Rev. D. 100, 016004 (2019)

Simple Unitarity Tests with ν_τ Appearance in DUNE

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

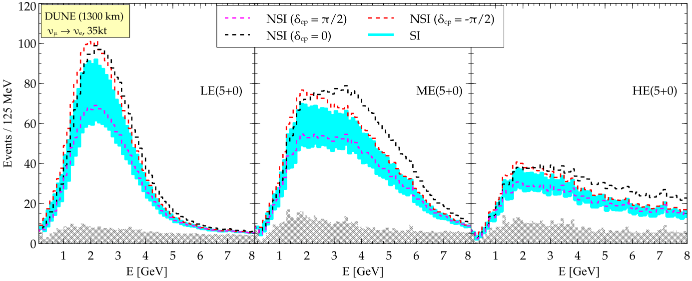
$$U \rightarrow NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$



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

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:

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



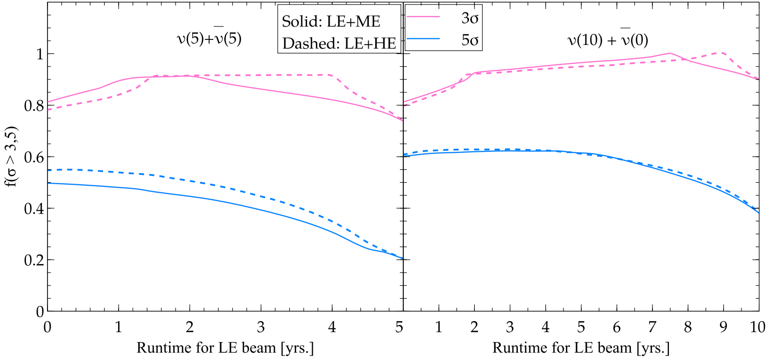
NSI effects in $\nu_\mu \rightarrow \nu_e$ are larger at higher energy

* 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 $3/5\sigma$ level:



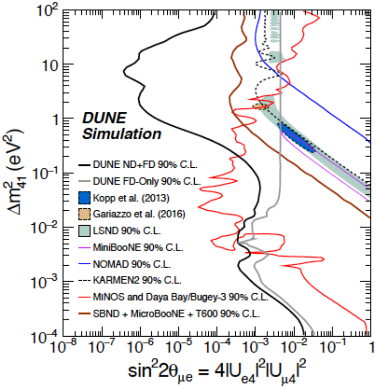
Can achieve 3σ separation for $>80\%$ of true δ_{cp}

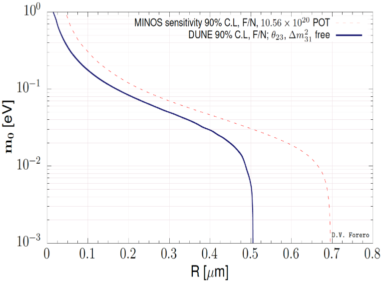
No beam optimization attempted yet!

Sterile/LED Searches with LBNF/DUNE

From the TDR (running only in CPV optimized beam)

Sterile | **Large Extra Dimensions**





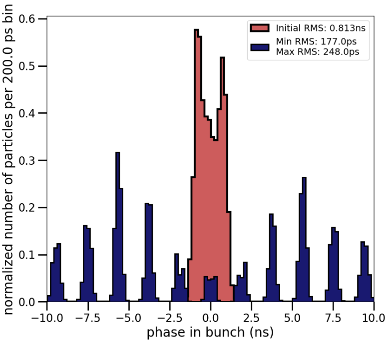
HE beam would greatly improve sensitivity

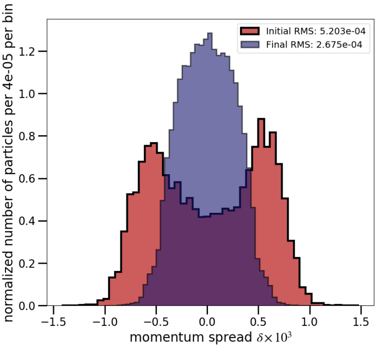
Study of CPV+HE running should be done for Snowmass

Stroboscopic beams

Energy and Flavor Discrimination using Precision Time Structure

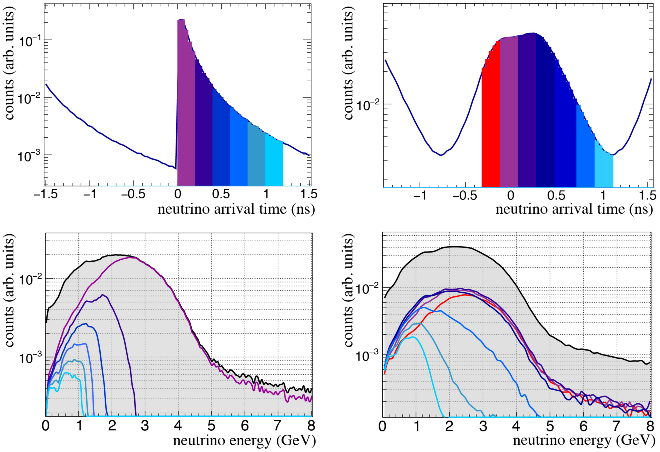
Phys. Rev. D100 no3, 032008 Proposal to upgrade the Fermilab 53MHz Main Injector complex to deliver a higher frequency RF bunch structure (531 MHz). This will result in sub-ns bunch width:





Initial (53MHz) and final (531 MHz) bunches projected onto phase space variables δ and ϕ

Energy and Flavor Discrimination using Precision Time Structure



0 bunch width perfect det. timing **250ps bunch width 100ps det. res.**

ND Physics ?

DISCUSSION: ND physics possibilities

- **HE beams + intense neutrino source: new measurements of θ_W**
- **Stroboscopic beams: new phase space from heavy neutrals and new physics - esp when coupled with off-axis.**
- **ν scattering physics: xF_3, nuclear shadowing (Stan Brodsky's comment yesterday)**

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:

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

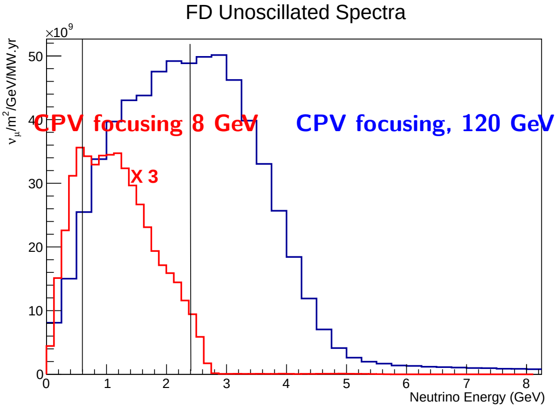
L.Whitehead
University of Houston

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 $\nu_\mu \rightarrow \nu_e$ 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 $\pm(5-10)°$. This document is submitted for inclusion in Snowmass 2013.

Study is being redone with DUNE setup for the PIPII SC Linac option- publication by 2020

V. PRELIMINARY: 8 GeV beam with CPV focusing



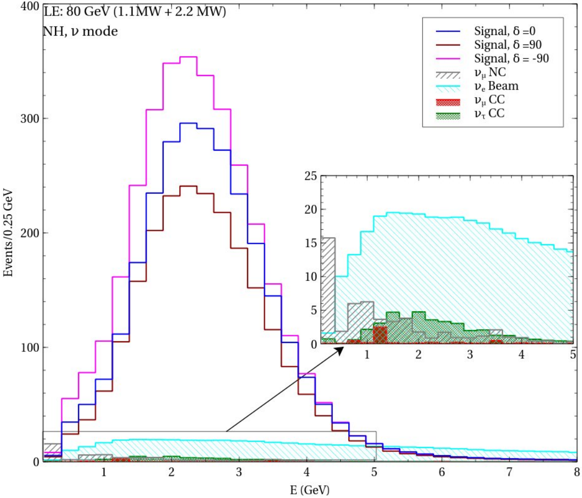
Assume a 4 MW SCLinac at 8 GeV with 3 MW for LBNF/DUNE

With PIPIII expect 2.4MW at 120 GeV from Main Injector

Assume we can interleave 8 GeV pulses with 120 GeV pulses

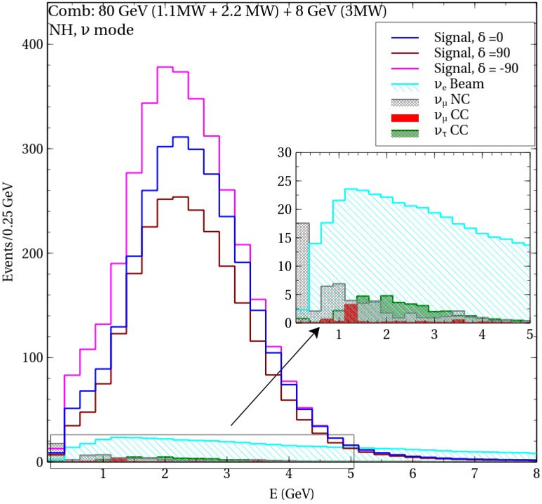
V. PRELIMINARY: Event Spectra

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

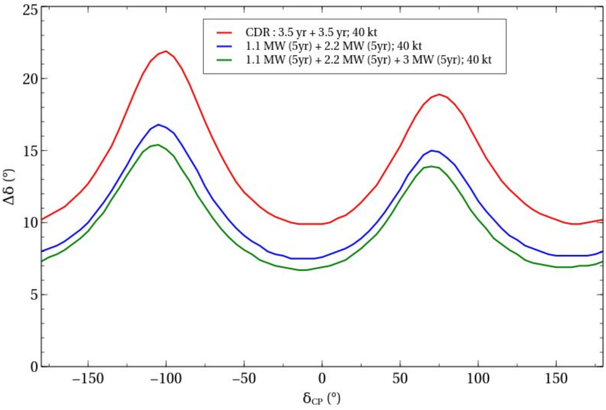


V. PRELIMINARY: Event Spectra

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)



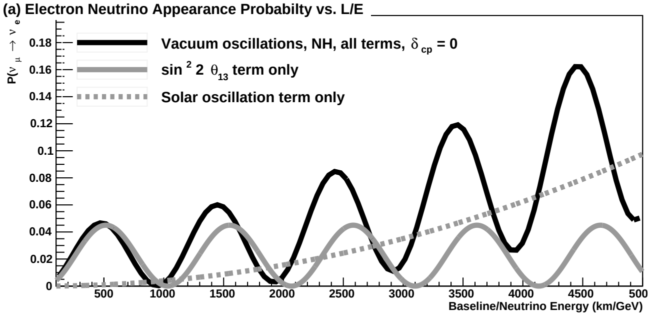
V. PRELIMINARY: δ_{cp} Resolution



Meh... but still looks like we can push down on δ_{cp} resolution

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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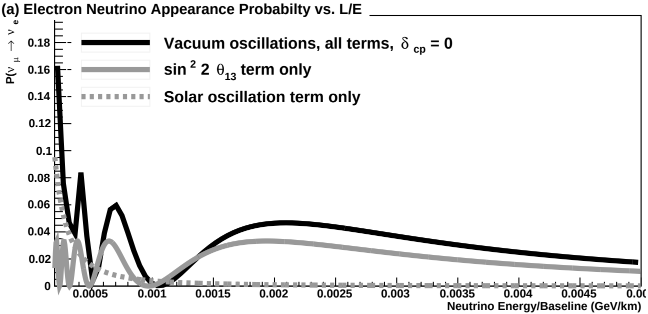

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Summary

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 $x = e, \mu, \tau$.

- **Lets be honest ... T2HK is 10x larger - it comes online earlier or at the same time and will reach desired CPV sensitivity first. Japans commitment to the project has grown stronger.**
- **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.**
- **a wider ND physics program should be considered**