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Long Baseline ν Oscillations
Ferimlab ν beams
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LBNE Beam Neutrinos and the 3-flavor Paradigm

ISOUPS 2013, Asilomar, CA May 24-27, 2013

Mary Bishai
Brookhaven National Laboratory

May 25, 2013

Outline

1 Introduction
- Neutrino Mixing
- Long Baseline ν Oscillations

2 Ferimlab ν beams
- Beams
- Which Baseline?

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4 Summary and Conclusions

NEUTRINO MIXING AND OSCILLATIONS

3-flavor Oscillations: Two Different Mass Scales!

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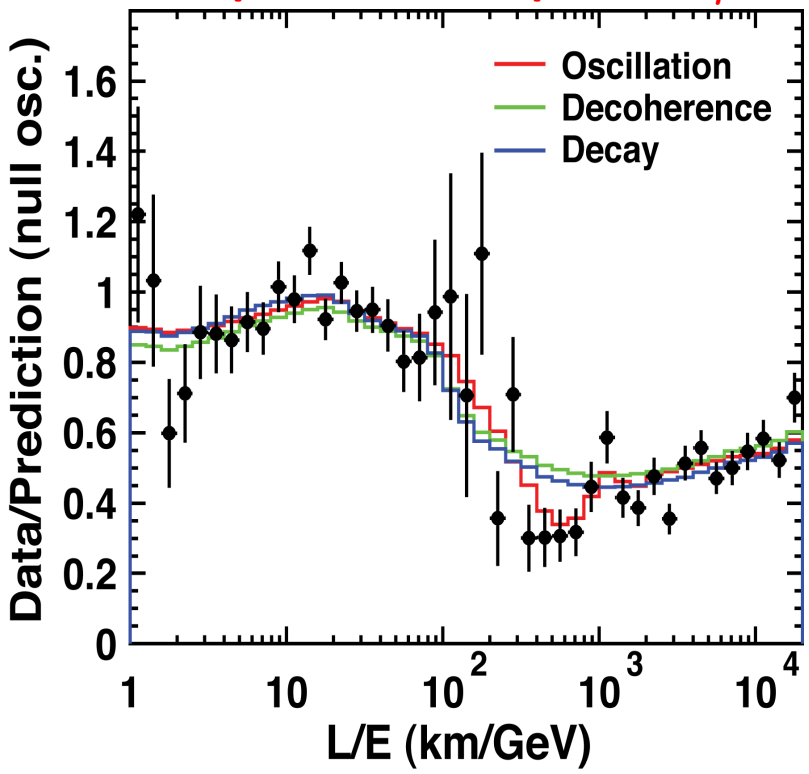
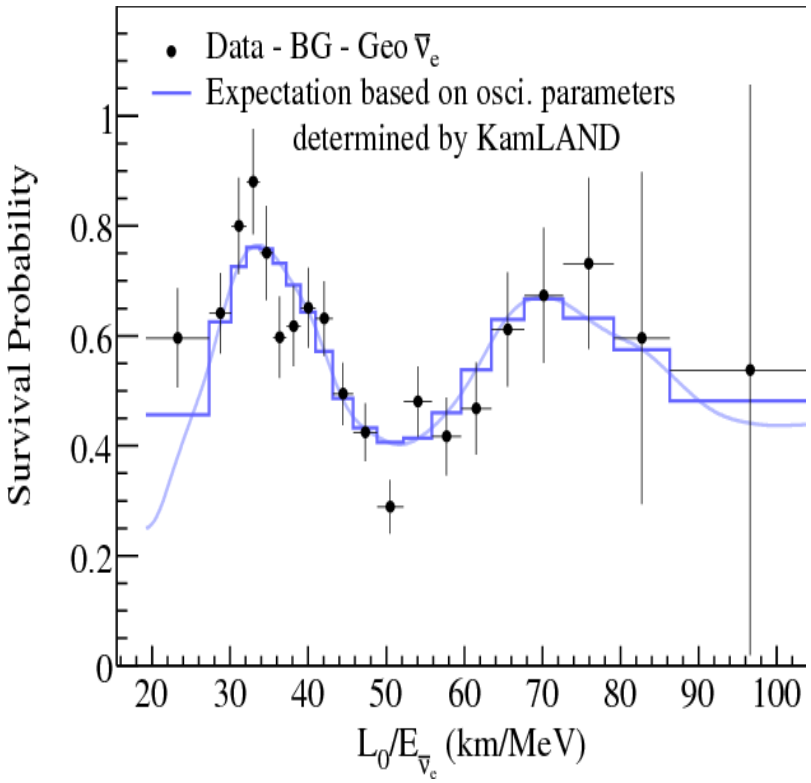
Super-K, atmospheric ν_μ



KamLAND, reactor $\bar{\nu}_e$



Global fit 2013:

$$\Delta m^2_{atm} = 2.43^{+0.06}_{-0.10} \times 10^{-3}\ eV^2$$

$$\sin^2\theta_{atm} = 0.386^{+0.24}_{-0.21}$$

Atmospheric L/E $\sim$ 500 km/GeV

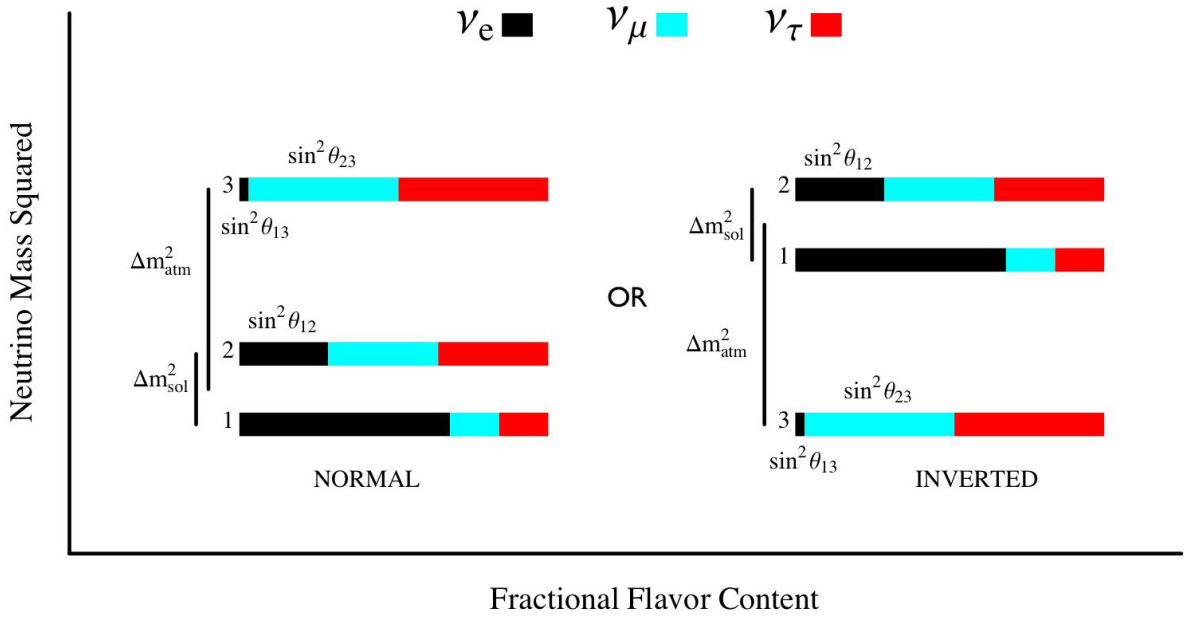
Global fit 2013:

$$\Delta m^2_{solar} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ eV^2$$

$$\sin^2\theta_{solar} = 0.307^{+0.18}_{-0.16}$$

Solar L/E $\sim$ 15,000 km/GeV

Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales, and a CP violating phase



Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
θ_{12} (solar)	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$
θ_{23} (atm.)	$38 \pm 1^\circ$	$2.38 \pm 0.06^\circ$
θ_{13}	$8.9 \pm 0.5^\circ$	$0.201 \pm 0.011^\circ$
Δm^2_{solar}	$+(7.54 \pm 0.22) \times 10^{-5}$ eV^2	
$\lvert\Delta m^2_{atm.}\rvert$	$(2.43^{+0.10}_{-0.06}) \times 10^{-3}$ eV^2	$m_3 >> m_2$
δ_{CP}	$-170 \pm 54^\circ$	$67 \pm 5^\circ$

Unknown: Is $m_1 < m_3$ or vice versa?. Whats the value of δ_{cp}?

Neutrino Interaction Cross-sections (G. Zeller)

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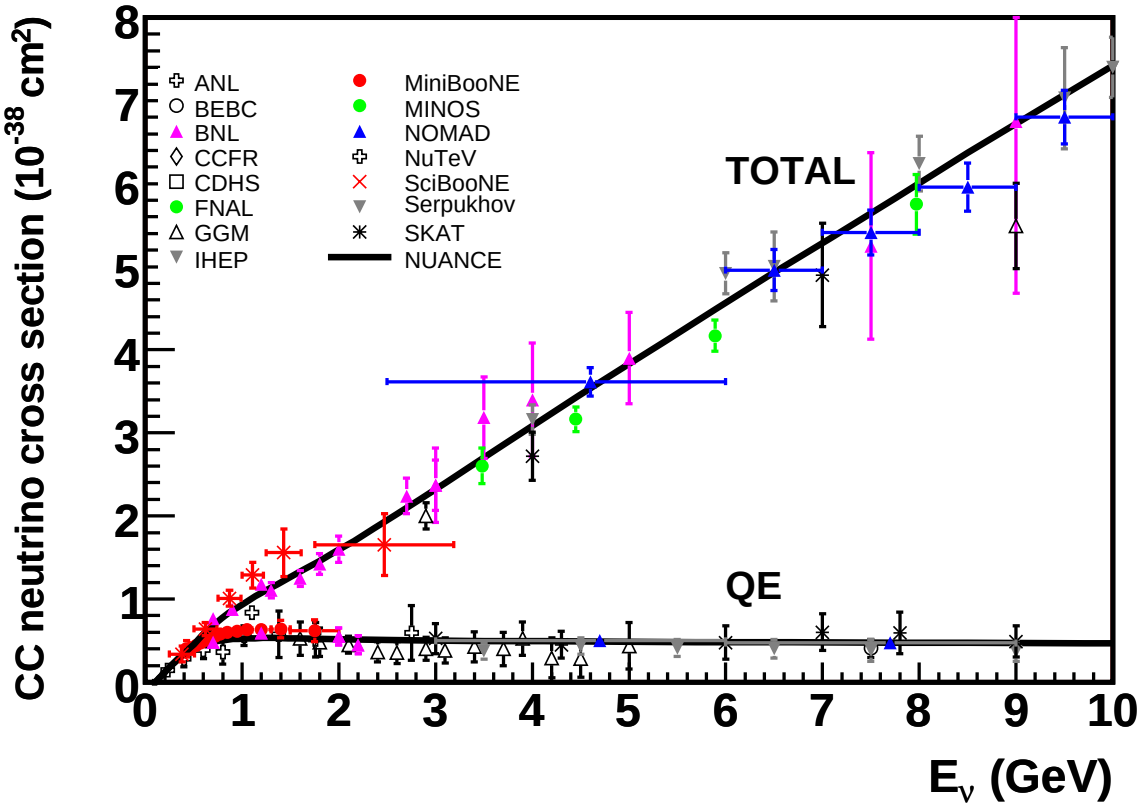
Neutrino CC cross-sections are very small and scale with energy:

Neutrino cross-sections



Long baseline oscillations over 100's km and $\geq$ 200 MeV energies needed to probe CPV

Neutrino Interaction Cross-sections (G. Zeller)

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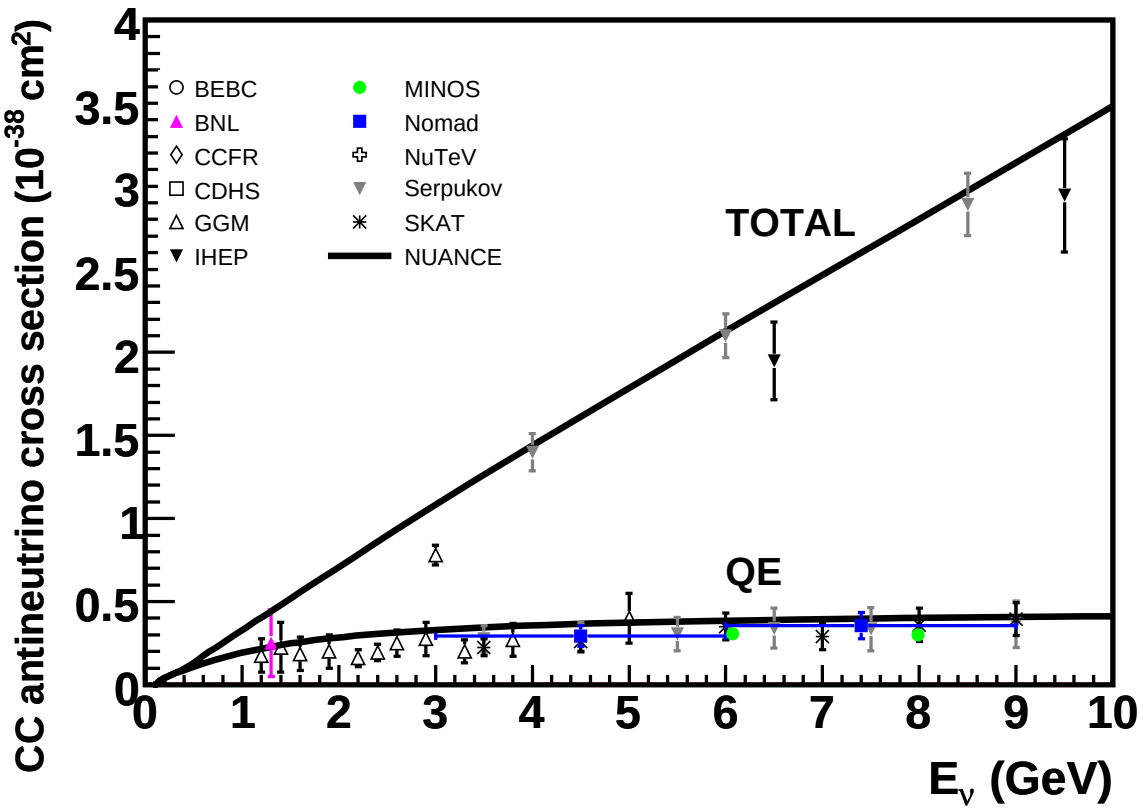
Anti-neutrino cross-sections



Long baseline oscillations over 100's km and $\geq$ 200 MeV energies needed to probe CPV

Matter and CP effects on Oscillations

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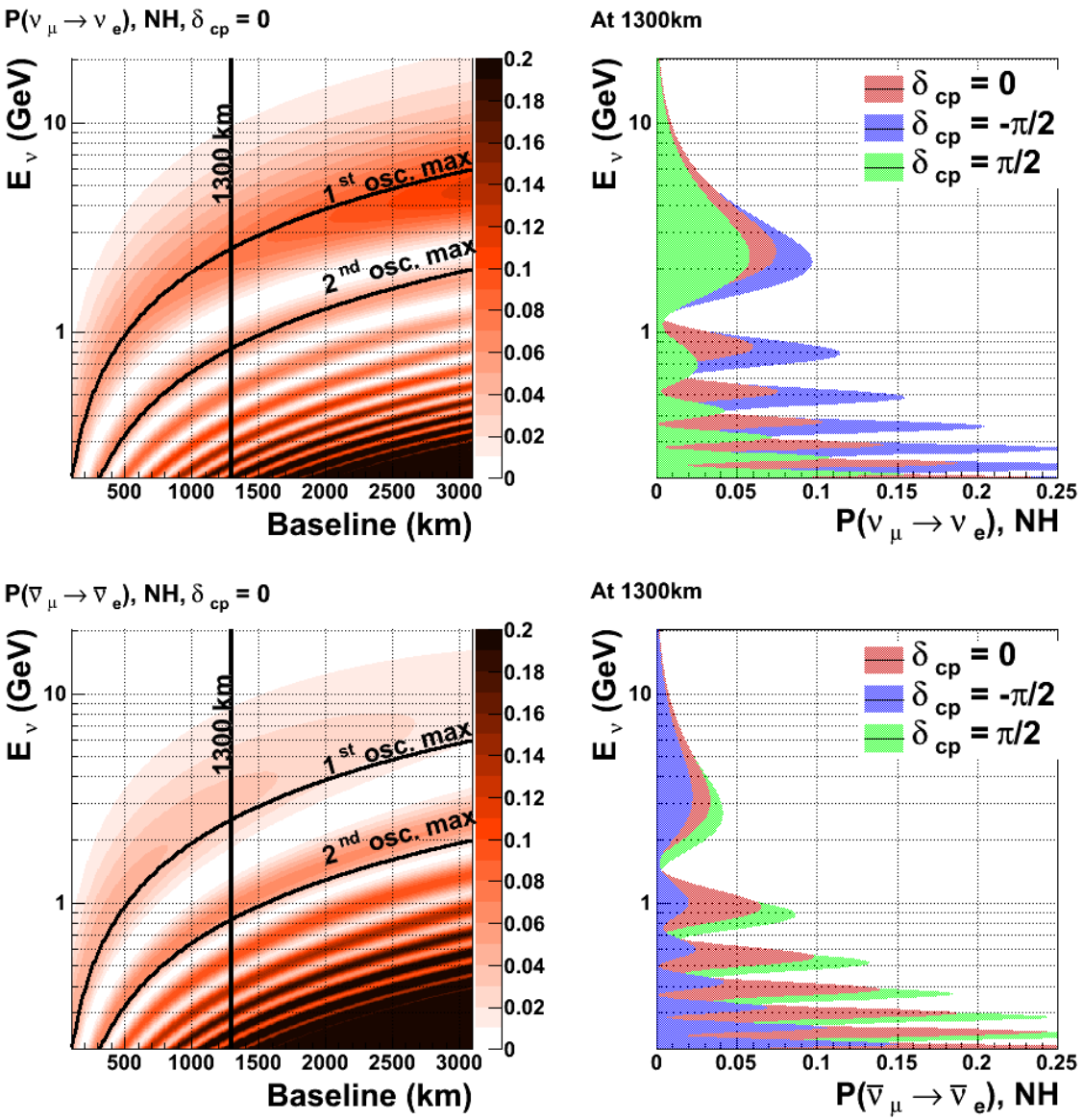

Matter and CP effects on Oscillations

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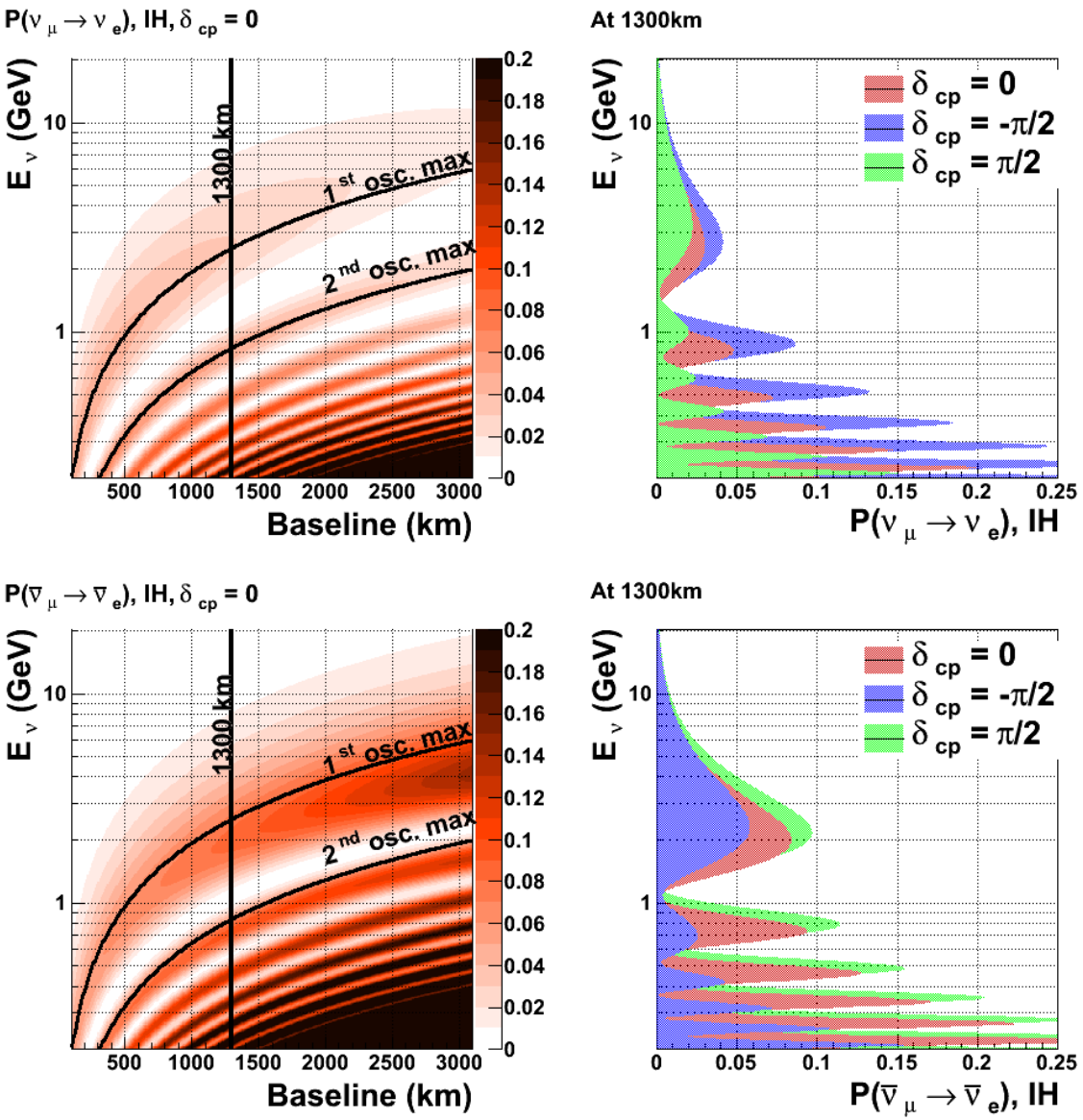


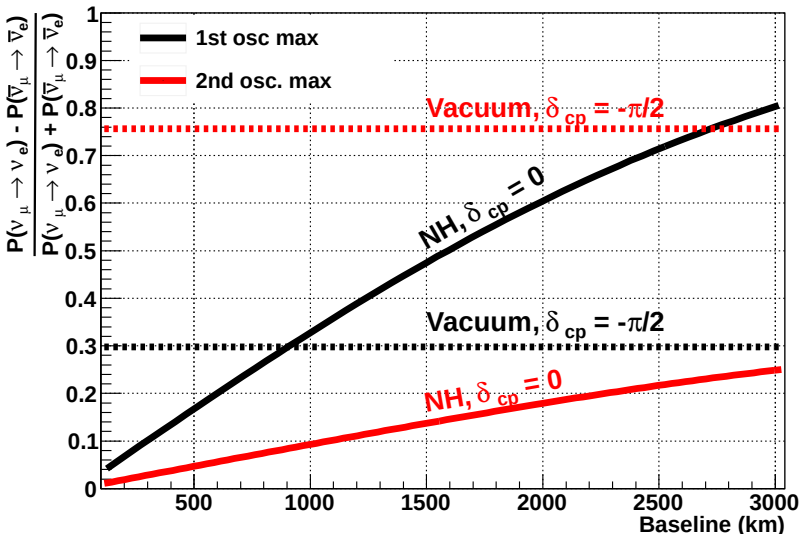
CP and Matter Asymmetries vs. Baselines for fixed L/E

The charge-parity (CP) asymmetry is defined as

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

$$\mathcal{A}_{cp} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$

Z. Parsa, W. Marciano, BNL



Matter and CP asymmetries have opposite effects at the 1st and 2nd oscillation maxima.

CP Asymmetries and the Mass Hierarchy

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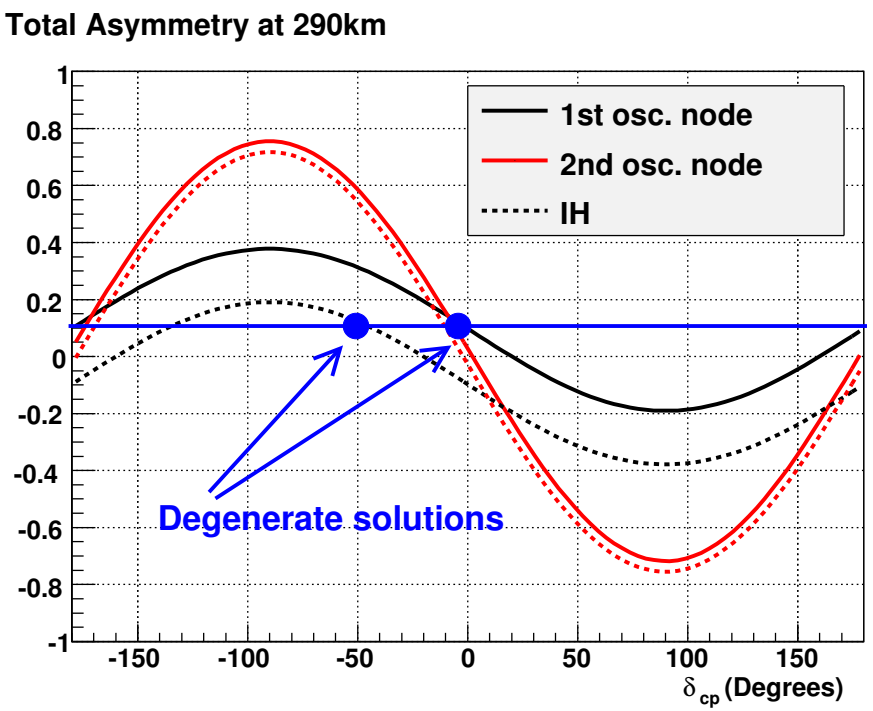
$\nu_\mu \longrightarrow \nu_e$ **oscillation maxima occur at**

$$E_\nu^n(\mathrm{GeV}) = \frac{2.5\Delta m_{32}^2(\mathrm{eV}^2)L(\mathrm{km})}{(2n-1)\pi} \quad n = 1, 2, 3...$$

L = 290km



At short baselines, irreducible degeneracies with MH,δ_{cp} at E_1

CP Asymmetries and the Mass Hierarchy

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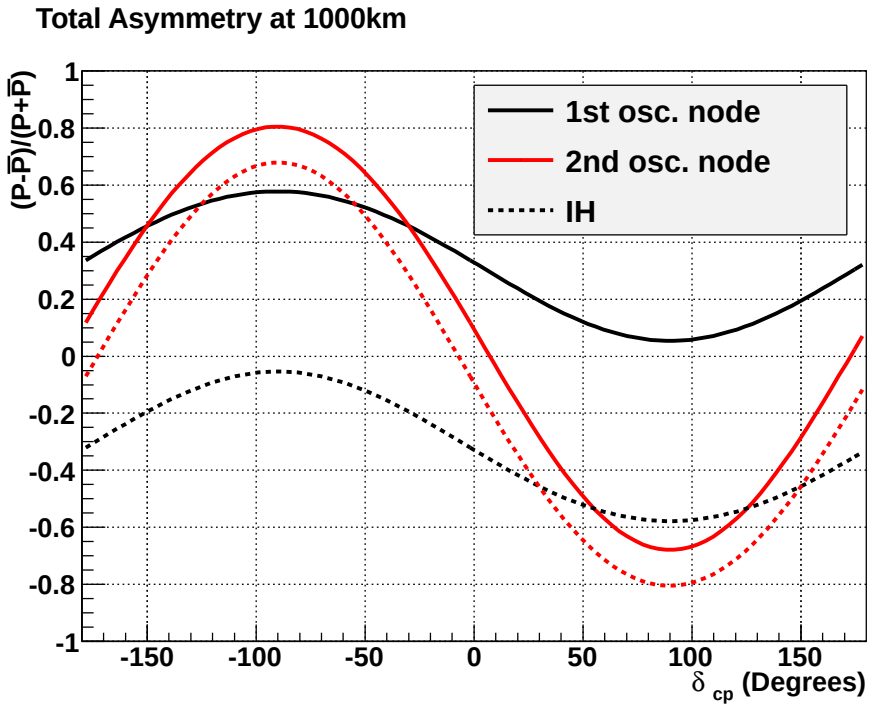
$\nu_\mu \longrightarrow \nu_e$ **oscillation maxima occur at**

$$E_\nu^n(\mathrm{GeV}) = \frac{2.5\Delta m_{32}^2(\mathrm{eV}^2)L(\mathrm{km})}{(2n-1)\pi} \quad n = 1, 2, 3...$$

L = 1000km



A baseline > 1000km is needed separate MH from δ_{cp}

ACCELERATOR ν FROM FERMILAB

The Fermilab Accelerator Complex 2012

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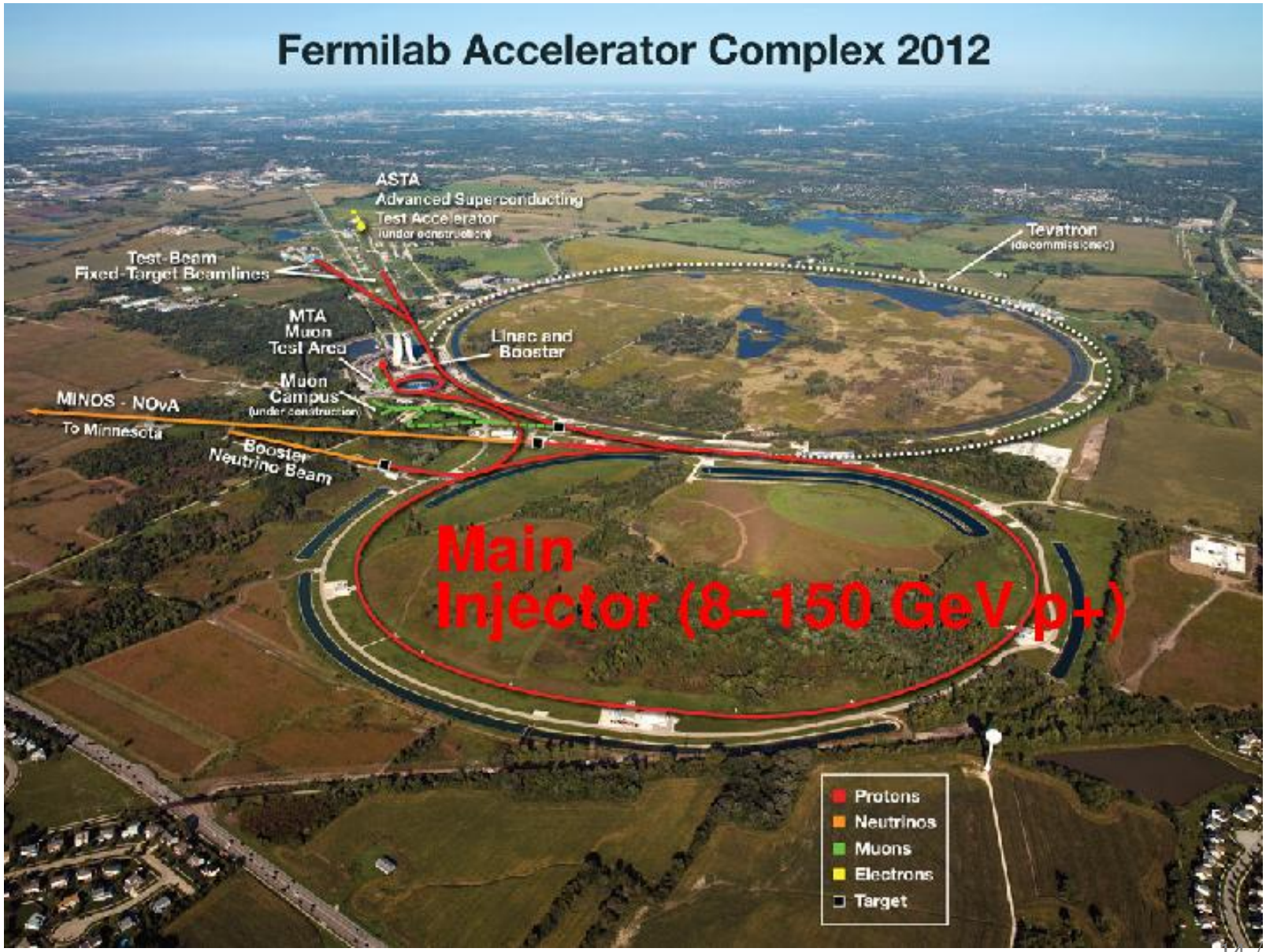

Fermilab Proton Plan

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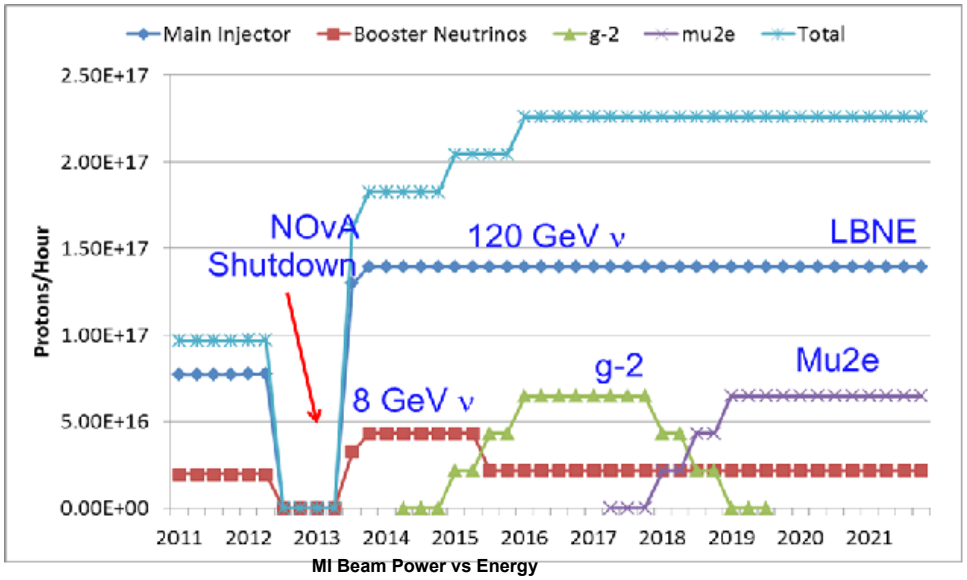

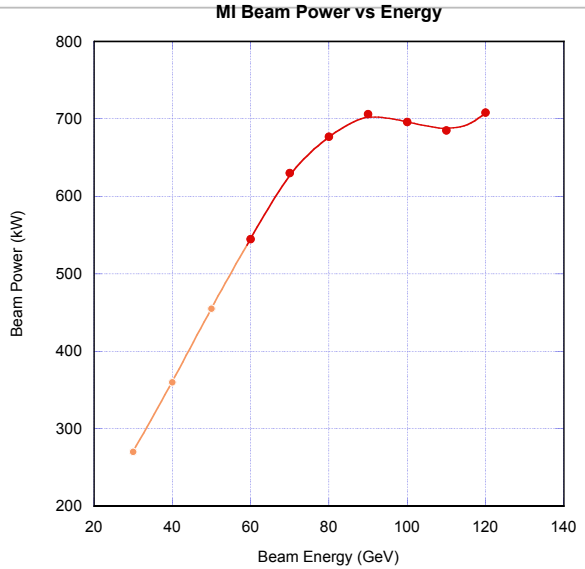

Fermilab proton improvement plan: MI: 700 kW at 80-120 GeV by 2014

Future plans at Fermilab: Project X

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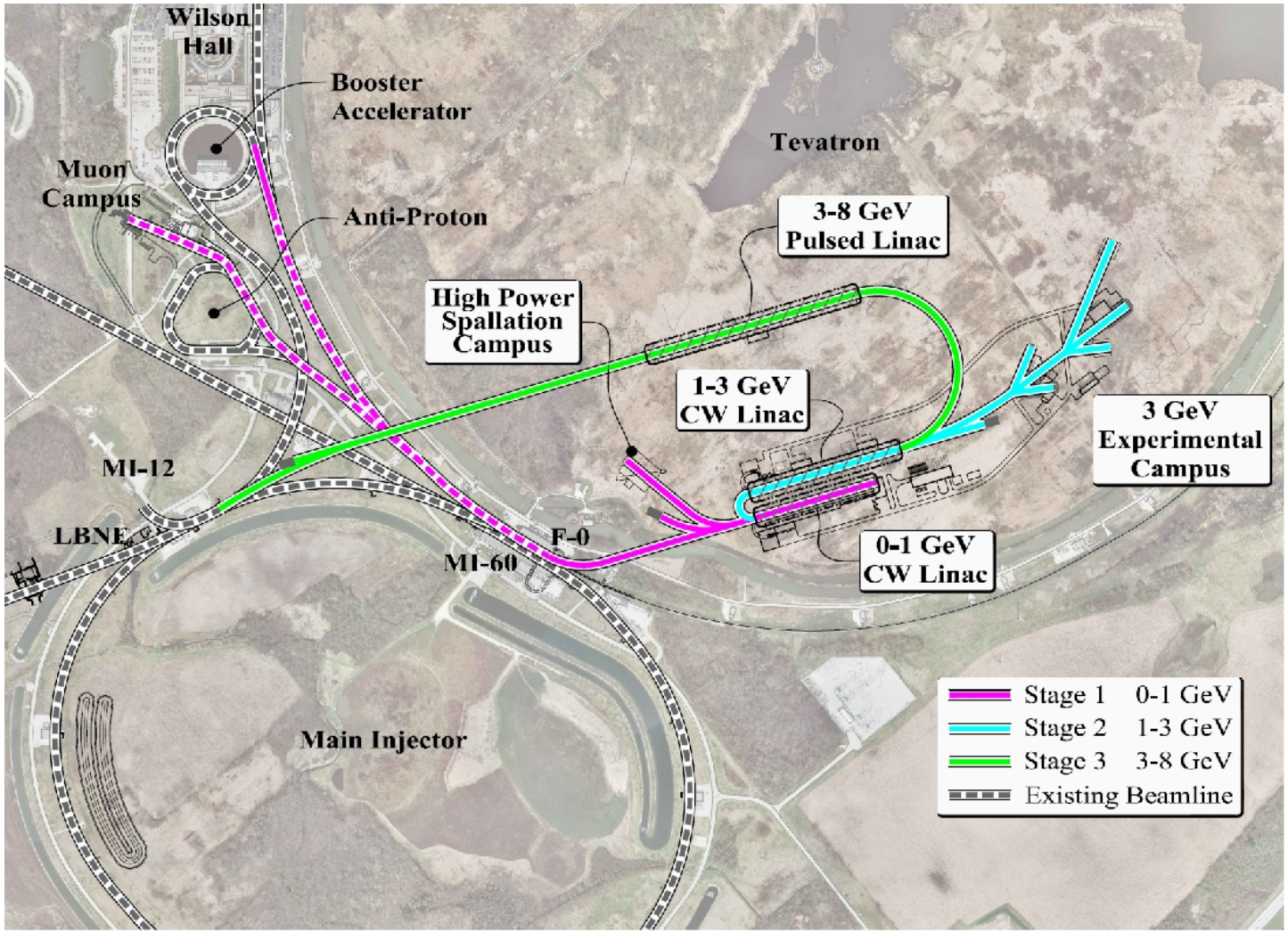
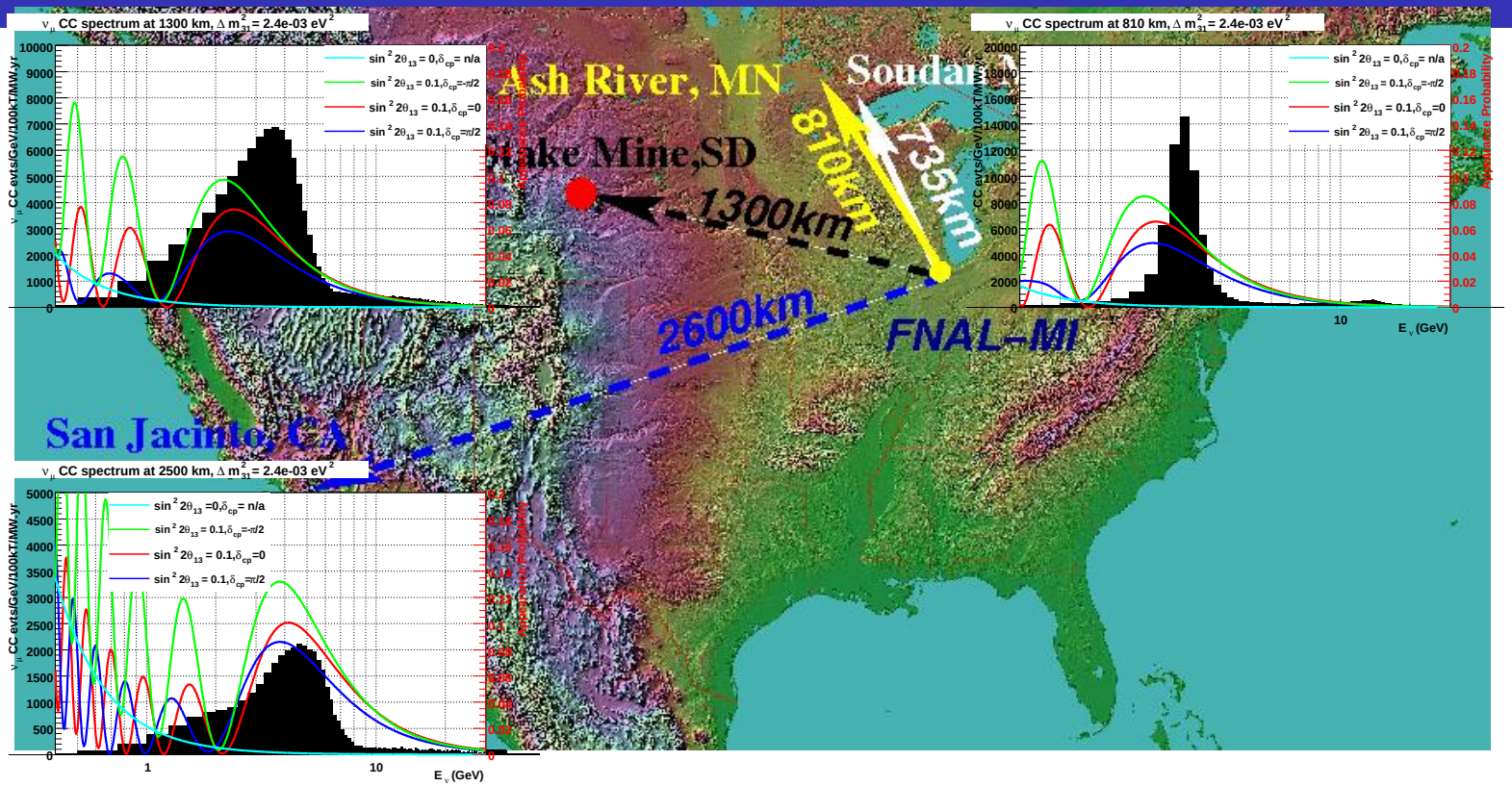


Beyond 2025?: 2.3 MW at 60-120 GeV

Superbeam Baselines in the U.S.



CC rates per 100kt.MW.yrs (1 MW.yr= 1×10^{21} p.o.t at 120 GeV)

$\theta_{13} = 0.156,\ \theta_{12} = 0.587,\ \theta_{23} = 0.670,\ \delta_{cp} = 0,\ \Delta m^2_{21}/m^2_{31} = 0.0754/2.47 \times 10^{-31}$ eV^2:

Expt	ν_μ CC	ν_μ CC osc	ν_μ NC	ν_e beam	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\tau$
Soudan 735km	59K	37K	16K	590	1100	383
Ash River 810km	16K	4.9K	4.0K	246	560	33
Hmstk 1300km	25K	9.4K	6.5K	210	930	300
Hmstk ME beam	38K	23K	11K	140	780	1300

Need MW beams and 100 kton detectors regardless of baseline!

Sensitivities vs Baseline

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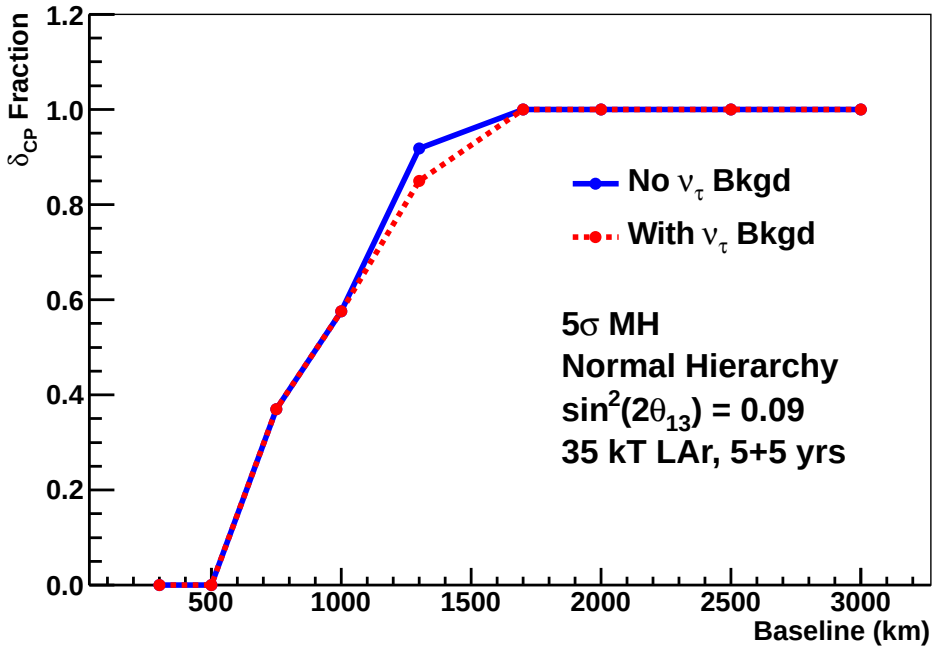
Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

Mass hierarchy senstivity at $\geq 5\sigma$



Baselines of 1500-1700km sufficient to resolve MH

Sensitivities vs Baseline

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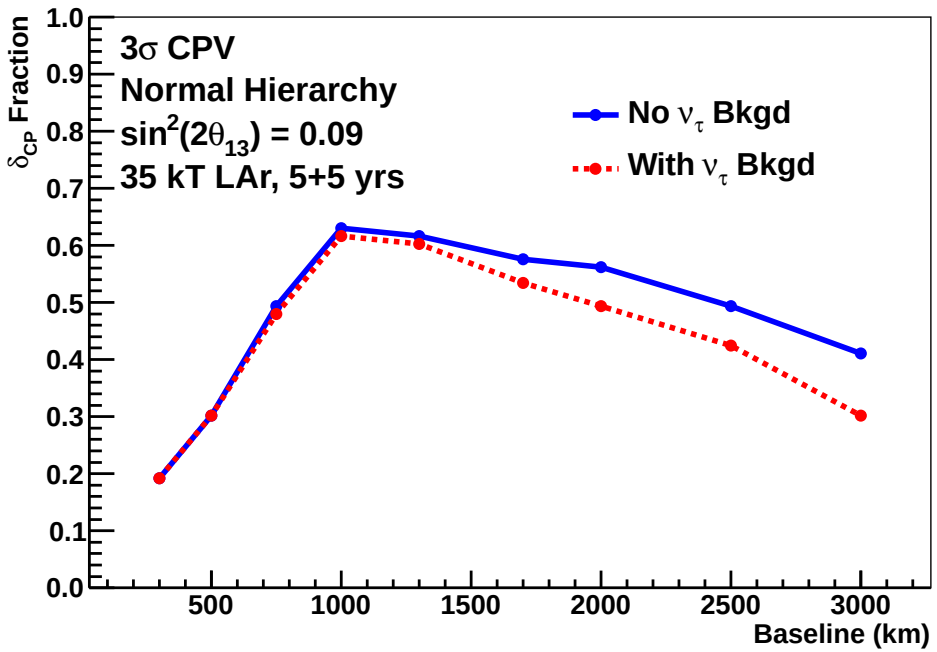
CP violation sensitivity at 3σ



Baselines of 1000-1500km best CPV sensitivity

The Long Baseline Neutrino Experiment

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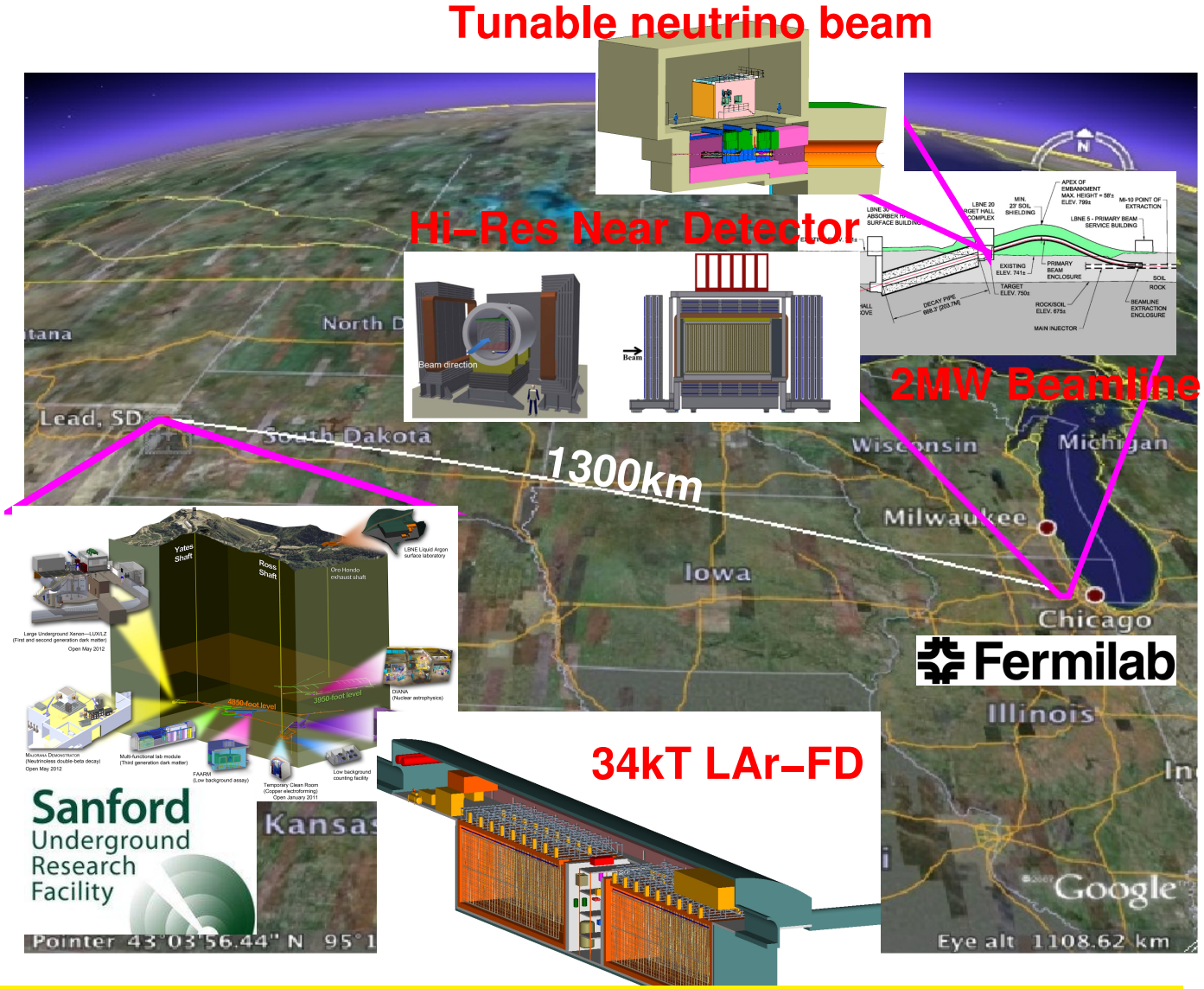

$\sim$ 350 people, 60 institutions from US, India, Italy, Japan, UK

LBNE Staging (M. Diwan)

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Summary and Conclusions

- **US-DOE has asked us to phase LBNE with the first phase $\sim$ \$850M. This has been given a high priority in the US. The full cost is $\sim$ \$1.4B.**
- **We have chosen to proceed with the most important aspect of the experiment:1300 km baseline and the full capability beam. To keep the project cost down we chose to consider a 10 kt LAr detector on the surface.**
- **Construction will start on the beam first with site investigation to begin this year !**
- **The goal of the first phase is to place this detector underground and have a full capability near detector.**
- **New partnerships will enable this expanded scope in a timely way. The US-DOE is very supportive of this strategy.**

The LBNE ν Beamline

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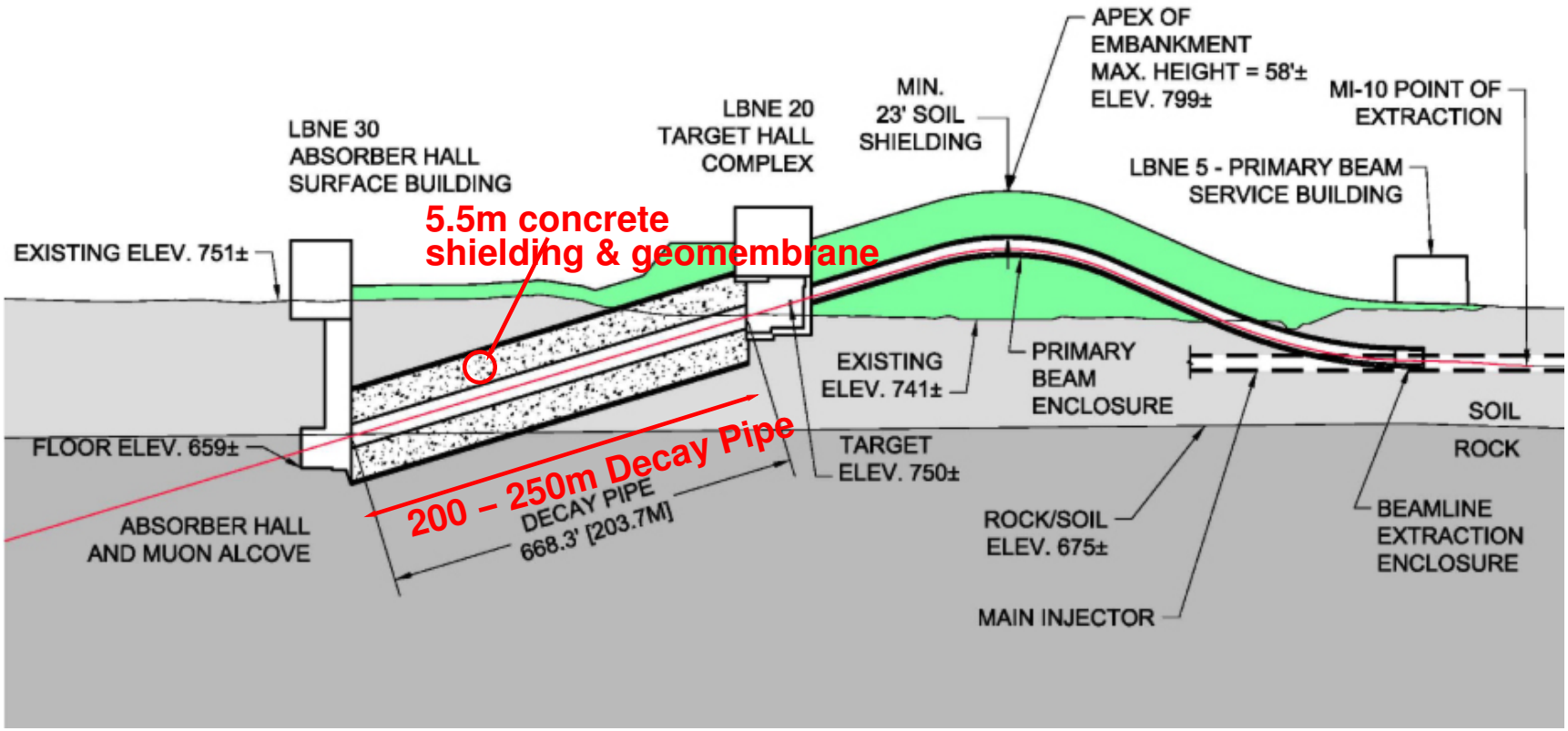
Novel beam-on-a-hill construction for 2.3MW from 60-120GeV



Cost: $\sim$ 390$M AY (CD1) with 204m decay pipe

(incl 30% cont. and conventional facilities)

The LBNE ν Beam

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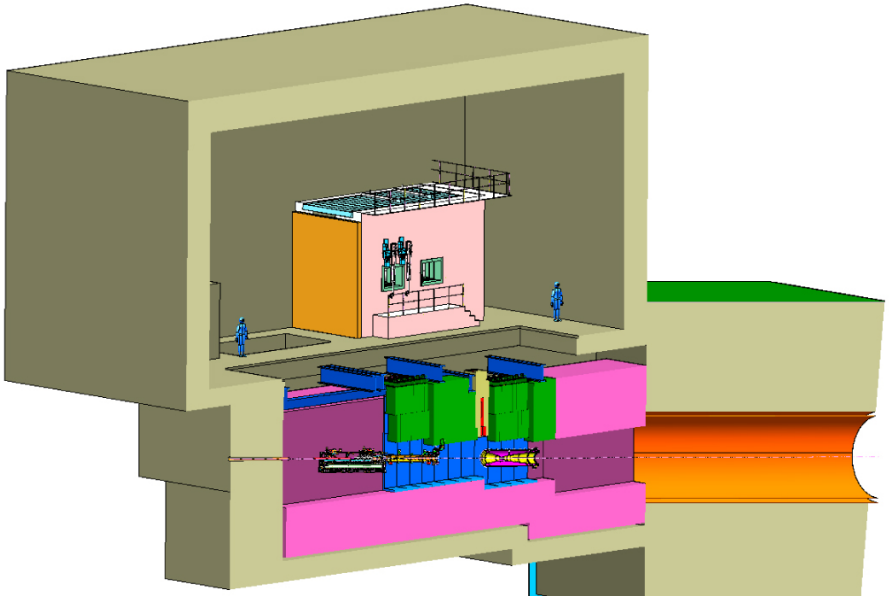
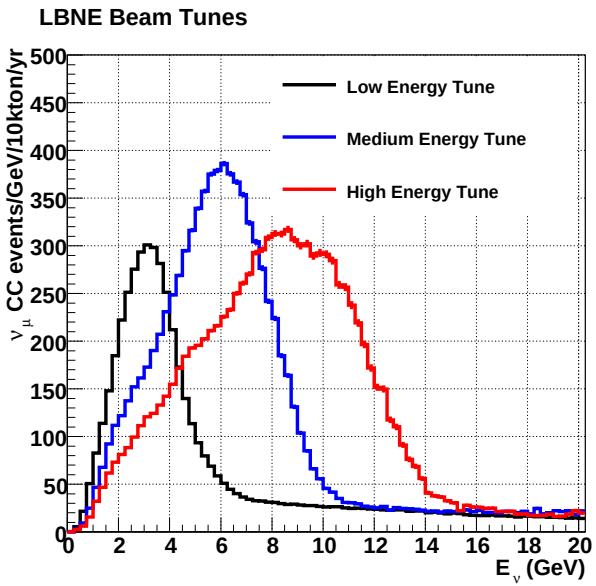
Using NuMI focusing = tunable beam energies





The LBNE ν beam improvements under consideration:

Impact on $\nu_\mu \longrightarrow \nu_e$ appearance rates at the far site:

Changes	0.5-2GeV	2-5GeV
Decay pipe air $\longrightarrow$ He	1.07	1.11
DP length 200m$\longrightarrow$ 250m	1.04	1.12
Horn current 200kA $\longrightarrow$ 230kA	1.00	1.12
E_p 120 $\longrightarrow$ 80GeV,700kW	1.14	1.05
Tgt NuMI $\longrightarrow$ Be	1.00	1.03
DP diameter =4m $\longrightarrow$ 6m	1.06	1.02
Total	1.3	1.5

Detailed optimization of the beam has large impact on experiment

Conceptual design of CD1 10 kTon

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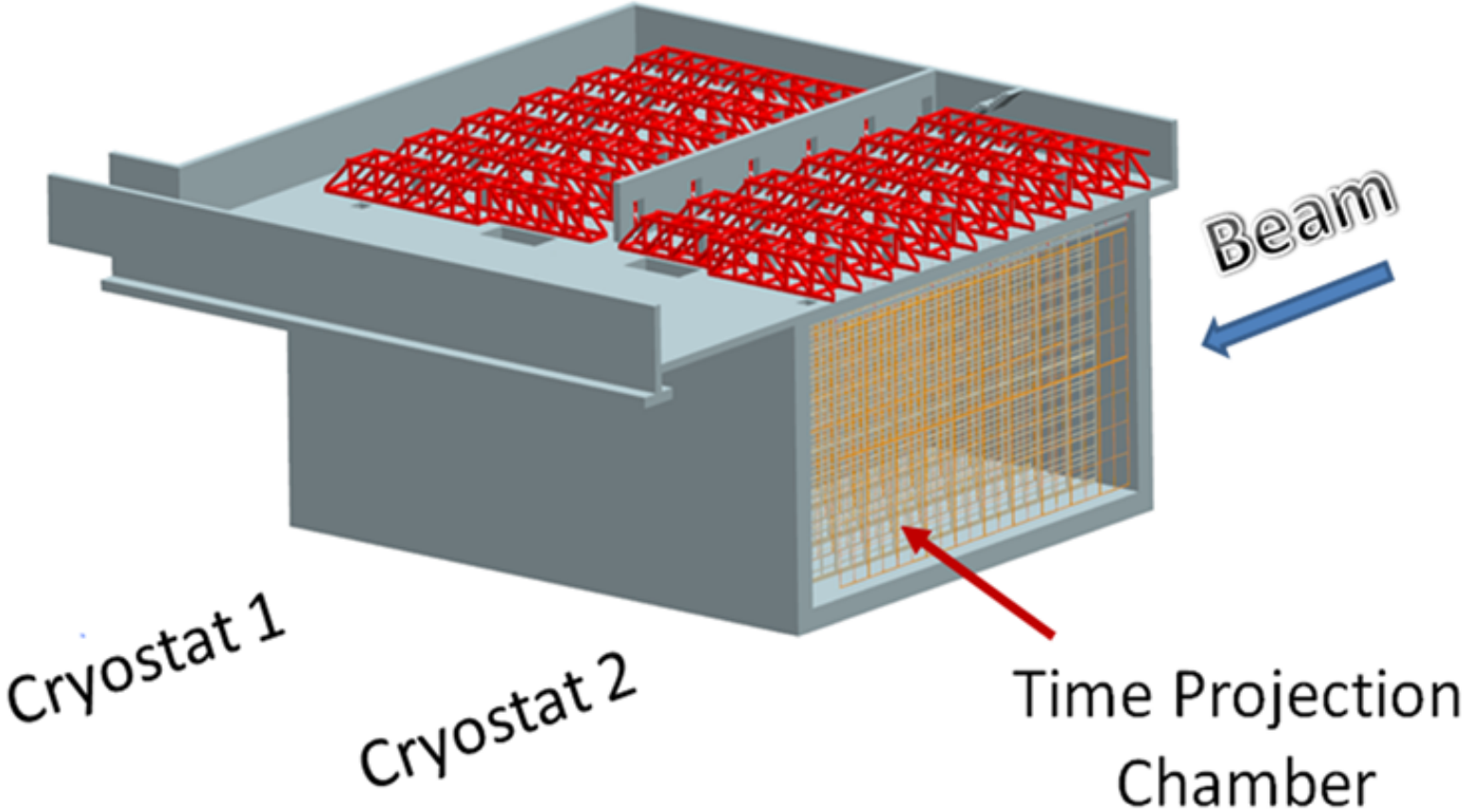

Cost: $\sim$ 260 \$ M AY (incl 40% cont, no CF), Ready 2022

Extra cost to go underground: $\sim$ 135 M\$

Conceptual design of 35 kTon Underground

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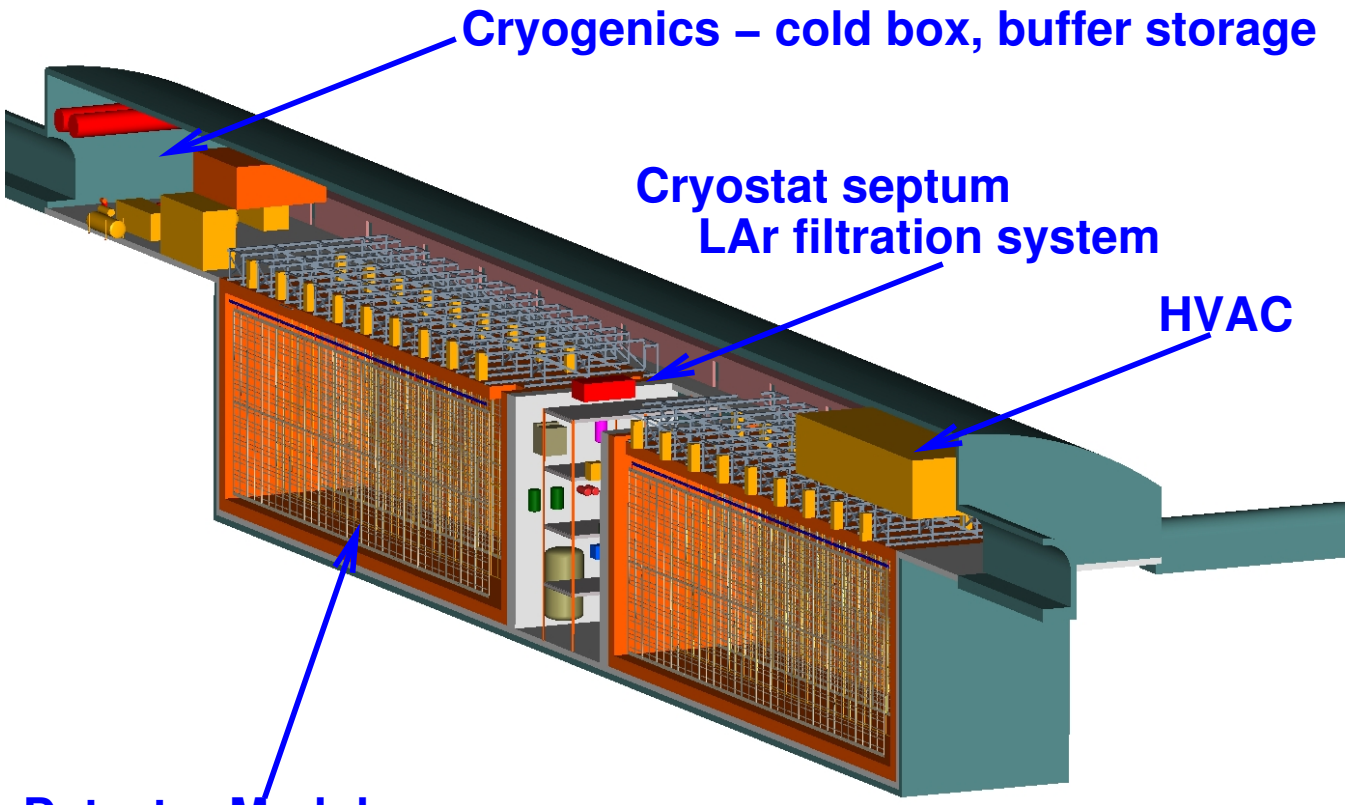
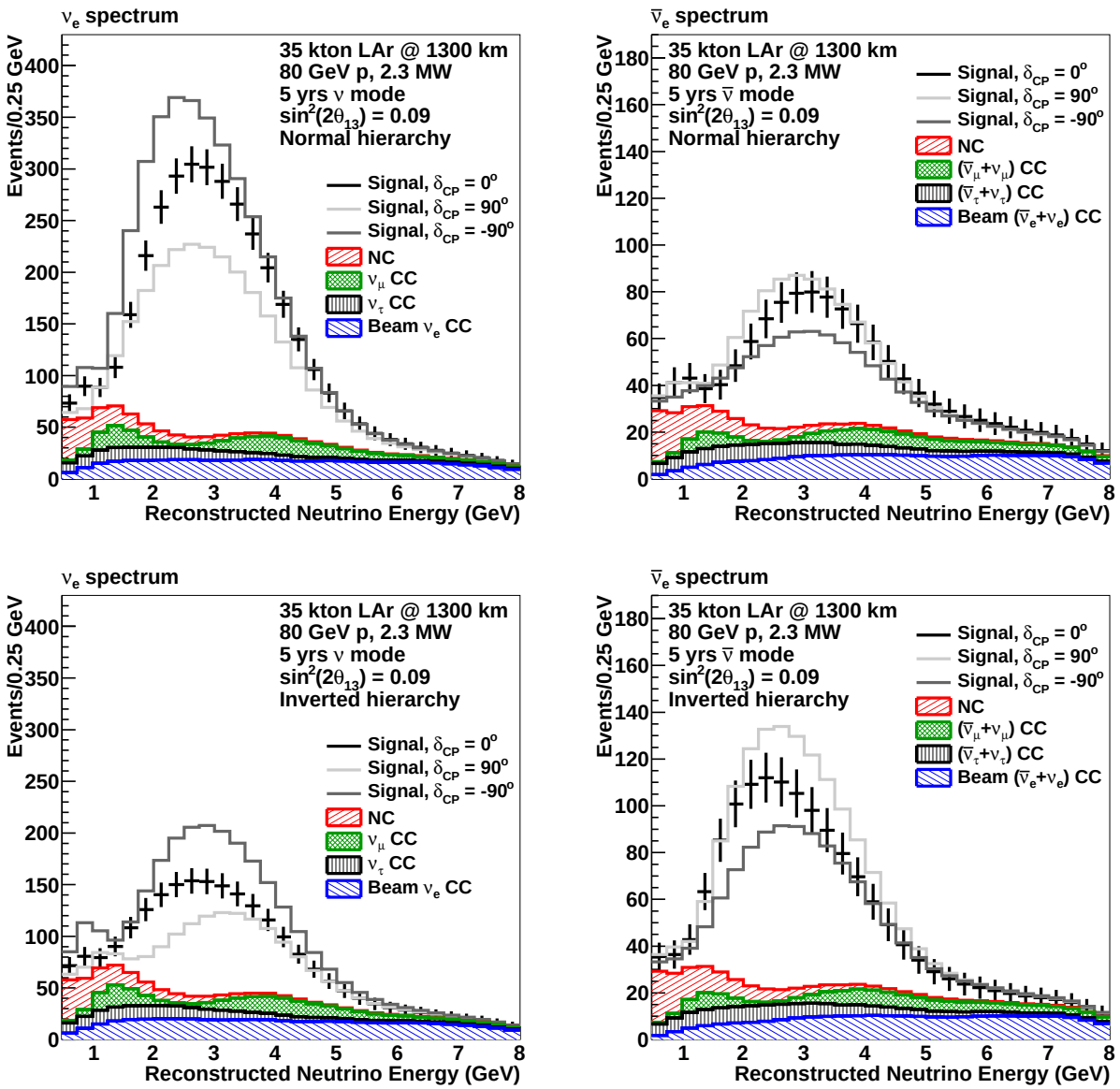


35 kton (underground) : $\sim$ 660$M FY10$ (incl. 40% contingency)

ν_e Appearance Signals in LBNE 35 kton LAr-TPC with 2.3MW 80 GeV

L. Whitehead, UH



LBNE MH/CPV Sensitivities with LBNE10, 700kW (Phase I)

M. Bass, CSU

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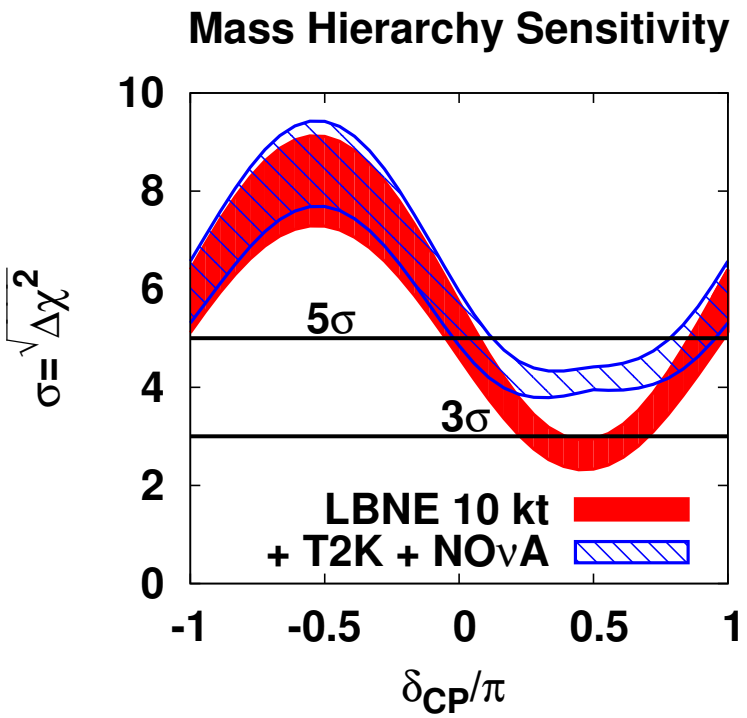
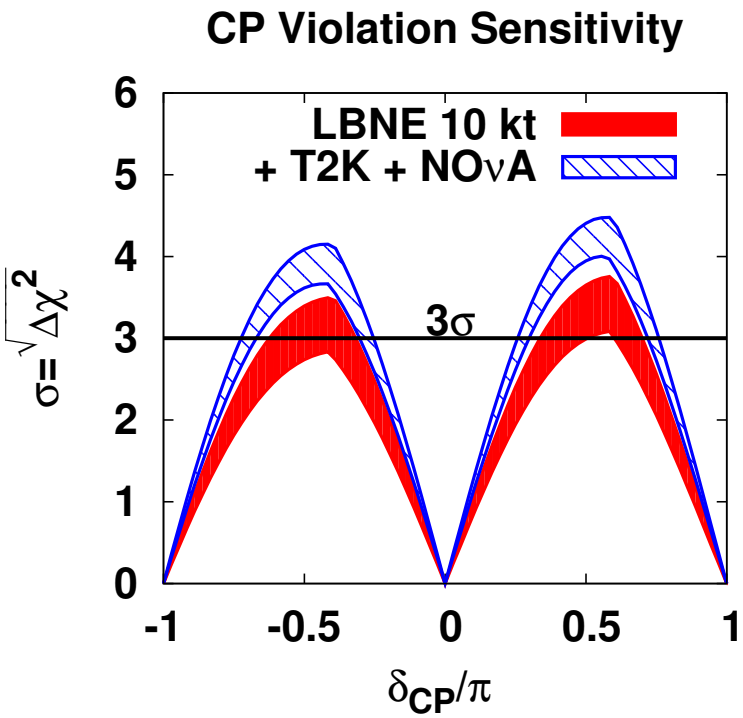
Band: range of beam upgrades under consideration





Can resolve MH with $\geq 5/4\sigma$ for 50%/all δ_{cp} combined

Can resolve CPV with $\geq 3\sigma$ for 45% δ_{cp} combined

Assumes 1%/5% signal/background normalization uncertainties. Disappearance and appearance modes are combined, all 3-flavor parameters included with constraints based on uncertainties from current best fit. θ_{13} constraint using Daya Bay systematics only uncertainty.

LBNE MH/CPV Sensitivities vs. Exposure

M. Bass, CSU

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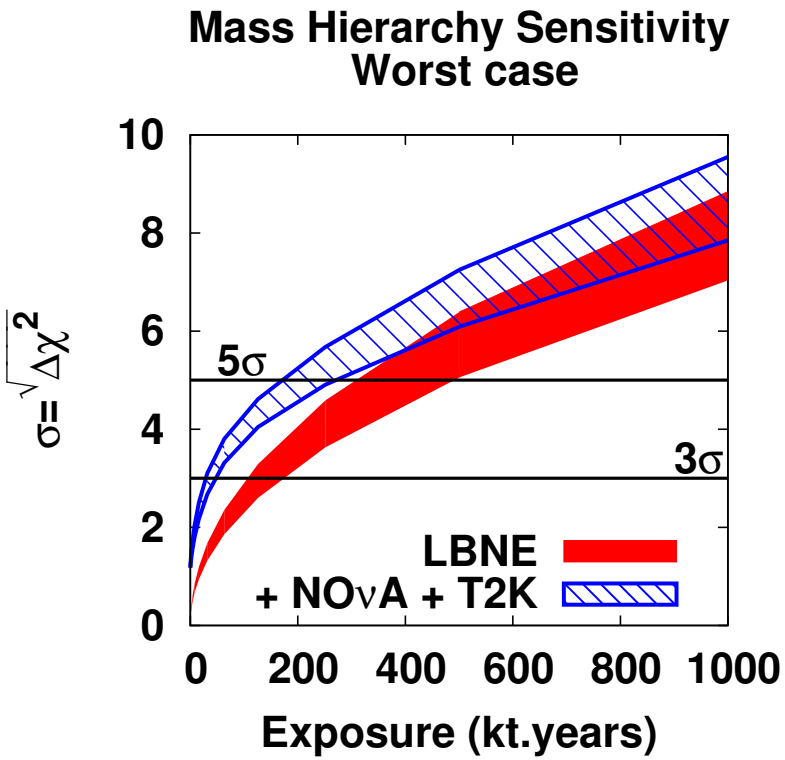

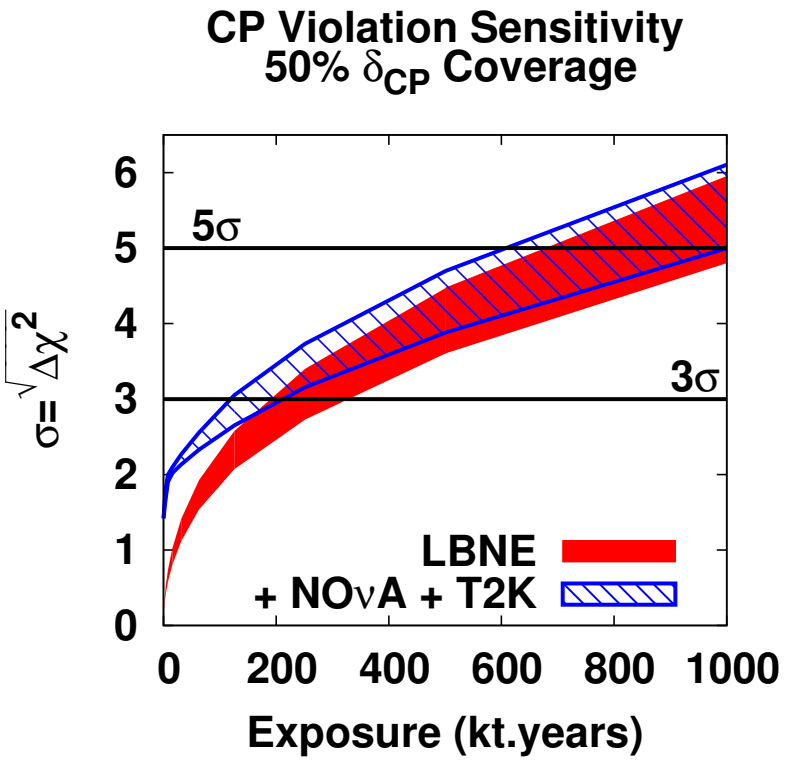

with LBNE ONLY + beam upgrades:

Need 100kt.yrs at 700kW to resolve MH with $\geq 3\sigma$

Need 200kt.yrs at 700kW to resolve CPV with $\geq 3\sigma$ for 50% δ_{cp}

Need 700kt.yrs at 700kW to resolve CPV with $\geq 5\sigma$ for 50% δ_{cp}

CPV with higher power beam from Project X

M. Bass, CSU

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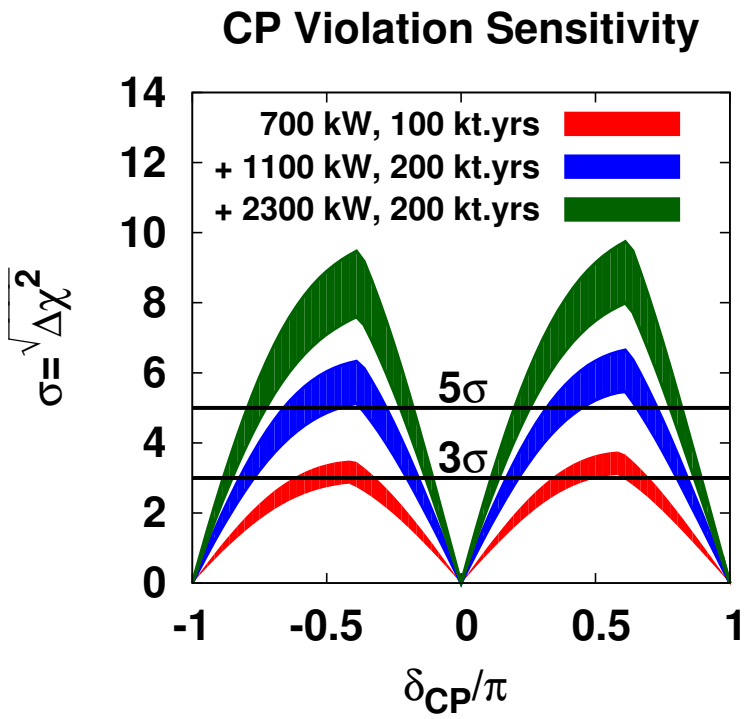

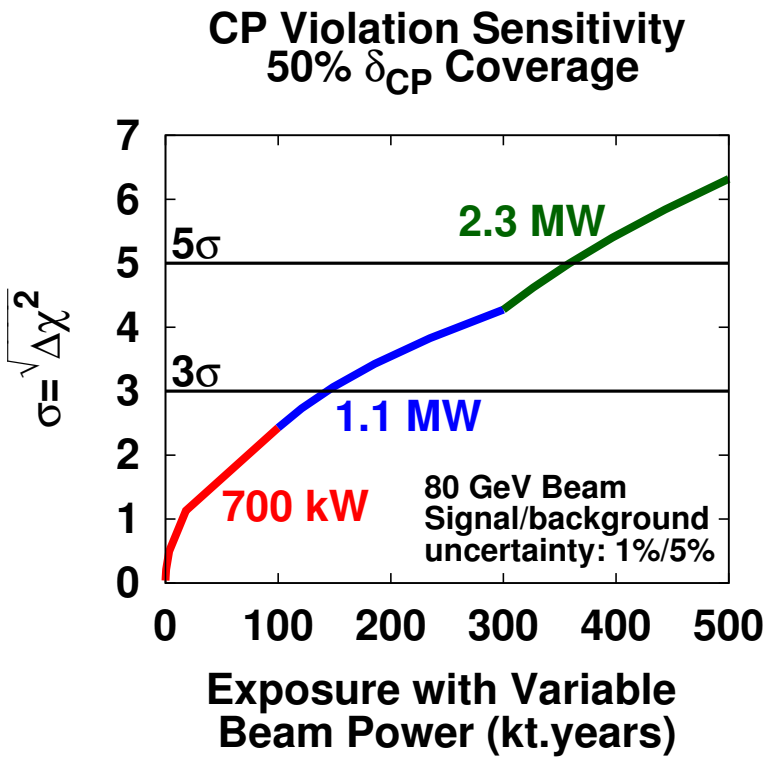

Need 35kt, 10 years, PX staging to resolve CPV with $\geq 5\sigma$ for 50% δ_{cp}

CPV with higher power beam from Project X

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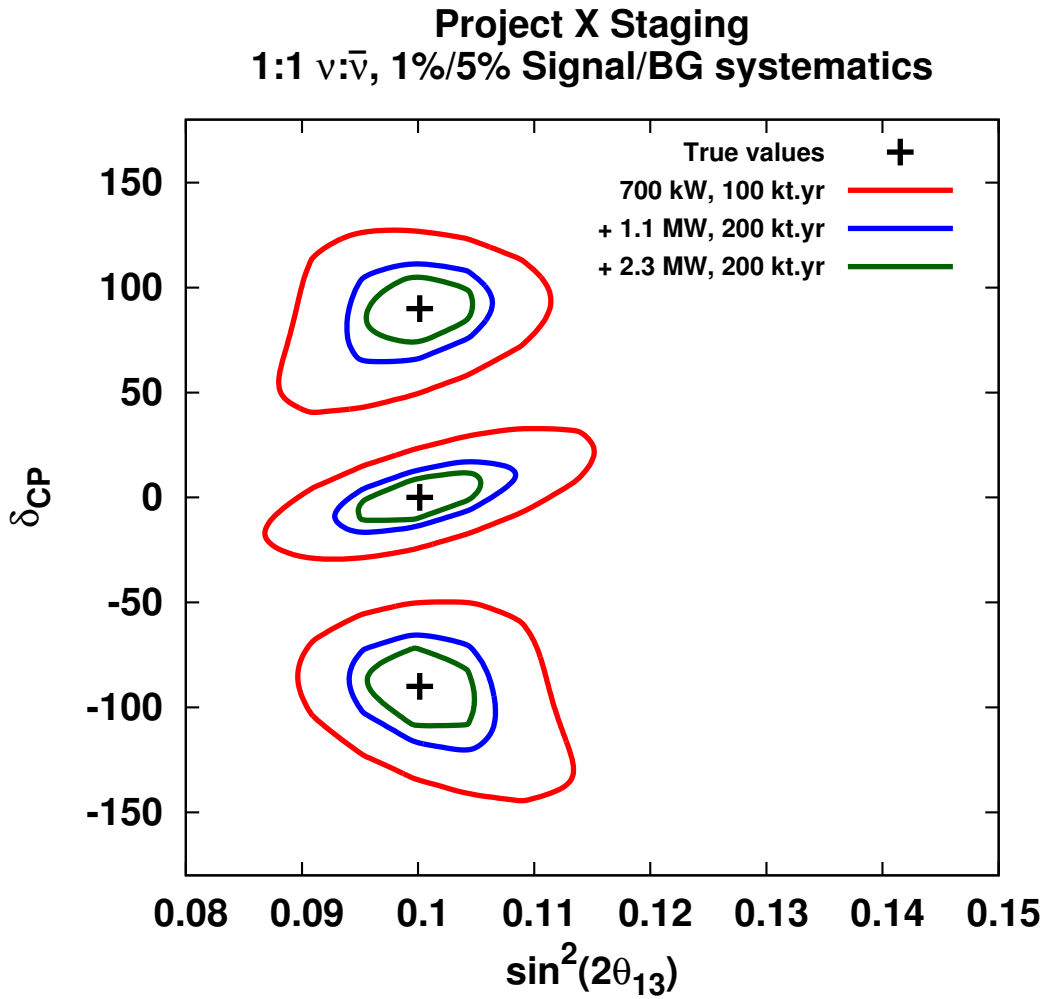

With sufficient exposure we can reach $5-10^\circ$ resolution on δ_{cp}.

3-flavor Parameter Resolutions with 700kW

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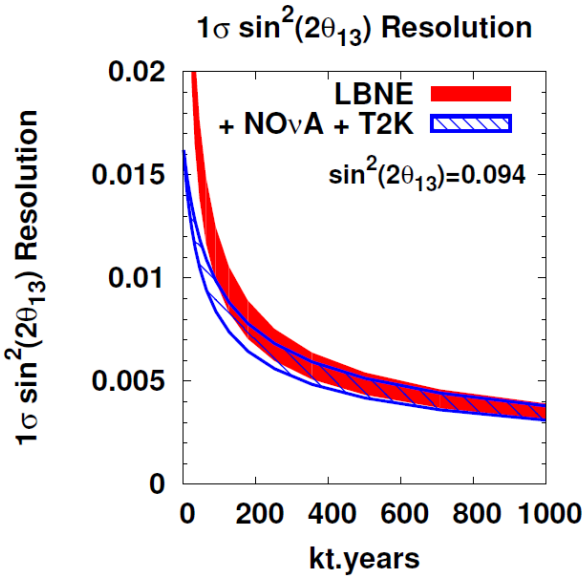

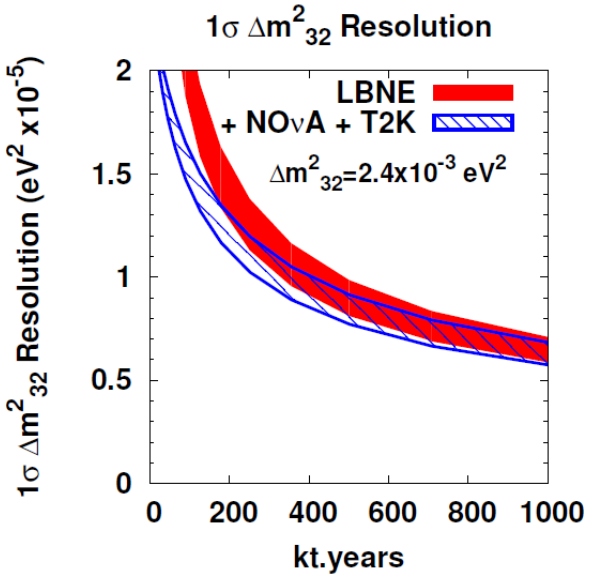

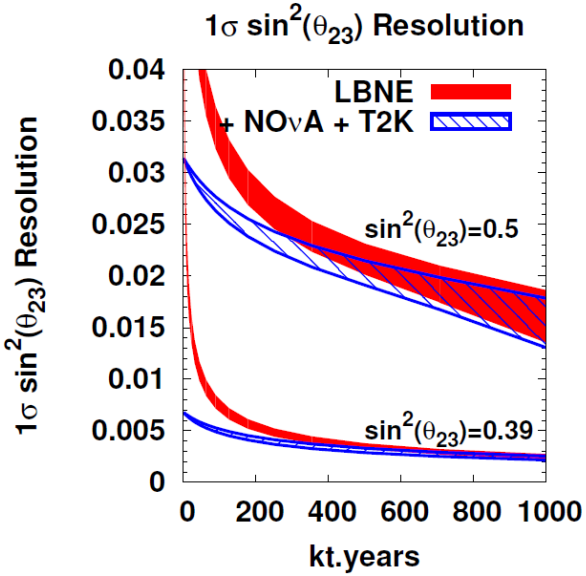

With an exposure of 350 kt.yrs and 700kW:

Parameter	1σ	best fit
$\sin^2 2\theta_{13} = 0.094$	0.005	0.010
$\sin^2 \theta_{23} = 0.5$	0.021	
$\sin^2 \theta_{23} = 0.39$	0.003	
$\Delta m^2_{32} = 2.43 \times 10^{-3}$ eV^2	0.9×10^{-5} eV^2	1.0×10^{-4} eV^2

Resolution of δ_{cp}: Comparison with other Proposals

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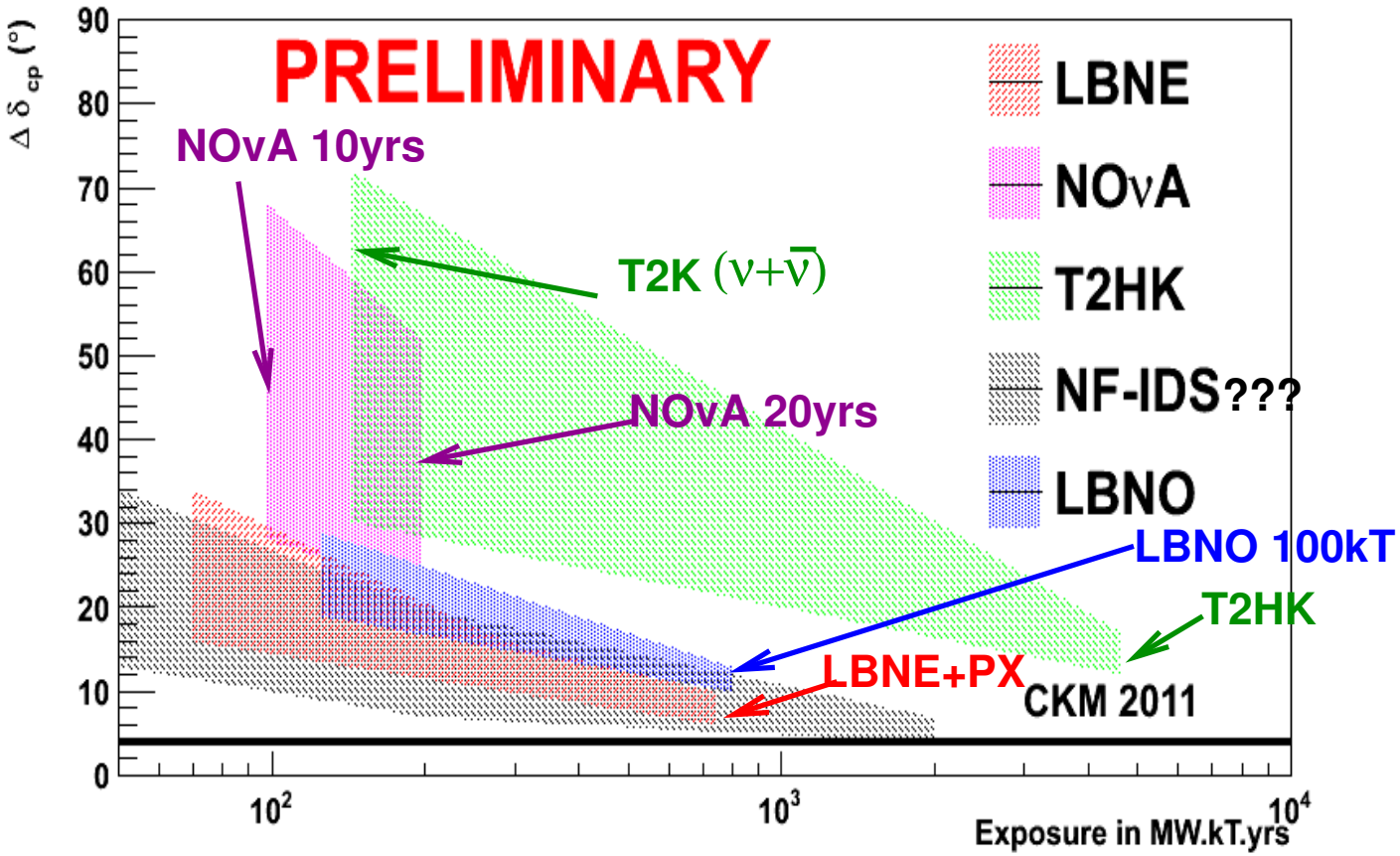

Very long baseline superbeams (or NF) with MT.MW.yrs

= CKM precision

Resolving the Octant Degeneracy

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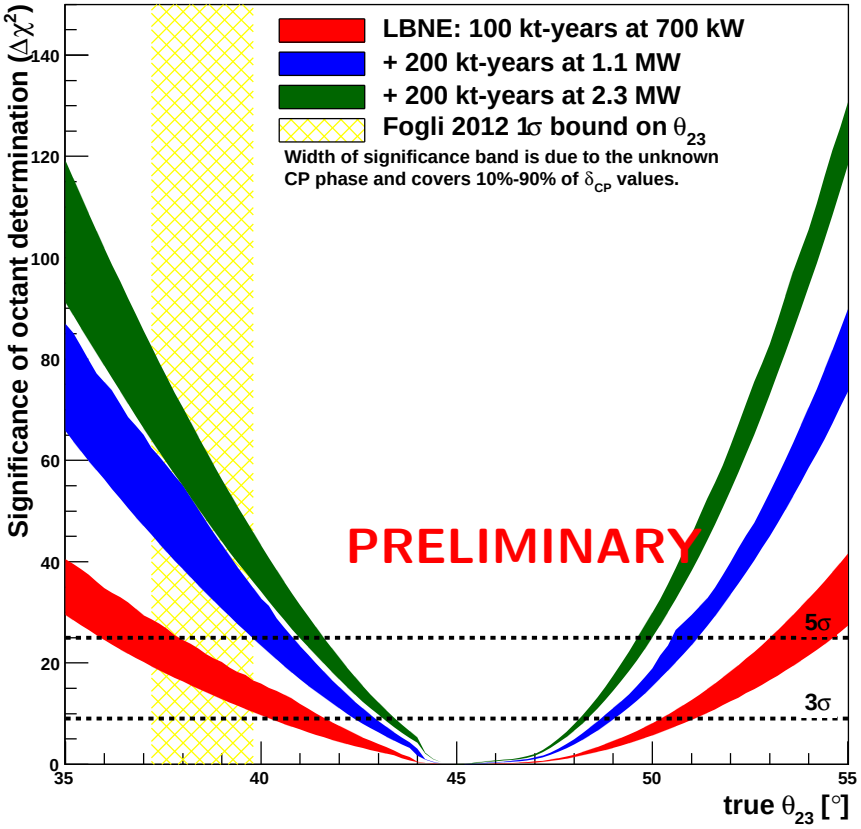
Resolving the θ_{23} octant:

Octant Sensitivity



(E. Worcester)

Physics Opportunities at the 2nd Maximum

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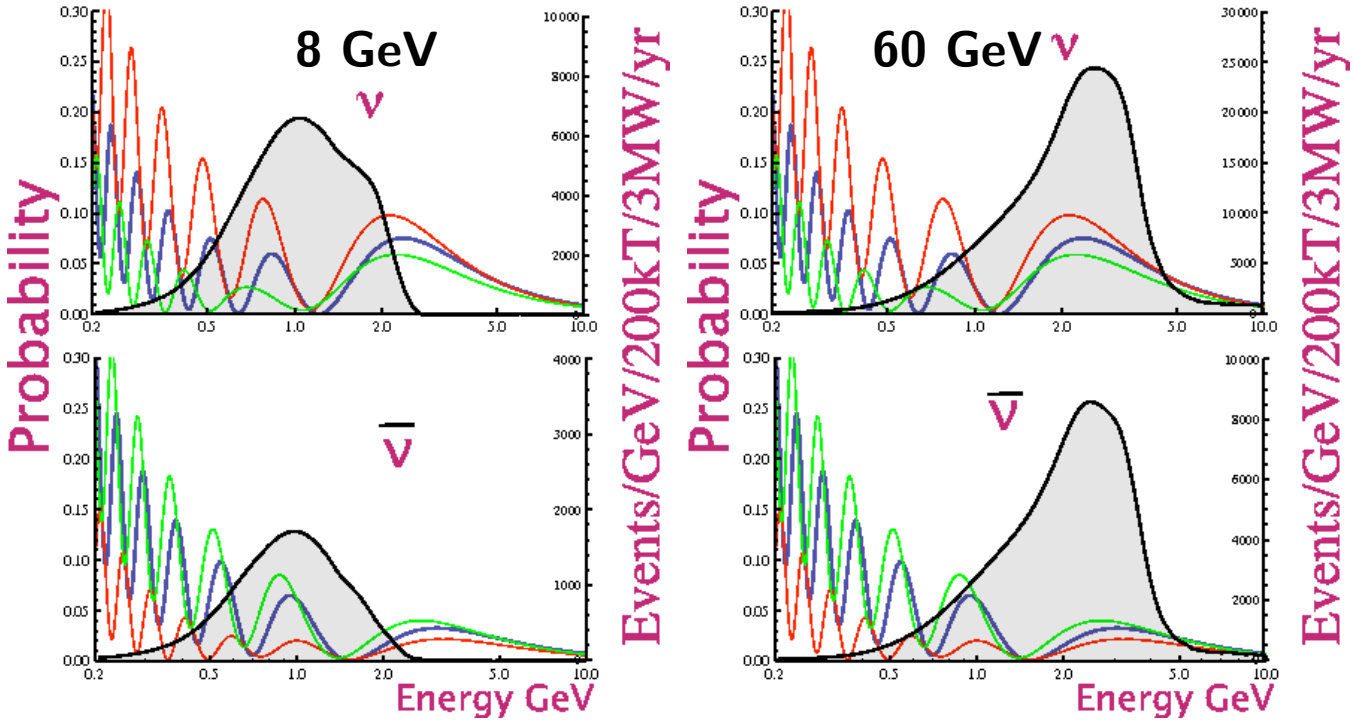
A proposal to use low energy multi-MW beams to probe CP viola tion at the 2nd maximum using massive water Cherenkov detectors in LBNE beam: **"Precision Neutrino Oscillation Measurements using Simultaneous High-Power, Low-Energy Project-X Beams" M.Bishai, M.Diwan, S.Kettell, J.Stewart, B.Viren, L.Whitehead, E.Worcester, arXiv 1203.4090**



Project X will allow SIMULTANEOUS multi-MW 8 GeV and 60 GeV.

Work is progressing on 2nd maximum CP measurements

Beyond 3-flavor Paradigm: Non-Standard Interactions:

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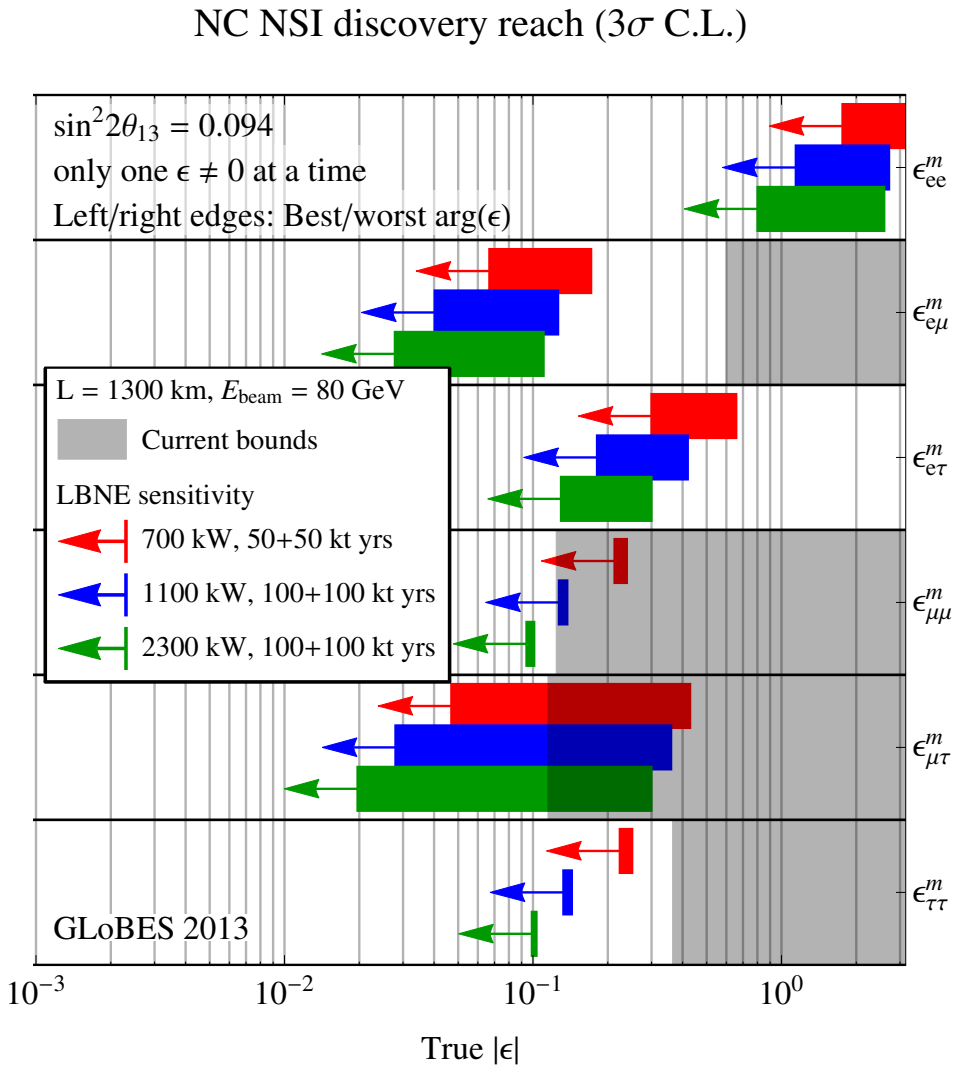
Sensitivity to new physics:



(J. Kopp)

SUMMARY AND CONCLUSIONS

Summary

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The 3 flavor framework for neutrino oscillations is well established

- **What is the mass ordering (hierarchy) of the 1 and 3 mass states? Is CP violated in neutrinos? Is the mixing between 2-3 states maximal?**
- **The measurement of the hierachy using the matter effect in long baseline accelerator $\nu_\mu \rightarrow \nu_e$ is the most effective technique.**
- **Baselines of $>$ 1000 km are needed to cleanly separate CPV effects from matter effects AND new physics.**
- **Discovering ν CPV requires many 100kt .MW .yr exposures!**. **Multi MW proton beams with energies $\sim 50 - 60$ GeV are optimal for the LBNE baseline.**
- **CPV effects are largest at 2nd osc. max.**. **Proton beams $\geq$ 4MW at 3-8 GeV matched to 100kT detectors at 1100-1300km on-axis can probe this region.**
- *The LBNE experiment has the 1) optimal baseline, 2) multi-MW beam design and 3) best detector technology*. **LBNE phase I preserves all 3 features. With additional partners, phase 1 would include a larger underground detector and a near detector.**

Thank you