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- NF Baselines
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Long Baseline Neutrino Physics Prospects with Project X

Project X Physics Study, 6/15/2012

Mary Bishai
Brookhaven National Laboratory

June 15, 2012

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Neutrino Oscillations

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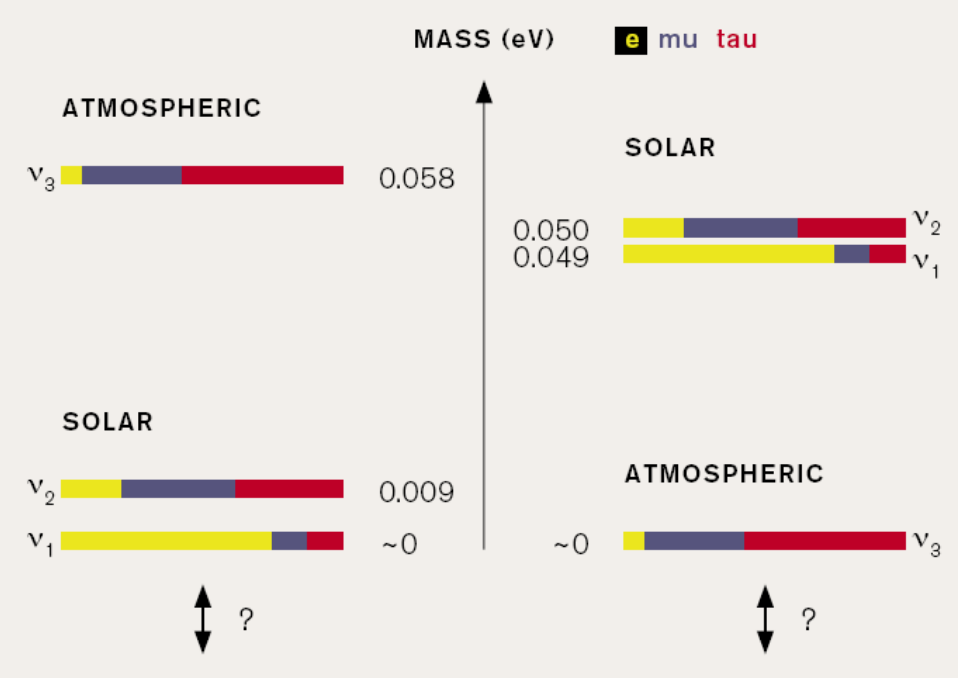
The 3 known neutrino flavors are MIXED states:



$\sin^2\theta_{13}$: Amount of ν_e in ν_3

$\tan^2\theta_{23}$: Ratio of $\frac{\nu_\mu}{\nu_\tau}$ in ν_3

$\tan^2\theta_{12}$: $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$

Neutrino mixing is LARGE:

Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
θ_{12}	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$
θ_{23}	$43 \pm 4^\circ$	$2.38 \pm 0.06^\circ$
θ_{13}	$9 \pm 1^\circ$	$0.201 \pm 0.011^\circ$
Δm^2_{21}	$+(7.58 \pm 0.22) \times 10^{-5}$ eV^2	
$\lvert\Delta m^2_{32}\rvert$	$(2.35 \pm 0.12) \times 10^{-3}$ eV^2	$m_3 >> m_2$
δ_{CP}	unknown	$67 \pm 5^\circ$

Neutrino Mixing and Long Baseline Oscillations

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The mass-squared differences Δm^2_{21} (solar) and Δm^2_{32} (atmospheric) drive 2 very different oscillation scales:

$$
\begin{aligned}
L/E^{\nu}_{n}\ (\mathrm{km/GeV}) &= (2n-1)\frac{\pi}{2}\frac{1}{(1.267\times\Delta m^2\ (\mathrm{eV}^2))} \\
&\approx (2n-1)\times 500\ \mathrm{km/GeV}\ \text{for}\ \Delta m^2_{32}\ (\mathrm{atmos.}) \\
&\approx (2n-1)\times 15,000\ \mathrm{km/GeV}\ \text{for}\ \Delta m^2_{21}\ (\mathrm{solar})
\end{aligned}
$$

where E^{ν}_{n} is the neutrino energy at the maximum of oscillation node n.

$\nu_{\mu,e} \rightarrow \nu_{e,\mu}$ probe CP violation ($\delta_{cp} \neq 0, \pi$) and the mass hierarchy (sign of Δm^2_{32} from the MSW effect) and are driven primarily by the atmospheric mass scale:

Oscillations of GeV scale accelerator neutrinos occur at $\mathcal{O}(1000)$km

Superbeams

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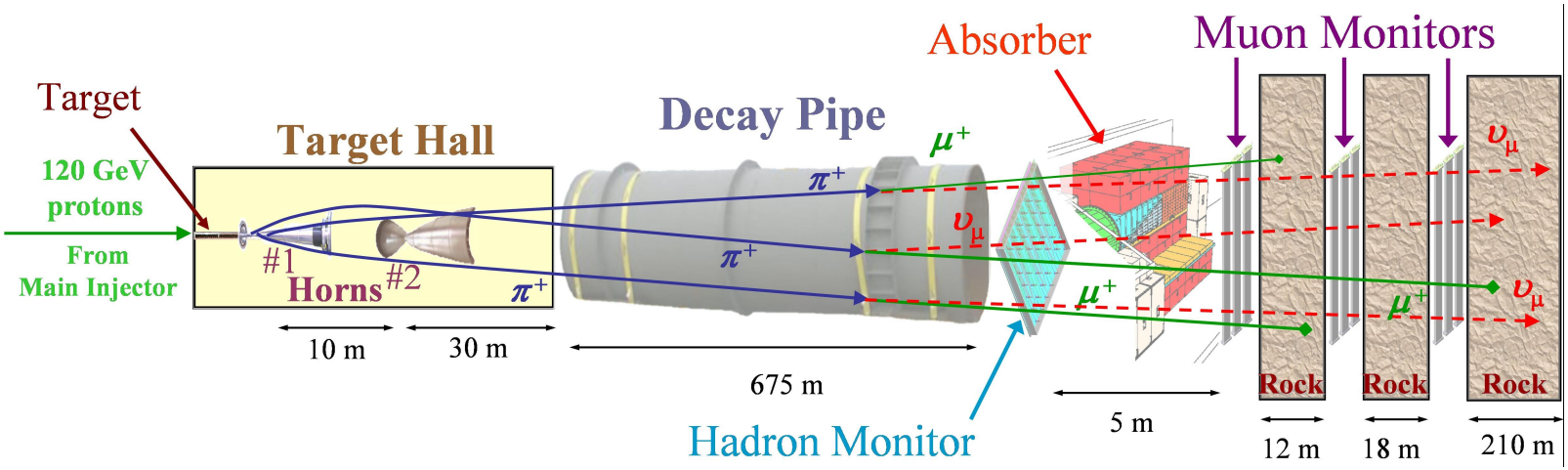
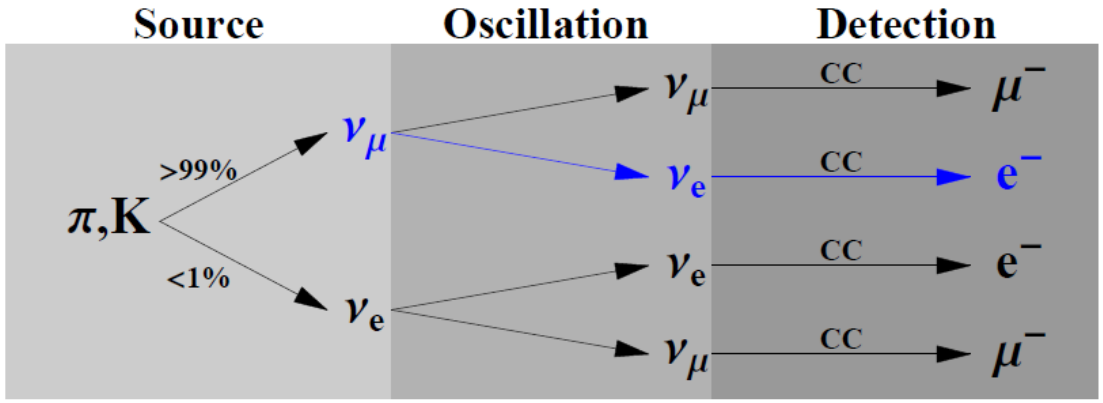
High power conventional neutrino beams:





Neutrino Factories

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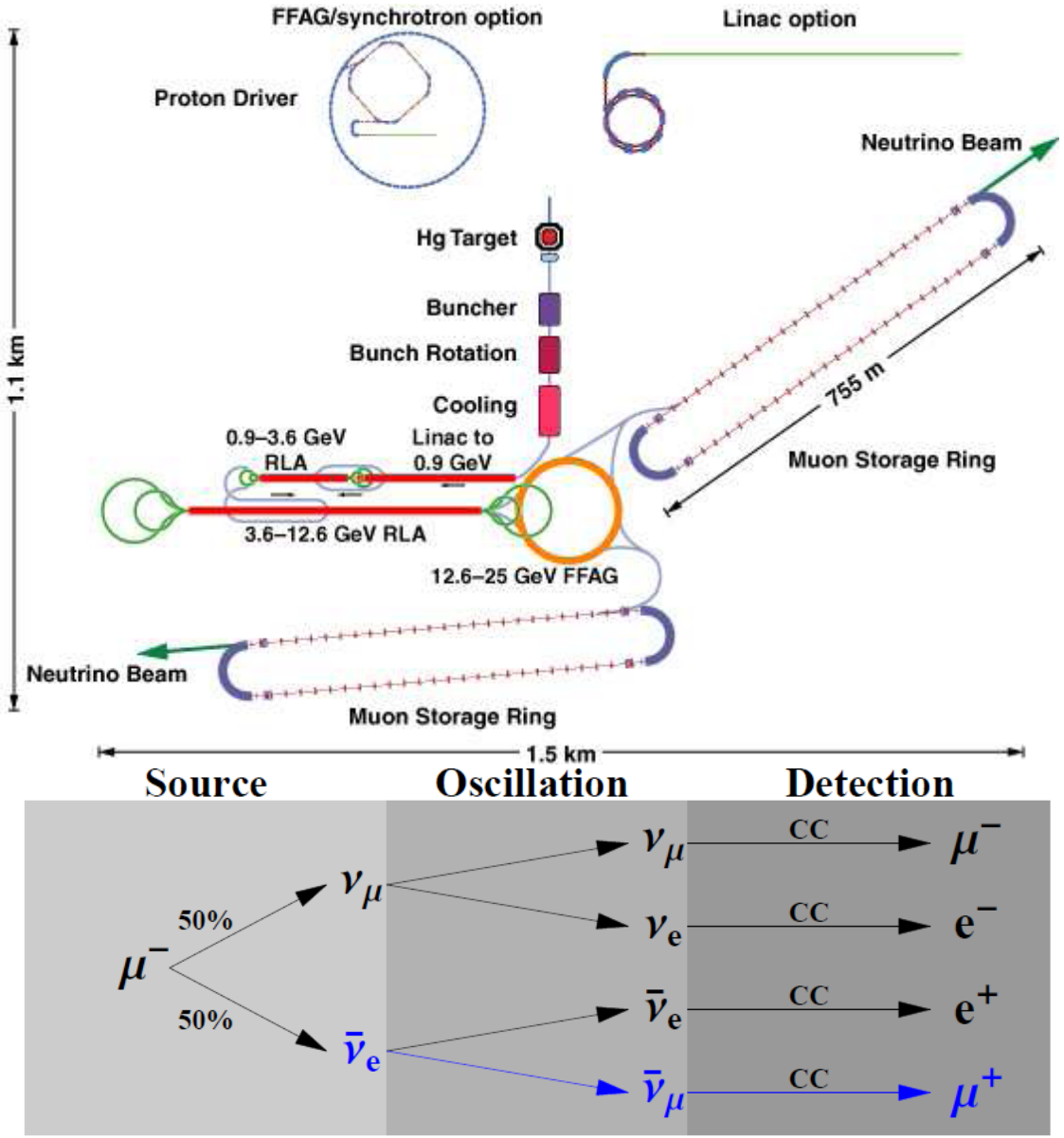

Oscillations of $\nu_\mu \longrightarrow \nu_e$ at different baselines

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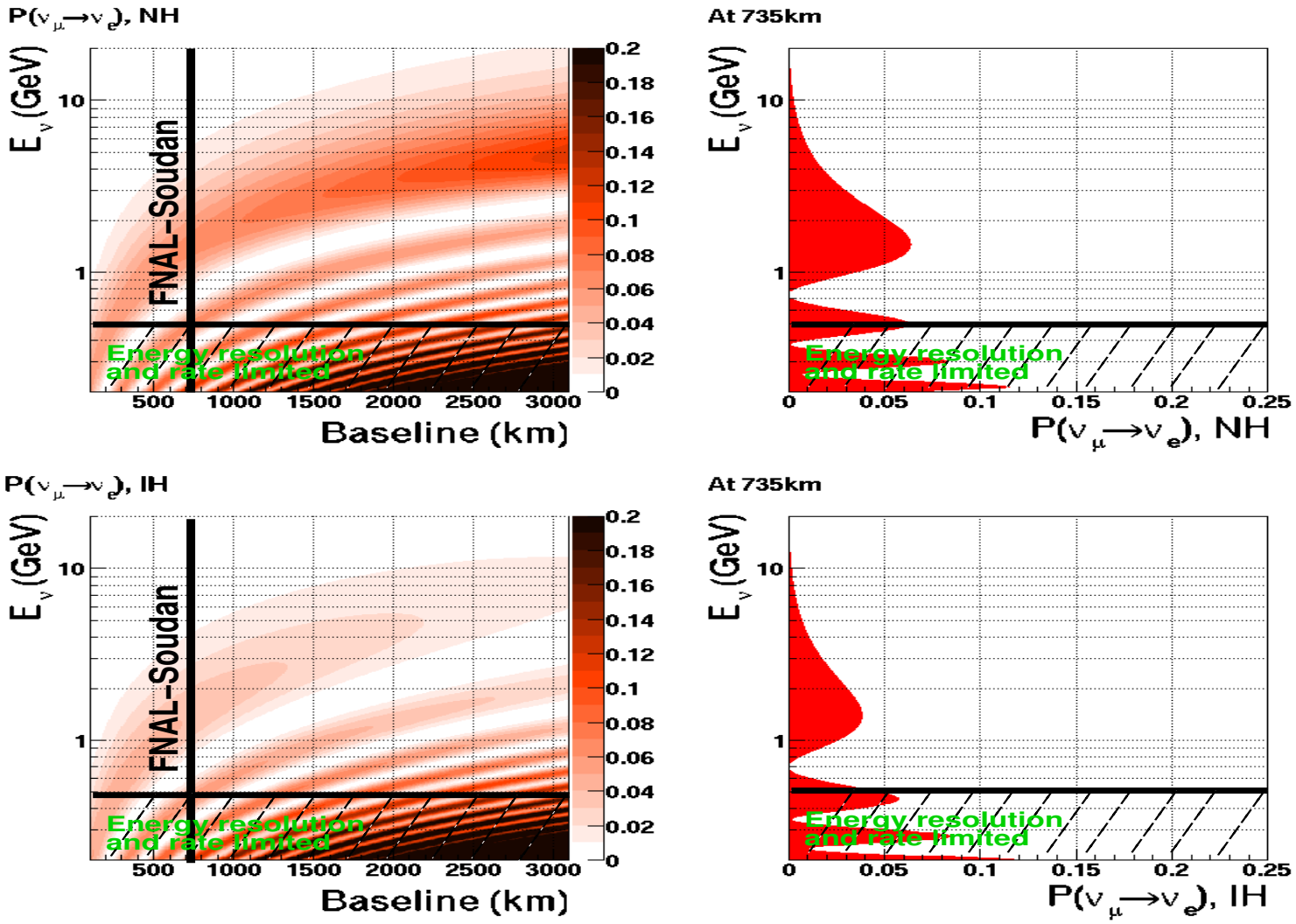

$P(\nu_\mu \rightarrow \nu_e)$ maxima: $E_\nu^n(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$

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

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

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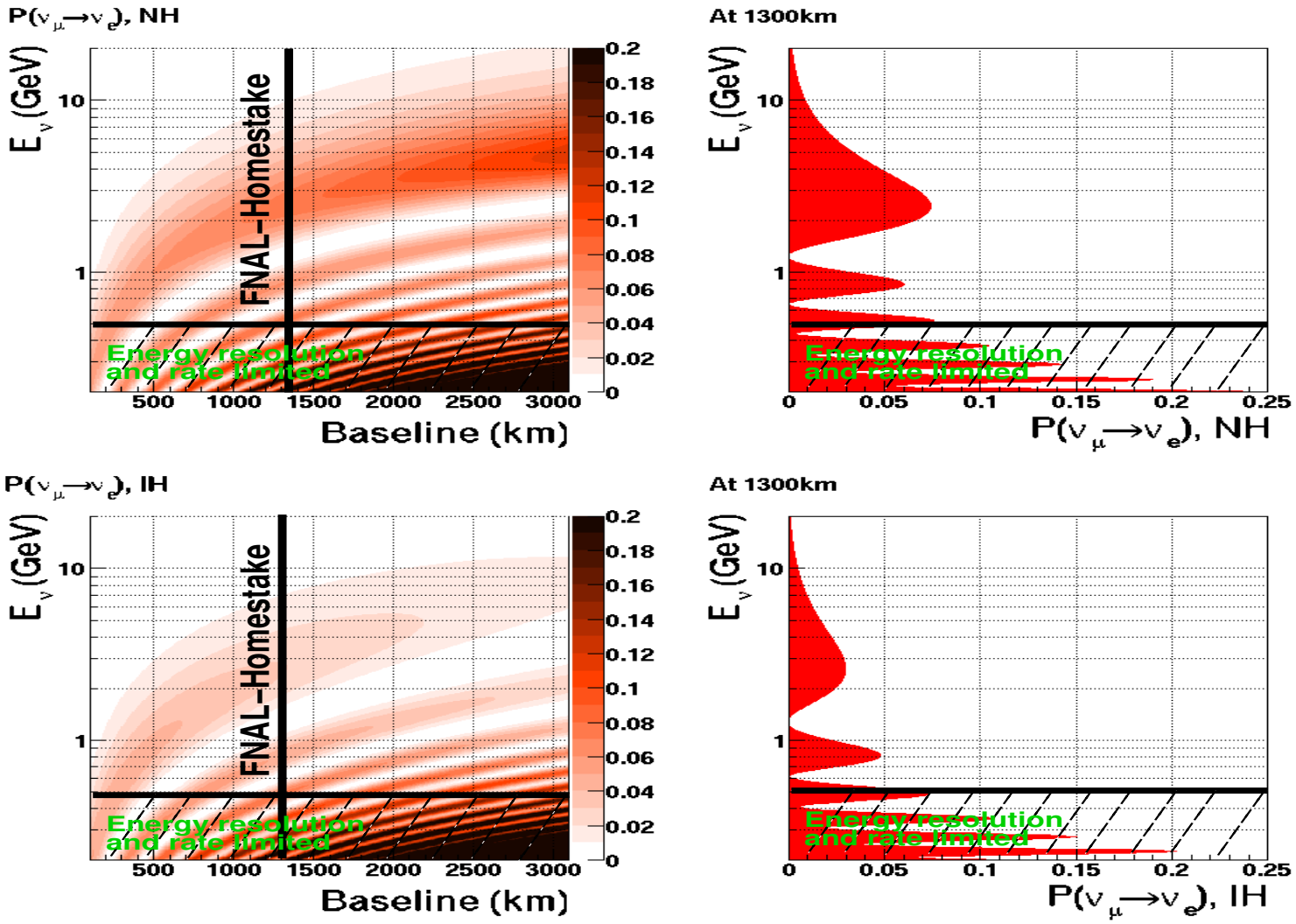

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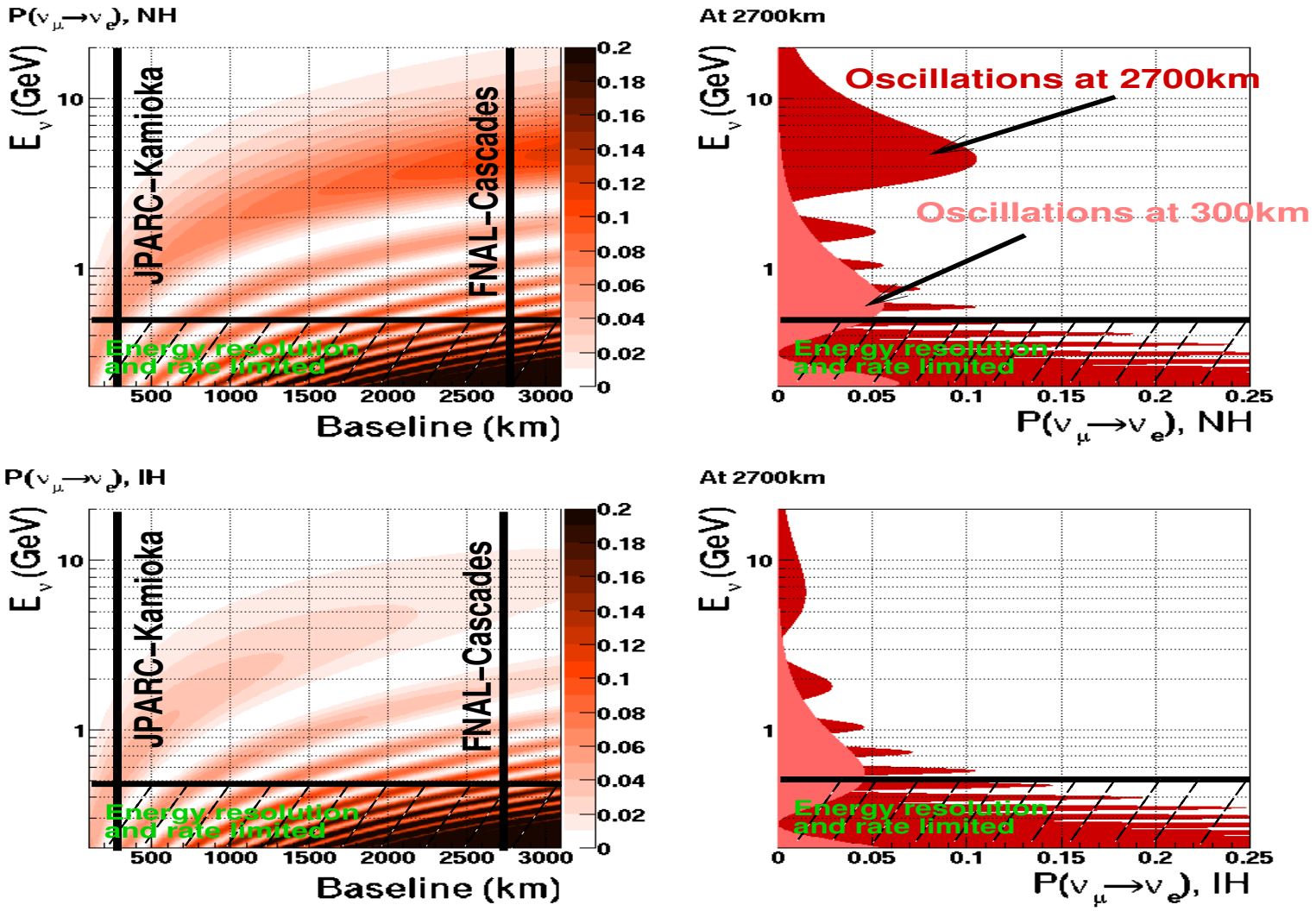

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CP and Matter Asymmetries vs Baselines

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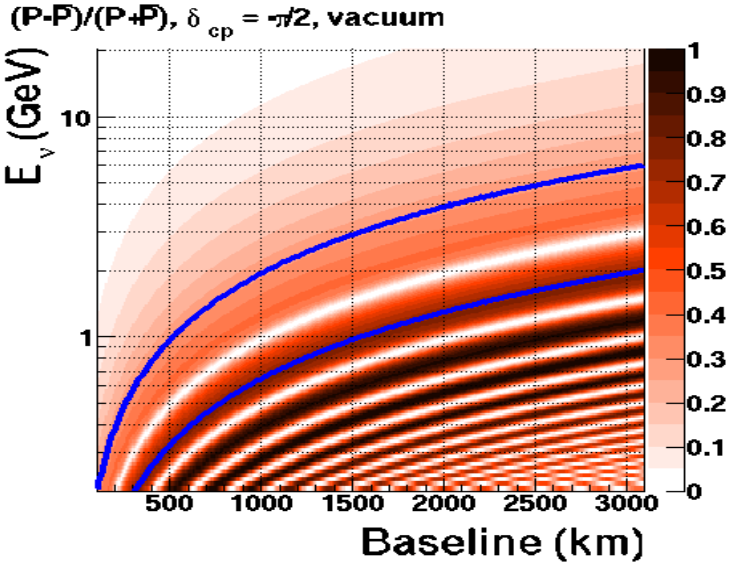
The CP asymmetry is defined as

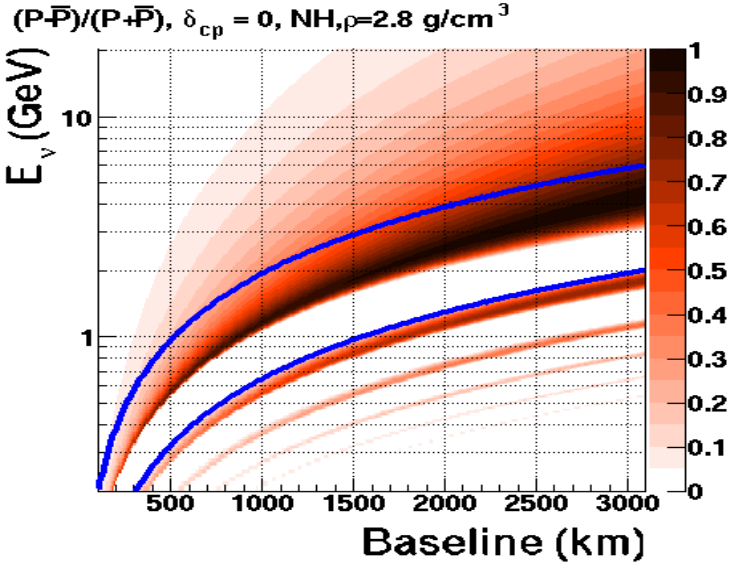
$$\mathcal{A}(E_\nu) = \left[\frac{P(\nu_\mu \to \nu_e) - \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right]$$

At $\sin^2 2\theta_{13} = 0.1$:

Maximal CP asymmetry in vacuum $\delta_{cp} = -\pi/2$



Matter asymmetry with no CPV



CP asymmetries are largest at the secondary nodes.

Matter asymmetry dominates at the 1st node

Longer baselines, wide-band beams to resolve degeneracies.

CP Asymmetries vs θ_{13}

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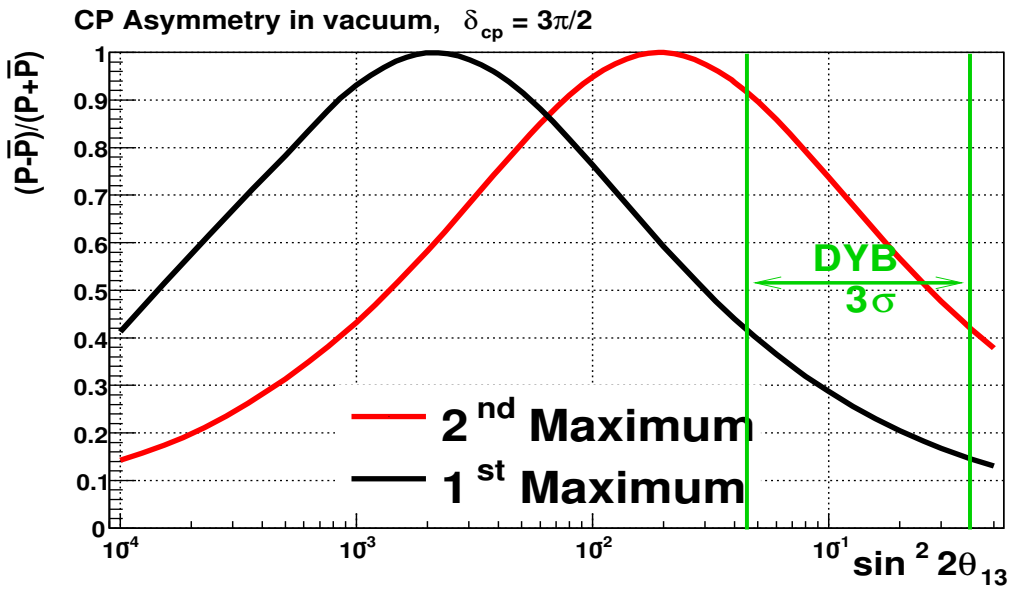
MAXIMAL CP asymmetry in vacuum ($\delta_{cp} = -\pi/2$)



Large values of θ_{13} = SMALLER CP asymmetries

Superbeam Baselines in the U.S.

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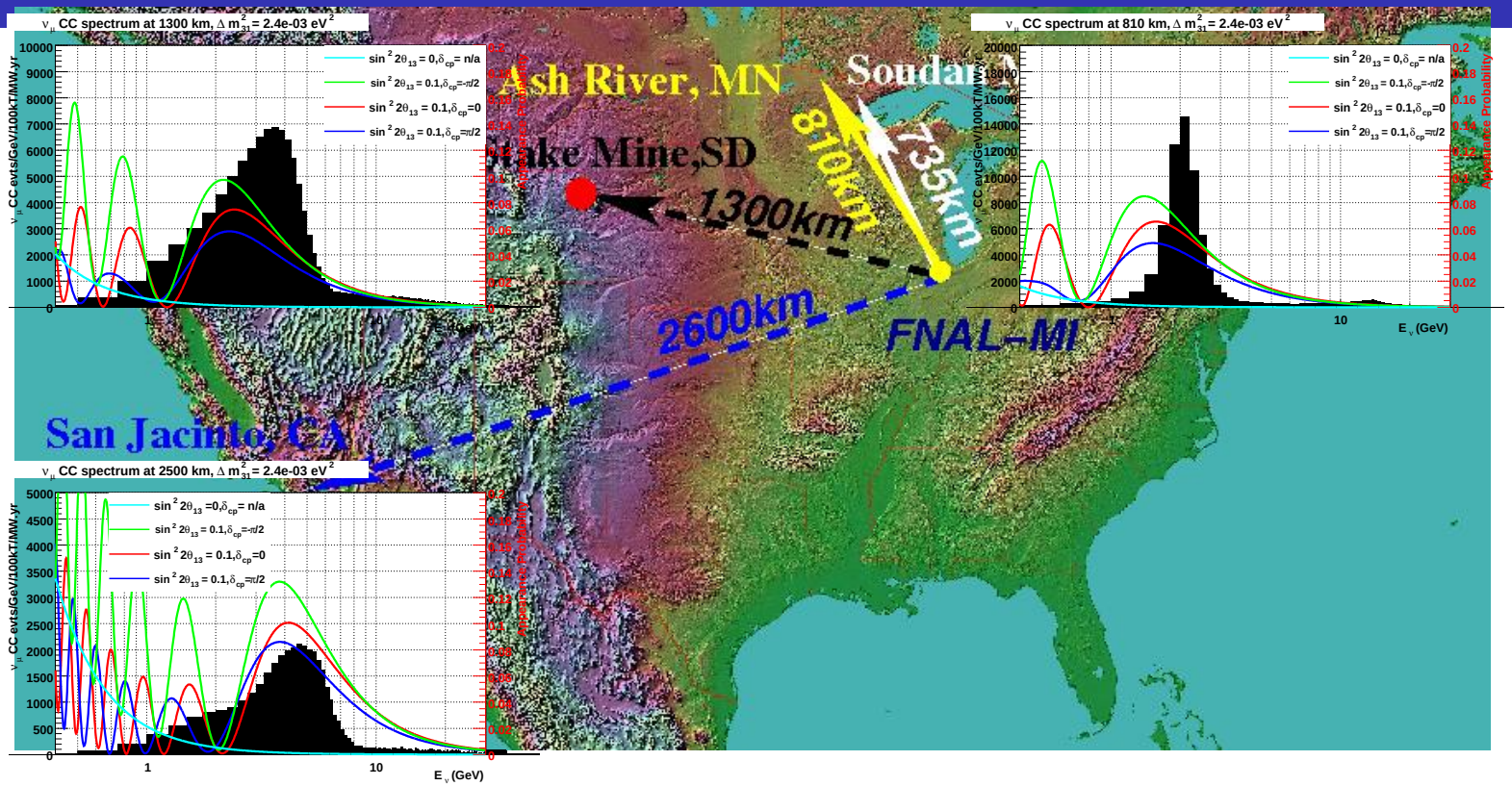

CC event rates per 100kt.MW.yrs (1 MW.yr= 1×10^{21} p.o.t) for $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$, NH:

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	73K	49K	15K	820	1500	166
Ash River 810km	18K	7.3K	3.6K	330	710	38
Hmstk 1300km	29K	11K	5.0K	280	1300	130
CA 2500km	11K	2.9K	1.6K	85	760	290

Need exposures of 100kt.MW.yrs INDEPENDENT of baseline

Superbeam Detector: Liquid Argon Time-Projection-Chamber (LArTPC)

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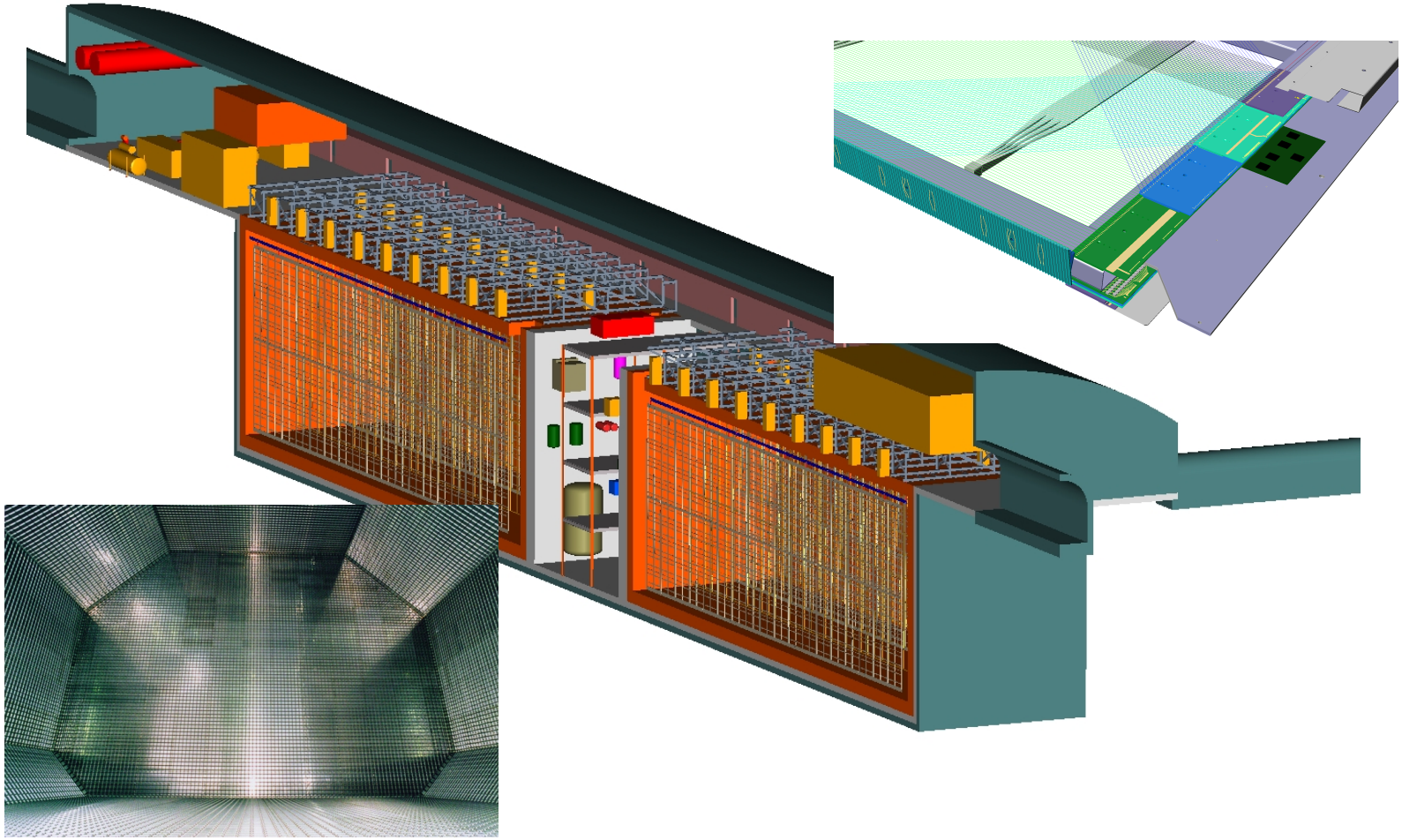
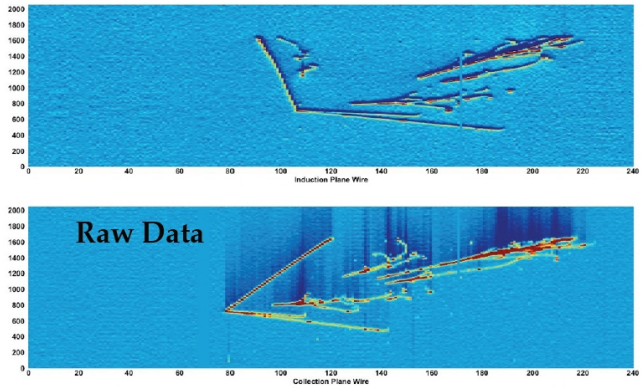


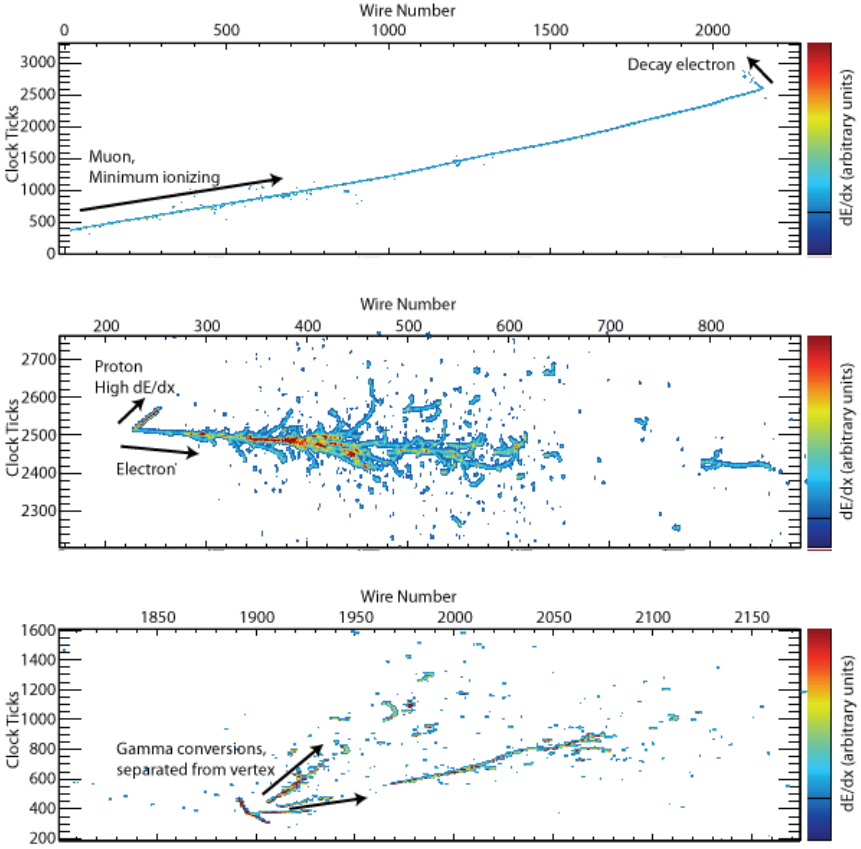
2 membrane cryostats with dimensions: 24m x 18m x 51m

LBNE proposal: fiducial mass 2x16.3kt, total mass=2x20kt

LArTPC Performance

ArgoNeuT Neutrino Event





Parameter	Range of Values	Value Used
For ν_e CC appearance studies		
ν_e CC eff.	70-95%	80%
ν_μ NC mis-id	0.4-2.0%	1%
ν_μ CC mis-id	0.5-2.0%	1%
Signal uncert	1-5%	1%
Bkgd uncert	2-15%	5%
For ν_μ CC disappearance studies		
ν_μ CC eff.	80-95%	85%
ν_μ NC mis-id	0.5-10%	0.5%
Signal uncert	1-5%	5%
Bkgd uncert	2-10%	10%

With a 34 kt LAr-TPC. 700kW 5yrs, ν, NH (E. Worcester)

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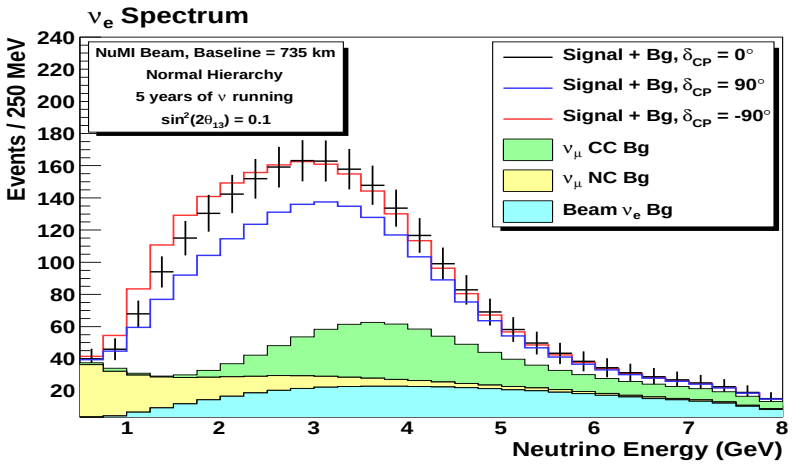
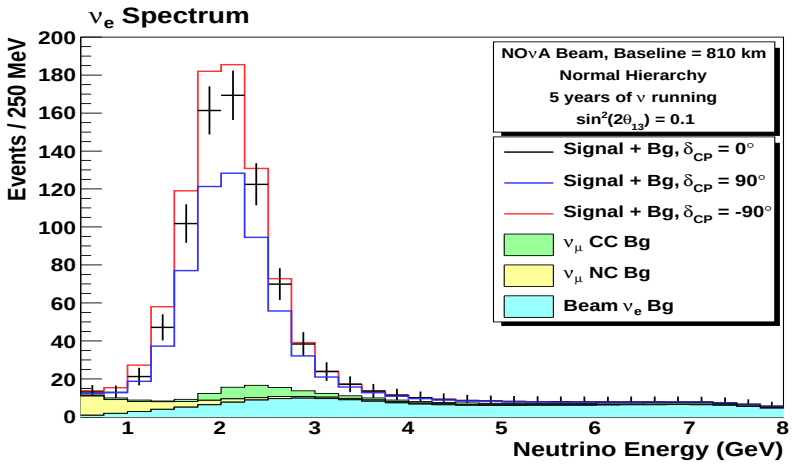
735km, NuMI LE at Soudan



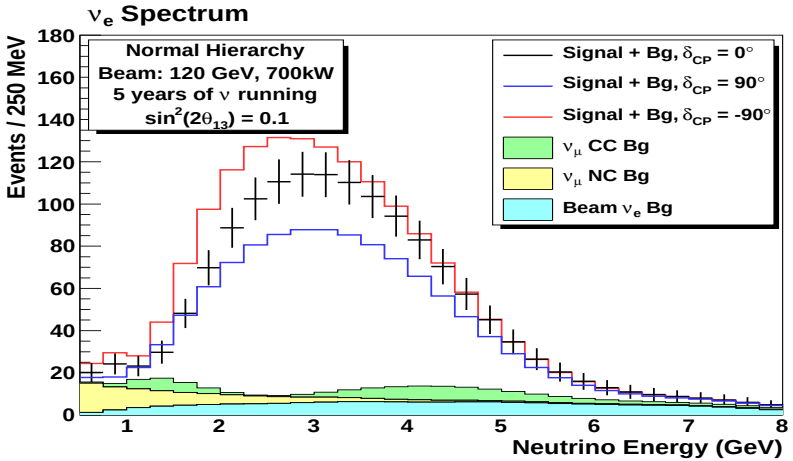
SG: (1386,1338,1011), BG: 1135

810km, NuMI ME at Ash River



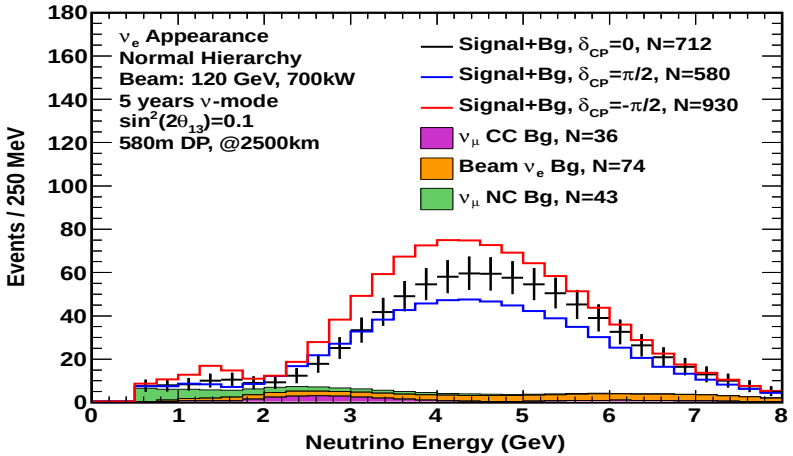
SG: (758,673,497), BG: 278

1300km, LBNE LE at Hmstk



SG: (1366,1157,889), BG: 317

2500km, LBNE pME (580m DP)



SG: (777,559,427), BG: 153

With a 34 kt LAr-TPC. 700kW 5yrs, $\bar{\nu}$, NH

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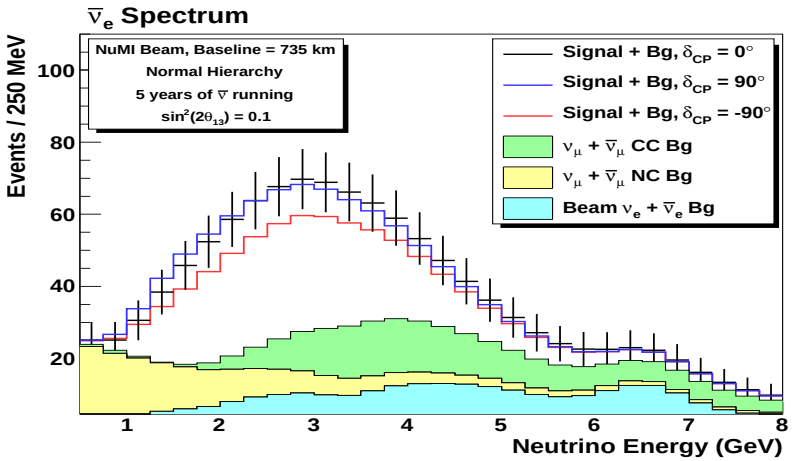
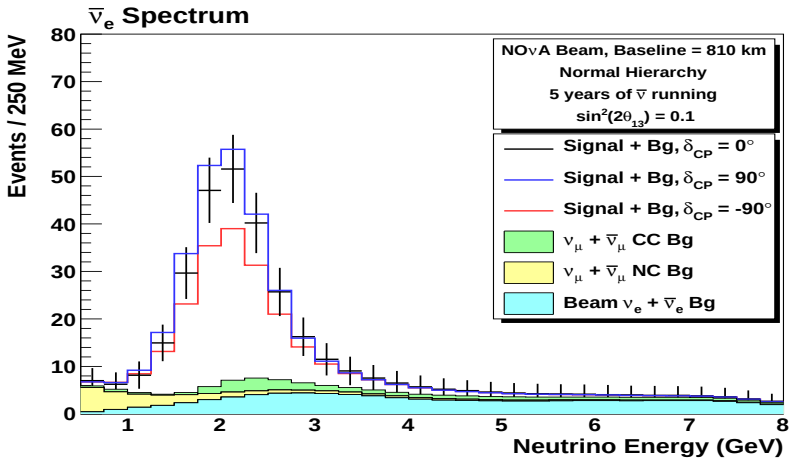
735km, NuMI LE at Soudan



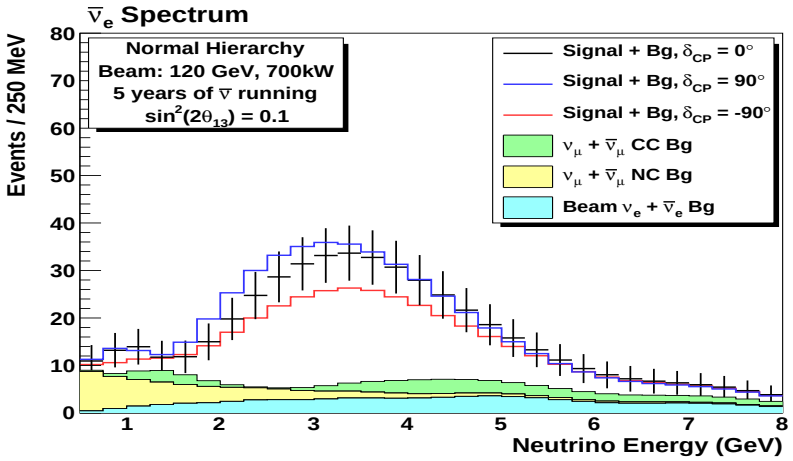
SG: (398,512,502), BG: 644

810km, NuMI ME at Ash River



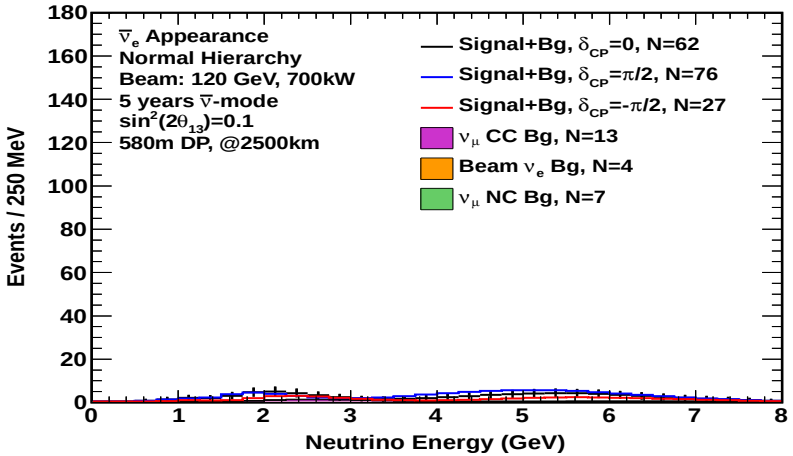
SG: (161,213,228), BG: 136

1300km, LBNE LE at Hmstk



SG: (250,327,353), BG: 176

2500km, LBNE pME (580m DP)



SG: (3,38,52), BG: 24

LBNE Developments in 2012

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The Long Baseline Neutrino Experiment (LBNE) conceptual design comprised a 33kt LArTPC located underground at a depth of 4850ft in the Homestake Mine in SD at a baseline of 1297km from Fermilab. A new neutrino beamline from Fermilab is in the early stages of design.

March 19, 2012 letter from W. F. Brinkman, director of DOE OSTP to Pier Odone, director of Fermilab:

Based on our considerations, we cannot support the LBNE project as it is currently configured. This decision is not a negative judgment about the importance of the science, but rather it is a recognition that the peak cost of the project cannot be accommodated in the current budget climate or that projected for the next decade.

In order to advance this activity on a sustainable path, I would like Fermilab to lead the development of an affordable and phased approach that will enable important science results at each phase. Alternative configurations to LBNE should also be considered. Options that allow us to independently develop the Homestake Mine as a future facility for dark matter experiments should be included in your considerations.

Mass Hierarchy and CP Violation Sensitivities with a 5% constraint on $\sin^2 2\theta_{13}$ (M. Bass)

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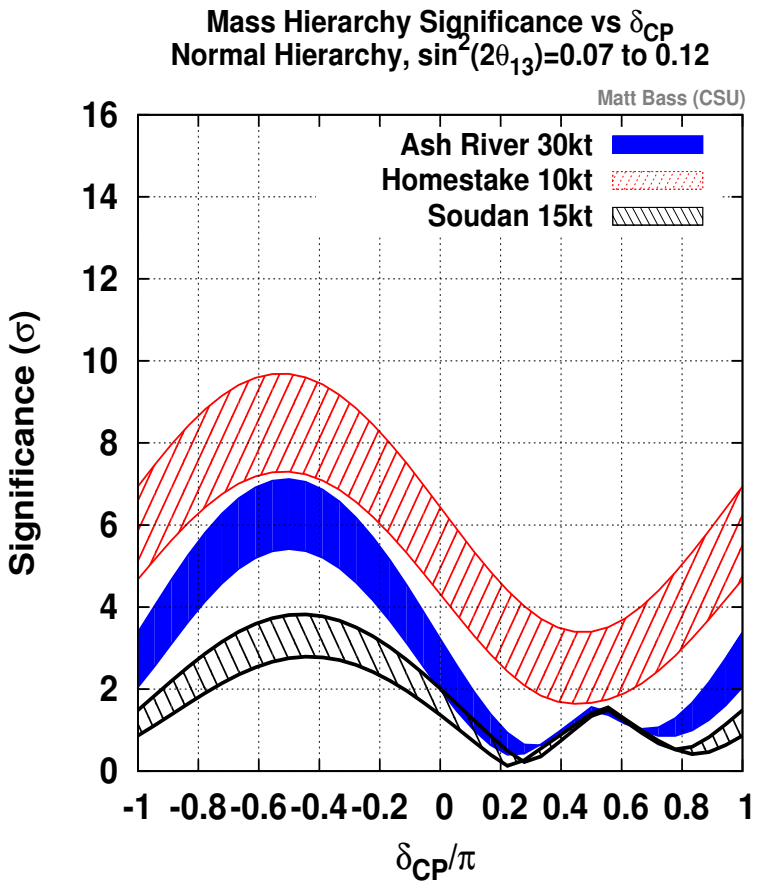
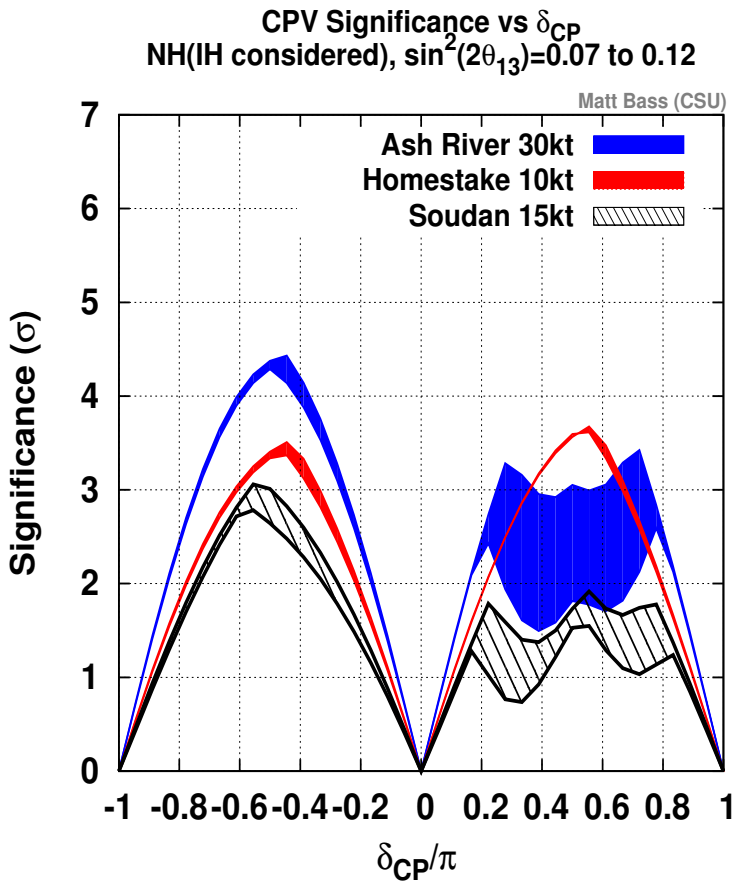
June 4, 2012: first DRAFT of the LBNE Reconfiguration Steering Committee Report identifies the following 3 Phase 1 options for the next generation long baseline experiment:





The Steering Committee "strongly favored" the 10kt Homestake option

Possible Phasing of Long Baseline Expts Phasing with Project X

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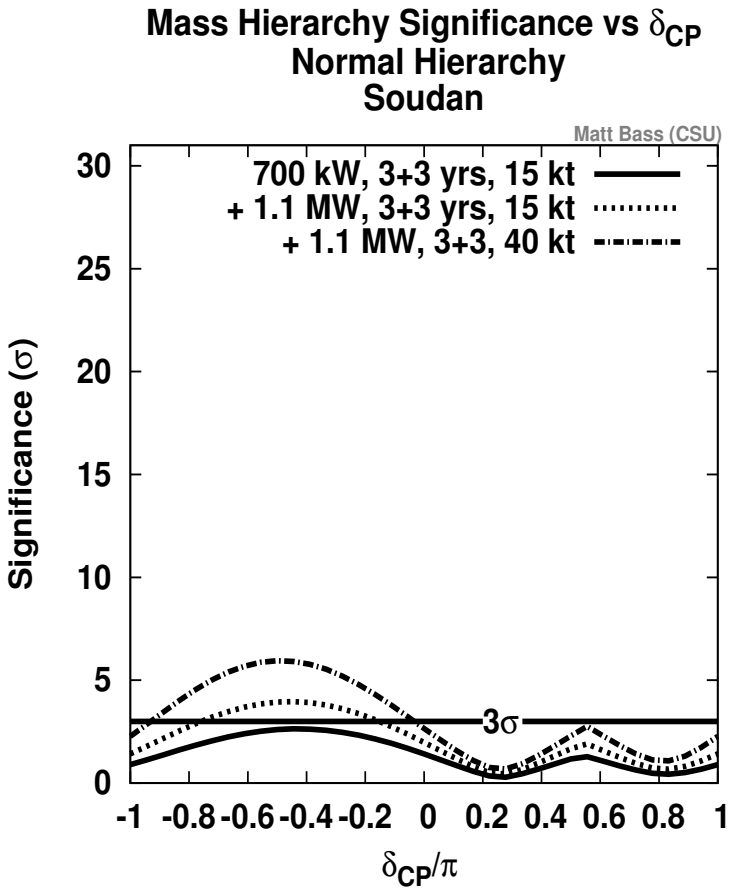

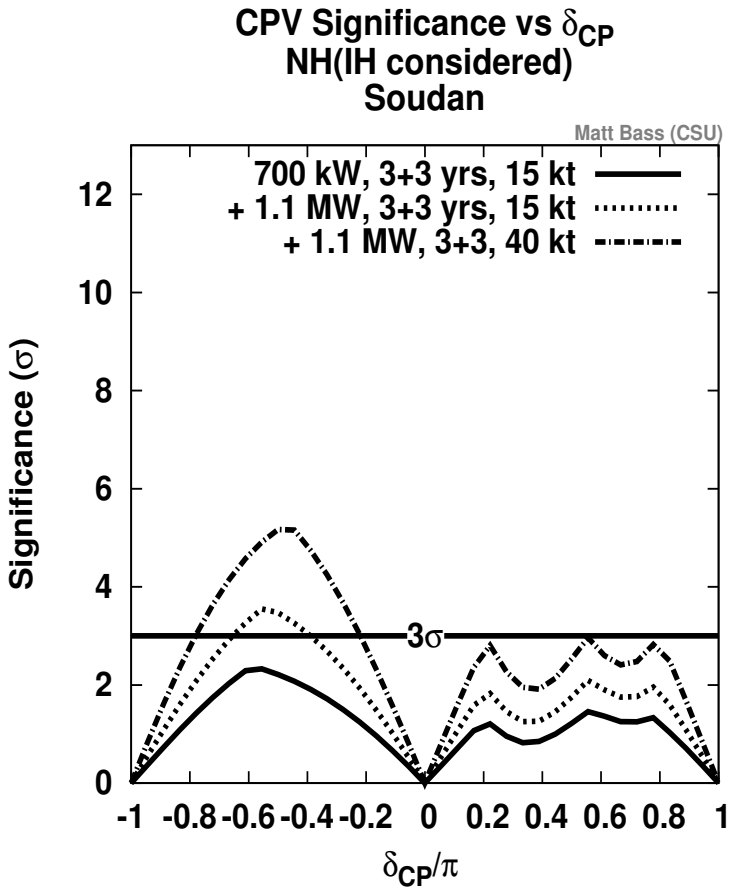

Soudan option has limited physics potential, even with Proj. X phase 1

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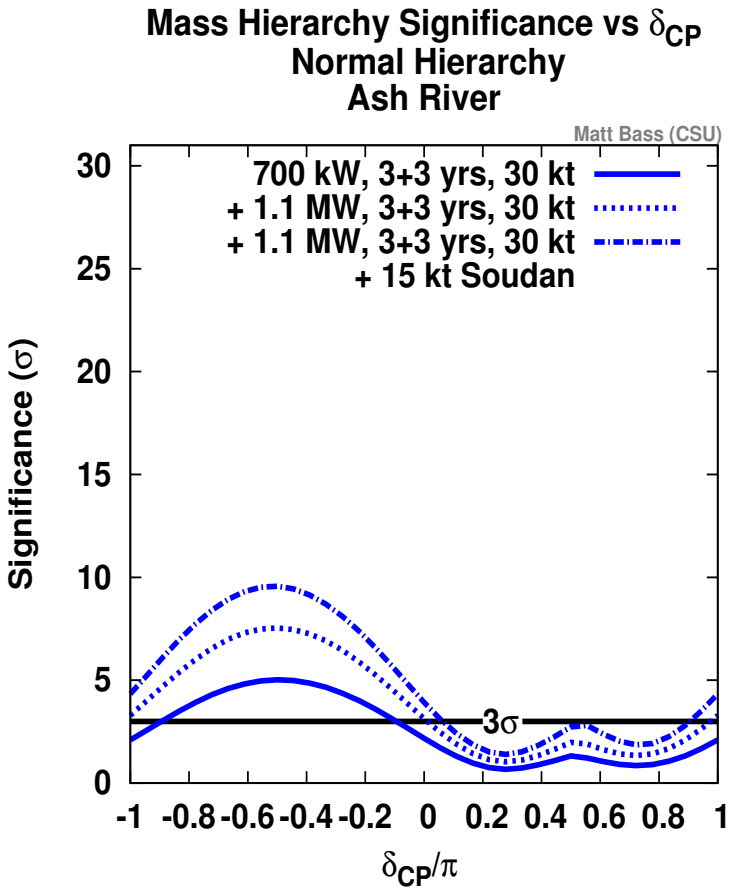

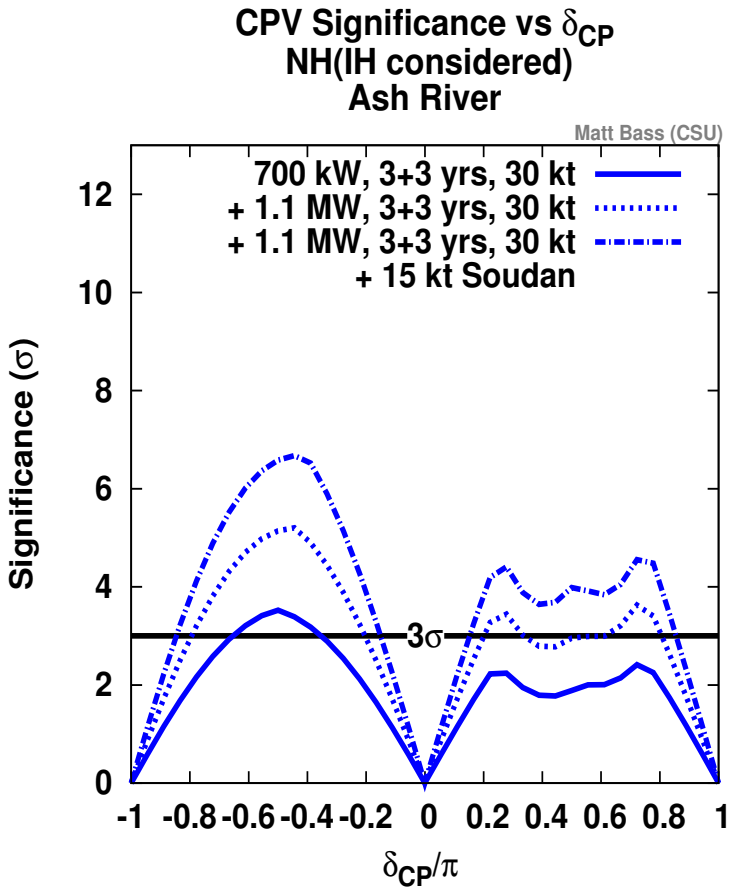

Project X phase 1 + 30kt at Ash River - EVIDENCE ($> 3\sigma$) for CPV

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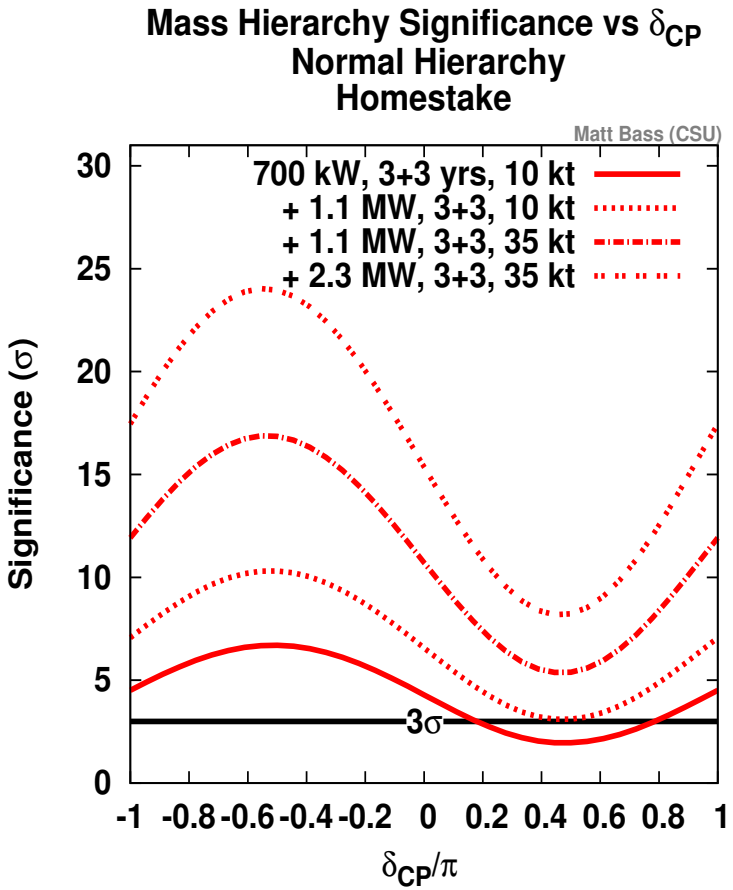

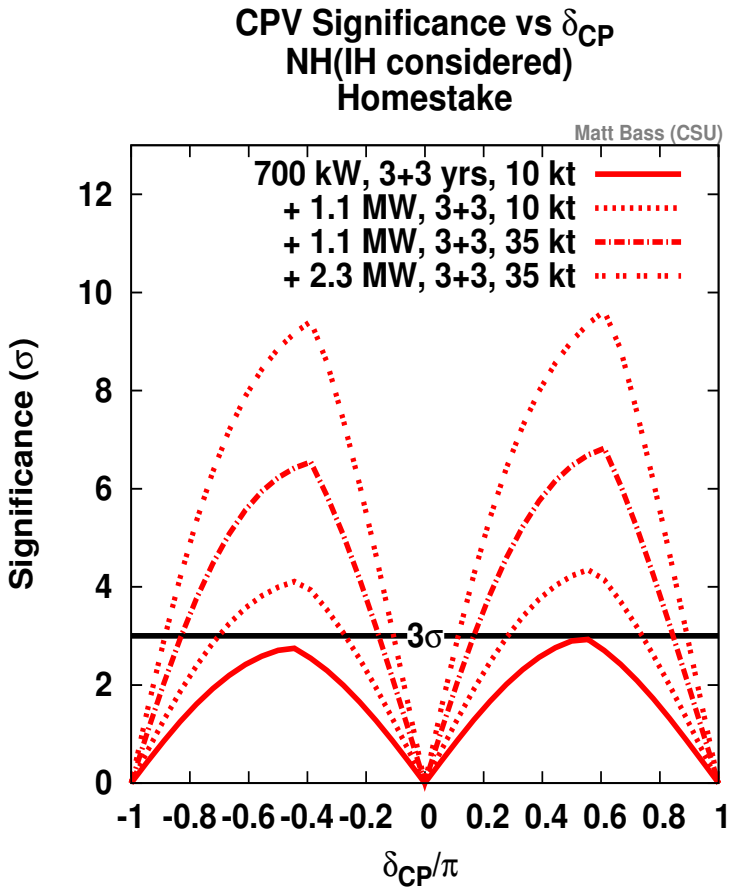

Project X + phase 2 LBNE/Homestake = DISCOVERY ($> 5\sigma$) of CPV

Measuring Δm^2_{23}, $\sin^2 2\theta_{23}$

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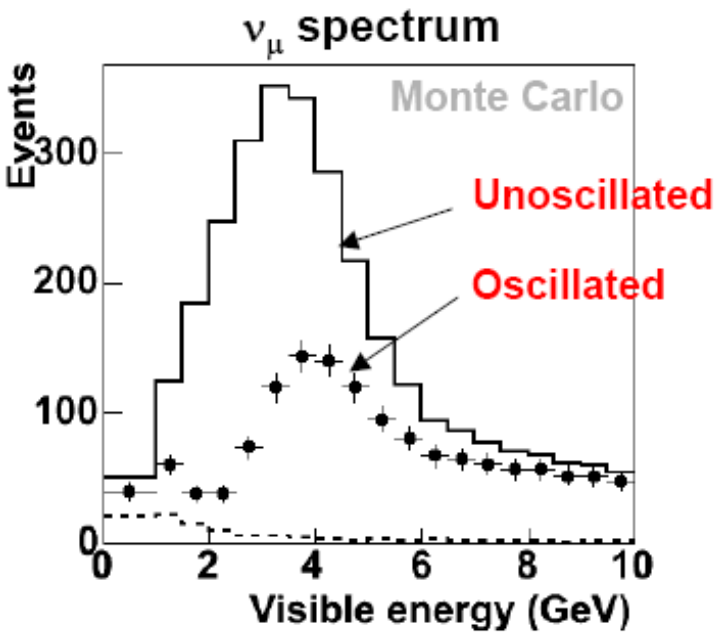
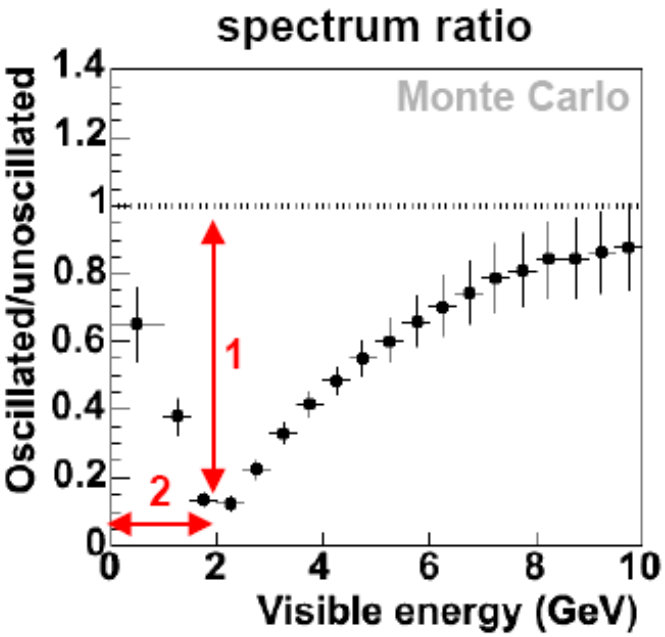
ν_μ and $\bar{\nu}_\mu$ disappearance measurements.

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \underbrace{\sin^2 2\theta_{23}}_{1} \sin^2(1.267\, \underbrace{\Delta m^2_{32}}_{2}\, L/E)$$





Disappearance Spectra - Neutrinos (Z. Isvan)

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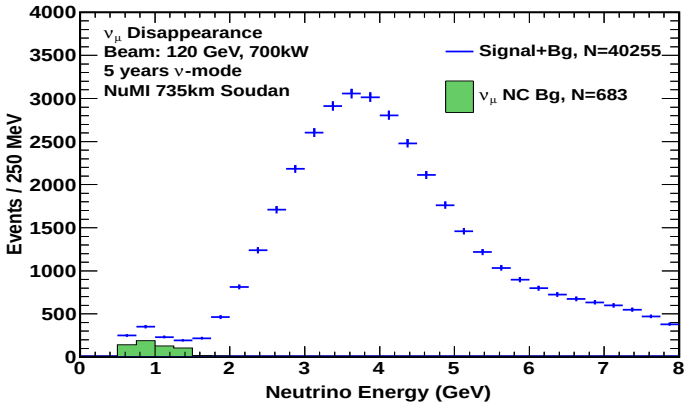
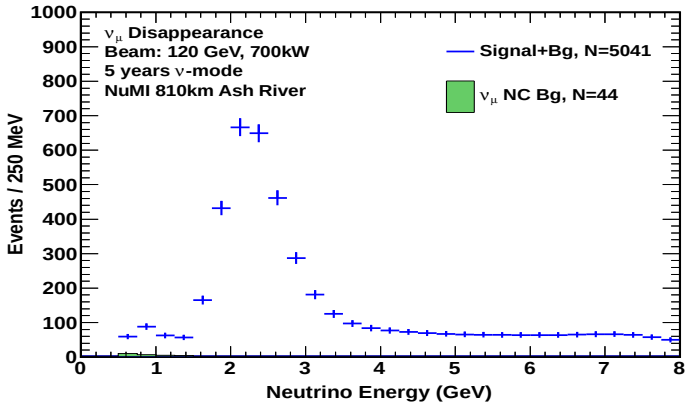
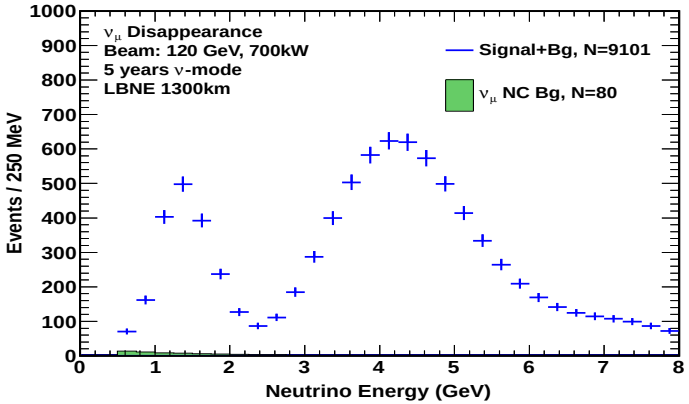
735km, NuMI LE at Soudan



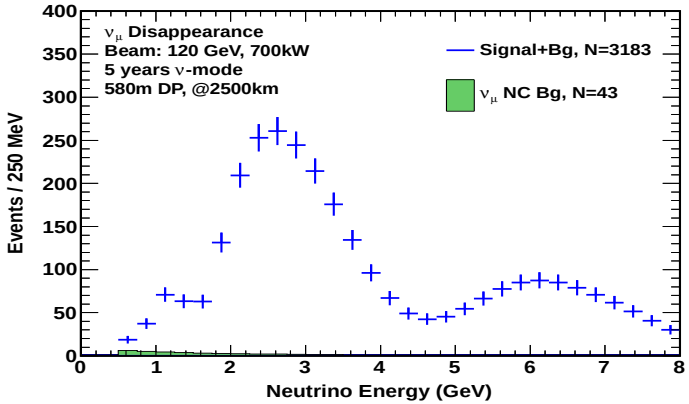
810km, NuMI ME at Ash River



1300km, LBNE LE at Hmstk



2500km, LBNE pME (580m DP)



Observe detailed oscillation structure at baselines $\geq$ 1300km .

Impact of the θ_{23} Octant. (E Worcester)

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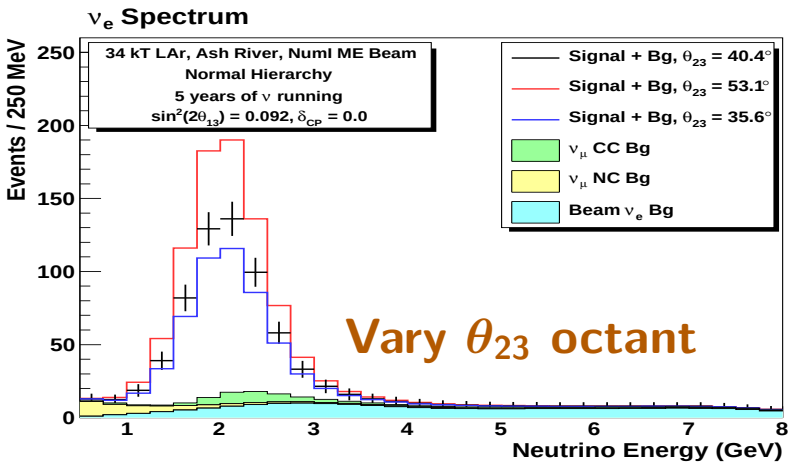
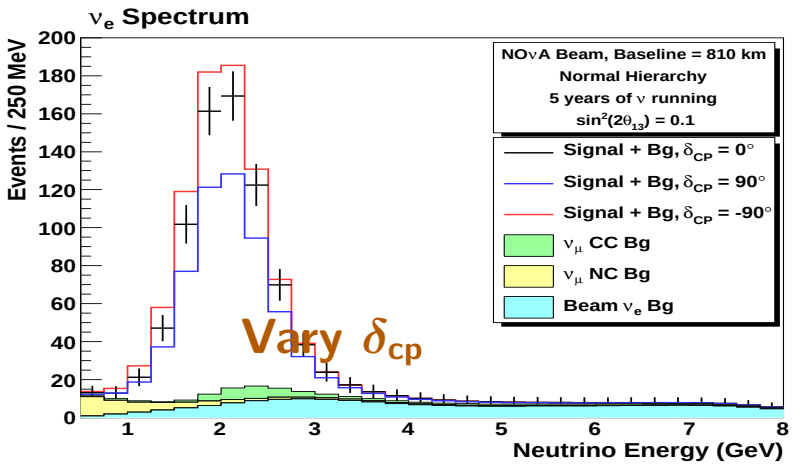
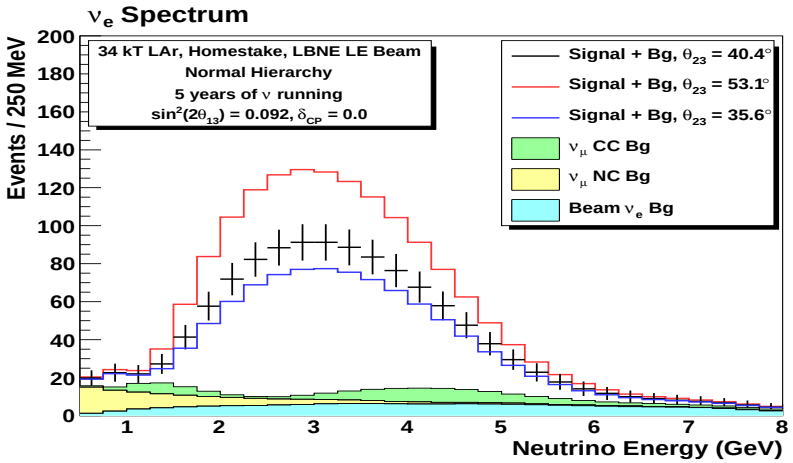
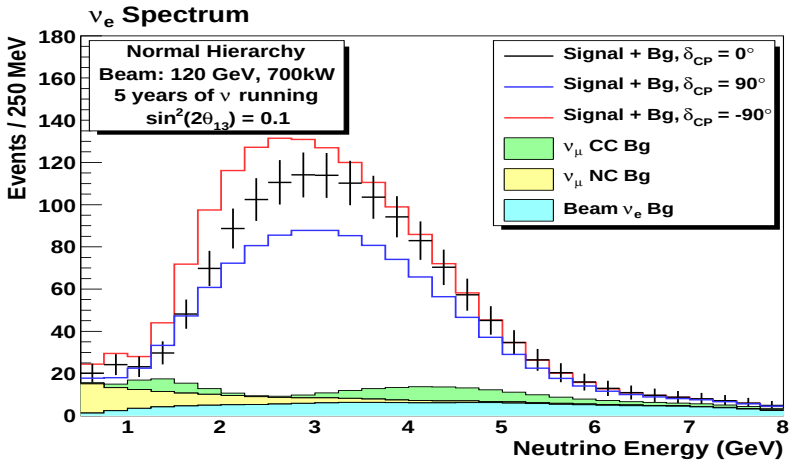
L=810km, NuMI ME 14mrad off-axis





L=1300km, LBNE LE





Larger spectral differences on-axis help break degeneracies

Resolution of the θ_{23} Octant - LBNE-Homestake 34 kt

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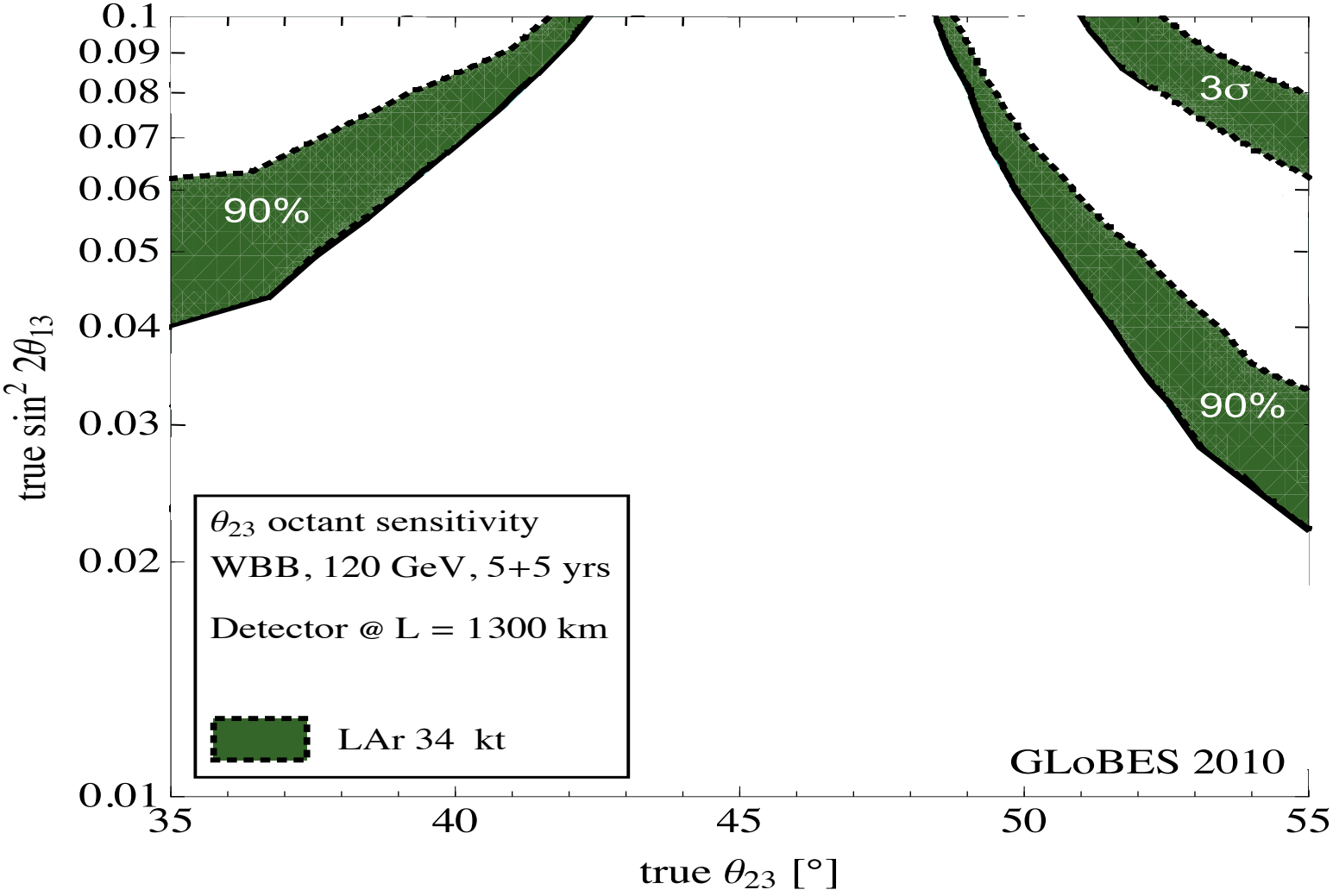

New Physics in $\nu_\mu/\bar{\nu}_\mu$ Disappearance

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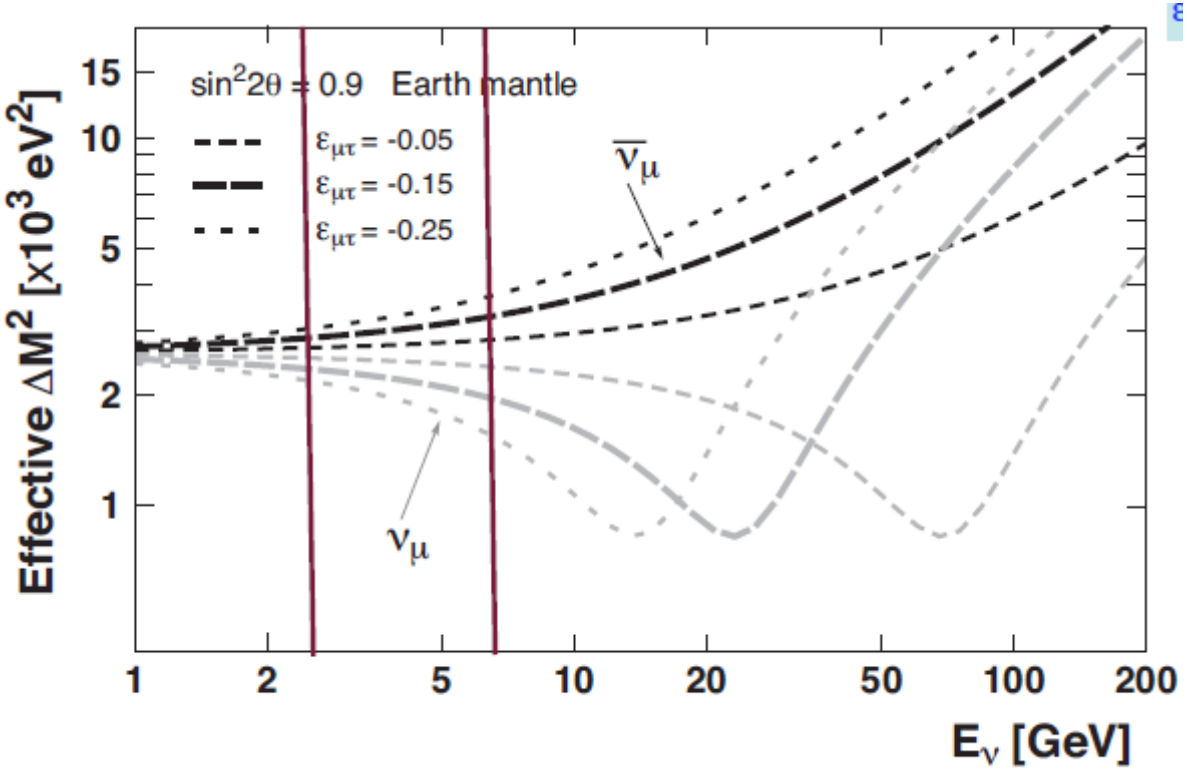
Phys.Rev. D82 (2010) 113010:

$$\mathcal{P}\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu \right) \simeq 1 - \sin^2\left(\left| \frac{\Delta m^2_{32}}{4E_\nu} \mp \epsilon_{\mu\tau}|V_e| \right| L \right). \quad (10)$$

$$\Delta M^2_{\rm eff} = \Delta m^2_{32}\Big\{1 \mp \sin 2\theta\, \epsilon_{\mu\tau}\, |V_e|\, (4E_\nu/\Delta m^2_{32}) + (\epsilon_{\mu\tau}V_e)^2 \cdot (4E_\nu/\Delta m^2_{32}))^2\Big\}^{1/2}. \quad (11)$$



Mann A.W. et al., arxiv 1006.5720

Oscillations at larger E_ν (longer baselines) = larger effects

Expected Limits on Non-Standard Interactions in LBNE with 34kt LAr (J. Kopp)

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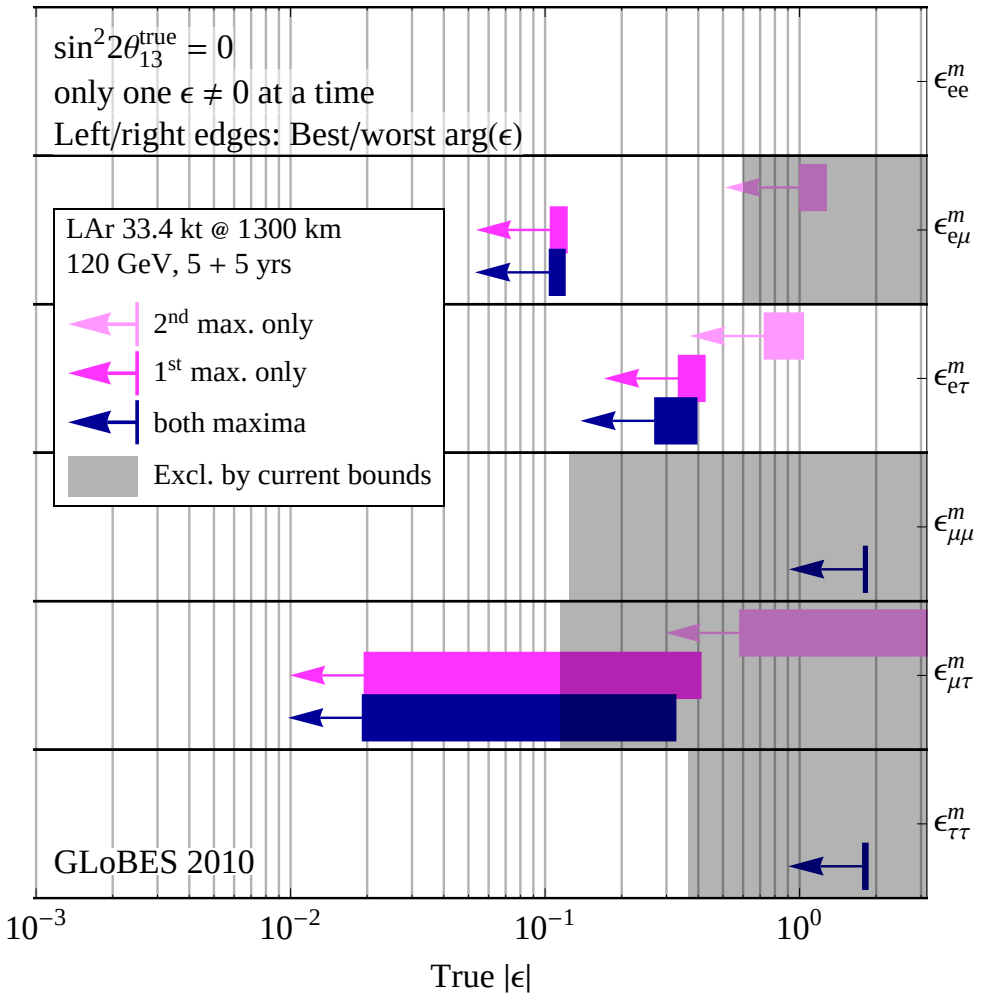
NC NSI discovery reach (3σ C.L.)



Requires precision determination of 3-flavor oscillation parameters

Optimization of NF Baseline and μ Energy (P.A. Huber)

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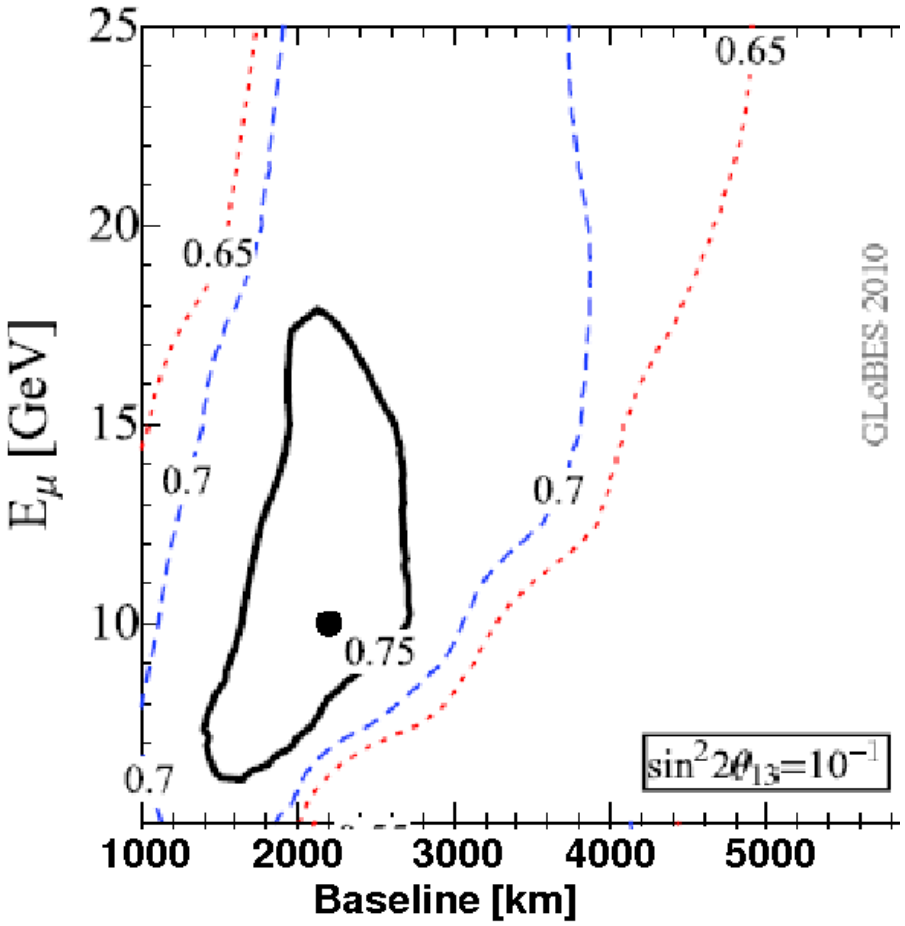

Using MIND (Magnetized Iron Neutrino Detector) and a single baseline:

The optimal range is 1400-2600km for E_μ from 7 - 15 GeV.

CPV coverage with Neutrino Factories (P.A. Huber)

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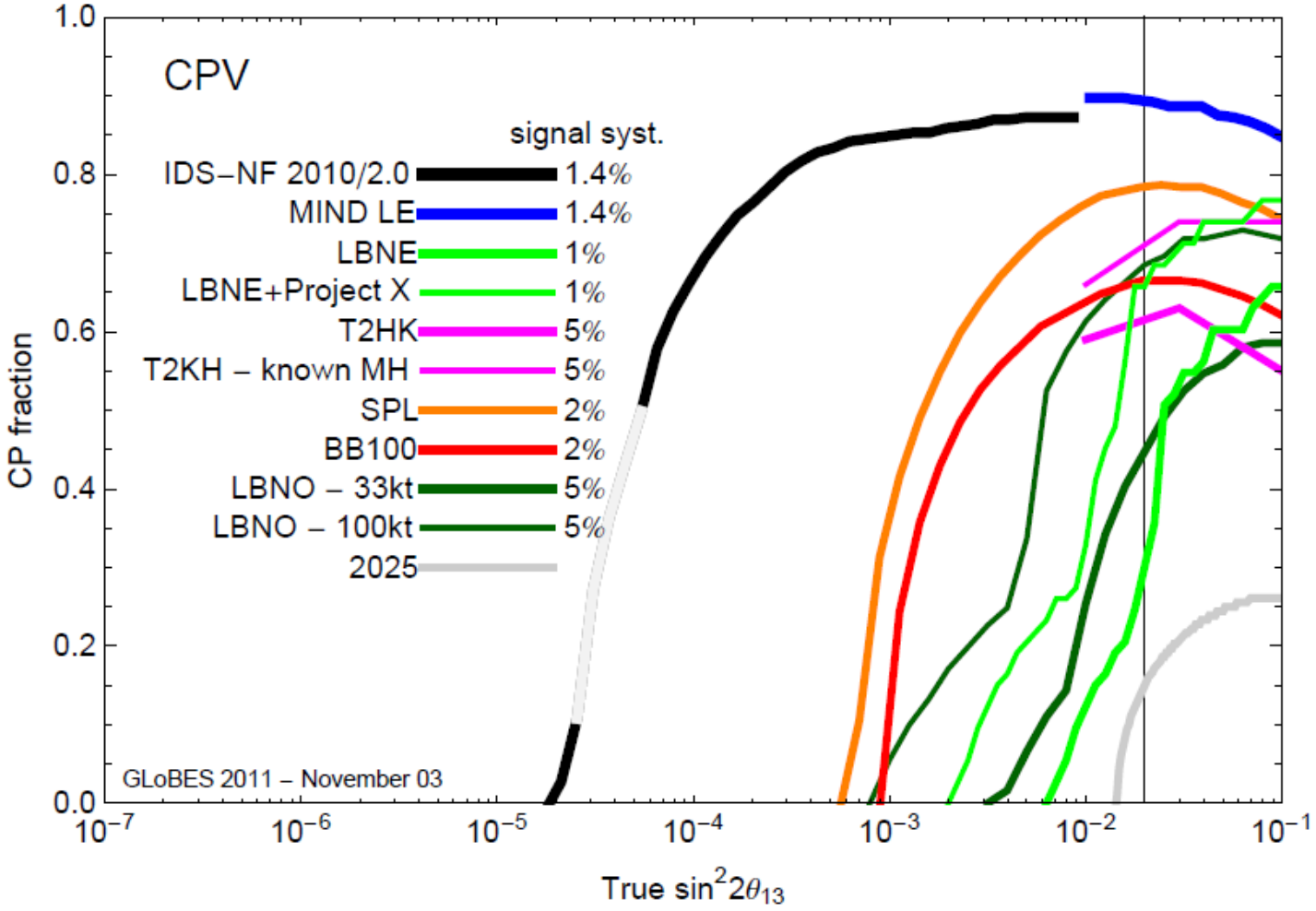

Neutrino factories can determine CPV for values of δ_{cp} close to 0 and π

Neutrino Factories and Precision Measurements of Parameters (P.A. Huber)

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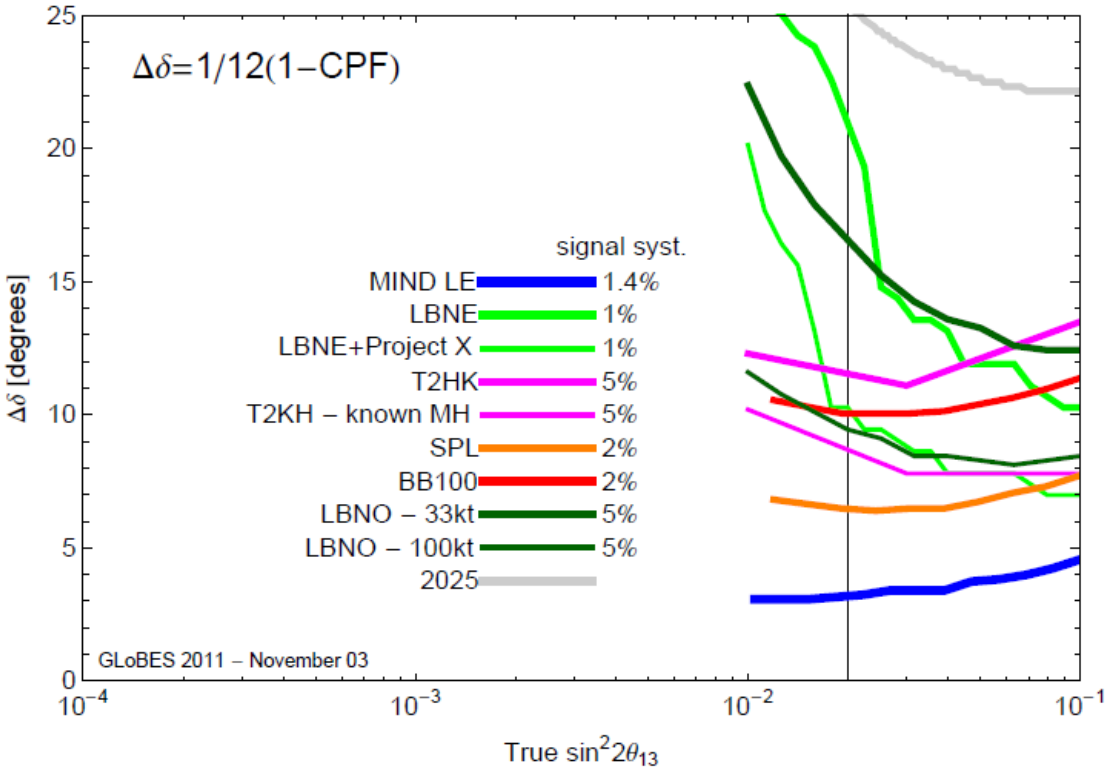
Sensitivity to physics beyond 3-flavor mixing REQUIRES high precision measurements of PMNS



Comparison not very accurate because of different assumptions of expt. uncertainties

Neutrino factories can determine PMNS parameters with a precision approaching CKM

Summary and Conclusions

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- **Long baseline neutrino experiments are the BIGGEST CUSTOMER of Project X.**
- **DISCOVERY ($> 5\sigma$) of CPV in ν requires many 100kt. MW. yrs.**
  Massive detectors + Proj X essential
- **The FNAL-Homestake baseline is close to optimal for both superbeams and low-energy neutrino factories.**
- **Searches for new physics beyond 3-flavor oscillations requires high PRECISION measurements of ν parameters.**
- **Neutrino factories face many technical hurdles but are necessary for high precision measurements and searches for new physics beyond our current understanding of the ν sector.**
- **Unique probes of CPV possible with LBNE-Homestake and Phase 3 of Project X (3MW at 8 GeV) - see talk by Z. Isvan on Tuesday June 19.**

Acknowledgements

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I'd like to thank the following members of the LBNE Physics Working Group who have worked incredibly hard in a very short amount of time to repeat the study of all the long baseline options in the U.S. after the letter from Brinkman:
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Milind Diwan, Zeynep Isvan, Elizabeth Worcester (BNL)
Byron Lundberg, Gina Rameika, Sam Zeller (FNAL)

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