LBNE long-baseline physics in the Project X era

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Project X Physics Study, Fermilab

Project X and LBL Beam Neutrino Physics

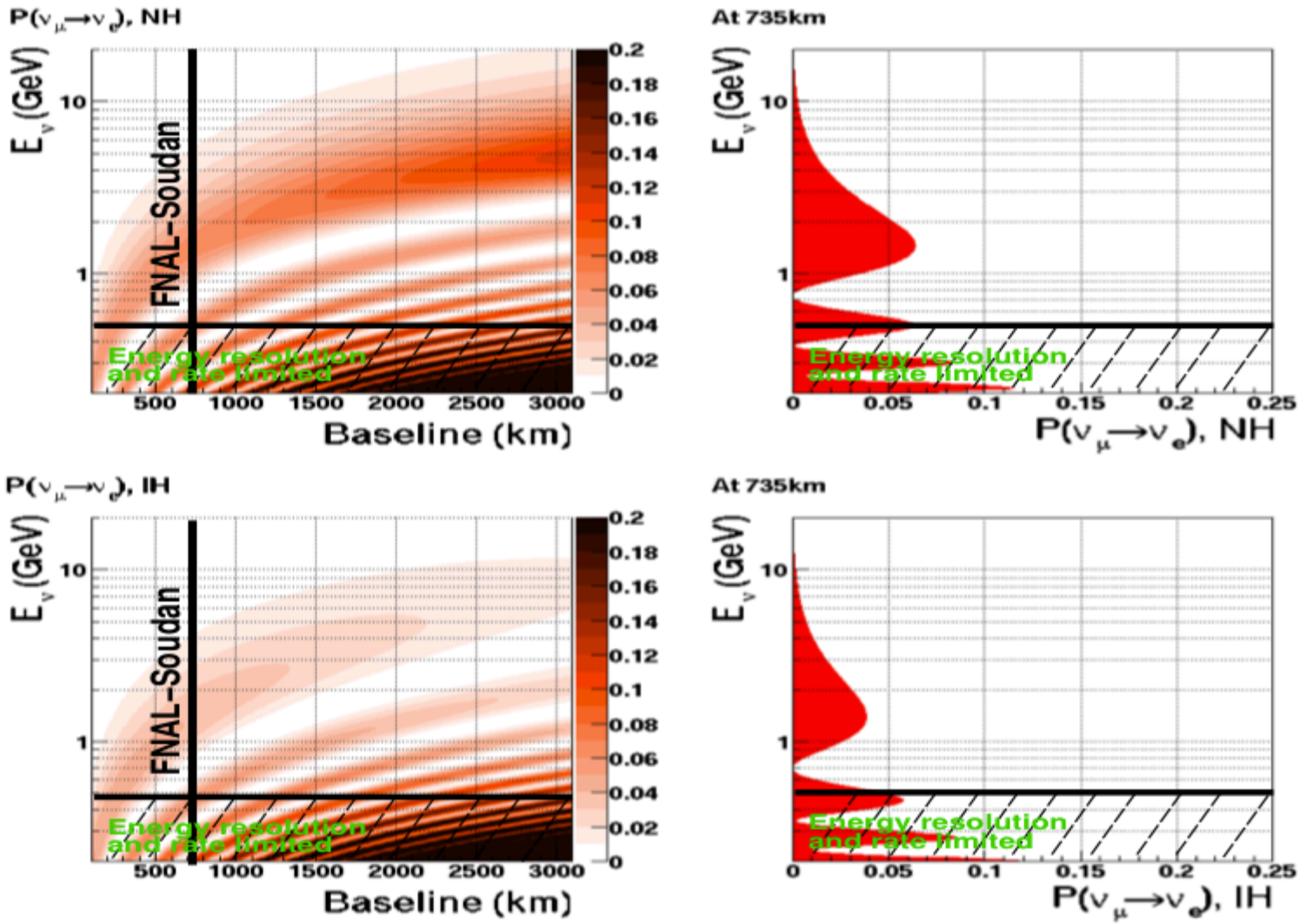
- "A high-power proton source with proton energies between 1 and 120 GeV would produce intense neutrino sources and beams illuminating near detectors on the Fermilab site and **massive detectors at distant underground laboratories.**"

- Long-baseline beam physics goals of LBNE: **To resolve CPV and mass hierarchy.**

- LBNE and Project X will both be 'phased' in parallel.

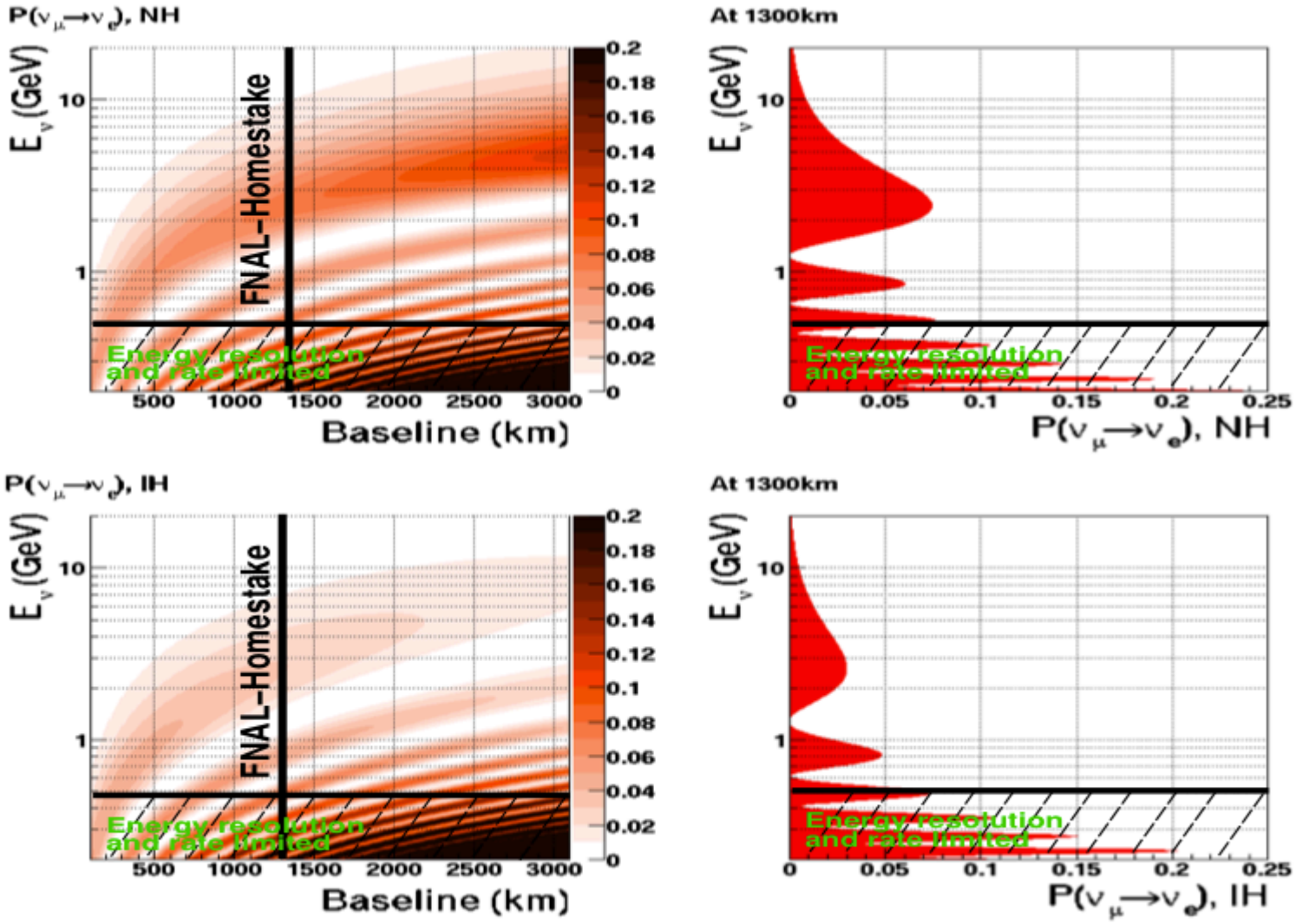
  - LBNE phase 1 starts running, PX stage 1 starts around phase 2 of LBNE.

$\nu_\mu \rightarrow \nu_e$ oscillations at 735 km



- Appearance probability as a function of energy and baseline

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

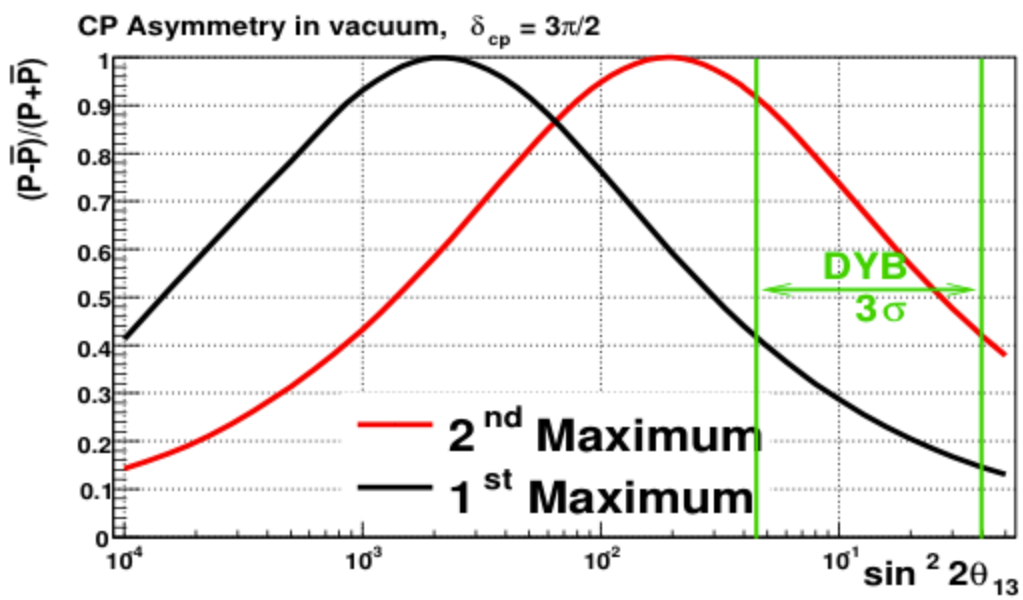


- Appearance probability as a function of energy and baseline

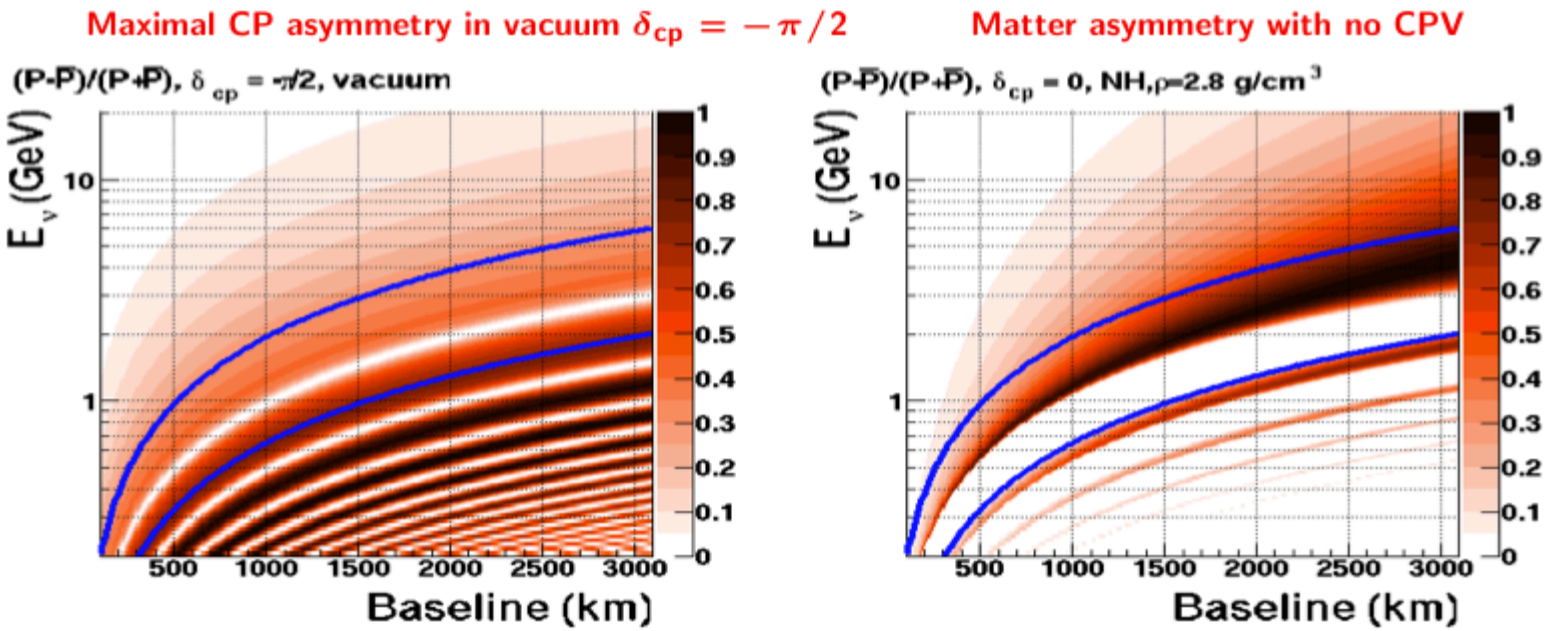
CP Asymmetry

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

- Largest CP asymmetry at $\delta_{CP}=-\pi/2$
- Effect gets smaller with large $\sin^2\theta_{13}$
- Larger effect in the second maximum



CP and matter asymmetries



- CP asymmetry are largest at the secondary oscillation nodes.
- Matter asymmetry largest at the first oscillation node.
- Need wide band beam to resolve degeneracies.
- For CP, need high signal/background in 2nd maximum.
- $\nu_\mu \rightarrow \nu_e$ appearance signal size O(1000) events per 100kT·MW·years; need large detectors *and* powerful beams.

Example Research Program, definitive space on PXPS website.

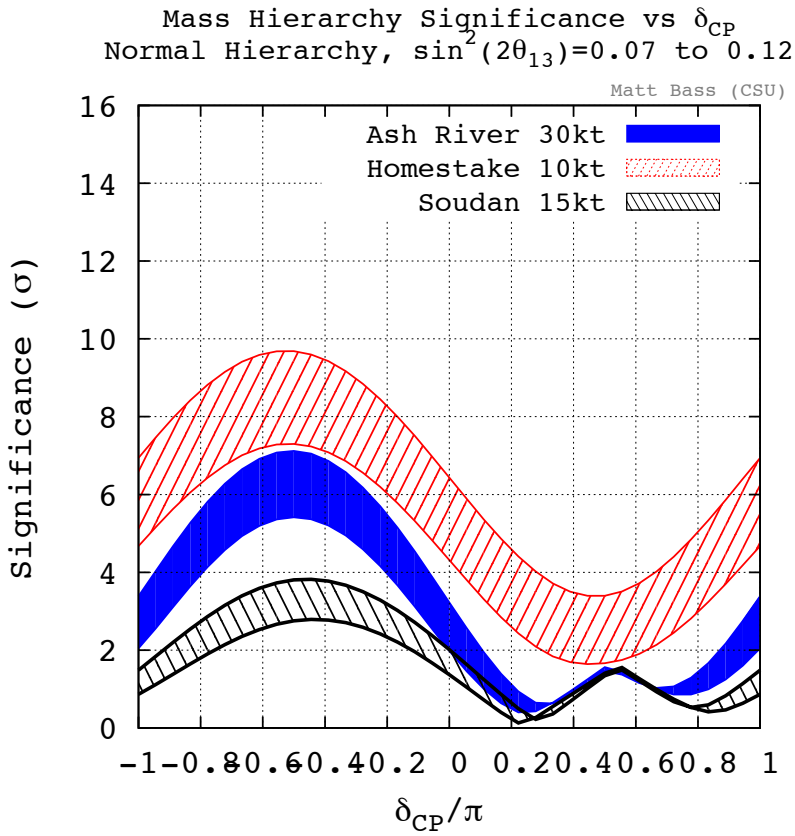
Project X Campaign

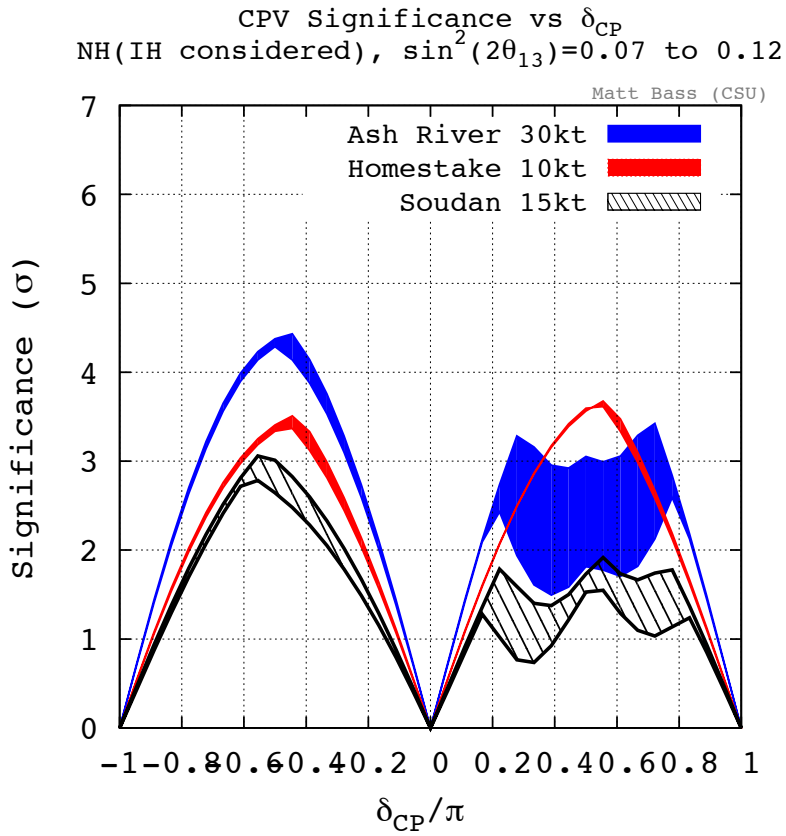
Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

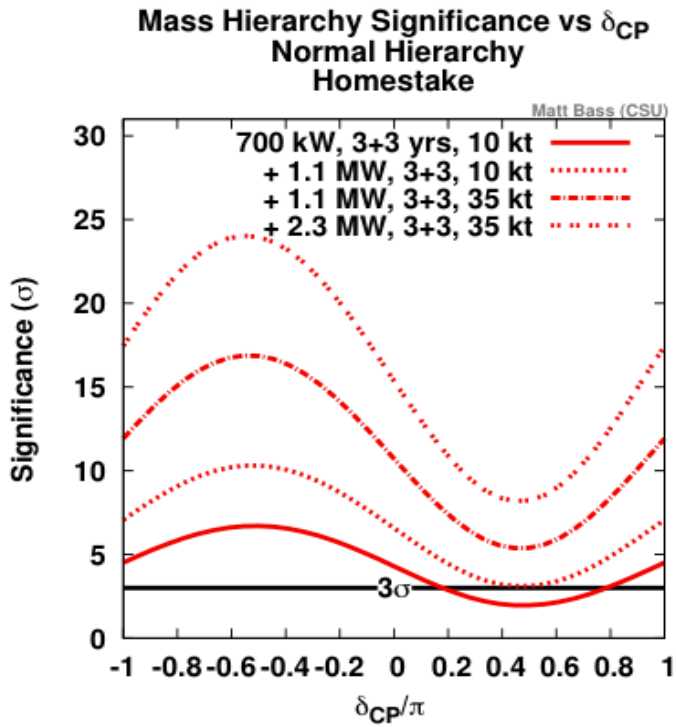
LBNE Options: Phase 1

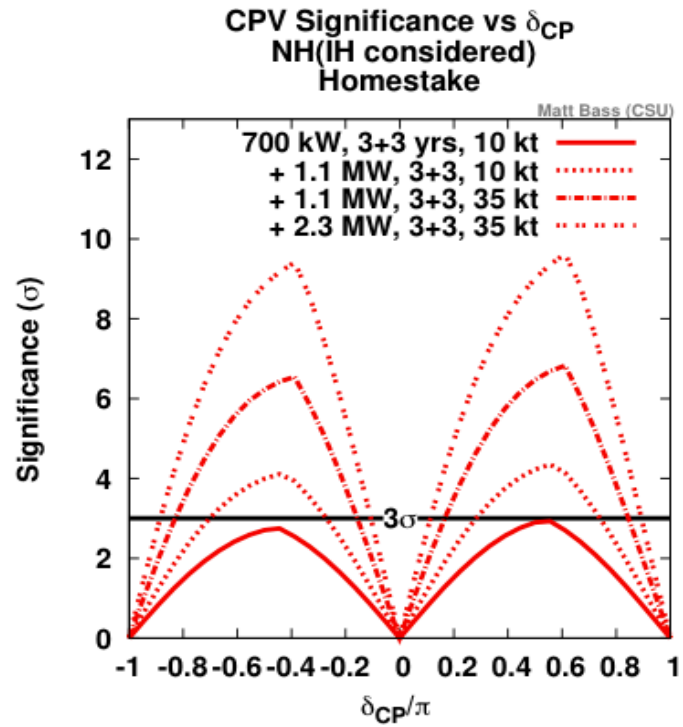




- Steering committee **strongly favored** the 10kT Homestake option.
- Most promising option both by its standalone physics reach and its compatibility with a longer term program including PX.

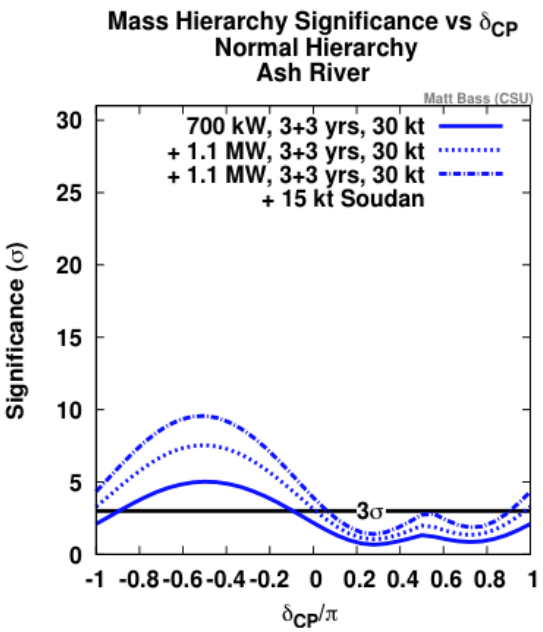
LBNE Phase 2 + Project X Stage 1

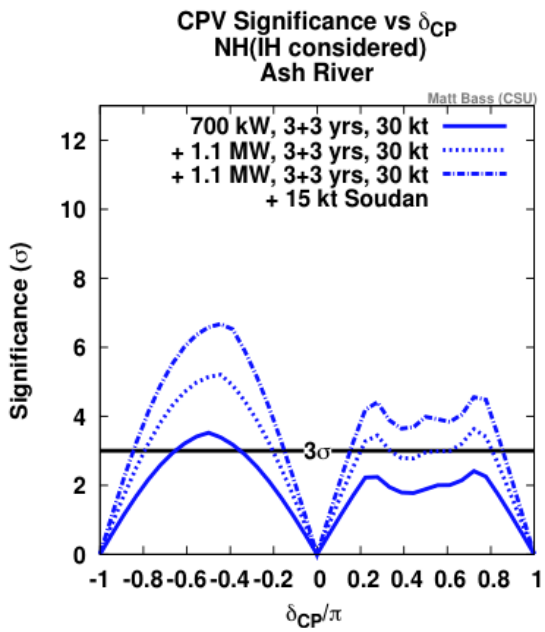


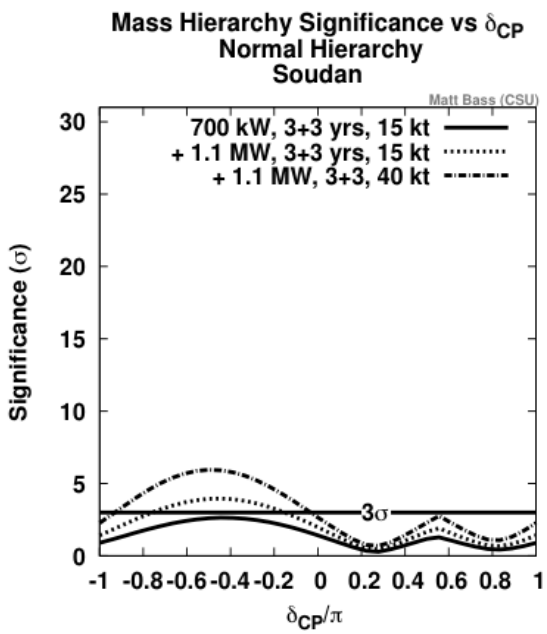


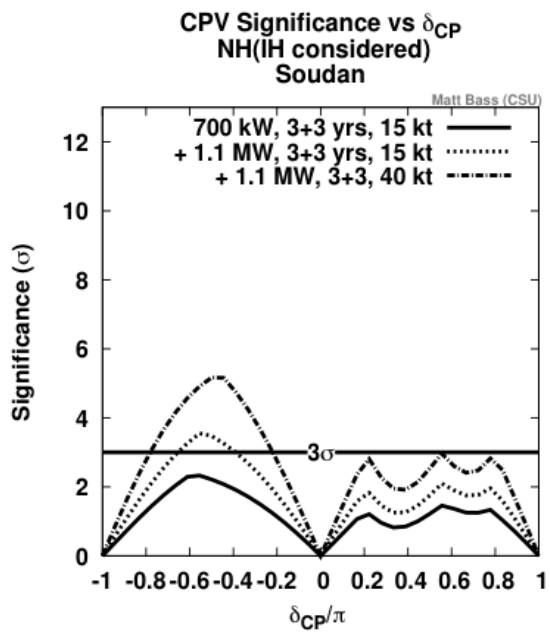
- Stage 1 of PX increases the MI beam power to MW range
- LBNE/Homestake Phase 2 + PX Phase 1 = **Discovery (>5σ) CPV**

LBNE Phase 2 + Project X Stage 1









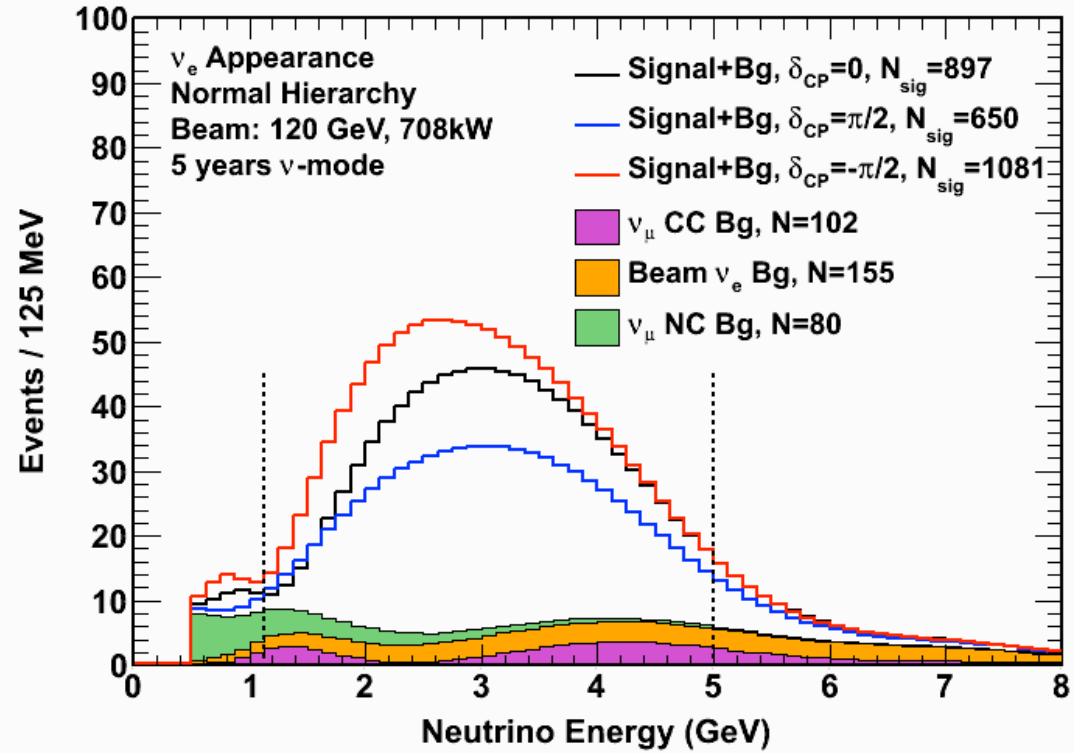
- LBNE/Ash River (30kT) Phase 2 + PX Phase 1 = **Evidence (>3σ) CPV**
- LBNE/Soudan (15-40kT) Phase 2 + PX Phase 1 = **< 3σ CPV even with Project X Stage 1**

Project X Stage 2 Possibilities

- Stage 2 will allow MW-power lower energy beams
- Can we gain low energy flux (at long baselines) by going to lower energies?
- This can populate the second maximum and improve the signal/background in the CPV-sensitive region.
- Consider 30, 60, 90 GeV energies and 1MW beam power
- Separation power figure of merit:

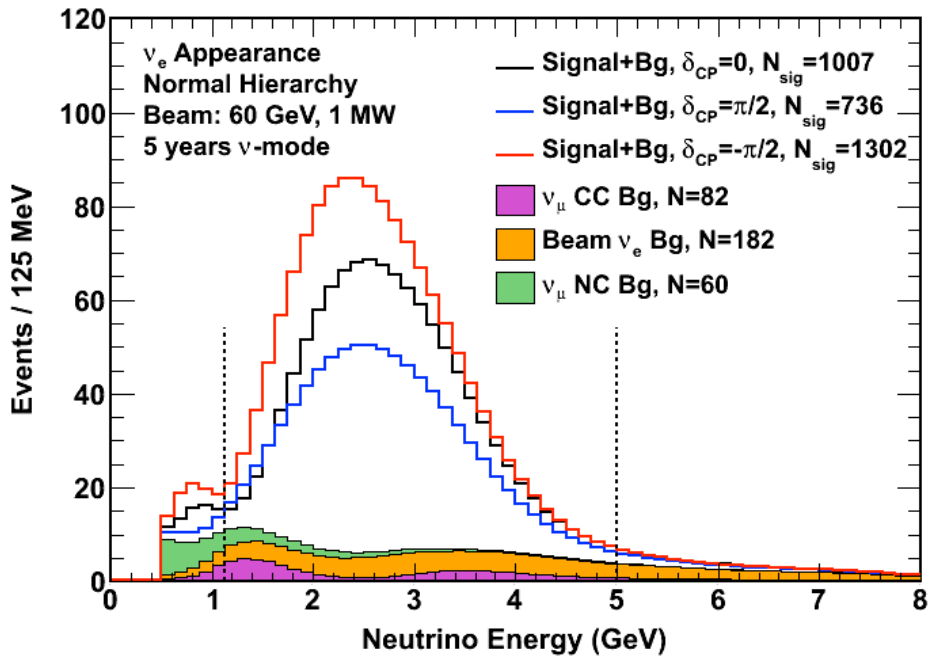
$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 23.5$$

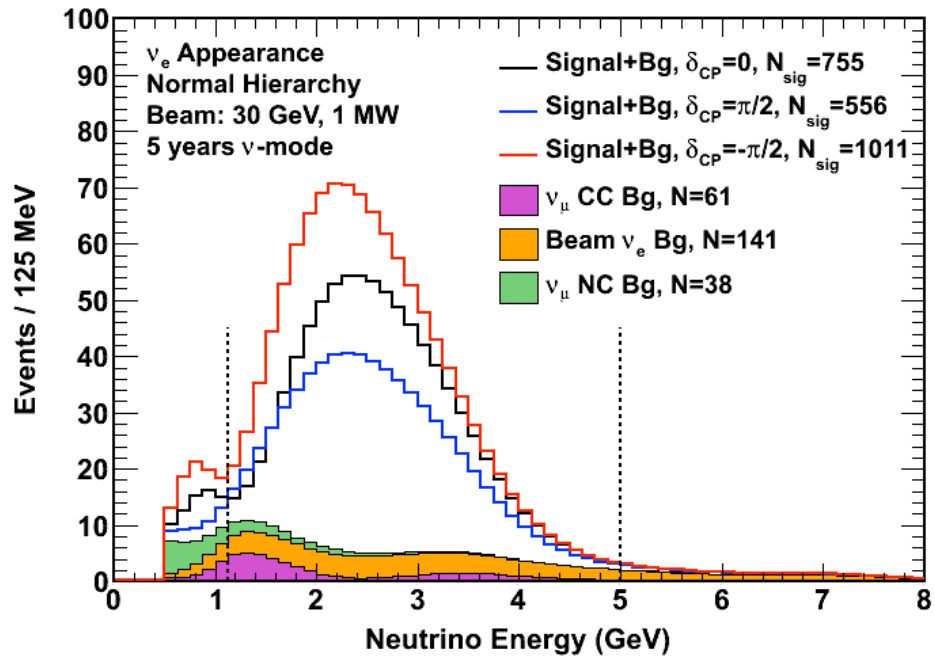
Standard 120 GeV 700kW



δ_{CP}	N	N_{second}	N_{first}	$N/\sqrt{B}$	$N_{second}/\sqrt{B}$	$N_{first}/\sqrt{B}$
0	897	14	817	48.86	2.27	57.34
$\pi/2$	650	5	597	35.41	0.81	41.90
$-\pi/2$	1081	24	994	58.89	3.89	69.77

60 GeV 1MW, 30 GeV 1MW





δ_{CP}	N	N_{second}	N_{first}	$N/\sqrt{B}$	$N_{second}/\sqrt{B}$	$N_{first}/\sqrt{B}$
0	1007	26	955	55.94	3.92	64.83
$\pi/2$	736	10	707	40.89	1.51	47.99
$-\pi/2$	1302	45	1231	72.33	6.78	83.57

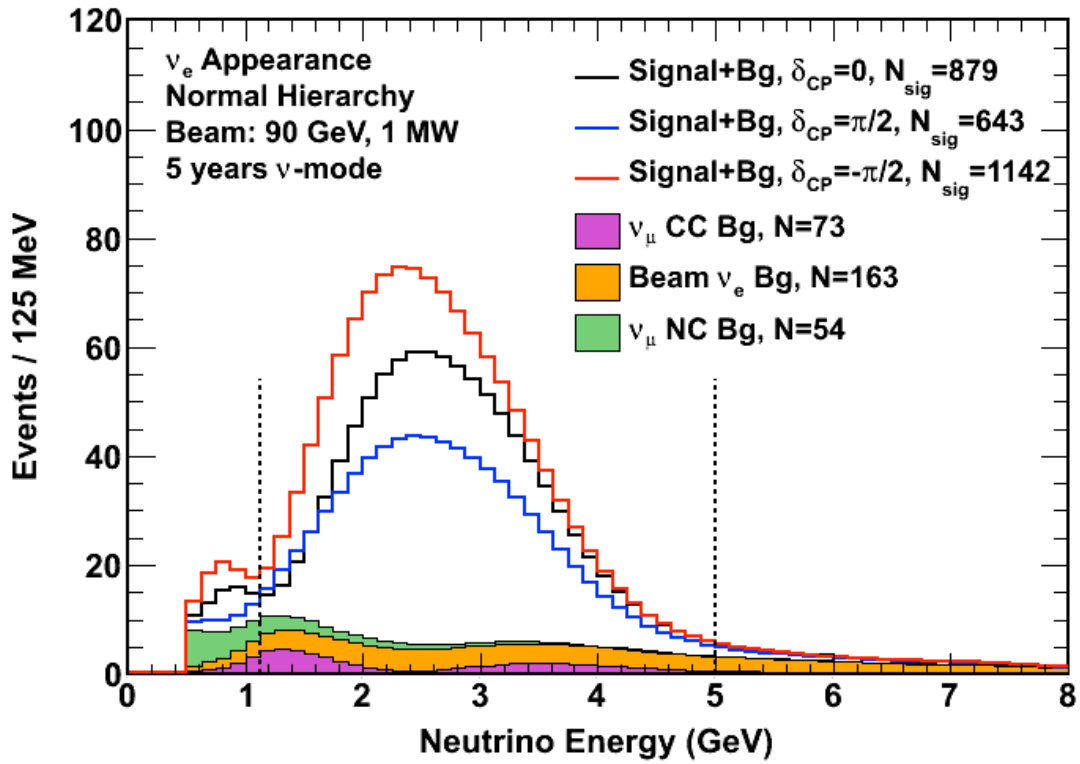
$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 31.4$$

δ_{CP}	N	N_{second}	N_{first}	$N/\sqrt{B}$	$N_{second}/\sqrt{B}$	$N_{first}/\sqrt{B}$
0	755	30	716	48.74	4.93	55.08
$\pi/2$	556	11	538	35.89	1.81	41.38
$-\pi/2$	1011	51	951	65.26	8.38	73.15

$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 29.4$$

- Can do better CPV than 120 GeV with the same amount of running
- Technical: High density graphite target inserted into horn 1 unlike standard NuMI LE at z=-30cm

90 GeV 1MW, Hybrid Tantalum-Carbon Target

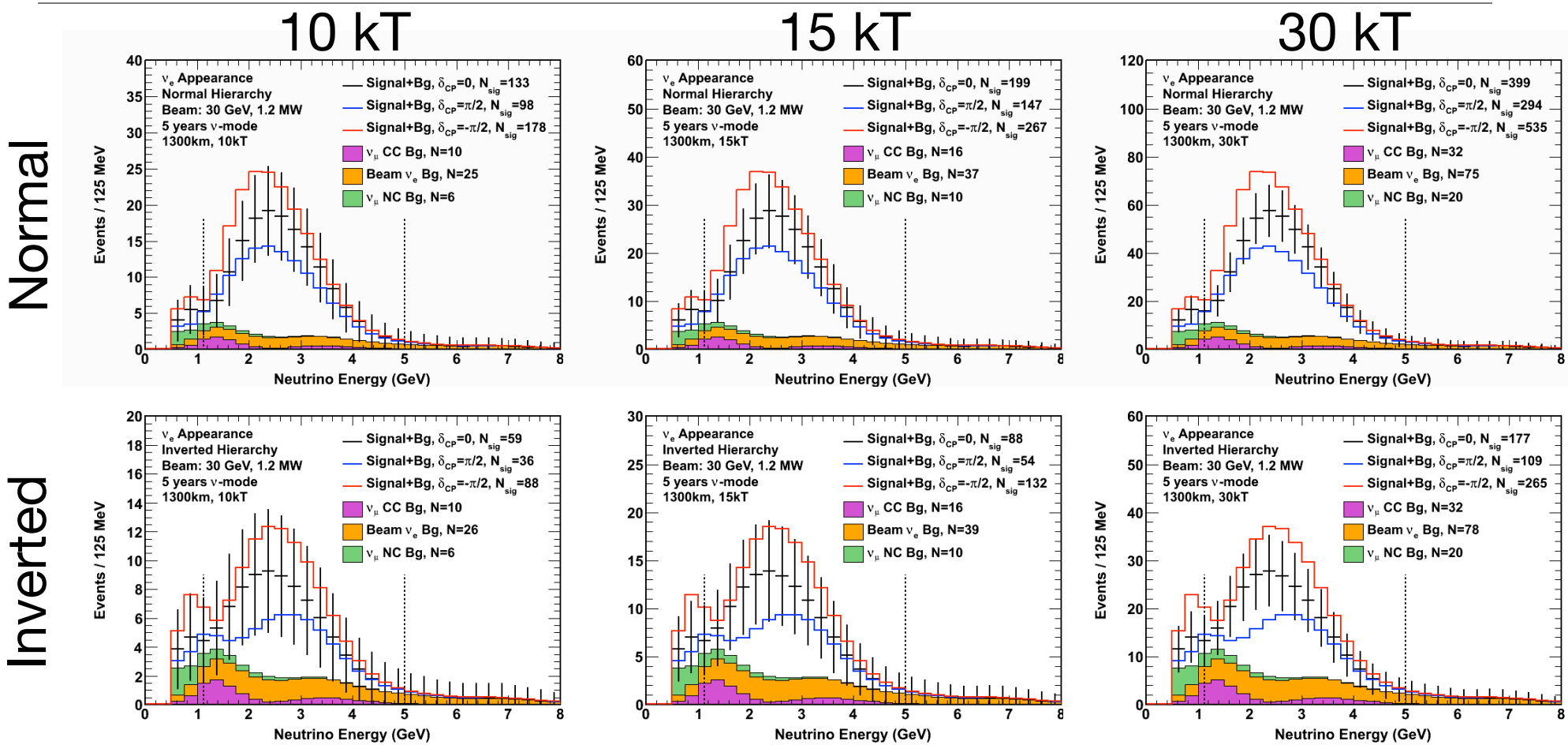


- Technical: High density graphite target inserted into horn 1 unlike standard NuMI LE at z=-30cm

$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 29.3$$

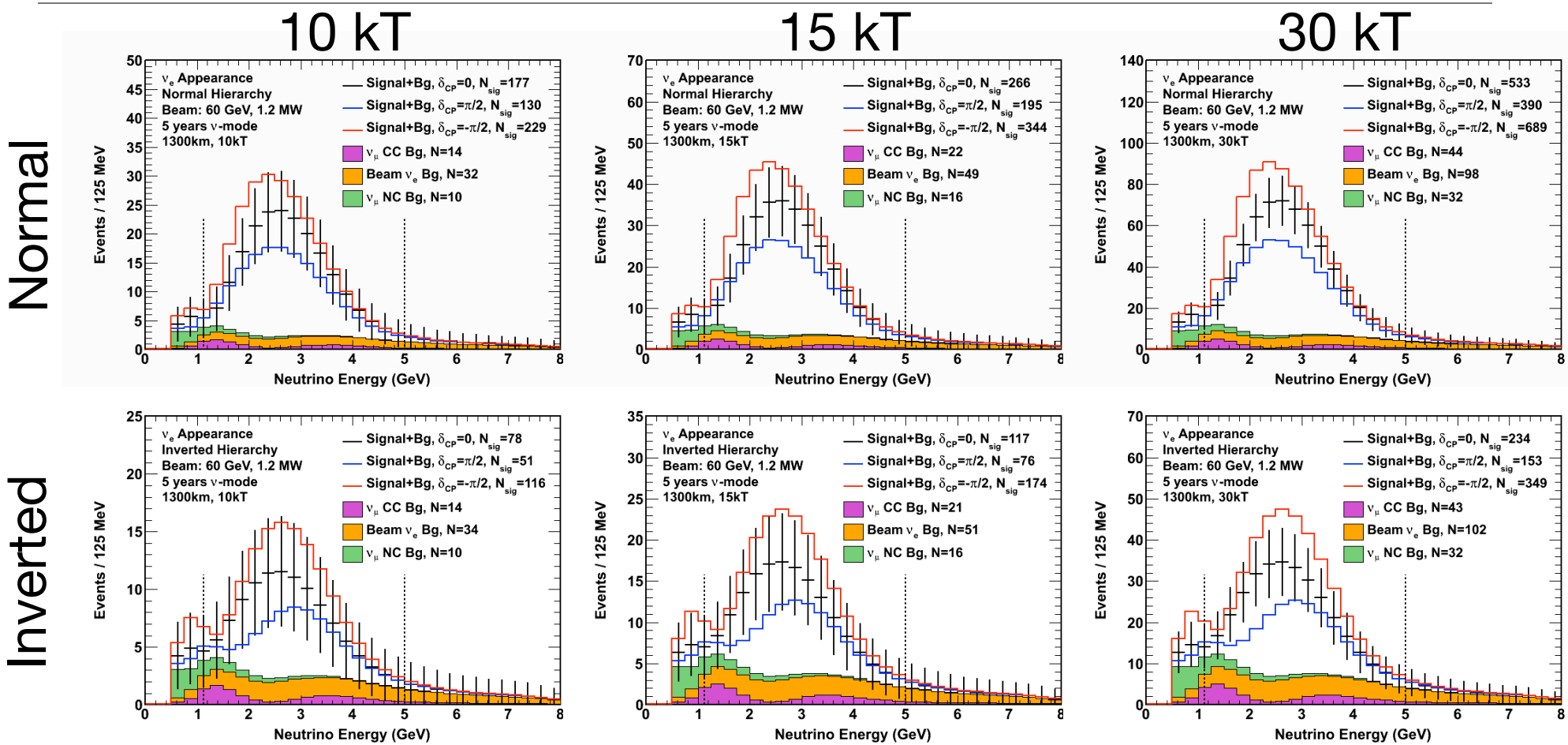
δ_{CP}	N	N_{second}	N_{first}	$N/\sqrt{B}$	$N_{second}/\sqrt{B}$	$N_{first}/\sqrt{B}$
0	879	27	832	51.62	4.22	60.20
$\pi/2$	643	10	617	37.76	1.56	44.64
$-\pi/2$	1142	46	1075	67.06	7.18	77.78

30 GeV 1.2 MW Beam, 1300km baseline



- CP separation in conjunction with pre-Stage 2 datasets - fills in low energy spectrum
- Sensitivity studies coming

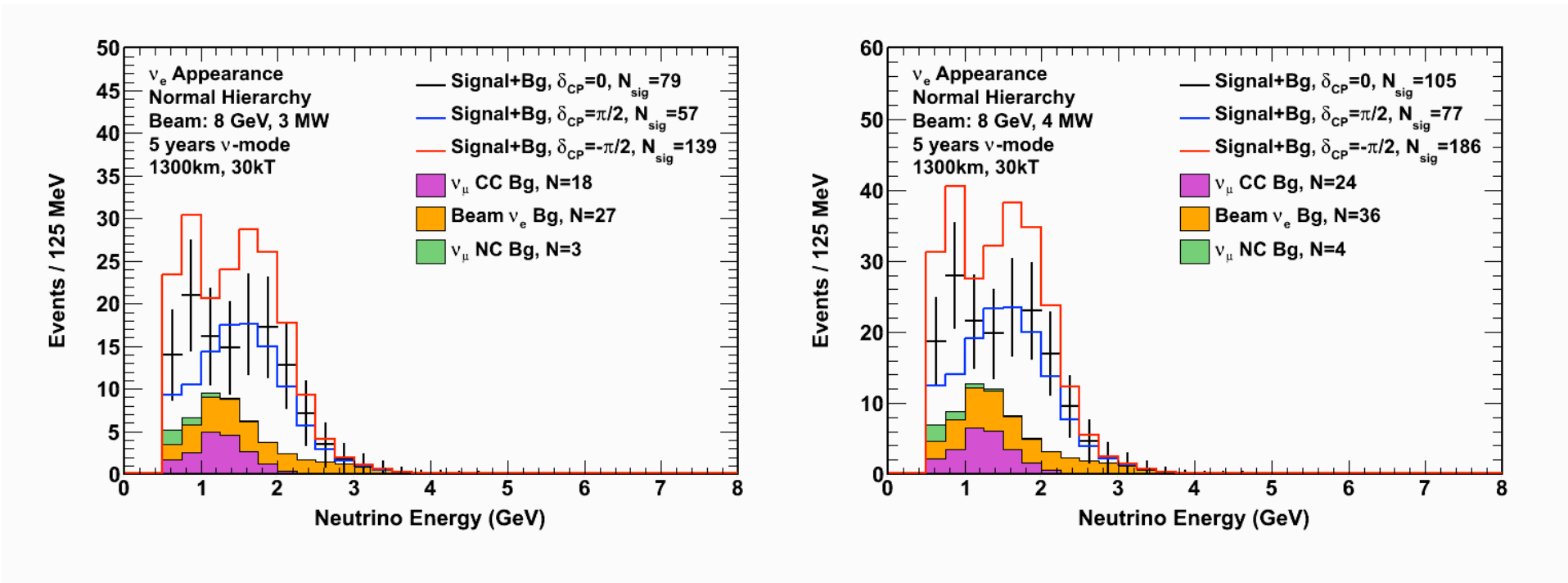
60 GeV 1.2 MW Beam, 1300km baseline



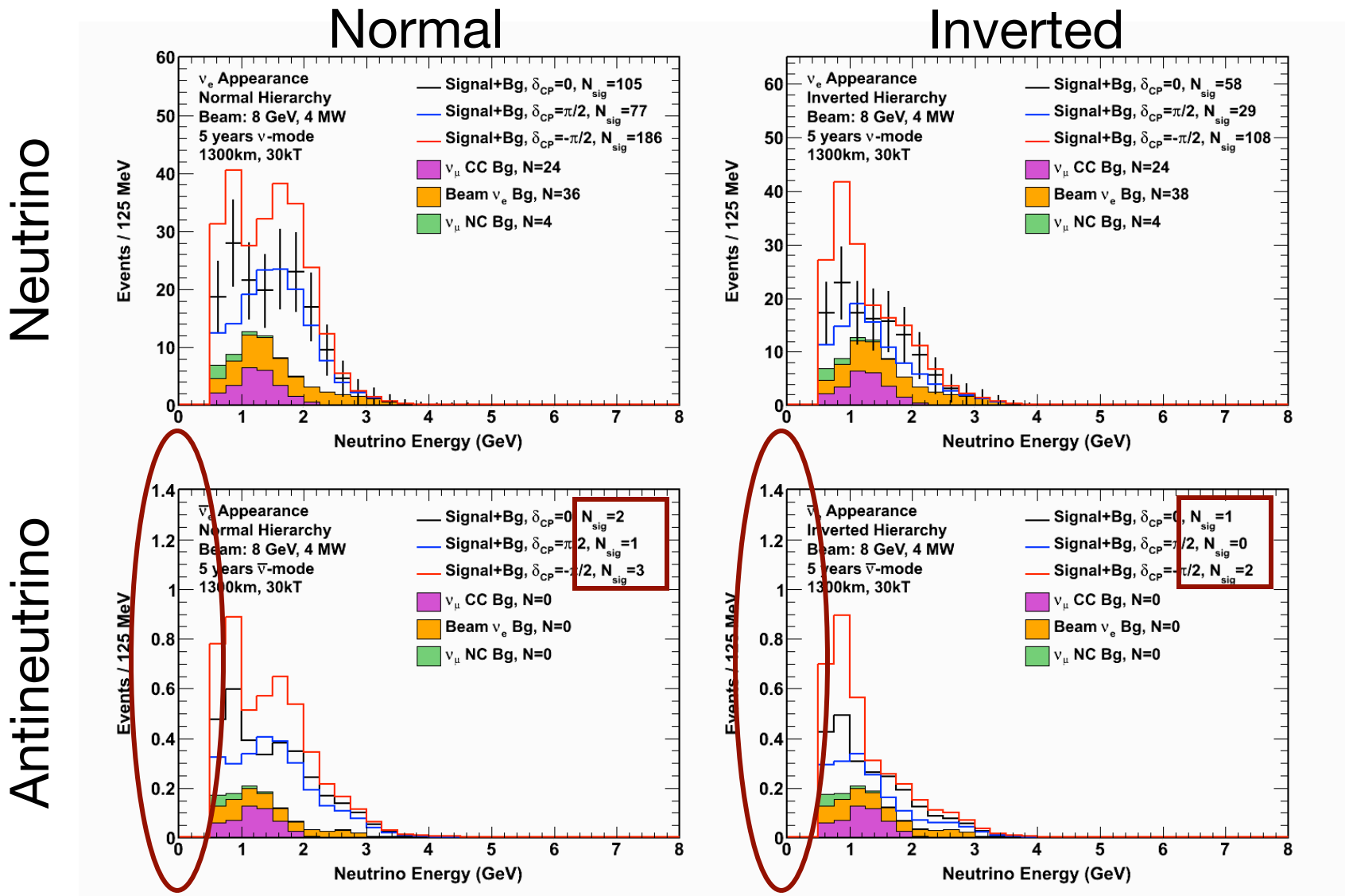
- Larger flux but slightly higher energy.
- Further studies ongoing to optimize and determine combination that gives the best sensitivity soonest in a viable phasing scenario.

Stage 3: 8GeV and 3-4 MW

- With this super high intensity beam it is possible to do long-baseline physics at very low energies: second maxima can be illuminated
- Degeneracy between $\delta_{CP} < 0$ and $\delta_{CP}=0$.

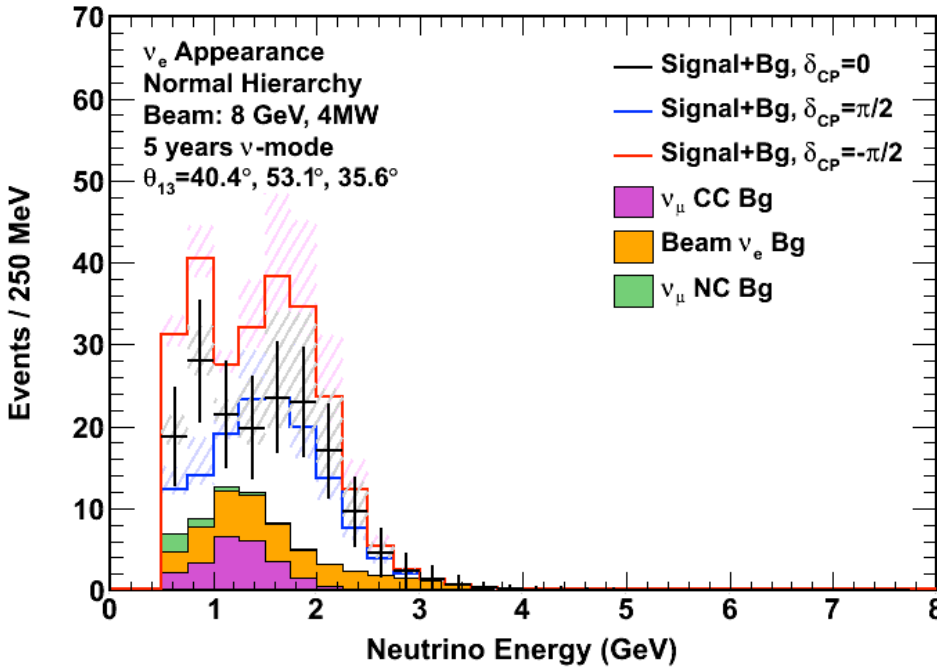


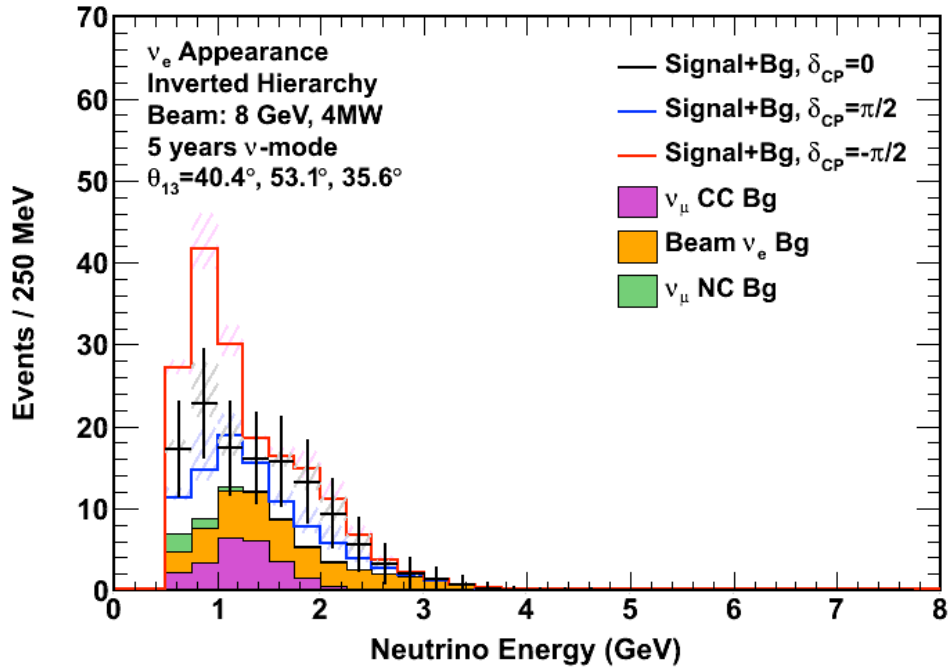
Matter vs CP effect with 8 GeV



- Mass hierarchy and CP asymmetry non-degenerate - they're completely disentangled!

Theta23 octant variation





- Also disentangled from theta23 octant - especially at the lowest of energies.
- With a high-power low energy beam the asymmetry is ONLY driven by CP: even a counting experiment can be sufficient.

Summary and outlook

- LBNE is able to resolve the mass hierarchy with high significance.
- The CPV sensitivity moves into the discovery regime with the boost in power from Project X Stage 1.
- With Stage 2 and low energy configurations the CPV sensitivity is improved compared to the standard 120 GeV configuration. (60 GeV best among those studied so far).
- Multimegawatt 8 GeV (Stage 3 and beyond) illuminates the second maximum and separates CP from other sources of asymmetry.
- Sensitivity studies in progress as well as studies of different configurations and optimizations.