Neutrino Superbeam Scenarios at the Peak

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We discuss options for U.S. long baseline neutrino experiments using upgraded conventional neutrino beams, assuming L/E_ν is chosen to be near the peak of the leading oscillation. We find that for $L = 1290$ km (FNAL–Homestake) or 1770 km (FNAL–Carlsbad, or BNL–Soudan) it is possible to simultaneously have good $\sin^2 2\theta_{13}$ reach and $\mathrm{sgn}(\delta m^2_{31})$ determination, and possibly sizeable τ rates and some δ sensitivity.

In this report we discuss possible three-neutrino scenarios for long baseline neutrino experiments using upgraded conventional neutrino beams (superbeams). In each case we examine their ability to measure $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ appearance, discover CP violation, and to determine the sign of the leading δm^2. Details of our calculations can be found in Ref. [1]. For the $\nu_\mu \to \nu_e$ oscillation probability we use the approximate analytic expressions of Ref. [2, 3], which are particularly helpful in determining the general properties described below. We emphasize that many other beam design and source–detector configurations are possible; the scenarios discussed here illustrate some of the capabilities of such facilities.

We choose five distances that could be appropriate for likely proton driver and detector sites (see Table I): 350 km (BNL–Cornell, or similar to the 295 km of JHF–SK), 730 km (FNAL–Soudan or CERN–Gran Sasso), 1290 km (FNAL–Homestake, or similar to the 1200 km of JHF–Seoul), 1770 km (FNAL–Carlsbad, or similar to the 1720 km of BNL–Soudan), and 2900 km (FNAL–SLAC, or similar to the 2920 km of BNL–Carlsbad). The latter distance would also be similar to FNAL–San Jacinto (2640 km) or BNL–Homestake (2540 km).

Table I Baseline distances for some detector sites (shown in parentheses) for neutrino beams from FNAL, BNL, JHF, and CERN.

Beam source			
FNAL	BNL	JHF	CERN
	350 (Cornell)	295 (Super-K)	
730 (Soudan)			730 (Gran Sasso)
1290 (Homestake)		1200 (Seoul)	
1770 (Carlsbad)	1720 (Soudan)		
2640 (San Jacinto)	2540 (Homestake)		
2900 (SLAC)	2920 (Carlsbad)		

For each L, we choose $\langle E_\nu \rangle$ such that $\Delta = 1.27\delta m^2_{31}\ (\mathrm{eV})^2 L\ (\mathrm{km})/\langle E_\nu\rangle\ (\mathrm{GeV}) = \pi/2$, i.e., $L/E_\nu = 353$ km/GeV for $\delta m^2_{31} = 3.5 \times 10^{-3}$ eV^2. This has three important advantages: (i) the $\nu_\mu \to \nu_\tau$ oscillation (which has only small matter effects) is maximal, (ii) the $\nu_\mu \to \nu_e$ oscillation is nearly maximal, *even when matter effects are taken into account* [1], and (iii) in the relevant limits that θ_{13} and $\delta m^2_{21}/\delta m^2_{31}$ are small, the δ dependence is pure $\sin\delta$, *even in the presence of matter* [1]. The latter fact implies that there is no δ–θ_{13} ambiguity for a given $\mathrm{sgn}(\delta m^2_{31})$. There is a δ–$(\pi-\delta)$ ambiguity, but it does not confuse a CP violating (CPV) solution with a CP conserving (CPC) one. However, for small enough θ_{13} and/or L, there is a (δ, θ_{13})–$\mathrm{sgn}(\delta m^2_{31})$ ambiguity, which sometimes can confuse CPV and CPC solutions; when combined with the δ–$(\pi-\delta)$ ambiguity it results in an overall four-fold ambiguity in parameters in these cases [1]. Thus distinguishing the sign of δm^2_{31} may be essential for determining the existence of CPV.

We assume a narrow band beam (NBB) with flux $4\times10^{11}/\mathrm{m}^2/\mathrm{yr}$ at $L = 730$ km (and proportional to $1/L^2$), which would be about 1/5 of the flux (to represent the flux loss in making a NBB) of an upgraded NuMI ME beam with a 1.6 MW proton driver. The NBB has two advantages: (i) the lack of a significant high-energy tail reduces backgrounds, and (ii) nearly all of the neutrinos will be at the same L/E_ν, which is chosen near the peak of the oscillation. For simplicity, we work in the monoenergetic approximation.

We assume an effective 70 kt-yr of data accumulation for detecting ν_e's, which could be achieved by 2 years of running with a 70 kt liquid Argon detector [4] at 50% efficiency [5]. For ν_τ detection we assume 3.3 kt-yr (2 years with a 5 kt detector at 33% efficiency). For $\bar{\nu}$'s, we assume approximately 6–12 years of running (a factor of two longer to account for the lower $\bar{\nu}$ cross section and another factor of 1.5–3 longer, depending on E_ν, to account for the reduced $\bar{\nu}$ flux in the beam). Thus in the absence of matter and/or CPV the number of ν and $\bar{\nu}$ events would be the same. We assume a ν_e background of 0.4% of the unoscillated CC signal, and a fractional uncertainty of the background of 10%.

Table II Scenarios with $\delta m^2_{31} > 0$ (2 years ν, 6–12 years $\bar{\nu}$); the last entry in the table shows the results for JHF–SK [11] (5 years, ν only). $\theta_{23} = \pi/4$, $\theta_{12} = 0.55$ is assumed.

δm^2_{31}	L	E	$\langle N_e \rangle$	$\langle \bar{N}_e \rangle$	B_e	N_τ	$\sin^2 2\theta_{13}$ reach at 3σ			$\lvert\delta\rvert$ (°) at 3σ
(eV^2)	(km)	(GeV)	$\sin^2 2\theta_{13} = 0.01$				$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	sgn(δm^2_{31})	$\sin^2 2\theta_{13} = 0.01$
$\delta m^2_{21} = 5 \times 10^{-5}$ eV^2										
2×10^{-3}	350	0.57	180	148	116	–	0.0020	0.0025	–	26
	730	1.18	95	63	56	–	0.0026	0.0042	0.10	35
	1290	2.09	64	27	32	–	0.0031	0.0082	0.036	49
	1770	2.86	53	15	23	–	0.0033	0.014	0.020	67
	2900	4.70	39	4	14	10	0.0038	0.055	0.011	–
3.5×10^{-3}	350	0.99	293	237	204	–	0.0024	0.0029	–	39
	730	2.07	156	100	97	–	0.0026	0.0042	0.050	52
	1290	3.65	106	42	55	14	0.0027	0.0073	0.015	–
	1770	5.01	88	22	40	36	0.0028	0.012	0.0091	–
	2900	8.22	67	5	25	51	0.0029	0.043	0.0057	–
5×10^{-3}	350	1.41	412	331	289	–	0.0024	0.0030	0.098	54
	730	2.96	219	139	139	–	0.0025	0.0040	0.028	83
	1290	5.21	150	57	79	77	0.0025	0.0066	0.0095	–
	1770	7.16	125	30	58	100	0.0025	0.011	0.0061	–
	2900	11.74	95	7	35	102	0.0025	0.036	0.0041	–
$\delta m^2_{21} = 10^{-4}$ eV^2										
2×10^{-3}	350	0.57	233	201	116	–	0	0	–	14
	730	1.18	120	88	56	–	0	0	–	18
	1290	2.09	78	41	32	–	0.0007	0.0019	0.10	24
	1770	2.86	62	24	23	–	0.0014	0.0059	0.055	30
	2900	4.70	44	9	14	10	0.0025	0.036	0.023	51
3.5×10^{-3}	350	0.99	324	268	204	–	0.0013	0.0016	–	19
	730	2.07	170	114	97	–	0.0017	0.0026	–	24
	1290	3.65	114	50	55	14	0.0020	0.0052	0.040	32
	1770	5.01	94	28	40	36	0.0022	0.0092	0.021	40
	2900	8.22	69	8	25	51	0.0025	0.037	0.010	76
5×10^{-3}	350	1.41	433	353	289	–	0.0018	0.0023	–	25
	730	2.96	229	149	139	–	0.0020	0.0032	0.081	31
	1290	5.21	148	55	79	77	0.0021	0.0056	0.022	40
	1770	7.16	129	34	58	100	0.0022	0.0092	0.012	50
	2900	11.74	96	9	35	102	0.0023	0.033	0.0063	–
3×10^{-3}	295	0.7	12	–	22	–	0.016	–	–	–

We expect δm^2_{21} to be measured to 10% accuracy at KamLAND [6], and δm^2_{31} to be measured to about the same accuracy by K2K, MINOS, and ICANOE, and OPERA. Since E_ν is chosen to be at the peak of the leading oscillation, the choice of E_ν depends critically on the value of δm^2_{31}; also, the size of the CPV and the potential for confusion between $\delta m^2_{31} > 0$ and $\delta m^2_{31} < 0$ increases with increasing δm^2_{21}. Our results for $\delta m^2_{31} > 0$ with $\theta_{23} = \pi/4$, $\theta_{12} = 0.55$ are presented in Table II for two values of $\delta m^2_{21} = 5 \times 10^{-5}$ eV^2 (the value preferred from recent analyses [7, 8, 9, 10] of solar neutrino data) and $\delta m^2_{21} = 10^{-4}$ eV^2; the corresponding results for $\delta m^2_{31} < 0$ are found by interchanging $\langle N_e \rangle \leftrightarrow \langle \bar{N}_e \rangle$ and $(\nu_\mu \to \nu_e) \leftrightarrow (\bar{\nu}_\mu \to \bar{\nu}_e)$. For each value of δm^2_{21} we show results for three values of δm^2_{31} that cover the range inferred from Super-K atmospheric neutrino data. Given in the table are (i) the numbers of e and $\bar{e}$ events (for $\sin^2 2\theta_{13} = 0.01$ and averaged over δ), background e events (B_e, assumed the same for e and $\bar{e}$), and τ events, (ii) the $\sin^2 2\theta_{13}$ reach at 3σ for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance, and the minimum $\sin^2 2\theta_{13}$ for which sgn(δm^2_{31}) can be determined, and (iii) the smallest value of the CP phase δ that can be distinguished from $\delta = 0, \pi$ at the 3σ level for $\sin^2 2\theta_{13} = 0.01$ (not accounting for a possible sgn(δm^2_{31}) ambiguity). The $\sin^2 2\theta_{13}$ reaches and δ sensitivity include the effects of statistical and systematic experimental uncertainties. The e and $\bar{e}$ event rates approximately scale with $\sin^2 2\theta_{13}$. Results for JHF–SK running for 5 years with neutrinos only [11], using a 2° off axis beam, are also shown in the table.

In most cases the $\nu_\mu \to \nu_e$ appearance reach is about 0.002–0.003 for $\delta m^2_{21} = 5 \times 10^{-5}$ eV^2, and improves in the larger δm^2_{21} case (where even for $\sin^2 2\theta_{13} = 0$ there is a signal due to the subleading oscillation). The $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance reach is generally about 0.003 at small L, decreasing to about 0.04–0.05 near $L = 2900$ km, primarily due to the matter suppression of antineutrinos for $\delta m^2_{31} > 0$. This matter suppression and the $1/L^2$ dependence of the flux leads to decreased CPV sensitivity at larger L, especially for larger δm^2_{31}. However, larger L does better at distinguishing sgn(δm^2_{31}) due to strong matter effects, and has higher τ event rates because of the higher E_ν, well above the τ production threshold at $E_\nu = 3.56$ GeV. Shorter L values have better δ sensitivity, except that there is potential confusion with a different value of δ having the opposite sgn(δm^2_{31}), which in some cases could include a CPV/CPC confusion; also, E_ν is generally below the τ threshold.

If δm^2_{21} is at the low end of its expected range, CPV can only be tested at shorter L, with the loss of the τ signal and sgn(δm^2_{31}) determination sensitivity, and potential CPV/CPC confusion due to sgn(δm^2_{31}) (the four-fold ambiguity mentioned above) [1]. Longer L (such as $L = 2900$ km) could potentially do everything except for CPV, although if δm^2_{31} is too low τ's are not observable. If $\delta m^2_{31} \simeq 2 \times 10^{-3}$ eV^2 and a large τ signal is desired, then the strategy outlined in this report will not work; E_ν must be increased, which would force L/E_ν to be off the peak of the oscillation.

For $L = 1290$ or 1770 km it is possible to simultaneously have good $\sin^2 2\theta_{13}$ reach and sgn(δm^2_{31}) determination, and possibly sizeable τ rates and some δ sensitivity if both δm^2_{21} and δm^2_{31} are at the high end of their expected ranges (see Table II); $L = 1770$ km is probably preferred in these cases due to its larger τ rate and better sgn(δm^2_{31}) determination.

We note that while a larger δm^2_{21} in principle improves the CPV sensitivity, it also makes a sgn(δm^2_{31}) ambiguity more likely, leading to an overall four-fold ambiguity. Even if sgn(δm^2_{31}) is determined, measurements on the oscillation peak will leave a two-fold ambiguity between δ and $\pi - \delta$. Measurements at different L and/or E_ν will be required to resolve these ambiguities [1].

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