Opportunities for Leptonic CP Violation and Neutrino Mass Hierarchy at Medium Baselines[1]

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Abstract. A large value of θ_{13}, as recently observed by reactor and accelerator experiments, is a major opportunity for precision neutrino physics. In this paper we discuss implications for Superbeams at medium baselines. In particular, we emphasize the impact on the determination of mass hierarchy for experiments that exploit matter effects. We demonstrate that unlike mass hierarchy, the measurement of the CP phase remains a major experimental challenge: the study of CP violation in the leptonic sector will require MW class proton drivers even with massive far detectors in the $\mathcal{O}(1000\text{ km})$ baseline range.

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SUPERBEAMS AT LARGE θ_{13}

In 2012 we finally achieved precise information on the size of the mixing angle between the first and third neutrino family (θ_{13}) [1, 2, 3, 4]. The θ_{13} value is definitely large - indeed, very close to previous limits set by CHOOZ and Palo Verde. This discovery is going to reshape the experimental strategy to perform precision physics in the neutrino sector and encourage the development of a novel generation of Superbeam experiments to study CP violation and determine the neutrino mass pattern ("mass hierarchy"). The experimental proposals will take advantage of the large $\nu_\mu \to \nu_e$ oscillation probability due to $\theta_{13} = 8.9^\circ \pm 0.4^\circ$ [5], likely relieving the constraints on the detector mass and accelerator power.

Still, a few key issues need to be properly investigated:

- is it true that a large value of θ_{13} ease substantially both the determination of the mass pattern and the search for CP violation in neutrino oscillations?
- in the framework of the Superbeams, do we still need MW-class proton drivers or present facilities can be adapted to reach the above-mentioned physics goals?
- should R&D and funding efforts be focused on the increase of the power for proton drivers or the sensitivities will be dominated by the detector systematics and feasible fiducial masses?
- is an "all-in-one" Superbeam facility conceivable both for mass hierarchy and for CP violation?

In order to address these issues, we reconsidered a general Superbeam configuration as a function of the baseline. Unlike other studies performed in the past, the beam-line was optimized employing as figure of merit the sensitivity to θ_{13} for each source-to-detector distance in the 730-2300 km range; we hence avoided the use of intermediate observables as, for instance, the rate of unoscillated neutrinos. The most important beam-line parameters are the distances among the target, the upstream focusing horn and the downstream focusing horn (i.e. the "reflector"), the target length and the length and width of the decay tunnel. Similarly, we considered the possibility of re-optimizing existing facilities: we used as benchmark the SPS accelerator, which is currently operated as a sub-MW proton driver for the CNGS beam.

The far detector technology considered in this study is the Liquid Argon TPC. In ν_e appearance this technology exhibits very high efficiencies both for quasi-elastic (80%) and deep-inelastic (90%) interactions combined with high NC rejection power. In the study presented at Nufact 2012 and deepened in [6] a contamination of NC due to $\pi \to e$ misidentification not exceeding 0.1% of the ν_μ CC rate was considered. For quasi-elastic interaction, the neutrino energy can be fully reconstructed by the lepton energy and direction, since the direction of the incoming neutrino is known in advance. Liquid

[1] Presented by F. Terranova

Argon detectors are able to reconstruct E_ν with a resolution mostly dominated by the electron energy resolution: $\sigma_{E_\nu}/E_\nu \simeq 0.05/\sqrt{E_\nu}$, E_ν being expressed in GeV. On the other hand, the energy resolution for deep inelastic ν_e interactions is driven by the resolution on the hadronic system. In liquid argon TPC's, it amounts to $\sigma_{E_h}/E_h \simeq 0.2/\sqrt{E_h(\mathrm{GeV})}$. In this study, the energy resolution and efficiency for ν_e and $\bar{\nu}_e$ were implemented smearing the final state momenta of the electrons and hadrons. Interactions were simulated using the GENIE Monte Carlo generator [7] and the corresponding migration matrices were implemented in the detector description of GLoBES. The smearing matrices were calculated for ν_e and $\bar{\nu}_e$ separately.

RESULTS

The analysis described above have shown that a clear determination of the mass hierarchy can be easily achieved by long-baseline Superbeams ($L > 1500$ km), where the $\nu_\mu \to \nu_e$ transition probability is matter dominated. This enhancement of sensitivity directly results from the perturbative expansion of

$$P(\nu_\mu \to \nu_e) \quad \simeq \quad O_1 \, + \, O_2(\delta) \, + \, O_3(\delta) \, + \, O_4$$

where the large size of θ_{13} enhances the CP-blind O_1 term (for a definition of the O_i terms see [8]). O_1 contains information on the mass pattern through the sign of $\hat{A} \equiv 2\sqrt{2} G_F n_e E/\Delta m^2_{31}$, G_F being the Fermi coupling constant and n_e the electron density in matter. The change in O_1 due to the mass pattern is therefore clearly visible even at moderate exposures. This is not the case for facilities at L=730 km (CERN to LNGS), where a unique determination of mass hierarchy for any value of δ can be achieved only with exposures ~ 1 MW$\times$Mton$\times 10^7$s (see Fig. 1).

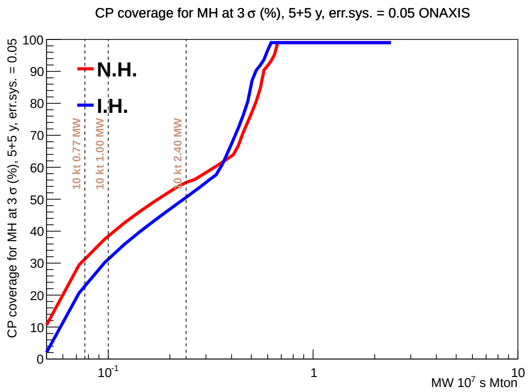

FIGURE 1. Mass hierarchy coverage for a 50 GeV on-axis facility at L=730 km as a function of exposure.

The situation is quite different for CP violation, where the O_1 term is in fact a nuisance parameter. Here, a major deterioration of sensitivity is expected if the mass pattern is unknown ("sign ambiguity") and any realistic configuration that exploits existing facilities (in Europe, the SPS and/or the underground halls of LNGS) cannot exceed CP coverages of $\simeq 50\%$ (see the vertical bands of Fig. 2). In addition, there is no advantage in working in off-axis mode since a wide spectral band is rewarding to extract δ and disentangle the size of O_2 against O_1. A high power on-axis detector with L>700 km is appropriate to address CP violation provided that its integral exposure is greater than 2 MW$\times$Mton$\times y_{eff}$, where $y_{eff} \simeq 10^7$s is the running time corrected for the typical duty cycle of the machine. For larger exposure, the CP coverage is systematics limited and it amounts to 70% for a 5% overall systematic error. Fig. 3 shows the CP coverage for an on-axis (ONA) facility based on a MW-class proton driver with a far detector located at 730 and 2290 km (CERN to LNGS and CERN to Phyasalmi, respectively) as a function of the exposure. "NH known" versus "NH unknown" signals the loss of sensitivity due to the missing knowledge of the mass hierarchy. Here we assumed normal hierarchy (NH) as the true one. Very similar results are obtained considering the inverted hierarchy (IH) as the true mass pattern.

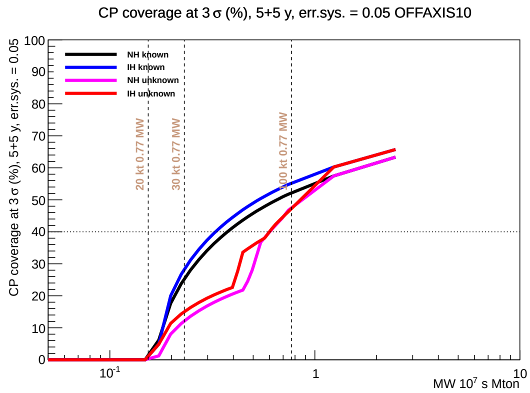

FIGURE 2. CP coverage at 3σ level for 5 years of ν and 5 years of $\bar{\nu}$ running with the off-axis 10 km configuration at L=730 km, a 400 GeV proton driver and a systematic error on flux normalization of 5%. We consider normal and inverted hierarchy assuming this information to be available or not (color codes).

CONCLUSIONS

The study performed above suggests a few guidelines that should be considered when designing a new generation of Superbeams, given the unexpected large size

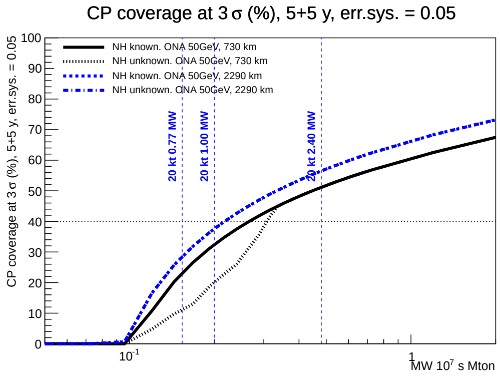

FIGURE 3. CP coverage at 3σ level for 5 years of ν and 5 years of $\bar{\nu}$ running with the on-axis configuration (ONA), a 50 GeV proton driver, a far detector at L=730, 2290 km and a systematic error on flux normalization of 5%. We consider normal and inverted hierarchy assuming this information to be available or not (color codes).

of θ_{13}. These guidelines answer most of the questions raised in the Introduction.

- A large value of θ_{13} eases substantially the determination of the mass hierarchy. Even existing facilities (NOvA) have reasonable chances to establish the sign of Δm^2_{31} and a new facility at long baseline can achieve $> 5\sigma$ discovery reach for any value of δ [9]. Due to the dominance of the O_1 term, however, the study of CP violation will require major upgrades of the Superbeams.
- No existing facility can be adapted to establish CP violation in the leptonic sector with a coverage larger than $\simeq 50\%$. Superbeams, however, are the technology of choice for coverages in the 70% ballpark provided a MW-class proton driver becomes available.
- Superbeams are statistically limited for exposures smaller than 2 MW$\times$Mton$\times y_{eff}$. Beyond this value, in order to exceed the 70% coverage limit an R&D effort should be carried out to lower systematics below 5% (in a way similar to what has been done in the last decade for reactor experiments).
- Superbeam configurations that tackle simultaneously both the mass hierarchy and the determination of the CP phase can be envisaged even at baselines $\simeq 730$ km. The exposure, however, must significantly exceed $O(1)$ MW$\times$Mton$\times y_{eff}$.

REFERENCES

1. F. P. An *et al.* [DAYA-BAY Collaboration], Phys. Rev. Lett. **108** (2012) 171803
2. J. K. Ahn *et al.* [RENO Collaboration], Phys. Rev. Lett. **108** (2012) 191802
3. M. Ishitsuka for the Double Chooz Collaboration, Talk at Neutrino 2012, Kyoto, 6-9 June 2012, available at `http://neu2012.kek.jp`.
4. K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **107** (2011) 041801; K. Sakashita for the T2K Collaboration, Talk at ICHEP 2012, Melbourne, 4-11 July 2012, available at `www.ichep2012.com.au`
5. G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo and A. M. Rotunno, Phys. Rev. D **86** (2012) 013012
6. S. Dusini, A. Longhin, M. Mezzetto, L. Patrizii, M. Sioli, G. Sirri and F. Terranova, arXiv:1209.5010 [hep-ph].
7. C. Andreopoulos, A. Bell, D. Bhattacharya, F. Cavanna, J. Dobson, S. Dytman, H. Gallagher and P. Guzowski *et al.*, Nucl. Instrum. Meth. A **614** (2010) 87
8. A. Cervera *et al.*, Nucl. Phys. **B579** (2000) 17, erratum ibid. Nucl. Phys. **B593** (2001) 731; M. Freund, Phys. Rev. **D64** (2001) 053003.
9. A. Rubbia, Talk at Neutrino 2012, Kyoto, 6-9 June 2012, available at `http://neu2012.kek.jp`.