Physics Reach of the Beta Beam

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1. Introduction

The Beta Beam concept has already been presented in [1], more details on the acceleration scheme can be found in [2]. The possibility to produce a pure $\overline{\nu}_e$ or ν_e beam from ^{6}He or ^{18}Ne ion beams opens a unique scenario in the long term search for leptonic CP violation.

This paper is focussed to a well defined scenario, namely a Beta Beam produced ad CERN and fired at a gigantic water Čerenkov detector, à la UNO (440 kton fiducial volume) [4], located under the Frejus at a baseline of 130 km.

The intrinsic capability to detect θ_{13} and the CP phase δ with a pure Beta Beam will be studied together with the possibility to detect T, CP and CPT violating effects combining Beta Beam with the CERN SPL SuperBeam [3] fired to the same detector.

2. Signal and backgrounds

The signal in a Beta Beam looking for $\nu_e \rightarrow \nu_\mu$ oscillations would be the appearance of ν_μ charged-current events, mainly via quasi-elastic interactions. These events are selected by requiring a single-ring event, the track identified as a muon using the standard Super-Kamiokande identification algorithms, and the detection of the muon decay into an electron. The backgrounds and signal efficiency have been studied in a full simulation, using the NUANCE code [5], reconstructing events in a Super-Kamiokande-like detector.

The Beta Beam is intrinsically free from contamination by any different flavour of neutrino. However, background can be generated by inefficiencies in particle identification, such as single-pion production in neutral-current (NC) ν_e ($\overline{\nu}_e$) interactions, electrons (positrons) mis-identified as muons, or by external sources such as atmospheric neutrino interactions.

Electrons (positrons) produced by ν_e ($\overline{\nu}_e$) can be mis-identified as muons, therefore giving a fake signal. Standard algorithms for particle identification in water Čerenkov detectors are quite effective to suppress such backgrounds. Furthermore, the signal of the decay electron in muon tracks can be used to reinforce the muon identification.

Atmospheric neutrino interactions are estimated to be ~ 50/kton/yr in the energy range of interest for the experiment, a number of interactions that far exceeds the oscillation signal. The atmospheric neutrino background has to be reduced mainly by timing of the parent ion bunches. For a decay ring of 6.9 km and a bunch length of 10 ns, which seems feasible [2], a rejection factor of $2 \cdot 10^4$ can be achieved. The directionality of the (anti)neutrinos can be used to suppress further the atmospheric neutrino background by a factor ~ 4. With these rejection factors, the atmospheric neutrino background can be reduced to the order of 1 event/440 kton/yr. Moreover, out-of-spill neutrino interactions can be used to normalize this background to the 1% accuracy level.

3. Beam optimization

The Lorentz boost factor γ of the ion accelerator can be tuned to optimize the sensitivity of the experiment. Optimization is performed assuming $\delta m^2_{23} = 2.5 \cdot 10^{-3}$ eV^2, a baseline of 130 km and a ^{6}He beam. In principle, baselines in the range 100-250 km are possible considering that at present SPS can accelerate ^{6}He ions up to $\gamma = 150$.

The number of quasi-elastic events in the far detector scales roughly as γ^3 (this factor comes from the beam focusing, which is $\propto \gamma^2$, and the cross section, which is $\propto \gamma$) and so the number of quasi-elastic events at a given L/E is proportional to γ.

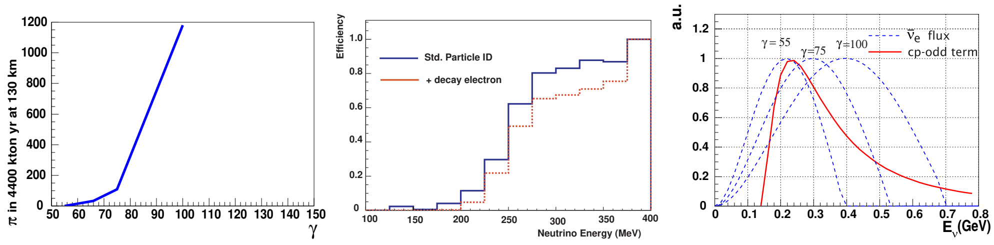

Figure 1. Left panel: backgrounds from single-pion production for a 4400 kt-y exposure, as function of γ. Middle panel: signal efficiency as function of the neutrino energy computed with and without the detection of the decay electron. Right panel: energy spectra for different values of γ compared with the CP-odd term of $p(\overline{\nu}_e \to \overline{\nu}_\mu)$.

On the other hand the number of background events from NC pion production increases very rapidly with γ, as shown in Fig. 1(left). The threshold for this process is about 400 MeV and for $\gamma < 55$ no pions are created above the Čerenkov threshold.

A third factor is the signal efficiency as function of energy, Fig. 1(middle), which severely disfavours neutrino energies below 300 MeV. The signal efficiency decreases slightly above 0.7 MeV where the fraction of quasi-elastic, single ring events decreases.

Finally the true signal of the experiment, ν_μ produced by the CP-odd term in $p(\nu_e \to \nu_\mu)$, should be matched by the neutrino energy spectrum. It is evident from Fig. 1(right) that this is no longer true when $\gamma \geq 100$.

Based on these considerations, a γ value of 75 seems to approach the optimal value for CP sensitivity. For $\gamma = 75$ we will assume a flux of $2.9 \cdot 10^{18}$ ^{6}He decays/year and $3.6 \cdot 10^{17}$ ^{18}Ne decays/year, as discussed in [1]. Table 1 reports signal and background rates for a 4400 kt-y exposure to ^{6}He and ^{18}Ne beams.

4. Systematic errors

The cross-section estimates for signal and background production at energies below 1 GeV are quite uncertain, the systematic errors being of the order of 20 and 30% respectively. On the other hand, a Beta Beam is ideal for measuring these cross

Table 1. Event rates for a 4400 kt-y exposure. The signals are computed for $\theta_{13} = 3°$, $\delta m^2_{12} = 0.65 \cdot 10^{-4} eV^2$, $\sin^2 2\theta_{12} = 0.8$, $\delta = 90°$.

10 years	Beta Beam		SuperBeam	
	$^6He(\gamma = 75)$	$^{18}Ne(\gamma = 75)$	π^+ focus	π^- focus
CC events (no osc, no cut)	40783	18583	183488	29150
Total oscillated	32	66	565	85
CP-Odd oscillated	-47	24	-390	61
Beam background	0	0	703	126
Detector backgrounds	60	10	182	62

sections, provided that a close detector of 1 kton at least is placed at the distance of about 1 km from the decay tunnel.

The energy and the flux of the neutrino beam is completely defined by the acceleration complex and the near/far residual error is extremely reduced, because in a Beta Beam the divergence of the beam is completely defined by the decay properties of the parent ions. The γ factor of the accelerated ions can be varied, in particular a scan can be initiated below the background production threshold, allowing a precise measurement of the cross sections for resonant processes. It is estimated that a residual systematic error of 2% will be the final precision with which both the signal and the backgrounds can be evaluated.

θ_{13} and δ sensitivities are computed taking into account a 10% error on the solar δm^2 and $\sin^2 2\theta$, as expected from the Kamland experiment after 3 years of data taking [6] and a 2% error on the atmospheric δm^2 and $\sin^2 2\theta$, as expected from the JHF neutrino experiment [7]. Only the diagonal contributions of these errors are considered in the following.

Correlations between θ_{13} and δ are fully accounted for, and indeed they are negligible in this configuration, while the sign of δm^2_{13} and the $\theta_{23}/(\pi/2 - \theta_{23})$ ambiguities are not considered.

5. Sensitivity to CP violation

A search for leptonic CP violation can be performed running the Beta Beam with ^{18}Ne and ^{6}He, and fitting the number of muon-like events to the $p(\nu_e \to \nu_\mu)$ probability. The fit can provide simultaneous determinations of θ_{13} and the CP phase δ. Given the relative interaction rates for quasi-elastic events, a sharing of 3 years of ^{6}He and 7 years of ^{18}Ne has been considered.

The results of this analysis are summarized in Table 1, for an arbitrary choice of the mixing matrix parameters. Since the sensitivity to CP violation is heavily dependent on the true value of δm^2_{12} and θ_{13}, we prefer to express the CP sensitivity for a fixed value of δ in the δm^2_{12}, θ_{13} parameter space. The CP sensitivity to separate $\delta = 90°$ from $\delta = 0°$ at the 99%CL as a function of δm^2_{12} and θ_{13}, following the convention of [8], is plotted in Fig. 2.

The ^{6}He Beta Beam sensitivity to θ_{13}, computed for $\delta = 0$ and solar SMA solution, is $\theta_{13} \geq 1.2°$ (90%CL) in a 2200 kton/years exposure.

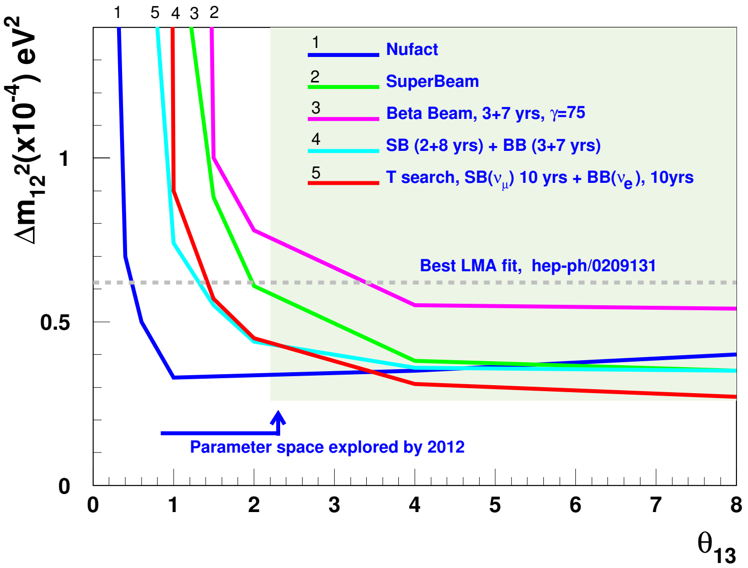

Figure 2. CP sensitivity of the Beta Beam, of the SPL-SuperBeam, and of their combination, see text. Two different time sharing are considered: 3+7 years of $\overline{\nu}_e$, ν_e Beta Beam combined with 2+8 years of ν_μ, $\overline{\nu}_\mu$ Super Beam and 10 years of ν_e Beta Beam with 10 years of ν_μ Super Beam. Sensitivities are compared with a 50 GeV Neutrino Factory producing $2 \cdot 10^{20} \mu$ decays/straight section/year, and two 40 kton detectors at 3000 and 7000 km [8]. The shaded region corresponds to the allowed LMA solution and the θ_{13} sensitivity of JHF.

6. Synergy between the SPL-SuperBeam and the Beta Beam

The Beta Beam needs the SPL as injector, but consumes at most $\sim 3\%$ of the SPL protons. The fact that the average neutrino energies of both the SuperBeam and the Beta Beam are below 0.5 GeV, with the beta beam being tunable, offers the fascinating possibility of exposing the same detector to two neutrino beams at the same time.

The SPL-SuperBeam is a ν_μ ($\overline{\nu}_\mu$) beam, while the Beta Beam is a ν_e ($\overline{\nu}_e$) beam and so the combination of the two offers the possibility of CP, T and CPT searches at the same time:

- Searches for CP violation, running the SuperBeam with ν_μ and $\overline{\nu}_\mu$, and the Beta Beam with ^{6}He ($\overline{\nu}_e$) and ^{18}Ne (ν_e).
- Searches for T violation, combining neutrinos from the SuperBeam ($\nu_\mu \to \nu_e$) and from the Beta Beam using ^{18}Ne ($\nu_e \to \nu_\mu$), or antineutrinos from the SuperBeam ($\overline{\nu}_\mu \to \overline{\nu}_e$) and from the Beta Beam using ^{6}He ($\overline{\nu}_e \to \overline{\nu}_\mu$).
- Searches for CPT violation, comparing $P(\nu_\mu \to \nu_e)$ to $P(\overline{\nu}_e \to \overline{\nu}_\mu)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ to $P(\nu_e \to \nu_\mu)$.

It is evident that the combination of the two beams would not result merely in an increase in the statistics of the experiment, but would offer clear advantages in the reduction of systematic errors, and would offer the redundancy needed to establish firmly any CP-violating effect within reach of the experiment.

It should also be stressed that the Super+Beta beams offer the only known possibility of measuring CPT violation combining signals from the same detector, a crucial issue for the control of systematic errors.

Fig. 2 summarizes the CP sensitivity of different combinations of Super Beam and Beta Beam compared with the Neutrino Factory sensitivity. The combined sensitivity shown in Fig. 2 is competitive with that of a Neutrino Factory, offering a truly complementary approach to the search of leptonic CP violation. In particular in the parameter space defined by the solar LMA solution and the JHF phase I sensitivity on θ_{13} ($\theta_{13} \geq 2.2°$) the Beta+Super Beam sensitivity is very similar to the Neutrino Factory sensitivity. We consider solar LMA plus a θ_{13} value within the reach of JHF the only possible trigger for a Leptonic CP search.

Since the boundary condition of this study is quite arbitrary, namely a 440 kton detector and Beta Beam fluxes extrapolated from the present knowledge of the production rate ^{6}He and ^{18}Ne ions (cfr. ref. [1]), it is of interest to study the Super+Beta beam capabilities with a bigger detector or with higher ^{18}Ne fluxes. Statistics and ν_e fluxes are indeed the two major bottlenecks of Beta Beam. Improvements on CP sensitivity with a 1 Mton detector, à la HyperK [7] and with a ^{18}Ne flux increased by a factor two, are shown on Fig. 3. Another possible improvement could be the exploitation of the event spectral distribution, not studied here, by using the algorithms studied in ref. [9].

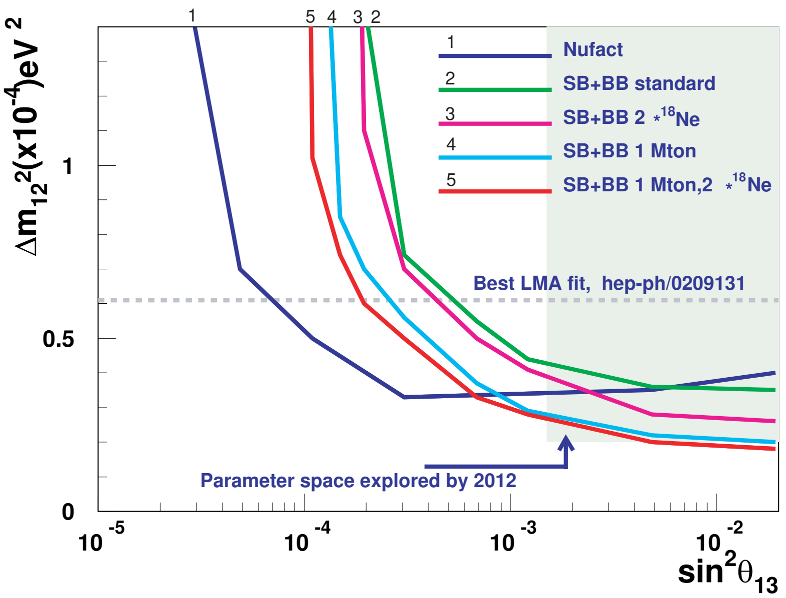

Figure 3. CP sensitivity of the combination of the Beta Beam with the SPL-SuperBeam, for different choices of the detector size and ^{18}Ne fluxes, see text. Time sharing is 3+7 years of $\overline{\nu}_e$, ν_e Beta Beam combined with 2+8 years of ν_μ, $\overline{\nu}_\mu$ Super Beam. Sensitivities are compared with a 50 GeV Neutrino Factory producing $2 \cdot 10^{20} \mu$ decays/straight section/year, and two 40 kton detectors at 3000 and 7000 km [8]. The shaded region corresponds to the allowed LMA solution and the $\sin^2\theta_{13}$ sensitivity of JHF.

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