PROCEEDINGS OF SCIENCE

A European neutrino program based on the machine upgrades of the LHC

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In the next decade, a significant upgrade of the LHC injection system is planned with the aim of fully exploiting the physics potential of this collider. In particular, the upgrade of the SPS (Super-SPS) would allow proton injection with energy twice the one of the current system and would ground on a firm basis the luminosity upgrade of the Large Hadron Collider. Beyond LHC physics, this machine offers an unprecedented opportunity for the experimental determination of the leptonic mixing matrix, particularly of Dirac CP violation. In this talk, we show that a Beta Beam based on the Super-SPS and on a 40 kton iron detector at Gran Sasso can address CP violation in the leptonic sector for any value of the θ_{13} angle that gives a positive $\nu_\mu \to \nu_e$ signal in the forthcoming SuperBeam experiments (e.g. T2K). In general, we show that a Beam Beam driven by the Super-SPS has a physics potential comparable to so-called "Phase II" SuperBeams (e.g. JAERI to HyperKamiokande) but does not require the construction of ultra-massive detectors and offers a fascinating synergy with high energy collider physics and nuclear physics.

International Europhysics Conference on High Energy Physics
July 21st - 27th 2005
Lisboa, Portugal

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1. Introduction

In the next decades, long baseline experiments will provide access to the currently unknown entries of the leptonic mixing matrix (PMNS) if the mixing angle between the first and third family (θ_{13}) turns out to be larger than $\simeq 1^\circ$. A large experimental effort is in progress to test the size of θ_{13} and in ten years from now (i.e. at the completion of the so called "Phase I" experiments like T2K, Nova, DoubleChooz) we expect to gain evidence for subdominant $\nu_\mu \rightarrow \nu_e$ transitions at the atmospheric scale as far as $\theta_{13} \lesssim 3^\circ$. In this case, however, new facilities will be needed to close up the PMNS. They should perform precision measurements of the 1-3 sector and particularly of the CP violating phase. Moreover, exploiting the perturbations of the oscillation probabilities occurring in matter, additional information concerning the neutrino hierarchy (sign of Δm^2_{32}) could be obtained. A possible vision for these "Phase II" setups is based on the novel concept of Beta Beam and the strong potential synergy with the machine upgrades of the LHC planned beyond 2015, i.e. at a timescale comparable to the end of Phase I.

2. The acceleration complex and the far detector

A Beta Beam [1] is made by accelerating radioactive ions with a short beta-decay lifetime, by storing them in a ring with straight sections and by letting them decay. The focusing of the beam is provided by the Lorentz boost. Having the possibility to accelerate either β^- (e.g. ^{6}He) or β^+ (e.g. ^{18}Ne) ions, pure $\overline{\nu}_e$ or pure ν_e beams can be produced, respectively. In particular, the Beta Beam concept offers a strong synergy with nuclear physics (high intensity radioactive beams) and low background contamination in the $\nu_e \rightarrow \nu_\mu$ channel. At present, the main drawback of this technique is related to the small energy of the parent ions. Working at ν energies of a few hundreds of MeV implies an enormous reduction of the cross section, complicates the kinematic reconstruction of the event and forces the choice of small baselines so that matter effects are suppressed. In this scenario, the physics performances of a Beta Beam equipped with a very large (1 Mton) water Cherenkov would be very similar to a multi-megawatt SuperBeam since the outstanding purity is compensated by the limited statistics. An increase of the Beta Beam energy [2] could be envisaged by a fast cycling superconducting SPS ("Super-SPS") at CERN. This machine is currently considered as an option for the luminosity upgrade and, possibly, the energy upgrade of the LHC [3]. In this case, the detector mass could be significantly reduced and the baseline would match the CERN-LNGS distance. In this configuration, denser detectors operating in ν_μ appearance mode can be exploited [4] and therefore smaller experimental halls are needed. Particularly, the existing halls of the Gran Sasso underground labs would be appropriate to host the far detector.

Working at high (above 1 GeV) neutrino energies opens the possibility to exploit iron calorimeters. On top of a good muon identification, these detectors provide energy measurement of the hadronic shower produced in the neutrino interaction. The measurement of the muon momentum and of the hadronic shower allows for the reconstruction of the incident neutrino energy. The detector we considered for this study has been derived from a digital RPC based calorimeter proposed for the reconstruction of the energy flow at the ILC detector [5]. It consists of a sandwich of 4 cm non-magnetized iron and glass RPC. The active part of the RPC is segmented in 2×2 cm^2 elementary cells. A full Monte Carlo simulation has been carried out in order to evaluate the detector response, but the event classification capability has only been based on inclusive variables (total number of hits and event length expressed in terms of number of crossed iron layers). The typical efficiency for identifying a neutrino or anti-neutrino CC interaction is of the order of 50-60%. The probability for the background to be identified as a CC-like event is smaller than 1%. A detailed description of the analysis can be found in [6].

3. Sensitivity

Since a detailed study of the expected fluxes from a Super-SPS based Beta beam is currently unavailable, we plot in Fig. 1 (left panel), for $\delta = 90^\circ$, the minimum θ_{13} that can be distinguished from zero at 99% C.L. as a function of the flux (1 corresponds to F_0, i.e. the nominal fluxes assumed for the baseline design [7, 8]). Notice that, if the flux is at least half of F_0, it is possible to discover a non vanishing θ_{13} even in the case of no signal observed in the T2K experiment. Assuming a flux equal to F_0, values of θ_{13} down to 1° can be distinguished from zero. Fig. 1 (right panel) shows, for $\theta_{13} = 3^\circ$, the minimum δ that can be distinguished from zero, at at 99% C.L., as a function of the neutrino flux. The value $\theta_{13} = 3^\circ$ has been chosen being the minimum value for which T2K may discover a non-zero θ_{13}. Also in this case, unless the flux is smaller than $F_0/10$, it would be possible to establish CP violation in the leptonic sector for the whole θ_{13} range covered by T2K. A comparison with the baseline design for a Beta Beam at CERN can be found in [6, 9] together with the sensitivity in the occurrence of a null result (θ_{13} limits as a function of δ). Moreover, due to the large baseline and the capability of identifying spectral distortion of the ν_μ signal, a Super-SPS based Beta Beam is able to distinguish normal from inverted neutrino mass hierarchies (sensitivity to the sign of Δm^2_{31}) for $\theta_{13} \gtrsim 6^\circ$ [6].

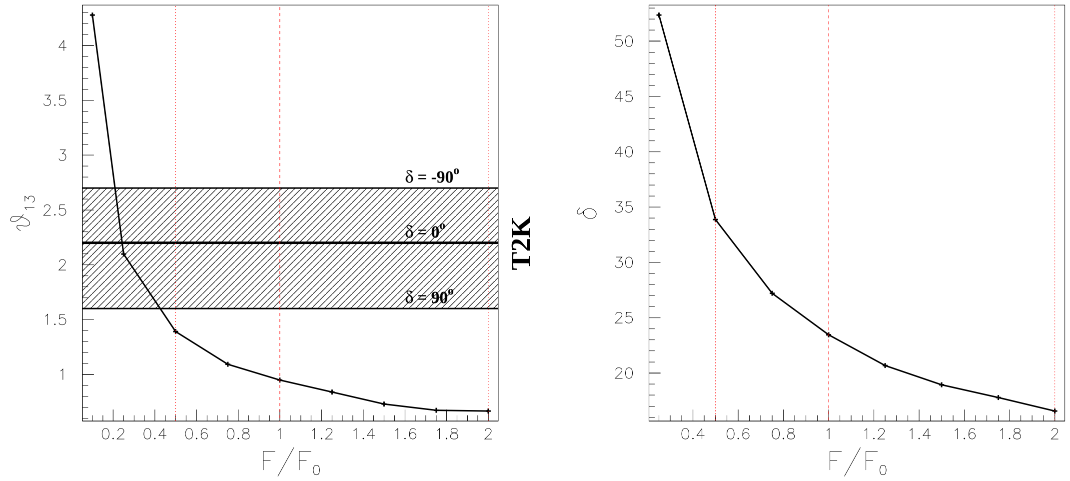

Figure 1: Left plot: minimum θ_{13} that can be distinguished from zero at 99% C.L. as a function of the flux (1 corresponds to F_0). Right plot: minimum δ that can be distinguished from zero, at 99% C.L., as a function of the neutrino flux.

4. Conclusions

The Super-SPS option for the luminosity/energy upgrade of the LHC is optimal for the construction of a Beta Beam facility where ions can be accelerated up to Lorentz γ's of 350 (^{6}He) and 580 (^{18}Ne). The physics case of this complex would be enormously strengthened in the case of θ_{13} discovery after the completion of the Phase I experiments ($\sim$ 2015). Since the upgrade of the injection complex of the LHC is foreseen after 2015, we see a window of opportunity for a Phase II neutrino program in Europe compatible with the LHC running. Moreover, the neutrino energy obtained exploiting the Super-SPS allows the use of very dense detectors (e.g. iron slabs interleaved with RPC) with a few tens of kiloton mass. This would fit into the existing underground facilities at Gran Sasso, whose distance from CERN happens to be at the peak of oscillation probability at the γ's mentioned above.

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