Perspectives for a neutrino program based on the upgrades of the CERN accelerator complex

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Abstract

In this paper, we discuss the possibilities offered to neutrino physics by the upgrades of the CERN accelerator complex. Emphasis is on the physics reach of a medium γ (350-580) β-beam that fully exploits the improvements in the CERN accelerator complex for the luminosity/energy upgrade of the LHC. We show that, this design not only profits of the ongoing efforts for the upgrades of the LHC, but also leverage out the existing infrastructures of the LNGS underground laboratory. Furthermore, given the involved high neutrino energies, above 1 GeV, a non-magnetized iron detector could efficiently exploit the neutrino beam.

We show that the performance of this complex for what concerns the discovery of the CP violation in the leptonic sector, in case θ_{13} is discovered by Phase I experiments, is comparable with the current baseline design based on a gigantic water Cherenkov at Frejus. Furthermore, this complex has also some sensitivity to the neutrino mass hierarchy.

INTRODUCTION

The hypothesis of neutrino oscillations [1] is strongly supported by atmospheric [2], solar [3], accelerator [4] and reactor [5] neutrino data. If we do not consider the claimed evidence for oscillations by the LSND experiment [6], that must be confirmed or excluded by the ongoing MiniBooNE experiment [7], oscillations in the leptonic sector can be accommodated in the three family Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix U_{PMNS}

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}- & c_{12}c_{23}- & s_{23}c_{13} \\ \quad c_{12}s_{23}s_{13}e^{i\delta} & \quad s_{12}s_{23}s_{13}e^{i\delta} & \\ s_{12}s_{23}- & -c_{12}s_{23}- & c_{23}c_{13} \\ \quad c_{12}c_{23}s_{13}e^{i\delta} & \quad s_{12}c_{23}s_{13}e^{i\delta} & \end{pmatrix}$$

where the short-form notation $s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$ is used. Further Majorana phases have not been introduced, since oscillation experiments are only sensitive to the two neutrino mass squared differences $\Delta m^2_{12}, \Delta m^2_{23}$ and to the four parameters in the mixing matrix of Eq. (1): three angles and the Dirac CP-violating phase, δ.

There are several global fits of all available data. As an example we report the $\pm\sigma$ ranges (95%) as obtained in Ref. [8]:

$$\sin^2\theta_{13} = 0.9^{+2.3}_{-0.9}\times 10^{-2}$$

$$\Delta m^2\theta_{12} = 7.92 \pm 0.09\times 10^{-5}\ \text{eV}^2$$

$$\sin^2\theta_{12} = 0.314^{+0.18}_{-0.15}$$

$$\Delta m^2\theta_{23} = 2.4^{+0.21}_{-0.26}\times 10^{-3}\ \text{eV}^2\ .$$

The next steps on the way of a full understanding of neutrino oscillations by using neutrino beams produced at accelerators are

- confirm the source of atmospheric neutrino oscillations, i. e. observe the oscillation $\nu_\mu \to \nu_\tau$;
- measure the remaining parameters of the PMNS mixing matrix: θ_{13} and δ;
- measure the sign of Δm^2_{23};
- perform precision measurements of the angles θ_{12} and θ_{23}, and of Δm^2_{12} and Δm^2_{23}.

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It is worth noting that there are other searches (like β-decay and double-β decay experiments, and space experiments studying anisotropies in cosmic background radiation) which provide very important information like the absolute value of the neutrino mass or whether the neutrino is a Dirac or a Majorana particle. For a comprehensive review of the analysis of these experiments we refer to [8] and references therein.

Among the oscillation parameters, a relevant role is played by the mixing angle θ_{13}. Indeed, as discussed in Ref. [9, 10], a vanishing or too small value for θ_{13}, would make impossible the observation of the CP violation in the leptonic sector and fix the neutrino mass hierarchy (sign of Δm^2_{23} exploiting matter effects). If θ_{13} is large enough ($> 3°$) to allow for its discovery by the forthcoming experiments [11] (Phase I experiments), new facilities and new experiments [9, 10] (Phase II experiments) would be needed in order to precisely measure the PMNS matrix.

Several projects have been proposed for the Phase II (see Ref. [9, 10] and references therein). In this paper we investigate a possible window of opportunity for the neutrino oscillation physics compatible with the upgrade of the LHC (after 2015) that fully exploits european infrastructures and that has an adequate sensitivity to the 1-3 sector of the PMNS matrix.

This paper is organized as follow. After a review of the proposed neutrino beams in Europe , we focus on the β-beam concept and in particular on a β-beam set-up based on the so-called Super-SPS. We then discuss the proposed detector to exploit the neutrino beam and finally present its physics reach.

NEUTRINO BEAMS

Current neutrino oscillation experiments are based on beams where neutrinos come from the decay of mesons produced in the interaction of high energy protons impinging onto a target (typically Be or graphite). However, such conventional beams have some limitations that could be overcome by using new beam-line concepts: β-beams or Neutrino Factories. For a comprehensive discussion of future beams and their comparison we refer to [9, 10] and references therein.

Conventional Neutrino Beams

One can identify the main components of a conventional neutrino beam line at a high energy accelerator as

- the target onto which protons are sent to produce pions and kaons;
- the focusing system which guides the mesons along the desired neutrino beam direction;
- the decay tunnel (usually evacuated) where mesons decay and produce neutrinos and muons.

From meson decay kinematics it follows that the neutrino energy is given by

$$E_\nu = \frac{m^2_{\pi(K)} - m^2_\mu}{m^2_{\pi(K)}} \frac{E_{\pi(K)}}{(1+\gamma^2\theta^2)} \qquad (1)$$

where γ is the Lorentz boost of the parent meson, $E_{\pi(K)}$ its energy and θ the angle of the neutrino with respect to the meson flight direction.

There are three types of conventional neutrino beams: the Wide Band Beams (WBB), the Narrow Band Beams (NBB) and the Off-Axis Beams (OAB). WBB are characterized by a wide energy spectrum (they could spread over a couple of order of magnitude) and correspondingly high neutrino flux. Given these features, WBB are the optimal solution to make discoveries. The drawback is that, if the signal comes from a small part of the energy spectrum, it could be overwhelmed by the background also induced by neutrinos outside the signal region. Conversely, NBB may produce almost monochromatic energy spectra. This can be obtained by selecting a small momentum bite of the parent π and K. However, the neutrino yield is significantly reduced. This is an important drawback for oscillation searches.

A good compromise between the requirements of a high flux and a narrow energy spectrum is obtained by means of Off-Axis Beams [12]. This technique involves designing a beam-line which can produce and focus a wide range of mesons in a given direction (as in the WBB case), but then putting the detectors at an angle with respect to that direction. Since the pion decay is a two-body decay, a given angle between the pion direction and the detector location corresponds to a given neutrino energy (almost) independently of the pion energy. Furthermore, the smaller fraction of high energy tails reduces the background from neutral-current (NC) events, which can be misidentified for a ν_e charged-current (CC) interaction due to the early showering of gamma's from the π^0 decay.

It is worth noting that, independent of the adopted solution, there are common problems to all conventional neutrino beams

- the hadron yield in the proton-target interaction has large uncertainties due to lack of data and to theoretical difficulties in describing hadronic processes. This implies difficulties in predicting the neutrino flux and spectrum with good accuracy;
- in addition to the dominant flavor in the beam (typically ν_μ) there is a contamination (at the few percent level) from other flavors ($\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$).

The knowledge of the beam spectrum and composition has a strong impact both on the precision measurements of the angle θ_{23}, on the mass squared difference Δm^2_{23} and on the sensitivity to the mixing angle θ_{13}. For instance, from the CHOOZ limit on θ_{13} we know that the $\nu_\mu \to \nu_e$ appearance probability is smaller than 5%, which is of the same order of magnitude of the beam contamination. Therefore, the observation of ν_e appearance and the related θ_{13} measurement are experimentally hard. Consequently, the usage of a close detector, to solve the experimental problem related to the knowledge of the beam, is mandatory.

In the last years a new concept of conventional beam (the so-called “Super-Beam”) has been put forward in order to maximize the sensitivity to θ_{13} [13]. Super-Beams will provide a much higher neutrino flux, but at low energy (below 1 GeV). This will open the possibility to perform long-baseline experiments with high statistics and tuned at the oscillation maximum even at moderate distances between source and detector.

In Europe a 4 MW Superconducting Proton Linac (SPL) [14], to be built from scratch, would deliver a proton beam (with energy in the range 2.2 GeV [15]-3.5 GeV [16]) on a Hg target to generate an intense (anti-)neutrino flux from the π^+ (π^-) decay. This intense neutrino beam, whose fluxes are shown in Fig. 1, has been proposed to be sent from CERN towards the Frejus Laboratory. The average energy of neutrinos produced with this facility is of the order of few hundred MeV. The physics potential and the accelerator complex needed for such a Super-Beam are discussed in Refs. [10] and references therein. Here, we only recall that a SPL based neutrino program will improve by about one order of magnitude the T2K θ_{13} sensitivity, while it will be able to address neither the CP violation in the leptonic sector nor the neutrino mass hierarchy.

The SPL is the not a mandatory solution for the energy/luminosity upgrade of the LHC [17], while it is an essential component of a Neutrino Factory complex [9]. The low energy of neutrinos produced with this facility has an important drawback on the detector choice. Indeed, in order to compensate the small cross-section and to allow an efficient particle identification huge and low density detectors are mandatory. The typical detector proposed to exploit a neutrino beam from a SPL is a Megaton water Cerenkov detector [10]. The proposed location for this detector is the Frejus laboratory, where a cavern capable to host it should be built. All in all, we think that an experimental program based on a SPL is uprooted with respect to a possible common effort of the elementary particle community in Europe. Moreover, it assumes the construction of a million cubic meter cavern capable to host the detector. Last but not least, the neutrino beam has no special advantages (the main sources of systematics are still there) with respect to the existing ones, but the higher intensity. Conversely, being a low energy beam one has to deal with a region where Fermi motion has an energy comparable with the one of the incident neutrino beam. Consequently it is not possible to measure the neutrino energy spectrum, but only count neutrinos of a given flavour.

Neutrino Factory

The first stage of a Neutrino Factory is similar to that of a Super-Beam. Namely, protons are sent onto a target producing pions and kaons that are collected by means of magnetic lenses. However, while in those beams hadrons are let decay launching neutrinos toward the detector site, in a Neutrino Factory daughter muons are collected and accelerated in a ring with long straight sections. Muon decays in each straight section generate highly collimated neutrino beams. The expected layout for a Neutrino Factory at CERN is shown in Fig. 2. If μ^+ are stored, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decays generate a beam consisting of 50% ν_e and 50% $\bar{\nu}_\mu$. Similarly, if μ^- are stored the beam consists of 50% ν_μ and 50% $\bar{\nu}_e$. Since the kinematics of muon decay is well known, we expect minimal systematic uncertainties on the neutrino flux and spectrum. Hence, compared to conventional neutrino beams, Neutrino Factories provide ν_e and $\bar{\nu}_\mu$ beams or ν_μ and $\bar{\nu}_e$ beams, with small systematic uncertainties on the flux and spectrum. Radiative effects on the muon decay have been calculated and amount to about 4×10^{-3} with a much smaller error. Overall, the flux is expected to be known with a precision of the order of 10^{-3}. Another important feature of a Neutrino Factory beam is its sharp cut-off at the energy of the stored muons. In a conventional neutrino beam there is a high-energy tail which, as already mentioned, gives rise to background from NC events in which a leading π^0 is mis-interpreted as an electron, faking $\nu_\mu \to \nu_e$ signal. Furthermore, the possibility to store high-energy muons that in turn produce high-energy neutrinos opens the study of oscillation channels like $\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_\tau$, whose combined physics potential has been discussed in [18].

Summarizing, the Neutrino Factory provides an excellent neutrino beam optimal for both neutrino oscillation searches and other physics [9]. However, it is based on a very challenging technology and it has no relevant overlap with the present (and future) CERN accelerators. As far as the exploitation of existing infrastructure, while there is no need for a large cavern to host a megaton detector, the Gran Sasso halls could be too close, if the Neutrino Factory is built at CERN. Consequently, a new underground laboratory has to be built in order to host the far detector. It is worth noting that given the very high intensity and high energy of a Neutrino Factory the far detector will have a reasonable size ($\mathcal{O}(10^4\, m^3)$ not $\mathcal{O}(10^6\, m^3)$).

β-beams

A β-beam [19] 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 $\bar{\nu}_e$ or pure ν_e beams can be produced, respectively. In order to illustrate the value of the β-beam concept, we briefly discuss the production of an anti-neutrino beam. A good beta-emitter for anti-neutrino production is the ^{6}He^{++} ion that decays into $^6_3$Li$^{++} e^- \bar{\nu}_e$ with a β-decay endpoint (E_0) of about 3.5 MeV. The anti-neutrino spectrum is precisely known from laboratory mea-

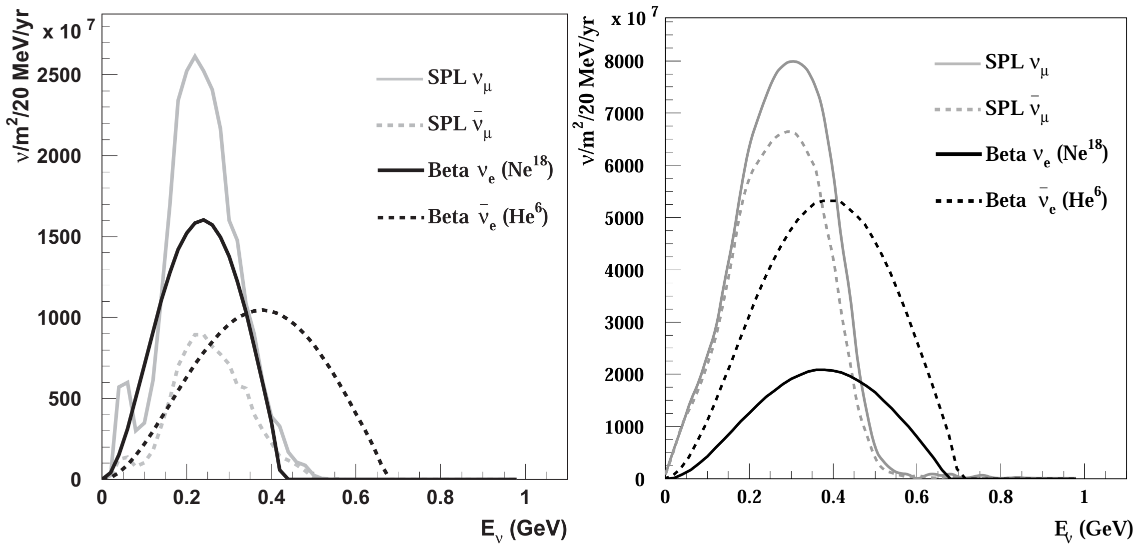

Figure 1: Left: neutrino flux of β-Beam ($\gamma_{^6\mathrm{He}} = 60$, $\gamma_{^{18}\mathrm{Ne}} = 100$, shared mode) and CERN-SPL SuperBeam, 2.2 GeV, at 130 Km of distance. Right: the same for $\gamma_{^6\mathrm{He}} = 100$, $\gamma_{^{18}\mathrm{Ne}} = 100$, (non shared mode, that is just one ion circulating in the decay ring) and a 3.5 GeV SPL Super-Beam.

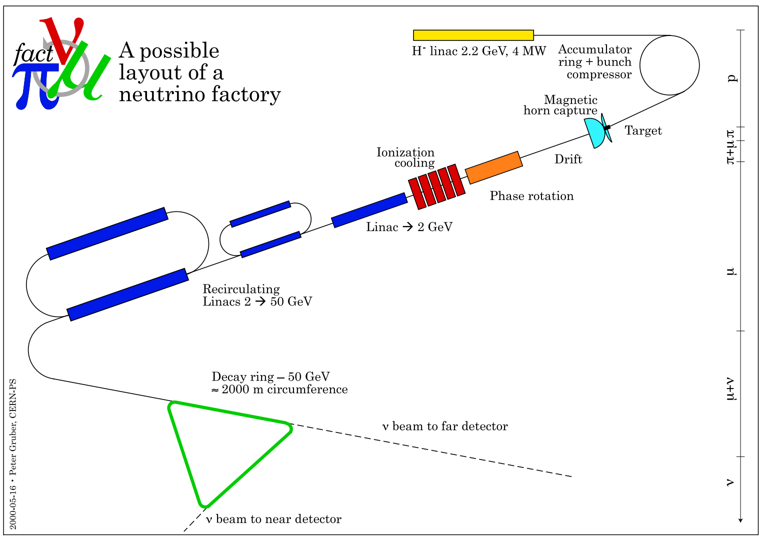

Figure 2: Expected layout for a Neutrino Factory at CERN.

surements of the associated electron, since $E_e + E_\nu \approx E_0$. Since the ion is spin-less, decays at rest are isotropic. When ions are accelerated (γ values up to 150 are possible) the neutrino transverse momentum in the laboratory frame is identical to that observed in the rest frame, while the longitudinal momentum is multiplied by a factor γ. Therefore, neutrino beam divergence is of the order of $1/\gamma$ (less than 10 mrad for $\gamma = 100$), and the average neutrino energy in the forward direction is $2\gamma E_{cms}$ ~500 MeV.

The technical feasibility of accelerating ions, although at relatively low energies, has been already demonstrated in nuclear physics experiments such as at ISOLDE at CERN. Given the small neutrino energy, a potential drawback of this approach is the substantial background from atmospheric neutrinos. To overcome this problem, ion beams should be bunched. At present, this is a major technical issue.

In the baseline design, the proton driver for a β-beam is the proposed SPL [14]. However, contrary to naive expectation, a multi-megawatt booster is not necessary for the construction of a beta beam or a nuclear physics (EURISOL-like [20]). Indeed, independently of the γ, a β-beam requires a $\sim$ 200 kW proton driver operating in the few GeV region. The collection and ionization of the ions is performed using the ECR technique. Hereafter ions are bunched, accelerated and injected up to the high energy boosters.

Summarizing, the main features of a neutrino beam based on the β-beam concept are:

- the beam energy depends on the γ factor. The ion accelerator can be tuned to optimize the sensitivity of the experiment;
- the neutrino beam contains a single flavor with an energy spectrum and intensity known a priori. Therefore, unlike conventional neutrino beams, close detectors are not necessary to normalize the fluxes;
- neutrino and anti-neutrino beams can be produced with a comparable flux;
- Differently from Super-Beams, β-beams experiments search for $\nu_e \to \nu_\mu$ transitions, requiring a detector capable to identify muons from electrons. Moreover, since the beam does not contain ν_μ or $\bar{\nu}_\mu$ in the initial state, magnetized detectors are not needed. This is in contrast with the neutrino factories (see below) where the determination of the muon sign is mandatory.

A baseline study for a β-beam complex has been carried out at CERN [22]. The SPS could accelerate $^6\mathrm{He}$ ions at a maximum γ value of $\gamma_{^6\mathrm{He}} = 150$ and $^{18}\mathrm{Ne}$ ions up to $\gamma_{^{18}\mathrm{Ne}} = 250$. In this scenario the two ions circulate in the decay ring at the same time. A feasible option provided that their γ are in the ratio $\gamma_{^6\mathrm{He}}/\gamma_{^{18}\mathrm{Ne}} = 3/5$. The reference β-beam fluxes are 2.9×10^{18} $^6\mathrm{He}$ useful decays/year and 1.1×10^{18} $^{18}\mathrm{Ne}$ decays/year if the two ions are run at the same time in the complex. Novel developments, suggesting the possibilities of running the two ions separately at their optimal γ [23], have recently triggered a new optimal scheme for the β-beam. In this scheme both ions are accelerated at $\gamma = 100$. The expected fluxes for the baseline scenario are shown in Fig. 1.

β-beam capabilities for ions accelerated at higher energies than those allowed by SPS have been computed in [24, 25, 26]. In the next Section we focus on a possible accelerator complex needed to build a β-beam with γ in the range 350-580 and we compare it to the baseline design. We refer in the following to this set-up as the medium γ scenario.

THE MEDIUM γ SCENARIO

The accelerator complex

The choices and timescale for the upgrades of the LHC will depend on the feedbacks from the first years of data taking. Still, three phases can already be envisaged [27, 28]: an optimization of present hardware ("phase 0") to reach the ultimate luminosity of 2×10^{34} cm^{-2} s^{-1} at two interaction points; an upgrade of the LHC insertions ("phase 1") and, finally, a major hardware modification ("phase 2") to operate the LHC in the $\mathcal{L} \simeq 10^{35}$ cm^{-2} s^{-1} regime and, if needed, prepare for an energy upgrade. The most straightforward approach to "phase 2" would be the equipment of the SPS with fast cycling superconducting magnets in order to inject protons into the LHC with energies of about 1 TeV. The 1 TeV injection option ("Super-SPS") would have an enormous impact on the design of a β-beam at CERN. This machine fulfills simultaneously the two most relevant requirements for a high energy β-beam booster: it provides a fast ramp ($dB/dt = 1.2 \div 1.5$ T/s [29]) to minimize the number of decays during the acceleration phase and, as noted in ref.[25], it is able to bring $^6\mathrm{He}$ up to $\gamma \simeq 350$ ($^{18}\mathrm{Ne}$ to $\gamma \simeq 580$)[1]. The mean neutrino energies of the $\bar{\nu}_e$, ν_e beams corresponding to a $\gamma = 350$ are 1.36 GeV and 1.29 GeV, respectively. Fig. 3 shows the β-Beam neutrino fluxes computed at the 735 Km baseline, keeping $m_e \neq 0$ as in Ref. [25].

The increase of the ion energy in the last element of the booster chain represents a challenge for stacking [30]. Ions of high rigidity must be collected in a dedicated ring of reasonable size. In the baseline design, this is achieved by a decay ring made of small curved sections (radius $R \sim$ 300 m) followed by long straigth sections ($L = 2500$ m) pointing toward the far neutrino detector. In this case, the decays that provide useful neutrinos are the ones occurring in the straigth session where neutrinos fly in the direction of the detector and the useful fraction of decays ("livetime") is limited by the decays in the opposite arm of the tunnel. For the CERN to Frejus design the livetime

[1] It is worth mentioning that the Super-SPS eases substantially injection of β ions in the LHC to reach $\gamma \gg 350 - 580$. For a discussion of this option we refer to [26].

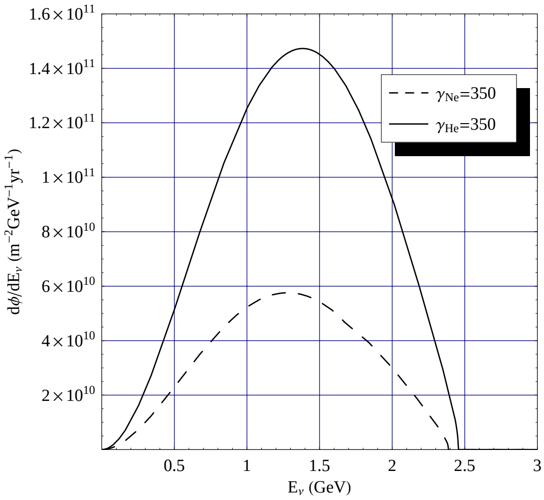

Figure 3: β-Beam fluxes at the Gran Sasso location (735 km baseline) as a function of the neutrino energy for $\gamma = 350$.

is $L/(2\pi R + 2L) \sim 36\%$ and the overall length has been fixed to 6880 m. A decay ring of the same length equipped with LHC dipolar magnets (8.3 T) would stack ion at the nominal Super-SPS rigidity with a significantly larger radius (~ 600 m). The corresponding lifetime is thus 23%. The actual intensities that can be achieved with a high energy booster and possible losses with respect to the baseline design still need a dedicated machine study[2]. Hence in the following, physics performances are determined as a function of fluxes. Nevertheless, the looser constrains on the time structure of the beam and the occupancy of the decay ring [32] offers a way out for compensation of the losses due to the decrease of the number of decay per unit time. We remind that the baseline β-beam design aims at 2.9×10^{18} $^6\mathrm{He}$ and 1.1×10^{18} $^{18}\mathrm{Ne}$ decays per year. Fig. 4 sketches the main components of the β-beam complex up to injection into the decay ring. In the lower part, the machines considered in the baseline option are listed. The alternatives that profit of the upgrade of the LHC injection system are also mentioned (upper part). For a review of technical challenges of β-beams, we refer to [34].

Baseline versus medium γ scenario

The comparison of the two scenarios can be performed at two different levels: the first one considering the synergies with both the CERN accelerator complex and the existing underground laboratories; the second looking at their physics reach.

From the previous discussions it is straightforward that the baseline scenario presents a strong synergy with the present CERN accelerator complex. On the other hand, it could profit of an upgrade of the PS machine. Indeed, at the present one of the main limitations comes from the losses in the PS for He that make very difficult the maintenance of the machine. Furthermore, it foresees the construction of a very expensive SPL. Conversely, the medium γ scenario fully exploits the machine upgrades for the LHC energy/luminosity upgrade. At the typical energies of the medium γ scenario the peak of oscillation probability is comparable to the CERN to Gran Sasso distance. Therefore, it would leverage the existing infrastructure at the Gran Sasso Laboratories as possible site for the far detector. Furthermore, due to the large increase of cross-section the use of dense detectors (reduction of the detector mass/volume) would be possible compared with the baseline design. The latter foresees a Megaton water Cerenkov detector to be installed in an underground laboratory that should be built from scratch at the Frejus site.

One of the problems of the baseline scenario is the measurement of the ν_μ and $\bar{\nu}_\mu$ cross-sections. Indeed, a near detector may measure with high accuracy the ν_e and $\bar{\nu}_e$ cross-sections, but the signal ones. On the other hand, given the smallness of the neutrino energy, the mass difference between the electron and the muon starts to be important. The medium γ has another advantage with respect to the baseline scenario. Indeed, while there are already planned experiments aiming at the few percent precision cross-section measurement for both ν_μ and $\bar{\nu}_\mu$ in the 1 GeV region, there are no plans for such a measurements in the few hundred MeV region. Therefore, in the baseline scenario one plans to use the SPL beam to measure the ν_μ and $\bar{\nu}_\mu$ cross-sections, while it is not so important for the oscillation measurements [36]. The impact of the systematic error on the CP-violation discovery potential has been studied in Ref. [35]

THE DETECTOR AT THE GRAN SASSO AND ITS PERFORMANCES

As already pointed out in the previous Sections, the main advantage of working with a β-beam is that there is no need of a magnetized detector to discriminate among neutrinos and anti-neutrinos. The only requirement is a good muon identification in order to observe ν_μ or $\bar{\nu}_\mu$ coming from ν_e or $\bar{\nu}_e$ oscillations, respectively. Consequently, working at high (above 1 GeV) neutrino energies opens the possibility to exploit non-magnetized iron calorimeters, i.e. high density detectors that can operate beyond the "single ring" region of Water Cherenkov and that can be hosted in relatively small underground sites. On top of a good muon identification, these detectors also guarantee the 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.

Several experimental techniques can be employed for the detector design. Among them, in [32] we considered a design derived from a digital RPC based calorimeter pro-

[2]for recent progresses in the framework of the baseline design (SPS-based), see [31].

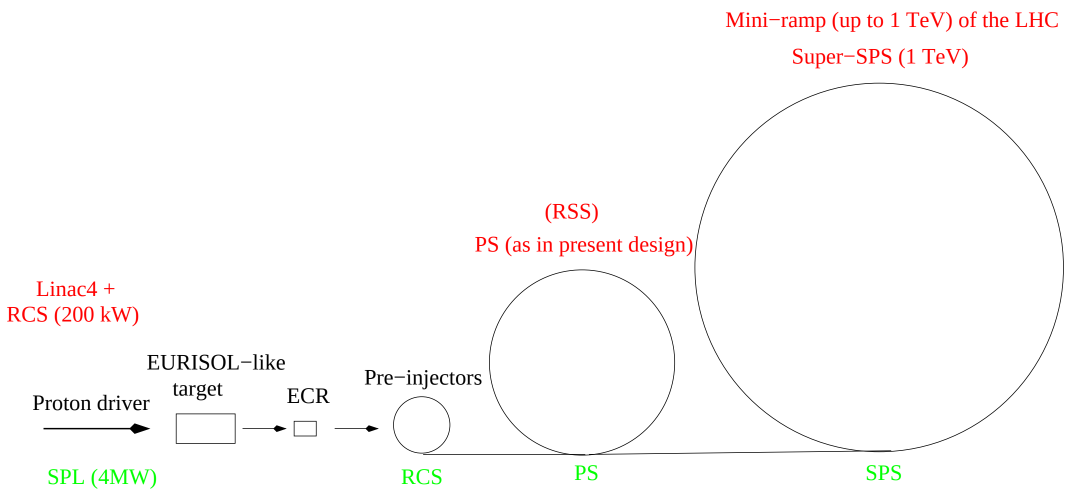

Figure 4: The main component of the β-beam complex up to injection into the decay ring [32]. In the lower part, the machines considered in the baseline option are indicated. The alternatives that profit of the upgrade of the LHC injection system are also mentioned (upper part). RCS stands for Rapid Cycling Syncrotron, RSS for Rapid Superconducting Syncrotron [33].

posed for the reconstruction of the energy flow at the ILC detector [37] (DHCAL). It consists of a sandwich of 4 cm non-magnetized iron and glass RPC with an overall mass of 40kton. This detector could be hosted in an underground site of LNGS. The active part of the RPC is segmented in 2×2 cm^2 elementary cells. Details on the detector structure and on the performance of the RPC's may be found in Ref. [37]. A full Monte Carlo simulation of the DHCAL has been implemented with the GEANT3 package and validated by comparing its response with pion data with energy in the range from 2 GeV to 10 GeV [38]. We used the full Monte Carlo simulation in order to evaluate the detector response, but the event classification capability is only based on inclusive variables (total number of hits, event length (expressed in terms of number of crossed iron layers)). The scatter plot of the event length versus the total number of hits of the event is shown in Fig. 5 for neutrinos (left panel) and anti-neutrinos (right panel) both coming from ions accelerated at $\gamma = 350$. We plot all together ν_μ and ν_e charged-current (CC) interactions as well as neutrino neutral-current (NC) interactions. We classify an interaction as a ν_μ CC-like event if both the event length and the total number of hits in the detector are larger than 12. In the case the $^{18}\mathrm{Ne}$ is ran at $\gamma = 580$, we classify an event as a CC-like interaction if the event length and the total number of hits are larger than 15 and 17, respectively. The typical efficiency for identifying a neutrino or anti-neutrino CC interaction is, averaged out over the whole spectrum, of the order of 50-60%. Conversely, the probability for the background to be identified as a CC-like event is smaller than 1%.

The efficiencies to correctly identify ν_μ and $\bar{\nu}_\mu$ charge-current interactions are shown, separately for deep-inelastic (DIS), quasi-elastic (QE) and resonance (RES) production, in Fig. 6 as well as the probability that ν_e and $\bar{\nu}_e$, separately for DIS, QE and RES production, and neutral-current interactions are identified as a CC-like interaction.

PHYSICS REACH OF THE MEDIUM γ SCENARIO

As discussed in the previous Sections, the expected neutrino flux as a function of the γ is still under evaluation. Therefore, in the following we evaluate the physics reach as a function of the flux normalized to the one assumed in the baseline design (F_0). Finally, we note that in this work only the intrinsic degeneracy is taken into account. For an exhaustive discussion on the problem of the degeneracies at a β-beam complex, we refer to [36] and references therein.

The expected number of events as a function of δ and θ_{13} has been obtained in the framework of a three family scenario and it is shown in Table 1. For the already measured parameters, we assumed the following values: $\Delta m^2\theta_{12} = 8\times10^{-5}$ eV^2; $\theta_{12} = 30°$; $\Delta m^2\theta_{23} = 2.5\times10^{-3}$ eV^2.

Extraction of the neutrino oscillation parameters in presence of signal

Since the neutrino flux from a β-beam is not yet well defined, we plot in Fig. 7 (left panel), for $\delta = 90°$, 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). 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. 7 (right panel) shows, for $\theta_{13} = 3°$, the minimum δ that can be distinguished from zero, at 99% C.L., as a function of the neutrino flux. The value $\theta_{13} = 3°$ has been chosen

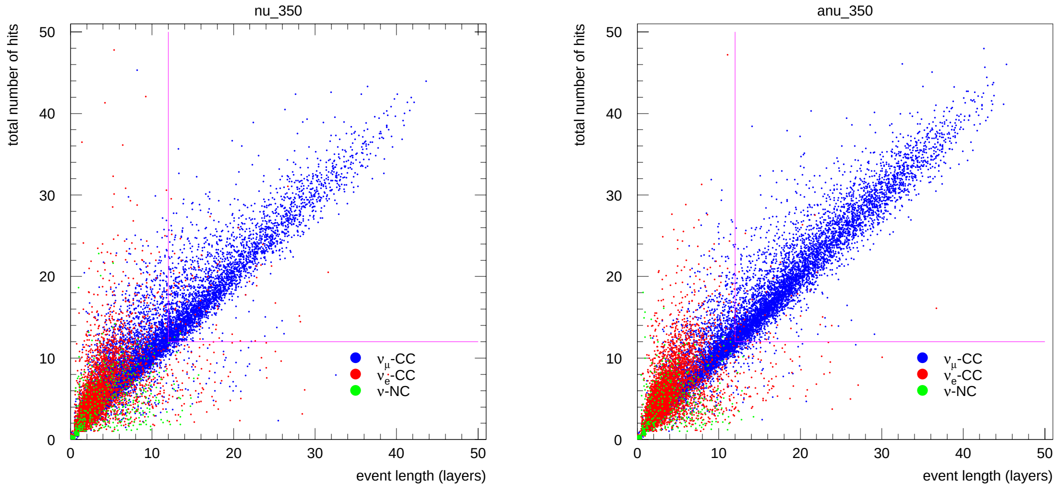

Figure 5: Scatter plot of the total number of hits recorded in the detector versus the total length (given in number of crossed layers) of the event for neutrinos (left) and anti-neutrinos (right) with $\gamma = 350$. .

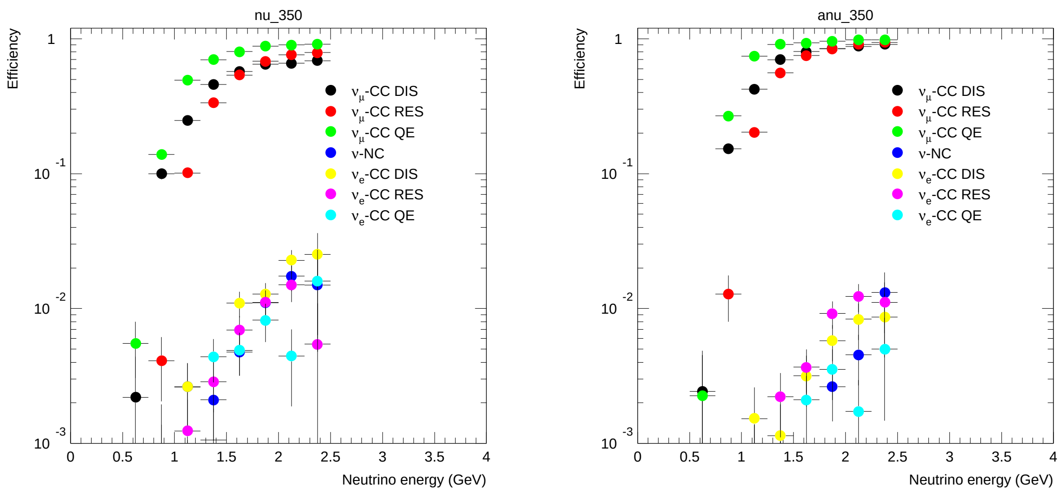

Figure 6: Efficiencies for the signal (ν_μ and $\bar{\nu}_\mu$ charged-current interactions) to be identified as CC-like event and for the background (ν_e and $\bar{\nu}_e$ interactions, and ν_μ and $\bar{\nu}_\mu$ neutral-current interactions) to be mis-identified as a CC-like events.

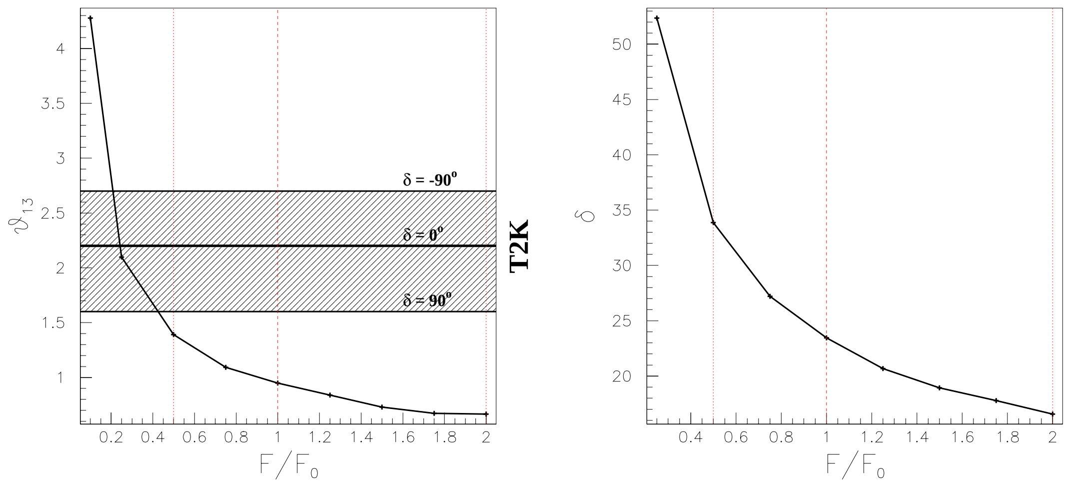

Figure 7: Left plot: minimum θ_{13} that can be distinguished from zero at 99% C.L. as a function of the flux (1 corresponds to F_0). Right plot: minimum δ that can be distinguished from zero, at 99% C.L., as a function of the neutrino flux.

Table 1: Event rates for a 10 years exposure at a medium γ β-beam of a 40 kton detector. The observed oscillated charged-current events for different values of δ and θ_{13}, assuming the normal neutrino mass hierarchy and $\theta_{23} = 45°$, are given. The expected background is also reported.

θ_{13}	δ	ν_μCC	$\bar{\nu}_\mu$CC	ν-back.	$\bar{\nu}$-back.
1°	−90°	1.45	37.67	126.02	77.28
5°	−90°	103.46	271.05	126.02	77.28
10°	−90°	532.23	863.18	126.02	77.28
1°	0°	18.18	22.74	126.02	77.28
5°	0°	187.02	196.49	126.02	77.28
10°	0°	698.70	714.63	126.02	77.28
1°	90°	32.04	2.57	126.02	77.28
5°	90°	256.23	95.75	126.02	77.28
10°	90°	836.60	513.91	126.02	77.28

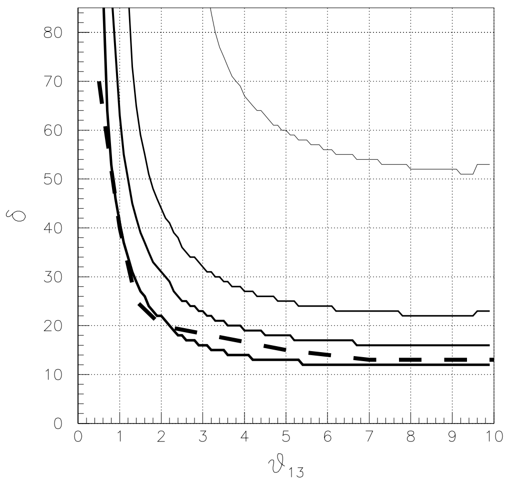

Figure 8: δ_{CP} discovery potential at 99% C.L. as a function of θ_{13}. The different solid lines corresponds at different fluxes. From left to right: $2{\times}F_0$, F_0, $F_0/2$ and $F_0/10$. The dashed line show the discovery potential for the baseline scenario as computed in Ref. [35].

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 for the whole θ_{13} range covered by the T2K discovery potential discover CP violation in the leptonic sector. The minimum δ_{CP} that can be discovered at 99% C.L., as a function of θ_{13}, is shown in Fig. 8 [3]. As for comparison, the discovery potential of the baseline scenario is also reported. We can argue that, down to fluxes half of F_0 and for $\theta_{13} > 3°$ (the discovery region of T2K), the discovery potential of the baseline and of the medium γ scenarios are comparable.

[3]A more extensive analysis, exploiting particularly the energy resolution of the detector is in progress [32].

Exclusion plots in absence of signal

In Fig. 9 we draw the 90% C.L. contour defining the sensitivity limit on θ_{13} in case of absence of a signal, with δ_{CP} as a fixed free parameter. The sensitivity has been computed applying a χ^2 analysis including the expected background and a 2% systematic error. The sensitivity is rather good, as can be argued from Fig. 9, but it is systematically worse than the one of the baseline scenario.

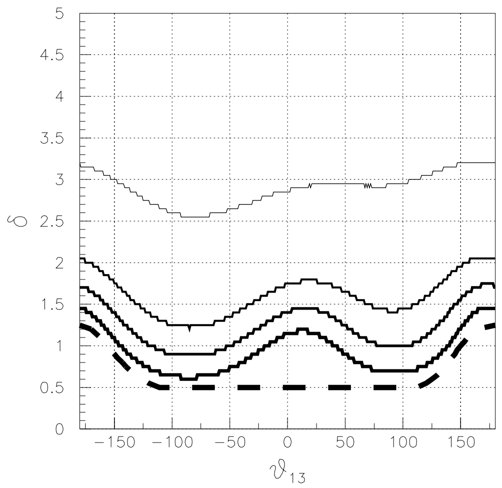

Figure 9: θ_{13} discovery potential at 90% C.L. as a function of δ. The different solid lines corresponds at different fluxes. From down to top: $2\times F_0$, F_0, $F_0/2$ and $F_0/10$. The dashed line show the discovery potential for the baseline scenario as computed in Ref. [35].

CONCLUSION

The next generation of accelerator based neutrino oscillation experiments has the challenging purpose to discover the missing oscillation parameter θ_{13}. The relevant role played by this parameter in the neutrino oscillation physics and the wide experimental program developed to discover it are related to its strong correlation with the CP violation in the leptonic sector. Indeed, a vanishing or too small value for θ_{13} would make impossible the observation of the CP violation parameter δ and of to fix the neutrino mass hierarchy.

In this paper we discussed in particular a neutrino program based on the machine upgrades of the LHC. Indeed, it turns out that the Super-SPS option for the luminosity/energy upgrade of the LHC has the ideal features for the construction of a β-beam facility with a γ in the range $350-580$ whose physics case would be enormously strengthened in the case of θ_{13} discovery in Phase I experiments. Given that the luminosity/energy upgrade of the LHC is foreseen after 2015, and that Phase I experiments are expected to complete their program around that date, we see a window of opportunity for a Phase II neutrino program in Europe compatible with the LHC (and its upgrade) running. This would allow, contrarily to other proposed neutrino physics program, the full exploitation of european accelerator facilities during the LHC era. Other advantages are that the proposed experimental program does not imply the construction of a Megaton detector, but of a very dense detector (iron slabs interleaved with e.g. glass RPC segmented into 2×2 cm^2 cells) with a few tens of kiloton mass. This would fit into the underground facilities existing at the Gran Sasso, whose distance from CERN, given the neutrino energy of this facility, happens to be at the peak of oscillation probability!

The proposed detector will be able not only to identify ν_μ and $\bar{\nu}_\mu$ charged/current interactions, but also to measure the energy of the incident neutrino. This opens, given the long baseline, the possibility to measure the neutrino mass hierarchy. In case Phase I experiments will discover a non vanishing θ_{13} ($>3°$), the proposed set-up will be able to discover CP violation for δ values down to $30°$. These performances are comparable with the one obtained by the baseline β-beam that foresee the construction of an accelerator complex with no overlap with the LHC program and the excavation of a very large cavern able to host a megaton water Cerenkov detector. Note, however, that the sensitivities at small values of θ_{13} of the medium γ facilities result to be worse than the ones for the baseline β-beam scenario, mainly due to the large difference of mass (40 vs 1000 kton) of the corresponding detectors.

Finally, we want to point out that at the present, although very promising, a detailed study of a β-beam complex is still missing. There is an EURISOL design study group that is scrutinizing the baseline option, but the medium γ scenario is beyond its scope. Nevertheless, the latter option surely deserves careful consideration.

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