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An intermediate γ beta-beam neutrino experiment with long baseline

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Abstract

In order to address some fundamental questions in neutrino physics a wide, future programme of neutrino oscillation experiments is currently under discussion. Among those, long baseline experiments will play a crucial role in providing information on the value of θ_{13}, the type of neutrino mass ordering and on the value of the CP-violating phase δ, which enters in 3-neutrino oscillations. Here, we consider a beta-beam setup with an intermediate Lorentz factor $\gamma = 450$ and a baseline of 1050 km. This could be achieved in Europe with a beta-beam sourced at CERN to a detector located at the Boulby mine in the United Kingdom. We analyse the physics potential of this setup in detail and study two different exposures (1×10^{21} and 5×10^{21} ions-kton-years). In both cases, we find that the type of neutrino mass hierarchy could be determined at 99% CL, for all values of δ, for $\sin^2 2\theta_{13} > 0.03$. In the high-exposure scenario, we find that the value of the CP-violating phase δ could be measured with a 99% CL error of $\sim 20^o$ if $\sin^2 2\theta_{13} > 10^{-3}$, with some sensitivity down to values of $\sin^2 2\theta_{13} \simeq 10^{-4}$. The ability to determine the octant of θ_{23} is also studied, and good prospects are found for the high-statistics scenario.

I. INTRODUCTION

In recent years, compelling evidence for neutrino oscillations has been obtained in atmospheric [1, 2], solar [3, 4, 5], reactor [6, 7, 8] and long-baseline accelerator [9, 10] neutrino experiments. They have measured with good accuracy the oscillation parameters: two mass squared differences, Δm^2_{31} and Δm^2_{21}, where $\Delta m^2_{ji} \equiv m^2_j - m^2_i$, and two mixing angles, θ_{12} and θ_{23}. The third mixing angle θ_{13} is small and strongly constrained. A combined analysis of all present data gives for the best fit values and the 2σ allowed ranges of the measured oscillation parameters [11]:

$$(|\Delta m^2_{31}|)_{\rm BF} = 2.4 \times 10^{-3}\,{\rm eV}^2, \qquad 2.1 \times 10^{-3}\,{\rm eV}^2 \leq |\Delta m^2_{31}| \leq 2.7 \times 10^{-3}\,{\rm eV}^2, \tag{1.1}$$

$$(\Delta m^2_{21})_{\rm BF} = 7.6 \times 10^{-5}\ {\rm eV}^2, \qquad 7.3 \times 10^{-5}\ {\rm eV}^2 \leq \Delta m^2_{21} \leq 8.1 \times 10^{-5}\ {\rm eV}^2, \tag{1.2}$$

$$(\sin^2\theta_{23})_{\rm BF} = 0.50, \qquad 0.38 \leq \sin^2\theta_{23} \leq 0.63, \tag{1.3}$$

$$(\sin^2\theta_{12})_{\rm BF} = 0.32, \qquad 0.28 \leq \sin^2\theta_{12} \leq 0.37\,. \tag{1.4}$$

The combined limit on the θ_{13} mixing angle reads [11]

$$\sin^2\theta_{13} < 0.033\ (0.050) \quad \text{at} \quad 2\sigma\,(3\sigma)\ . \tag{1.5}$$

Despite the remarkable, recent progress in our understanding of neutrino physics, fundamental questions need to be addressed in the future in order to shed light on the theory beyond the Standard Model of particle interactions which is responsible for neutrino masses and mixing. We need to establish the nature of neutrinos (whether Dirac or Majorana particles), the neutrino mass ordering (normal or inverted), the absolute neutrino mass scale, the value of the unknown mixing angle θ_{13}, and if the CP-symmetry is violated in the leptonic sector. In addition, it will be important to determine with better precision the already known oscillation parameters.

A wide, future programme of neutrino oscillation experiments, under discussion at present, addresses some of the issues mentioned above [12, 13]. In particular, long baseline experiments will aim at providing information, first on the values of θ_{13}, and then on the type of neutrino mass ordering and on the value of the CP-violating phase δ, which enters in 3-neutrino oscillations. Superbeams, neutrino factory and beta-beams are studied in detail. Superbeams extend the present experimental concepts for conventional beams with an upgrade in intensity and in detector size. Various proposals are under consideration or construction: T2K [14] in Japan, NOνA [15] in the US, and the possibility of a wide-band beam if θ_{13} turns out to be large [16]. Neutrino factories [17] and beta-beams [18, 19, 20] are novel concepts. In a neutrino factory, muons (antimuons) are produced, cooled and accelerated to high Lorentz factor before stored in a decay ring. Muon neutrino (antineutrino) and electron antineutrino (neutrino) beams are produced and aimed at a magnetised detector at very far distance. Magnetisation is necessary in order to separate the right muon disappearance signal from the wrong muon appearance signal, which is sensitive to matter effects and CP violation. Beta-beams [18, 19, 20] exploit ions which are accelerated to high Lorentz factors, stored and then β-decay, producing a collimated electron neutrino beam. The typical neutrino energies are in the 200 MeV–GeV range, requiring detectors with hundred-of-MeV thresholds and good energy resolution. Lower energies imply shorter baselines and, typically, baselines of few hundred of km are considered. The only requirement is good muon identification in order to detect the appearance of muon neutrinos (or antineutrinos) from the initial electron neutrino (or antineutrino) beam. Hence, in principle, no magnetisation is required and therefore water Čerenkov, totally active scintillator, liquid argon detectors and non-magnetised iron calorimeters could be used, depending on the peak energy.

As it is well known, the determination of the mixing angle θ_{13}, the type of neutrino mass hierarchy, if the CP-symmetry is violated in the leptonic sector and the octant of the mixing angle θ_{23}, is severely affected by degeneracies [21, 22, 23, 24, 25]. For a fixed baseline and neutrino energy different sets of the unknown parameters $(\theta_{13}, \delta, \mathrm{sgn}(\Delta m^2_{31}), \theta_{23} \neq \pi/4)$ provide an equally good fit to the probability for neutrino and antineutrino oscillations. Therefore, a measurement of these probabilities in an experiment, even if very accurate, might not allow to discriminate between the various allowed solutions. Various strategies have been envisaged in order to weaken or resolve this issue: from exploiting the energy dependence of the signal in the same experiment [16], to the combination of different experiments [26, 27, 28, 29, 30, 31, 32, 32, 33, 34], to using more than one baseline for the same beam [35, 36, 37, 38, 39, 40, 41]. On the other hand, the mixing angle θ_{13} also controls the Earth matter effects in multi-GeV atmospheric [42, 43, 44, 45, 46] and in supernova [47] neutrino oscillations, and the magnitude of the T-violating and CP-violating terms in neutrino oscillation probabilities is directly proportional to $\sin\theta_{13}$ [48]. Therefore, the determination of θ_{13} is crucial for the future possibilities at neutrino oscillation experiments of pinning down the type of mass hierarchy, if the CP-symmetry is violated in the lepton sector and the octant of θ_{23}.

In beta-beam experiments, due to the energy dependence of the neutrino flux and of the relevant cross sections for the interactions in the detector, in general a better sensitivity to the type of hierarchy and CP violation can be reached for higher gammas and consequently longer baselines [49, 50]. In particular, matter effects increase with distance and energy. Neutrino oscillation experiments with baselines of few hundred km, as the CERN-Frejus option or the T2K superbeam, turn out to have no sensitivity to the sign of Δm^2_{31}, for the allowed values of θ_{13} [30, 50, 51, 52]. Higher energy setups for baselines > 500 km have also been studied in detail [41, 49, 50, 53, 54, 55].

Equipping the CERN Super Proton Synchrotron (SPS) with a fast cycling superconducting magnet would provide a fast ramp which would avoid a significant loss of ions by decay in the accelerating phase and would allow to reach high gammas. The studies in Ref. [54] considered the reach of this setup using an iron magnetised detector located at Gran Sasso. They showed a very good physics reach, using both neutrinos from ^{18}Ne and antineutrinos from ^{6}He. However, longer baselines can be considered in Europe. In particular, it has been recently pointed out that the Boulby mine on the north-east coast of England has excellent potential for expansions [56]. This would allow to excavate laboratories able to host detectors with mass of a few tens of ktons, as required in a long baseline experiment. Therefore, Boulby constitutes a very interesting option for a future long baseline experiment in Europe, allowing for longer distances from CERN than Frejus, Canfranc and Gran Sasso. In the present article, we exploit this new opportunity and consider a neutrino beta-beam sourced at CERN and a detector located in the Boulby mine. This choice of setup has a baseline of 1050 km that allows a superior sensitivity to matter effects, as well as to CP violation with respect to lower energy possibilities. As just mentioned, our choice is motivated on one side by the possibility of an upgrade of the accelerator complex at CERN and on the other by the recent studies at the Boulby mine which indicate the possibility to build large caverns in hard stable rock at this site [56]. Differently from Ref. [54], we consider a detector with low energy threshold and good energy resolution. This has important physics implications as it allows one to fully exploit the oscillatory pattern of the signal and in particular to be sensitive to both the first and the second oscillation maximum. As the dependence of the signal on CP violation and matter effects is very different at different energies, it is possible to resolve degeneracies and reach an excellent sensitivity with a neutrino run only. In fact, sufficient information can be extracted from the neutrino signal alone and the antineutrino run, suppressed by small cross sections, does not improve the physics reach and it has not been included in our study.

The paper is organised as follows. In Section II we describe the beta-beam setup and the resulting neutrino flux. In Section III we discuss the strategy beyond the choice of experimental setup and in particular we discuss how a neutrino run can resolve degeneracies if the oscillatory pattern of the probability is fully exploited. In Sections IV and V we give the details of the numerical analysis and its results for the physics reach of the setup. Finally, in Section VI we draw our conclusions.

II. THE BETA-BEAM SETUP

First introduced by Zucchelli [18], a beta-beam experiment exploits a well collimated neutrino beam produced by the acceleration and subsequent decay of stored β-emitting ions. The neutrino flux is very well known since the beta decay is well understood theoretically and all forward going neutrinos are collimated into a cone with opening angle $1/\gamma$, γ being the ion boost in the laboratory frame. The dominant factor in the choice of ion is the need for a high luminosity at the detector site. Potential ions need to have a small proton number to minimise space charge, and half-lives ~ 1 second to reduce ion losses during the acceleration while still maintaining a large amount of useful decays per year. The most promising candidate ions are ^{18}Ne and ^{8}B for neutrinos, and ^{6}He and ^{8}Li for anti-neutrinos. In Table I we show, for each of these four isotopes, the energy at the peak of the beta-beam spectrum in the rest frame and the value of this energy in the boosted frame for the current SPS and for the upgraded SPS. We also show the baseline for which the peak energy would correspond to the first oscillation maximum of the probability of transition of ν_e into ν_μ.

In the rest frame of the ion, the electron neutrino flux depends on the neutrino energy, E_ν, as

$$\frac{d\Phi^{\rm rf}}{d\cos\theta dE_\nu} \sim E_\nu^2(E_0 - E_\nu)\sqrt{(E_\nu - E_0)^2 - m_e^2}\ . \tag{2.1}$$

Here, E_0 is the end-point energy of the decay and m_e is the mass of the electron. The neutrino flux per solid angle at the detector located at distance L from the source after

		Current SPS			Upgraded SPS		
Isotope	$E_{\rm P}$ (MeV)	γ	E_ν (GeV)	$L_{\rm max}$ (km)	γ	E_ν (GeV)	$L_{\rm max}$ (km)
^{18}Ne	1.86	270	1.0	510	590	2.2	1130
^{6}He	1.94	160	0.6	320	355	1.4	710
^{8}B	7.37	300	4.4	2270	670	9.8	5060
^{8}Li	6.72	180	2.4	1240	400	5.4	2770

TABLE I: Energy at the peak of the beta-beam spectrum in the rest frame ($E_{\rm P}$) and in the boosted frame for the current (maximum proton energy of 450 GeV) and upgraded (maximum proton energy of 1 TeV) SPS. Also shown the maximum achievable γ factor in both cases for each isotope. The maximum baseline, $L_{\rm max}$, represents the distance at which the first oscillation maximum of the probability of conversion of ν_e into ν_μ is located.

boost γ is [49]

$$\left.\frac{d\Phi^{\rm lab}}{d\Omega dy}\right|_{\theta\simeq 0} \simeq \frac{N_\beta}{\pi L^2}\frac{\gamma^2}{g(y_e)}y^2(1-y)\sqrt{(1-y)^2-y_e^2}\;, \tag{2.2}$$

where $0 \le y = \frac{E_\nu}{2\gamma E_0} \le 1 - y_e$, $y_e = m_e/E_0$, N_β is the number of useful ion decays per year, and

$$g(y_e) \equiv \frac{1}{60}\left\{\sqrt{1-y_e^2}(2-9y_e^2-8y_e^4)+15y_e^4\log\left[\frac{y_e}{1-\sqrt{1-y_e^2}}\right]\right\}\;. \tag{2.3}$$

A neutrino with energy $E^{\rm rf}$ in the rest frame will have a corresponding energy $E_\nu = 2\gamma E^{\rm rf}$ in the laboratory frame along the $\theta = 0°$ axis. Consequently, ions with lower end-point values in the ion rest frame require higher γ in order to achieve the neutrino energies appropriate to a given baseline. Most studies consider ^{18}Ne and ^{6}He due to their low Q-values. For similar ion production rates, this choice will provide a more focused beam and, the flux scaling as γ^2, higher fluxes at the detector. It is noted also that placing a detector off-axis still constitutes a Lorentz boost so that, unlike a superbeam, the spectral shape is maintained although the mean energy will be lower than in the on-axis case.

The initial study of a beta-beam [18] considered a ‘low-γ’ machine which experimentally had three stages: nuclide production via the Isotope Separation OnLine (ISOL) technique; acceleration using existing technology such as the CERN Proton Synchrotron (PS) and SPS before storing the ions in a decay ring. The feasibility of such scheme has been demonstrated [57], the current magnetic rigidity of the SPS allowing a maximum $\gamma \sim 160$ for ^{6}He and $\gamma \sim 270$ for ^{18}Ne. The ions will be accelerated to 300 MeV/amu through the use of a linac and rapid cycling synchrotron before being fed into the CERN PS. It is envisaged that there will be 16 bunches of 2.5×10^{12} ions which will be merged to 8 upon acceleration to $\gamma = 9$. The final phase of the acceleration requires the transfer to the SPS where they will be accelerated to the γ required for the experiment. The ions are then stacked in a decay ring so that enough ions decay to achieve a useful neutrino flux. For the $\gamma = 100$ scenario, it is proposed to have a decay ring with the same circumference as the SPS (6880 m) but in a 'racetrack' design with 2500 m straight sections. For a single baseline beta-beam, $\sim 35\%$ of the neutrinos will be available from a single straight section. With the current SPS, the CERN-Frejus baseline ($L \sim 130$ km) is the only option available. However, the short distance does not allow sensitivity to matter effects and to the neutrino mass ordering.

Some LHC upgrade scenarios conceive implementation of the SPS with fast cycling superconducting magnets leading to the injection of 1 TeV protons into the LHC. Such a setup would allow the acceleration of ^{18}Ne and ^{6}He up to γ of 580 and 350, respectively. Various studies have exploited this possibility [41, 49, 54, 55]. A number of issues (e.g., the achievable intensities or the size of the decay ring) need to be studied in detail in order to understand the feasibility of these higher-γ beta-beams and their physics reach. Another option which emerged in the recent past is the possibility of high-Q value beta-beams [58]. These beams exploit the decay of high Q-valued ions, namely ^{8}B and ^{8}Li. The same neutrino energies can be achieved with a boost factor 4 times smaller than for ^{18}Ne and ^{6}He. In order to obtain useful luminosities at the detector, a much higher number of beta decays is therefore required.

The intensity of the beam plays a crucial role in the physics reach of the setup as it controls the statistics available. It depends mainly on the production rate of the isotopes and on space-charge limitations. At present, three possibilities for ion production have been considered: ISOL method at medium energy and direct production with and without a storage ring. The ISOL technique [59] uses typically (0.1–2) GeV protons from the proposed 2.2 GeV Super Proton Linac, which will be used to activate the nuclear reactions producing the nuclide of interest. For ^{6}He production, a heavy metal target, such as mercury or water-cooled tungsten, will be used to transform the proton beam into a neutron flux which then impacts on a cylinder of BeO surrounding the target. ^{6}He is then produced via the ^{9}Be(n,α) reaction. The ^{18}Ne can be created directly by proton spallation on a MgO target. The present studies indicate that with a 200 kW power, one could achieve a number of ions per second $> 10^{13}$/s for ^{6}He and $< 8 \times 10^{11}$ for ^{18}Ne. For direct production, low energy and high intensity ion beams are used on solid or gas targets. Compound nuclei form at low energy due to the high cross section and the required ions are generated. Various preliminary studies show that a production rate of 10^{13} ions per second could be achieved for ^{18}Ne and ^{6}He. Direct production can be enhanced using a storage ring in which primary ions which did not interact at the first passage are recirculated and reaccelerated. This technique is possible thanks to ionisation cooling [58] and might allow high production rates of ^{8}B and ^{8}Li, up to 10^{14}/s for ^{8}Li and 10^{13}/s for ^{8}B.

III. RESOLVING NEUTRINO OSCILLATION DEGENERACIES IN A NEUTRINO RUN

In our analysis we consider a beam of neutrinos only, but exploit the rich oscillatory pattern of the signal. In particular, requiring a low energy threshold for the detector, we can access more than one oscillation maximum. This allows one to obtain a very good physics reach and to efficiently resolve the problem of degeneracies.

The oscillation probability $P(\nu_e(\overline{\nu}_e) \to \nu_\mu(\overline{\nu}_\mu)) \equiv P^{\pm}_{e\mu}$ for $\nu_e\,(\overline{\nu}_e)$ into $\nu_\mu\,(\overline{\nu}_\mu)$ conversion can be expanded in the small parameters $\bar{\theta}_{13}$, Δ_{12}/Δ_{13}, Δ_{12}/A and $\Delta_{12}L$ [60], where the shorthand $\Delta_{ji} \equiv \Delta m^2_{ji}/(2E)$ is being used,

$$P^{\pm}_{e\mu}(\bar{\theta}_{13}, \bar{\delta}) = \sin^2 2\bar{\theta}_{13}\, \sin^2 \bar{\theta}_{23} \left(\tfrac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\tfrac{B_\mp L}{2}\right) + \cos^2 \bar{\theta}_{23}\, \sin^2 2\bar{\theta}_{12} \left(\tfrac{\Delta_{21}}{A}\right)^2 \sin^2\left(\tfrac{AL}{2}\right)$$
$$+ \cos\bar{\theta}_{13}\, \sin 2\bar{\theta}_{13}\, \sin 2\bar{\theta}_{12}\, \sin 2\bar{\theta}_{23}\, \tfrac{\Delta_{21}}{A}\tfrac{\Delta_{31}}{B_\mp} \sin\left(\tfrac{AL}{2}\right) \sin\left(\tfrac{B_\mp L}{2}\right) \cos\left(\pm\bar{\delta} - \tfrac{\Delta_{31}L}{2}\right) \;, \quad (3.1)$$

where the ± corresponds to neutrinos/anti-neutrinos and $B_\mp \equiv A \mp \Delta_{31}$. Here we are using $A = \sqrt{2} G_F \bar{n}_e(L)$ (the constant density approximation for the index of refraction) where $\bar{n}_e = 1/L \int_0^L n_e(L')dL'$ is the average electron density and $n_e(L)$ is the electron density along the baseline.

The number of neutrino (antineutrino) events in the i-th neutrino (antineutrino) energy bin for a given pair $(\bar{\theta}_{13}, \bar{\delta})$ is given by

$$N_i(\bar{\theta}_{13}, \bar{\delta}) = \mathcal{N}_{\rm T}\, t \int_{E_i}^{E_i+\Delta E} \epsilon(E_\nu)\ \sigma_{\nu_\mu(\overline{\nu}_\mu)}(E_\nu)\ P^{\pm}_{e\mu}(E_\nu, \bar{\theta}_{13}, \bar{\delta})\ \Phi_{\nu_e(\overline{\nu}_e)}(E_\nu)\ dE_\nu\ , \qquad (3.2)$$

where $\mathcal{N}_{\rm T}$ is the number of targets in the detector, t is the time of data taking, $\epsilon(E_\nu)$ is the detector efficiency, $\sigma(E_\nu)$ is the interaction cross section, $\Phi(E_\nu)$ is the beam spectrum and ΔE is the neutrino energy resolution of the detector. As it is apparent from Eq. (3.1), the extraction of θ_{13}, the sign of Δm^2_{31}, δ and θ_{23} from Eq. (3.2) suffers from the problem of degeneracies [21, 22, 23, 24, 25]. In addition to the true solution ($\bar{\theta}_{13}$, $\bar{\delta}$, sign(Δm^2_{31}), $\bar{\theta}_{23}$), other fake (clone) solutions (θ_{13}, δ, $\pm$sign(Δm^2_{31}), θ_{23}) are allowed.

In order to get an analytical understanding of the degeneracies, we consider the simplified case of infinite energy resolution, for which the integrals in Eq. (3.2) reduce to products. We compare the number of events at the neutrino energy of the first oscillation maximum, E_1, with the number at the second oscillation maximum, E_2. In the approximation considered, we have $N_1(E_1) = c_1 P^+_{e\mu}(E_1)$ and $N_2(E_2) = c_2 P^+_{e\mu}(E_2)$, where c_1 and c_2 are the product of the number of targets, time of data taking, efficiency, the neutrino flux and cross section at each of the two energies, respectively. Although a more realistic analysis should be performed taking into account the finite energy resolution, statistical and systematic errors, backgrounds and the full differential cross section for the detection processes, we use this simplified approach to show the potentialities of using the spectral information with only one polarity. As it will be shown in Section V, a more detailed analysis confirms the qualitative results obtained here.

Let us first consider the intrinsic degeneracy, for which given the true value of the pair $(\bar{\theta}_{13}, \bar{\delta})$, the clone solution (θ_{13}, δ) is located by solving [21]

$$N_1(\bar{\theta}_{13}, \bar{\delta}, {\rm sign}(\Delta m^2_{31}), \bar{\theta}_{23}) \ = \ N_1(\theta_{13}, \delta, {\rm sign}(\Delta m^2_{31}), \bar{\theta}_{23})\ , \qquad (3.3)$$

$$N_2(\bar{\theta}_{13}, \bar{\delta}, {\rm sign}(\Delta m^2_{31}), \bar{\theta}_{23}) \ = \ N_2(\theta_{13}, \delta, {\rm sign}(\Delta m^2_{31}), \bar{\theta}_{23})\ . \qquad (3.4)$$

As it is straightforward to show, only one solution is allowed for θ_{13} and δ for a measured number of events N_1 and N_2. The CP-violating effects become more important at low energy and in particular at the second oscillation maximum. Therefore, the intrinsic degeneracy is fully resolved by exploiting the neutrino signal at first and second oscillation maximum. In the case of a neutrino and antineutrino beam considered at first oscillation maximum, a similar result is obtained.

We study next the sign degeneracy. The clone solution satisfies [22]

$$N_1(\bar{\theta}_{13}, \bar{\delta}, \mathrm{sign}(\Delta m^2_{31}), \bar{\theta}_{23}) \;=\; N_1(\theta_{13}, \delta, -\mathrm{sign}(\Delta m^2_{31}), \bar{\theta}_{23}) \;, \tag{3.5}$$

$$N_2(\bar{\theta}_{13}, \bar{\delta}, \mathrm{sign}(\Delta m^2_{31}), \bar{\theta}_{23}) \;=\; N_2(\theta_{13}, \delta, -\mathrm{sign}(\Delta m^2_{31}), \bar{\theta}_{23}) \;, \tag{3.6}$$

and is found to be

$$\sin^2 2\theta_{13} \;\simeq\; \sin^2 2\bar{\theta}_{13} \left(1 + 4\frac{A}{\Delta_{31}}\right) \;, \tag{3.7}$$

$$\sin\delta \;\simeq\; \sin\bar{\delta} \;, \tag{3.8}$$

where we have only kept terms up to first order in A/Δ_{31}. This shows that the sign degeneracy affects only mildly the determination of $\bar{\theta}_{13}$ and very weakly that of $\bar{\delta}$. The signal at first and second oscillation maximum is not sufficient to determine the type of neutrino mass ordering. However, including information on the neutrino oscillation probability at other energies breaks this degeneracy. In particular, matter effects increase with energy and the high energy bins turn out to play a very important role in breaking the sign degeneracy. In the case of combining the first oscillation maximum for neutrinos and antineutrinos, we have also a clone solution, with information from additional energy bins also necessary to fully resolve this degeneracy.

Finally, we study the octant degeneracy, for which the clone solution is such that [23]

$$N_1(\bar{\theta}_{13}, \bar{\delta}, \mathrm{sign}(\Delta m^2_{31}), \bar{\theta}_{23}) \;=\; N_1(\theta_{13}, \delta, \mathrm{sign}(\Delta m^2_{31}), \pi/2 - \bar{\theta}_{23}) \;, \tag{3.9}$$

$$N_2(\bar{\theta}_{13}, \bar{\delta}, \mathrm{sign}(\Delta m^2_{31}), \bar{\theta}_{23}) \;=\; N_2(\theta_{13}, \delta, \mathrm{sign}(\Delta m^2_{31}), \pi/2 - \bar{\theta}_{23}) \;, \tag{3.10}$$

and is given by

$$\sin^2 2\theta_{13} \;\simeq\; \tan^2\bar{\theta}_{23}\, \sin^2 2\bar{\theta}_{13} + (1 - \tan^2\bar{\theta}_{23}) \sin^2 2\bar{\theta}_{12} \left(\frac{\Delta_{21}}{\Delta_{31}}\right)^2 \frac{\pi^2}{4} \;, \tag{3.11}$$

$$\sin\delta \;\simeq\; \frac{\sin\bar{\delta}}{\tan\bar{\theta}_{23}} \left(1 + \frac{\pi^2}{8}\left(1 - \frac{1}{\tan^2\bar{\theta}_{23}}\right) \frac{\sin^2 2\bar{\theta}_{12}}{\sin^2 2\bar{\theta}_{13}} \left(\frac{\Delta_{21}}{\Delta_{31}}\right)^2\right) \;. \tag{3.12}$$

This is valid in the whole allowed range of the oscillation parameters for $\sin^2 2\bar{\theta}_{13} > 10^{-3}$ and only terms up to $\mathcal{O}(\Delta_{21}/\Delta_{31})^2$ have been retained. As it has been discussed [61], the information from the low energy bins plays a crucial role in resolving this degeneracy. Similar considerations can be done for the case of a neutrino and antineutrino run.

Our simplified analysis suggest that even with the neutrino run alone, by exploiting the oscillatory pattern of the signal, it is possible to resolve degeneracies and obtain a very good sensitivity to the unknown neutrino parameters. In the following, we substantiate these claims with a detailed numerical analysis.

IV. NUMERICAL SIMULATIONS AND ANALYSIS OF THE DATA

The physics strategy followed here exploits electron neutrino beams from boosted ^{18}Ne β^+ decays for a single baseline. Future CERN accelerator facilities could provide the production environment. The neutrino detector would be ideally placed at Boulby, located at $L =$ 1050 km from CERN. The Lorentz factor we assume here corresponds to a conservative (for the upgraded SPS) $\gamma = 450$, for which the mean electron neutrino energy is $\langle E_\nu \rangle \simeq \gamma E_0 \sim 1.5$ GeV, $E_0 = 3.41$ MeV being the positron end-point energy for ^{18}Ne. With such a setup, both the first and second oscillation maxima of the appearance probability could, in principle, be studied. This is illustrated in Fig. 1 where we show the transition probability of ν_e into ν_μ for two values of the CP-violating phase δ and for both mass orderings.

The results of this study are shown for two possible experimental scenarios, which only differ in their statistics. This analysis allows us to quantify the benefits of increased detector sizes, ion intensities and/or exposure times. We first consider an exposure corresponding to 10^{21} ions-kton-years. This could be obtained, for example, assuming 2×10^{18} useful ion decays per year and a 50 kton detector located at Boulby with 10 years of data taking. As we will show, the statistics plays a crucial role in the physics reach of the setup. Therefore, we also study a rather optimistic scenario, obtained by upgrading the first scenario by a factor of five in statistics, i.e., with an exposure of 5×10^{21} ions-kton-years. Considering that the time of data taking cannot be substantially extended, this exposure could be achieved by using a larger detector or increasing the ion luminosity or both. Obviously, the results for exposuree.s larger than the first scenario but not as quite optimistic as the second one will interpolate between the two. Possible detector technologies considered in the literature include water Čerenkov, liquid argon, totally active scintillator or iron calorimeter detectors. For our purposes low energy threshold and good neutrino energy resolution are requirements for the choice of detector technology. For instance, liquid argon and totally active scintillator detectors might have these characteristics.

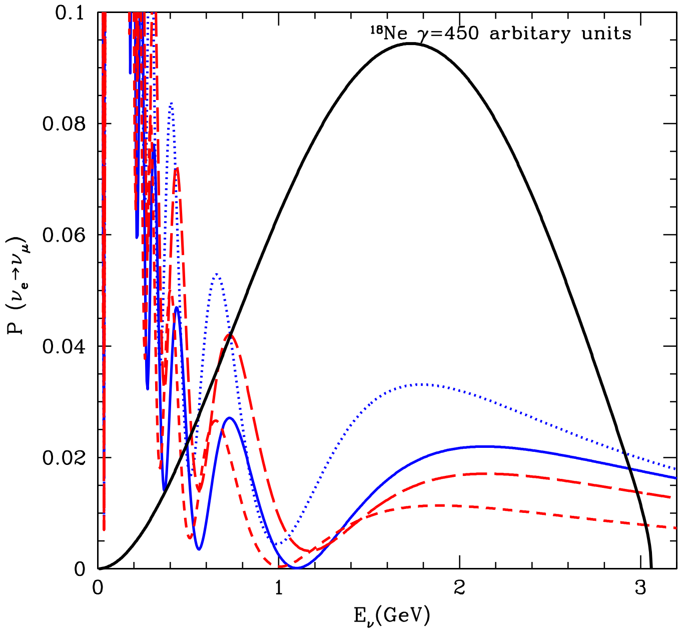

FIG. 1: *Transition probability of* ν_e *into* ν_μ *as a function of the neutrino energy for normal hierarchy and* $\delta = 0^\circ$ *(blue solid line), normal hierarchy and* $\delta = 90^\circ$ *(blue dotted line), inverted hierarchy and* $\delta = 0^\circ$ *(red short dashed line) and inverted hierarchy and* $\delta = 90^\circ$ *(red long dashed line). Also shown in arbitrary units the unoscillated beta-beam neutrino spectrum from* ^{18}*Ne decays and* $\gamma = 450$.

As mentioned above, a crucial aspect of the analysis performed here is to use the spectral information, and hence the energy binning of the signal becomes fundamental. As carefully described in the previous section, our main strategy consists in exploiting simultaneously many E/L's, and therefore we assume a 200 MeV bin width and an energy detection threshold of 400 MeV. In what follows, the muon-neutrino appearance signal is binned in eleven bins with a bin width of 200 MeV in the [0.4, 2.0] GeV energy range, plus a unique, last bin, filled with the neutrino events from 2.0 GeV up to the end point of the spectrum at 3.06 GeV. For our numerical analysis, we use the following χ^2 definition:

$$\chi^2 = \sum_{i,j} (n_i - N_i) C^{-1}_{ij} (n_j - N_j) \,, \tag{4.1}$$

where N_i is the predicted number of muons for a certain oscillation hypothesis, $n_{i,p}$ are the

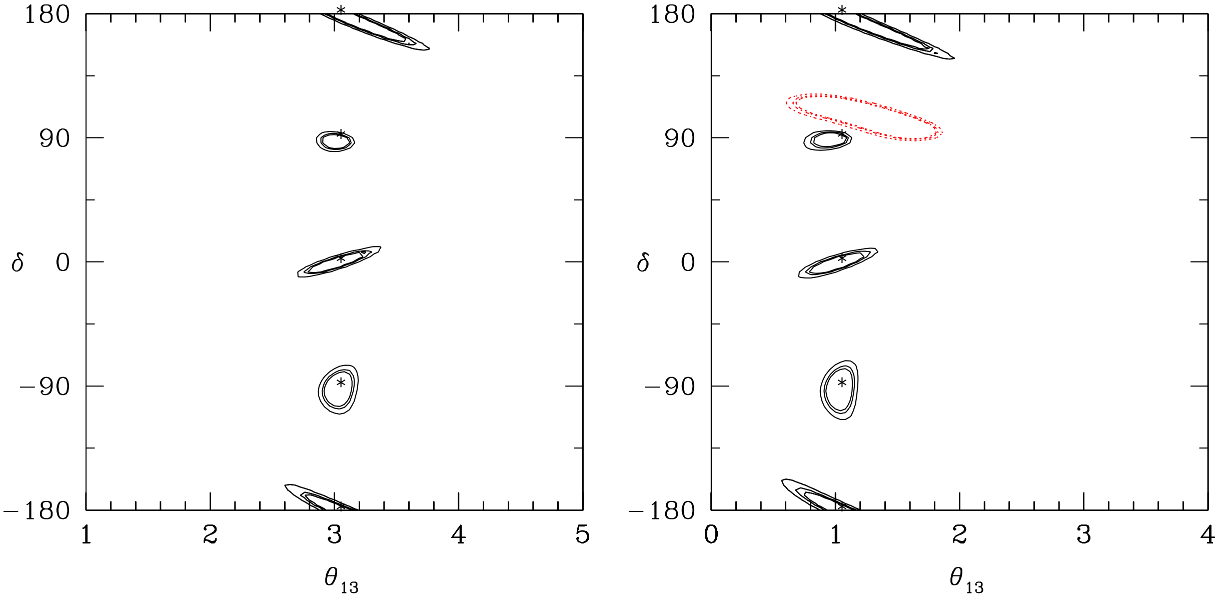

FIG. 2: *For an exposure of* 5×10^{21} *ions-kton-years,* 90%, 95% *and* 99% *(for 2 d.o.f) CL contours resulting from the fits if the true values Nature has chosen are* $\theta_{13} = 3°$ *(left panel) or* $\theta_{13} = 1°$ *(right panel), and* $\delta = 0°,\ 90°,\ -90°$ *or* 180°*. Dashed-red contours represent the hierarchy-clone solution.*

simulated "data" from a Gaussian or Poisson smearing. The $2N_{\rm bin} \times 2N_{\rm bin}$ covariance matrix C, which is given by

$$C^{-1}_{i,j} \equiv \delta_{ij} (\delta n_i)^2 \tag{4.2}$$

where $(\delta n_i) = \sqrt{n_i + (f_{sys} \cdot n_i)^2}$, contains both statistical and a 2% overall systematic error ($f_{sys} = 0.02$). The confidence level (CL) contour plots presented in the figures in the next section have been calculated for 2 degrees of freedom (d.o.f.) statistics.

Realistic background assumptions have been included when computing the simulated data. We have considered two types of backgrounds: an intrinsic beam-induced background (taken as a constant fraction, 0.1%, of the unoscillated events) plus the atmospheric neutrino contribution. In the energy range of interest, there are about 30 atmospheric neutrino interactions per kton-year which could mimic a muon coming from the oscillated $\nu_e \rightarrow \nu_\mu$ [20, 62, 63]. Assuming a beam duty factor of 10^{-3}, the number of muon background events induced by atmospheric muon neutrino interactions would be ~ 0.03 per kton-year,

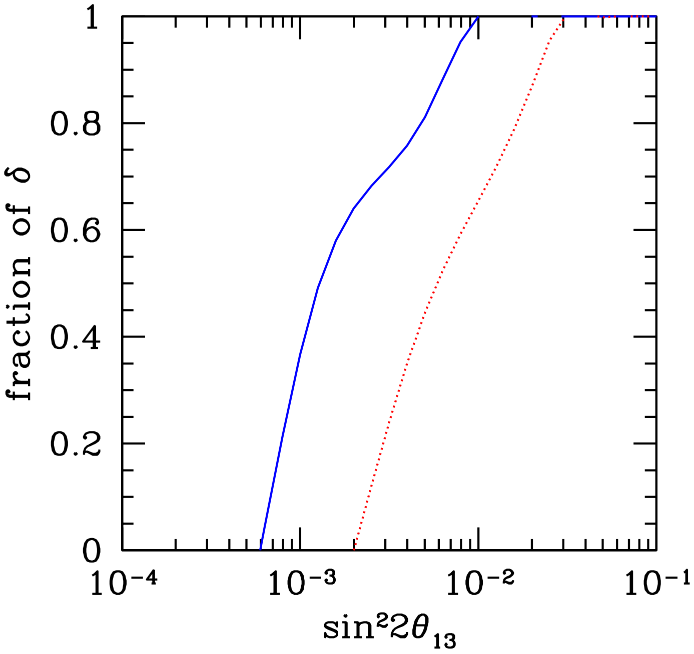

FIG. 3: 99% *CL hierarchy resolution (2 d.o.f). The dotted red curve depicts the results assuming an exposure of* 10^{21} *ion-kton-years in Boulby. The solid blue curve depicts the results assuming the statistics quoted before is improved by a factor of five.*

to be rescaled accordingly to the detector size and the exposure time. We think the treatment of the backgrounds presented here is conservative.

V. RESULTS

We present in Fig. 2 the 90%, 95% and 99% CL contours for a fit to the simulated data from the beta-beam experiment described in the previous section. The "true" parameter values that we have chosen for these examples are depicted in the figures with a star: we have explored four different values of $\delta = 0°$, $90°$, $-90°$ and $180°$ and two possible values of $\theta_{13} = 3°$ (left panel) and $1°$ (right panel). The simulations are for the normal mass hierarchy and θ_{23} in the first octant ($\sin^2\theta_{23} = 0.41$ which corresponds to $\theta_{23} = 40°$). The statistics considered corresponds to the optimistic high-statistics scenario, with an exposure of 5×10^{21} ions-kton-years. The analysis depicted in Fig. 2 includes the study of the discrete degeneracies. That is, we have fitted the data assuming the wrong hierarchy (i.e., negative

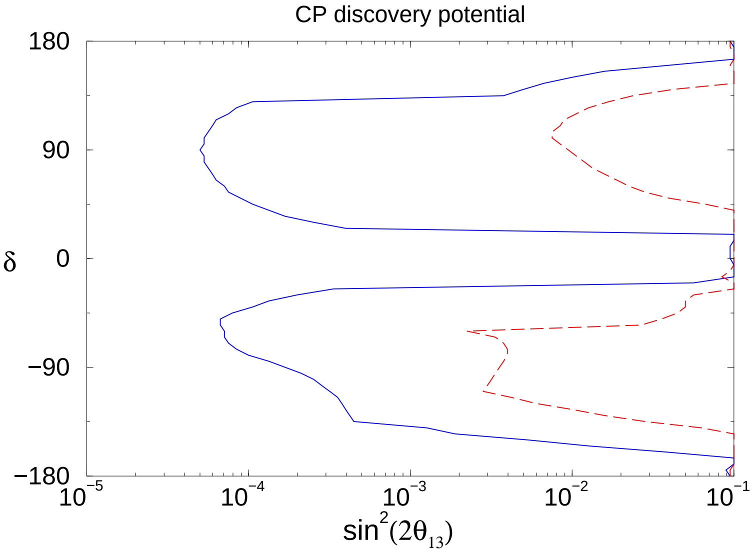

FIG. 4: *Discovery at* 99% *CL of CP violation (2 d.o.f). The dashed red curve depicts the results assuming an exposure of* 10^{21} *ions-kton-years in Boulby. The solid blue curve depicts the results for an exposure of* 5×10^{21} *ions-kton-years.*

hierarchy) and the additional clone solutions (if present) are shown in dashed red. We have also considered the impact of the wrong choice for the θ_{23} octant (we fitted the data assuming $\sin^2\theta_{23} = 0.59$, which corresponds to $\theta_{23} = 50^\circ$). Notice that in Fig. 2 the θ_{23}-octant ambiguity is solved at the 99% CL for the values of δ illustrated. The additional solutions associated to the wrong choice of the mass hierarchy are not present at the same CL if θ_{13} is small enough, i.e., $\theta_{13} < 6^\circ$. For *larger* values of θ_{13} the sign degeneracy is present for some values of the CP-violating phase δ, but its location is very similar to the simulated true value and therefore the presence of these degeneracies will hardly interfere with the measurement of CP violation. This behaviour of the θ_{23} degenerate solutions is opposite to the normal case, in which the resolution of the degeneracies gets harder as the value of θ_{13} decreases. The reason for that is the enormous impact of the solar term at the lower energies and the long baseline exploited here. For instance, for $\langle E_\nu \rangle \simeq 1$ GeV, the solar term contribution is larger than that of the atmospheric term for all the values of $\theta_{13} < 6^\circ$.

Figs. 3, 4 and 5 summarise, for the low- and high-statistics scenarios, the physics reach of the beta-beam experiment considered here. The analysis takes into account the impact

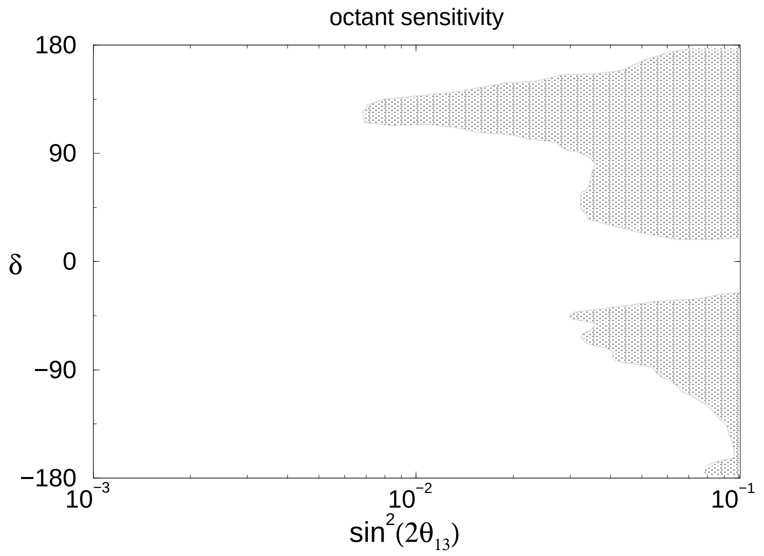

FIG. 5: 99% *CL determination of the* θ_{23} *octant. The grey region denotes the parameter space for which the octant degeneracy is not resolved at the* 99% *CL. Results are shown for an exposure of* 5×10^{21} *ions-kton-years.*

of both the intrinsic and discrete degeneracies. Fig. 3 shows the region in the ($\sin^2 2\theta_{13}$, "fraction of δ") plane for which the mass hierarchy can be resolved at the 99% CL (2 d.o.f). Note that, with a background level of 0.1% and a beam duty cycle of 10^{-3}, the hierarchy can still be determined in both scenarios if $\sin^2 2\theta_{13} > 0.03$ (i.e., $\theta_{13} > 5°$) for all values of the CP-violating phase δ. Fig. 4 shows the region in the ($\sin^2 2\theta_{13}$, δ) plane for which a given (non-zero) value of the CP-violating phase δ can be distinguished at the 99% CL (2 d.o.f.) from the CP-conserving case, i.e., $\delta = 0, \pm 180°$. The results are given for both the low- and high-statistics scenarios. Again, even in the presence of non negligible beam-induced plus atmospheric background levels, the CP-violating phase δ could be measured with a 99% CL error smaller than $\sim 20°$ if $\sin^2 2\theta_{13} > 10^{-3}$ in the high-statistics scenario. Finally, the white area in Fig. 5 represents the region in the ($\sin^2 2\theta_{13}$, δ) plane for which the octant in which θ_{23} lies can be determined at the 99% CL (2 d.o.f). The result is illustrated for the high-statistics scenario. In general, the resolution of the θ_{23} octant ambiguity is extremely difficult, and in order to eliminate this degeneracy, combining data from different experiments might be crucial [64]. Here, we benefit from the solar term contribution in the lower energy bins and therefore, the octant ambiguity is resolved for relatively small values of θ_{13}, if the statistics is high enough. For the low luminosity scenario, the degeneracy is harder to resolve and it is present (at the 99% CL) in almost all the parameter space explored here.

VI. SUMMARY AND CONCLUSIONS

In the present article, we have studied the physics reach of a beta-beam with intermediate γ and long baseline. We have considered a neutrino beam sourced by ^{18}Ne decays with $\gamma = 450$ and a baseline of 1050 km corresponding to the CERN-Boulby mine distance. This choice of setup is motivated by the recent studies about the possible upgrade of the SPS at CERN which would allow to obtain high boost factors for the ions and by the possibility of locating few-ten-kton size detectors at the Boulby mine.

In a qualitative way, we have analytically studied the capability that a neutrino run alone could have to resolve the problem of degeneracies and we have shown that, by exploiting the oscillatory behaviour of the signal, it is possible to fully resolve such degeneracies in a large part of the allowed parameter space. We have performed a numerical analysis simulating the data for a future beta-beam experiment with an exposure of 10^{21} useful ion decays-kton-years. Realistic backgrounds (intrinsic plus atmospheric neutrino contamination) and beam-duty factor (10^{-3}) have been considered when computing the χ^2 function used for this analysis. By exploiting the neutrino data only, the beta-beam setup presented here can determine the type of neutrino mass hierarchy at the 99% CL, regardless of the value of the CP-violating phase, for values of the mixing parameter $\sin^2 2\theta_{13}$ larger than 0.03, and establish leptonic CP violation if $\sin^2 2\theta_{13} > 0.01$.

If the mixing angle θ_{13} turns out to be very small, a quest for physics answers would evidently require an increase of the exposure quoted above. We illustrate the physics reach of this beta-beam setup assuming a factor of five improvement in the statistics, considering 5×10^{21} ions-kton-years. In this high-luminosity scenario, the value of the CP-violating phase δ can be measured with a 99% CL error of $\sim 20^\circ$ if $\sin^2 2\theta_{13} > 10^{-3}$, with some sensitivity down to very small values of $\sin^2 2\theta_{13} \simeq 10^{-4}$. If θ_{13} turns out to be small, the octant degeneracy can be resolved through the solar mixing term contribution.

In summary, we have analysed a beta-beam setup with a neutrino run and we have found that, by exploiting the oscillatory behaviour of the signal, this option provides a very good overall physics reach, competitive with other setups explored in the literature.

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