Optimized Two-Baseline Beta-Beam Experiment

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We propose a realistic β-Beam experiment with four source ions and two baselines for the best possible sensitivity to θ_{13}, CP violation and mass hierarchy. Neutrinos from ^{18}Ne and ^{6}He with Lorentz boost $\gamma = 350$ are detected in a 500 kton water Čerenkov detector at a distance $L = 650$ km (first oscillation peak) from the source. Neutrinos from ^{8}B and ^{8}Li are detected in a 50 kton magnetized iron detector at a distance $L = 7000$ km (magic baseline) from the source. Since the decay ring requires a tilt angle $\vartheta = 34.5°$ to send the beam to the magic baseline, the far end of the ring has a maximum depth of $d = 2132$ m for magnetic field strength of 8.3 T, if one demands that the fraction of ions that decay along the straight sections of the racetrack geometry decay ring (called livetime) is 0.3. We alleviate this problem by proposing to trade reduction of the livetime of the decay ring with the increase in the boost factor of the ions, such that the number of events at the detector remains almost the same. This allows to substantially reduce the maximum depth of the decay ring at the far end, without significantly compromising the sensitivity of the experiment to the oscillation parameters. We take ^{8}B and ^{8}Li with $\gamma = 390$ and 656 respectively, as these are the largest possible boost factors possible with the envisaged upgrades of the SPS at CERN. This allows us to reduce d of the decay ring by a factor of 1.7 for 8.3 T magnetic field. Increase of magnetic field to 15 T would further reduce d to 738 m only. We study the sensitivity reach of this two baseline two storage ring β-Beam experiment, and compare it with the corresponding reach of the other proposed facilities. We find that for values of $\sin^2 2\theta_{13} > 10^{-3}$ this β-Beam setup outperforms the Neutrino Factory sensitivities.

I. INTRODUCTION

Neutrinos have been providing some of the most illuminating as well as intriguing insights into the theory of elementary particle physics. Neutrinos are naturally massless within the framework of the Standard Model of particle physics. The presence of tiny neutrino masses therefore demands for a theory beyond the Standard Model. The neutrino mass and mixing pattern, once determined to a sufficient level of accuracy could (hopefully) show the path to this theory underlying the Standard Model. Existence of neutrino masses and mixings has now been established by a series of outstanding experimental endeavors involving neutrinos coming from the Sun [1], Earth's atmosphere [2], nuclear reactors [3] and accelerator sources [4, 5]. The global neutrino data prefers [6] $\Delta m_{21}^2 = 7.7 \times 10^{-5}$ eV^2, $\Delta m_{31}^2 = 2.4 \times 10^{-3}$ eV^2, $\sin^2 \theta_{12} = 0.31$ and $\sin^2 \theta_{23} = 0.5$.

The third mixing angle θ_{13} is mainly constrained by the results from the Chooz reactor experiment [7], which is consistent with no positive signal for oscillations and hence a zero value for this mixing angle. This data, when combined with the world neutrino data, gives $\sin^2 \theta_{13} < 0.05$ at the 3σ C.L. However, while the Chooz data do not support any evidence for non-zero θ_{13}, it has been observed that inconsistency between the global solar data and

KamLAND results can be reduced with a non-zero θ_{13} [8] (see also [9]). While the evidence is still weak[1], we do have an indication for non-zero θ_{13} at the 1σ level. This claim for non-zero θ_{13} could be *just* within the reach of the next-generation neutrino experiments involving reactor antineutrinos, [10, 11, 12, 13] and accelerator (anti)neutrinos [14, 15]. In Fig. 1 of Ref. [16] the 90% CL. sensitivities to θ_{13}, CP violation and the mass hierarchy expected for these next generation of experiments are presented as well as the sensitivities achievable by an eventual combination of all of them. The combination of all the facilities would grant sensitivity to θ_{13} down to $\sin^2 2\theta_{13} > 3 - 6 \times 10^{-3}$ allowing to probe the present hint for non-zero θ_{13}. If next-generation reactor- and accelerator-based experiments fail to observe any positive signal for non-zero θ_{13}, however, more powerful experiments involving bigger detectors and improved beams in order to pin down this elusive mixing angle will be needed. Two other oscillation parameters, indispensable for the reconstruction of the full neutrino mass matrix, are the ordering of the neutrino mass ($sgn(\Delta m_{31}^2)$), *aka* the neutrino mass hierarchy, and[2] the CP phase δ. It is quite unlikely that these will be discovered in the next generation experiments. Indeed, as can also be seen from Fig. 1 of Ref. [16], the sensitivities to these parameters of the next generation of facilities is very limited even after combining all of them. CP violation might only be discovered for less than 20% of the possible values of δ and only if $\sin^2 2\theta_{13} > 0.02$. As for the mass hierarchy, it can only be distinguished for less than 40% of the possible values of δ and only if $\sin^2 2\theta_{13} > 0.04$. Moreover, these limits are only for a 90% CL. significance and, therefore, even if the combination of all experiments hints at its precesnce, an independent confirmation at higher significance would be desirable. Therefore, there are good reasons to consider larger dedicated experiments, with very well known beams, higher statistics and lower systematics and beam backgrounds, even if a signal for non-zero θ_{13} is found by next generation facilities.

Two kind of such experiments, to improve over the next generation of facilities, have been envisaged. The first category, called "Neutrino Factory" [17], would exploit very high intensity neutrino beams coming from the decay of muons, which are collected, accelerated and subsequently stored in a decay ring. As it is well known, such an experiment necessarily requires a far detector with charge identification capability to tag the initial neutrino flavor. The second kind of high intensity beam proposed is the so-called "β-Beam" [18]. This entails producing β-unstable radioactive ions, collecting, bunching, accelerating and then finally transferring them into a storage ring [19, 20]. In this case, in principle, one could use any kind of detector[3] with good muon identification.

For both beam categories, the oscillation channel which is expected to give us information on all the three parameters is the $\nu_e \to \nu_\mu$ channel (proportional to the oscillation probability $P_{e\mu}$) – also called the "golden channel" [21]. However, given that only one channel is used to determine three parameters and that the octant of the atmospheric mixing angle remains unknown[4], "parameter degeneracies", which limit the sensitivity of the experiment, appear. For every true set of $\theta_{13} - \delta$ the analysis of the data could give degenerate solutions arising due to (i) the $\delta - \theta_{13}$ correlation (the so-called "intrinsic degeneracy" [22]), (ii) the $\delta - sgn(\Delta m_{31}^2)$ correlation (the "sign degeneracy" [23]), and (iii) the octant of θ_{23} (the "octant degeneracy" [24]), leading, in total, to an eight-fold degeneracy in the $\delta - \theta_{13}$ plane [25] (the fourth degeneracy being the "mixed degeneracy", *i.e.* a wrong choice of both $sgn(\Delta m_{31}^2)$ and of the θ_{23}-octant). Notice that the intrinsic and sign (and, hence, the mixed) degeneracies involve the CP phase. These degeneracies could severely limit the sensitivity to δ and to other observables of the experiment, threatening to wash-out all the advantages coming from the well known, high intensity beam source. Extensive efforts have been made to constrain the fake solutions and thereby improve the sensitivity of these expensive experiments. A variety of ways have been suggested in the literature. These include combining experiments using the golden channel but at different baselines [26, 27], combining different channels [28, 29, 30] at long baseline experiments, and combining data from other type of experiments [31, 32, 33]. It has been noted [34, 35, 36] that $P_{e\mu}$ can be made independent of δ at a baseline which corresponds to the characteristic oscillation wavelength of the neutrinos in Earth matter, the so-called "magic baseline" [34]. This baseline can be shown to be independent of all oscillation parameters, as well as the neutrino energy. Since the $P_{e\mu}$ probability at this baseline is independent of δ, and hence is not affected by the intrinsic, sign and mixed degeneracies, it provides a clean bedrock for the measurement of θ_{13} and $sgn(\Delta m_{31}^2)$. In fact, an optimizing exercise in L confirms that a magic baseline experiment is indeed the best baseline option to measure θ_{13} and $sgn(\Delta m_{31}^2)$ for both Neutrino Factory and high energy β-Beam. However, since CP violation cannot be measured at the magic baseline, we should perform the experiment at an additional baseline which has good sensitivity to δ. Optimization studies have revealed that this baseline turns out to be about 4000 km for the Neutrino Factory [37].

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[1] There also might be an indication of non-zero θ_{13} coming from the Super-Kamiokande atmospheric neutrino data, however this claim is still considered to be controversial (see [8] for a detailed discussion).
[2] The absolute neutrino mass scale and two additional phases (if neutrinos are Majorana fermions) are also unknown and required in order to complete the neutrino mass matrix. These parameters are inaccessible in neutrino oscillation experiments and must be measured elsewhere.
[3] The optimum choice of the detector depends on the beam characteristics, which we will discuss in the next section.
[4] Current experiments measure $\sin^2 2\theta_{23}$, and hence two values of θ_{23} can fit the data.

For the β-Beam, the choice of this second baseline is more involved and depends on the choice of the β-unstable ion at the source and on the boost factor γ [38].

Two sets of radioactive ions have been considered extensively in the literature as possible β-Beam sources: ^{18}Ne (for ν_e) and ^{6}He (for $\bar{\nu}_e$), which were introduced in the pioneering β-Beam beam proposal by Piero Zucchelli [18]; and ^{8}B (for ν_e) and ^{8}Li (for $\bar{\nu}_e$) [39, 40]. The main difference between the two sets lies in their Q-values, which is about 4 times larger for the latter set. Therefore, neutrino beams produced through the decay of ^{8}B and ^{8}Li have an energy about 4 times larger than those produced with the decay of ^{18}Ne and ^{6}He, when using the same boosting factor. It was shown in [41, 42] that using ^{8}Li and ^{8}B ions and performing the experiment at the magic baseline returns excellent sensitivity to θ_{13} and the mass hierarchy. A baseline optimization study [38] showed that indeed the magic baseline is the best place to measure these two oscillation parameters if one uses a β-beam fueled with ^{8}B and ^{8}Li ions. The mass hierarchy, in particular, demands a β-beam set-up with ^{8}B and ^{8}Li as the source ions and a detector located at the magic baseline. This is easily explained: for the boost factor $\gamma \sim 350$, the neutrinos produced in the β-decay of these ions are seen to have energies peaked in the range $E_\nu \in [4, 6]$ GeV, where $P_{e\mu}(E_\nu)$ picks up near-resonant matter effects and becomes very large. On the other hand, neutrinos produced in the β-decay of ^{6}He and ^{18}Ne ions with the same γ are peaked at only $E_\nu \sim 1.5$ GeV, and $P_{e\mu}$ is non-resonant. As it was the case for Neutrino Factory beams, since the magic baseline smothers the CP dependence of $P_{e\mu}$, the CP violation studies will require another baseline. It was seen [38] that $L \simeq 1000 - 2000$ km was the optimal choice for CP studies if one uses ^{8}B and ^{8}Li also for this second baseline. On the other hand, if one uses the lower Q ^{18}Ne and ^{6}He ions, the best results come at $L \simeq 600 - 700$ km. Sensitivity reach for a two-baseline β-Beam set-up with ^{8}B and ^{8}Li as source ions and 50 kton magnetized iron detector at both baselines ($L = 7000$ km and $L = 2000$ km) was studied in [43]. Another two-baseline set-up, using ^{8}B and ^{8}Li as source for a 50 kton magnetized iron detector at the magic baseline and ^{18}Ne and ^{6}He as the source for a 50 kton Totally Active Scintillator Detector (TASD) at $L = 730$ km was proposed in [44]. The sensitivity reach for both two-baseline β-Beam set-ups was seen to be remarkable, and for very high values for the number of useful radioactive ion decays and γ, even comparable to the Neutrino Factory.

However, all studies on the β-Beam set-ups with the magic baseline as the source-detector distance suffer from one major drawback. They require E_ν to be peaked around [4-7] GeV. In order to produce such high neutrino beams, even ^{8}B and ^{8}Li will have to be accelerated to $\gamma \gtrsim 350$. It is seen that the sensitivity of the experiment depends crucially on high boost factors, and falls sharply as γ drops below 350 [42]. Such high values of γ not only demand bigger accelerators, they make the bending of the source ions difficult in the storage ring. While the acceleration of the ions could be feasible with the planned replacement of the SPS at CERN with a new machine, the SPS+ [45, 46], the demand on the storage ring appears to be rather unrealistic. The original storage ring design [18], for ^{6}He and ^{18}Ne boosted at $\gamma = 100$, consisted of a racetrack ring with straight section of $L_s = 2500$ m, curved sections of radius $R = 300$ m (using 5 T magnets) and a total ring length $L_r = 6885$ m. As it has been be discussed before [43], and will be again discussed at length in this paper, $\gamma = 350$ for ^{6}He ($\gamma = 390$ for ^{8}Li) requires a racetrack storage ring with curved sections of radius $R \sim 632$ m, exploiting LHC magnets with maximum magnetic field of 8.3 T. If we keep the straight sections of the racetrack storage ring unchanged, we end up with a ring with a longitudinal section of 3764 m, to be compared with the 3100 m of the original design. The main problem in using this ring design to send a ^{8}Li beam to $L = 7000$ km is the following: the ring plane should be tilted by $34.5°$ inside the Earth for the beam to be shot at the magic baseline, and the corresponding depth of the ring at its far end is a whopping $d = 2132$ m. This is well beyond any realistic possibility.

In this paper, we modify the two-baseline β-Beam set-up in order to alleviate this problem with the storage ring. We propose a more realistic β-Beam set-up for the next to next generation of neutrino oscillation facilities, where we produce, accelerate and store ions of the four kinds (^{6}He , ^{18}Ne , ^{8}Li and ^{8}B) at CERN, each of them running for a period of 2.5 years. The experiment time-length is therefore of 10 years in total. We aim ^{6}He - and ^{18}Ne -generated low-energy neutrino beams to a megaton water Čerenkov detector located at $L = 650$ km from the source, possibly at Canfranc in Spain, and ^{8}Li - and ^{8}B -generated high-energy neutrino beams to a 50 kton iron detector at a distance close to the magic baseline, possibly at INO in India. We use two separate storage rings for this purpose. The first ring corresponds to the design sketched above, called hereafter "the long ring", with $L_s = 2500$ m straight sections and $R = 632$ curvature radius and it will be used to store ^{6}He and ^{18}Ne ions boosted at $\gamma = 350$. The same ring design, with 8.3 T magnets, can be used to store ^{8}Li (^{8}B) ions accelerated up to $\gamma = 390$ ($\gamma = 656$). For ^{8}Li ions such a small increase in the boost factor corresponds, on the other hand, to a 50% increase of the statistics that can be collected in the far detector. We can, therefore, design a dedicated ring to aim at the far detector with smaller straight sections, such that the maximal depth d of the far end of the ring can be made smaller than for the "long ring". The price to pay is that the total number of useful ^{8}B and ^{8}Li decays towards the iron detector at INO is reduced by 40%. We show that this does not drastically impair the performance of the experiment, and that actually the sensitivity to the mass hierarchy is similar to that that can be obtained with the "long ring" with ^{8}Li and ^{8}B boosted at $\gamma = 350$. This ring will be called hereafter "the short ring".

Since detailed results on the response of the iron detector for this kind of experiment are unavailable, we assume

Element	A/Z	$T_{1/2}$ (s)	E_0 eff (MeV)	Decay Fraction
^{18}Ne	1.8	1.67	3.41	92.1%
			2.37	7.7%
			1.71	0.2%
^{8}B	1.6	0.77	13.92	100%
^{6}He	3.0	0.81	3.51	100%
^{8}Li	2.7	0.83	12.96	100%

TABLE I: A/Z, half-life and end-point energies for three β^+-emitters (^{18}Ne and ^{8}B) and two β^--emitters (^{6}He and ^{8}Li). All different β-decay channels for ^{18}Ne are presented [47].

very conservative estimates for the energy threshold, energy resolution and backgrounds. We study the effect of these detector characteristics on the sensitivity reach of the experiment.

The paper is organized as follows. In section II, we discuss in more detail the experimental set-up, and in particular propose the modified "short" storage ring for ^{8}B and ^{8}Li aimed at the magic baseline. In section III we present our results and compare the sensitivity of our modified two-baseline set-up against some of the other high γ β-Beam options proposed and studied before. In section IV we study the effect of reducing the storage ring length, by comparing our results with one "long" and one "short" ring with those where two identical "long" storage rings are assumed. We also study the effect of "improved" iron detector characteristics. Finally, we present our conclusions in section V.

II. TWO-BASELINE β-BEAM EXPERIMENT

In this section we will discuss in more detail the various aspects related to the β-Beam experiment. As stated before in the Introduction, we have two widely accepted set of candidate source ions which could be effectively used to produce a high intensity beam. We give the characteristics of these ions in Table I. The other aspects which determine the (anti)neutrino beam are the number of useful ion decays N_β and the Lorentz boost γ. It is well known (see for instance [38] for a discussion) that for two different isotopes producing a ν_e beam, if one demands the same spectral shape of the neutrino flux, *i.e.* the same peak energy and normalization, then the following relations hold:

$$\frac{N_\beta^{(1)}}{N_\beta^{(2)}} \simeq \left(\frac{E_0^{(1)}}{E_0^{(2)}}\right)^2 , \quad \frac{\gamma^{(1)}}{\gamma^{(2)}} \simeq \frac{E_0^{(2)}}{E_0^{(1)}} \qquad \Rightarrow \qquad \frac{N_\beta^{(1)}}{N_\beta^{(2)}} \simeq \left(\frac{\gamma^{(2)}}{\gamma^{(1)}}\right)^2 , \tag{1}$$

where $E_0^{(i)}$ is the end-point energy of the ion-decay, and where we have neglected the effect of the electron mass. Clearly, the higher the end-point energy of the β-decay of an ion, the lower the γ needed to reach a given neutrino energy in the lab frame. Recall that the maximum energy of the neutrino in the lab frame is given by $E_\nu^{max} = 2\gamma(E_0 - m_e)$, where m_e is the electron mass. Therefore, it is easier to reach higher neutrino energies using ions with higher end-point energy. At the same time, however, to have the same number of events in the far detector for two sets of ions with different E_0 boosted at the same γ, we need larger number of useful ion decays for source ions with higher E_0. For our candidate source ions we can see that the following conditions hold

$$N_\beta^{B+Li} \simeq 12 \cdot N_\beta^{Ne+He} , \quad \gamma^{Ne+He} \simeq 3.5 \cdot \gamma^{B+Li}, \tag{2}$$

in order to obtain the same neutrino flux spectrum.

Experimental challenges on both N_β and γ are in fact intimately related to a large extent. The boost directly depends on the amount of acceleration possible. The number of useful ion decays, on the other hand, is affected due to losses during the acceleration process and hence impacts the amount of acceleration possible. Another important way N_β and γ get related is through the design of the storage ring. Higher boost factors of the source ions make them harder to bend. Thus, for the same magnetic field strength, a larger curved section of the storage ring is required to bend ions boosted at high γ than at low γ. Unless the straight sections are increased proportionally, the fraction of stored ions that decays in the straight sections of the ring (the so-called "livetime" $l = L_s/L_r$) decreases. We will discuss this in detail in section II.B.

On the other hand, one of the most challenging constraints on the achievable neutrino fluxes comes from the requirement of reducing the atmospheric neutrino background in comparison to the β-Beam signal. The reason is the following: in the original β-Beam proposal, the typical neutrino energy for neutrinos produced by the decay of

^{6}He and ^{18}Ne ions boosted at $\gamma = 100$ is $E_\nu \sim 200$ MeV. The number of muons produced by atmospheric neutrinos crossing the detector aligned with the β-Beam flux in this range of energies was found to be of the order of tens of events per kton per year. This background would completely dominate over the oscillation signal. Reduction of the atmospheric neutrino background demands stringent bunching of the source ions in the decay ring so as to pulse the signal in the detector to the required level. In order to have a good time correlation of the signal with the neutrino flux produced at the source, the ions circulating in the storage ring must occupy a small fraction of the latter. The fraction of the ring filled by ions at a given time, also called "suppression factor" S_f, is:

$$S_f = \frac{v \times \Delta t_b \times N_b}{L_r} \tag{3}$$

where $v \sim c$ is the ion velocity, Δt_b is the time length of the ion bunch (the product $v \times \Delta t_b$ is the spatial length of a bunch in the lab frame), N_b is the number of circulating bunches and L_r is the total length of the ring. For ^{6}He/^{18}Ne ions boosted at $\gamma = 100$, the suppression factor must be $S_f \sim 10^{-3}$. Such a tight S_f can be achieved with a challenging $\Delta t_b = 10$ ns time-length, with a maximum of $N_b = 8$ bunches circulating at the same time. Since both the time-length of the bunch and the number of bunches that can be injected into the ring at the same time depends on the details of the acceleration chain and cannot be modified easily, a large value of L_r permits to keep S_f at the desired level at the cost of a bigger ring. This means that, in turn, only a small 10^{-3} fraction of the storage ring is occupied by the ion beam. Notice that the atmospheric neutrino flux decreases rapidly with energy. In fact, the atmospheric neutrino events are known to fall faster than E_ν^{-2}, where E_ν is the neutrino energy. Therefore, for $\gamma = 350$ with the same ions, neutrino energies achievable are a factor of 3.5 higher and the atmospheric neutrino background reduces by a factor of more than ten. Hence the suppression factor needed to smother the atmospheric neutrino background can be relaxed by about an order of magnitude to 10^{-2}. This allows a larger fraction of the storage ring to be used by the neutrino beam, and N_β could be increased consequently. In the case of neutrinos from high γ ^{8}Li and ^{8}B decays, their even higher energies would allow to increase the pulse size and hence relax the suppression factor even further. In fact, since their end-point energies are about a factor 3.5 larger, one can naively expect that the number of stored ions $N_\beta^{(^8Li)}$ and $N_\beta^{(^8B)}$ can be increased by another order of magnitude compared to ^{18}Ne and ^{6}He source beams with the same γ. For the very high γ ^{8}B and ^{8}Li beams, the atmospheric backgrounds are not an important constraint on N_β at all, so that the only limitation on the ring design is the livetime l, $i.e.$ the ring geometry.

The original β-Beam proposals assumed useful fluxes of 1.1×10^{18} and 2.9×10^{18} decays per year for ^{18}Ne and ^{6}He respectively when accelerated to $\gamma = 100$. These fluxes have been considered as "standard" and are commonly assumed in the literature. Similar "standard" numbers regarding ^{8}B and ^{8}Li are lacking. However, preliminary studies on the production rates of ^{8}B and ^{8}Li show that they are both produced more easily than ^{18}Ne and ^{6}He respectively. This is particularly true for neutrinos produced from the decay of ^{8}B since the production of ^{18}Ne is very challenging. Lacking any definite prediction for the achievable fluxes at the higher γ considered here, we will assume that 10^{19} ions per year can be stored into the ring [48], for all ion species[5].

A. The choice of the two baselines

The approximated expanded form of the expression for the golden channel probability keeping only up to the second order terms in the small parameters θ_{13} and Δm_{21}^2 [21], can be written as in Ref. [49],

$$
\begin{aligned}
P_{e\mu} \simeq\ & \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& \pm\ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\delta_{\rm CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& +\ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\delta_{\rm CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& +\ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},
\end{aligned}
\tag{4}
$$

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[5] For ^{6}He and ^{18}Ne boosted at $\gamma = 100$ with the original ring design proposed in Ref. [18], with a livetime $l = 0.36$, this corresponds to 3.6×10^{18} useful ion decays per year.

where

$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E_\nu}, \quad \hat{A} \equiv \frac{A}{\Delta m_{31}^2}, \tag{5}$$

and $A = \pm 2\sqrt{2} G_F N_e E_\nu$ [50, 51, 52] is the matter potential (plus/minus sign is for neutrino/antineutrino), given in terms of the electron density N_e and (anti)neutrino energy E_ν. It is easy to see from Eq. (4) that a way to get rid of all δ dependent terms is by considering a baseline where

$$\frac{\sin(\hat{A}\Delta)}{\hat{A}} = 0, \tag{6}$$

which is called the condition of the magic baseline. From the PREM density profile of the Earth [53], this baseline comes out to be about $L \simeq 7000$ km. As discussed before, we will use this as one of our baseline options. The position of the magic baseline depends mainly on the density profile of the Earth and not on the oscillation parameters or the energy of the beam[6]. However, the size of the oscillation probability does depend critically on the neutrino energy at the magic baseline. Indeed, the density encountered by the (anti)neutrinos at this baseline allows for the denominators $1 - \hat{A}$ in Eq. (4) to cancel when $E_\nu \sim 6$ GeV if the mass hierarchy is normal (inverted). Even if the conditions under which Eq. (4) was expanded are, therefore, not satisfied in this case, the exact oscillation probability reveals a resonant enhancement when this condition is met [41]. The advantage of tuning the beam energy to the resonant one is two-fold: first, the increase in the oscillation probability compensates the loss of events due to the very long baseline, increasing the statistics at the far detector and improving its sensitivity to smaller values of $\sin^2 2\theta_{13}$; second, the resonance only occurs for (anti)neutrinos if the mass hierarchy is normal (inverted), therefore providing an extremely good probe of the mass ordering.

For the second baseline the most important criterion is the measurement of CP violation. For that we want the second term to dominate in the probability. Moreover, matter effects can fake true CP violation stemming from the phase δ and, therefore, short baselines and low energies are better for those studies. In this small matter effect regime, when $\hat{A} \to 0$ in Eq. (4), maximizing the CP violating terms amounts to require that $\sin \Delta = 1$. For $\Delta m_{31}^2 = 2.4 \times 10^{-3}$ eV^2 this translates into $L/E = 515$ km/GeV. The mean neutrino energy of neutrinos from ^{6}He and ^{18}Ne decays at $\gamma = 350$ is $E_0 \gamma \sim 1.2$ GeV which translates to an on-peak baseline of $L = 618$ km matching perfectly the 650 km baseline between CERN and the Canfranc laboratory.

In the following, we will thus consider detectors located at $L = 650$ km and $L = 7000$ km down the source.

B. The Storage Ring

Two geometries for the β-Beam storage ring have been considered in the literature so far: the racetrack geometry, first proposed for this facility in Ref. [18], and the triangle geometry, [43]. Both geometries have been considered also in the framework of the Neutrino Factory studies, see Ref. [54].

The main advantage of the triangle geometry with respect to the racetrack one is the possibility of using, simultaneously, two of the three straight sections to aim to two different far detectors. For this reason, a larger number of useful ion decays is achieved in triangle-shaped rings than racetrack-shaped ones. Imagine now that one of the long straight sections of a triangle ring aims at a detector located at $L = 7000$ km and that a second one aims at a detector located at $L = 650$ km. If we inject ^{6}He and ^{18}Ne ions in the storage ring and let them decay, neutrinos produced in the straight section aiming at the "near" detector give a very good sensitivity to θ_{13} and to the CP violating phase δ. On the other hand, neutrinos produced in the straight section aiming at the "far" detector will contribute scarcely to the measurement of the sign of the atmospheric mass difference, since their energy is too small to have a resonant behavior in matter and compensate the very long baseline (see Sect. II A). A similar situation can be observed when ^{8}Li and ^{8}B ions are injected in the ring: those ions that decay aiming at the "far" detector produce a neutrino flux that provides a very good sensitivity to the mass hierarchy, whereas those that decay in the straight section that points to the "near" detector contribute very little to the measurement of θ_{13} and δ, since the neutrino flux is strongly off the oscillation peak, their energy being too high for the oscillations to develop at the 650 km baseline. For this reason, it is easy to understand that no particular advantage arises in using a triangle geometry storage ring in the set-up that we are considering. We will thus consider here two racetrack geometry storage rings, each of them with

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[6] A mild dependence on the oscillation parameters and energy creeps in for large values of θ_{13} [35, 42]. However, the effects are still mild.

one of the straight sections aiming at one of the two detectors. Notice that this set-up is similar to the one considered in the Neutrino Factory IDS baseline proposal [54].

Let us now recall the main characteristics of the storage ring proposed for a β-Beam in the original design by Piero Zucchelli back in 2002, [18]. The ring was conceived to store ^{6}He and ^{18}Ne ions boosted at $\gamma = 100$ (the maximum boost achievable using the PS and the SPS at CERN being $\gamma = 150$ for ^{6}He and $\gamma = 250$ for ^{18}Ne, respectively). The proposed ring has a racetrack geometry with two long straight sections of $L_s = 2500$ m each and two arcs with curvature radius of $R = 300$ m if a 5 T magnetic field is used to bend the ions in the curved section of the ring. The total length[7] of the ring is $L_r = 2L_s + 2\pi R = 6885$ m, and the livetime is $l = L_s/L_r = 0.36$. The ring, with a longitudinal section of 3100 m, is tilted at a very small angle ($\vartheta = 0.6°$) with respect to the ground, so as to aim at a detector located in the Fréjus tunnel, at a distance of 130 km from the source. The maximum depth d of the far end of the ring with such a small tilt angle is just $d = 32$ m.

The original design of the ring must be modified when the boost factor γ is increased. If the magnets used are LHC dipolar magnets with a maximum magnetic field of 8.3 T, the curvature radius R needed to bend ^{6}He ions boosted at $\gamma = 350$ is $R \sim 633$ m. If the straight sections are kept untouched, the total length of the decay ring becomes $L_r = 8974$ m [48], whereas the livetime decreases to $l = 0.28$. Since the neutrino flux is aimed at a detector located at 650 km from the source, the tilt angle in this case is $\vartheta = 3°$. With a longitudinal section of the ring of 3764 m, this means that the maximum depth of the far end of the ring is $d = 197$ m. Notice that in the same ring we can store ^{8}Li ions boosted up to $\gamma = 390$ and ^{18}Ne and ^{8}B ions with $\gamma = 583$ and 656, respectively.

It is useful at this point to compare the decay ring design proposed for a β-Beam facility, depicted above, with the ring design considered in the framework of Neutrino Factory studies, [54]. The racetrack storage ring design for the Neutrino Factory consists of two straight sections of $L_s = 600$ m each, with two arcs with curvature radius $R = 60$ m. The total length of the ring is $L_r \sim 1580$ m, with a livetime $l = 0.37$. The curved sections of the ring are equipped with superconducting dipole and quadrupole magnets. In the *International Scoping Study of a future Neutrino Factory and Super-Beam facility* [55], two distances have emerged as optimal locations for far detectors: $L \sim 3500$ km and the magic baseline, $L \sim 7500$ km. The tilt angle to aim at these two baselines are $\vartheta = 16°$ and $\vartheta = 36°$, respectively. Since the longitudinal section of the storage ring is 720 m, the maximum depth at the far end of the ring is $d = 198$ m for the $L = 3500$ km baseline and $d = 423$ m for the $L = 7500$ km one. Notice that the Neutrino Factory racetrack geometry ring is much more compact than the analogous device proposed for the β-Beam. The different size is motivated by two important differences between the β-Beam and the Neutrino Factory: first, shorter arcs are needed to bend muons with respect to ions, for similar magnetic fields; second, the occupancy of a β-Beam ring must be very small to reduce the atmospheric background as stressed at the beginning of this section (*i.e.*, either we inject very few ions into the ring, or the size of the ring must be very large) . The atmospheric background, however, is not a significant problem at the Neutrino Factory[8], the neutrino energy being of the order of several GeVs (in this range of energy the atmospheric background is at least two orders of magnitude smaller than in the case of $O(100)$ MeV neutrinos).

From the comparison with the Neutrino Factory ISS/IDS study, it emerges that the original design by Piero Zucchelli for a racetrack ring aiming at $L = 650$ km (modified to take into account the higher ions boost factor) is not unrealistic: albeit longer than the ring conceived for the Neutrino Factory, the decay tunnel for this ring reaches the same depth d as the Neutrino Factory ring aiming at $L = 3500$ km. However, if a ring of the same type is used to aim at a detector located at $L = 7000$ km from the source, the tilt angle to be considered is $\vartheta = 34.5°$. In this case, the maximum depth of the far end of the ring is $d = 2132$ m, something well beyond any realistic possibility. As it was stressed in the beginning of this section, however, two storage rings will be used to aim to the detectors located at $L = 650$ km and $L = 7000$ km. Therefore, it is possible to design two rings of different characteristics, each of them optimized for a different detector. In particular, the ring aiming at the magic baseline could be more compact than the other one. One possibility is to use the slightly more favorable Z/A ratio of ^{8}Li with respect to ^{6}He to build a ring with curvature radius $R \sim 562$ m, $L_r = 8531$ m and maximal depth $d = 2053$ m. It is clear that the gain achievable with this option is not significant, although the livetime increase to $l = 0.29$. A second, more interesting, possibility is to reduce the straight sections of the ring to reduce its longitudinal size, and correspondingly d, at the price of a reduced livetime. A relevant question is, then, how much can we reduce the livetime of the ring so as to increase its technical feasibility, but with only a small loss in the sensitivity to the mass hierarchy? Even more important, which loss of sensitivity to the mass hierarchy is acceptable without a significant loss of sensitivity to the CP violating phase δ?

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[7] The length of the ring was chosen so as to match exactly the length of the SPS, under the assumption that this size was a realistic one. Notice that the ring design has not been optimized since its first proposal.

[8] Notice that the so-called "*low-energy Neutrino Factory*", proposed in Ref. [56, 57], could be affected by the same problem as the β-Beam. In this case, the storage ring design for this facility should be modified accordingly.

An answer to these questions is offered by Table II. We can see that increasing the boosting factor of ^{8}Li and ^{8}B ions to the maximum γ for which these ions can still be stored into a ring with $R \sim 633$ m, a significant increase of the number of events in the far detector can be achieved. Such increase depends on the hierarchy and on the fulfillment of the resonant condition of the oscillation probability in matter: for example, a 10% increase of the boost of ^{8}Li ions from $\gamma = 350$ to $\gamma = 390$ implies a 50% (25%) increase in the number of events observed at the detector for inverted (normal) hierarchy. Similar results are obtained for ^{8}B ions.

	$\gamma^{^8Li}$	350	360	370	380	390
+	$N_{ev}(\gamma)$	1.84	1.94	2.05	2.18	2.33
	$N_{ev}(\gamma)/N_{ev}(350)$		1.05	1.11	1.18	1.27
-	$N_{ev}(\gamma)$	55.80	62.46	69.40	76.54	83.86
	$N_{ev}(\gamma)/N_{ev}(350)$		1.12	1.24	1.37	1.50
	$\gamma^{^8B}$	583	600	617	633	650
+	$N_{ev}(\gamma)$	477.16	499.72	521.64	541.68	562.34
	$N_{ev}(\gamma)/N_{ev}(583)$		1.05	1.09	1.14	1.18
-	$N_{ev}(\gamma)$	15.20	16.58	17.99	19.34	20.79
	$N_{ev}(\gamma)/N_{ev}(583)$		1.09	1.18	1.27	1.37

TABLE II: Number of muons observed at a 50 kton magnetized iron detector [58] with perfect efficiency located at 7000 km from the source after 5 years of data taking as a function of the boost factor of ^{8}Li (upper table) and ^{8}B ions (lower table), for $\theta_{13} = 5°$ and $\delta = 90°$. A livetime $l = 0.3$ was also assumed for the storage ring. The ratio of the number of events obtained with a given γ with respect to those obtained storing ^{8}Li (^{8}B) ions boosted at $\gamma = 350$ (583) is also shown.

The increase in the statistics can be used for two different purposes: the first possibility, of course, is to use it to achieve a higher sensitivity to the mass hierarchy. However, the sensitivity increase is not dramatic (as it should be expected, since for Gaussian statistics the sensitivity scales with the square root of the statistics). The second possibility, that could open the path to a feasible β-Beam facility with long baseline, is to use the higher statistics to reduce significantly the size of the storage ring: the physics reach of a set-up with a racetrack ring with $L_r = 8531$ m and $l = 0.29$ (described above) with ^{8}Li ions boosted at $\gamma = 350$ is identical to the reach of a racetrack ring with a much shorter straight section, $L_s = 998$ m, if the ^{8}Li ions are boosted at $\gamma = 390$. This ring has a total length $L_r = 5970$ m, a longitudinal section of 2263 m and a livetime $l = 0.6 \times 0.28 \sim 0.17$. The maximum depth of the far end of this ring is $d = 1282$ m. Such a depth is still much larger than what is needed for the Neutrino Factory rings (we remind that $d = 423$ m is the maximum depth of the far end of the ring aiming at $L = 7500$ km), but is almost 1 km shorter than for the standard design of the ring. Note that for the higher energy ^{8}Li/^{8}B beams, the problem of atmospheric neutrino background is almost non-existent, as discussed before. Therefore, the reduction of the total ring size does not pose any serious threat to the experiment.

We therefore propose a β-Beam set-up with two storage rings of different design:

- One ring for the ^{6}He/^{18}Ne ions with $l = 0.28$, sending the beam to $L = 650$ km (to Canfranc, Spain). Both ^{6}He and ^{18}Ne ions are boosted at $\gamma = 350$ (no significant gain is achieved by boosting ^{18}Ne ions to higher γ's);

- A second ring for the ^{8}Li/^{8}B ions with $l = 0.17$, sending the beam to $L = 7000$ km (to INO, India). In this case, ^{8}Li ions are boosted at $\gamma = 390$ and ^{8}B ions at $\gamma = 656$ (i.e., the maximum γ that permits to store the ions in a ring with 8.3 T magnets).

Both rings have curvature radius $R = 633$ m, with straight sections of length $L_s = 2500$ m and 998 m, respectively. The maximal depth at the far end of each ring is $d = 197$ m for the 650 km baseline and $d = 1282$ m for the magic baseline.

A more compact ring (with a higher l) could be obtained by increasing the magnetic field in the curved section, taking advantage of the R&D programme for LHC upgrades aimed to the development of high field magnets (with $B \in [11 - 15]$ T). If one assumes that magnetic field strengths of 15 T could be used for the storage ring [48], then

Detector Characteristics	MIND [58, 69] (Only $\mu^{\pm}$)	TASD [15] (Both $\mu^{\pm}$ & $e^{\pm}$)	WC [60]
Fiducial Mass	50 kton	50 kton	500 kton
E_{min}	1 GeV	0.5 GeV	0.5 GeV
E_{max}	18 GeV	2.5 GeV	2.5 GeV
Bin Size	$\in [0.6, 2.3]$ GeV	0.2 GeV	0.25, 0.5 GeV
Background Rejection	0.0001	0.001	$\in [0.0001, 0.001]$
Signal error (syst.)	2.5%	2.5%	2.5%
Background error (syst.)	5%	5%	5%
Detection Efficiency (ϵ)	$\in [5, 70]\,\%$	80% ($\mu^{\pm}$) & 20% ($e^{\pm}$)	$\in [20, 50]\,\%$
Energy Resolution (σ)	0.15 E(GeV)	$0.03\sqrt{\mathrm{E(GeV)}}$ for $\mu^{\pm}$ $0.06\sqrt{\mathrm{E(GeV)}}$ for $e^{\pm}$	$\lesssim 0.15\mathrm{E(GeV)}$
Charge Id Efficiency (f_{ID})	Yes	No	No

TABLE III: Comparison of the typical detector characteristics expected for the three most popular β-Beam detectors.

^{6}He ions boosted at $\gamma = 350$ could be stored in a ring with curvature radius $R = 350$ m. If the straight sections of the ring are kept fixed to $L_s = 2500$ m, the total length of the ring is $L_r = 7200$ m with a livetime $l = 0.35$. The longitudinal section of this ring would be 3200 m, with a maximal depth d at the far end of the ring when tilted at $\varphi = 34.5°$ of 1812 m. If we now fill a ring equipped with the same magnets with ^{8}Li and ^{8}B ions boosted at $\gamma = 390/656$, we can still achieve a good sensitivity to the mass hierarchy reducing the livetime to $l = 0.17$ (as discussed above), corresponding to straight sections of length $L_s = 556$ m. Such a ring has a total length $L_r = 3311$ m, a longitudinal section of 1256 m and a maximal depth at the far end of the ring aiming at the magic baseline detector $d = 711$ m. This depth is not much larger than the depth required for the Neutrino Factory magic baseline ring, and hence it could represent an extremely interesting option to be investigated further.

C. The Detectors

Unlike the Neutrino Factory, or the Super-Beams, the β-Beam is a truly mono-flavor neutrino beam. Therefore, while for the detector of the Neutrino Factory beam charge identification capability is mandatory in order to tag the initial neutrino flavor, this needs not be the case for β-Beams. The only criterion is that the detector should have a good particle identification sensitivity, and in particular should be able to distinguish a muon from an electron. Most known detector technologies have been considered in the literature for this class of experiment. Each of these detectors offer the best performance for only a certain energy range of the neutrinos. A detailed report card on the detector performance in terms of energy threshold, energy resolution, backgrounds, statistics and costs is required for deciding the best detector option. The detector choice is also directly dictated by the energy of the β-Beam.

For the ^{18}Ne and ^{6}He β-Beam, it was argued in Ref. [59] that the water Čerenkov detector would be best for $\gamma \lesssim 300$, while for larger boost factors one should use the TASD detector. In fact, most studies have used megaton scale water Čerenkov detectors as detector option for a $L \leq 1000$ km [45, 60, 61, 62, 63, 64, 65]. In Refs. [66, 67] the idea of observing high γ β-Beam neutrinos with magnetized iron detectors was introduced for the first time. This prospect was further perused in Refs. [41, 42, 68] and later in Refs.[38, 43, 44]. We show in Table III the comparative catalogue of detector characteristics. The first relevant difference between the different technologies is the energy threshold: both the TASD [15] and water Čerenkov detectors [60] have a very low energy threshold and are, hence, ideal for neutrino beams of relatively low energy (up to a few GeV). Magnetized iron detectors of the MIND type [69] (see also [58]), on the other hand, are a good option only for higher energy beams. The energy resolution of TASD is impressive up to a few GeV, whereas that of water Čerenkov detector is good, but only for the energy regime which has a predominance of quasi-elastic events ($E \lesssim 1$ GeV). Eventually, iron detectors energy resolution is limited by the present segmentation design. The background rejection fraction, on the other hand, is seen to be best for the magnetized iron detector. It is in fact expected to be better for magnetized iron by at least an order of magnitude compared to water Čerenkov and TASD. Scaling of the detector mass is difficult for TASD and magnetized iron detectors beyond 50 kton, whereas megaton scale water Čerenkov detectors are currently under study [14, 70]. Notice, however, that a 50 kton magnetized iron detector represents, at present, the cheapest option between the

three detectors technologies and design considered in Table III.

Based on the comparative performance of the detectors and our physics goals we make the following choices: (1) Since the shorter baseline is the optimal one to perform CP violation studies, and since CP measurements are better at lower energies with ^{18}Ne and ^{6}He as source ions than at higher energy with ^{8}Li and ^{8}B [43, 44], it is preferable to have a detector with lower threshold and good energy resolution. Therefore, the choice would be between TASD and water Čerenkov detectors. Since the latter can be made larger than TASD, we opt for a water Čerenkov detector with 500 kton fiducial mass at the shorter baseline (as in Refs. [45, 60]). This detector could be housed at Canfranc, for example, at a distance of 650 km from the β-Beam at CERN; (2) Mass hierarchy measurement is the main motivation for the experiment at the magic baseline, for which higher energy neutrinos from highly boosted ^{8}B and ^{8}Li ions will be used. We prefer thus to use a magnetized iron detector at this baseline. This far detector could be the ICAL@INO detector in India [58] which is at a distance of 7152 km, tantalizing close to the magic baseline, and which will soon go under construction. We will assume 50 kton of detector mass for this case, though it is possible that INO will be upgraded to 100 kton. Notice that the numerical analysis has been performed for a baseline $L = 7000$ km.

In order to simulate the response of the water Čerenkov and magnetized iron detectors when exposed to the β-Beam fluxes, we follow the analyses performed in Refs. [45] and [69]. The efficiencies and beam-induced backgrounds expected in a water Čerenkov detector for the $\gamma = 350$ β-Beam fluxes from ^{18}Ne and ^{6}He decays are given in [45] as migration matrices that we use to simulate our "near" detector. Unfortunately, a similarly detailed analysis of the performance of the iron detector exposed to the β-Beam fluxes is lacking. We therefore follow the efficiencies and backgrounds derived in [69] for the Neutrino Factory fluxes instead (see, also, Ref. [71]). Notice that this is a very conservative assumption since charge ID is not mandatory in a β-Beam, unlike for the Neutrino Factory, given the purity of the beam. Moreover, the Neutrino Factory spectrum is much wider than the β-Beam one and reaches much higher energies. Higher energy events, in turn, can induce neutral current interactions that feed down background to lower energies. The largest uncertainties in the performance of the iron detector are on the efficiencies and backgrounds for the events of lowest energy, around $1 - 5$ GeV. However, the main role of the iron detector considered in this set-up is to observe the resonant enhancement of the oscillation probability that happens around $6 - 7$ GeV to measure the mass hierarchy. Therefore, the performance of the proposed set-up does not depend critically on the efficiency and background of the lowest energy events, unlike in the Neutrino Factory IDS baseline design where these events are crucial to solve degeneracies and improve the sensitivity to CP violation for large θ_{13}. We will illustrate the mild dependence of the performance of the set-up on the energy threshold of the detector in the next section.

III.   COMPARATIVE SENSITIVITY REACH

In this section we probe the sensitivity reach of the β-Beam set-up that we have defined in the previous section. We are interested in looking at the performance of a given experiment to discover θ_{13}, CP violation, and the mass hierarchy. We therefore quantify the sensitivity reach of the experiments in terms of three different performance indicators.

1. The $\sin^2 2\theta_{13}$ discovery reach: This is the minimum true value of $\sin^2 2\theta_{13}$ for which the experiment can rule out at 3σ 1 d.o.f. the value $\sin^2 2\theta_{13} = 0$ in the fit, after marginalizing over all the other parameters. This gives the limiting true value of $\sin^2 2\theta_{13}$ for which the data can statistically distinguish a positive θ_{13}-driven oscillation from the $\theta_{13} = 0$ prediction.

2. The CP violation reach: This is the range of δ as a function of $\sin^2 2\theta_{13}$ which can rule out no CP violation ($\delta = 0$ and $180°$) at 3σ 1 d.o.f., after marginalizing over all the other parameters.

3. The $sgn(\Delta m_{31}^2)$ reach in $\sin^2 2\theta_{13}$: This is defined as the limiting value of $\sin^2 2\theta_{13}$ for which the wrong hierarchy can be eliminated at 3σ. Below this value of $\sin^2 2\theta_{13}$, the predictions for the wrong hierarchy cannot be separated from the data corresponding to the right hierarchy, at a statistical significance of 3σ. We will show these results for both normal and inverted hierarchies.

In Fig. 1 the black lines show the sensitivity reach of our proposed set-up in terms of the three performance indicators defined above. We also compare its performance with three other high γ β-Beam set-ups, the sensitivity reaches for which are also shown. To make a fair comparison, we (re)calculate the sensitivities for each of the benchmark set-ups assuming the same total number of radioactive ions injected in the storage ring(s) and the same total number of years of running of the experiment. We assume that, at a given time, only one source ion is accelerated and fed into a storage ring. Expected performance of each of these benchmark set-ups is shown by a particular line type, and they are defined as follows:

1. Solid, black lines: This corresponds to the two-baseline β-Beam set-up proposed in this paper. Neutrino beams produced by ^{18}Ne and ^{6}He decays, each accelerated to $\gamma = 350$ and detected in a 500 kton water Čerenkov detector located at 650 km. A second set of beams from ^{8}B and ^{8}Li decays with $\gamma = 656$ and $\gamma = 390$, respectively, are detected at 7000 km by a 50 kton magnetized iron detector. The straight sections of storage ring of the ^{8}B and ^{8}Li source ions are 60% *shorter* than in the original ring design, and the total ^{8}B and ^{8}Li fluxes at the far detector is 40% smaller.

2. Blue, dotted lines: The two-baseline β-Beam set-up proposed in [43]. Here neutrino beams from decay of ^{8}B and ^{8}Li with boost factor $\gamma = 350$, are detected in two 50 kton magnetized iron detector located at 2000 km and 7000 km respectively.

3. Orange, dashed lines: The two-baseline β-Beam set-up proposed in [44]. Here all four ions are used. Beams from decays of ^{18}Ne and ^{6}He accelerated to $\gamma = 575$ are detected in a 50 kton TASD detector at 730 km. Beams from decays of ^{8}B and ^{8}Li accelerated to $\gamma = 656$ are detected in a 50 kton magnetized iron detector at 7000 km.

4. Purple, dot-dashed lines: The one-baseline β-Beam set-up proposed in [45, 60]. Neutrino beams produced by ^{18}Ne and ^{6}He decays, each accelerated to $\gamma = 350$ are detected in a 500 kton water Čerenkov detector located at 650 km.

For all the four set-ups we assume that there are 10^{19} *total decays per year*, irrespective of the choice of the ion [48]. Of these, only ions which decay along the straight section of the storage ring aimed at one of the two detectors are useful. For the "standard" storage ring considered in set-ups 2, 3 and 4, the livetime is $l = 0.28$. We have, thus, used 3×10^{18} *useful decays per year* for each ion species to reproduce the reach to the three observables for these earlier proposals. However, for the proposal made in this paper, the storage ring for the ^{8}B and ^{8}Li ions have straight sections which are shorter by 60%, giving a livetime that is 40% smaller than for the standard storage ring. Accordingly, for the ^{8}B and ^{8}Li generated fluxes, we have only $0.6 \times 3 \times 10^{18}$ *useful decays per year*. We conservatively assume that only one type ion can be accelerated at a time and consider a total runtime of 10 years for all the set-ups we compare. We thus consider 5 years run per source ion for the experiments with two ions[9], and 2.5 years run per ion for those with four ions. We have considered 2.5% and 5% systematic errors on the signal and on the beam-induced background, respectively. They have been included as "pulls" in the statistical χ^2 analysis. The following 1σ errors for the oscillation parameters were also considered: $\delta\theta_{12} = 1\%$, $\delta\theta_{23} = 5\%$, $\delta\Delta m_{21}^2 = 1\%$ and $\Delta m_{31}^2 = 2\%$. Eventually, an error $\delta A = 5\%$ has been considered for the Earth density given by the PREM model [53]. Marginalization over these parameters has been performed for all observables. The Globes 3.0 [72, 73] software was used to perform the numerical analysis.

The upper left hand panel of Fig. 1 shows the $\sin^2 2\theta_{13}$ discovery reach. As it can be seen, the four set-ups perform in a very similar way. While for particular values of $\delta \simeq \pm 90°$, the best reach comes from set-up 4, with ^{6}He/^{18}Ne ions and water Čerenkov detector (purple dot-dashed line), $\sin^2 2\theta_{13} \leq 7 \times 10^{-5}$, its δ-marginalized sensitivity is seen to be the poorest. This happens due to the very strong δ-dependence of the probability at $L = 650$ km. On the other hand, the two baseline set-ups 2 (blue dotted line) and 3 (orange dashed line) which involve the magic baseline as well, show very little δ-dependence. The set-up proposed in this paper (black solid line), apparently shows some δ-dependence despite having one of the detectors at the magic baseline because the near detector in this case is 10 times larger than the near detectors for set-ups 2 and 3. Therefore, while the δ-marginalized $\sin^2 2\theta_{13}$ discovery reach of our proposed set-up is similar to that for both the earlier two baseline set-ups, we see more δ-dependence here due to the 10 times larger detector at the shorter baseline. Note that while the flux is comparatively lower at the magic baseline, the probability is higher. The latter therefore compensates the effect of the former and we expect the same statistics per kton of the detector at both baselines. However, the detector size for water Čerenkov has been taken as 10 times larger compared to magnetized iron or TASD. Therefore, the statistics at the water Čerenkov detector at $L = 650$ km is 10 times larger compared to the statistics at the magnetized iron detector at $L = 7000$ km. For this reason, the results of set-up 1 follows closely those of set-up 4: the ultimate $\sin^2 2\theta_{13}$ reach for our setup $\sin^2 2\theta_{13} \leq 2 \times 10^{-4}$, is also obtained for $\delta \simeq \pm 90°$.

The upper right hand panel shows the CP violation discovery potential. This is best at the shorter baselines. Thus, the facilities with larger number of events at short baseline outperform the others in their CP violation reach. This

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[9] For set-up 2 where we have two ions but two baselines, we are therefore assuming that both detectors are irradiated simultaneously with neutrino beams from each ion for 5 years each. This can be done, as suggested in Ref. [43], using a triangular geometry storage ring, with a total livetime $l = 0.46$, *i.e.* with a flux aimed at each detector of 0.23×10^{19} useful decays per year.
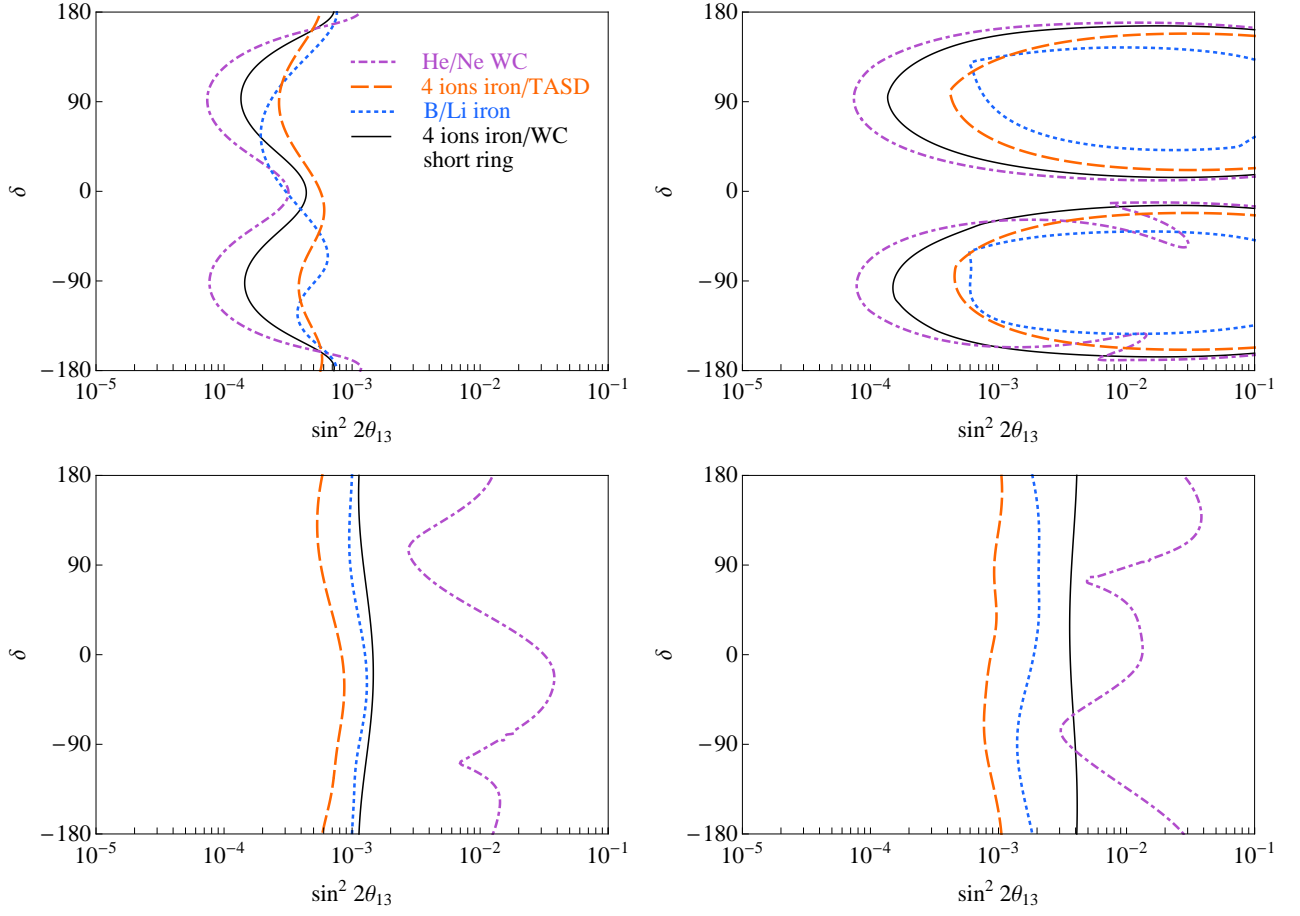
FIG. 1: Sensitivity reach of the different β-Beam set-ups in terms of the three performance indicators defined in the text. The upper left hand panel shows $\sin^2 2\theta_{13}$ discovery reach, the upper right hand panels shows the CP violation reach, while the lower panels show the mass hierarchy discovery reach. The lower left hand panel is for normal hierarchy as true while the lower right hand panel shows the corresponding reach when inverted hierarchy is true. The different line types are for different β-Beam set-ups as described in the text. Note that the black lines are for the set-up proposed in this paper and has the ^{8}B and ^{8}Li storage ring which has straight sections shorter by 60% compared to all other set-ups (*i.e.*, a 40% smaller flux at the far detector).

means that set-up 4, from [45, 60] has sensitivity to CP violation for the smallest values of $\sin^2 2\theta_{13}$, since the short baseline water Čerenkov detector is exposed to the beam for ten years (*i.e.*, all the considered runtime). Unsolved sign degeneracies due to the lack of events at longer baselines, however, spoil the sensitivity for negative values of δ around $\sin^2 2\theta_{13} \sim 10^{-2}$ (the so-called "π-transit" [74]). This problem is solved when a magic baseline detector is added to the on-peak one. For this reason, no loss in the discovery potential is found for set-ups 1, 2 and 3 for particular values of θ_{13}. Notice that the set-up that we propose in this paper has the next-to best performance (the near detector is exposed to the beam for five years instead of ten) and no π-transit problem. Finally ,the worst performance for CP violation is that of the set-ups 2 and 3, in which the near detector has a fiducial mass of 50 kton, only.

The lower panels show the sensitivity to the mass hierarchy. This is best at the far detectors and thus, the facilities with larger number of events at the magic baseline perform best. That explains the much smaller sensitivity of set-up 4 from [45, 60] with no events at the longer baseline. The best sensitivities are in this case achieved for set-up 3 from [44] due to the higher statistics granted by the larger gamma factor assumed of $\gamma = 656$ for both ^{8}B and ^{8}Li . This plots shows the advantage of accelerating the ions to higher energies. Since for the set-up we propose here we restrict to the maximum γ attainable at the SPS+, which for ^{8}Li is $\gamma = 390$, the difference between the two set-ups is larger for the inverted hierarchy (lower right hand panel), where the sensitivity stems mainly from the antineutrinos from ^{8}Li decays. The ultimate sensitivity to the mass hierarchy for our set-up is $\sin^2 2\theta_{13} \leq 1 \times 10^{-3} (4 \times 10^{-3})$ for normal (inverted) hierarchy, independently from δ. This must be compared with $\sin^2 2\theta_{13} \leq 6 \times 10^{-4} (1 \times 10^{-3})$ for normal (inverted) hierarchy, achievable with set-up 3 [44].
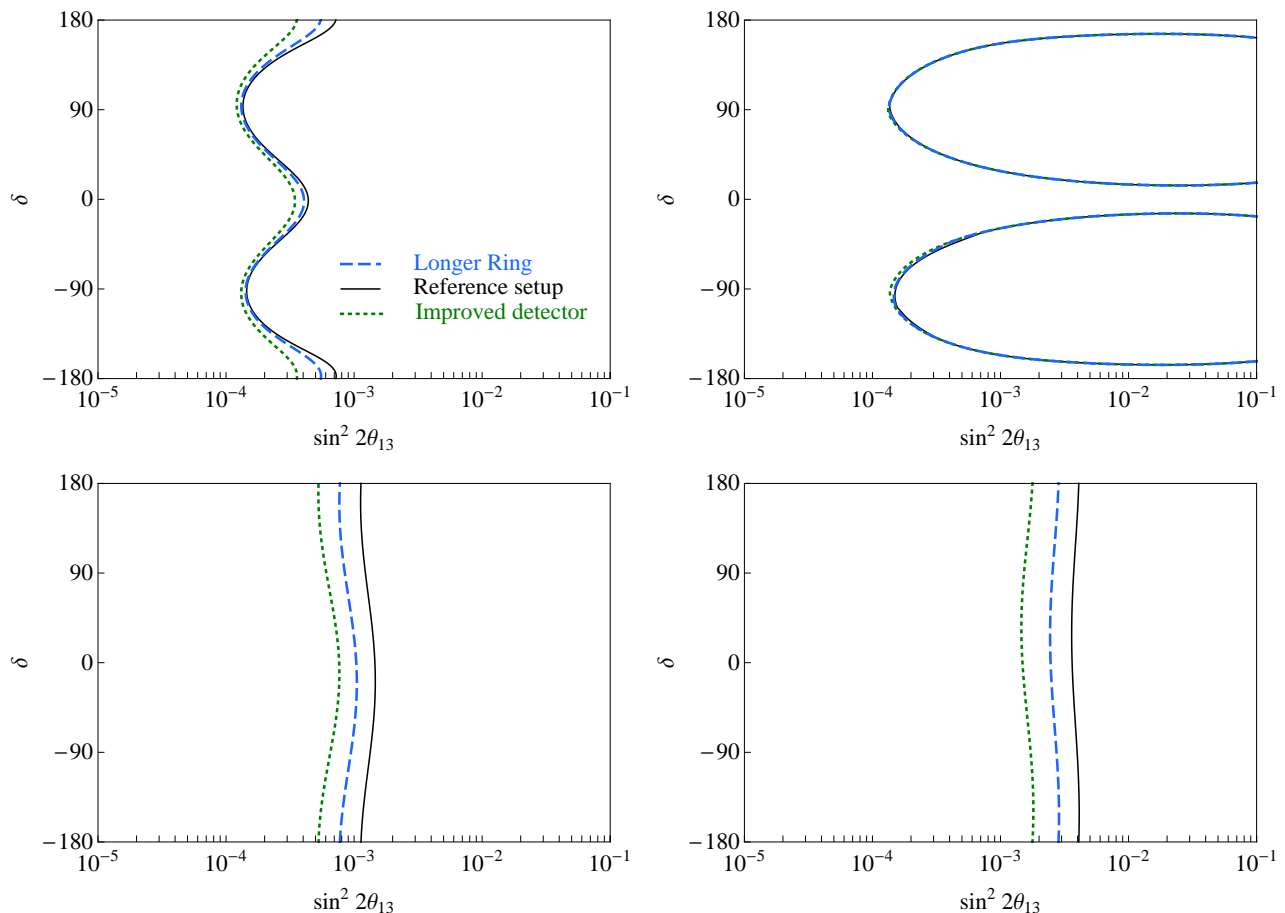
FIG. 2: Comparison of the set-up proposed in this paper (black solid lines) with a set-up with longer decay rings (blue dashed lines) and longer decay plus improved detector characteristics (green dotted lines). Comparisons are shown for the three performance indicators and the layout of the panels are as for Fig. 1.

A. Detector and decay ring specification dependence

As stressed before, we have made a very conservative proposal for the two-baseline β-Beam set-up. In this subsection we study how stable the results presented here are to modifications of the experimental set-up described. In particular, we focus on two effects. The first is the gain in number of useful ion decays by increasing the length of the straight sections of the storage ring. The second is the uncertainty on the achievable low energy threshold, efficiency and background at the iron detector. The sensitivity reach of our proposed set-up is shown in Fig. 2 by the black solid lines. We first probe the effect of increasing the number of useful ion decays by increasing the length of the straight sections of the storage ring for ^{8}B and ^{8}Li ions. This is shown by the blue dashed lines where we restore the straight sections to 2500 km. This increases the ^{8}B and ^{8}Li flux at the far detector by 40% compared to the black reference lines of our set-up. As it can be seen from the figure the impact of increasing the flux at the far detector is mainly on the sensitivity to the mass hierarchy (that becomes $\sin^2 2\theta_{13} \leq 8 \times 10^{-4} (3 \times 10^{-3})$ for normal and inverted hierarchy, respectively), but is still mild even for that observable. Smaller and more feasible designs of the decay rings are therefore possible without affecting significantly the physics reach of the proposed facility.

The second effect concerns the detector specifications. For the reference set-up (black solid lines) we have assumed the same efficiencies and backgrounds as a function of the neutrino energy as those derived for the MIND detector when exposed to a Neutrino Factory beam in Ref. [69]. As we argued above, this is a conservative choice for the β-Beam, since this purer beam does not demand charge ID. Also, the spectrum is not as wide in energy as that of the Neutrino Factory and hence the problems with neutral current backgrounds are also less severe. However, the task of the iron detector at the long baseline is to determine the mass hierarchy and this will be achieved as long as the efficiency at around $6-7$ GeV is high enough to observe the matter resonance enhancement. The effect that a more optimistic assumption of a lower energy threshold of 1.5 GeV with a flat efficiency of 70% and background of 10^{-4}

would imply for the different observables is shown in Fig. 2 by the green dotted lines. For these lines we also work with the longer decay ring with 40% more fluxes at the far detector. As it can be seen from the figure the gain is not very significant for any of the observables, this confirms that the challenging efficient discrimination of the lowest energy events mandatory for a Neutrino Factory, is not as critical for the set-up proposed here.

IV. CONCLUSIONS

We have presented a new β-Beam set-up that combines the strengths of the best set-ups in the literature trying to probe with the same facility the key remaining unknown neutrino oscillation parameters: θ_{13}, the existence of leptonic CP violation and the neutrino mass ordering in the challenging regime of small θ_{13}, trying to make the storage ring design more realistic than in previous studies.

The best CP discovery potentials can be achieved at low energies and short baselines that guarantee that matter effects are not strong enough to mimic true CP violation and spoil the measurement of δ. On the other hand, the statistics at the detector grows with the γ factor to which the ions are accelerated. We therefore follow Ref. [45, 60] for a compromise, choosing the highest γ accessible at the SPS+ but exploiting the decay of the ions with smallest end-point energy, that is, ^{6}He and ^{18}Ne. This guarantees good statistics at the detector, since the flux and cross sections grow with γ, while maintaining a relatively low energy around 1 GeV, which allows to consider the detection via a Mton class water Čerenkov detector. Furthermore, the oscillation baseline can be kept short, matching the CERN to Canfranc baseline of 650 km, so as to further increase the statistics and to avoid strong matter effects that could spoil the CP discovery potential.

On the other hand, the small matter effects preferred for the δ measurement strongly limit the sensitivity of this set-up to the mass hierarchy. We then consider the opposite regime, proposed in [41], where these effects are strongest in order to improve this situation, that is, the resonant enhancement due to the matter interactions. The resonance occurs for energies around 6 GeV, these energies can only be attained at a β-Beam combining high γ with ions with large end-point energy, like ^{8}Li and ^{8}B. The enhancement will only take place in the (anti)neutrino channel if the hierarchy is normal (inverted) therefore providing a very clean probe of the mass ordering. Since the neutrino energies are in the multi-GeV regime, one could use a 50 kton magnetized iron calorimeter as the far detector option. Moreover, a long baseline is required so that the density encountered by the neutrino beam is high enough. If the baseline is chosen to be close to the magic baseline, where all the dependence in δ is lost, the possible intrinsic degeneracies between θ_{13} and δ are also solved, thus increasing the synergy between the two baselines further. We then believe that the combination of the four ions and two baselines will provide the best β-Beam sensitivity to the remaining unknown neutrino oscillation parameters.

While two-baseline β-Beam set-ups have been proposed and studied before, our proposal is unique. We propose two different racetrack geometry decay rings – one for storing the ^{18}Ne and ^{6}He ions, and another for storing the ^{8}B and ^{8}Li ions. For magnetic field strength of 8.3 T, the storage ring for ^{18}Ne and ^{6}He with $\gamma = 350$, has straight sections of 2500 km (as in the original proposal by Piero Zucchelli) and hence a livetime fraction of 0.28. Since the neutrino beams generated from ^{18}Ne and ^{6}He are sent over a baseline $L = 650$ km to Canfranc, the maximum depth at the far end of the storage ring has to be $d = 197$ m only. The ^{8}B and ^{8}Li beam, on the other hand, has to be sent over a baseline $L = 7000$ km to INO, and hence its storage ring requires an inclination of $\vartheta = 34.5°$. For ^{8}Li ions boosted at $\gamma = 350$, using the same ring as for the short baseline beam, this would require a maximum depth $d = 2132$ m at the far end of the storage ring. In order to alleviate the problem of the large d needed for the beam going to the magic baseline, one necessarily has to reduce the size of the straight sections of the ring. This, however, would reduce the livetime and hence the number of muon events for the ^{8}B - and ^{8}Li -generated neutrino beams. In order to compensate for this loss in the number of events, we propose to increase the γ for the ^{8}B and ^{8}Li ions. We point out that the number of events increase by 40% with a small 10% increase in the Lorentz boost from $\gamma = 350$ to 390 for the ^{8}Li ions. Therefore, we take $\gamma = 390$ and 656 for ^{8}Li and ^{8}B ions respectively, as these are the limiting boost factors possible with the upgrades forecast for the SPS at CERN. This allows us to reduce the straight sections of the decay ring without significantly reducing the number of events at the detector, and hence the sensitivity of the experiment to oscillation parameters. Therefore, for a magnetic field of 8.3 T, one could have a decay ring with maximum depth at the far end of $d = 1282$ m. Such a decay ring would give a livetime fraction of 0.17. We point out that magnetic fields as large at 15 T are under discussion for further LHC upgrades. With these larger magnets, one could design more compact decay rings with d up to 1.8 times smaller for the ring for the magic baseline. For the ring for $L = 650$ km, one could use the larger magnets to increase the livetime of the beam from $l = 0.28$ to $l = 0.35$.

Even though the storage ring design proposed in this paper is more realistic than in former studies, it is still quite challenging. However, these are the kind of aggressive proposals being discussed for the next-to-next generation of facilities in order to probe CP violation and the mass hierarchy and to hunt for θ_{13} if it turns out to be beyond the sensitivity of the next generation of reactor and accelerator experiments. Indeed, the sensitivity gain that such
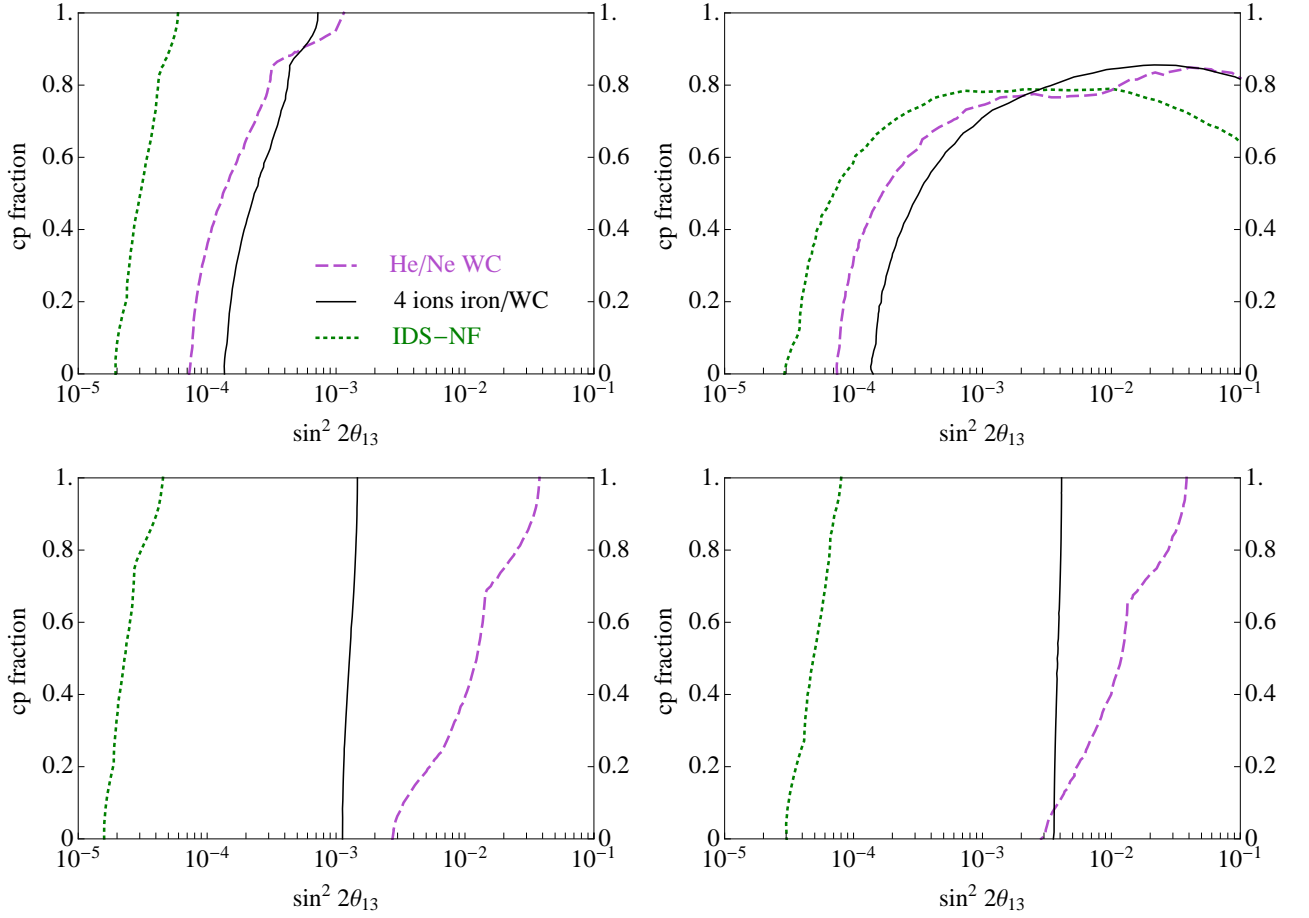
FIG. 3: Comparison of our proposed set-up (black solid lines) with the IDS Neutrino Factory baseline design (green dotted lines) and the high γ β-Beam set-up from [45, 60]. The upper left hand panel shows $\sin^2 2\theta_{13}$ discovery reach, the upper right hand panels shows the CP violation reach, while the lower panels show the mass hierarchy discovery reach. The lower left hand panel is for normal hierarchy as true while the lower right hand panel shows the corresponding reach when inverted hierarchy is true.

a facility would provide compared to the combination of all the forthcoming reactor and accelerator experiments is remarkable. As can be seen from Fig. 1 of Ref. [16] all the forthcoming facilities combined will be sensitive to θ_{13} down to $\sin^2 2\theta_{13} > 3 - 6 \times 10^{-3}$ at a 90% CL., the facility presented here would improve that sensitivity by one order of magnitude and with a 3σ significance, see Fig. 1. Even more striking is the gain in the ability to probe CP violation and the mass hierarchy. The discovery potential of CP violation of the forthcoming facilities is very limited, covering just a 20% of the δ parameter space and only if $\sin^2 2\theta_{13} > 0.02$ at the 90% CL. Conversely, the setup proposed here would cover a 80% of the values of δ down to $\sin^2 2\theta_{13} > 10^{-3}$ with still some sensitivity down to $\sin^2 2\theta_{13} > 10^{-4}$ at 3σ. As for the mass hierarchy, the combination of all the next generation experiments would grant a detection for less than 40% of the values of δ and $\sin^2 2\theta_{13} > 0.04$ at a 90% CL., while the two-baseline β-Beam can go down to $\sin^2 2\theta_{13} > 10^{-3}$ ($\sin^2 2\theta_{13} > 3 \times 10^{-3}$) for normal (inverted) hierarchy at 3σ, regardless of the value of δ.

It is important to study how the sensitivities of the proposed set-up compare with other facilities of the next-to-next generation proposals. We compare the performance of our two-baseline β-Beam with the other two facilities typically considered for the small θ_{13} regime: the IDS Neutrino Factory baseline design [55] and the high γ β-Beam based on ^{6}He and ^{18}Ne of Ref. [45, 60]. For this comparison we present in Fig. 3 the same observables as in the previous figures but as a function of the fraction of the values of δ for which they can be discovered instead of the true values of δ. This translates into a loss of information about the specific values of δ for which sensitivity is achieved but allows a better comparison of the relative performance of the different facilities.

From Fig. 3 it is clear that the facility with sensitivity to the different observables down to smallest values of $\sin^2 2\theta_{13}$ is the Neutrino Factory. This can be understood from the very large fluxes assumed for the IDS baseline as compared to the ones assumed here for the β-Beam set-ups: 10^{21} useful muon decays per year to be compared to the 3×10^{18} assumed for the β-Beams. This translates into much higher statistics that provide sensitivities to smaller

values of θ_{13}. On the other hand, the high energy of the Neutrino Factory beams implies a very small value of L/E_ν. This translates in a stronger suppression of the CP violating term of the oscillation probability with respect to the one suppressed by two powers of θ_{13} for large values of this parameter. Therefore, the CP discovery potential of β-Beams outperforms that of the Neutrino Factory in Fig. 3 when $\sin^2 2\theta_{13} > 10^{-3}$. Since this large values of $\sin^2 2\theta_{13}$ also guarantee a discovery of the mass hierarchy and $\sin^2 2\theta_{13}$ regardless of the value of δ, this makes β-Beams the better option when $\sin^2 2\theta_{13} > 10^{-3}$. Furthermore, even if the statistics in the near β-Beam detector is reduced by half in the present set-up compared to the one in Ref. [45, 60] in order to illuminate the second detector, the CP-discovery potential for $\sin^2 2\theta_{13} > 10^{-3}$ is better in the two-baseline set-up due to the lifting of the degeneracies that can mimic CP-conservation when combining the information from the two detectors.

While the presently assumed β-Beam fluxes cannot compete with the expectations from a Neutrino Factory and cannot probe values of θ_{13} much smaller than $\sin^2 2\theta_{13} \sim 10^{-4}$, we find that β-Beam set-ups are better optimized for regions with $\sin^2 2\theta_{13} > 10^{-3}$, providing sensitivity to the different observables in larger fractions of the parameter space. In particular, we believe that the combination of ions and baselines proposed here represents an optimal β-Beam set-up, that takes advantage of the properties of the different achievable beams, with very good sensitivity to all of the three observables considered, $\sin^2 2\theta_{13}$, δ and the mass hierarchy (contrary to other β-Beam options, that are optimized for only one of them).

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