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## A low energy neutrino factory with non-magnetic detectors

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## ABSTRACT

We show that a very precise neutrino/anti-neutrino event separation is not mandatory to cover the physics program of a low energy neutrino factory and thus non-magnetized detectors like water Cerenkov or liquid Argon detectors can be used. We point out, that oscillation itself strongly enhances the signal to noise ratio of a wrong sign muon search, provided there is sufficiently accurate neutrino energy reconstruction. Further, we argue that apart from a magnetic field, other means to distinguish neutrino from anti-neutrino events (at least statistically) can be explored. Combined with the fact that non-magnetic detectors potentially can be made very big, we show that modest neutrino/anti-neutrino separations at the level of 50% to 90% are sufficient to obtain good sensitivity to CP violation and the neutrino mass hierarchy for  $\sin^2 2\theta_{13} > 10^{-3}$ . These non-magnetized detectors have a rich physics program outside the context of a neutrino factory, including topics like supernova neutrinos and proton decay. Hence, our observation opens the possibility to use a multi-purpose detector also in a neutrino factory beam.

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## 1. Introduction

A neutrino factory is a neutrino source based on the decay of muons stored in a decay ring with long straight sections [1]. The muons are moving at relativistic speed in the decay ring and hence, the isotropic decay in their rest frame becomes a highly collimated beam in the laboratory system. The neutrino beam consists for the decay of  $\mu^+$ , assuming no net muon polarization, of equal numbers of  $\bar{\nu}_\mu$  and  $\nu_e$ . The resulting charged current (CC) muon signals in the detector are, schematically,

$$\begin{array}{l} \mu^+ \nearrow \bar{\nu}_\mu \xrightarrow{P_{\bar{\mu}\bar{\mu}}} \bar{\nu}_\mu \xrightarrow{\sigma_{CC}^{\bar{\mu}}} \mu^+ \\ \mu^+ \searrow \nu_e \xrightarrow{P_{e\mu}} \nu_\mu \xrightarrow{\sigma_{CC}^{\mu}} \mu^- \end{array} \quad (1)$$

The appearance signal due to the oscillation probability  $P_{e\mu}$  is thus proportional to the number of  $\mu^-$  events, which have the opposite sign with respect to the initial decaying  $\mu^+$  and therefore are called “wrong sign” muon events, in contrast to the “right sign” muons from disappearance channel, appearing for a non-vanishing survival probability  $P_{\bar{\mu}\bar{\mu}}$  for the  $\bar{\nu}_\mu$ . Of course, the analogous relations hold for  $\mu^-$  decaying. Throughout this Letter, whenever we talk about  $\mu^+$  in the storage ring, the CP analogous channel stemming from  $\mu^-$  stored is implied, unless otherwise mentioned. In

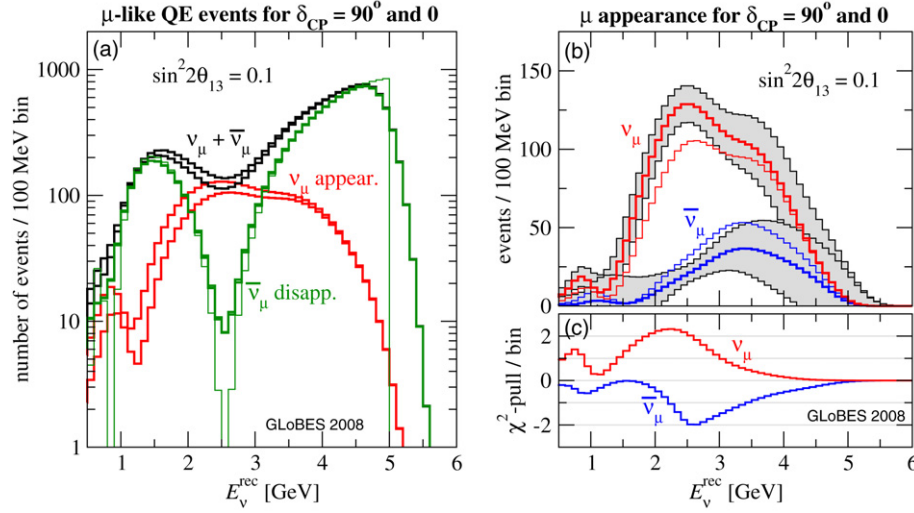
a traditional neutrino factory with energies around 25 GeV of the decaying muons one uses a magnetized iron calorimeter and the resulting curvature of the muon track to identify the muon charge with backgrounds at the  $10^{-4}$ – $10^{-3}$  level, which is the key to the extraordinary sensitivity of a neutrino factory to even small values of  $P_{e\mu}$ . For a current, comprehensive review, see [2–4].

It has been realized, however, that a traditional neutrino factory does not perform very well for large values of  $\sin^2 2\theta_{13} > 10^{-2}$  and therefore, a so-called “low energy” neutrino factory has been proposed [5,6] with a muon energy of around 5 GeV, see also [7]. At those energies, muon tracks in iron are too short to allow a unique determination of the curvature and thus charge. The solution put forward in [5,6] is to use a totally active scintillator detector (TASD), like MINERVA [8] immersed in a magnetic field of about 0.5 T. Preliminary simulations presented in [5,6] indicate that the performance of such a magnetized TASD is satisfactory. However the very large number of readout channels and the need to magnetize a large volume make it difficult to scale this detector to fiducial masses much larger than 10–20 kt.

In this work we will demonstrate that a very precise charge identification is not mandatory to cover the physics program of a low energy neutrino factory and thus non-magnetized detectors like water Cerenkov (WC) or liquid Argon (LAr) detectors can be used (see also [9,10]). We argue that apart from a magnetic field, other means to distinguish neutrino from anti-neutrino events (at least statistically) can be explored. Combined with the fact that such detectors potentially can be made very big, we show that modest charge identification abilities (at the level of 50% to 90%)

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**Fig. 1.** Event rate spectra for  $\sin^2 2\theta_{13} = 0.1$  for quasi-elastic charged current events in a LAr detector as described in Table 1. For panel (a) we assume stored  $\mu^+$  and show the right-sign muon events (“ $\bar{\nu}_\mu$  disapp.”), the wrong sign muon events (“ $\nu_\mu$  appear.”) and the sum of all muon events (“ $\nu_\mu + \bar{\nu}_\mu$ ”). The upper thick lines are for  $\delta = +90^\circ$  and the lower ones are for  $\delta = 0^\circ$ . The thin line shows the right sign muon events in the case of perfect energy resolution. Panel (b) shows the background subtracted wrong sign events for stored  $\mu^+$  (“ $\nu_\mu$ ”) and for stored  $\mu^-$  (“ $\bar{\nu}_\mu$ ”) with their resulting  $1\sigma$  error bars (gray shaded regions) for  $\delta = +90^\circ$ . Thin lines correspond to  $\delta = 0^\circ$ . Panel (c) shows the significance per bin in the difference between  $\delta = +90^\circ$  and  $0^\circ$ .

are enough to be competitive with the above mentioned magnetized TASD detector. These non-magnetized detectors have a vast physics program outside the context of a neutrino factory, including topics like supernova neutrinos and proton decay. For a recent review, see [11]. Hence, our observation opens the attractive possibility to use a multi-purpose detector also in a neutrino factory beam.

The outline of the Letter is as follows. In Section 2 we show that oscillations by themselves suppress the background of wrong sign muons, and therefore, in principle even without any charge identification there is some sensitivity to the appearance signal. In Section 3 we discuss some means to separate neutrino and anti-neutrino events without using a magnetic field and we introduce a simple (idealized) parametrization to describe statistically neutrino/anti-neutrino-enhanced data samples. In Section 4 we present the results of sensitivity calculations for CP violation and the neutrino mass hierarchy, comparing non-magnetized detectors with some modest neutrino/anti-neutrino separation abilities to the reference magnetized TASD. We conclude in Section 5.

## 2. A neutrino factory without charge identification

The central observation, this Letter is based on, is that the  $\nu_\mu$  from the disappearance channel, which give rise to the so-called right sign muons, will have almost completely turned into  $\nu_\tau$  for energies around the first oscillation maximum, which we denote by  $E_{1st}$  and is defined by  $\Delta \equiv \Delta m_{31}^2 L / (4E) = \pi/2$ . For exactly maximal mixing, i.e.  $\theta_{23} = \pi/4$ , the survival probability  $P_{\mu\mu}$  becomes practically zero at  $E_{1st}$  and stays small within a narrow energy range centered on  $E_{1st}$ :

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \mathcal{O}(\Delta m_{21}^2, \theta_{13}). \quad (2)$$

On the other hand, the appearance probability  $P_{e\mu}$  leading to the wrong sign muons will peak around  $E_{1st}$ . In vacuum, for simplicity, one has

$$P_{e\mu} \approx 4s_{13}^2 s_{23}^2 \sin^2 \Delta + 2\tilde{\alpha} s_{13} \sin 2\theta_{23} \sin \Delta \cos(\Delta \mp \delta) + c_{23}^2 \tilde{\alpha}^2, \quad (3)$$

with  $s_{ij} \equiv \sin \theta_{ij}$ ,  $c_{ij} \equiv \cos \theta_{ij}$ ,  $\tilde{\alpha} \equiv \sin 2\theta_{12} \Delta m_{21}^2 L / (4E)$ , and ‘-’ (‘+’) holds for neutrinos (anti-neutrinos). Thus using events in the region around  $E_{1st}$  a reasonable signal to noise ratio can be obtained even if there is no possibility to distinguish neutrino from

anti-neutrino events. Therefore, a good energy resolution of the detector will be crucial to maximally exploit the suppression of right sign muons due to oscillation. At the typical energies of a low energy neutrino factory of a few GeV the contribution of quasi-elastic scattering is still large enough to provide sufficient energy resolution without the need of accurate hadronic calorimetry.

Fig. 1 shows event rate spectra expected in a 100 kt liquid Argon detector at a distance of 1290 km from a neutrino factory. The energy of the stored muons is 5 GeV and we assume a total of  $10^{22}$  useful muon decays, equally divided into  $\mu^-$  and  $\mu^+$  running. The events shown are quasi-elastic events and we assume  $\sin^2 2\theta_{13} = 0.1$ . Fig. 1(a) corresponds to  $\mu^+$  decays and shows the spectra for right sign muons ( $\bar{\nu}_\mu$  disappearance) and wrong sign muons ( $\nu_\mu$  appearance), as well as the sum of all muon events. First we observe, that in the energy region from about 2–3 GeV the wrong sign signal exceeds the right sign background; the maximal signal to background ratio is about 10, which happens at approximately  $E_{1st}$ . This proves that oscillation on its own provides an effective mechanism to suppress the right sign muon background to a wrong sign muon search. The thick lines do include an energy resolution of  $\Delta E = 0.05\sqrt{E} + 0.085$  in units of GeV, whereas the thin line shows the right sign muon background in the case of perfect energy reconstruction. The effect of a finite energy resolution is to move events into the oscillation dip and thereby to increase the background for the wrong sign muon signal.

In principle, the  $\nu_\tau$  resulting from  $\nu_\mu \rightarrow \nu_\tau$  oscillations can give rise to right sign muons as well, for those cases where the  $\tau$  lepton from a charged current interaction decays leptonically into a muon. The branching fraction for this decay mode is only about 17% [12]. Moreover, there is strong suppression of the charged current cross section due the finite mass of the  $\tau$  lepton [13]. We have estimated that a total of  $\sim 600$   $\nu_\tau$  charged current events would be obtained in 100 kt detector mass. Of these, only 17% would produce a right-sign muon, i.e. about 100 events. Assuming that the tau lepton carries all the energy of the parent  $\nu_\tau$ , we can compute the resulting muon spectrum. The result is about 10 events per bin in the peak of their distribution, which however happens at energies well below  $E_{1st}$ . Thus right-sign muons from tau decay never make up more than a few percent of the right-sign muons from genuine  $\nu_\mu$  charged current events in the relevant energy range. Therefore, these events are not included in our analysis. Note, that

these numbers depend sensitively on the chosen muon energy in the storage ring, since the  $\nu_\tau$  events stem exclusively from the high energy part of the neutrino spectrum from 4–5 GeV; thus a decrease in muon energy to 4 GeV would virtually eliminate the  $\nu_\tau$  events, whereas an increase to 6 GeV would lead to 6-fold increase in  $\nu_\tau$  events.

Fig. 1(a) displays two sets of thick lines: the upper set of lines is computed for  $\delta = 90^\circ$ , whereas the lower set of curves is computed for  $\delta = 0^\circ$ . We observe, that the right sign muon signal exhibits only a very weak dependence on the value of  $\delta$ , which is crucial in order to allow for a clean extraction of CP effects. As a result, the full dependence on  $\delta$  shown by the wrong sign muons is preserved in the sum of both signs of muons. Fig. 1(b) shows the background subtracted appearance signal event spectra. The gray bands depict the resulting statistical  $1\sigma$  errors, which are computed from the sum of right and wrong sign events. This is shown for  $\mu^+$  stored ( $\nu_\mu$  appearance) and for  $\mu^-$  stored ( $\bar{\nu}_\mu$  appearance). The thick lines are for  $\delta = 90^\circ$ , whereas the thin lines are for  $\delta = 0^\circ$ . We see, that in the bins with the best signal to noise ratio, each bin provides around  $2\sigma$  of significance as shown in panel (c). We also see that the effect goes in opposite directions for neutrinos and anti-neutrinos thus manifestly displaying CP violation. This remains true if also the second CP conserving case,  $\delta = 180^\circ$ , is taken into account. Note that one can even discern the effects from the second oscillation maximum around 1 GeV.

The discussion so far has assumed maximal mixing  $\theta_{23} = \pi/4$ . From Eq. (2) follows that if  $\theta_{23} \neq \pi/4$  the survival probability  $P_{\mu\mu}$  will not go to zero at the first oscillation maximum and therefore somewhat more wrong sign muons will end up in the signal region around  $E_{1st}$ . Nevertheless, as we will show in Section 4, for values of  $\theta_{23}$  within the currently allowed  $2\sigma$  range the suppression of wrong sign events around  $E_{1st}$  is still sufficient and does not alter our results significantly.

### 3. Neutrino/anti-neutrino separation without a magnetic field

Neutrino and anti-neutrino quasi-elastic (QE) charged current events differ by a number of obvious and also more subtle signatures. The reactions are given by

$$\nu_x + N \rightarrow l_x^- + p + N' \quad \text{and} \quad \bar{\nu}_x + N \rightarrow l_x^+ + n + N', \quad (4)$$

where  $l_x$  denotes a charged lepton with  $x$  being  $\mu$  or  $e$  and  $N$  is the nucleus. A traditional neutrino factory experiment aims at measuring the charge sign of the outgoing lepton  $l_x$  by using a magnetic field and the resulting curvature of the track. This technique, currently, is planned to be applied only to muons, since electron tracks are considered neither long nor clean enough. In the following we mention three other signatures which can be used in principle to distinguish neutrino from anti-neutrino events without using a magnetic field, where we do not exclude that in a specific detector additional signatures beyond these three examples might be available.

- For  $\nu_\mu$  events another signature is the life time of the resulting muon, see e.g. [14,15]: a  $\mu^-$  can be captured by an atom to form a muonic atom and subsequently muon capture on the nucleus takes place. In this case, there will be no Michel electron. This process competes with ordinary muon decay, whereas for  $\mu^+$  no such process is possible. The capture probability is approximately<sup>1</sup> given by the lifetime ratio  $\tau_{\mu^-}/\tau_{\mu^+}$ , where  $\tau_{\mu^+}$  is the vacuum lifetime of 2.197  $\mu\text{s}$  [12].  $\mu^-$  life times in common

detector materials are [16]: 2.026  $\mu\text{s}$  for Carbon, i.e. liquid scintillator,<sup>2</sup> yielding a capture probability of 8%; 1.795  $\mu\text{s}$  for Oxygen, i.e. water,<sup>2</sup> yielding a capture probability of 18%; 0.537  $\mu\text{s}$  for Argon, yielding a capture probability of 76%. This effect has been used by the Kamiokande Collaboration to determine the charge ratio of cosmic ray muons with an accuracy of 6% [17]. Here problems can arise due to the need, at least in some detectors like a WC, to positively identify the muon decay in order to distinguish the muon from a pion. For these detectors, the effect would be a reduced efficiency for  $\nu$  events compared to  $\bar{\nu}$  events. On the other hand, detectors which do not require the muon decay as particle identification tag,  $\bar{\nu}_\mu$  charged current events which lead to muon capture, i.e. have no Michel electron, would constitute a very clean sample of  $\bar{\nu}$  events. In the case of LAr, this sample would have an efficiency of about 0.5–0.6.

- Another difference between  $\nu$  and  $\bar{\nu}$  QE events is the distribution of  $\cos\theta$ , where  $\theta$  is the angle between the incoming neutrino and the outgoing lepton in the laboratory frame. Therefore, fitting the angular distribution of the charged leptons from QE events with respect to the neutrino beam direction provides a statistical handle on the  $\nu/\bar{\nu}$  content of the beam. The MiniBooNE Collaboration reports that they can use this effect in combination with the muon life time to determine a neutrino contamination of their anti-neutrino beam of 30% with an accuracy of better than 10%, i.e. the error in subtracting the neutrino background relative to all events is of the order 3% [18]. The difference in angular distributions is largest for neutrino energies around 1 GeV and is somewhat smaller at those energies we are looking at. Thus, this discriminant most likely has to be used in combination with other techniques.

- Finally, the outgoing nucleon from a QE interaction is different for neutrino and anti-neutrino events: a proton for a  $\nu$  event and a neutron for a  $\bar{\nu}$  event, see Eq. (4). Tagging the proton (being a charged particle) requires a sufficiently low energy threshold and sufficient spatial resolution to uniquely identify the proton track. Clearly, a liquid Argon detector fulfills both these conditions [19]. On the other hand the proton tagging efficiency in water is very low, due to the Cerenkov threshold [20]. Tagging the neutron can be achieved by observing neutron capture onto a sufficiently heavy nucleus, which in turn will emit a  $\gamma$ -cascade with a total energy release of several MeV. The problem here is the competition between capture on light nuclei, which produces too little energy in  $\gamma$ -rays, and heavy nuclei. For a water Cerenkov detector the addition of a about 0.2% of Gadolinium would allow to tag neutrons with an efficiency of about 90% [21]. Apart from the proton/neutron detection efficiency, charge exchange reactions where a proton becomes a neutron or *vice versa* would limit the achievable purity of this tag. Especially, since most detectors will be only able to tag either neutrons or protons and not both. The K2K Collaboration has reported [22] that about 70% of nucleons in a quasi-elastic charged current events leave the nucleus without further interaction. The energy range of incoming neutrinos is 0.5–3.5 GeV, i.e. close to the energies considered here. The remaining 30% of events have the nucleon undergo elastic scattering inside the nucleus. Production of pions due to re-interactions happens only for proton momenta in excess of 1 GeV, which is a small fraction of the overall events. Assuming an iso-scalar target, the probability to hit a neutron is 0.5; further, assuming that in all elastic collisions full energy transfer between projectile and target takes place, we obtain that  $0.5 \cdot 0.3 = 0.15$  of all events undergo a charge exchange. Thus purities at the level of 80% seem possible using this technique.

<sup>1</sup> There is a small correction to the lifetime of a captured  $\mu^-$ , due to the binding energy [16].

<sup>2</sup> The muon capture rate on Hydrogen is negligibly small.

These examples indicate that at least a statistical separation of  $\nu$  and  $\bar{\nu}$  events seems possible without the use of magnetic fields. While we do not claim that any of these methods has been proved to work with sufficient accuracy for our purposes, the obtainable efficiencies and purities seem reasonably high to merit a detailed investigation. In the following we will consider the impact of various levels of statistical  $\nu/\bar{\nu}$  separation on the obtainable physics sensitivities, with the hope that our results will trigger dedicated studies on statistical  $\nu/\bar{\nu}$  separation in different detectors. Therefore, we will resort to a highly idealized parametrization of statistical separation of  $\nu$  and  $\bar{\nu}$ , which nevertheless is sufficient to illustrate the principle. We group all events into two samples  $N_1$  and  $N_2$ , which will be a mixture of neutrino  $N_\nu$  and anti-neutrino events  $N_{\bar{\nu}}$ :

$$\begin{aligned} N_1^i &= \frac{1-p}{2} N_\nu^i + \frac{1+p}{2} N_{\bar{\nu}}^i, \\ N_2^i &= \frac{1+p}{2} N_\nu^i + \frac{1-p}{2} N_{\bar{\nu}}^i, \end{aligned} \quad (5)$$

where  $p$  is the separation coefficient ( $0 \leq p \leq 1$ ), and  $i$  labels the energy bins. A value  $p = 0$  is equivalent to no separation at all, whereas  $p = 1$  stands for perfect separation. Thus for  $p \sim 1$ ,  $N_1$  contains more anti-neutrino events and  $N_2$  more neutrino events. In some sense,  $(1+p)/2$  is the efficiency of the separation and  $(1-p)/2$  is the contamination of the sample. Clearly, in a real detector efficiency and contamination need not add up to 1, nor need the anti-neutrino efficiency and contamination in sample  $N_1$  be the same as the neutrino efficiency and contamination in sample  $N_2$ . Furthermore, in general one expects that  $p$  depends on the neutrino energy (and hence on the index  $i$  in Eq. (5)), an effect we neglect here. Furthermore, we assume that  $p$  has been determined by the near detector complex of the neutrino factory with negligible errors.

Note, that in principle, polarization of the initial muons can serve a similar purpose, i.e. improving the ratio of wrong sign to right sign muons. From initial estimates it seems that a muon polarization of about 50% is equivalent to a value of  $p \simeq 0.2$ – $0.3$ . Thus it may not be sufficient on its own, since 50% polarization is already quite ambitious [23], but in combination with the other techniques mentioned above it could be very useful.

In this Letter we will neglect all possible backgrounds, like neutral current or charged current events with a leading pion. This approximation can be justified by looking at the statistical error derived from Eq. (5). For the signal being neutrinos  $N_\nu^i$  we obtain

$$\sigma_{\text{stat}}^2 = \frac{1+p}{2} N_\nu^i + \frac{1-p}{2} N_{\bar{\nu}}^i + \frac{B_i}{2} \xrightarrow{N_{\bar{\nu}}^i \rightarrow 0} \frac{1-p}{2} N_\nu^i + \frac{B_i}{2}, \quad (6)$$

where  $B_i$  is the background in bin  $i$ . The factor  $1/2$  for  $B_i$  arises from the assumption that the background is equally divided between the samples  $N_1$  and  $N_2$ , i.e. no  $\nu/\bar{\nu}$  separation is applied. Thus, for  $B_i \lesssim N_\nu^i$  the effect of the background will be small. To conservatively estimate the permissible background fraction we will assume that all backgrounds migrate from the bin containing the most right sign neutrinos  $N_{\text{max}}$  into that bin which contains the least right sign neutrinos  $N_{\text{min}}$ . The ratio  $r = N_{\text{min}}/N_{\text{max}}$  is  $r \sim 1/100$  for the energy resolution of a TASD or LAr detector, cf. Fig. 1(a), and it is  $r \sim 1/10$  for the energy resolution of a WC. The maximally allowable background fraction is thus given by  $r(1-p)$ , which translates into a range of 0.001–0.003 for TASD and LAr and 0.03–0.1 for WC. These levels of background rejection are within the margins of the current understanding of these detectors, see e.g. [5,24,25]. In any case, a full detector simulation with a special emphasize on nuclear effects will be required to obtain a quantitatively reliable result for both the obtainable background fraction and  $\nu/\bar{\nu}$  separation.

**Table 1**

Summary of relevant detector parameters. Further details of our simulations can be found the references given in the first line of the table.

	TASD [5,6]	WC [26]	LAr [25]
Fiducial mass [kt]	20	500	100
Efficiency	0.73	0.9*	0.8
Magnetized	yes	no	no
$\Delta E$ at 2.5 GeV [MeV]	165	300**	165
$p$ for muons	0.999	0–0.7	0.7–0.9
$p$ for electrons	0	0	0.7–0.9

\* On top of the single ring selection efficiency and an efficiency of 82% for  $\nu_\mu$  events.

\*\* Equivalent Gaussian width.

#### 4. Sensitivity calculations

For the following results we considered three types of detectors: a totally active magnetized scintillator detector (TASD) [5], a megaton scale water Cerenkov (WC) detector [27–29], and a liquid Argon time projection chamber (LAr) [30]. Our TASD has similar properties to the detector considered in [5,6] and it will serve as benchmark setup for the performance of a low energy neutrino factory. For the purposes of this Letter, the main difference between different detector technologies is mainly given by the energy resolution for QE events, the attainable fiducial mass and whether they can be magnetized. The relevant detector properties are summarized in Table 1; the simulations follow the details given in the references shown in the table.

For both, the TASD and LAr we assume that QE and non-QE events can be separated and we parametrize the energy resolution as  $\Delta E = r\sqrt{E} + 0.085$  in units of GeV, with  $r = 0.05$  for QE events for both, TASD and LAr, and  $r = 0.2(0.3)$  for non-QE events for LAr (TASD). For the TASD we assume charge identification at the level of  $10^{-3}$  for muons [5], and hence we take  $p = 0.999$ . We do include also  $e$ -like events in the TASD without charge identification. In the case of LAr we assume that  $\nu/\bar{\nu}$  separations in the range  $0.7 \lesssim p \lesssim 0.9$  can be obtained for  $\mu$ -like and  $e$ -like QE events; non-QE events are included without  $\nu/\bar{\nu}$  separation ( $p = 0$ ). For the WC we use only single ring events, and the energy resolution is obtained from a full simulation based on the SuperK Monte Carlo taken from [24], including the contribution of non-QE events which pass the single ring criterion. We account for the fact that for captured  $\mu^-$  no Michel electron can be observed by an additional efficiency of 82% for  $\nu_\mu$  events. We consider  $\nu/\bar{\nu}$  separations in the range  $0 \leq p \lesssim 0.7$  for  $\mu$ -like events. Although some of the separation methods mentioned above might work also for  $\nu_e$  events ( $\cos\theta$  distribution and neutron tagging), we conservatively assume here no  $\nu/\bar{\nu}$  separation for  $e$ -like events in a WC.

For the neutrino factory we use a stored muon energy  $E_\mu$  of 5 GeV<sup>3</sup> and total of  $10^{22}$  useful muon decays, equally divided into  $\mu^-$  and  $\mu^+$  running. This luminosity corresponds to 10 years total running time of the baseline setup of the International Design Study for a neutrino factory [31].<sup>4</sup> We assume a baseline of 1290 km, which corresponds to the distance from Fermilab to the Deep Underground Science and Engineering Laboratory (DUSEL) at Homestake. For the sake of comparison with conventional neutrino beams we also will show results for a 500 kt WC in a wide-band neutrino beam stemming from 120 GeV protons with the same baseline (1290 km) and at an off-axis angle of 58 mrad. The beam power (4 MW) and the running time (10 yr) is assumed to be the

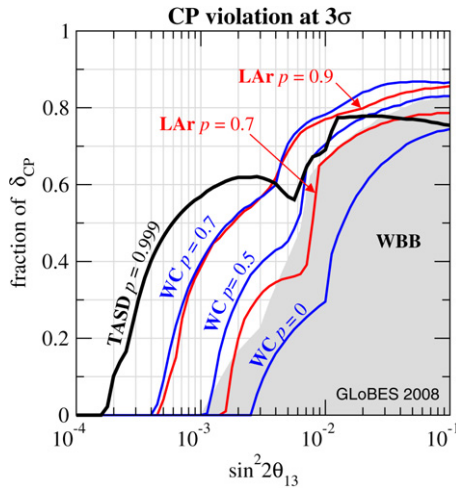
<sup>3</sup> We have verified that this energy is close to optimal for the baseline considered here, in agreement with [7].

<sup>4</sup> This setup assumes a 4 MW proton beam, for  $10^7$  s a year. Fermilab's project X will deliver 2.3 MW of protons for  $1.7 \times 10^7$  s per year. As a result the expected neutrino luminosity per calendar year should be approximately the same.

same as for the neutrino factory. This corresponds (except for the larger detector mass) to the setup considered in [26] and will be labeled as WBB.

To calculate the sensitivities we will use  $\Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2$ ,  $\sin^2 \theta_{23} = 0.5$ ,  $\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$  and  $\sin^2 \theta_{12} = 0.3$ , which corresponds to the results found in version 6 of [32]. For  $\theta_{13}$  and  $\delta$  we assume that they have to be determined by the experimental setups considered. The analysis is performed with GLoBES [33,34] using a 4% error on the solar parameters  $\Delta m_{21}^2$  and  $\sin^2 \theta_{12}$  and a 5% error on the matter density. We impose no external information on  $\Delta m_{31}^2$  and  $\theta_{23}$  since these parameters are measured by the considered experiment with good precision. We always assume a true normal neutrino mass hierarchy, but we have checked that your results are not significantly changed when the mass hierarchy is inverted. We assume a 2.5% systematic error on each signal. All sensitivities are evaluated at the  $3\sigma$  confidence level for 1 degree of freedom, i.e.  $\Delta\chi^2 = 9$ .

In Fig. 2 we show the obtainable sensitivities to CP violation as a function of the true value of  $\sin^2 2\theta_{13}$  for the different detectors as described in Table 1. First, we note that the conventional WBB setup performs very well for large values of  $\sin^2 2\theta_{13} > 0.03$ .

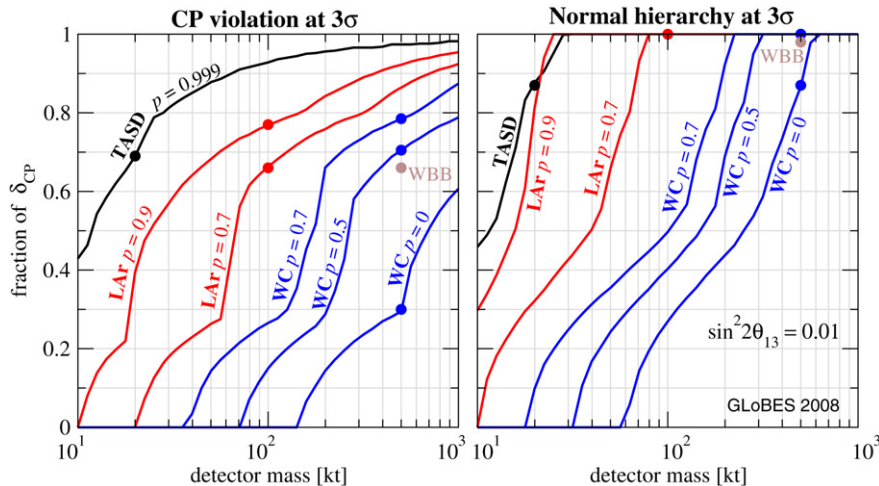


**Fig. 2.** Fraction of  $\delta$  for which CP violation can be discovered at  $3\sigma$  confidence level for different experiments as described in Table 1. The numbers next to the lines correspond to different values of the  $\nu/\bar{\nu}$  separation coefficient  $p$  as defined in Eq. (5). The shaded region corresponds to the WBB.

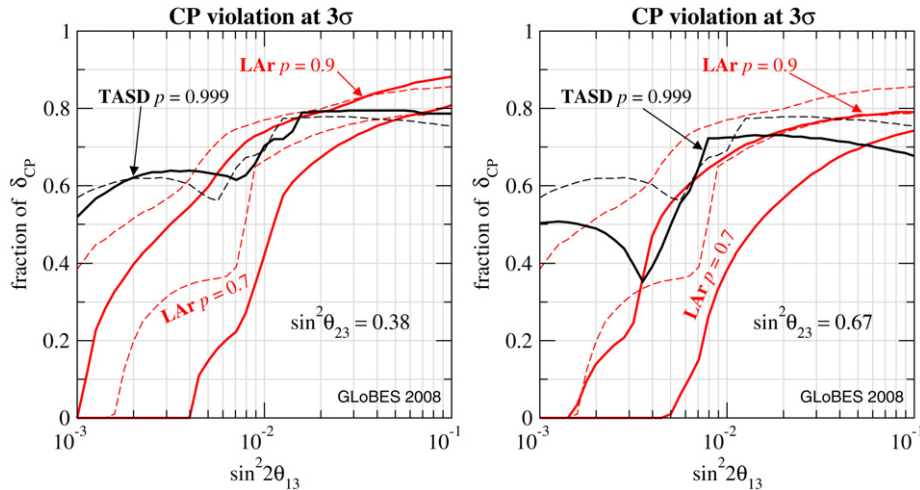
For  $0.006 < \sin^2 2\theta_{13} < 0.03$ , a low energy neutrino factory with a magnetized TAsD performs marginally better than a WBB and only for  $\sin^2 2\theta_{13} < 0.006$  the neutrino factory yields a considerable improvement in sensitivity. A WC with  $p = 0$ , i.e. no  $\nu/\bar{\nu}$  separation at all, will perform worse in a neutrino factory beam than in a wide band beam. However, already for a modest separation of  $p = 0.5$ , the WC would have the same or even better performance than a TAsD for  $\sin^2 2\theta_{13} > 0.006$ . For good  $\nu/\bar{\nu}$  separation,  $p = 0.7$ , the WC outperforms a TAsD down to  $\sin^2 2\theta_{13} > 0.004$ . For LAr the better energy resolution largely allows to compensate the smaller mass and for a somewhat larger value of  $p = 0.9$  it is more or less equivalent to the WC with  $p = 0.7$ . These results clearly demonstrate that non-magnetized detectors can exploit their relatively larger mass compared to magnetized ones in order to address the same physics in a low energy neutrino factory beam. The question which technology yields better sensitivities depends on the value of  $\sin^2 2\theta_{13}$ , the degree of  $\nu/\bar{\nu}$  separation and the relative detector mass.

Therefore, we study the physics reach as a function of the detector mass. This is shown in Fig. 3 for a true value of  $\sin^2 2\theta_{13} = 0.01$ . The left hand panel shows the fraction of  $\delta$  for which CP violation can be discovered, whereas the right hand panel shows the fraction of  $\delta$  for which a normal mass hierarchy can be identified. The dots indicate the sensitivity obtained for the detector masses as specified in Table 1. From the right hand panel it is obvious that the determination of the mass hierarchy can be achieved by any technology for almost all values of the CP phase. Let us note that for the hierarchy determination  $\nu_e$  events contribute significantly to the sensitivity, even with  $p = 0$ , and this contribution is further enhanced if some  $\nu/\bar{\nu}$  separation is assumed also for  $e$ -like events (see [35] for an explanation). This is important also for the CP violation measurement, since the hierarchy degenerate solution often is located at CP conserving values of  $\delta$ . Indeed, the kink visible in the curves shown in the left panel, above which the sensitivity improves drastically, corresponds roughly to the detector mass for which the sign degeneracy can be lifted. Therefore, the inclusion of electron events (and increasing  $p$  for them) shifts this kink to lower detector masses; though it has very little impact on the CP sensitivity at high luminosities, which is dominated by  $\mu$ -like events.

The left-hand panel shows that, depending on the detector type and level of  $\nu/\bar{\nu}$  separation, a larger detector mass is needed to achieve the same sensitivity as the usual magnetized TAsD with a fiducial mass of 20 kt. For the WC, we find equivalent masses



**Fig. 3.** Fraction of  $\delta$  as function of the detector mass for which CP violation (left-hand panel) or the mass hierarchy can be discovered (right-hand panel) at  $3\sigma$  confidence level for different experiments as described in Table 1 for  $\sin^2 2\theta_{13} = 0.01$ . The numbers next to the lines correspond to different values of the  $\nu/\bar{\nu}$  separation coefficient  $p$  as defined in Eq. (5).



**Fig. 4.** Fraction of  $\delta$  for which CP violation can be discovered at  $3\sigma$  confidence level as a function of  $\sin^2 2\theta_{13}$  for the TASD and LAR ( $p = 0.7$  and  $0.9$ ) setups from Table 1, for  $\sin^2 \theta_{23} = 0.38$  (left) and  $\sin^2 \theta_{23} = 0.67$  (right). For comparison we show also the CP fractions for  $\sin^2 \theta_{23} = 0.5$  (dashed curves).

in the range from 200–500 kt for  $p = 0.7 - 0.5$  and for the LAR the mass range is from 50–110 kt for  $p = 0.9 - 0.7$ . The equivalent masses increase for smaller values of  $\theta_{13}$  and for  $\sin^2 2\theta_{13} = 0.003$ , the equivalent mass ranges become  $m = 500 - 900$  kt for WC and  $m = 110 - 300$  kt for LAR.

So far we have assumed maximal mixing  $\theta_{23} = \pi/4$ . Let us now investigate the impact of non-maximal values for  $\theta_{23}$  on our results. Similar to a finite energy resolution also non-maximal values of  $\theta_{23}$  will lead to a wrong sign muon background at the first oscillation maximum, since the survival probability  $P_{\mu\mu}$  goes not to zero. In the example shown in Fig. 1(a), the background from the energy resolution is about 10 events per bin. The unoscillated event rate in that bin would be about 300 events, thus we have a background suppression by about a factor of 30 for  $\theta_{23} = \pi/4$ . We can estimate the excursion of  $\theta_{23}$  from maximality which would cause the same level of events by solving  $1 - \sin^2 2\theta_{23} = 1/30$ . We find that  $\theta_{23} \simeq \pi/4 \pm 0.1$  satisfies this constraint; this is equivalent to a variation of  $\sin^2 \theta_{23} = 0.5 \pm 0.1$ , which is about the  $2\sigma$  range currently allowed by global neutrino data [32]. Since the significance of the signal is due to not only one bin at  $E_{1st}$ , but due to the cumulative effect of many bins close by, which experience reduction of right sign muon events much smaller than 30, one can expect that the proposed scheme will not be spoiled by reasonable deviations from maximal mixing.

Fig. 4 shows the sensitivity to CP violation for the LAR detector compared to the magnetized TASD for the current [32] lower  $2\sigma$  bound (left panel) and upper  $3\sigma$  bound (right panel) on  $\sin^2 \theta_{23}$ . As expected we find a somewhat worse sensitivity for non-maximal values, however the relative performance of the magnetic and non-magnetic detectors is similar to maximal mixing. Note that the CP signal itself becomes smaller for  $\theta_{23} \neq \pi/4$  since it is proportional to  $\sin 2\theta_{23}$ , cf. Eq. (3). We conclude that for reasonably non-maximal values of  $\theta_{23}$  our results are not significantly affected.

## 5. Conclusions

The results presented in this Letter show that a sufficiently well performing non-magnetized detector may be able to cover the physics needs of a low energy neutrino factory for  $\sin^2 2\theta_{13}$  larger than about  $10^{-3}$ . Detector requirements are a statistical neutrino/anti-neutrino separation at the level of 50% to 90%, a good energy resolution, and large fiducial masses in the range of 100 to 500 kt. In this way, a neutrino factory beam does not *a priori* exclude the use of multi-purpose detectors, which have other in-

teresting applications in astrophysics or proton decay. Furthermore, a low energy neutrino factory exploiting an already existing, large non-magnetized detector can serve as intermediate step between the super beam program and a full scale, high energy neutrino factory. We hope that the results presented here will stimulate a detailed investigation of the required detector capabilities.

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