Future Neutrino Beam Facilities

Pasquale Migliozzi
Istituto Nazionale Fisica Nucleare, Napoli
E-mail: migliozzi@na.infn.it

Abstract. After a brief summary of the status of neutrino oscillation searches, we discuss the proposed Neutrino Beam Facilities and compare their sensitivity in the $\theta_{13} - \delta_{\text{CP}}$ plane. Finally, we also recall the detector technologies that have been proposed to exploit neutrino beams for future facilities.

1. Introduction
The experimental evidences for neutrino oscillations collected in the last fifteen years represent a major discovery in modern particle physics. The oscillation phenomenon allows the measurement of fundamental parameters of the Standard Model and provides the first insight beyond the electroweak scale [1]. Moreover, neutrino oscillations are important for many fields of astrophysics and cosmology and open the possibility to study CP violation in the leptonic sector [2].

Neutrino flavor oscillations can be described in terms of three mass eigenstates $\nu_1, \nu_2, \nu_3$ with mass values $m_1, m_2$ and $m_3$ that are connected to the flavor eigenstates $\nu_e, \nu_\mu$ and $\nu_\tau$ by a mixing matrix $U$ (Pontecorvo, Maki, Nakagawa and Sakata (PMNS) matrix), usually parameterized as

$$U(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\text{CP}}) = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{\text{CP}}} \\ -c_{23}s_{12} - s_{13}c_{12}e^{i\delta_{\text{CP}}} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta_{\text{CP}}} & -s_{23}c_{23}s_{12}e^{i\delta_{\text{CP}}} \\ s_{23}s_{12} - s_{13}c_{12}e^{i\delta_{\text{CP}}} & -s_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta_{\text{CP}}} & c_{13}s_{23} \end{pmatrix}$$

where the short-form notation $s_{ij} \equiv \sin \theta_{ij}, c_{ij} \equiv \cos \theta_{ij}$ is used. As a result, the neutrino oscillation probability depends on 3 mixing angles, $\theta_{12}, \theta_{23}, \theta_{13}$, 2 mass differences, $\Delta m_{21}^2 = m_2^2 - m_1^2, \Delta m_{32}^2 = m_3^2 - m_2^2$, and a CP phase $\delta_{\text{CP}}$. Additional phases are present in case neutrinos are Majorana particles, but they do not influence at all neutrino flavor oscillations. Furthermore, the neutrino mass hierarchy, the ordering with which mass eigenstates are coupled to flavor eigenstates, can be fixed by measuring the sign of $\Delta m_{32}^2$. In vacuum the oscillation probability between two neutrino flavors $\alpha, \beta$ is:

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4 \sum_{k>j} \text{Re}[W_{\alpha\beta}^{jk}] \sin^2 \frac{\Delta m_{jk}^2 L}{4E_\nu} \pm 2 \sum_{k>j} \text{Im}[W_{\alpha\beta}^{jk}] \sin^2 \frac{\Delta m_{jk}^2 L}{2E_\nu}$$

where $\alpha = e, \mu, \tau, j = 1, 2, 3, W_{\alpha\beta}^{jk} = U_{\alpha j}U_{\beta j}^* U_{\alpha k}^* U_{\beta k}$. In the case of only two neutrino flavor oscillation it can be written as:
\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \Delta m^2 (eV^2) \cdot L(km)}{E_\nu (GeV)}. \]  

Therefore, two experimental quantities are relevant for neutrino oscillations: the neutrino energy \( E_\nu \) and the baseline \( L \) (distance of the neutrino source from the detector). They can be varied in order to explore different values of the mixing parameters. When neutrinos pass through matter, the oscillation probability is perturbed (the so-called MSW effect \[3\]) depending on \( \text{sign}(\Delta m^2_{23}) \). 

The present knowledge of the PMNS is summarized in Ref. [5]. The numerical values of the matrix elements are:

| GS98 with Gallium cross-section | AGSS09 with modified Gallium cross-section |
|--------------------------------|------------------------------------------|
| \( \Delta m^2_{21} \) = 7.59 \pm 0.20 (^{+0.61}_{-0.69}) \times 10^{-5} \text{ eV}^2 |
| \( \Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11 (\pm 0.37) \times 10^{-3} \text{ eV}^2 \\ +2.46 \pm 0.12 (\pm 0.37) \times 10^{-3} \text{ eV}^2 \end{cases} \) |
| \( \theta_{12} = 34.4 \pm 1.0 (^{+3.2}_{-2.9})^\circ \) |
| \( \theta_{23} = 42.8^{+4.7}_{-2.9} (^{+10.7}_{-7.3})^\circ \) |
| \( \theta_{13} = 5.6^{+3.0}_{-2.7} (\leq 12.5)^\circ \) |
| \( \left[ \sin^2 \theta_{13} = 0.0095^{+0.013}_{-0.007} (\leq 0.047) \right] \) |
| \( \left[ 0.008^{+0.012}_{-0.007} (\leq 0.043) \right] \) |
| \( \delta_{\text{CP}} \in [0, 360] \) |

Although gigantic steps forward have been achieved in the past fifteen years and with the recent observation of a \( \tau \) candidate from the appearance of a \( \nu_e \) in a pure \( \nu_\mu \) beam [6], there are still two unknown angles (\( \theta_{13} \) and \( \delta_{\text{CP}} \)), the mass hierarchy is still to be determined, the evidence for neutrino oscillations in the \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) channel at a scale of \( \Delta m^2 \approx 0.1 \text{ eV}^2 \) is still debated and needs more solid confirmation [7]. Furthermore, the absolute neutrino mass is still unknown [8]. In the coming year the T2K experiment [9] should provide an unambiguous evidence for a non-zero \( \theta_{13} \) if above 3\(^\circ\). The discovery of a non-zero value for \( \theta_{13} \) will disclose the possibility to search for CP violation in the leptonic sector. Many ideas have been put forward to measure a non-zero value of \( \delta_{\text{CP}} \): Super-Beams, Beta-Beams and Neutrino Factory and will be reviewed in the next Sections. For details on the future facility sensitivities we refer to [10].

### 2. Super-Beams

In a Super-Beam facility neutrinos are produced in the standard manner, by bombarding a target with a proton beam and focusing the produced pions. However, the Super-Beam projects are different in two respects from the long-baseline facilities currently under construction: (1) the proton beam power is higher, around 4 MW, and (2) the neutrino detector is much bigger, typically around 1 Mt.

An interesting option for the Super-Beams is the possibility to tilt the beam axis a few degrees with respect to the position of the far detector (Off-Axis beams). According to the two body \( \pi \)-decay kinematics, all the pions above a given momentum produce neutrinos of similar energy at a given angle \( \theta \neq 0 \) with respect to the direction of parent pion (contrary to the \( \theta = 0 \) case where the neutrino energy is proportional to the pion momentum). These neutrino beams have several advantages with respect to the corresponding on-axis ones: they are narrower, lower energy and with a smaller \( \nu_e \) contamination (since \( \nu_e \)'s mainly come from three body decays) although the neutrino flux can be significantly smaller.
Figure 1. A schematic layout of the BetaBeam complex. At left, the low energy part is largely similar to the EURISOL project. The central part (PS and SPS) uses existing facilities. At right, the decay ring has to be built.

The technology of the Super-Beam is considered the most straightforward way to explore leptonic mixing in case of positive result from T2K and/or Double-Chooz [11] and, therefore, it is viewed as a solid option in Japan (Tokai to HyperKamiokande) and US (Fermilab/Project X to DUSEL) [12]. Unfortunately, it also shows evident limitations:

- It is not a “pure” source of neutrinos of a given flavor, being plagued by the $\nu_e$ produced by the decay-in-flight of the kaons and of the muons. When seeking for subdominant $\nu_\mu \to \nu_e$ transitions, the systematics on the knowledge of the $\nu_e$ contamination will likely be the main limitation for a precise determination of CP violation in the leptonic sector [13];
- It produces mainly $\nu_\mu$ and, therefore, the leptonic mixing is studied through $\nu_\mu \to \nu_e$ and its CP conjugate $\bar{\nu}_\mu \to \bar{\nu}_e$, i.e. looking for electrons in the final state instead of muons. It thus requires huge, low density detectors to be hosted in underground sites (see below);
- in a Super-Beam, CP violation appears as an asymmetry between the probability of transition $\nu_\mu \to \nu_e$ and its CP conjugate $\bar{\nu}_\mu \to \bar{\nu}_e$. At low proton energies, the production yield of $\pi^-$ is suppressed with respect to $\pi^+$. This suppression, together with the suppression due to the cross section ($\sigma_{\nu} / \sigma_{\bar{\nu}} \simeq 1/2$), makes the antineutrino run much more time-consuming than the neutrino run.

A multi-MW proton accelerator and the corresponding neutrino beamline is considered feasible in less than a decade [14] but it requires a substantial effort in accelerators and targetry, a major resource investment and feedback from the operation of neutrino facilities in the sub-MW range (firstly T2K).

3. Beta-Beams

The enormous progress in the technology of Radioactive Ion Beams has led P. Zucchelli [15] to the proposal of a neutrino facility based on the decay in flight of $\beta$-unstable ions (for a full review see [16]). “Beta-Beams” (BB) are pure sources of $\bar{\nu}_e$ or, in the occurrence of $\beta^+$ decays, of $\nu_e$. Hence, they are ideal tools to study $\nu_e \to \nu_\mu$ transitions and their CP-conjugate. They share with the Neutrino Factory (NF) the nearly complete absence of systematics in the knowledge of the source with the bonus of no “right sign muon” background (no $\nu_\mu$ in the initial state). On the other hand, due to the very different mass-to-charge ratio between muons and $\beta$-unstable ions, the energy of the neutrinos are typically much smaller than what can be obtained at the
NF. The original proposal of [15] was tuned to leverage at most the present facilities of CERN - the PS and the SPS - and it was based on $^6$He and $^{18}$Ne as $\nu_e$ and $\nu_\mu$ sources respectively, see Figure 1. Beta-Beam triggered the interest of nuclear physics community, which was offered a stimulating synergy with the neutrino programme at CERN. As a result, such proposal [17, 18] was studied in a systematic manner within the framework of the EURISOL Design Study. The study aimed at $2\times10^{18}$ antineutrinos per year from $^6$He and $1.1\times10^{18}$ neutrinos per year from $^{18}$Ne. The outcome was extremely encouraging, except for the production of $^{18}$Ne, which cannot attain the needed rate using standard methods and medium-intensity proton accelerators (200 kW). Along this line, the most straightforward alternative would be direct production on MgO based on a 2 MW, few MeV, proton accelerators, which are quite similar to the linacs that have to be built for the International Fusion Materials Irradiation Facility [19]. In this case, the BB would partially miss the advantage of a low-power front-end compared with the multi-MW accelerators needed for the Superbeams and for the NF, although a few tens of MeV MW accelerator is anyway a much simpler machine than a few GeV MW Linac. From the point of view of the physics performance, an additional weakness stems from the fact that the SPS is able to accelerate these ions up to relatively low energies, so that the corresponding emitted neutrinos are just in the sub-GeV range. This impacts on the choice of the detectors and on the cross-sections, which are highly depleted.

To improve the performance of the Eurisol Beta-Beam several alternatives to the SPS have been considered: a high energy SPS (“SuperSPS” [20]) accelerating protons up to 1 TeV (a machine originally envisaged for the energy and luminosity upgrade of the LHC) or even the LHC itself [21, 22]. These configurations improve the sensitivities to CP violation and the mass hierarchy at the expense of a large increase of costs: large investments are needed especially for the construction of the decay ring since the length of the ring depends from the magnetic rigidity of the circulating ions, which is proportional to their Lorentz $\gamma$ factor, and for the compensation of potential flux reduction due to the longer lifetime of the ion in the laboratory frame. In 2006, C. Rubbia et al. [23] proposed the use of $^8$Li and $^8$B as neutrino sources noting that these isotopes could be produced in a multturn passage of a low-energy ion beam through a low-Z target. In this case, ionization cooling techniques could increase the circulating beam lifetime and thus enhance the ion production to a level suitable for the BB. This option has the advantage of employing isotopes with higher $Q$-value than $^{18}$Ne and $^6$He, increasing correspondingly the neutrino energy (from $\sim0.5$ to $\sim1.5$ GeV for the SPS-based BB). This alternative approach will be at focus in the framework of the EURO$\nu$ Design Study [24]. A drawback with respect to the use of low-$Q$ ions is that the flux at the far location is smaller due to the larger beam divergence and a larger amount of ions stacked in the decay ring is needed. Although the BB optimization is a complex task [25, 26, 27], some simple scaling laws can be used as reference. For a given number of decays per year $N_\beta$, if we label with $\gamma$ the Lorentz factor of the ion (which depends on the machine employed to accelerate the ion), with $Q$ the $Q$-value of the isotope and with $L$ the source-detector distance, the events at the far location are proportional to the convolution of the flux ($\phi \sim \gamma^2/L^2$), of the cross section ($\sigma \sim E_\nu \sim Q\gamma$) and of the oscillation probability, times $N_\beta$. If the facility is operated at the maximum of the oscillation probability, then $1.27\Delta m^2 L/E_\nu = \pi/2$; therefore, $L \sim Q\gamma$. As a result the number of events are proportional to $N_\beta\gamma/Q$. Note, however, that also $N_\beta$ has a dependence on $\gamma^{-1}$ due to the increase of the ion lifetime in the lab frame at larger $\gamma$.

1 The EURISOL Design Study was a Project funded by the European Community within the 6th Framework Programme as a Research Infrastructures Action under the "Structuring the European Research Area Specific Programme". The Project started officially on Feb 2005, and has been completed on spring 2009.

2 EURO$\nu$ [24] is a FP7 Design Study which started on Sept 2008 and will run for 4 years. The primary aims are to study three possible future neutrino oscillation facilities for Europe (a Superbeam from CERN-to-Frejus, a RAL or CERN based NF and high-$Q$ BB) and do a cost and performance comparison.
Summarizing, a high-Q BB needs a smaller $\gamma$ for the same neutrino energy, with the advantage that an accelerator of larger energy than the SPS would not be needed and that the length of the decay ring could be shortened. On the other hand, given the Beta Beam kinematics, for the same baseline $L$ an high-Q BB needs an order of magnitude more ions at the source to match the performance of a high-$\gamma$ BB.

In general, the clarification of the issue of the ion production yield is considered a crucial milestone for the BB. Given an appropriate yield, the acceleration and stacking is viewed as less demanding than what is needed for a NF both from the point of view of R&D and cost. Clearly, the possibility of employing existing facilities (e.g. the CERN PS-SPS complex or its upgrades) might substantially strengthen this option.

4. Neutrino Factory

Production, acceleration and stacking of high intensity muon beams for muon colliders have been envisaged since the 60’s and it has been noted very early that their decays might produce useful beams of $\nu_\mu$ and $\overline{\nu}_\tau$ (exploiting $\mu^-$ decays into $e^-\overline{\nu}_\tau\nu_\mu$) or $\overline{\nu}_\mu$ and $\nu_e$ ($\mu^+$ decays into $e^+\nu_e\overline{\nu}_\mu$). However, realistic layouts to get intense neutrino sources have become available only in recent times [28]. In the modern formulation of the “Neutrino Factory” concept, muons are created from an intense pion source at low energies, their phase space compressed to produce a bright beam, which is then accelerated to the desired energy and injected into a storage ring with long straight sections pointing in the desired direction. In 1997 S. Geer [29] noted that this source could be ideal to study $\nu_e \leftrightarrow \nu_\mu$ oscillations at the atmospheric scale, i.e. the T-conjugate of the channel observed in Superbeams ($\nu_\mu \leftrightarrow \nu_e$). Since $\mu^+$ decays into $e^+\nu_e\overline{\nu}_\mu$, it is possible to investigate $\nu_e \rightarrow \nu_\mu$ oscillations seeking for the appearance of $\mu^-$ from $\nu_\mu$ CC events ("wrong sign muons"), provided that we are able to separate these events from the bulk of $\mu^+$ ("right sign muons") coming from unoscillated $\overline{\nu}_\mu$. A. De Rujula et al. [30] underlined that the simultaneous exploitation of $\mu^-$ and $\mu^+$ decays would be an ideal tool to address CP violation in the leptonic sector, with outstanding performance compared with pion-based sources. The only condition to be fulfilled was a large ratio $\Delta m^2_{12}/\Delta m^2_{23}$ and, of course, the finite size of $\theta_{13}$. The results from KAMLAND and SNO [31] confirming $\Delta m^2_{23} \simeq 1/30$ boosted enormously Geer’s proposal, together with the above-mentioned proposals for Superbeams. The realization of the NF represents a major accelerator challenge compared with Super-Beams.

It is met through a world-wide R&D programme [32]; in Europe this programme is especially fostered by UK. Among the NF-oriented projects we recall MICE [33] at the Rutherford Appleton Laboratories (ionization cooling), HARP [34] at CERN (hadroproduction for the front-end proton accelerator), MERIT [35] at CERN (targetry), EMMA [36] at Daresbury (fixed-field alternating-gradient accelerators) and the MUCOOL R&D [37] at Fermilab (radio-frequency and absorbers). Moreover, the NF has to be seeded by a very powerful low-energy proton accelerator (4 MW); its realization requires similar R&D as for the Superbeams, although its optimal energy lays in the few-GeV range (e.g. the aforementioned SPL). Current designs aim at $10^{21}$ muons per year running with a muon energy of 50 GeV, although more realistic scenarios suggest decay rates in the ballpark of $2 - 5 \times 10^{20}$ decays/y and with energies in the 20-50 GeV range (corresponding to neutrinos in the 10-30 GeV range) [38]. After the work of the International Scoping Study (ISS) [12, 39, 40], there is a rather widespread consensus on the fact that the Neutrino Factory can be considered the most performing facility for the determination of $\theta_{13}$, CP violation and the mass hierarchy. With respect to Super-Beams, neutrino factories profit of much smaller systematics in the knowledge of the source and much higher energies (i.e. statistics, due to the linear rise of the deep-inelastic $\nu_\mu$ cross section with energy). In fact, the energy is so high that for any realistic baseline (< 7000 km) the ratio $L/E$ will be off the peak of the oscillation maximum at the atmospheric scale. This condition is the main cause of the occurrence of multiple solutions when the mixing parameters are extracted.
from the physics observables, i.e. the rates of appearance of wrong sign muons. In jargon, this issue is dubbed the “degeneracy problem” [12, 41]. It also affects other facilities than NF but it is particularly severe for experiments running off the peak of the oscillation probability. The ISS suggests as an ideal solution the positioning of two detectors at baseline around 3000 and 7000 km. An alternative to the second 7000 km detector could be the detection of $\nu_e \rightarrow \nu_\tau$ at baseline around 1000 km (“silver channel”) [42] (see below). The exploitation of the silver channel, moreover, is useful to investigate the occurrence of non-standard interactions in the neutrino sector [43]. Although the superior physics reach of the Neutrino Factory is nearly undisputed and no evident showstoppers have been identified, the R&D needed to build this facility remains impressive. In turn, the time schedule for its realization and the cost estimate are vague (∼2020 after an investment of 1-2 Billion$). On the other hand, a clear indication on the size of $\theta_{13}$ will enormously boost the interest of particle physics on this technology. Neutrino Factories are virtually capable of performing real precision physics on the leptonic mixing in a way that resembles the former physics potential of the b-factories on quark mixing.

![Figure 2. Expected layout for a neutrino factory at CERN.](image)

5. Detectors
A discussion of the possible detector technologies that will exploit future neutrino facilities is not the goal of this paper. Therefore, we only briefly recall the optimal technology for each facility and we refer to the detector group of the International Scoping Study for details [40]. The baseline detector options for each possible neutrino beam are defined as follows:

- a very massive (Megaton) water Cherenkov detector is the baseline option for a sub-GeV Beta-Beam and Super-Beam facility;
- there are a number of possibilities for either a Beta-Beam or Super-Beam medium energy facility between 1-5 GeV. These include a totally active scintillating detector (TASD), a liquid argon TPC or a water Cherenkov detector;
- A 100 kton magnetized iron neutrino detector (MIND) is the baseline to detect the wrong sign muon final states (golden channel) at a high energy (20-50 GeV) neutrino factory from...
muon decay. A 10 kton hybrid neutrino magnetic emulsion cloud chamber detector for wrong sign tau detection (silver channel) is a possible complement to MIND, if one needs to resolve degeneracies that appear in the $\delta_{\text{CP}} - \theta_{13}$ parameter space.

6. Conclusion

We want to conclude this paper by comparing the CP violation discovery reach of the different experiments, see Fig. 3. From this figure it is clear that the current generation of experiments will explore a very small region of the CP phase and most likely will not be able to establish CP violation. The Super-Beam upgrades discussed before can measure CP violation for most of the parameter space if $\sin^2 2\theta_{13} > 0.01$. It is worth noting that values of $\sin^2 2\theta_{13}$ larger that 0.01 will be in the reach of the current generation of accelerator and reactor experiments. For smaller values of $\sin^2 2\theta_{13}$ ($\ll 0.01$) the Super-Beams are useless and only different versions of the Neutrino Factory or of the Beta-Beam can measure CP violation. For details on the physics reach of future neutrino facilities we refer to [10].

References

[1] A. De Gouvea, Mod. Phys. Lett. A 19 (2004) 2799 [arXiv:hep-ph/0503086].
[2] A. Strumia, F. Vissani, [hep-ph/0606054].
[3] L. Wolfenstein, Phys. Rev. D17 (1978) 2369. S.P. Mikheev and A.Y. Smirnov, Nuovo Cim. C9 (1986) 17.
[4] K. Kimura, A. Takamura and H. Yokomakura, Phys. Rev. D 66 (2002) 073005 [arXiv:hep-ph/0205295].
[5] E. K. Akhmedov, R. Johansson, M. Lindner, T. Ohlsson and T. Schwetz, JHEP 0404 (2004) 078 [arXiv:hep-ph/0402175]. M. Freund, Phys. Rev. D 64 (2001) 053003 [arXiv:hep-ph/0103300].
[6] M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, JHEP 1004 (2010) 056. [arXiv:1001.4524 [hep-ph]].
[7] N. Agafonova et al. [ OPERA Collaboration ], Phys. Lett. B691 (2010) 138-145. [arXiv:1006.1623 [hep-ex]].
[8] A. A. Aguilar-Arevalo et al. [The MiniBooNE Collaboration], Phys. Rev. Lett. 105 (2010) 181801 [arXiv:1007.1150 [hep-ex]].
[9] Y. Itow et al. [The T2K Collaboration], arXiv:hep-ex/0106019.
[10] M. Mezzetto, these proceedings.
[11] F. Ardellier et al. [Double Chooz Collaboration], arXiv:hep-ex/0606025.
[12] A. Bandopadhyay et al. [JSPS Physics Working Group], arXiv:0710.4947 [hep-ph].
[13] P. Huber, M. Mezzetto and T. Schwetz, JHEP 0803 (2008) 021.
[14] J. Hylen, talk at 11th International Workshop on Neutrino Factories, Superbeams and Beta Beams (Nufact09), Chicago, IL, July 20-25, 2009.
[15] P. Zucchelli, Phys. Lett. B 532 (2002) 166.
[16] M. Lindroos and M. Mezzetto, “Artificial Neutrino Beams: Beta Beams”, Imperial College Press, Aug. 2009.
[17] J. E. Campagne, M. Maltoni, M. Mezzetto and T. Schwetz, JHEP 0704 (2007) 003.
[18] J. Bouchez, M. Lindroos and M. Mezzetto, AIP Conf. Proc. 721 (2004) 37.
[19] M. Martone et al., “International Fusion Materials Irradiation Facility Conceptual Design Activity”, RT/ERG/FUS/96-11.
[20] O. Bruning et al., “LHC luminosity and energy upgrade: A feasibility study,” CERN-LHC-PROJECT-REPORT-626.
[21] J. Burguet-Castell, D. Casper, J. J. Gomez-Cadenas, P. Hernandez and F. Sanchez, Nucl. Phys. B 695 (2004) 217; F. Terranova, A. Marotta, P. Migliozzi and M. Spinetti, Eur. Phys. J. C 38 (2004) 69; S. K. Agarwalla, A. Raychaudhuri and A. Samanta, Phys. Lett. B 629 (2005) 33.
[22] A. Donini, E. Fernandez-Martinez, P. Migliozzi, S. Rigolin, L. Scotto Lavina, T. Tabarelli de Fatis and F. Terranova, Eur. Phys. J. C 48 (2006) 787; A. Donini et al., Eur. Phys. J. C 53 (2008) 599.
[23] C. Rubbia, A. Ferrari, Y. Kadi and V. Vlachoudis, Nucl. Instrum. Meth. A 568 (2006) 475.
[24] Information and documentation available at http://www.euronu.org/.
[25] A. Donini and M. Lindroos, “Optimisation of a beta beam,” Talk at 10th International Workshop on Neutrino Factories, Superbeams and Betabeams: Nufact08, Valencia, Spain, 30 Jun - 5 Jul 2008.
[26] S. K. Agarwalla, S. Choubey, A. Raychaudhuri and W. Winter, JHEP 0806 (2008) 090.
[27] W. Winter, Talk given at 10th International Workshop on Neutrino Factories, Superbeams and Betabeams: Nufact08, Valencia, Spain, 30 Jun - 5 Jul 2008, arXiv:0809.3890 [hep-ph].
[28] S. Geer, Lecture at the 1st International Neutrino Factory Summer Institute, Abingdon, UK, June 24-29, 2002.
[29] S. Geer, Phys. Rev. D 57 (1998) 6989 [Erratum-ibid. D 59 (1999) 039903].
[30] A. De Rujula, M. B. Gavela and P. Hernandez, Nucl. Phys. B 547 (1999) 21.
[31] Q. R. Ahmad et al. [SNO Collaboration], Phys. Rev. Lett. 87 (2001) 071301.
[32] A. Bross, “The Neutrino Factory: The Final Frontier in Neutrino Physics?” FERMILAB-CONF-09-169-APC, Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.
[33] G. Gregoire et al. [MICE Collaboration] “MICE: Muon Ionisation Cooling Experiment, Technical Reference Document.”, MICE-TRD-2005 (2005).
[34] M.G. Catanesi et al., [HARP Collaboration] “Proposal to study hadron production for the neutrino factory and for the atmospheric neutrino flux”, CERN-SPSC/99-35 (1999).
[35] H.G. Kirk et al., “The MERIT High-Power Target Experiment at the CERN PS”, EPAC08-WEPP169, FERMILAB-CONF-08-224-APC, presented at the European Particle Accelerator Conference (EPAC 08), Genova, Italy, 23-27 Jun 2008.
[36] R. Edgecock et al., “EMMA - the World’s First Non-scaling FFAG”, EPAC08-THPP004 (2008), presented at the European Particle Accelerator Conference (EPAC 08), Genova, Italy, 23-27 Jun 2008.
[37] J. Norem et al. “The MUCOOL RF Program.”, FERMILAB-CONF-06-387-AD, JLAB-ACC-06-481; presented at the European Particle Accelerator Conference (EPAC 06), Edinburgh, Scotland, 26-30 Jun 2006.
[38] S. Geer and M. S. Zisman, Prog. Part. Nucl. Phys. 59 (2007) 631.
[39] J. S. Berg et al. [ISS Accelerator Working Group], JINST 4 (2009) P07001.
[40] T. Abe et al. [ISS Detector Working Group], JINST 4 (2009) T05001.
[41] V. Barger, D. Marfatia and K. Whisnant, Phys. Rev. D 65 (2002) 073023.
[42] A. Donini, D. Meloni and P. Migliozzi, Nucl. Phys. B 646 (2002) 321. D. Autiero et al., Eur. Phys. J. C 33 (2004) 243.
[43] J. Kopp, T. Ota and W. Winter, Phys. Rev. D 78 (2008) 053007.
[44] J. Bernabeu, M. Blennow, P. Coloma et al., ”EURONU WP6 2009 yearly report: Update of the physics potential of Nufact, superbeams and betabeams,” [arXiv:1005.3146 [hep-ph]].