PROCEEDINGS OF SCIENCE

Summary of Working Group I: Theory

S. Choubey[a], **P. Hernández**[b]*, **and C. W. Walter**[c]
(a) Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad 211019, India.
(b) IFIC-Universidad de Valencia and CSIC, Edif. Institutos de Investigación, Valencia 46071.
(c) Department of Physics, Duke University, Durham NC 27708, USA
E-mail: sandhya@hri.res.in, pilar.hernandez@ific.uv.es, chris.walter@duke.edu

We present the highlights of the parallel sessions of Working Group I at Nufact08.

10th International Workshop on Neutrino Factories, Super beams and Beta beams
June 30 - July 5 2008
Valencia, Spain

*Speaker.

PoS(Nufact08)026

1. Introduction

The main motivation of a future neutrino physics programme is to understand what new physics is associated with the neutrino masses. If the scale of this new physics, Λ, is much larger than the electroweak scale, there is a natural explanation of why neutrinos are so light. Indeed the effects of *any* such new physics must be generically well described at low energies by an effective Lagrangian which contains the Standard Model, plus a tower of higher dimensional operators constructed with the SM fields and satisfying all the gauge symmetries:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{\alpha_i}{\Lambda}\mathscr{O}_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2}\mathscr{O}_i^{d=6} + \ldots \tag{1.1}$$

The effective operators, $\mathscr{O}_i$, are ordered by their mass dimension, since the higher the dimension, the higher the power of Λ that suppresses them. The dominant operator is therefore the lowest dimensional one, with $d = 5$, which is precisely the Weinberg's operator:

$$\mathscr{O}^{d=5} = \bar{L}^c \Phi\Phi L, \tag{1.2}$$

which as is well known induces three new ingredients to the minimal SM:

- Neutrino masses
- Lepton flavor mixing
- Lepton number violation

In this context, neutrino masses are very small, because they come from an effective operator which is suppressed by a high energy scale. If we go to operators of $d = 6$, that are suppressed by two powers of Λ, these will generically induce new physics in dipole moments, rare decays, etc. Beyond $d = 6$ we would find operators inducing non-standard neutrino interactions (NSI).

It is also possible that the scale Λ is at or below the electroweak scale, or in other words that neutrino masses are linked to a *hidden* sector which we have not detected yet, because it is so weakly interacting. Such scenarios do nor offer an explanation of why neutrinos are light, but neutrinos are the natural messsengers with such hidden sectors, since they are the only particles in the SM carrying no conserved charge. Such new physics could be related to other fundamental problems in particle physics such as the origin of dark matter and dark energy.

Although we probably cannot fully understand the new physics associated with neutrino masses by measuring them, it is quite clear that we have a good chance to learn something more about it by testing the standard scenario of 3ν mixing with future and more precise neutrino experiments. In particular we should be able to measure all the fundamental parameters: three mass eigenstates (m_1^2, m_2^2, m_3^2), three angles $(\theta_{12}, \theta_{13}, \theta_{23})$ and one or three CP-violating phases $(\delta, \alpha_1, \alpha_2)$.

2. Testing the standard 3ν scenario

Many studies in the last ten years have shown that we can measure the unknown angle θ_{13}, discover leptonic CP violation and determine the neutrino hierarchy in more precise neutrino oscillation experiments which look $\nu_e \leftrightarrow \nu_\mu$ oscillations with a frequency driven prodominantly by the "atmospheric mass squared difference" Δm^2_{31}. The status of last year's comparitive summary of the reach of the different facilities is shown in Fig. 1 [1]. In these figures, it is clear that the discovery potential of neutrino factories (NF) and β-beams (BB) is much better than other alternatives. However, the comparison between the two themselves is not quite fair in these figures. While the Neutrino Factory setups involve two baselines and higher neutrino energies, the ones of the β-beam involve only one baseline and lower neutrino energy.

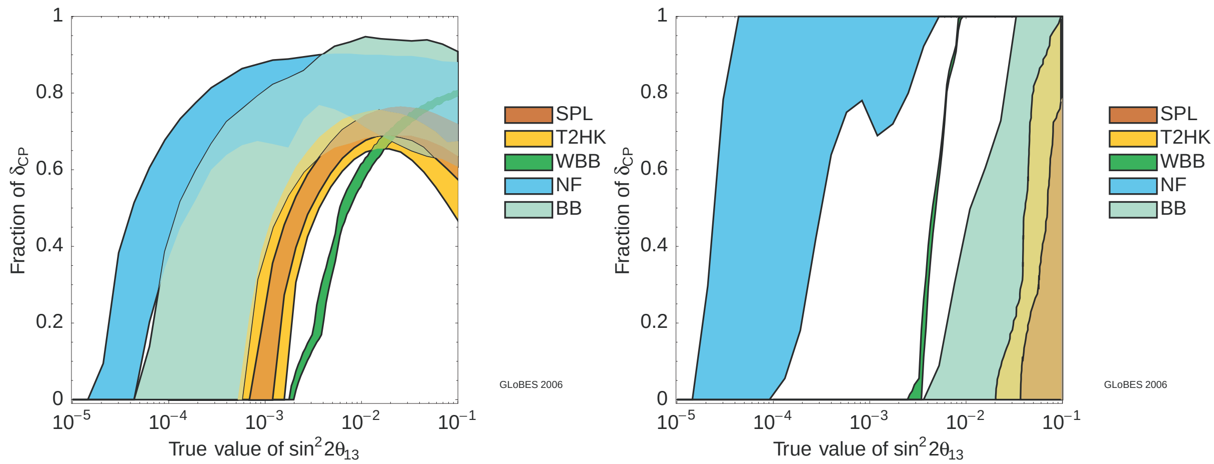

Figure 1: Comparison of the physics reach of different future facilities in leptonic CP violation (left) and the neutrino mass hierarchy (right). Taken from [1].

We had several parallel talks concerning further upgrades of the β-beam to match the NF optimal setup standards [2, 3]. In particular, the sensitivity to the neutrino hierarchy of the BB in Figure 1 is rather limited. A possible way to improve the situation is to increase the energy of the BB. This can be achieved by increasing γ or by changing the ions. The use of Li and B instead of the standard He and Ne with a boost of $\gamma = 350$ produces a BB with energies of a few GeV as shown in Figure 2. For such large energies, water Cerenkov detectors are no longer optimal, so a MIND-type iron calorimeter detector was considered in this context. The left plot of Figure 3 shows the CP-violation reach of a setup consisting of two baselines: one close to the first atmospheric maximum (L=2000 km) and the other at the *magic* baseline (L=7000 km). A comparable sensitivity to CP violation as compared to the He/Ne BB [4] requires a increase in the ion production of a factor 5 to compensate the smaller detector mass. The sensitivity to the hierarchy is however very significantly improved even for the lower intensities, as shown on the right plot of the same figure. A possible set-up for implimenting this magic baseline BB experiment could be to shoot a beam from CERN to INO [5].

A two baseline BB setup based at CERN was also presented in [3]. In this case a He/Ne BB with $\gamma = 250 - 650$ and a TASD detector located in Gran Sasso was combined with a B/Li BB with $\gamma = 650$ and the INO detector at 7152 Km distance. The sensitivity to CP violation as shown in Figure 4 is clearly spectacular. In fact, this set-up with larger flux intensity could return sensitivity to all the three quantities, θ_{13}, CP studies and mass hierarchy, which is comparable to that possible with a neutrino factory [3]. It is unclear however whether such high γ's could be efficiently produced at CERN.

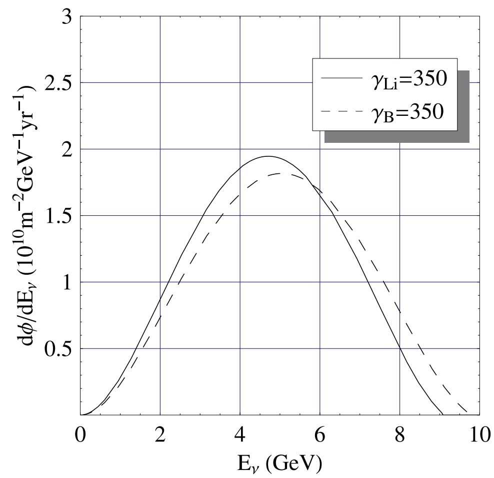

Figure 2: Neutrino fluxes of a BB from Li and B at $L = 2000\ km$ for 10^{18} ion decays per year. Taken from [2].

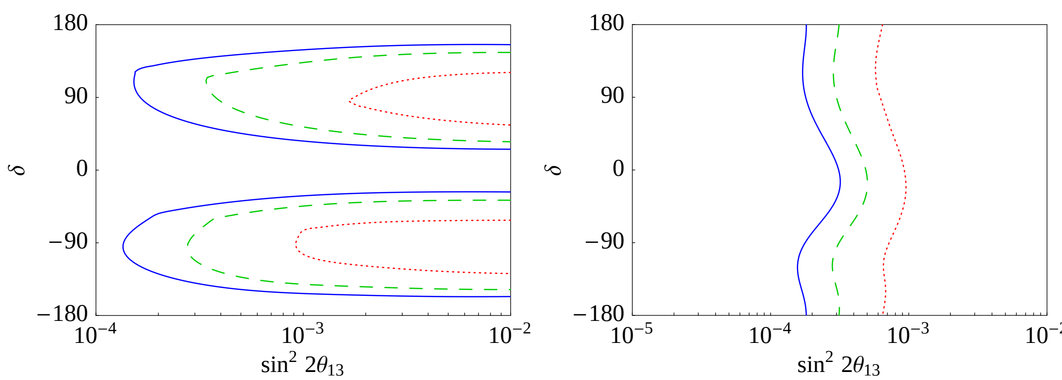

Figure 3: Left: Discovery potential of CP violation for the Li/B BB with two baselines. The different curves correspond to different ion intensities from 2×10^{18} per year to 10^{19} per year. Right: Sensitivity to the hierarchy of the same option. Taken from [2].

Of course the most pressing question is if a BB with neutrino energies of a few GeV and a ion rate $\geq 10^{19}$ is possible. We had an interesting joint session of WG1 and WG3 to discuss this issue (see summary of the discussion in [6]). It was pointed out that there is a physics-reach scaling law: the same physics is obtained for two ions with end-point energies $E_0^{(1)}$ and $E_0^{(2)}$ if the number of decaying ions, N_β and boost factors γ are scaled like:

$$\frac{N_\beta^{(1)}}{N_\beta^{(2)}} \simeq \left(\frac{E_0^{(1)}}{E_0^{(2)}}\right)^2 \qquad \frac{\gamma^{(1)}}{\gamma^{(2)}} \simeq \frac{E_0^{(2)}}{E_0^{(1)}}. \tag{2.1}$$

Therefore one can trade intensity for boost by changing the parent ions. There are several critical issues that must be studied carefully: achievable ion production rates, activation issues, the design of the decay ring, etc. The good news is that such greenfield scenarios will be considered within

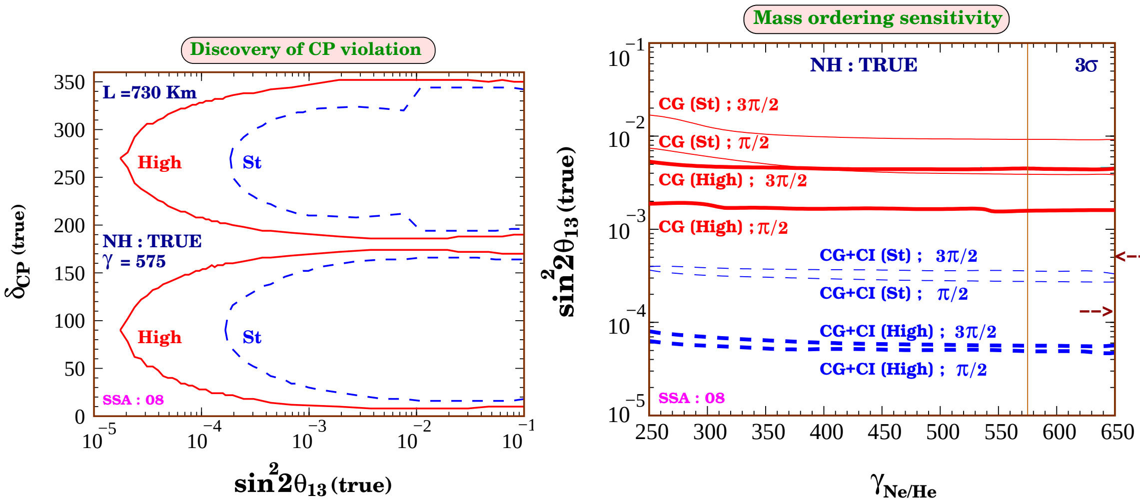

Figure 4: Left: Discovery potential of CP violation for the He/Ne BB with two baselines at 730 km (CERN-Gran Sasso) with a TASD detector and at 7000 km (CERN-INO) with INO detector. *St.* refers to the standard luminosities of [1], while *High* refers to five times more. Right: Sensitivity to the hierarchy of the same option (blue lines) only the long baseline (red). Taken from [3].

the EUROnu design study that has just been funded by the EU [7].

Another avenue that was presented in the meeting was the downgrading of these facilities, with the goal of finding cheaper options to do the same physics if the angle θ_{13} turns out to be large, ie. within 90% of D-Chooz reach. If this is the case, the *minimal* BB that can provide a 5σ confirmation of $\theta_{13} > 0$, a 3σ determination of the mass hierarchy for any value of δ and a 3σ discovery of leptonic CP violation for 80% of the possible values of δ is the He/Ne with L$\sim$ 730 km and $\gamma > 150$ BB as shown in Fig. 5 [8].

In the context of the NF, we had a talk on the low-energy NF [9] that refers to a setup which assumes 10^{21} muon decays per year, $E_\mu = 5$ GeV and a baseline of 1290 km. The main idea was to use a non-magnetized detector such as a large Water Cerenkov or Liquid Argon in order to achieve a larger detector mass. Even though at the NF it is important to distinguish the charge in order to establish the appearance signal, a significant discrimination of ν and $\bar{\nu}$ is still possible from: 1) the different spectral shapes of ν and $\bar{\nu}$ events, 2) the separation of events with μ decays versus those with μ capture, 3) the angular dependence of the events and 4) the neutron tagging. Figure 6 shows the reach in CP violation of such a LE-NF with two different detector technologies for various values of the discrimination power, as compared to the wide-band-beam (WBB), showing a significant improvement if the charge can be measured with a probability above 50 %.

3. Synergies with other physics searches

The advantage of the setups that involve a very massive Megaton detector, such as the one involved in most BB setups is that they would be very usefull for other complementary physics searches. We had three presentations on a few of such possibilities:

- Atmospheric neutrinos [10]

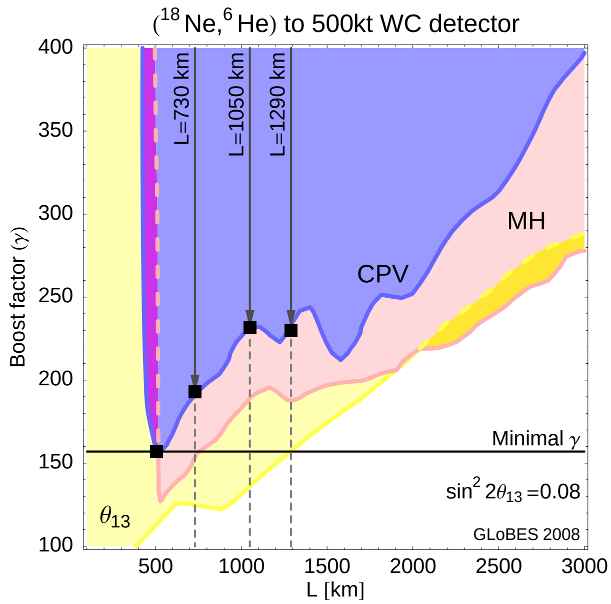

Figure 5: Regions where a 5σ confirmation of $\theta_{13} > 0$ (yellow), a 3σ determination of the mass hierarchy (pink) and 3σ discovery of CP violation (blue) in the (γ, L) plane for a He/Ne BB. Taken from [8].

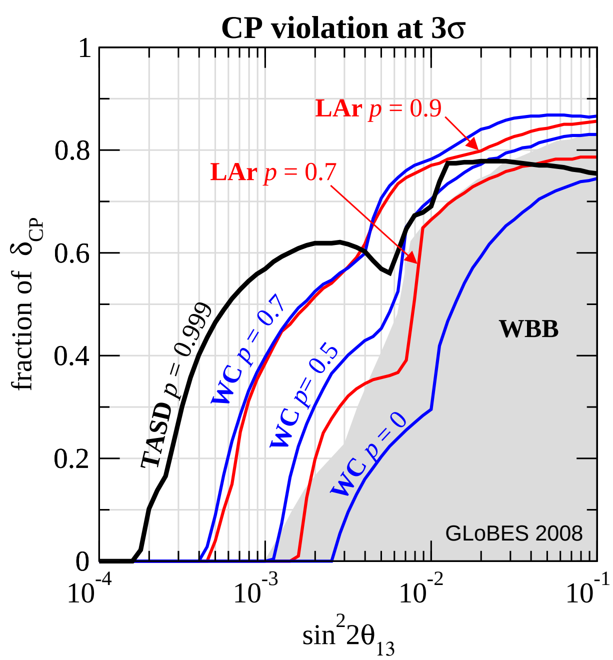

Figure 6: CP violation discovery reach for a LE-NF with various levels of charge discrimination as compared to the Wide Band Beam. Taken from [8].

- Solving dark-matter degeneracies [11]
- Supernova neutrinos [12]

Atmospheric data is for free and Maltoni [10] showed how these data in principle contain very valuable information on the fundamental parameters θ_{13}, δ and the hierarchy. The combination of these data with beam measurements could be very usefull in solving degeneracies. Revealing this rich structure requires however a significant refinement of the data analysis technique. These improvements and optimizations are foreseable and most welcome.

We had a talk on the possibility to solve dark-matter degeneracies by measuring neutrino spectra from dark matter annihilation in a MIND-type detector. The spectra could help discriminate between different decay channels of the dark matter particle, therefore providing complementary information to that provided by dark matter searches.

Finally we also had a talk on supernova neutrinos [12]. A deep revision of predictions of supernova neutrino fluxes has recently taken place. Interesting collective effects of neutrino propagation in a supernova core have been found, which are very sensitive to the type of neutrino hierarchy. Indeed measuring the neutrino flux of a galatic supernova could actually be the only chance to determine the hierarchy for extremely small values of the angle θ_{13}! The strategy is to measure the ratio of neutrino fluxes in a detector shadowed by the Earth and another one that is not. For $\sin^2\theta_{13} \leq 10^{-5}$, it might be possible to determine the hierarchy from this measurement. It will be important to find the detector in a location with a significant shadowing probability for a Galactic SN. For example Canfranc's underground laboratory has a shadowing probability of 0.57.

4. Non-standard Neutrino Interactions

Beyond the standard 3ν scenario, future facilities could significantly improve the search for non-standard neutrino interaction. The smallest dimension operator which could give NSI is of $d = 6$. However, due to $SU(2)_L$ gauge invariance, it gets severely constrained from charged lepton sector. Therefore, in order to have large NSI effects for neutrinos one could consider effective operators with $d = 8$ which impact only neutrinos and not charged leptons. They could be of the form:

$$\lambda_{\alpha\beta}\,\bar{f}\Phi^\dagger\gamma_\mu P_L L_\beta \bar{L}_\alpha \gamma_\mu P_L \Phi f \tag{4.1}$$

Even though there are no a priori theoretical reason why these interactions should be significant, they can only be searched for in neutrino oscillations experiments. We had three talks on this hot topic. First, Mitsuka [13] presented the first analysis of these searches at SK. Two studies of future constraints that are expected from Opera were presented in [14, 15], while future constrains at the Nufact were shown in [16, 17]. The latter studies show that if the combination of baselines in the NF was very important for resolving degeneracies in the standard scenario, it is even more so if there are NSI. Figure 7 shows the expected contraints on NSI at the NF, and how the presence of such interactions modify the determination of standard parameters.

It will be important to continue exploring what type of generic new physics the future facilities could access: NSI, but also low-energy see-saws, light sterile species, as well as other exotic explanations of LSND, dark matter or dark energy that involve neutrinos.

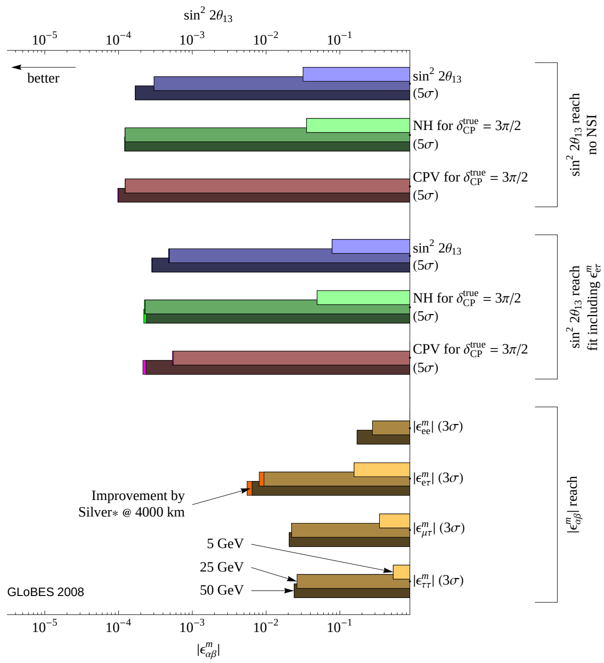

Figure 7: Sensitivity to the standard parameters without and with NSI interactions at the NF for three values of the μ energy: 5 GeV, 25 GeV and 50GeV. Taken from [17].

We could expect that the old faithfull ν will continue to bring surprises. One such possible surprise would be a signal for a heavy scalar triplet at LHC. Weinberg's operator of eq. (1.2) could be the result of integrating out a heavy scalar triplet: the scale Λ would be related to its mass. Such a particle could be produced in pairs at LHC giving rise to an extremely powerfull signal of same-charge lepton pairs. The flavour structure of such decays would be in one-to-one correspondance to that in the neutrino mass matrix providing therefore sensitivity to the standard 3ν mixing parameters [18].

References

[1] A. Bandyopadhyay *et al*, arXiv: 0710.4947 [hep-ph]. A. Donini *et al* AIP Conf. Proc. **981** (2008) 43 [arXiv:0712.0909 [hep-ph]].

[2] E. Fernández-Martinez in these proceedings and P. Coloma *et al*, JHEP 0805 (2008) 050.

[3] S. Agarwalla in these proceedings and S. Agarwalla *et al*, Nucl. Phys. B805 (2008) 305.

[4] J. Burguet-Castell *et al*, Nucl. Phys. B 695 (2004) 217.

[5] S. K. Agarwalla *et al*, Nucl. Phys. B 798, 124 (2008).

[6] A. Donini, *Optimization of a beta-beam* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)51`.

[7] http://hepwww.rl.ac.uk/euro-neutrino/.

[8] W. Winter in these proceedings and in arXiv: 0804.4000 [hep-ph].

[9] P. Huber in these proceedings and P. Huber and T. Schwetz, arXiv:0805.2019 [hep-ph].

[10] M. Maltoni, *Prospects and synergies between future atmospheric and LBL experiments* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)37`.

[11] S. Palomares-Ruiz, *Breaking Dark Matter Degeneracies with Neutrino Detectors* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)35`.

[12] A. Mirizzi, *Prospects of measuring theta13 and mass hierarchy via a supernova signal* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)39`.

[13] G. Mitsuka, *Limit on Non-Standard Interactions from the atmospheric neutrino data* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)59`.

[14] A. Esteban-Pretel*et al*, *Can OPERA help constraining neutrino NSI* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)57`.

[15] M. Blennow, *Non-standard interactions using the OPERA experiment* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)58`.

[16] S. Uchinami, *Probing non standard neutrino physics at T2KK and Nufact* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)56`.

[17] T. Ota in these proceedings and J. Kopp, T. Ota and W. Winter, 0804.2261 [hep-ph].

[18] J. Garayoa and T. Schwetz, *Neutrino mass hierarchy and Majorana CP phases* in proceedings of *10th International Workshop on Neutrino Factories, Super beams and Beta beams (NuFact08)*, June 30 – July 5 2008, Valencia, Spain `PoS(NUFACT08)38`.