

Physics Working Group Summary

2nd International Scoping Study Meeting of a Future
Neutrino Factory and Super-beam Facility

23-25 January, 2006

KEK, Tsukuba, Japan

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Chapter 1

Theory

As pointed out by Hitoshi Murayama in his plenary talk, theoretical neutrino physics is targeted towards answering “big questions”, such as

- What is the origin of neutrino mass?
- Did neutrinos play a role in forming galaxies?
- Did neutrinos play a role in the birth of the universe?
- Are neutrinos telling us something about unification of matter or forces?

Since it is not (yet) possible to answer these questions in general, the aim of the theory talks in this workshop was to illuminate on more specific questions related to these “big ones”.

A major issue for this workshop was the connection between quarks and leptons. Since Lisa Everett was not able to attend at short notice, Hitoshi Murayama replaced her talk by a presentation on flavor symmetry. While different generations share the same gauge quantum numbers, but have very different masses, this may point to a hidden flavor quantum number. Especially, the connection between small mixings and a hierarchy of masses for the quarks and charged leptons is very “unnatural”. Therefore, this hidden quantum numbers may be the same for the neutrino generations, but different for the charged lepton and quark generations. Since according to Noether’s theorem, a symmetry is always connected with a conserved quantity, the name “flavor symmetry” is used for this approach. In order to predict the quark and charged lepton mass hierarchies, the flavor symmetry is broken by a small vacuum expectation value. Since the underlying symmetries do not distinguish the three neutrino generations, all entries in the neutrino mass matrix should be of similar magnitude. Now one can use a random sampling of many such models (“anarchy”) to derive hints for the neutrino parameters. For instance, one prediction is a not too small value of θ_{13} .

A different approach to the connection between quarks and leptons was presented by Hisakazu Minakata. By quark-lepton complementarity, theorists want to understand phenomenological relationships between quarks and leptons at a deeper level. One example for such a relationship is

$$\theta_{\text{solar}} + \theta_{\text{Cabibbo}} = \theta_{\text{atm}} = \frac{\pi}{4}?. \quad (1.1)$$

This relationship may either have a deeper underlying reason, or it might be completely accidental. In order to implement quark-lepton complementarity, one interesting approach might be direct relationships between quark and leptons, such as identical charged lepton and up quark mass matrices ($U_\nu = V_{up} = V_{CKM}^\dagger$). Since the MNS and CKM mixing matrices are each composed of two such matrices (*e.g.*, $U_{MNS} = U_{lepton}^\dagger U_\nu$), simple (but different) textures in the lepton and down parts may account for the difference in lepton and quark mixing. Such approaches could allow the implementation in terms of GUT theories. Note that Eq. (1.1) may point towards the importance of future precision measurements of the neutrino oscillation parameters in order to verify such relationships.

Some different of the “big questions” were touched by the talk from Masataka Fukugita, who talked about applications of massive neutrinos in cosmology. According to him, the two most relevant remaining such applications are leptogenesis and neutrino mass bounds, where he mainly focused on the mass bounds. Since the evolution of large scale structure is now well understood (*i.e.*, massive neutrinos damp fluctuations on the horizon scale), neutrino mass bounds can be derived from the power spectrum. The power spectrum is measured by different approaches in different wave number ranges, such as by the cosmic microwave background (small k), galaxy and cluster surveys (medium k), weak gravitational lensing (medium-high k), and the Lyman Alpha Forest (high k). The limits for the neutrino mass is about 2 eV from CMB alone and can be improved to up to 0.43 eV including the Lyman Alpha Forest. However, as the speaker pointed out, the limit from CMB alone might actually be the most robust one, whereas systematics is an issue for the combination of techniques. Future large cluster surveys might, among other methods, improve these bounds down to about 0.03 eV. Though the number may not be directly comparable, this number is below the lower bound coming from neutrino oscillation $\sqrt{\Delta m_{31}^2} \sim 0.05$ eV. Better information on the neutrino parameters from oscillation experiments (such as the mass hierarchy and $|\Delta m_{31}^2|$) could be important at that time to compare the lower and upper bounds more adequately.

In summary, it was one of the main conclusions that neutrinos may play an important role in the origin of the universe and may be the key to understand the connection between quarks and leptons. The information from neutrino oscillation experiments will provide valuable information together with other particle physics experiments to infer on the nature of the universe.

Chapter 2

Phenomenology

Phenomenology talks in this workshop were mainly concerned with the question if there is anything else beyond three-flavor neutrino oscillations relevant for future neutrino oscillation facilities, and how one could test such contributions. In addition, the current and expected knowledge on the neutrino parameters especially from non-accelerator experiments was reviewed.

A rather general approach to unitarity tests for neutrino oscillations was shown by Zhi-zhong Xing. He translated the use of unitarity triangles from quarks to leptons. Though the CKM matrix is constrained to be unitary in the standard model, the MNS matrix originating from physics beyond the standard model may not be exactly unitary in see-saw models. However, it is expected to be almost unitary in all “realistic” see-saw models. Very interestingly, effective unitarity triangles in matter can be defined which change shape as function of the effective matter potential $\propto n_e E$ due to matter effects. For instance, increasing the energy makes the sides of some unitarity triangles more even, which means that it becomes easier to derive the area and therefore it the related quantity CP violation may be easier accessible. Constructing such unitarity could be one possible approach to test new physics effects in neutrino oscillations.

Michel Sorel discussed the status of the (3 + 2) scheme, which is constructed by three active neutrinos with small admixtures of two sterile neutrinos. The mass squared splittings would be of the order of 1 – 10 eV. Since one sterile neutrino is not sufficient anymore to accomodate the LSND data and all short baseline experiments with a null result, two sterile neutrino might be the next plausible alternative. If confirmed, this model would imply wrong assumptions for the backgrounds of superbeams, as well as the non-oscillation assumption for the near detectors would be wrong. This model may be challenged by atmospheric neutrino data after the Super-Kamiokande re-analysis, and may be finally tested by MiniBOONE. As a very interesting implication of this model, the two additionally introduced oscillation frequencies (such as Δm_{41}^2 and Δm_{51}^2) together with a CP violating phase in the 5-4 sector (different from δ_{CP}) may actually lead to CP violation in short baseline experiments.

As pointed out by Joe Sato, lepton flavor violating (LFV) effects may contribute to three-flavor neutrino oscillations. The description and incorporation of these effects faces many challenges. First of all, the effects could be present in the production or detection processes, or in the propagation of the neutrinos. Any contribution to the production process can usually be described by a superposition of states (compared to a “pure” flavor eigenstate). Similarly, one can treat the detection process in a simplified manner. For the propagation, however, one needs to modify the matrix describing the matter effects which could have many entries in flavor space. Note that the observed states (“in” and “out” states) of the Feynman diagrams representing the production-oscillation-detection mechanism are identical for different contributions, the effects need to be introduced at the amplitude level by a coherent summation of amplitudes. This implies strong correlations between the LFV and standard oscillation parameters, which may actually be different for different types of experiments. In addition, Joe Sato showed several models for LFV, such as they could come from MSSM penguins.

As far as the status and prospects of non-accelerator based neutrino property measurements are concerned, Sandhya Choubey reviewed many different approaches with an emphasis on future expectations. For example, better results for Δm_{21}^2 are expected from increased KamLAND statistics. This experiment is, however, at the “wrong” baseline for θ_{12} . A new long baseline reactor experiment at about $L \sim 60$ km might improve the θ_{12} precision. In addition, a Gadolinium loaded Super-Kamiokande experiment could improve the precisions of the solar parameters. For the atmospheric parameters, a large magnetized iron detector may provide results comparable to the long-baseline experiments. In addition, it could be used to test deviations from maximal mixing, and maybe the octant degeneracy.

Note that if the disappearance information at an accelerator experiment turned out to be one of the primary objectives in some physics cases of this study (such as for very small $\sin^2 2\theta_{13}$), a quantitative comparison between non-accelerator tests and the long-baseline experiments could be appropriate.

Chapter 3

Experiment

In the more experimental talks, possible superbeam alternatives were discussed and updates on the superbeam and neutrino factory experiment simulations were given. Takaaki Kajita presented the idea of “T2KK”, an experiment using the T2K neutrino beam targeted towards two identical half megaton-sized (or possibly quarter megaton-sized) Water Cherenkov detectors at the same off-axis angle. One of the detectors is supposed to be operated at the Kamioka site ($L = 295$ km), whereas the other one is supposed to be located at a much longer baseline ($L \simeq 1050$ km) in Korea. Though the event rates would be lower at the longer baseline, the stronger CP phase dependence (especially on the energy) and larger matter effects would lead to excellent correlation/degeneracy resolution capabilities and to a good mass hierarchy sensitivity. In addition, through the use of identical detectors, systematics errors (partially) cancel, which means that even an uncorrelated 10% systematics error would not limit the measurement severely.

Elena Couce gave an update on neutrino oscillation facilities using a Water Cherenkov detector. She used the different setups as given in Table 3.1. As a major new step, improved migration matrices were used. For instance, the mapping from incident neutrino energy to reconstructed energies can be described by such a matrix. Therefore, such matrices allow for a very realistic simulation of the detector response especially if the reconstructed energies of some interaction types (esp. for non-QE events) often lie off the actual (incident) neutrino energies. Because the beta beams are not intrinsically limited by the beam background, they, in principle, can go beyond $\sin^2 2\theta_{13} < 10^{-3}$. As she demonstrated, even the low intensity high energy beta beam option has therefore very competitive sensitivity reaches for CP violation and $\sin^2 2\theta_{13}$. In addition, the high energy beta beam option was the only one with a significant mass hierarchy sensitivity. Note that in this comparison so far neither correlations (uncertainties in the oscillation parameters other than θ_{13} and δ_{CP}) nor disappearance channels were included (work in progress). The competitiveness of the beta beam has lead to a vivid discussion about the principle differences between μ - π^\pm (relevant for beta beams) and e - π^0 (relevant for superbeams) discrimination. As pointed out later by J.J. Gomez-Cadenas and D. Casper in an E-mail discussion,

Name	T2HK	Low energy β -beam	High energy β -beam
L [km]	295	130	700
OA [°]	2	0	0
γ	n/a	100	350
m_{det}	500	500	500
$t_\nu + t_{\bar{\nu}}$	2.5+7.5	5+5	5+5
Intensity option “low”	2 MW	$2.9 \cdot 10^{18}$ He dpy	$2.9 \cdot 10^{18}$ He dpy
		$1.1 \cdot 10^{18}$ Ne dpy	$1.1 \cdot 10^{18}$ Ne dpy
Intensity option “high”	4 MW	10^{19} He dpy	10^{19} He dpy
		10^{19} Ne dpy	10^{19} Ne dpy

Table 3.1: Different setups as used by Elena Couce. The abbreviation “dpy” refers to useful decays/year.

the simulation was fully realistic. In addition, backgrounds are not at all low for the beta beams, but the reconstructed energy is very different from the incident neutrino energy (and therefore the diagonal terms in the migration matrices are less affected).

In my (Walter Winter) talk, two issues were addressed. First of all, physics with a “better” detector for a neutrino factory was discussed. For this purpose, an abstract detector with a better low energy threshold and better energy resolution was defined to identify the requirements to the detector working group. The physics results were shown as function of muon energy and baseline. It turned out that a better threshold would help very much for all measurements. However, despite extremely optimistic values were assumed, a better energy resolution would only contribute somewhat to mass hierarchy and CP violation measurements. In particular, the better threshold could make the 2000 to 4000 km baseline the more efficient $\sin^2 2\theta_{13}$ sensitivity baseline compared to the “magic baseline”. However, note that increasing the confidence level or decreasing the luminosity would lead to the re-appearance of the intrinsic degeneracy at this baseline. For the mass hierarchy and CP violation sensitivities, the $\sin^2 2\theta_{13}$ ranges could be substantially improved with a better detector. For $\delta_{\text{CP}} \sim 3\pi/2$, though, the degeneracy problem could not be completely solved with this improvement alone. For large values of θ_{13} , a better detector could be the key component in the comparison with superbeams. For example, a lower threshold, a much better energy resolution, and a lower matter density uncertainty were found to be three independent factors improving the CP fraction for the sensitivity to CP violation. In the second part of the talk, I stressed other physics measurements beyond the $\sin^2 2\theta_{13}$, mass hierarchy, and CP violation sensitivities. For example, precision measurements could be important to establish quark-lepton complementarity relationships, and the physics case $\theta_{13} = 0$ may allow for additional applications beyond the theoretical argument to establish a symmetry (such as for the high confidence level MSW effect test in Earth matter or for a mass hierarchy measurement using large luminosities).

In addition to the talks above, several talks presented by the other working groups were given in the joint session with the detector and accelerator working group on Tuesday. Kenzo Nakamura spoke about “T2K-II (T2HK), T2KK, and Hyper-Kamiokande R&D”, Wu-Tsung Weng about “Comparison of Proton Driver Approaches”, and Carol Johnstone about “20-50GeV muon storage rings”.

Chapter 4

Muon physics

Muon physics could be one of the major non-oscillation physics cases for a neutrino factory. As pointed out by Yoshitaka Kuno, charged lepton flavor violation (LFV) is a messenger of GUT scenarios, which means that future high precision measurements will be very useful and complementary to constrain physics at very high energy scales. Current proton drivers can deliver about 10^8 protons/s (such as for MEG), whereas future few megawatt proton driver could deliver about 10^{11} to 10^{12} muons/s (such as for PRISM). Using a neutrino factory front end, up to 10^{14} muons per second could be achievable. In addition, polarized muons could be very useful to reduce backgrounds and to discriminate models. They could be produced by pion decays at rest and by changing the spin by crossing electric and magnetic fields. There are many possible processes and decay modes to be tested, such as $\mu \rightarrow e + \gamma$ or $\mu \rightarrow e + e + e$. Depending on the process, the experiment is detector- or beam-limited. In either case, there are many beam requirements, such as intensity, low pion contamination, narrow energy spread, and especially the use of a continuous or pulsed beam.

Junji Hisano emphasized that flavor physics may be an important component to establish SUSY. In particular, one could probe the origin of SUSY breaking terms, as well as models beyond the MSSM from studies of flavor and CP violation. He also mentioned that charged LFV (especially the modes $\tau \rightarrow \mu \gamma$ and $\mu \rightarrow e \gamma$) and neutrino oscillations provide very independent information on the see-saw. In addition, large mixing angles, in particular, large θ_{13} , might enhance charged LFV. This implies that a θ_{13} would very useful for better predictions for charged LFV predictions. This example demonstrates very nicely that accumulating the information from many different sources will be necessary and useful to establish a more complete picture of particle physics in the future.

Eventually, Shin-ya Kanemura discussed τ -associated LFV, which is interesting for processes mediated by the Higgs boson. One possibility to look for these processes are rare τ decays at B-factories and other methods. However, another alternative useful for neutrino factories might be the deep inelastic scattering (DIS) process $\nu N \rightarrow \tau X$. For this process, $\mathcal{O}(10^2)$ events are expected for a 50 GeV neutrino factory. Since the cross sections rapidly increase with energy, a factor of two higher

muon energy corresponds to a factor of ten more taus produced. This means that high muon energies are in favor of this application. The speaker pointed out that misidentification of events and backgrounds are important issues, and a Monte Carlo simulation is work in progress. In addition, it might be possible to use the neutrino beam instead of the muon beam for similar processes.

Chapter 5

Towards the final product?

In this chapter, I subjectively summarize a part of the workshop which does not explicitly appear in the parallel talks, but which I consider relevant for the discussion towards the final report: Performance indicators and presentation of results. Many of the following aspects have been discussed during the workshop in and in between the talks, as well as they come from earlier discussions. The material presented here may serve as a (hopefully provocative) discussion base for the coming Boston workshop.

Performance indicators

There are many performance indicators in circulation, which are a matter of

1. Definition
2. Tested hypothesis
3. Purpose
4. Taste
5. Computation power.

For the final report, it is important to have identical indicators to be able to compare the results. Typical examples for different θ_{13} performance indicators are the θ_{13} exclusion limit (sensitivity limit), which tests the hypothesis of $\theta_{13} = 0$, and the θ_{13} discovery reach, which tests the hypothesis of nonzero θ_{13} (and particular values for the mass hierarchy and δ_{CP}). The first indicator corresponds to the new limit after the experiment has been (unsuccessfully) performed. Correlations and degeneracies have to be included in a way that any combination of fit parameters which fits $\theta_{13} = 0$ destroys the sensitivity. The second indicator represents the discovery potential for the assumption of a particular set of parameters. Since the fit $\theta_{13} = 0$, correlations and degeneracies are of rudimentary importance. However, the parameter space of possible assumptions is rather large, which means that a visualization is difficult.

Performance indicator	Purpose
Allowed region in θ_{13} - δ_{CP} -plane	Identify how much parameter space remains for a specific assumption of simulated values
Sensitivity to max. CP violation	Show range in which max. CP violation ($\delta_{\text{CP}} = \pi/2$ or $3\pi/2$) can be detected
Sensitivity to “any” CP violation	Show range in which “any” CP violation ($\delta_{\text{CP}} \neq 0$ and π) can be detected; often: use of “CP fraction” plots
Precision of δ_{CP}	Show how precisely δ_{CP} can be measured. Problem: Only defined in high-precision limit (δ_{CP} cyclic, not Gaussian).
CP coverage	Show which fraction of possible values of δ_{CP} fit a chosen simulated value. Describes high precision and exclusion measurements for all possible values of δ_{CP} .

Table 5.1: A number of performance indicators for δ_{CP} .

This comparison demonstrates several of the above points, such as purpose (3.): For instance, if one wants to know when a certain range of θ_{13} can be excluded (such as to choose a new technology), the sensitivity limit is the relevant indicator. However, if one wants to show the ability of an experiment to establish nonzero θ_{13} , the discovery reach may be the better choice. In addition, the indicators test different hypotheses (2.), and the incorporation of correlations and degeneracies may be a matter of definition (1.). The different visualization may be a matter of taste (4.), and computation power is certainly larger for the indicator with the marginalization over more parameters, *i.e.*, the θ_{13} sensitivity (5.).

For δ_{CP} , the situation is more complicated because the measurement intrinsically depends on more parameters (such as the performance indicators always depend on the simulated and fit values of δ_{CP}). In Table 5.1, a number of often chosen performance indicators for δ_{CP} are shown. These indicators ordered in a way that the purpose shifts from a presentation as close as possible to the actual result (top) to risk minimization with respect to the most relevant impact parameters (bottom). Naturally, the computation time increases with going down in this table. A good compromise between computation power and risk minimization potential for many applications is the sensitivity to maximal CP violation (second row). However, it is an intrinsic feature of the neutrino factory (and has been demonstrated in this workshop, see e.g. my WG talk) that degeneracies add up in certain corners of the parameter space which are not close to $\delta_{\text{CP}} = 0, \pi/2, \pi,$ and $3\pi/2$, *i.e.*, $\delta_{\text{CP}} \sim 7/4\pi$. This can only be seen by performance indicators in the lower rows in Table 5.1, which are, however, “expensive” in terms of computation power. Therefore, the optimization of

a neutrino factory with respect to risk minimization is a complicated issue for which a number of factors have to be taken into account. The discussion of performance indicators will be relevant both for the establishment of the “optimal representative” finally to be presented in the study, as well as for the choice of indicators used for the presentation of the results.

Presentation of results: Physics cases?

The primary objective of the final presentation should be to build a strong physics case, *i.e.*, to identify the relevant physics scenarios, to identify the experiments necessary for these, and to link these physics cases to their motivation from theory. Since the future accelerator complex needs to be established in each physics scenario, one may want to improve on particular physics scenarios at a certain point.

In the following, I will mainly focus on the point of view of a neutrino factory as an example, as well as I will not include muon physics implying additional physics cases. There are, of course, three major objectives for such an experiment: Find θ_{13} , establish the mass hierarchy, and measure leptonic CP violation. In doing so, two physics scenarios may be especially interesting:

θ_{13} large: In this case, there are many different options for experiments (different superbeam upgrades and lower gamma beta beams). The neutrino factory faces two major challenges for large θ_{13} : First, the oscillation maximum is off the peak (or, if the muon energy is reduced, the efficiencies will be low in the oscillation maximum range), and second, matter density uncertainties affect the extraction of θ_{13} and δ_{CP} . As suggested in this workshop, a better detector (better threshold) may be the key component for the competitiveness of the neutrino factory for large θ_{13} . However, it needs to be clarified if this is an intrinsic problem, or it can be solved with a substantial increase in the physics potential, since superbeams and beta beams could also come up with more competitive approaches (e.g. T2KK).

θ_{13} zero: This may be a limit very relevant for funding agencies, *i.e.*, how much physics can be actually done in this limit. Though vanishing θ_{13} is theoretically very interesting (which should be somehow demonstrated by the final document), other physics ranging from leading atmospheric parameter measurements, over sensitivity to the MSW effect (by the solar appearance term), to a possible mass hierarchy measurement (by the disappearance channel) for large luminosities can be done. Of course, δ_{CP} is meaningless in this limit. One may want to at least qualitatively address this case.

In addition, there is a long list of possible phenomenology which can be done with a neutrino factory beyond finding θ_{13} , mass hierarchy, and CP violation, such as:

- Precision measurement of θ_{13} as soon as found

- Precision measurement of δ_{CP} as soon as θ_{13} found
- Measure leading atmospheric parameters
- Test deviations from maximal atmospheric mixing
- Resolution of octant degeneracy
- Test unitarity and “new physics” ad-mixtures?
- High confidence level MSW effect test in Earth matter
- Matter density measurements?
- ...

What may be missing so far is the link ranging from different physics cases including their theoretical motivation to these specific measurements. For instance, leading atmospheric parameter measurements could be interesting independent of the magnitude of θ_{13} , and might be theoretically motivated by the test of quark-lepton complementarity relationships. Similarly, deviations from maximal mixing could serve as an important indicator for neutrino mass models. Furthermore, so far many different possible theoretical models for new physics ad-mixtures have been presented. However, the link to specific phenomenological tests needs further investigation, such as

1. ν_τ detection: Test, for instance, $P_{ee} + P_{e\mu} + P_{e\tau} = 1$?
2. Neutral currents: May be a hard measurement, but is 1. really better?
3. Construction of unitarity triangles?
4. Spectral signature from effects on probability level (such as decay, decoherence *etc.*): Characteristic depletion/enhancement in certain regions of spectrum while oscillation nodes remain unshifted
5. More complicated: Hamiltonian-level effects (such as LFV) because “coherent” summation of amplitudes; therefore: oscillation nodes shifted and more confusion with standard oscillation parameters

Note that one could as well deal with this issue by the general strategy to just wait until some inconsistency is discovered before one suspects new physics. However, at least 1. requires some action before that case!

Finally, here come some very biased conceptualities which will be relevant for the coming phase. In order to present the results, multiple options will need to be discussed even for one experiment, such as different systematics, detector options, luminosities *etc.*. In order to do so and have a “clean line of argumentation”, it

may be necessary to agree on one representative for each experiment. The effects of changing specific parameters can then be discussed in the respective chapters. As far as I can judge at this point, if September is the goal for the study, we will need to find and define these representatives as soon as possible. As it also has turned out in the last months, computation power is a serious issue for more complex figures, such as $L-E_\mu$ -plots. So far, only very opportunistic systems could have been used, which means that the obtained computation time varies tremendously. At a certain point, we may want to have access to more powerful and reliable resources (at least for limited time), such as large parallel clusters.

Chapter 6

Open questions and next steps

Here I summarize the open questions raised at the workshop arranged by working group, as well as I summarize the issues which have been so far raised for the Boston workshop.

Physics–Detector

As pointed out by Ken Long in his opening talk, we need to “close the loop” such as for the optimal neutrino factory detector. In this workshop, the main issues for the physics potential have been demonstrated to the detector working group, *i.e.*, better low-energy detection efficiencies and possibly a higher energy resolution. We need now the best possible detection concept the detector working group can come up with, which can also be a hybrid technology (at the same baseline). In particular, a “better detector” may be a key component in the large θ_{13} -discussion.

Additional issues to be worked on by both working groups are channel requirements (ν_e , ν_τ detection), *i.e.*, feasibility, their relevance for the physics cases, and their requirements for baseline and muon energy.

Physics–Accelerator

One question to the accelerator working group was how much a lower muon energy would actually reduce the effort. As calculations in the L - E_μ -plane demonstrated, muon energies around 40 GeV could be sufficient for the main measurements. However, such lower muon energies require a somewhat better baseline tuning.

A question from the accelerator working group (Scott Berg) was how large flux uncertainties actually are acceptable, because they affects the accelerator optimization.

Another very important aspect may be the storage ring. While different shapes (racetrack, triangle, “egg”) are compared by the accelerator working group, there may be motivation for several technology choices depending on physics and geometry. For example, one could think about a scenario in which a racetrack starts at the 3 000 km

baseline with both polarities. After a certain running time, a different triangular storage ring (which is built in parallel) is connected and operated towards a “magic” and “silver” channel baseline in one polarity. It needs to be clarified by the physics working group in which physics cases which baseline configurations are necessary and how many different baselines make sense. If, for instance, a silver channel detector is substantially more efficient at a baseline other than 3 000 or 7 000 km, a single storage ring will probably not be enough.

Detector–(Physics)–Accelerator

An interesting result presented during the workshop was that a lower muon energy could be sufficient if one had a “better” detector (better threshold). This implies that there may be some balance between the muon energy and detector optimization which makes the complex most cost efficient.

Goals for Boston?

A very important goal may be that the conceptual physics cases be identified in order to allow the different subgroups work on them. For example, there should be clear theoretical or phenomenological motivation to test specific cases and there should be clear statements about the choice of technology. In addition, such a classification would allow an identification of “weak” cases, *i.e.*, cases which require more work. For example, a possible scheme of θ_{13} cases could look like that:

Large θ_{13} : $\sin^2 2\theta_{13} \gtrsim 0.01$ In this case, the choice of technology may be the most relevant issue (superbeam versus beta beam versus neutrino factory).

Medium θ_{13} : $10^{-4} \lesssim \sin^2 2\theta_{13} \lesssim 10^{-2}$ This may be the “golden age” of the neutrino factory (or a higher gamma beta beam). Different subcases may need special attention for the neutrino factory:

$0 \lesssim \delta_{\text{CP}} \lesssim \pi$ Few degeneracy problems. Use large luminosities at $L = 3\,000$ km?

$\pi \lesssim \delta_{\text{CP}} \lesssim 2\pi$ Many degeneracy problems. Use silver channels or “magic baseline”?

Others?

Small θ_{13} : $10^{-5} \lesssim \sin^2 2\theta_{13} \lesssim 10^{-4}$ In this case, possible luminosity upgrades to push the θ_{13} discovery reach may be the main issue. The discovery of CP violation may become secondary.

“Zero” θ_{13} : $\sin^2 2\theta_{13} \lesssim 10^{-5}$ This case implies that we know that θ_{13} is extremely small, but not exactly how small (or exactly zero). Important questions are: What does this mean theoretically? What other physics can still be done in this case?

For example, one important outcome of this study could be that for $\sin^2 2\theta_{13} > 0.01$, contrary to the common belief, no (neutrino oscillation) physics case for a neutrino factory can be identified. Instead, the neutrino oscillation physics might be done by a superbeam upgrade or a beta beam. This means that the strongest argument *for* a neutrino factory may be that Double Chooz and currently planned superbeams do *not* find a signal. Therefore, the case of large θ_{13} deserves special attention. Other conceptual cases might be identified for muon physics, in particular in connection with possible LHC findings.

Another issue raised during the workshop was how to deal with a last-minute MiniBOONE signal. Furthermore, phenomenological “new physics” tests need to be linked to theory, which could be done in a number of different ways. For instance, one could give specific examples from theory and discuss their effects in the experiments while assuming that the exclusive three-flavor hypothesis holds (easiest). Vice versa, one could introduce general “testing schemes” (such as silver channel, neutral currents, spectral signature *etc.*) and discuss how the different theoretical effects fit into those (more complicated). At the end, there has to be sufficient motivation if additional experimental resources are needed (such as a ν_τ detector), which is rather pointing to the second approach (or a mixture of both).

Finally, the open questions in this section may want to be further investigated, such as the channel and baseline requirements.