International scoping study of a future

Neutrino Factory and super-beam facility

Physics working group

Summary of the first workshop of the Physics Working Group

Imperial College London, 14 – 21 November 2005

December 13, 2005

Chapter 1

Theoretical subgroup

The theoretical subgroup session took place on Friday 18 November.

Silvia Pascoli talked about Leptogenesis and Low Energy CP Violation, and how the CP phases could be determined in future experiments, specifically long base line experiments, and also neutrinoless double beta decay (where the measurement of CP phases will be "challenging".) She then reviewed the see-saw mechanism and leptogenesis, and explored the connection between low energy CP violation and leptogenesis. Such a connection may be posssible in specific reduced see-saw models (e.g. involving two right-handed neutrinos). In conclusion the link between leptogenesis and the CP phases is not direct, but depends on understanding the see-saw mechanism. Such an understanding would also have implications for charged lepton flavour violation.

Stefan Antusch talked about renormalisation group corrections, emphasising their importance in connecting the predictions at the grand unification scale to experiment at low energy. Such corrections can be important in the see-saw extension of the standard model, as well as supersymmetric extensions with large ratio of vacuum expectation values of the Higgs doublets. They are especially important if the lightest neutrino mass is of order 0.1 eV or higher. The RG corrections are important for future precision neutrino experiments, since they could give observable deviations from maximal atmospheric mixing, or a zero reactor angle.

There then followed two talks which could have easily been placed in the phenomenology section. Sandhya Choubey talked about how the octant of the atmospheric mixing angle could be determined from the large matter effects expected in the muon neutrino survival probability. This could be observed in a large magnetised iron calorimeter such as the INO proposal. Then Paul Harrison talked about Unitarity Triangles, which is a subject that was postponed from the last plenary ISS meeting at CERN. In particular Paul talked about some recent work with Bjorken and Scott on this subject.

Andrea de Gouvea talked about Neutrino Oscillations and the Particle Physics Road Map, in which he discussed the issues in neutrino physics in the context of particle physics and cosmology. He gave an overview of the tasks facing this study, and in particular discussed the strength of the case that needs to be made if major funding for a future large scale facility (or facilities) is to be achieved. In making the case, he distinguished between "what we know we don't know" from some more speculative possibilities of things that could be discovered. His wide ranging talk also included a discussion of neutrino as probes of astrophysics. He also mentioned the relevance of neutrino physics to questions of dark matter and leptogenesis.

One of the important arguments supporting the theoretical case for future neutrino experiments is related to the understanding of the problem of flavour in the framework of grand unified theories. This theme was discussed in the final talk of the theory session, where it was also emphasised that neutrinos could play an important part in theories of inflation and dark energy.

As well as these plenary sessions, a theory parallel session was also held on Thursday in which the structure of the Theory part of the document was discussed. It was agreed that it would be necessary for the different overlapping physics subjects to be presented correctly as a coherent picture of a single whole. To this end, the flavour, leptogenesis, RG and charged lepton flavour violation discussions must and should involve people involved in these different aspects talking to each other and actively working together, rather than in isolation. Since many of these subjects are linked together via the see-saw mechanism they really should not be considered separately. It was resolved to try to make some initial draft of the introductory parts of the document by Christmas.

Two key theorists involved in the study could not attend the meeting, but should be mentioned here. The first is Lisa Everett from the US, who has worked on "Cabibbo Haze" (the theoretical corrections to predictions which link quark mixing angles to lepton mixing angles). The second is Steen Hannestad from Denmark, who is one of the world experts on cosmological limits on neutrino masses and their possible contribution to dark matter. Both have agreed to contribute to the document, and both would be candidates to give talks at future meetings.

Chapter 2

Phenomenology

2.1 Overview

Just like at the B factories, after the mixing matrix elements are roughly determined, the next important issue is to look for signatures of physics beyond νSM (=the standard model with massive neutrinos) by testing unitarity etc. At present there are two possibilities to give deviation from νSM. One is existence of flavor changing interactions due to new physics, and the other one is existence of light sterile neutrinos.

2.2 What was achieved at the workshop

2.2.1 New physics effects in neutrino oscillations

There were four talks related to flavor changing interactions due to new physics (Huber, Zralek, Romanino, Grossman), and they gave reviews on their works in the past. If there is new physics above the weak scale, then there can be interactions like $(\varepsilon/\Lambda)\bar{f}\gamma_\mu f\bar{\nu}_\alpha\gamma^\mu\nu_\beta$ $(f = e,u,d;\alpha,\beta = e,\mu,\tau)$. These induce the flavor changing interactions $\mu^- \to \nu_\alpha\bar{\nu}_\beta e^-$, $\pi^- \to \bar{\nu}_\alpha\mu^-$ at the production point, or $\nu_\mu n \to \ell_\alpha p$ at the detection point. Also in this case the matter effect is modified, i.e., the off-diagonal terms of the matter effect appear in the flavor basis, and we have additional contribution in the neutrino flavor conversion. In general the new physics effects in production or in detection become larger for shorter baselines compared to the standard oscillations, while that in propagation become larger for larger neutrino energy. This helps discriminating the new physics effects from the standard oscillations.

2.2.2 Light sterile neutrinos

Although no talk was given at the workshop on light sterile neutrinos, some updated status on the scenarios is given here. So far the most promising scenario which accounts for all the data including LSND is the (3+2)-scheme [1]. In that scheme the mixing matrix elements which are relevant to the atmospheric neutrinos are $U_{\mu 4} = 0.204$, $U_{\mu 5}$=0.224. On the other hand, the constraint on the (3+2)-scheme from the atmospheric neutrinos can be read off from the result on the (3+1)-scheme (Fig. 19) in [2] by replacing $d_\mu = |U_{\mu 4}|^2$ by $d_\mu = |U_{\mu 4}|^2 + |U_{\mu 5}|^2$. Since $d_\mu = 0.09$ for the (3+2)-scheme, this scheme has tension with the atmospheric neutrino bound $d_\mu < 0.065$ (99%CL), if not excluded (the significance is about 3.6σCL). At present some effort is being made to look for a new best fit point including the atmospheric neutrinos [3]. Until the new solution is found and until the fit of the solution to all the data is shown to be acceptable, it is probably premature to discuss phenomenology of schemes with light sterile neutrinos.

2.3 Works toward the second plenary meeting at KEK

Analyses on the interactions due to new physics do not seem to be comprehensive so far, and more extensive discussions are necessary to derive the conclusion on the possibility to observe the new physics effects at long baseline experiments.

As for scenarios with light sterile neutrinos, there are two ways to go. One way is to stick to the scenarios which account for all the data including LSND. In this case one has to wait until the updated analysis on the (3+2)-scheme is published. The other way is to forget about the LSND data and look for schemes which are consistent with all other data. One could work on a scenario with the number on sterile neutrinos $n_{\nu_s} = 1, 2, 3$ or even with $n_{\nu_s} > 3$, but perhaps it is a good idea to start with the simplest case with $n_{\nu_s} = 1$.

All the problems may be difficult to work out completely by the next meeting at KEK, but we hope that we can make some progress along these lines by then.

Chapter 3

Experimental subgroup

The goals of the Experimental subgroup are to evaluate the performance of the various facilities that have been proposed to serve the programme of precision neutrino-oscillation measurements [4]. In order to allow meaningful comparisons to be performed, and to allow the precision that can be achieved by combining information from two or more facilities to be estimated, it is essential that realistic assumptions are made for the fluxes that can be provided by the various facilities, for the performance of the various detectors that will be used, and for the systematic errors on the fluxes, neutrino cross sections, detector responses, etc. In addition, it will be important to review the optimisation of the facilities in terms of the optimum combinations of base line and neutrino energy.

3.1 The need for a comparison of codes

It is clear from the brief outline of the Experimental subgroup objectives given above that a large number of independent studies is required. To make the required number of calculations requires that several groups contribute, and that the results obtained by the different groups are directly comparable. Three independent codes have been developed for the performance evaluation of neutrino oscillation experiments [5, 6, 7]. A set of benchmark experiments in the super-beam, beta-beam, and Neutrino Factory classes were defined at the first plenary ISS meeting [8]. Each of the three codes was used to study these reference experiments in preparation for the workshop [9, 10, 11]. Though the general trends in the results obtained were similar, large descrepancies were observed where flux assumptions, or the performance of the detectors (efficiency, resolution, etc.) that were used differed. These differences highlight the need to define a set of realistic assumptions for the performance of the accelerator facilities and the detectors. In order to benchmark the codes against one-another, it was decided to compare results on a single reference scenario in detail, the T2K phase 2 super-beam was used for this purpose. The following assumptions were made:

- The oscillation parameters assumed for the fit were:
  - $\Delta m^2_{31} = 2.4 \times 10^{-3}\text{eV}^2$;
  - $\Delta m^2_{21} = 7.9 \times 10^{-5}\text{eV}^2$;
  - $\sin^2\theta_{23} = 0.44$; and
  - $\sin^2\theta_{12} = 0.3$;
- A running time of 2.5 years with neutrinos and 7.5 years with anti-neutrinos;

- The efficiency for neutrino and anti-neutrino detection was assumed to be equal to 0.5 and not to vary with neutrino energy;
- The neutral current event rate was assumed to be 0.0018 times the charged current event rate;
- A perfect detector (one that made perfectly precise measurements) was assumed.

The results of the comparison are shown in figure 3.1 [12]. The event rate as a function of neutrino energy E_ν predicted by GLoBES is compared to that predicted by the Valencia and Madrid codes in figures 3.1a and 3.1b. For clarity only one point is used to show the results obtained using the Madrid and Valencia codes as the results are almost indistinguishable. The distributions predicted by the various packages agree well in shape but the rate predicted by GLoBES is $\sim 9\%$ lower than that predicted by the Madrid/Valencia codes. This is demonstrated in figures 3.1c and 3.1d show the same comparison with the rates obtained using GLoBES multiplied by a scaling factor of 0.91. This difference is due to small differences that remain in the fluxes assumed ($\sim 6\%$ or so) and the fact that the numerical implementation of matter effects differs between GLoBES and the Madrid and Valencia codes. Figure 3.1e shows the sensitivity in the $\delta - \sin^2 2\theta_{13}$ plane obtained by the various calculations when fitting the simulated data. The calculations show good agreement. The workshop therefore concluded that the results obtained with the various packages, at the level of rates and statistical errors, would be directly comparable.

3.2 Joint session with the Detector group

Thursday was dedicated to joint discussion with the detector group. In a series of presentations [13], the sub-group conveners of the Detector working group summarised the detector concepts that were being studied. These presentations were followed by a general discussion in which it was agreed that the input required to generate GLoBES AEDL files would be provided for each detector option being studied. The information would be presented in the form of tables with cells labelled by the type of neutrino incident on the detector and the neutrino type reconstructed by the detector. The various grids of efficiency, resolution, systematic error, etc. that are required would be stored in the form of ntuples and archived on the web. It was recognised that, for some studies, it might be necessary to go beyond the performance tables defined above. It was therefore agreed that, in the longer term, 'event ntuples' could also be exchanged.

The Detector group is working towards a first specification of the performance of the various detector types and expected to have a first iteration available in time for the second ISS plenary meeting in KEK. It was emphasised that the various resolutions and systematic errors assumed must be appropriate for the technology under consideration.

3.3 Goals for the second plenary ISS meeting in KEK

Having verified that the various codes give comparable results, it was agreed to work towards a performance optimisation of the Neutrino Factory facility. It was recognised that a different energy/base-line combination might be required for large values of $\sin^2 2\theta_{13}$ than those that give optimum performance for small $\sin^2 2\theta_{13}$. In preparation for the ISS meeting in KEK, P. Huber agreed to propose a 'high-performance' and a 'medium-performance' detector through AEDL files. These detectors would be used with the standard 3000 km and 7000 km base lines for the 20 GeV and 50 GeV Neutrino Factories to quantify the performance gain over the present assumption of a MINOS-like detector. This study is envisaged as a step on the way to a more complete performance optimisation study. In parallel, the Madrid and Valencia teams will make a comparison of the performance of those facilities that use a mega-ton scale water Cherenkov to detect the neutrinos. The goal of this study is to identify the dependence of the performance of the facilities on the properties of the neutrino beams.

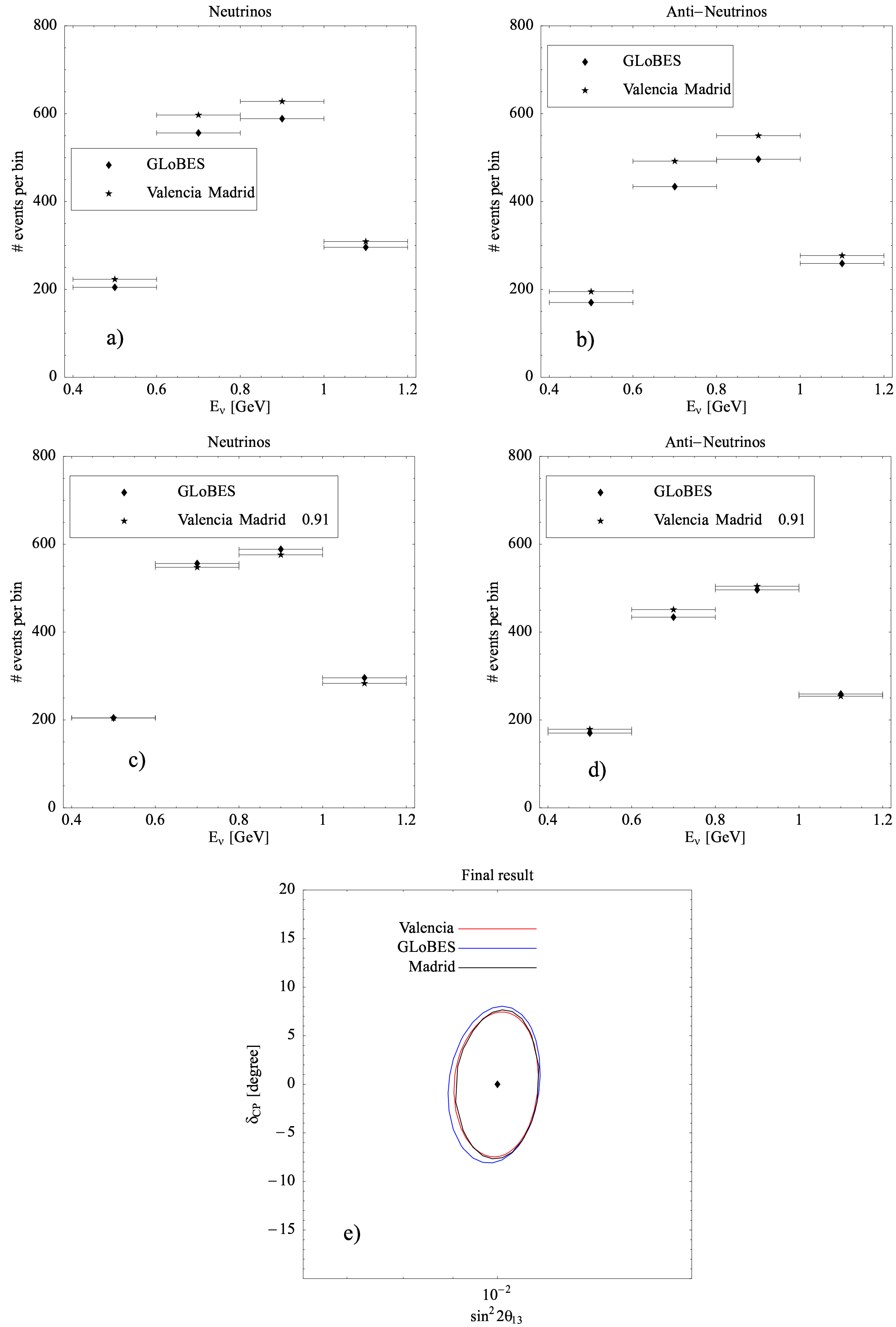

Figure 3.1: Comparison of the results of the calculations described in the text which were made using the GLoBES, Madrid, and Valencia packages [5, 6, 7]. The rates for a T2K-II type super-beam illuminating a megaton-scale water Cherenkov obtained with the various packages are shown in (a) and (b). In (c) and (d) the rate estimated using GLoBES has been multiplied by 0.91. The result of a fit to the simulated data performed with the three packages is shown in (e).

Chapter 4

Muon Working Group

On Tuesday morning we heard an informal presentation from Y, Kuno on the flavor workshop the previous week at CERN. The presentations were primarily theoretical, with a few experimental talks. The scope of their document covers more than just muon physics, and their time-scale is about five to six months longer than ours, so it is clear that our document will have to be prepared separately, but we welcome participation of anyone from the CERN working group.

We met on Tuesday afternoon, and discussed the format of our document, and assigned responsibility (in a preliminary way) for the preparation of our portion of the ISS document. We identified the following categories:

- Muon $(g-2)$
- Search for a permanent electric dipole moment of the muon
- Lepton Flavor Violation

On Friday, we heard two nice theory talks by Yasuhiro Okada and André de Gouvêa, focused on, but not limited to lepton flavor violation.

4.1 Muon $(g-2)$

The motivation for further measurement of $(g-2)$ depends on whether the proposed upgrade to E821 at Brookhaven goes ahead, and also on the prospects for further improvements in the strong interaction part of the theory. Certainly the theory will improve by at least a factor of two in the near term. L. Roberts will lead the writing of this section.

4.2 Muon EDM

A dedicated search for a permanent electric dipole moment of the muon can only be carried out at a very high-intensity muon facility. To reach a level of 10^{-24} e-cm will require the product of number of muons times polarization squared to be 10^{16}. Since 10^{-24} e-cm represents the scaling of the present limit on the electron EDM, any plans should include going beyond this sensitivity by several orders of magnitude. Note that this represents the only possibility of measuring an EDM for a second generation particle. L. Roberts will lead the writing of the experimental section with the help of his colleagues Jim Miller and Yannis Semertzidis, and W. Marciano will help with the theoretical part.

4.3 Lepton Flavor Violation

The following processes were discussed:

$$\mu^+ \rightarrow e^+\gamma \tag{4.1}$$
$$\mu^- N \rightarrow e^- N \tag{4.2}$$
$$\mu^+ \rightarrow e^+ e^+ e^- \tag{4.3}$$
$$\mu N \rightarrow \tau N \tag{4.4}$$
$$\mu^+ e^- \rightarrow \mu^- e^+ \tag{4.5}$$

and the more exotic channels

$$\mu^- + N \rightarrow e^+ + N' \tag{4.6}$$
$$\mu^- + N \rightarrow \mu^+ + N' \tag{4.7}$$

were also suggested for study. Y. Kuno will coordinate these topics, save muonium to antimuonium conversion, with help from Y. Okada, and other theorists and experimentalists. L. Roberts will work with K. Jungmann on the muonium to antimuonium conversion experiment.

4.4 Goals for the KEK and Boston Workshops

At KEK, a more specific list of topics and responsible authors will be drawn up. At the Boston workshop, we should be working on drafts of various sections, since we hope that a number of those interested in muon physics will be able to attend.

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