Energy reconstruction in quasi elastic events: unfolding physics and detector effects

Alain Blondel† Mario Campanelli†‡, Maximilien Fechner‡

† DPNC université de Genève, CH-1211 Geneva Switzerland

‡ Ecole Normale Superieure, Paris France

Abstract. In this paper, we study the use of spectral information in measuring neutrino oscillation parameters in a Super Beam. Low enery neutrino interactions are dominated by quasi elastic charged-current interactions, where the final state is solely composed of a lepton and a proton. In water Cherenkov detectors the proton is below detection threshold and the only visible particle is the lepton. Using knowledge of the beam direction it is possible to reconstruct the neutrino energy from lepton information alone, but this reconstruction is heavily affected by nuclear physics effects and detector resolution. We show that it is possible to unfold such effects using a Monte Carlo reweighting technique, and present details of the method and improvements on examples of fits to oscillation parameters.

1. Introduction

Neutrino SuperBeams are the obvious next step in accelerator neutrino experiments, on the road to the Neutrino Factory. With respect to the latter, the average energy is normally considered to be smaller, even in the sub-GeV range [1, 2, 3]. At these energies, also given the smaller neutrino interaction cross section, the obvious detector choice would be a large water Cerenkhov[4]. Most of the neutrino charged-current interaction events are quasi-elastics, where the final state is composed of a proton (undetected since below Cerenkhov threshhold) and a negative lepton. The knowledge of the initial neutrino direction and on the final lepton direction and energy are sufficient constraints to determine the neutrino energy, in the hypothesis of an elatic scattering of a neutrino on a nucleon at rest, using the following formula:

$$E_\nu = \frac{m_n E_l + \frac{m_p^2 - m_n^2 - m_l^2}{2}}{m_n - E_l + P_l \cos(\theta)}, \tag{1}$$

Fermi motion of nucleons and detector resolution disturb this picture, making the reconstruction of the energy a much more complicated business. In the following, we show how a MonteCarlo reweighting method can be used to correct for these effects, and be able to extract usable information out of the reconstructed energy even in the presence of distortions.

‡ Presented by M.Campanelli

2. Event simulation

To demonstrate the validity of the algorithm in a practical case, we have considered the neutrino spectrum foreseen for the proposed CERN-Frejus long-baseline experiment [2], a low-energy beam neutrino where nuclear effects are particularly important.

To describe the nuclear effects, neutrons are generated isotropically in a sphere with Fermi momentum $k_F = 225$ MeV/c. The nuclear potential well is taken to be 50 MeV deep, and the double differential cross section from [6] was used. Pauli blocking was implemented by requiring that the outgoing proton lies outside the Fermi sphere of radius k_F. Based on Super-Kamiokande data [7, 8], the momentum resolution for electrons is set to $2.5\%/\sqrt{E(\mathrm{GeV})}$+0.5%; for muons it is constant and equal to 3% in this energy range; the angular resolution is estimated to be 3 degrees, constant for electrons and muons.

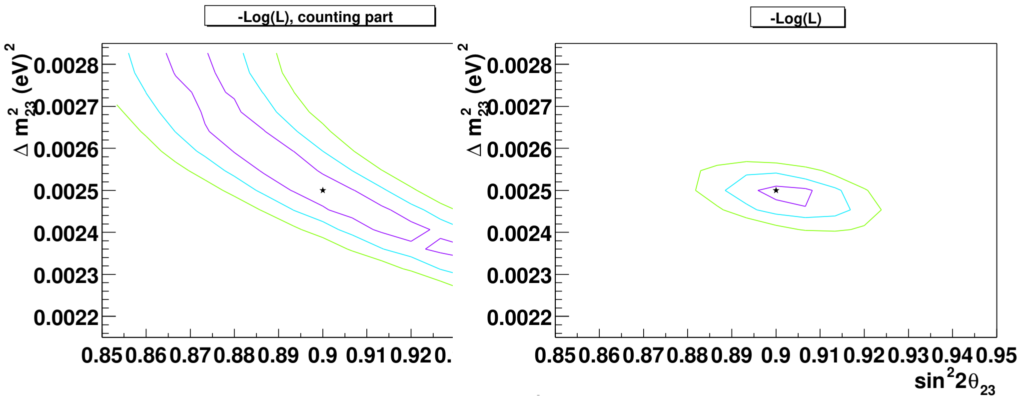

Figure 1. *Contour plots of the different terms and the total of the log likelihood function. The star indicates the true value of the experimental parameters. The contours are the 1σ, 2σ and 3σ confidence levels.Both plots are made with the (2.5×10^{-3} eV^2, 0.9) sample. In each case, the star indicates the parameters at which the 'experimental' sample was produced. Left panel: contours of the likelihood using counting information only. Right panel: contours of the total likelihood.*

3. Energy reconstruction

The analysis method is based on the construction, for each data event, of a distribution of all the Monte Carlo events with a visible energy close to that of the data event. It is based on the method described in [9]. For each data event, a box is defined with a small volume around its reconstructed energy. All MC events whose reconstructed energy lie close to that of the data event are considered to be good approximation to the data event, and their value of the generated energy is used in the likelihood function. The total likelihood can be found in [5], and maximizes information from the total number of events and unfolded spectral information. The weight of the each MC event in the box is the ratio between the number of events for the value of the candidate oscillation parameter set and the number of events for the value of the oscillation parameters at which the MC sample was produced.

The results of a two-dimensional fit of the likelihood for the atmospheric parameters are displayed in figure 2. It is clear that the atmospheric parameters

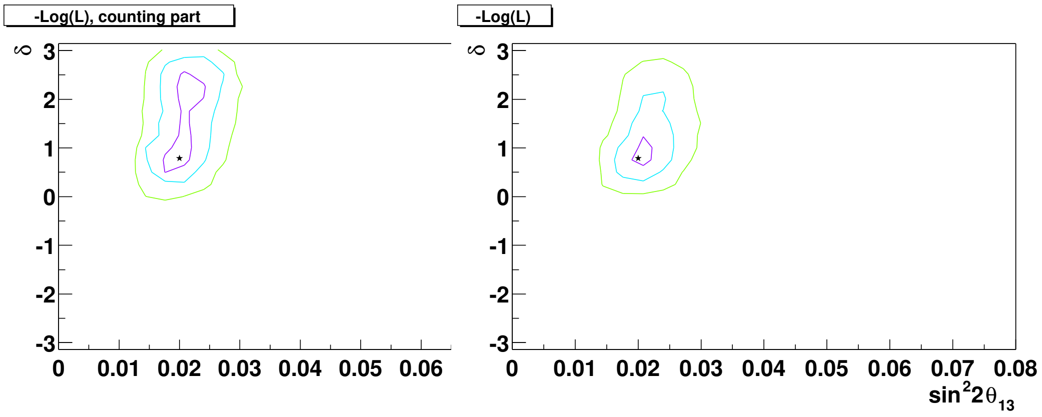

Figure 2. *Contours of the likelihood, assuming 200 kt-y of electron neutrino data and 1000 kt-y of electron antineutrino data. The star indicates the position at which the 'experimental' sample was produced, and δ is measured in radians. Left panel: contours of the likelihood using counting information only. Right panel: contours of the total likelihood.*

are correlated, therefore counting the number of events is not enough to obtain a measurement. The use of the reweighting method dramatically improves the precision, showing the efficiency of the unfolding procedure: Δm^2_{23} can be measured with a standard deviation of $\sim 0.7 \times 10^{-4}$ eV^2, and $\sin^2 2\theta_{23}$ is measured with a precision of $\sim 1.5\%$.

The results are also very promising for CP violation in the neutrino sector: using neutrinos with an exposure of 200 kt-y and antineutrinos with 1000 kt-y to compensate for the lower cross section, we have obtained the results plotted in Fig. 2. In this case, the number of events (left-hand side plot) contains most of the information, but reconstructing the spectral information reduces the 1σ error on δ by roughly a factor three, from 120° to 35°. We find that $\sin^2 2\theta_{13}$ can be measured with precision $\sim 20\%$.

Systematic uncertainties have not been discussed in this study. They can arise from detector descriprion, and the nuclear models used to apply the MonteCarlo-based correction. They have to be estimated observing the difference in the determination of parameters for high-statistic samples, changing the reference Monte Carlo for detector and nuclear model alike.

4. Conclusions

The results presented here show that nuclear effects and detector resolutions do not spoil the energy information present in quasi-elastic events, and that actually if properly trated the energy information can be extremely effective in fitting the oscillation parameters, including a possible measurement of CP violation.

[1] Y. Itow *et al.* , hep-ex/0106019.
[2] B. Autin *et al.*, CERN report CERN-2000-012 (2000).
[3] see e.g. G. Barenboim, A. de Gouvêa, M. Szleper and M. Velasco, FERMILAB-Pub-02/066-T, nuhep-exp/2002-01, hep-ph/0204208.
[4] Preprint SBHEP01-3, June 2001.
[5] A. Blondel, M. Campanelli and M. Fechner, CERN Neutrino Factory Notes 112-2002 and 119-2002.
[6] T.K. Gaisser and J.S. O'Connell, Phys. Rev. **D34**, 822.

[7] Shiozawa, Ph.D. thesis, unpublished, and
D. Casper, private communication.
[8] Super-Kamiokande Coll. (Y. Fukuda *et al.*), Phys. Lett. **B433**, 9 (1998).
[9] D. M. Schmidt *et al* , Nucl. Instr. Meth. Phys. Res. **A328**, 547 (1998); M. Campanelli, Ph. D. Thesis, ETH Zürich, 12742 (1998); L3 Coll., CERN-EP/98-167 (1998); M. Diehl and O. Nachtmann, Z. Phys. **C62**, 397 (1994); E. Lançon *et al* , ALEPH 97-073 (1997).