The τ-contamination in the golden channel at the Neutrino Factory

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Abstract. Experimental results could lead to wrong measurements of the neutrino oscillation parameters if the so-called τ-contamination is not properly taken into account in the data analysis. It was shown in [1] that, if a migration matrix giving the energy distribution of muon neutrinos coming from tau-decays in the detector is included, the analysis can be done in the reconstructed neutrino energy and the problem is solved for the golden channel. We will also present some preliminary results for the disappearance channel, where the τ-contamination is more severe.

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THE SOURCE OF THE τ-CONTAMINATION

In a Neutrino Factory (NF), a very intense neutrino beam would be obtained from muon decays in the straight sections of a storage ring aiming at a far detector. The so-called golden signature [2] is due to the oscillation $\nu_e \to \nu_\mu$, followed by the interaction $\nu_\mu N \to \mu N'$ at the detector. This channel would provide extremely good sensitivities to the three main unknown parameters in the neutrino mixing: θ_{13}, δ and the neutrino mass hierarchy.

However, if neutrinos oscillated through the silver channel instead, $\nu_e \to \nu_\tau$, then a certain number of τ particles would be produced at the detector. In principle this would constitute a separate signal itself. However, the conventional detector considered at the NF is a large iron calorimeter, the so-called Magnetized Iron Detector (MIND), unable to detect taus. Notice that the branching ratio for the decay $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ is roughly 17%. These muons, which cannot be distinguished from the "true" golden sample, tend to accumulate in low energy muon bins, since the missing neutrinos in the decay result in a "secondary" muon which has, on average, 1/3 of the tau energy. As a result, the event sample will be enlarged for the lower energy bins, leading to a wrong fit of the data.

In the early stages of the MIND detector design studies, stringent cuts were imposed on the signal in order to achieve very low background levels. This led to very low efficiencies for events corresponding to neutrino energies below 10 GeV [2], and therefore the τ-contamination was not considered. However, it was first understood in Ref. [3] that removing the low-energy neutrino bins from the analysis introduced serious problems in the joint determination of θ_{13} and δ, namely the appearance of correlations and degeneracies. Recent refined analyses [4] show much better neutrino efficiencies than the original studies, which greatly mitigate the degeneracy problem at the NF [5]. In this case, though, the τ-contamination needs to be taken into account in the analysis.

We show in Fig. 1 the fraction of muons coming from τ decays with respect to the total number of wrong-sign muon events at the detector, after binning in the reconstructed neutrino energy. Data correspond to the neutrino event rates at 4000 km (upper panel) and 7500 km (lower panel), obtained for $\theta_{13} = 2^\circ$ and $\delta = -90^\circ$. Red and blue bars correspond to normal and inverted hierarchy. We have checked that these ratios do not change dramatically with the input values of θ_{13} and δ.

THE SOLUTION TO THE PROBLEM

In Fig. 2 we show in blue the confidence regions resulting from a fit to the data in the (θ_{13}-δ) plane performed for the input value $\theta_{13} = 6.8^\circ$ and three representative values of δ, $\delta = 160^\circ$, 30° and -90°, without taking the τ-contamination into account in the theoretical distribution of the events. Data have been obtained from a MonteCarlo simulation which includes both the golden muon sample and the τ-contamination, for a 25 GeV NF with two 50 kton MIND detectors located at 4000 and 7500 km from the source, with 5×10^{20} useful muon decays per year and polarity, and 5 years of data taking per polarity. Events are binned in the reconstructed neutrino energy, with five bins of constant size $\Delta E_\nu = 5$ GeV. Efficiencies have been taken from [4], and 2% systematic uncertainty has been taken into account. It can be clearly seen that the theory does not fit the data for any of the

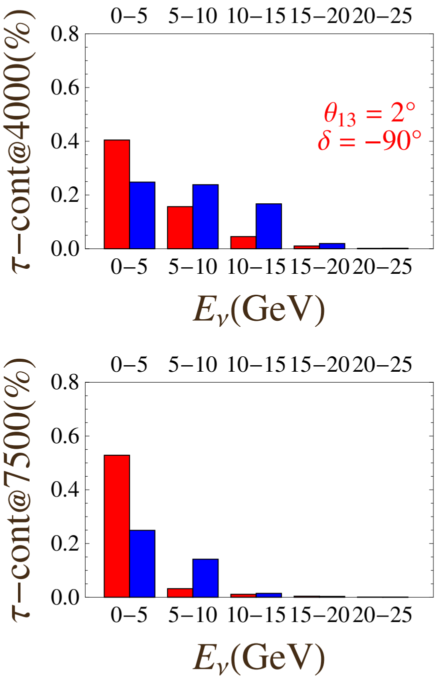

FIGURE 1. Fraction of muons coming from τ decays with respect to the total number of wrong-sign muon events at a 50 kton MIND detector, located at 4000 km (upper panel) and 7500 km (lower panel). Data correspond to the neutrino event rates for $\theta_{13} = 2^\circ$ and $\delta = -90^\circ$, both for normal (red) and inverted (blue) hierarchy.

input values chosen (represented by dots), thus leading to a wrong measurement of θ_{13} and δ.

We will now explain how to include the τ-contamination as part of the signal. Consider a ν_τ which produces a τ at the detector finally decaying into a muon. Then, the incident neutrino energy will be:

$$E_{\nu_\tau} = E_\tau + E_{hadr} = E_\mu + E_{miss} + E_{hadr},$$

where the missing energy is carried away by the two neutrinos in the decay. Therefore, we observe a muon and a hadronic jet, and this is esentially indistinguishable from a "true" golden event. Notice that a 17% of the produced taus will decay in muons, which will have all possible energies between m_μ and the τ energy. For a certain ν_τ with energy E_i^τ the final muon will be assigned to a given fake ν_μ energy bin with E_j^μ with a certain probability. If we compute these probabilities for each bin in E_{ν_τ}, the complete set of probabilities will give us a migration matrix, M_{ij}, with i and j running over all the ν_μ and the ν_τ energy bins. Then, the number N_i of wrong-sign muons expected in a given neutrino energy bin can be computed:

$$N_i = N_i^\mu + \sum_{i=j,N_{bins}} M_{ij} N_j^\tau, \tag{1}$$

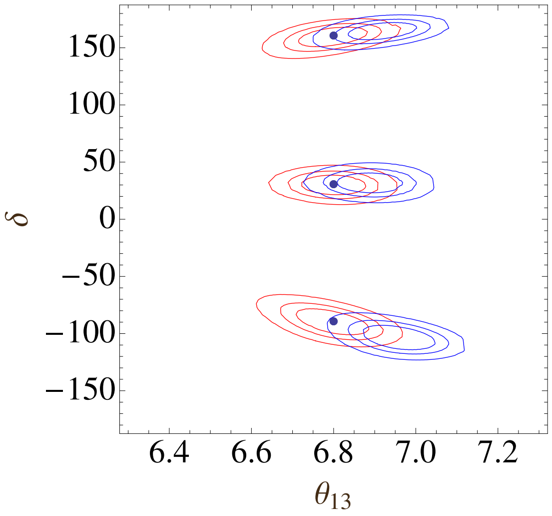

FIGURE 2. $\Delta\chi^2$ contours in the (θ_{13}-δ) plane at 1, 2 and 3 σ (2 d.o.f.) of a fit of the corrected muon theoretical distribution, in red, and the golden muon theoretical distribution (without the τ-contamination), in blue. Data have been simulated with a MonteCarlo event generator including both the golden muon sample and the τ-contamination. The fit has been performed for the input value $\theta_{13} = 6.8^\circ$ and three representative values of δ, $\delta = 160^\circ$, 30° and -90°. See the text for details.

where N_i^μ is the number of "true" golden muons and N_j^τ is the number of muons coming from tau decays. Notice that the number of observed muons at the detector is obtained after multiplying N_i by the efficiency.

The M_{ij} migration matrix has been computed using the GENIE neutrino generator [6] with 10^6 simulated ν_τ's per neutrino energy bin, and 25 bins in the range $E_{\nu_\tau} \in [0,25]$ GeV. The explicit form of the migration matrix M_{ij} is depicted in Fig. 3. In this figure, we show the statistical distribution of the fraction of events with a ν_τ of energy E_i^τ which produce a wrong-sign muon whose energy, combined with the hadronic energy E_{hadr}, will be erroneously assigned to the ν_μ energy bin E_j^μ.

Once we know the theoretical distribution of the expected experimental muon sample, including both the true golden muon component and the corresponding τ-contamination, we can use Eq. 1 to fit the experimental data. This is shown in the red contours in Fig. 2, where the corrected muon theoretical distribution has been used to fit the data obtained with a MonteCarlo simulation including both the pure golden muon sample and the τ-contamination. It can be seen that the τ-contamination problem has been completely solved, since the best fit points now coincide with the true values for the three input pairs considered.

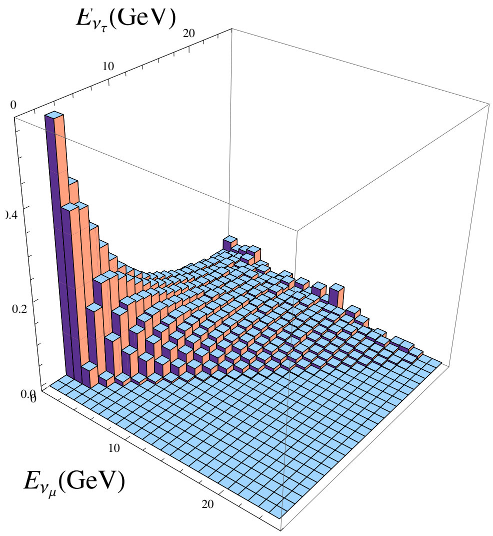

FIGURE 3. The migration matrix M_{ij}. See text for details.

PRELIMINARY RESULTS ON DISAPPEARANCE

In the previous sections we have shown that, once the τ-contamination is included in the golden channel analysis, the problem is solved and we can correctly fit the data, without any further consequences. In the disappearance channel, however, the τ-contamination comes through the $\nu_\mu \to \nu_\tau$ channel, which presents much larger statistics. Therefore, the contamination in this case is more severe, and even if we take it into account in the analysis, the precision measurement on the atmospheric parameters is partially lost [7]. This can be seen in Fig. 4, where we show the $\Delta\chi^2$ contours at 3σ in the $\theta_{23} - \Delta m^2_{23}$ plane obtained with and without taking the τ-contamination into account in the theoretical distribution of the events, in red and blue, respectively. Data have been obtained from a MonteCarlo simulation which includes both the golden muon sample and the τ-contamination, as in Fig. 2. Dashed contorus correspond to the sign degeneracies. Notice that, even though we can correctly fit the data after the inclusion of the τ-contamination, the confidence regions are enlarged and therefore the precision measurement on θ_{23} is partially lost.

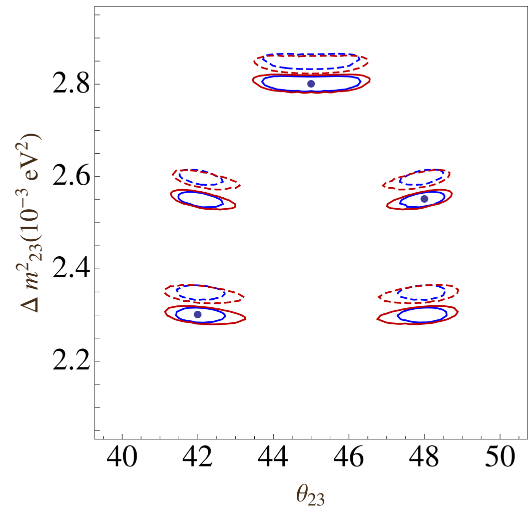

FIGURE 4. $\Delta\chi^2$ contours at 3σ in the $\theta_{23} - \Delta m^2_{23}$ plane obtained with and without taking the τ-contamination into account in the theoretical distribution of the events, in red and blue, respectively. Data have been obtained from a MonteCarlo simulation which includes both the golden muon sample and the τ-contamination. Dashed contours correspond to the sign degeneracies, and dots to the true input values.

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