Tau contributions to muon/electron events at a neutrino factory

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Abstract. The oscillation of the muon and electron neutrinos (anti-neutrinos) to tau neutrinos (anti-neutrinos) adds to the muon and electron events sample (both right sign and wrong sign) via leptonic decays of the taus produced through charge current interactions in the detector. We focus on how this contribution affects a precision measurement of the atmospheric mixing parameters and the deviation of $\nu_\mu \leftrightarrow \nu_\tau$ mixing from maximality. We also comment on the tau contamination in the golden and platinum channels.

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INTRODUCTION

Neutrino factories [1] provide a multitude of channels for precision measurement of oscillation parameters. In the absence of a detector capable of identifying tau lepton production, the appearance as well as disappearance signals of muon and electron neutrinos (anti-neutrinos), have contamination from oscillations of the initial neutrino (anti-neutrino) to tau neutrino (anti-neutrino) which through charge current (CC) interactions in the detector, produce tau leptons, that subsequently decay into muons or electrons and hence add to the muon or electron samples.

We focus on how this contribution alters the right sign (RS) muon events and affects a precision measurement of θ_{23} and deviation of $\nu_\mu \leftrightarrow \nu_\tau$ mixing from maximal (i.e. deviation from $\theta_{23} = \pi/4$). Measurement of deviation from maximality is of significance in developing models for neutrino masses and mixings.

In spite of CC cross-section suppression for the massive tau production, there is still a sizeable production rate above threshold ($\sim$3.4 GeV) due to the large $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, driven by a nearly maximal θ_{23}. The subsequent tau decays ($\sim$17% rate into muons) enhance the RS muon event rates, especially at small muon energies. This tau contribution alters the precision to which we can determine the mixing parameters. Neglect of the tau contribution will lead to an incorrect conclusion about the precision possible for the deviation from maximality.

We point out that the wrong sign (WS) muon events (the golden channel) which are sensitive to the reactor angle θ_{13}, the CP violating phase δ_{CP}, the mass hierarchy and the octant of θ_{23}, will also have (although rather smaller) tau contamination. For precision parameter measurements, it will have to be carefully incorporated. We also discuss the large tau contribution to the platinum channel ($\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$), this channel could help in resolving correlations and degenaracies of the golden channel measurements [2].

NUMERICS

We assume a basic muon storage ring configuration [3] with muon beam energy $E_b = 25$ GeV and with 5×10^{20} useful muon decays per year. The muon (tau) neutrinos produce direct muons (taus) in a 50 kton iron detector such as the proposed INO/ICAL or MIND at a distance L from the source through CC quasi-elastic, resonant or deep inelastic interactions. The taus are forward peaked and subsequently decay to produce muons of mostly low energy; see Ref. [4] for details.

Both μ^+ and μ^- beams with equal exposure are considered. While RS events are sensitive to deviations of θ_{23} from maximality, inclusion of WS events may only marginally worsen the results; however, the advantage in being "charge-blind" is significant, hence, all muon events are simply added. Assuming 7% energy resolution and 90% recontruction efficiency of muons, typical event rates accumulated over five years at L=7400 km for oscillation parameters, $\Delta m^2 \equiv m_3^2 - (m_1^2 + m_2^2)/2 = 2.4 \times 10^{-3}$ eV^2, $\theta_{23} = 42^\circ$, $\theta_{13} = 1^\circ$, $\sin^2\theta_{12} = 0.304$ and $\Delta_{21} \equiv m_2^2 - m_1^2 = 7.65 \times 10^{-5}$ eV^2 are shown as a function of the observed lepton energy in Fig. 1

It can be seen that there is a substantial contribution to the RS events from tau decay into muons. Since tau production in neutrino-nucleon interactions is extremely forward-peaked, one obvious way to remove the tau contribution is with an angular cut (a muon energy cut can also be contemplated). However (see Fig. 2), the only cut effective in removing the tau contribution is one ($\theta_\mu > 25^\circ$) that removes the signal itself! A muon en-

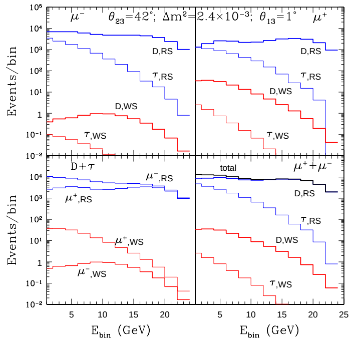

FIGURE 1. Muon event rates as a function of the observed muon energy. RS and WS events from μ^- and μ^+ beams are shown in the upper panels. Contributions from direct muon production (denoted by D) and that of muons from tau decay (labeled as τ) are separately shown. The left lower panel shows the sum $D+\tau$. Oscillation parameters are as given in text.

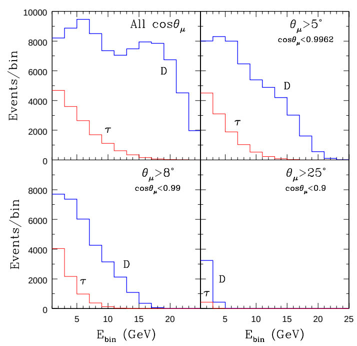

FIGURE 2. Effects of angular cuts on the tau contribution to muon events at neutrino factories. For details, see the text.

ergy cut of $E > 10$–15 GeV can substantially remove the tau contribution, but this will worsen the measured precision of the mixing parameters. In short, it is not feasible to cut out the tau contribution and still make a precision measurement of the deviation of θ_{23} from maximality.

The θ_{23} dependent terms in $P_{\mu\mu}$ and $P_{\mu\tau}$ have opposite signs, hence the combination of muons from direct production and from tau decays marginally *decreases* the event rates sensitivity to this angle. The inclusion of muons from tau events also alters the uncertainties considerably. A near detector sensitive to muons, measures the combination of flux times cross-section of the muons. This also appears in the RS event rate for direct muon production and is therefore well constrained. However, for tau production and decay, the RS event rate has the combination of muon flux and the tau production cross-section. The heavy tau cross-sections have larger uncertainties, where mass corrections are large. Furthermore,

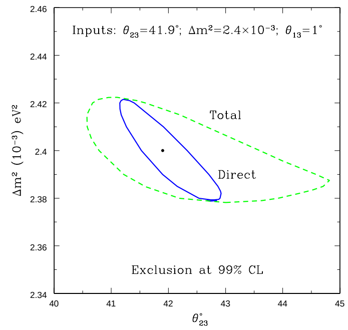

FIGURE 3. Allowed Δm^2-θ_{23} parameter space at 99% CL from CC muon events, directly produced (solid line) and with inclusion of those from tau decay (dashed line). See text for values of input parameters.

since these contributions result from oscillations, no near detector can help reduce the uncertainties. Hence overall uncertainties are much larger for the tau contribution than for direct muons.

Hence, in our numerical calculations we use an overall normalization error of 0.1% for direct, while a modest 2% is used for the total (direct+tau), muon events. We use typical input values of $(\Delta m^2, \theta_{23}, \theta_{13})$ to estimate how well the generated "data" can be fitted, and calculate the resulting precision on the parameters. We keep the solar parameters fixed at their best-fit values of Ref. [6] and set δ_{CP} to zero. The best fits (and regions of confidence levels in parameter space) are obtained by minimizing the chi-squared with a pull corresponding to the normalization uncertainties specified.

Fig. 3 shows the allowed Δm^2–θ_{23} parameter space at 99% CL. The 99% CL contour is much more constrained with direct than for total muons. In particular, it is the Δm^2 values that are smaller than the input value, that broaden the contour and limit the discrimination. The largest true value of θ_{23} that can be discriminated from maximal is shown in Fig. 4, as a function of Δm^2 again, for $\theta_{13} = 1^\circ$. It is seen that tau contamination worsens the ability to discriminate θ_{23} from maximal, thus making this measurement harder than originally expected.

In the golden channel, since $P_{e\tau} \sim P_{e\mu}$, the smaller tau production cross-section and decay rate to muons results in a much smaller tau contribution. However, since this channel is to be used for precision measurements of θ_{13}, CP violation, mass hierarchy and octant of θ_{23}, it is important to correctly handle this contamination so as to achieve the required accuracy in the parameter measurements. While for RS muons, the effect of tau contamination could be analyzed by using muon energy bins itself, for the golden channel this is not possible. The wrong sign events being a small fraction of all the muon events, require excellent charge identification and all the backgrounds need to be treated carefully. Hence

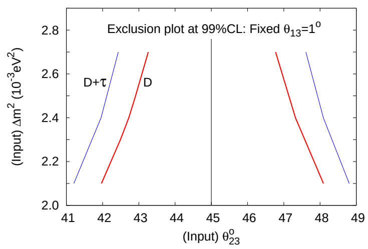

FIGURE 4. The largest (smallest) true value of θ_{23} in the first (second) octant that can be discriminated from $\theta_{23} = \pi/4$, as a function of Δm^2 are shown when only Direct (D) and total ($D+\tau$) events are considered; Here θ_{13} is fixed at 1°.

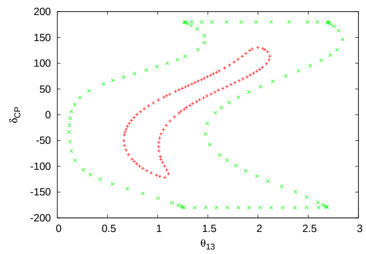

FIGURE 5. Allowed δ_{CP}-θ_{13} parameter space at 99% CL from CC electron events, for a 25 GeV HENF, directly produced (red dots) and with inclusion of those from tau decay (green dots). Input parameters, $\theta_{13} = 1$, $\delta_{CP} = 0$ and others as in Ref. [6].

the neutrino energy reconstruction is important. For the muons that come from the decay of the taus, the missing energy in the tau decays can lead to incorrect assignment of the reconstructed neutrino energy. A detailed analysis of this has been performed in ref. [7] and was presented in this conference [8].

Another channel where the tau contributions will be significant is the platinum channel or electron(anti-electron) appearance. This channel has been proposed for lifting degeneracies in parameter measurements at neutrino factories. With totally active scintillator detectors or with liquid Argon detectors, it should be possible to have good electron identification also. Since $P_{\mu\tau} >> P_{\mu e}$ the tau contribution to this channel is very large. Not only is this contribution significant [10] for high energy neutrino factories (HENF) with muon energy of 25 GeV, but surprisingly even for low energy neutrino factories (LENF) with beam energy of 4.5 GeV [9]. Figs. 5, 6 show the allowed $\delta_{CP} - \theta_{13}$ parameter space at 99% CL for HENF(25 GeV, 15Kton detector at 4000Km) and LENF(4.5 GeV, 20 Kton TASD detector and other specifications as in ref. [9]) for the platinum channel events. See Ref. [10] for more details.

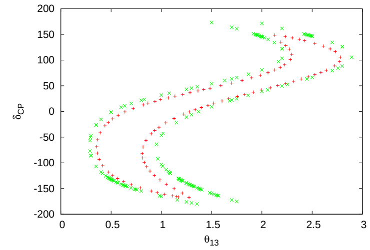

FIGURE 6. Allowed δ_{CP}-θ_{13} parameter space at 99% CL from CC electron events, for a 4.5 GeV LENF, directly produced (red dots) and with inclusion of those from tau decay (green dots). Input parameters, $\theta_{13} = 1$, $\delta_{CP} = 0$ and others as in Ref. [6].

CONCLUSION

The oscillations of the muon or electron neutrinos (anti-neutrinos) to tau neutrinos (anti-neutrinos) results in tau leptons produced through CC interactions in the detector which on leptonic decay add to the right as well as wrong sign muon and electron events obtained directly. As an example, we specifically showed how this tau contamination worsens the ability to discriminate against maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing. It is practically impossible to devise satisfactory cuts to remove this tau contamination. Uncertainties from this tau background in all the channels must be brought under control before making precision parameter measurements at neutrino factories.

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