Tau contamination in the platinum channel at neutrino factories

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Abstract

The platinum channel (νe or νe appearance) has been proposed at neutrino factories as an additional channel that could help in lifting degeneracies and improving sensitivities to neutrino oscillation parameters, viz., θ13, δCP, mass hierarchy, deviation of θ23 from maximality and its octant. This channel corresponds to νµ → νe (ν̄µ → ν̄e) oscillations of the initial neutrino flux, with the subsequent detection of electrons (positrons) from charged current interactions of the νe (ν̄e) in the detector. For small values of θ13, the dominant νµ → ντ (ν̄µ → ν̄τ) oscillation results in this signal being swamped by electrons arising from the leptonic decay of taus produced in charge-current interactions of ντ (ν̄τ) with the detector.

We examine for the first time the role of this tau contamination to the electron events sample and find that it plays a significant role in the platinum channel compared to other channels, not only at high energy neutrino factories but surprisingly even at low energy neutrino factories. Even when the platinum channel is considered in combination with other channels such as the golden (muon appearance) or muon disappearance channel, the tau contamination results in a loss in precision of the measured parameters.

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I. INTRODUCTION

In the last decade, evidence for neutrino oscillations has been obtained from experiments with various neutrino sources. The parameters that characterize neutrino oscillations within a three-flavor neutrino mixing framework are the two mass squared differences $\Delta m_{21}^2$ and $\Delta m_{31}^2$ ($\Delta m_{ij}^2 = m_i^2 - m_j^2$), the three mixing angles $\theta_{12}$, $\theta_{13}$, and $\theta_{23}$, and the Dirac phase $\delta_{\text{CP}}$. While the parameters $\theta_{12}$, $\theta_{23}$, $\Delta m_{21}^2$ and the magnitude of $\Delta m_{31}^2$ are relatively well known, the sign of $\Delta m_{31}^2$ and hence the neutrino mass hierarchy, as well as the across-generation mixing angle $\theta_{13}$ are unknown, the latter having just an upper bound [1]. The hardest to measure will be the CP phase. Many experiments are set to measure one or more of these parameters, with new upcoming super-beam experiments proposing precision measurements of various oscillation parameters although these experiments may not be sufficient to determine all the sub-leading parameters accurately, particularly for all fractions of the CP violating phase $\delta_{\text{CP}}$.

Neutrino factories have been proposed to provide neutrino beams from future muon storage rings where the muons decay in long straight sections, producing both muon- and electron-type neutrinos (and anti-neutrinos). Neutrino factories have been mooted as an excellent set up for precision measurement of neutrino oscillation parameters when the across-generation mixing angle $\theta_{13}$ is small, $\sin^2 2\theta_{13} \lesssim 10^{-2}$ [2]. These future facilities have the advantage of high neutrino fluxes with suppressed beam backgrounds and can provide baselines from about 1000 km for low energy neutrino factories (LENF) to baselines as long as the magic baseline $\sim 7500$ km for the high energy neutrino factories (HENF). Precision measurements of $\theta_{13}$, leptonic CP violation, the type of neutrino mass hierarchy, i.e, the sign of $\Delta m_{31}^2$, deviation of $\theta_{23}$ from $\pi/4$ (maximal) and if found, its octant, may be feasible only at neutrino factories.

The key to this high sensitivity is the clean separation of wrong sign (WS) events from the right sign (RS) ones by lepton charge identification. For instance, if the source of the neutrino beam in a muon storage ring is $\mu^-$, then the beam is a (precisely known) mixture of $\nu_\mu$ and $\bar{\nu}_e$. In the absence of oscillations, we would expect to see muons (from charged current (CC) interactions of $\nu_\mu$) at a far detector; detection of anti-muons, or WS leptons, would then be an unambiguous signal of neutrino oscillations (via $\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$, the last step occurring during interactions with the detector). Such a WS muon (or appearance) signal from $\nu_e \rightarrow \nu_\mu$ oscillations, called the ‘golden channel’, has been studied extensively as it is sensitive to all the above mentioned oscillation parameters.
There are, however, correlations and degeneracies which in turn deteriorate the achievable precision. Even with neutrino and anti-neutrino running, there is an eightfold ambiguity [3] due to the intrinsic ($\delta_{CP}, \theta_{13}$) degeneracy, the unknown sign of $\Delta m_{31}^2$ and the unknown octant of $\theta_{23}$.

These correlations and degeneracies can be reduced [4, 5] by improving the statistics or including two other appearance channels [6]: ‘silver’ ($\nu_e \rightarrow \nu_\tau$) and ‘platinum’ ($\nu_\mu \rightarrow \nu_e$). To date, the design of a detector capable of a large sample of CC $\nu_\tau$ or $\overline{\nu}_\tau$ has been a challenge. Hence in this study we assume that the neutrino factory set up has detectors with capability of muon as well as electron charge identification; however no tau detection capability is present. Detection of electrons (positrons) at a far detector for a $\mu^-(\mu^+)$ beam, called appearance or wrong sign electrons, would then be an unambiguous signal of the platinum channel.

In the absence of a detector capable of identifying $\nu_\tau$ or $\overline{\nu}_\tau$, the $\nu_\tau$’s from $\nu_e \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations will produce taus from CC interactions in the detector, which can subsequently decay to muons. These muon events will not be distinguishable from the ‘direct’ muons (i.e., those produced from $\nu_\mu$ CC interactions) and hence will add to the golden channel and muon disappearance events, respectively. This tau contamination in the disappearance channel has been discussed in detail in Ref. [7]. The issue of the tau contribution to the golden channel muon sample was also briefly mentioned in Ref. [7], but the detailed analysis and quantitative results were presented in Ref. [8].

In this note, we highlight the hitherto neglected electron events from $\nu_\mu \rightarrow \nu_\tau$ oscillations with leptonic decay of taus produced in CC interactions in the detector to electrons; these add to the usual or direct ‘platinum’ channel, i.e., $\nu_\mu \rightarrow \nu_e$ oscillations with electrons produced in CC interactions of $\nu_e$’s with the detector. Since $P_{\mu\tau} \gg P_{\mu e}$, this tau contribution to WS electron (appearance) events will in fact be larger than the direct electron appearance events. This is in great contrast to the case of the muons where the tau contributes dominantly to the right sign muon signal. It is expected therefore that this tau contribution has a stronger impact on the electron appearance channel and hence the sensitivity of this channel to the various neutrino oscillation parameters; this additional contribution to the WS electron events in neutrino factories has not been discussed so far. In particular, we focus on how this large tau contamination to the electron events can alter the sensitivity to the mixing angle $\theta_{13}$ and the CP violating phase $\delta_{CP}$.

The paper is organized as follows. In Section II, we briefly describe details of the neutrino factory set up and show typical rates at typical detectors of choice. In Section III, we report our results for various processes and their sensitivity to the yet unknown mixing angle $\theta_{13}$ and $\delta_{CP}$. We conclude
in Section IV.

II. DETECTOR AND BEAM SET UP

The reach of various neutrino factory set ups with respect to various neutrino oscillation parameters has been discussed in many papers in great detail [9]. Here we examine two cases, one a high-energy neutrino factory (HENF) from muons at 25 GeV as in Ref. [6], and a low energy neutrino factory (LENF) set up with a muon source at 4.5 GeV with a totally active scintillator detector (TASD) or a liquid argon detector (LAr) as in Ref. [11].

The event rates for production of leptons of flavor \( j \) in the detector from ‘direct’ and ‘tau-induced’ channels are defined as

\[
N^\text{direct}_{ij} = \kappa \int \Phi_i P_{ij}(\nu_j \to j) \epsilon_j ,
\]

\[
N^\tau_{ij} = \kappa \int \Phi_i P_{i\tau} \sigma_{\tau}(\nu_\tau \to \tau) \Gamma(\tau \to j) \epsilon_j ,
\]

where \( \kappa \) accounts for the exposure (size of detector and years of running), the initial flux \((\Phi \equiv d^2\Phi/dE d\cos\theta)\) corresponds to \( i = e, \mu \) type neutrinos, the differential cross-section \((\sigma \equiv d^2\sigma/dE d\cos\theta)\) is for CC interactions (quasi-elastic, resonance and deep inelastic processes) producing lepton \( j \) or \( \tau \) in the detector and \( \epsilon_j \) are the detection efficiencies. Note that the oscillation probability \( P_{ij} \) is a function of both \((E, \cos\theta)\) of the neutrino. In addition, for the \( \tau \)-induced channel, we include the decay rate, \( \Gamma \equiv d^2\Gamma/dE d\cos\theta \) for \( \tau \to j \) where \( j = e \) is the case of interest here. The integration is over all the relevant variables, including resolution functions, corresponding to bins in the observed lepton energy and direction \((E_{\text{obs}}^j, \cos\theta_{\text{obs}}^j)\). For the analysis, we have added the events from both \( \mu^- \) and \( \mu^+ \) beams. For details of computation of the kinematics, cross section, and flux, we refer to Ref. [7]. Here we merely highlight four different sets of events: \((ij) = (\mu e), (e\mu)\) corresponding to WS electron and muon (appearance) channels respectively, and \((ij) = (ee), (\mu\mu)\) corresponding to RS electron and muon (disappearance) channels respectively. When the process occurs via \( \tau \) production and decay, it simply adds to one of these channels and is labelled as a ‘tau-induced’ appearance or disappearance event.

While the \( \Phi_e \) flux gives rise to RS electron events in the detector, the \( \Phi_\mu \) flux gives rise to WS events. Hence, while \( \tau \)-induced events contribute to both the RS and WS events, they contribute dominantly to the WS contribution since the \( \nu_\mu \to \nu_\tau \) oscillation probability is driven by a nearly maximal mixing angle \( \theta_{23} \) so that \( P_{\mu\tau} \gg P_{e\tau} \).
Despite the kinematic suppression of the CC cross section for tau production due to the large tau mass, there is a sizeable amount of tau production rate above threshold ($E_{\nu}^{\text{thr}} \sim 3.4 $ GeV). Even with the total tau decay rate into electrons of about 17%, these tau induced events are substantially larger than the direct events, particularly in the low electron energy bins. This turns out to be true not only for a HENF of 25 GeV, but surprisingly even for an LENF of 4.5 GeV. Hence, tau contamination must be taken into account while analyzing the platinum channel at any neutrino factory.

While analyzing the effects of this tau contamination we use typical oscillation parameters, $\Delta m^2 = 2.4 \times 10^{-3} $ eV$^2$, $\theta_{23} = 45^\circ$, $\sin^2 \theta_{12} = 0.304$ and $\Delta m_{21}^2 = 7.65 \times 10^{-5} $ eV$^2$ (we use the symmetric notation: $\Delta m^2 \equiv m_3^2 - (m_1^2 + m_2^2)/2$). We analyze the events for sensitivity to $\theta_{13}$ and $\delta_{CP}$ for a small input value of $\theta_{13}$, $\theta_{13} = 1^\circ$. A threshold of 0.5 GeV for electron detection is used. We use an overall normalization error of 0.1% for direct electron events. However, for the total (direct+tau) events, due to the larger uncertainties in the tau production cross-section, a larger 2% error is used. (Note that the presence of a near detector will not help reduce the uncertainties in the CC tau production cross-section and this forms an important factor in limiting the precision measurement of neutrino oscillation parameters). We deal with a HENF and LENF in turn.

### III. SENSITIVITY TO NEUTRINO OSCILLATION PARAMETERS $\theta_{13}$ AND $\delta_{CP}$

#### A. Results for 25 GeV HENF

For our analysis we assume detector characteristics as specified in Ref. [6]. The neutrino beam interacts with a 15 kton detector [6] located at a distance $L = 4000$ km from the source. At this baseline there is sensitivity to $\delta_{CP}$ as well as $\theta_{13}$. We assume $5.0 \times 10^{20}$ useful muons per year, per polarity, and a running time of 5 years. The energy resolution of electrons is taken to be 15% and efficiency is 20%. It can be seen from Fig. 1 that the tau contribution to the electron events (marked $\tau$ in the figure) is substantial and can in principle alter the sensitivity to the oscillation parameters. Neglect of the tau contribution will lead to measuring incorrect values of these parameters. The magnitude of the direct (tau-induced) events is driven by the small $\theta_{13}$ (large $\theta_{23}$); the direct events (marked D in the figure) will be more appreciable for larger $\theta_{13}$. However, the shape difference between the two contributions will remain: note that the shape of the direct events is almost flat at low energies, while the number of events quickly falls with increasing energy for the tau contribution)
resulting in rather different sensitivity of the total events (labelled “Tot”) to the parameters.

![Graph showing electron event rates as a function of observed electron energy at a HENF with 25 GeV $\mu^\pm$ beams (both polarities) over a 5 year exposure with a 15 kton detector located at a baseline of $L = 4000$ km.](image)

**FIG. 1:** Electron event rates as a function of observed electron energy at a HENF with 25 GeV $\mu^\pm$ beams (both polarities) over a 5 year exposure with a 15 kton detector located at a baseline of $L = 4000$ km.

We generate allowed regions in $\theta_{13}$–$\delta_{CP}$ parameter space, for input values of $(\theta_{13}, \delta_{CP}) = (1^\circ, 0^\circ)$, keeping the other parameters fixed at their present best-fit values [10] with the normal hierarchy for the 2–3 sector. The 99% CL contours obtained by minimizing the chi-squared with a pull corresponding to the normalization uncertainties as specified in Section II are shown in Fig. 2.

The region within the two leftmost contours is the parameter space allowed as a result of neglecting tau contributions both in the “data” and in the theoretical fits. When these are taken into account correctly, only an upper bound (rightmost curve) is obtained: hence this input value of $\theta_{13}$ cannot be discriminated from zero. A substantial increase in exposure and detector size and characteristics is required in order to regain sensitivity to this value of $\theta_{13}$, as can be seen from the contours in the right side of this figure. Even then, sensitivity to $\delta_{CP}$ is entirely lost for this choice of input parameters when the tau contribution is included; in addition, sensitivity to $\theta_{13}$ is substantially reduced as well.

Note that it is hard to find “reasonable” contours to fit the “true” data if tau-induced events are not included in the theoretical fits at all, within the normalization uncertainty. No other uncertainties or backgrounds have been taken into account here (and elsewhere in the paper) since we primarily wish to emphasize the change in sensitivity with the inclusion of the tau-induced events.
FIG. 2: (L) 99% CL contours in $\theta_{13}$–$\delta_{CP}$ space at a HENF with 25 GeV $\mu^\pm$ beams (both polarities) over a 5 year exposure with a 15 kton detector located at a baseline of $L = 4000$ km. The region within the leftmost contours is the allowed space when tau-induced events are neglected; including tau-induced events dramatically worsens the sensitivity to these parameters, giving only an upper bound on $\theta_{13}$ (rightmost curve). (R) Doubling the efficiency and exposure as well as increasing the detector mass to 50 kton improves the sensitivity to $\theta_{13}$ but the sensitivities are always worse than in the case when the tau contribution is neglected.

B. Results for 4.5 GeV LENF

We now examine whether there is any effect of the tau contamination for a low energy neutrino factory. With the tau production threshold at 3.4 GeV, one would naively expect the tau contamination not to play any role in a LENF set up [12]. The details of the performance of a low energy neutrino factory with muon energy 4.5 GeV and its excellent sensitivity to oscillation parameters such as $\theta_{13}$ and $\delta_{CP}$ for $\sin^2 2\theta_{13} > 10^{-4}$, and to the mass hierarchy for $\sin^2 2\theta_{13} > 10^{-3}$, when tau events are neglected, are given in Ref. [11]. We repeat these calculations, including the tau contribution, for a 4.5 GeV LENF with $1.4 \times 10^{21}$ useful muon decays per year, per polarity, and a running time of 10 years, with a baseline $L = 1300$ km.

Here we consider two different detectors whose characteristics are given in Ref. [11]: a magnetized 20 kton totally active scintillator detector (TASD), with electron detection efficiency 37% (47%) below (above) 1 GeV, and 10% energy resolution. We also consider a future possible 100 kton magnetized liquid argon detector (LAr) with a substantially higher (80%) electron detection
efficiency and a somewhat worse energy resolution of 20% (except for quasi-elastic events, where it is 5%). We also use a larger normalization error of (5% for direct and 5.5% for the total events), due to the higher systematic error expected for LAr detectors.

It is obvious from Fig. 3 that the tau contribution (labelled $\tau$) is significant compared to the direct events (labelled D) even for a low energy neutrino factory. (The difference in shape of the events at TASD and LAr detectors at low energy is due to the jump in the electron efficiency above $E_e = 1$ GeV for the TASD; however, the tau-induced events are a sizeable fraction in both). This is a surprise, and can be understood from the fact that the $\nu_\tau$’s arise dominantly from $\nu_\mu \rightarrow \nu_\tau$ oscillations and that the $\nu_\mu$ spectrum peaks near the parent muon beam energy. Hence a substantial fraction of the $\nu_\tau$’s have sufficient energy, $E > E^{\text{thr}}_\nu \sim 3.4$ GeV, to produce taus in the detector. These taus decay preferentially into low energy leptons [7]. Thus one needs to take into account the contribution coming from the tau neutrinos to the total WS electron events (labelled “Tot” in the figure) in order to obtain the correct constraint on the oscillation parameters such as $\theta_{13}$ and $\delta_{CP}$.

This situation is in contrast to the tau contribution to the muon sector, where these dominant $\nu_\tau$’s contribute to the muon disappearance (RS) events. The tau contribution to the golden channel (WS events) arise from the highly suppressed $\nu_e \rightarrow \nu_\tau$ oscillations; tau production is further suppressed at a LENF since the $\nu_e$ spectrum peaks at about only two-third of the parent muon beam energy, so that relatively fewer $\nu_\tau$’s have energies larger than the threshold energy for CC tau interaction.

The corresponding 99% CL allowed contours in $\theta_{13}$–$\delta_{CP}$ parameter space are shown for the same input parameters, for the TASD detector, in Fig. 4. While $\theta_{13}$ can still be discriminated from zero, in this case again, there is little sensitivity to $\delta_{CP}$ which is worsened by the tau contribution.

Again inclusion of backgrounds will further worsen the sensitivity to the various channels; in fact, the inclusion of tau-induced events can be considered as an additional background to the main signal; this can seriously limit the efficacy of the platinum channel, as has been discussed in Ref. [4].

Recall that the tau-induced events add dominantly to RS muon events, in contrast to their substantial contribution to WS electron events. This is seen by the relatively small sensitivity to tau events of the golden channel in a TASD detector in Fig. 5. Here we have used 73% (94%) muon efficiencies below (above) 1 GeV muon energy with 10% muon energy resolution [11].

Due to the very different sensitivities of these two channels to the oscillation parameters, the combined ‘golden + platinum’ channels are very sensitive to $\theta_{13}$ and $\delta_{CP}$, as can be seen from
FIG. 3: Event rates as a function of the observed electron energy at a TASD detector (L) and LAr detector (R), in the platinum channel alone; for more details, refer the text. It is seen that the tau-induced events dominates over the direct WS electron events at low values of the observed electron energy.

FIG. 4: 99% CL contours with (outer) and without (inner curve) inclusion of tau-induced electron events as in Fig. 2 with platinum channel alone, for a LENF with TASD detector at a baseline of \( L = 1300 \) km and 10 years running time.

Fig. 6. The inclusion of the tau-induced events clearly worsens the sensitivity to both parameters, especially at the CP-odd point, \( \delta_{CP}^{\text{input}} = 90^\circ \). This is also true for the LAr detector, as shown in Fig. 7 for this set of input parameter values.

Finally, Fig. 8 shows the sensitivity using the combined data from the golden and platinum channel as well as from muon disappearance (RS muons). The more the number of channels,
FIG. 5: 99% CL contours with and without inclusion of tau-induced muon events in the golden channel alone (WS muons), for the same oscillation parameter inputs, at a LENF with TASD detector.

FIG. 6: 99% CL contours with (outer) and without (inner curve) inclusion of tau-induced muon events from the combined electron and muon wrong sign events, or combined golden and platinum channels, for the oscillation parameter inputs, $\theta_{13} = 1^\circ$ and $\delta_{CP} = 0^\circ, 90^\circ$, at a LENF with TASD detector.

the tighter the constraints expected; while this is true for the ‘direct events’ alone, the tau-induced events continue to worsen the sensitivity to these parameters in all cases. This situation is somewhat ameliorated but still not completely compensated by the combined analysis of golden and platinum channels, or by the additional inclusion of muon disappearance events.

A particularly vexing question is that of the corresponding $\nu_\tau$ CC cross-section in the detector. This will remain unconstrained even with the presence of a near detector which will measure only CC
\( \nu_e \) and \( \nu_\mu \) cross-sections. As long as the normalization uncertainties associated with the tau channel remain large, the ultimate reach of neutrino factories for these oscillation parameters, particularly for \( \theta_{13} \) and \( \delta_{CP} \) with the platinum channel, will remain limited. There are proposals to measure the \( \nu_\tau \) CC interaction cross-sections [13]; this will be a crucial input to reduce the systematic uncertainties of the \( \tau \)-induced events.

FIG. 8: As in Fig. 6, for a LENF with TASD detector, on combining the golden and platinum appearance channels (muon and electron WS events) as well as the muon disappearance (muon RS) channel.
IV. CONCLUSION

Precision measurements of the oscillation parameters are the main goal of future advanced neutrino oscillation experiments. Neutrino factories have particularly good sensitivity to parameters such as the 1–3 mixing angle $\theta_{13}$, the Dirac CP phase $\delta_{CP}$, and the neutrino mass hierarchy, especially when $\theta_{13}$ is small and inaccessible at current or near-future reactor and short-baseline accelerator experiments. While the golden channel (observation of wrong sign muons) is best suited for these measurements, degeneracies and correlations worsen the sensitivities obtainable. These can be lifted by a judicious choice of baselines, improved statistics, as well as inclusion of wrong sign electron events—the so-called platinum channel—and has extensively been discussed in the literature [4, 5].

However, muon neutrinos in such factory fluxes can oscillate to tau neutrinos, driven by the relatively large mixing angle $\theta_{23}$, which is nearly maximal. These $\nu_\tau$ produce taus in CC interactions in a detector, which can promptly decay into muons or electrons (each 17% of the time). The golden channel is relatively insensitive to the tau contribution since taus contribute dominantly to muon right sign events [7] and hence do not substantially spoil the results in this sector [5, 8]. This paper studies for the first time the impact of the contribution that comes from decay of taus to the total electron wrong sign events (platinum channel) in a detector. Studies of both high energy (25 GeV muon beam) as well as low energy (4.5 GeV) neutrino factories reveal that the tau contribution is substantial and alters (in fact worsens) the sensitivity to precision measurements of $\theta_{13}$ and $\delta_{CP}$. Uncertainties from the tau background in all the channels must be brought under control to obtain precision measurements at neutrino factories.

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