Tau contamination in Platinum channel at Neutrino factories

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Brief overview

- Within three flavor oscillation framework, neutrino oscillation is described in terms of three mixing angles (θ_{13}, θ_{23}, θ_{12}), two mass squared differences (Δm^2_{21}, Δm^2_{31}), and one CP violating phase (δ_{CP}).

- θ_{12} and Δm^2_{21} are known to a very good accuracy.

- Current best fit value of $\theta_{23} = 45^\circ$. The deviation from maximal mixing is not statistically significant.

- Currently the unknown are:

> Size of θ_{13}, value of the CP phase δ_{CP}, sign of the atmospheric mass splitting Δm^2_{31}, and the deviation of θ_{23} from maximality.

Status of oscillation parameters

[Thomas Schwetz, Marlam Tortola and Jose W. F. Valle; 2010]

parameter	best fit	2σ	3σ
Δm^2_{21} [10^{-5} eV^2]	$7.59^{+0.23}_{-0.18}$	$7.22 - 8.03$	$7.03 - 8.27$
$\|\Delta m^2_{31}\|$ [10^{-3} eV^2]	$2.40^{+0.12}_{-0.11}$	$2.18 - 2.64$	$2.07 - 2.75$
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	$0.29 - 0.36$	$0.27 - 0.38$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	$0.39 - 0.63$	$0.36 - 0.67$
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039	≤ 0.053

Ultimate goal is to determine all the neutrino mixing parameters to a very good precision.

Why precision measurements?

- Neutrino mass $\Longrightarrow$ NP
  Many New Physics models have been proposed to explain the neutrino mass.

- Non-zero value of δ_{CP} can be very important in explaining the matter-antimatter asymmetry in the universe.

- Non zero value of θ_{13} is particularly important because it would characterize the magnitude of δ_{CP} as well as the sign of Δm^2_{31}.

Neutrino factory

- Intense beam of muons (μ^+, μ^-) are created from proton source.
- Neutrinos are produced from muon decays.
  $\mu^+ \rightarrow \bar{\nu}_\mu \, \nu_e \, e^+$ and $\mu^- \rightarrow \nu_\mu \, \bar{\nu}_e \, e^-$
- Various oscillation channels:
  $\nu_\mu \rightarrow \nu_\mu$
  $\nu_\mu \rightarrow \nu_e \Longrightarrow$ Platinum Channel
  $\nu_\mu \rightarrow \nu_\tau$
  $\nu_e \rightarrow \nu_e$
  $\nu_e \rightarrow \nu_\mu \Longrightarrow$ Golden Channel
  $\nu_e \rightarrow \nu_\tau \Longrightarrow$ Silver Channel

Tau contamination

Tau contamination in appearance ($\nu_e \rightarrow \nu_\mu$) and disappearance ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$) channels have been studied recently.

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ (signal)
  $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \rightarrow \tau^+ \rightarrow \mu^+$ (contamination)
  Tau contamination is substantial in this case and it is not possible to devise effective cuts to eliminate the tau contribution. [Nita Sinha and D. Indumathi, arXiv: 0910.2020]

- $\nu_e \rightarrow \nu_\mu \rightarrow \mu^-$ (signal)
  $\nu_e \rightarrow \nu_\tau \rightarrow \tau^- \rightarrow \mu^-$ (contamination)
  Tau contamination in this case is smaller. [Donini, Gomez Cadenas and Meloni; arXiv: 1005.2275]

Platinum channel and tau contamination

- In the Neutrino factory, the μ^+ and μ^- beam decays to $\bar{\nu}_\mu$ and ν_μ.

$$\mu^+ \to \bar{\nu}_\mu \, e^+ \, \nu_e \,, \qquad \mu^- \to \nu_\mu \, e^- \, \bar{\nu}_e$$

- Direct events: $\bar{\nu}_\mu$ and ν_μ oscillate to $\bar{\nu}_e$ and ν_e which after CC interaction will produce final e^+ and e^- events.

$$\bar{\nu}_\mu \to \bar{\nu}_e \to e^+ \,, \qquad \nu_\mu \to \nu_e \to e^-$$

- Tau induced events: $\bar{\nu}_\mu$ and ν_μ can oscillate to $\bar{\nu}_\tau$ and ν_τ as well which after CC interaction will produce τ leptons. The τ leptons then decay to final e^+ and e^- events.

$$\bar{\nu}_\mu \to \bar{\nu}_\tau \to \tau^+ \to e^+ \,, \qquad \nu_\mu \to \nu_\tau \to \tau^- \to e^-$$

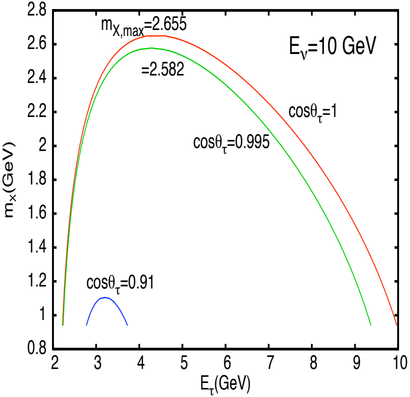
Tau decay and kinematics

- CC cross section for tau production is kinematically suppressed due to its large mass.
- Tau decay rate to muons and electrons is about 17%.
- However, the $\nu_\mu \to \nu_\tau$ oscillation is large. Thus tau contribution can be substantial.
- Need to take into account the contribution coming from tau or else it will lead to fake measurements on θ_{13} as well as δ_{CP}.

ν_τ - nucleon interactions

[Nita Sinha and D. Indumathi, arXiv: 0910.2020]

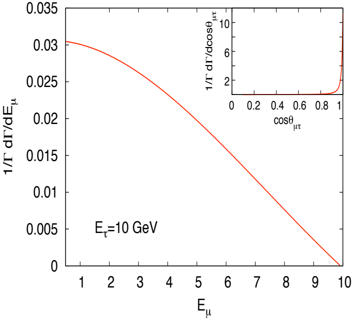
- The end points of the parabola defines the allowed limit on tau lepton energy.
- Tau leptons are produced in a very forward direction.
- Available phase space is restricted in tau production.



Tau decay rate

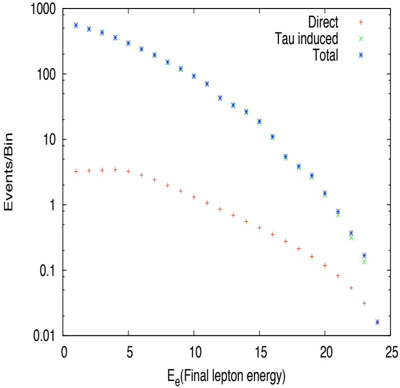
[Nita Sinha and D. Indumathi, arXiv: 0910.2020]

- Typical tau decay rate with energy $E_\tau = 10\ \mathrm{GeV}$.
- Mostly contribute at low energy.



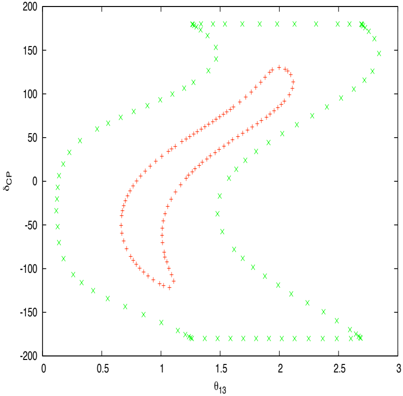
High energy neutrino factory

- Muon beam energy, $E_\mu = 25\,\mathrm{GeV}$
- Mass 15 KT
- Base-line, $L = 4000$ km
- 5×10^{20} useful muons per year, per polarity
- $|\Delta m^2_{31}| = 2.4 \times 10^{-3}\,\mathrm{eV}^2$, $\theta_{23} = 45^\circ$
- $\theta_{13} = 1^\circ$ and the CP phase $\delta_{CP} = 0$



$\theta_{13} - \delta_{CP}$

- Base-line, $L = 4000$ km
- Input: $\theta_{13} = 1^\circ$ and $\delta_{CP} = 0$.
- Systematic uncertainty 0.1% for direct events and 2% for total events.
- 99% CL contours.

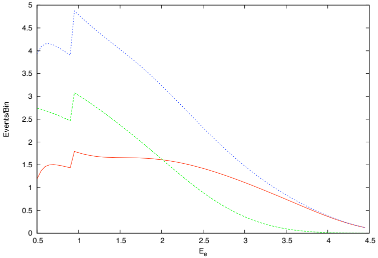


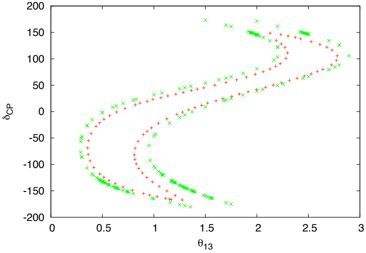
Low energy neutrino factory

[Alan Bross et. al, AIP Conf. Proc.]

	TASD
Beam energy	4.5 GeV
flux	1.4×10^{21}/year/polarity
Running time	10 years
Baseline	1300 km
Mass	20 KT
Energy resolution	10%
Electron detection efficiency	37% below 1 GeV 47% above 1 GeV

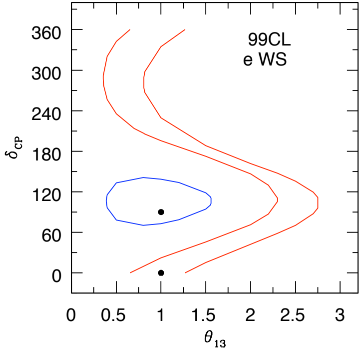
$$\theta_{13} = 1^\circ,\ \delta_{CP} = 0,\ \theta_{23} = 45^\circ,\ |\Delta m^2_{31}| = 2.4 \times 10^{-3}$$





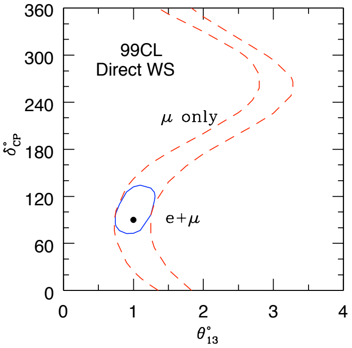
$\theta_{13} = 1^{\circ}, \delta_{CP} = 0$ and 90°

- Systematic uncertainty 0.1% for direct events.
- $\delta_{CP} = 90^{\circ}$ is better fitted with the platinum channel.



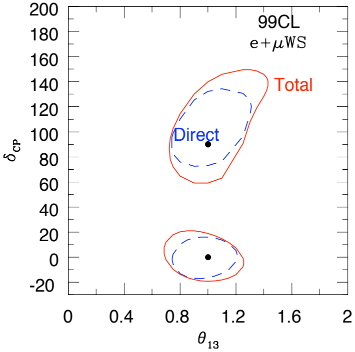
$\theta_{13} = 1^\circ, \delta_{CP} = 90^\circ$

- Systematic uncertainty 0.1% for direct events.
- Inclusion of the electron events have improved the constraints much further.



$\theta_{13} = 1^\circ, \delta_{CP} = 0$ and 90°

- Systematic uncertainty 0.1% for direct events and 2% for total events.
- Tau contribution does not affect the golden channel much. However, it does worsen the electron WS events. Thus, the joint $(e + \mu)$ WS events no longer constrains the parameters so well.



Summary

- We study the impact of the contribution coming from the decay of tau lepton to the total electron events.
- Inclusion of WS electrons to the "Golden" muons improve the constraints much further.
- However, once we include the tau contribution, it worsens the fit.
- It is crucial to include this contribution in the global analysis.