The $\nu_e \to \nu_\tau$ channel as a tool to solve ambiguities‡

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Abstract. In this talk I show how considering at the same time the $\nu_e \to \nu_\tau$ and the $\nu_e \to \nu_\mu$ oscillation channels the errors in the leptonic CP-violating phase δ measurement could significantly be reduced.

The present atmospheric [1] and solar [2] neutrino data are strongly supporting the hypothesis of neutrino oscillations and can be easily accommodated in a three family mixing scenario. In particular, data on atmospheric neutrinos are interpreted as oscillations of muon neutrinos into neutrinos that are not ν_e's, with the corresponding mixing angle $\sin^2 2\theta_{23} > 0.92$ and $|\Delta m^2_{23}|$ in the range 1.5 to 3.8×10^{-3} eV^2 [3]. The recent SNO results for solar neutrinos [4] favour the LMA-MSW solution of the solar neutrino deficit with ν_e oscillations into active neutrino states with a large corresponding mixing angle (θ_{12}).

By the end of the current decade, the θ_{13} angle could still be poorly known (or even unknown) and no information whatsoever will be at hand regarding the leptonic CP violating phase δ. For this reason it has been proposed to build the "Neutrino Factory" [6, 7] and suitably optimized detectors located far away from the neutrino source.

The problem...

In [8] it has been noticed that the probability $P_{\alpha\beta}(\bar\theta_{13}, \bar\delta)$ obtained for neutrinos at a fixed energy and baseline with input parameter $(\bar\theta_{13}, \bar\delta)$, can be reproduced varying accordingly the values of θ_{13} and δ. Considering at the same time the equiprobability curve for antineutrinos at the same energy and with the same input parameters, the two equiprobability curves have two intersections: the input pair $(\bar\theta_{13}, \bar\delta)$ and a second, energy dependent, point $(\tilde\theta_{13}, \tilde\delta)$, the "clone". This second intersection introduces an ambiguity in the measurement of the physical values of θ_{13} and δ (the so-called (θ_{13}, δ) ambiguity). In this case a fitting procedure to reconstruct the physical parameters will identify two low χ^2 regions: one close to the input value and the other in the restricted area in which the other intersections are present (a "clone" region).

...and its solution

Different proposals have been suggested to solve this ambiguity (see [8, 9] for possible solutions to the problem using the combination of different baselines or detectors with

‡ Talk presented by Davide Meloni.

improved energy resolution). We notice [10] that muons proceeding from τ decay when τ's are produced via a $\nu_e \to \nu_\tau$ transition (the "silver channel") show a different (θ_{13}, δ) correlation from those coming from $\nu_e \to \nu_\mu$ (the "golden channel"). This can be seen by looking at the equal-number-of-events (ENE) curves, computed solving $N^i(\theta_{13}, \delta) = N^i(\bar{\theta}_{13}, \bar{\delta})$, where N^i is the number of "wrong-sign" muons produced in the detector in the i-th energy bin (see Fig.1 and [10] for details).

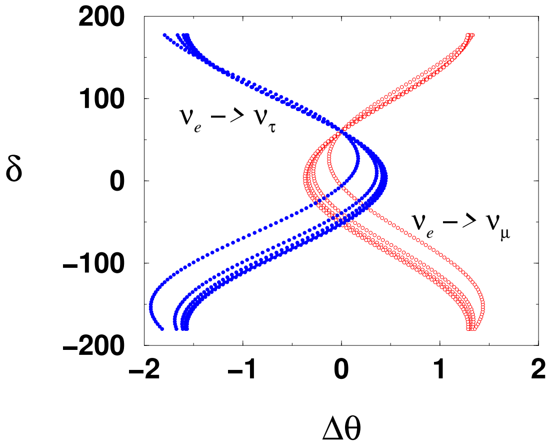

Figure 1. *Superposition of the equal-number-of-events curves for the transition $\nu_e \to \nu_\mu$ (light lines) and $\nu_e \to \nu_\tau$ (dark lines), for $L = 732$ Km and $\bar{\theta}_{13} = 5°, \bar{\delta} = 60°$. $\Delta\theta$ is the shift of θ_{13} with respect to its input value $\bar{\theta}_{13}$. Four ENE curves for each transition have been shown corresponding to four neutrino energy bins, from 10 GeV to 50 GeV.*

The different (θ_{13}, δ) correlation between two channels comes from the different structure of the transition probabilities, which have an opposite sign in front of the CP-violating term. In principle, this different behaviour of the ENE curves should reduce or eliminate the impact of the clone solutions when fitting simultaneously the two sets of data to reconstruct the physical parameters. To take full advantage from the "silver" channel, we should use a detector able to distinguish muons originated from τ decay from the "golden" muons. For this reason we consider an OPERA-like detector with a mass of 2 Kton and spectrometers capable of muon charge identification (see the OPERA proposal for details, [12]) located at $L = 732$ Km down the neutrino source.

The improvement in the reconstruction of the physical parameters can be seen comparing the plots in Fig.2. On the left we consider two realistic iron detector (including efficiencies and background as quoted in [11]) located at two different baselines $L = 732$ Km and $L = 3000$ Km (the optimal distance for the measurement of leptonic CP violation). The best fit point, obtained following the strategy presented in [11], is close to the input parameter ($\bar{\theta}_{13} = 1°$ and $\bar{\delta} = 90°$) but a clone region is present and the determination of the physical parameters is affected by ambiguity. On the right plot, we show the results of the fit obtained combining at the same time both the "golden" and the "silver" channels at the ideal near emulsion detector and the "golden" channel at the magnetized iron detector located at $L = 3000$ Km. The clone region completely disappears and the input parameters can be determined with an error of tens of degrees on δ and tenths of degrees on θ_{13}.

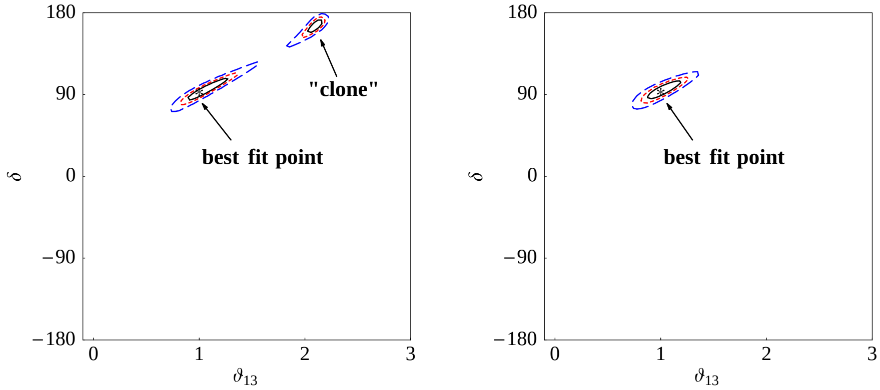

Figure 2. *68.5, 90 and 99 % C.L. contours resulting from a χ^2 fit of θ_{13} and δ, for $\bar{\theta}_{13} = 1^\circ$ and $\bar{\delta} = 90^\circ$, for the combination of an iron detector at $L = 3000$ Km and an emulsion detector at $L = 732$ Km: (left) only "golden" muon events are taken into account; (right) both "silver" and "golden" muon events are taken into account. Five years of data taking for both polarities in the distant detector and only five years in the μ^+ polarity in the near detector have been considered.*

Considering a realistic estimate of the reconstruction efficiency and of the main backgrounds both for "golden" and "silver" muon events at the emulsion detector [12], the clone regions for $\theta_{13} \simeq 1^\circ$ do appear and our results are comparable to those obtained with a combination of two realistic magnetized iron detectors located at $L = 732$ Km and $L = 3000$ Km. However, at the time the Neutrino Factory will be operational, several improvement of the lead-emulsion detector could be done. In particular, we observed that a moderate scaling in the detector mass from 2 to 4 Kton completely eliminates the clone regions for any value of $\theta_{13} \geq 1^\circ$. On the other hand, a moderate increase in the main background rejection does not seem to improve in a significant way the previous results.

[1] T. Toshito [SuperKamiokande Collaboration], arXiv:hep-ex/0105023.
[2] Y. Fukuda *et al.* [Kamiokande Collaboration], Phys. Rev. Lett. **77** (1996) 1683;
W. Hampel *et al.* [GALLEX Collaboration], Phys. Lett. **B447** (1999) 127;
J. N. Abdurashitov *et al.* [SAGE Collaboration], Phys. Rev. **C60** (1999) 055801;
Y. Suzuki [Super-Kamiokande Collaboration], Nucl. Phys. Proc. Suppl. **77** (1999) 35.
[3] T. Nakaya, arXiv:hep-ex/0209036.
[4] Q. R. Ahmad *et al.* [SNO Collaboration], Phys. Rev. Lett. **87** (2001) 071301.
[5] M. Apollonio *et al.*, Phys. Lett. **B 338** (1998) 383.
[6] S. Geer, Phys. Rev. D **57** (1998) 6989 [Erratum-ibid. D **59** (1998) 039903].
[7] A. De Rujula, M. B. Gavela and P. Hernandez, Nucl. Phys. B **547** (1999) 21.
[8] J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez and O. Mena, Nucl. Phys. B **608** (2001) 301; J. Burguet-Castell and O. Mena, arXiv:hep-ph/0108109.
[9] M. Freund, P. Huber and M. Lindner, Nucl. Phys. B **615** (2001) 331.
[10] A. Donini, D. Meloni and P. Migliozzi, arXiv:hep-ph/0206034.
[11] A. Cervera *et al.*, Nucl. Phys. B **579** (2000) 17 [Erratum-ibid. B **593** (2001) 731].
[12] M. Guler *et al.* [OPERA Collaboration], CERN-SPSC-2000-028.