PHENOMENOLOGICAL INVESTIGATION OF MUON NEUTRINO DISAPPEARENCE VIA CC INTERACTION

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Abstract

Experimental evidences showed that the time evolution of a particular neutrino flavor state can produce the transition to a different flavor state, a phenomenona called neutrino oscillation. In this work we aim to study the oscillation model by doing a phenomenological analysis using the MINOS (Main Injector Neutrino Oscillation Search) published data. We first review the muon neutrino CC disappearance results from SK, K2K and MINOS, then we show some quality tests of the data extracted, including a comparison with the allowed region countour plots. We also show preliminary results of our analysis including 3-flavor oscillation model. This study could contribute to test different sub-dominant models, such as decay and decoherence, trying to improve the oscillation model.

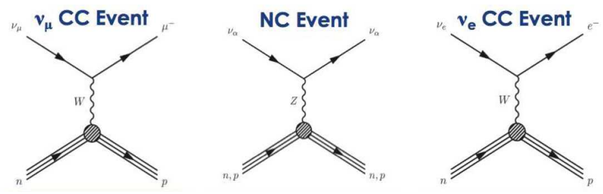
1 Introduction

- Neutrino beam (NuMI) since 2005[1, 2].

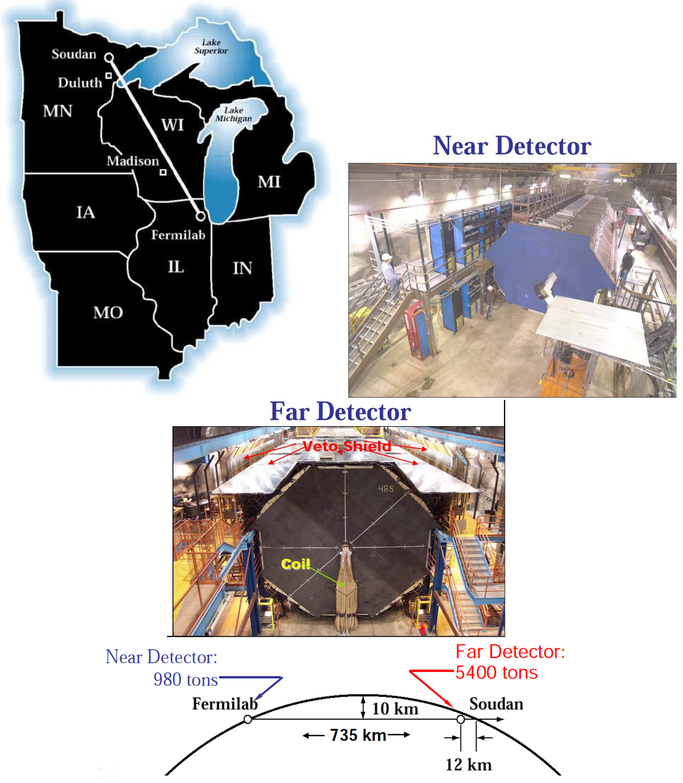
$$\pi^+ \longrightarrow \mu^+\nu_\mu(\sim 100\%) \quad K^+ \longrightarrow \mu^+\nu_\mu(63.5\%)$$
$$K^+ \longrightarrow \pi^+\pi^0(20.6\%) \quad K^+ \longrightarrow \pi^0 e^+\nu_e(5.1\%)$$
$$K^+ \longrightarrow \pi^0\mu^+\nu_\mu(3.4\%) \quad K^+ \longrightarrow \pi^+\pi^+\pi^-(5.6\%)$$

1. ν_μ configuration (focus π^+ and K^+).
   $92.9\%\ \nu_\mu$; $5.8\%\ \overline{\nu}_\mu$; $1.3\%\ (\nu_e + \overline{\nu}_e)$.
2. $\overline{\nu}_\mu$ configuration (focus π^- and K^-).
   $58.1\%\ \nu_\mu$; $39.9\%\ \overline{\nu}_\mu$; $2.0\%\ (\nu_e + \overline{\nu}_e)$.

- Principal MINOS study is the investigation of disappearance muon neutrino via CC (charged current).
- Events NC (neutral current) are also considered.



- Neutrinos are directed to Soudan (MN), 735 km.
- MINOS detectors [2]
  1. Scintillator calorimeters + steel plates immersed in a toroidal field **B**.
  2. 1 km (Near Detector) and 735 km (Far Detector) from the target.
  3. Total mass: 980 (ND) e 5400 (FD) tons.



2 Neutrino Oscillation

- Flavor state and mass state:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e_1} & U_{e_2} & U_{e_3} \\ U_{\mu_1} & U_{\mu_2} & U_{\mu_3} \\ U_{\tau_1} & U_{\tau_2} & U_{\tau_3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Probability survival:

TWO FLAVOR MODEL:

$$P_{(\nu_\mu \to \nu_\mu)} = 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{L \cdot \Delta m^2_{32}}{4E}\right) \quad (1)$$

THREE FLAVOR MODEL:

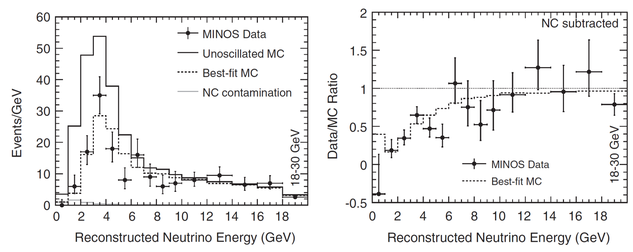
$$P_{(\nu_\mu \to \nu_\mu)} = 1 - (\sin^2 2\theta_{23} \cdot \cos^2\theta_{13} + \sin^2 2\theta_{13} \cdot \sin^4\theta_{23}) \sin^2\left(\frac{L \cdot \Delta m^2_{32}}{4E}\right) \quad (2)$$

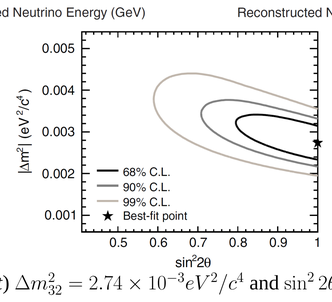
- for $\theta_{13} = 0$ in the probability of 3-flavors, turn to probability of 2-flavors.
- Where $\sin^2 2\theta$ and Δm^2 are oscillation parameters.

3 Evolution of MINOS Results

- 2006–Statistics: 1.27×10^{20} POT [1].

  Events: 215 observed; 336 ± 14 expected (no oscillation).

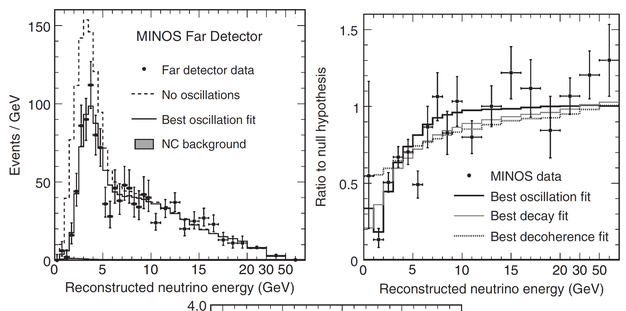


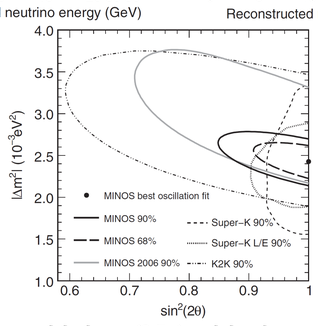


  oscillation (*best fit*) $\Delta m^2_{32} = 2.74 \times 10^{-3} eV^2/c^4$ and $\sin^2 2\theta_{23} = 0.87$.

- 2008–Statistics: 3.36×10^{20} POT [2].

  Events: 848 observed; 1065 ± 60 expected (no oscillation).

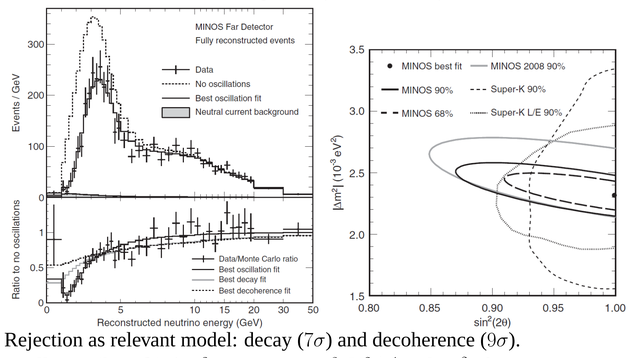




  Rejection as relevant model: decay (3.7σ) and decoherence (5.7σ).
  oscillation (*best fit*) $\Delta m^2_{32} = 2.43 \times 10^{-3} eV^2/c^4$ and $\sin^2 2\theta_{23} = 1.00$.

- 2011–Statistics: 7.25×10^{20} POT [3].

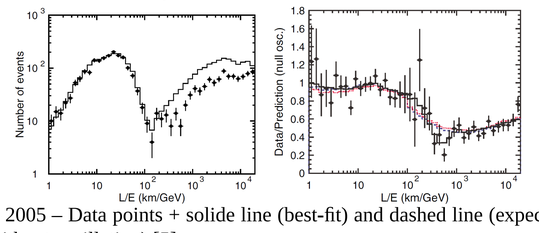
  Events: 1986 observed; 2451 expected (no oscillation).



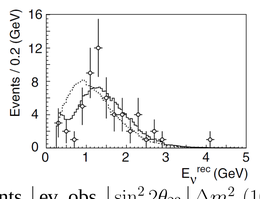
  Rejection as relevant model: decay (7σ) and decoherence (9σ).
  oscillation (*best fit*) $\Delta m^2_{32} = 2.32 \times 10^{-3} eV^2/c^4$ and $\sin^2 2\theta_{23} = 1.00$.

4 Others Results

- SK (L/E) – 2004 – left result - number of events observed and the expected events without oscillations (histogram).
- SK (L/E) – right result - Ratio of data to the MC events (points) and the bes-fit expectation [4].
  oscillation (*best fit*) $\Delta m^2_{32} = 2.4 \times 10^{-3} eV^2/c^4$ and $\sin^2 2\theta_{23} = 1.00$.



- K2K – 2005 – Data points + solide line (best-fit) and dashed line (expected spectrum without oscillation) [5].
  oscillation (*best fit*) $\Delta m^2_{32} = 2.8 \times 10^{-3} eV^2/c^4$ and $\sin^2 2\theta_{23} = 1.00$.

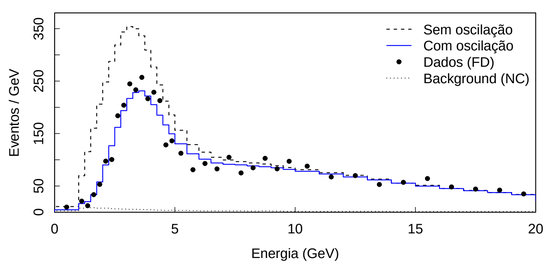


Experiments	ev. obs.	$\sin^2 2\theta_{23}$	$\Delta m^2_{32}(10^{-3}eV^2)$
MINOS 2006	215	0.87	2.74
MINOS 2008	848	1.00	2.43
MINOS 2011	1986	1.00	2.32
SK	—	1.00	2.40
K2K	—	1.00	2.80

5 Preliminary Results (Phenomenology)

5.1 Methodology

- Data scan (MINOS-2011) with package *G3Data Graph Analyzer*.
- Simulations and plots made using with the package *R* [6].
- Data Extracted:



Distributions:

Distributions	Description
N_d	Data (Events)
N_u	Events no oscillation
N_o	Events with oscillation
N_b	Events NC (*Background*)
E_c	Central Energy of each *bin*
$P_{av}(E_c)$	Average probability by numerical integration over each *bin*
N_s	Simulated events with oscillation

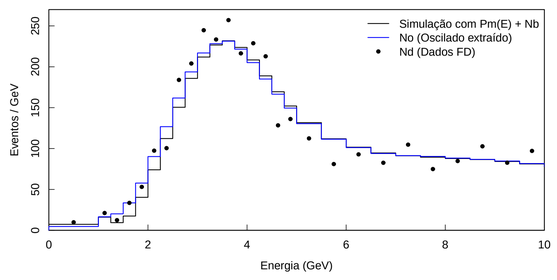
Probability calculation:

- Numerical Integration:

$$P_{\text{av.}} = \frac{1}{\delta} \int_{(E_c - \delta/2)}^{(E_c + \delta/2)} P(E) dE \quad (3)$$

  δ is the length of the *bin*.
- $N_s = P_{av}(E_c) \cdot (N_u - N_b \cdot \alpha) + N_b \cdot \alpha$.
- α is a correction factor of NC events.

- Comparison between extracted curves, and simulated data ($\alpha = 1.0$).



5.2 χ^2 Method

- Least Square [7]:

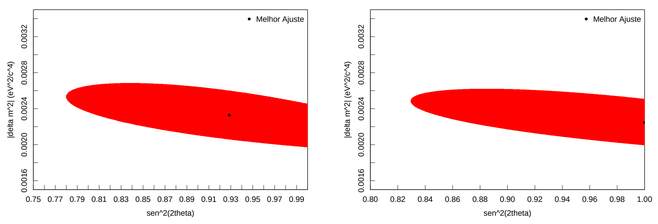
$$\chi^2_{LS} = \sum_i \frac{\left(\frac{N_{s_i}}{N_{u_i} - N_{b_i}} - \frac{N_{d_i} - N_{b_i}}{N_{u_i} - N_{b_i}}\right)^2}{err^2_{[(N_{d_i} - N_{b_i})/(N_{u_i} - N_{b_i})]}} \quad (4)$$

$$err^2_{[(N_d - N_b)/(N_u - N_b)]} = \left[\frac{N_d - N_b}{N_u - N_b}\right]^2 \left[\frac{\sigma_d{}^2}{(N_d - N_b)^2} + \frac{\sigma_u{}^2}{(N_d - N_b)^2}\right] \quad (5)$$

  and σ = extracted error.

5.3 Allowed Region to 2-flavor model (90 % C.L)

α	χ^2	$\sin^2 2\theta_{23}$	$\Delta m^2_{32}(10^{-3}eV^2)$
1.0	16.865	0.9286	2.327
1.9	16.811	1.0000	2.245

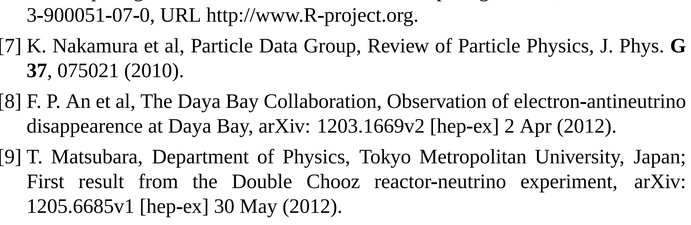


5.4 Allowed Region to 3-flavor model (90 % C.L)

- The θ_{13} effect in disappearance experiment.
- Combined experiment's values to, $\sin^2 2\theta_{13} = 0.091$ [3, 8, 9].

α	χ^2	$\sin^2 2\theta_{23}$	$\Delta m^2_{32}(10^{-3}eV^2)$
1.0	16.865	0.9333	2.333
1.8	16.818	1.0000	2.240

- Region 90% CL MINOS $\rightarrow \Delta m^2_{23}(10^{-3}eV^2)$ $\rightarrow$2.0 – 2.5 $\sin^2 2\theta_{23}$ $\rightarrow$0.86 – 1.00.



6 Conclusions and Next Steps

- The effect of θ_{13} in the disappearance analysis is small as expected.
- Study differents χ^2 methods.
- We are able to test different sub-dominant models, such as decay and decoherence, trying to improve the oscillation model [9-15].
  We will first investigate the decay model.

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