Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

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Abstract

The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km with much higher accuracy than previous studies conducted with accelerator neutrinos. The measurement is based on high-statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light $(v-c)/c = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$.

1. Introduction

The OPERA neutrino experiment [1] at the underground Gran Sasso Laboratory (LNGS) was designed to perform the first detection of neutrino oscillations in direct appearance mode in the $\nu_\mu \rightarrow \nu_\tau$ channel, the signature being the identification of the τ^- lepton created by its charged current (CC) interaction [2].

In addition to its main goal, the experiment is well suited to determine the neutrino velocity with high accuracy through the measurement of the time of flight and the distance between the source of the CNGS neutrino beam at CERN (CERN Neutrino beam to Gran Sasso) [3] and the OPERA detector at LNGS. For CNGS neutrino energies, $\langle E_\nu \rangle = 17$ GeV, the relative deviation from the speed of light *c* of the neutrino velocity due to its finite rest mass is expected to be smaller than 10^{-19}, even assuming the mass of the heaviest neutrino *eigenstate* to be as large as 2 eV [4]. Hence, a larger deviation of the neutrino velocity from *c* would be a striking result pointing to new physics in the neutrino sector. So far, no established deviation has been observed by any experiment.

In the past, a high energy ($E_\nu > 30$ GeV) and short baseline experiment has been able to test deviations down to $|v-c|/c < 4\times10^{-5}$ [5]. With a baseline analogous to that of OPERA but at lower neutrino energies (E_ν peaking at ~3 GeV with a tail extending above 100 GeV), the MINOS experiment reported a measurement of $(v-c)/c = 5.1 \pm 2.9\times10^{-5}$ [6]. At much lower energy, in the 10 MeV range, a stringent limit of $|v-c|/c < 2\times10^{-9}$ was set by the observation of (anti) neutrinos emitted by the SN1987A supernova [7].

In this paper we report on the precision determination of the neutrino velocity, defined as the ratio of the precisely measured distance from CERN to OPERA to the time of flight of neutrinos travelling through the Earth's crust. We used the high-statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the timing systems for the time tagging of the CNGS beam at CERN and of the OPERA detector at LNGS resulted in a reduction of the systematic uncertainties down to the level of the statistical error. The measurement also relies on a high-accuracy geodesy campaign that allowed measuring the 730 km CNGS baseline with a precision of 20 cm.

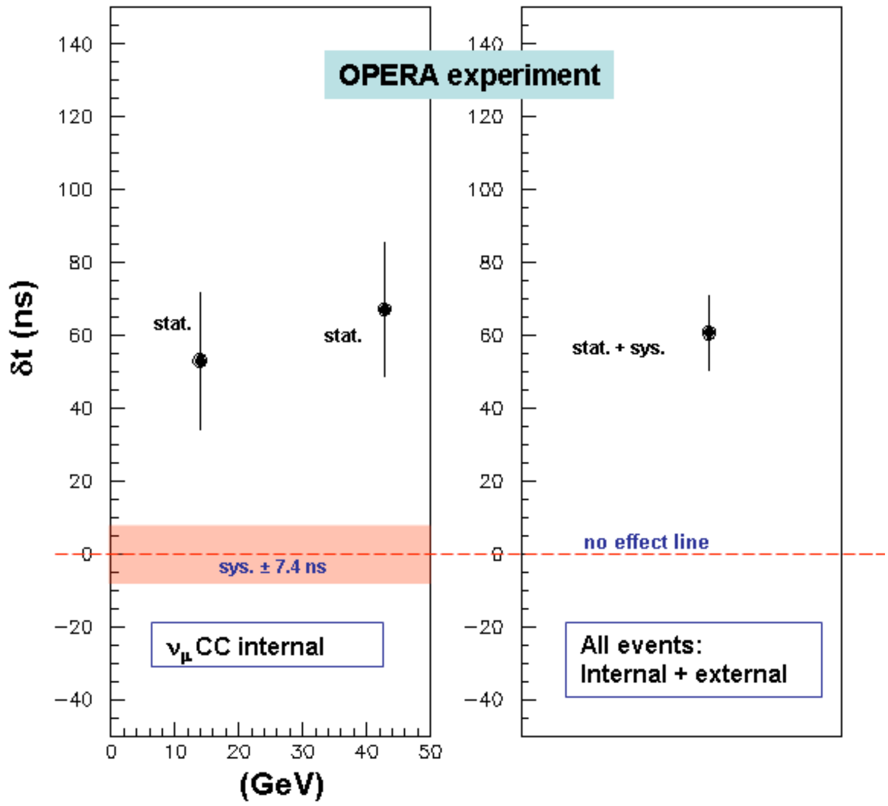

Fig. 13: Summary of the results for the measurement of δt. The left plot shows δt as a function of the energy for ν_μ CC internal events. The errors attributed to the two points are just statistical in order to make their relative comparison easier since the systematic error (represented by a band around the no-effect line) cancels out. The right plot shows the global result of the analysis including both internal and external events (for the latter the energy cannot be measured). The error bar includes statistical and systematic uncertainties added in quadrature.

Conclusions

The OPERA detector at LNGS, designed for the study of neutrino oscillations in appearance mode, has provided a precision measurement of the neutrino velocity over the 730 km baseline of the CNGS neutrino beam sent from CERN to LNGS through the Earth's crust. A time of flight measurement with small systematic uncertainties was made possible by a series of accurate metrology techniques. The data analysis took also advantage of a large sample of about 16000 neutrino interaction events detected by OPERA.

The analysis of internal neutral current and charged current events, and external ν_μ CC interactions from the 2009, 2010 and 2011 CNGS data was carried out to measure the neutrino velocity. The sensitivity of the measurement of (v-*c*)/*c* is about one order of magnitude better than previous accelerator neutrino experiments.

The results of the study indicate for CNGS muon neutrinos with an average energy of 17 GeV an early neutrino arrival time with respect to the one computed by assuming the speed of light in vacuum:

$$\delta t = (60.7 \pm 6.9 \text{ (stat.)} \pm 7.4 \text{ (sys.)}) \text{ ns.}$$

The corresponding relative difference of the muon neutrino velocity and the speed of light is:

$$(v-c)/c = \delta t /(TOF'_c - \delta t) = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}.$$

with an overall significance of 6.0 σ.

The dependence of δt on the neutrino energy was also investigated. For this analysis the data set was limited to the 5489 ν_μ CC interactions occurring in the OPERA target. A measurement performed by considering all ν_μ CC internal events yielded δt = (60.3 ± 13.1 (stat.) ± 7.4 (sys.)) ns, for an average neutrino energy of 28.1 GeV. The sample was then split into two bins of nearly equal statistics, taking events of energy higher or lower than 20 GeV. The results for the low- and high-energy samples are, respectively, δt = (53.1 ± 18.8 (stat.).) ± 7.4 (sys.)) ns and (67.1 ± 18.2 (stat.).) ± 7.4 (sys.)) ns. This provides no clues on a possible energy dependence of δt in the domain explored by OPERA within the accuracy of the measurement.

Despite the large significance of the measurement reported here and the stability of the analysis, the potentially great impact of the result motivates the continuation of our studies in order to investigate possible still unknown systematic effects that could explain the observed anomaly. We deliberately do not attempt any theoretical or phenomenological interpretation of the results.

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