Recent results from the OPERA experiment

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Updated results of the OPERA neutrino experiment are presented covering both the direct search for $\nu_\mu \to \nu_\tau$ transition and the measurement of the neutrino time-of-flight over a 730 km baseline.

1 Introduction

OPERA is a long baseline (730 km), high-energy neutrino oscillation experiment aimed at providing direct evidence of the process $\nu_\mu \to \nu_\tau$ through the detection of the appearance of τ leptons on an event-by-event basis. The experiment is exposed to a ν_μ beam (CNGS) produced from the 400 GeV SPS at CERN with a mean energy of about 17 GeV. The flux energy spectrum is optimized to maximise the convolution of oscillation probability (favoring low energies, ~ 1.5 GeV) and τ cross section (favoring high energies). In order to be able to resolve the submillimetric decay topologies of the short-lived τ leptons (mean decay length ~ 450 μm), the experiment is designed for an exceptional granularity over a large mass (1.25 kt) through the use of nuclear emulsions. The basic unit is the so-called brick, a stack of 57 layers of nuclear emulsions (300 μm thick) and lead plates (1 mm thick) with a size of ($10 \times 12.5 \times 8$ cm^3) and a weight of 8.3 kg. The target is composed of about 150000 such bricks. The brick walls are interspersed with scintillator planes with analog read-out (Target tracker, TT) in order to reconstruct the event kinematics and locate the brick containing the neutrino interaction which will be then extracted and analysed with optical scanning microscopes. Final state muons are measured by two magnetic spectrometers being composed of bipolar magnets instrumented with RPC and drift tube detectors. A full description of the detector can be found in this reference [1].

The number of protons on target (pot) accumulated at the end of the 2011 run amounts to $14.2 \cdot 10^{19}$. The machine underwent a steady improvement through the years with increasing exposures of 1.8, 3.5, 4.0 and 4.9 $\cdot 10^{19}$ pot going from 2008 to 2011. On the other hand the nominal value of $4.5 \cdot 10^{19}$ was exceeded only in 2011. If the CNGS performance in 2012 will be at the level of 2011 OPERA could complete the running having accumulated about 84% of the design luminosity.

2 Oscillation analysis results

We will report the physics results obtained with the 2008-2009 data sample (2738 fully analysed events) for which the analysis in the nuclear emulsions is completed [2]. This corresponds to an increase in statistics of a factor 2.6 with respect to the sample used for reference [3] where the first candidate for $\nu_\mu \to \nu_\tau$ was reported. All the available events have been analysed for this data taking period in order to get an inclusive selection on which to study the reconstruction efficiencies. The current strategy which is being followed for 2010-2011 data relies on a pre-selection of a signal-enriched sample obtained with the electronic detectors. Charged current interactions with low momentum negative muons ($p_{\mu^-} < 15$ GeV/c) and NC-like interactions are prioritized restricting the analysis to the brick to which the location algorithm associates the highest probability.

Since the publication of the first τ candidate in 2010 several improvements have been introduced in the analysis:

- A new Monte Carlo framework integrating emulsion and electronic detector data has been finalized. It allows a detailed simulation of all the steps of the reconstruction process, from brick location to the tagging of the τ decay topology.
- Tools performing a systematic search for highly ionizing tracks (HIT) in a wide field of view (2.5×2.1 mm^2) have been developed. The tagging of nuclear fragments allows to better distinguish genuine decays from hadron reinteractions. This results in a background reduction in the $\tau \to h$ channel of about 20 %. The rate of production and the angular distributions of HIT have been cross-checked with pion test beam data. Good agreement is found with expectations based on the FLUKA Monte Carlo.
- A new procedure has been introduced which consists in following the vertex tracks in the downstream direction using, eventually, data from several bricks ("track follow-down"). Profiting of correlations between momentum and range it is possible to obtain an increased μ identification efficiency. The result is a reduction of background from both charm and mis-identified hadronic tracks from ν_μ^{CC} interactions.
- The state-of-the art charm cross section from the CHORUS [4] experiment has been introduced. The updated analysis, which is based on about one thousand charged charm events, implies an increase of the charm background by a factor 1.6 to 2.4 depending on the decay channel, the main contribution coming from D^+ decays.

Data driven hadron background constraints are being pursued:

- Hadronic tracks from real CNGS neutrino interactions have been followed for a length in lead of 14 m which is equivalent to a sample of 2300 NC events [a]. No events are found in the signal region defined by requiring 1-prong hadronic interactions with $\theta_{kink} > 20$ mrad, $p > 2$ GeV/c and $p_T > 0.6$ GeV/c [b]. In the side-band defined by $p_T > 0.2$ GeV/c, we observe 10 events while 10.8 are expected.
- Interactions with charm production have been studied. This sample offers the opportunity to benchmark the τ efficiency thanks to the similarity of the decay topologies. The observed events for the 2008-09 sample (39 events) are compared to the full Monte Carlo expectation (42.2 ± 8.3 events) in Fig. 1a in bins of the charm decay charged multiplicity. The comparison between data and Monte Carlo for the angle between the muon and the hadronic system in the transverse plane and the charmed meson decay length is shown in Figs. 1b and 1c.

Including all the improvements in the analysis, in the considered 2008-09 sample one τ candidate has been observed in the $\tau \to h$ channel [3] with a signal expectation of 1.65. The expected background in $\tau \to h$ amounts to 0.05 ± 0.01 events while, considering all channels the number of background events becomes 0.16 ± 0.03. The prediction for signal and background in

[a] To mimic a τ decay the interaction should happen within the first two 1 mm thick lead plates.
[b] Considered with respect to the daughter particle.

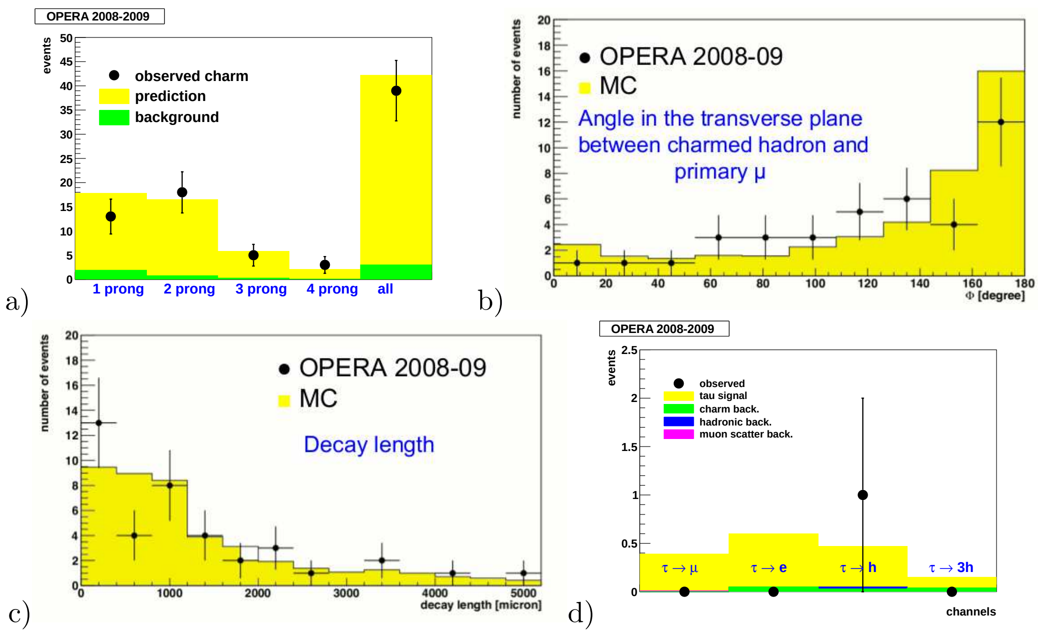

Figure 1: a) Data (bullets) and Monte Carlo prediction (solid histogram) are shown for the 2008/09 charm control sample, in bins of charged multiplicity of the charm decay ("prongs"). b) Distribution of the angle between the muon and the hadronic system in the transverse plane. c) Decay length of the charmed meson. d) The τ signal and backgrounds divided by decay channel.

all the channels is given in Fig. 1d. It can be noticed that the cleanest decay channel is $\tau \to \mu$ mainly thanks to the recent developments in the analysis.

Future releases are expected with a time scale of a few months including the findings for the τ search, obtained with a larger data sample and the analysis of ν_e events in the 2008-09 data.

3 Measurement of the neutrino time-of-flight

In the first release [5] on the neutrino time-of-flight (ToF) measurement OPERA reported a significant deviation from the speed of light, in the direction of neutrino superluminality, which could not be explained at that time in terms of known instrumental effects. The result was obtained using the standard CNGS beam (2009-11 data), which, due to its time structure, allows the extraction of the time-of-flight on a statistical basis only, and then (Nov. 2011) confirmed by a special beam consisting of four well separated (524 ns) narrow peaks (about 3 ns wide). With the so-called "bunched-beam" data taking, concerns related to the statistical extraction of the time-of-flight and additional possible systematics were removed.

Further investigations, being pursued since the first release, have indicated the presence of two instrumental effects which are actually able to reconcile the measured value of the neutrino time-of-flight with the expected value. Before describing them we will briefly recall how the measurement is performed.

The proton beam time-structure of the SPS extracted beam, is accurately measured by a fast Beam Current Transformer (BCT) detector (400 MHz bandwidth) read out by a 1 GS/s Wave Form Digitiser (WFD) with a 250 MHz bandwidth. The waveforms recorded for each extraction by the WFD are UTC (Coordinated Universal Time) time-stamped with a standard GPS receiver and stored in the CNGS database.

The time profile of protons crossing the BCT can then be compared with the time distribution of the interactions detected in OPERA, in order to measure ToF_ν. The quantity $\delta t = ToF_c - ToF_\nu$ is obtained by an un-binned maximum likelihood analysis of the time tags of the OPERA events with respect to the proton time profile[c].

The ignorance on the point of production of neutrinos in the decay tunnel introduces a negligible inaccuracy in the measurement of ToF_ν, thanks to the fact that the decaying mesons are ultra-relativistic. The difference in the ToF computed assuming a particle moving from the target down to LNGS at c, with respect to the value derived by taking into account the real speed of the parent meson down to its decay point is less than 0.02 ns (from a full FLUKA simulation of the CNGS beam). Similar arguments apply to muons produced in ν_μ^{CC} interactions in the rock in front of the OPERA detector (external events): a full GEANT simulation indicates a bias for external events smaller than 2 ns with respect to internal events.

The required accuracy of the relative time tagging at CERN and at the OPERA detector is achieved by adopting two identical systems, composed of a GPS receiver for time-transfer applications operating in "common-view mode" and a Cs atomic clock, installed at both sites. The two systems were calibrated by two national metrology institutions, the Swiss METAS in 2008 and independently by the German PTB in 2011 by taking data at CERN and LNGS with a portable time-transfer device. The difference between the time base of the two GPS receivers was measured to be (2.3 ± 0.9) ns and subsequently corrected for.

The travel path of protons from the BCT to the focal point of the CNGS target is known with millimetric accuracy $L_{\mathrm{BCT-targ}} = (743.391 \pm 0.002)$ m. This precision degrades to about 2 cm when these coordinates are transformed into the global geodesy reference frame (RF) ETRF2000 by relating them to external GPS benchmarks. The coordinates of the origin of the OPERA RF were measured in 2010 by establishing GPS benchmarks at the two sides of the 10 km long Gran Sasso highway tunnel and by transporting their positions with a terrestrial traverse down to OPERA. A common analysis in the ETRF2000 of the 3D coordinates of the OPERA origin and of the target focal point allowed the determination of $L_{\mathrm{targ-OP}} = (730534.61 \pm 0.20)$ m. The 20 cm uncertainty is dominated by the long underground link between the outdoors GPS benchmarks and the benchmark at the OPERA detector. Finally, the baseline considered for the measurement of ToF_ν is: $L_{\mathrm{BCT-targ}} + L_{\mathrm{targ-OP}} = (731278.0 \pm 0.2)$ m.

Three delays characterise the CERN timing chain: 1) $\delta t_{UTC} = (10085 \pm 2)$ ns: propagation through the General Machine Timing chain of the time base of the Control Timing Receiver (CTRI-1) in the proximity of the BCT to a corresponding device at the Prévessin site (CTRI-2); 2) $\delta t_{trigger} = (30 \pm 1)$ ns, the time needed to produce the replica of the kicker magnet signal from CTRI-1; 3) $\delta t_{BCT} = (580 \pm 5)$ ns: interval between the transit of protons through the BCT to the arrival of the signal to the WFD.

At LNGS every ms a pulse synchronously derived from the 1PPS of the ESAT2000 GPS system (PPmS) is transmitted from the surface laboratory to the OPERA master clock (OMC) in the underground via an 8.3 km long optical fibre. The OMC is disciplined by a high-stability oscillator (Vectron OC-050, Allan deviation of $2 \cdot 10^{-12}$ over 1 s) which keeps the local time in between synchronisations from the external GPS. The PPmS signal is tagged with respect to the uncorrelated internal frequency of the 20 MHz OMC, thus producing a ± 25 ns time jitter. The frequency of the oscillator was measured after the end of the 2011 CNGS run and found to be larger than the specification by 0.124 ppm. We will return on this point later on.

The delays characterising the LNGS timing chain are the following: 1) $\delta t_{UTC-LNGS}$: the delay on the PPmS signal from the external laboratory to the OMC. It was measured with a two-way fibre procedure in July 2006 to be (40996 ± 1) ns and confirmed with a transportable Cs clock in June 2007. The fiber delay was re-measured in December 2011 obtaining a value of 41069 ns, 73 ns larger than the value quoted above. We will discuss this point later on.

[c] Proton waveforms associated to selected neutrino interactions in OPERA are individually normalised to unity and summed in order to build a global probability density function. A second approach, which has also been used, consists in building the likelihood function by associating each neutrino interaction to the corresponding proton waveform instead of the average one.

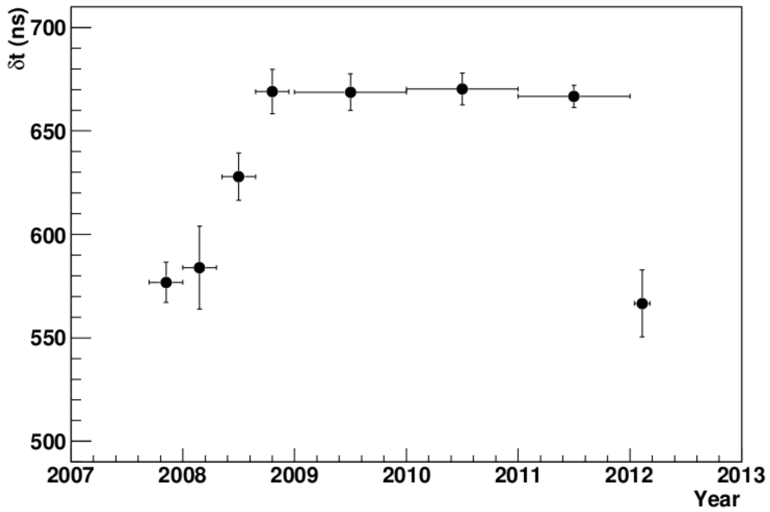

Figure 2: Distribution of the $t_{LVD} - t_{OPERA}$. For each year all events are grouped in one single point but for 2008 which is subdivided in three periods: before May, May-August, and after August.

2) δ_{TT-FE} = (50.2 ± 2.3) ns: the delay from the PMT photocathode signal, to the time-stamping by the OMC FPGA (measured inclusively with a ps laser). When also including the correction related to the transverse event distribution inside the detector the correction becomes $\delta_{TT} = 59.6$ ns. 3) $\delta t_{clock} = (4263 \pm 1)$ ns: the delay in the transmission of the time base of the OMC to the TT front-end cards. 4) $\delta_{FPGA} = (24.5 \pm 1.0)$ ns: the internal delay of the FPGA processing the OMC signal to reset the counter which is incremented every 10 ns to time-stamp TT hits.

The time of the neutrino interaction is defined as that of the earliest TT hit. Since ToF_c is computed with respect to the origin of the OPERA RF (ORF), located beneath the most upstream spectrometer magnet, the time of the earliest hit is corrected for its distance to the ORF along the beam line.

We will briefly give some further description on the two flaws which were discovered more recently leaving the reader to [10,9,7] for more detailed reports:

- The mis–calibration of the OPERA master clock resulted in a time drift of 124 ns/s accumulating in between re-synchronizations occurring every 0.6 s ("DAQ" cycle). This cycle remains in phase with the CNGS cycle over time-scales of several months introducing a practically constant time-offset. The effect goes in the direction of artificially decreasing the anticipation effect by about 15 ns.

- The re-measurement of the $\delta_{UTC-LNGS}$ component [10] evidenced a discrepancy with the previously measured value of 73.2 ns going in the direction of an artificial increase of the neutrino anticipation. The delay effect is related to an anomalous attenuation of the light signal introduced by an improper match of the optical fiber underground introducing a reproducible and stable condition. The existence of this anomalous condition during the bunched-beam data taking in November 2011 was confirmed by the inspection of pictures taken before that time. Furthermore the analysis of the OPERA-LVD horizontal cosmic muon coincidences[8] which was promoted by OPERA in collaboration with LVD to confirm the direct measurement of the fiber delay and determine its stability in time, has provided a strong evidence for the presence of this condition throughout the full period of the data taking considered for the analysis (confirming both the extra delay and the OMC drift)[8,9]. The analysis is based on coincidences of almost horizontal high energy cosmic ray muons penetrating a region with limited overburden and crossing both the OPERA and LVD detectors. The timing of these events allows to profit of a natural time scale (the ToF of cosmic muons over the 162 m separating the experiments) which can be used to monitor anomalous states of one of the two timing systems (Fig. 2).

The total sample used for the analysis consists of 15223 events (7235 internal, CC and NC, and 7988 external CC) detected in OPERA, corresponding to about 10^{20} protons on target (pot) collected during the 2009-2010-2011 runs. The updated results[6] using the standard timing structure after all corrections are fully consistent with neutrinos travelling at the speed of light within the experimental accuracy both using the standard beam or the bunched beam data of autumn 2011 (6 internal and 14 external events). The dominant uncertainty comes from the calibration of the BCT time response and the a posteriori value for the $\delta_{UTC-LNGS}$ correction. There is furthermore no indication for a dependence on the period of the year, time of the day, neutrino energy, beam intensity or containement in the detector[5].

In preparation for a new bunched-beam run which took place during two weeks in May 2012 the experiment has improved the timing system by using a new oscillator for the OMC and introduced the possibility for an offline correction for the 25 ns jitter between the PPmS and the OMC clock. Furthermore data from the RPC system have been successfully employed[11] both with the standard OPERA DAQ and with an ad-hoc stand-alone TDC system which by-passes the complexity introduced by the full DAQ system. All these results will be the subject of reports in the near future.

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