

## ANALYSIS OF THE MACRO EXPERIMENT DATA TO COMPARE PARTICLE ARRIVAL TIMES UNDER GRAN SASSO

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**ABSTRACT.** The claim of a neutrino velocity different from the speed of the light, made in September 2011 by the Opera experiment, suggested the study of the time delays between TeV underground muons in the Gran Sasso laboratory using the old data of the MACRO experiment, ended in 2000. This study can also give hints on new physics in the particle cascade produced by the interaction of a cosmic ray with the atmosphere.

**KEYWORDS:** neutrino velocity, new massive particles, tachyons, supersymmetry.

### 1. INTRODUCTION

In September 2011 there was a measurement of the speed of neutrino faster than the speed of light by  $(v-c)/c = 2.48 \pm 0.28(\text{stat}) \pm 0.30(\text{sys}) \times 10^{-5}$  [2]. After many checks, we know now that this result was due to hardware problems and the Opera 2012 result is that the speed of the neutrinos traveling from CERN to the Gran Sasso is  $(v-c)/c = -0.7 \pm 0.5(\text{stat})_{-1.5}^{+2.5}(\text{sys}) \times 10^{-6}$  [8]. This result is in agreement with the results of the other Gran Sasso experiments [6].

However the interest in this claim suggested the possibility to compare neutrino and muon velocity in a cosmic ray cascade [12]. The interaction of a primary cosmic ray with the atmosphere produces a cascade with many kind of particles, and in particular neutrinos and muons. Muon neutrinos and muons are produced mainly via the decay of charged pions and kaons produced in the primary cosmic ray interactions. Above about 10 TeV they can also come from prompt decays of charmed hadrons. This component has not yet been observed. In a deep underground detector only muon and neutrino are detected. If the neutrino velocity is different from  $c$  the neutrinos in this cascade, should arrive with times different from the times of the muons from the same parent decay, or from another decay, with a time delay that should change according to the neutrino path length which depends on its zenith angle  $\theta$ . In underground detectors muon neutrinos are detected looking for induced muons produced by neutrino charged current interactions in the rock, or in the ice around or inside the instrumented region. Hence, a time spread should be observed between the muons produced directly by the pion or kaon decay and the muons produced by neutrino interactions.

The path length from the meson decay point is a few tens of kilometers for vertical neutrinos and up to  $\sim 300$  km for near horizontal neutrinos. Assuming the original time difference observed in OPERA, nearly horizontal neutrinos should arrive up to 28 ns before

the other secondaries. In [10] a table of average production heights neutrinos in the atmosphere has been reported. The typical production height for neutrinos of energy above 20 GeV can be 17.6 km at the vertical, 94.9 km at  $\cos \theta = 0.25$  and 335.7 km at  $\cos \theta = 0.05$ , which would correspond to 1.4, 78 and 27.6 ns.

There are already limits of tachyons or anomalous delayed particles in cosmic rays. The limits are obtained searching for example signals before or after the main front of the electromagnetic shower. But of searches of this kind stopped some time ago and the last particle data book review of those data is the review of 1994 [11]. The limits obtained are of small interest in the framework of the OPERA result. However, if neutrinos were tachyons, it is likely that some other kind of tachyons could exist and this search in very high energy cosmic rays could have a new interest.

It is important to note that the Gran Sasso mountain minimum depth  $\sim 2700 \text{ g/cm}^2$  corresponds to a minimum muon energy of 1.4 TeV. It is easy to compute that, requiring a minimum threshold of 50 MeV in the detector, the time difference between two muons underground should be  $\ll 0.2$  ns. Therefore anomalous time differences should be a signal of “new physics”, for example a signal of supersymmetric massive particles produced in a cosmic ray cascade. For example, let us assume a hypothetical hadron of mass 100 GeV, produced by an interaction of a proton with center of mass energy 7 TeV (the LHC energy). If this hypothetical hadron interacts or decays after 10 km producing at the end muons, the delay between the underground muon from the massive particle and the muon produced in the primary vertex is of the order of 13 ns. LHC experiments have put limits for new hadron-like massive particles [1, 7], but it is important to remember that the cosmic ray energy could be larger than the LHC energy. Under Gran Sasso the fraction of multiple muons produced by cosmic rays with center of mass energy  $\geq 7$  TeV is estimated of the order of  $10^{-3}$  in MACRO, corresponding to several thousand

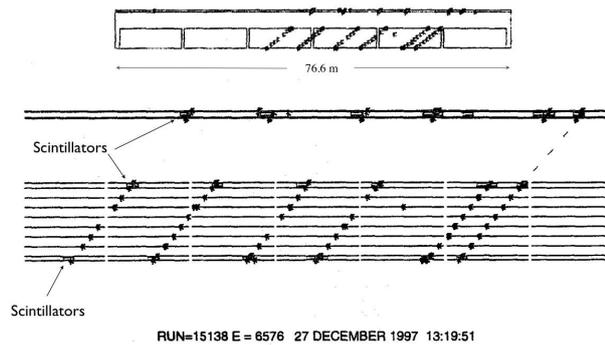


FIGURE 1. Event with six parallel muons in 3 MACRO “supermodules”. At the top there is the full MACRO display, on the bottom the zoom of the 3 supermodules interested by the event. The 12 streamer tube horizontal planes are shown as horizontal lines, the back points are the streamer tubes fired; the scintillator boxes fired are shown as rectangles.

multiple muon events in the MACRO data set. One should also consider the possibility that new massive relic particles are directly in the primary cosmic radiations.

The MACRO experiment has made several searches for possible anomalies of the time differences between muons [3]. The search was made mainly to study time differences of the order of a few ms or more, but this paper contains also a study of time differences at the ns-level. The statistics was limited to 35 832 tracks in events with two or more tracks. In 1992 noone was thinking about tachionic neutrinos, and therefore there was no estimate of the number of tracks due to down-going neutrino together with the primary muons. In [13], this study was extended to about 140 000 tracks of multi muon events, corresponding to about 4% of the total MACRO statistics. The time distribution was in agreement with the predictions.

In this paper, I present an analysis of the full MACRO statistics. This was not an easy job. The main reason is that MACRO ended in 2000, and most of the analysis software was designed for VAX/AlphaVAX computers and data formats around 1990 (a geological era for computers!). A lot of time was needed to convert programs and to find data files, sometimes stored on data tape cassette of old formats, obsolete and not supported by modern computers.

## 2. THE MACRO EXPERIMENT AND THE TIMING SYSTEM

The MACRO experiment [5] was located in Hall B of the Gran Sasso underground laboratory. The modularity allowed data-taking also with partial configurations of the apparatus, starting from March 1989. The full detector was operative in the period April 1994–December 2000.

MACRO was a large rectangular box ( $76.6 \times 12 \times 9.3 \text{ m}^3$ ) divided longitudinally in 6 supermodules and vertically in a lower and an upper part (called *attico*).

The active elements were liquid scintillator counters for time measurement and streamer tubes for tracking, with  $27^\circ$  stereo strip readouts. The lower half of the detector was filled with trays of crushed rock absorber alternating with streamer tube planes, while the *attico* was hollow and contained the electronics racks and work areas. The rock absorber sets a minimum energy threshold for vertical muons of 1 GeV.

The tracking system was designed to reconstruct the particle trajectory in different views ( $x$ - $z$  for horizontal streamer tubes,  $d$ - $z$  for horizontal strips,  $y$ - $z$  for vertical streamer tubes combined with central hits). To perform this analysis the standard MACRO tracking software was improved to have greater efficiency for near horizontal tracks.

The intrinsic angular resolution for muons typically ranges from  $0.2^\circ$  to  $1^\circ$  depending on track length. This resolution is lower than the angular spread due to multiple scattering of downward-going muons in the rock.

The scintillator system consisted of horizontal and vertical layers of counters filled with a mixture of mineral oil (96.4%), pseudocumene (3.6%) and wavelength shifters (2.88 g/l). The counters had an active volume of  $11.2 \times 0.73 \times 0.19 \text{ m}^3$  in the horizontal planes and  $11.1 \times 0.22 \times 0.46 \text{ m}^3$  in the vertical planes.

The total charge and the time of occurrence of the signals were measured at the two ends of each counter with two independent systems, the Energy Response Processor (ERP) and the Pulse Height Recorder and Synchronous Encoder (PHRASE). The analysis described in this paper is based on ERP data. The time and longitudinal position resolution for a single muon in a counter were about 0.6 ns and 12 cm, respectively. The photomultiplier signal is split into a direct output and one attenuated by a factor of 10, in order to be on-scale also for very large pulses. Two different thresholds are used for the timing of these two outputs. The redundancy of the time measurement helps to eliminate spurious effects. Each MACRO supermodule is connected to a dedicated independent ERP system. The timing between the ERP systems is insured by standard CAMAC TDC. Due to the random noise the possibility to have wrong times in the inter ERP TDCs is quite high, and this is the main source of non-Gaussian tails in the time distributions for events interesting different supermodules.

## 3. TIME DIFFERENCES IN THE MACRO MUON BUNDLES

Thanks to its large area and fine tracking granularity the MACRO detector was a proper tool for the study of multiple parallel muons. Many papers were published by MACRO on this topic to study the muon multiplicity, the distance between muons and the impact on cosmic ray composition from the multiple muon measurement. The last MACRO paper on this argument is in [4]. One important number to consider is that the average distance between muon pairs is

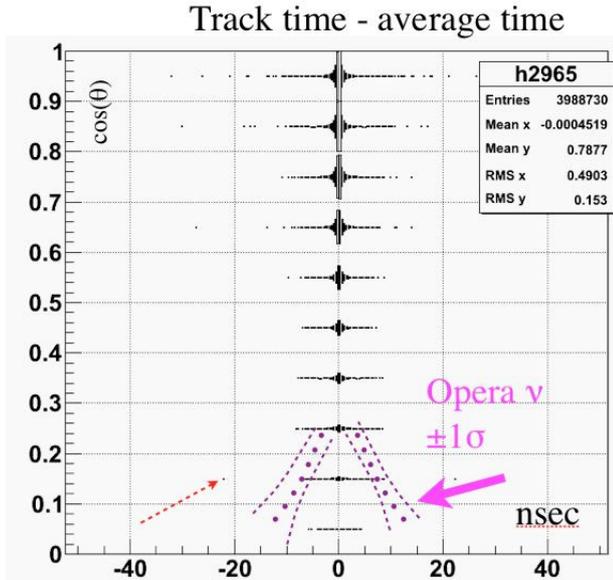


FIGURE 2. Difference between track time and average time for multiple parallel muons with 2 or 3 tracks as function of  $\cos(\theta)$ . The dot size is proportional to the logarithm of the bin content. If the original OPERA claim had been correct, a few tracks would be expected inside the dashed region (see text).

$\langle r \rangle \sim 9.4$  m. For vertical tracks and average depth  $3800 \text{ g/cm}^2$ . The value of  $\langle r \rangle$  changes slowly with depth and zenith angle. Figure 1 shows a typical multiple muon event. From this picture is easy to understand one of the problems of this analysis: the large dimension of the scintillator boxes compared to the average value of  $\langle r \rangle$ . The probability of having more than one track intercepting the same counters is high. In this case, the time could be wrong. This is because the analysis software could fail to compute the light propagation time from the intercept of the track to the photomultipliers. This is the second source of non-Gaussian tails in the time distributions (the first is the timing between different supermodules).

For each track the analysis program computes the  $\beta = v/c$  and the “track time” (average between the scintillator times along the track). To remove noise, the analysis program uses only the scintillators in which the position along the scintillator computed by the time differences between the PM at the ends is in agreement with the position given from the streamer chambers. Therefore the analysis program computes the differences between the “track times” and the average time of all the tracks in the bundle. This is done including a correction due to the incidence angle. A  $5^\circ$  angular cut is applied to require parallel tracks. To have a valid track time a single scintillator is sufficient, but in the case of events between different supermodules there is the requirement that at least one track between two different supermodules has two scintillators and that the beta value is consistent with one. This is to reduce the noise due to the inter ERP TDCs.

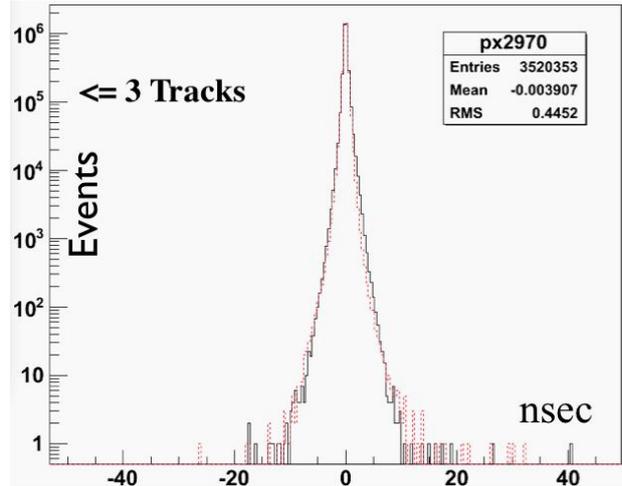


FIGURE 3. Difference between track time and average time for multiple muons with 2 or 3 tracks (continuous line) compared with a “simulation” using the data (dashed line).

The calculation of the expected number of events, if the original OPERA claim was correct, is done considering the probability to have a neutrino and a muon from the same decay, computed in [12] and the probability to have a neutrino and a muon from different decays, computed using the approximated Elbert formulas [9]. The detector and analysis efficiencies were evaluated using the standard multiple muon MACRO simulation software, with a modification to allow a delay in one of the muons. This calculation gives 2 delayed tracks with time delay  $|\delta t| \geq 10$  ns expected in MACRO the data set.

In the case of events with a muon from a neutrino interaction there is unlikely more than one muon directly from the hadronic cascade, so the analysis is limited to events with less than 3 tracks (one track could be a spurious track). The results are in Fig. 2. Figure 2 also shows the times expected if the original Opera result would have been correct. Considering the region with  $\cos(\theta) \leq 0.2$  and  $|\delta t| \geq 10$  ns there is one event with two tracks with a time track – average time  $\sim 22$  ns (the dot of Fig. 2 near the dashed arrow). However this time is outside the Opera region. In the Opera region there are no tracks. This result should be compared with the 2 tracks expected.

To understand if the distribution tails in the full angular region are real or due to detector effects I made a comparison, computing for each track with two scintillator counters the time difference between times (instead of the average). This is shown in Fig. 3 as a dashed line. This plot shows that there is agreement between the two distributions and therefore we can conclude that most of the tails are indeed due to effect of the detector.

Finally Fig. 4 shows the time difference, including all the multiple muon multiplicity. Since a possible signal due to massive particles or exotic relics is expected at high path length, I have divided the angular region

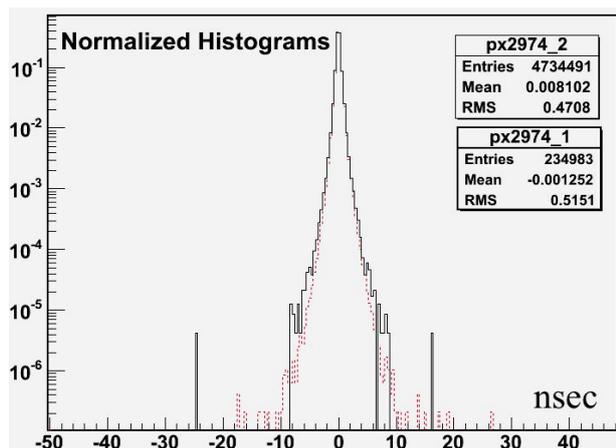


FIGURE 4. Difference between track time and average time for multiple muons with all multiplicities: continuous line  $\cos(\theta) \geq 0.5$ , dashed line  $\cos(\theta) \leq 0.5$  (histograms normalized to 1).

in two parts:  $\cos(\theta) \geq 0.5$ , and  $\cos(\theta) \leq 0.5$ . The two distributions are comparable. But the  $\cos(\theta) \leq 0.5$  distribution has two tracks with time differences  $\geq 15$  ns, compared with 0.4 tracks expected from the  $\cos(\theta) \geq 0.5$  distribution (Poisson probability 0.06).

#### 4. CONCLUSIONS

This work ended some time after the solution of the superluminal neutrino puzzle, but I think that has been very useful to remember that cosmic rays are still important tools in particle physics. For the superluminal neutrino, 2 tracks were expected but 0 were found. Considering the different mean-lives of the pion and the kaon, an “exotic” limit can be derived from the horizontal tracks of Fig. 2 on the equality of the pion and kaon speed in a cascade produced by a primary with  $E \geq 3$  TeV:  $|\beta_\pi - \beta_k| \ll 1.5 \times 10^{-4}$ . This result at the moment is of very low interest but the superluminal neutrino saga has shown that nothing can be given as guaranteed. More investigations

are necessary on the delayed tracks in events with multiplicity bigger than 3 and on massive particles in cosmic rays.

This work has shown once again the importance of saving past experiment data for further analysis. I must thank the MACRO collaboration which built and run the detector and many MACRO people who helped me to recover data and programs and particularly Nazareno Taborgna of the Gran Sasso laboratory, who was able to save a working alphaVAX with several MACRO original disks. Particular thanks go to Teresa Montaruli for useful and deep discussions.

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