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Annual modulation of the atmospheric muon flux measured by the OPERA experiment

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Abstract. The OPERA experiment, designed to search for $\nu_\mu \to \nu_\tau$ oscillations, reached its main goal by observing the appearance of ν_τ in the CNGS ν_μ beam. Thanks to its location in the underground Gran Sasso laboratory, under 3800 m.w.e., it has also been exploited as an observatory for TeV muons produced by cosmic rays in the atmosphere. In this paper the preliminary measurement of the annual modulation of the atmospheric muon flux with the OPERA detector is reported.

1. Introduction

Atmospheric muons constitute the penetrating charged remnants of cosmic rays under the Earth's surface. They are produced when primary cosmic rays, typically protons, impinge on the Earth's atmosphere initiating a particle cascade. Most of the interaction products are π and K mesons which in turn decay or interact, depending on their energy and on the air density profile they pass through. The decay of π^0 gives rise to the electromagnetic component of the showers, the decay of $\pi^\pm$ and $K^\pm$ yields mostly atmospheric muons and neutrinos. Due to their energy loss, only high energy muons can reach underground experiments, with an energy threshold, E_{thr}, depending on the depth. At the Gran Sasso laboratory (LNGS) located under 1400 meters of rock overburden, corresponding to an average depth of 3800 m.w.e., the surface muon energy threshold is ~ 1 TeV (1.4 TeV when averaged over all the directions and rock depths). The flux of atmospheric muons detected deep underground shows seasonal time variations correlated with the temperature of the stratophere, where the primary cosmic rays interact [1]. An increase in temperature of the stratosphere causes a decrease of the air density, thus reducing the chance of mesons to interact, and resulting in a larger fraction decaying to produce muons. This leads to a higher rate of muons observed deep underground. The effect increases with the muon energy, because higher energy mesons with larger lifetimes (due to time dilation) are involved. This effect has been known and studied for many decades and has been reported by other experiments at LNGS (MACRO [2, 3], LVD [4], Borexino [5] and GERDA [6]) and elsewhere (ICECUBE [7], MINOS [8] and Double Chooz [9]).

2. The OPERA detector

The OPERA experiment was designed to observe neutrino flavour oscillations through the appearance of ν_τ in the CERN Neutrinos to Gran Sasso (CNGS) ν_μ beam. The OPERA detector [10] was located in the Hall C of LNGS and exposed from 2008 to 2012 to the CNGS. OPERA was a hybrid electronic detector/emulsion apparatus composed of two identical parts, each one consisting of a target section and a magnetic spectrometer. In the target, Emulsion Cloud Chambers were arranged in 29 vertical "walls" transverse to the beam direction interleaved with electronic Target Tracker (TT) walls. Each TT wall consisted of a double layer of 256 scintillator strips, for vertical and horizontal coordinate measurements. The spectrometer was a large dipolar iron magnet instrumented with Resistive Plate Chambers and drift tube detectors.

Cosmic ray induced events in OPERA were reconstruted with a dedicated software procedure effective at identifying single and multiple muon tracks (muon bundles). Beam events, tagged on the basis of their absolute time and correspondance with the CNGS spill window, were not considered for this analysis. OPERA continuously accumulated cosmic ray data with the target electronic detectors over the whole period from 2008 to 2012. However, the magnetic spectrometers were active only during the CNGS Physics Runs, being switched off during the CNGS winter shutdowns. The acceptance to cosmic ray muons coming from above was evaluated as $A = 599$ m^2 sr for the full detector, and $A = 197$ m^2 sr for muons crossing the spectrometer sections [11].

3. Atmospheric muon flux and modulation

As already mentioned, summer lower air density allows a longer mean free path of π and K mesons. This results in a higher fraction of mesons decaying into muons before their first interaction. So the atmospheric muon rate varies during the year increasing in summer and decreasing in winter, as the atmospheric temperature do. The variation can be modelled as a sinusoidal function, which is a first order approximation since the average temperature is not precisely constant over the years and short term effects occur leading to local maxima and minima.

In Fig. 1 (top) the flux of single muons measured by OPERA from January 2008 to December 2012 is shown. There are no data in the first 5 months of 2009 because the acquisition was stopped due to a DAQ upgrade initially and then to the earthquake in L'Aquila. The flux has been fitted to $I_\mu(t) = C + A\cos(2\pi/T \cdot (t-\phi))$. Preliminary results show the presence of a component modulated with period T=(365 ± 2) days, with an amplitude amounting to ∼1.5% of the average flux. The maximum is observed around day (176 ± 4) corresponding to June 25th.

The atmospheric temperature data are taken from the European Center for Medium-range Weather Forecasts (ECMWF) at the LNGS coordinate location. Atmospheric temperatures are provided at 37 discrete pressure levels ranging from 1 to 1000 hPa four times per day. The atmosphere can be described by many layers with a continuous distribution of temperature and pressure. A suitable modelization, reported in [12], describes the atmosphere as an isothermal body with an effective temperature T_{eff} obtained from a weighted average:

$$T_{eff}(t) = \frac{\int_0^\infty dX\ T(X,t)\ W(X)}{\int_0^\infty dX\ W(X)} \simeq \frac{\Sigma_{n=0}^{N} \Delta X_n\ T(X_n,t)\ W(X_n)}{\Sigma_{n=0}^{N} \Delta X_n\ W(X_n)}$$

where the integral extends over the atmospheric depth, approximated as a sum over discrete atmospheric levels X_n. The weights $W(X)$ [12] reflect the dependence on the altitude of the production of mesons in the atmosphere and their decay into muons that eventually are observed underground. The four measurements in each day are averaged and the variance used as an estimate of the uncertainty on the mean. The results are shown in Fig. 1 (bottom) for the same period of the OPERA data taking. The average effective temperature is 220.5 K, and a modulation is observed with period and phase similar to those observed for the single muon rate.

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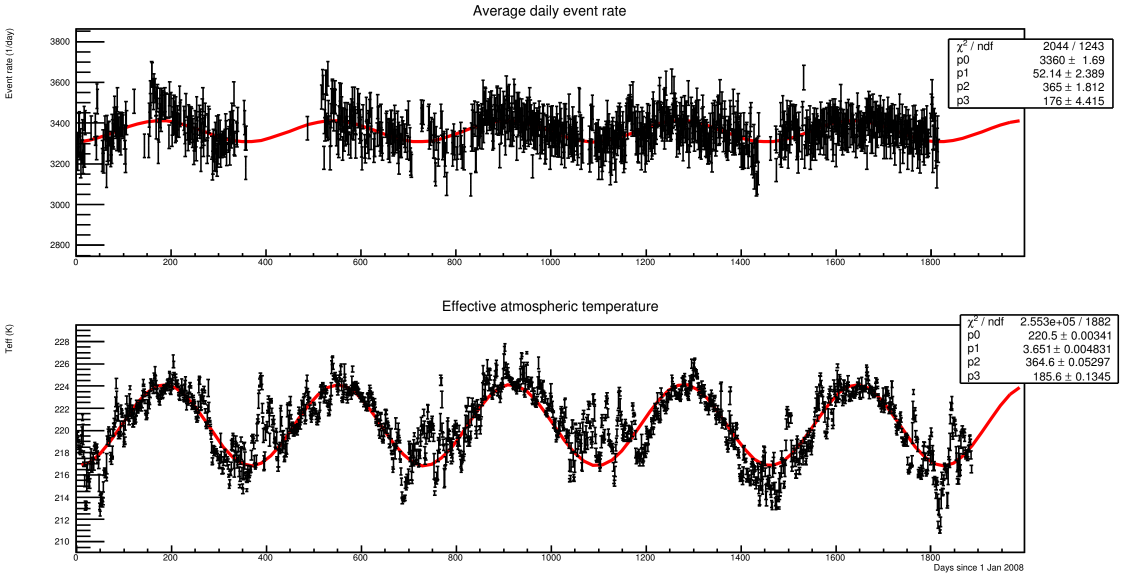

Figure 1. Single muon rate measured by the OPERA detector (top) and effective atmospheric temperature T_{eff} (bottom) from January 2008 to December 2012.

More refined analyses based on Lomb-Scargle and maximum likelihood techniques have been performed to study the period and phase of the modulation observed in the cosmic ray flux. Lomb-Scargle (LS) periodograms [13, 14] are a common tool to analyze binned data with periodical modulations like the sinusoidal approximation here adopted. For this analysis the generalized LS periodogram, which takes into account the non-zero average value of the event rate, is considered. The periodogram shows the most significant peak at 365 days, but other less significant peaks are also present, probably as a consequence of the fact that the sinusoidal modelization is only a simplification. According to our simulations, part of the less significant peaks may also arise because of detector down-times.

In studying the correlation between the phase and the period, a Maximum Likelihood approach has been followed, defining the likelihood as $L = \prod e^{-\mu_i} \mu_i^{n_i}/n_i!$, where the product runs over the days with muon flux measurement n_i. The corresponding expected muon rate μ_i is estimated using the sinusoidal function. Allowed regions in phase and period are obtained assuming a 2 degree of freedom distribution for $\Delta\chi^2 = -2\ln\widetilde{L} - \chi^2_{min}$, χ^2_{min} being the minimum value in the parameter space and $\widetilde{L}$ being the likelihood maximized, for every couple of period and phase values, over the constant term I_0 and the amplitude of the modulated contribution A. In Fig. 2, the preliminary 68%, 90% and 95% C.L. allowed regions are shown in the phase versus period parameter space.

The relative phase between the two time series, rate and temperature, has been studied using the correlation function defined as

$$R(\tau) \;=\; \int (I_\mu(t) - I_\mu^0)(T_{eff}(t-\tau) - T^0_{eff})dt \;\simeq\; \Sigma_i \; (I_\mu(t_i) - I_\mu^0)(T_{eff}(t_i - \tau) - T^0_{eff})$$

where the sum is extended to all the days with a measurement of the single muon flux with the OPERA detector. I_μ^0 and T^0_{eff} are the average values obtained from the fits on the atmospheric muon flux and on the effective atmospheric temperature, 3360 μ/day and 220.5 K respectively. The cross-correlation function shows a peak at zero day shift between rate and

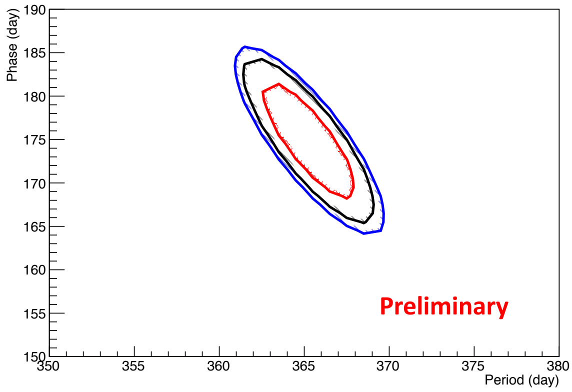

Figure 2. Preliminary 68% (red), 90% (black) and 95% (blue) C.L. allowed regions in the phase versus period parameter space for the atmospheric single muon flux.

effective temperature time series.

4. Correlation between rate and temperature seasonal variations

The muon flux variation, $\Delta I_\mu = I_\mu - I_\mu^0$, can be related to variations from the average atmospheric temperature at a given altitude X, $\Delta T(X) = T(X) - T^0(X)$. Considering every altitude layer, the muon flux variation is given by:

$$\Delta I_\mu(t) = \int_0^\infty dX\ W(X)\ \Delta T(X,t)$$

where the integral extends over the atmospheric depth. Defining an "effective temperature coefficient", α_T:

$$\alpha_T = \frac{T^0_{eff}}{I^0_\mu} \int_0^\infty dX\ W(X)$$

the relationship between atmospheric temperature fluctuations and intensity variations can be written as:

$$\frac{\Delta I_\mu(t)}{I^0_\mu} = \alpha_T \frac{\Delta T_{eff}(t)}{T^0_{eff}}$$

In Fig. 3, left panel, the percentage deviation of the single muon flux, $\Delta I_\mu / < I_\mu >$, is shown as a function of the relative effective temperature variation, $\Delta T_{eff} / < T_{eff} >$, using data of the days with both measurements available. The effective temperature coefficient α_T is obtained by means of a linear fit and its preliminary value is $\alpha_T = 0.94 \pm 0.04$. In Fig. 3, right panel, the OPERA preliminary result is shown together with the values measured by other experiments at different depths. The theoretical prediction of α_T depends on the relative contribution of pions and kaons to the atmospheric muon flux, and is a function of the muon energy threshold and thus of the detector depth. The comparison between the measured coefficient α_T and the theoretical expectation will allow to infer the ratio of kaons to pions produced in the primary cosmic ray interactions, $r(K/\pi)$.

5. Conclusions

The OPERA experiment achieved its primary goal assessing the discovery of $\nu_\mu \to \nu_\tau$ oscillations in appearance mode with a significance greater the 5σ [15]. Moreover, the OPERA detector was exploited to study the annual modulation of atmospheric muons. Preliminary results were

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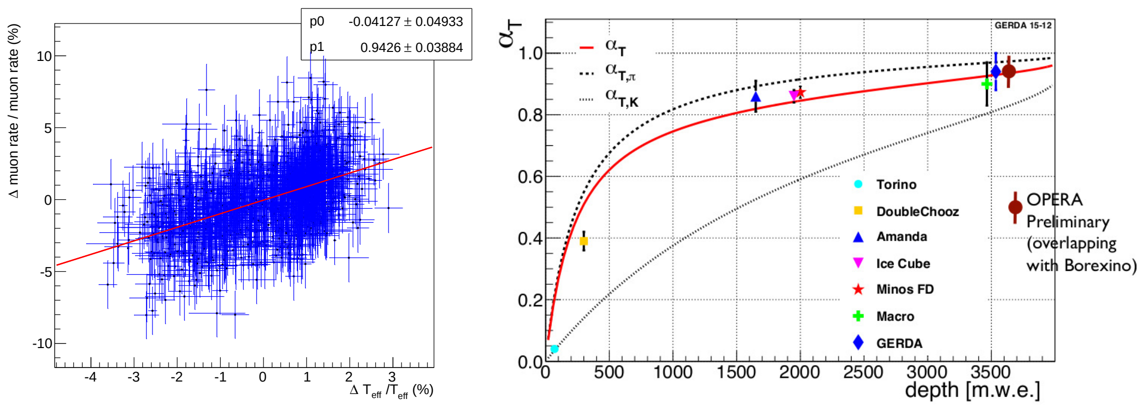

Figure 3. Left: correlation between the muon rate and effective temperature relative variations. Right: Effective temperature coefficient α_T vs depth as measured by different underground experiments. The red line is the value predicted assuming muon production from pions and kaons; the dashed lines correspond to the single production mechanisms.

presented using the 2008-2012 data set. Modelling the variations of the single muon flux with a sinusoidal function, the modulated component results with an amplitude $\sim$1.5% with a period of one year, $T = (365 \pm 2)$ days, and a phase corresponding to a maximum on June 25th. The cross-correlation between the rate I_μ and the effective air temperature T_{eff} time series has been evaluated and shows a peak at zero day shift. Muon rate fluctuations are shown to be positively correlated with atmospheric temperature variations, with an effective temperature coefficient $\alpha_T = 0.94 \pm 0.04$. The results are in agreement with theoretical expectations for the LNGS site and with previous measurements.

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