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Ten years of cosmic muons observation with Borexino

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***on behalf of the Borexino collaboration**
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Abstract. The Borexino detector at Gran Sasso has now accumulated over ten years of continuous data which represent a magnificent opportunity to study the cosmic muon flux at a deep underground location. We present here a precision measurement of the flux and of the expected seasonal modulation. We present the correlation with the atmospheric temperature variations from global atmospheric models. We measure the correlation parameters and infer the kaon-to-pion ratio in the production of cosmic muons from high energy primaries. We also find evidence of a long term modulation that is not present in the atmospheric data and we investigate a possible positive correlation with the solar activity. Finally we observe a seasonal modulation of the production rate of cosmogenic neutrons that is in phase with the muon modulation but shows a surprisingly larger amplitude.

The Borexino experiment is a neutrino detector designed for precision spectroscopy of low energy neutrinos from the Sun. The neutrino detection occurs via elastic scattering on electrons in a large volume of highly purified organic liquid scintillator. Over the past 12 years Borexino has performed a complete spectroscopy of neutrinos from the solar pp chain of reactions[1] and is now aiming at the first detection of neutrinos from the CNO cycle. At the same time Borexino has delivered plenty of non-neutrino physics results. We present here the latest analysis performed on the first ten years of Borexino data and pertaining the cosmic muon flux underground, its time modulations, its correlation with the atmospheric temperature, some insights on the meson decay mechanisms that generate the muons, a discussion on possible correlation with the solar activity and finally the modulation of the neutron flux induced by cosmic muons, called cosmogenic neutrons.

Borexino [2] is located at the Gran Sasso National Laboratories (LNGS) in central Italy, at a depth of 3800 m w.e.. The active mass consists of 278 tons of pseudocumene (PC), doped with 1.5 g/l of PPO.

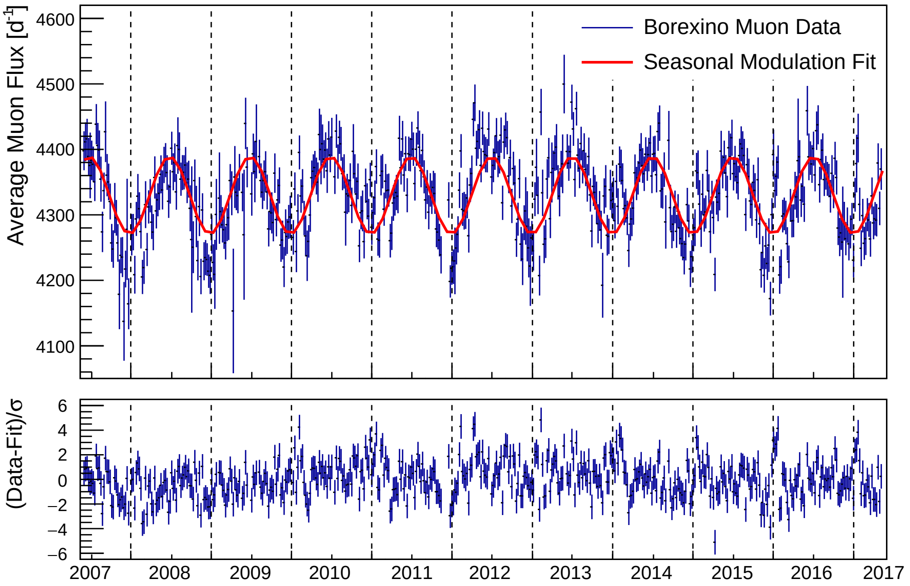

Figure 1. Muon Flux observed by Borexino (weekly binning). The seasonal modulation is evident.

The scintillator is contained in a thin (125 μm) nylon Inner Vessel (IV), 8.5 m in diameter. The IV is surrounded by two concentric PC buffers doped with a light quencher. The scintillator and buffers are contained in a Stainless Steel Sphere (SSS) with a diameter of 13.7 m. The scintillation light released in the PC is detected by 2212 8" PhotoMultiplier Tubes (PMTs) uniformly distributed on the inner surface of the SSS. All this is named Inner Detector (ID). The SSS is enclosed in a Water Tank (WT), containing 2100 tons of ultra-pure water as an additional shield against backgrounds from the laboratory environment. Additional 208 8" PMTs instrument the WT and detect the Cherenkov light radiated by cosmic muons that cross the water shield. This is named the Outer Detector (OD). The data used in the present analysis covers 3218 days in ten astronomical years starting May 16th 2007 (beginning of data taking) and until May 15th 2017 with no significant interruptions. We use here muons that cross both ID and OD with a cross section of 146 m^2 independent from the muon's incident angle. We achieve a total exposure of 4.2 $10^5\,\mathrm{m}^2\,\mathrm{d}$.

The upper atmosphere is affected by seasonal temperature variations that alter the mean free path of the muon-producing mesons at the relevant production heights. These fluctuations are expected to be mirrored in a seasonal modulation of the underground muon flux since the high energies necessary for muons to pass through the rock overburden require that the parent mesons have decayed in flight without any former virtual interaction.

In Figure 1 we show the muon flux observed by Borexino. At first order, the muon flux may be described by a simple sinusoidal behaviour, with perturbations arising from short- or long-term effects. Fitting with the function

$$I_\mu(t) = I_\mu^0 + \delta I_\mu \cos\left(\frac{2\pi}{T}(t - t_0)\right) \tag{1}$$

we measure an average muon rate $R_\mu^0 = (4329.1 \pm 1.3)\,\mathrm{d}^{-1}$, which corresponds to a mean muon flux $I_\mu^0 = (3.432 \pm 0.001) \cdot 10^{-4}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$. The modulation amplitude is $\delta I_\mu = (58.9 \pm 1.9)\,\mathrm{d}^{-1} = (1.36 \pm 0.04)\%$, the period is $T = (366.3 \pm 0.6)\,\mathrm{d}$, and the phase is $t_0 = (174.8 \pm 3.8)\,\mathrm{d}$. The phase can be better constrained folding the data set onto a single year and fitting with the period fixed to one year. In this way we obtain the same rate and amplitude, while the phase is $t_0 = (181.7 \pm 0.4)\,\mathrm{d}$.

In order to investigate the awaited correlation with the atmospheric temperature we have obtained the absolute temperature from the weather forecasting center ECMWF for the location of the laboratory. A common parametrization involves the definition of a weighted mean temperature T_{eff} over the 0-60 km

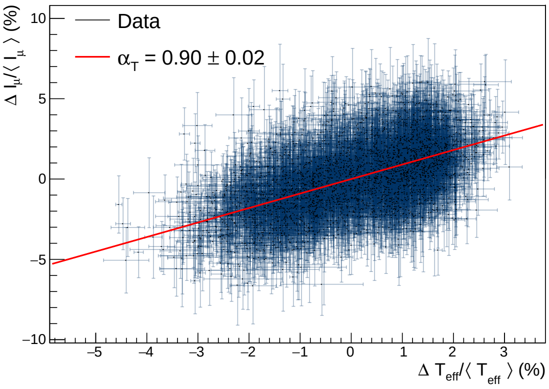

Figure 2. Correlation between muon flux and temperature fluctuations.

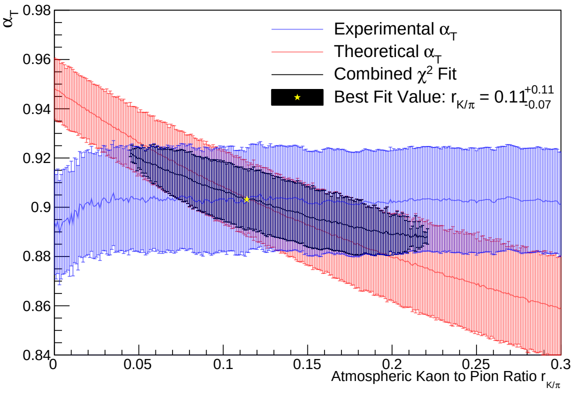

Figure 3. Expected and measured α_T for different values of $r_{K/\pi}$.

height range, where the weights reflect the muon production rate occurring at each height. Indeed $T_{\rm eff}$ shows a matching yearly modulation over the same ten years of figure 1. Relative muon flux changes relate to relative $T_{\rm eff}$ changes by

$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_{\rm T} \frac{\Delta T_{\rm eff}}{T_{\rm eff}} \tag{2}$$

where and α_T quantifies the correlation between these two observables. The correlation is shown in figure 2 (R-value = 0.55). A linear regression accounting for error bars on both axes returns $\alpha_T = 0.90 \pm 0.02_{stat}$, which halves the error of our previous measurements[3] and is in good agreement with it as well as with other experiments at LNGS. We have analyzed possible systematic effects and found them small with respect to the statistical uncertainty. The theoretical prediction for α_T can be written as:

$$\alpha_{\rm T} = \frac{1}{D_\pi} \frac{1/\epsilon_{\rm K} + A_{\rm K}(D_\pi/D_{\rm K})^2/\epsilon_\pi}{1/\epsilon_{\rm K} + A_{\rm K}(D_\pi/D_{\rm K})/\epsilon_\pi}, \qquad D_{\pi,{\rm K}} \equiv \frac{\gamma}{\gamma+1} \frac{\epsilon_{\pi,{\rm K}}}{1.1\langle E_{\rm thr} \cos\theta \rangle} + 1 \tag{3}$$

where $A_K = 0.38 \times r_{K/\pi}$ describes the kaon contribution to the cosmic muon flux [4]. $\langle E_{thr} \cos\theta \rangle$ is the threshold energy for muons to reach deep underground averaged over the incoming zenith angle. For LNGS it was so far computed assuming a flat overburden as $\langle E_{thr} \cos\theta \rangle = 1.833$ TeV [4]. We have instead simulated the muon flux propagation through the mountain using its actual profile and obtained $\langle E_{thr} \cos\theta \rangle = 1.34$ TeV. This leads to a predicted $\alpha_T = 0.895 \pm 0.15$ also in good agreement with our measurement.

We have also indirectly measured the ratio of muon production from kaon decay over pion decay. Figure 3 shows the theoretical α_T computed for different values of $r_{K/\pi}$ as well as the measured α_T. The latter also has a weak dependence on $r_{K/\pi}$ which enters the computation of $T_{\rm eff}$. The intersection point and $1\,\sigma$ regions are highlighted in black. Although several other more accurate measurements of $r_{K/\pi}$ exist from accelerator experiments, this is one of the few obtained in atmosphere using cosmic rays data. We estimate a center-of-mass energy of (190 ± 28) GeV, calculated assuming an average collision of a primary 18 TeV proton on a fixed nucleon target. Our result agrees with former measurements [4, 5].

We performed a Lomb-Scargle (LS) analysis for the observed muon rate and the effective atmospheric temperature (figure 4). In addition to the main peak at 1 yr we observe e second significant component in the muon data with a period of ~ 3000 days, which is not present in the temperature data. This was already evident in figure 1 but it can be appreciated in year-wide bins in figure 5.

Fitting the spectrum allowing for both annual and long term modulation we obtain for the latter $T^{\rm long} = (3010 \pm 299)\,{\rm d} = (8.25 \pm 0.82)\,{\rm yr}$, in good agreement with the Lomb-Scargle analysis, a phase $t_0^{\rm long} = (1993 \pm 271)\,{\rm d}$, and an amplitude $\delta I_\mu^{\rm long} = (14.7 \pm 1.8)\,{\rm d}^{-1} = (0.34 \pm 0.04)\%$. $T^{\rm long}$. A long term modulation of the cosmic muon flux has been observed before, also in comparison with the solar activity. We performed a LS analysis of the daily sunspot data provided by the World Data Center SILSO for

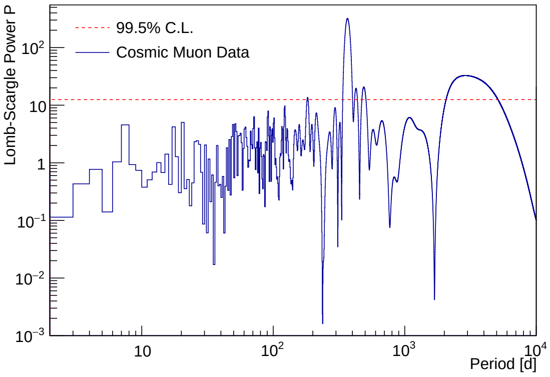

Figure 4. Lomb-Scargle periodogram of the muon data.

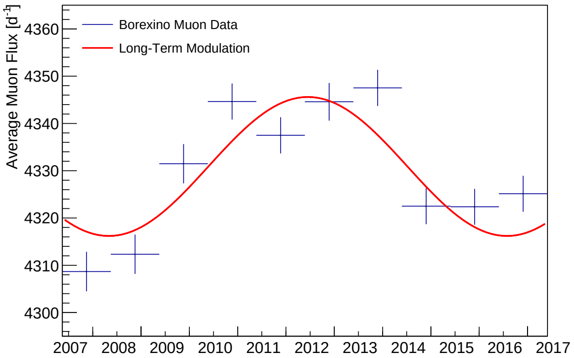

Figure 5. Cosmic muon flux in year-wide bins. The red line depicts the observed long-term modulation.

the same time frame. We find the most significant peak at T $= \sim 3000$ d, although other periods also exceed the significance threshold. An individual solar cycle can be described by a cubic power law and a Gaussian decline. Fitting the sunspots activity with this model we obtain a semi-period of (1578 ± 3) days consistent with the period observed on the muon data. The phases are Jun 16^{th} 2012 and Apr 8^{th} 2013 for muon and sunspot activity data, respectively. While our observation could be regarded as a hint of a positive correlation between the solar sunspot activity and the flux of high energy cosmic muons, this can presently neither be ruled out nor clearly be proven.

In Borexino we observe capture gammas (2.2 or 4.9 MeV) from cosmogenic neutrons in the wake ($\tau \sim 260\mu s$) of muons. We investigated the presence of a seasonal modulation in neutron-producing muons. We find the phase of such modulation to be 6.3 ± 0.4 months in agreement with the muon modulation reported above $(181.7 \pm 0.4$ d). However the amplitude is as high as $2.3 \pm 0.5\%$ of the observed rate. We have also analyzed the neutron rate observing a matching seasonal modulation only for low multiplicity events (< 10). We attribute this to the presence of showering muon events where several tens or hundreds of neutrons are produced by the same muon. Such events follow a non-Poissonian probability distribution. We have asked ourselves if the significantly larger modulation amplitude with respect to the one observed for the muon rate could be attributed to a modulation of the mean energy. However this would require a variation of the order of 4-5 GeV. We have run our simulation including such a variation and we obtain a variation on the muon flux larger than 10% which is not observed. An energy dependence of the cross section more complex than a power law must be hypothesized to explain our observations.

In conclusion we have presented a new precision measurement of the cosmic muon flux at LNGS using ten years of Borexino data. We have confirmed the awaited seasonal modulation of the flux, which results to be correlated with the fluctuations of the atmospheric temperature. The correlation coefficient was measured with a new precision and was used to indirectly measure the kaon-to-pion ratio in muon production in the atmosphere. We have found evidence of a long term modulation of the muon flux that is not present in the atmospheric temperature data and that could possibly be in agreement with the solar activity variations. We have observed a seasonal modulation also in the flux of cosmogenic neutrons and of neutron-producing muons with a larger than expected amplitude that cannot simply be explained with a modulation of the mean energy of muons underground. A more complete description of the results and analyses presented here can be found in [6].

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