Measurement of the cosmic ray flux seasonal variation with the OPERA detector

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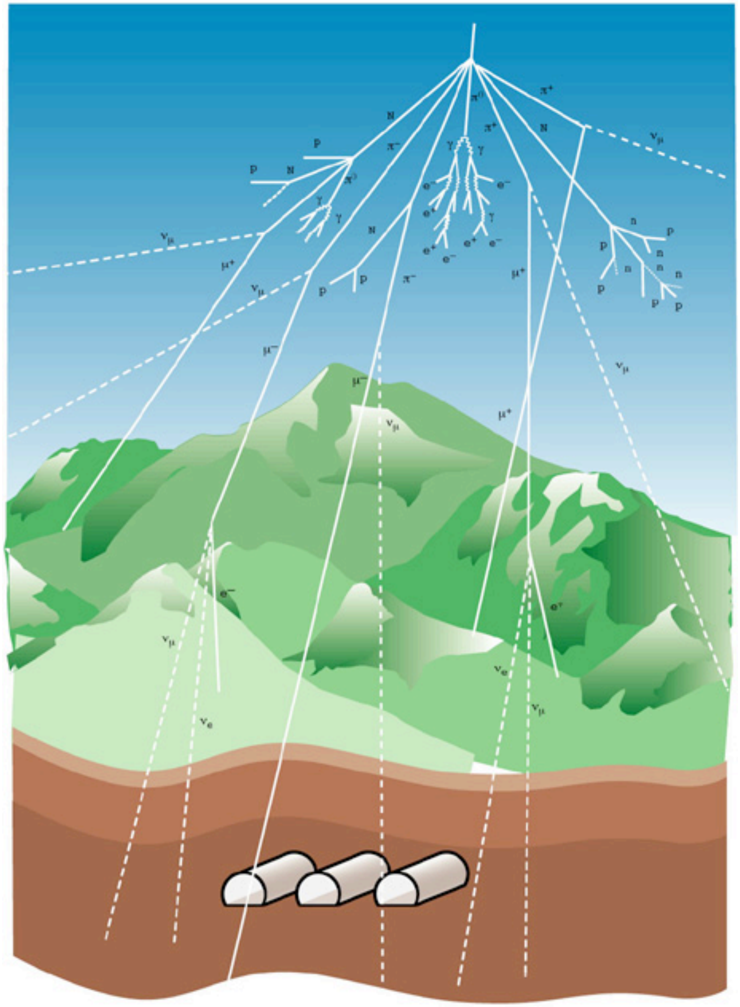
The atmospheric muon flux modulation

- The atmospheric muon flux modulation has been studied and measured by several underground experiments
  - Depends on the relative weight of muons **from pion and kaon** decays
  - Depends on the **depth (E_μ)**
  - No modulation expected for the **prompt component** (up to 10^7 GeV)
- Characteristics of the annual modulation in terms of period/phase → sinusoidal fit and Lomb-Scargle analysis → comparison with Dark Matter modulated signals
- Correlation between relative variations of the effective temperature T_{eff} and of the measured rate I_μ → α_T → K/π production ratio



Correlation between cosmic rays and atmospheric temperature

• Cosmic ray muons are produced by π/K decays. π/K are produced in hadronic interactions by primary cosmic rays in atmosphere

• π/K decay is alternative to interaction depending on the atmospheric density: the higher the temperature, the higher the probability of decay (and of muon production)

ΔT in the upper atmosphere
→ Δρ variations
→ Variations in the fraction of (ordinary) mesons decaying before interacting

➡ **Annual modulation of muon rate**

More muons in summer than in winter

Atmospheric muon flux in OPERA

- Sinusoidal modulation approximation
  - Comparison with Dark matter modulated signals

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

→ **period T** and **phase t_0**

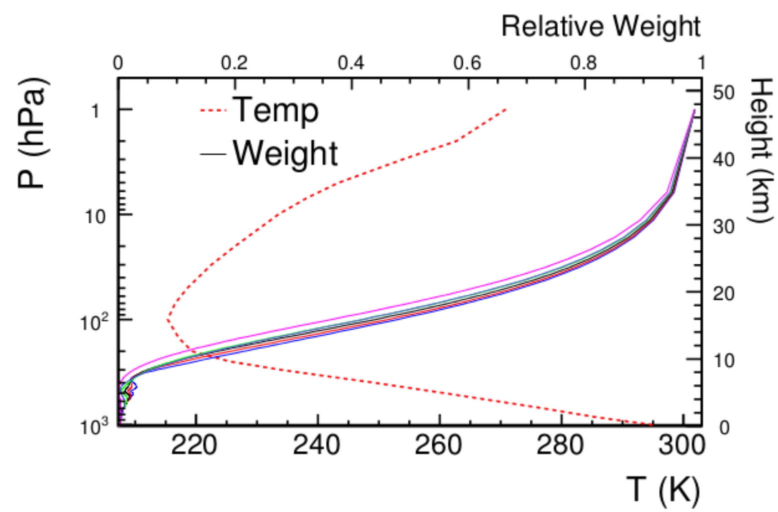
- Correlation between relative variations in rate I_μ and temperature T_{eff}

$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\rm eff}}{T_{\rm eff}^0}$$

→ Effective temperature correlation coefficient α_T

- Temperature data extracted from European Center for Medium-range Weather Forecasts (ECMWF)

$$T_{\rm eff} = \frac{\int_0^\infty dX T(X) W(X)}{\int_0^\infty dX W(X)}$$



Processing of the complete data set (2008→ 2013)

• Different daily rate during CNGS-on (TT+RPC) and CNGS-off (TT-only) periods:

- TT+RPC: average rate (single muons) I_μ^0 = 3360 events/day
- TT-only: average rate (single muons) I_μ^0 = 1960 events/day

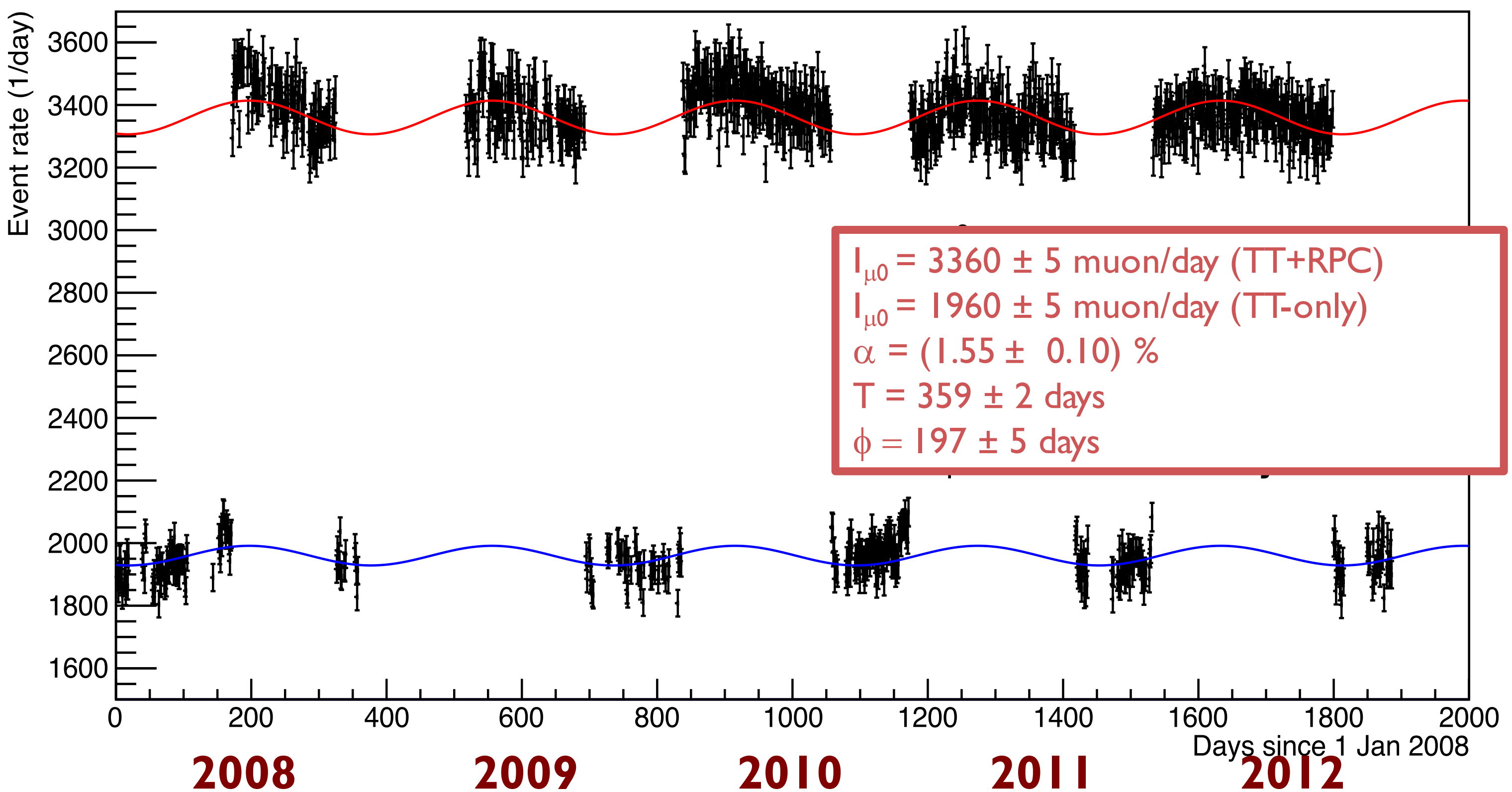
(nearly stable over the 5 years 2008→2013)

Time dependence approximated as a sinusoid, with a constant term and the addition of a modulated component

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

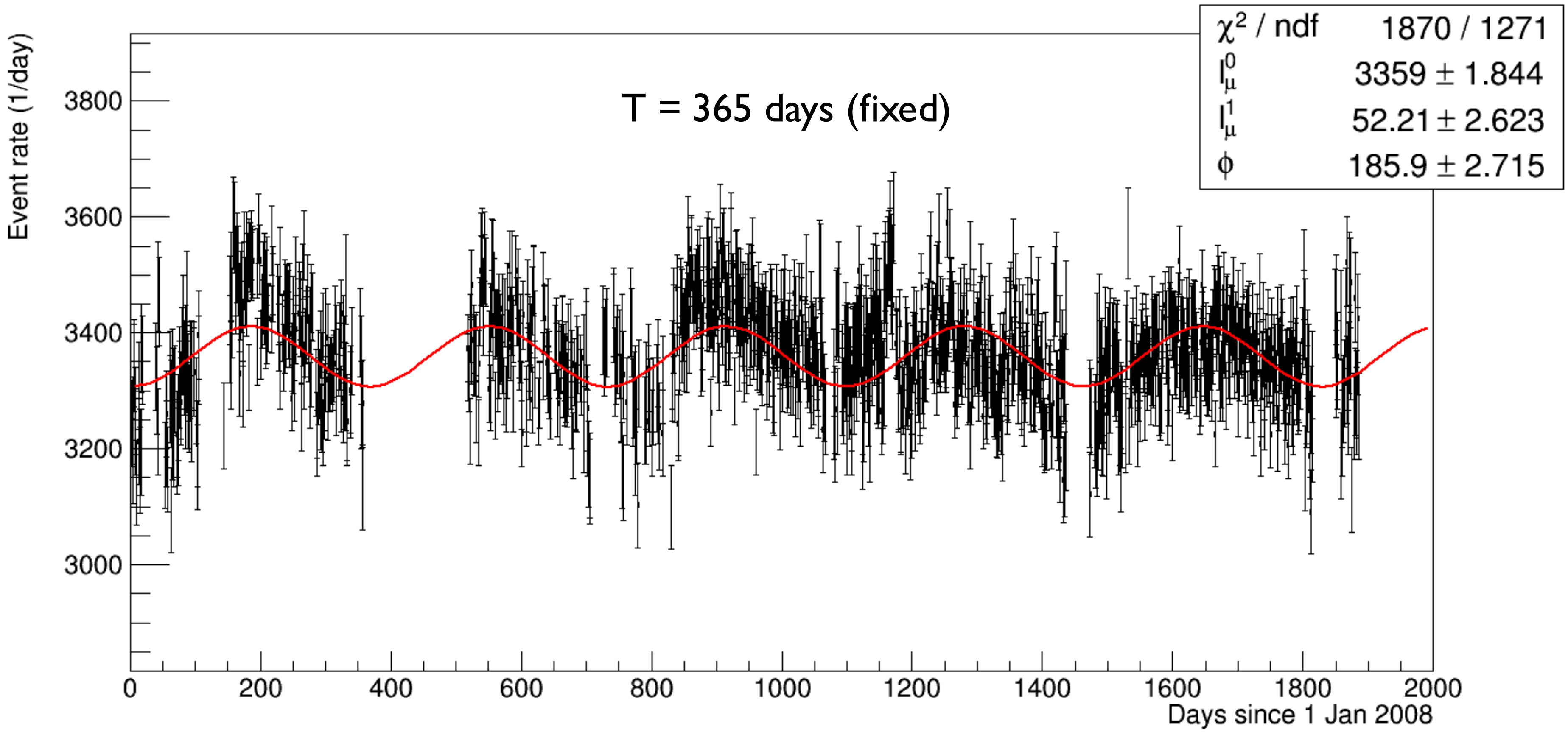
Note however that there is no reason for the constant term to be the same every year (as the average temperature can change year by year) → systematics study (see later)

Rate modulation



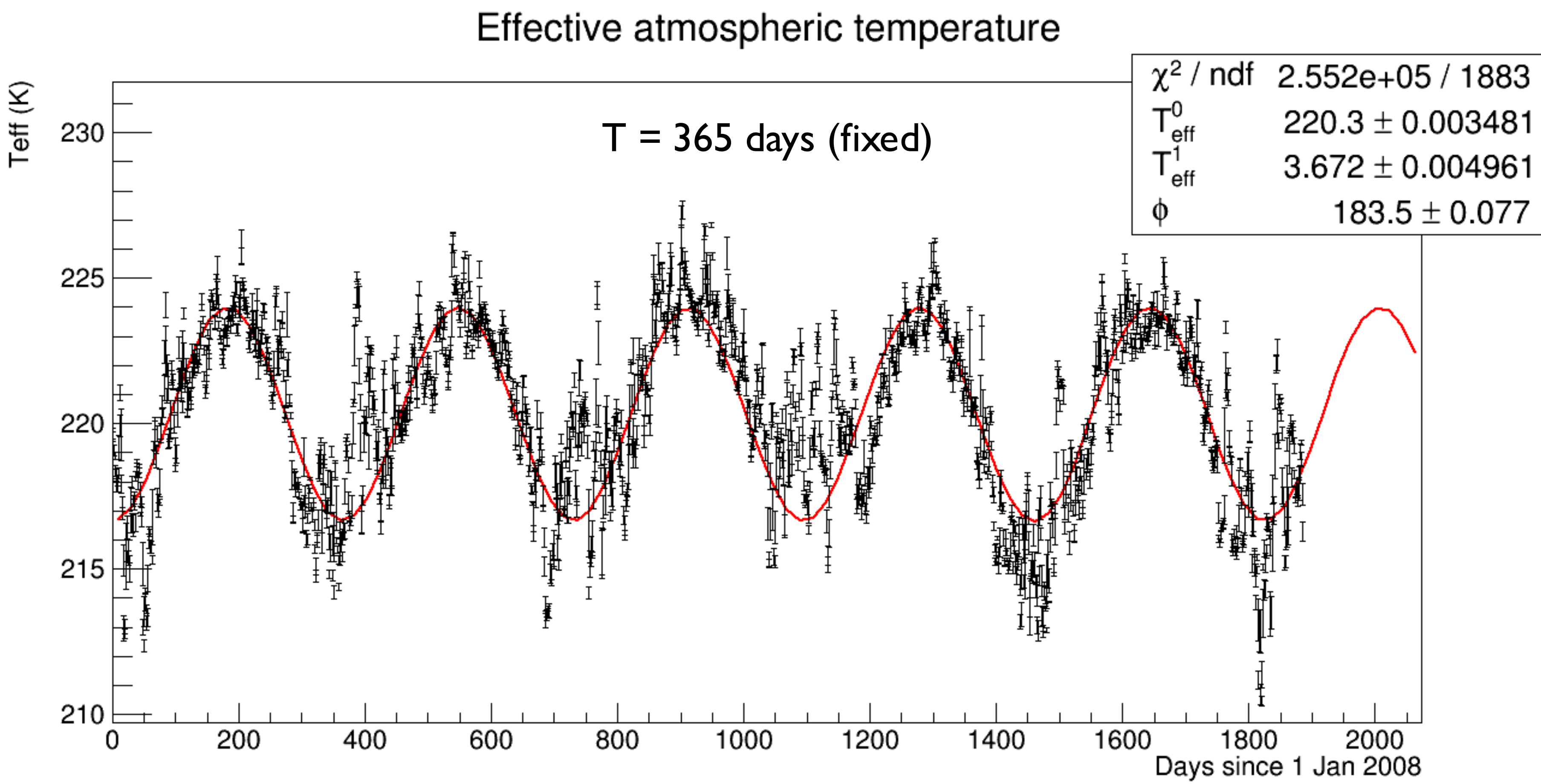
- Complete OPERA data set 2008-2013
- Only single muons (reconstructed multiplicity in 3D == 1)

Rate modulation



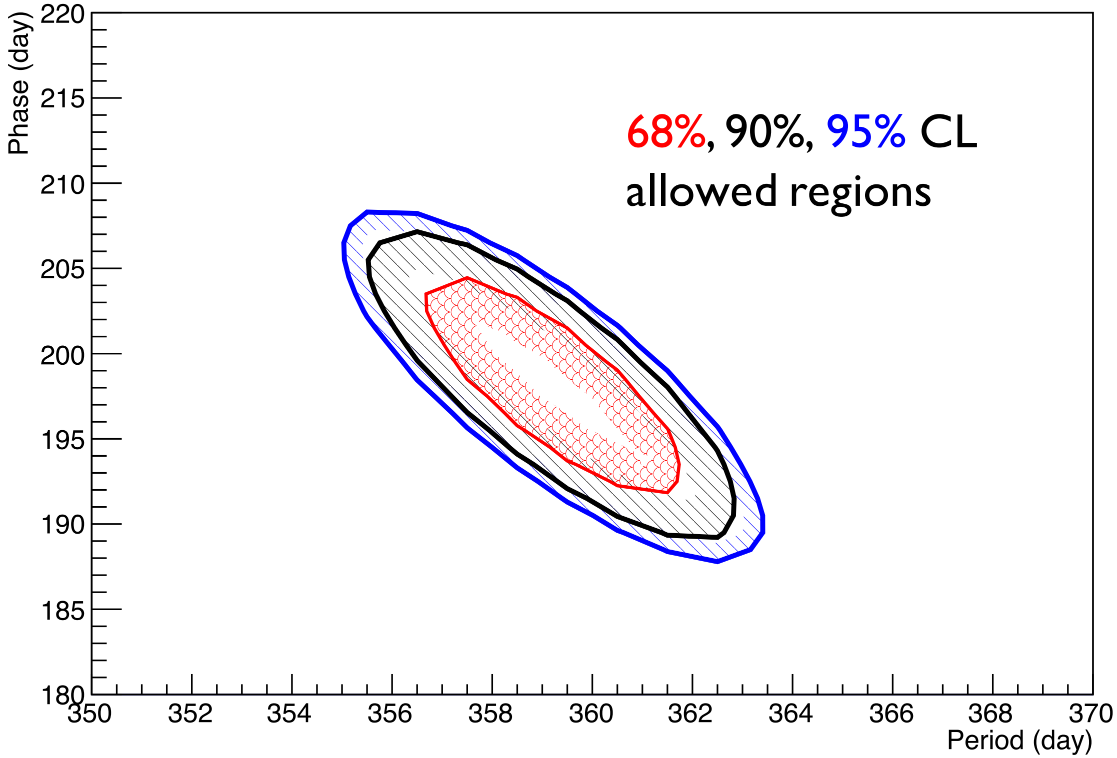
TT-only rate normalized to the (TT+RPC) rate using the results of the maximum likelihood for the constant terms, then sinusoidal fit at **period fixed to 365 days**

Temperature modulation



Relative rate variations (1.55 ± 0.10)%
Relative temperature variations (1.667 ± 0.003)%

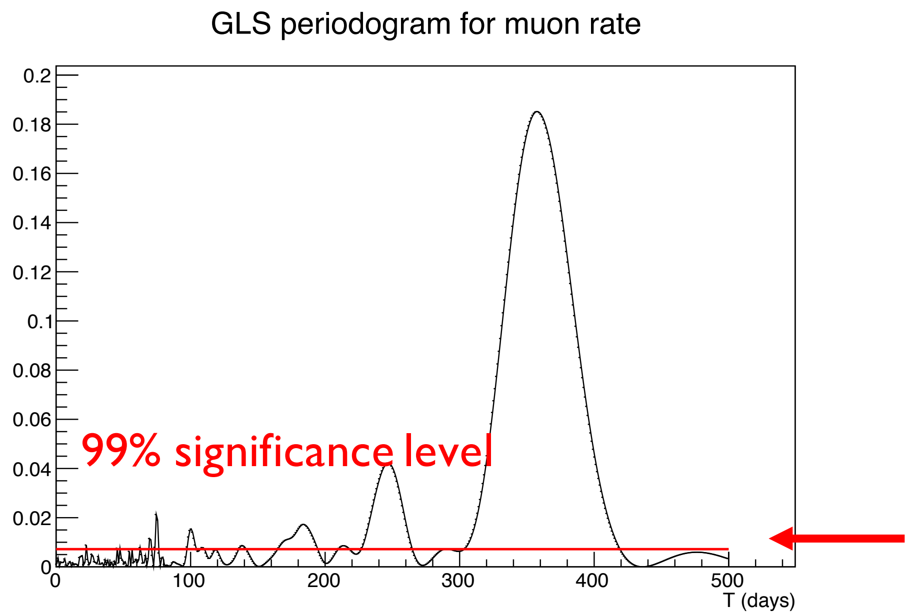
Modulation Period and Phase



Maximum Likelihood approach:

Correlation between rate period and phase

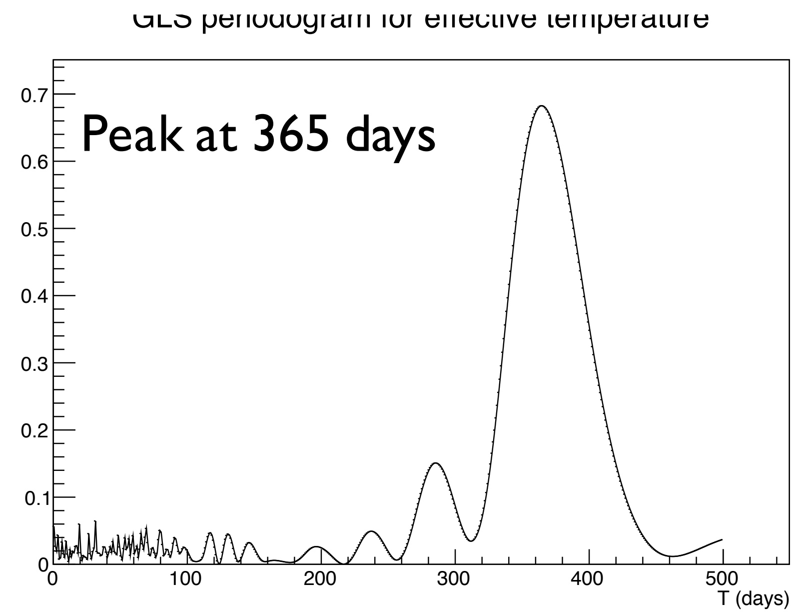
Lomb-Scargle periodograms



Generalised Lomb-Scargle periodogram (arXiv:0901.2573)

Period independently from the phase

99% CL value from 10^5 toy experiments assuming a constant muon flux



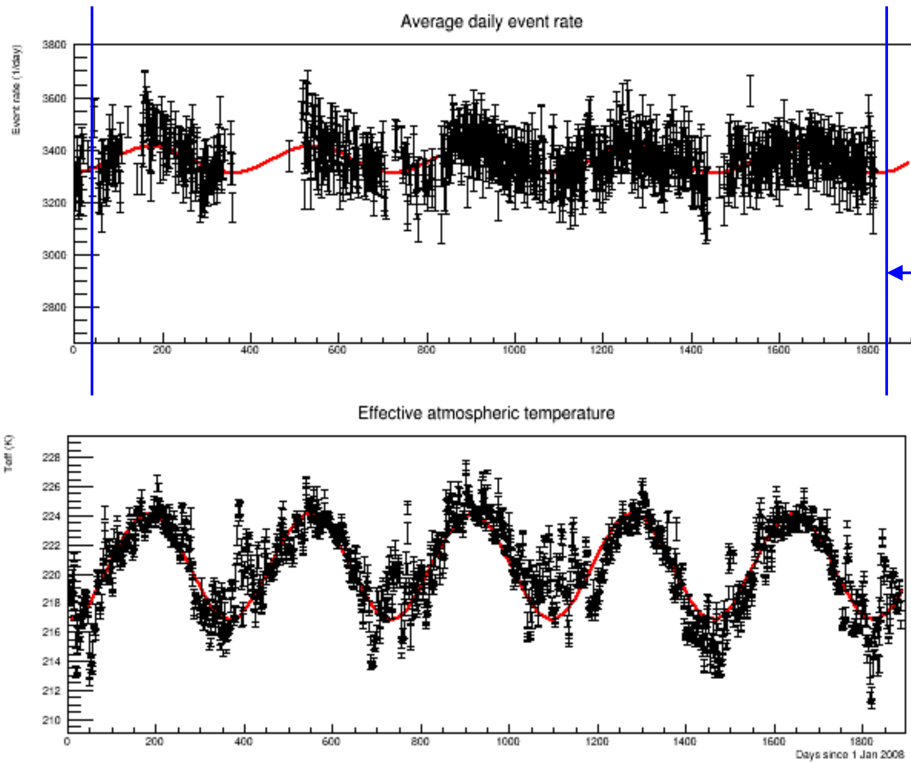
The most significant peak is at T=365 days

Other significant peaks:

- sinusoidal behavior is only an approximation
- effect of detector downtime (from a MC study)

Cross-correlation between T_{eff} and I_{μ}

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

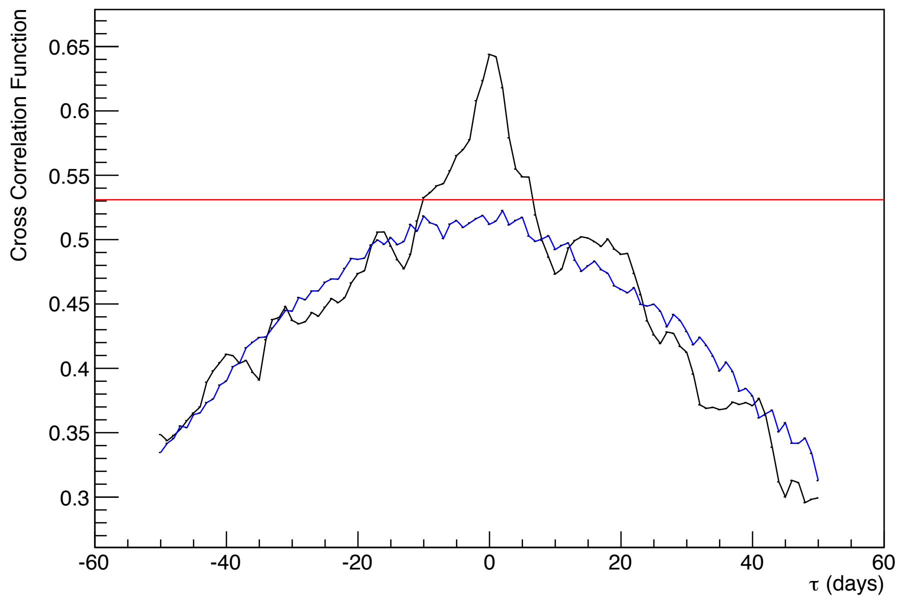


Sum over days with measured muon rate
Excluding first and last 50 days

Cross-correlation between T_{eff} and I_μ

Cross correlation of temperature and rate time series

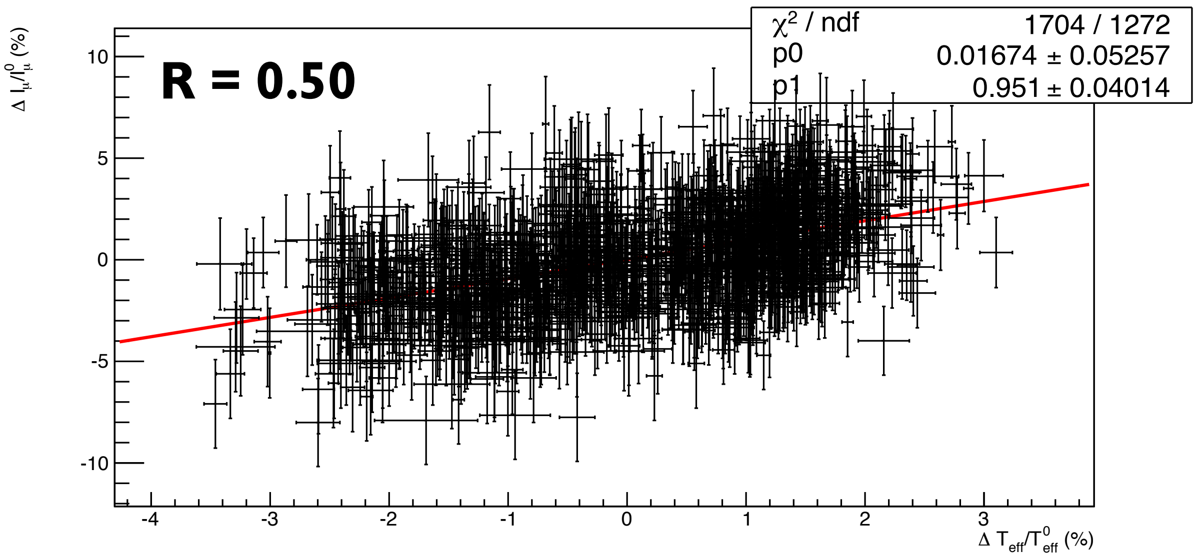
$$R(\tau) = \int_0^{\Delta t} \frac{I_\mu(t) - I_\mu^0}{I_\mu^1} \frac{T_{eff}(t-\tau) - T_{eff}^0}{T_{eff}^1} \frac{dt}{\Delta t} \simeq \frac{1}{N_{data}} \Sigma_i \frac{I_\mu(t_i) - I_\mu^0}{I_\mu^1} \frac{T_{eff}(t_i-\tau) - T_{eff}^0}{T_{eff}^1} \tag{4.1}$$



τ = relative phase between T_{eff} and I_μ time series

Figure 4. Cross correlation function (black) between the measured daily muon rate and the effective atmospheric temperature. In blue the result of a Monte Carlo simulation is reported, where the muon rate and the effective temperature have been extracted according to the fit results, but with equal time period and phase. In red the 99% significance level is also shown (see text for the definition).

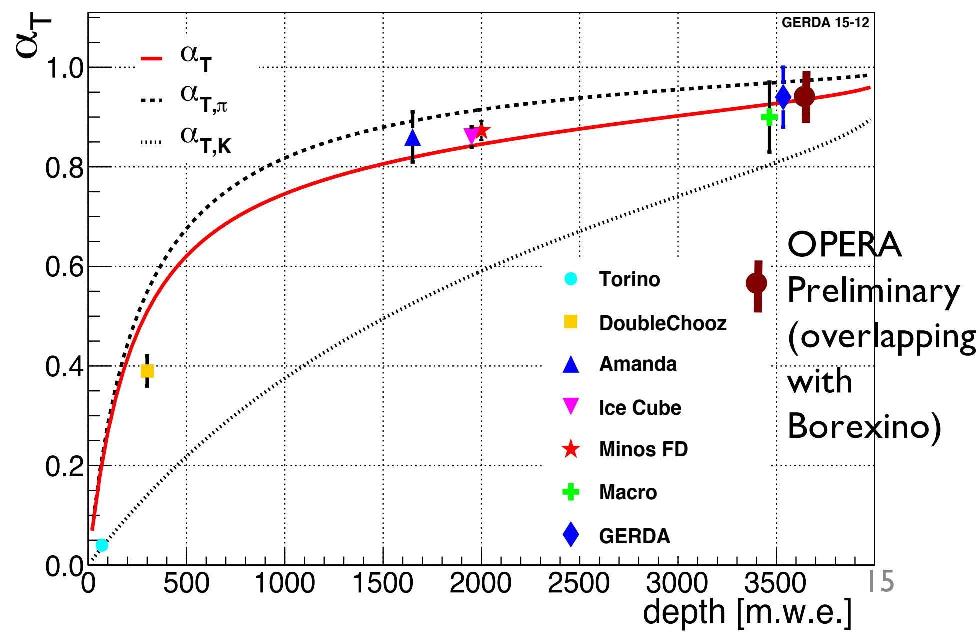
Effective temperature coefficient α_T



$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\rm eff}}{T_{\rm eff}^0}$$

$\alpha_T = 0.95 \pm 0.04$

In agreement with predictions for LNGS site and with other experiments

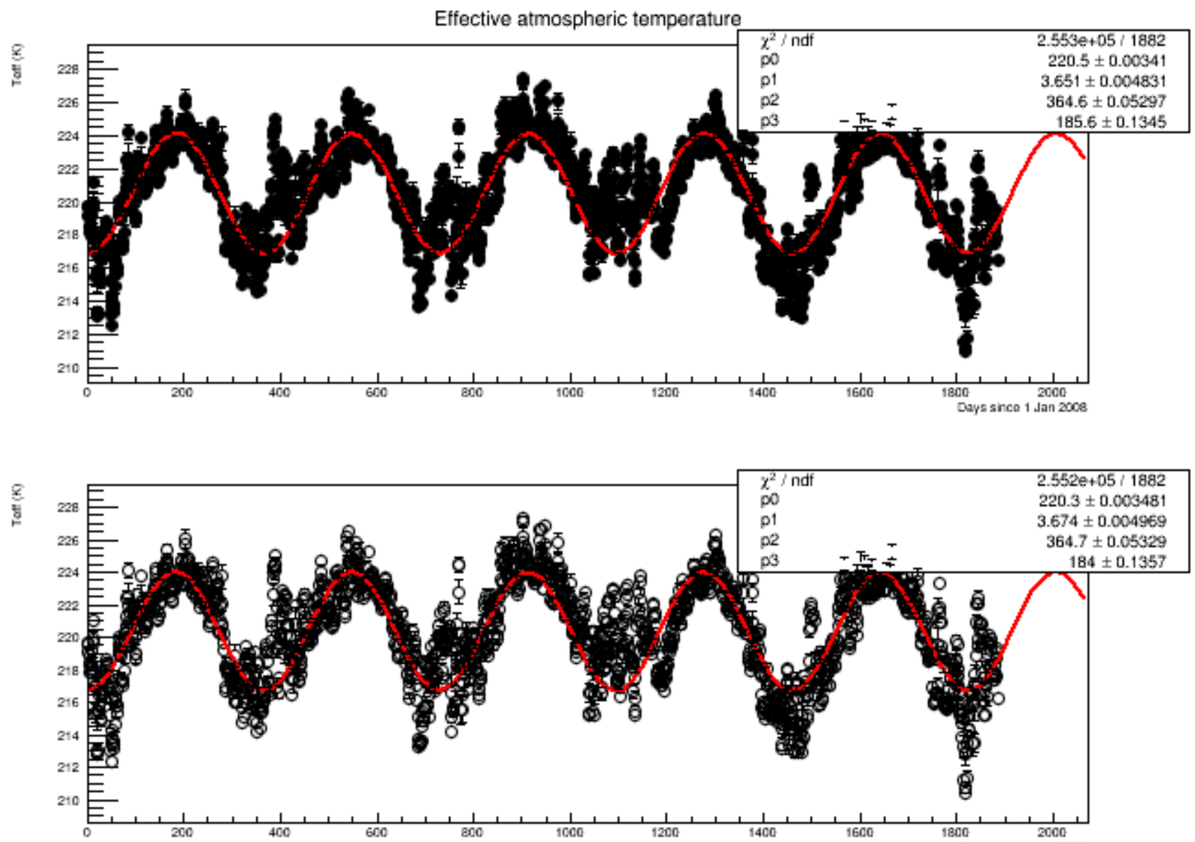


Systematics: E_{thr}

Effective temperature depends on the energy threshold of muons detected by OPERA, which in turn depends on the rock overburden surrounding the detector.
Comparison of estimation of T_{eff} using E_{thr}=1.8 TeV
(used by other LNGS experiments and derived in Astropart. Phys. 33 (2010) 140)

The effective atmospheric temperature is on average 0.2 K above the E_{thr}=1.4 TeV value

No significant effect on the results



Systematics: DAQ and stability effects

Checked possible systematics effects due to data taking stability
→RPC+TT and TT-only rates normalized applying scale factors on yearly basis (overall yearly difference at few ‰)

$$\alpha_T = 0.93 \pm 0.04$$

Compatible with the prevously quoted value
Systematic error neglected, dominated by the statistical uncertainty

$$T = 364 \pm 2 \text{ days}$$
$$\phi = 179 \pm 5 \text{ days}$$

Used to evaluate the systematics related to the phase measurement?

Conclusions

- First paper draft distributed to the internal referees
- We received corrections and comments, we are implementing them
- Distribution of the second draft to the referees in the next days