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

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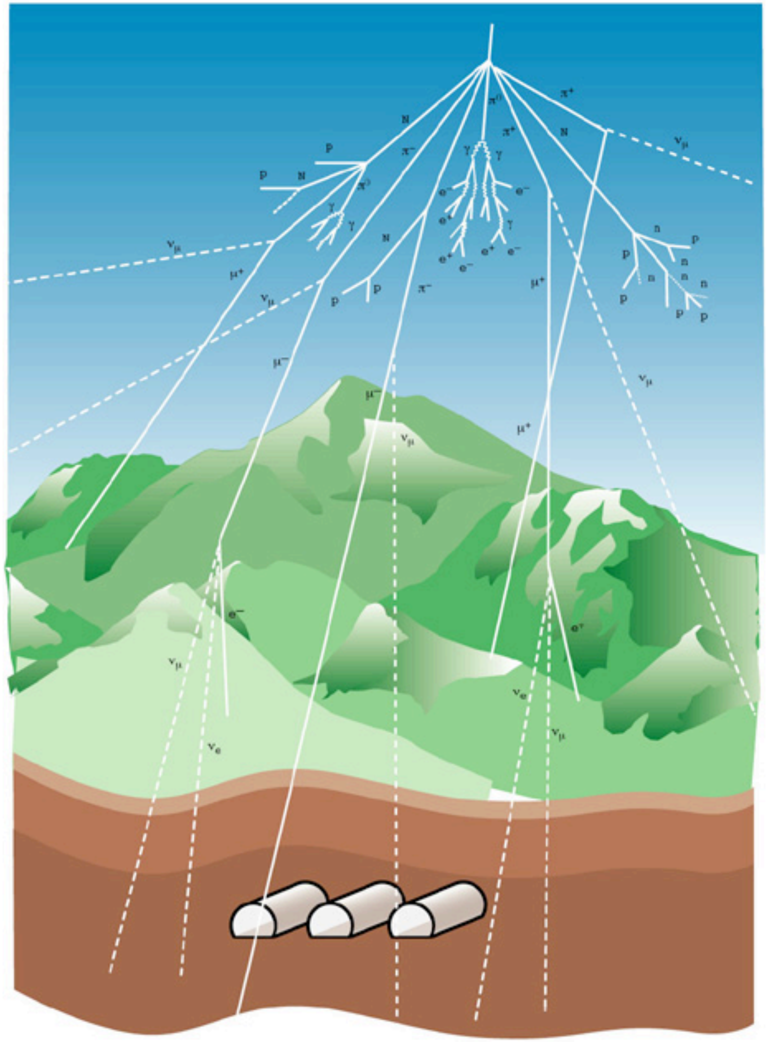
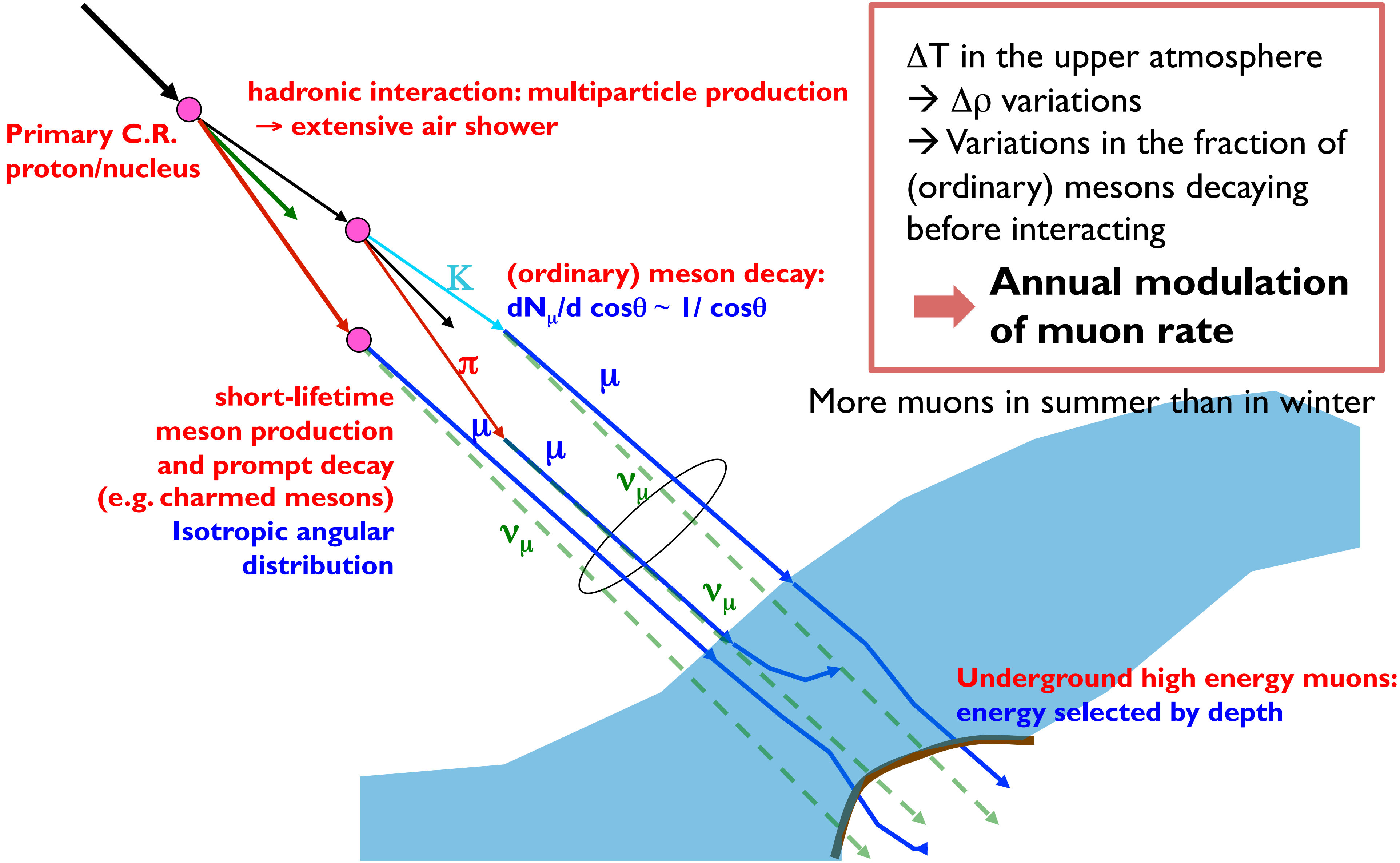
The atmospheric muon flux modulation

- 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 $I_\mu \rightarrow \alpha_T \rightarrow K/\pi$ production ratio



Inclusive production of muons



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

→ **Annual modulation of muon rate**

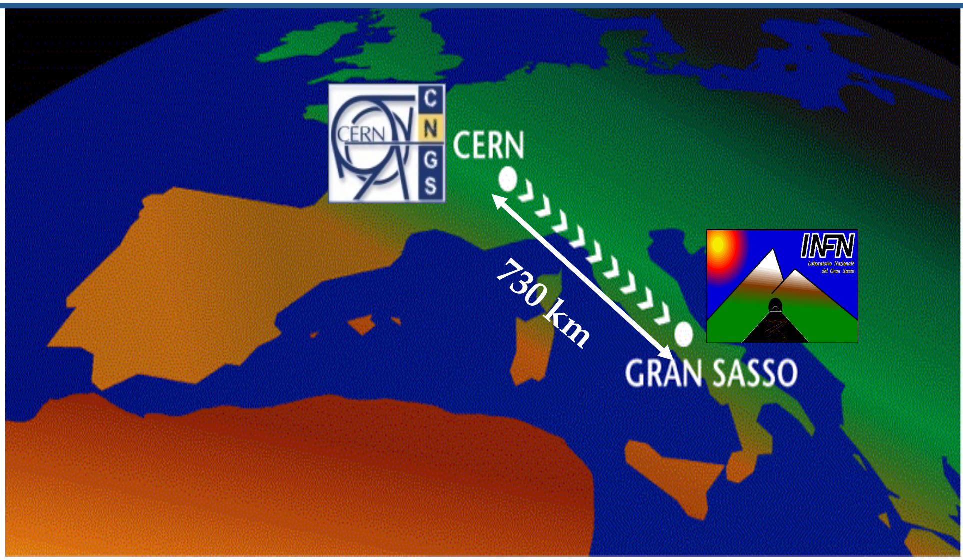
More muons in summer than in winter

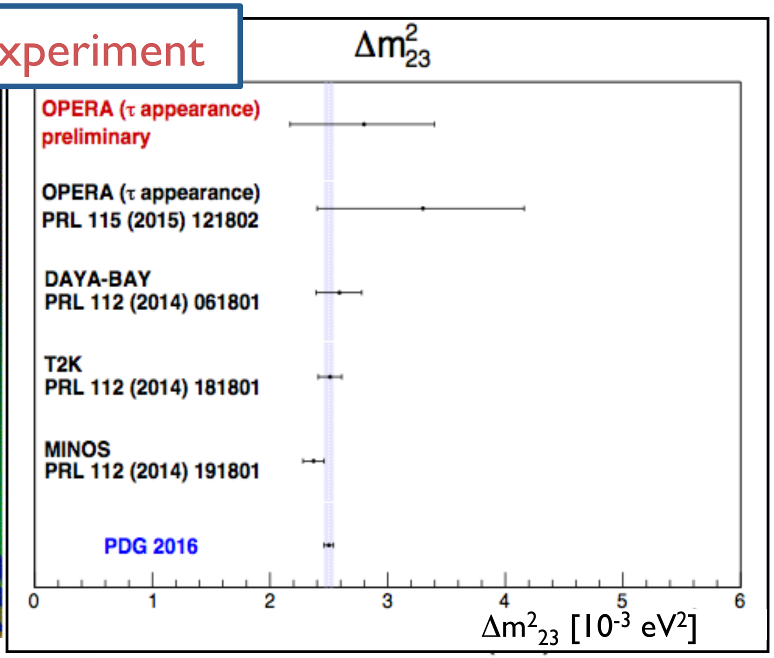
The OPERA experiment

Discovery of $\nu_\mu \to \nu_\tau$ **oscillations in appearance mode**

Phys. Rev. Lett. 115, 121802 (2015)

See today talk: More results from the OPERA experiment



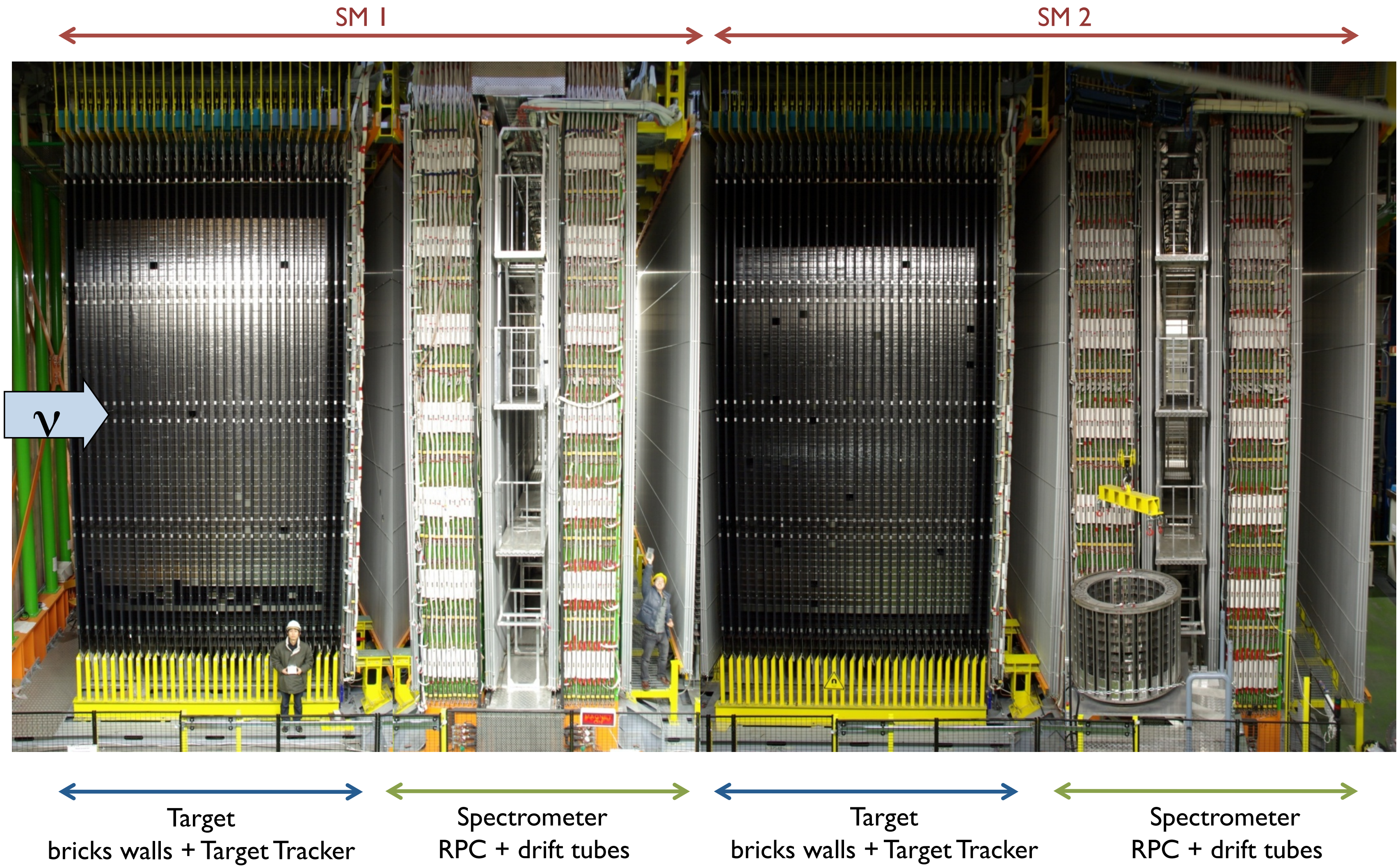


Full coverage of the parameter space for the atmospheric neutrino sector

- Long baseline neutrino oscillation experiment located in the CNGS (CERN Neutrinos to Gran Sasso) ν_μ beam
- Direct search for $\nu_\mu \to \nu_\tau$ oscillations detecting the τ lepton produced in ν_τ CC interactions (appearance mode)

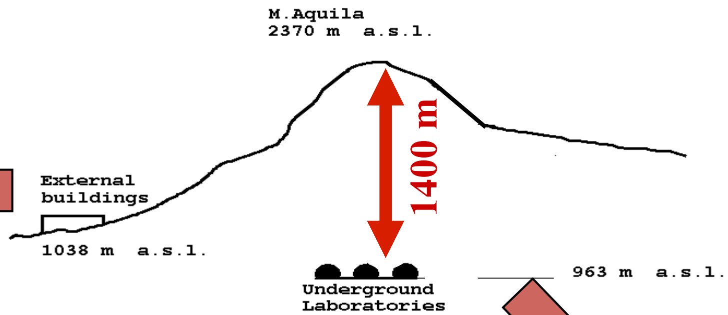
The OPERA detector

Target + magnetic spectrometer (1.53 T) at LNGS, average overburden ~3800 m.w.e., drift tubes + RPC + scintillators, detector angular window 0° < θ < 90°



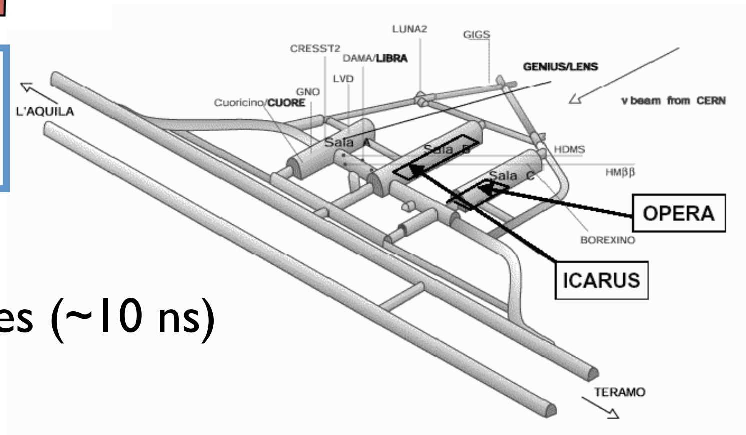
OPERA as a cosmic ray detector

CNGS beam events identified through a timing coincidence with the beam spill
→ cosmic events collected during the physics run



Gran Sasso underground lab: 1400 m of rock (3800 m.w.e) shielding, cosmic ray flux reduced by a factor 10^6 w.r.t. surface

$\langle E_\mu \rangle$ underground: ~270 GeV
$\langle E_\mu \rangle$ surface cut-off: ~1500 GeV



OPERA: a deep underground detector with charge and momentum reconstruction and excellent timing capabilities (~10 ns)

- **Atmospheric muon charge ratio**
- **Annual modulation of atmospheric muons**

OPERA: $\langle E_\mu \cos\theta \rangle \approx 2$ **TeV**

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**

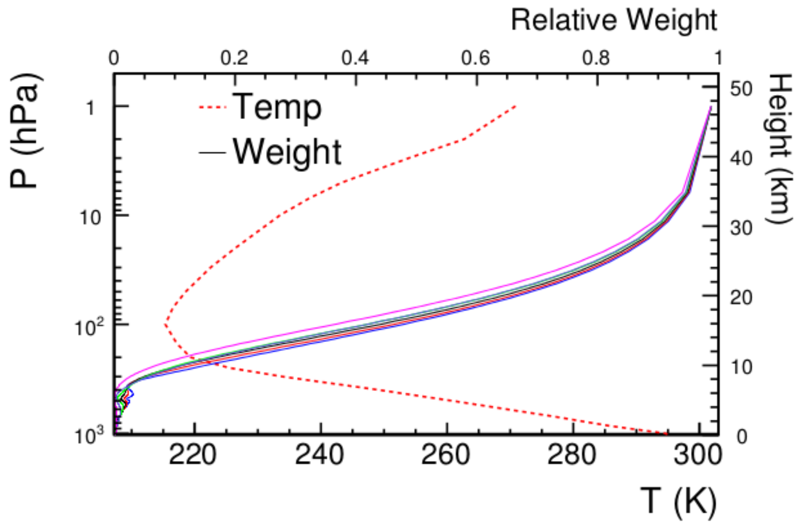
- Correlation between relative variations in rate I_μ and temperature T_{eff}

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

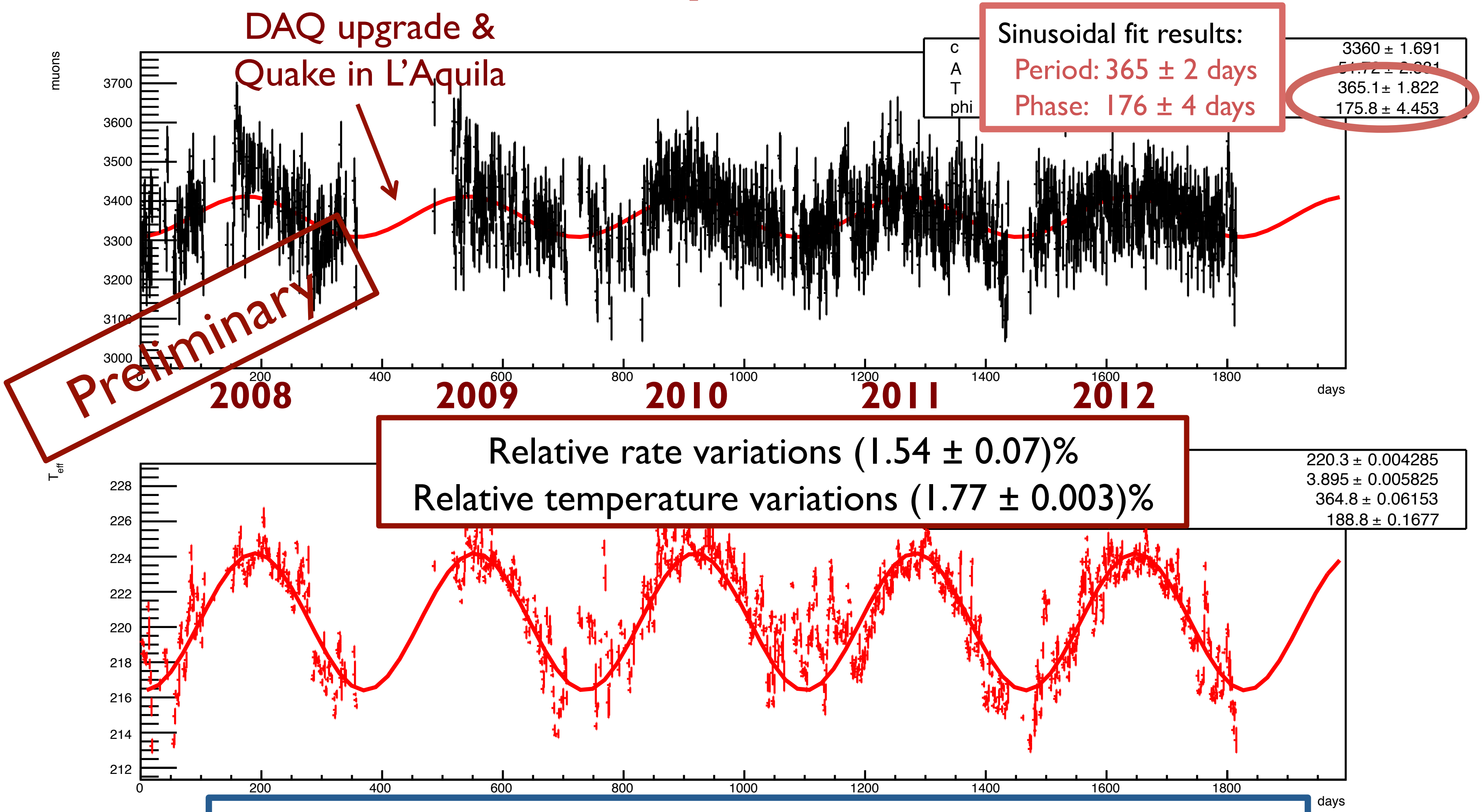
→ Effective temperature correlation coefficient α_T

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

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



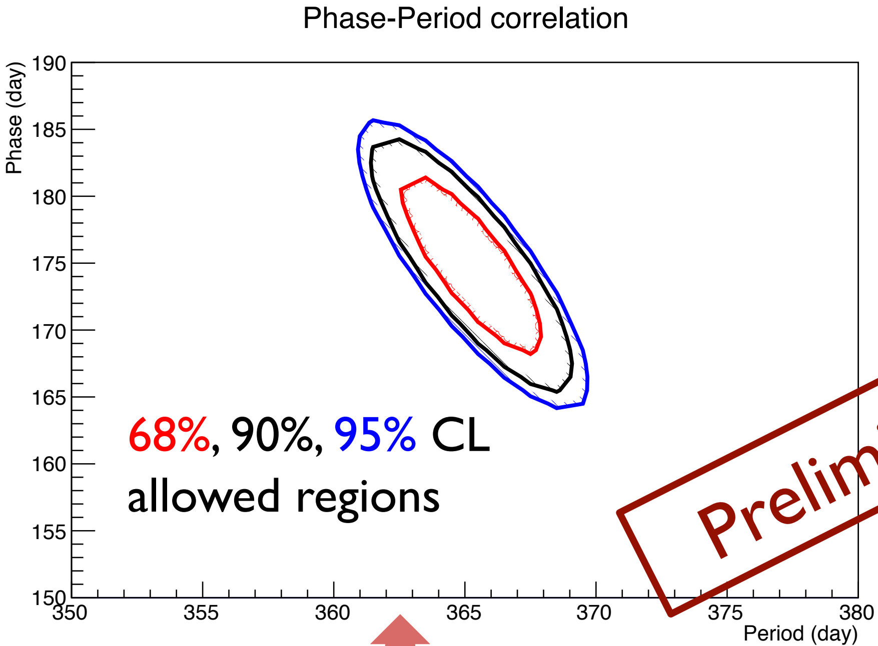
Rate and temperature vs time



• Complete OPERA data set 2008-2012

• Only single muons (reconstructed multiplicity in 3D == 1)

Modulation Period and Phase



Preliminary

Sinusoidal fit results:

Period: 365 ± 2 days

Phase: 176 ± 4 days

→ Rate Maximum on 25 June

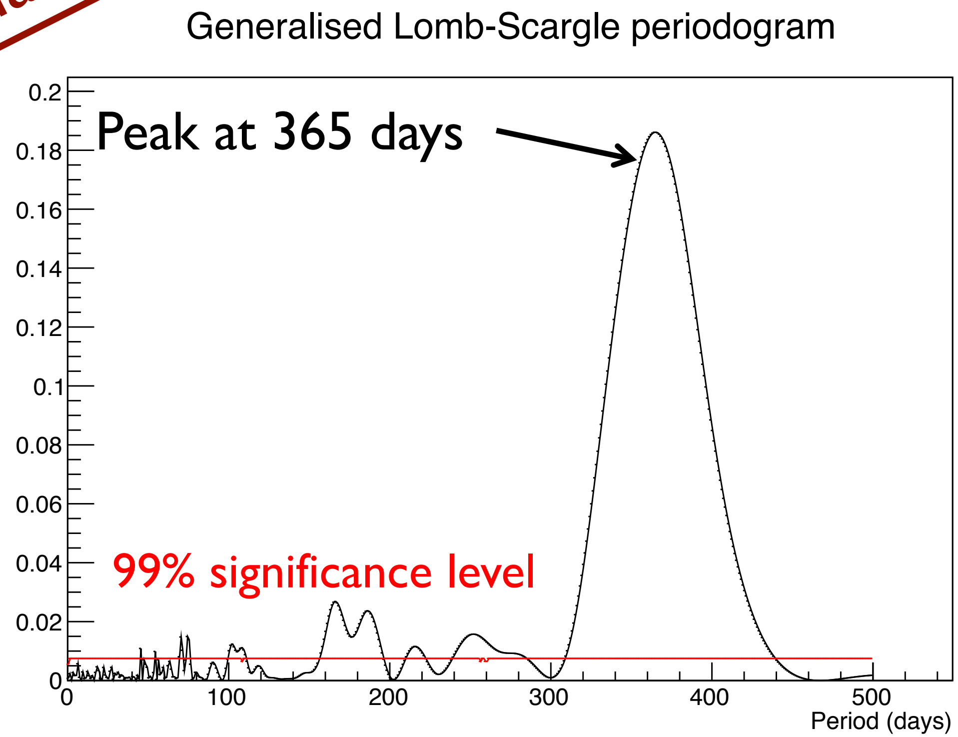
Maximum Likelihood approach:

Correlation between period and phase

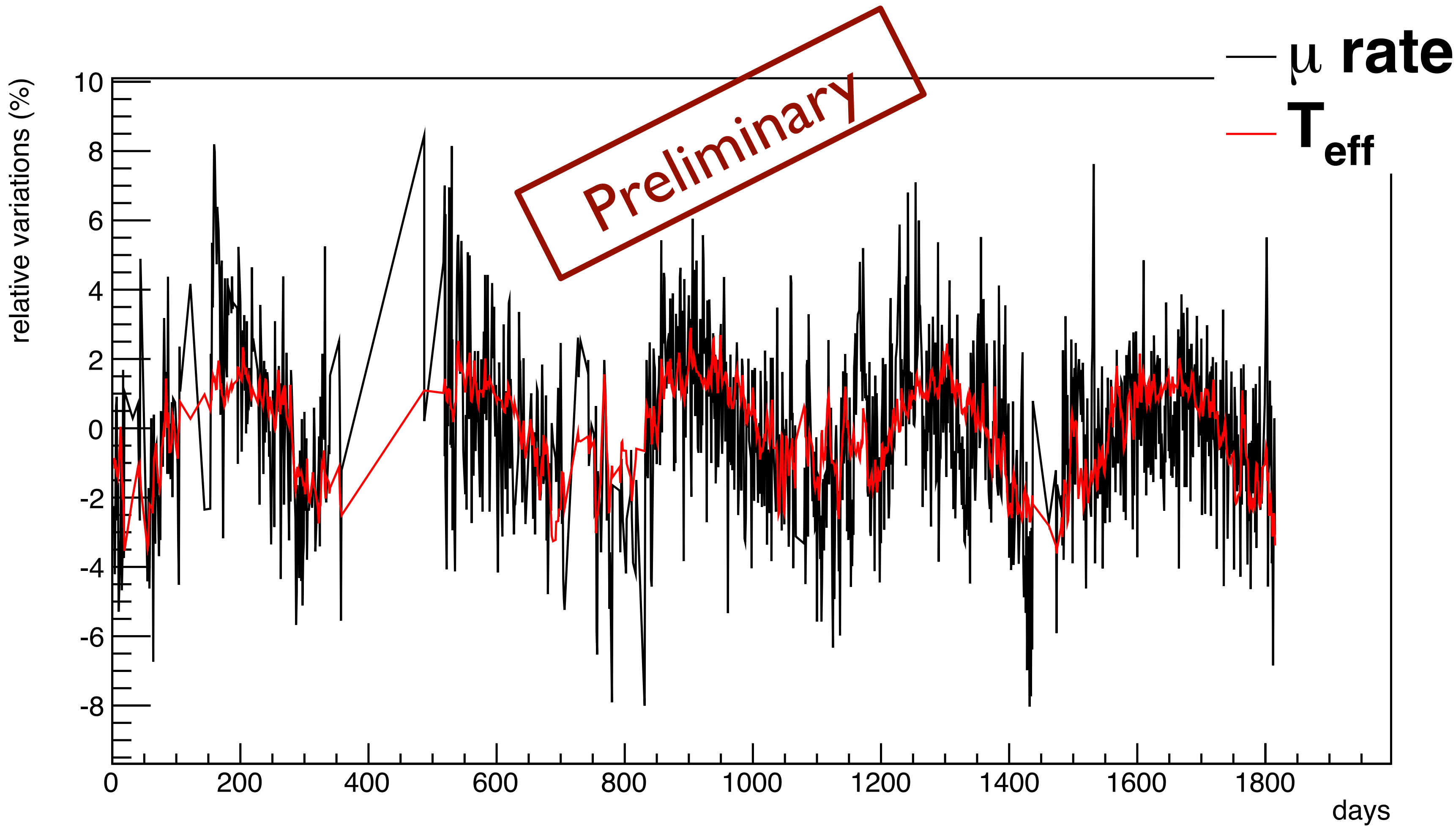
Lomb-Scargle periodogram: →

Period independently from the phase

Small peaks due to non-uniformities in the time series (MC study on detector downtimes)



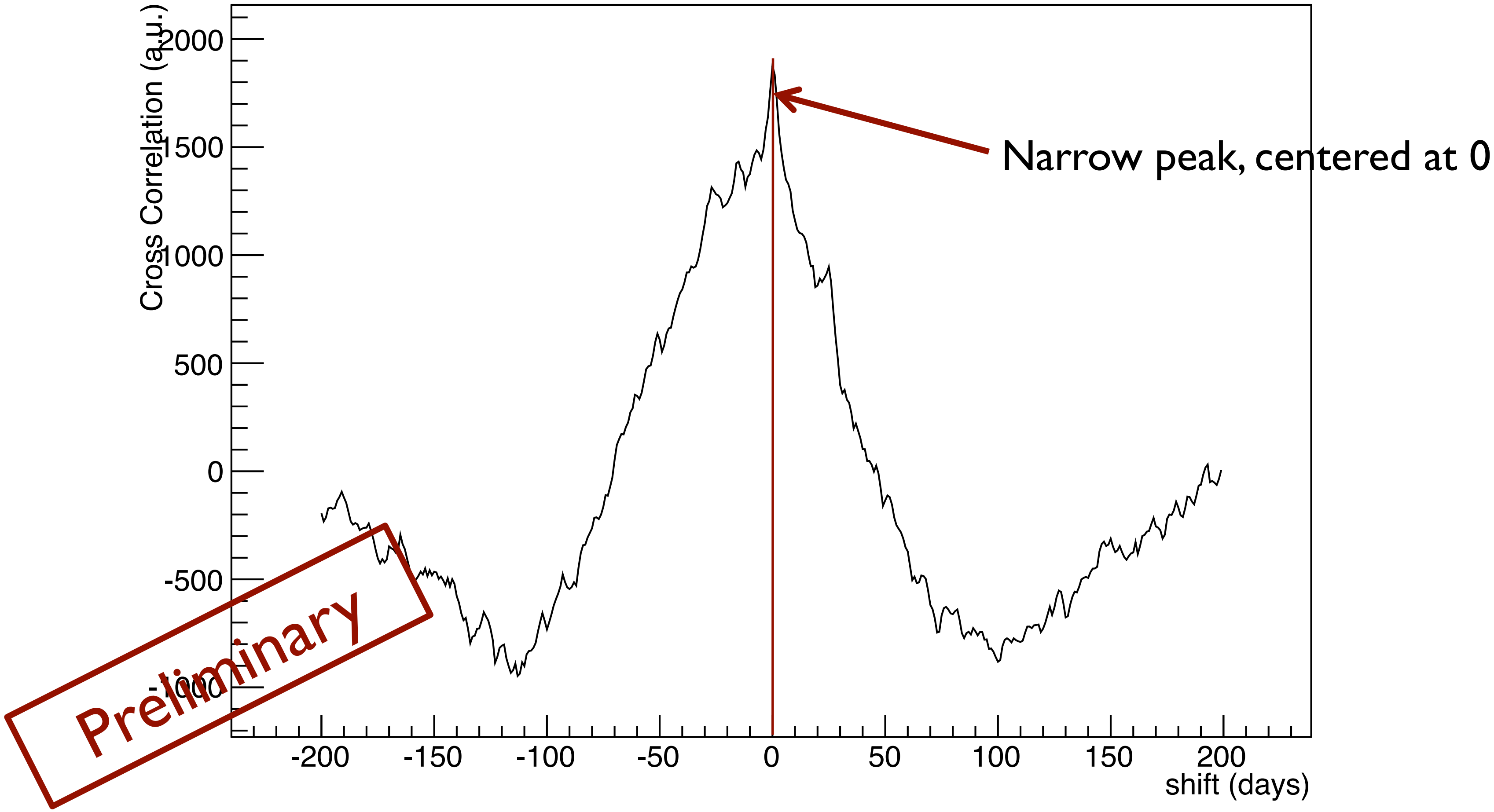
Correlation with temperature variations



Variations in temperature closely reflected by variations in muon rate (also on small time scales)

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

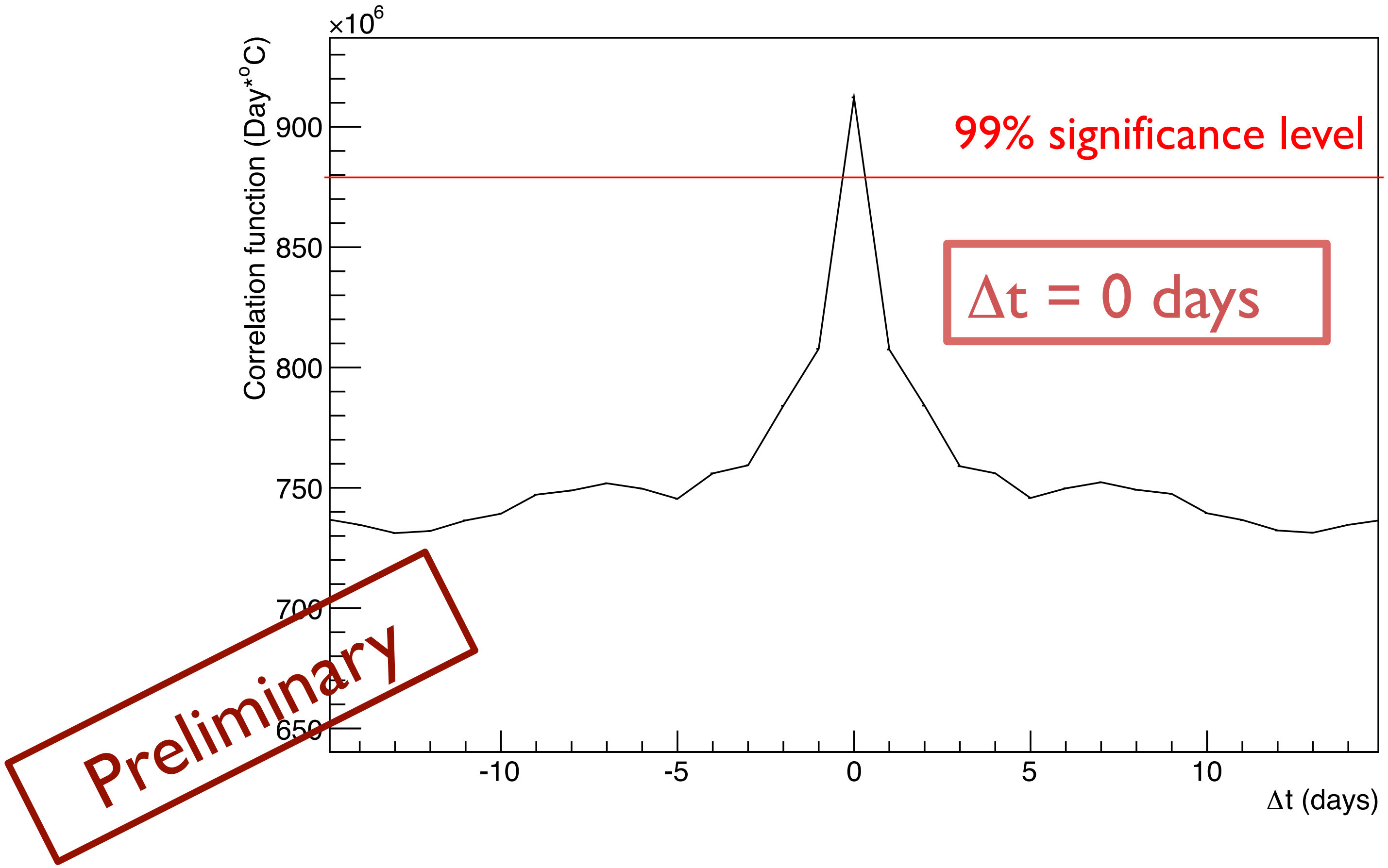
Cross correlation of temperature and rate time series



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

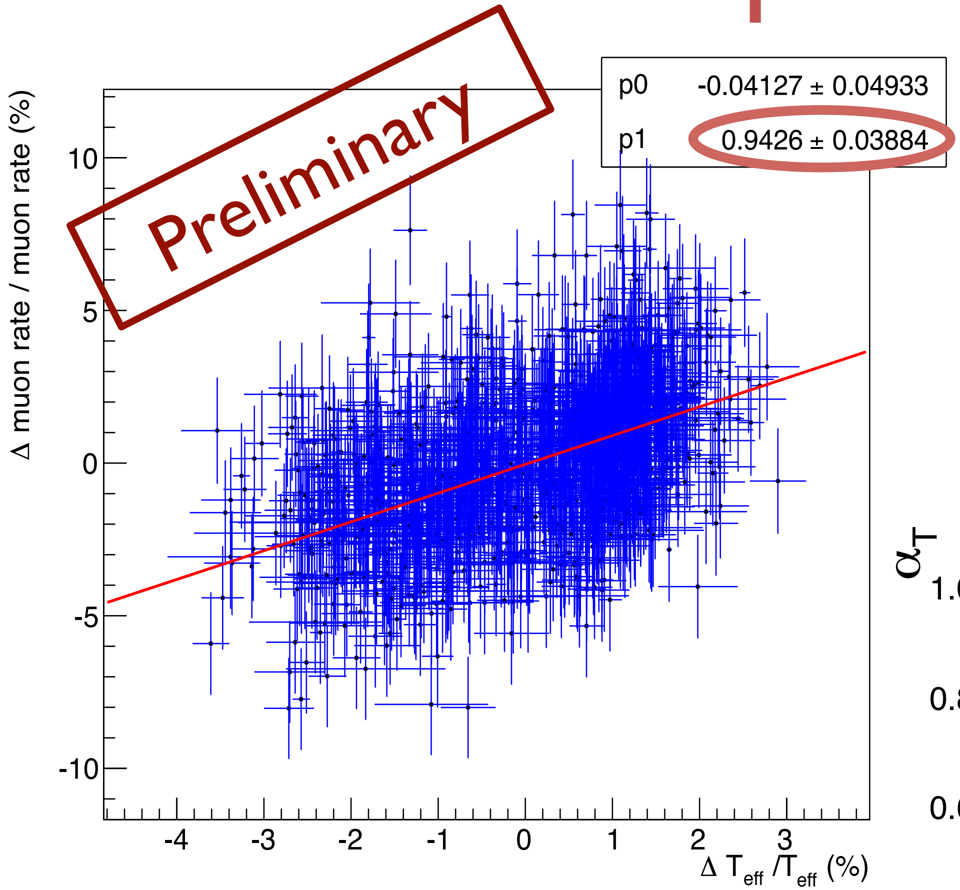
Correlation function of temperature and rate time series

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



Relative phase between T_{eff} and I_{μ} time series

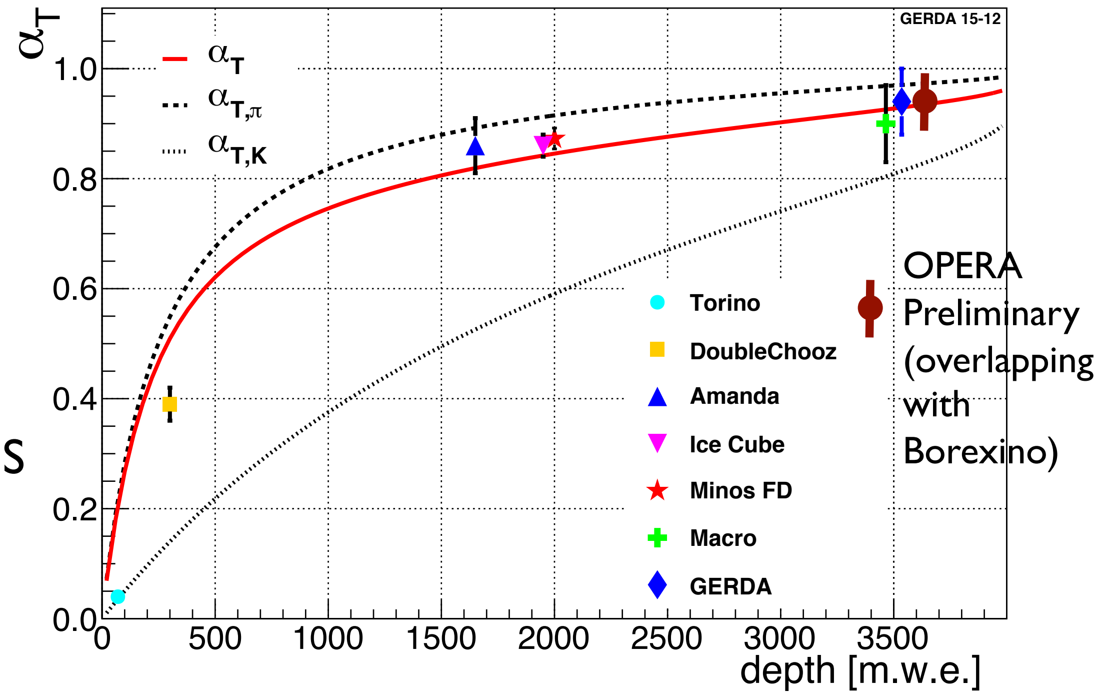
Effective temperature coefficient α_T



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

α_T = 0.94 ± 0.04

In agreement with predictions for LNGS site and with other experiments



Conclusions and Outlook

- The OPERA detector was exploited for the measurement of the atmospheric muon rate seasonal modulation at LNGS → 3800 m w.e. depth corresponding to E_{μ} > 1 TeV
  - Preliminary data with the complete OPERA statistics 2008-2012
  - Modulation measured for single muon events
  - Preliminary results:
    - Period and phase of the modulation compatible with expectations and other experiments: **T = (365 ± 2)** days and **phase = (176 ± 4)** days (Maximum on 25 June)
    - Cross correlation between muon rate and temperature time series: correlation function peaked at **Δt = 0 days**!
    - Effective temperature correlation coefficient α_T **= 0.94 ± 0.04** compatible with expectations based on π-K contributions and other LNGS experiments
  - Outlook:
    - Possibility to determine the K/π production ratio, combining the results from the muon charge ratio measurement (Z_{pK+} moment → $R_{K/\pi}$)
    - Paper soon!

Thank you for your attention!

Image taken using an **OPERA nuclear emulsion film**
with a pinhole hand made camera
courtesy by Donato Di Ferdinando