# THE ATMOSPHERIC MUON FLUX MEASURED WITH THE LARGE VOLUME DETECTOR FOR 24 YEARS

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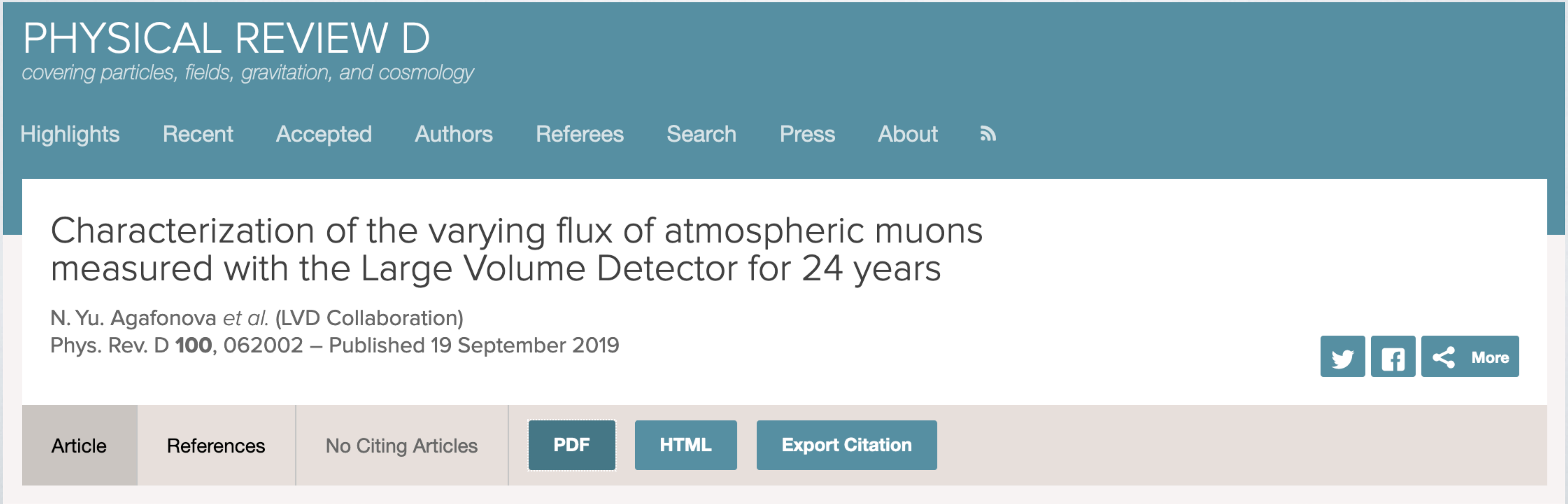
*Tev Particle Astrophysics - Sydney 2-6 December 2019*

# OUTLINE

- The LVD experiment @ Gran Sasso National Laboratory
- Cosmic Rays TeV Muons: Origin & Correlation with the Atmospheric Temperature
- Data sets Selection
- Analysis & Results
- Conclusions


PHYSICAL REVIEW D
*covering particles, fields, gravitation, and cosmology*

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Characterization of the varying flux of atmospheric muons measured with the Large Volume Detector for 24 years

N. Yu. Agafonova *et al.* (LVD Collaboration)
Phys. Rev. D **100**, 062002 – Published 19 September 2019

More

Article References No Citing Articles PDF HTML Export Citation

# THE LARGE VOLUME DETECTOR


LVD @ LNGS, Italy
1992- Running

- *1 kton liquid scintillator + 0.8 kton Fe*
- *Depth 3600 m w.e*
- *840 counters, each viewed by three 15" PMTs - 3-fold coincidence mode*
- *Energy Calibration via atmospheric muons*
- *μ rate ~ 0.1Hz*

- *Energy Threshold: $E_H$~4 MeV ($E_L$~0.5 MeV for 1ms)*
- *50% trigger efficiency @ 4 MeV*
- *15% energy resolution @ 10 MeV*
- *Timing accuracy 12.5 ns (relative) / 100 ns (absolute)*

# LVD MAIN TASK
# SN NEUTRINOS BURST

| | $\nu$ Interaction Channel | $E_\nu$ Threshold | % |
|---|---|---|---|
| 1 | $\bar{\nu}_e + p \rightarrow e^+ + n$ | (1.8 MeV) | (88%) |
| 2 | $\nu_e +^{12} C \rightarrow^{12} N + e^-$ | (17.3 MeV) | (1.5%) |
| 3 | $\bar{\nu}_e +^{12} C \rightarrow^{12} B + e^+$ | (14.4 MeV) | (1.0%) |
| 4 | $\nu_i +^{12} C \rightarrow \nu_i +^{12} C^* + \gamma$ | (15.1 MeV) | (2.0%) |
| 5 | $\nu_i + e^- \rightarrow \nu_i + e^-$ | (-) | (3.0%) |
| 6 | $\nu_e +^{56} Fe \rightarrow^{56} Co^* + e^-$ | (10. MeV) | (3.0%) |
| 7 | $\bar{\nu}_e +^{56} Fe \rightarrow^{56} Mn + e^+$ | (12.5 MeV) | (0.5%) |
| 8 | $\nu_i +^{56} Fe \rightarrow \nu_i +^{56} Fe^* + \gamma$ | (15. MeV) | (2.0%) |

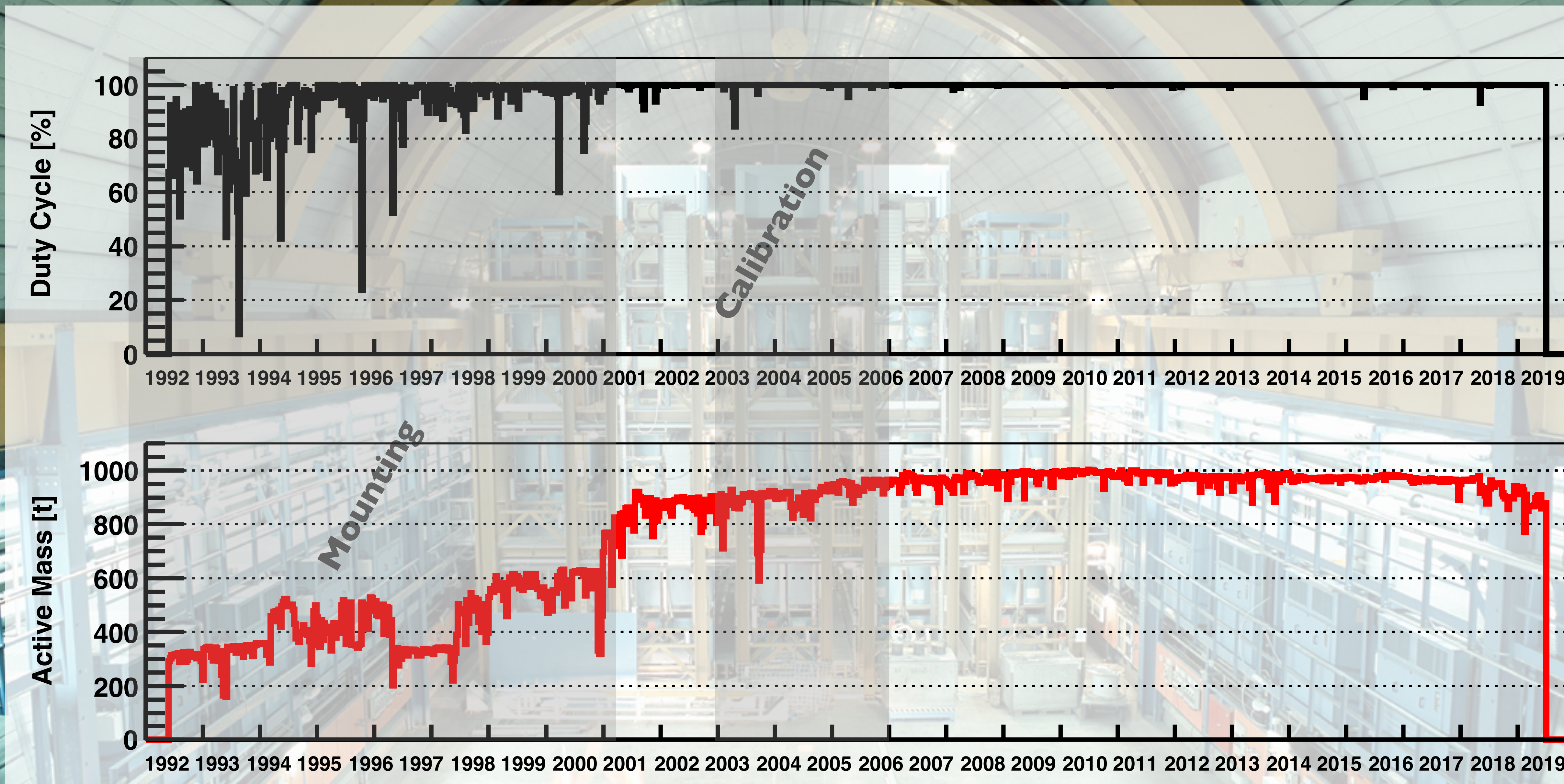
Trigger mode & thresholds optimized for IBD interaction

**Expected signal @ 10 kpc**

| Neutrino interaction channels | Expected events |
|---|---|
| $\nu_e$+p -> $e^+$+n | 250 |
| $\nu_e$+$^{12}$C -> $^{12}$N+$e^-$ | |
| $\nu_e$+$^{12}$C -> $^{12}$B+$e^+$ | 15 |
| $\nu_i$+$^{12}$C -> $\nu_i$+$^{12}$C+$\gamma$ | |
| $\nu_i$+$e^-$ -> $\nu_i$+$e^-$ | 10 |
| $\nu_e$+$^{56}$Fe -> $^{56}$Co+$e^-$ | |
| $\nu_e$+$^{56}$Fe -> $^{56}$Mn+$e^+$ | 25 |
| $\nu_i$+$^{56}$Fe ->$\nu_i$+ $^{56}$Fe+$\gamma$ | |
| *Total* | 300 |


*N.Yu Agafonova et al., Astroparticle Physics 28 (2008) 526-522*
*N.Yu Agafonova et al., Astrophysical Journal 802 (2015) 47*
*ICRC reports 1993-2019*

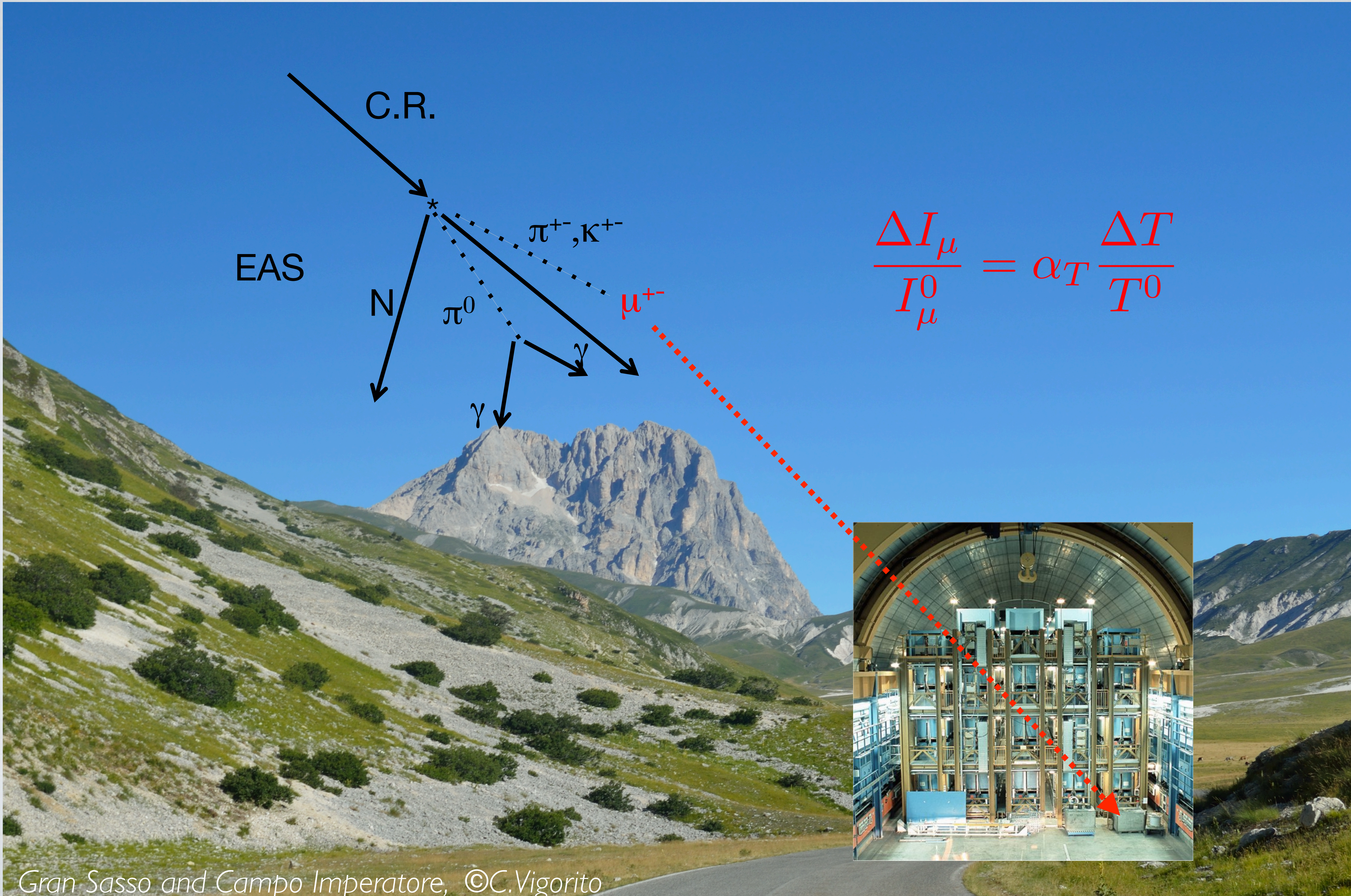
# LVD FACTS




***Very long data set for Muons and Neutrons studies***

*LVD- Hall A Underground laboratory*

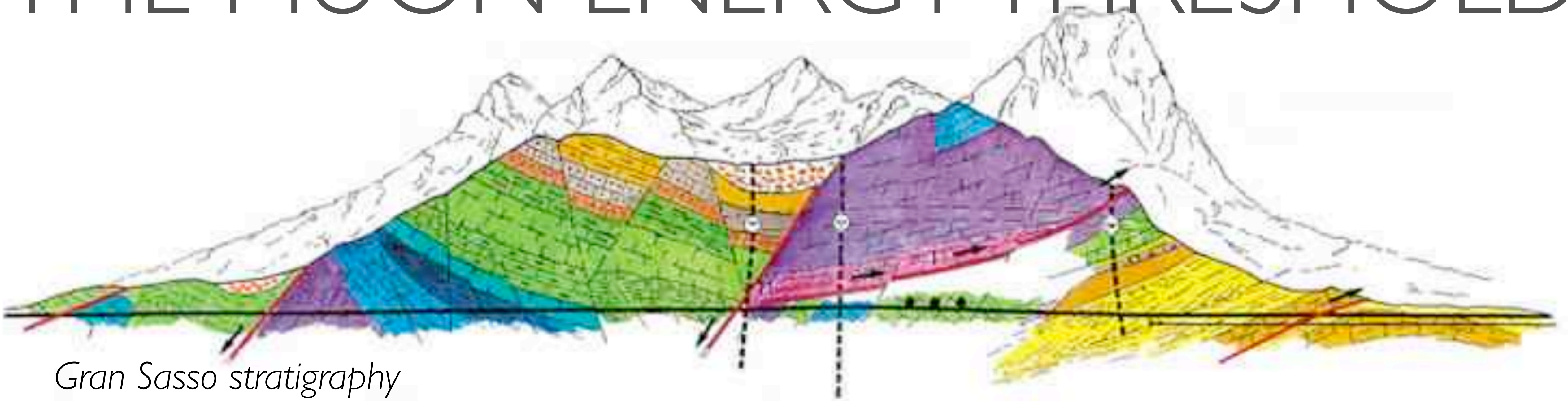
# CR ATMOSPHERIC MUONS IN LVD




$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T}{T^0}$$

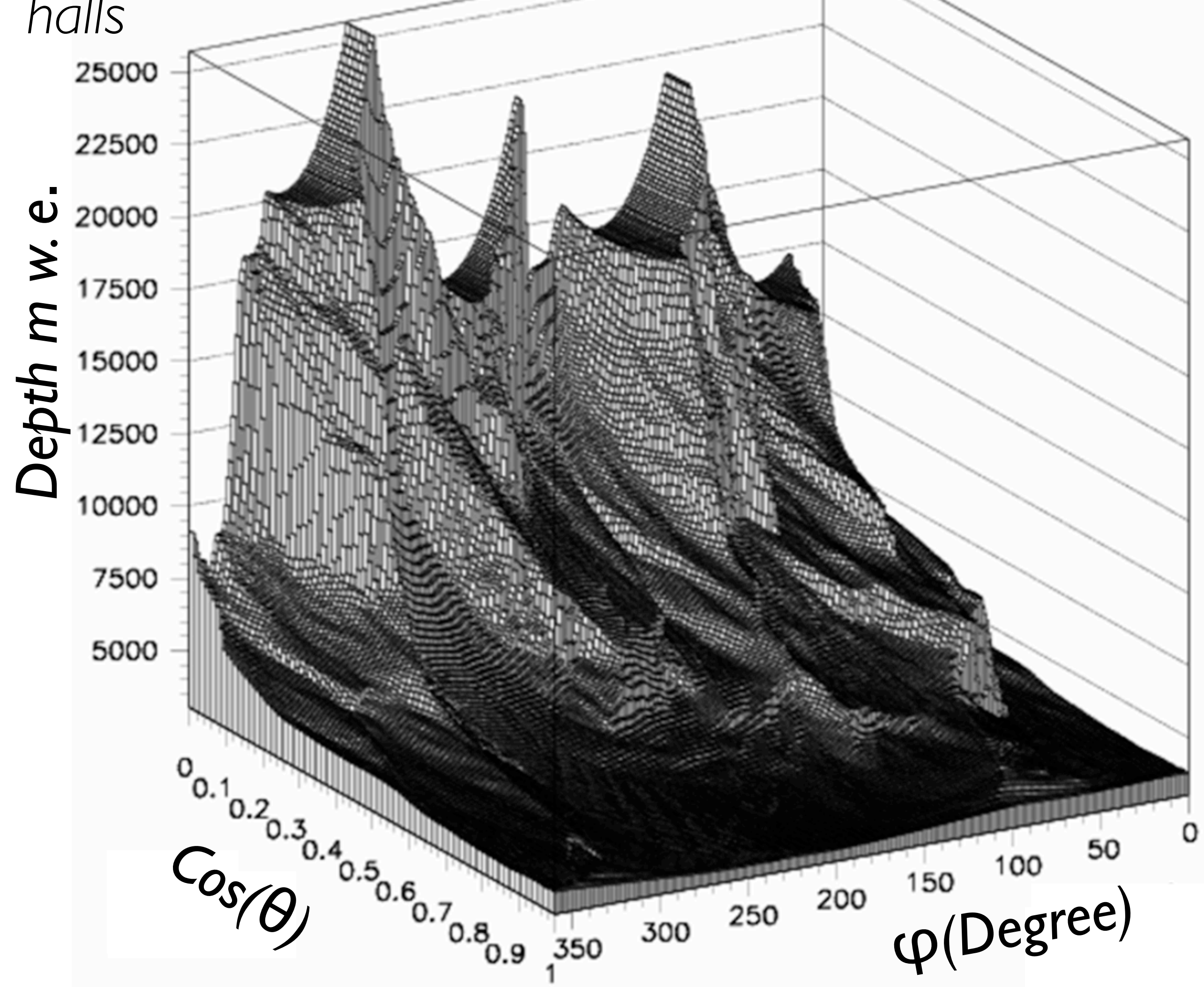
*Gran Sasso and Campo Imperatore, ©C.Vigorito*

# THE MUON ENERGY THRESHOLD



*Gran Sasso stratigraphy*

*Depth map for the underground halls*




$$E_{thr} = 1.3\ TeV$$

@

*LNGS (minimal depth 3100 m w.e.)*

# MUONS: WHY WE SHOULD CARE OF ?

- TeV **Muons** unavoidable background in underground laboratories for experiments searching for rare events

  *Dark Matter*

  *Neutrino-less double Beta Decay*

  *Supernova & Solar neutrinos*

  Muons can be rejected efficiently through HDWR vetoes & SOFT selection

- Muon induced **Neutrons**: rate smaller 10% of radiogenic neutrons but harder spectrum ( several GeV)

  → They can easily penetrate the detectors shielding and interact and generate secondary neutrons in the MeV range that mimic rare events.

*How to correlate Muons and Temperature ?*

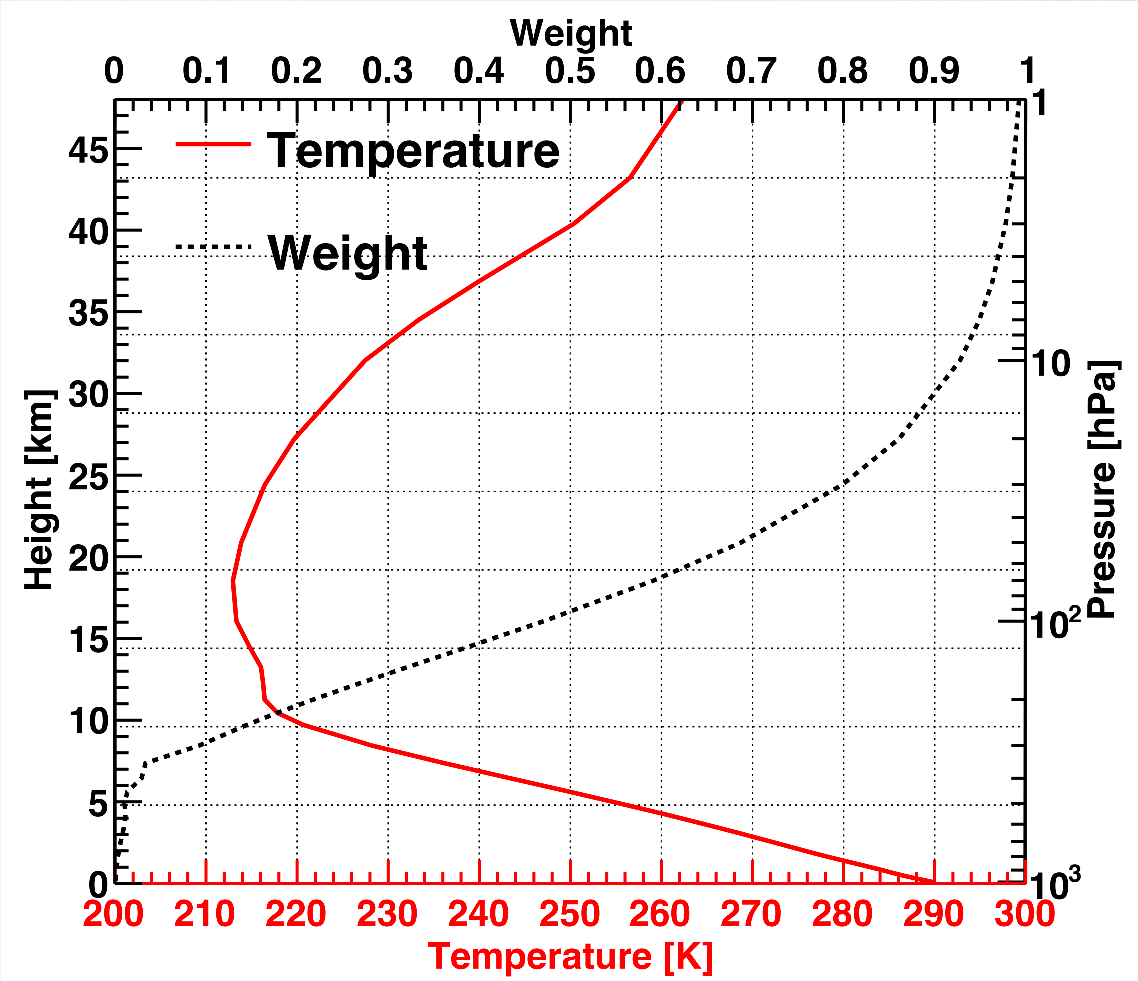
# THE EFFECTIVE TEMPERATURE

*Definition:*

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

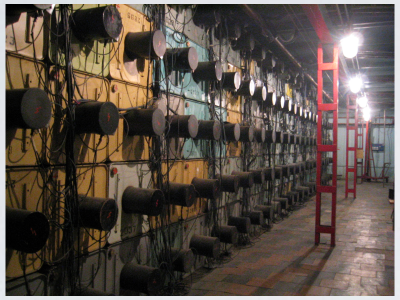
*T(X) atmospheric temperature profile and W(X) the weight at the atmospheric depth X.*

*W(X) depends on the energy required for muons to reach the experiment and also on the meson decay/interaction channels (π,K).*



# PREVIOUS MEASUREMENTS

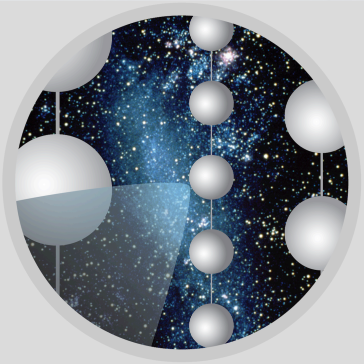
**BAKSAN**



**1990**

**1997**

**AMANDA/ICECUBE**



**1999/2011**

**2007**

*Seminal paper*

*P.H. Barrett et al., Rev. Mod. Phys., 24 (1952) 133*

**2018**

**2009/2019**

**2017**

**2016**

**2012/2019**

# THE LVD DATA SET

***Time Window:***

*Period 1994-2017*

*1992 & 1993, discontinuous data acquisition.*

***Muon Trigger:***

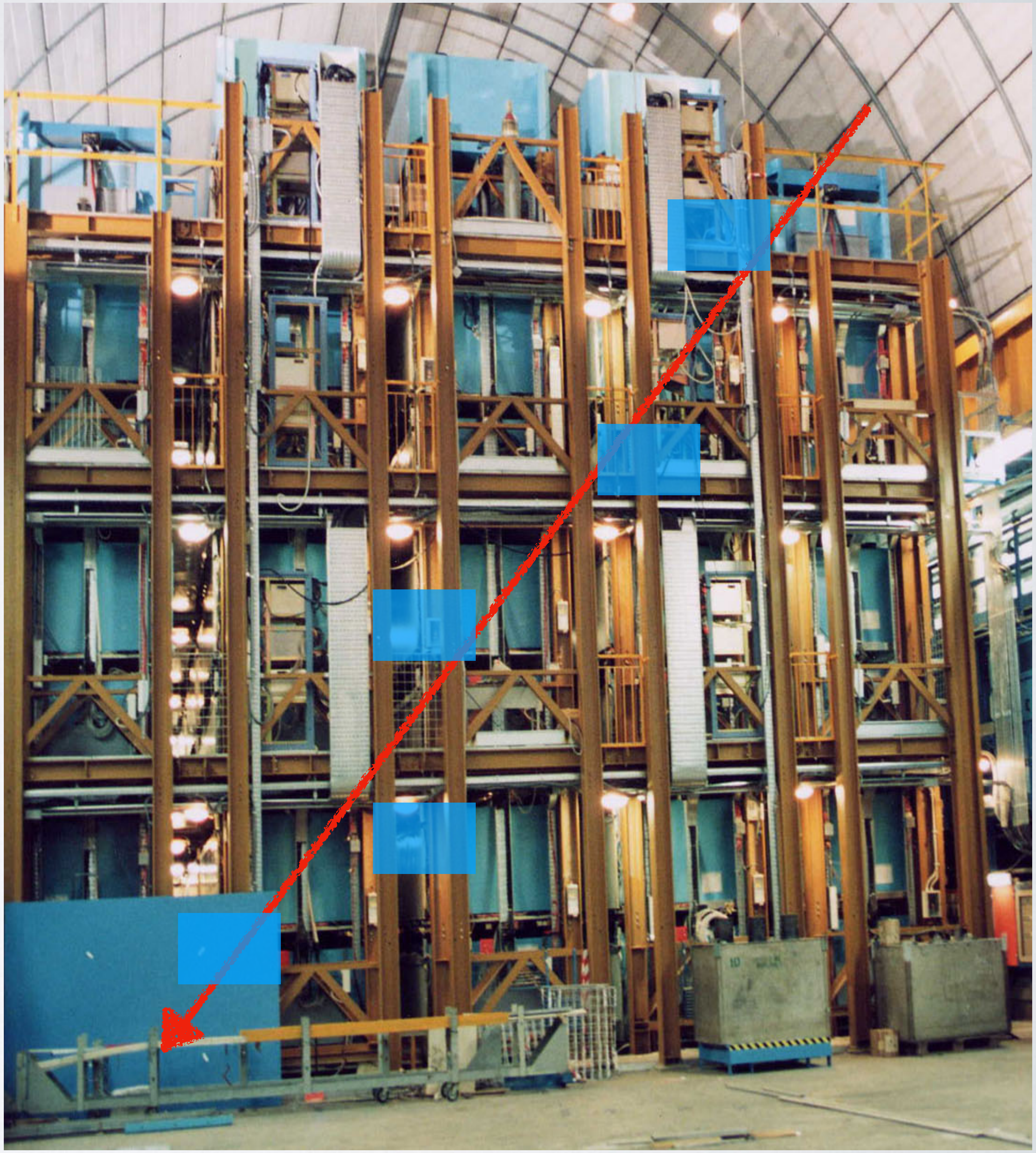
*≥2 counters with E≥10 MeV in time coincidence within 175 ns*

*$N_{\mu}$~56 x10$^{6}$*

*Livetime 8569 days (98.8%)*

***Muon Rate:***

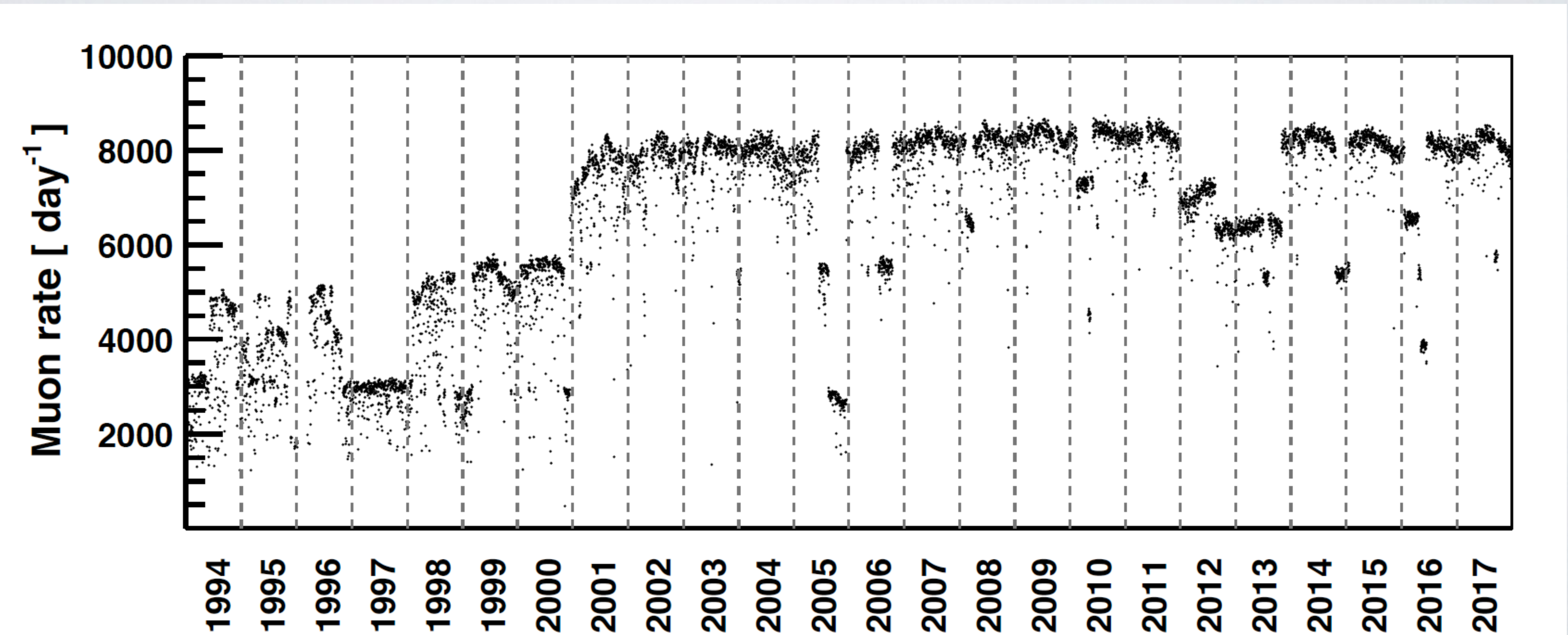
*0.1 Hz for the full detector configuration (1 kton) after quality cuts*



# THE DAILY MUON RATE

*1994-2017:*

- *Daily number of muon event*
- *42140 detector configurations*
- *Standard quality cuts applied (<5% in mass)*
- *CNGS* μ*-like events vetoed 2006-2012*



# THE DETECTOR ACCEPTANCE

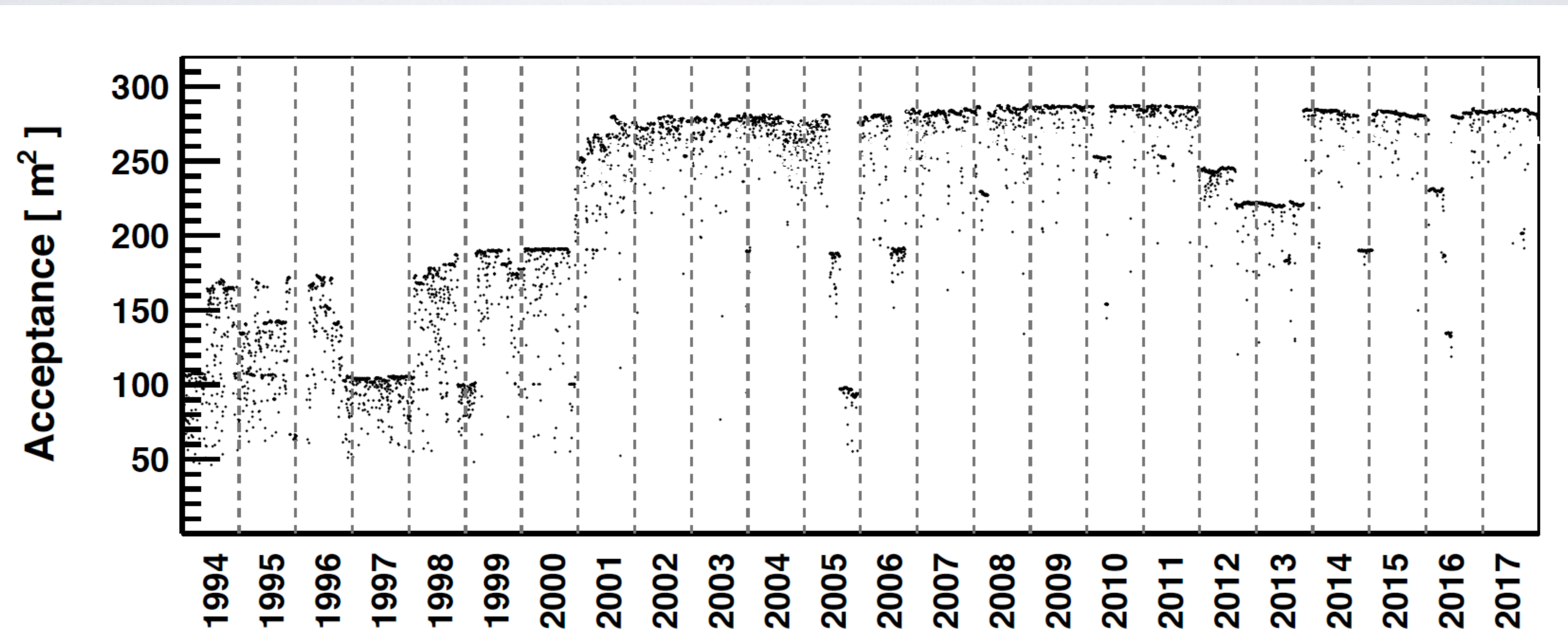
- *Atmospheric muon energy and angular distributions underground via MUSUN & MUSIC codes*

*P.Antonioli et al., Astroparticle Physics 7 (1997) 357*
*V.A.Kudryatsev, Computer Physics Comm. 180 (2009) 339*

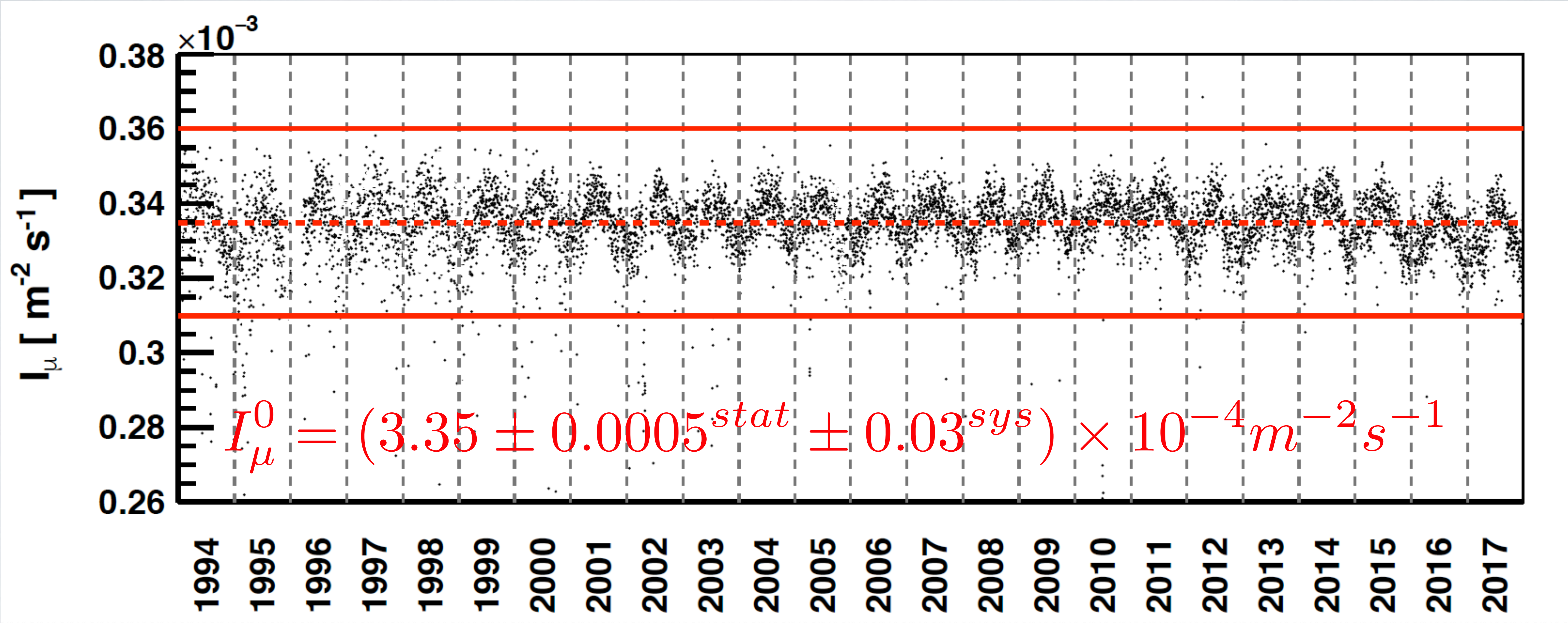
- *Detector Geometry by G4 simulation*

*MC data set: 100000 muons*

1. *Full detector acceptance: $A_{LVD}$=(298+-3) $m^2$*
2. *Relative acceptance for each detector configuration*



# THE ABSOLUTE MUON FLUX

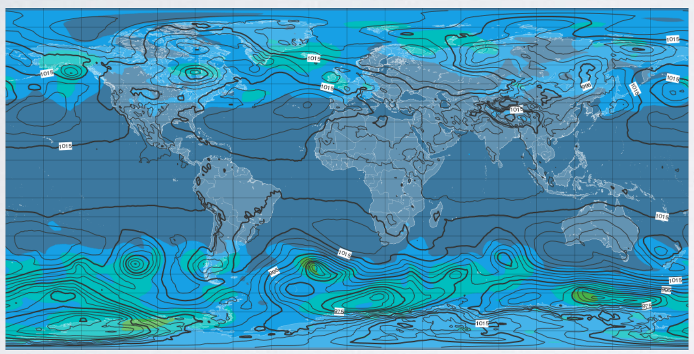



- ***Seasonal modulation:*** *clear evidence in the data*
- ***Errors*** *: Stat. [1.1 - 2.2]% + Syst. 1% , both not shown in the picture*
- ***Outliers:*** *due to overestimation of the exposure induced by misclassification of good counters / 3 s.d. cut applied*
- ***Final data set:*** *8402 days, 55 x$10^6$ muons*

# THE TEMPERATURE DATA SET

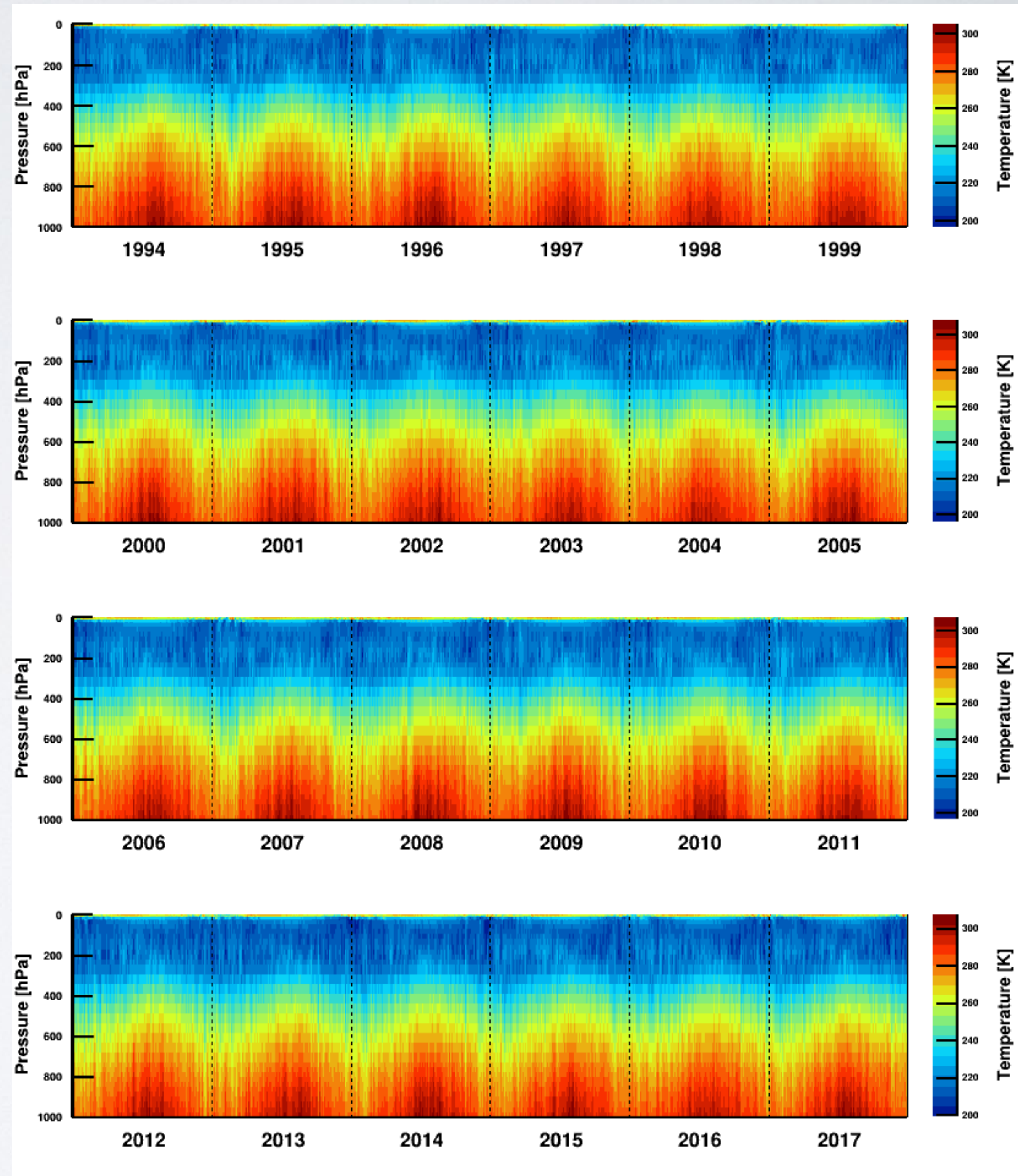
*Temperature profiles T(X) provided by*

ECMWF



*ERA Interim data set:*

- *37 pressure levels $X_i$ in the [1-1000] hPa range, variable ΔXi from 1 up to 25 hPa*
- *4 times daily @ LNGS (15.5333⁰ E 42.4275⁰ N)*

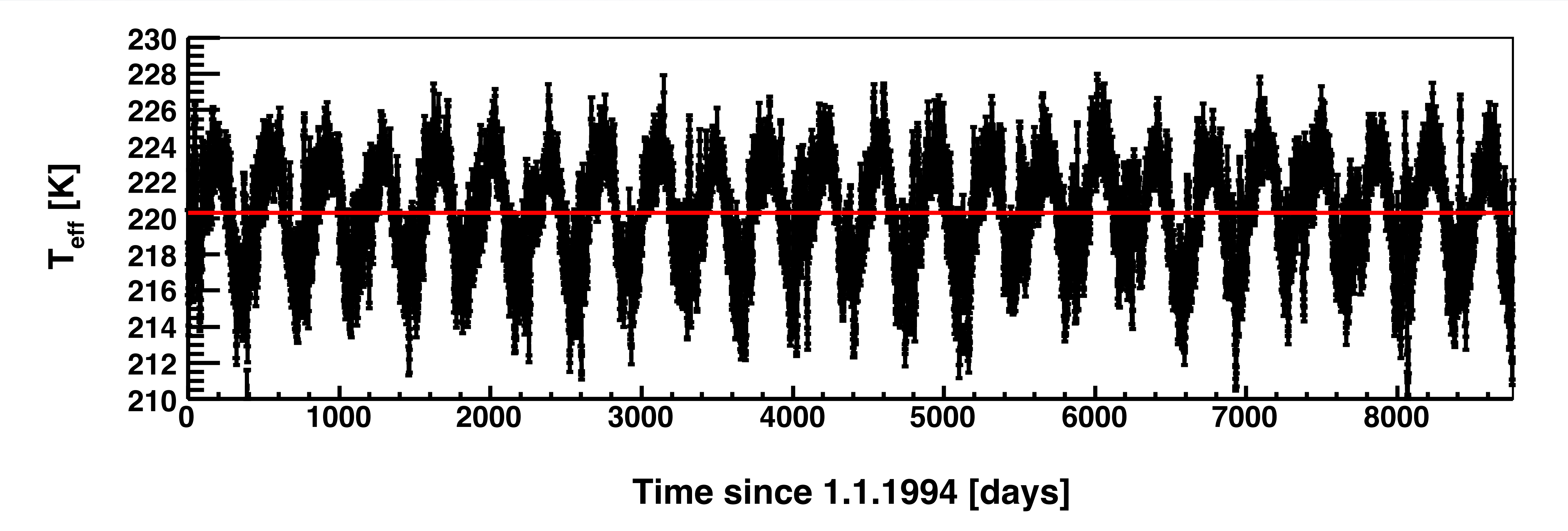


# THE DAILY EFFECTIVE TEMPERATURE

*1994-2017:*

- *Mean daily values*
- *Daily error: RMS of the 4 daily values*

$$T_{eff} = \frac{\sum_{i=1}^{N} W(X_i)T(X_i)\Delta X_i}{\sum_{i=1}^{N} T(X_i)\Delta X_i}$$




*1994-2017 mean value*

$$T_{eff}^{0} = 220.307 \pm 0.006 K$$

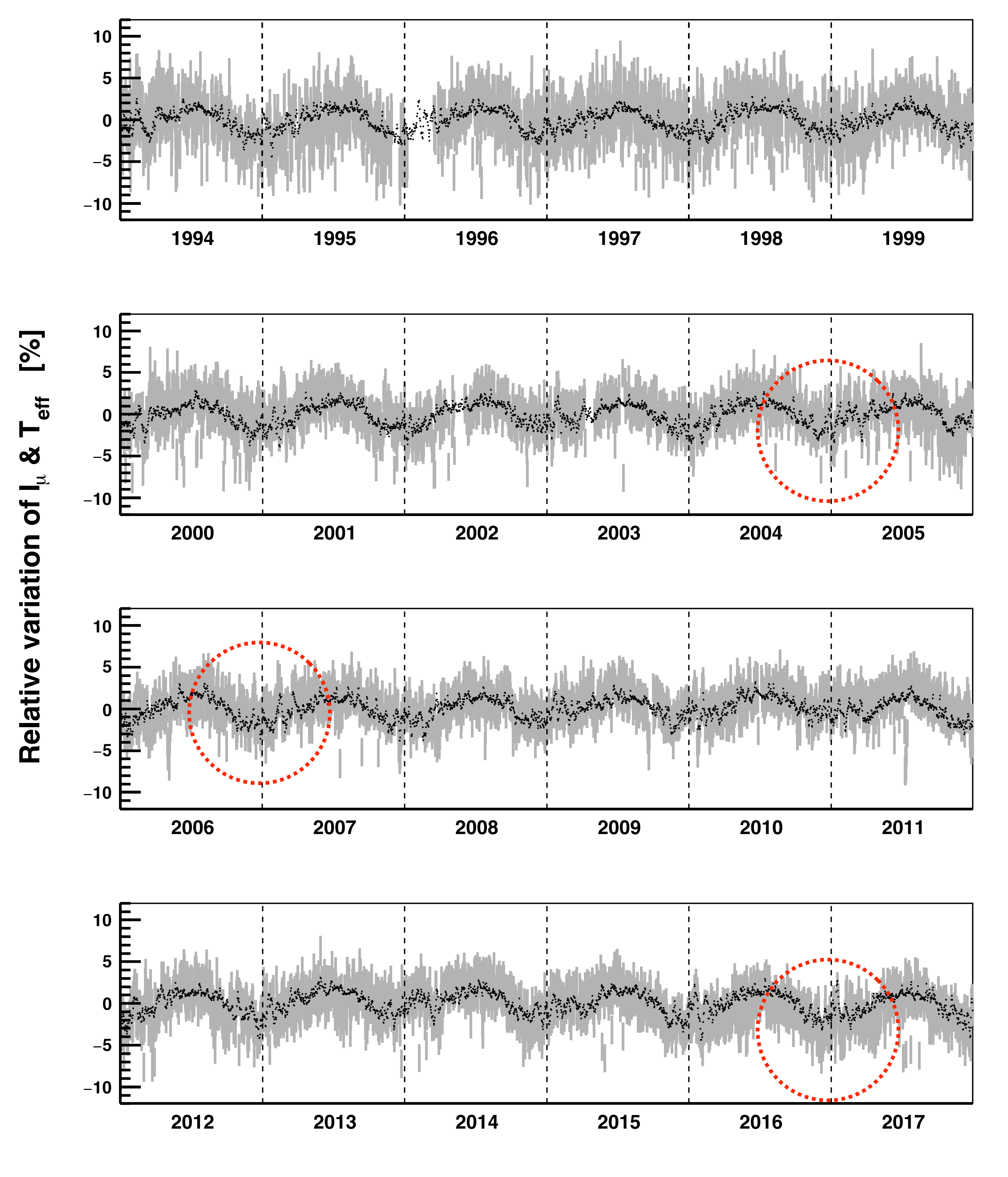
# RELATIVE VARIATIONS

$$\frac{\Delta I_\mu}{I_\mu^0} = \frac{I_\mu(t) - I_\mu^0}{I_\mu^0}$$

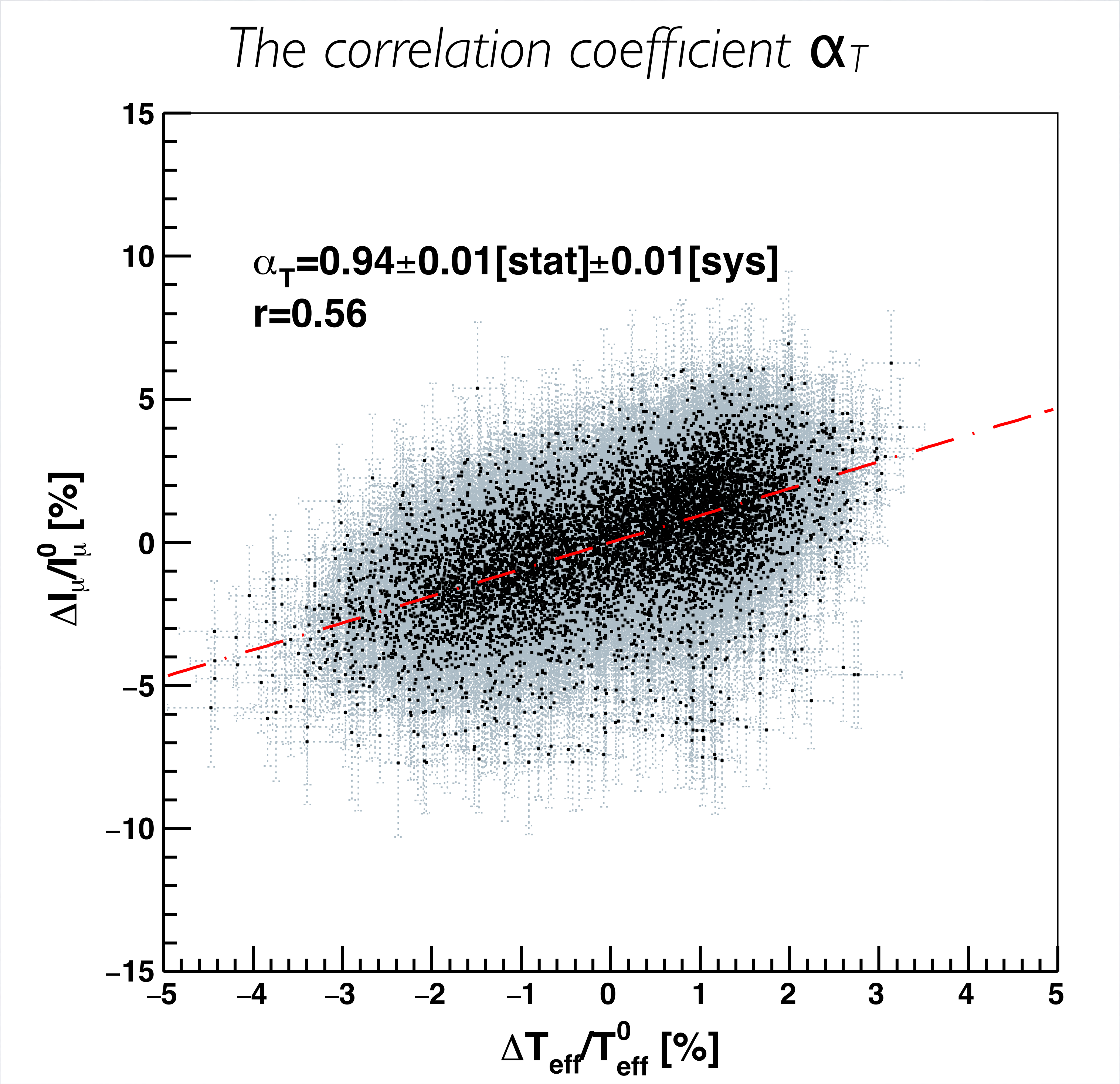
$$\frac{\Delta T_{eff}}{T_{eff}^0} = \frac{T_{eff}(t) - T_{eff}^0}{T_{eff}^0}$$

# RELATIVE VARIATIONS

- *Well correlated along the time (gray=Muons, black=Temperature)*
- *Several SSWs during winter time appear in both series.*



# MUON VS TEMPERATURE

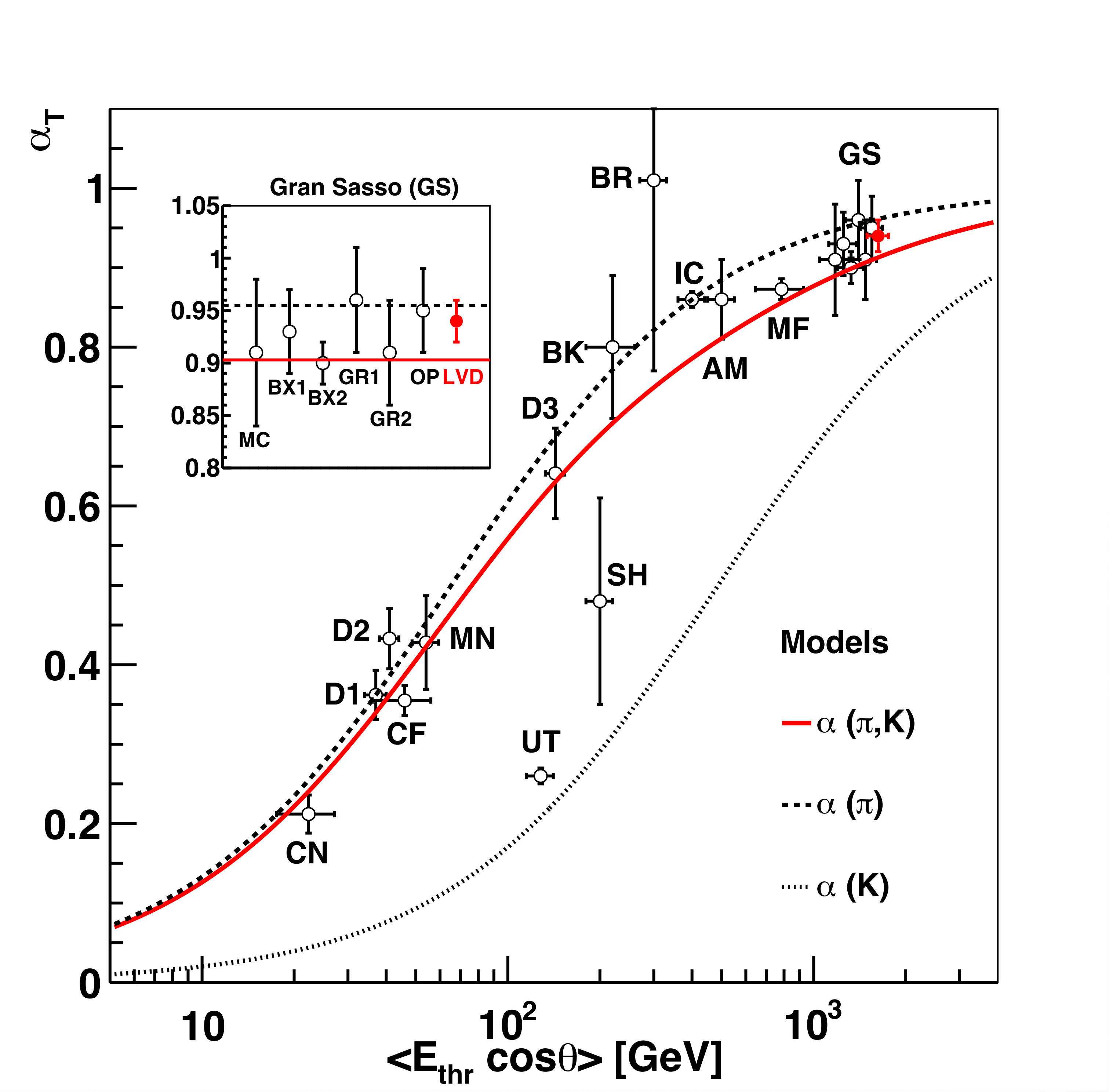



Systematics error mainly from the detector acceptance

# THE $\alpha_T$ COLLECTION

*CN/CF= Double Chooz Near & Far*
*D1/D2/D3= Daya Bay*
*MN/MF= MINOS Near & Far*
*SH= Sherman*
*UT= Utah*
*BK=Baksan*
*BR= Barrett*
*AM=AMANDA*
*IC=ICECUBE*

*GS= Gran Sasso Experiments*
*MC=MACRO*
*BX=Borexino*
*GR1/GR2=GERDA*
*LVD*
*OP=Opera*



# SPECTRAL ANALYSIS OF THE TIME SERIES

Goals to reach:

1. Spectral content & correlated power
2. Year by year modulation

Way to do:

1. Lomb-Scargle Method

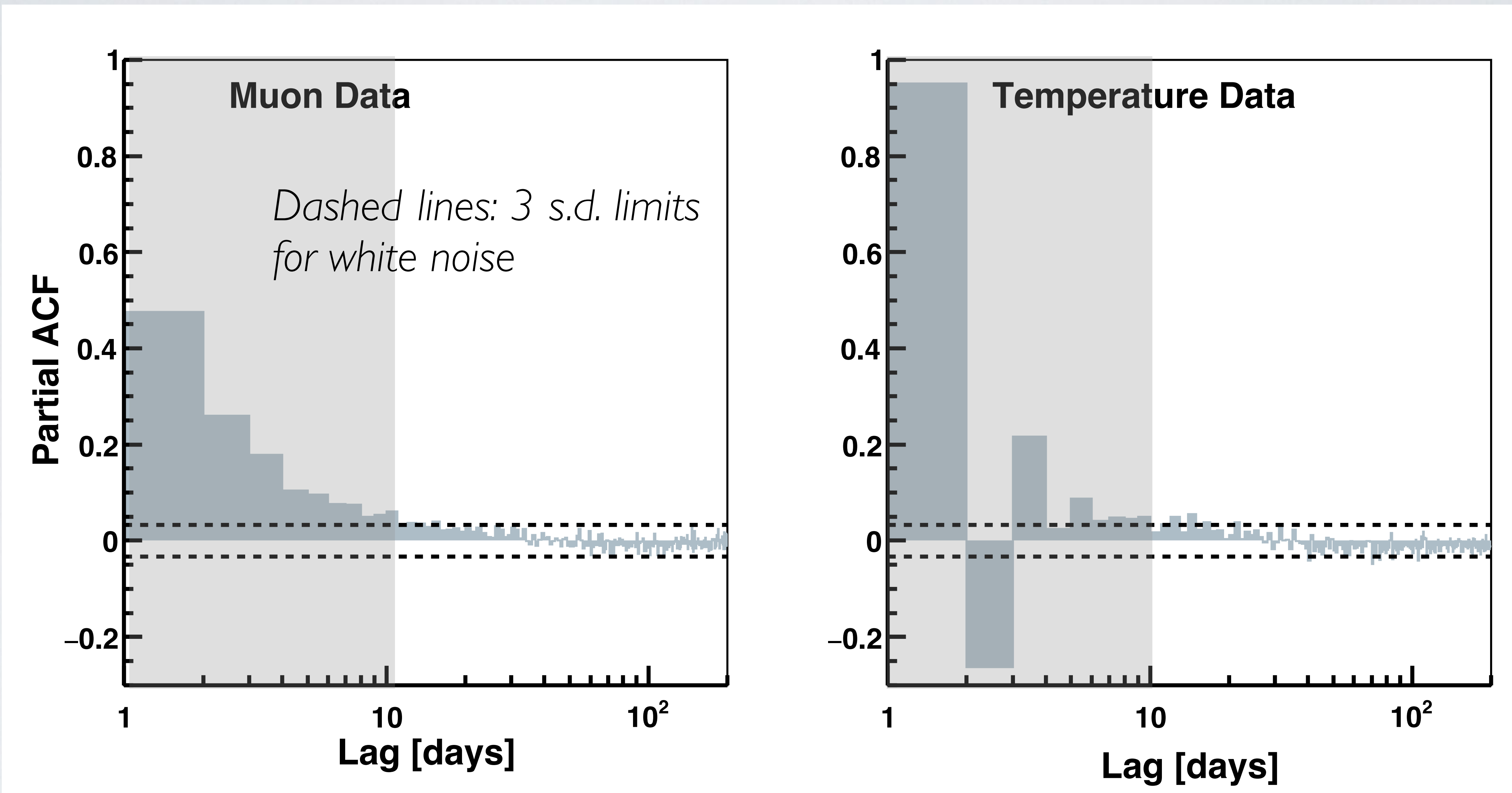
*N. R. Lomb, Astrophys. Space Sci. 39, 447 (1976).*
*J. D. Scargle, Astrophys. J. 263, 835 (1982).*

2. Singular Spectrum Analysis

*M. Ghil et al., Rev. Geophys. 40, 3, (2002).*

# THE PARTIAL AUTO-CORRELATION

A way to quote the intrinsic correlation/noise in the time series




*Pure white noise  fluctuations excluded*

*Auto Regressive model of order 10 (AR10) for both series*

# LOMB-SCARGLE METHOD

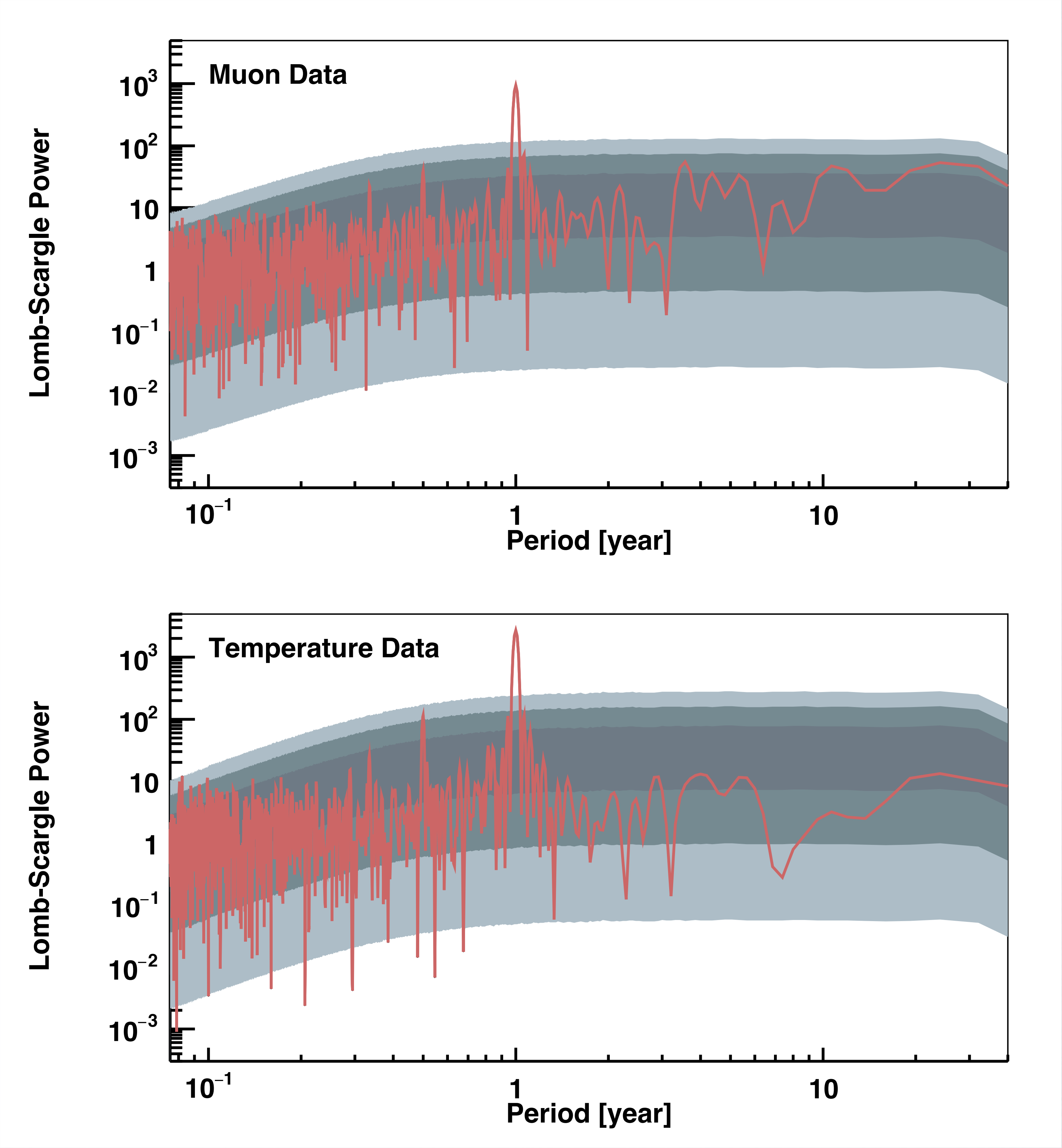
*Red Line= LS power of the time series as a function of period*

*Grey bands=LS power fluctuations at 1, 2 and 3 s.d. of $10^5$ simulated background time series modeled by an AR10 model.*

*Only the seasonal modulation is clearly above 3 s.d. band in both time series*

*Other periodicities: at 1.5 s.d. are noticeable 0.5 years for both series, and at about 3 and 10 years for the muon series.*

Fourier-like power spectrum

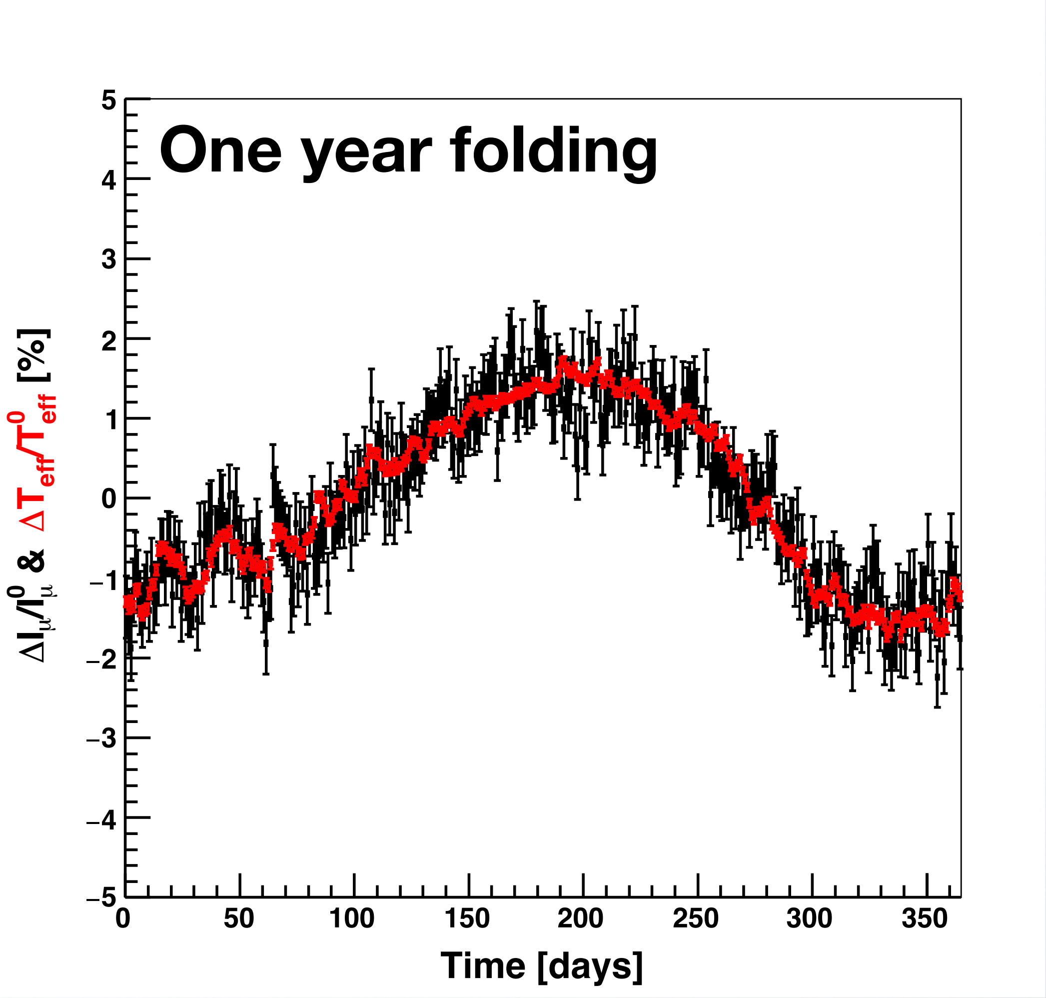


# THE SEASONAL MODULATION

*First harmonic approximation:* $f(t) = K + A\ cos\frac{2\pi}{T}(t - t_0)$

| | $K$ [%] | $A$ [%] | $T$ [days] | $t_0$ [days] |
|---|---|---|---|---|
| Temperature series | $-0.05 \pm 0.01$ | $1.47 \pm 0.01$ | $365.1 \pm 0.1$ | $184 \pm 1$ |
| Muon series | $-0.00 \pm 0.02$ | $1.41 \pm 0.03$ | $365.1 \pm 0.2$ | $186 \pm 2$ |

- T & $t_0$ agrees each other in both series and also with other experiment at LNGS
- $\chi^2$/dof (2.8 for T & 2.1 for Muons) shows a clear deviation from the first approximation as clear in the asymmetry in the rising and decay phases also due to SSW perturbations during winters.

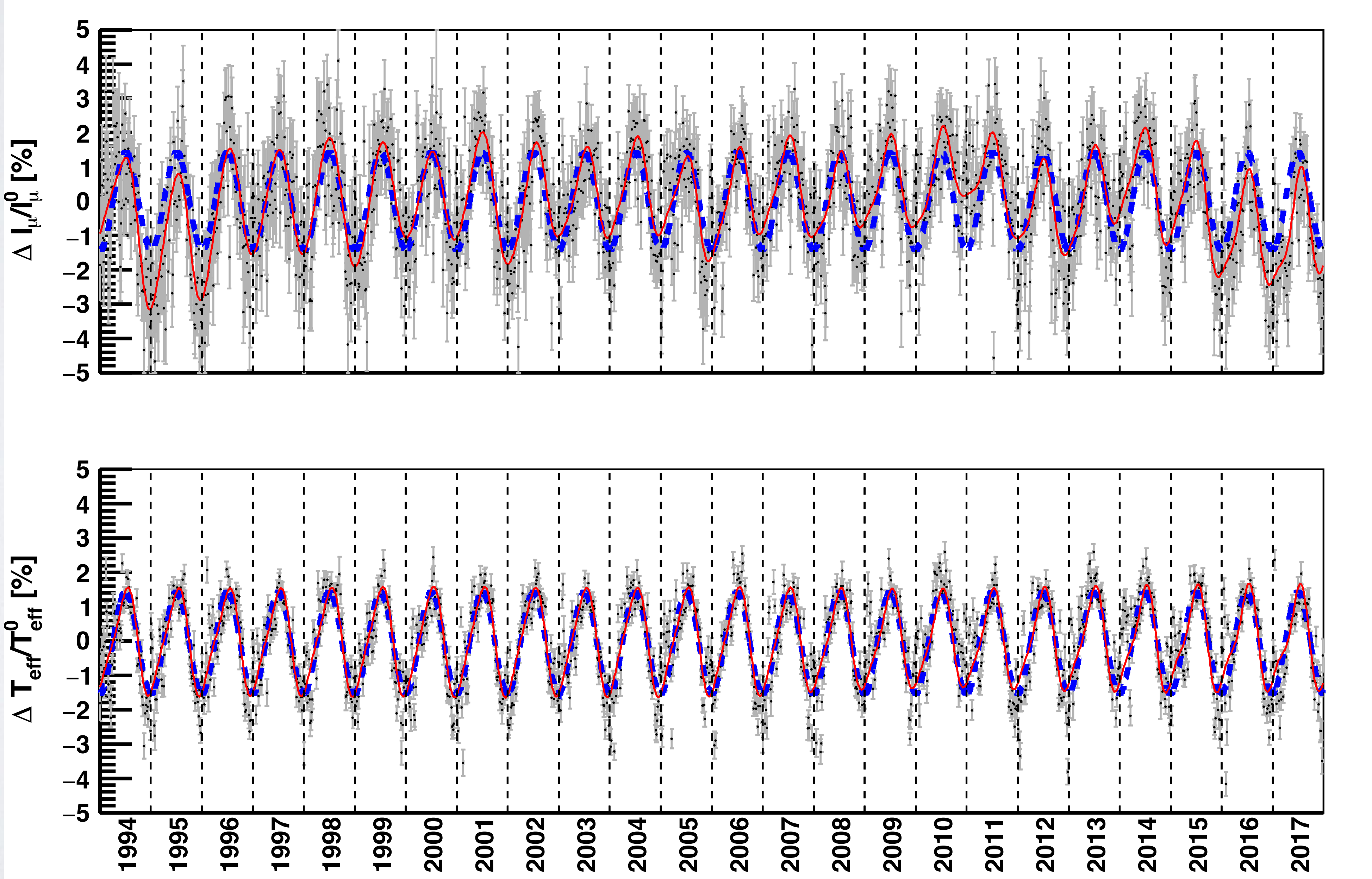


# SSA: SINGULAR SPECTRUM ANALYSIS

- Based on a data-adaptive basis functions instead of sinusoidal ones (Fourier) to extract amplitudes and frequencies of quasi periodic components

*M. Ghil et al., Rev. Geophys. 40, 3, (2002)*

Best fit via SSA (red)
First approximation (blue)



# SSA: YEAR BY YEAR MODULATION

- The SSA provides a better definition of maxima et minima evolution avoiding constant amplitude and phase

TABLE IV. Amplitude, expressed in terms of percentage with respect to the total average, and position of the minimum and maximum in the $I_\mu/I_\mu^0$ and $T_{eff}/T_{eff}^0$ series, calculated year by year.

| Muon flux | | | | | | $T_{eff}$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | $A_{max}$[%] | Day | Date | $A_{min}$[%] | Day | Date | $A_{max}$[%] | Day | Date | $A_{min}$[%] |
| 183 | 02.07.1994 | 0.99 | 358 | 24.12.1994 | −2.99 | 203 | 22.07.1994 | 1.56 | 348 | 14.12.1994 | −1.61 |
| 563 | 17.07.1995 | 0.86 | 723 | 24.12.1995 | −2.89 | 568 | 22.07.1995 | 1.56 | 713 | 14.12.1995 | −1.61 |
| 933 | 21.07.1996 | 1.41 | 1088 | 23.12.1996 | −1.54 | 933 | 21.07.1996 | 1.56 | 1078 | 13.12.1996 | −1.62 |
| 1288 | 11.07.1997 | 1.52 | 1453 | 23.12.1997 | −1.62 | 1298 | 21.07.1997 | 1.56 | 1443 | 13.12.1997 | −1.62 |
| 1653 | 11.07.1998 | 1.82 | 1828 | 02.01.1999 | −1.89 | 1663 | 21.07.1998 | 1.56 | 1808 | 13.12.1998 | −1.62 |
| 2028 | 21.07.1999 | 1.66 | 2188 | 28.12.1999 | −1.15 | 2028 | 21.07.1999 | 1.57 | 2173 | 13.12.1999 | −1.63 |
| 2383 | 10.07.2000 | 1.50 | 2543 | 17.12.2000 | −1.21 | 2393 | 20.07.2000 | 1.56 | 2543 | 17.12.2000 | −1.63 |
| 2743 | 05.07.2001 | 1.90 | 2918 | 27.12.2001 | −1.77 | 2758 | 20.07.2001 | 1.57 | 2908 | 17.12.2001 | −1.63 |
| 3128 | 25.07.2002 | 1.70 | 3278 | 22.12.2002 | −1.22 | 3123 | 20.07.2002 | 1.56 | 3273 | 17.12.2002 | −1.63 |
| 3493 | 25.07.2003 | 1.54 | 3638 | 17.12.2003 | −0.93 | 3488 | 20.07.2003 | 1.56 | 3638 | 17.12.2003 | −1.64 |
| 3853 | 19.07.2004 | 1.79 | 4003 | 16.12.2004 | −1.17 | 3853 | 19.07.2004 | 1.55 | 3998 | 11.12.2004 | −1.62 |
| 4213 | 14.07.2005 | 1.31 | 4358 | 06.12.2005 | −1.57 | 4218 | 19.07.2005 | 1.56 | 4363 | 11.12.2005 | −1.58 |
| 4583 | 19.07.2006 | 1.56 | 4723 | 06.12.2006 | −1.17 | 4583 | 19.07.2006 | 1.56 | 4728 | 11.12.2006 | −1.55 |
| 4948 | 19.07.2007 | 1.82 | 5098 | 16.12.2007 | −0.94 | 4948 | 19.07.2007 | 1.55 | 5093 | 11.12.2007 | −1.50 |
| 5308 | 13.07.2008 | 1.50 | 5453 | 05.12.2008 | −1.00 | 5313 | 18.07.2008 | 1.55 | 5458 | 10.12.2008 | −1.46 |
| 5673 | 13.07.2009 | 1.85 | 5818 | 05.12.2009 | −0.68 | 5678 | 18.07.2009 | 1.54 | 5818 | 05.12.2009 | −1.41 |
| 6043 | 18.07.2010 | 2.24 | 6183 | 05.12.2010 | −0.10 | 6043 | 18.07.2010 | 1.55 | 6183 | 05.12.2010 | −1.39 |
| 6398 | 08.07.2011 | 1.88 | 6558 | 15.12.2011 | −1.04 | 6408 | 18.07.2011 | 1.57 | 6548 | 05.12.2011 | −1.42 |
| 6763 | 07.07.2012 | 1.22 | 6908 | 29.11.2012 | −1.59 | 6773 | 17.07.2012 | 1.58 | 6913 | 04.12.2012 | −1.43 |
| 7133 | 12.07.2013 | 1.56 | 7268 | 24.11.2013 | −0.71 | 7138 | 17.07.2013 | 1.59 | 7273 | 29.11.2013 | −1.45 |
| 7488 | 02.07.2014 | 2.15 | 7643 | 04.12.2014 | −1.22 | 7503 | 17.07.2014 | 1.61 | 7638 | 29.11.2014 | −1.47 |
| 7853 | 02.07.2015 | 1.76 | 8018 | 14.12.2015 | −2.38 | 7868 | 17.07.2015 | 1.63 | 8003 | 29.11.2015 | −1.50 |
| 8228 | 11.07.2016 | 0.97 | 8378 | 08.12.2016 | −2.50 | 8233 | 16.07.2016 | 1.64 | 8373 | 03.12.2016 | −1.52 |
| 8603 | 21.07.2017 | 0.77 | 8738 | 03.12.2017 | −1.73 | 8598 | 16.07.2017 | 1.62 | 8738 | 03.12.2017 | −1.49 |

# CONCLUSIONS

***LVD on-line since 1992 waiting for a SN signal in the Milky Way***

***1994-2017 muon data analysed: 8402 days / 55 millions of events, the longest data set for a single underground detector***

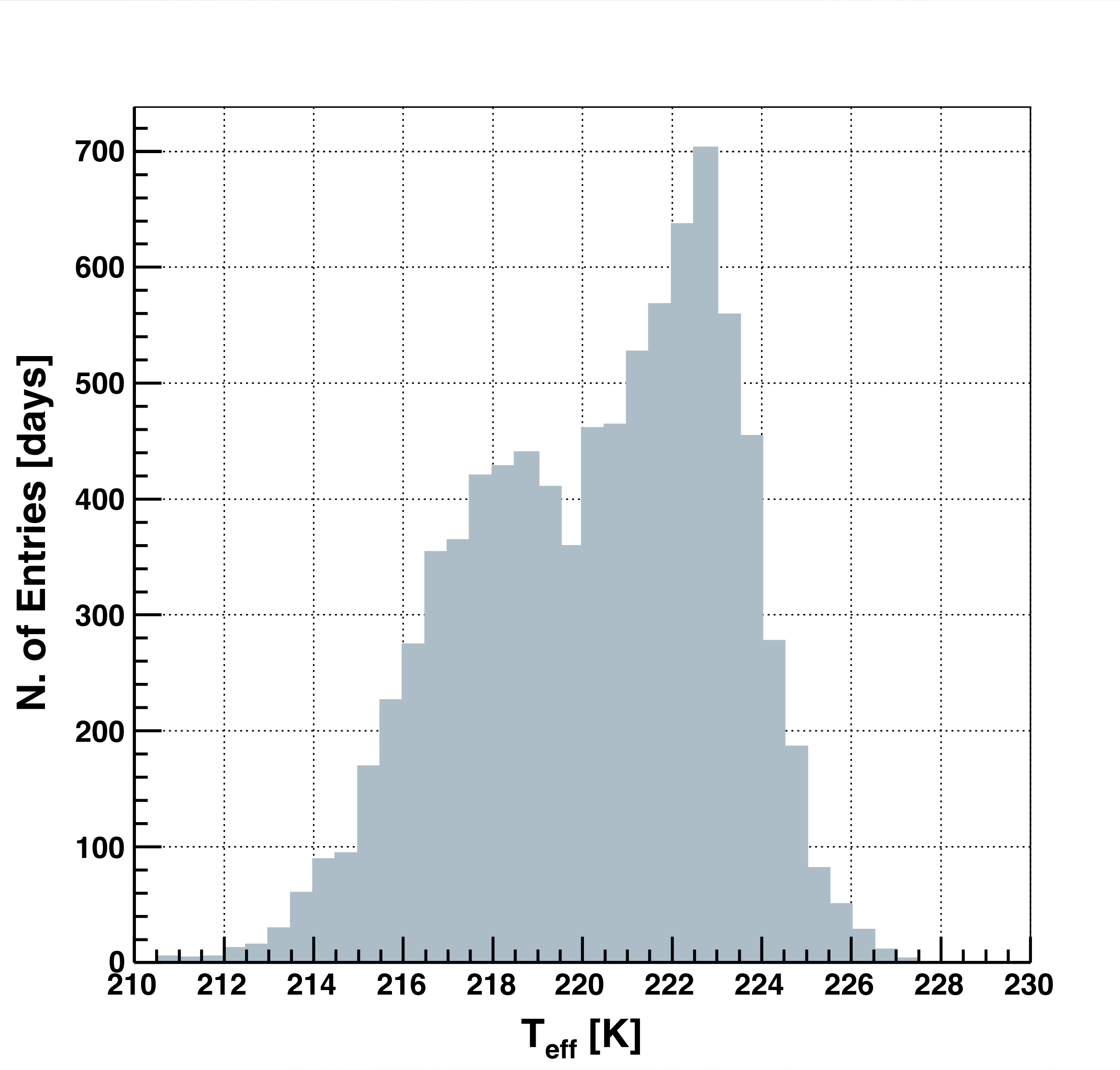
***Evidence for a dominant seasonal modulation with T= 1 year and amplitude 1.40%***

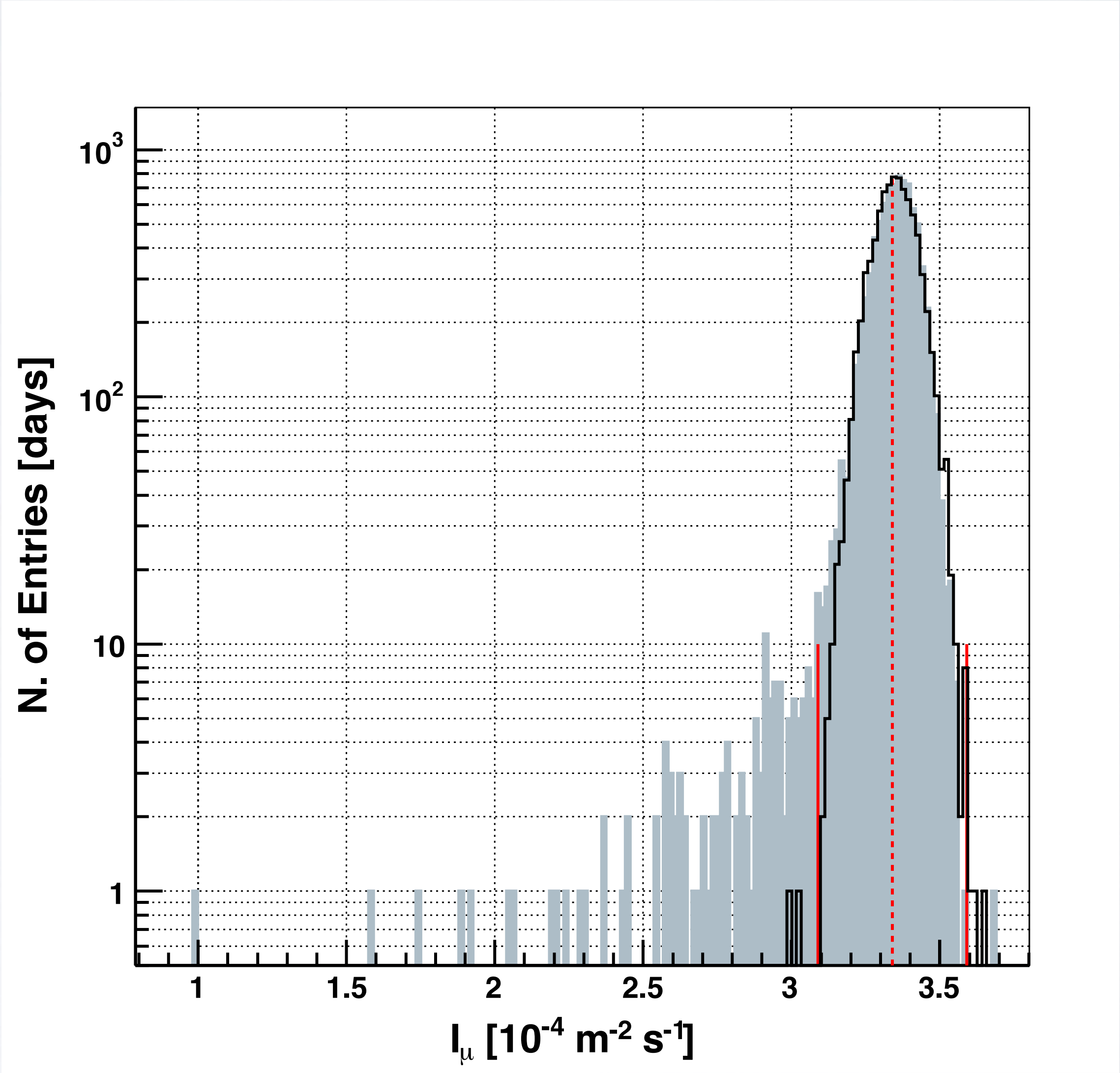
***Strong correlation: $\alpha_T$ =0.94±0.01(stat)+0.01(sys) in agreement with the expected value and other experiments @ LNGS***

***Indications of other periodicities in the muon flux***
***The SSA approach on going***

# BACKUP SLIDES

# THE $T_{EFF}$ & MUON DISTRIBUTIONS




*Black line= Teff ⊗ Muon Error*

*Low tail excluded at 3 s.d. (+-7.5%)*

# THE SELECTION STEPS

| | Livetime (days) | Efficiency (%) | N.of muons ($10^6$) |
|---|---|---|---|
| Effective Time | 8766 | 100 | —— |
| Muon Trigger | 8659 | 98.8 | 55.8 |
| Standard Analisys Quality cuts | 8543 | 97.4 | 55.4 |
| $I_\mu^0$+-7.5% | 8402 | 95.8 | 54.8 |

**Final data set**

$$I_\mu^0 = (3.35 \pm 0.0005^{stat} \pm 0.03^{sys}) \times 10^{-4} m^{-2} s^{-1}$$

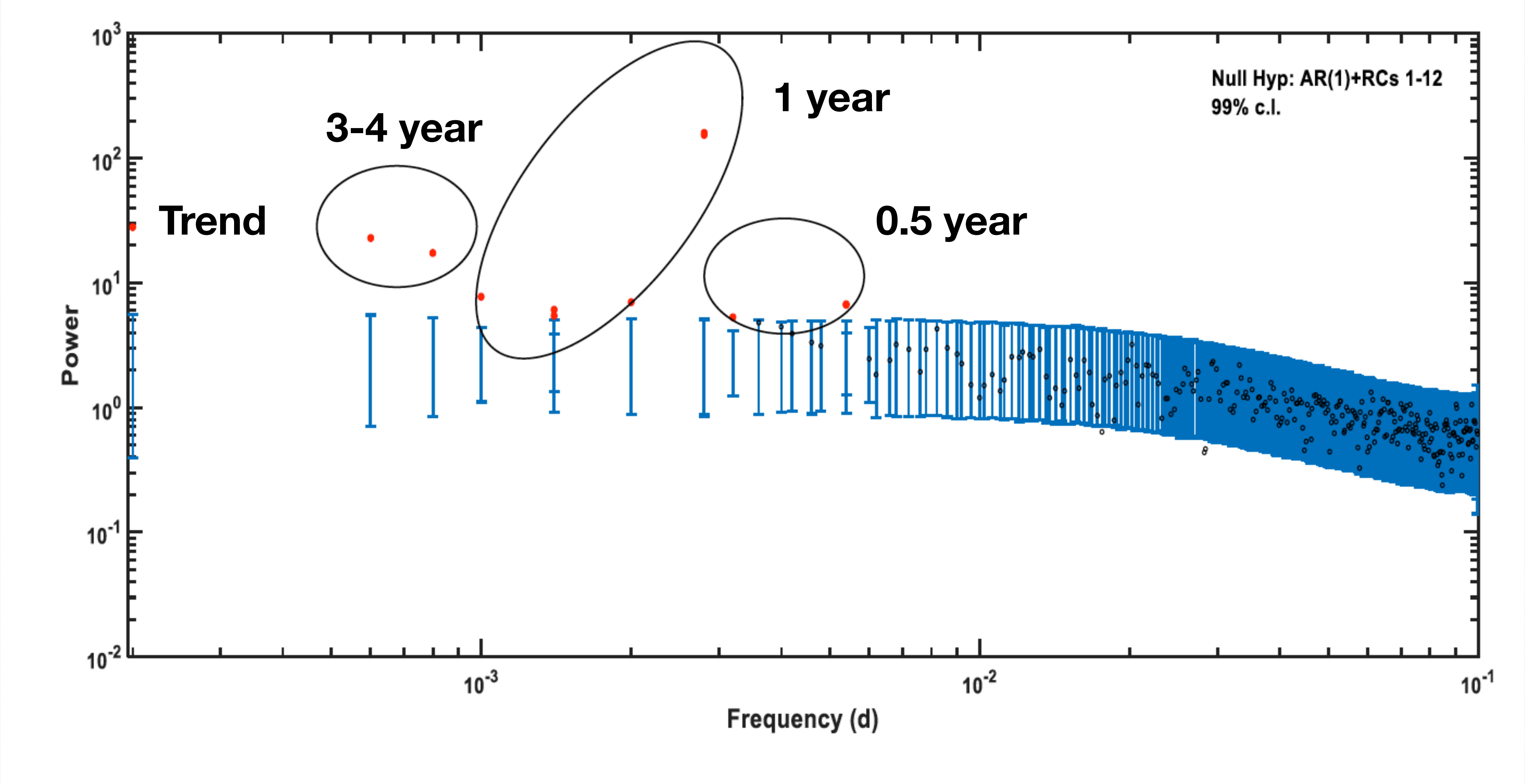
# SYSTEMATICS ON ALPHA$_T$

TABLE II. Systematic errors on the parameter inputs to $\alpha_T$.

| | Value | $\Delta\alpha_T$ |
|---|---|---|
| Meson production ratio, $r_{K/\pi}$ | $0.149 \pm 0.06$ from Ref. [30] | 0.002 |
| Mean effective temperature | $220.3 \pm 0.9$ K our calculation | 0.004 |
| Threshold energy, $\langle E_{\mathrm{thr}} \cdot \cos\theta \rangle$ | $1.40 \pm 0.13$ TeV our calculation | 0.002 |
| LVD acceptance | $298 \pm 3$ m$^3$ our simulation | 0.01 |
| Total systematic error budget | | 0.011 |

# SSA COMPONENTS: MUON

SSA power spectrum decomposition



# SSA COMPONENTS: $T_{EFF}$

SSA power spectrum decomposition