Multi Muons seasonal modulation under Gran Sasso and dark matter

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• Interest for **dark matter** experiment like COGENT (Soudan), DAMA (Gran Sasso), SABRE.. having seasonal modulation as signature (expected peak at day ~ 152.5)

• Needed a large area experiment==>> analysis of the 1994-2000 multiple-muons data **from MACRO** (Gran Sasso)

Muon seasonal variation - theory

The muon rate depends from atmospheric density (temperature), and from pressure. In deep underground locations, negligible pressure effect. We expect **a positive correlation** with temperature (bigger distances for pion decay). At the first order:

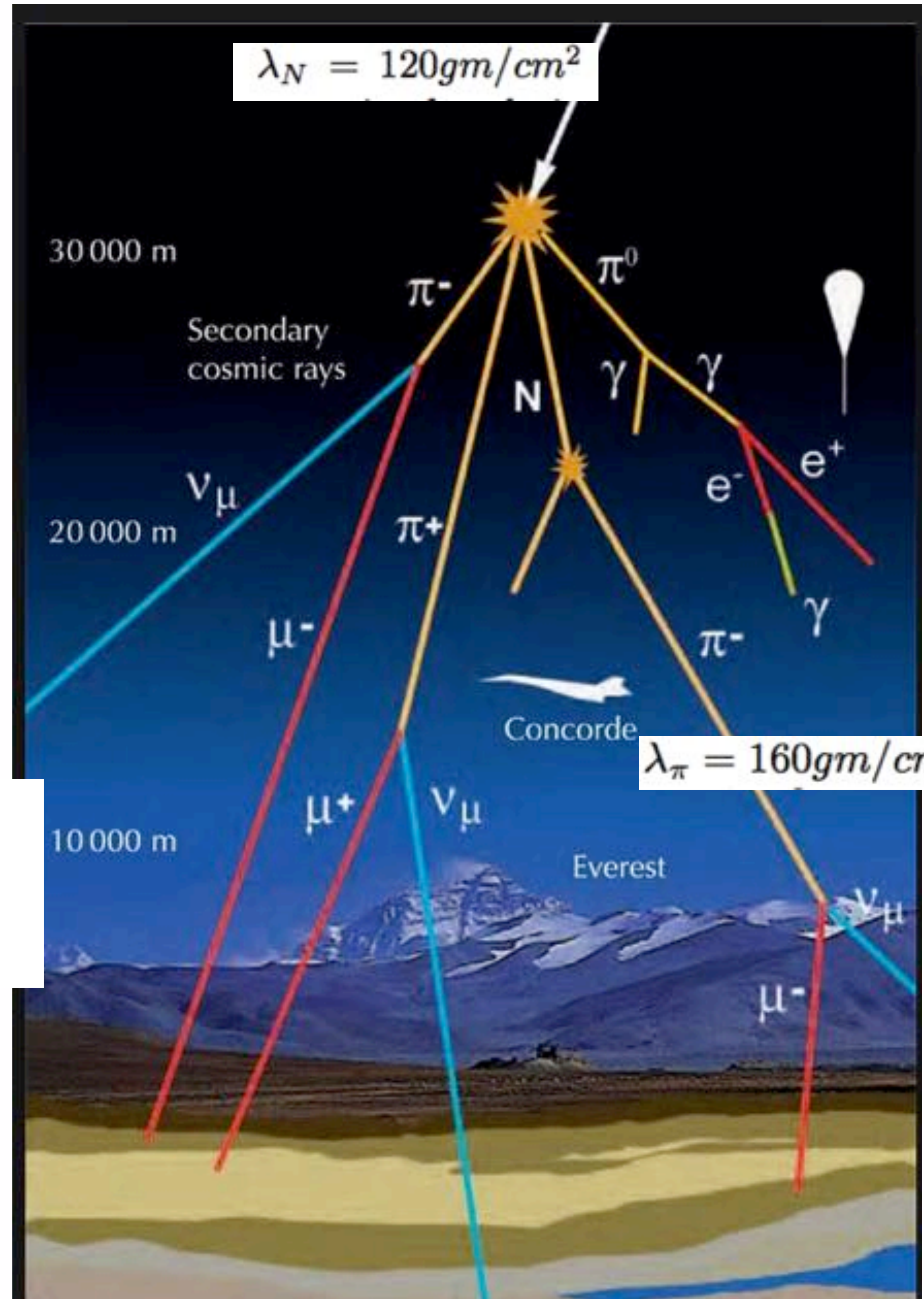
$$\frac{\Delta I_\mu}{I_\mu^0} = \int_0^\infty \alpha(X) \frac{\Delta T}{T(X)} dX$$

or

$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta_{Teff}}{< T_{eff} >} \qquad T_{eff} = \sum_i w_i \frac{T(i)}{w_{tot}}$$

***w_i* used by MACRO (1997):**

$$w_i = \frac{dX_i}{X_i} (exp(-X_i/\lambda_\pi) - exp(-X_i/\lambda_N))$$



Muon seasonal variation - theory

the w_i used by MACRO in 1997 are very simple, but the cascade is very complicated!

A **more complete expression** including decay lengths, kaons ecc., is used **by MINOS**

$$W^{\pi,K}(X) \simeq \frac{(1 - X/\Lambda'_{\pi,K})^2 e^{-X/\Lambda_{\pi,K}} A^1_{\pi,K}}{\gamma + (\gamma + 1) B^1_{\pi,K} K(X)(\langle E_{\text{th}} \cos\theta\rangle/\epsilon_{\pi,K})^2},$$

TABLE I. Input $W(X)$ parameter values.

Parameter	Value	
A^1_π	1 [18,19]	mesons in the forward direction
A^1_K	$0.38 \cdot r_{K/\pi}$ [18,19]	
$r_{K/\pi}$	0.149 [20] ± 0.06 [21]	kaon pion fraction
B^1_π	1.460 ± 0.007 [18,19]	meson relative attenuation
B^1_K	1.740 ± 0.028 [18,19]	
Λ_N	120 g/cm^2 [20]	
Λ_π	180 g/cm^2 [20]	
Λ_K	160 g/cm^2 [20]	
$\langle E_{\text{th}} \cos\theta\rangle$	0.785 ± 0.14 TeV	threshold energy LNGS 1.3 TeV
γ	1.7 ± 0.1 [5]	muon spectral energy
ϵ_π	0.114 ± 0.003 TeV [18,19]	critical energies
ϵ_K	0.851 ± 0.014 TeV [18,19]	equal probability for decay and interactions

Muon seasonal variation - theory

atmospheric temperature data in 37 layers from European Centre for Medium-Range Weather Forecasts,http://www.ecmwf.int/, *thanks to A. Longhin*

At Gran Sasso **practically no difference** between the MACRO and MINOS weights

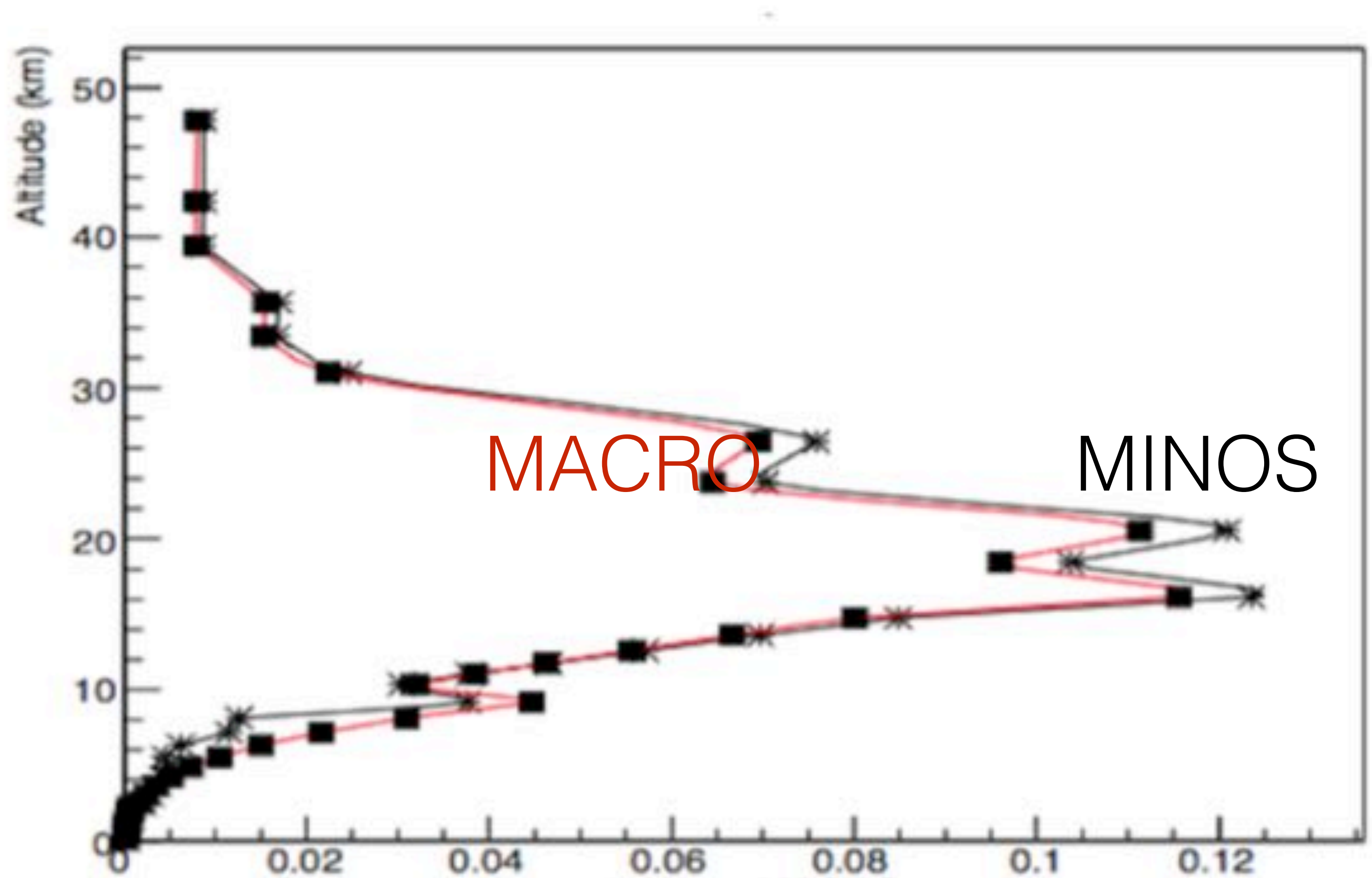
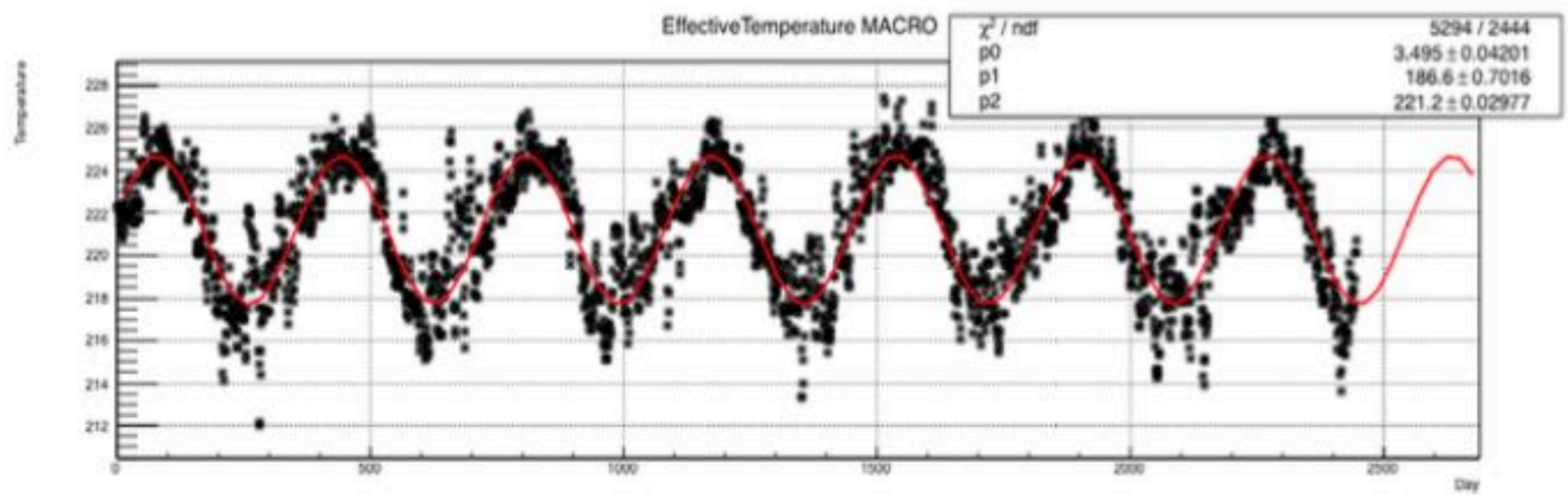


Figure 1: The normalized weights of Eq.4 used by MACRO (filled squares) and the weights used by MINOS (*) (see text)

Muon seasonal variation - T_{eff} first harmonic 1994-2000

Teff with the MACRO
peak at day 187
A=1.5%



Teff with the MINOS
peak at day 183
A=1.5%

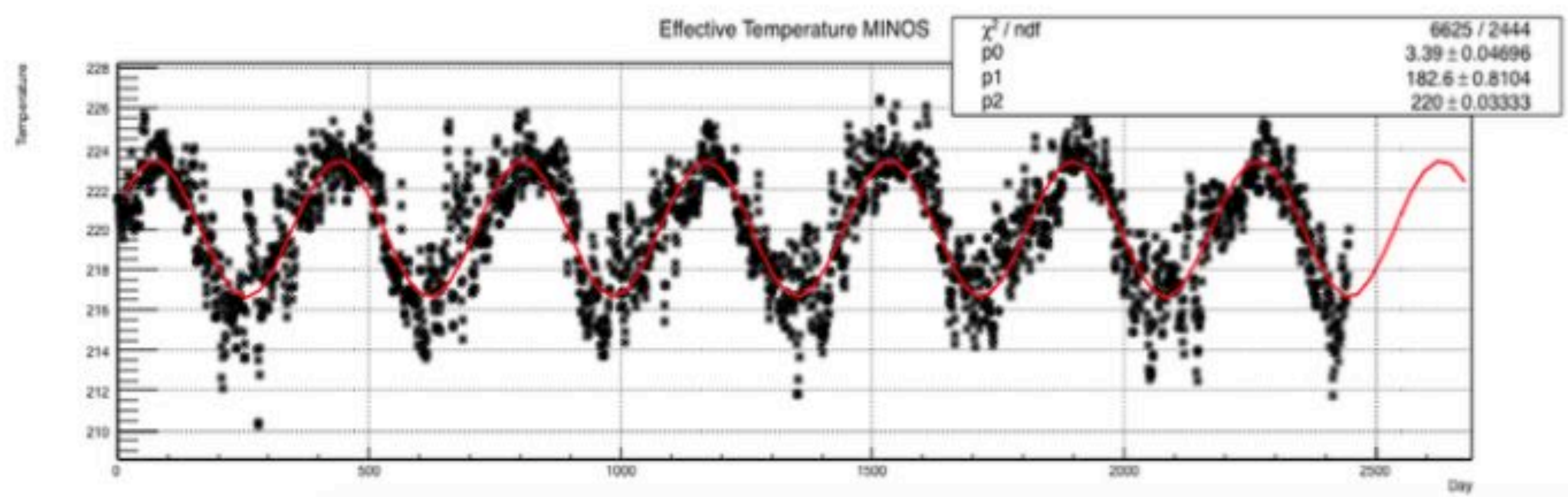


Figure 2: The daily effective temperatures computed using the MACRO and MINOS weights and the ECWMF temperature data. The origin is April 20 1994. The Fourier first harmonic is obtained with a fit as function of the day of the function $p2 + p0 * cos(2\pi(day + day_{start} + p1)/365.2)$, where day_{start}=110 (April 20). There is a difference of 4 days in the peak position between $T_{effMACRO}$ and the $T_{effMINOS}$.

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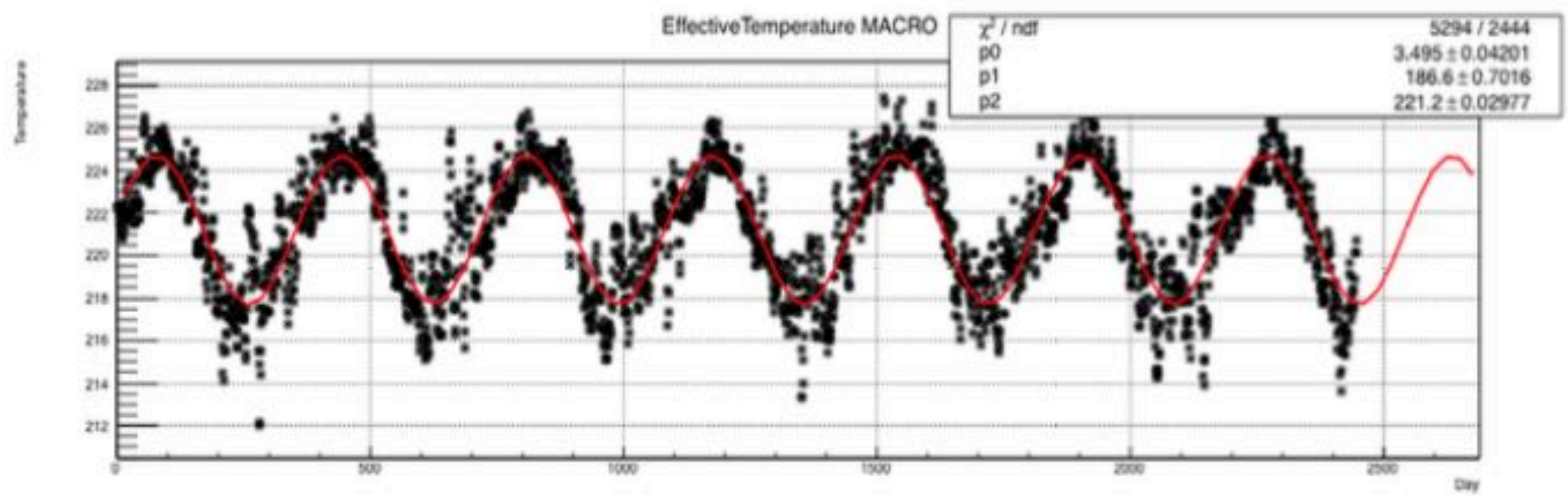

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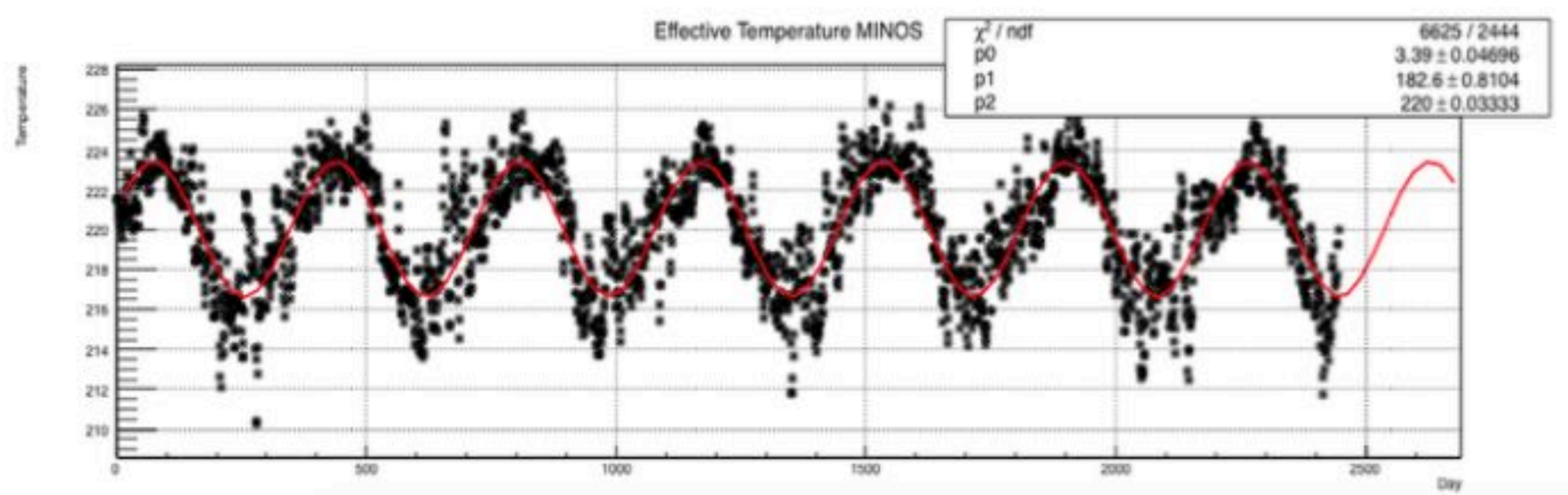

In the following slides I will use generally the MACRO weights

Figure 2: The daily effective temperatures computed using the MACRO and MINOS weights and the ECWMF temperature data. The origin is April 20 1994. The Fourier first harmonic is obtained with a fit as function of the day of the function $p2 + p0 * cos(2\pi(day + day_{start} + p1)/365.2)$, where day_{start}=110 (April 20). There is a difference of 4 days in the peak position between $T_{effMACRO}$ and the $T_{effMINOS}$.

Bari, Bologna, Boston, Caltech, Drexel, Indiana, Frascati, Gran Sasso , L'Aquila, Lecce, Michigan, Napoli, Pisa, Roma I, Texas, Torino

MACRO at GRAN SASSO

Monopole, Astrophysics, and Cosmic Ray Observatory

Bari, Bologna, Boston, Caltech, Drexel, Indiana, Frascati, Gran Sasso, L'Aquila, Lecce, Michigan, Napoli, Pisa, Roma I, Texas, Torino

MACRO = Monopole And Cosmic ray Observatory, **the largest area** experiment under Gran Sasso

USA-ITALY collaboration, spokesman B. Barish G. Giacomelli E.Iarocci

- data taking started in 1989 with 1/12 of the apparatus, with the **full apparatus started in 1994 end in December 2000**

M onopole , A strophysics , and C osmic R ay O bservatory

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The **only experiment able to confirm** the SuperKamiokande atmospheric neutrino oscillations in 1998 during the Takayama conference.

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arXiv:hep-ex/9807005 the same day of the S.K. archive preprint arXiv:hep-ex/9807003.

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arXiv:hep-ex/9807005 the same day of the S.K. archive preprint arXiv:hep-ex/9807003.

Presented here a reanalysis of 1994-2000 data, based on MACRO muon DST, I used for neutrino oscillations (and saved in 2000!)

Not a simple Job!: a geological time for computer and software!!

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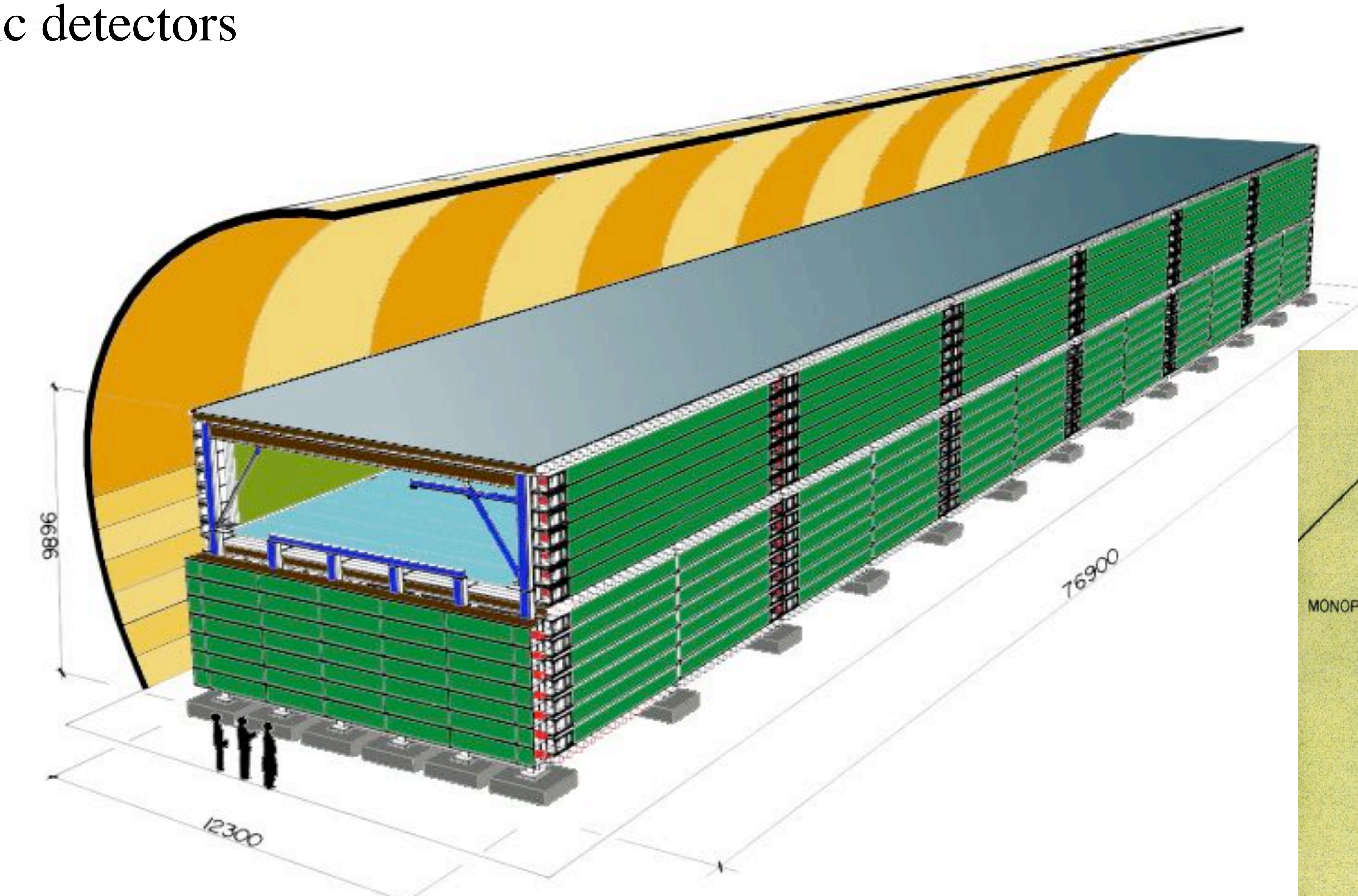
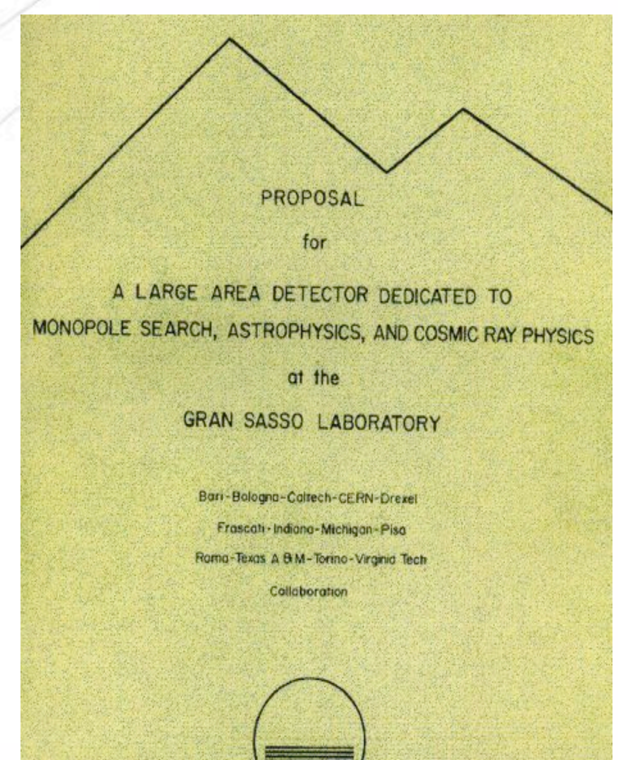
The MACRO detector in hall B of the Gran Sasso Laboratory - proposed in 1984

dimensions 76.9 x 12.3 x9.9 m^3

Detectors : liquid scintillator counters (in green), streamer tube chambers, CR39 plastic detectors




PROPOSAL

for

A LARGE AREA DETECTOR DEDICATED TO MONOPOLE SEARCH, ASTROPHYSICS, AND COSMIC RAY PHYSICS

at the

GRAN SASSO LABORATORY

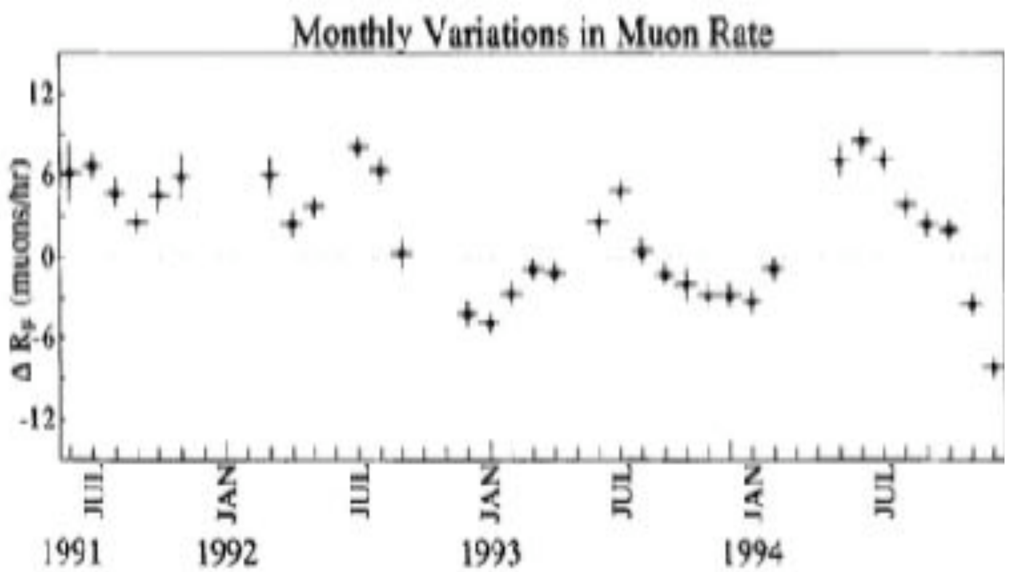
Bari-Bologna-Caltech-CERN-Drexel
Frascati-Indiana-Michigan-Pisa
Roma-Texas A&M-Torino-Virginia Tech
Collaboration

Single muons seasonal variations 1994-2000

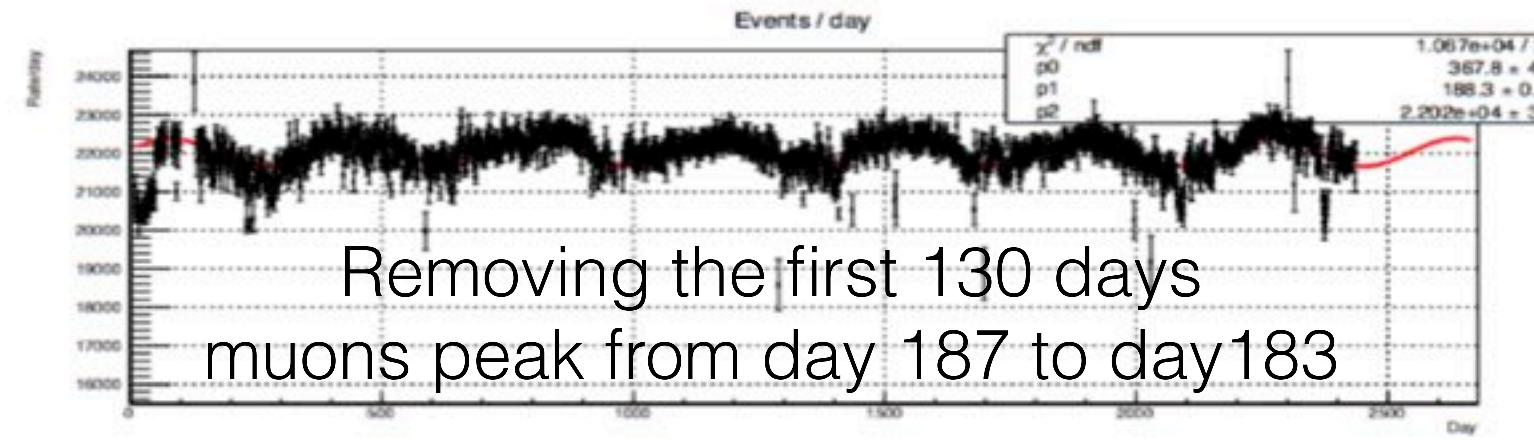
MACRO 1991 - 1994 published 1997

MACRO 1994 - 2000 (this analysis)

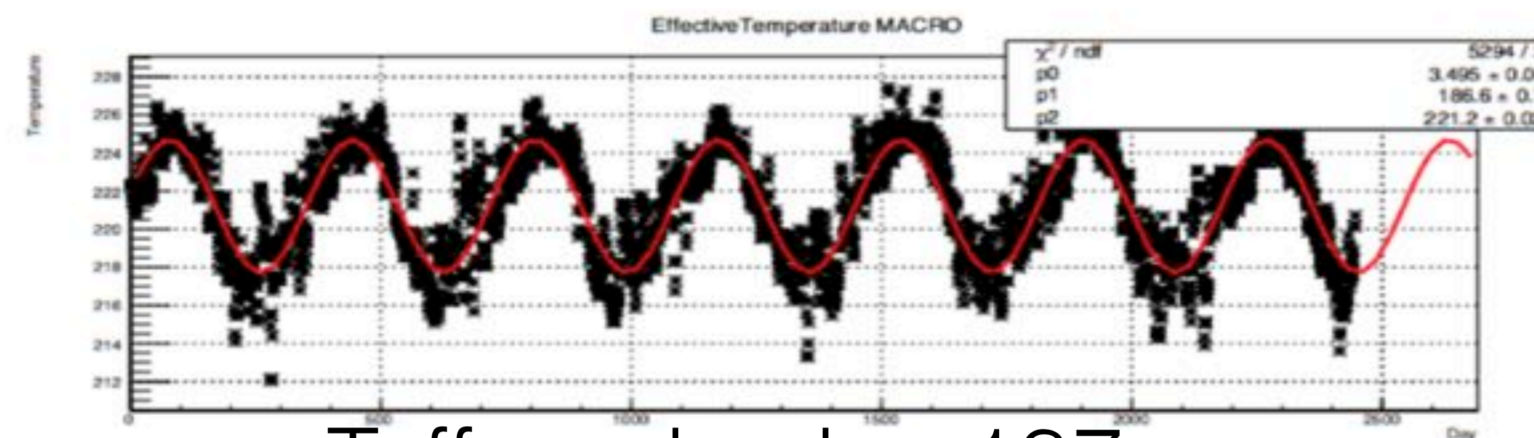
MACRO Collaboration/Astroparticle Physics 7 (1997) 109-124



. Monthly variations in the mean muon rate, $\Delta R_{\mu} = (R_{\mu} - \bar{R}_{\mu})$. R_{μ} is the mean monthly rate and $\bar{R}_{\mu}$ = 364.8 m
omputed for the December 1992–1994 data set. The errors are dominated by statistical errors in the rates.



Removing the first 130 days
muons peak from day 187 to day183



Teff peak=day 187

Figure 6: Events per day of events with one track (excluding multi-muon). The first day is April 20 1994, date for which the data are available. The last day is December 31 2000. The red line is a sinusoidal fit. The peak is at the day 187 of the year (July 6 in in normal years). The MACRO effective temperature is peaked at the same day 187. The MINOS effective temperature is peaked at day 183. Even if the results is quite good the figures shows some anomaly in the days of data taking. Therefore In the following results the first 130 days have been removed. The Fourier first harmonic is obtained with a fit with the function $p2+p0*cos(2\pi(day+p1)/365.2)$, with the period fixed to 1 year and day_{start}=110 (April 20). Short time variations of the rate correlated to short time temperature variations are evident

Single muons day by day correlation with T_{eff}

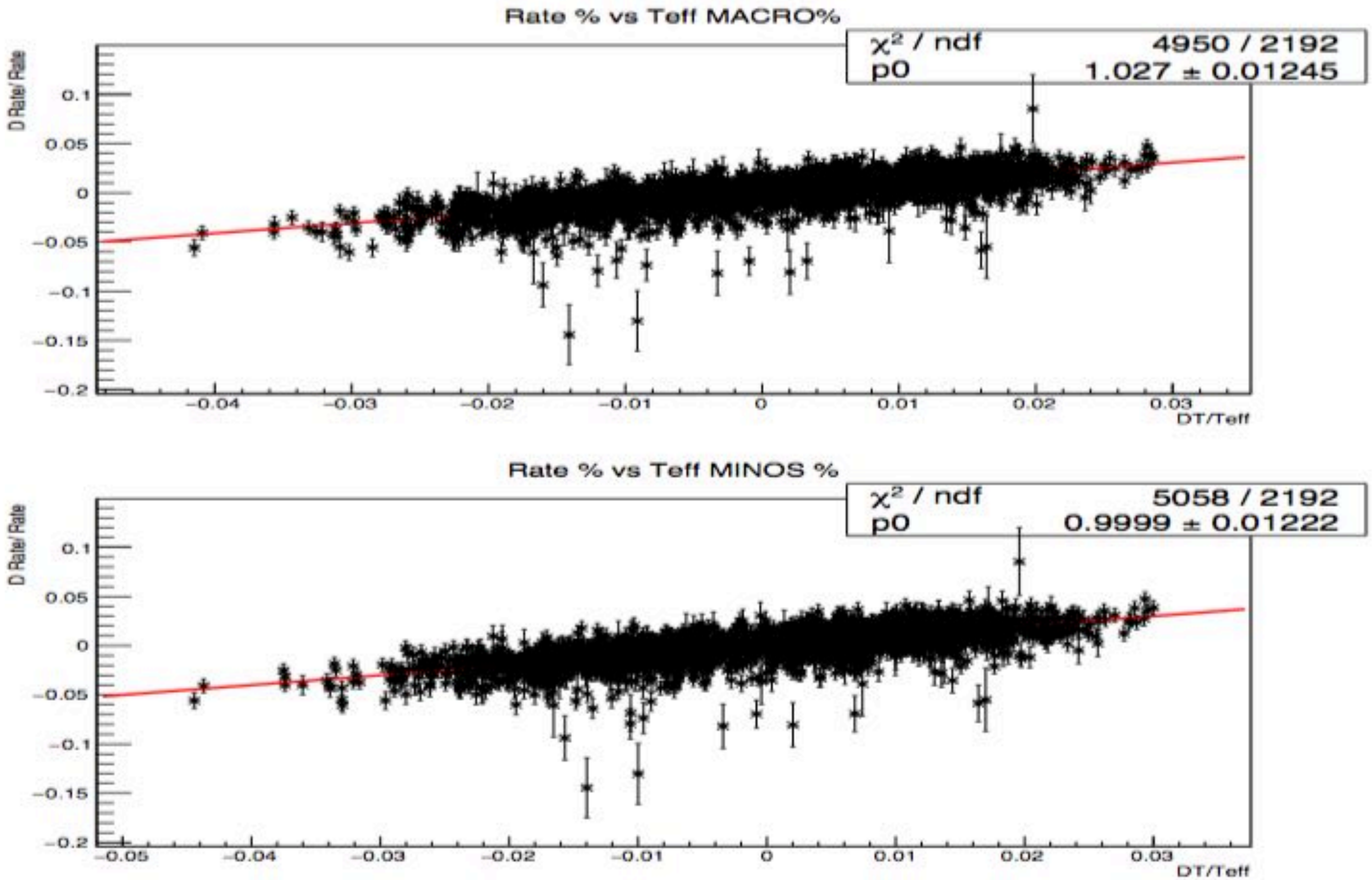


Figure 8: Daily deviation of the rate respect to the average value as function of the deviation of the effective Temperature Teff. A strong correlation is seen.

Single muons correlation with T_{eff} (α_T)

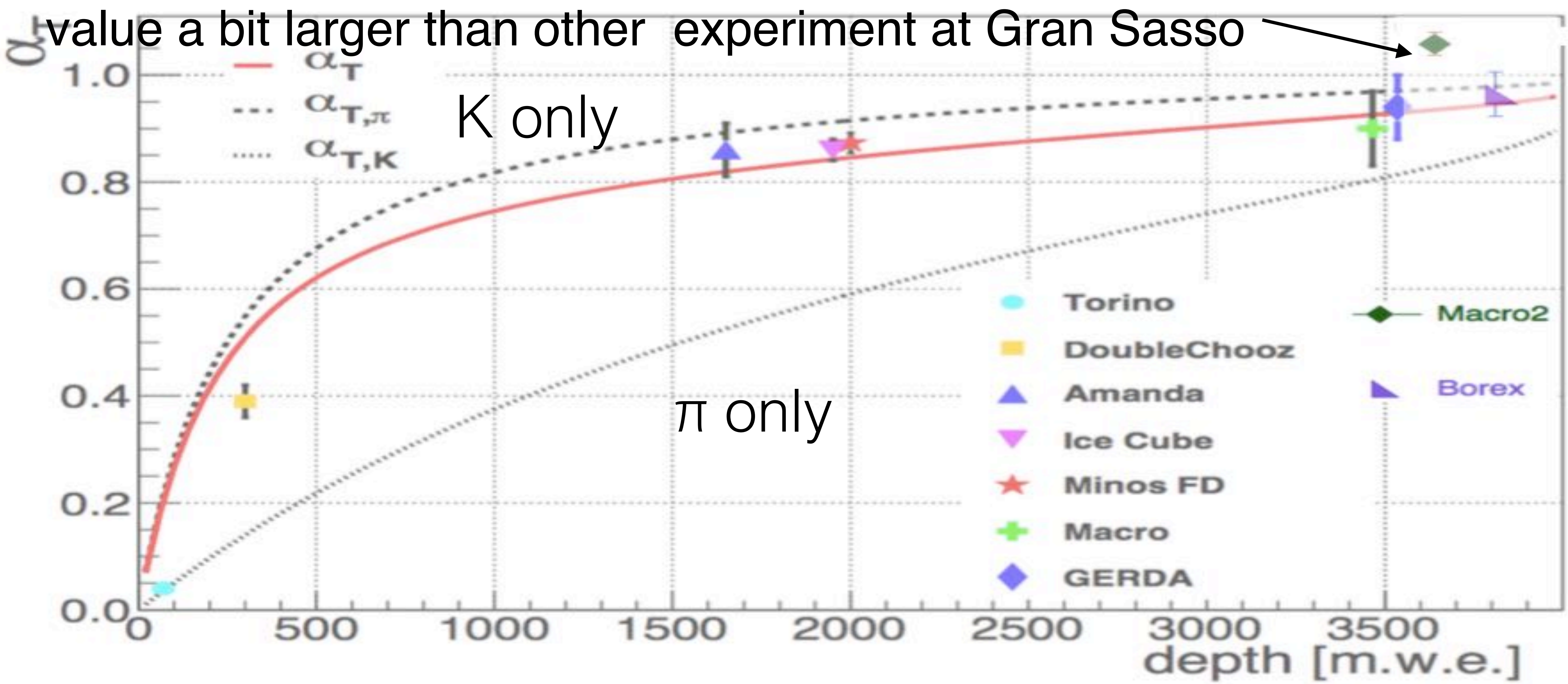


Figure 16: Modified from [5].Correlation coefficient α_T as a function of depth. Experiments with different m.w.e. of rock overburden are listed. Added respect to the original pictures the MACRO2 point (this work) and the Borex value. The curves show muon generation models based on either purely pionic (dashed) or only kaonic (dotted) processes[14]. The full red line notes the literature value for the atmospheric kaon/pion ratio[15]. It it's important to note that the calculations are semii-analitycal and not full-Montecarlo

Single muons seasonal variation in Gran Sasso

experiment	LVD[8]	MACRO[4]	Macro this work	Borexino[9]	Gerda
site	LNGS-A	LNGS-B	LNGS-B	LNGS-C	LNGS-A
cicles [yr]	8	7	7	4	2.5
years	2001-08	1991-97	1994-2000	2007-11	2010-13
period [d]	367 ± 15	-	366±1	375.6 ± 5	366 ± 3
phase [d]	185 ± 15	–	183±1	179 ± 6	191 ± 4
temp. data	Aer.Mil.	Aer.Mil.	ECWMF	ECWMF	ECWMF
α_T	–	0.83 ± 0.13	1.02±0.02	0.93 ± 0.04	0.97 ± 0.05

Table modified from:

Flux Modulations seen by the Muon Veto of the GERDA Experiment
GERDA Collaboration (M. Agostini (Munich, Tech. U.) et al.). Jan 22, 2016. 7 pp. e-Print: arXiv:1601.06007

Multiple muons : MINOS results

The Far Detector

Detector Dimensions : 8mx8mx30m
Detector Mass 5.4 kTon
Location: Soudan, MN
~ 735 km from Fermilab

NearDet 0.98 kTon 225 mwe

OverBurden	~2100mwe(0.72km)
Cosmic Muon Rate	0.5 Hz
Minimum Energy	~ 730 GeV
Average Muon Energy	~ TeV range

Two identical detectors and two depths, we can probe the same physics process at two different energy scales !!

Gran Sasso Eμ>1.3 TeV

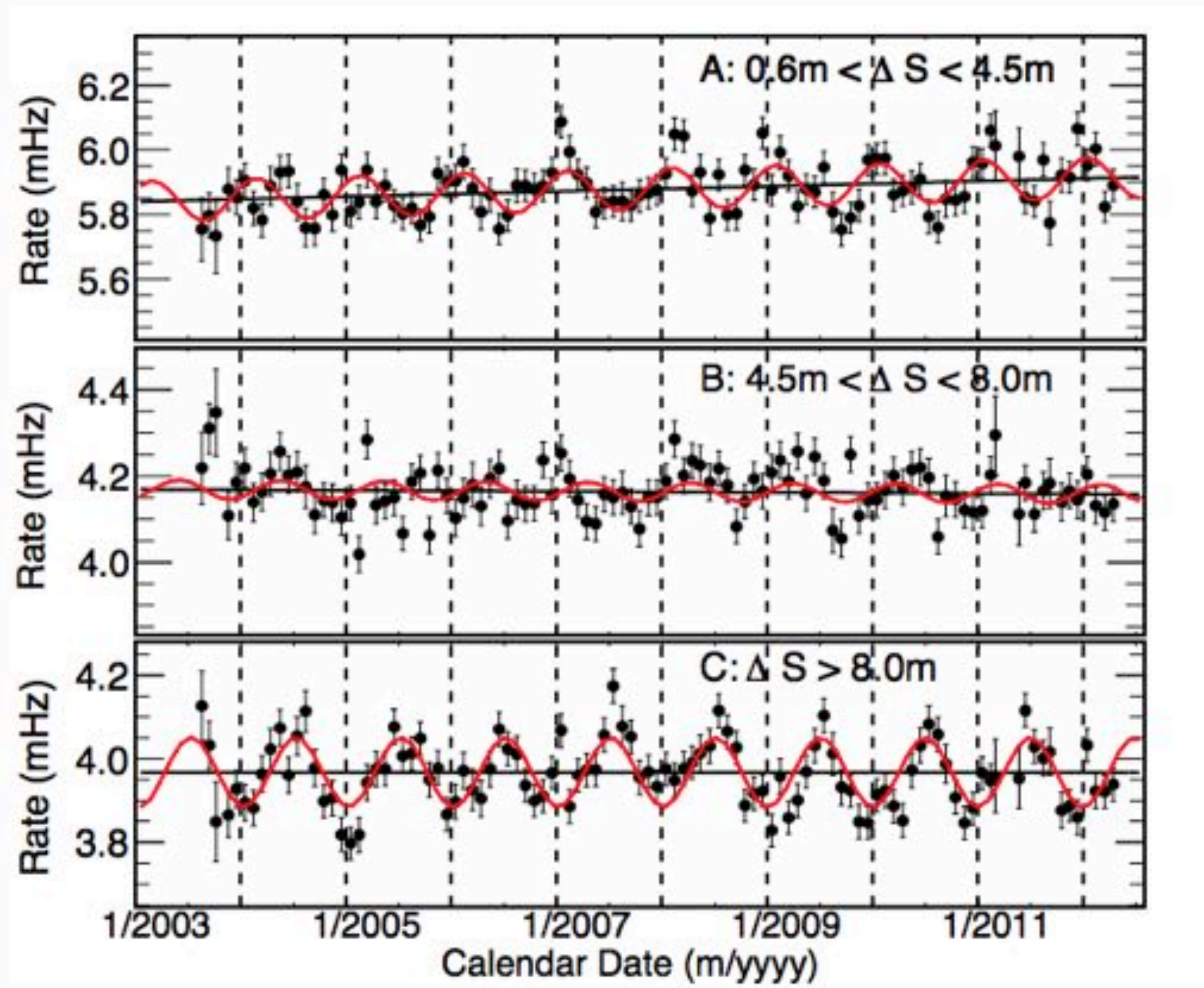
Multiple muons: MINOS FD results as function of ΔS

ΔS=minimum muon distance

A=1%, peak=day 28

A=0.5%,peak=day 79

A=2%, peak=day 185



Single muons A~1.3% peak=day 183

In the ND detector
A~2.5% peak ~ day 22-26

FIG. 4: The multiple-muon rate in the FD as a function of time for different track separations. Each data point corresponds to one calendar month of data. The solid red lines are the best fit to Eq. 2. The top graph is for the smallest track separation, the middle graph for mid-range and the bottom graph for the largest. The vertical lines are year boundaries and the solid horizontal line represents the fit without the cosine term.

Multiple muons: MINOS FD results

Overlapping years

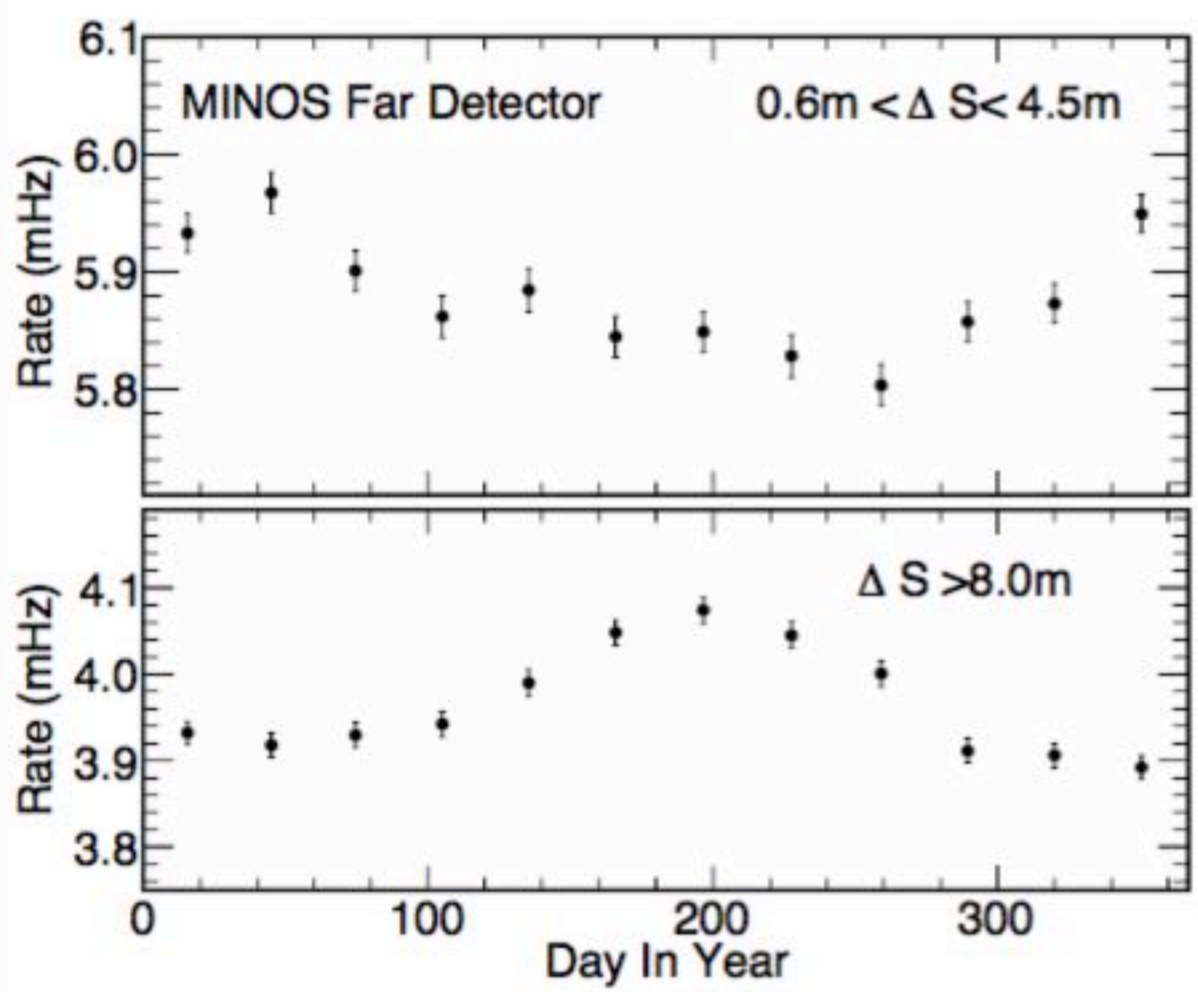


FIG. 5: The multiple-muon rate in the FD for events with ΔS range A from 0.6 m to 4.5 m (top graph) and for events with ΔS range C larger than 8 m (bottom) binned according to calendar month. The top figure shows a winter maximum. The bottom figure shows a summer maximum.

Multiple Muons peak in winter possible effects examined by MINOS

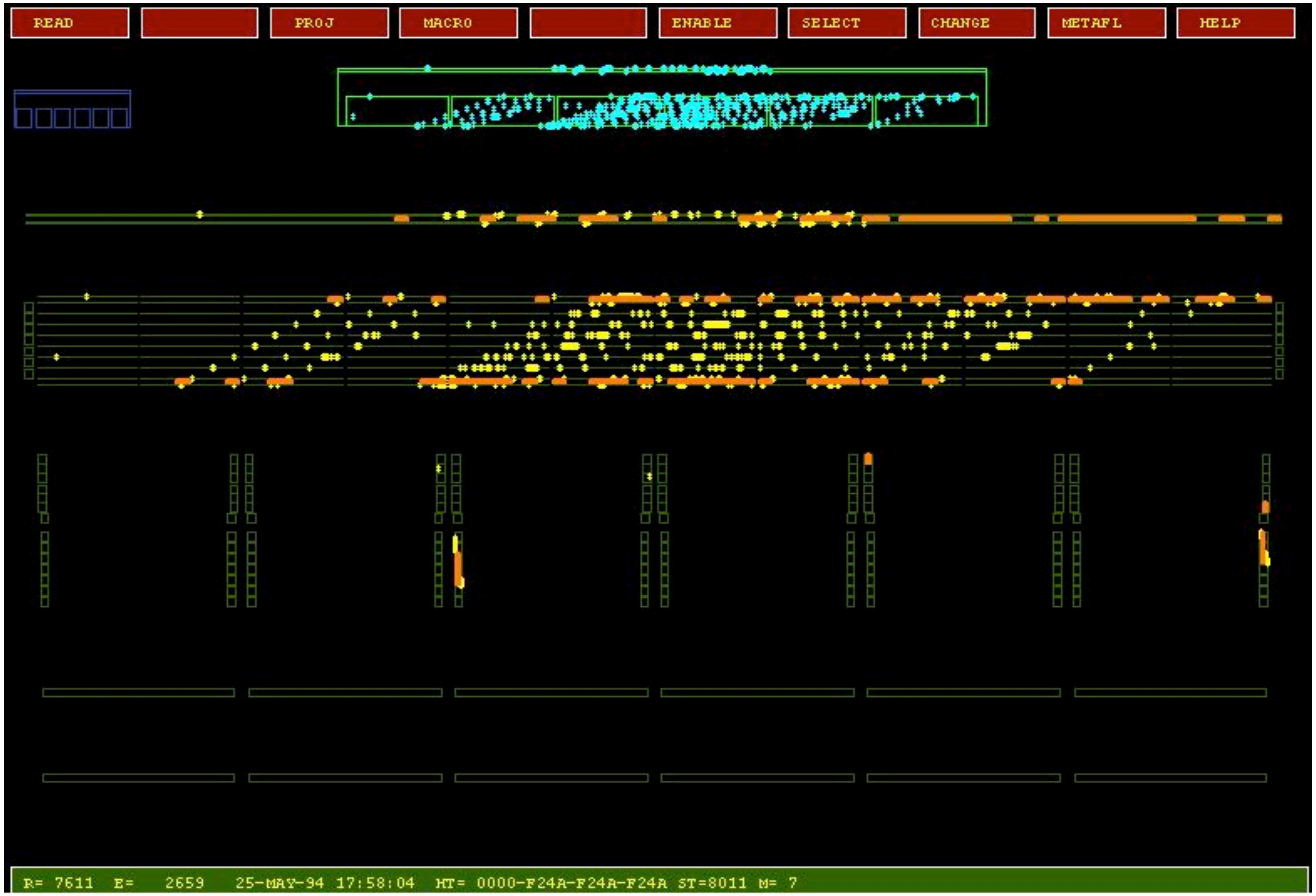
1)**hadronic dimuons** decay (ρ , η) produced by π .
ρ , η branching ratio in two muon very small ==> less than $6*10^{-6}$ effect

2) **geometrical effect** : if dimuons are produced higher in the atmosphere, the distance increases and there are fewer events in the short distance region : possible a 4% effect in the distance separation; but no track separation effect seen in the Near Detector

3) **temperature effect of layers around 13 Km** (maximum T in the winter). Studied with a montecarlo simulation and the temperature dependence of the the different atmospheric layers: multi-muons rate maximum always in the summer

4) **anticorrelations of primary and secondary decays**: multiple muons comes from higher energy primaries with further interactions deeper in the atmosphere, **slightly favored by MINOS particularly for the Near Detector data**

Gran Sasso: Multiple muons in MACRO (E>50 TeV)



Multiple muons: MACRO

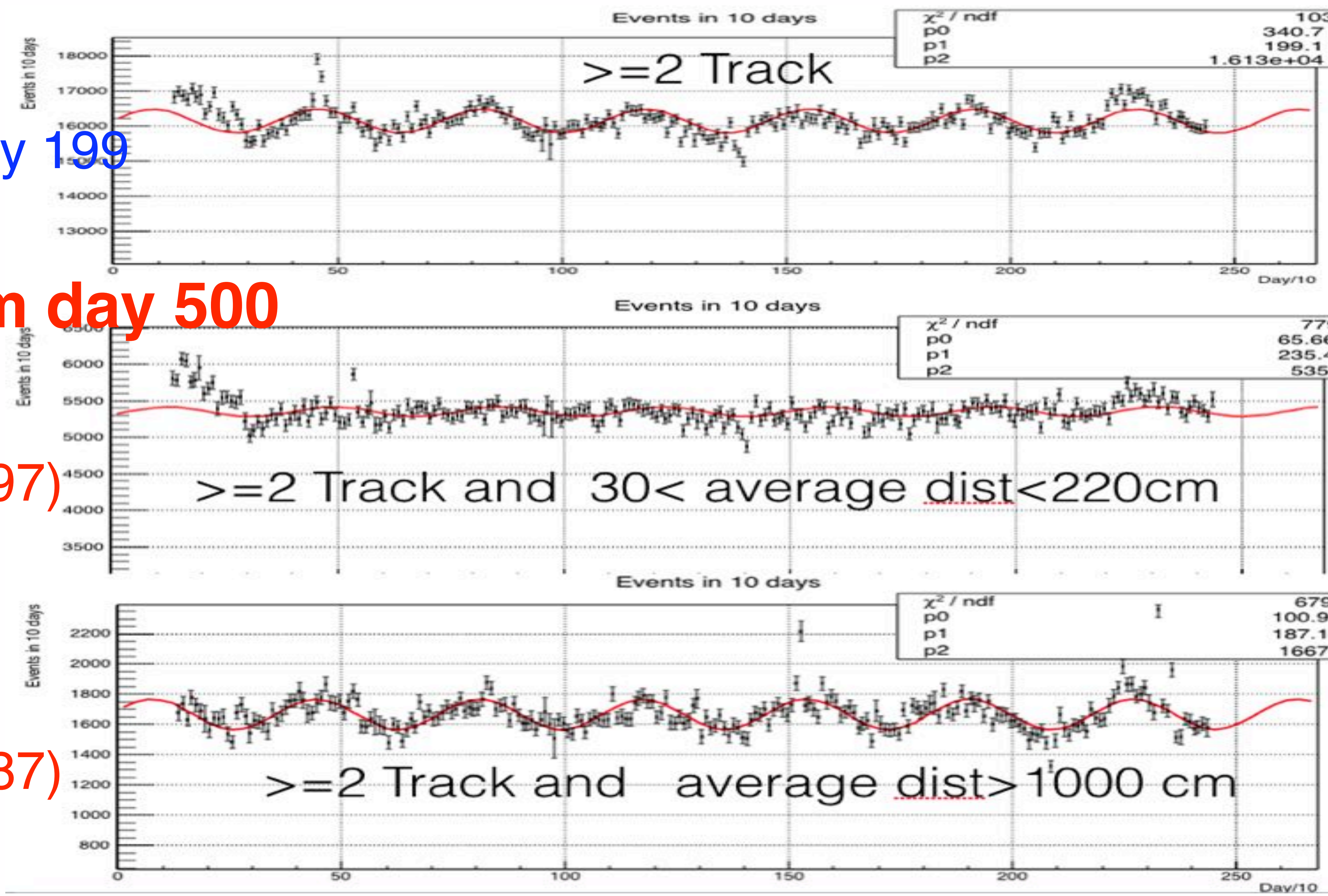
- No data quality selection, cuts only on single muon rate to avoid runs with only a fraction of apparatus (6 super-module almost independent)
- Multiple -muons sensitive to ghost tracks due to the streamer tube noise

A=2.1%, peak=day 199 (188)

in red fits from day 500

A=1.2%, peak=day 235 (197)

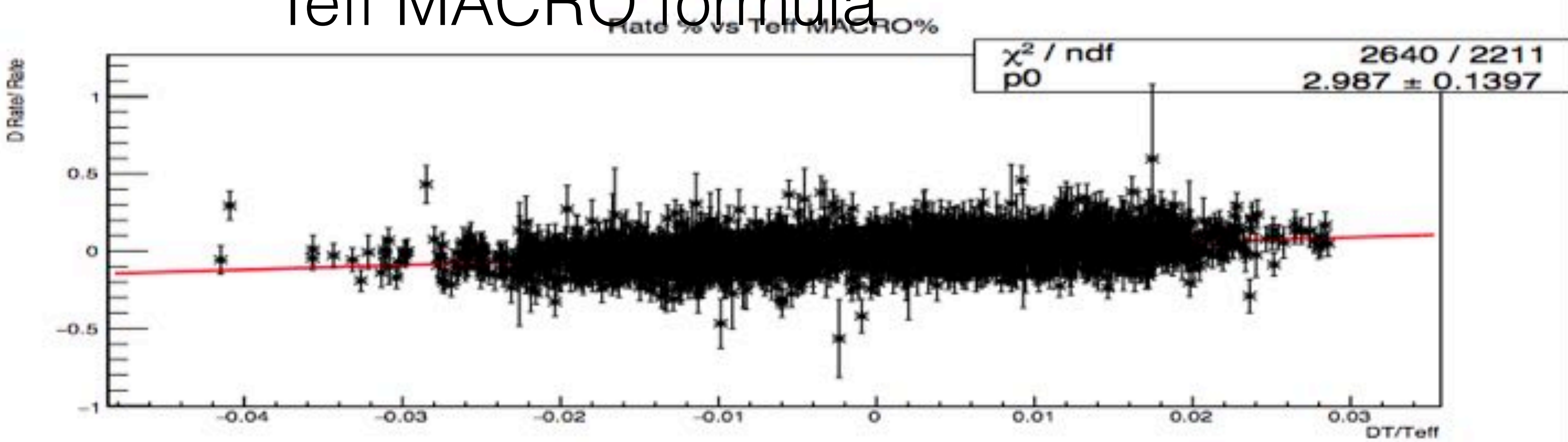
A=6%, peak=day 187 (187)

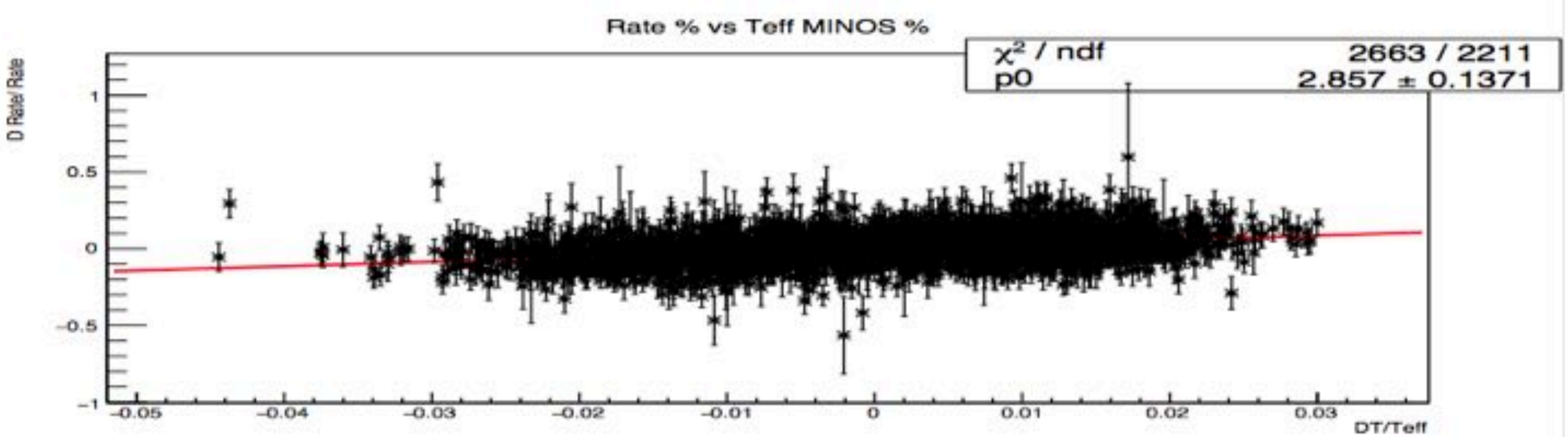


Multiple muons in MACRO: correlation

Daily deviation of the rate of multi muon events, having average distance **bigger than 10 m,** respect to the average value as function of the deviation of the effective Temperature Teff. If multiple_muons produced as "single muons" we expect roughly $\alpha_{T\ \text{multi muons}} \sim N\mu * \alpha_{T\ \text{single}}$

Teff MACRO formula



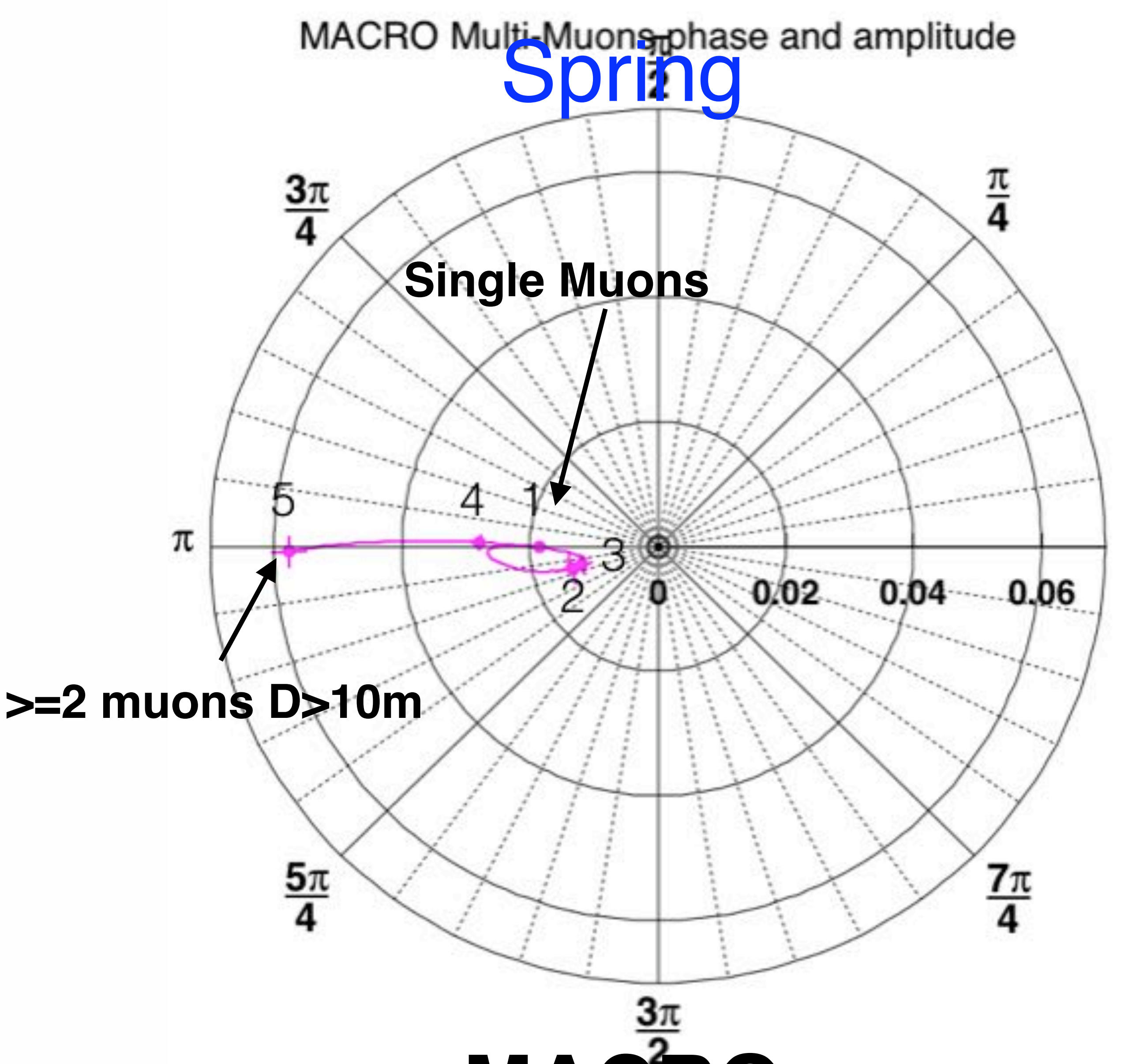


α_T multiple muons depends from distance D>10m $\alpha_T \sim 3$.

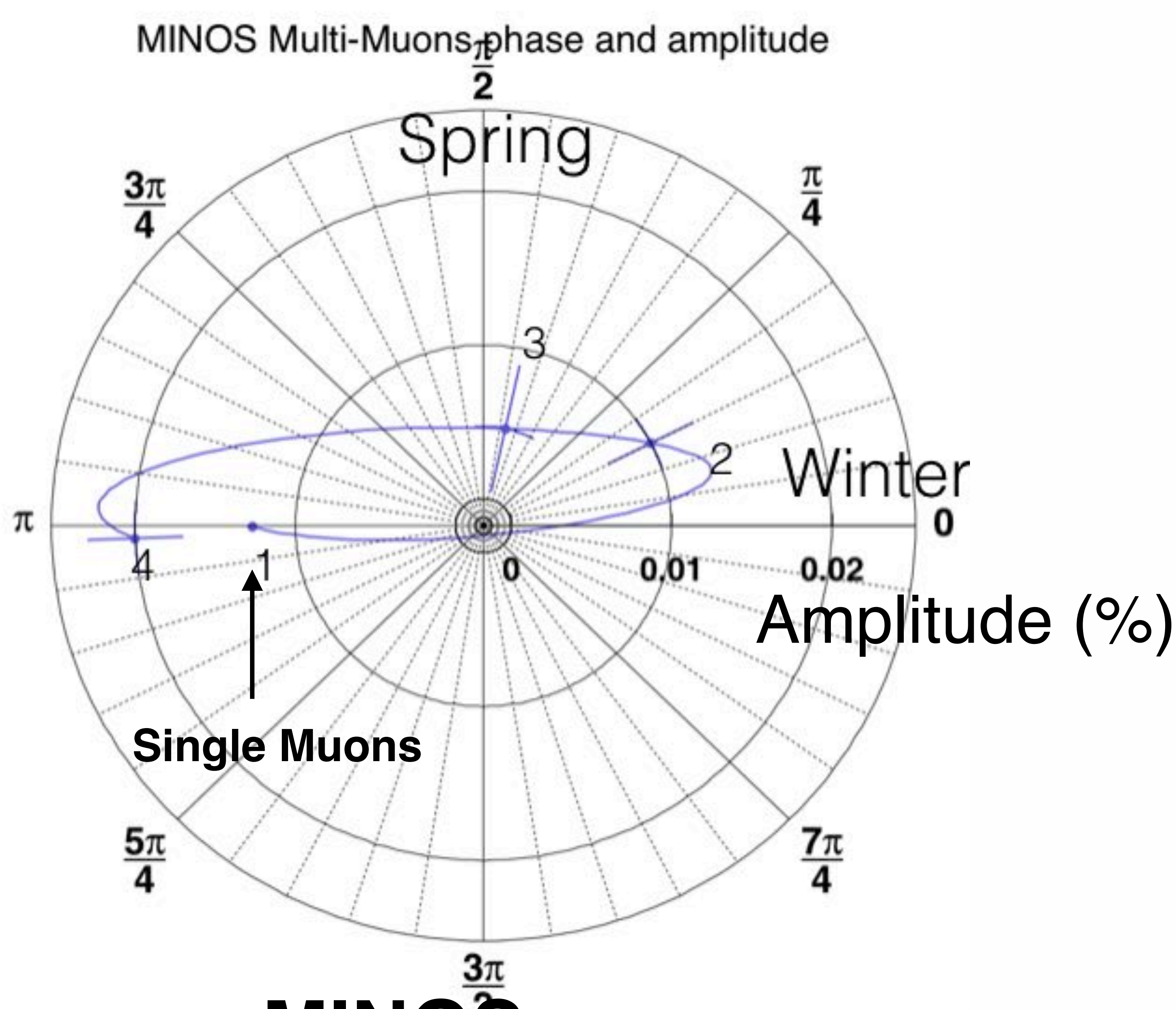
$\alpha_{T\ \text{single muons}} \sim 1.03$

Multiple Muons in polar coordinates

- Comparison in polar coordinate with increasing distance between muons
- MACRO-MINOS common features : **decrease of the amplitude** for smal distances and increase for large distance (MACRO 2=5-30cm 3=30-220,4=220-1000cm)
- Different features : **the peak at low distances**



MACRO

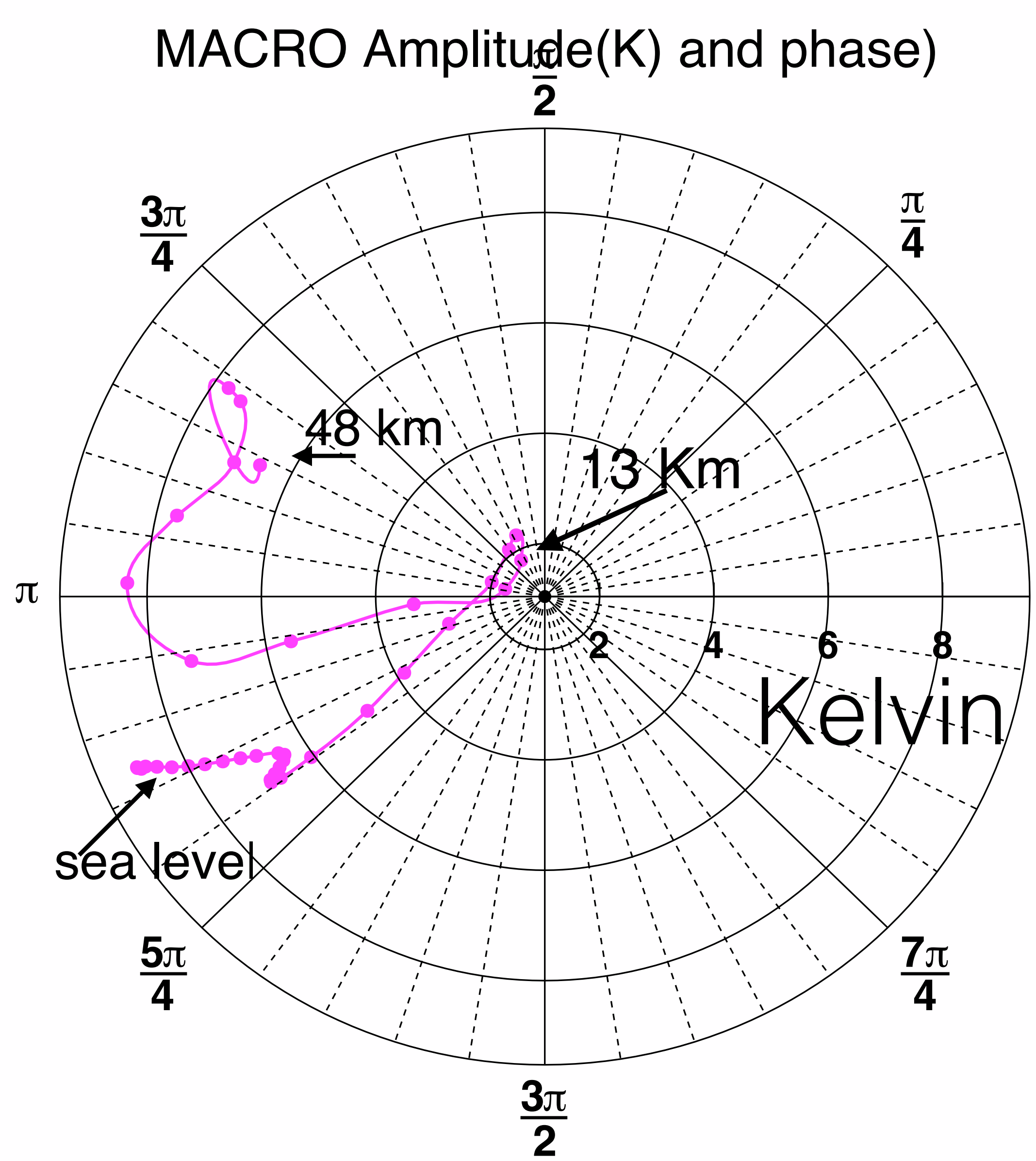


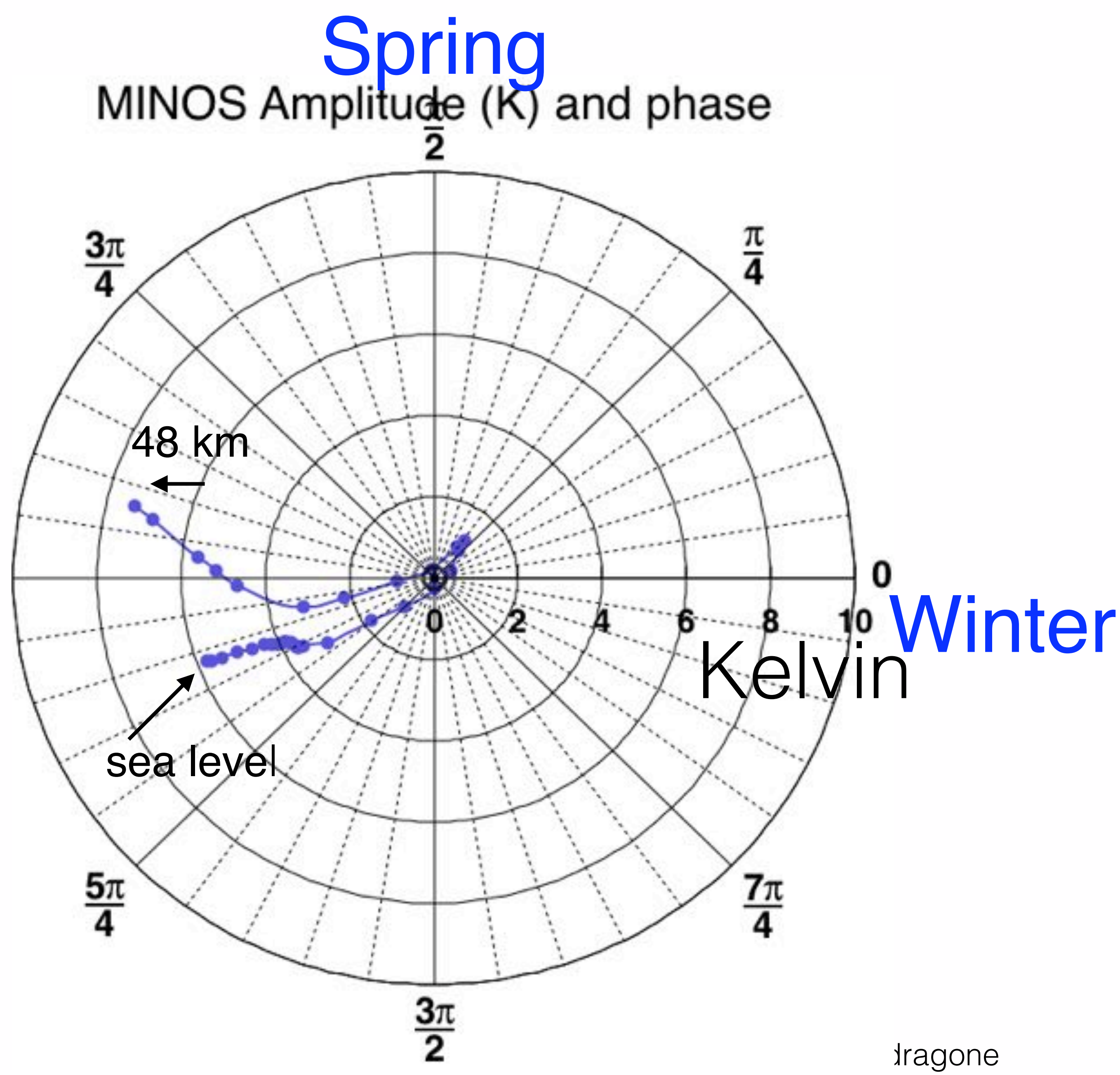
MINOS

Gran Sasso - Soudan: atmospheric temperature oscillations

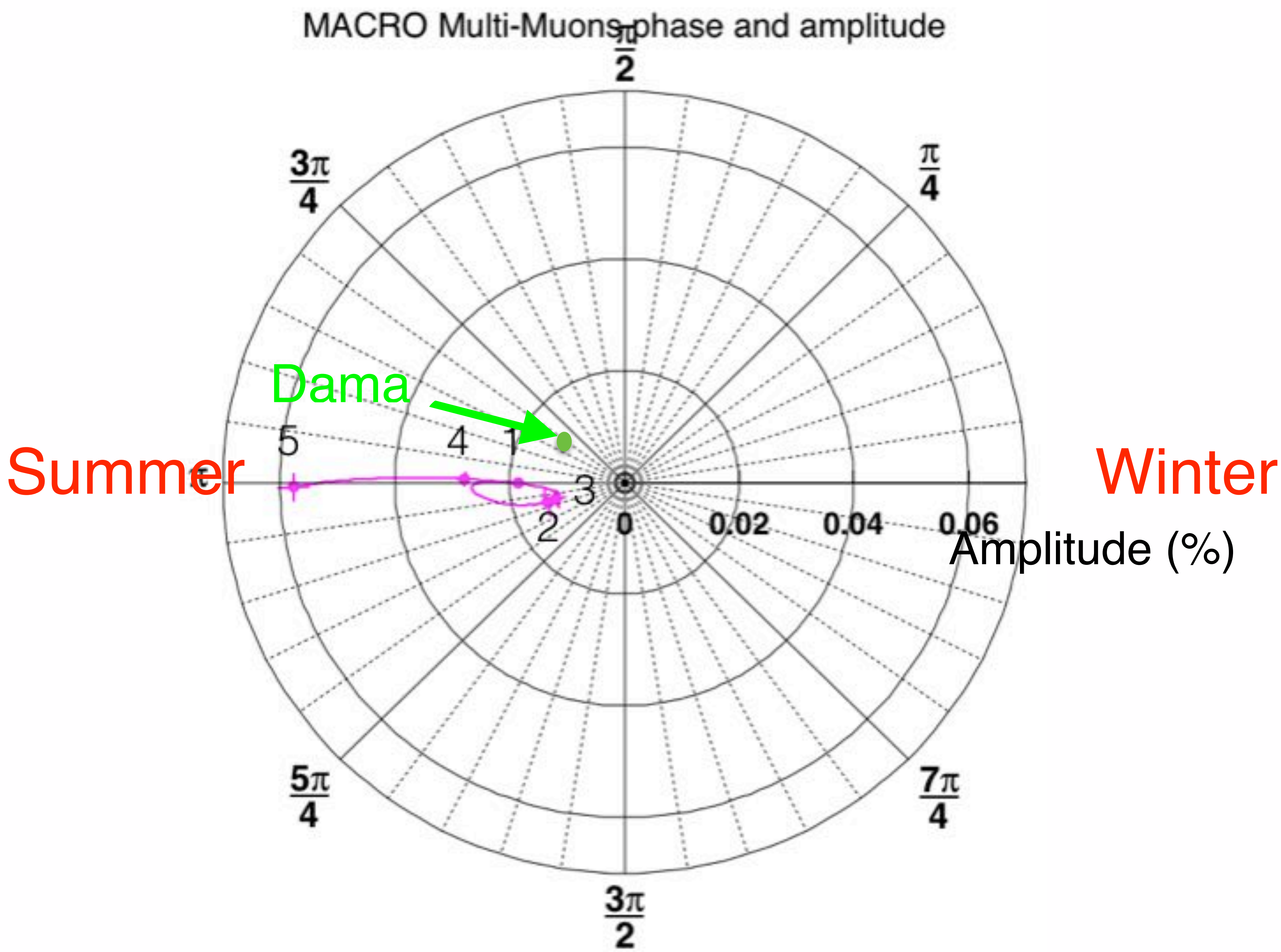
• Plot of the first harmonic of the temperature in the 37 atmospheric layers(average of years 1994-2000):

• In MINOS at ~ 13 Km (jet stream region) **the temperature peak is in winter**





Comparing apple and oranges at Gran Sasso (Single and Multi-muons and DAMA….)



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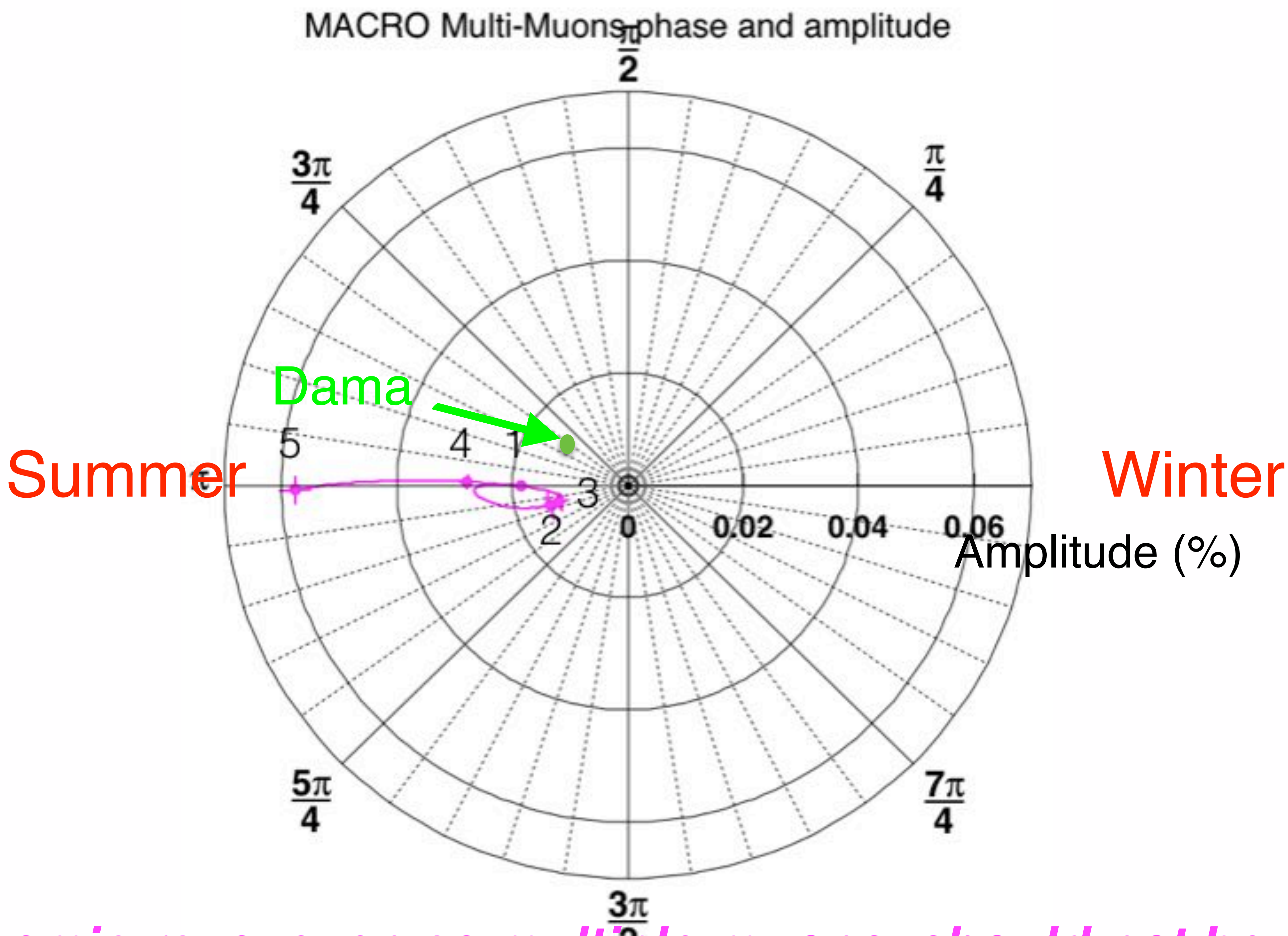

Cosmic rays, even as multiple muons, should not be a background or produce a background (neutrons..) compatible with the phase of dark matter at Gran Sasso.

Summary and Conclusions

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1) In MACRO and in MINOS the multi-muons have seasonal effects **different from single muons**

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2) **At very large distances** between muons the day of the peak of the rate in MACRO and MINOS is the same than the single muons but the amplitude is much larger.
3) **At short distances** between muons the peak of rate in MACRO is at day ~200 and MINOS is ~28. Perhaps this difference is connected to the different depths ($E_\mu > 1.3$ and 0.7 TeV) and to the temperature at 13 Km. 13 Km is the region of the strong jet streams that depends from latitudes. *Gran Sasso (Lat 42.4^0) and SOUDAN (Lat 47.9^0)*

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3) **At short distances** between muons the peak of rate in MACRO is at day ~200 and MINOS is ~28. Perhaps this difference is connected to the different depths (E_{μ} > 1.3 and 0.7 TeV) and to the temperature at 13 Km. 13 Km is the region of the strong jet streams that depends from latitudes. *Gran Sasso (Lat 42.4^0) and SOUDAN (Lat 47.9$^{0)}$*
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5) In the Gran Sasso laboratory **the peak of muons is always far from the signal expected for dark matter (day 152.5)**

SPARES

MACRO

F Ronga - Munich May 7 2002

Barometric coefficient (Sagisaka 1986

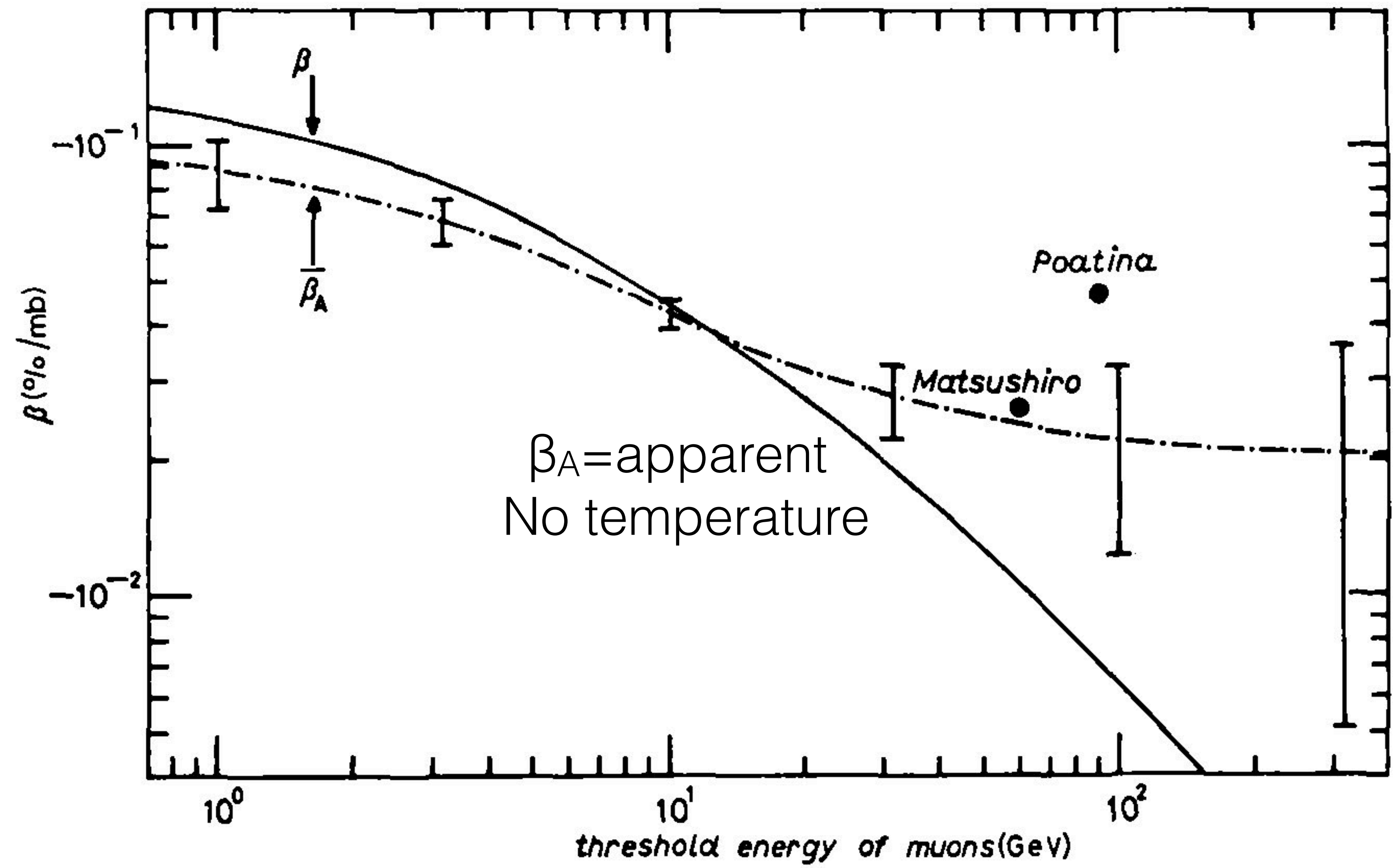


Fig. 7. – Real barometer coefficient β, averaged apparent barometer coefficient $\bar{\beta}_A$ at Wajima with its standard deviations, and observed coefficients at Matsushiro (5) and Poatina (3). Both β and $\bar{\beta}_A$ are the values for $\theta = 0°$ at sea-level, and $\bar{\beta}_A$ has been calculated in the period July 1981 - June 1982 during which the observed values at Matsushiro have been obtained.

MINOS atmospheric data

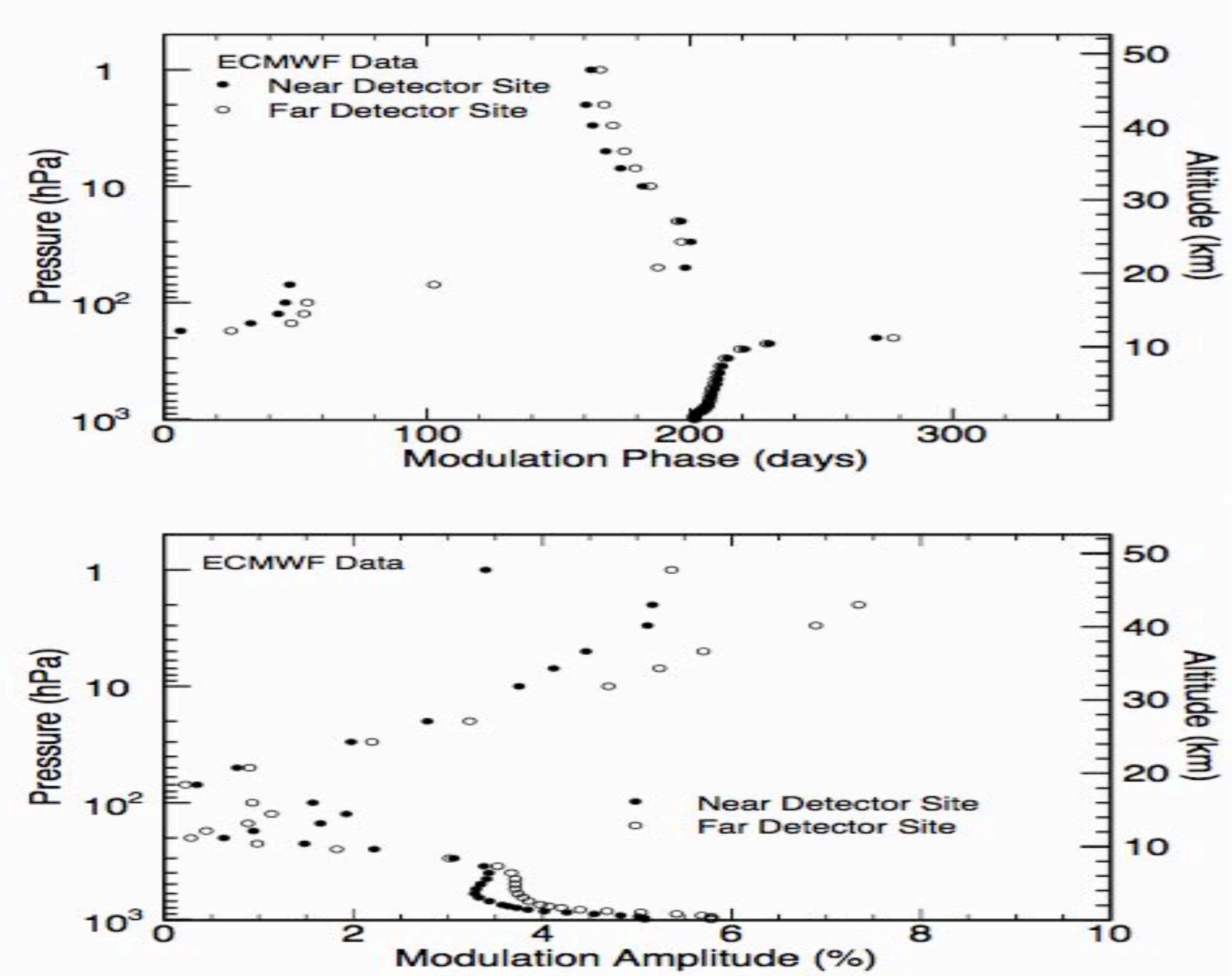


FIG. 9: The (top) modulation phase and (bottom) amplitude in the ECMWF temperature data based on a cosine fit are shown as a function of altitude and detector site. These distributions were used to study both the geometry effect (B) and the temperature effect (C).

LVD muons and neutrons

Start= Jan 2001

A=1.5%
peak=185±15

A=14%
peak=185±18

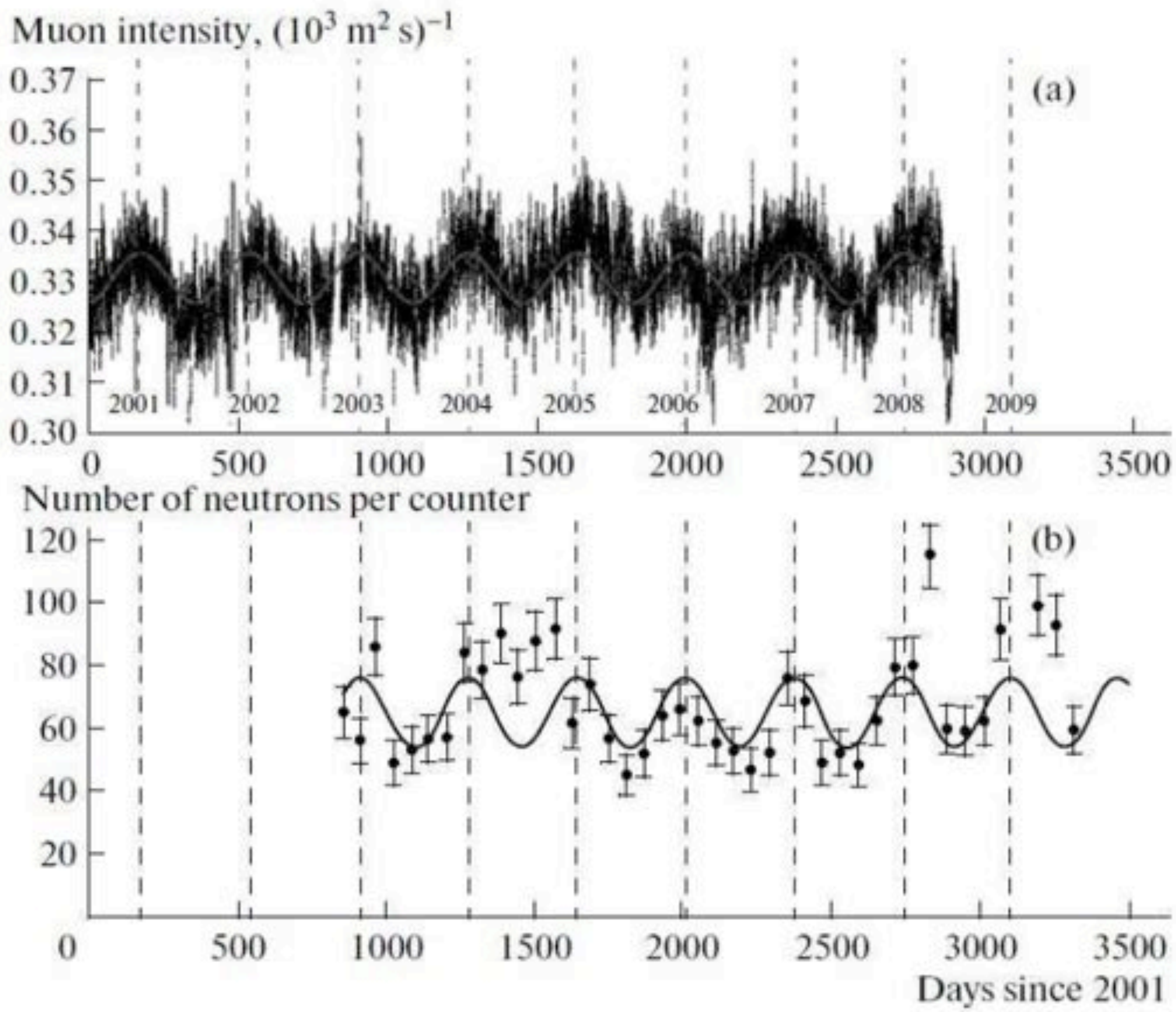


Figure 1: (a) Muon intensity variations per day over 8 years of LVD operation. (b) The number of neutrons from muons per counter; each point represents the data obtained over two months of LVD operation.

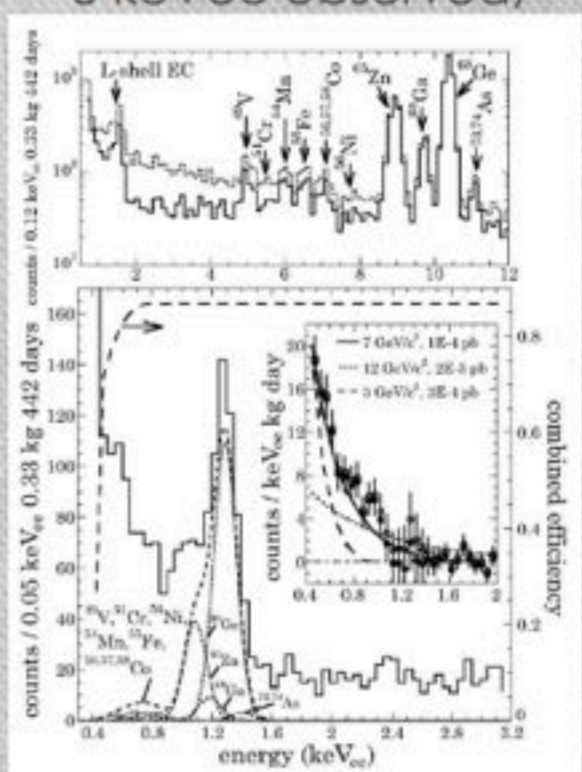
Problems for COGENT at SOUDAN?

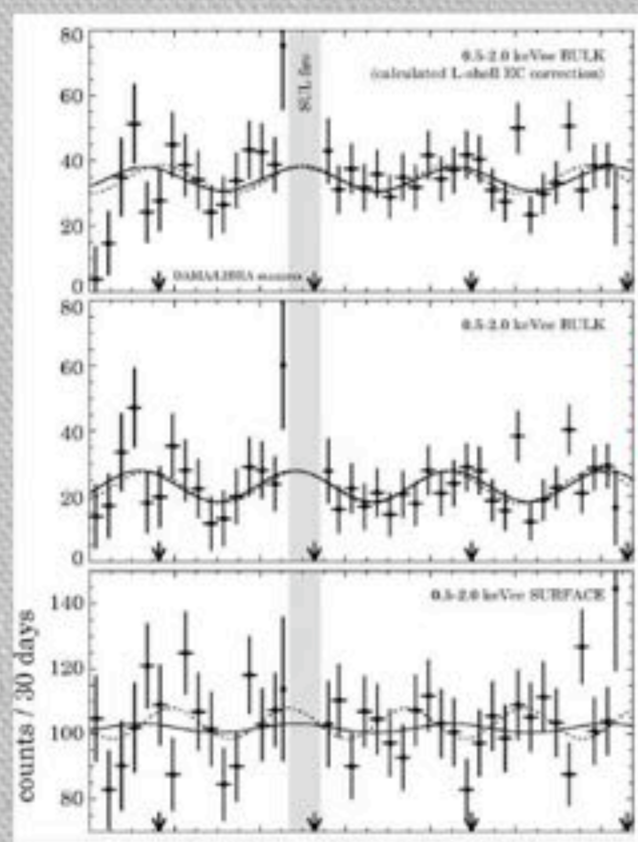
Positive hints from CoGeNT (ionization detector)

arXiv:1401.3295

Experimental site: Soudan Underground Lab (2100 mwe)
Detector: 440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure: 146 kg x day (dec '09 - mar '11)

- ✓ Irreducible excess of bulk-like events below 3 keVee observed;
- ✓ annual modulation of the rate in 0.5-4.5 keVee at ~2.2σ C.L.





format. A straightforward analysis indicates a persistent annual modulation exclusively at low energy and for bulk events. Best-fit phase consistent with DAMA/LIBRA (small offset may be meaningful). Similar best-fit parameters to 15 mo dataset, but with much better bulk/surface separation (~90% SA for~90% BR)

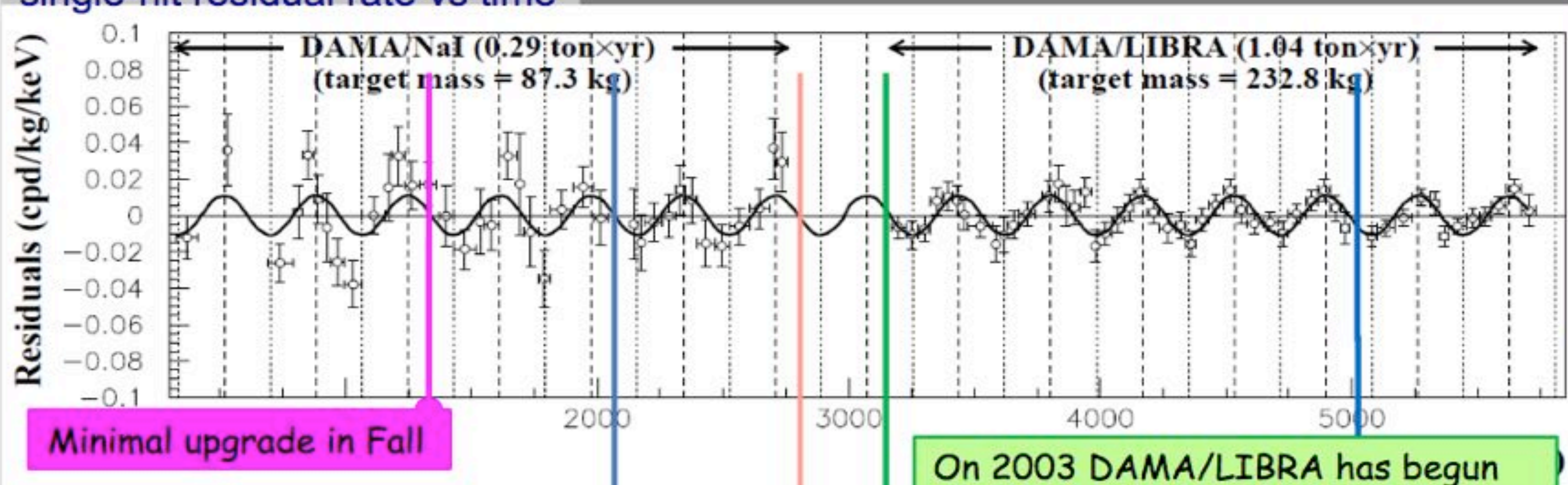
Unoptimized frequentist analysis yields ~2.2σ preference over null hypothesis. This however does not take into account the possible relevance of the modulation amplitude found...

- 6 years of data at hand.
- CoGeNT upgrade: C-4 is coming up very soon
- C-4 aims at x4 total mass increase, bckg decrease, and substantial threshold reduction. Soudan is still the lab

DAMA at LNGS

DAMA/NaI & DAMA/LIBRA main upgrades and improvements

single-hit residual rate vs time



PHASE2

On 2003 DAMA/LIBRA has begun first operations (one TD channel for each PMT; two for each detector)

July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector): (i) TD VXI Tektronix; (ii) Digital Unix DAQ system; (iii) GPIB-CAMAC.

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:
(i) one detector has been recovered by replacing a broken PMT
(ii) new optimization of some PMTs and HVs performed
(iii) All TD replaced with new ones
(iv) new DAQ with optical read-out installed

July 2002 DAMA/NaI data taking completed

The second DAMA/LIBRA upgrade in Fall 2010: replacement of all the PMTs with higher Q.E. ones
(+ new preamplifiers in fall 2012 & other developments in progress)

DAMA/LIBRA-phase2 *in data taking*

DAMA at LNGS

Final model independent result
DAMA/NaI+DAMA/LIBRA-phase1

Presence of modulation over 14 annual cycles at 9.3σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 14 independent experiments of 1 year each one

The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.33 ton × yr (14 annual cycles)

In fact, as required by the DM annual modulation signature:

1) The *single-hit* events show a clear cosine-like modulation, as expected for the DM signal

2) Measured period is equal to (0.998±0.002) yr, well compatible with the 1 yr period, as expected for the DM signal

3) Measured phase (144±7) days is well compatible with the roughly about 152.5 days as expected for the DM signal

4) The modulation is present only in the low energy (2—6) keV energy interval and not in other higher energy regions, consistently with expectation for the DM signal

5) The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal

6) The measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2-6) keV energy interval is: (0.0112 ± 0.0012) cpd/kg/keV (9.3σ C.L.).

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

Decor (Moscow) sea level

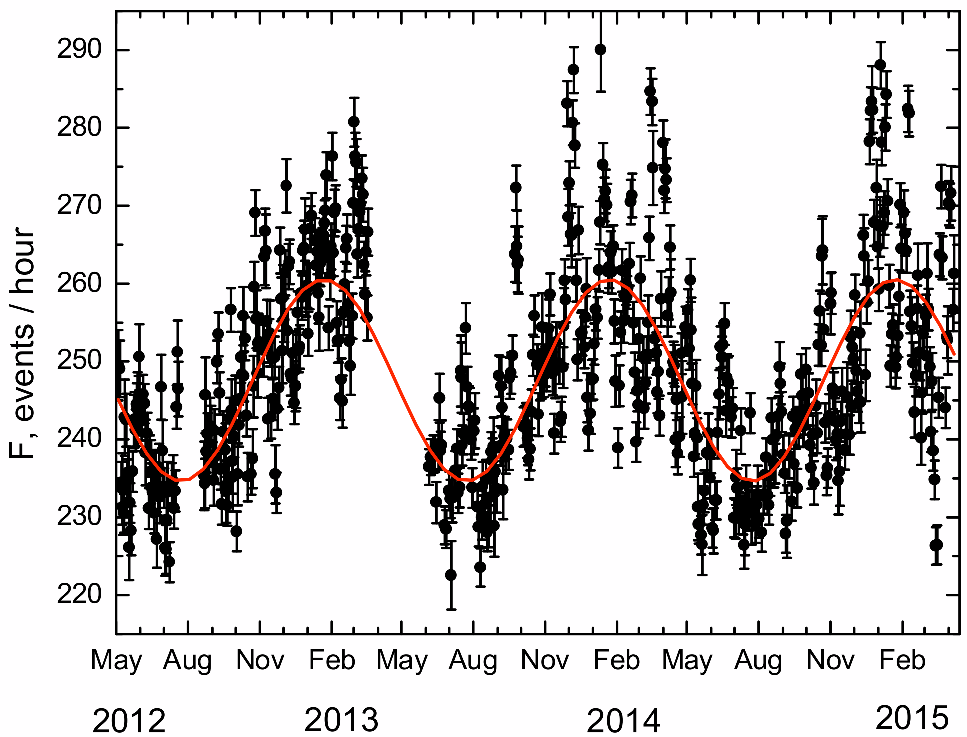


Figure 1. Temporal variations of the muon bundle detection rate. The smooth curve represents the first annual harmonic.

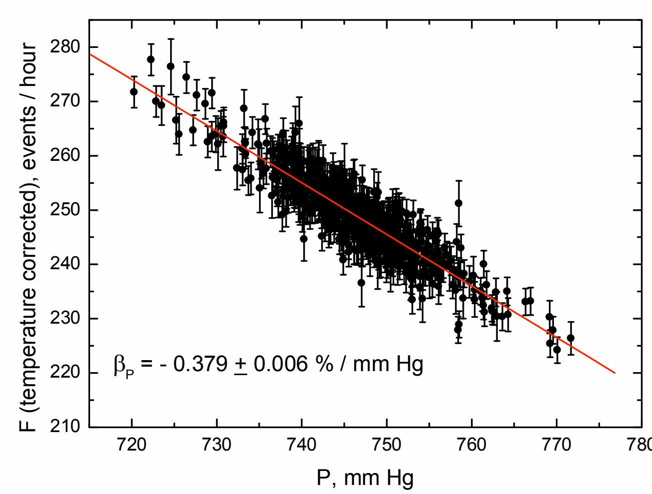


Figure 2. Correlations of the event rate (corrected for the temperature effect) with barometric pressure at the observation point.

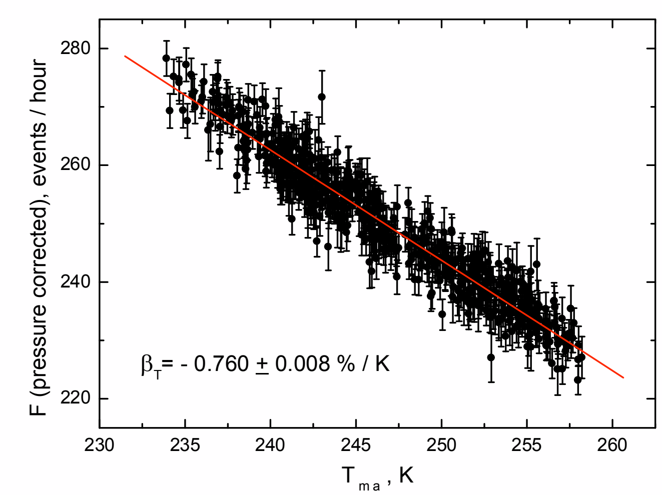


Figure 3. Correlations of the event rate (corrected for the barometric effect) with the mass average air temperature T_{ma}.

Finally a Recommendation…

Importance to save data of past experiments (often on old tapes), programs and documentation for many decades

this now is recognized, but only in words! In practice is left to volunteers.

For example if you look to the LNGS web site there is no page for MACRO (or other past experiments)…but for MACRO we have a pirate site!!!!

The MACRO PIRATE WEBSERVER

http://www.macro-lngs.org/

thanks to Erik Katsavounidis and others

At last, a web server at LNGS that is on a VMS machine and not crippled with tiny disks and no general access. Heck, we want to run **scripts!**, we want to put **lots of stuff on the web!**.

Bunches of MACRO information can be found here. As well as a week's worth of FMT events and other cSPAM/FMT related stuff here.

A guide to authoring web stuff on this server can be found here.

And if you want to join the crew and have your web pages on this server, you should send in a request.

This file was last modified on [an error occurred while processing this directive] by lane@lngs.infn.it.