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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

\[ \frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\text{eff}}}{< T_{\text{eff}} >} \]

\[ T_{\text{eff}} = \sum_i w_i \frac{T(i)}{T_{\text{tot}}} \]

\[ w_i \text{ used by MACRO (1997):} \]

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

\[ W_{\pi,K}(X) \approx \frac{(1 - X/\Lambda^1_{\pi,K})^2 e^{-X/\Lambda^1_{\pi,K}} A^1_{\pi,K}}{\gamma + (\gamma + 1)B^1_{\pi,K}K(X)(\langle E_{th} \cos \theta \rangle/\epsilon^1_{\pi,K})^2}, \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$A^1_{\pi}$</td>
<td>1 [18,19]</td>
</tr>
<tr>
<td>$A^1_{K}$</td>
<td>$0.38 \cdot r_{K/\pi}$ [18,19]</td>
</tr>
<tr>
<td>$r_{K/\pi}$</td>
<td>$0.149 [20] \pm 0.06 [21]$</td>
</tr>
<tr>
<td>$B^1_{\pi}$</td>
<td>$1.460 \pm 0.007 [18,19]$</td>
</tr>
<tr>
<td>$B^1_{K}$</td>
<td>$1.740 \pm 0.028 [18,19]$</td>
</tr>
<tr>
<td>$\Lambda_N$</td>
<td>$120 \text{ g/cm}^2 [20]$</td>
</tr>
<tr>
<td>$\Lambda_{\pi}$</td>
<td>$180 \text{ g/cm}^2 [20]$</td>
</tr>
<tr>
<td>$\Lambda_K$</td>
<td>$160 \text{ g/cm}^2 [20]$</td>
</tr>
<tr>
<td>$\langle E_{th} \cos \theta \rangle$</td>
<td>$0.785 \pm 0.14 \text{ TeV}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$1.7 \pm 0.1$ [5]</td>
</tr>
<tr>
<td>$\epsilon_{\pi}$</td>
<td>$0.114 \pm 0.003 \text{ TeV} [18,19]$</td>
</tr>
<tr>
<td>$\epsilon_K$</td>
<td>$0.851 \pm 0.014 \text{ TeV} [18,19]$</td>
</tr>
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</table>

mesons in the forward direction
kaon pion fraction
meson relative attenuation
threshold energy LNGS 1.3 TeV
muon spectral energy
critical energies
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 - $T_{\text{eff}}$ first harmonic 1994-2000

$T_{\text{eff}}$ with the MACRO peak at day 187
A=1.5%

$T_{\text{eff}}$ 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 $p2 + p0 \times \cos(2\pi(day + day_{\text{start}} + p1)/365.2)$, where $day_{\text{start}}$=110 (April 20). There is a difference of 4 days in the peak position between $T_{\text{effMACRO}}$ and the $T_{\text{effMINOS}}$. 
Muon seasonal variation - $T_{\text{eff}}$ first harmonic 1994-2000

$T_{\text{eff}}$ with the MACRO peak at day 187
$A=1.5\%$

$T_{\text{eff}}$ with the MINOS peak at day 183
$A=1.5\%$

In the following slides I will use generally the MACRO weights.
MACRO at GRAN SASSO

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

dimensions 76.9 x 12.3 x 9.9 m³

Detectors: liquid scintillator counters (in green), streamer tube chambers, CR39 plastic detectors
Single muons seasonal variations
1994-2000


MACRO 1994 - 2000 (this analysis)

Removing the first 130 days
muons peak from day 187 to day 183

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 $p_2 + p_0 \times \cos(2\pi (day + p_1)/365.2)$, 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 $T_{eff}$. A strong correlation is seen.
Single muons correlation with $T_{\text{eff}}$ ($\alpha_T$)

value a bit larger than other experiment at Gran Sasso

$\pi$ only

$K$ only

Figure 16: Modified from [5]. Correlation coefficient $\alpha_T$ 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’s important to note that the calculations are semi-analytical and not full-Montecarlo.
Single muons seasonal variation in Gran Sasso

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>site</td>
<td>LNGS-A</td>
<td>LNGS-B</td>
<td></td>
<td>LNGS-C</td>
<td>LNGS-A</td>
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<tr>
<td>cycles [yr]</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>2.5</td>
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<tr>
<td>period [d]</td>
<td>367 ± 15</td>
<td>-</td>
<td>366±1</td>
<td>375.6 ± 5</td>
<td>366 ± 3</td>
</tr>
<tr>
<td>phase [d]</td>
<td>185 ± 15</td>
<td>-</td>
<td>183±1</td>
<td>179 ± 6</td>
<td>191 ± 4</td>
</tr>
<tr>
<td>temp. data</td>
<td>Aer.Mil.</td>
<td>Aer.Mil.</td>
<td>ECWMF</td>
<td>ECWMF</td>
<td>ECWMF</td>
</tr>
<tr>
<td>$\alpha_T$</td>
<td>-</td>
<td>0.83 ± 0.13</td>
<td>1.02±0.02</td>
<td>0.93 ± 0.04</td>
<td>0.97 ± 0.05</td>
</tr>
</tbody>
</table>

**Table modified from:**
Flux Modulations seen by the Muon Veto of the GERDA Experiment
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 : ~2100 mwe (0.72 km)
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 $\Delta S$

$\Delta S =$ 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 \( \Delta S \) range A from 0.6 m to 4.5 m (top graph) and for events with \( \Delta S \) 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 ($\rho$, $\eta$) produced by $\pi$. $\rho$, $\eta$ branching ratio in two muon very small $\Rightarrow$ less than $6 \times 10^{-6}$ 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 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)

>=2 Track

>=2 Track and 30< average dist<220cm

>=2 Track and average dist>1000 cm
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 $T_{eff}$. If multiple muons produced as “single muons” we expect roughly $\alpha_T^{\text{multi muons}} \sim N\mu \cdot \alpha_T^{\text{single}}$

Teff MACRO formula

$\alpha_T^{\text{multiple muons}}$ depends from distance $D>10m \alpha_T \approx 3$.

$\alpha_T^{\text{single muons}} \approx 1.03$
Multiple Muons in polar coordinates

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

MACRO Multi-Muons phase and amplitude

Amplitude (%)
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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4) A full study of the multiple muons seasonal modulation needs a detailed Montecarlo simulation combining data of different experiments and locations.

5) In the Gran Sasso laboratory the peak of muons is always far from the signal expected for dark matter (day 152.5)
MACRO

F Ronga - Munich  May 7 2002
Barometric coefficient (Sagisaka 1986)

![Graph](image)

**Fig. 7.** – Real barometer coefficient $\beta$, averaged apparent barometer coefficient $\beta_A$ at Wajima with its standard deviations, and observed coefficients at Matsushiro (5) and Poatina (3). Both $\beta$ and $\beta_A$ are the values for $\theta = 0^\circ$ at sea-level, and $\beta_A$ 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)

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.

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

- DAMA/NaI (0.29 ton×yr) (target mass = 87.3 kg)
- DAMA/LIBRA (1.04 ton×yr) (target mass = 232.8 kg)

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-phase 1

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.
2. Experimental data and seasonal variations

The events with at least three (of eight) hit SMs are recorded. At the off-line data processing, the generated in the atmosphere (at large distances from the setup) are nearly parallel. At a trigger level, spatial and angular accuracies of muon track reconstruction in the SM are better than 1 cm and 1º, respectively.

3. Barometric and temperature effects

Selection of muon bundles in DECOR is based on the assumption that the tracks of muons bundles lie in the range from 21º to 65º with a median value near 42º. According to earlier estimates [4], these bundles are mainly formed as a result of interactions of primary cosmic ray particles with typical energies of $10^{15}$ eV.

As follows from the figure, clear seasonal variations repeated every year are observed in the event intensity. Among other parameters, information on the altitude of the isobar surface for a set of residual pressure levels, average atmospheric pressure at the setup location and other parameters have been measured time dependence of the rate of muon bundle detection over the period of observations is iteratively. Iteration procedure rapidly converges, and the estimates of the parameters for the second moment, average atmospheric pressure at the setup location and other parameters have been summarized in table 1. As seen from the table, the most close correlations (coefficient of a linear regression. The results for several values of the residual pressure are evidences for an almost functional dependence) are obtained for the residual pressure of 500 mbar. Comparison of the data with a linear fit for this pressure level is given in figure 4.

$
\beta_r = -0.379 \pm 0.006 \% / \text{mm Hg}
$

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 $T_{\text{mas}}$. 

$\beta_r = -0.760 \pm 0.008 \% / \text{K}$
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