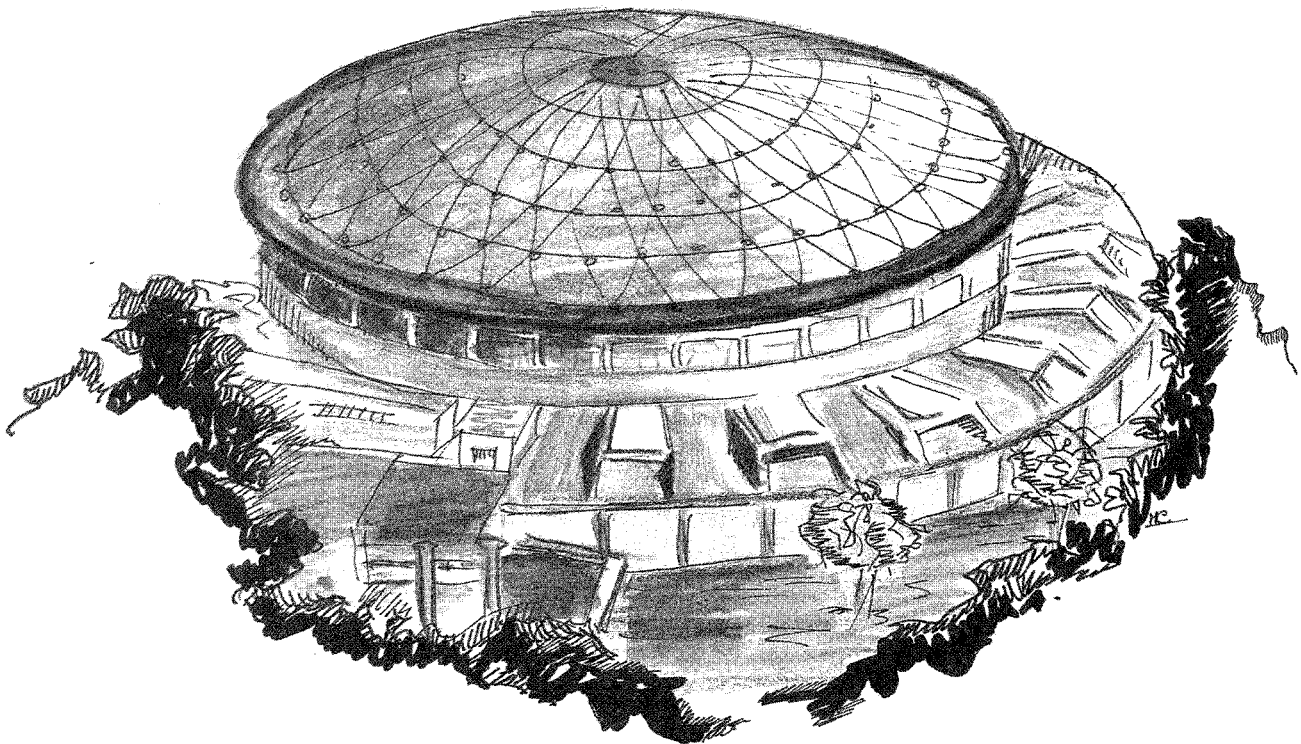# Laboratori Nazionali di Frascati

M.Aglietta, G.Badino, G.Bologna, C.Castagnoli, A.Castellina, B.D'Ettorre Piazzoli, W.Fulgione, P.Galeotti, G.Mannocchi, P.Picchi, O.Saavedra, G.Trinchero, S.Vernetto:

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OBSERVATION OF EXCESS MUON EVENTS FROM THE DIRECTION OF CYGNUS X-3 IN THE NUSEX EXPERIMENT

M. Aglietta[1], G. Badino[2], G. Bologna[2], C. Castagnoli[2], A. Castellina[1], B. D'Ettorre Piazzoli[1], W. Fulgione[1], P. Galeotti[2], G. Mannocchi[1], P. Picchi[2], O. Saavedra[2], G Trinchero[1], S. Vernetto[1]

(1) Istituto di Cosmogeofisica del C.N.R., Torino
(2) Istituto di Fisica Generale dell'Universita', Torino

Cygnus X-3 has been continuously monitored with NUSEX detector since June 1982. Data recorded during the year 1982-1984 yielded evidence for a time modulated flux of high energy muons pointing back to this source. A muon excess is observed again in data collected in the years 1987-1988. The updated analysis of all data recorded by NUSEX between June 1982 and December 1988 is presented here.

1. - INTRODUCTION

NUSEX collaboration reported the observation of a time modulated emission of high energy muons (>3.5 TeV) from the direction of Cygnus X-3 [1]. A similar effect, however less significant, has been reported by the Soudan I experiment[2]; the large area detectors Kamioka[3] and Frejus[4], working in the later part of the period of NUSEX observation of the signal, failed to confirm it. Homestake[5] and IMB[6] experiments, on the other hand, produced upper limits not incompatible with NUSEX fluxes. Moreover, both the Soudan and IMB experiments have reported enhanced muon signals in coincidence with large radio flares from Cygnus X-3[7,8].

The experimental situation is so contraddictory and unclear; a real understanding of the data requires continuous monitoring of the source and careful analysis.

Conventional interactions of high energy γ rays, the particles which are presumed to initiate the extensive air showers detected from the direction of Cygnus X-3 and other point sources, cannot give rise to the large flux of deep underground muons. Thus, if confirmed, NUSEX result would imply unconventional physics (a new, neutral and light primary or a new photon or neutrino-nucleus interaction above 100 TeV).

In the subsequent years, the NUSEX observation has been continued. Data collected in the years 1985-1986 did not show any excess[9]. However, data recorded in 1987-88 exhibit again a time modulated enhancement with similar characteristics. The present analysis concerns the whole period of data taking (1982-1988) and follows the criteria given in[10] with the only exception of the use of the new quadratic ephemeris of van der Klis and Bonnet-Bidaud[11], accounting for the most recent X-ray data.

2. - APPARATUS

The NUSEX (Nucleon Stability Experiment) detector[12] is located in the Mont Blanc tunnel (45° N latitude, 6.9° E longitude) at a vertical depth of about 5000 hg/cm^2 of standard rock. The rock thickness is known with high accuracy ($\Delta h/h \sim 1\%$) in every direction at zenith angles $\Theta < 75^{\circ}$. The muon threshold energy averaged on the mountain pattern is 3.5 TeV.

The detector is a digital tracking calorimeter, consisting of 134 iron plates 3.5 x 3.5 m^2, 1 cm thick, interleaved with planes of tubes having 1 cm x 1 cm cross section operated in limited streamer mode. The bidimensional readout makes it possible to record the detailed spatial pattern of tracks with an angular resolution of 1 mrad and 2 mrad for zenithal and azimuthal angles respectively. The two tracks resolution is better than 2 cm.

The absolute time of each event is recorded with a precision better than 100 μsec. The reference signal is provided by the Italian Insitute of Metrology Galileo Ferraris (Turin).

The muon rates and the response of a few test tubes to a β source are daily examined in order to check the detector performances and electronic stability.

Except for some periods of shut-down due to normal maintenance and gas system upgrading, the NUSEX detector has been operating with high stability and efficiency; the effective working time was about 77% of the total time, in such a way providing a continuous monitoring of the source.

The single muon intensity as a function of depth did not change within statistics during the whole period of data taking. The intensity-depth curve obtained from data collected over the entire operation period (June 1982-December 1988) is in excellent agreement with the one measured at Mont Blanc by the spark chamber experiment operating in the seventies[13]. This

confirms the high efficiency and stability of NUSEX detector over more than 6.5 years of operation.

3. - DATA ANALYSIS AND RESULTS

3.1 - Event selecion and analysis.

Muons are identified as penetrating particles crossing at least 10 planes of streamer tubes. 47219 single muon events with zenith angle up to 75° have been recorded during an effective working time of $1.5867119 \ 10^8$ sec between June 1982 and December 1988.

In a cone of 4.5^o half angle aperture centered on the source 274 events are found. This represents a $1.5 \ \sigma$ excess respect to the average counting rate in the same declination band, as shown in Fig. 1, where we report the number of events recorded in 29 contiguous background cones of 4.5^o half angle aperture selected in the $\pm 4.5^o$ off-Cygnus declination band and covering 345.3^o in right ascension around the source position.

The arrival times are corrected to the time at the solar barycenter and then folded to the v.d.K. and B.-B. parabolic ephemeris

$$T_0 = JD \ 2440949.89622$$
$$p_0 = 0.19968354 \ d$$
$$\dot{p} = 0.904 \ 10^{-9} \ ss^{-1}$$

where p_0 is the system orbital period at the reference time T_0 and $\dot{p}$ is the temporal derivative of the period. The recent quadratic ephemeris of Molnar[14] ($T_0 = JD \ 2443052.975$, $p_0 = 0.19968513 \ d$, $\dot{p} = 0.960 \ 10^{-9} \ ss^{-1}$) is not contraddictory, providing phases less than 0.01 cycles ahead of the Van der Klis and Bonnet-Bidaut phase in the whole period of NUSEX data taking.

Phaseograms of data collected in each couple of operation years are compared in Fig. 2. This subdivision is quite arbitrary, but it follows the sequence of data presentation at the 1985 and 1987 ICRCs (data presented at La Jolla included January 1985, updating at Moscow included data up to November 1986).

The muons recorded in the years '82-'84 provided a reasonable support for a modulated signal. 27 events are observed in the phase interval 0.7-0.8, when 11.4 ± 0.2 are expected according to the off-source background. The Poisson chance probability of observing this excess in anyone of the 10 phase bins is $5.9 \ 10^{-4}$.

It is worthwhile to note that in the previous analysis of 1982-84 data (La Jolla) the excess observed using the old v.d.K. and B.-B. ephemeris was of 19 events, with a corresponding

chance probability of 6 10^{-5}. The reason for this difference is that the new ephemeris provides phases about 0.02 cycles ahead for this epoch.

While the phase plot of data collected in 1985-86 is compatible with uniformity, data recorded in the period '87-'88 show again a muon excess of 10 events above a background of 5.1 $\pm$ 0.3 in the same phase interval. The Poisson probability for chance occurrance of such a peak exactly in this bin is 2.8 10^{-4}.

The resemblance to '82-'84 data (La Jolla Conference) concerns also the angular dispersion of the signal (Fig. 3). Counts in the phase bin 0.7-0.8 show an increasing positive excess up to about 5°. For larger opening angles, the entries follow the expected background. This dispersion is much larger than what would be expected on the basis of scattering and resolution effects. Using a Gaussian distribution for point source resolution, a mean angle of about 2.5^{o} is required to get a fair agreement with data. On the contrary, the experimental angular resolution is better than 1° and the multiple Coulomb scattering is expected to contribute with a mean dispersion angle of ~ 0.6^{o} as obtained by means of a Monte Carlo calculation for underground muon transport. This result agrees with the experimental distribution of the angle between muon pairs in NUSEX[10]. These effects cannot therefore account for the observed dispersion.

The phase distribution of the whole set of 6.5 years of data (Fig. 4) shows an excess of 22 events above a background off-source of 25.0 $\pm$ 0.2. Background out-phase is in excellent agreement, 25.2 $\pm$ 1.9 events/bin. The probability of getting such an excess by chance anywhere in the phase histogram is 6.7 10^{-4}.

3.2 - Background statistical properties.

Statistical properties have been studied by considering the 29 contiguous cones selected in the $\pm$ 4.5^{o} off Cygnus declination band. Taking into account only the periods in which the apparatus was ON, the exposure profile versus depth for these directions (and for each phase bin) has been calculated and found to be uniform, as expected for long time measurements (this can be easily obtained from that published in Ref.10 increased by a factor of 2.1 in order to account for the different time of data taking).

In this way 7247 off-source muons, traversing exactly the same rock coverage as the on-source ones, allow an accurate and unbiased estimate of the expected background. Thus we expect on average the same counting rate (250 events) in each of the off source directions and flat phase distributions.

Experimental data confirm that the distribution of events around the average (Fig. 5) and the distribution of the χ^2 calculated for each phase plot (Fig. 6) are in excellent agreement with the expectations based on Poisson fluctuations.The phase distribution of the background data is

shown in Fig. 7. The flatness of this distribution confirms the absence of effects due to the rock thickness and that the exposure of the detector is independent of the Cygnus X-3 phase.

The control data set thus indicates that no systematic effects or biases were introduced in data taking or in the analysis procedure.

3.3 - Muon intensity and spectrum.

The depth distribution of the off-source (and out-phase) events follows the one expected for atmospheric muons. Thus from the 47 "in phase" events we subtract the background ones according to the depth distribution of the atmospheric muons, so obtaining the depth distribution of the 22 excess events. Then, using the calculated exposure profile, the muon intensity at four mean depths can be obtained (Fig. 8). Soudan I result is also shown for comparison. These intensities (average over 6.5 years) are about 50% lower than the ones reported at the La Jolla Conference. Depth distribution of events does not support the hypothesis of a muon generation by neutrinos in the surrounding rock.

The time evolution of the signal is shown in Table I, where the muon intensities at a typical depth of 5500 hg/cm^2 obtained in the three run periods are compared. Fluxes corresponding to the positive excesses in the phase bin 0.7-0.8 detected in the years 1982-84 and 1987-88 are comparable, while the upper limit (95% C.L.) in the same bin obtained from 1985-86 data is about a factor of two lower.

TABLE I - Time evolution of the muon excess fluxes $(cm^{-2}s^{-1})$ from June 1982 to December 1988.

1982-84	1985-86	1987-88
$(2.4 \pm 0.9)\ 10^{-12}$	no excess U.L. (95%) 1.2 10^{-12}	$(2.6 \pm 1.0)\ 10^{-12}$

Folding a power spectrum to the survival probability P(E,h) an integral muon spectrum $E^{-(1.3 \pm 0.3)}$ is found, rather flatter than the ordinary atmospheric muon one.

3.4 - Correlation with radio flares.

A possible correlation between muon events and the October '85 radio-burst, the largest since Cygnus X-3 discovery, has been investigated. The phase histogram of muons recorded in the period September 26 - October 19 contains 5 events, 4 of which are in the same phase bin

0.8-0.9. The measured background is 0.33 events/bin. If the analysis is restricted to the period October 2-17, 3 events are found in the phase bin 0.8-0.9 on a total of 4; the measured background in each phase bin is 0.24, in agreement with the results of a simulation showing that even for such a short period there is no dependence on the Cygnus X-3 phase.

This bin is not coincident with the 0.7-0.8 bin where the excess has been observed in '82-'84 and '87-'88 data. On the other hand, there are no firm theoretical predictions about the exact nature of any correlation between radio-bursts and processes producing high energy particles.

No other similar configurations have been found in the background cones in the same declination band. The probability of finding 4 or more events in any of the 10 bins is about 4 10^{-3}.

4. - CONCLUSIONS

NUSEX has been providing since June 1982 a continuous monitoring of high energy (>3.5 TeV) muons coming from the direction of Cygnus X-3. A muon excess modulated according to the X-ray period has been observed in years '82-'84 and '87-'88 with similar characteristics. The excess is due to an enhanced flux in the phase interval 0.7-0.8 within 4.5° around the source direction. The time evolution of the signal suggests a renewal of activity starting from the first months of 1987.

The muon excess in the phase bin 0.7-0.8 after 6.5 years of data taking has a chance probability of ~7 10^{-4}. The corresponding flux at a depth of 5500 hg/cm^2 (averaged over the Cygnus X-3 period) is ~1.8 10^{-12} cm^{-2} s^{-1} .

A possible correlation between muon events and the October 1985 radio-burst has been observed, with an excess in the phase bin 0.8-0.9 whose chance probability would be 4 10^{-3}.

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FIG. 1 - Single muon events recorded in 30 contiguous cones in the same declination band of Cygnus X-3 (see text) versus right ascension. The average muon number in each cone (249.9 ± 2.0) is indicated by a dashed line.
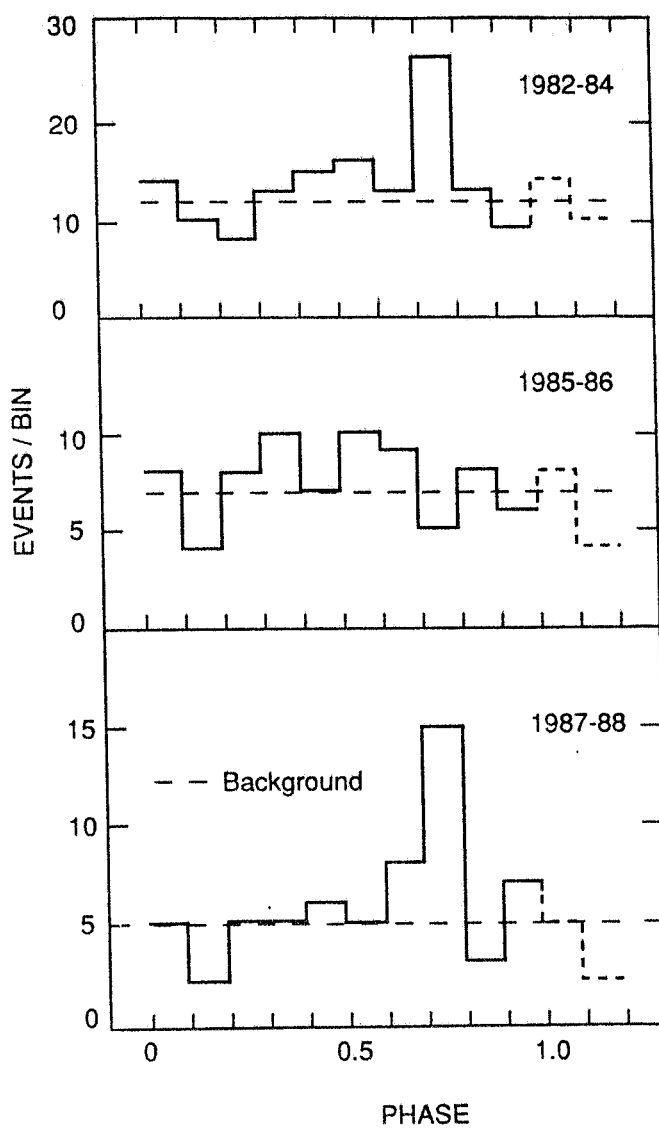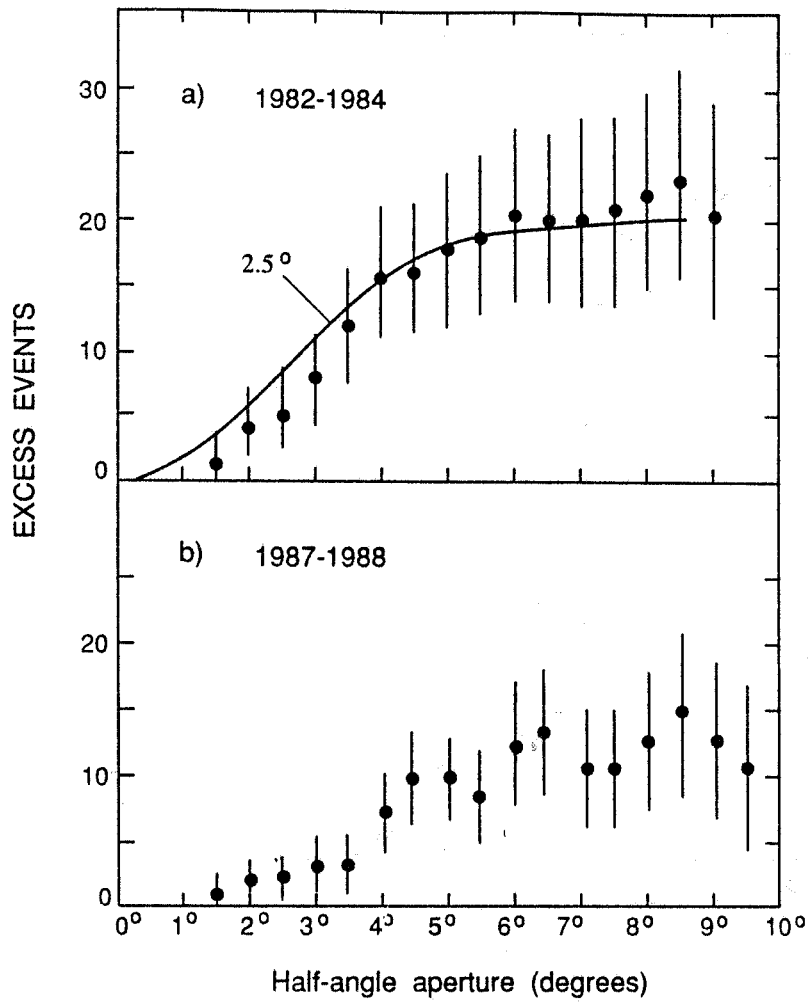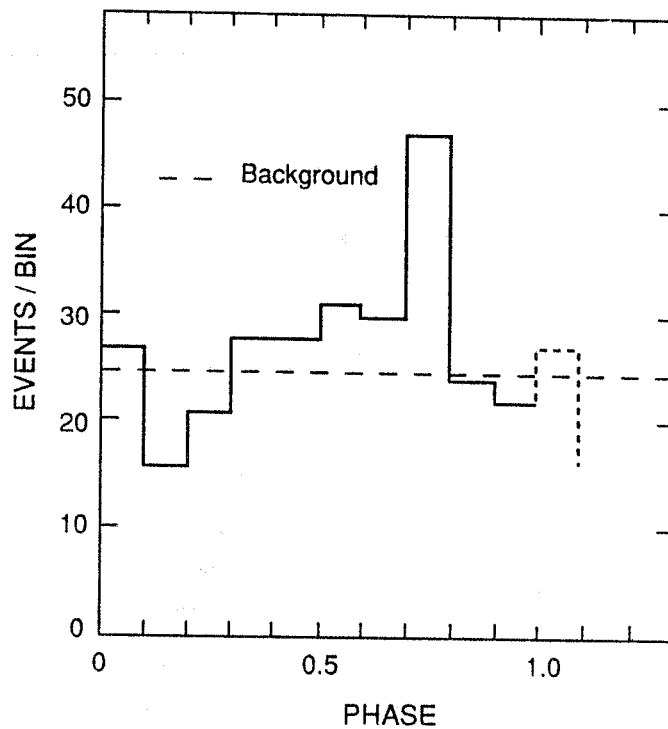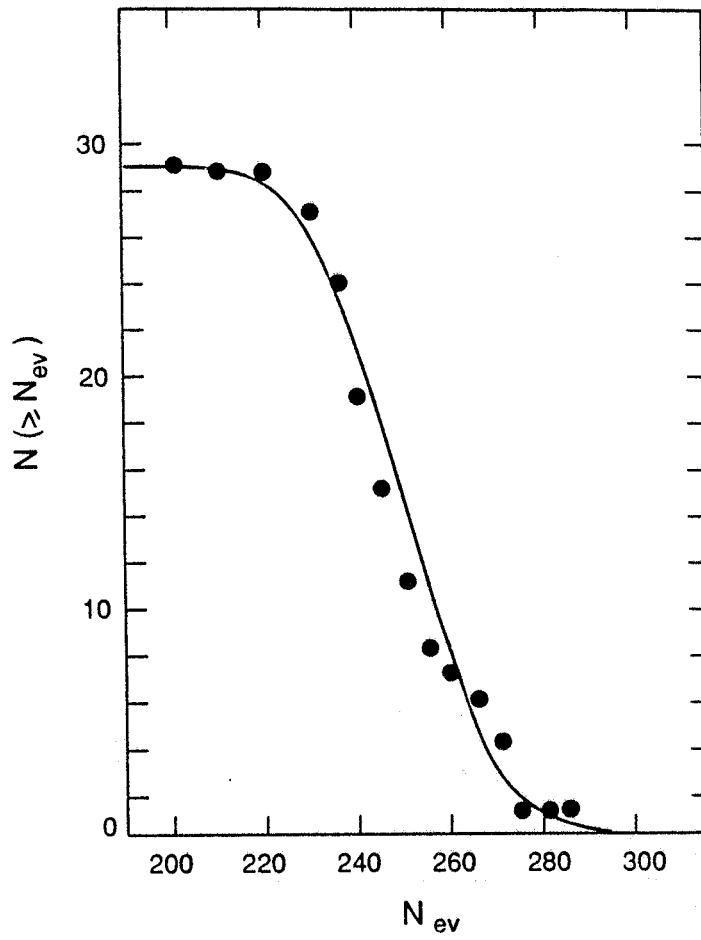
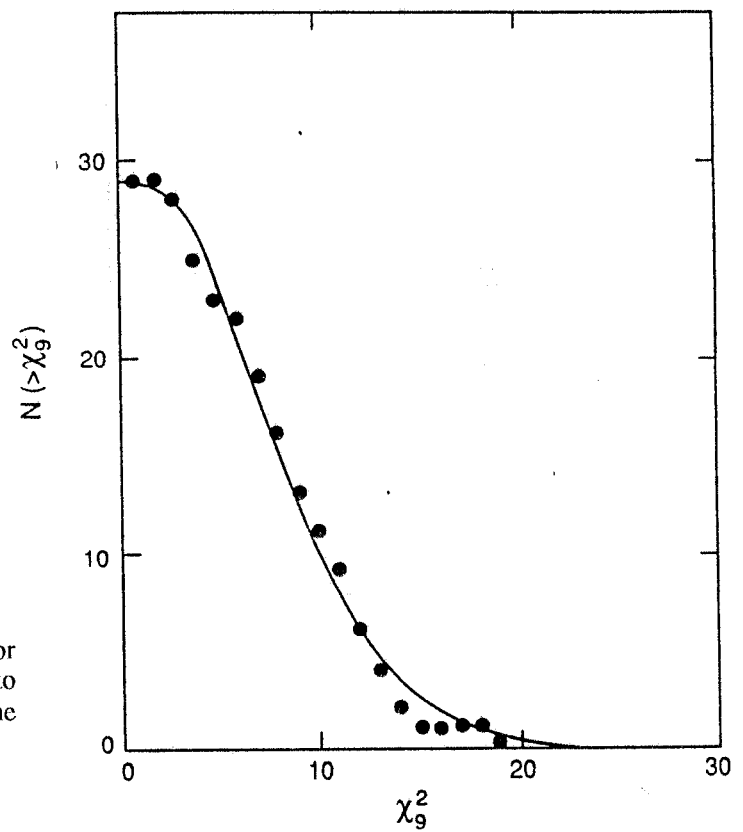FIG. 2 - Phase histograms of muons from the direction of Cygnus X-3 splitted into two-year intervals.

FIG. 3 - The excess in the phase bin 0.7-0.8 plotted versus the cone half angle aperture. The expected distribution according to a Gaussian with 2.5° mean angle is shown for comparison.
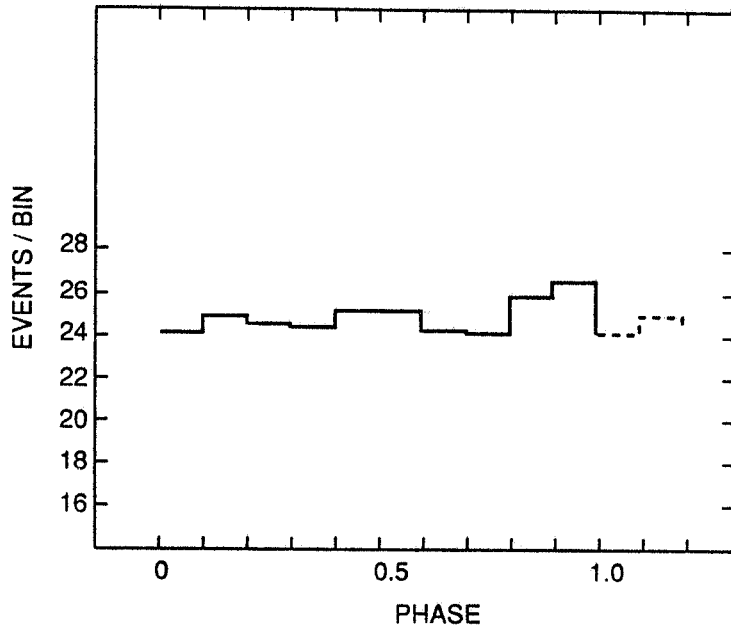
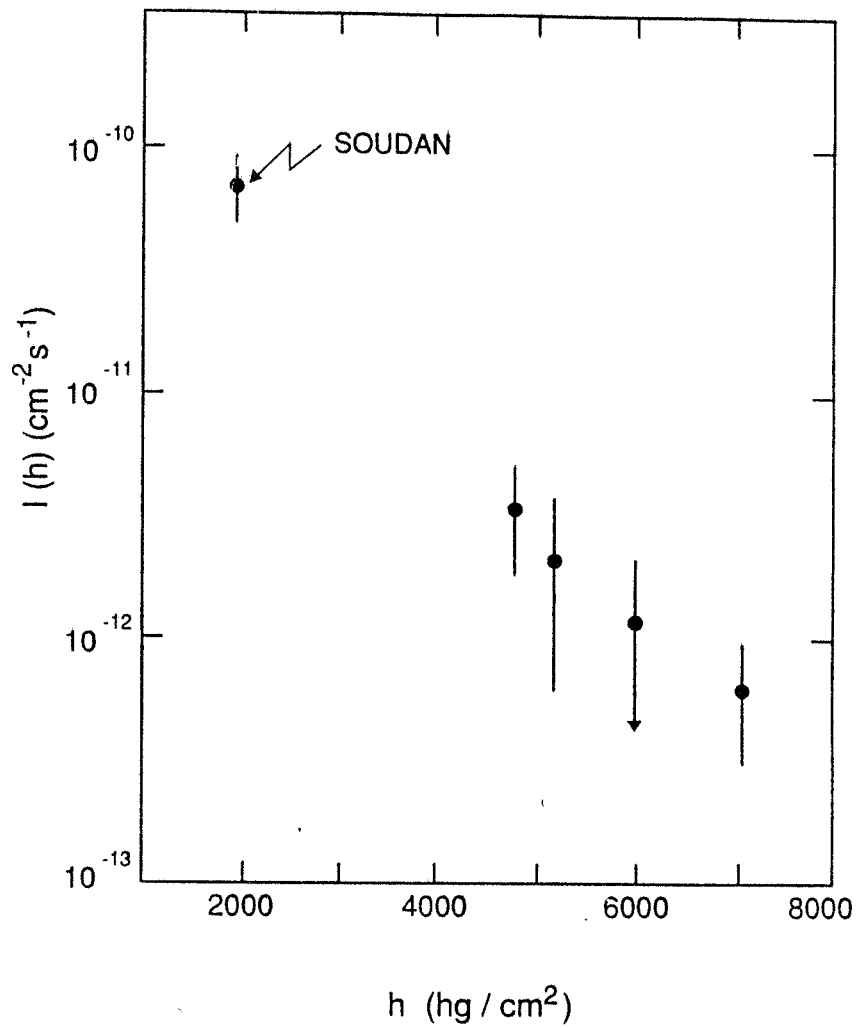

FIG. 4 - Phase distribution for June '82-December '88 data.

FIG. 5 - Cumulative distribution of the number of events recorded in the 29 off-source cones (points). The curve is the expectation according to Poisson statistics.

FIG. 6 - Cumulative χ^2 distribution for the 29 off-source phase plots compared to the expected one (curve). The χ^2 of the Cygnus X-3 phase histogram is 25.6.

FIG. 7 - Phase distribution of the 7247 off source events. The mean value is 25.0 ± 0.2 events/bin.

FIG. 8 - Underground intensity of excess muons from the direction of Cygnus X-3. Soudan I result at 1800 hg/cm^2 is also shown.