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Astronomy with charged particles

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Abstract. The L3+C experiment takes advantage of the high precision muon spectrometer of the L3 detector installed at LEP, CERN, Geneva, to measure precisely cosmic ray muons. Several physics topics in the field of astrophysics and particle physics are being studied. In this paper a description of the detector is given. The possibility to record high energy gamma ray bursts, or burst signals from point sources is discussed.

Key words: Cosmic ray muons, atmospheric neutrinos, point sources, GRBs

1. INTRODUCTION

In the mid 80's, and even way back in 1976 (Bhat 1976), high energy gamma ray signals from point sources have been observed, e.g. from Cyg-X3 (Alkofer 1983). The fact that underground detectors also such as Soudan (Marshak 1985), (Thomson 1991) and (Battistoni 1985) have recorded muons pointing back to this source have triggered in 1987 the proposal to hunt for these signals also with the L3 detector at LEP, CERN, Geneva (Adewa 1990). Located 30 m below ground (well shielded from electromagnetic and hadron cascades) with a muon energy threshold of only $\approx$ 15 GeV, and an excellent momentum and angular resolution (good pointing capability), it consists of a huge solenoidal magnet of 1000 m^3 volume with a field of 0.5 T and a set of high precision drift chambers, as well as of calorimeters and vertex detectors. L3 has been designed to measure accurately muons, electrons, gammas and hadrons produced in e^+e^- collisions. With the addition of timing scintillators on the top of the magnet, drift chamber signals can also be detected from cosmic ray muons. The latter originate from showers initiated by cosmic ray primary particles interacting in the atmosphere. In particular primary high energy gammas can produce muons which deviate by less than 6 mrad from the incoming direction if their energy is above 40 GeV. A pointing back to a given source is therefore

possible. A scintillator array has been installed on the roof of the surface hall above the L3 detector, giving the possibility to estimate the energy of the shower associated with the measured muon.
In the following we shall discribe the L3+C detector, enumerate shortly the different physics topics to be studied and describe in particular the method L3+C is using to search for possible burst signals from point sources and GRBs.

2. THE L3+C DETECTOR

The L3+C detector consists of two parts: The underground muon spectrometer and the surface scintillator array (Adriani 2001). For the discussions treated in this paper we concentrate on the first part, the second being the topic of another contribution to this conference (Tonwar 2000).

Location:
The center of the L3 detector is located 44.8 m below ground, the longitude and latitude are $6^0 01'17''$ E and $46^0 15'06''$ N respectively. The axis of the L3 detector is oriented by $33^0 45'$ to the West relative to the North, and has a slope of 1.39 %. The surface altitude is 449 m above sea level. The molasse above the detector has a thickness of 28.75 m. Three access shafts are located around the detector, as shown in Figure (1). Also shown is the air shower scintillator array installed on the roof of the surface hall above the L3 detector.

The L3 detector:
The L3 detector is shown in Figure (2). It has a huge solenoidal magnet of 12 m diameter, 12 m length, which produces a field of 0.5 Tesla. Inside this magnetic cave of 1000 m^3 a high precision muon detector is installed. The central part of the detector (not used for the cosmic ray studies) consists of a sampling Uranium hadron calorimeter, a barrel shaped trigger scintillator system, a BGO crystal electromagnetic calorimeter, and vertex detectors.

Muon chambers:
The muon chambers are arranged in layers around the vertex in an octagonal structure. The lever arm between inner and outer layer is 2.9 meters.
Each octant is made of three layers of drift chambers (P-chambers) which measure the track coordinates in the direction perpendicular to the magnetic field. Additional drift chambers (Z-chambers),which measure the track coordinates along the direction of the magnetic field, are installed above and below of the inner and outer P-chambers . A track is measured in the three P-layers consisting of cells containing 16, 24 and 16 wires respectively. The single wire resolution is around 200 μm depending on the distance of the track from the wire. Within an octant the relative positions of the chambers are known to better than 30 μm.
The principle of the momentum measurement is illustrated in Figures (3) and (4).

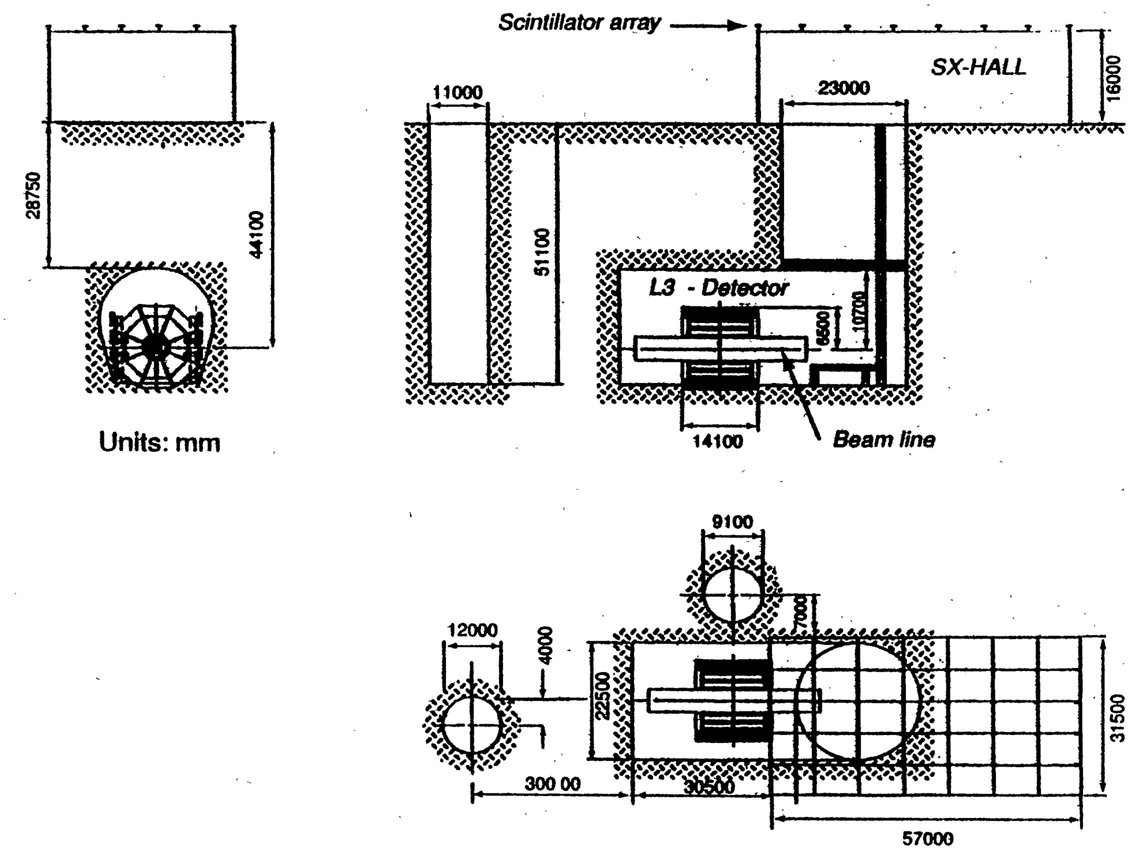

Figure 1. The neighbourhood of the L3+C detector. Shown are the surface hall with the scintillator array, three access shafts and the caverne with the L3 detector.

A complete reconstruction of a muon track passing through the detector requires an excellent knowledge of the time when a muon passes through each of the layers of the muon detector. This time can be calculated from the precise timing obtained from the scintillator set-up (202 m^2) installed for this purpose on top of the L3 magnet and the time of flight from the scintillator to each of the layers for each muon. Information from the scintillator detector is also used in the trigger.

The LEP collider provides the unique possibility to calibrate the momentum measurement, as well as to check the detection efficiency through muons from Z-decays at 45.6 GeV/c. In addition the momentum resolution can be measured accurately. At this momentum we get a resolution of 4.6 % for tracks measured in one octant alone. It is possible to measure a momentum resolution for a subset of the cosmic muon data, namely for those muons that are measured

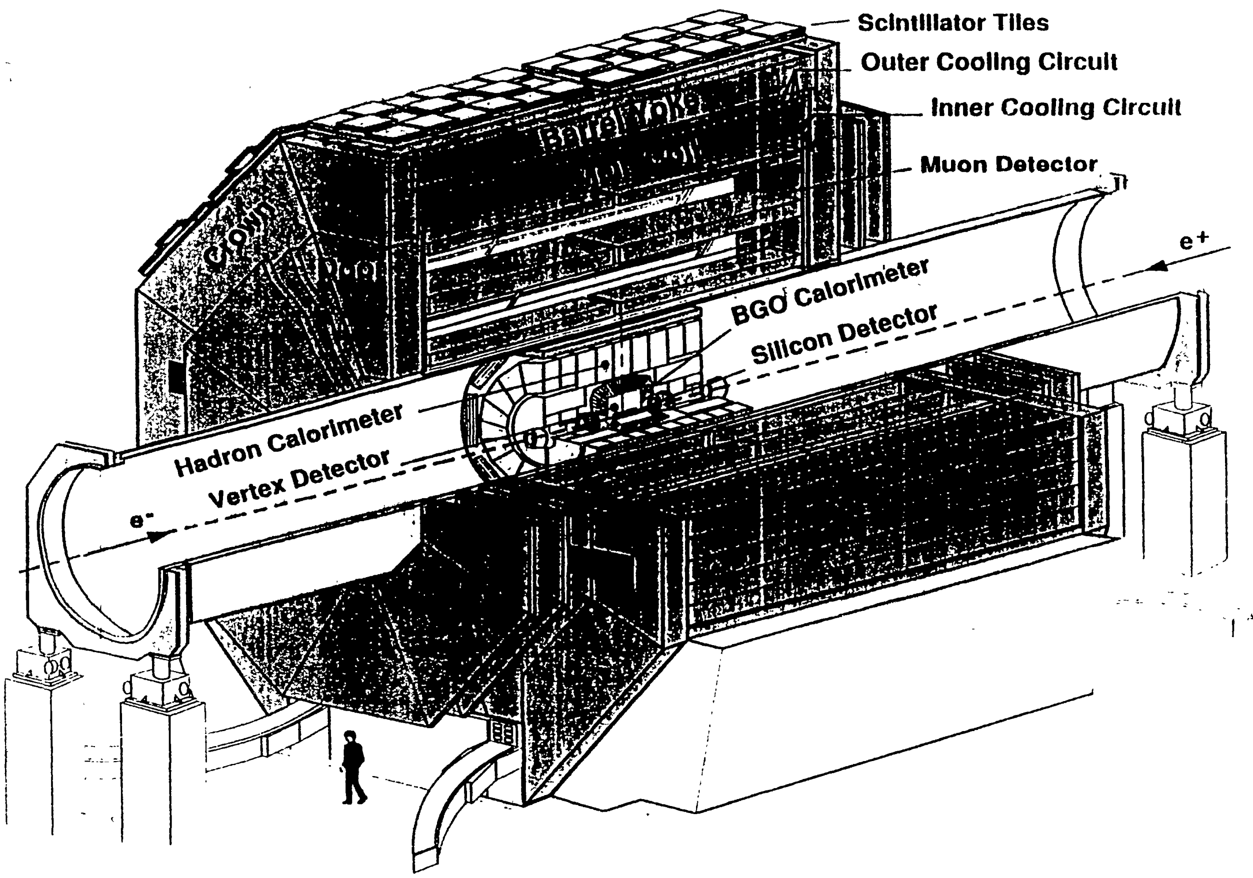

Figure 2. The L3 detector.

in three layers per octant through two octants. For these tracks two nearly independent momentum measurements exist, which allow for a measurement of the resolution of the average momentum. E.g. the resolution around 100 GeV/c has been measured and found to be 7.4 % (Figure (5)).

In order not to interfere with the L3 e^+e^- activity, a completely independent trigger-, readout- and data- acquisition system has been designed. However running the experiment was only possible while L3 was on duty, since the manpower needed to control and monitor the data taking requires a big effort by the whole collaboration. In addition the magnet power was quite expensive. Data collection started in 1998 and ended after the LEP shutdown in November 2000. We have collected $\approx 1.2 \cdot 10^{10}$ events over a total of 312 days of effective livetime. The trigger conditions were such that practically any type of event was accepted, and the trigger rate was $\approx$ 420 Hz.

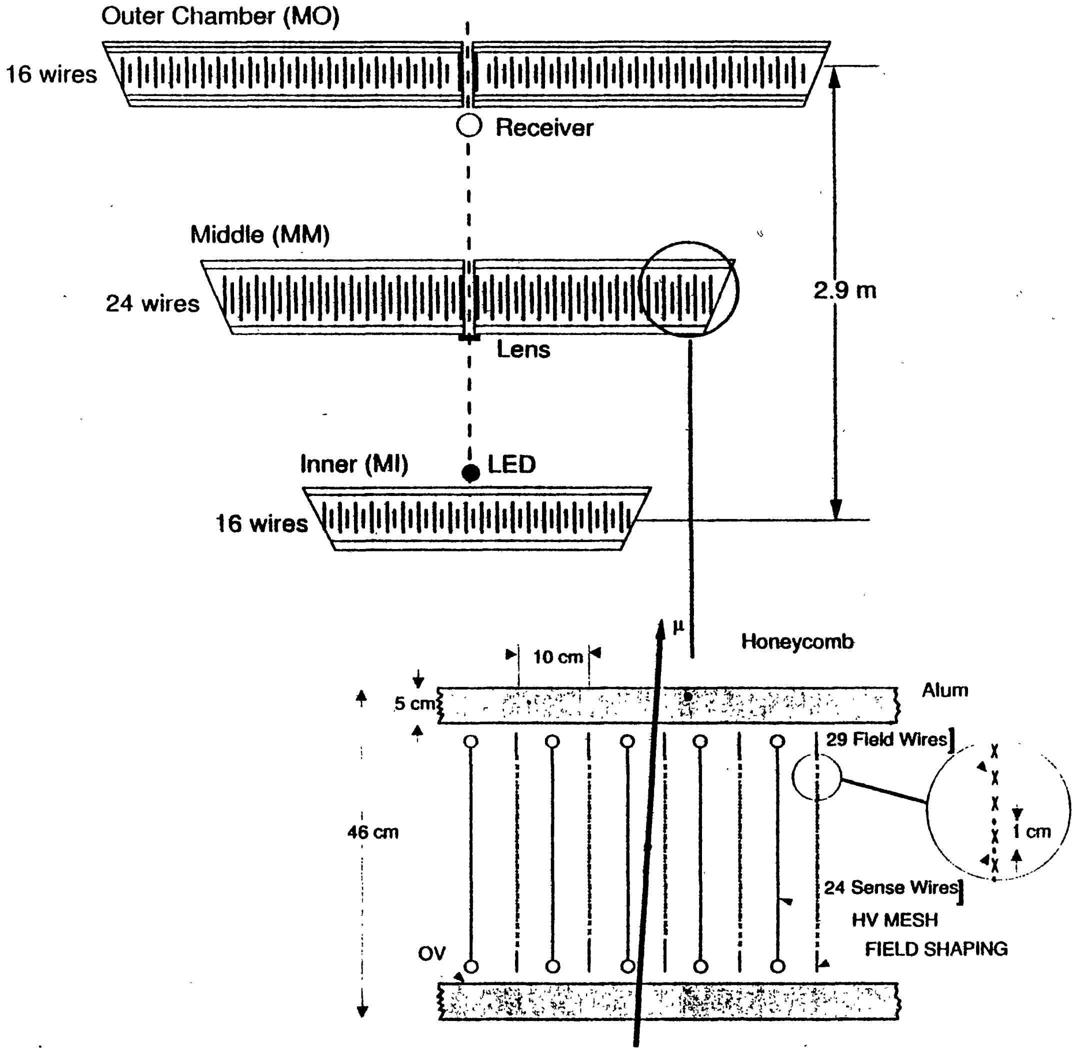

Figure 3. The principle of the momentum measurement (P-chamber layers and wires).

3. PHYSICS TOPICS

Atmospheric muon momentum spectrum:

L3+C's main topic of interest is the measurement of the atmospheric muon momentum spectrum. In the range 10 to 1000 GeV/c this spectrum has presently systematical uncertainties of the order of 25 % (Bugaev 1998). L3+C aims to get the spectrum at the 2.5%-level of precision in the energy range 20 to 2000 GeV.

The precise determination of the muon flux values as a function of charge, energy and zenith angle (Agrawal 1996), (Zatsepin 1960) gives new, and better informations about the primary composition (of interest for astrophysical questions), the shower development in the atmosphere, the inclusive pion and kaon (production-) cross-section (specifically the "π/K" ratio) at high energies (of interest for particle physics questions).

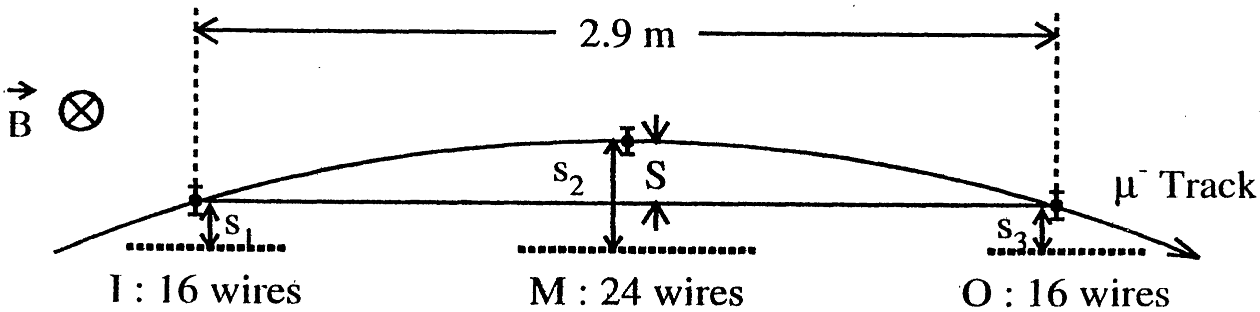

Figure 4. The principle of the momentum measurement (sagitta S).

Most interesting is the possibility to gain confidence in the calculated muon neutrino flux, which is directly related to the muon flux. Neutrino oscillation can therefore be discussed by getting reliable predictions on absolute event numbers. Also the background signals in large neutrino detectors searching for point sources can be estimated with more precision.
A very preliminary vertical momentum spectrum can be found in (Timmermans 1999). Final results are expected in 2002.
Many other physics topics are currently under study. Here we focus onto the question wether L3+C has a chance to observe burst signals from point sources or GRBs.

Burst signals from point sources- and GRB ?

The γ - flux from pulsars, AGNs and GRBs can be expressed by the following formula:

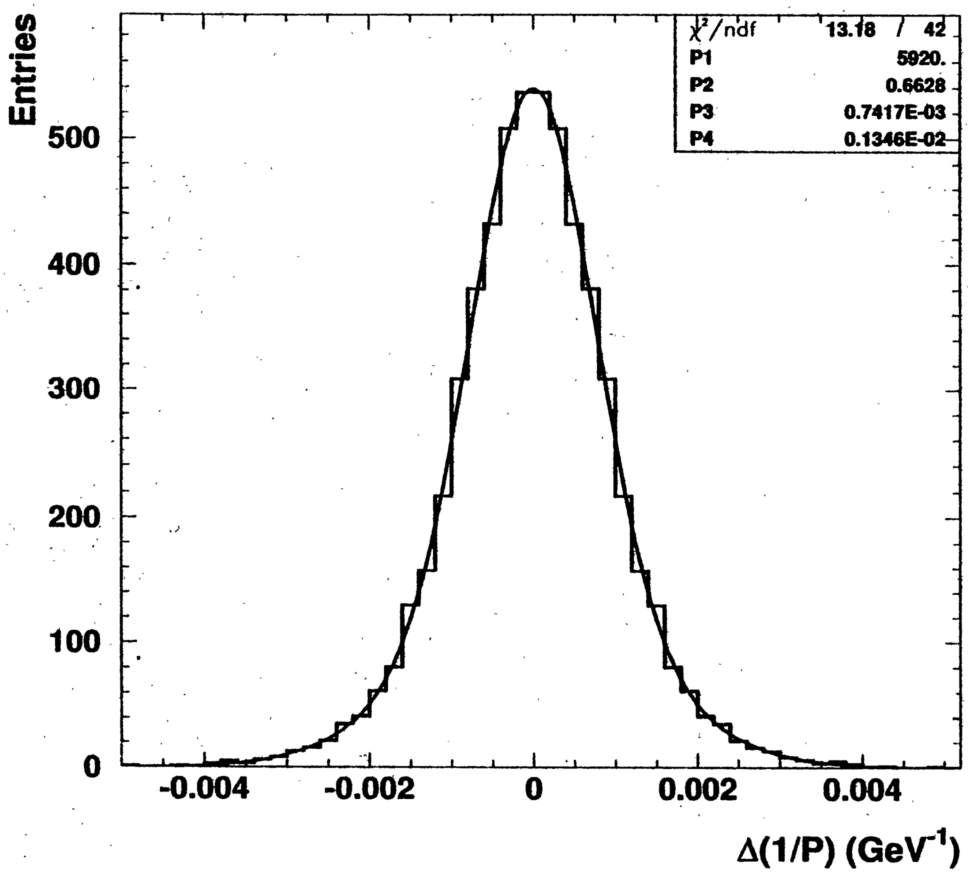

Figure 5. Momentum resolution $\Delta(1/p)$ measured between 100 and 120 GeV.

$$\frac{dN_\gamma}{dE_\gamma} = \frac{F_\gamma}{E_\gamma^{\gamma+1}} \cdot 10^{-12}\ cm^{-2}s^{-1}TeV^{-1}\ ,$$

where the energy is in TeV units. F_γ and the exponent γ are parameters for each source or source type.

The number of muons with energies above a given energy threshold (E_μ) produced by γ - rays in the atmosphere may be estimated according to Halzen, Stanev and Yodh (Halzen 1997), according to:

$N_\mu(E_\gamma, > E_\mu) \approx 2 \cdot 10^{-5} \cdot \frac{E_\gamma}{E_\mu^2}$ valid for $E_\gamma \geq 1TeV, E_\mu \geq 0.1TeV, \theta_{Zenith} \doteq 0^o$.

and $N_\mu(> E_\mu) = \int_{E_\gamma^{min}}^{E_\gamma^{max}} N_\mu(E_\gamma, > E_\mu) \cdot \frac{dN_\gamma}{dE_\gamma} \cdot dE_\gamma\ [cm^{-2}s^{-1}]$ (1)

where $E_\gamma^{min} \approx 10 \cdot E_\mu/cos\theta$ and θ = zenith angle.

This has to be compared to the muon background rate from inside a cone of say 1^o around the source position, which (for L3+C) is less than 0.3 s^{-1} for all accessible zenith angles.

The significance (number of signals $/\sqrt{b.g.events}$) for d.c. signals has been estimated first for different pulsars and AGNs (inserting measured values of F_γ and γ at lower γ - energies).
It turns out to be always significantly below one standard deviation for steady flux. However strong burst signals can still be detected as several sources are known to be bursting type.
(A review of the 12 known point sources emitting γs above 300 GeV is e.g. given in (Lorentz 2000).)
The estimation of the significance for high energy signals from GRBs turns out to be much more promising according to more recent models:
Assuming at high energies an exponent $\gamma \doteq 0.5$ the main part of GRB energy would lie in the TeV-region, since

$$\int_{E_\gamma^{min}}^{E_\gamma^{max}} E_\gamma \cdot \frac{dN_\gamma}{dE_\gamma} \cdot dE_\gamma \sim \sqrt{E_\gamma^{max}}$$

and putting $E_\gamma^{min} \doteq 1$ TeV $\rightarrow E_\mu^{Thr} \approx 100$ GeV

The fluency is the expressed as

$$F_{GRB} = \Delta t \cdot \int_{E_\gamma^{min}}^{E_\gamma^{max}} E_\gamma \cdot \frac{dN_\gamma}{dE_\gamma} \cdot dE_\gamma = 2 \cdot 10^{-12} \cdot F_\gamma \cdot \Delta t \cdot (\sqrt{E_\gamma^{max}} - \sqrt{E_\gamma^{min}})$$

$$F_\gamma = 0.5 \cdot 10^{12} \cdot \frac{F_{GRB}}{\Delta t} \cdot \frac{1}{\sqrt{E_\gamma^{max}} - \sqrt{E_\gamma^{min}}}$$

$$\frac{dN_\gamma}{dE_\gamma} = \frac{1.5 \cdot 10^{-5}}{\Delta t \cdot E_\gamma^{3/2} \cdot (\sqrt{E_\gamma^{max}} - \sqrt{E_\gamma^{min}})} \cdot \left(\frac{F_{GRB}}{3 \cdot 10^{-5} erg/cm^2}\right)$$

Inserting these conditions into formula (1), one gets for the the integral number of observable muons with an energy larger than E_μ :

$$N_\mu(> E_\mu) \approx \frac{6. \cdot 10^{-10}}{(E_\mu^{Thr.})^2 \cdot \Delta t} \cdot \left(\frac{F_{GRB}}{3 \cdot 10^{-5} erg/cm^2}\right)$$

For L3+C with $\approx 100\ m^2$ of effective surface one gets the number of muons expected per burst:

$$N_\mu \approx 0.15 \cdot \left(\frac{F_{GRB}}{3 \cdot 10^{-5} erg/cm^2}\right)$$

The commonly accepted GRB fluency of $F_{GRB} \sim 3 \cdot 10^{-5}\, erg/cm^2$ (for a distance to the source of 3000 Mpc) has been estimated from low energy γ spectrum and corresponds to $E_{GRB} = 3 \cdot 10^{52}\, erg$. Inserting this value gives also no significant number of events.

But IF $E_{GRB} \approx 5 \cdot 10^{53}\, to\, 10^{54} \cdot (M_{BH}/M_\odot)\, erg$

from NS-BH, or NS-NS mergers, or hypernovae (collapsars), ... as suggested in (Meszaros ....), (Rees 2000); or (Vazquez 1998), explaining the diffuse γ - ray spectrum), then for say $F_{GRB} = 10^{-3}$ we would expect:

$N_\mu = 0.15 \cdot 30 = 4.5$ muons.

IF "beaming" exists up to 10 to 100 times more.

Since our background is less than $0.3\,\mu\,/\,s$ inside a cone of 1^o this would be a very significant signal.

Remark: In this estimation the absorption of the high energy γs (Stecker 1992) has been neglected, which means that this estimate is only valid for "nearby" GRBs. At the gamma energies discussed here (10 to 100 TeV) the absorption by the IR-radiation is of importance.

Experimental hints that such signals may exist have been given by HEGRA (HEGRA 1999), GRAND (Lin 1999), MILAGRITO (Milagito 1999), EAS-TOP (Aglietta 1999) and Dublin (Plunkett 1999). A recent review on GRBs and a list of references are given by (Rees 2000).

L3+C search procedure for high energy GRB signals:

The search technique developed for L3+C may be described in the following way: The muon background is continuously recorded over the full acceptance. Data sets collected over every 12 hours are compared to the previous ones, in order to check the stability of the rate across the whole visible sky. A 24 hour data collection allows to get a high precision measurement of the background rate along a 1^o wide trajectory of a given GRB in the sky. One then scales this number down to minute or sec time bins and scans with off-line set threshold muon energy along the trajectory for any excess of events (GRBs may produce several bursts, and have therefore to be observed over longer periods than just the first seconds at the discovery time). As mentioned before, only a very few muons in such a short time bin would represent a very significant signal compared to the low background of less than 0.3 muons per sec and per $(1^o)^2$. The pointing accuracy has been verified by the observation of the "moon shadow". Primary protons are absorbed by the moon and a lack of muons from this direction is observed (more precisely: due to the earth magnetic field and according to the protons energy, this shadow is in fact slightly deviated from the geometrical line of sight).

4. CONCLUSIONS

The L3+C detector has successfully collected $1.2 \cdot 10^{10}$ cosmic ray muons from end 1998 to November 2000, with an effective livetime of 312 days. Data analysis has started and the results are expected to demonstrate that the L3+C muon spectrometer together with its surface scintillator array, is a unique tool to study cosmic ray muon physics, particle and astroparticle physics. In particular the detection of GRB signals at 10ths of TeV would be of fundamental interest.

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