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Searching for Point Source Signals through Muons

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The results from an analysis of muon data on cosmic ray source signals collected with the L3+C experiment at LEP CERN are presented. A general-purpose sky survey method for any detectors with anisotropic acceptance is described.

1. Motivation

The energy spectrum of charged cosmic rays spans a very broad range, from sub-GeV to energies larger than 10^{11} GeV. The origin of Ultra-High Energy (UHE) cosmic rays have been studied for about 50 years. Since 1989 several Very High Energy (VHE) gamma ray sources have been discovered by means of different experimental techniques, the Imaging Atmospheric Cherenkov Telescope (e.g. Whipple, HEGRA, HESS, CONGAROO) and the EAS array (e.g. MILAGRO,AS_γ,KASCADE, ... etc). The spectrum of gamma rays can be explained by "lepton models" (synchrotron radiation from accelerated electrons, inverse self-Compton effect). However the origin of nuclei sources of UHE cosmic rays is still unclear, though various theoretical models exist [1, 2].

The unique properties of the L3+C muon spectrometer [3, 4], as well as its location at a shallow depth (low muon energy threshold), offered a new opportunity to search for large flares from known as well as yet unknown sources at relatively low energies, $\sim$ 100-1000 GeV. New data on high energy gammas are expected to constrain models of particle acceleration at the source. However, the sensitivity of a muon tracking detector is significantly smaller for the detection of cosmic γ-rays due to the very small cross-section for photo-production of charged pions. This disadvantage is partially offset by the fact that the muon tracking detector can have a lower energy threshold (larger gamma fluxes !), even lower than the presently operational Cherenkov telescopes.

2. The L3+C muon spectrometer and the data

The L3 detector (Figure 1) [3, 4] was designed to measure accurately muons, electrons, gammas and hadrons at the large electron positron collider LEP, CERN. It consisted 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.

The detector is located under only 30 m of overburden, at an altitude of 450 m above sea level, and the energy threshold for atmospheric muons is $\approx$ 15 GeV. The coordinates of the L3+C site are 6.02° E, 46.25° N.

The addition of timing scintillators on the top of the magnet, as well as a trigger and readout system different from the L3 experiment, enabled the acquisition of cosmic ray muon data, independently of the running of L3 and LEP. The arrival time of an event was recorded with an accuracy of 1 μsec (GPS timing). The chamber, scintillator, and trigger efficiencies have been discussed in detail elsewhere [5].

The data were taken during two periods, mid-July to November 1999, and April to November 2000. Overall $1.2 \cdot 10^{10}$ triggers have been recorded, during an effective live-time of 312 days.
Concerning the detection properties important for this discussion: The angular resolution is less than 2^o for

muon energies above 20 GeV and for muons crossing at least three drift chambers. The acceptance of L3+C depends on the zenith and azimuthal direction, and is slightly different for positive and negative muons.

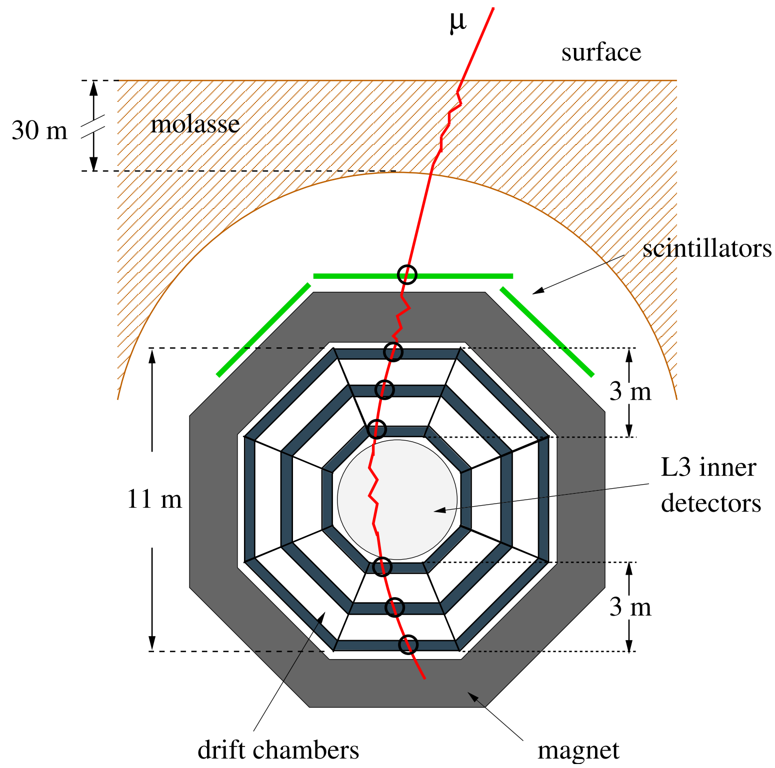

Figure 1. Schematic view of the experimental setup

3. Search for steady cosmic muon sources

A particular sky survey has been made in the following way. The sky field covered by L3+C has been subdivided into 40 by 90 cells, with a cell width $\Delta\delta$ of 2° in declination and $\Delta\alpha$ = 4° in right ascension. The trajectory of each cell across the sky has itself been subdivided into 40 zenith angle segments from zenith angle θ = 60° towards the south east, to 60° towards northwest, each segment having a width of $\Delta(\cos\theta)$ = 0.025. All muon events were distributed in a 3 dimensional frame (40 × 90 × 40 bins). $N(\alpha, \delta, \theta)$ is the number of muon events in each bin. The background for a given zenith angle bin (which is fixed with respect to a particular detection direction of the detector - with its particular acceptance and efficiency) has been measured from the content of the given declination band swept from α = 0 to 24 h across the particular bin. For each of the 90 bins in α, with given δ and θ, the event distributions have been found to be quite uniform. Figure 2 shows two typical examples.

In a given declination band of $\delta \pm 1^o$, for the cell of α_j at zenith angle θ_i, the significance of excess events above the background $N^{\rm bkg}$ is calculated according to [6]

$$U_{i,j} = \sqrt{2}\left\{ N_{i,j}^{\rm obs} \cdot ln\left[\frac{1+\beta_{i,j}}{\beta_{i,j}}\left(\frac{N_{i,j}^{\rm obs}}{N_{i,j}^{\rm obs}+N_{i,j}^{\rm bkg}}\right)\right] + N_{i,j}^{\rm bkg} \cdot ln\left[(1+\beta_{i,j})\left(\frac{N_{i,j}^{\rm bkg}}{N_{i,j}^{\rm obs}+N_{i,j}^{\rm bkg}}\right)\right]\right\}^{1/2}, \quad (1)$$

where $N_{i,j}^{obs}$ is the number of events in the $(\delta, \alpha_j, \theta_i)$-bin; i is the index of the zenith angle bin and runs from 1 to 40 for given δ and α; j the index of the right ascension bin, ranging from 1 to 90 for given δ and θ. $\beta_{i,j}$ is the live-time ratio:

$$\beta_{i,j} = \frac{T(\alpha_j, \theta_i \mid \delta)}{\sum_{k=1,k\neq j}^{90} T(\alpha_k, \theta_i \mid \delta)}. \tag{2}$$

here $T(\alpha, \theta \mid \delta)$ is the exposure time corresponding to $N(\alpha, \theta \mid \delta)$, and

$$N_{i,j}^{obs} = N(\alpha_j, \theta_i \mid \delta), \qquad N_{i,j}^{bkg} = \sum_{k=1,k\neq j}^{90} N(\alpha_k, \theta_i \mid \delta).$$

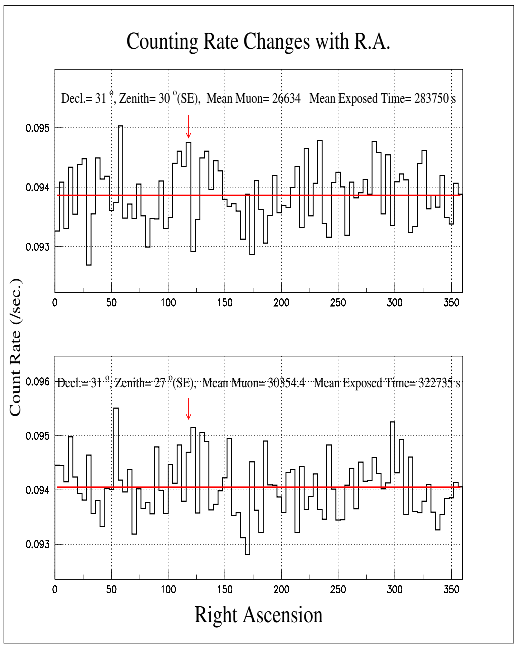

Figure 2. Two examples of the muon rate distribution from various right ascension cells with $\delta = (31 \pm 1)^o$, $\theta = 30^o$ (towards the South East) and $\delta = (31 \pm 1)^o$, $\theta = 27^o$ respectively. The arrow indicates the bin of R.A. = $(118 \pm 2)^o$.

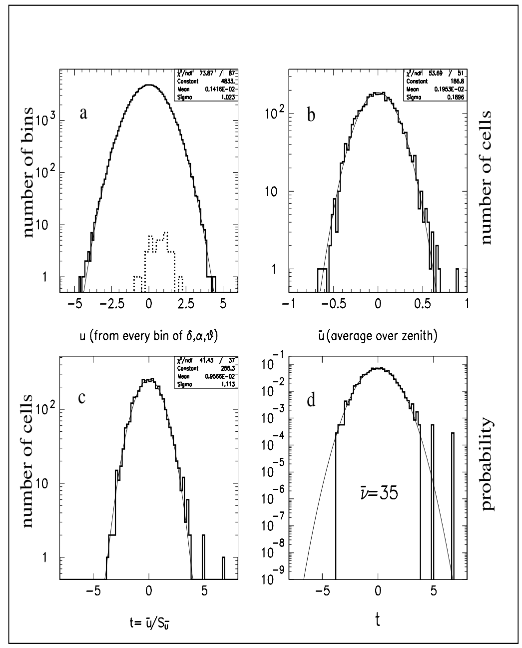

Figure 3. a.) U-distribution from each (α, δ, θ) -bin. The inserted dotted line is the U-distribution for the cell located at $\alpha = 118^o$ and $\delta = 31^o$, with an apparent "excess" of events. b.) Distribution of $\overline{U_j}$, averaged over all zenith bins for each α cell. c.) and d.) t-distribution. The maximum one is five orders of magnitude higher than the background.

Figure 3a shows that the observed $U_{i,j}$ are distributed as a Gaussian around a mean $\mu = 0$ with a variance of 1.

In order to estimate the significance of this "excess" in this particular $(\alpha_j\ ,\ \delta)$-cell, the Student's t was calculated by taking $U_{i,j}$ from all zenith bins of the cell and taking the corresponding distribution width into consideration,

$$t_j = \frac{\overline{U_j} - \mu}{S_{\overline{U_j}}}, \tag{3}$$

where

$$\overline{U_j} = \frac{\sum_{i=1}^{n} U_{ij}}{n}, \qquad \mathrm{S}^2_{\overline{U_j}} = \frac{\overline{U_{ij}^2} - \overline{U_j}^2}{n-1}.$$

Here n is the number of zenith angle bins with $\beta\cdot$ $\mathrm{N}^{\mathrm{bkg}}$ larger than 15 for each (α, δ)-cell. It ranges from 25 to 40, depending on the upper culmination of each declination band.

The U distribution shown with dotted line in Figure 3a represents an unusual distribution for two cells (α = 118°± 2° and δ = 31°± 1°, or alternatively α = 198°± 2° and δ =-31°± 1° in case of up going muons). The mean is positive and the distribution is narrow ($\overline{U_j}$ = 0.691, $S_{\overline{U_j}}$ = 0.1038 $\rightarrow$ t_j = 6.66, see Figure 3c). The normalized t-distribution, represented as a probability is plotted in Figure 3d, suggesting that the observed effect may be due to an excess. The chance to be a statistical fluctuation of the background is $10^{-5.5}$, with a total number of trials for this excess being 40 × 90 = 3600. Therefore no significant excess can be claimed for the flux from this particular direction. 90 % CL upper limits can be placed on the flux of muons from various directions which are in the range, 1 to 10 $\cdot 10^{-9}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at a muon energy threshold of 20 GeV.

4. Discussions and Conclusions

A general-purpose sky survey method for any detector with anisotropic acceptance has been proposed and applied for a cosmic ray point source search with the high resolution muon spectrometer of the L3+C experiment. Data collected for 312 days over the periods July-November 1999 and April-November 2000 have shown no evidence for a significant excess of events. Low gamma flux values and too low muon detection efficiency are the reason.

Acknowledgments

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