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Recent results from the CosmoALEPH experiment

A. Mailov[1], A. Böhrer[1], A. Brühl[1], H. Besier[2], C. Grupen[1], S. Luitz[3], A. S. Müller[4], A. Putzer[5], B. Rensch[6], H. G. Sander[2], S. Schmeling[2,4], M. Schmelling[7], H. Wachsmuth[2,4], Th. Ziegler[2], and K. Zuber[8]

[1]University of Siegen, D-57068 Siegen, Germany
[2]Mainz University, D-55099 Mainz, Germany
[3]CERN, CH-1211 Geneva 23, Switzerland; now at SLAC, PO Box 4349, Stanford, CA 94309, USA
[4]CERN, CH-1211 Geneva 23, Switzerland
[5]University of Heidelberg, D-69120 Heidelberg, Germany
[6]University of Heidelberg, D-69120 Heidelberg, Germany; now at erphi electronics GmbH, Gewerbering 15, D-83607 Holzkirchen, Germany
[7]CERN, CH-1211 Geneva 23, Switzerland; now at Max-Planck-Inst. f. Kernphysik, D-69029 Heidelberg, Germany
[8]University of Dortmund, D-44221 Dortmund, Germany

Abstract. The ALEPH detector at LEP has been supplemented with five scintillator telescopes. This CosmoALEPH experiment is operating at a depth of 320 m.w.e. underground measuring the muon component of extensive air showers. One aim of the experiment is to probe the chemical composition of primary cosmic rays and to investigate the interaction characteristics of energetic protons and nuclei in the atmosphere in the PeV region. A first look at the cosmic ray data taken in dedicated ALEPH runs with the CosmoALEPH experiment shows agreement of underground muon data with gross features based on expectations from the muon content of extensive air showers in the atmosphere.

1 Introduction

The investigation of cosmic ray muon showers in the ALEPH detector operated at a depth of 320 meter water equivalent underground was motivated by the observation of high multiplicity events along with normal data taking of electron-positron interactions (Besier, 2000; Avati, 2000). ALEPH, which was designed as a general purpose detector for electroweak physics at the Large Electron Positron collider (LEP), provides a large, sophisticated high resolution particle detector to study cosmic rays underground. The ALEPH detector was available for cosmic ray studies in parasitic mode along with e^+e^- physics. In addition, during periods without LEP beams, also measurements dedicated to cosmic ray studies were possible. To our knowledge no cosmic ray experiment has properties like momentum resolution, multi-track separation and spatial resolution comparable to the Time Projection Chamber (TPC) of ALEPH (ALEPH, 1990, 1995). Therefore it was only natural to propose to use ALEPH and the other LEP detectors for cosmic ray studies (Wachsmuth, 1993; Ball, 1994). Cosmic ray events could be recorded in individual detector stations together with a precise time-stamp allowing for an off-line search for coincidences. Even though normal extensive air showers are not expected to produce long range coincidences (Grupen, 1995; Jones, 1994), the detectors would be sensitive to unexpected phenomena with showers of large lateral widths.

In a pilot experiment ALEPH was supplemented by five scintillator stations distributed around the LEP detector over distances of up to one km (“CosmoALEPH”). The results presented in this paper originate from a subsample of data taken in two dedicated cosmic ray runs with ALEPH and its nearby scintillator stations.

2 Experimental Setup

The layout of CosmoALEPH with the relative distances between all stations is shown in Fig. 1. The scintillator stations consist of stacks of plastic scintillator 1-2 cm thick, 30-40 cm wide and 220-250 cm long, each having photomultipliers at both ends. Two scintillators on top of each other are called a stack. Each station of typically 6 m^2 consists of 4-8 stacks. An event is recorded if all four phototubes of at least one stack have fired. The ALEPH detector and its performance is described in detail elsewhere (ALEPH, 1990, 1995). We use for this analysis only the hadronic calorimeter (HCAL,

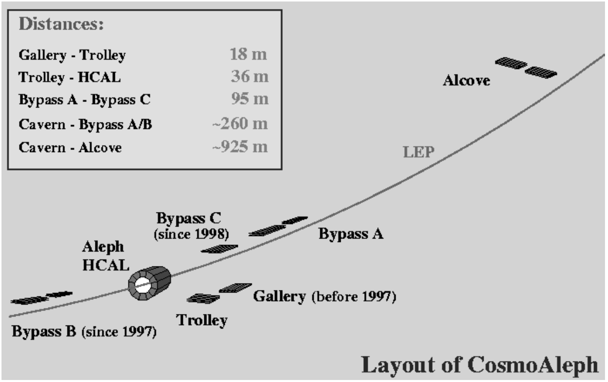

Fig. 1. Layout of the CosmoALEPH experiment in 2000.

50 m^2 area) and the time projection chamber (TPC, 16 m^2 area). The HCAL allows an unambiguous muon identification, and the TPC provides an excellent momentum resolution of $\sigma_p/p^2 < 10^{-3}$ GeV^{-1}. The tracking capability of the TPC enables an angular resolution of $\approx$ 3 mrad, corresponding to the typical multiple scattering error of muons in the overburden.

The muon momentum cut-off for vertical incidence at 320 m.w.e. is 70 GeV. Since the overburden is essentially flat in the geometrical acceptance the effective zenith angle dependent cut-off is at 70 GeV$/cos\theta$.

3 Results

The CosmoALEPH experiment only measures the muon component of extensive air showers which develop in the atmosphere. The electron and hadron components of the EAS are completely absorbed in the overburden (125 m of rock). The trigger rate of muon events is $\approx$ 2.5 Hertz. Each event carries a time stamp of 12.5 ns granularity. So far 500000 events have been analysed. This represents only a fraction ($\approx$ 20%) of the data taken in dedicated ALEPH cosmic ray runs.

In this paper we concentrate on data that have been taken with the ALEPH detector alone irrespective of coincidences with the scintillator stations in the ALEPH cavern or the LEP tunnel. The angular distribution of muon events as measured in the ALEPH TPC is shown in Fig. 2. The distribution shows an almost linear rise with $\cos\theta$ up to $\cos\theta = 0.6$. A standard approach which includes an energy dependent muon energy loss of the form

$$-dE/dx = a + b \cdot E \quad (1)$$

(a represents the energy loss for ionisation and b the energy loss deriving from bremsstrahlung, direct electron pair production and nuclear interactions losses), leads to a zenith angle dependent depth-intensity relation

$$N(>E, R, \cos\theta) = A \cdot [\frac{a}{b}(e^{bR/cos\theta} - 1)]^{-\gamma} \quad (2)$$

with R representing the depth of the experiment, and γ the spectral index of the integral sea-level spectrum (Grupen, 1976). The acceptance curve for the TPC is essentially flat for angles above 50°, so the zenith angle distribution can be reproduced inside the interval [0°,50°].

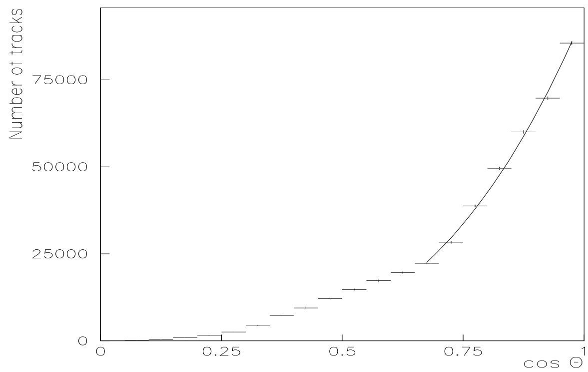

Fig. 2. Zenith angle distribution of tracks in multi-muon events. The solid line represents a fit of Eq.(2) to the data in the range [0°,50°] resulting in the spectral index $\gamma = 2.71 \pm 0.02$.

The reason for the particular shape of the distribution in Fig. 2 could originate from a zenith angle and azimuthal angle dependence of the acceptance of the ALEPH TPC. The TPC (diameter 360 cm, length 470 cm) has been built to encompass the beam pipe of LEP. For near vertical directions the acceptance is uniform in azimuth. For large zenith angles the acceptance along the axis of the TPC shows an angular dependence starting at around 50°, allowing more large angle muons to be accepted. A careful Monte Carlo study of the detector properties will clarify the understanding of the TPC acceptance.

The momentum spectrum of muons in the ALEPH TPC is shown in Fig. 3. This spectrum includes muons from all arrival directions in the acceptance of ALEPH's TPC. The shape of the spectrum is influenced by the error in the momentum resolution. The observed momentum distribution is the convolution of the resolution function (Gaussian in $1/p$ with an error corresponding to $\sigma_p/p^2 = 10^{-3}$ GeV^{-1}) and the unsmeared "true" momentum distribution. For each momentum bin the ratio of the ansatz function (determined from the best fit by power-law of the smeared distribution) and the observed momentum distribution has been calculated and used as correction factor to take additional smearing into account (Abbott, 2000). A full unfolding procedure for the muon spectrum is in progress.

Because of the symmetry of ALEPH around the beam pipe of the LEP ring, the detector acceptance – even though not uniform – extends down to the horizon, i.e. to zenith angles of 90°. If one wants to compare the spectrum of Fig. 3 with muons at sea-level, one has to consider that the underground spectrum is substantially modified by absorption effects in the overburden. This correction exhibits a strong zenith angle dependence.

Fig. 4 shows the vertical spectrum for single muons in ALEPH corrected for sea-level for a zenith angle range of

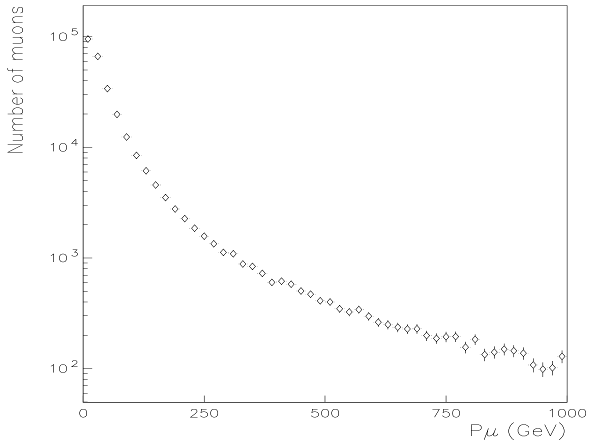

Fig. 3. Underground muon momentum spectrum. The error bars represent the statistical errors.

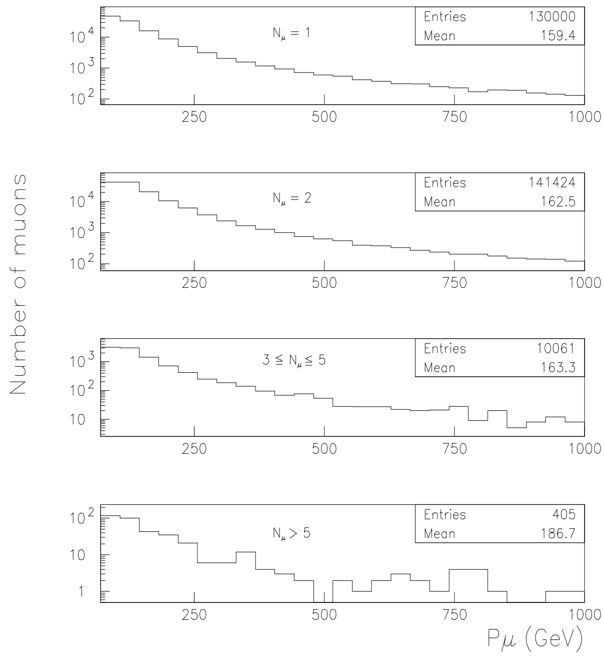

Fig. 5. Muon momentum spectra for different muon bundle multiplicities.

$\pm 10°$ around vertical directions. The correction consisted simply in adding a zenith angle dependent energy loss of 70 GeV/ $\cos\theta$ to the measured energy and applying the unsmearing factor for the momenta as explained previously. The exponent of the corrected vertical sea-level spectrum obtained from a power-law fit to momenta between 200 and 1000 GeV is obtained to be $\gamma = 2.675 \pm 0.008$.

The muon momentum spectra for different bundle multiplicities are shown in Fig. 5. The average muon energy is observed to increase with bundle multiplicity from 159.4 GeV ($N_\mu = 1$) to 186.7 GeV ($N_\mu > 5$), which may indicate an increase in the spectral index of the distribution. This will be analysed further using the full data sample.

This may be just a reflection of the fact that higher multiplicities correspond to higher primary energies. Since the charged particle multiplicity only rises like $\ln E$, the average momentum per particle is expected to increase with primary energy.

The overall charge ratio of all muons recorded in the CosmoALEPH experiment is $N_{\mu^+}/N_{\mu^-} = 1.265 \pm 0.004$ (the error is the statistical uncertainty). This result is consistent with measurements of the muon charge ratio in other experiments (Cecchini, Sioli, 2000).

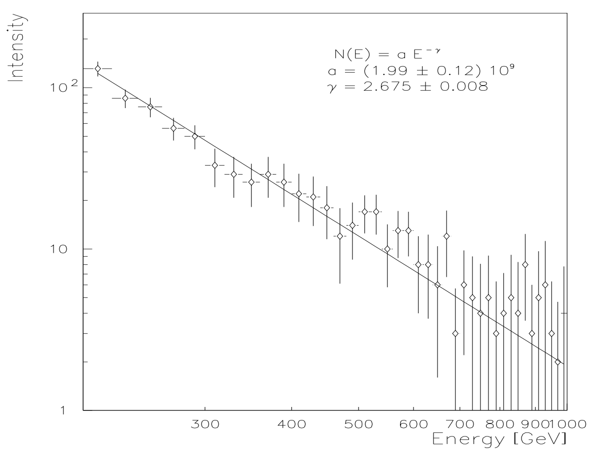

Fig. 4. Vertical sea-level muon momentum spectrum. The solid line is the result of a power-law fit to the data.

The muon multiplicity ditribution carries a lot of information on the chemical composition of primary cosmic rays and their interactions in the atmosphere. Lighter elements will – on average – produce smaller multiplicities than heavier elements. The observed multiplicity is also correlated to the primary energy. A first look at the data (Fig. 6) does not allow us to draw firm conclusions about the chemical abundance of primary cosmic rays or their interaction characteristics. More data – which are available, but have not been analysed yet – and a careful study of Monte Carlo models and detector simulations are necessary to attack these problems.

There seems, however, to be no hint for an excess of events with three muons in ALEPH. Such an excess for triple muons at low separation was claimed by the MACRO collaboration (Battistoni, Scapparone, 1999) being due to direct muon pair production by muons ($\mu + N \rightarrow \mu + N' + \mu^+ + \mu^-$). We have no evidence for this process.

In the dedicated cosmic runs we have observed one high multiplicity event with 75 charged particles in the TPC alone (and many more muons in HCAL). The event display of the muon shower is shown in Fig. 7.

4 Discussion and Outlook

First results from the dedicated runs of the CosmoALEPH experiment have been obtained. The increase of the average

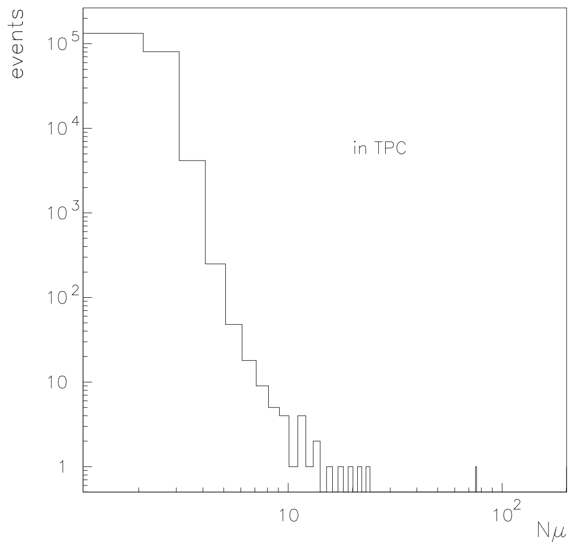

Fig. 6. Muon multiplicity distribution determined from tracks in the ALEPH TPC.

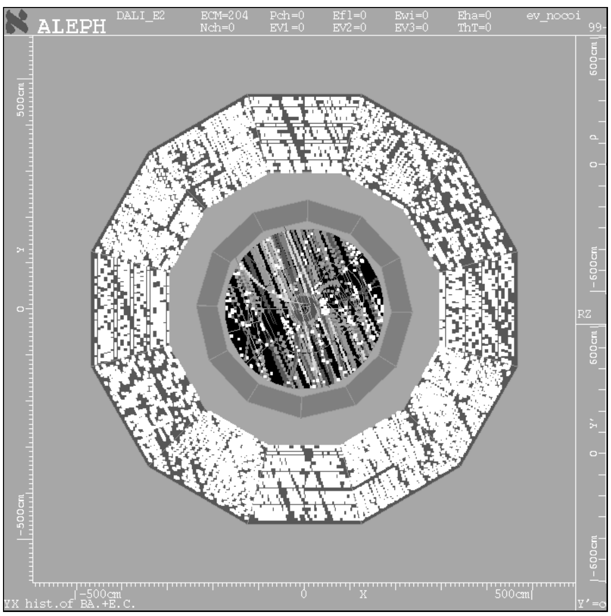

Fig. 7. High multiplicity event in the ALEPH detector. There are 75 charged particles in the TPC alone. The high muon density continues into the hadron calorimeter.

muon momentum with increasing bundle multiplicity is consistent with the standard interaction characteristics of energetic primaries in the atmosphere. For a detailed comparison of our data with different assumptions of the chemical composition of primary cosmic rays in the PeV range and their interaction behaviour in the atmosphere careful Monte Carlo simulations for extensive air showers are being developed. There are various simulations available (Ranft, 1999; Heck, 1998), but before firm conclusions can be drawn, the parameters of these simulations must be tuned to known interaction characteristics and compositions of primary cosmic rays where they are known from direct measurements (Kampert, 2001; Swordy, 1992, 2000). Preliminary our results show general agreement with gross features based on 'classical expectations' from normal extensive air showers developing in the atmosphere.

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