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Cosmic multi-muon events in ALEPH as part of the CosmoLep project

Abstract

This note describes the status of the analysis of the cosmic multi-muon events taken with the ALEPH detector. A preliminary comparison with the air shower Monte Carlo (Corsika) indicates that the rate of the spectacular highest multiplicity muon events cannot be explained. We argue that a dedicated one week cosmic ray run before the next start of LEP will improve the understanding of the data taken during normal LEP runs. A possible scenario for a larger cosmic ray set-up in the Aleph underground area to study further the extension of these multi-muon showers is also briefly sketched.

1 INTRODUCTION

Over the last decades cosmic ray muons have been measured with large area experiments on the surface (ref.1) or deep underground (ref.2). The muons originate from hadronic cascades started by the interaction of cosmic ray particles with the atmosphere. One of the principal goals of these experiments is the measurement of the spectrum and the chemical composition of high-energy (10^{15} to 10^{17} eV) primary nuclei which can be inferred from the muon distribution in the produced extensive air showers (EAS). By now, this composition is known from direct measurements in satellites and balloon experiments only for energies below 10^{14} eV due to rate limitations in the small detectors. Higher energies have to be studied at ground level with large detector arrays. The composition in the accessible energy range of 10^{14} to 10^{17} eV may shed light on the origin of cosmic rays and their acceleration mechanisms. However, the cascade calculations of the EAS need a detailed understanding of the hadronic particle production both at high energies and at very forward angles, which can only be obtained by extrapolation of accelerator data. In fact, most of the relevant kinematical region is unexplored in particle accelerator experiments and therefore new phenomena in high-energy hadronic interactions may also reflect themselves in the muon distributions in EAS. As an example, coherent pion production, disoriented chiral condensate states or large heavy flavour production in the very forward regions would significantly influence the hadronic cascade and hence the multi-muon distributions.

Another aspect is the astrophysical connection. If not explainable by shower simulations the spectacular highest multi-muon events as seen in the LEP detectors could be a first sign for extra-atmospheric radiation created at large distances, e.g. from cosmic beam dumps (ref.3), from interactions of highest-energy cosmic nuclei with interstellar matter or from energetic cosmic dust grains partially disintegrated far from the earth and thereby causing anomalously extended air showers (ref.4). The observations of time correlations in cosmic rays over distances of several hundred kilometers (ref.5) hints at such a possibility since showers with such a large lateral width are not expected from normal EAS at measurable rates. If sufficiently long-living neutral particles or neutral (or almost neutral) dust grains would be involved, these events could even be used as a telescope to search for pointlike sources. Possible candidates for high energy acceleration sources are Supernova Remnants (SNR) , Pulsars and cold microquasars in our galaxy or high energy gamma ray sources and blazars outside of our galaxy.

The use of the sophisticated and large (20 -100 m^2) detectors at CERN for cosmic ray studies has been suggested already a long time ago by several groups (UA1: ref.6; the LEP detectors: ref.7). The underground locations of these detectors between 30 and 140 m is ideal. The electromagnetic and hadronic components of the cosmic ray showers are completely absorbed while the cut-off on the muon momentum varies between 15 and 70 GeV for perpendicular incidence. This is in contrast to the deep underground measurements with TeV cut-offs (e.g. MACRO and Super-Kamiokande) and to the surface experiment with a sizeable hadron punch-through. The LEP detectors with strong magnetic fields, powerful tracking devices and calorimetry allow an excellent muon momentum measurement even for large multiplicities. However, it is worth mentioning that the observed highest-multiplicity cosmic muon events exceed the limit of the LEP detector capacities. Being complemented by additional counter arrays, the LEP detectors allow measurements unprecedented in cosmic ray physics.

The CosmoLep project, recently accepted as a CERN-EP supported activity, proposes to measure cosmic ray muons individually within the four LEP experiments and in coincidence between the experiments. Additional counter arrays mounted around and between the experiments will help to interpret the events. A pilot experiment (ref. 8) has been performed which observed coincidences between the ALEPH detector and scintillation counter arrays up to a distance of 1.15 km. The rate is probably in agreement with the assumption that the observed particles are coming from the same large energetic shower.

Precise muon measurements with a LEP independent read-out have started with the L3 experiment (ref. 9) which is 30 m underground and hence has a muon momentum cut-off of about 15 GeV, to be compared with 70 GeV at the ALEPH location. DELPHI has devoted a one week run to cosmics, unfortunately without a magnetic field. OPAL is interested in participating in a general coincidence measurement. H1 at DESY has started to take muon data with a cut-off of about 5 GeV. All of these future data will help to understand the muon content in cosmic ray showers in the momentum range of 5 to a thousands GeV. At lower muon energies, the Kascade experiment and the MIA-CASA experiment (ref. 1) with their large muon and electron arrays at the surface will complement the information.

2 The ALEPH data

The normal LEP triggers of ALEPH are also sensitive to cosmic muon events, in particular to multi-muons, if they happen to occur in a time window around the beam-crossings. The cosmic events were mainly triggered by energy deposition in the electromagnetic (trigger bit 2) and the hadronic (bit 30) calorimeters. The total of the 1997/98 data has been analyzed. The selection criteria were simple and straight forward: no reconstructed vertex and at least 1 track with momentum $p > 5$ GeV and more than 7 hits in the TPC. Remaining LEP events in this data sample were removed by cutting on the smallest distance of the tracks to the vertex (the cuts were along the beam: ± 2.3 cm and perpendicular: ± 0.2 cm). To avoid loosing high multiplicity events, these cuts were not applied to events with track multiplicities above 15. The highest-multiplicity events overflowed the data buffer and were flagged as DAQ errors. Therefore all DAQ errors were scanned separately.

All events went through the standard Julia reconstruction which, however, splits a cosmic muon track into two, sometimes even three, tracks due to the requirement that LEP event tracks should come from the vertex. If tracks fit together in the x-y plane and the z projection they were merged to one track. The time difference of the muon arrival time and the beam crossing causes an opposite z-shift for tracks crossing the central membrane, which was corrected. This procedure determines the muon arrival time which independently could be measured by the time information from the electromagnetic calorimeter. The obtained time distribution of the cosmic events (flat in the time interval between ~ 1 and 1.5μsec) was used to calculate the duty cycle needed for normalization of the Monte Carlo. To check the above selection a representative subsample of the total data set was scanned as well as all events with multiplicities above 6. The latter scan was used to remove beam gas and muon interaction events which simulate large multiplicities. The direction of the primary particle was estimated by averaging over the directions of all tracks.

Tab.1 summarizes the statistics from the years 1997 and 98, i.e. the data taking time, the duty cycle of the TPC, the sensitive time and the number of events after all cuts. It has to be remarked that the open time of the hadron calorimeter and the muon chambers were much shorter (~ 1 μsec) than the sensitive time of the TPC (~ 2.5 μsec)

	97 data	98 data	97+98
Run time (sec)	3485700	5854320	9340020
Duty cycle	11.0 %	11.6 %	
Effective run time (sec)	383400	681660	1065060
Number of events	150897	222112	373009

Table 1:

which explains why, in most of the events, the hadron calorimeter information is missing. As an example with HCAL information, one of the highest-multiplicity events is displayed in fig.1 with the views along the LEP ring , along the shower direction and the side view also showing the forward hadron calorimeters. The particle density seems not to change over the ALEPH detector.

3 The Corsika Monte Carlo

To study possible anomalies in the data they have to be compared with the expectations from Monte Carlo (M.C.) simulations. Fortunately, with the Corsika program (ref.10) a sophisticated M.C. had been developed over the past years for the Kascade experiment. Since then it has been used in many other cosmic ray experiments. Corsika describes the interaction of the primary particles with the atmosphere and then follows the electromagnetic and hadronic shower cascade down to the observation level. Several input models to describe proton and nuclei interactions with air have been compared. These models use as an input the data from the numerous accelerator experiments which are then extrapolated with some theoretical prejudice. A comparison of the different models (ref. 11) showed that the small differences between the models are irrelevant for our conclusions. In the following we used the QGSJET model. However, it has to be stressed that data at high energies and for the extreme forward cones do not exist and hence there is room for surprises.

Only the hadronic component with the hadron decays into muons was followed in the cascade since the contributions of the electromagnetic component seem to be negligible. A cut on the muon momentum of 70 GeV/$\cos\theta$ was applied to take into account the muon energy loss in the overburden above ALEPH.

M.C. samples with statistics comparable to that of the data were simulated for two incident particle types: protons and Fe-ions. To obtain good statistics over the entire relevant cosmic ray energy range (10^{12} -10^{18} eV) the interactions were generated in primary energy bins and weighted according to the spectrum (fig.2). The shower axes were then scattered over an area of 200 x 200 m^2 and the muons hitting the area of the TPC were registered. The Aleph TPC has a sensitive area of 16m^2 almost independent of the incident zenith angle.

4 Results

After a check of the consistency of the two data samples the 97 and 98 data were combined and compared with the Corsika simulation. The distribution of the muon multiplicity in the TPC is given in fig. 3. The Corsika simulation shown assumes only protons as primary particles and is absolutely normalized according to the effective running time given in Tab.1. It becomes evident that the LEP trigger had a low efficiency of only a few percent for single muons. This was also concluded from the comparison with a dedicated cosmic ray trigger in a test run of 13 hrs in Sept.1998. For multiplicities above two, several LEP triggers start to participate and the trigger efficiency should approach 100%. The agreement between simulation and data (excluding the first two bins) over several orders of magnitude is impressive and gives confidence in simulation and measurement. Furthermore, the absolute muon rate of the simulation (dominated by the single muons) coincides well with scintillation counter measurements of CosmoAleph and with published literature (compiled in ref. 12). Deviations from the M.C. start to develop for multiplicities above 20-30, corresponding to muon densities above $1/m^2$. In particular, the five largest events cannot easily be explained by the Corsika simulation. The event with the largest multiplicity, above 150 muons in one half of the TPC (the other half could not be readout due to data overflow), exhibits a muon density of some $20/m^2$. At the largest multiplicities the simulation is almost an order of magnitude below the data.

This high-multiplicity excess can be better demonstrated with the integral multiplicity distribution in fig.4. which now includes also the simulation for Fe primaries often used as an explanation for high-multiplicity events. Whereas the Fe fraction of primaries at 10^{13} eV is low (about 15%), it might dominate the spectrum around 10^{16} to 10^{17} eV. For the same nucleus energy, the nucleon energy is reduced by a factor A=56. Higher nucleus energies are therefore needed to produce muons above 70 GeV, but then the 56 overlapping interactions (in first approximation) can cause larger multiplicities. This can be seen in fig. 4 where the Fe curve is below the proton curve at small and above it at larger multiplicities. However, even 100% Fe cannot explain the highest-multiplicity events but a Fe- proton-mixture might lead to a better agreement at medium multiplicities (around 20).

For the relevant primary energies the muon densities for Fe- and proton- initiated showers are plotted in fig.5 as a function of the distance to the shower core. Above 10^{14} eV the central muon densities are similar for Fe and proton. But Fe- showers start higher in the atmosphere due to the larger Fe-air cross-section and hence its radial distribution is flatter compared to proton-induced showers. As a consequence, events with large muon densities can be produced over a wider area and are therefore more frequent. A measurement of the radial distribution of the muon densities allows the determination of the primary particle composition up to energies of around 10^{17} eV, only limited by statistics and by the interaction model. The measurement of the muon momenta with the ALEPH detector would further improve the Fe-proton separation. The central muon density grows almost linearly with the primary energy. If close enough to the shower core, choosing multiplicity bins is equivalent to selecting primary energy bins. Fig. 6 shows the contribution of different primary energies to the multiplicity bins.

For each event the direction of the shower axis was determined by averaging over all muon directions in the event. The muons are parallel within a few mrad, dominated by the multiple scattering in the overburden.The momentum cut of the muon increases with its zenith-angle ($1/\cos\theta$). It is therefore interesting to plot the $\cos\theta$ distributions for selected multiplicity bins (fig.7) and to fit them with a powerlaw in the variable $\cos^n\theta$, where the exponent of the fit is coming from the simulation. The higher the multiplicity the steeper is the distribution. It is known from other measurements that the single muon distribution has an exponent of 2 up to muon energies of ~ 1 TeV.

5 Conclusions, outlook and request to ALEPH

The cosmic ray data obtained from the LEP runs in 1997/8 have been analyzed with respect to muon multiplicities and angles. Good agreement with the Corsika M.C. has been obtained except for the largest multiplicities which remain outstanding and may hint at new phenomena if confirmed with larger statistics. The immediate goals are the analysis of the LEP data from the other years and the study of the muon momenta. Unfortunately, the LEP data are incomplete for cosmic ray studies since in most of the events the track information from the hadron calorimeter is missing due to a different time window. A specialized one week run with the ALEPH detector including the read-out of the hadronic calorimeter would therefore be more than welcome. This would help to better understand the data taken with the LEP triggers and also would increase the sensitive area from 16 m^2 (TPC alone) to 50 m^2 (hadron calorimeter included). For trigger studies, one or two days would be needed before the cosmic run. Technical details about trigger masks (for Julia), buffer sizes and timing gates have and will be further discussed with the experts. Such a run could ideally take place before the start-up of LEP in April.

To further study the multi-muon bundles larger detector areas of several hundred square meters would be desirable. The change of the muon densities with the distance from the core would permit separation of Fe from proton primaries and an estimation of the primary particle energy. Are the spectacular high-multiplicity events coming from very high energy primaries, in which case the muons would be distributed over a large area, or are they rare processes in the very forward cones of lower energy interactions and hence a rather collimated phenomenon? Using the drift chambers which recently became available from NOMAD and CHORUS, a set-up with an area of about 200 m^2 could be installed in the free space of the ALEPH underground area. With such an addition to ALEPH, triggered and read-out independently, a 100 times larger data sample could be obtained in less than a year. It also complements the information of the ALEPH-triggered events. Furthermore, about 200 scintillation counters (1m^2 each) will become available from the HEGRA experiment during the summer of this year. Being installed underground at larger distances (up to 1 km) around ALEPH they would improve the shower core and energy determination and would also improve the search for long distance coincidences. Could a common working group with members of ALEPH and CosmoLep be created with the aim to study the implementation of such a cosmic ray detector and to make recommendations to the ALEPH steering committee?

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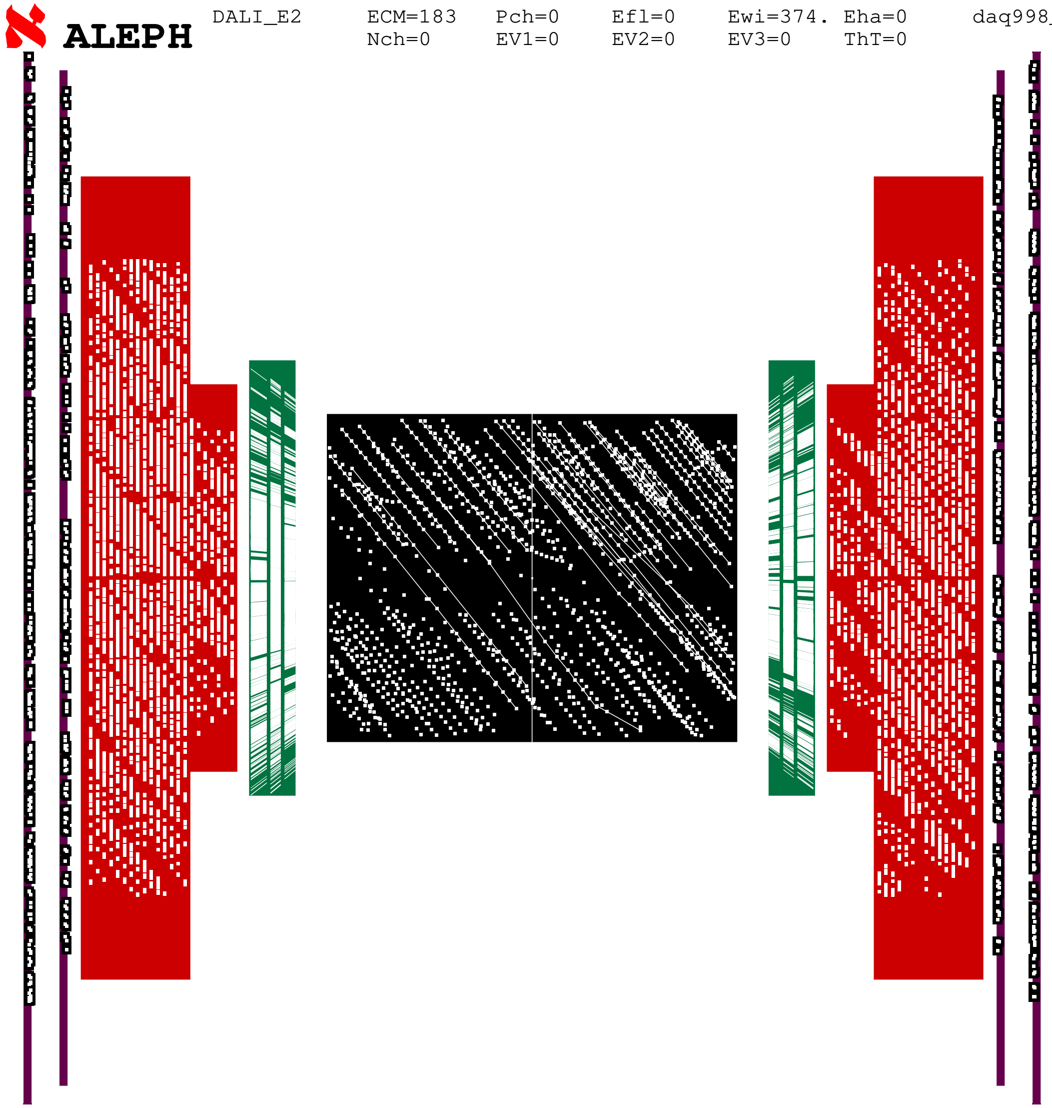

Tracks in TPC = 78

Zenith angle = 40

Right asc. = 7h 40

Declination = 64.3

T0 = 500ns

Fig. 1b

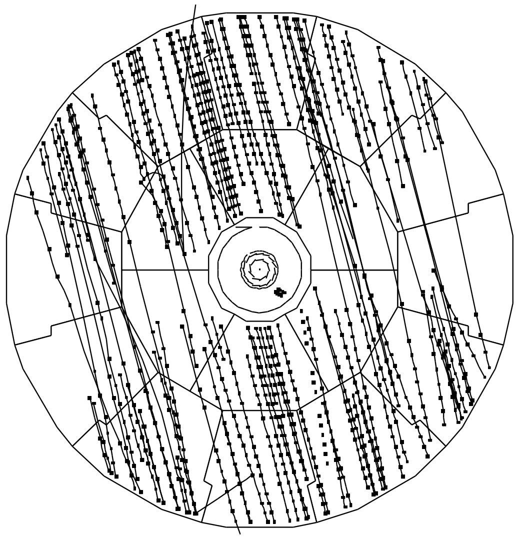

Fig. 1c

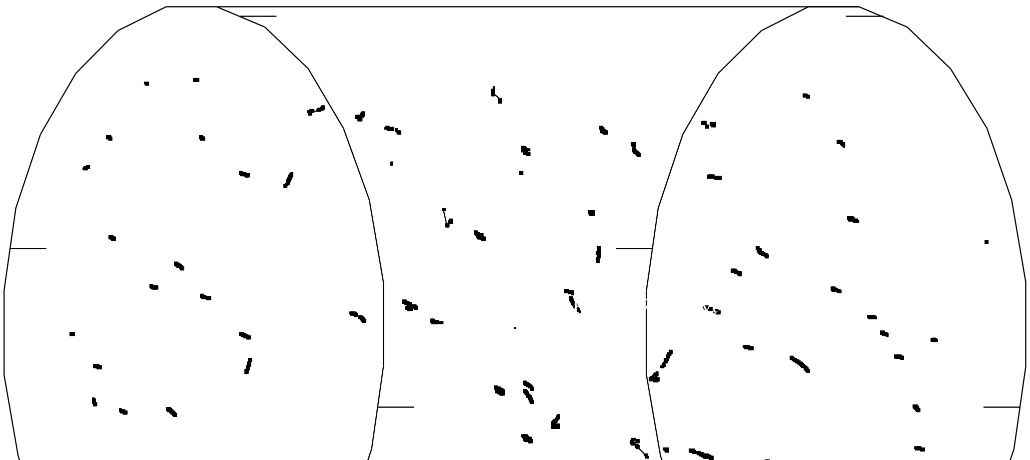

Figure 1: Display of a multi-muon event observed during normal data taking in Aleph: side view a), view along the beam line b) and along the shower axis c).

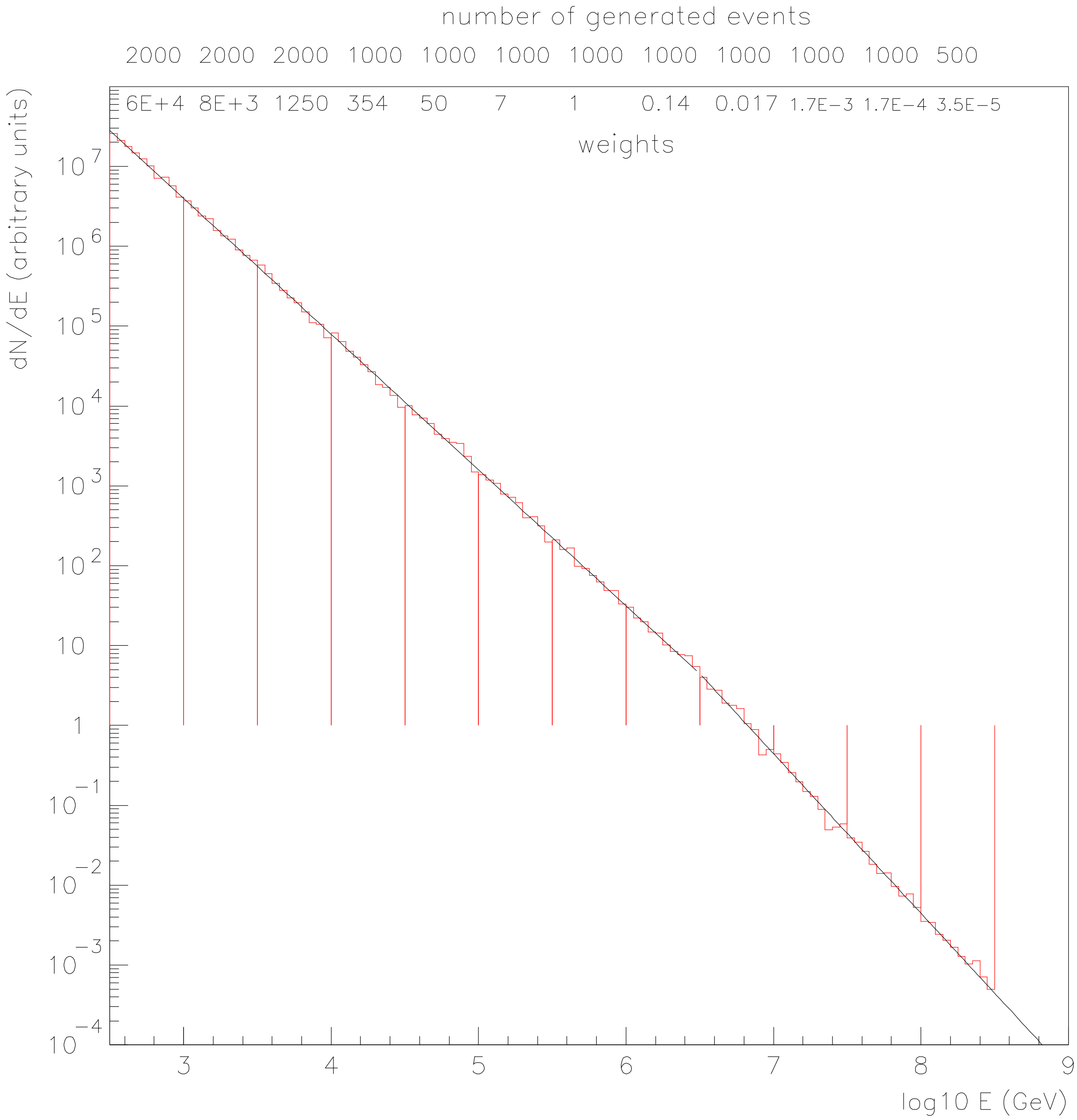

Figure 2: Energy spectrum of primary cosmic rays (arbitrary units) as input to Corsika. The number of generated events per bin and their weight are also given.

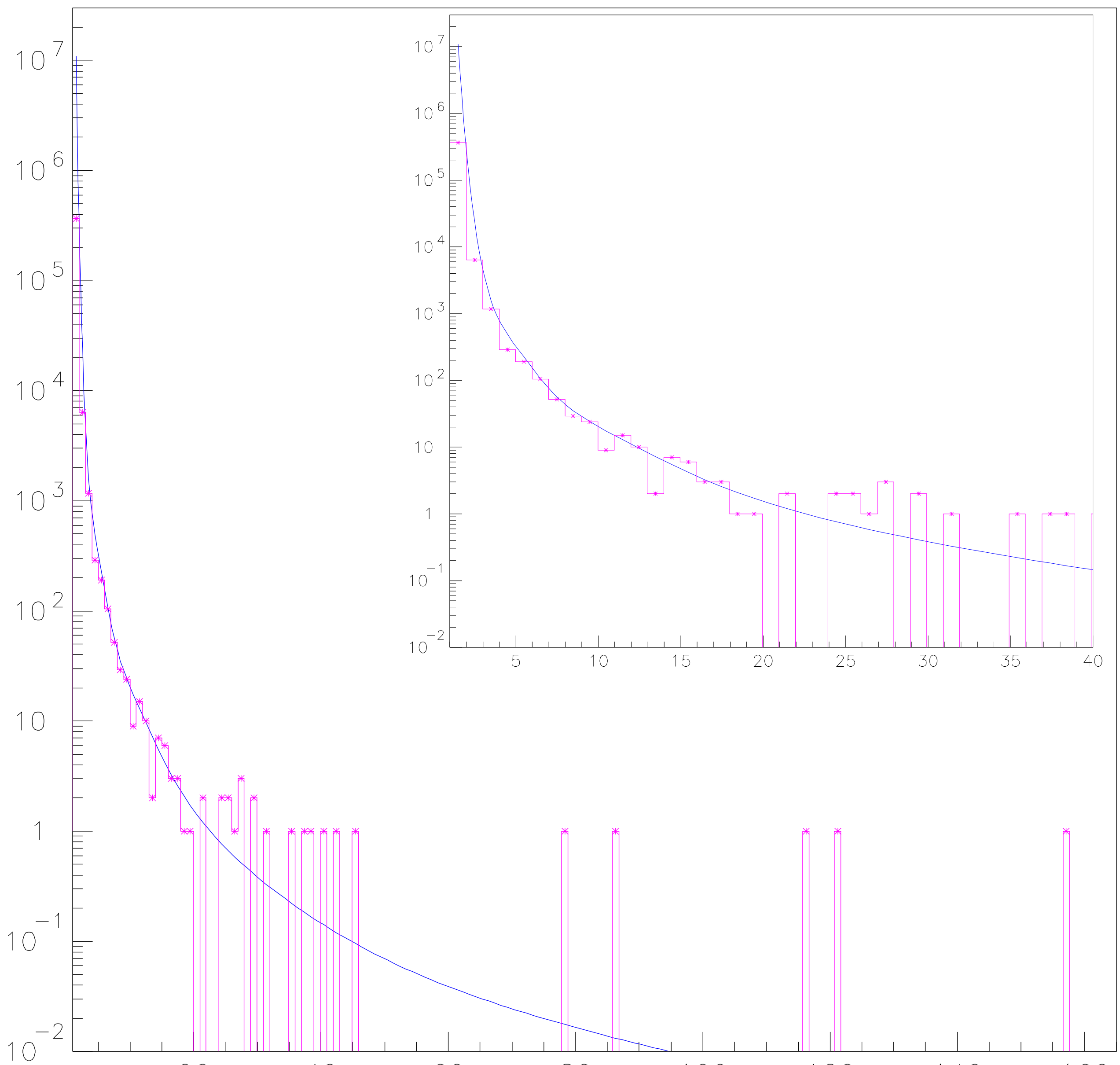

Figure 3: Multiplicity distribution of muons in the TPC for the data (stars) and the Corsika simulation for protons, normalized to the data taking time.

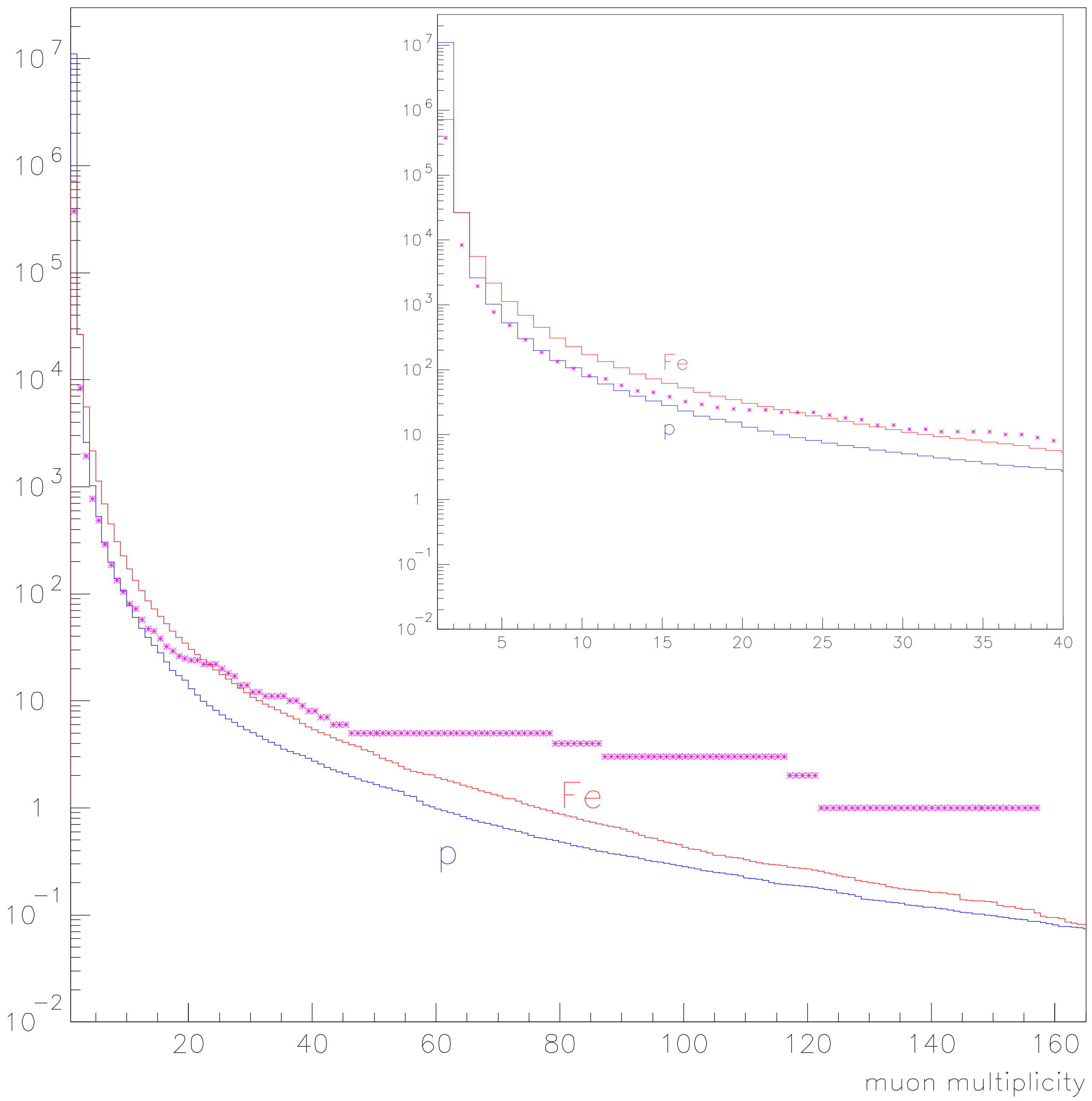

Figure 4: Integral multiplicity distribution of muons in the TPC for the data (stars) and the Corsika simulation for protons and Fe.

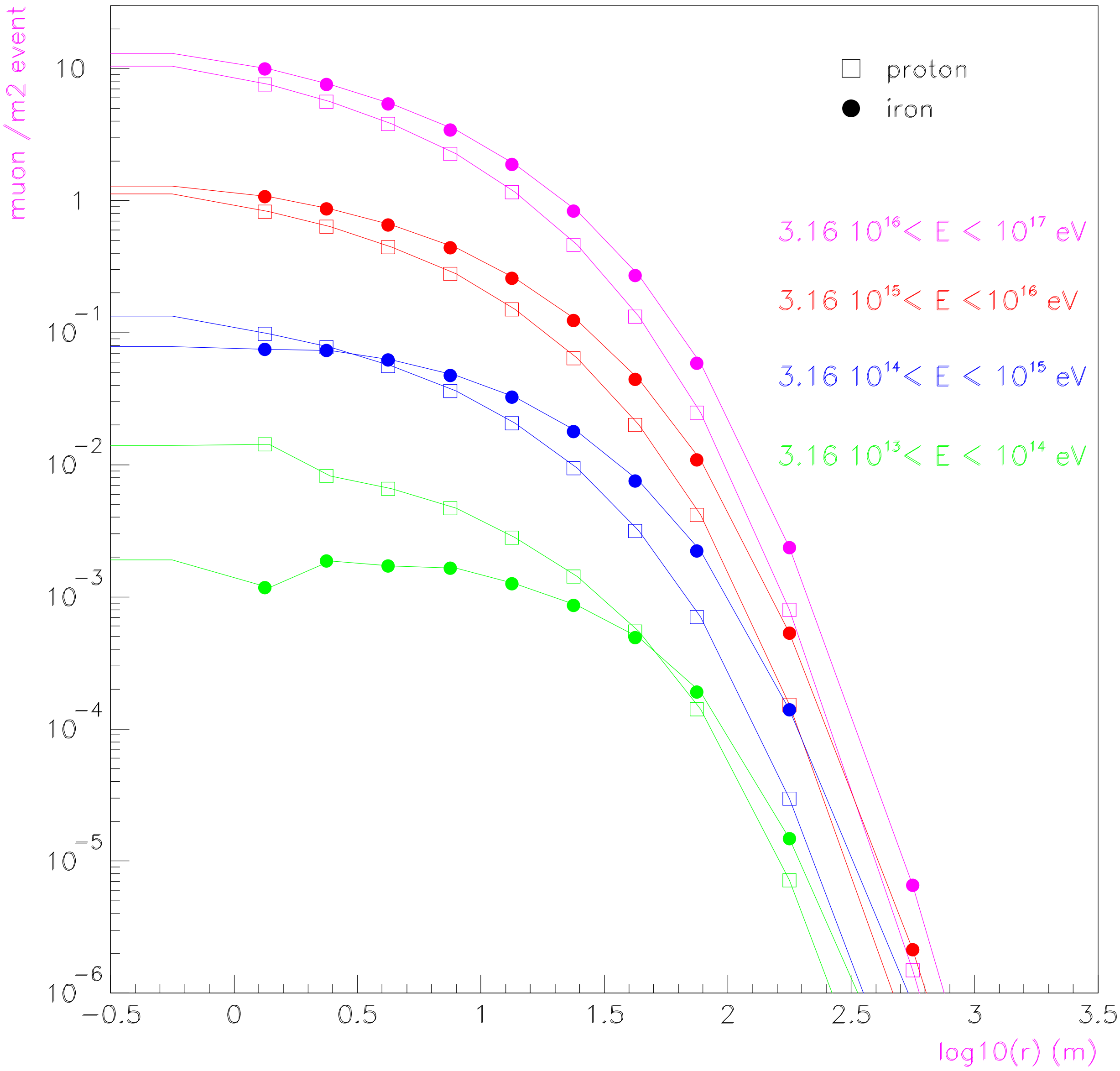

Figure 5: Lateral density distribution of muons for proton- and Fe-induced showers in 4 energy bins.

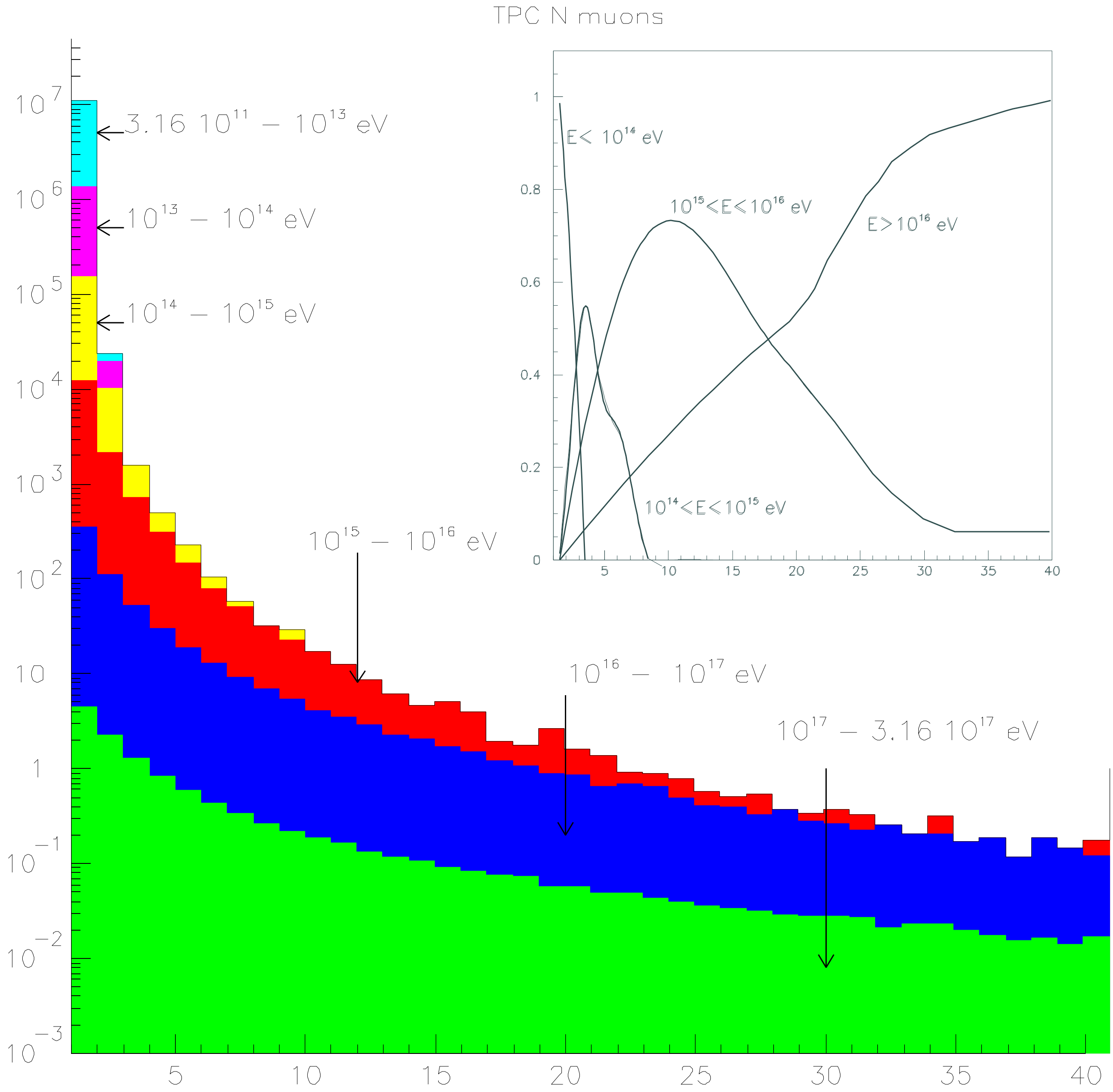

Figure 6: Contributions of the different primary energy intervals to the multiplicity bins. The insert shows the fractional contributions of the energy intervals.

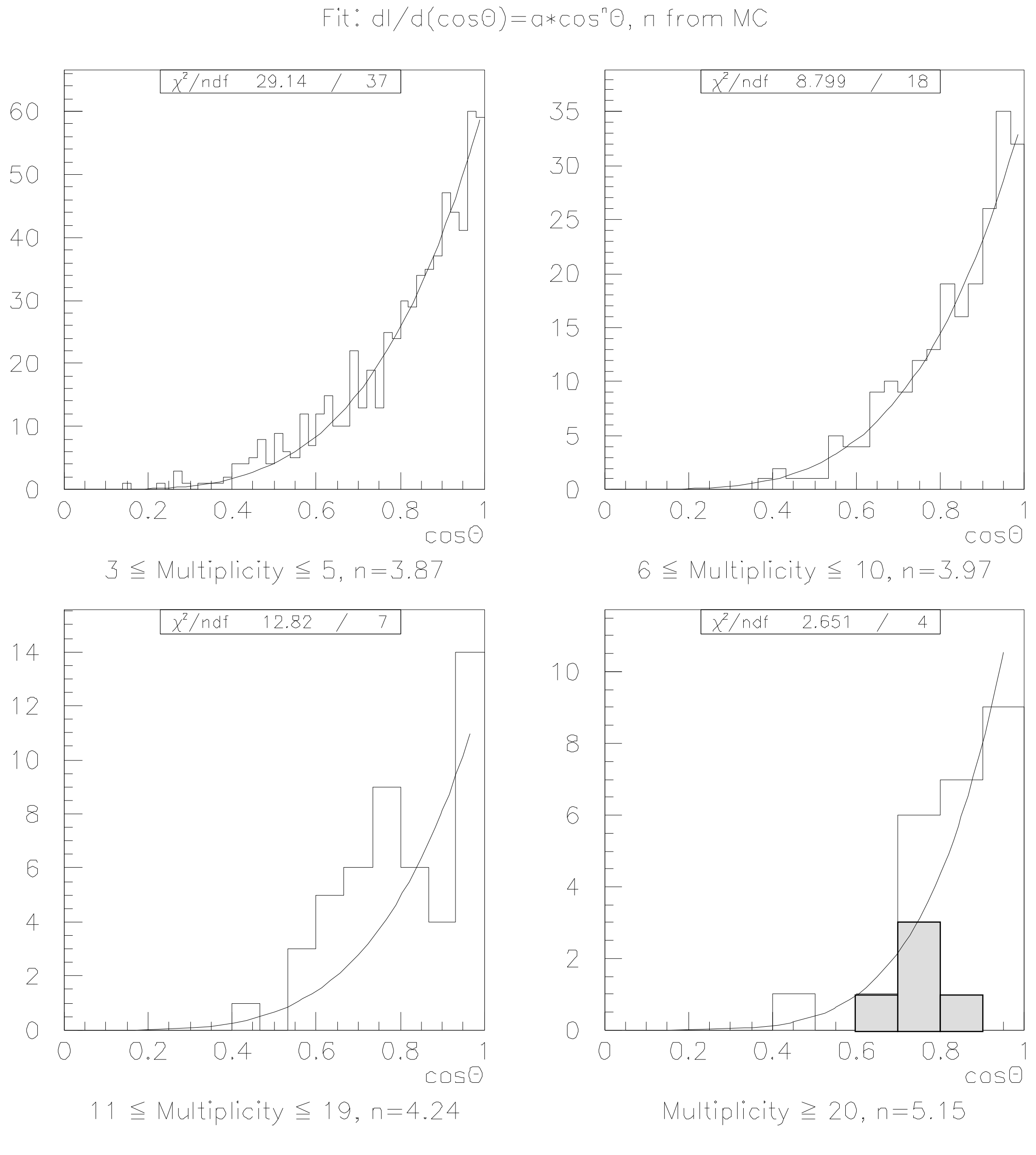

Figure 7: Zenith angle distribution for selected multiplicity bins.The curves (normalized to the data) represent cosnq distributions where the exponent n is taken from Corsika. The five highest-multiplicity events are filled.