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COSMIC MULTI-MUON BUNDLES DETECTED BY DELPHI*

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The DELPHI detector located at LEP accelerator has been used also to measure multi-muon bundles originated from cosmic ray interactions. Two subdetectors — Hadron Calorimeter and Time Projection Chamber, are used for this purpose. The 1999 and 2000 data are analyzed over wide range of multiplicities. The multiplicity distribution is compared with prediction of Monte Carlo simulation based on CORSIKA/QGSJET. The Monte-Carlo does not describe the large multiplicity part of data. Even the extreme assumption on the cosmic ray composition (pure iron nuclei) hardly predicts comparable number of high-multiplicity events.

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1. Detector

The DELPHI (DEtector with Lepton Photon and Hadron Identification) experiment has been installed at CERN largest collider LEP (Large Electron Positron collider). The experiment was designed for studies of e^+e^- collisions. However, cosmic events were also taken in parasitic mode to e^+e^- data. Short calibration runs without LEP beams in the accelerator registered only cosmic data which are also studied in this work.

In 1996 the cathode readout of hadron calorimeter (HCAL) was installed (hatched area in Fig. 1). This device improved granularity of the calorimeter and enabled us to observe and reconstruct multi-muon events. In 1998 the cosmic trigger was implemented in order to improve the quality of events.

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When possible also the time projection chamber (TPC) is used for multi-muon reconstruction (cylinder in the middle of Fig. 1). A thorough description of hadron calorimeter, TPC and other components of DELPHI detector can be found in [1].

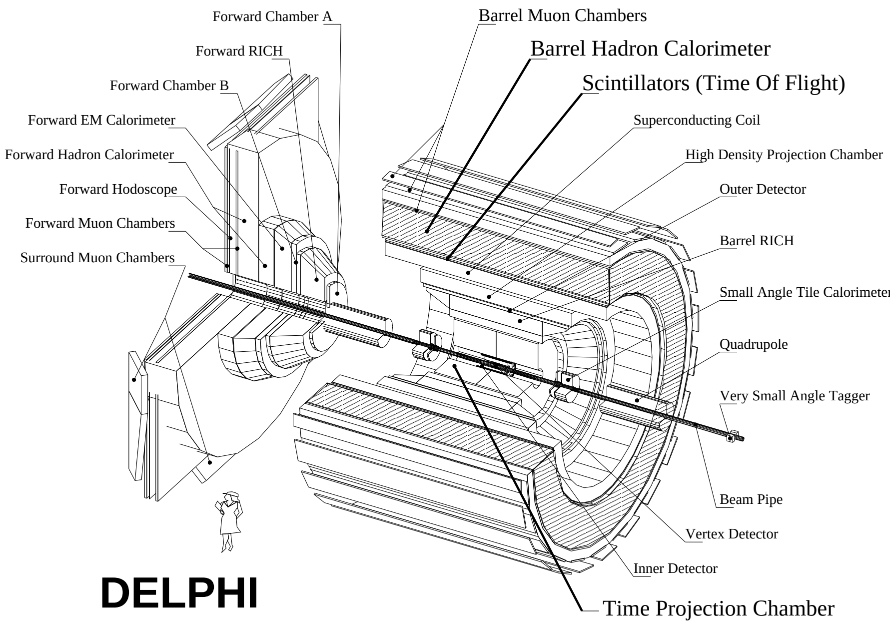

Fig. 1. The layout of DELPHI detector, hatched area represents hadron calorimeter. Subdetectors used in the work are marked by larger letters.

1.1. Location

The apparatus was situated about 100 m underground. The surface altitude is 428 m above the sea level. The composition of the rock above the DELPHI experiment is known from geological survey performed for civil engineering purposes. The simplified picture of the overburden is approximated by 5 major geological layers with different mass densities. The density along the vertical line through the rock varies between 2.2 $\mathrm{g\,cm^{-3}}$ and 2.5 $\mathrm{g\,cm^{-3}}$ depending on the layer. The resulting energy cutoff for vertical cosmic muons is ~ 50 GeV. The detector was placed in large experimental cavern equipped with three access shafts shown in Fig. 2.

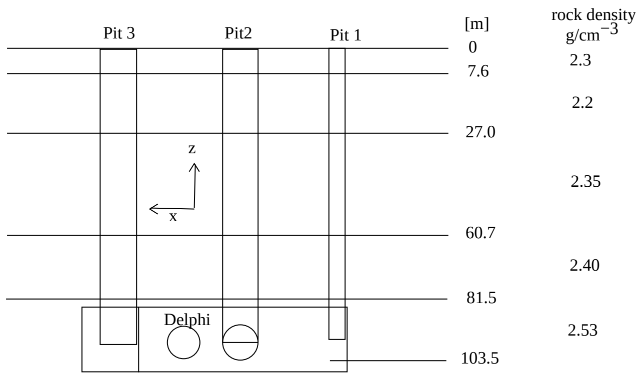

Fig. 2. Schematic picture of rock overburden above DELPHI detector.

1.2. Trigger

To detect cosmic events, DELPHI cosmic trigger has been added to the DELPHI trigger system. It requires 3 active time of flight (TOF) detector sectors to trigger the event. The TOF counters are ready to trigger the event during 4 μs after each beam crossing. The beam crossing frequency depends on the number of e^+e^- bunches in the machine. When running with 4 bunches in the machine, the beam crossing period is 22.23 μs, while in the 8 bunch mode it is the half of that value, *i.e.* 11.12 μs. Consequently, the detector is open to trigger cosmic events in $100 \times 4/22.23 = 18\%$ of the total data taking time in 4 bunch mode and 36% in 8 bunch mode.

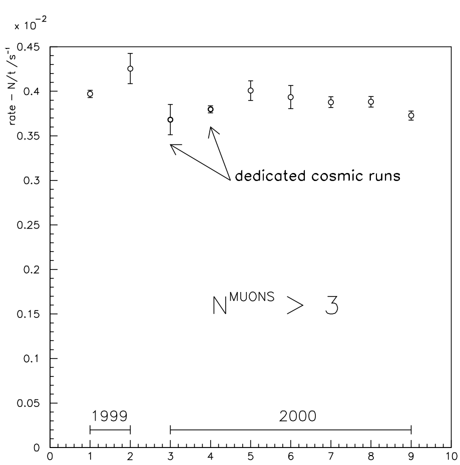

Fig. 3. Event rates ($N_\mu > 3$) for different run periods corresponding to different trigger settings.

The dedicated cosmic runs (without the beams in the collider) have been performed mainly at the beginning of each year. Although there were no e^+e^- collisions, the beam crossing signals (BCOs) were simulated in such a way, that the detector was in fact running in 8 bunch mode.

Fig. 3 plots the rate of events with muon multiplicity higher than 3 for different run periods with different trigger configurations. The event rates are consistent within statistical errors for all the periods when the cosmic trigger was working correctly and permanently. The total time of selected trigger/run periods is 8.66×10^6 s. When corrected to the effect of beam crossings and 4 μs detection window, the total effective live time is $T_{\rm eff} = 1.6 \times 10^6$ s.

1.3. Reconstruction

The track reconstruction in hadron calorimeter is done by ECTANA program [2], which scans signals in barrel modules of HCAL and finds track patterns of hit streamer tubes. This package has advantage that it was developed not only for studying e^+e^- collisions, *i.e.* tracks coming from the interaction point in the middle of the detector, but it has the option for the cosmic events as well. When running in cosmic mode it allows to reconstruct tracks originating anywhere in the calorimeter without explicit cut on the track impact parameter. This is the unique feature of the program, because most of other reconstruction programs at DELPHI were generally developed for e^+e^- events only.

The search for active streamer tubes starts from the outer layers of a given module and continues inwards. A group of at least 4 aligned hits is taken as the track element. The track element is also required to have reasonable density of hits, at least 30% of tubes along the track element have to be active. Furthermore the length of the track has to be larger then 50 cm. All possible hypotheses starting from a certain hit found during the scan are analyzed, they are fitted by a line. The best fit in terms of the number of hits and χ^2 is stored. Before storing the similarity with other hypotheses is checked to avoid double counting.

An example of ECTANA reconstructed event with muon multiplicity ~ 120 is shown in Fig. 4. Most of the tracks are nicely parallel within $\pm 2°$. The event presented in Fig. 4 is one of the highest multiplicity events in data.

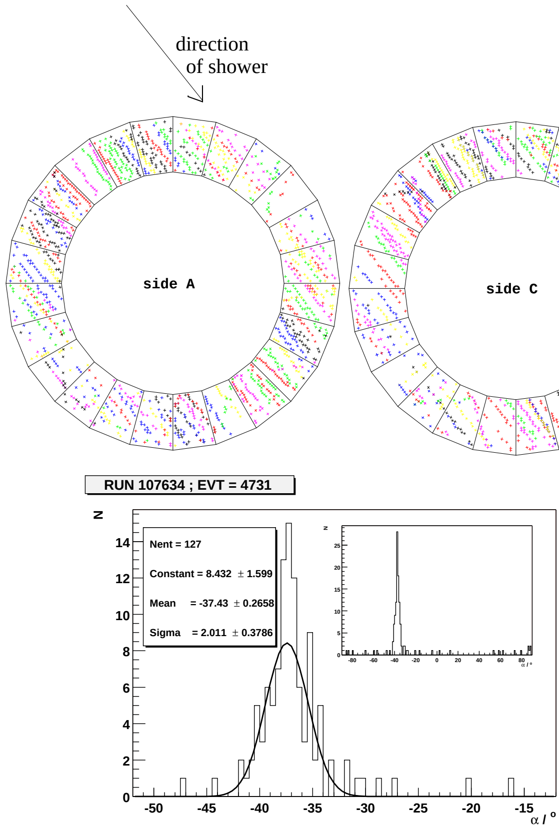

Fig. 4. Example of cosmic event as seen by HCAL cathode readout.

2. Data

The selected data sample consists of 54201 events with muon multiplicities higher than 3 ($N_\mu > 3$). The number of events with at least 30 muons in the apparatus is 1065 as seen from Table I. The scanning of all events

TABLE I

Event statistics in selected data sample.

	number of events
$N_\mu > 3$	54201
$N_\mu \geq 30$	1065
$N_\mu \geq 70$	78
$N_\mu \geq 100$	24

with $N_\mu \geq 30$ has been performed in order to check the events and ensure the rejection of electro-magnetic showers originating from muon interactions in the cavern ceiling or detector material. We found 14 shower like events corresponding to 1.3% of 1065 scanned events. The parallelism of reconstructed tracks was checked also by the cut that requires more than 50% of reconstructed tracks to be aligned within 5° from the mean value of all track angles in the event. The cut rejected the same events as the scanning.

The multiplicity distribution measured in HCAL from selected runs is plotted in Fig. 5. In addition to reconstructed events another 7 events with almost all HCAL tubes active have been detected. These events are proved to be cosmic events because vacancies in almost saturated HCAL can be fitted by parallel lines.

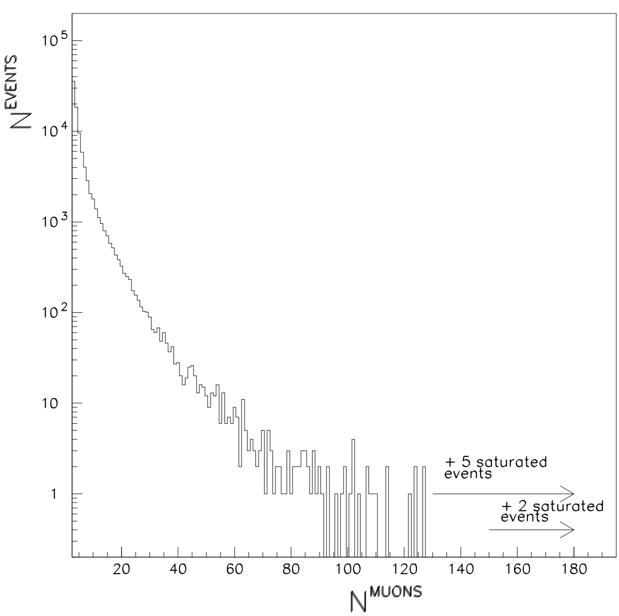

Fig. 5. Muon multiplicity distribution from selected runs.

We have tried to use additional information from muon chambers in order to find approximative estimate of the muon multiplicity from number of anode hits. In case of cosmic events the muon chambers provide information about events with smaller efficiency because their channel readout is active after BCO for shorter time compared to HCAL. As a result only 2 out of these 7 saturated events have full information from muon chambers. Even if the track reconstruction in muon chambers is not available for the multi-muon bundles, the approximative estimation of multiplicity is done according to the total number of anode hits. Sample of events with information from both HCAL and muon chambers has been studied in order to find the correspondence between the HCAL multiplicity and the number of anode hits in muon chambers. Results are plotted in Fig. 6. It seams reasonable to expect that these two events have multiplicity about 150 or higher should it be possible to reconstruct them. Remaining 5 saturated events are just expected to have multiplicity higher than the highest multiplicity reconstructed from unsaturated events ($N_\mu > 127$).

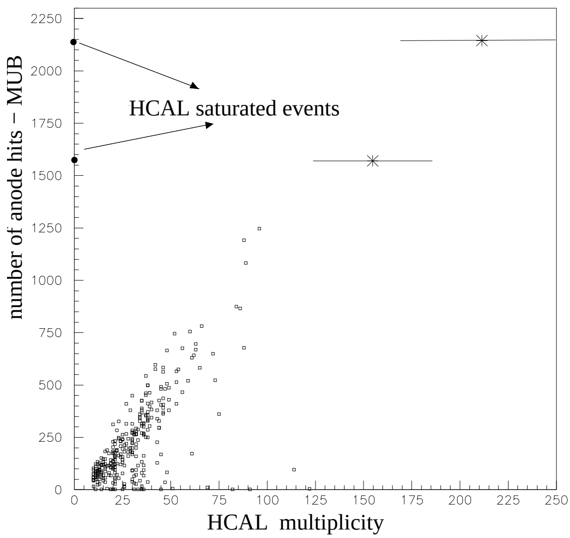

Fig. 6. Correlation between the HCAL multiplicity and the number of anode hits in muon chambers.

3. Simulation

In order to be able to simulate the cosmic ray induced showers in the DELPHI environment, a chain of simulation programs has been set up. The interaction model (QGSJET) is implemented to the CORSIKA [3] simulation package which simulates passage of particles through the atmosphere and shower development. Model of interactions QGSJET is the most common model used in the community of astroparticle physicists, because it can be used at the highest energies and it has been shown that it best describes various correlations between different shower components [4]. The rock above the DELPHI detector is described by 5 layers of materials with different densities in GEANT3 simulation [5]. Full simulation of the detector response is provided by the DELSIM simulation package.

Data sets were simulated for protons and iron nuclei as primary particles in 12 energy ranges: 10^{12}–$3\,10^{12}$ eV, ..., 10^{17} eV, $3\,10^{17}$–10^{18} eV. The energy distribution for all simulated data samples was generated with the energy spectrum E^{-1} in order to obtain sufficient representation of the events at the upper part of the energy spectrum (*i.e.* in the range of large multiplicities). Events were then re-weighted to obey $E^{-2,7}$ (E^{-3}) spectrum at energies below 3×10^{15} eV (above 3×10^{15} eV).

Shower centers were smeared over circular area ($R = 200$ m) around the DELPHI detector and each shower was reused 10 times. Smaller values of radius R lead to increased fraction of lost events with small muon multiplicities. On the other hand, larger radii imply necessity of large data samples to produce enough events with high muon multiplicities. The value $R = 200$ m makes reasonable compromise and ensures fraction of lost events with low multiplicities (3, 4) to be smaller than 0.5%. When starting with too small value of parameter R the produced multiplicity distribution is quiet different from what is obtained at large radii. Fig. 7 shows the characteristics of produced multiplicity distribution in terms of ratios of two subsequent bins in the final distribution. When increasing parameter R the produced multiplicity distribution becomes stable and at $R = 200$ m the stability for $N_\mu > 3$ is guaranteed at all energies.

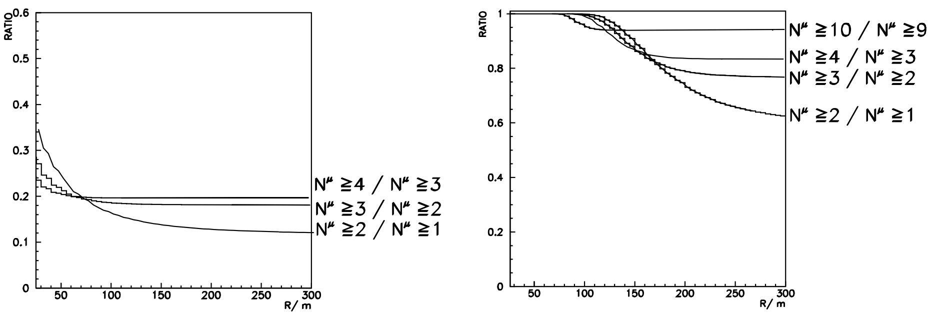

Fig. 7. Ratio of two subsequent bins in integral multiplicity distribution (see legend on the right side of the plots) as a function parameter R. Two energies 10^{14} eV (left) and 10^{17} eV (right) for iron primary are chosen. $R > 200$ guarantees the stable shape of multiplicity distribution for $N_\mu > 3$.

In the events with large multiplicity some muons in HCAL overlap and consequently the reconstructed multiplicity is smaller than the real one. This shadowing effect is demonstrated in Fig. 8 where the reconstructed multiplicity is plotted as a function of the number of muons entering the calorimeter. The shadowing effect requires detailed simulation of DELPHI HCAL. This was done with the DELSIM simulation package and the MC simulation is compared with the data in terms of reconstructed multiplicity, *i.e.* when the shadowing effect is already taken into account.

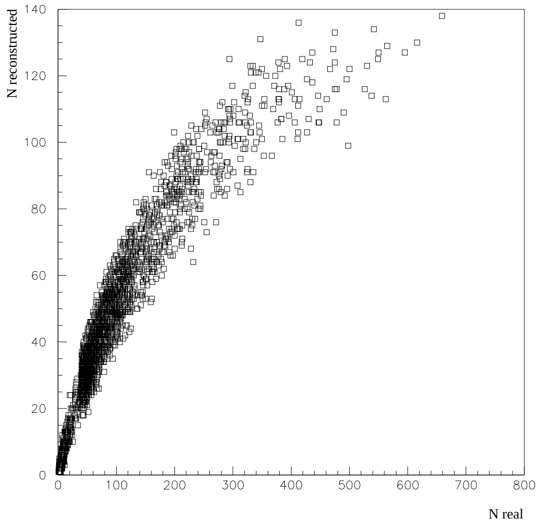

Fig. 8. The proportionality between real and reconstructed number of muons.

The results of MC simulation in case of iron primary particles with different energies are presented in Fig. 9.

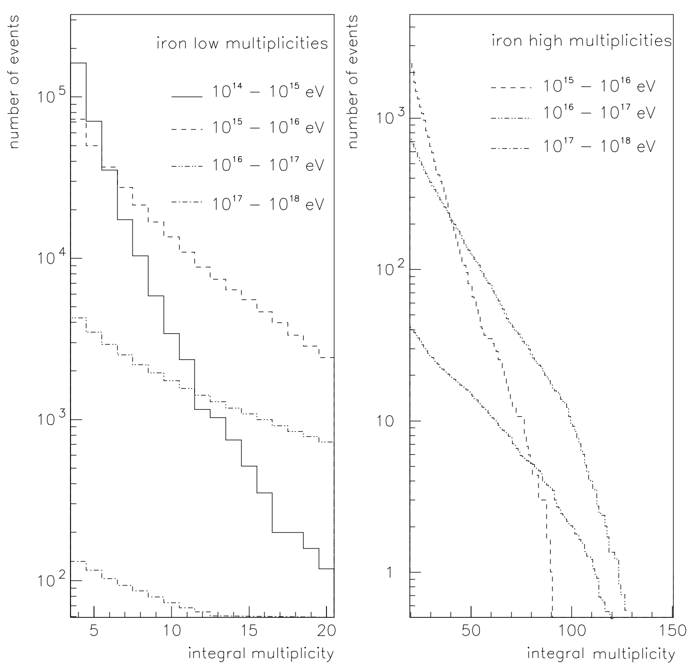

Fig. 9. Contribution of different energy intervals to the final integral multiplicity distribution. Primary particles are iron nuclei.

4. Results

The comparison between MC prediction for protons and iron nuclei as primary particles with the measured data is plotted in Fig. 10. The simulated histograms correspond to the absolute number particles that would reach circular area (with $R = 200$ m) during the data taking time of 1.6×10^6 s. The

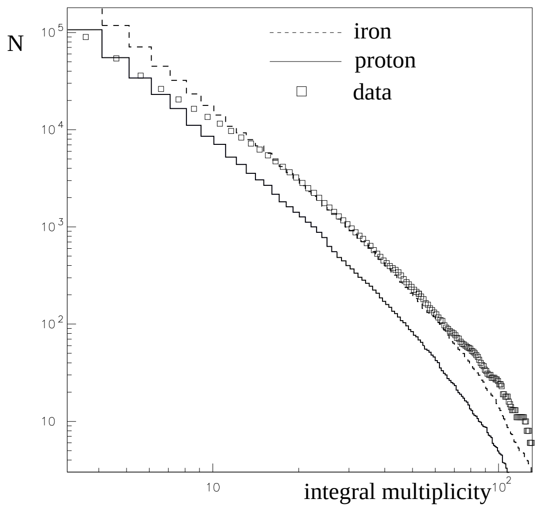

Fig. 10. Integral multiplicity for MC protons, irons and the data.

data are compatible with the proton spectrum in first several bins at low multiplicities. In the multiplicity range 10–20 data could be described as a mixture of light (proton) and heavy (iron) component of primary cosmic rays. Higher multiplicities could be described only by the extreme assumption that all primary particles are iron nuclei. At the highest multiplicities even the MC prediction for iron nuclei is not sufficient to reproduce the measurement.

5. Conclusions

The cosmic multi-muon data registered at the DELPHI experiment are analyzed. The distribution of muon multiplicities is measured. Only up to the multiplicity ~ 20 the data can be understood in terms of reasonable composition of primary cosmic rays. Medium multiplicities $N_\mu > 20$ could be described only by the extreme assumption that all primary particles are iron nuclei. At the highest multiplicities even the MC prediction for iron nuclei is not sufficient to reproduce the measurement.

Qualitatively similar results are obtained from another LEP experiments COSMO-ALEPH and L3+C. COSMO-ALEPH group [6] also observed the event excess at the highest multiplicities, however the medium multiplicities were consistent with reasonable mixture of iron and proton. L3+C precisely measured the spectrum of muon momenta in energy range 20 GeV–2 TeV using reconstruction of bended tracks in muon chambers [7]. They were also able to reconstruct multi-muon events up to the multiplicity ~ 30. It was found that dominance of heavy ions (iron) would be necessary to describe their data. In terms of multiplicity distribution, pure iron component was consistent with the data in almost whole range of multiplicities [8, 9]. The necessity of unnatural assumption that almost all primary particles are heavy nuclei was typical not only for QGSJET model but also for other models used (SIBYLL, VENUS, NEXUS).

The three experiments used different measurement techniques: COSMO-ALEPH reconstructed muons using their large volume TPC, DELPHI main reconstruction detector was HCAL with fine granularity, while in case of L3+C the muon chambers were of the greatest importance. These experiments differ also by the thickness of overburden: L3 — 30 m, DELPHI — 100 m and ALEPH — 140 m. Consequently it is difficult to make direct comparison of individual results. However, all experiments deal with the same problems when comparing the amount of observed multi-muon events with the MC simulations based on QGSJET interaction model. The source of this discrepancy may come directly from the interaction model.

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