1 Motivation for the COSMOLEP experiment

COSMOLEP is dedicated to the study of multi-muon bundles arising from cosmic ray air showers. It will perform unique measurements complementary to existing or planned cosmic ray experiments. Significant motivation for the experiment is provided by preliminary data acquired by the ALEPH detector, indicating the possible existence of anomalous production of very high multiplicity events. COSMOLEP will provide information about the radial distribution and muon momentum and transverse momentum distributions of such events, as well as about the generic lower-multiplicity events. While COSMOLEP is not designed to give the definitive answer, in isolation, to questions such as the cosmic ray composition as a function of energy, the data acquired will allow stringent checks of any proposed solution of this problem.

Why have we proposed this experiment? The problems related to the precise measurement of the cosmic ray flux in the vicinity of the knee, and in particular the particle composition, have not been satisfactorily solved.

Take for example the Kascade results from Utah: the energy dependence of the composition, expressed by the variable $< lnA >$, is significantly different for ground hadron measurements and for electron-muon measurements. This discrepancy may result from the poor knowledge about the forward physics. Indeed, there are no accelerator data for particle production in the very small forward angles and in the energy region which dominate the cosmic ray interactions. Accordingly, the interpretation of the cosmic ray data depends crucially on models extrapolated well beyond the range in which they have been tuned or tested. While it may be that some of the models will converge on a common interpretation, they may still be incorrect. The greater the diversity of the measurements which the models must confront, the greater the likelihood of converging to the correct answer.

We therefore believe that as many complementary measurements as possible in different kinematical regions should be made to understand more about the forward particle production and hence about the cosmic spectrum, and to provide cross-checks on the interpretation of the results. We believe that we will be able to bring measurements of new quantities to the table which, taken together with what is already known and is currently being learned, will prove very useful in disentangling the various issues with confidence.

The unique contributions which COSMOLEP can make to cosmic ray studies result from three characteristics of the experiment:

(1) The experiment is located at a depth corresponding to a momentum cutoff of approximately 70 GeV. This is in contrast to other cosmic ray muon measurements, which are typically at either very shallow depths, with cutoffs of the order of a few GeV, or very deep with cutoffs of the order of 1 TeV. The COSMOLEP cutoff is well-matched to the characteristic energy at which pions have similar probabilities for interaction and decay at the top of the atmosphere. Consequently, measurements by COSMOLEP are sensitive to very different convolutions of particle production than those performed by other experiments.

(2) The ALEPH TPC provides exquisite pattern recognition, tracking resolution and momentum measurement, and is a unique tool for cosmic ray experiments giving information previously unavailable in cosmic ray studies.

(3) The proposed muon array will use large-area muon chambers with good multi-particle capability (16 hits per wire), 1 mm resolution, and the ability to reconstruct some 100 particles per chamber if the incident angle is known. Used together with the ALEPH detector, this will provide unprecedented measurements of cosmic ray muons.

In order to benchmark the performance of our detector, we have carried out extensive Monte-Carlo simulations using CORSIKA, a sophisticated program developed by the KASCADE group. As with all Monte-Carlo simulations which require extrapolation to unexplored regions of phase space, considerable skepticism is warranted regarding any particular details. Rather, our studies at this stage are designed to illustrate the capabilities of the detector.

We have demonstrated the ability of the detector to locate the shower cores with good precision throughout the muon array. This permits detailed analysis of the radial distribution of the muon bundles, and, together with information from the ALEPH detector, will yield some information about the p_t distribution. Within the context of the CORSIKA Monte-Carlo, we have demonstrated some ability to discriminate between primaries of different composition, as well as to characterize the energy spectrum.

Final analysis of the actual data will benefit from the fact that the total data base of the field is rapidly evolving, providing impetus to similar evolution (and perhaps convergence?) of the various Monte-Carlos. Because of the unique character of the data provided by COSMOLEP, we expect to play an important role in validating any such convergence.

The dramatic high multiplicity muon events reported from the earlier studies using ALEPH will be a major focus of COSMOLEP. Such events might be related to changes in the character of multi-particle production in regions of phase space not explored by accelerator experiments. (Theoretical suggestions for such changes were reviewed in the FELIX LoI.) The larger size of the muon array together with longer measurement time will increase the statistics of the existing data set by a factor of 200, while providing significant information in each event beyond that of the ALEPH detector alone. Regardless of the eventual understanding of these events, COSMOLEP will significantly improve their characterization.

COSMOLEP is surely not the best experiment that one can imagine in an ideal world. Rather, it aims to use available resources and a limited window of opportunity to provide unique data, and to better characterize a provocative anomaly. There is no other way to obtain this data in the foreseeable future.

There is, however, a way to improve COSMOLEP if it is permitted to run after the end of LEP operation. This alone would permit increased statistics, but also opens the possibility of adding a large surface array to obtain information about the electromagnetic component of the showers which cause the muon bundles. Such an addition to COSMOLEP is beyond the financial scope of the present proposal, but would represent a dream of many cosmic ray physicists.

2 Questions of the referees

1. Introduction: There is no doubt that the possibility of measuring muons in the central region (core) of extensive air showers with a combination of the ALEPH detector and additional tracking detectors would be an extremely exciting one if the detector system was located within a conventional shower array such as KASCADE, or, even better, one which also had the capability of measuring air-Cerenkov signals. Unfortunately this is not possible in the near future and therefore the proposal must, we believe, be evaluated in comparison with the present state of work in the knee energy region. This has advanced significantly recently, as reported at the recent International Cosmic Ray conference in Salt Lake City.

2. Energy Spectrum: The energy spectrum is deduced by means of the application of model calculations to observables at the ground. From a typical experiment the systematic uncertainty arising from the different models is around 15% while between experiments there are differences as great as 50%. A summary was given at the Durban conference (Watson: 25th ICRC Proceedings Vol 8 p 257 fig 7). The new data are in the available proceedings of the Salt Lake City ICRC (e.g. Vol 2 p 125, p 156, p 159, 191, 199). In the proposal it is claimed that the muon density above 70 GeV within about 10 m is a measure of the primary energy independent of the mass. This is an interesting proposal but it is necessary to quantify the precision with which it is possible to measure energy (what is the fractional error in E?) and what is the systematic error in the spectrum resulting from the absence of knowledge of the mass composition or the correct model. Can this method improve on what has been done most recently by shower arrays?

3. Mass composition: First it should be noted that the mass composition is unlikely to be a mixture simply of protons and iron. At 100 TeV the balloon measurements (see Watson loc. cit. for details) have shown that there is protons, helium, C-N-O, Ne-Si and Fe present in the ratios 0.28:.21:0.35: 0.04:0.12. The accuracy is not high and $< lnA >$ is estimated as 1.8 $\pm$ 0.4 with the (p + He)/All ratio 0.54 $\pm$ 0.09. Above 1 PeV there are only four nuclei which have been recorded directly: 1 p, 1 He and 1 in each of the C-N-O and Fe-Group. There has been much effort put into mass composition measurements in recent years (see SLC proceedings Vol 2 p 125, p 152 and p 159). There is evidence that near the knee the mass spectrum becomes lighter - perhaps over a range of a factor of three in energy near the knee - before becoming heavier again. A model by Swordy (Rome Conference 1995 and reference already passed to the proposers) appears to agree with these measurements. How much better will the information be from the COSMOLEP project? Can the postulated mass change be resolved and can the present experimental results be confirmed?

4. LEPC wish to have details as to how this experiment is an improvement over L3C.

5. LEPC wish to have more details of the strength and commitment of the collaboration.

6. The trigger is based soley on muons. It must be shown that there is not a bias in favour of Fe in the energy range of interest.

7. The simulations studies appear to consider only propagation through the atmosphere, with an energy threshold above which all muons are assumed to reach the detector. What is the effect of interactions of high energy shower particles in the rock? In addition to the hadrons, which may be fully absorbed, the high energy muons in the shower core would be expected occasionally to interact and generate punch-through in the detector. In addition to a possible contribution to the measured multiplicity, a local subshower could affect the core location scheme (Fig. 4.5). Could this contribute to the tail of high multiplicity events in Fig. 2.3? (One notes that the excess is mostly for large-angle events.)

8. What fraction of the time will the Aleph detector be running in coincidence with the muon array?

3 Answers

Ad 2, 3 and 6

In order to answer the referee's questions, the response of the COSMOLEP set-up to multi-muon bundles has been simulated with the CORSIKA Monte-Carlo developed by the Kascade group. QGSJET was used as a generator; comparisons with other models will follow. In most of the plots proton and iron induced muon showers are compared, but we also carried out some simulations for other elements such as He, C-N-O and Si. A principle aim of these simulations was to explore our ability to measure the cosmic ray energy spectrum and the composition, as requested in the first two questions of the referees. As already stressed in the introduction, these measurements are by far not the only motivation for COSMOLEP. On the contrary, they have to be seen in connection with results from already existing cosmic ray experiments.

We start the discussion with the most inclusive distributions and will then proceed to the more specific reconstruction of individual events. Most of the plots have been normalized to a data taking time of 2 10^7 sec which we hope to achieve in the year 2000.

	p	He	O	Si	Fe
Jacee (all energies)	.24	.31	.21	.12	.12
Swordy					
($10^{14} < E < 3 \cdot 10^{15}$ eV)	.35	.28	.14	.1	.13
($3 \cdot 10^{15} < E < 10^{16}$ eV)	.22	.23	.2	.15	.2
($10^{16} < E < 10^{17}$ eV)	.2	.2	.16	.15	.29

Table 1: Composition models used in the simulations.

The differential and integral multiplicity distributions for the proposed muon array (sketched in Fig. 1) and for an individual muon module of 20 m^2 are given in Figs 3 and 2. The energy interval considered ranges between 10^{14} and 10^{17} eV and the zenith angle between 0 and 60 degree. A trigger condition of at least four scintillation counter hits has been applied. The higher the primary energy, the further away from the array the shower core can be and still contribute to the trigger. The distributions are calculated for five primary elements (p, He, C-N-O, Si and Fe). The multiplicity distribution will give a first indication to the particle composition. If the primary composition becomes heavier with increasing energy and hence multiplicity the measured distribution should shift gradually from the lower to the upper curves with increasing multiplicity. Fig. 4 shows a comparison of two particle composition models (described in Tab.1): the "Jacee" composition, as it was measured at energies below 10^{14} eV, and the model of Swordy for the higher energy range. The statistics should be sufficient to get some clues about the particle composition. About 200 events will exhibit a multiplicity in the array exceeding 200 muons, corresponding to energies above 10^{16} eV.

Fig. 2 shows the multiplicity distribution in one of the modules. It demonstrates that, in the extreme case, the chambers have to identify on the order of 100 muons in one chamber. If the high-multiplicity excess seen in the ALEPH TPC would persist we should observe 500 to 1000 events with these high muon densities, a good sample for the study of their properties, e.g. the radial distribution.

We now turn to the reconstruction of individual events. Already in the proposal, it was demonstrated that the shower core can be reconstructed within a few meters if it falls within the array. The core position could be further improved if the individual muon coordinates rather than the global chamber multiplicity will be used. Subsequently, we consider the cases where the shower cores are situated around the center of module 4 (see Fig. 1). The primary energy can be calculated either from the muon number (N_{max}) in the chamber hit by the core or from the total number of muons (N_{tot}) in the array, assuming the primary particle type is known. Fig. 5 shows the dependence of theses two quantities on the primary energy for proton and iron primaries. The indicated errors present the fluctuation of a single measurement. They are larger than Gaussian ones and decrease only slightly with energy. The energies for proton primaries were reconstructed from the total number of muons for three energy intervals. The relative error of the energy determination is plotted in Fig. 6. For the same muon multiplicity N_{max} (N_{tot}), the reconstructed energy for iron primaries would be 25% (40%) lower. For the determination of the energy spectrum the primary particle should therefore be known. Under the assumption of a pure proton sample, the energy spectrum was reconstructed using the total number of muons in the array. In Fig. 7 the input spectrum (solid line) is compared with the spectrum fulfilling the trigger condition (dotted) of at least four fired counters and with the measured spectrum after energy smearing. To answer question 6 of the referees, there is a small ($\sim$ 10%) bias towards iron at the lowest energy of 10^{15} eV due to the trigger condition, which can be calculated, and no bias at energies above 3 10^{15} eV.

The identification of proton and iron primaries (the two extreme cases) on an event-to-event basis is difficult but necessary for the individual energy determination. It is based on the difference of the radial muon density distribution which is flatter for iron primaries than for protons. This is a consequence of the higher starting point of the shower and the lower average momentum in iron interactions. For a given core position and for different energies, a normalized multiplicity distribution in each chamber is simulated for proton and iron primaries. The multiplicities are then rescaled such that the average multiplicity in the core is the same for proton and iron induced showers. In this way, the identification is only based on the radial muon distribution. These masks are then applied to the individual events and a likelihood is calculated for the proton and iron assumption. Fig. 9 shows in a two-dimensional plot these two likelihood values per event for protons and iron as primaries. Separating the two distributions by the indicated lines we are able to identify correctly 86% (81%) of the protons and 85% (82%) of the iron for 10^{16} eV (3 10^{15} eV).

Further studies have still to be made to investigate the interplay of the identification method and the energy determination. To get a feeling for these effects, we simulated the spectrum from 10^{15} eV to 3 10^{16} eV and assumed a ratio of protons to iron of 1.28 , corresponding to (p + He)/(Si + Fe) of Swordy in the energy interval of 0.3 - 1. 10^{16} eV. The primary energy was reconstructed from the total number in the array for proton and iron as primary particles. Using the corresponding masks the likelihood for proton and iron was calculated and the same cut as in Fig. 9 was applied for identification. Fig. 8 shows the reconstructed spectrum for protons and for iron. The input ratio of 1.28 has changed to 1.41.

Obviously, additional detectors, on the ground level or further away underground, would add valuable information either about the primary energy or particle which would make the reconstruction more reliable.

Ad 4

L3-C is a cosmic ray experiment at LEP. Using newly installed trigger counters on top of L3 and an independent read-out system, they run in parallel with L3, triggering on cosmic ray muons. The experiment is optimized for the precision measurement of muon momenta which they achieve using three multi-chamber stations separated by several meters in a modest magnetic field. In addition, the collaboration is preparing to install scintillation counters above ground, below the roof of the L3 access hall. This array will provide information complementary to the muon measurements below ground. L3-C is not well-optimized for the high multiplicity multi-muon studies proposed for COSMOLEP. Indeed, according to L3-C claims, they will not be easily able to measure muon bundles with multiplicities above a few muons over their detection area of more than 100 m^2 This is a consequence of the chamber arrangement, the read-out along the beams over about 11 m, and the left-right ambiguity inherent in their drift chambers. Furthermore, since L3 is at a depth of only 30 m, corresponding to a lower momentum cut-off of about 15 GeV, muon densities will be significantly higher than at ALEPH where the cutoff is about 70 GeV. This makes the pattern recognition problem in the highest multiplicity events dramatically more difficult. L3-C is also hampered by the fact that there is no space in the underground area to install further chambers for the radial studies of muon showers. Finally, there is a possibility that COSMOLEP will be able to run during at least part of the period between

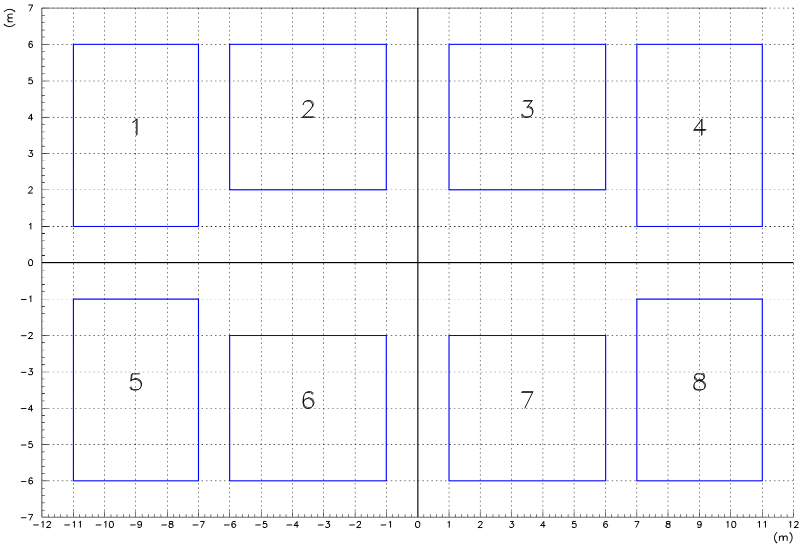

Figure 1: A sketch of the proposed muon chamber array close to the ALEPH detector.

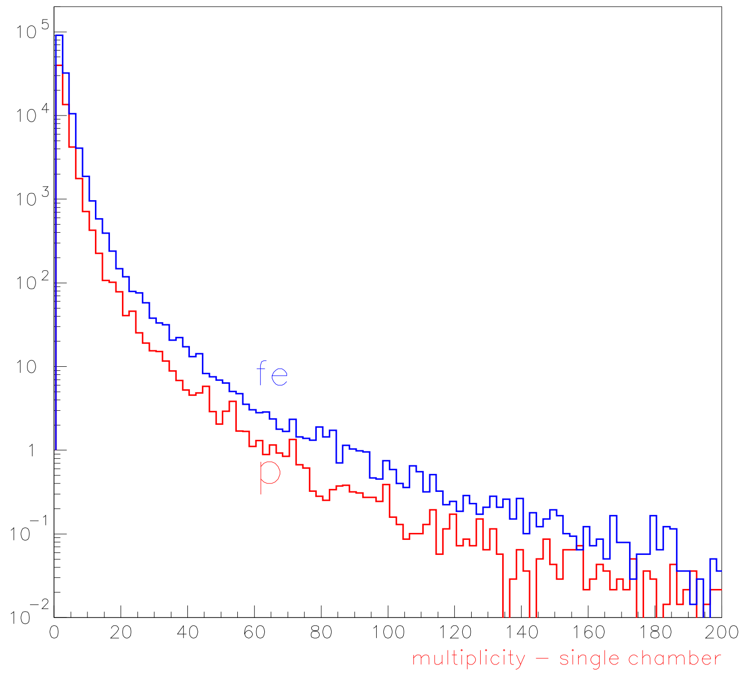

Figure 2: The multiplicity distribution in one of the eight modules of Fig.1.

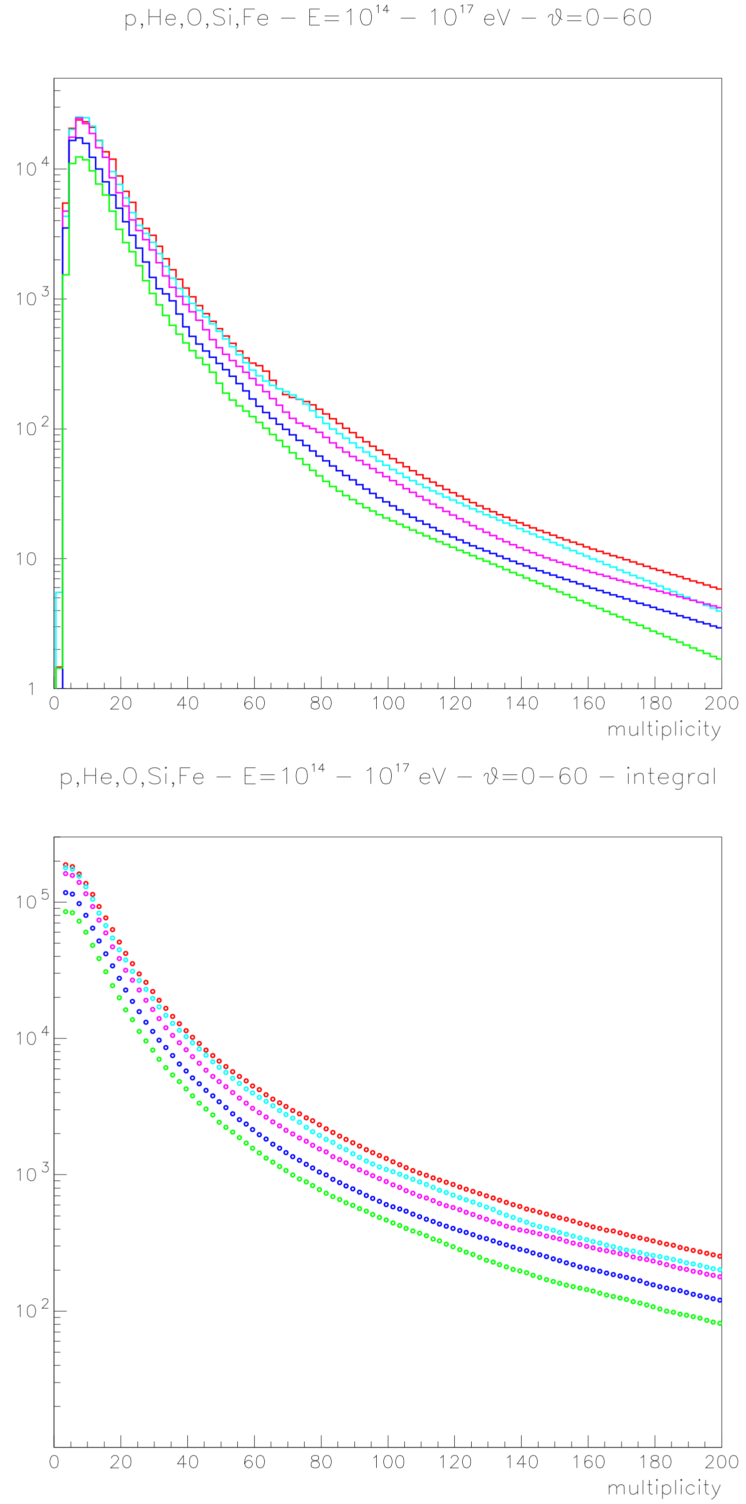

Figure 3: The differential and integral muon multiplicity distributions in the proposed array for different primary particles for a measurement time of 2 10^7 sec.

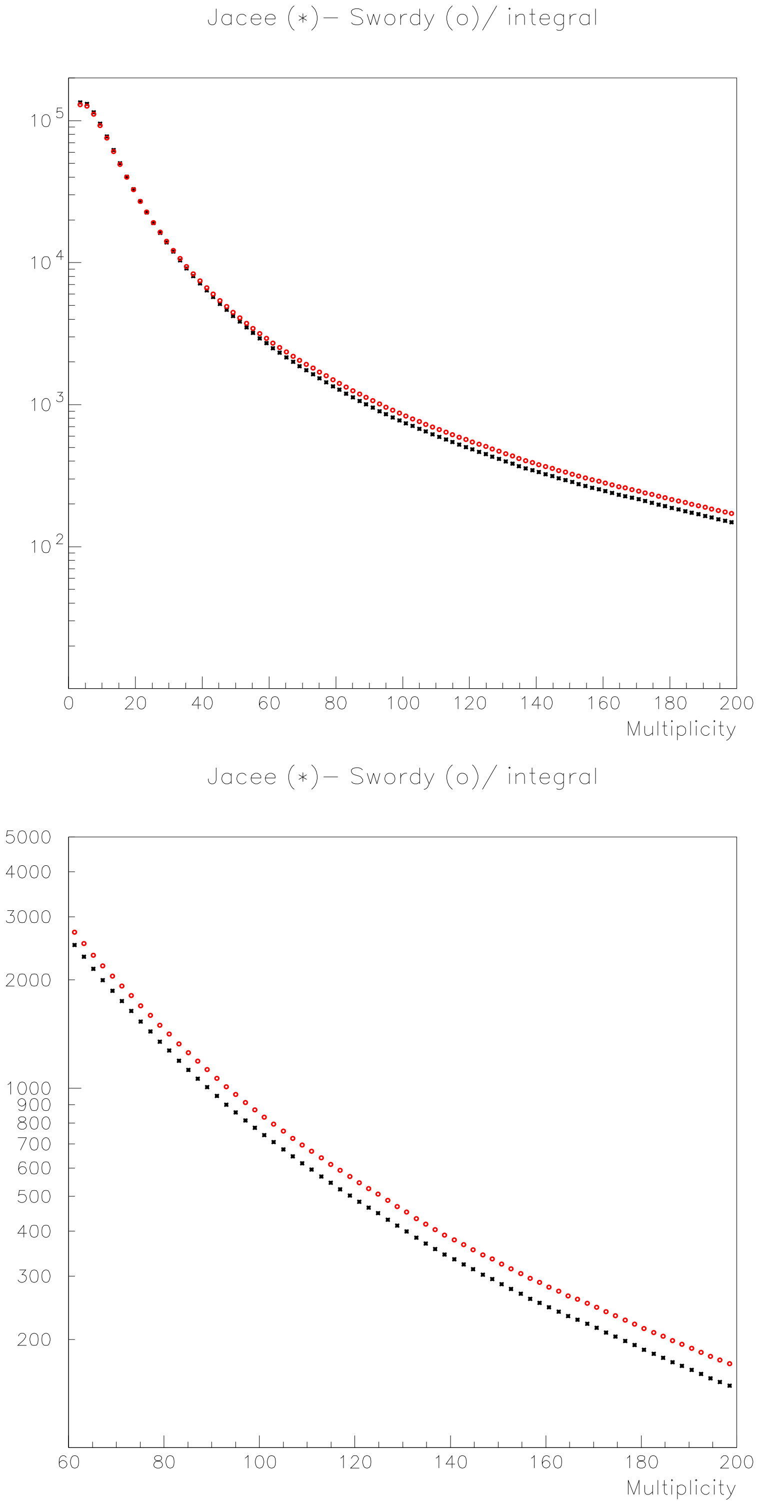

Figure 4: Comparison of two particle composition models, described in Tab.1.

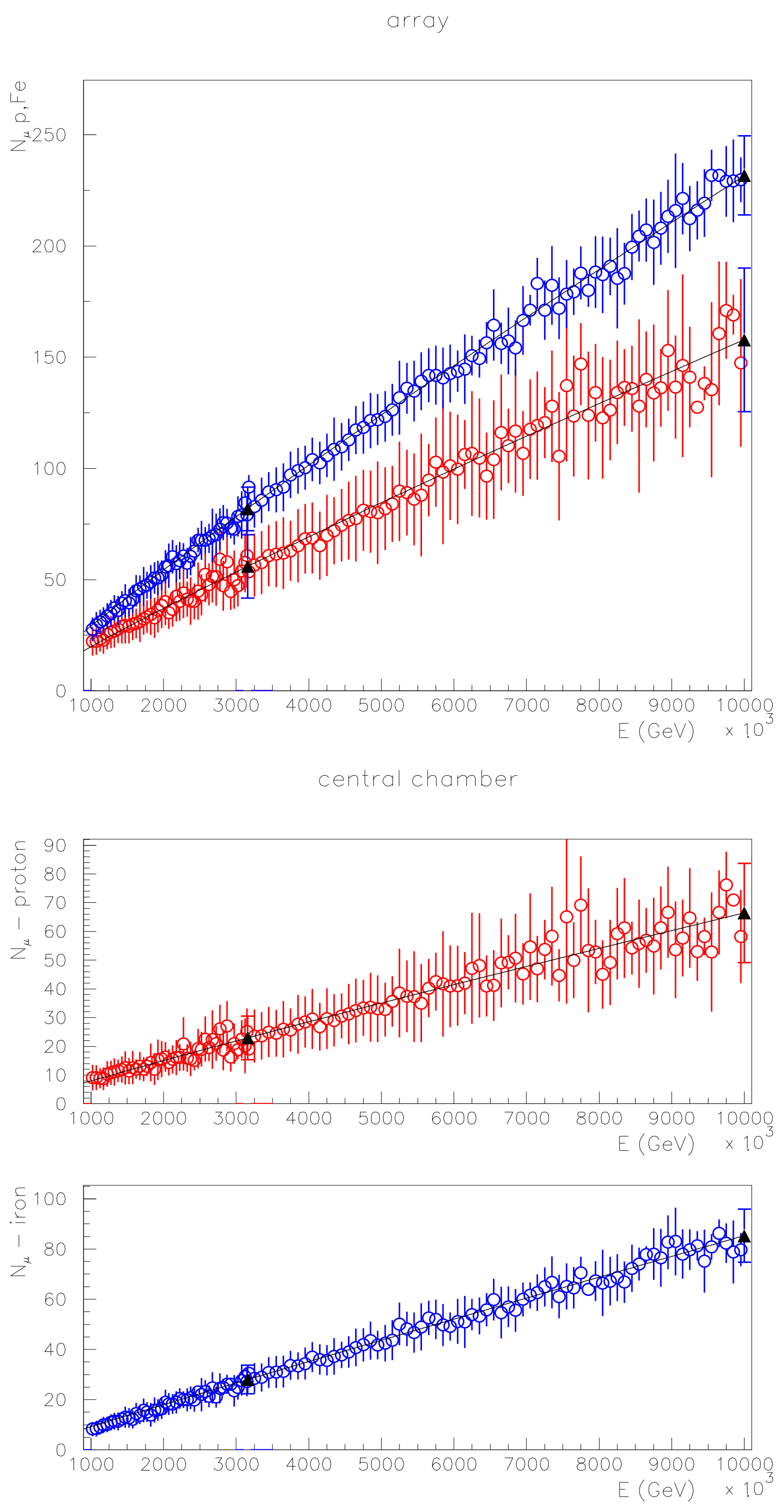

Figure 5: Number of muons (N_{tot}) in the array and in the chamber of the shower core location (N_{max}) as function of energy, for p and Fe. The black triangles refer to simulation at fixed energy. The fit through these points is also shown ($N_{tot} \sim E^{0.9}$ (p,Fe); $N_{max} \sim E^{0.92}$ (p) ; $N_{max} \sim E^{0.96}$ (Fe)).

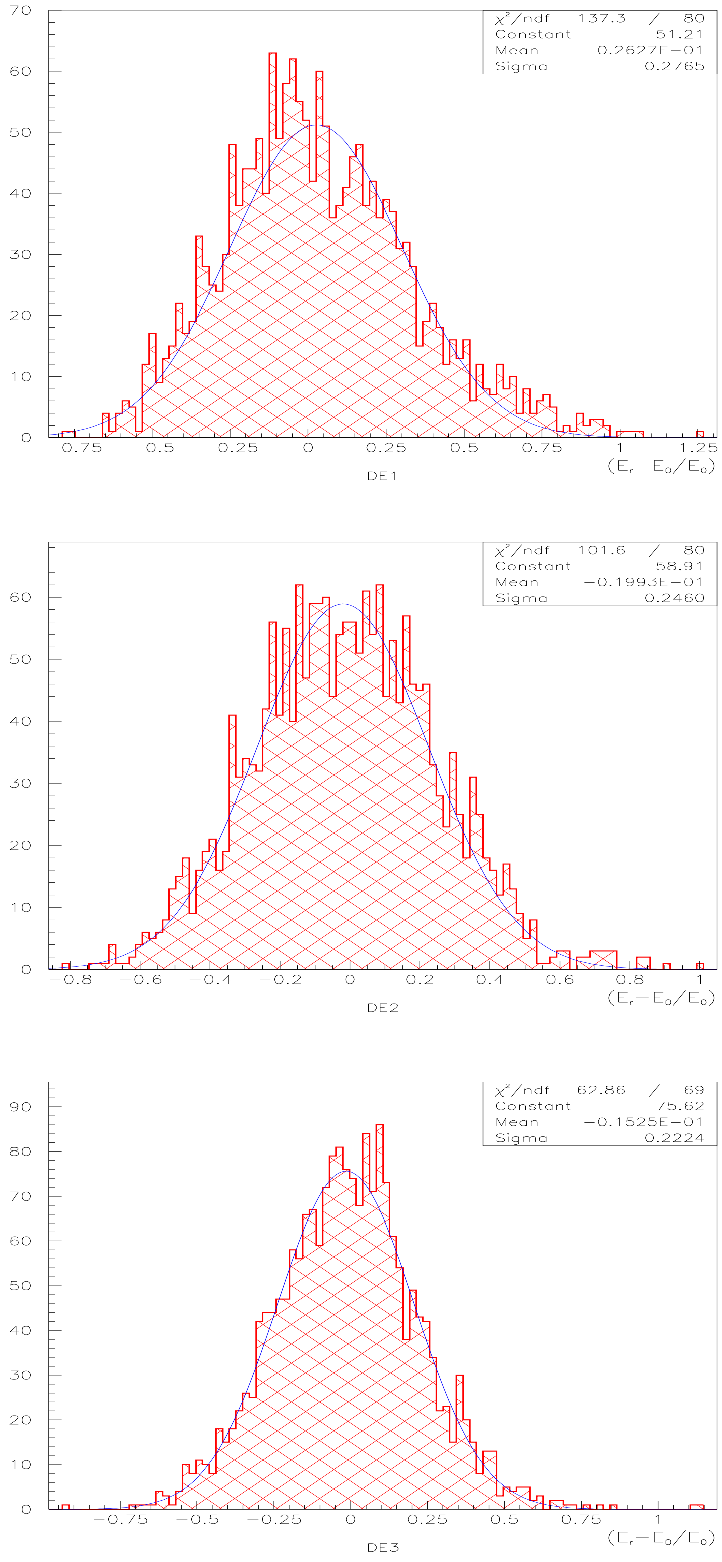

Figure 6: $(E_{reconstr} - E_0)/E_0$ for three energies interval: $10^{15} - 3 \cdot 10^{15}$ eV; $3 \cdot 10^{15} - 10^{16}$ eV; $10^{16} - 3 \cdot 10^{16}$ eV.

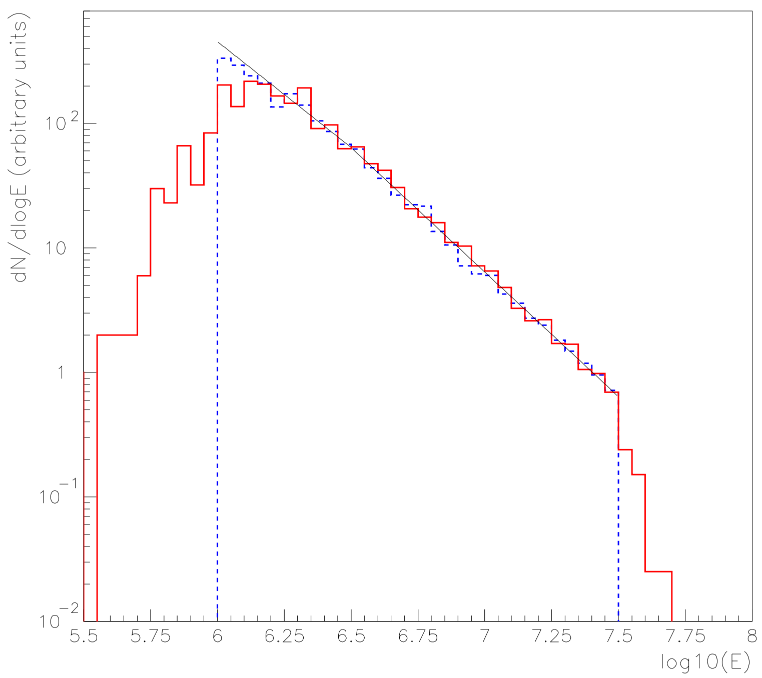

Figure 7: Input (dotted) and reconstructed energy spectrum (solid) for a “pure” proton sample. Assumed was the standard spectrum (solid line) $E^{-2.7}$ below and $E^{3.0}$ above the knee.

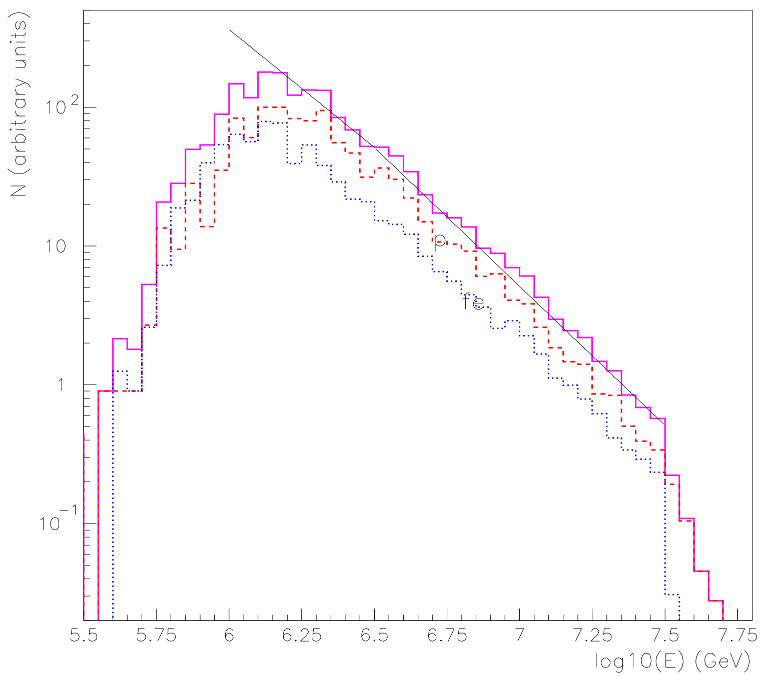

Figure 8: Reconstructed energy spectrum (solid) assuming an input mixture of 45% p and 35% Fe (line); the reconstructed spectra (dotted) for the two elements after the identification are also shown.

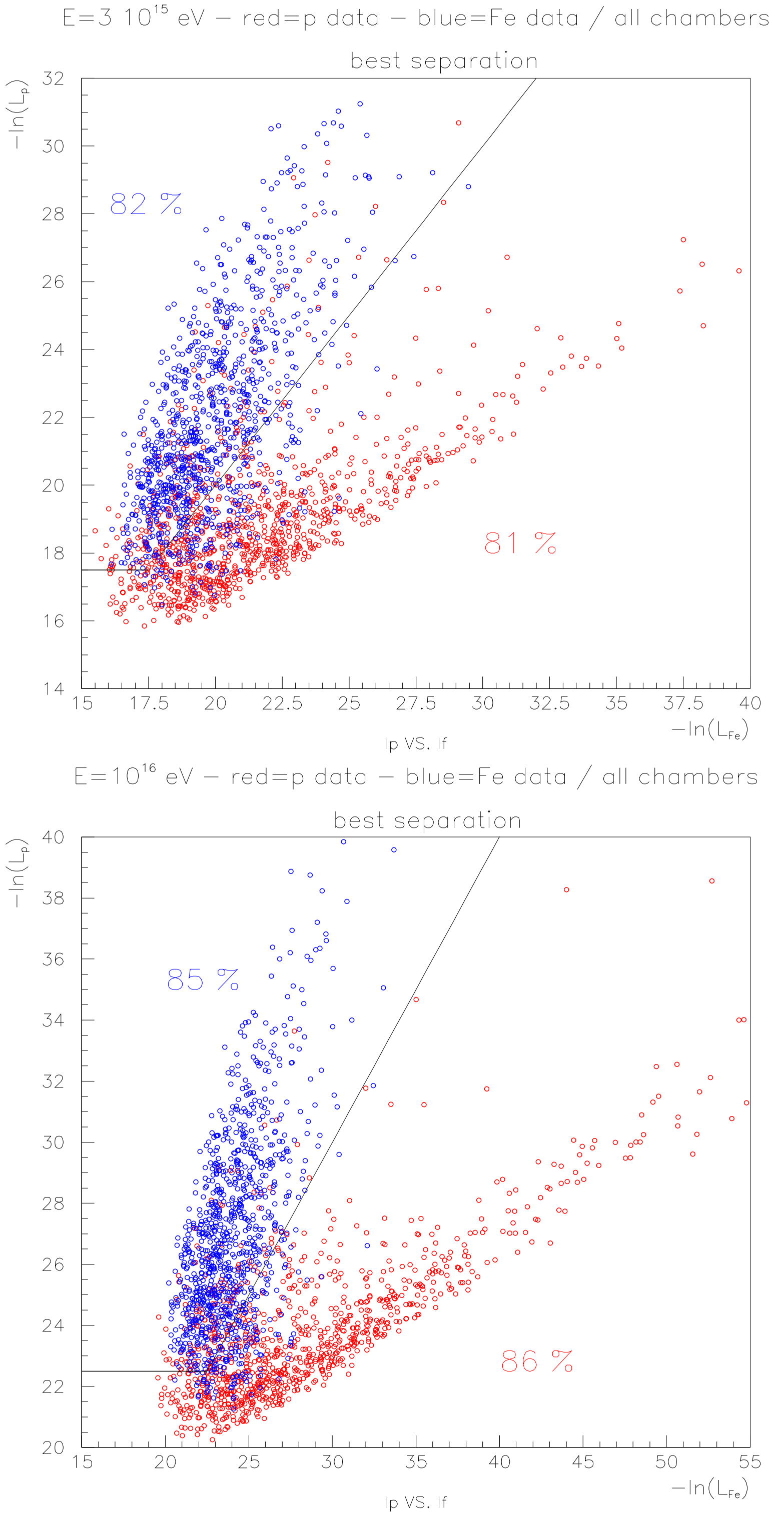

Figure 9: $-\ln(L_p)$ vs $-\ln(L_{fe})$, where $L_{p(fe)}$ is the likelihood, for a proton (iron) sample. The fraction of correctly identified events refer to the cuts shown in the plots.

the end of LEP and the start of the LHC. This will be much more difficult in the case of L3-C since the area will be needed for the installation of the ALICE experiment.

Ad 5

We have commitments from the institutes that signed the proposal for supplying manpower, when approved.
E.g. the CERN group consists of 1 full-time and 3 part time contributors.
Siegen University will contribute 2 full time and 3 part time persons to the project.
Various Finnish institutes have committed manpower with about 10 persons in total who will work a major fraction of their time on the experiment.
The University of Prague will contribute a full physicist and a technician for times of installation, etc.
Furthermore in the last week we had expressions of interest from a Mexican group and a group from Alma Ata (which has been involved in balloon cosmic ray experiments) and can provide a total of up to 4 persons.
Hence we believe that the number of people to install, run and analyse the data of this experiment is above critical mass. annexed.

Ad 7

It is correct that for the study for the proposal we have made the simplification of taking the rock above the experiment into account only as a momentum cut-off for the muons. This is at present done mainly for computing time consumption reasons. The cross section for a nuclear interaction of a muon of e.g. 3 TeV is approx 1 microbarn (scaling as $E^{0.25}$ with increasing energy). The μ-N interactions which can give a hadronic punch through which would reach the detector array have to originate from the last few meters of the rock/concrete above the experiment, otherwise the hadronic shower gets absorbed.

The interaction probability for a 100 GeV muon the last 3 m is 0.03-0.05%. Hence the number of muon showers for which one of the muons interacts in the rock close to the experimental hall will be of the percent level for multiplicities around 100, and therefore a rather small effect. Final calculations which will be confronted with future data of the experiment can take the exact value of this effect into account using a detailed GEANT simulation.

For the ALEPH high multiplicity events, we have checked the theta angle of the individual tracks in each event, and these were found to cluster all along the same value with a spread of about 20 mrad (see Fig. 10).An interaction in the rock above us would hence be identified due to the angular spread of $\pm$ 100 mrad over $\pm$ 1m. These are not seen in the data. Hence there is no evidence in the data that the high multiplicity events suffer from a significant contribution from nuclear muonic interactions close to the experiment.

Ad 8

The common runs of the proposed muon array with ALEPH are vital for the study of the muon showers. The two detectors are complementary: ALEPH allows precise tracking even at high particle densities and momentum measurements, while the array has a large acceptance, useful for core determination and radial muon shower studies.

During normal LEP data taking in the year 2000, three triggers will be used for the muon array: LEP event triggers in the ALEPH detector, a trigger based on the scintillation counters

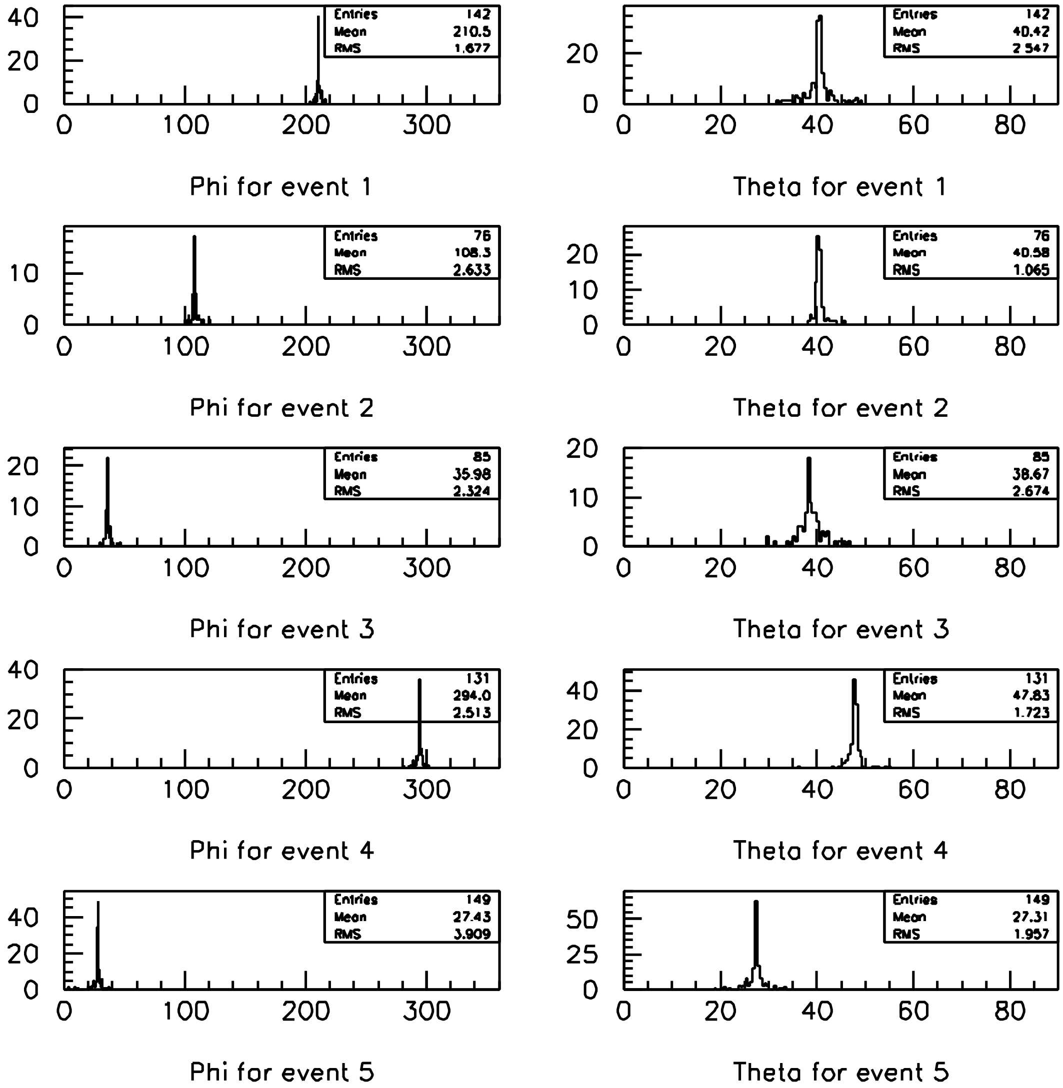

Figure 10: Azimuthal and zenith angle of the muons in the highest multiplicity events observed with the ALEPH detector.

on top of the muon chambers, and the barrel ALEPH trigger used by CosmoALEPH. These different triggers will be complementary, and will provide powerful handles on understanding some of the systematics and trigger biases. In the case of the ALEPH trigger, the shower core will be close to the ALEPH detector and the muon array will determine the radial extension of the high multiplicity showers. In the case of an array trigger, the shower core will be situated in the array and the ALEPH central barrel (30 m from the array center, with a total area of 50 m^2 and complete angular acceptance) will provide information about the radial distribution. This information will be used to discriminate between proton and iron induced showers.

With the ALEPH triggers we will accumulate an effective running time of less than 0.5 10^6 sec, i.e. about half of the present statistics. It is important to note, though, that the muon array will provide significant information in these events not available in the existing data.

In addition, it would be useful to get one to two months of dedicated data-taking with the ALEPH detector in the year 2000. In these runs, the TPC and the barrel hadron calorimeter, together with the muon trackers, need to be operational. It is very desirable that the magnetic field be on, though we could also run with no magnetic field in the event of difficulties. These common runs could be scheduled before and between the LEP runs when the ALEPH detector is operational, and at the end of LEP data taking.

These common runs have still to be negotiated with the ALEPH group, but there is precedent with the running in the Spring of 1999. The referees' recommendations will be important input into these negotiations.

The scintillation trigger of the muon array and the barrel trigger of ALEPH will be continuously operational. With these triggers we hope to accumulate a running time of 2 10^7 sec in the year 2000.