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Muon Identification in Hadron Calorimeter at DELPHI and Muons as Probes of Particle Interactions.

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Acknowledgments

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Contents

1 Introduction

The presented dissertation consists of the papers [A.1, A.2, A.3, A.4, A.5, A.6, A.7] on DELPHI hadron calorimeter (HAC) [B.1]. These papers deal with signal simulations, performance and major upgrade of HAC after the period LEP1 (production of Z^0 around the resonance peak). This upgrade resulted from extensive tests of streamer tube[1] properties and studies of possible utilisation of tube signals for data analysis. The aim was to improve the capabilities of HAC for the second period of the LEP collider operation, so called LEP200 program when the energy of e^+ and e^- beams has been gradually increased up to the energy 104 GeV per beam. The above mentioned studies led to the conclusion, that with the constraints imposed by HAC construction, the upgrade can improve significantly the muon identification of DELPHI [A.7] and on this ground the upgrade project has been defended and realized in the years 1994-1996.

The muon identification has been used in standard analyses (part 3.1). However, it turned out that HAC upgrade brings benefits not foreseen previously. These features have been employed in searches for particles predicted by some supersymmetry models in topologies which are very difficult from the point of view of trigger and background suppression [A.8, A.9].

The large volume of HAC with good muon identification capability led naturally to increased interest in cosmic muons. DELPHI has adopted a cosmic trigger which led to regular cosmic muon detection even during data taking at LEP operation. The registered data initiated study which resulted in proposal to use muon identification to unfold the dynamics of cosmic ray interactions at very high energies [A.10, A.11, B.5]. This method cannot be used in collider experiments and it increases potential of muon identification beyond its standard use like Drell-Yan pair detection, *b* or *c* quark identification, semileptonic or leptonic decays of various particles etc.

2 DELPHI Hadron Calorimeter

The DELPHI detector at LEP has been conceived in the beginning of 80's as an apparatus based on novel technologies with increased particle identification capability. DELPHI is an acronym for 'DEtector with Lepton Photon and Hadron Identification' and its most prominent feature were state of the art (at that time) Ring Image Čerenkov counters (RICH) based both on liquid and gas radiators. Inclusion of the RICH counters into design put additional constraints on other sub-detectors and somewhat compromised the hadron calorimetry. HAC with the depth 7 nuclear interaction lengths was preceded by passive material of 1. $\div$ 1.2 nuclear interaction lengths depending on the polar angle. This led to deterioration of the energy resolution and serious effort has been made to improve the hadron calorimetry before start of the phase LEP200 of LEP collider operation.

2.1 Calorimeter Design

DELPHI hadron calorimeter construction was based on Iarocci tubes operated in limited streamer mode [A.3]. The tubes were assembled in planes covered by cuprexite boards with etched readout pads. The readout units were organized in 'towers' which consisted of five pads in consecutive layers in radial direction and the whole readout setup formed a pointing geometry structure [B.1]. The smallest readout unit, i.e. one tower, occupied a

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[1] sensitive elements of DELPHI hadron calorimeter

volume of about 25 × 25 × 35 cm^3 depending on the position inside the calorimeter. The granularity in angular variables was 2.96 deg in polar angle and 3.75 deg in azimuthal angle.

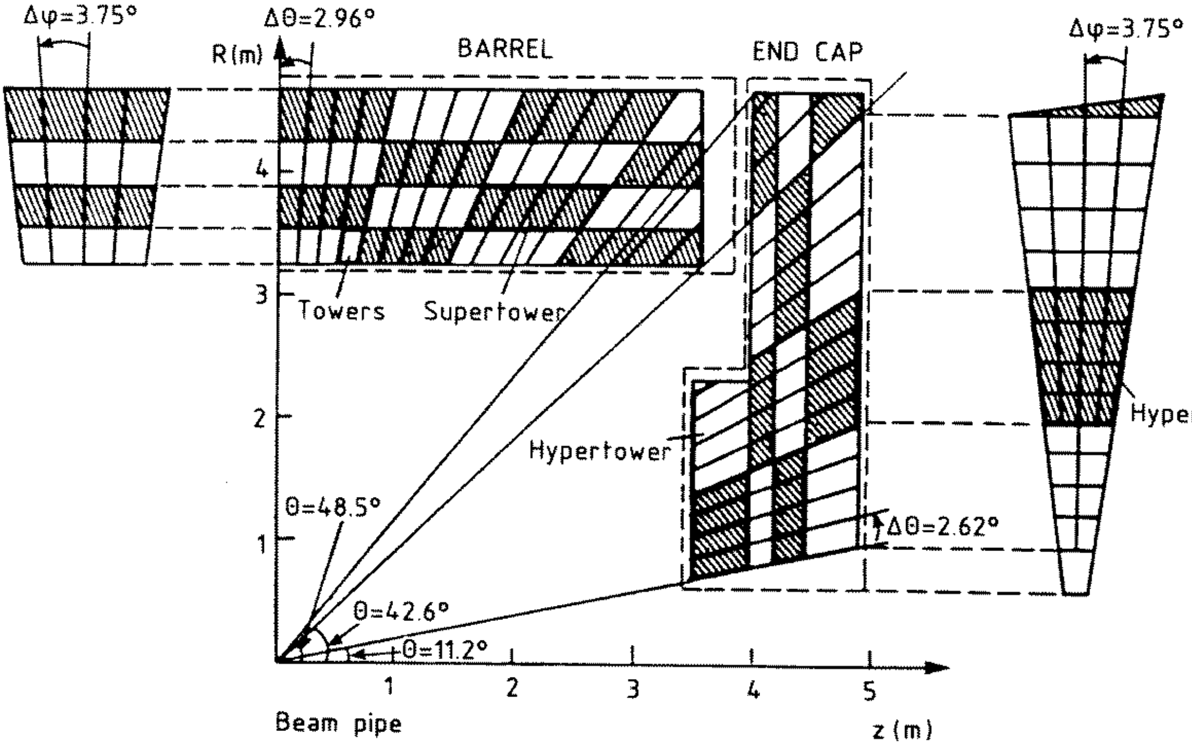

Figure 1: Hadron calorimeter towers layout

The early studies have shown that such geometrical structure is insensitive to the details of the shower development [A.1], [A.2]. Moreover it turned out during the later prototype tests of the assembled calorimeter modules that the homogeneity of the resistive paint inside the tubes is of inferior quality and the charge induced by streamers diffuses along the tubes. As a consequence the muon signal in the hadron calorimeter was several towers long in z direction in the barrel part and in $r\phi$ direction in the end-cap parts. This all complicated the muon identification only by hadron calorimeter. However, it has to be noted that the original design of the experiment relied basically on muon chambers and it used only passive material of hadron calorimeter for distinguishing muons from other particles. This approach fully complied with the philosophy of muon identification at that time.

The energy of e^+e^- events was reconstructed with the precision

$$\sigma(E)/E = 1.12/\sqrt{(E)} \oplus 0.21$$

(E expressed in GeV). The fixed term is due to the material between the hadron calorimeter and the electromagnetic calorimeter [A.6]. From the point of view of the hardware the hadron calorimeter construction was very stable and robust. The whole hadron calorimeter contained nearly 20 000 limited streamer tubes and after twelve years of operation only less then 2 % of them failed.

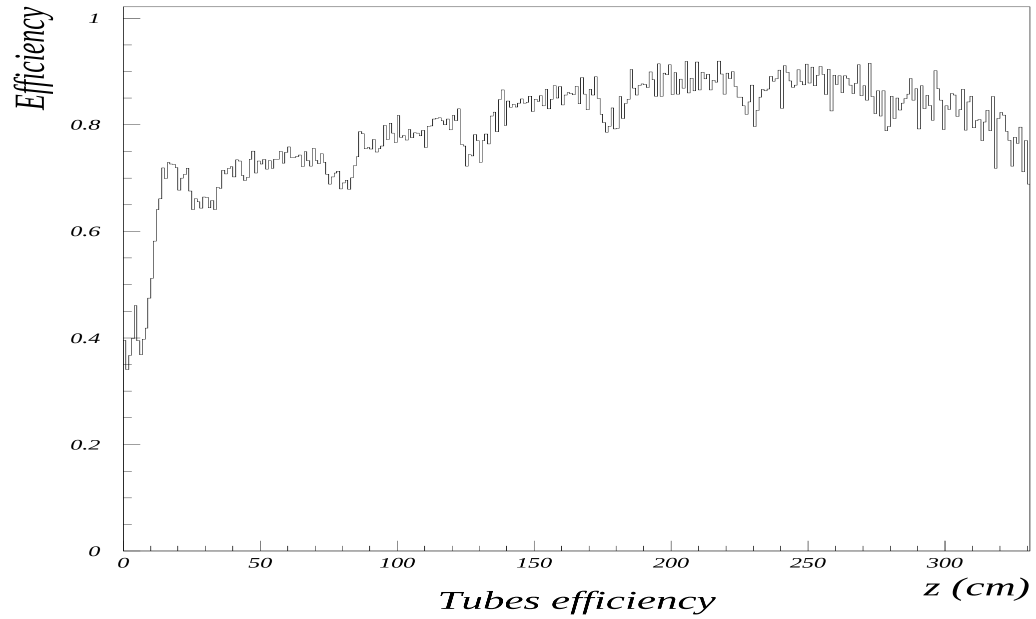

Figure 2: Dependence of the muon detection efficiency on the position of hit along the tube.

2.2 Cathode Readout

The above mentioned problems led to serious effort to improve the performance of HAC. It has been clear that all possible solutions were constrained by existing hard-ware and by necessity to keep HAC running during LEP operation periods. After thorough testing it turned out that the best possibility is to read out signals from cathodes of individual limited streamer tubes. The tube lengths varied from 60 cm to 360 cm. This, combined with inhomogeneous varnish mentioned earlier, posed a big problem as the signals varied significantly both in amplitude and duration. The final accepted design integrated charge on the accessible end of a tube for 350 μs and the signals exceeding the discrimination level were accepted. Thus the final output was *yes* or *no* [A.4]. This is quite a long time compared to the standard HAC readout which integrated charge from towers for 2 μs only and the signal passed 8 bit digitizer. The final efficiency for one tube to detect passing muon is shown in Fig. 2. The periodic structure along z-axis is caused by plastic spacers 5 mm wide which kept the anode wires in proper positions.

Due to small cross-section of a tube ($1 \times 8\ cm^2$) the granularity of the HAC readout grew finer significantly. The new cathode readout was thus able to count all hit tubes and to show signals distribution in (x, y) plane (perpendicular to the beams) in the barrel region [A.4, A.5]. The information on z-coordinate was lost in this region. The situation in end-caps was somewhat more complicated as the tubes in consecutive layers along the beam crossed at 15 deg in (x, y) projection so that the granularity in (x, y) was not that fine as in the barrel. On the other hand the z-coordinate was given by the plane number.

Already the Monte Carlo (MC) studies have shown that counting of signals within a hadronic shower does not improve the energy resolution. However, the muon identification based on the track fit using the positions of hit tubes improved significantly the identification. Demonstration of this feature in MC studies led DELPHI collaboration to accept the project of 'HAC cathode readout'. Realization of this project took part from 1994 till 1996 and during the winter shut-down periods in these years all 20 000 limited streamer tubes of HAC were equipped by individual readout, connected to front-end electronics and integrated into central data acquisition automated system. The contribution of the Prague group amounted to 50 % of the whole work.

Since the beginning of the HAC upgrade and the cathode readout project the major concern has been the possible noise in the running conditions of the accelerator and of the whole DELPHI apparatus with its numerous sub-detectors and many technical components. As this was impossible to test in the laboratory, the limited number of HAC modules have been equipped by cathode readout in 1994 and the electronics design of the cathode readout has been changed properly after this test so that the noise would not affect the system. The only system drawback, which remained uncured, was a cross-talk in the cathode readout data acquisition system. This cross talk appeared when a signal with large amplitude was detected near the connection of a limited streamer tube to the cathode readout circuit. The cross talk then appeared as if two adjacent tubes were hit. This feature had consequences on the purity of muon identification and it will be discussed later.

2.3 Muon Identification in Hadron Calorimeter

The 'classical' approach to the muon identification based on stopping power of calorimeter used as passive absorber and muon chambers data has been improved already in the years 1989 - 1994 by taking into account the signals of hadron calorimeter. The necessary conditions for a particle to be identified as a muon were signals at least in three towers out of four in radial direction with one of these signals in the fourth layer and a corresponding level of signal amplitude in each of the towers. These conditions improved the muon identification. However, there had been still left space for faked muons due to rather coarse granularity of towers and dependence of the signal amplitude on electronic channel calibration. This identification works clearly better for isolated muons and cannot treat well those muons which stop inside the calorimeter. Thus this identification improves the purity of identification by muon chambers but it leaves the momentum cutoff imposed by passive material in front of the muon chambers which in case of DELPHI is about 3 GeV depending on the polar angle.

The fine granularity of the cathode readout allows to treat the hadron calorimeter almost as a tracking device. To make use of the full potential of the new data with fine granularity, the new analysis package has been written [A.7] and implemented into general DELPHI analysis software.

The muon identification based on cathode readout signals is divided into three steps

1. pattern recognition and search for track elements
2. fit of the track elements to the charged tracks found by track detectors
3. sorting the results and imposing the additional criteria in order to achieve the desired purity

The search for track elements in e^+e^- interaction has been eased by the condition that all tracks roughly point to the interaction region. In the case of cosmic muons this was not true any more and the search had to be quite general.

The search for track elements has to find optimum between the efficiency, i.e. not to loose real muon tracks and the purity on the other hand, i.e. not to pick up too many noise signals. The optimal value turned out to be four hits. In standard applications the tracks of accepted muons consist of larger number of hits and this value would influence mostly efficiency of search for muons with very low momenta. The whole program is written so that all important variables (e.g. minimal number of hits per track) are kept as parameters. This flexibility is quite useful. There are various goals of physical analysis which may have different needs. For example in b-quark physics it is necessary to identify muon inside a jet. Thus one needs to ignore the remnants of jet - hadron signals which die out in initial layers of HAC (in radial direction) and to look for track patterns emerging from such cluster of hits. On the other hand the search for J/ψ particle production in $\gamma\gamma$ interactions or certain aspects of τ physics deal with the processes with very little background and the whole volume of HAC can be utilised.

After the first stage, when all track elements have been found, the muon identification package attempts to match each of these elements with charged tracks reconstructed from track detectors (e.g. vertex detector, Time Projection Chamber (TPC) [B.1]). The extrapolation of a track with momentum measured by track detectors is calculated throughout HAC and compared to the tracks found in cathode readout signals. The fit takes into account ionization losses and it also incorporates the multiple scattering. The differences between the extrapolation and the track inside HAC are then expressed in terms of χ^2/ND, where the number of degrees of freedom is basically given by number of tube hits ND. Despite the rather large tube cross-section ($1 \times 8\ cm^2$), this procedure is quite accurate as the tubes are located at large radii measured from the interaction point. The accuracy can be assessed from Fig. 3, where the χ^2 distribution is shown before and after alignment of the tubes in HAC barrel.

The tubes have been aligned using the high momentum muons from $Z \rightarrow \mu^+\mu^-$ decays measured by muon chambers. The average shift of a tube inside HAC slot to real position was about 4 mm. The peaks at $\chi^2 = 1$ are due to the tube layout geometry (see Fig. 4) - the tubes at the HAC module borders are not staggered and the tube hits therefore do not represent the independent position measurements.

After the stage of track fit the tracks inside HAC with good fit probability are further filtered with the aim to suppress faked muons. The main criterion is that the track should not be 'too wide'. This means that along the track there may be occasionally two hits in one plane - this might be caused e.g. by δ-electrons, but one has to reject the tracks where there are several hits in several consecutive planes, which correspond more likely to hadron induced showers in the HAC iron. It is this phase of identification where the above described cross-talk degrades the muon identification. One is unable to distinguish muon tracks wide due to electronics effects from narrow hadronic showers. This fault affects mainly the muons with polar angles $\theta \sim 40 \div 43\ deg$ (resp. $157 \div 160\ deg$) while in the region $\theta \sim 65 \div 115\ deg$ the purity of muon sample can reach at small penalty on efficiency the punch-through limit.

It has been a standard since the beginning of DELPHI operation to devote each year a week before LEP operation start to registration of cosmic events. The original purpose was just to check the functionality of detectors and to align individual DELPHI subdetectors. After the installation of cathode readout it become clear that due to the large volume of HAC and the tracking capability of the cathode readout, DELPHI was able to detect meaningful data on cosmic events, e.g. to measure the muon multiplicity density. Therefore in 1998 the trigger tests were performed and in the period 1999 - 2000 the cosmic events have been routinely registered by DELPHI throughout the full data taking season. It has been done in so called parasitic mode, i.e. whenever there has been triggered no e^+e^- event the DELPHI trigger opened to incoming cosmic particles. Due to small interaction rate at LEP this trigger had reasonable duty cycle and during the mentioned period the cosmic triggers equivalent to $1.6\ 10^6\ s$ of up-time have been registered.

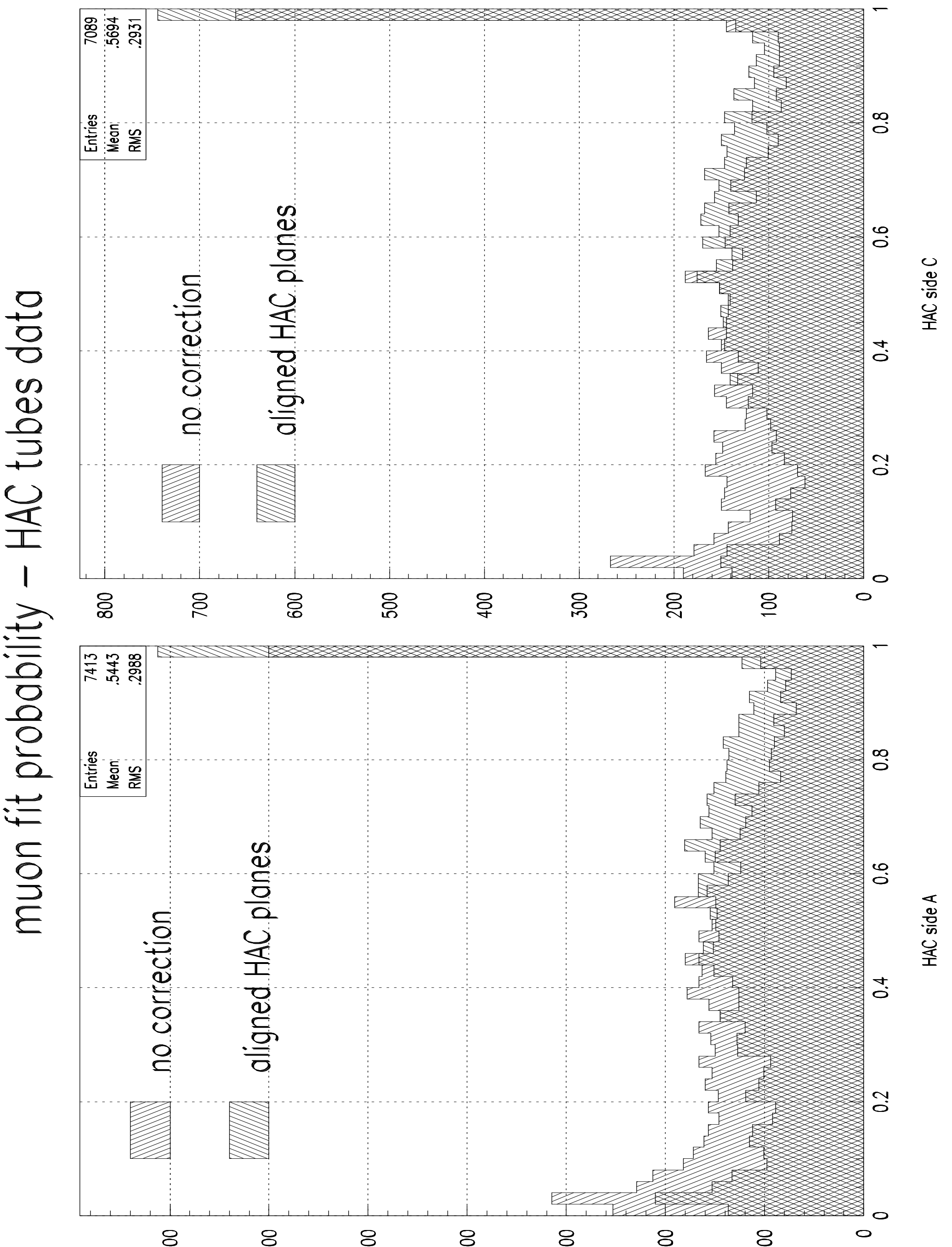

Figure 3: Comparison of χ^2 distribution before and after alignment of the tubes in both sides of HAC barrel.

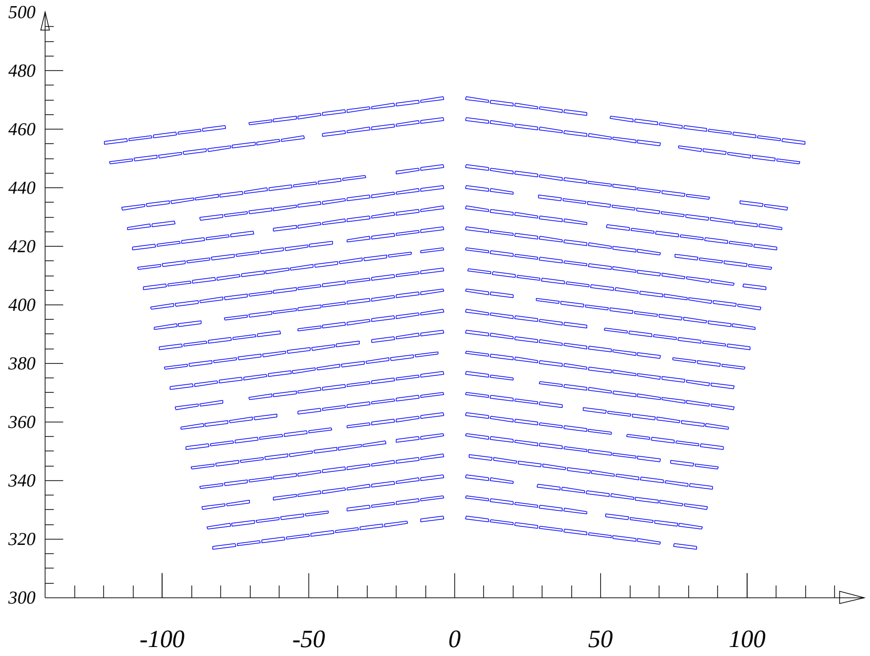

Figure 4: The projection to the x-y plane of the two adjacent barrel HCAL modules. The horizontal x axis and vertical y axis shows the dimensions in cm, the central point [0,0] is in the center of the DELPHI detector. The innermost plane contains 9 tubes, the widest outer plane has 13 tubes.

The adoption of cosmic ray program by DELPHI collaboration was entirely based on the capability of HAC to detect cosmic events. (The volume of TPC, the biggest DELPHI track detector, is too small to detect reasonable cosmic data and in fact the necessity of the knowledge of the time t_0 for drift determination even hinders the use of TPC for this purpose.) As already mentioned, the treatment of cosmic muons by the muon identification program [A.7] is different. In fact it led to its major upgrade. The algorithm used for track finding is completely general without any assumptions about the track, the fitting procedure fits muon momentum component from the track curvature and the final filtering is aimed to discard faked tracks, which might be 'found' in the events with large multiplicities.

The muon identification program [A.7] evolved during several years and it amounts to more then 14 000 lines of Fortran code. It provides DELPHI with versatile tool for large variety of physical analyses in e^+e^- interactions and for almost complete analysis of cosmic events. After basic analysis of the cosmic event by [A.7] the additional information on the event can be learned from Time of Flight detector and barrel muon chambers [B.1].

3 Muon Identification in Physical Analysis

Successful completion of the HAC cathode readout (HCRO) improved significantly the quality of muon identification by HAC. This is documented by results from the years 1995, 1996 and 1997 summarized in Tab. 1 [C.1]. The momentum dependence of the identification efficiency compared to muon chambers can be seen in the Fig. 5[C.1]. It shows the ratio of the number of HCRO tagged tracks to the DELPHI muon chambers Tight tagged tracks (purity > 90 %)[C.2] versus the momentum of the track. Actually the

	1995	1996	1997
$Z^0 \to \mu^+\mu^-$	$(56.8 \pm .7)\%$	$(87.9 \pm 4.0)\%$	$(86.0 \pm 2.9)\%$

Table 1: Efficiency of HCRO tag to tag muons from selected $Z^0 \to \mu^+\mu^-$ events [C.1].

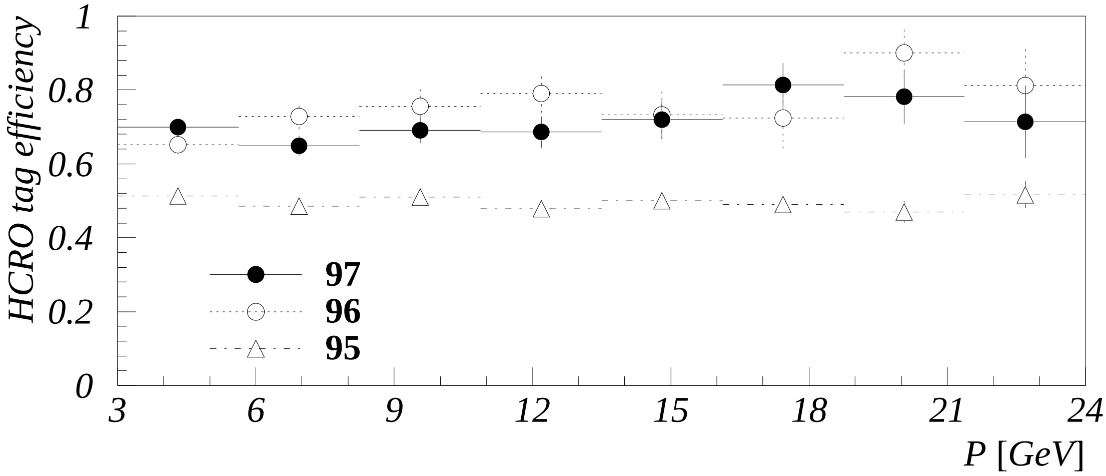

Figure 5: The dependence of the relative efficiency of HCRO tag to tight muons from hadronic Z^0 events on the momentum of the track [C.1].

results from 1996, 1997 do not represent the optimal values as in these years the operation of HCRO was still hampered by external noise picked up in a limited region of HAC. This is demonstrated by the dependence of the HCRO tag efficiency on the azimuthal angle ϕ and polar angle θ shown in the Fig. 6[C.1]. The drop in the central part of the detector around $\theta = 90$ deg is caused by the dead zones around the ends of the tubes. The external noise has been reduced to acceptable level during the shut down period 1997 - 1998 and the efficiency in ϕ become uniform.

The misidentification probability was evaluated from $\tau \to 3\pi$ decays. Events were selected according standard DELPHI tau selection cuts [C.3] within the frame of the package TAUPLUS. All the three particles in 3 prong τ decay were considered as π mesons and the corresponding muon tag was recorded. The combined results from the 1996 and 1997 Z^0 data give the misidentification probability of the HCRO tag $p = (4.93 \pm 0.45)\,\%$ where the error is the statistical one. This result is close to the Very Loose tag (efficiency $> 90\ \%$) [C.2] misidentification probability from muon chambers.

The absolute limiting factors are the rates of punch-through and δ-electrons. However, in practice this may be deteriorated by other effects. In the case of HCRO the earlier mentioned cross-talk worsened the purity of muon identification. The muon tracks were widened by this electronic effect, as the passage of the particle nearby the electronic red-out circuit resulted in signals in two adjacent tubes. Therefore is was necessary to loosen the criterion on muon track width in order not to reject muons. This on the other hand increased the probability of accepting hadrons.

3.1 Muon Identification in e^+e^- Events

The reviewed results of HCRO muon identification capabilities show that in fact a new muon detector has been added to the DELPHI apparatus. This increased the identifica-

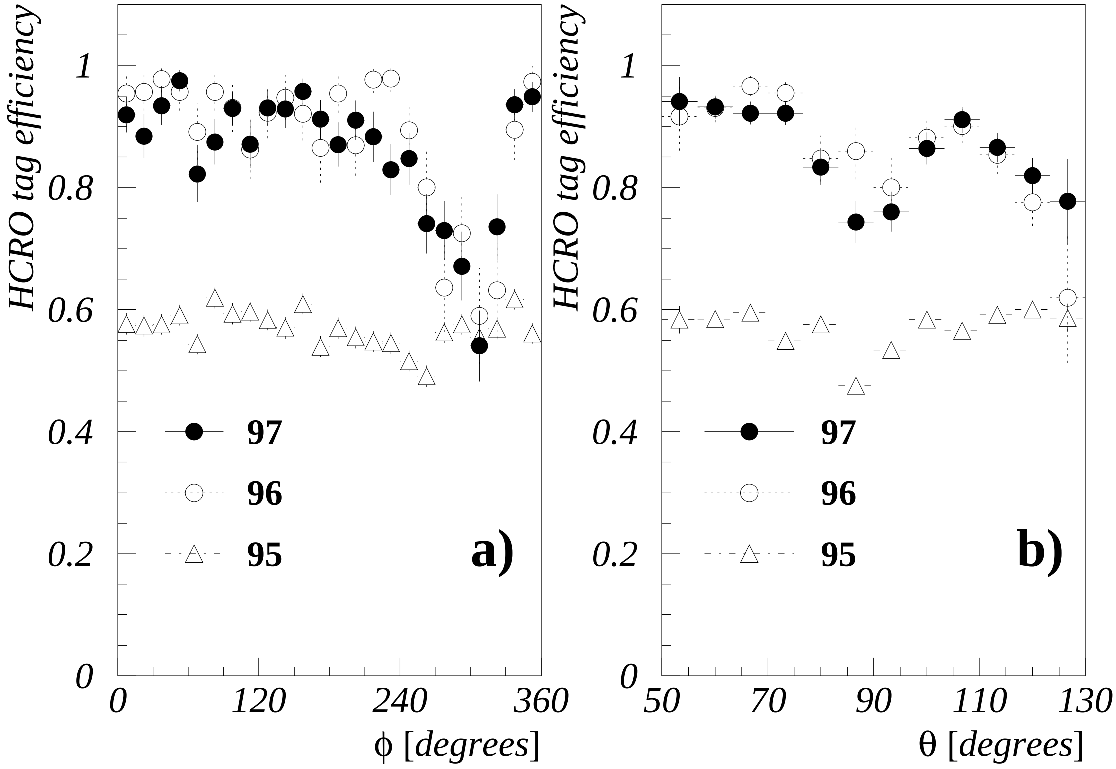

Figure 6: The dependence of the HCRO tag efficiency to muons from $Z^0 \to \mu^+\mu^-$ events on the azimuthal ϕ angle (a) and polar θ angle (b). The (a) plot shows worse performance of the modules 18 – 21, which correspond to the ϕ angle 255 deg – 315 deg [C.1].

tion redundancy and allowed to sharpen the analyses which rely on muon identification. However, it has to be noted that not all possible analyses could include the improved muon identification. The bulk of Z^0 data has been collected in the period 1992 - 1994 and thus all the analyses based on large samples of data, like e.g. searches for the new particles containing b-quark and many studies of τ lepton properties and decay modes cannot use HCRO identification as it would be desirable.

The integration of HCRO muon identification into general DELPHI particle identification coincided with the transition of the LEP collider to the energies above Z^0 peak. The muon identification improvement thus affected analyses of semileptonic W decays [B.2], b-tagging relevant for the Higgs boson search [B.3] and also b-tagging in $\gamma\gamma$-physics as the major part of the data in this case has been collected at LEP200.

Another rather unexpected benefit of HCRO appeared in searches for the exotic phenomena. In many theories going beyond Standard Model it is possible to observe appearance of new phenomena in channel with one single non-pointing photon or with multi-photons. This channels have been studied in LEP200 data.

After filtering large amount of data few events with single non-pointing photon were really found and only after careful scrutiny it turned out that the signal in electromagnetic calorimeter is in fact trace of cosmic muon passing through DELPHI apparatus slightly off-time. These muons left therefore no traces inside track detectors and only due to small jitter in electromagnetic calorimeter timing they left a signal there. Only scanning of all these events and looking at their appearance in HCRO data allowed to exclude them.

In the case of multi-photon events the missing mass spectra have to be compared with contribution from SM channel $e^+e^- \to \nu\bar{\nu}\gamma\gamma(\gamma)$ in order to observe any possible excess.

The implications of negative result are summarized in papers [A.8, A.9]. They concern the following models:

- *Production of an unknown neutral state.* Production of any such state would be accompanied in some events by initial state radiation. The observed spectrum of single photons is in agreement with Standard Model (SM) neutrino production.

- *Production of gravitons.* In theories with extra compact dimensions the production of undetectable gravitons would manifest itself again by single photons in reactions $e^+e^- \to \gamma G$. DELPHI is sensitive to this process at the highest beam energies in the region of low energy photons. The agreement with SM prediction puts the limit on radius of extra dimensional torus $R < 0.4\ mm$ for number of extra dimensions $d = 2$.

- *Compositness.* Composite models predict several new particles which would be constituents of particles considered by SM as elementary. Notably composite weak bosons would lead to deviations in number of single photon events from that given by SM cross-section.

- *Production of gravitinos.* In the models with gravitino as the lightest supersymmetric particle (LSP), the only kinematically accessible process at LEP may be $e^+e^- \to \tilde{G}\tilde{G}\gamma$. DELPHI is most sensitive to this process at low energy photon region and away from radiation return peak.

- *Production of neutralinos.* In the models with gauge mediated supersymmetry breaking, gravitino occurs as the lightest super-symmetric particle. This gravitino is supposed to be produced in decays of the “next to lightest super-symmetric particle” (NLSP) $e^+e^- \to \tilde{G}\tilde{\chi}_1^0 \to \tilde{G}\tilde{G}\gamma$ and $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tilde{G}\gamma\tilde{G}\gamma$ where $\tilde{\chi}_1^0$ would have a macroscopic decay length in certain mass range of gravitino. Production of such particle would appear as an energetic photon inside detector. This photon - also the decay product of the NLSP would not point to the interaction region. It is this process where the HCRO rejection of cosmic background was most important.

- *Production of neutralinos as LSP.* In SUSY models with neutral LSP and NLSP, the process $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma\tilde{\chi}^0\gamma$ has the same experimental signature as the previous case with somewhat different kinematics given by $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ masses.

It turned out that HCRO provides also certain “hermeticity” in time because of its long charge integration time (see part 2.2). Thus the activity inside HAC slightly before and after beam cross-over can be monitored in the off-line analysis. This helps to check the performance of other DELPHI subdetectors especially in such difficult channels.

3.2 Muons in Cosmic Ray Events Detected by DELPHI

As mentioned earlier (see parts 1, 2.3) DELPHI registered routinely cosmic events which time to time have quite spectacular density of muons (Fig. 7).

Apparently such cases correspond to the impact of a core of an extensive air shower. Given the sensitive volume of DELPHI and the observation times, the energy of impinging cosmic particles one can observe is in the region $3\ 10^{13} \div 10^{17}\ eV$. This is quite interesting region of so called “knee” in cosmic ray energy spectrum where the spectral parameter changes and it is known that also the chemical composition of cosmic rays changes [C.4]. The cosmic data collected by DELPHI are quite unique due to location of DELPHI

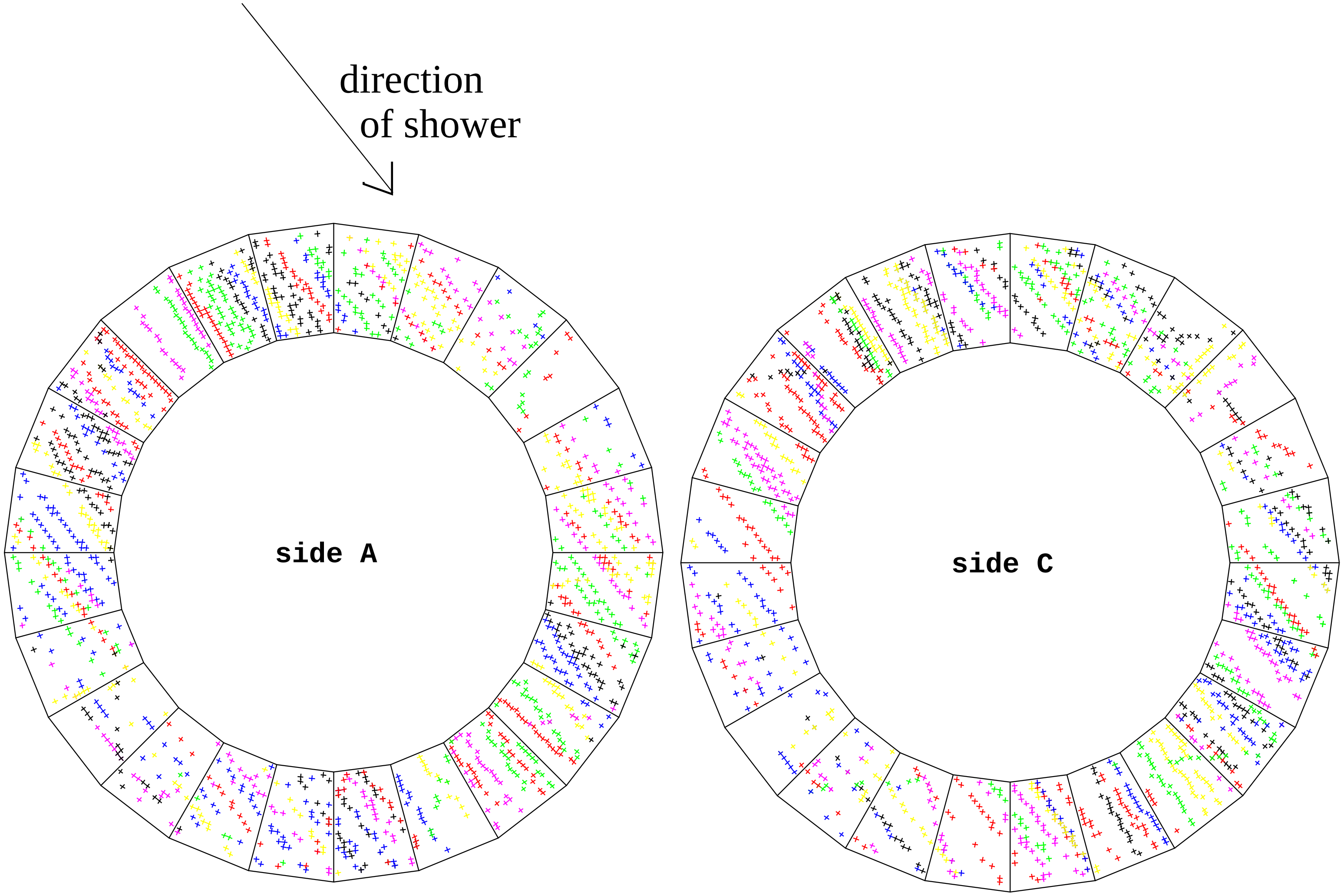

Figure 7: Cosmic event with high density of muons registered by HAC.

100 meters underground and corresponding overburden which imposes a cut of 52 GeV on muon momenta. Extensive simulations [A.11], [B.4] have shown that such energetic muons originate either directly or as the decay products from the first few interactions in the chain of development of an extensive air shower. Extensive air showers have been measured so far either on the ground (e.g. [C.5], [C.6], [C.7]) where the energetic muons (few hundreds per event) are entirely hidden in the overall shower with typically 10^5 muons per shower at the "knee" energies, or underground by former proton decay experiments with momentum cut-off around TeV [C.22], [C.20], [C.17], [C.25], [C.18]. In these cases one is left with very few muons $(1 \div 2)$ per event at very high energies. Thus the new data detected at medium depth underground are quite valuable as they can help to test the high energy models of elementary particles like e.g. QGSJET, NEXUS (VENUS) [C.15], [C.14] and several others. These models, extensively used by all cosmic ray experiments, are tuned to Tevatron data and then extrapolated up to energies 10^{20} eV. Although they describe the data from current experiments reasonably well they show notable differences in their predictions for a medium depth underground experiment as can be seen from Fig. 8.

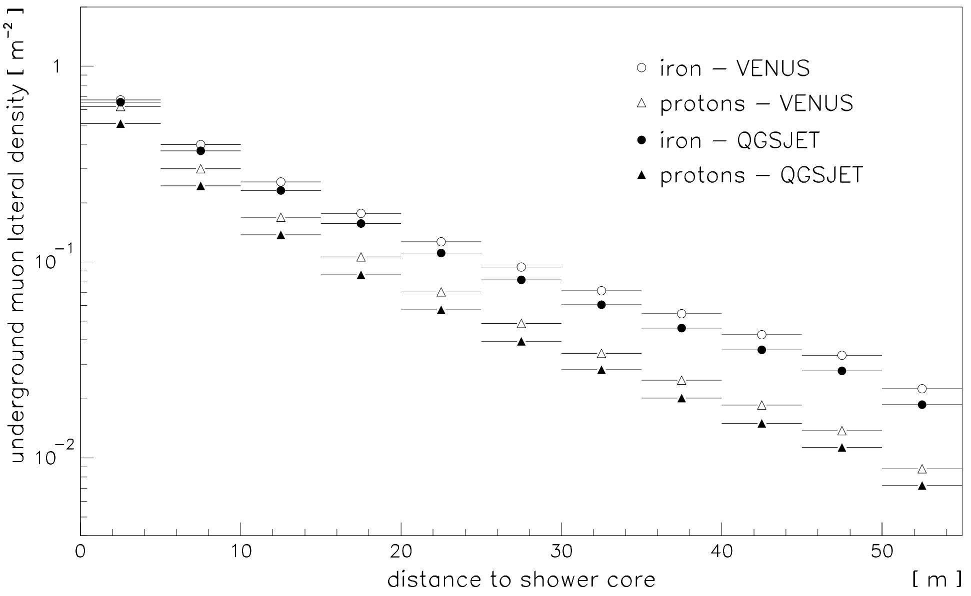

Figure 8: Comparison of muon lateral distribution functions obtained from VENUS and QGSJET at the depth of 100 m underground. Mean primary energy was $\sim 2.2\ 10^{15} eV$.

The aim of the DELPHI cosmic event analysis was to determine the flux of multi-muon events, to estimate the chemical composition and possibly to measure their other characteristics (time variation, zenith angle dependence etc.). The cosmic events registered during the years 1999 and 2000 correspond roughly to 1.6 10^6 s of effective run time. The analysis of DELPHI cosmic events is based on reconstruction program of HAC data [A.7] and time of flight detector (TOF) trigger. The analysis partially involved also other DELPHI sub-detectors (TPC, barrel muon chambers). The results have been reported at several conferences [A.10] and they were subject of PhD dissertation [B.5].

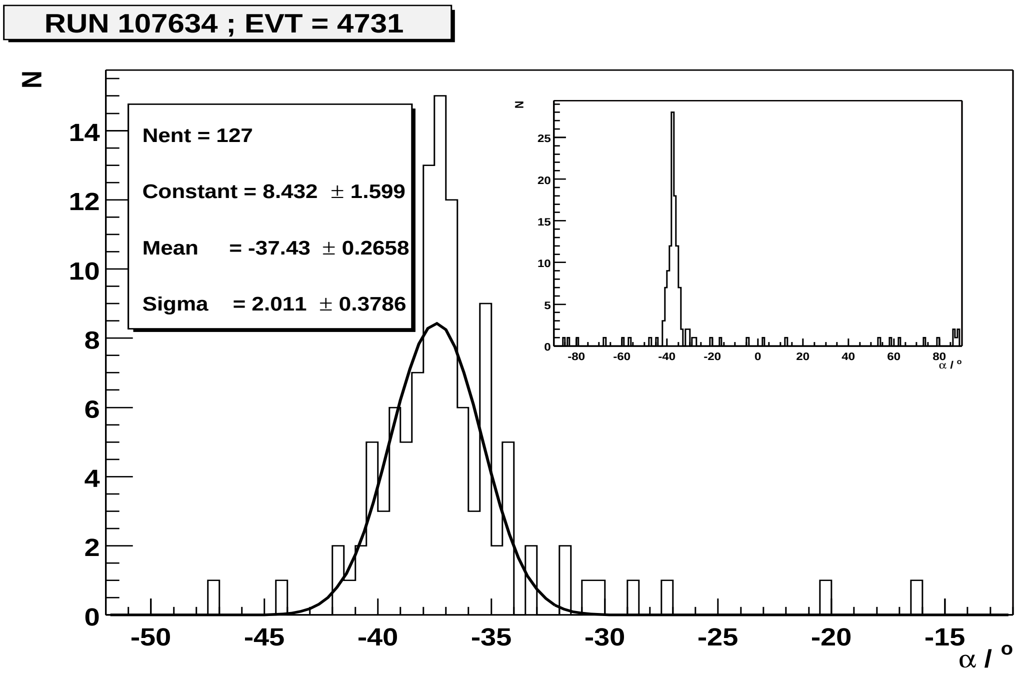

Figure 9: Direction of cosmic muons reconstructed from CRO data [A.10].

To detect the cosmic events, DELPHI cosmic trigger (DCT) has been implemented to the DELPHI trigger system. It requires 3 active TOF detector sectors (TOF MJ3) to trigger the event. The agreement of event rates during all detection periods and the agreement of event rates between different triggers was studied as a function of muon multiplicity measured in HCAL. The good agreement is obtained for all multiplicities starting from 4 and higher. The disagreement for smaller multiplicities could be explained by noise dependence of the trigger. In the ideal situation only two muons in TOF are enough to hit 3 TOF sectors and thus activate DCT. However, the TOF detection efficiency together with possible noise in the different TOF counters may either decrease the trigger efficiency or to fake false triggers at small multiplicities. Thus at small multiplicities the efficiency of event to be triggered depends more on the actual state of TOF than in case of events with bigger multiplicities. Therefore the further analysis includes only events with at least 4 muons ($N_\mu > 3$) detected by the HCAL cathode readout in order to ensure 3 TOF counters to be hit by muons and to avoid the noise dependent trigger decision. At multiplicity higher then 3 almost all reconstructed events are triggered by DCT (99.4%). ECTANA reconstruction package ([A.7]) is applied to reconstruct muon tracks from HCAL cathode readout in all accepted runs. The minimal track length of 50 *cm* is required. No explicit assumption of track parallelness is used in the reconstruction. The parallelness of reconstructed tracks was checked according to the cut that requires more than 50% of reconstructed tracks to be be within 5^o from the mean value of all track angles in the event. This condition rejects electromagnetic showers due to secondary interaction in the ceiling of DELPHI pit or inside the detector material. We have found 14 such shower like events out of 1065 high multiplicity ($N_\mu \geq 30$) events. As an example of event reconstruction by [A.7], the direction of muons in event shown in Fig. 7 is given in Fig. 9.

The multiplicity distribution measured in HCAL from selected runs is plotted in Fig. 10. Energy values marked by arrows in the upper part of the figure box are minimal primary energies of proton induced showers which can still produce events with multiplicities corresponding to the values given on the x axis but not higher.

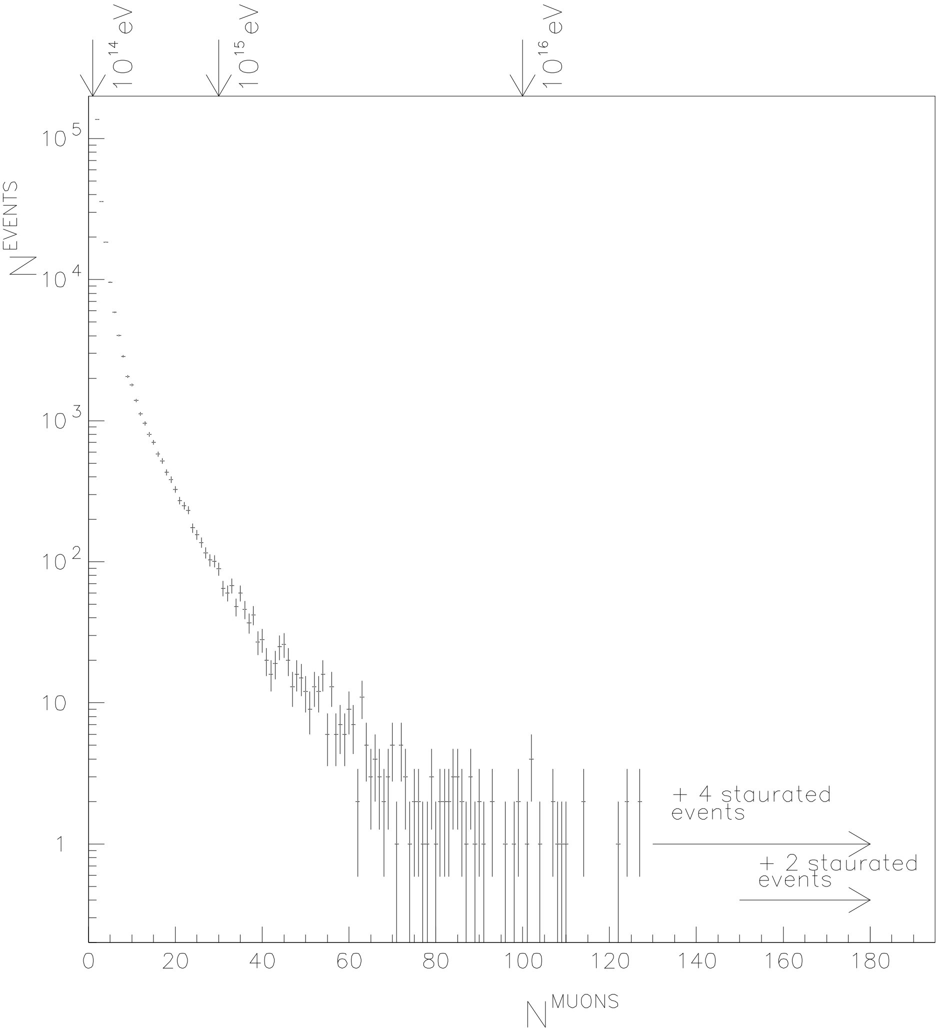

Figure 10: Distribution of muon multiplicity in HCAL.

The comparison between MC prediction for protons and iron nuclei as primary particles with the measured data is plotted in Fig. 11. In this figure the integral multiplicity (integrated from the value indicated on the x axis up to the end of the spectrum) is compared with MC predictions in *absolute normalization.* Up to the multiplicity $\sim$ 80 the data could be described by composition of the two extreme cases - pure proton and pure iron primary particles. In this region of high multiplicity ($\leq$ 80) the necessity to include the heavy component is evident. For even higher multiplicities the MC prediction is not sufficient to reproduce the measurement. The excess of events is apparent similarly as in the analysis [C.27]. The multiplicity spectrum is sensitive to the primary energy of the impinging particles, as one would expect and as observed also at the ground based experiments. However, compared to the ground experiments, the multiplicity spectrum seems to be more sensitive to the chemical composition of the primary radiation. These two variables are correlated and thus with precise independent measurement of the primary energy spectrum one is able to estimate with good resolution the heavy fraction of the mass spectrum of primary cosmic rays from these underground data. The increased fraction of heavier elements as a function of energy (multiplicity) is necessary to obtain agreement between data and MC prediction. This observation is in agreement with dedicated cosmic ray experiments that study cosmic particles at the knee energies ($\sim 10^{15}eV$) [C.5]. The excess indicated at high multiplicities (≥ 80) cannot be explained even with unrealistic assumption of cosmic rays as a flux of pure iron nuclei. Therefore it is clear that with current MC models one cannot establish chemical composition of primary particles from underground cosmic data.

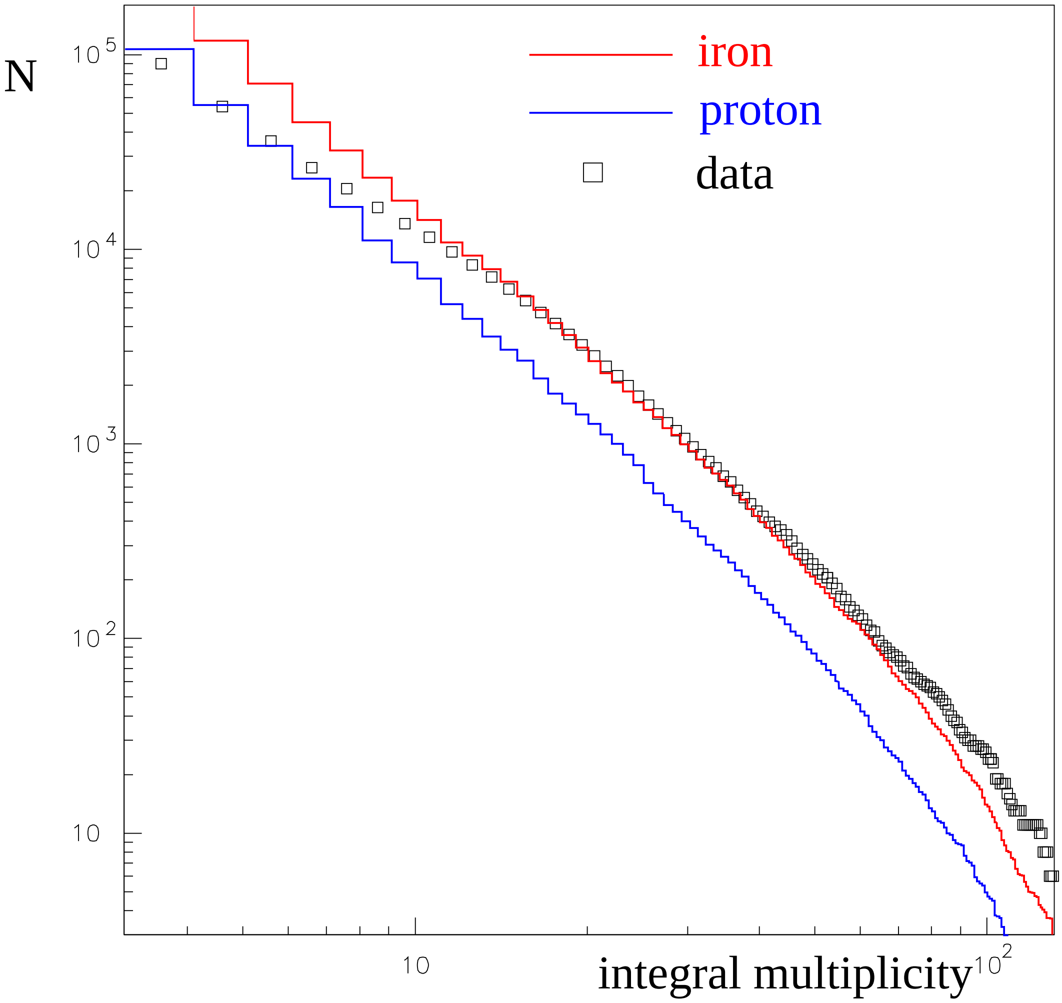

Figure 11: Integral multiplicity for MC protons, irons and the data.

Instead of that one can investigate how much the data are sensitive to the details of dynamical model used for description. Such attempts were made also in case of QGSJET [C.33]. In this paper the sensitivity of the results on proton-proton total cross-section and elasticity of proton interactions is tested. The total cross-section is lowered within the experimental errors of measurements at TEVATRON and the elasticity is also lowered accordingly. These changes result in somewhat improved agreement with our data as shown in Fig. 12. However, the main conclusion one can draw from this excercise is that the underground data are quite sensitive and therefore also useful for tuning of the models.

The LEP cosmic ray measurements and the DELPHI cosmic muon data in particular are unique in the sense that only QGSJET somewhat described the data as shown in Fig. 11. All other high energy interaction models failed so badly that it has no point to

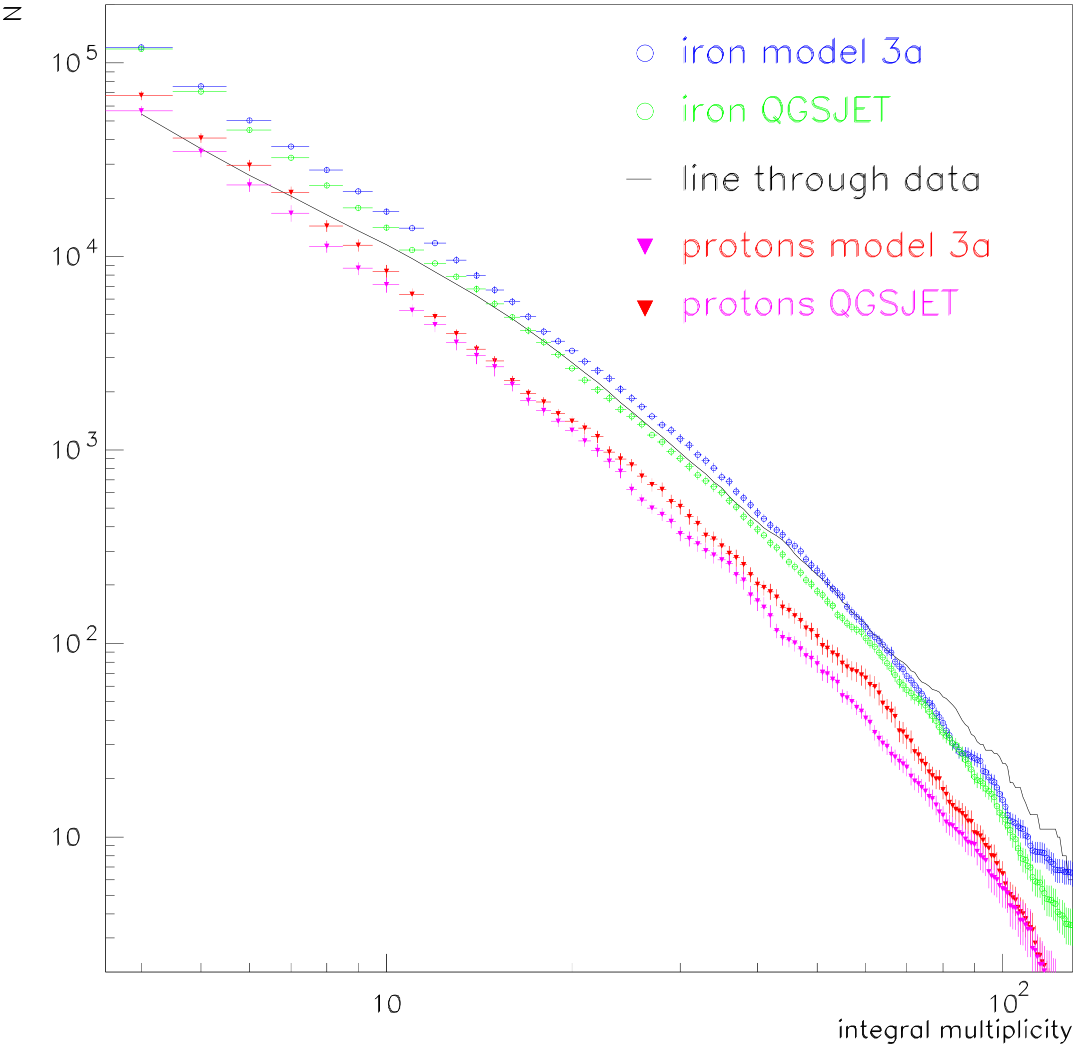

Figure 12: Comparison of original QGSJET model and its modification *3a* in [C.33].

use them for chemical potential fits. The only conclusion one can do is, that at the 'knee' energy interval the heavy component in cosmic primaries becomes indispensable. We have tested the sensitivity of QGSJET [C.14] to its internal parameters describing the interaction dynamics. This has been already investigated in the data from ground measurements by Hörandel [C.33]. The results of [B.5] lead to conclusion that the DELPHI data are very sensitive to the value of total nucleon-nucleon cross section and inelasticity used in the model. It should be noted that data correspond to interactions at LHC energy.

4 Muons as Probes of Cosmic Ray Interactions

The interactions of cosmic rays take place at altitudes higher than 20 km and the secondary charged pions and kaons have large chance to decay into muons due to the thin air at these altitudes. While the decay products of the neutral pions undergo interactions throughout the whole depth of atmosphere, the muons in a sense decouple from further shower development and are subjected only to multiple scattering and ionization losses. Moreover the big Lorentz factor helps to collimate the secondary particles into a narrow cone. As a result of all such phenomena there is a possibility to observe differences in muon production in some extensive air showers from what one would expect on the basis of standard models of high energy interactions. The fact that the hard component of muons in extensive air showers carries information on the pion production in the initial stage of the shower development is of great importance and it has been studied in [B.4]. It is interesting to study the sensitivity of energetic muons to the details of the primary interaction dynamics. The paper [A.11] is an example of such sensitivity study. It has been motivated by high multiplicity events seen by DELPHI.

Although the more precise determination of the chemical composition at the 'knee' energy region ($5 \times 10^{14}\ eV$ up to almost $10^{17}\ eV$) is not yet feasible, the 10 % presence of Fe^{56} is quite plausible. This rises an interesting possibility to observe iron nitrogen and iron oxygen nucleus-nucleus interactions at energies beyond possibilities of terrestrial accelerators. Though both N^{14} and O^{16} are light nuclei, the number of participating nucleons in head on collisions with iron nuclei goes to several tens. Thus given the available energy per nucleon, the formation of quark-gluon plasma might be possible. Although the baryon density is due to the light participating nucleus only half of the density in Pb-Pb interaction, the energy density can reach sufficient value. Due to the absence of a comprehensive QGP theory and also due to the lack of solid experimental evidence there are many models, sometimes with quite opposing predictions. This is true also in the case of secondary particles multiplicity. There are predictions of a decrease of multiplicity [C.9] in high energy nuclear collisions. However, many statistical thermal models predict increase of multiplicity [C.10]. In any way the secondary particle multiplicity is an important variable and a change of the interaction dynamics may be indicated by particle production change depending on the size of the effect and the sensitivity of measurements.

To study this, a very simple model of QGP formation is presented in [A.11]. It uses only two parameters - $\mathcal{R}_h = N_{hot}/N_{int}$, which denotes the fraction of interacting nucleons N_{int} melting down to QGP and the mean momentum $< p^{\pi} >$ of pions which evaporate from freezing QGP with Boltzmann distributed kinetic energy and isotropically in the center of mass system. Thus the whole energy of N_{hot} nucleons is converted mostly to pions. Varying the two parameters one is able to simulate wide range of conditions. The two limit cases of those studied in [A.11] are 10 % of melted nucleons with $< p^{\pi} >= 1\ GeV$ and 40 % of melted nucleons with $< p^{\pi} >= 60\ MeV$ (denoted further as $QGP(0.1, 1.0)$ resp.

$QGP(0.4, 0.06)$). They differ by one order in the average number of evaporated pions. The model is used to simulate the QGP and the results are then compared with the outcome of programs currently used for simulations of extensive air showers [C.11, C.15]. The sensitivity of the muon component of air showers to the QGP effects is studied. Apparently the change in the interaction dynamics, i.e. in the first interaction, has to appear in the hard component of the muon spectrum. One simple method, how to observe this muon spectrum part is to place the muon detection area underground at such depth that the overburden will filter out the energetic muons in an amount sufficient to carry the information on the initial interaction. The simulations in [A.11] show that at the 'knee' energies of initial interaction, the appropriate depth is just the one imposing momentum cut-off of only several tens GeV. This is demonstrated in Fig. 13 showing the momenta of different types of muons.

The main detected quantities used to describe extended air showers are the electromagnetic and muon size and corresponding lateral distribution functions (LDF). These quantities are related as follows (e.g. for muons)

$$N_\mu = \int_{r_1}^{r_2} 2\pi \rho_\mu(r) dr,$$

where $\rho_\mu(r)$ is the density of particles (LDF) in the detection plane and $r = 0$ corresponds to the shower center. These LDF both at ground level and underground have been compared in [A.11]. The results of performed studies lead to conclusion that while at the ground level the effects caused by changed dynamic of pion production in the first interaction leave no observable traces, underground one can notice in principle some differences. This is indicated in Fig. 14 where the ratios of underground muon LDF functions are given.

Thus the inclusion of a very simple model of QGP production and freeze-out into high energy interactions of iron nuclei with air in cosmic ray showers has shown that under certain kinematic conditions one could observe the QGP induced effects in the high energy muon component of extensive air showers. These kinematic conditions are mainly the availability of sufficient energy E_{hot} of melted nucleons and not too high mean momentum $< p^\pi >$ of the evaporated pions. The model has been intentionally chosen so simple that it can cover sufficiently large interval of these two quantities with minimum parameters. Moreover the simulations have shown that the underground data on muons are rather insensitive to the isotropy of initial QGP pion distribution. It is interesting that none of the simulated QGP systems increases the muon density in the very center of the shower and this number is essentially determined by the unmodified high energy interaction model (VENUS in this case).

Results obtained from simulations discussed above cannot be compared at present with real data as the muon detectors are either located at ground level where the high energy component is entirely hidden in the overall muon flux or they are located so deep underground that the muon momentum cutoff is of the order of TeV or larger and only few muons penetrate to the detector ([C.17],[C.18],[C.19], [C.20],[C.21],[C.22]). The few experiments with medium overburden have either crude spatial resolution like the underwater experiments [C.23] and [C.24] or they have relatively small detection area like [C.25] ($6 \times 6\ m^2$).

The insensitivity of the ground level LDF to the details of the high energy interaction dynamics is quite important and in fact useful. In ideal case the simultaneous measurements both at the ground level and underground can reveal many interesting features of high energy hadron interactions. The ground measurements provide information on the

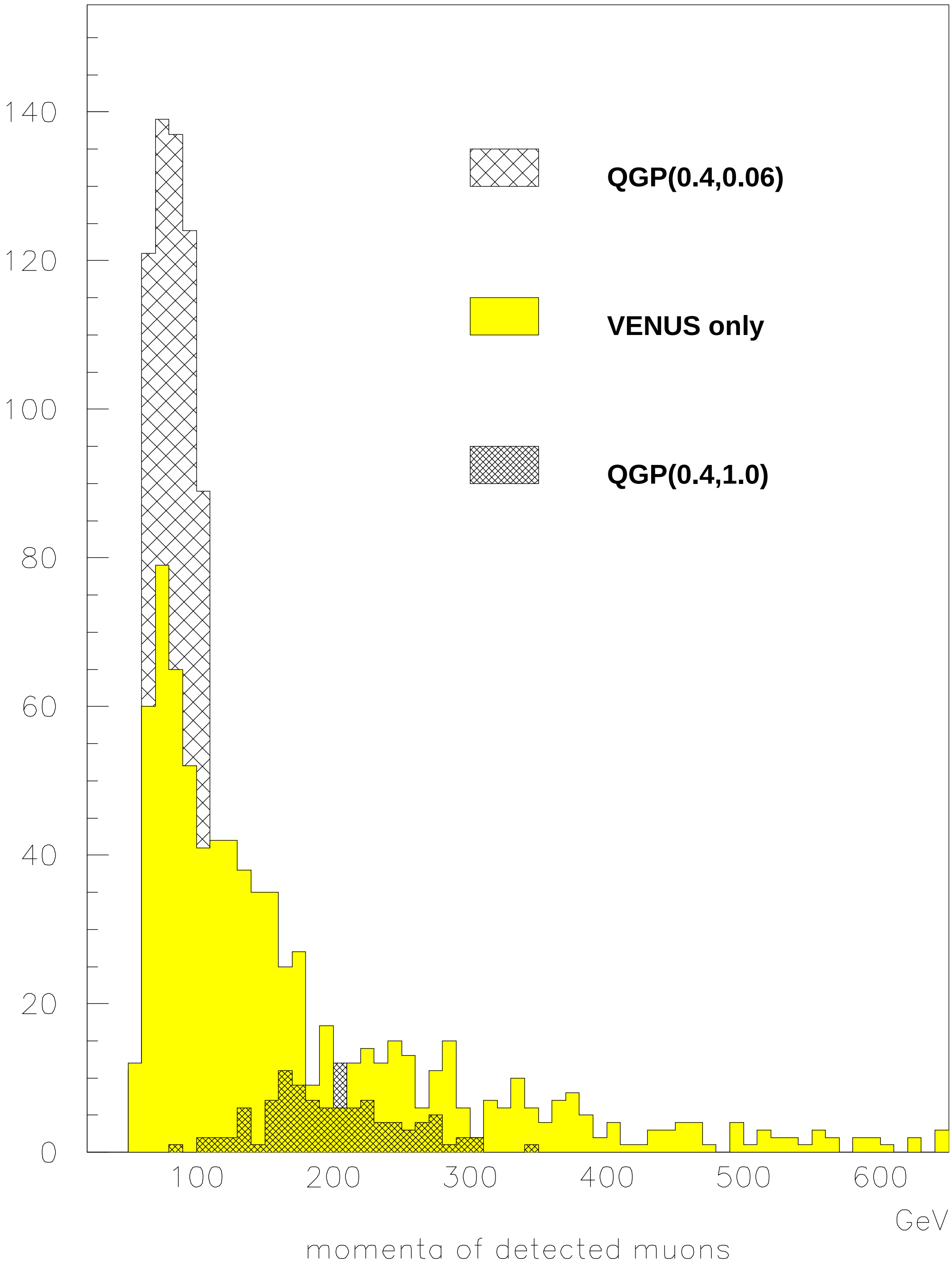

Figure 13: Momenta of muons from QGP and from standard production. Altitude of interaction is 33.1 km, $E_{inc} = 2.25\ 10^{15} eV$, $N_{int} = 36$ and $N_{hot} = 14$.

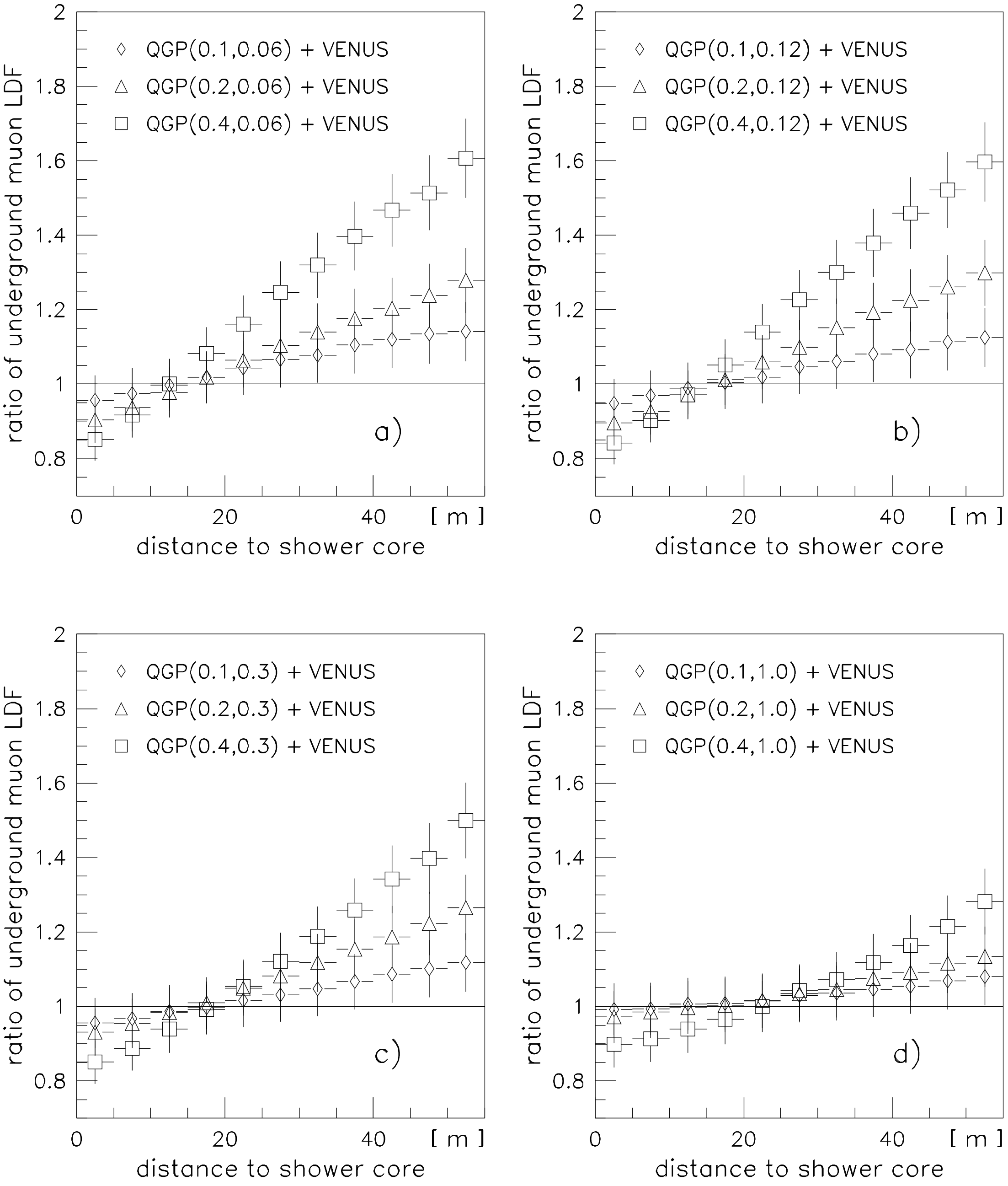

Figure 14: Ratio of underground lateral muon densities with QGP simulation to simulations done by VENUS only (events with $N_\mu^u > 990$). Mean primary energy was $\sim 2.2\ 10^{15} eV$.

energy of the projectile particle and the location of the shower core. The underground data will yield information on anomalously high or low muon multiplicity events. Both cases would signal departure from standard scenario at energies beyond reach of current accelerators.

The estimations show that the underground detector with area of about $100m^2$ is capable to register reasonable amount of high multiplicity events per year. The incident particles with energies of $E_{inc} > 10^{16}\ eV$ are already accessible with detector of this size. Moreover, as the measurements by DELPHI indicate, this phenomenon is more frequent then expected.

5 Results

The common basis of the papers [A.1]-[A.11] is the detection of muons in a hadron calorimeter, its hard-ware and soft-ware realization and use of the muons in physical analysis as probes of the interaction dynamics with the extension of the use to the domain of the high energy cosmic rays. The main results of these studies can be summarized as follows:

1. *Muon detection by hadron calorimeters.* It has been demonstrated both by MC simulations and in practice that hadron calorimeters with tracking capability can detect muons very precisely. The read-out electronics may be quite simple (and cheap) without amplitude measurement capabilities. The space resolution of several millimetres or 1 cm is quite sufficient as the calorimeters of collider experiments are placed in the distance of several meters from the interaction point. The detector volume equipped by such sensing devices has not necessarily to be very large as the measurements placed at proper radii (in terms of nuclear lengths) will be sufficient, depending on physical goals of particular experiment - the softer muons one needs to measure, the more precise data from the inner parts of calorimeter are necessary. By tracking muons inside hadron calorimeter one can in general reach the purity of muon sample in desired momentum range at the level given by punch-through limit.

2. *Detection of cosmic muons at medium depths.* The importance of the measurements on the cosmic muons at the depth of about 100 meters of standard rock equivalent has been realized when data from three LEP experiments became available. These data have quality unusual for cosmic ray experiments and they are unique as the measurements at this depth have been not yet performed with precision allowing to count individual muons. These data show that the cosmic muons in the momentum range of few hundreds GeV show phenomena which are poorly described by standard Monte Carlo programs for cosmic shower simulation. It is too early to conclude whether this is signature of unknown phenomena or just bad tuning of MC programs. Even in the latter case the data are important for correct tuning of high energy models as they are extrapolated to energies $10^{20}\ eV$ and the knowledge of correct muon flux underground is indispensable for studies of neutrino oscillations and neutrino astronomy.

3. *Sensitivity of high momentum cosmic muons to the dynamic of the initial high energy interaction.* The simulations necessary to describe LEP underground data have shown that the muons detected at the depth of about 100 meters underground originate from the first few interactions in development of the shower initiated by particle with primary energy up to about $10^{17}\ eV$. Further studies have shown that certain

details of the particle production in the very first interaction can be still observed in the underground measurements.

Sensitivity of the high energy interaction models to the data on high momentum muons has been experimentally verified in [B.5]. It is shown that changes on the level of several % of the value of total proton-proton cross section and inelasticity are observable.

The importance of the detection technique described in point 1) is becoming to be widely recognized. Although the results became known late to be incorporated into LHC detector design, they are taken into account in R&D programs for linear collider. In this context the possibility of "digital calorimeter" is investigated (see [C.28]).

The importance of the measurements on cosmic muons by three LEP experiments (ALEPH, DELPHI and L3+C) has been pointed out by rapporteurs at ISVHECRI2002 ([C.29]) and at ICHEP2002 ([C.30]). DELPHI data are important in this context as the event statistics of DELPHI is ten times higher then that of ALEPH and although DELPHI cannot measure momentum of cosmic muons it can count the multiplicity of muon bundles up to more then 100 while L3+C can count the multiplicity up to 30 only ([A.10, B.4, C.31]).

The sensitivity of high momentum cosmic muons to the dynamic of the initial high energy interaction is important in the context of narrowing gap between terrestrial accelerators and cosmic rays. RHIC results are of great relevance for the cosmic ray physics at the "knee" energies. However, even the LHC range will reach only 10^{17} eV in Lab system. Thus the measurements on high energy cosmic rays performed simultaneously at ground level and preferably at several underground levels with relatively large area detectors may bring results valuable for particle physics. Based on the results of cosmic ray measurements at LEP and [B.4] proposal, a new experiment is currently under preparation in the Center for Underground Physics in Pyhälmi mine [C.32] in Finland. The experiment will utilise DELPHI muon chambers.

6 Published Papers and References

A Dissertation

References

[A.1] J.Ridky: Simulation of Hadronic Showers in DELPHI Hadron Calorimeter, DELPHI 86-59 CAL 35.

[A.2] J.Ridky, M.Lokajicek: Some Characteristics of the Signals From DELPHI Hadron Calorimeter, DELPHI 87-48 PROG 84 CAL 47.

[A.3] G.D. Alekseev, Yu.E. Bonushkin, S. Czellar, B. Fialovszki, B.A. Khomenko, N.N. Khovansky, A.V. Korytov, P.A. Kulinich, M. Lokajicek, G.V. Mitselmakher, J. Patocka, V.D. Ryabtsov, J. Ridky, Yu.V. Sedykh, V.V. Tokmenin, R. Toledo, E. Tarjan: The Results of mass Testing of the Plastic Streamer Tubes for the DELPHI Hadron Calorimeter. Nucl.Instrum.Meth. **A305** (1991),344-353.

[A.4] By DELPHI Collaboration (I. Azhinenko *et al.*): The Cathode Readout of the DELPHI Hadron Calorimeter. IEEE Trans.Nucl.Sci. **42** (1995),485-490.

[A.5] DELPHI HAC Collaboration (I. Azhinenko *et al.*): The Performance of the DELPHI Hadron Calorimeter at LEP, IEEE Trans.Nucl.Sci. **43** (1996), 1751-1756.

[A.6] DELPHI Collaboration (P. Abreu *et al.*): Performance of the DELPHI Detector. Nucl.Instrum.Meth. **A378** (1996),57-100. (Erratum-ibid. **A396** (1997), 281).

[A.7] J.Ridky, V.Vrba, J.Chudoba: ECTANA, User's Guide, DELPHI 99-181 TRACK 96.

[A.8] DELPHI Collaboration (P. Abreu *et al.*): Search for pair-produced neutralinos in events with photons and missing energy from e^+e^- collisions at $\sqrt(s) = 130 - 183\ GeV$, Eur.Phys.J. **C6** (1999), 371-384.

[A.9] DELPHI Collaboration (P. Abreu *et al.*): Photon Events with Missing Energy at $\sqrt(s) = 183\ GeV$ to $189\ GeV$, Eur.Phys.J. **C17** (2000), 53-65.

[A.10] J. Ridky, P. Travnicek: Cosmic Multimuon Bundles Measured by DELPHI, Contributed Paper for ICHEP 2002 (Amsterdam), DELPHI 2002-075-CONF-609, DELPHI Collaboration (J. Abdallah *et al.*): Study of multi-muon bundles in cosmic ray showers detected with the DELPHI detector at LEP, CERN-PH-EP-2007-008, Jun 2007. 22pp, Astropart. Phys. **28**(2007),273-286, e-Print: arXiv:0706.2561 [astro-ph]

[A.11] J. Ridky: Astropart. Phys. **17**(2002),355-365 and Nucl. Phys. Proc. Suppl. **110**(2002),481-483.

B Author's Publications Related to the Dissertation

References

[B.1] By DELPHI Collaboration (P. Aarnio *et al.*): The DELPHI Detector at LEP. Nucl.Instrum.Meth. **A303** (1991),233-276.

[B.2] By DELPHI Collaboration (P. Abreu *et al.*): Measurement of the Mass and Width of the W Boson in e^+e^- collisions at $\sqrt(s) = 189\ GeV$, Phys.Lett. **B111**(2001), 159-177.

[B.3] By DELPHI Collaboration (P. Abdallah *et al.*): Searches for Neutral Higgs Bosons in e^+e^- Collisions from $\sqrt(s) = 191.5\ GeV$ to $201.7\ GeV$, Eur.Phys.J. **C23** (2002), 409-435.

[B.4] A Cosmic Ray experiment in and above the LHC tunnel, proposal SPSC 2001-003/P321.

[B.5] Petr Travnicek, PhD thesis (supervisor J. Ridky), MFF UK, Prague, 2004. The complete thesis is available at the web address:
http://www-hep2.fzu.cz/∼travnick/thesis.ps.gz

C Other Related Papers

References

[C.1] J. Chudoba: Measurement of the W Boson Mass, doctoral thesis, Charles University, 1998.

[C.2] G.Wilkinson: Improvements to the Muon Identification in the 94C Short DST production, DELPHI 97-37 PHYS 690.

[C.3] S. de Brabandere, D. Edsall, M. Dam: TAUPLUS - A Tau physics Analysis Package - Version 5.4, DELPHI 98-15 PROG 229.

[C.4] A.A. Watson: Proc. '25th International Cosmic Ray Conference', Durban, South Africa, 1997, Vol. 8, p257.

[C.5] K-H. Kampert *et al.*: Contribution to '26th International Cosmic Ray Conference', OG 1.2.11, Salt Lake City, Utah, August 17-25, 1999.

[C.6] S.P. Swordy and D.B. Kieda: Elemental Composition of Cosmic Rays Near the Knee by Multiparameter Measurements of Air Showers, Astropart. Phys. **13**,(2001), 137-150.

[C.7] J.W. Fowler *et al.*: A Measurement of the Cosmic Ray Spectrum and Composition at the Knee, Astropart.Phys. **15**,(2001), 49-64.

[C.8] J.D. Bjorken: Phys. Rev. **D27** (1982), 140.

[C.9] K.J. Eskola, K. Tuominen: Phys. Lett. **B 489**,(2000),329.

[C.10] N. Armesto, C. Pajares; Int. Journal of Mod. Phys. A, Vol. 15, No. 14 (2000), 2019.

[C.11] D. Heck *et al.*: CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers, Forschungszentrum Karlsruhe, Technik und Umwelt, Wissenschaftliche Berichte **FZKA 6019**, 1998.

[C.12] T. Antoni *et al.*:J. Phys. G, Nucl. Part. Phys. **25**(1999), 2161-2175.

[C.13] T.Antoni *et al.*: Electron, Muon and Hadron Lateral Distributions Measured in Air-Showers by the KASCADE Experiment, Astropart. Phys. **14**,(2001) 245-260.

[C.14] N.N. Kalmykov and S.S. Ostapchenko: Yad. Fiz. **56** (1993), 105.
N.N. Kalmykov and S.S. Ostapchenko: Phys. At. Nucl. **56** (1993), 346.
N.N. Kalmykov, S.S. Ostapchenko and A.I. Pavlov: Bull. Russ. Acad. Sci. (Physics) **58** (1994), 1966.

[C.15] K. Werner: Strings, Pomerons and the VENUS model of hadronic interactions at ultrarelativistic energies, Phys. Rep. 232, Nos. **2-5** (1993), 87-299.

[C.16] R.Brun *et al.*: GEANT CERN Program Library Writeup W5013, 1993.

[C.17] MACRO Collaboration, M. Ambrosio *et al.*: Phys. Rev. **D** 52,(1995) 3793.

[C.18] SOUDAN Collaboration, Internal Report No.PDK-435, 1990 (unpublished).

[C.19] C.Castagnoli and O.Saavedra: Nuovo Cimento C **9**,(1986) 111.

[C.20] NUSEX Collaboration, M. Aglietta *et al.*: Proceedings of the topical seminar 'Astrophysics and Particle Physics', San Miniato, Italy, 1989, edited by G. Castellini *et al.* [Nucl. Phys. B(Proc. Suppl.) **14B**, (1990) 193.]

[C.21] LVD Collaboration, M. Aglietta *et al.*: Astropart. Phys. **3**,(1995) 311.

[C.22] Fréjus Collaboration, W. Rhode *et al.*: Astropart. Phys. **4**,(1996) 217.

[C.23] E.V. Bugaev *et al.*: Phys. Rev. **D** 58,(1998) 1.

[C.24] Yu.M. Andreyev, A.E. Chudakov, V.I. Gurentsov and I.M. Kogai: Proceedings of the 21st International Cosmic Ray Conference, Adelaide, Australia, January 6-19, 1990, edited by R.J. Protheroe (Dept. of Physics and Mathematical Physics, Univ. of Adelaide, Northfield, South Australia, 1990), Vol. **9**, p. 301.

[C.25] N. Ito (for the KGF Collaboration): Proceedings of the International Symposium on Underground Physics Experiment, Tokyo, Japan, 1990, edited by K. Nakamura (ICRR, Tokyo, 1990), p. 101.

[C.26] J. Cleymans, R.V. Gavai and E. Suhonen: Phys. Rep. Vol. 130, **4**,(1986) 217-292.

[C.27] V. Avati *et al*: *CERN EP/*2000-192.

[C.28] P. Collins: "R&D for future detector", rapporter's talk at ICHEP2002, Amsterdam, 2002.

[C.29] P. Lippari: Rapporter's talk at ISVHECRI2002, CERN, Geneva 2002.

[C.30] T. Geisser: "Particle astrophysics", rapporter's talk at ICHEP2002, Amsterdam, 2002.

[C.31] C. Timmermans: "Cosmic rays with the LEP detectors", talk at ICHEP2002, Amsterdam, 2002.

[C.32] T. Enqvist *et al.*: XXVIII International Cosmic Ray Conference (ICRC), Tsukuba, Japan, 2003 (proceedings) (997-1000)

[C.33] J.R. Hörandel: On total inelastic cross-sections and the average depth of the maximum of extensive air showers, J. Phys. G **29**, 2439 (2003) [arXiv:astro-ph/0309010].

7 APPENDIX - the publications

References

[A.1] J.Ridky: Simulation of Hadronic Showers in DELPHI Hadron Calorimeter, DELPHI 86-59 CAL 35.

[A.2] J.Ridky, M.Lokajicek: Some Characteristics of the Signals From DELPHI Hadron Calorimeter, DELPHI 87-48 PROG 84 CAL 47.

[A.3] G.D. Alekseev, Yu.E. Bonushkin, S. Czellar, B. Fialovszki, B.A. Khomenko, N.N. Khovansky, A.V. Korytov, P.A. Kulinich, M. Lokajicek, G.V. Mitselmakher, J. Patocka, V.D. Ryabtsov, J. Ridky, Yu.V. Sedykh, V.V. Tokmenin, R. Toledo, E. Tarjan: The Results of mass Testing of the Plastic Streamer Tubes for the DELPHI Hadron Calorimeter. Nucl.Instrum.Meth. **A305** (1991),344-353.

[A.4] By DELPHI Collaboration (I. Azhinenko *et al.*): The Cathode Readout of the DELPHI Hadron Calorimeter. IEEE Trans.Nucl.Sci. **42** (1995),485-490.

[A.5] DELPHI HAC Collaboration (I. Azhinenko *et al.*): The Performance of the DELPHI Hadron Calorimeter at LEP, IEEE Trans.Nucl.Sci. **43** (1996), 1751-1756.

[A.6] DELPHI Collaboration (P. Abreu *et al.*): Performance of the DELPHI Detector. Nucl.Instrum.Meth. **A378** (1996),57-100. (Erratum-ibid. **A396** (1997), 281).

[A.7] J.Ridky, V.Vrba, J.Chudoba: ECTANA, User's Guide, DELPHI 99-181 TRACK 96.

[A.8] DELPHI Collaboration (P. Abreu *et al.*): Search for pair-produced neutralinos in events with photons and missing energy from e^+e^- collisions at $\sqrt(s) = 130 - 183\ GeV$, Eur.Phys.J. **C6** (1999), 371-384.

[A.9] DELPHI Collaboration (P. Abreu *et al.*): Photon Events with Missing Energy at $\sqrt{(s)} = 183\ GeV$ to $189\ GeV$, Eur.Phys.J. **C17** (2000), 53-65.

[A.10] J. Ridky, P. Travnicek: Cosmic Multimuon Bundles Measured by DELPHI, Contributed Paper for ICHEP 2002 (Amsterdam), DELPHI 2002-075-CONF-609, DELPHI Collaboration (J. Abdallah *et al.*): Study of multi-muon bundles in cosmic ray showers detected with the DELPHI detector at LEP, CERN-PH-EP-2007-008, Jun 2007. 22pp, Astropart. Phys. **28**(2007),273-286, e-Print: arXiv:0706.2561 [astro-ph]

[A.11] J. Ridky: Astropart. Phys. **17**(2002),355-365 and Nucl. Phys. Proc. Suppl. **110**(2002),481-483.