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Muon pair production by muons and narrow muon bundles underground

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Summary. —We consider the process of muon pair production by high-energy muons and its consequences for the characteristics of muon flux underground. It is shown that the accounting of this process in the muon propagation through the rock results in an additional flux of narrow double- and triple-muon events which is comparable to the conventional flux of narrow muon bundles with low multiplicity.

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Muon bundles, discovered independently by G. Wataghin in 1941 [1] and E. Amaldi and C. Castagnoli in 1952 [2], are produced in Extensive Air Showers (EAS) initiated by primaries with energies more than 100 TeV. The study of muons in EAS provides information about the energy spectrum, composition and cross-section of cosmic-ray particles at very high energies. Multiplicity and pair separation distribution of muons in the bundles are studied usually in the underground experiments. The former distribution is connected with the primary isotopic composition and the latter one is connected with the cross-section of primary cosmic-ray particles. The new methods of muon bundle analysis are developing now. These methods include the measurement of the dependence of the angle between muons in the bundle on their lateral separation ("decorrelation function") [3] and search for muon clusters in the high-multiplicity events [4, 5]. For the analysis of muon bundles, it is very important to be sure that all detected muons were produced in EAS.

The process of muon pair production by muons is usually neglected in the propagation of muons because of its small cross-section which is 4 orders of magnitude less than the cross-section of electron pair production. However, for muon interactions with high-energy transfer ($v = E/E_\mu \gg 10^{-2}$, where E_μ is the muon energy and E is the energy transferred to the secondary particle(s)), the cross-section of muon pair production is about 100 times less than the bremsstrahlung cross-section which is the most important stochastic process for the propagation of high-energy muons through large thickness of matter. If the energy transferred to the muon pair is high enough, the muons produced in such interaction (or at least one muon) can reach the level of observation together with the initial muon. This can result in the observation of double- (or triple-) muon events.

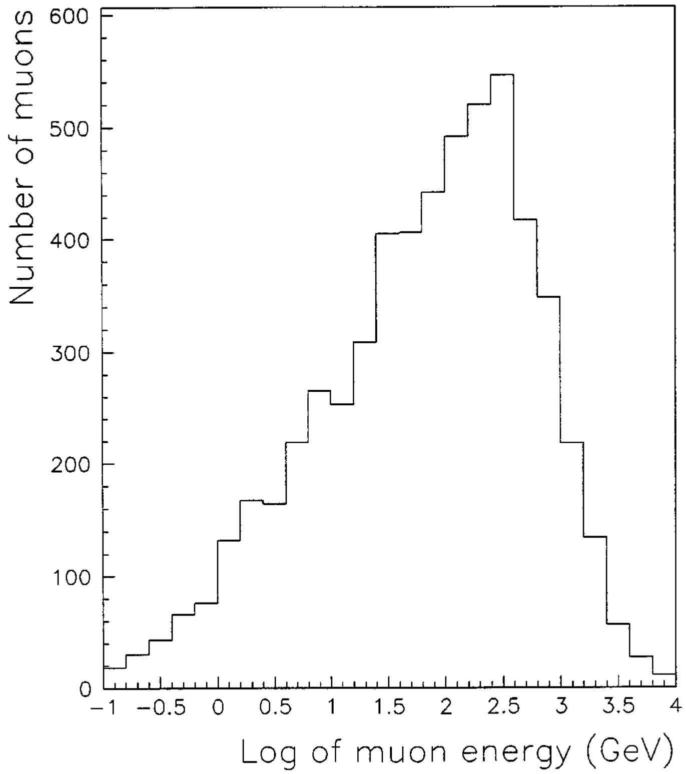

Fig. 1. – Energy distribution of muons in double- and triple-muon events at the depth of 3 km w.e.

In this paper we estimate this effect and discuss its applications for underground muon physics.

The new three-dimensional Monte Carlo code MUSIC [6] has been used to propagate muons from the sea level to the level of observation. The code takes into account the stochasticity of all processes (bremsstrahlung, inelastic scattering, electron pair production, knock-on electron production) with the energy transfer $v > 10^{-3}$. It calculates the angular deviation and lateral displacement of muons due to multiple scattering and stochastic processes. The process of muon pair production is not included originally in this code. We have added this process with the differential cross-section from [7, 8]. We have taken into account the energy transfers $v > 10^{-3}$. The cross-section given in [8] is calculated in the case of full screening with the logarithmic accuracy. In the muon propagation through the standard rock we consider only one (if this takes place) interaction with muon pair production. Actually, the mean muon path to the interaction with muon pair production ($v > 10^{-3}$) is about 60 km w.e. (for $E_\mu > 1$ TeV). It is obvious that the probability of two interactions up to the relevant depth is an order of magnitude less than that of one interaction. However, this fact together with the uncertainty of the cross-section, mentioned above, increases the uncertainty of the result up to about 10%. When the interaction with muon pair production occurred during the muon transport through the rock, all three muons have been propagated up to the observation depth using the original code. We did not take into account the scattering of muons due to the process of

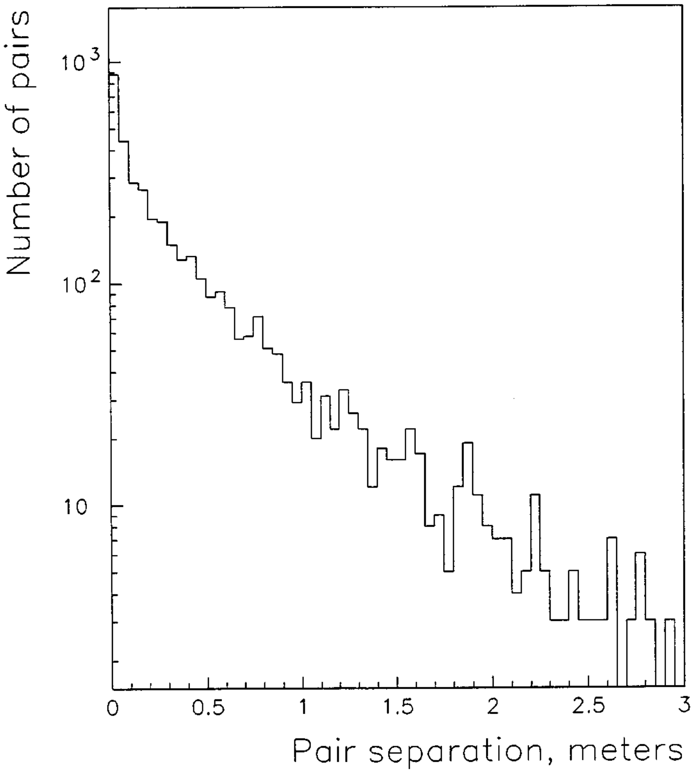

Fig. 2. – Distribution of lateral separations of muons in double- and triple-muon events at the depth of 3 km w.e.

muon pair production. As is shown in [6], the scattering of muons due to stochastic processes can be neglected, because the resulting angular deviation and lateral displacement are much less than those due to multiple-scattering process.

Ten millions of muons were sampled according to the initial sea-level muon energy spectrum in power law form with power index -3.7 and were propagated up to the depths of 3 and 10 km w.e. The low-energy edge of the muon spectrum at sea level was equal to 900 GeV for 3 km w.e. and 9 TeV for 10 km w.e. These energies correspond to the muon survival probabilities ≤ 0.003. 3404569 and 399421 muons were survived at the depth $x = 3$ and 10 km w.e., respectively. The muon survival probabilites averaged over the sea level muon spectrum are lower by $(0.2 \pm 0.2)\%$ and $(0.1 \pm 0.2)\%$ for $x = 3$ and 10 km w.e. than those obtained using the original code without muon pair production process (the error is determined by the statistics used in the original code). This result proves that the muon pair production process gives a small contribution to the muon intensity underground and can be neglected for this purpose. Among the survived muons we have found 1958 double- and 631 triple-muon events at the depth of 3 km w.e. and 382 double- and 53 triple-muon events at the depth of 10 km w.e. Since most of the existing detectors are placed at small or median depths ($x \leq 5$ km w.e.), we will discuss below the characteristics of these events at the depth of 3 km w.e.

The energy distribution of muons in double- and triple-muon events at the depth of 3 km.w.e. is shown in fig. 1. The distribution of the lateral separations of muons in such events is shown in fig. 2.

The mean energy of muons is equal to 342 GeV. This energy is higher than that of conventional single muons with the same initial spectrum (247 GeV). The mean initial energy of muons at sea level is equal to 3810 GeV which is also higher than the value obtained for conventional single muons (1923 GeV). This fact can be explained in the following way. To produce a muon pair with an energy sufficient to reach the level of observation (for at least two muons), the initial muon should have an energy higher than the mean initial muon energy for survived muons. Of course, the higher the mean initial muon energy is, the higher the mean energy should be at the observation depth. The fact that muon energy is divided between three muons and these muons lose the energy during the propagation through the rock is less important at this depth.

The distribution of pair separations (r) presented in fig. 2 differs from that for conventional multiple-muon events (muon bundles). The distribution shown in fig. 2 is narrow with a peak at $r \approx 0$. This is due to the fact that muon pairs are produced along all path of muons down to the observation level. The main contribution to the distribution at small r is given by triple-muon events when the muon pair is produced near the observation level. The distribution of pair separations in conventional muon bundles is determined by two effects: i) the spread of muons in EAS due to the transverse momentum transferred to pions and kaons; ii) the spread of muons due to the multiple scattering along the muon path in the rock. The mean separation ($\langle r \rangle$) is equal to 0.43 m for the events presented in fig. 2 (0.63 m for double-muon events), while it is of the order of several meters for conventional muon bundles.

The ratio of multiple-muon events obtained with the code (hereafter we will call them “narrow muon bundles”) to the conventional single muons is $7.6 \cdot 10^{-4}$. This ratio is much less than the ratio of conventional muon bundles to the single muons which is of the order of several percent. However, the ratio of narrow muon bundles to the conventional muon bundles is increased with the decrease of r. We have calculated this ratio using the experimental data of LVD [9]. The ratio of multiple-muon events measured by the first LVD tower to single muons is about 0.027 [9]. For simplicity, we have considered only double-muon events and found the ratio of muon pairs with $r < 0.5$ m to the single muons to be $7.6 \cdot 10^{-4}$. Among 1958 double-muon events (narrow muon budles) we have found 1171 events with $r < 0.5$ m. Some fraction of these muon pairs cannot be resolved with tracking detectors due to their finite spatial resolution. The geometrical resolution of existing tracking detectors is of the order of 1-2 cm. The “physical” resolution is limited by the muon interactions inside the detector volume and the properties of the tracking detectors (streamer tubes, for example). We estimate the real resolution to be of the order of 5 cm. Thus, we assume that the narrow muon bundles (muon pairs) can be resolved if $r > 0.05$ m. The number of muon pairs with $0.05 < r < 0.5$ m is equal to 978, and the ratio of such events to the single muons is equal to $2.9 \cdot 10^{-4}$. This ratio has to be compared with $7.6 \cdot 10^{-4}$, which is the ratio of muons pairs with $r < 0.5$ m in detected muon bundles to the single muons. We can conclude that one third of the narrow muon pairs ($r < 0.5$ m) observed by an underground detector should be due to the events initiated in the muon pair production process.

The number of double-muon events with $r < 0.5$ m detected by one LVD tower during 7154 hours of operation can be estimated as 470 [9]. According to our calculations, during the same time one LVD tower should detect about 180 double-muon events (narrow muon bundles) initiated by the muon pair production process, while the remainder of 290 events are due to the conventional muons bundles. The excess of 180 events over the predicted number of 290 conventional muon bundles can be easily seen by a high-resolution tracking detector. A narrow pair separation distribution of the events can be a signature of this excess.

The relative contribution of narrow muon bundles will increase with a decrease of the upper limit of r. Our estimates based on LVD [9] and Frejus [10] data show that the change of an upper limit of r from 0.5 m down to 0.25 m results in the increase of the fraction of narrow muon bundles in the total sample of muon bundles up to about 60% or even higher. This decreases, however, the predicted number of events.

The unresolved muon tracks can be seen as a single-muon track with the energy loss which is about two or three times more than the most probable energy loss of single muons. Such events are clearly seen in the detector "BARS" [11]. The possibility to select such events statistically from the background of single muons with a high-energy loss depends on the detector structure and characteristics (thickness of matter crossed by muon in the detector volume, energy resolution of the detector etc.). Our estimates based on the calculations [12] for one LVD tower with reasonable selection criteria for muon energy loss and number of "hitted" scintillation counters show that unresolved double-muon events can contribute up to (20-30)$\%$ to the tail of the distribution of single-muon energy loss. However, the number of such events after the selection criteria applied will be about one order of magnitude less than the number of resolved muon tracks.

The same estimations can be done for triple-muon events. The ratio of narrow-to-conventional triple-muon boundles is higher than for double muons. The analysis of triple-muon events is more complicated, however, because they can be seen as triple-, double- or single-muon events depending on the spatial resolution of the detector.

After the simulation of muon transport through the standard rock taking into account the process of muon pair production by muons, and the estimation of the effects caused by multiple muons in the underground detectors, we can conclude that: i) the process of muon pair production by muons, being negligible for the calculation of muon survival probabilities and single-muon intensities underground, is quite important for the study of muon bundles in the range of pair separation $r < 0.5$ m; ii) the distribution of pair separations in events initiated by muon pair production process is very narrow and differs from that in conventional muons bundles; iii) such narrow muon bundles can be selected statistically from the background of conventional muon bundles using underground detectors with high spatial resolution; iv) the cross-section of muon pair production by muons can be evaluated from these measurements.

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