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ON THE USE OF THE LA SPECTROMETER BARS FOR HORIZONTAL MUON SPECTRUM MEASUREMENTS

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Abstract

Belikov S.V. et al. On the Use of the LA Spectrometer BARS for Horizontal Muon Spectrum Measurements: IHEP Preprint 96-65. – Protvino, 1996. – p. 11, figs. 12, refs.: 8.

A Big liquid ARgon Spectrometer BARS was used to detect horizontal cosmic ray muons. Large thickness and fine granularity of BARS make it possible to measure muon energy losses due to ionization, bremsstrahlung and e^+e^- production with high precision. The estimation of muon energy by the energy loss measurements is discussed. Preliminary results of experimental data analysis are presented.

Аннотация

Беликов С.В. и др. Использование жидкоаргонного спектрометра БАРС для измерения спектра горизонтальных мюонов: Препринт ИФВЭ 96-65. – Протвино, 1996. – 11 с., 12 рис., библиогр.: 8.

Большой жидкоаргоновый спектрометр БАРС был использован для регистрации мюонов в горизонтальных потоках космических лучей. Большая толщина и тонкая структура БАРСа позволяют с высокой точностью измерять потери энергии мюона на ионизацию, тормозное излучение и образование e^+e^- пар. Даны оценки энергии мюона по измерениям потерь энергии. Представлены предварительные результаты анализа экспериментальных данных.

Introduction

Investigation of energy distribution of horizontal cosmic ray muons in multi-TeV region can provide the important information on primary cosmic ray spectrum and composition. Conventional methods of muon energy measurements (magnetized steel spectrometers, TRDs) have a practical limit of 5-10 TeV. Another technique of the HE muon spectrometry which is free of limitations of the above mentioned methods was proposed by Alekseev and Zatsepin in 1959 [1].

The idea of this technique is rather simple. In the TeV energy range the average muon energy loss is determined mainly by e^+e^- production and bremsstrahlung and is proportional to E (fig.1). But the losses due to e^+e^- and γ emissions are different: average energy transferred to e^+e^- is about 1% of muon energy while the average energy of γ is much higher (fig.2). So when passing through a thick layer of matter a high energy (> 1 TeV) muon produces a set of EM showers mainly due to e^+e^- production (fig.3) and it is possible to estimate the muon energy by counting the number of showers and measuring their energies. Because of the important role of e^+e^- production this method is often called the pair meter technique.

Theoretical consideration of the pair meter technique and a review of early works can be found in refs [2,3]). The most important advantage of this technique is the absence of the upper limit on muon energy measurements. Asymptotically, the pair meter energy resolution is given by the formula

$$\frac{\sigma}{E} = \sqrt{\frac{9\pi}{28\alpha T}} \approx \sqrt{\frac{1}{\alpha T}}, \tag{1}$$

where T is the pair meter thickness in r.l. and $\alpha = 1/137$ is the fine structure constant.

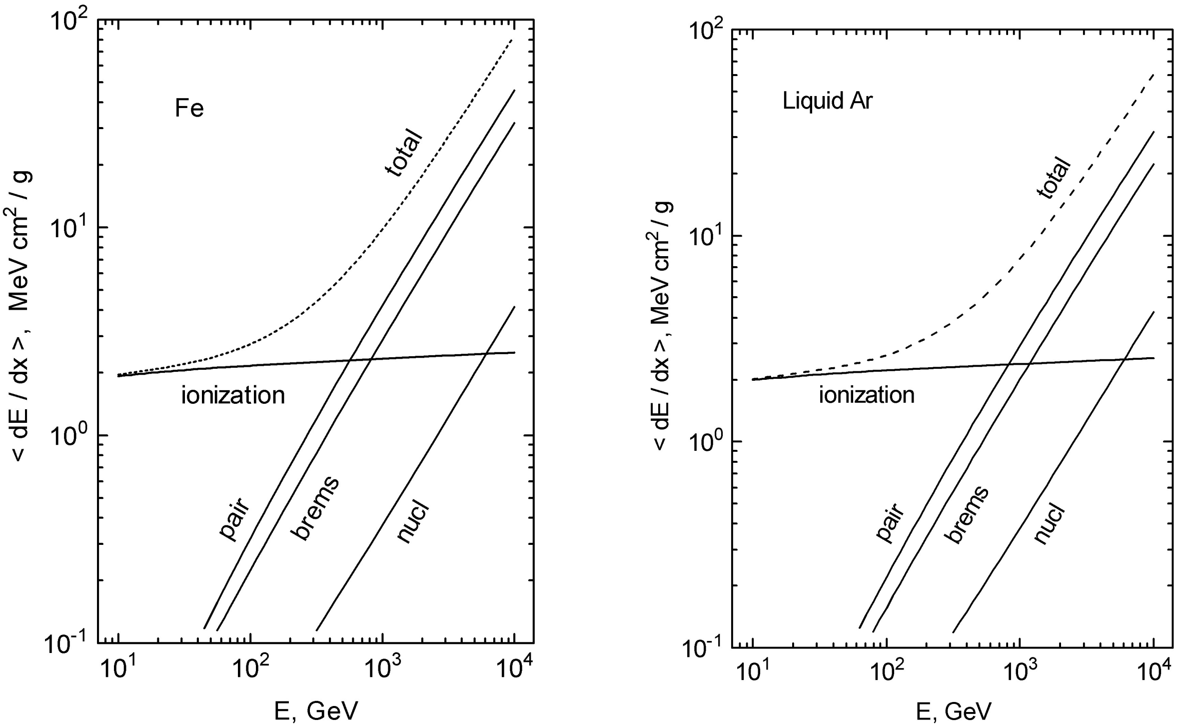

Fig. 1. The average energy loss of muons in iron and liquid argon as a function of energy.

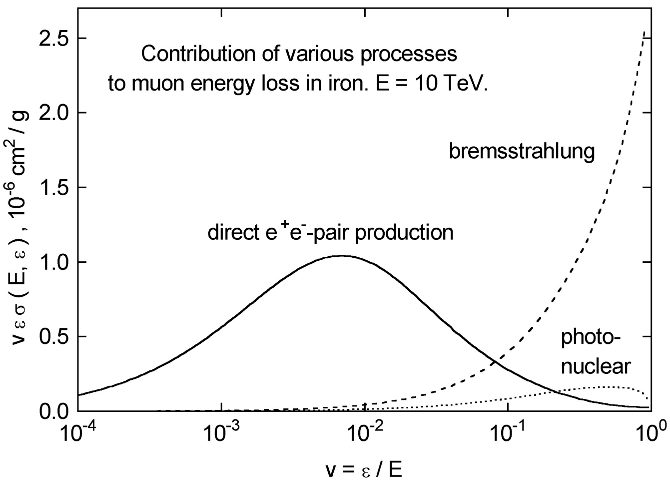

Fig. 2. Energy loss distributions of 10 TeV muon for e^+e^- production, bremsstrahlung, and photonuclear interaction.

From (1) it follows that the spectrometer should be thick ($T > 137$ r.l.). On the other hand it should have a fine granularity to measure low energy ($\varepsilon < 10^{-3}E$) EM showers and large acceptance to detect the low flux of HE cosmic ray muons. Though the physical grounds of the pair meter technique seem to be well understood, it has not been properly tested experimentally, mainly due to the small thickness and/or coarse granularity of the detectors used.

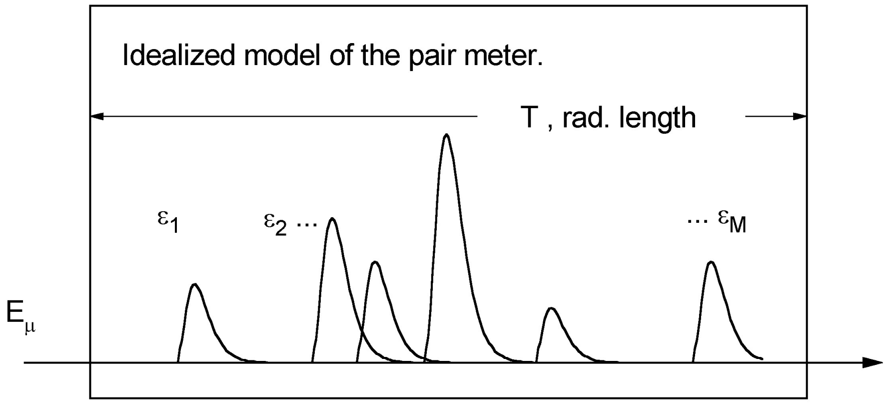

Fig. 3. Longitudinal energy distribution in the ideal pair meter.

In February 1996 we started experiments with the Big liquid ARgon Spectrometer BARS to study the pair meter technique and to measure the flux of horizontal cosmic ray muons. Although BARS was designed for tagged neutrino experiments at the IHEP accelerator, its size and structure are quite adequate for the pair meter technique and its acceptance is sufficient to obtain high statistics of muon events in the TeV energy range.

1. Detector BARS

The detector BARS consists of two identical LA calorimeters BARS1 and BARS2 (fig.4). Each calorimeter contains 216 t of LA, 154 t of those being in the fiducial volume. There are two types of detectors inside the cryostat: ionization chambers and scintillation hodoscopes.

Double-gap ionisation chambers of the calorimeter are formed by interleaved signal and grounded planes. Signal electrodes are made of Al strips, 3 mm thick and 61 mm wide. Grounded Al electrodes are 6 mm thick. The gap width is 24 mm. Each signal plane consists of 48 strips. The strips in adjacent planes are rotated by 120^o thus forming u, v, and x coordinates. 12 signal planes are combined into a section. There are 24 sections in the calorimeter (288 signal planes). Total calorimeter thickness is 18 m (137.4 r.l., 25 i.l.). The diameter of electrode system is 3 m.

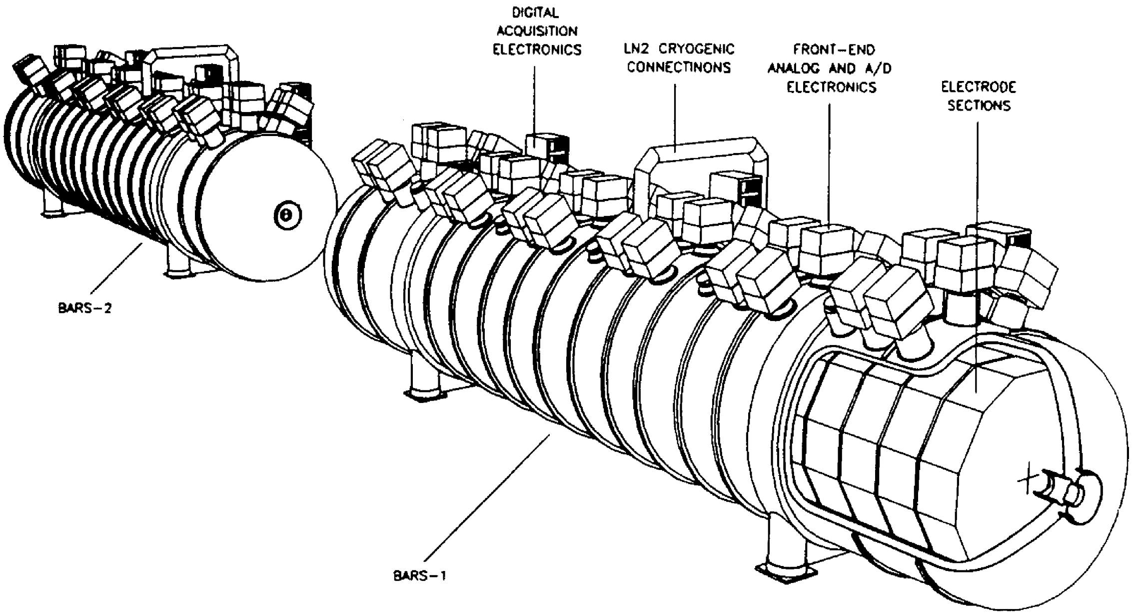

Fig. 4. BARS calorimeters.

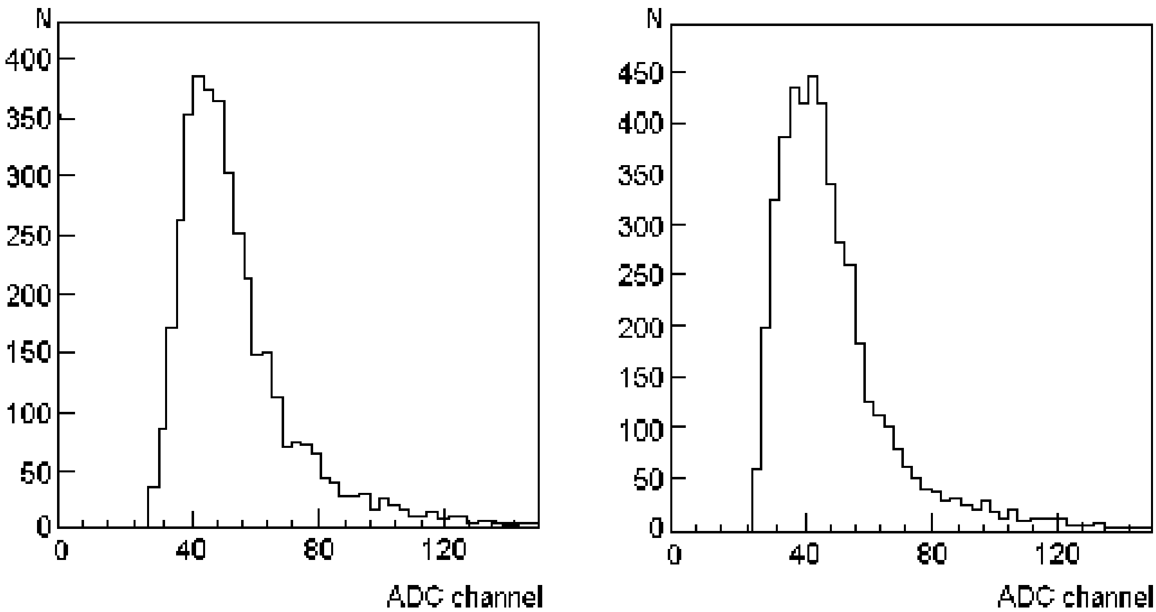

Fig. 5. Typical pulse height distributions for relativistic muons.

A plane of 8 scintillation counters is positioned in front of each section. Scintillation light is collected by the WLS bars placed between the counters. The WLS bars are viewed from both ends by FEU-84 PMs. Both counters and PMs with bases are in the LA.

The electronics for ionization signals includes low-noise charge preamplifiers with matching transformers at inputs, $(CR - RC)^2$ bipolar shaping amplifiers with a shaping time of 15 μs and a peaking time at 2 μs, peak sensitive 20 MHz 12 bit ADCs. The total number of channels in each calorimeter is 13824.

The signals from PMTs viewing the same WLS bar after amplification and shaping are transmitted to "mean timer" units with a guaranteed 5 ns time resolution.

The DAQ electronics sends to the host computer only signals with pulse heights above preprogrammed thresholds $k\sigma_n$, where k is in the range from 2 to 3 and σ_n is the RMS of the noise signal distribution. For most of the channels σ_n is close to 10 counts of ADC while the average pulse height of a relativistic muon signal is about 50 counts (fig.5).

BARS energy resolutions for EM and hadron showers are $0.04/\sqrt{E} \oplus 0.08/E$ and $0.55/\sqrt{E} \oplus 0.02$, correspondingly. The e/h rejection factor is less than 0.04 at 99% electron detection efficiency, using the RMS of the transverse energy distribution as the only discriminating parameter. More information about the BARS parameters and characteristics can be found in ref. [4].

2. Measurements and results

Measurements were performed during a two-week run in February, 1996. As a trigger for horizontal cosmic ray muon selection, double coincidences between the following scintillation planes were used: 1 and 18, 2 and 19, 3 and 20, 4 and 21. Geometric acceptance for this trigger configuration is equal to 0.26 $m^2 \cdot$ sterad, zenith angle interval is 78^o to 90^o. Trigger efficiency did not depend on muon direction and was as high as 99% for muons crossing all trigger planes. Trigger rate was about 0.4 Hz. Preliminary analysis shows that about 1/3 of registered events correspond to detection of horizontal muons, while remaining events are mainly due to random coincidences, air showers (fig.6a) and groups of muons near vertical direction (fig.6b). In total, about 10^5 horizontal muons were detected.

Examples of muon events are presented in figs.7 - 9. Fig.7a shows a track of low energy stopping muon which lost its energy due to ionization. The track shown in fig.7b belongs to a high energy muon. It produced as many as 7 EM showers (see fig.8), 6 of them having energies between 1 and 10 GeV. The estimated energy of this muon (taking into account the bias due to steep cosmic ray muon spectrum) is about 2 TeV.

Another interesting event (possible muon pair production by high-energy muon in the detector volume) is presented in fig.9. In the initial part of the track (left side) the ionization corresponds to a single particle; at depths $t > 18$ r.l., 3-fold ionization accompanied by low-energy EM cascades has been observed. Path length of secondary particles within the fiducial volume is about 16 r.l. thus allowing one to identify them as muons. The opening angle does not exceed 10 mrad.

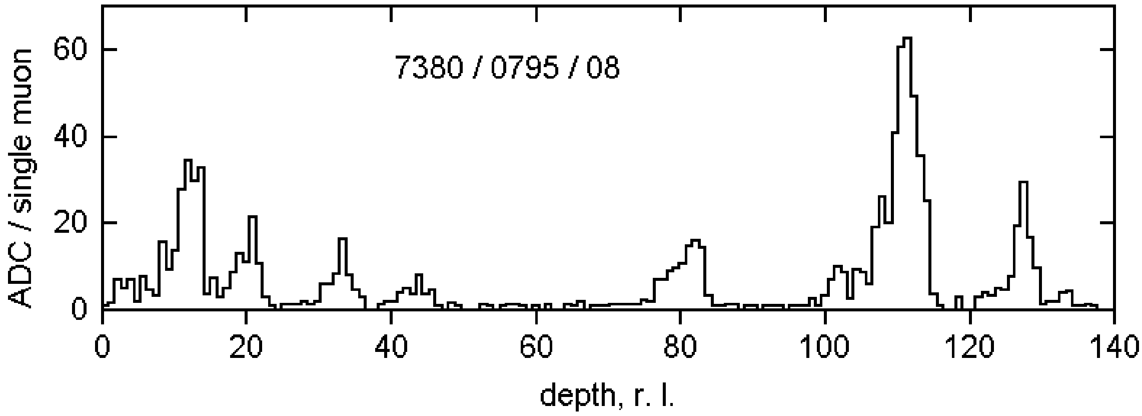

Fig. 8. Energy distribution along the BARS for the event shown in fig. 7b.

Muon energy spectrum measurement in the pair meter is based on the comparison of characteristics of multiple interaction events with expectations. In the simplest mode a distribution of the number of interactions with energy transfer above a fixed threshold ε_0 has been used. Selection of events with the given number of interactions M allows one to choose spectral bands with different effective muon energies (fig.10).

Experimental distributions of interaction multiplicities for different values of shower energy threshold ε_0 are given in fig.11. The data obtained during 12.8 h (about 1/15 of the total statistics) have been used. Dashed lines represent calculations based on the existing data on muon energy spectrum [5] and commonly used formulae for muon electromagnetic interaction cross sections (knock-on electron production [6], e^+e^- production [7], bremsstrahlung [8]). The agreement of experimental results with calculations seems quite reasonable.

Further analysis of all accumulated experimental data and MC calculations taking into account the detector response are in progress.

Fig.12 demonstrates the expected muon flux per year through one BARS. More than $2 \cdot 10^4$ muons in the energy range above 1 TeV may be detected in two BARS calorimeters during one year period.

Conclusions

The pair meter method of muon energy measurements has been tested using the BARS detector. Preliminary analysis of the data collected during the first two-week cosmic ray exposition shows that the detailed study of the pair meter technique, tests and comparison of its various modes, study of the influence of the detector structure on muon energy reconstruction may be successfully performed with BARS. Muon energy spectrum up to 10 TeV can be measured by means of a new independent method (free

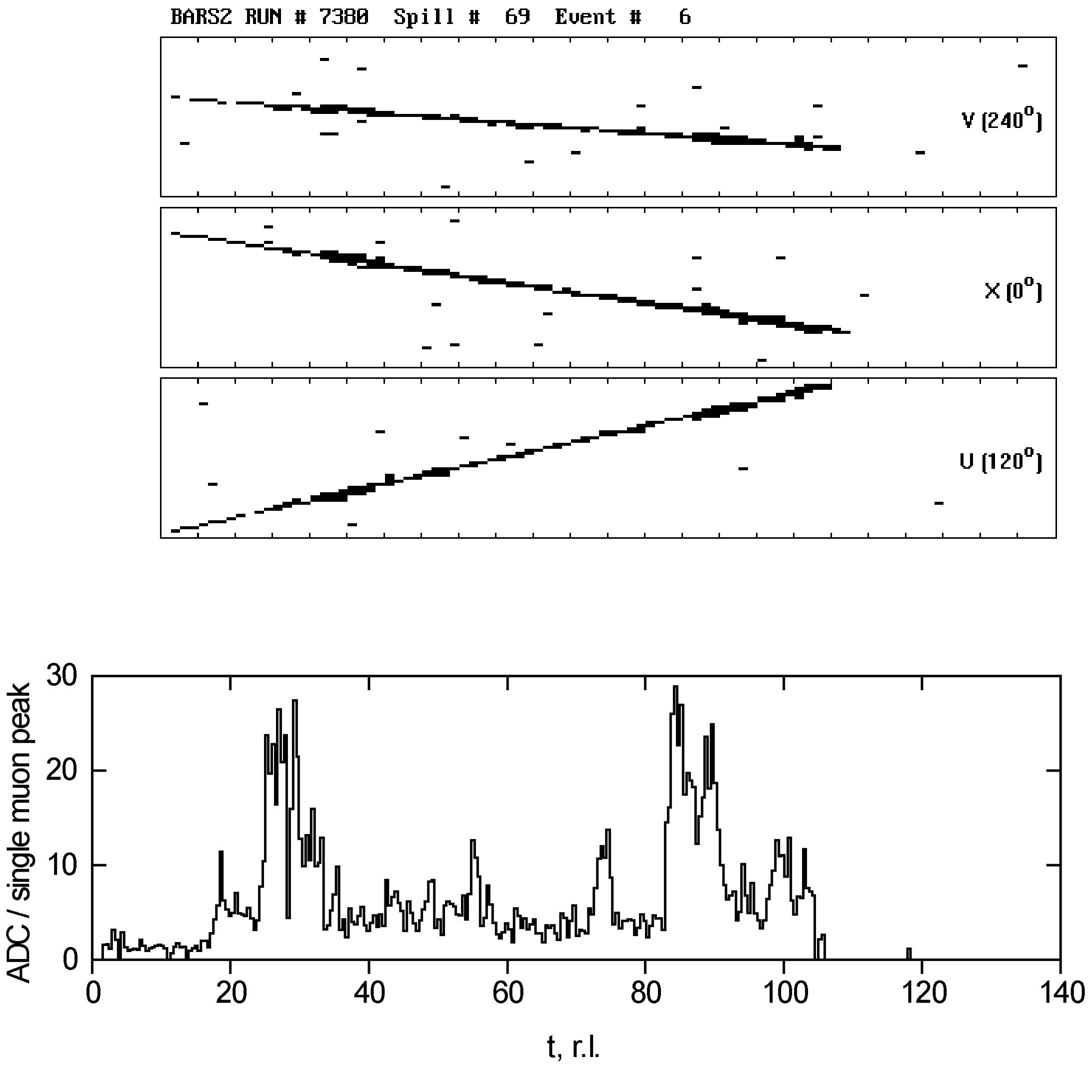

Fig. 9. Possible $\mu^+\mu^-$-pair production by high-energy muon. Top to bottom: x, u, v views and longitudinal profile of the event.

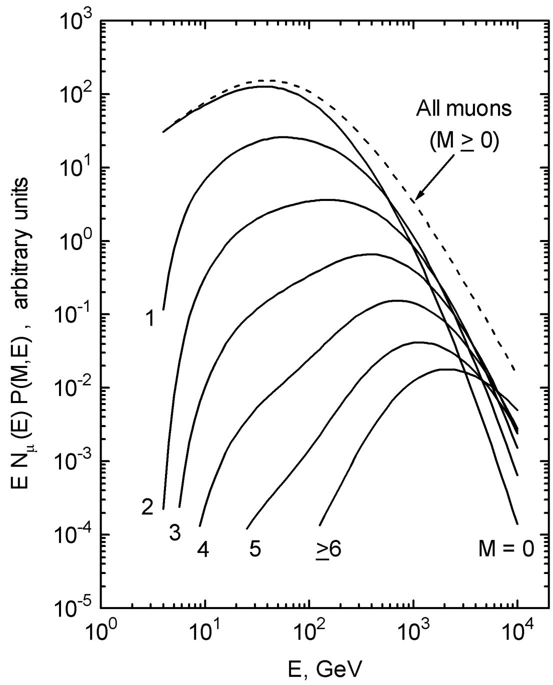

Fig. 10. Calculated spectra of cosmic ray muons corresponding to fixed number of interactions M with energy transfers $\varepsilon > 1$ GeV. $P(E, M)$ is the probability to produce M interactions for muon with energy E.

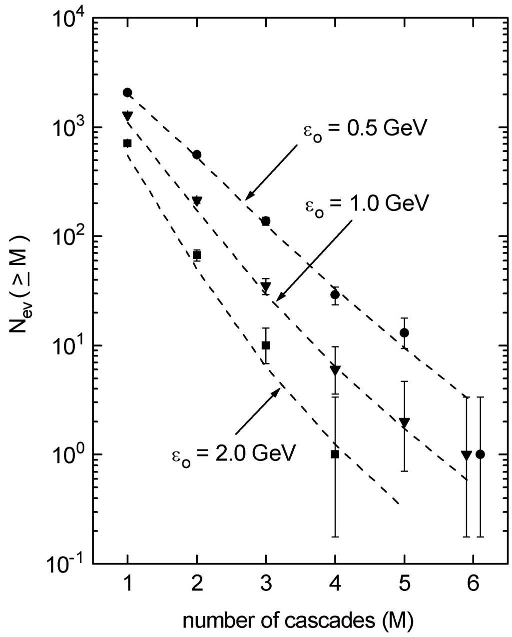

Fig. 11. Distribution of EM shower multiplicities for different values of the energy threshold ε_0.

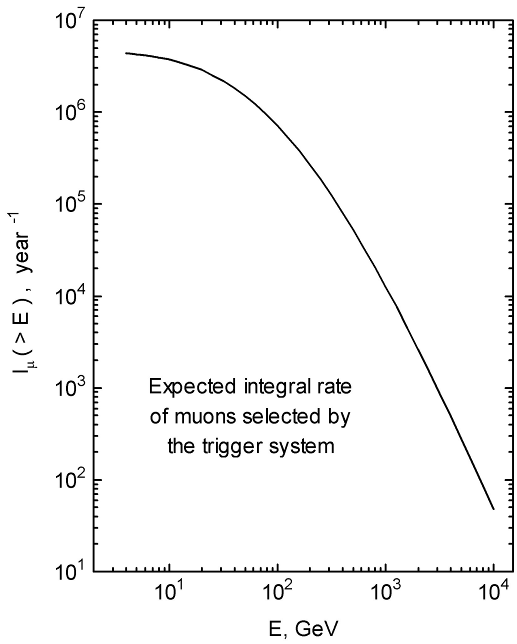

Fig. 12. Expected muon flux per year through one BARS.

of m.d.m. limitations). Due to its fine granularity, large thickness and high acceptance, BARS can be also used to search for new phenomena and to study rare processes (for example, narrow muon bundle production) in horizontal cosmic ray flux.

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References

[1] I.S.Alekseev, G.T.Zatsepin. In: Proc. Intern. Conf. on Cosmic Rays (Moscow, 1960), v. 1, p. 324.

[2] R.P.Kokoulin, A.A.Petrukhin.//NIM A263, 468 (1988).

[3] R.P.Kokoulin, A.A.Petrukhin.//Sov. Journ. Part. and Nucl., v. 21, p. 332 (1990).

[4] F.Sergiampietri. In: Proc. IV Intern. Conf. on Calorimetry in High Energy Physics (La Biodola, 1993), p. 357.

[5] O.C.Allkofer et al.//Nucl. Phys. B259, 1 (1985).

[6] H.J.Bhabha.//Proc. Roy. Soc. A164, 257 (1938).

[7] R.P.Kokoulin, A.A.Petrukhin. In: Proc. 11th Intern. Conf. on Cosmic Rays, Budapest, Hungary, 1969 [Acta Phys. Acad. Sci. Hung. 29, Suppl. 4,277(1970)];

In: Proc. 12th Intern. Conf. on Cosmic Rays, Hobart, Australia, 1971, v. 6, p. 2436.

[8] A.A.Pertrukhin, V.V.Shestakov.//Can. J. Phys. 46, 377 (1968).

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