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MUON SIGNALS OF COSMIC RAY INTERACTIONS *

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Muons originate from the decay of hadrons, produced in interactions of the primary cosmic particles with the nuclei of the atmosphere. The observation of the features of the muonic component, arising from the cascading processes induced by the primary particle, a phenomenon called extensive air shower (EAS), provides interesting information about the nature of the primary and its interactions. We illustrate this information potential by: (*i*) studies of the longitudinal development of EAS by measurements of the relative arrival time distributions of muons the KASCADE experiment, (*ii*) studies with the Bucharest electromagnetic calorimeter WILLI for energy estimates of TeV muons and for determination of the charge ratio of the atmospheric muon flux.

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1. Introduction

Every second, tens of cosmic ray muons traverse our bodies, leaving in their wake electron–ion pairs, disrupted molecules, and occasionally a mutated gene. When cosmic ray particles, mostly protons, that have journeyed from outer space smack into nuclei of the Earth's atmosphere muons rain down as debris, as calling cards from the other worlds that are sources of the highly energetic cosmic particles. Muons are messengers, too, from worlds that might have been. Cosmic rays muons originate from the decay of

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charged pions and kaons, which are produced by the collisions of the highly energetic protons, alpha particles and heavier nuclei from the Universe, with atomic nuclei of the air. Yet, in spite of more than 85 years after discovery, the primary cosmic rays provide still fundamental mysteries about their origin, acceleration and propagation through the interstellar space. Their energy spectrum, following a power law, extends to extremely high energies, with several orders of magnitudes beyond the energies of particles from man-made accelerators. In the region of 10^{15} eV the energy spectrum exhibits a conspicuous discontinuity ("knee") by changing the spectral index of the steep fall-off. The reason for that feature is an unsolved astrophysical riddle, and the elemental composition of cosmic rays, unknown for higher energies ($> 10^{14}$ eV), is expected to be a far-reaching key information to understand the origin and the features of high-energy cosmic rays. The experimental approach is the observation of the cascading interaction processes when the primary particle traverses the Earth's atmosphere and produces secondaries, observed by large detector arrays by the laterally extended soft electron-photon, the penetrating muon and, concentrated around the original direction of the primary, the hadron components (apart from other effects like air-Cherenkov radiation). A modern detector installation of that kind is the KASCADE (KArlsruhe Shower Core and Array DEtector) experiment [1], measuring the lateral and time structure of the main components of each registered EAS. By correlating various shower observables, sensitive to the nature of the primary, the influence of the considerable fluctuations gets minimized, and the information looked for is inferred by an analysis on basis of realistic Monte Carlo simulations of the stochastic EAS development. In the following we briefly illustrate the role of muon observations by a specific example of the KASCADE studies (with suggesting an improved scheme for investigations of the time dispersion of the muon component) and by studies with the Bucharest electromagnetic calorimeter setup WILLI [2].

2. Relative arrival time distributions of EAS muons

Due to their relatively long life time, their penetrability and reduced multiple scattering, fast muons travel approximately like light-rays through the atmosphere, from the loci of origin in high altitude to the ground-based detectors, which are assumed to measure the angle-of-incidence distributions relative to the shower axis and the arrival time distributions of the EAS muons relative to the arrival of the shower center, at an sufficiently large distance from the shower core in order to enhance the time-of-flight and angular effects. Thus, the arrival times *e.g.* map the production height distribution in high altitudes, which may be reconstructed in a most simple approximation by a triangulation. This establishes the origin of the sensitivity of muon arrival times to the interaction and mass of the primary due to differences of the longitudinal EAS development, as consequence of differences in the interaction lengths, in the transverse momentum distributions of the secondaries and the inelasticities. The idea has been confirmed by realistic Monte Carlo simulations, showing measurable differences of relative muon arrival time distributions for EAS induced by different primaries [3]. The basic features are illustrated with some Monte Carlo calculations for EAS of vertical incidence, considering muon timing detectors of $10 \times 10\text{m}^2$ area, located at different distances from the shower core (Figs 1 and 2).

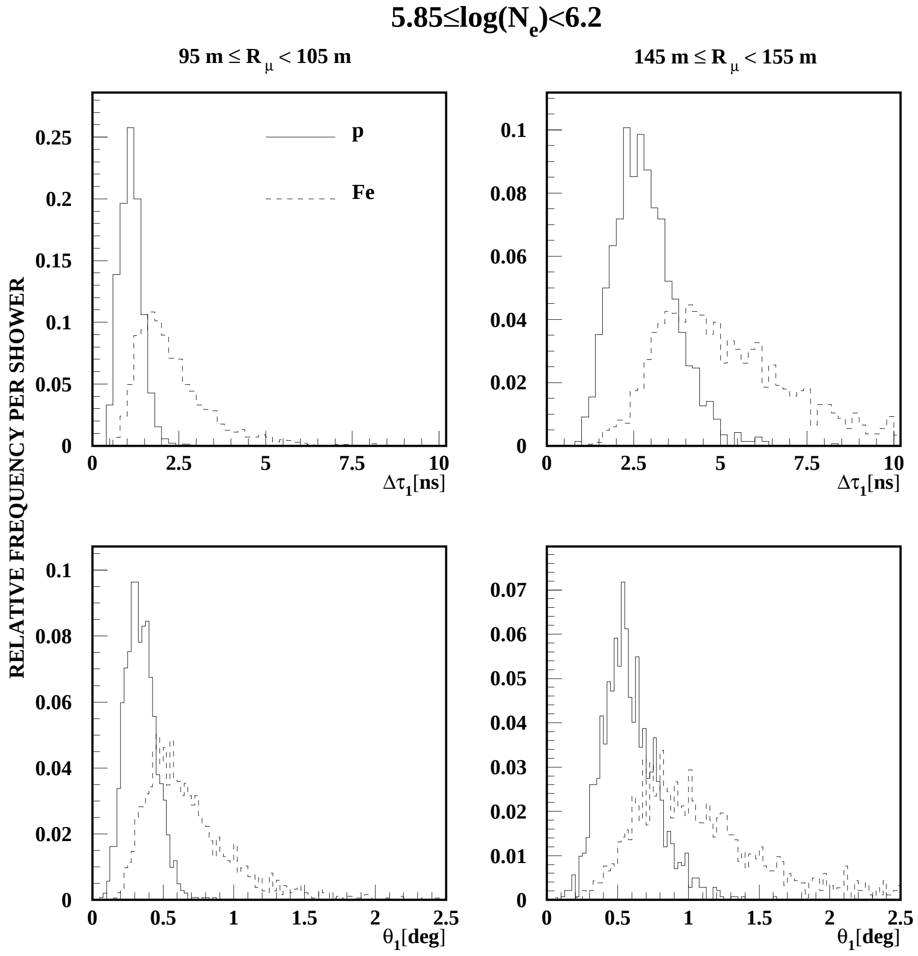

Fig. 1. Single muon time arrival and angle-of-incidence distributions corresponding to $R_\mu = 100$m si $R_\mu = 150$m for different primaries.

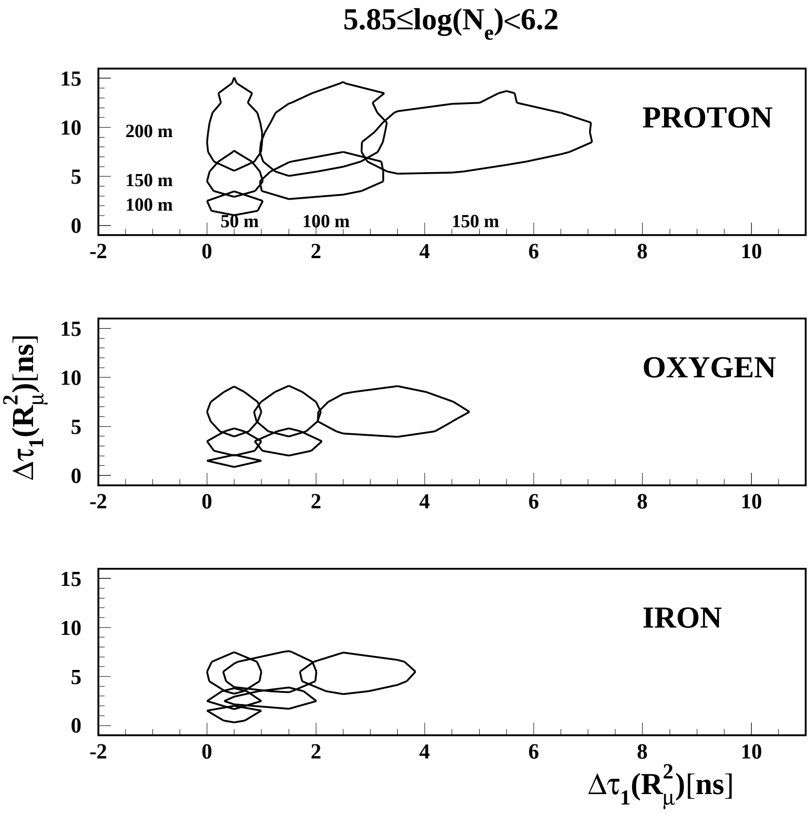

Fig. 2. Half-maximum contours of the distributions of correlated muon arrival time observed at different distances from the shower core for different types of primaries [4].

With measured distributions or re-analysing a sample of theoretical test distributions we meet the task to disentangle the superimposed time distributions in various mass components, equipped with the a priori knowledge we have got from the simulations including the detector response. Advanced techniques to quantify the extent to which a certain event may be associated to a particular class of showers are based on methods of nonparametric statistical analysis, estimating the overlap of multivariate distributions [5]. The strategy of such an estimate is based on the Bayes theorem, which links an initial assumption (*a-priori* probability) by the conditional probabilities (likelihood functions) of an event to the *a-posteriori* probability. The construction of the likelihood functions from training samples (actually from simulation results) is a technical question. The decision procedure enables to quantify the chance to misclassify a particular observed set and define the Bayes error.

Applying these analysis techniques to various observation modes of correlated observation, it turns out that a combined observation of muon arrival time distributions at different distances from the shower center enhances the information content and the efficiency for a good classification of the "observed" EAS [4]. This is in contrast to the correlation of arrival time and angle-of-incidence of muons observed at the same distance, since there exist a strong correlation of both (see Table I). The KASCADE experiment has successfully started measurements of arrival time distributions of EAS muons, using the timing facility of the KASCADE central detector. First results have been reported at the ICRC 1997 [6].

TABLE I

Classification probabilities using different subsets of EAS observables ($5.85 \leq N_e \leq 6.2$) [4]. Modes: 1 — $\Delta\tau_1$ at 100m, 2 — $\Delta\tau_1$ at 100m and Θ_1 at 100m, 3 — $\Delta\tau_1$ at 100m and $\Delta\tau_1$ at 150m, 4 — $\Delta\tau_1$ at 100m, $\Delta\tau_1$ at 150m and shower age.

Mode	$p \to p$	$p \to$O	$p \to$Fe
1	.73	.23	.04
2	.70	.25	.05
3	.77	.22	.07
4	.89	.11	.00
Mode	O$\to p$	O$\to$O	O$\to$Fe
1	.13	.40	.47
2	.12	.44	.45
3	.09	.61	.30
4	.08	.73	.19
Mode	Fe$\to p$	Fe$\to$O	Fe$\to$Fe
1	.00	.15	.85
2	.01	.16	.83
3	.04	.18	.82
4	.00	.10	.89

3. Prototype studies for TeV-muon spectrometry with the electromagnetic calorimeter WILLI

In addition to the intensity and lateral distribution of the EAS muon component, for specific investigations the multiplicity and energy distributions of muons of the shower center in the TeV range are of extreme interest.

As a prototype study related to the KASCADE experiment, an electromagnetic calorimeter WILLI has been built up in Bucharest for studying the feasibility of energy estimates of cosmic TeV muons, on the basis of observations of muon pair production and bremstrahlung in the matter [7]. It has a modular structure, each of 20 modules ($90 \times 90\text{cm}^2$) containing a thin absorber (10 mm Pb) and a 30 mm thick NE114 scintillator layer carried by a 12 mm thick Al support [2]. The idea of the set up is to sample and reconstruct the number and range of electromagnetic showers produced by a muon passing through the calorimeter.

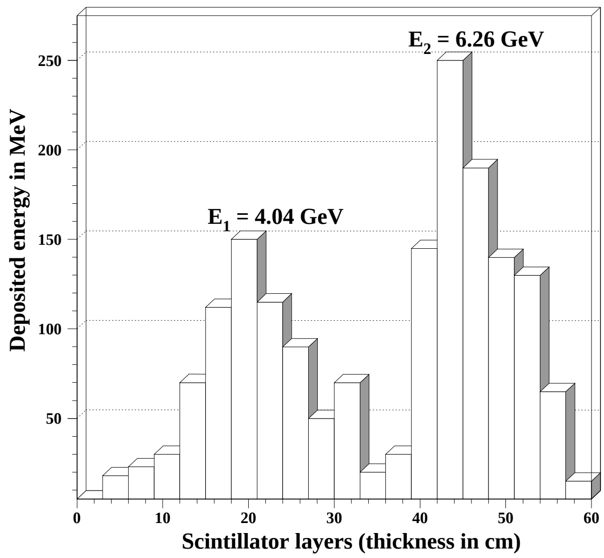

Fig. 3. Two cascades measured in a real event producing two secondaries with kinetical energy 4.04 GeV and 6.26 GeV, respectively.

Fig. 3 displays the measured profile of a double electromagnetic cascade. Using Maximum Likelihood Method for such a muon event, *e.g.* the initial muon energy is estimated to 2.39 TeV. Due to very asymmetric large shape of the logarithmic likelihood function, however, the confidence interval of 68% includes a rather broad range 0.85–7.85 TeV [8].

4. Charge ratio measurements of the inclusive atmospheric muon flux

While for EAS observed with Earth-bound detectors the intensity of the muonic component is only a small fraction of the total charge-particle intensity, the situation in the inclusive flux is different. The muons contribute on sea level with approximately 100 muons per second per square meter and steradian to ca. 80% of the total flux of the secondary radiation. The energy spectrum falls steeply down with the muon energy. The low energy end is influenced by geomagnetic effects, which deviate the primary particle on its travel and imply an energetic cutoff.

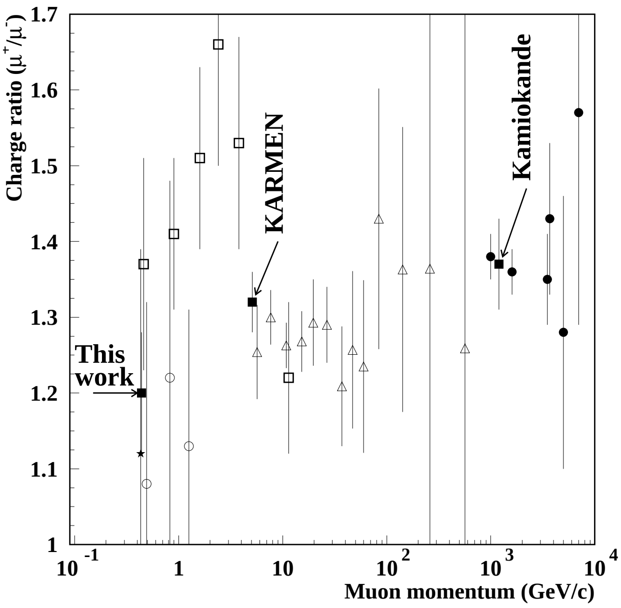

Fig. 4. Compilation of muon charge ratio results: □ Allkofer et al.(1972), △ Nandi et al.(1972), • Utah (1972), ○ MASS2 (1991), ⋆ IMAX(1992)

The ratio of the positive to negative cosmic muons provides various aspects of great interest for specific features of the hadronic interaction, it reflects the global neutron–proton ratio in primary cosmic ray nuclei and is some relevance for the atmospheric neutrino problem [9]. Fig. 4 compiles measured results for the charge ratio of atmospheric muons at different muon energies, mostly from measurements with magnetic spectrometers, implying lot of sources of systematic uncertainties due to different acceptance and detection efficiencies. The observed positive charge excess is not only a consequence of the excess of positively charged particles in the primary flux, it indicates also the asymmetry for pion and kaon production and their secondary interactions, favourising *e.g.* K^+ as compared to the K^- due to the quark content of these strange particles. An interesting aspect of muon charge ratio stems from the atmospheric neutrino problem. Measurements of the atmospheric neutrino flux with the KAMIOKANDE detector and other underground detector installation (see Ref. [9]) find a deficit of muonic neutrinos or an excess of electronic neutrinos. The interpretation of data is dependent on the ratio of electronic neutrinos to antineutrinos, since not only different flavours but also particles and antiparticles have a different response of the detector. The electron–neutrino–electron antineutrino ratio is directly reflected by muon charge ratio.

The principle of our measurements using the WILLI calorimeter is based on different behaviour of positive and negative muons in the matter: stopped positive muons decay by the lifetime of free muons, negative muons are captured in atomic orbits, where they may decay or be absorbed by the atomic nucleus, leading effectively to a reduced lifetime of negative muons dependent on the stopping material. The measured time spectra are a superposition of different decay curves, the parameters being determined by detector simulations. Fig. 5 displays the measured time spectra and the results of

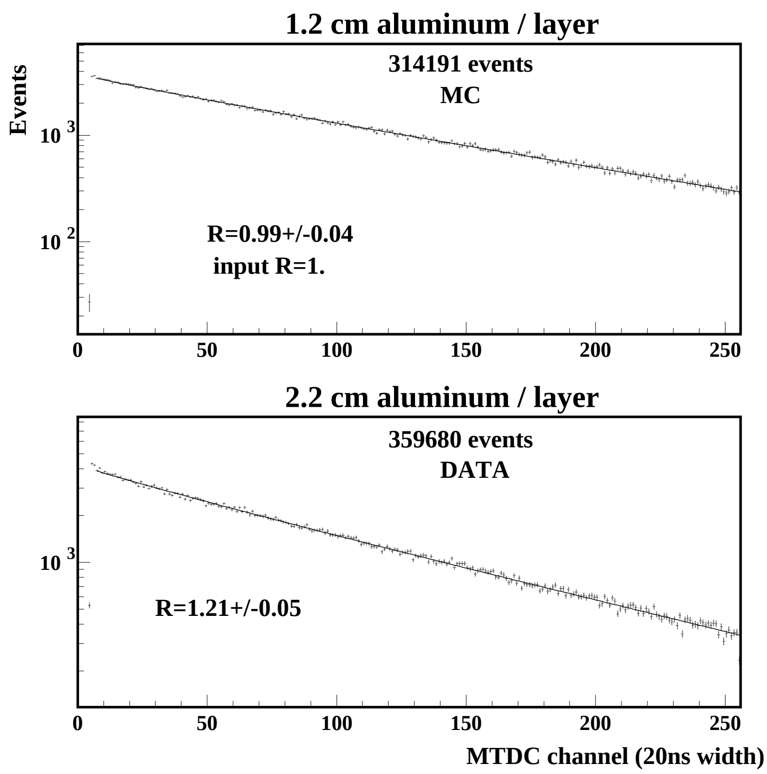

Fig. 5. The total decay curves corresponding to simulated data using input data with known value $R = 1$ and to measured data for a detector configuration with 1.2 cm Al layer.

an analysis of simulated data calculated for the muon charge ratio equal unity. The analysis of experimental results of 2 different runs [2] leads to $\mu^+/\mu^- = 1.20 \pm 0.06\text{stat} \pm 0.06\text{syst}$ demonstrating the merits of a relatively small and compact detector device, of a size of 1.2 m^3 and a weight of 900 kg, using aluminium absorbers for an efficient separation of the two charge-types of muons.

5. Concluding remarks

The presently highest particle energy provided by artificial accelerators amounts to 1.3×10^{15} eV (equivalent laboratory energy of the Fermi Lab TeV collider). Thus in near future, that means till the Large Hadron Collider will get in operation in the middle of the next decade, cosmic ray investigations are the only way to extend our knowledge about hadronic interactions to "*terra incognita*". This perspective adds to the extremely interesting astrophysical aspects of studies of the "Non-thermal Universe" by cosmic rays. The present contribution stresses the role of cosmic ray muons as messengers illustrated by selected examples. (*i*) For improved studies of the longitudinal development of EAS, which actually do directly tell us about the features of the interaction and the nature of the cosmic particles, we suggest an improved scheme for muon arrival time observations by "radial correlations", *i.e.* combined observations at different distances from the shower center. It has been shown to improve the mass discrimination *e.g.* of the primary cosmic rays. (*ii*) Muon charge ratio spectroscopy, a kind of investigations being still in its infancy, has an interesting information potential for various different aspects. It teaches about the ratio of electron–antineutrinos to electron–neutrinos in the atmospheric flux, about hadronic interactions, including the possibility to deduce the average neutron excess in nuclei of the primary cosmic rays.

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