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## Prompt muons in extended air showers

J. RIDKY[1], D. NOSEK[2], P. TRAVNICEK[1], P. NECESAL[1]
[1] *Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[2] *Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic*
*ridky@fzu.cz, nosek@ipnp.troja.mff.cuni.cz*

**Abstract:** We present results of simulations of a muon content in the air showers induced by very high energy cosmic rays. Muon energy distributions and muon densities at ground level are given. We discuss a prompt muon component generated by decays of charm mesons. The method combines standard Monte Carlo generators incorporated in the CORSIKA code and phenomenological estimates of the charm hadroproduction.

## Introduction

Extended air showers (EAS) are initiated by very energetic primary cosmic ray (CR) particles interacting with air by producing many secondary hadrons that may produce other hadrons in subsequent interactions. In the EAS development a special role is played by neutral pions that rapidly decay into gammas. These gammas start an electromagnetic shower carrying typically 90% of the initial energy. The rest of the energy showed up as muons from hadronic decays. Whereas the electromagnetic part of the shower is well understood, the muon component depends strongly on the mechanism of the hadronic interactions, properties of which are not well known at incident energies above a few hundred of GeV in c.m.s.

Available data in the GeV– TeV energy range obtained with surface and underground detectors are still too discrepant to draw definite conclusions on the muon spectra induced in EAS. It is known that direct measurements of low energy muons [1, 2] as well as experimental data on high energy muons [3, 4, 5] are not described satisfactorily by simulations using the currently employed hadronic interactions model [6, 7, 8, 9]. Some interesting features about the EAS muon production have been recently obtained using the high energy hadronic interaction model EPOS [10]. A preliminary analysis of EPOS results showed that due to the enhanced (anti)baryon production the number of muons in the EAS increases more rapidly with energy than in the currently used high energy hadroproduction models. Nonetheless, one cannot exclude the possibility that something important is missing in interaction models, especially, concerning the very high energy region.

In this work, we briefly discuss the relationship between the hadronic multiparticle production and EAS observables. A special attention is paid to charm secondaries that are accessible in hadronic interactions during the EAS development initiated by very high energy CR primaries, typically at energies greater than 1 PeV [11]. The main goal is to discuss the impact of the production of charm particles and their prompt decays on the EAS muon content that is relatively easily measured with great accuracy.

## Model of prompt muon production

The number of muons registered by a ground array is one of the most important observables in EAS physics. It depends on the primary energy and the details of consecutive collisions of shower hadrons with air nuclei.

At GeV energies the EAS muon component is dominated by conventional sources, i.e. the weak decays of relatively long–lived mesons, pions and kaons. At very high energy pion or kaon decays become very rare. For energies of the order of

1 TeV and greater, the probability increases that such particles interact in the atmosphere before decaying. This implies that even a small fraction of short–lived mesons and baryons containing heavy quarks, most notably charm, decaying into muons can give the important contribution to high energy EAS muons.

All the high–energy interaction models reproduce reasonably well accelerator data but differ in their predictions above few TeV in c.m.s. Specifically, the charm production is strongly suppressed in hadronisation models that are commonly used in EAS physics. A detailed critical discussion of the best possible choice of the charm production model and of the systematic uncertainties connected with it is beyond the scope of this study, for more details see e.g. [12]. Here, we use a simple phenomenological model of the charm hadroproduction.

We have modified the mechanism of hadronic collisions artificially to gain a number of charm particles. It is assumed that high energy hadrons that are present in the EAS core interact actively when they pass through the atmosphere and aside an abundant pion and kaon production also charm particles are produced in some events. The charm cross section was adjusted in accord with recent measurements [13, 14] that for the nucleon–nucleon collision yield $\sigma_{c\overline{c}} \approx 1$ mb at energies of 200 GeV in c.m.s. We assume that the charm cross section in p-Air collisions grows up logarithmically [12], $\sigma_{c\overline{c}} \approx 0.02\ \sigma_{\rm inel}$ at the incident energy of 100 TeV reaching a value $\sigma_{c\overline{c}} \approx 0.06\ \sigma_{\rm inel}$ slightly above the incident energy of 10 EeV, see also [15].

In the present approximation, mesons and nucleons are generated in nucleon–air collisions and in consecutive hadron–air collisions. Part of the initial energy of the interaction is carried by the involved conventional hadrons $(p, n, \pi, K, \eta)$. The number of these hadrons remains unchanged during the collision, their energies are degraded and a modest fraction of their total energy, typically less than 20%, is transformed into the energy of final charm degrees of freedom. Energy spectra of produced charm particles are mimicked using spectra of ordinary secondaries. Because at the energy of interest their secondary interactions seldom occur, it is assumed that charm particles $(D, \Lambda_{\rm c})$ decay very rapidly ($c\tau \approx 50 - 300\,\mu$m). Even though there are many semi–leptonic decay channels for charm particles and most of them have more than three particles in the final state we do not investigate these processes in detail. We assume that charm particles decay mostly into muons with typical branching ratios for semi–leptonic decays $\mathrm{BR}(\mathrm{D}, \Lambda_{\rm c} \rightarrow \mathrm{e}, \mu) \approx 10 - 20\%$; also hadronic decay modes producing secondary mesons are included in the model.

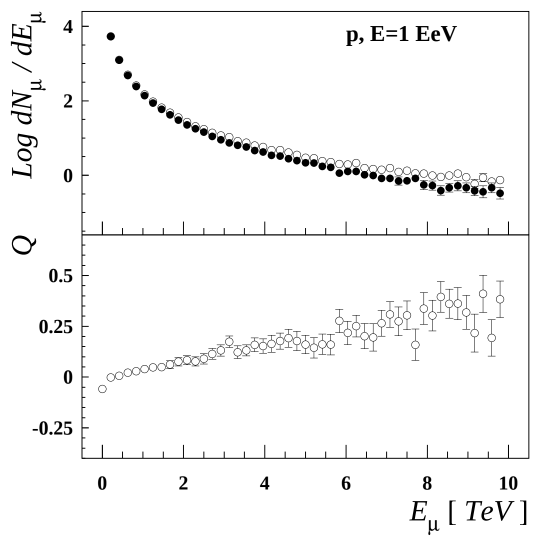


Figure 1: Ground level energy spectra of muons originated in EAS with (open circles) and without (full circles) charm production are shown in upper panel. The incident proton energy is set to 1 EeV. Corresponding excess of muons born in EAS with charm production is shown in lower panel as a function of muon energy.

## EAS simulations

Being formed during a multistep hadronic cascade, the EAS muon content is closely connected to the mechanism of hadron–air collisions. These collisions are investigated in the standard treatment. To obtain the energy spectra of conventional particles the QGSJET01 model [6] of hadronic interactions is employed. The GHEISHA procedure is used to treat hadronic collisions of secondary particles at small energies. To describe the propagation of the

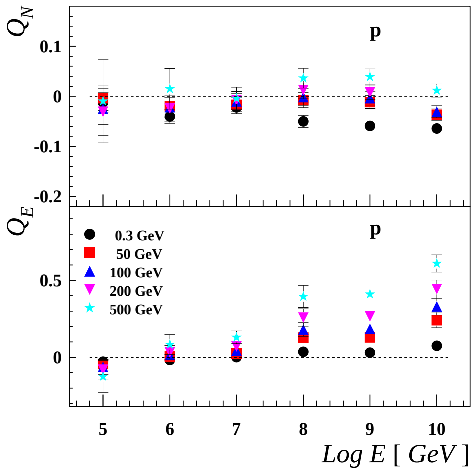


Figure 2: Ground level excesses of the total number (upper panel) and energy (lower panel) of muons in EAS with charm production are depicted as functions of the primary proton energy. Muon energies are constrained as $E_\mu \geq 0.3, 50, 100, 200$ and $500$ GeV.

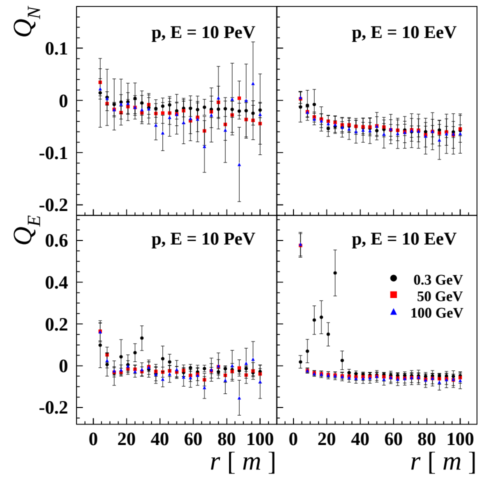


Figure 3: Ground level lateral excesses of the number (upper panels) and energy (lower panels) of muons in EAS with charm production initiated by the proton primary with the incident energy of 10 PeV and 10 EeV are depicted. Results for muon energies $E_\mu \geq 0.3, 50$ and 100 GeV are shown.

particles in EAS down through the atmosphere the EAS simulation code CORSIKA [16] is adapted.

Charm particles are produced at the expense of the energy of secondary baryons and mesons produced in subsequent hadron–air collisions in which the interaction energy exceeds 150 GeV in c.m.s.; no account of their energy spectra is taken. Electron–photon cascades due to the decays of neutral pions are treated by common standards.

The CR primary protons are assumed to interact with the air nuclei at various incident energies of 100 TeV–10 EeV. The primary zenith angle is fixed at zero degrees; the altitude of the initial interaction is left free. In all simulations, a standard U.S. atmosphere is used.

The kinetic energy cutoffs for EAS hadrons and muons are chosen to 0.3 GeV; for electrons/positrons and photons we use cutoffs of 20 MeV and 2 MeV, respectively. In all calculations a thinning level of $10^{-7}$ and a maximum weight factor of $10^{30}$ are adopted for both electromagnetic as well as hadronic particles. In order to minimise influence of shower to shower fluctuations we average over 100 air showers; statistical uncertainties are shown in figures.

To visualise effects associated with the EAS charm production we use the asymmetry–like quantity $Q = \frac{N'_\mu - N_\mu}{N'_\mu + N_\mu}$, where $N'_\mu$ and $N_\mu$ are the number or energy densities of muons originating respectively in EAS with or without charm production and registered by the ground detector. This quantity measures an excess of muons originated in EAS with charm production over muons in showers generated in conventional models.

## Numerical results

Depending on the primary energy, a fraction of charm particles with respect to hadrons produced in all consecutive collisions during the EAS development is $10^{-5} - 10^{-4}$ in our calculations. An energy fraction carried by these charm particles increases more rapidly with the increasing primary energy from a value of $10^{-5}$ at the PeV region reaching $10^{-2}$ at the energy of 10 EeV.

The energy spectra of muons initiated by the protons of the primary energy of 1 EeV and detected at the ground as obtained in our simulations with the QGSJET01 high–energy interaction model are depicted in Fig.1. Depending on the initial energy, the energy spectra of muons fall off by about 4–6 orders of magnitude in the 10 GeV–10 TeV range. These spectra have typical profiles with a visible excess of hard muons due to charm production. At the primary energies of interest, secondary pions and kaons are mostly above the critical energy ($E_{\rm cr} < 1$ TeV) and so predominantly generate conventional muons in interactions, while charm particles being below their critical energy ($E_{\rm cr} > 10$ PeV) give prompt muons of high energies. This effect is remarkably large reaching a factor of two for highest muon energies studied.

Some general features of our simulations that can be observed by the ground level detector or underground are summarised in Fig.2. Here excesses of the total number and energy of muons originated in EAS with charm production are shown as functions of the incident energy of the CR proton. The total number of muons and their energy are depicted for muons with energies $E_\mu \geq 0.3, 50, 100, 200$ and $500$ GeV that in our calculations imitate the rock overburden for underground experiments.

It is well visible that muons in EAS with charm production deposit remarkably more energy in the detector than muons in conventional showers. This effect is pronounced with the increasing lower energy cut for muons. Our simulations show that charm particles carrying away a non–negligible fraction of the incident energy can be responsible for the delay of the energy absorption along the EAS axis. On the other hand, the number of muons born in EAS with charm production and registered at the ground or underground remains relatively stable with the increasing primary energy and, although mostly smaller, it does not differ considerably from the number of muons in showers generated in conventional models.

Examples of the lateral number and energy densities of muons initiated by the protons of the primary energies of 10 PeV and 10 EeV are depicted in Fig.3. We have found a small but visible deficit of muons in very high energy EAS with charm production with respect to conventional showers. On contrary, due to charm production an excess of muon energy that should be deposited near the shower axis in the ground detector or underground is observed.

## Conclusions

The calculation of the EAS muon content suffers in principle a significant uncertainty due to the lack of knowledge of the properties of the charm production in the hadron–nucleus collisions. We showed that a simple phenomenological treatment of prompt muons can reveal interesting observable features. More precise analysis will be carried out in the future.

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