29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Hadronic multiparticle production in extensive air showers and accelerator experiments

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Using CORSIKA for simulating extensive air showers, we study the relation between the shower characteristics and features of hadronic multiparticle production at low energies. We report about investigations of typical energies and phase space regions of secondary particles which are important for muon production in extensive air showers. Possibilities to measure relevant quantities of hadron production in existing and planned accelerator experiments are discussed.

1. Introduction

One of the most promising approaches to determine the energy spectrum and composition of the cosmic rays with energies above 10^{15} eV is the measurement of the number of electrons and muons produced in extensive air showers (EAS). However the results of such a shower analysis are strongly dependent on the hadronic interaction models used for simulating reference showers [1]. Therefore it is important to study in detail the role of hadronic interactions and in particular the energy and secondary particle phase space regions that are most important for the observed characteristics of EAS.

The electromagnetic component of a shower is well determined by the depth of maximum and the energy of the shower. Due to the electromagnetic cascade, having a short radiation length of $\sim 36\,\mathrm{g/cm^2}$, any information on the initial distribution of photons produced in π^0 decays is lost. Therefore the electromagnetic shower component depends on the primary particle type only through the depth of shower maximum. In contrast, the muon component is very sensitive to the characteristics of hadronic interactions. Once the hadronic shower particles have reached an energy at which charged pions and kaons decay, they produce muons which decouple from the shower cascade. The muons propagate to the detector with small energy loss and deflection and hence carry information on hadronic interactions in EAS. Due to the competition between interaction and decay, most of the muons are decay products of mesons that are produced in low-energy interactions. Therefore it is not surprising that muons in EAS are particularly sensitive to hadronic multiparticle production at low energy [2]. Recent model studies show that even at ultra-high shower energies the predictions on the lateral distribution of shower particles depend strongly on the applied low-energy interaction model [3].

2. Muon production in extensive air showers

Motivated by the measurement conditions of the KASCADE array [4], we consider showers with a primary energy of 10^{15} eV and apply a muon detection threshold of 250 MeV. Using a modified version of the simulation package CORSIKA [5] we have simulated two samples of 1500 vertical and inclined ($60°$) proton and 500 iron induced showers. Below 80 GeV the low-energy hadronic interaction model GHEISHA 2002 [6] and above 80 GeV the high-energy model QGSJET 01 [7] are applied. In the following only vertical proton showers are discussed. The results are very similar for iron induced showers and also for zenith angles up to $60°$.

In Fig. 1 the energy distribution of muons at detector level (1030 g/cm^2) is shown for several lateral distance ranges. The maximum of this distribution shifts to lower energies for larger lateral distances. Most likely four to five consecutive hadronic interactions (number of generations) take place before a hadron decays into a muon, see Fig. 2. Here and in the following we consider only those muons that reach the ground level with an energy above the detection threshold. The number of generations show no significant dependence on the lateral distance. To study the hadronic *ancestors* of muons in EAS, we introduce the terms *grandmother* and *mother particle* for each observed muon. The grandmother particle is the hadron inducing the *last* hadronic interaction that finally leads to a meson (mother particle) which decays into the corresponding muon. Most of the grandmother and mother particles are pions, but also about 20% of the grandmother particles are nucleons and a few are kaons. Details of the composition of mother and grandmother particles are given in Tab. 1.

Table 1. Particle types of mother and grandmother particles in a vertical proton induced shower at 10^{15} eV.

	mother	grandmother
pions	89.2%	72.3%
kaons	10.5%	6.5%
nucleons	-	20.9%

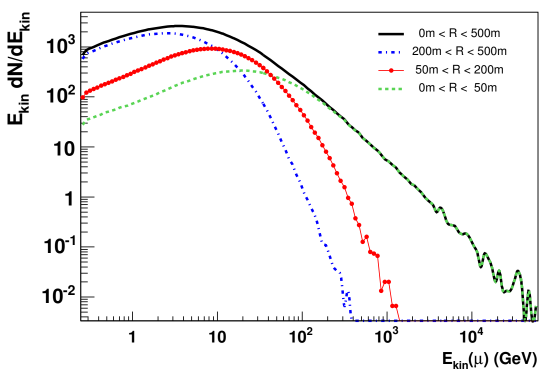

Figure 1. Simulated energy distribution of muons for different lateral distances.

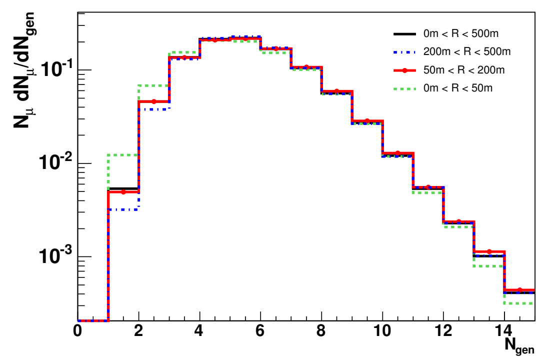

Figure 2. Averaged number of generations before producing a muon visible at ground level (shown for various lateral distances).

3. Energy and phase space regions

The energy spectra of different grandmother particles are shown in Fig. 3 (left). They cover a large energy range up to the primary energy with a maximum at about 100 GeV. The peak at 10^6 GeV in the nucleon energy spectrum shows that also a fraction of muons stems from decays of mesons produced in the first interaction in a shower. Furthermore, the step at 80 GeV clearly indicates a mismatch between the predictions of the low-energy model GHEISHA and the high-energy model QGSJET. In Fig. 3 (right) the grandmother particle energy spectrum is shown for different ranges of lateral muon distance. The maximum shifts with larger lateral distance to lower energies. Comparing the *last* interaction in EAS with collisions studied at accelerators, one has to keep in mind that the grandmother particle corresponds to the beam particle and the mother particle is equivalent to a secondary particle produced in e.g. a minimum bias p-N interaction. The most probable energy of the grandmother particle is within the range of beam energies of fixed target experiments e.g. at the SPS accelerator at CERN.

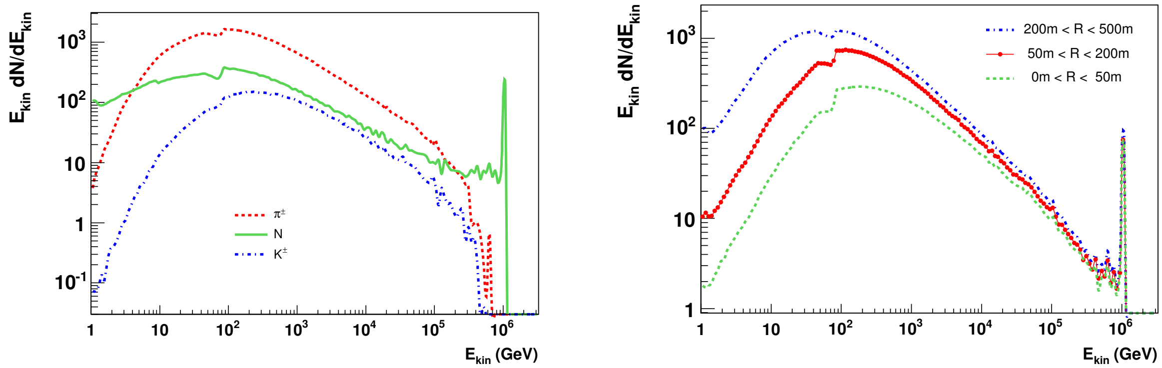

Figure 3. Energy distribution of grandmother particles. Left: different grandmother particle types; lateral distance range of muons at ground level: 0-500 m. Right: different lateral distances; all particle types are summed up.

Table 2. For the analysis used energy and lateral distance ranges.

energy range	average energy	lateral distance range
80-400 GeV	160 GeV	50-200 m
30-60 GeV	40 GeV	200-600 m

The further study of the relevant phase space of the mother particles is done for two different grandmother energy ranges and lateral distance ranges of muons at ground level, see Tab. 2. The lateral distance ranges are chosen to resemble typical lateral distances measured at KASCADE and KASCADE-Grande, respectively. In Fig. 4 the rapidity spectra of mother particles (left: pions, right: kaons) are compared to the spectra of secondary particles of proton-carbon collisions and proton-air collisions simulated with QGSJET labeled as *fixed target*. The spectra of mother particles in air showers are scaled to fit the falling tail of the fixed-energy collision spectra. No significant differences are found comparing the rapidity distributions of secondary particles in proton-carbon and proton-air collisions. As a consequence of the different selection criteria, the forward hemisphere in the mother rapidity spectra is clearly favoured compared to the spectra of secondaries in minimum bias collisions.

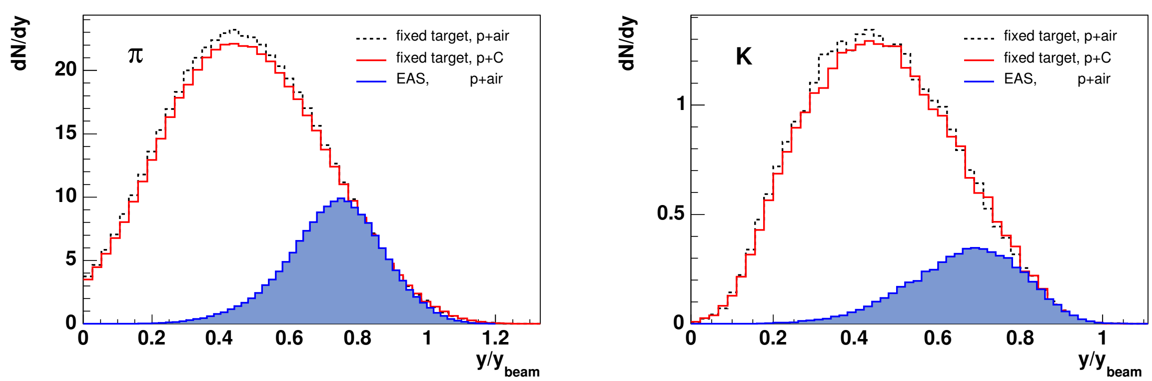

Figure 4. Rapidity distributions of mother particles (filled curves) compared with rapidity distributions of secondary particles in simulated single p+C (solid line) and simulated p+air (dashed line) collisions. Left: pions. Right: kaons. The energy range of the grandmother particle is limited to 80-400 GeV and the lateral distance of the muons to 50-200 m to match experimentally accessible regions. The fixed target collision simulation is done at 160 GeV, corresponding approximately to the mean grandmother energy. The rapidity is normalized to the rapidity of the beam and grandmother particles, respectively.

4. Conclusions and outlook

Due to the interplay between decay and interaction of pions and kaons, low energy hadronic interactions are very important for muon production in extensive air showers. With increasing lateral distance the mean energy of these interactions, which are mainly initiated by pions and nucleons, decreases. The phase space regions of relevance to EAS are shown in Fig. 5 and summarized in Tab. 3. The most important interaction energies and phase space regions fall in the range accessible to fixed target experiments with large acceptance detectors such as HARP, NA49, and MIPP (see also [8] and Refs. therein). Therefore fixed target measurements could be used to improve low energy interaction models that can be independently cross-checked by muon measurements in EAS.

Table 3. Phase space regions of hadronic interactions relevant for muon production in EAS.

average energy (GeV)	y/y_{beam}	$p_\perp$ (GeV/c)
160	0.3 - 1.1	0.0 - 0.7
40	0.3 - 1.1	0.0 - 1.0

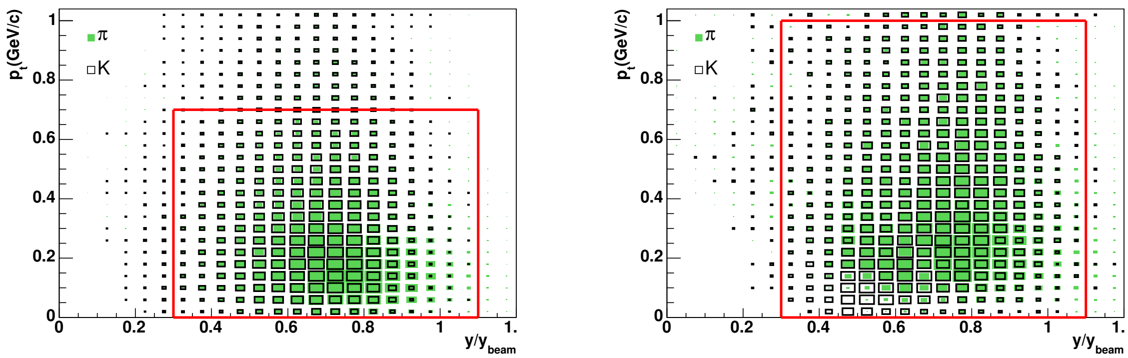

Figure 5. Phase space of mother particles. Left: grandmother energy range: 80-400 GeV. Right: 30-60 GeV. The filled symbols show the distribution for pions, the open symbols for kaons. The large box (red) indicates the most interesting phase space region which includes more than 90% of this particles.

Acknowledgements: The authors thank Dieter Heck for many fruitful discussions and help with modifying CORSIKA to include the muon ancestor information.

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