Precision Test of Hadronic Interaction Models with KASCADE Data

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Abstract

Extrapolations of hadronic interaction models into kinematical and energy regions beyond the limit of accelerator data may heavily influence the interpretation of EAS data, especially the estimation of primary energy spectra and mass composition. In order to test and possibly improve the model predictions, the muon trigger and hadron rate observed with the KASCADE central detector are analysed and compared to CORSIKA simulations. The hadrons detected result from primary particles in the energy range of 0.1 to 500 TeV. Taking the measured particle fluxes from direct observations, we find fewer hadrons than predicted. Adopting a slightly larger total cross-section for pp interactions, such as suggested by findings of the CDF experiment at Fermilab, a noticeable improvement but still unsatisfactory description is obtained. Investigations to further improve the predictions are under way; the physical implications of the results are discussed.

1 Introduction

For cosmic-ray research, the test of hadronic interaction models is interesting in terms of particle physics and necessary in terms of astrophysics. The particle physics interest, on the one hand, results from the fact that the very forward region of high-energy collisions, which determines the development of an extensive air shower, is unexplored by current (and planned) laboratory measurements. At the highest energies of $\sqrt{s} = 0.9$ TeV, the UA5 experiment detected only about 30% of the total energy, and the CDF experiment at $\sqrt{s} = 1.8$ TeV even only about 5%. Thus, the study of EAS, especially by comparing the predictions of different models with data, might provide new insights in the region beyond the kinematical and energetic limits of colliders. The astrophysical necessity, on the other hand, emerges when trying to deduce energy spectra and mass composition from EAS measurements. The interpretation is decisively influenced by using different models. A well-known example is the mass composition concluded from the depth of shower maximum. The composition varies from mixed to pure iron, depending on the model assumed (see e.g. Watson, 1997). Therefore, a reliable test of simulation models is desirable. The idea of the test described in the following is to check with the calorimeter, how many hadrons, propagated through the atmosphere, arrive at observation level, and this in an energy range where the primary flux is reasonably well known from direct observations, viz. 0.1 to 500 TeV. We trigger on the muon content of such low-energy EAS, which have developed somewhere in the atmosphere, ask for the hadrons at observation level, and compare with simulations.

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2 Observables

The main part of the KASCADE central detector is the hadron calorimeter, for experimental details see (Klages et al., 1997). Utilizing 40000 electronic channels of liquid ionization chambers in 8 sampling layers (with an area of $16 \cdot 20$ m^2), it allows to measure position, angle of incidence, and energy of individual hadrons with $\approx$ 100% efficiency above 100 GeV. Embedded is a layer of 456 plastic scintillation counters, used as a fast trigger. A muon trigger is given, if a minimum number of detectors (e.g. 9) have coincidently above 1/3 of a m.i.p.'s signal. After a successful muon trigger, it is looked for at least one hadron with more than 100 GeV in the calorimeter. The frequency of such events defines the muon trigger rate and the (muon selected) hadron rate. This approach of selecting the events in the muonic shower component and of comparing in the 'critical' hadronic one, which combines two components with different longitudinal shower developments, puts high demands on the models and therefore is an excellent testing instrument.

3 Measurement & Simulation

The measured rates show long-term stability on the percent level after being corrected for dead time and air pressure effects (each $\leq$ 10%). For a description of the calorimeter performance see also (Engler et al., 1999). The simulations are performed using the CORSIKA air shower program (Heck et al., 1999, and references therein), and the detector response is calculated with the GEANT package (GEANT, 1993). The five primary particle classes p, He, O, Mg, and Fe are simulated in accordance with the spectra given by direct measurements (e.g. Wiebel, 1994); for extrapolations to higher energies ($>$ 1 PeV), the individual spectral indices are assumed to be constant. The simulation covers the complete acceptance in terms of primary energy, zenith angle, and distance of shower core to the central detector. The hadronic interaction models VENUS (Werner, 1993), SIBYLL (Fletcher et al., 1994) and QGSJET (Kalmykov & Ostapchenko, 1993), as given in CORSIKA version 5.62, have been analysed. As a consequence, modifications in QGSJET have been implemented ($\Rightarrow$ CORSIKA 5.63) and examined, see section 4.

Figure 1 displays for QGSJET (5.63) the contribution of the primary energies to the rates. One observes

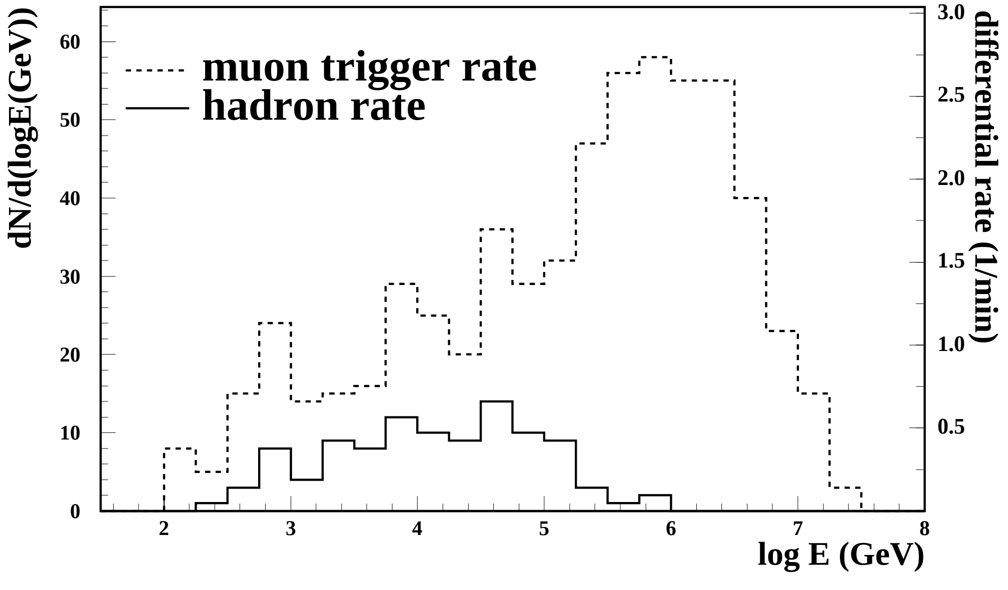

Figure 1: The contribution of primary particle energies to the muon trigger and hadron rate, in terms of absolute rates (right axis) and number of events in the simulation (left axis) for QGSJET (CORSIKA version 5.63, see text).

that the hadron rate originates from energies for which the flux is well determined by direct measurements: Thus, this observable does not suffer from the uncertainties in composition and absolute fluxes at high energies − an important aspect when trying to perform a precision test.

4 Results

The resulting integral rates are compiled in Figure 2, showing the muon trigger rates versus the hadron rates obtained by the simulations and compared with measured values. The error bars represent the statistical uncertainties of the simulations. It should be emphasized, however, that in the simulations an additional systematical error should be born in mind which results from the systematical uncertainties in the direct measurements. It can be estimated to $\pm(10...20)\%$. For the muon trigger rate, an additional error of roughly the same amount has to be considered because of contributions of higher primary energies. However, when regarding the ratio of the rates, the uncertainties in the absolute flux cancel out to first approximation.

From the figure it can be seen that the three interaction models (open symbols) predict fairly well the muon trigger rate but generate a too large hadron rate by more than a factor of 2 when compared to the measured

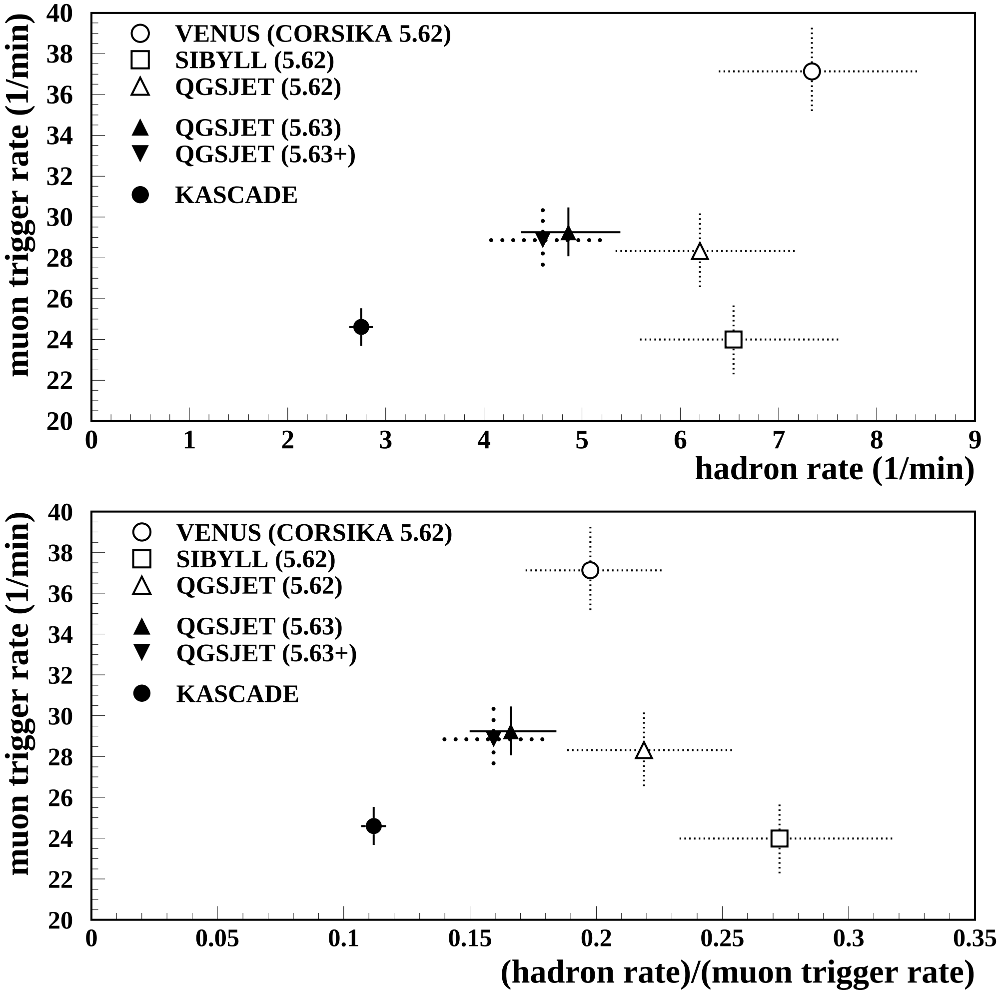

Figure 2: The integral muon trigger and hadron rates, resp. their ratio.

KASCADE value. All models propagate the showers too deeply into the atmosphere. In reality, hadronic cascades develop much faster than the models predict. VENUS also produces significantly more muons, which is consistent with findings of (Knapp, 1997). SIBYLL generates the highest ratio of hadrons to muons as seen in the lower part of Figure 2, mostly as a result of its relative low muon number. Other investigations have revealed the SIBYLL muon number being too low at high energies (see for instance Hörandel et al., 1999; Antoni et al., 1999). The data are explained better by QGSJET, but still not well enough. Several attempts have been undertaken by the authors of this model to improve the agreement (Ostapchenko, 1998). In CORSIKA version 5.63, the total inelastic cross-section has been increased by about 5%, which is justified by the new nucleon-nucleon inelastic cross-section of 80 mb obtained by the CDF Collaboration at an energy of $\sqrt{s} = 1.8$ TeV (Abe et al., 1994), corresponding to 1.6 PeV laboratory momentum. The inelastic cross-sections of mesons and of nuclei have been changed accordingly. Indeed, the simulated hadron rate is reduced without a noticeable effect on the muon trigger rate as shown in Figure 2: The decrease amounts to about 22% and reflects the sensitivity of this EAS observable on changes in basic model parameters.

A further modification of the authors concerns the restriction of diffractive collisions. A previous upper limit in the QGSJET model to diffractive masses $m_D < 5$ GeV has been omitted. However, as can be seen in Figure 2 (QGSJET 5.63+), this does not influence the shower development much; a minor improvement can be stated, nevertheless.

5 Conclusion

A precision test of air shower simulation models, especially sensitive to the hadronic part, has been developed by analysing the muon trigger and hadron rates of the KASCADE experiment. All hadronic interaction models examined so far predict a significantly larger hadron rate than observed. An improvement has been achieved in the QGSJET model by adopting higher inelastic cross-sections. Further improvements in the interaction model and extensions to the testing procedure are under way. On top of the calorimeter a complete layer of ionization chambers will be installed; with 100% coverage it will allow to check also the electromagnetic part of low-energy showers. In conclusion, EAS experiments reveal new insights in particle physics and hopefully might generate reliable models as a basis for solid astrophysical interpretations.

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