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Test and Analysis of Hadronic Interaction Models with KASCADE Event Rates

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Based on the KASCADE multi-detector system with its large hadron calorimeter and using the CORSIKA simulation program with the implemented high-energy hadronic interaction models QGSJET, VENUS, DPMJET, SIBYLL, and HDPM, a method for the test of models by comparing event rates is described. Preliminary results show differences of the model predictions both among each other and when confronted with measurements. The rates are strongly influenced by the inelastic cross sections and the elasticity, especially by the contribution of diffractive dissociation. The discrepancy to measurements at primary energies below $\simeq 3 \cdot 10^{13}$ eV can be reduced by increasing the non-diffractive inelastic cross section.

1. INTRODUCTION

The interpretation of extensive air shower (EAS) data often is closely connected to the use of high-energy hadronic interaction models. However, for the EAS development hadronic interaction processes which are beyond the kinematical and energy region of accelerators, such as diffraction, are of crucial importance. Perturbative QCD calculations are not applicable for particle production with low transverse momenta, and various model concepts and realizations exist for the necessary extrapolations. Apart from different extrapolations, an additional source of uncertainty for all models originates from the experimental situation especially concerning cross section measurements. For example, inelastic nucleon-carbon cross sections at energies of about E_{lab} = 200–280 GeV have been measured as 225±7 mb [1] and 237±2 mb [2], the errors being mainly systematical. At the highest energies of $\sqrt{s}$ = 1.8 TeV ($E_{lab} \simeq 1.7$ PeV), results obtained for the total proton-antiproton cross section are 72.8±3.1 mb (E710) [3], 80.03±2.24 mb (CDF) [4], and 71.71±2.02 mb (E811) [5] with a probability of the values being consistent of 1.6 % [5]. These systematic uncertainties of about 5–10 % are propagated when constructing hadron-air and nucleus-air cross sections. Effects on EAS predictions are large: An increase of 10 % of the inelastic cross section, e.g., reduces the number of high-energy hadrons (> 100 GeV) by 40–50 % and the electron number (> 3 MeV) by $\simeq$ 15 % (values for

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proton primaries of $10^{14}-10^{15}$ eV, $\Theta = 0°$, and KASCADE observation level, i.e., 110 m a.s.l.). The total muon number (> 300 MeV) changes only little ($\simeq +4$ %) but the lateral distribution becomes considerably flatter (reduction of up to 15 % of $\rho_\mu(r < 100\text{m})$).
Therefore, a test of the model predictions is not only important in terms of astrophysical interpretations, e.g., for the determination of the mass composition of cosmic rays, but also interesting information on particle physics might be revealed.

2. CONCEPT AND REALIZATION

A recent analysis [6] of the hadronic structure in EAS cores at energies around the knee exhibited differences between the models QGSJET [7], VENUS [8], and SIBYLL 1.6 [9]. Especially in the SIBYLL version an imbalance between the hadronic and muonic component pointed to an underestimation of the muon number, and new developments of the SIBYLL model have been started [10]. In order to test the simulations at primary energies where results of direct flux measurements are given, in this analysis event rates measured with the KASCADE experiment [11] are used. We start with a coincidence trigger of ≥ 9 out of 456 scintillators of the trigger layer in the central detector (Fig.1). After a trigger, it is searched for at least one hadron in the calorimeter [12] with a reconstructed energy of more than 90 GeV. The frequency of these events per time unit defines the trigger rate and the hadron rate.

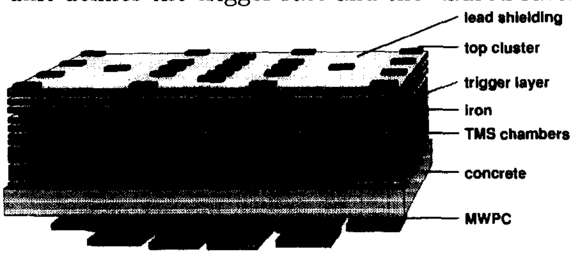

Figure 1. The KASCADE central detector (size $16 \times 20 \times 4$ m^3).

The measured rates show long-term stability on the percent level after being corrected for dead time and air pressure effects (each ≤ 10 %). Already with data of a few days statistical errors become negligible (< 1 %). No significant detector malfunctions have been found.
The air shower simulations are performed using the CORSIKA code [13]. The detector response is calculated with the GEANT package [14]. The five primary particle groups p, He, O, Mg, and Fe are simulated in accordance with the spectra given by direct measurements [15]. For extrapolations to higher energies ($> 5 \cdot 10^{14}$ eV), the individual spectra are assumed to drop with constant spectral indices up to a knee energy of $\lg(E/\text{GeV}) = 6.5$ and to steepen by about 0.3 after the knee. The complete acceptance in terms of primary energy, zenith angle, and distance of shower core to the central detector is considered. In addition to QGSJET (CORSIKA 5.62), VENUS 4.12, and SIBYLL 1.6, the models DPMJET 2.4 [16] and HDPM (CORSIKA 5.62) [13,17] have been used. For each model, the simulation statistics corresponds to a real time flux of about 20 min (HDPM: 10 min).

3. RESULTS

Figure 2 displays for VENUS and SIBYLL 1.6 the contribution of primary energies to the rates. The trigger rate of SIBYLL 1.6 is lower when compared with VENUS for energies above $\lg(E/\text{GeV})$=5.0. Simulations show that triggers at these energies mainly stem from muons while at smaller energies also cascading hadrons in the central detector contribute. Hence, the lowered trigger rate for SIBYLL agrees with the above mentioned results in reference [6]. The hadron rate originates from energies for which the flux is quite well determined by direct measurements. Thus, this observable does not suffer from the composition and flux uncertainties at high primary energies.
The integral values of all models are compiled in Figure 3 and compared with the measured KASCADE value. Differences of about a factor of 1.7 in the predicted trigger and of 2 in the hadron rates occur. No model prediction agrees well to another. The main contribution to the systematic errors of the predictions, which are mostly correlated in both rates, results from the uncertainty in the absolute fluxes and, for the trigger

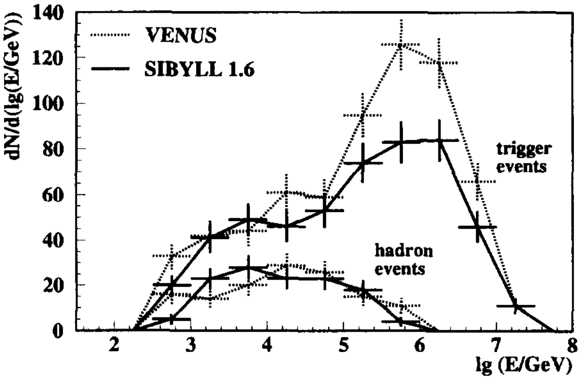

Figure 2. Contribution of primary energies to the trigger and hadron rate for the models VENUS and SIBYLL 1.6 (with statistical errors).

rate, its extrapolation to high primary energies (see reference [18] for details). However, to a first approximation all models would be effected in the same manner, and discrepancies between the predictions would persist. The trend of the rates can be understood in terms of the predicted muon lateral distribution and the number of high-energy hadrons which are closely connected to the inelastic cross section and the elasticity. For example, DPMJET adopts large cross sections and low elasticity values and produces early developing air showers. The hadron number on observation level is small. The muon lateral distribution is flat with low muon densities at distances which contribute to the trigger rate. Thus, small values for the rates emerge (vice versa for HDPM).

Compared to measurement, QGSJET, DPMJET, and SIBYLL 1.6 show reasonable agreement with respect to the systematic uncertainty. All models overestimate the hadron rate. In the modified version SIBYLL 2.0, the effect of an increased cross section and a reduced elasticity (corresponding to a different x_f-distribution of the leading particle) becomes apparent. Although the total muon number is increased in SIBYLL 2.0 compared to SIBYLL 1.6 ($\simeq$ 10 % at 10^{15} eV for a proton primary, the difference becoming larger with increasing energy), the early shower development causes a much flatter muon lateral distribution and therefore a strong suppression of trigger events in the region of 10^{13}–10^{15} eV.

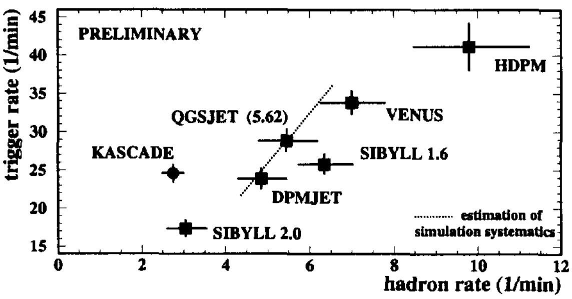

Figure 3. Measured (with total error) and predicted (with statistical error) trigger vs. hadron rates. An estimation of the systematic uncertainty for the simulations is indicated for QGSJET by the dashed line.

Since hadrons also contribute to the trigger, less hadrons reaching the detector will additionally reduce the trigger rate. The authors of the SIBYLL code are currently implementing further developments which will change the predictions [19]. The large decrease of the rates can be understood quantitatively when modifying cross section or elasticity by changing the diffraction dissociation in a sensitivity analysis, as has been performed with QGSJET calculations [18].

In order to classify the rates into different primary energy bins, the muon detectors of the KASCADE array are included in the analysis. Using them as a veto, low primary energies ($< 3 \cdot 10^{13}$ eV) are selected. Comparing with the measurements, the overestimation of the hadron rate can be adressed to these primary energies. The simulations show that these hadrons are mostly the highest energetic in the shower and have suffered either very few and/or mainly diffractive collisions. This is plausible, since otherwise the energy loss from the primary particle of a few TeV to the hadron energy cut in the analysis of 90 GeV would be too large. This selection effect decreases with primary energy. At energies above 10^{14} eV, also secondary hadrons contribute to hadron rate events. With higher simulation statistics, this high primary energy region can be investigated in more detail.

Consequently, at low primary energies the measurements show that the leading particles lose more energy while traversing the atmosphere. This can be accounted for in the simulations either by increasing the inelastic cross section (more interactions) or by decreasing the elasticity (enhanced energy loss per interaction). When keeping the inelastic cross section fixed, this leads to a reduction of the contribution of diffraction dissociation. In total, an increase of the non-diffractive inelastic cross section for energies below $\simeq 3 \cdot 10^{13}$ eV will yield a better agreement between the predicted and measured hadron rates.

4. CONCLUSIONS

The KASCADE detector system combined with the CORSIKA code allows to test high-energy hadronic interaction models. Preliminary results of the investigation of the models QGSJET, VENUS, DPMJET, SIBYLL 1.6, HDPM, and SIBYLL 2.0 reveal differences in the predictions which can be understood in terms of different shower development of the muonic and hadronic component. These are mainly related to the adopted inelastic cross sections and elasticities. Discrepancies to the measured rates are found in both rates and point out possible modifications. The overestimation of high-energy hadrons from small primary energies can be reduced by increasing the non-diffractive inelastic cross section. In close connection with the authors of the models, further studies which have not been discussed here concerning, e.g., the hadron multiplicity in hadron rate events, the inclusion of the electromagnetic component in the analyses, or selecting high primary energies will help to improve our understanding of the interaction processes in air showers.

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