Recent results from the KASCADE-Grande cosmic-ray experiment — Test of hadronic interaction models with air-shower data

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Cosmic rays provide an unique approach to study hadronic interactions at high energies in the kinematic forward direction. The KASCADE air shower experiment was the first to conduct quantitative tests of hadronic interactions with air shower data. A brief overview is given on results from KASCADE and its extension KASCADE-Grande with respect to investigations of hadronic interactions and the properties of cosmic rays.

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1 Introduction

Cosmic rays are ionized atomic nuclei impinging on the atmosphere from outer space. Particles with energies exceeding 10^{20} eV have been measured, being the highest-energy particles in nature [1, 2, 3]. When they impinge on the atmosphere they initiate cascades of secondary particles, the extensive air showers (EASs). The atmosphere with a thickness of ≈ 30 radiation lengths or ≈ 11 hadronic interaction lengths acts as a calorimeter. Cosmic rays are an unique probe to study hadronic interactions at energies well beyond the regime of human made accelerators. The center of mass energy of the LHC $\sqrt{s} = 14$ TeV corresponds to a laboratory energy of 10^{17} eV, relevant for cosmic-ray studies. The multiplicity of secondary particles in (central) collissions



Figure 1: Multiplicity (left) and energy flux (right) in hadronic interactions as a function of pseudorapidity. In addition, the coverage of detectors at the LHC is shown. RP refers to Roman Pots, ZDC means zero-degree calorimeter.

peaks around pseudorapidity^{*} values of $\eta = 0$. Thus, the main experiments e.g. at the LHC such as ATLAS and CMS cover these central regions up to $\eta \approx \pm 7$, see Fig. 1. However, the energy flux exhibits maxima at pseudorapidity values around $\eta \approx \pm 10$. At the LHC this region is covered by specialized forward detectors such as LHCf or TOTEM. The region in the extreme forward direction $\eta \approx \pm 10$ is of great importance for the development of extensive air showers. Thus, cosmic rays and extensive air showers are used to study hadronic interactions at highest energies in the kinematic forward direction.

The KASCADE air shower experiment was one of the first experiments to conduct quantitative studies of hadronic interactions with air shower data. In the following, a brief introduction to the KASCADE and KASCADE-Grande experiments is given. Followed by a review of results on hadronic interactions and the properties of cosmic rays.

2 The KASCADE-Grande experiment

The KASCADE-Grande [4] detector array was situated at the site of the Karlsruhe Institute of Technology KIT, Campus North, Germany (49°N, 8°E) at 110 m a.s.l. It had a roughly quadratical shape ($\approx 700 \times 700 \text{ m}^2$) and it comprised a multi-detector system. Several types of detectors enabled the measurement of different air-shower observables. Historically, the KASCADE-Grande detector was an extension of a smaller array, KASCADE [5], which has been operated from 1996 on. KASCADE was a complex detector system aimed to clarify the origin of the knee in the energy spectrum of cosmic rays at a few 10¹⁵ eV. It was designed to

^{*}The pseudorapidity is defined as $\eta = -\ln [\tan(\theta/2)]$, where θ is the angle between the primary particle (or the beam axis) and the secondary particle.

measure cosmic rays with energies between 10^{14} and 10^{16} eV, by simultaneously recording the electromagnetic, muonic, and hadronic shower components. A 200×200 m² scintillator array recorded the electromagnetic and muonic ($E_{\mu} > 230$ MeV) shower components.

Of particular interest for the study of hadronic interactions was a 320 m² hadronic sampling calorimeter $(E_h > 20 \text{ GeV})$ with a total depth of 11 hadronic interaction lengths, interspaced with nine layers of liquid ionization chambers [6], see Fig. 2. To extend the energy range up to 10^{18} eV was the motivation for the extension KASCADE-Grande, thereby focusing on the expected transition from Galactic to extragalactic cosmic rays in the energy range $10^{17} - 10^{18}$ eV. The Grande array comprised 37 detector stations with 10 m^2 plastic scintillator each (formerly part of the EAS TOP array [7]), which were arranged on a roughly hexagonal grid with a spacing of about 140 m. KASCADE-Grande was in operation from 2003 until 2013, after which it was dismantled.



Figure 2: Hadrons in the core of an air shower with an energy of $\approx 6 \cdot 10^{15}$ eV measured with the KASCADE hadron calorimeter. 143 individual hadrons have been reconstructed with energies exceeding 50 GeV.

For most investigations, the number of electrons, muons, hadrons is of interest. These are obtained by sampling the corresponding particle densities and fitting an empirical function to the particle densities as a function of distance to the shower axis [8]. The integral under these functions gives the number of electrons, muons, and hadrons in an air shower, respectively. They are used in turn to derive cosmic-ray properties, such as the energy and mass/particle type of the incoming cosmic ray.

3 Test of hadronic interaction models

The biggest challenge in using cosmic rays to investigate hadronic interactions is the fact that two properties are (partly) unknown: the precise mass composition of cosmic rays and the properties of hadronic interactions at high energies in the forward direction. To disentangle these problems, the following approach has been adopted [9, 10]: Cosmic rays comprise all elements known from the periodic table (e.g. [11]). However, the abundances of elements heavier than iron (Z > 26) are significantly lower (by several orders of magnitude) as compared to the elements with nuclear charge numbers Z up to 26 (hy-



Figure 3: Principal idea of the feasibility check, see text.



Figure 4: Left: Number of hadrons at ground level as a function of the number of muons (integrated over a certain distance range) in air showers. The number of hadrons is given relative to the expectations of simulations with the model QGSJET 01, assuming a mass composition as measured with the electromagnetic and muonic detectors of KASCADE [12]. Right: Attenuation length of muons in the atmosphere. Measurements are compared to predictions of post-LHC interaction models [13].

drogen/protons to iron). Thus, for a feasibility test, it can be savely assumed that cosmic rays are mostly comprised of elements from hydrogen/protons to iron.

Using the extrema protons and iron nuclei, air shower simulations are conducted with the standard tool CORSIKA [14], using a particular model to describe the hadronic interactions. The particles reaching ground level are treated in a detailed detector simulation, based on the standard tool GEANT [15]. This results in predictions for the correlation between the different shower components: electromagnetic, muonic, and hadronic. These predictions are compared to measurements of such correlations. If the measurements are outside the range protons to iron, a particular hadronic interaction model is not able to describe the air shower development consistently, see Fig. 3.

This method has been pioneered by the KASCADE group about two decades ago [9, 10]. Over time different hadronic interaction models used in air shower simulations have been studied systematically. In 1999 the model QGSJET 98 has been favoured over the models VENUS and SIBYLL 1.6 [16]. In 2007 the models DPMJET II.55, QGSJET 01, and SIBYLL 2.1 have been found in reasonable agreement with the air shower data, while NEXUS 2 exhibited incompatibilities [17]. In 2009 incompatibilities between EPOS 1.6 and air shower data have been found [18] and the model QGSJET II.2 has turned out to describe the air shower data best [19]. It has also been studied how the properties of individual hadronic interactions (such as the cross section or the multiplicity) affect the overall shower development [20].

The mass composition of cosmic rays as a function of energy as obtained from the measurements of the electromagnetic and muonic shower components (see next section) has been used to conduct specific air shower simulations to predict the hadronic component on ground level. Quantitative studies show that the models QGSJET 01 and SYBILL 2.1

predict the hadronic component with an accuracy of the order of 10% [12], see Fig. 4 left.

This work helped to fine-tune the hadronic interaction models used in air shower simulations. When first LHC data became available, it was interesting to realize that the air-shower optimzed hadronic interaction models did quite well in describing the properties of the first LHC data [21, 22, 23].

More recently, also post-LHC hadronic interaction models have been confronted with air-shower data. The influence of current hadronic interaction models on the interpretation of air shower data has been investigated [24]. The attenuation length of muons in the atmosphere has been measured and compared to post-LHC hadronic models such as QGSJET II 04, EPOS-LHC, and SIBYLL 2.1 [13]. While the models predict an attenuation length of the order of 700 to 850 g/cm², the KASCADE-Grande measurements yield a significantly higher value between 1200 and 1300 g/cm², see Fig. 4 right. It is interesting to note that at the Pierre Auger Observatory a similar effect has been observed at higher energies: more muons are measured as compared to the predictions of LHC-tuned models [25].

4 Properties of cosmic rays

Main objective of KASCADE and KASCADE-Grande is the measurement of the properties of cosmic rays, in particular to derive energy spectra for elemental groups in cosmic rays. The number of elec-

trons and muons in an air shower are obtained through integration of the lateral density distribution function, as described above. Applying a simple Heitler-type model, it can be seen that in the electron-muon number plane the showers are characterized by two axes, an energy axis roughly alined along the main diagonal and almost perpendicular to it a mass axis [27, 28]. This illustrates, that



Figure 5: The all-particle energy spectrum of cosmic rays. In addition, energy spectra for groups of elements are shown (protons/light blue, iron/heavy red), for details see [26].

from the simultaneous measurements of the electromagnetic and muonic components the energy spectra for groups of elements can be unfolded [29]. The KASCADE results indicate

that the spectra for elemental groups (protons, helium, CNO group) follow roughly a power law with a fall off aproximately proportional to the nuclear charge Z. This implies that the knee in the all-particle energy spectrum of cosmic rays at an energy of about $4 - 5 \cdot 10^{15}$ eV is caused by a fall-off for the light elements. Such a behaviour can be explained by astrophysical models (see e.g. [30]): The maximum energy attained during Fermi acceleration in Supernova Remnants is proportional to Z. Also leakage from the Galaxy during the difussive propagation of cosmic rays through the Milky Way causes a rigidity dependent fall-off of the spectra.

Following these ideas one would expect a fall-off of the heavy component (iron-like elements) at an energy $Z_{Fe} = 26$ times the energy of the hydrogen/proton fall-off. Such a fall-off of the heavy cosmic-ray component has been indeed observed by KASCADE-Grande [26, 31]. Thus, confirming the scenario that the individual cosmic-ray elements fall-off at energies proportional to their nuclear charge Z, see Fig. 5. It could also be shown that the light component in cosmic rays recovers at energies above the fall-off energy of the heavy component [32]. Such a behaviour would be expected from a contribution of another source class (e.g. extragalactic component) at higher energies.

Recently, the IceCube experiment at the South Pole has found a similar behaviour of a rigidity dependent fall-off of individual elemental groups in cosmic rays as a function of energy [33]. This confirms the findings by KASCADE and KASCADE-Grande and a general picture emerges (see e.g. [34]): The energy spectra for individual elements in cosmic rays follow roughly power laws in the GeV and TeV regime. At higher energies (PeV regime) they exhibit a fall-of proportional to their nuclear charge Z. Thus, the Galactic cosmic-ray component is expected to reach up to energies above 10^{17} eV.

5 Summary and outlook

During the last two decades KASCADE and KASCADE-Grande have significantly increased the knowledge about Galactic cosmic rays at high energies [35]. Both experiments also improved our understanding of hadronic interactions at high energies in the kinematic forward direction. This has been achieved through precise measurements of the individual components of extensive air showers: the electromagnetic, muonic, and hadronic components. The upgraded Pierre Auger Observatory [36] with improved capabilities to measure the electromagnetic and muonic shower components will allow to continue the quantitative tests of hadronic interaction models with air shower data, which have been pioneered by KASCADE two decades ago.

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