On the primary mass sensitivity of muon pseudorapidities measured with KASCADE-Grande


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Abstract: With the Muon Tracking Detector in the KASCADE-Grande experiment mean EAS muon pseudorapidities are investigated. Here we report on the results of studying the sensitivity of this quantity to the mass of primary cosmic ray particles. Obtained values of the mean logarithmic mass in the $10^{16}$ eV - $10^{17}$ eV range of primary energies, based on the QGSJetII - FLUKA interaction model combination, are compared with the results of other experiments. The validity of the model in reproducing experimentally measured pseudorapidity values and its comparison with the EPOS 1.99 is discussed.

Keywords: muons; air showers; pseudorapidity; mass composition; model tests.

1 Introduction

The Muon Tracking Detector (MTD) [1] is one of the detector components in the KASCADE-Grande EAS experiment [2] (see Fig.1), operated at the Karlsruhe Institute of Technology (KIT) - Campus North, in Germany, by an international collaboration. The MTD measures directions of muon tracks in EAS with excellent angular resolution of $\approx 0.35^\circ$. These directional data allow to investigate the longitudinal development of the muonic component in showers which is a signature of the development of the hadronic EAS core, being in turn dependent on the mass of the primary cosmic ray particle initiating a shower. Such studies can be done either by the determination of a mean muon production height [3] or by using the mean pseudorapidity ($\eta$) of EAS muons, expressed in terms of their tangential ($\tau$) and radial ($\rho$) angles (quantities reconstructed in the experiment) [4], [5]. In this work we investigate to what extent one can use the muon pseudorapidity for the determination of primary mass.

2 Muon pseudorapidities in KASCADE-Grande

In KASCADE-Grande muons can be registered up to 700 m from the shower core, but normally different anal-
yses are carried out in specific distance ranges. In Fig. 2 lateral distribution of mean EAS muon pseudorapidities measured with the MTD in KASCADE-Grande are shown, together with the results of CORSIKA [6] Monte-Carlo simulations, employing a QGSJetII [7] and FLUKA2006 [8] model combination. Requirement of shower size \( \log N_e > 6 \) ensures full experiment trigger efficiency for registration, both, proton- and iron-initiated showers. Muons from iron showers are, per average, produced higher than those from proton showers, and this leads to the observed difference in the mean pseudorapidities on ground, i.e., to the primary mass sensitivity of muon pseudorapidities. In Fig. 2 one can notice in the experimental data, below 200 m, a bias towards proton mass, resulting (for showers above \( 10^{16} \) eV) from some saturation effects in the MTD close to the shower core. Above 300 m, an increasing bias towards iron mass is observed, caused by non-equal MTD trigger efficiency for all types of primaries there. Therefore, all subsequent investigations are done in the distance range 200 m - 300 m, where, as it was checked with the \( N_\mu/N_e \) ratio of showers used in the analysis, registration efficiency of the MTD is primary mass independent.

3 Mean logarithmic mass calculated with muon pseudorapidities

The distribution of measured muon pseudorapidity in the range 200-300 m from the shower core shows, that its mean value is contained between the simulated values for proton and iron primaries (Fig. 3).

In order to assess the average mass composition of cosmic rays with the standard \( < \ln A > \) procedure one has to be sure, that the mean muon pseudorapidity linearly depends on primary mass. The results of the linearity check are shown in Fig. 4. Here, the \( < \ln A > \) was calculated from \( \eta \) distribution for simulated carbon showers and compared with the known value \( \ln 12 = 2.49 \). The mean value of calculated \( \ln A \) differs here by less than 2% from the true value for carbon primary, justifying the use of muon pseudorapidity for the determination of \( < \ln A > \) of cosmic rays above \( 10^{16} \) eV.
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In the following the results for the primary energy decade $10^{16} - 10^{17}$ eV will be given. The primary energy was calculated using total number of charged particles and total number of muons in showers, with a procedure described in [9]. The energy ranges in which the $\langle \ln A \rangle$ was calculated are shown in the first column of Table 1. In the second column mean energy values, taking into account the spectrum with an index -3.1, are given. Columns 3 and 4 contain calculated $\langle \ln A \rangle$ values for QGSJetII and EPOS 1.99 [10], respectively. Due to the very limited statistics of available simulations with EPOS not in all energy bins the calculation was possible. In those, where it was possible, the errors (only statistical were considered) are, anyway, much larger than in case of the QGSJetII.

The results from columns 3 and 4 of Table 1 are presented in Fig. 5, together with a collection of $\langle \ln A \rangle$ values (taken from Fig. 14 (top) in Ref. [11]) derived from the average depth of the shower maximum by various experiments.

### Table 1: Results of the $\langle \ln A \rangle$ calculated in the $10^{16} - 10^{17}$ eV primary energy range for two high-energy interaction models.

<table>
<thead>
<tr>
<th>$\log E_0/\text{GeV}$ range</th>
<th>$&lt; E_0 &gt;$ [GeV]</th>
<th>$\langle \ln A \rangle$ (QGSJetII-FLUKA)</th>
<th>$\langle \ln A \rangle$ (EPOS1.99-FLUKA)</th>
</tr>
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<tbody>
<tr>
<td>$7.0 - 7.3$</td>
<td>$(1.38\pm0.01)\times10^7$</td>
<td>$0.4\pm0.3$</td>
<td>$1.0\pm0.5$</td>
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<tr>
<td>$&gt; 7.0$</td>
<td>$(2.23\pm0.01)\times10^7$</td>
<td>$1.1\pm0.2$</td>
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<tr>
<td>$7.3 - 7.6$</td>
<td>$(2.69\pm0.01)\times10^7$</td>
<td>$1.6\pm0.3$</td>
<td>-</td>
</tr>
<tr>
<td>$&gt; 7.3$</td>
<td>$(3.92\pm0.03)\times10^7$</td>
<td>$2.0\pm0.2$</td>
<td>$1.5\pm0.5$</td>
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<tr>
<td>$7.6 - 7.9$</td>
<td>$(5.34\pm0.02)\times10^7$</td>
<td>$2.2\pm0.5$</td>
<td>$2.4\pm1.3$</td>
</tr>
<tr>
<td>$&gt; 7.6$</td>
<td>$(7.12\pm0.08)\times10^7$</td>
<td>$2.7\pm0.4$</td>
<td>$3.5\pm1.1$</td>
</tr>
<tr>
<td>$&gt; 7.9$</td>
<td>$(13.20\pm0.26)\times10^7$</td>
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Figure 3: Distribution of measured muon pseudorapidity in the range 200-300 m from the shower core together with the simulation results for proton and iron initiated showers.

Figure 4: Test of the linear dependence of mean EAS muon pseudorapidity on the logarithm of primary mass. Triangles - simulated $\langle \eta \rangle$ values for H, C and Fe versus true $\ln A$ on the x-axis. A full circle - $\langle \ln A \rangle$ calculated for carbon, using its $\langle \eta \rangle$ value.

### 4 Discussion and conclusions

As seen in Fig. 5 our results, obtained with EAS muons pseudorapidity measured on ground level, are compatible with the collection of mean logarithmic mass values derived from the average depth of the shower maximum. They show similar rise of $\langle \ln A \rangle$ with energy in the investigated primary energy range. This compatibility, rather with the results obtained from measurement of the light generated during the shower development than the ones measured on ground (e.g. electron/muon ratio) is because the mean muon pseudorapidity is also a signature of shower development.

Obtained values are generally lower than those from other experiments. The main reason for this can be, that the QGSJetII model, despite improvement with respect to QGSJet01, gives still too high mean pseudorapidity values compared with the measurements.

It was found in previous studies (e.g. [12]), that in the investigated distance range from the core about 40% of the registered muons is produced in the hadronic interactions above 200 GeV, i.e., they are modeled in the simulation-
s by QGSJetII. And this model creates more muons at the heights above 4-5 km, than observed experimentally [3]. Such muons have higher mean muon pseudorapidity than the ones created deeper in the atmosphere [13], thus affecting the determination of the $\langle l n A \rangle$.

The mean pseudorapidity values obtained in simulations suffer from the insufficient shower statistics in the simulations. A standard approach is to use the same simulated shower 5 or 10 times over the detector area in order to reduce the time needed for simulations to acceptable value. In this particular investigation such an approach creates additional, systematic error in the determination of $\langle l n A \rangle$, impossible to be quantified without using each simulated shower once, what would require very significant increase of the simulation time.

In Fig. 5 some $\langle l n A \rangle$ values obtained with the EPOS 1.99 model are shown for the comparison. Due to the much smaller number of simulated data the statistical errors are much larger than in case of QGSJetII (see also Table 1). Moreover, the above mentioned effect of shower statistics is influencing the results even more.

One can say that the general behaviour showing rise of the primary mass with the energy is also seen with this model, however it is not possible to compare the values of the logarithmic mass predicted by the two models in question.

In conclusion, the mean muon pseudorapidity in EAS is a primary mass sensitive parameter and, providing the large enough number of simulated showers is available for the analysis, the $\langle l n A \rangle$ of prymay cosmic rays can be derived. However, the small difference between $\langle \eta \rangle$ values for proton and iron initiated showers ($\approx 0.2$) would require a significant increase in the number of simulated showers and, even then, the remaining uncertainties would prohibit to make a convincing mass composition studies with, at least, 3 mass groups.

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**References**