The ⟨ ln A⟩ study with the Muon tracking detector in the KASCADE-Grande experiment – comparison of hadronic interaction models

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Abstract. With the KASCADE-Grande Muon Tracking Detector it was possible to measure with high accuracy directions of EAS muons with energy above 0.8 GeV and up to 700 m distance from the shower centre. Reconstructed muon tracks allow investigation of muon pseudorapidity (η) distributions. These distributions are nearly identical to the pseudorapidity distributions of their parent mesons produced in hadronic interactions. Comparison of the η distributions from measured and simulated showers can be used to test the quality of the high energy hadronic interaction models. The pseudorapidity distributions reflect the longitudinal development of EAS and, as such, are sensitive to the mass of the cosmic ray primary particles. With various parameters of the η distribution, obtained from the Muon Tracking Detector data, it is possible to calculate the average logarithm of mass of the primary cosmic ray particles. The results of the ⟨ln A⟩ analysis in the primary energy range 10^{16} eV–10^{17} eV with the 1st quartile and the mean value of the distributions will be presented for the QGSJet-II-2, QGSJet-II-4, EPOS 1.99 and EPOS LHC models in combination with the FLUKA model.

1. Introduction

1.1. Muon tracking in KASCADE-Grande

The KASCADE-Grande experiment [1] was an air shower ground-based detector system located in Germany at Karlsruhe Institute of Technology (KIT – Campus North). At the end of 2012 the active data acquisition of all the experiment components stopped, however, the collaboration continues the detailed analysis of nearly 20 years of high-quality air-shower data.

The KASCADE-Grande experiment (Fig. 1) contained several detector systems. The most important for the presented analysis are the KASCADE Array, the Grande Array and the large area Muon Tracking Detector (MTD). The KASCADE Array was situated in the North-East corner of the experimental setup. It was an array of 252 detector stations, covering an area of 200 m × 200 m. The stations were placed on a square grid with 13 m spacing and were organized in 16 clusters. Each station was equipped with scintillation counters registering the electromagnetic shower component ($E^{thr} = 5$ MeV), and in the outer 12 clusters, also the muonic part of EAS (E_μ^{thr}=230 MeV).

A second major part of KASCADE-Grande is the *Grande Array*, being an extension of the KASCADE Array. It consisted of 37 detector stations organized in a grid of 18 clusters of overlapping hexagons, covering an area of 0.5 km². In the centre there was a small

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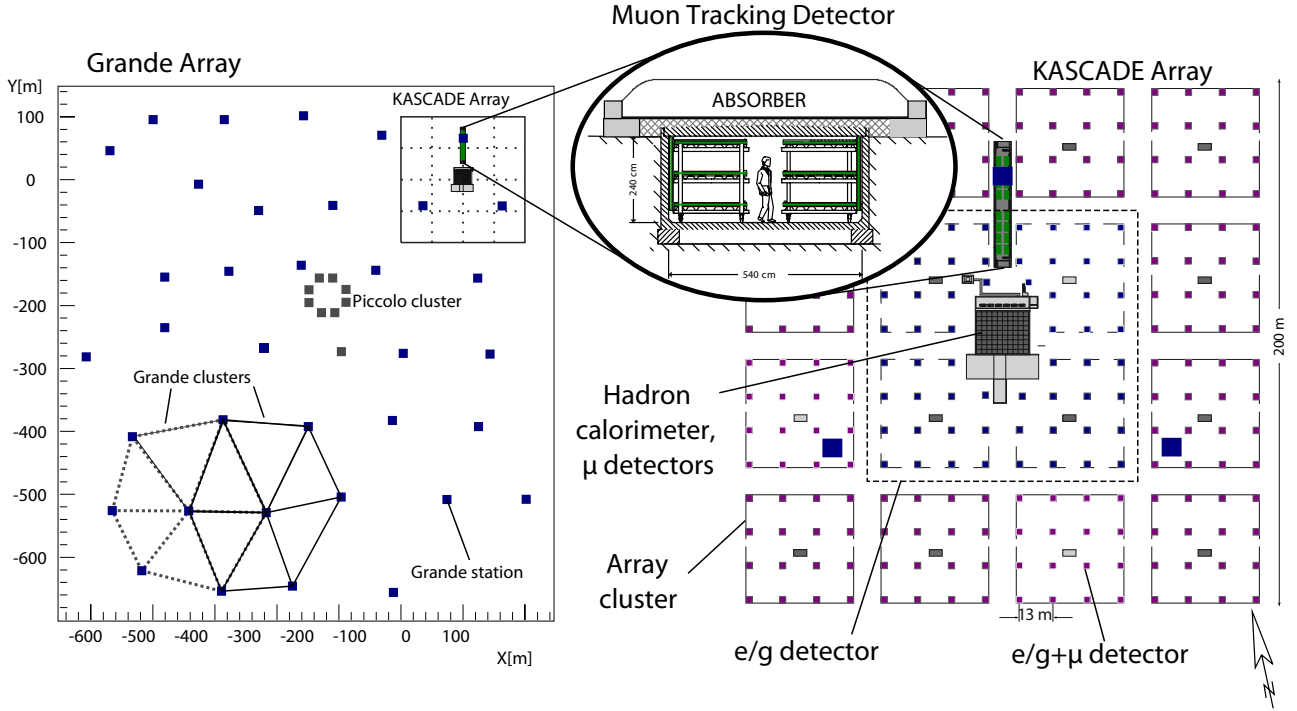f Now at: Stanford University (CA)

Figure 1. Layout of the KASCADE-Grande experiment distributed over the KIT – Campus North area. The KASCADE Array is situated in the North-East corner of the Campus; note the position of the Muon Tracking Detector.

trigger array of plastic scintillation stations, called *Piccolo*, built to provide additional fast triggers for some of the KASCADE detector components. Extended information about the KASCADE Array and Grande Array can be found in [1] and [2].

1.2. Design of the MTD

The large area Muon Tracking Detector was located in the northern part of the KASCADE Array (as shown in Fig. 1) and housed 16 muon telescopes made of streamer tubes. The telescopes were placed in a $5.4 \times 2.4 \times 44 \, \text{m}^3$ concrete tunnel, additionally buried under an absorber made of iron plates separated with sand. This shielding corresponds to an equivalent of 18 radiation lengths and absorbed most of the low-energy electromagnetic particles, thus allowing the identification of the tracks from muons with an energy larger than 800 MeV. The streamer tubes in each muon telescope were grouped in four $2 \times 4 \, \text{m}^2$ *detector modules*, three horizontal and one vertical (Fig. 1). The horizontal modules were separated by 820 mm. The middle module was located 1.7 m below the level of the KASCADE scintillator array. The total area for detection of vertical muons was 128 m^2.

An extended description of the design, performance and tests of the MTD can be found in refs. [3,4] and [5].

2. The mass sensitivity of the EAS muon pseudorapidity

The directional data obtained with the MTD enables to investigate the longitudinal development of the muonic component in air showers which is a signature of the development of the hadronic EAS core, being in turn
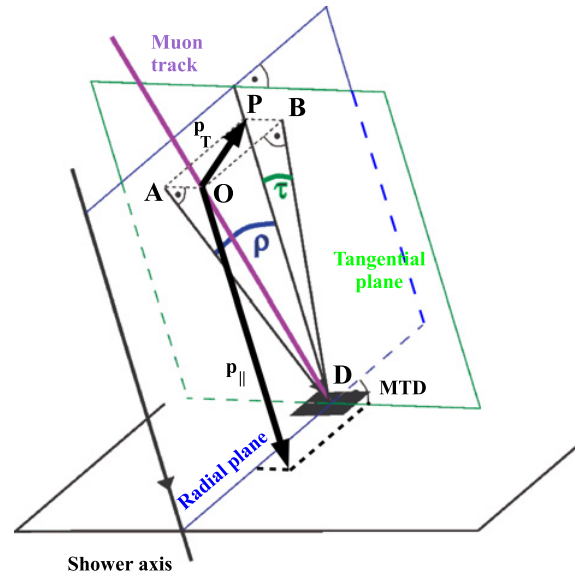

Figure 2. Definition of radial (ρ) and tangential (τ) angles.

dependent on the mass of the primary cosmic ray particle initiating a shower. Such studies can be done by quantities reconstructed from muon tracks obtained with the MTD: the mean muon production height [6] or by using the mean pseudorapidity (η) of EAS muons [7], expressed in terms of their tangential (τ) and radial (ρ) angles (Fig. 2) [8]. As shown in Fig. 2 the radial angle and tangential angle are angles between the shower direction and the orthogonal projections of the track onto the radial and tangential plane, respectively. The radial plane is defined by the position of the detector and the shower axis. The tangential plane is
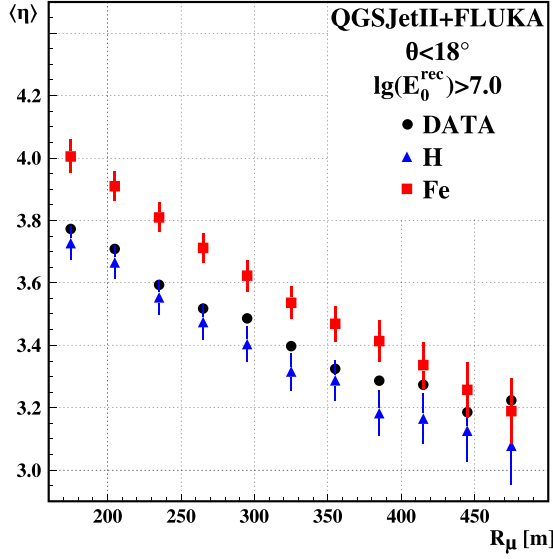
Figure 3. Lateral distribution of mean muon pseudorapidity in the limited distance range (see text) measured in KASCADE-Grande and compared with the CORSIKA simulation values for proton and iron CR primaries. Separation between distributions obtained with simulated and measured showers is clearly visible.

Table 1. R_μ distance ranges for each analysed energy range.

$\langle E_0^{rec} \rangle$ /10^7 GeV	R_μ [m]
1.34±0.01	250–370
2.07±0.01	250–370
2.69±0.01	280–400
5.34±0.02	280–430
7.15±0.07	280–430

the plane parallel to the shower axis at the position of the detector and perpendicular to the radial plane.

In the KASCADE-Grande experiment muons have been registered up to 700 meters from the shower core. For the presented analysis, the muon-to-shower-axis (R_μ) distance ranges (Table 1) were limited to the distances where the mass composition of the detected showers is constant in each energy range, not being affected by experimental inefficiencies. The selection of showers by their mass composition was done by taking into account the $\lg(N_\mu)/\lg(N_e)$ ratio which depends on the mass of the CR primary particle [5,9].

In this analysis EAS initiated by proton and iron primary CR particles were simulated with the CORSIKA code using QGSJet-II-2 [10] and QGSJet-II-4 [11] as the high energy hadronic (HE) interaction models and FLUKA [12] as the low energy (LE) hadronic interaction model. The QGSJet models were used to simulate hadronic interactions of particles with energy above 200 GeV while the FLUKA model was used to simulate those below this energy. In the measured and simulated data only showers with zenith angle up to 18° are analysed.

It was shown in [5,13], where the QGSJet-II-2 and EPOS1.99 [14] in combination with FLUKA were used, that the pseudorapidity of EAS muons is a parameter sensitive to the mass of the primary cosmic ray particles and can be used to calculate $\langle \ln A \rangle$ of CRs. It was
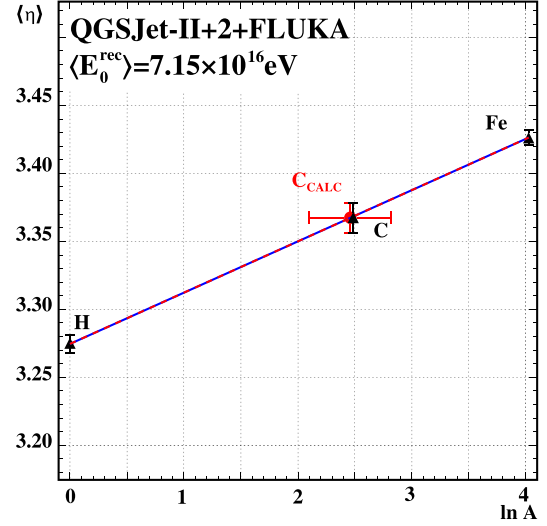

Figure 4. Test of the linear dependence of mean EAS muon pseudorapidity on the logarithm of primary mass. Triangles – simulated $\langle \eta \rangle$ values for H,C and Fe versus true $\ln A$ on the x-axis. A full circle – $\langle \ln A \rangle$ calculated for carbon, using its $\langle \eta \rangle$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

observed that the η distributions from the measured data are bracketed by the distributions from simulated showers and that $\langle \ln A \rangle$ and $\langle \eta \rangle$ are related linearly.

In Fig. 3 the lateral distribution of the mean η, experimental results are compared with simulations for two primary CR particles, H and Fe. Separation of the $\langle \eta \rangle$ for H and Fe initiated showers is clearly visible.

The results of the linearity check are shown in Fig. 4. Here, $\langle \ln A \rangle$ was calculated from the η distribution for simulated carbon initiated showers and compared with the known value $\ln 12 = 2.49$. The mean value of the calculated $\ln A$ differs here by less than 1% from the true value for carbon primaries, justifying the use of the mean muon pseudorapidity for the determination of $\langle \ln A \rangle$ of cosmic rays above 10^{16} eV.

In the investigation of the muon production height (h_μ) [6] it has been found that the measured values of h_μ above 4 km, where the interactions are described by the HE interaction model are not well described by the simulations. This is not the case for $h_\mu < 4$ km, where the interactions are described by the LE interaction model, and where the measurements are compatible with the simulations.

In the simulations it is possible to divide the muon sample into those originating from grandparent hadrons with energy above or below 200 GeV (HE and LE muon sample). In this way one can analyse contributions of these two groups to the combined η distribution which can be obtained with the MTD data. In the R_μ distance range that is valid in case of the MTD analysis (250–400 meters), there are about 70% muons from the LE sample and 30% from the HE sample. Most of the muons from the latter contribute to the $\eta > 4$ of the distribution, creating a long tail of high η muons. In this pseudorapidity range the number of muons from this HE sample is larger than from the LE sample (with ratio about 60% to 40%, respectively).
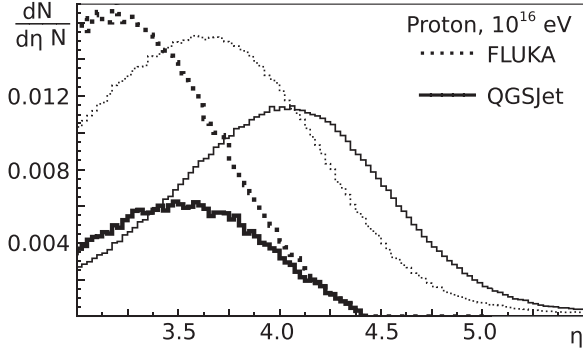
Figure 5. Comparison between η distributions from HE (solid lines, QGSJet) and LE (dotted lines, FLUKA) muon sample before (thin) and after (bold) the angular cuts – see text.

The differences in the LE and HE muon sample contributions suggest that the calculation of $\langle \ln A \rangle$ with the 1st quartile of the distribution, where LE interaction model dominates, will limit the influence of the HE interaction model. However, the value of the quartile is affected by the tail from the HE muon sample and the analysis is biased. To minimize this bias it is necessary to apply the angular cuts on the radial and tangential angle values. An example of the effect of such angular cuts is depicted in Fig. 5. Here the η distributions from the QGSJet-II-2 (solid lines) and FLUKA (dotted lines) muon sample are compared before (thin solid and dotted lines, $-0.5° < \rho < 17°$ and $|\tau| < 17°$) and after (bold solid and dotted lines, $1.4° < \rho < 17°$ and $0.8° < |\tau| < 17°$) the angular cuts. However, in the experiment conditions, it is necessary to take into account the statistics of available simulated and measured data. That is why it was not possible to eliminate the tails from the HE muon sample, as efficiently as shown in Fig. 5.

The angular cuts which provide an as small as possible decrease in muon statistics and suppress tails from the HE sample without significant distortion of the shape of the pseudorapidity distribution are: $0.75° < \rho < 17°$ and $0.2° < |\tau| < 17°$.

3. Results and conclusions

The results of the $\langle \ln A \rangle$ calculation are presented in Figs. 6, 7 and 8.

In the presented analyses we use as a reference the $\langle \ln A \rangle$ values derived from the analysis of the EAS electrons and muons measured in KASCADE experiment interpreted with the QGSJet01+FLUKA model combination [15,16].

In Fig. 6 the results of the $\langle \ln A \rangle$ analysis obtained with $\langle \eta \rangle$ for the QGSJet-II-2+FLUKA and QGSJet-II-4+FLUKA model combinations are shown.

The main conclusion from the analysis with the QGSJet-II-2+FLUKA model combination was that $\langle \ln A \rangle$ is increasing with the energy, but its values are lower than expected in the energy range 10^{16} eV – 10^{17} eV [17,18]. The reason for this are the distortions of the η distributions in simulations caused by the large number of high η muons that are shifting the $\langle \eta \rangle$ of the distributions towards higher values. As a result of this shift, the distributions from
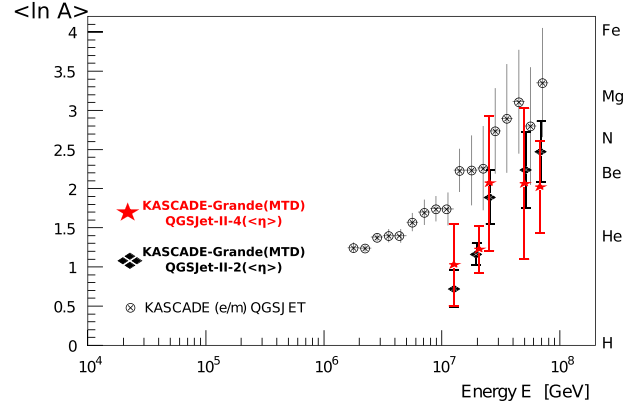

Figure 6. Results of the $\langle \ln A \rangle$ analysis obtained with the $\langle \eta \rangle$ with QGSJet-II-2 (❖) and QGSJet-II-4 (★) models in combination with the FLUKA model, compared with the KASCADE results (⊗) as a reference.
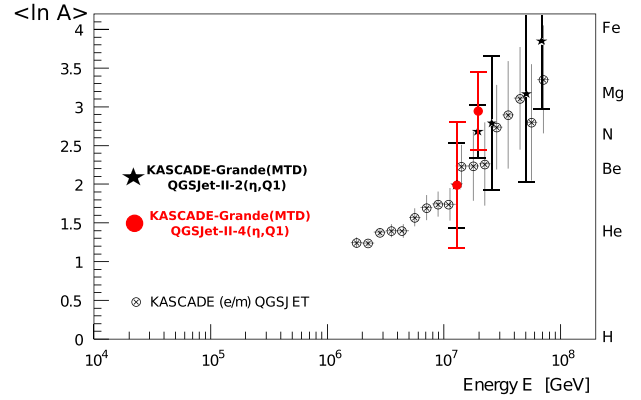

Figure 7. Results of the $\langle \ln A \rangle$ analysis obtained with the first quartile with QGSJet-II-2 (★) and QGSJet-II-4 (●) models in combination with the FLUKA model, compared with the KASCADE results (⊗) as a reference.

the measurement are close to these from proton initiated showers. This behaviour is caused by the QGSJet model which provides too many high η muons that reach the observation level.

In the case of the QGSJet-II-4+FLUKA model combination there is a trend of $\langle \ln A \rangle$ towards higher values in comparison with the previous version of the QGSJet model. However, the analysis requires larger statistics of simulated showers (work in progress).

In Fig. 7 the results of the $\langle \ln A \rangle$ analysis obtained with the first quartile of the η distributions for the QGSJet-II-2+FLUKA and QGSJet-II-4+FLUKA model combinations are presented. From this analysis we can conclude that the results obtained with both models are compatible with the KASCADE and Grande results. This suggests that this method can be used to investigate the mass composition using pseudorapidity of muons.

In Fig. 8 the comparison of the $\langle \ln A \rangle$ values obtained with the $\langle \eta \rangle$ for QGSJet-II-2+FLUKA, EPOS1.99+FLUKA and EPOS-LHC+FLUKA model combinations is shown. The $\langle \ln A \rangle$ values calculated with the EPOS1.99+FLUKA model combination are higher then those obtained with the QGSJet-II-2 model but
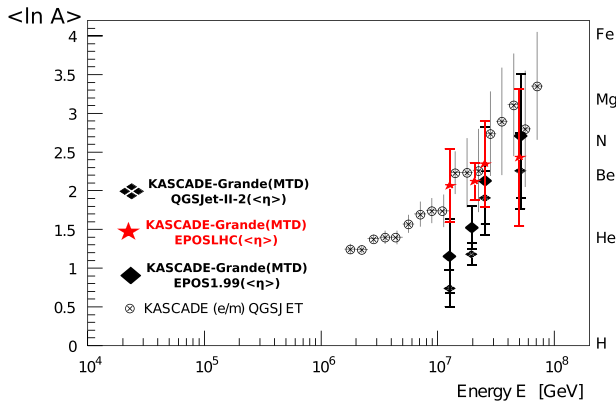
Figure 8. Comparison of the $\langle \ln A \rangle$ values obtained with $\langle \eta \rangle$ with QGSJet-II-2 (❖), EPOS1.99 (★) and EPOS-LHC(◆) models in combination with the FLUKA model, compared with the KASCADE results (⊗) as a reference.

lower that KASCADE results. A comparison between the EPOS1.99+FLUKA and EPOS-LHC+FLUKA model combinations shows that $\langle \ln A \rangle$ from the latter model combination has higher values. The increase in $\langle \ln A \rangle$ values is especially visible in the first three presented energy points, despite relatively large statistical errors. In the other energy ranges the $\langle \ln A \rangle$ values are similar within statistical errors. The results of the $\langle \ln A \rangle$ analysis for the EPOS-LHC model are compatible with the KASCADE and Grande results, they have similar values which rise with the primary energy at a similar rate. This is a significant improvement with respect to the previous version of EPOS model, where the $\langle \ln A \rangle$ values were lower than those from KASCADE analysis.

In conclusion, the changes introduced into the latest versions of the HE hadronic interaction models have noticeable effects onto the calculation of $\langle \ln A \rangle$ using muon pseudorapidity distributions. The most significant improvement with respect to the previous version of EPOS model can be seen in the results obtained with the EPOS-LHC model [19]. Now, the $\langle \ln A \rangle$ values are at the same level as those from the KASCADE analysis. In case of the QGSJet-II-4 model [11], there is a trend of the $\langle \ln A \rangle$ towards higher values, in comparison with the previous version of the QGSJet model. However, the analysis requires larger statistics of simulated showers (work in progress).

From the $\langle \ln A \rangle$ results obtained with the first quartile we can conclude that the results obtained with both QGSJet models are compatible with the KASCADE and Grande results which suggests that this method can be used to investigate the mass composition using the pseudorapidity of muons.

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