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Tests of hadronic interaction models with muon pseudorapidities measured with KASCADE-Grande

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Abstract: The Muon Tracking Detector in the KASCADE-Grande experiment allows the measurement of muon directions up to 700 m from the shower center. It means, that nearly all muons produced in a shower and surviving to the ground level are subject of investigation. It is important not only for studying mean muon production heights but also for investigations of EAS muon pseudorapidity distributions. These distributions are nearly identical to the pseudorapidity distributions of their parent mesons produced in hadronic interactions. Lateral distribution of muon pseudorapidity in extensive air showers (EAS) is a sensitive probe of hadronic interaction parameters embedded in the models. In this quantity lateral distribution of muon energy and lateral distribution of muon transverse momenta are hidden. Results of the analysis compared with the predictions of QGSJetII and FLUKA2002 models are discussed.

Introduction

The Muon Tracking Detector (MTD) [1] is one of the detector components in the KASCADE-Grande experiment [2] operated on site of the Research Center Karlsruhe in Germany by an international collaboration. The MTD with its detection acceptance of about 500 $\mathrm{m}^2\cdot$ sr measures in EAS tracks of muons, which energy exceeds 0.8 GeV, with the excellent angular resolution of ($\approx 0.35°$. The layout of the experiment is shown in Fig. 1.

Muons are very sensitive probe of the processes responsible for the development of an air shower in the atmosphere. They hardly interact and suffer only small deflection due to scattering in the air. Thus, in the directional information they conserve some of the kinematic parameters of their parent mesons - the most abundant products of hadronic interactions. Despite significant progress over the last decade, these interactions, at the en-

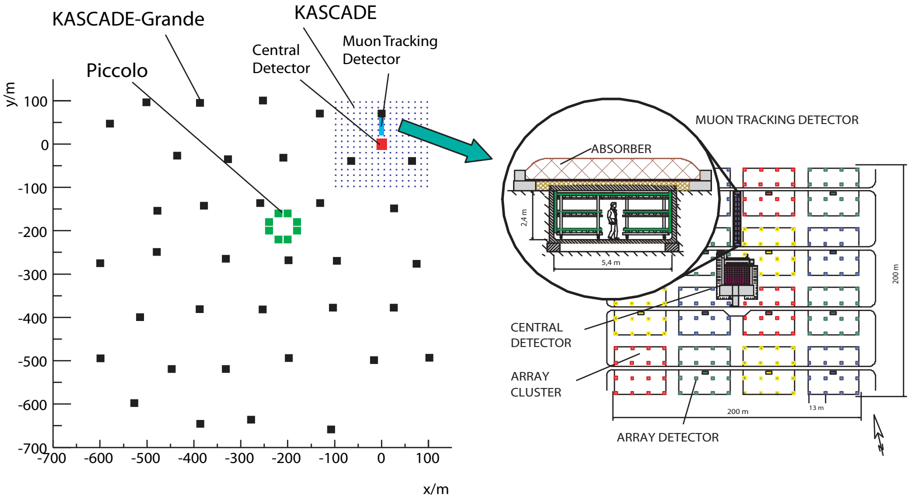

Figure 1: Layout of the KASCADE-Grande experiment distributed over the Research Center Karlsruhe. KASCADE is situated in the North-East corner of the Center; note the position of the Muon Tracking Detector.

ergies and kinematical regions relevant for the development of EAS, are still not well understood, mainly due to the lack of direct accelerator measurements. Therefore, tests of the models with the EAS data are the only accessible means to improve them.

Muon tracking

The muon tracking in KASCADE-Grande utilizes the concept of radial (ρ) and tangential (τ) angles (Fig. 2). The radial angle is a basic quantity in the determination of muon production heights [3]. A combination of both angles, as shown in [4], allow to determine the pseudorapidities of muons in EAS. Namely, a certain combination of τ and ρ is equal to the ratio of transversal to longitudinal momentum components of the muon with respect to the shower direction:

$$\zeta \equiv \sqrt{\tau^2 + \rho^2} = \frac{p_t}{p_\parallel} \qquad (1)$$

Hence, the pseudorapidity η of muons with energy > 0.8 GeV (MTD threshold) can be expressed as follows:

$$\eta = \ln \frac{2 \times p_\parallel}{p_t} \approx -\ln \frac{\zeta}{2} \qquad (2)$$

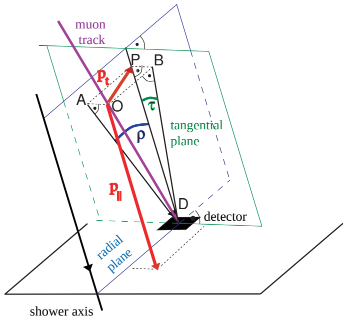

Figure 2: Definition of radial and tangential angles.

This muon pseudorapidity is highly correlated with pseudorapidity of their parent hadrons [5], thus being a powerful probe of high-energy hadronic interactions and can be used to test and improve existing hadronic interaction models.

Results and discussion

In KASCADE-Grande we have measured muon directions up to 600 m distance from the shower core. As simulations show, we track in this way nearly all muons surviving to the observation level [6]. A very good probe of the hadronic interaction is the lateral distribution of mean radial angle and, finally, of mean muon pseudorapidity. This

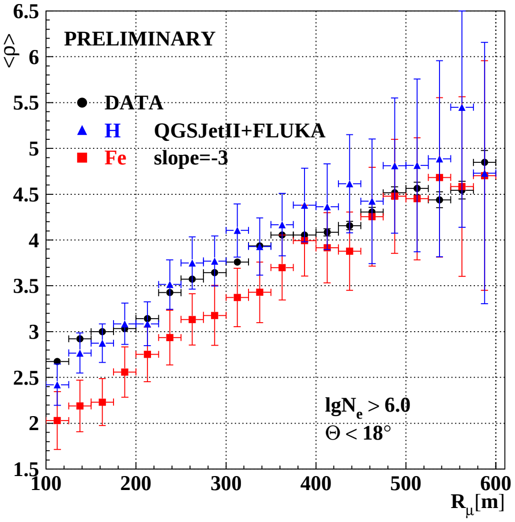

Figure 3: Lateral distribution of mean radial angle of EAS muons. Statistical errors only are shown.

is because with the MTD we examine the longitudinal development of the muonic shower component. At every given distance to the shower core we register muons from a certain window of production heights. Thus, lateral distribution of any measured muon parameter is a result of sliding this window over the whole shower development. The content of such a window is a result of hadronic interactions together with the propagation-related processes like multiple scattering and decays (of mesons and muons). Therefore, measured lateral distributions can be used to check how these distributions are predicted by hadronic interaction models.

In the following we shall analyze vertical air showers ($\theta \leq 18°$) efficiently triggered by the Grande Array, what means, having electron size $\lg(N_e) \geq 6$. The measured experimental values are compared with the predicted ones for proton and iron primaries by Monte Carlo CORSIKA [7] simulations using QGSJetII and FLUKA2002 [8] as high and low energy hadronic interaction models, respectively. In Fig. 3 the lateral distribution of mean radial angles of muons registered in such showers is shown. Limiting the value of ρ to maximum $10°$ removes from the analysis long tails of radial angle distributions produced by low energy muons created close above the detector.

Moving away from the shower core one observes a rise of the mean radial angle value, i.e. at large distances more muons are detected which are produced deeper in the atmosphere. The value of radial angle is dominated by the transversal momentum of a muon so, the distribution in Fig. 3 reflects the lateral distribution of mean transversal momentum of survived EAS muons, what is confirmed by CORSIKA simulations.

As it is seen from the figure in the range 100 - 400 m data points lay either above or very close to the points obtained for the proton initiated showers. At the distances below 200 m there seems to be a mismatch between simulations and the experiment. Above 400 m one observes a bend in the distribution causing the points fall close to the iron simulation results. Due to the large statistical errors there and not fully identical conditions in the experiment and in simulations (differences and their influence are under investigation), one cannot make any quantitative conclusions here, noting only that the rise of the mean values of ρ is maintained.

The lateral distribution of mean pseudorapidity of EAS muons which survived to the observation level is particularly well suited as a tool for testing interaction models. In this quantity such kinematical variables like muon energy and its transversal momentum are covered (pseudorapidity being proportional to the ratio of those two).

The results showing experimental data compared with the simulation results for proton and iron primaries are given in Fig. 4. As it is seen from equations (1) and (2) the value of η is dominated by the radial angle. Therefore, one observes the same relations between measured and simulated results as in the previously discussed distribution. The slope of the distribution is smaller in the measured data than in the simulated ones resulting in a growing discrepancy while aproaching the shower core. Previous analyses done with KASCADE data for distances 40 - 140 m are in agreement with the present one showing the continuation into the closer distances with the same slope [9]. Also the measured mean pseudorapidity values are below the simulated ones for proton showers in KASCADE distances, as it starts to be seen below 200 m in Fig. 4.

There may be several reasons why simulations result, apart from the largest distances, in too high mean pseudorapidity value of measured muons. Some part of this discrepancy can be probably attributed (it is under investigation) to the, mentionned above in case of ρ, differences in the experimental conditions and detector simulations. If this is accounted for, the rest can be a measure of the quality of the model. To have such a discrepancy the model should produce either muons with too high mean energy or too small mean transverse momentum. However, having in mind that the values are averaged for ”survived” muons one can also assume, that slightly higher energy of muons at production would give them a chance not to decay and be registered, adding their relatively low pseudorapidities to the measured sample.

Similar results one would get enlarging the muon survival probability by producing them deeper in the atmosphere. Since the low energy (below 10 GeV) muons are dominating in the registered sample even slight increase in their number (number of survived ones - not necessarily one should increase the pion multiplicity in the interactions) would give the shift of the mean values towards agreement with the measurements.

Apart from the above indicated drawbacks of the data at distances over 400 m one should note, that they cannot fully account for generally better agreement between data and simulations in the remote region. As indicated in [6] at different distances to the shower core we are sensitive with the MTD to muons produced in different ranges of hadronic interaction energies. In the close-by distances (KASCADE range: 40 - 160 m) the majority of registered muons orginate from mesons created at energies modelled by high-energy interaction model. With moving away from the shower core (KASCADE-Grande distances - up to 700 m) the input from the interactions goverened in simulations by a low-energy model becomes more and more important.

Therefore, one can make a preliminary conclusion that the largest discrepancies between measured and simulated results seen in Fig. 4 are likely to be due to the combination of experimantal limitations and the imperfections of high-energy hadronic interaction model, here QGSJetII.

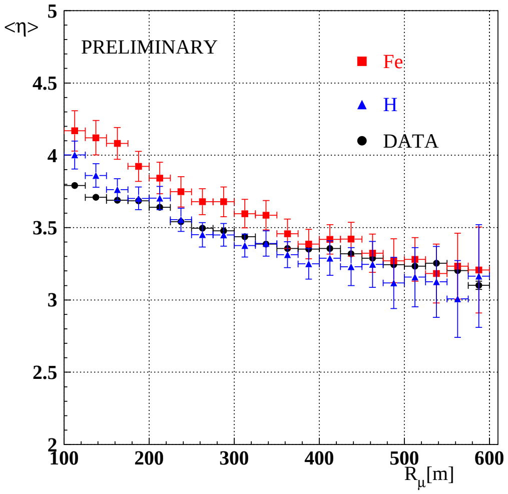

Figure 4: Lateral distribution of mean muon pseudorapidity measured in the MTD.

Acknowledgements

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