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Experimental Proof for the Sensitivity of Air Shower Radio Emission to the Longitudinal Shower Development

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Abstract: We observe a correlation between the slope of the radio lateral distribution measured with LOPES and the mean pseudorapidity of high-energy muons. The latter is reconstructed by combining the measurements of the muon tracking detector and the particle detector array of KASCADE-Grande. Since the mean muon pseudorapidity depends on the longitudinal shower development, the measured correlation is experimental evidence that also the radio signal is sensitive to the shower development – as has been predicted by simulations for a long time. For air showers interacting earlier in the atmosphere, i.e. old showers, the high-energy muons on average have a large pseudorapidity, and the lateral distribution of the radio signal is relatively flat. Contrary, young showers exhibit a smaller mean muon pseudorapidity and a steeper radio lateral distribution. The radio measurements seem to primarily depend on the geometrical distance between the shower maximum and the radio detector, and only as a consequence to the atmospheric depth of the shower maximum, X_{max}. The observed correlation is statistically significant and has been published in Physical Review D 85, 071101(R).

Keywords: LOPES Radio Antenna Air Shower

1 Introduction and Experimental Setup

Since a long time it has been predicted theoretically that the radio emission of air showers depends on the longitudinal shower development, cf. Refs. [1, 2, 3]. This is a crucial property for the usability of antenna arrays as cosmic ray detectors, since the sensitivity to the shower development implies a sensitivity to the mass composition of the primary cosmic rays. In Ref. [4], we have presented an experimental proof that the radio signal of air showers indeed depends on the longitudinal shower development.

For our analysis we used multi-hybrid measurements of the KASCADE-Grande experiment [5, 6] and the co-located LOPES radio array [7] (Fig. 1). In particular, KASCADE-Grande features among other detectors two dense arrays of particle detectors, and a muon-tracking detector (MTD) [8, 9]. We used the Grande particle-detector array to reconstruct the geometry of the air shower and its energy. The MTD measures the tracks of high-energy muons of the same air showers with an excellent angular resolution of $\approx 0.35^\circ$. These directional data allow us 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 [10] or by using the mean pseudorapidity of EAS muons, expressed in terms of tangential and radial angles between shower plane and individ-

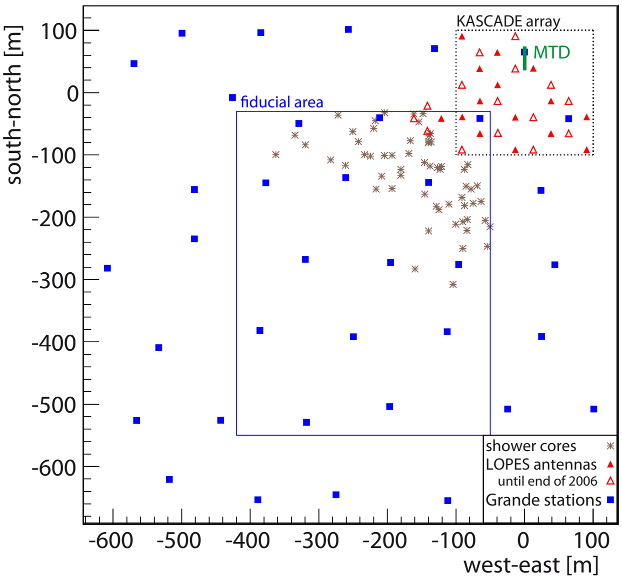

Figure 1: Map of the KASCADE-Grande and the LOPES experiments, including the centers of the 59 air showers selected for the present analysis. For these 59 events, the measurements of the KASCADE-Grande particle-detector array, the muon-tracking detector (MTD) and the east-west aligned antennas of the LOPES radio array passed all quality cuts applied during analysis.

ual muon directions [11]. For the present analysis, from these angles of these muons relative to the shower axis determined with the Grande array, we calculated the pseudorapidity of each muon and the average for each individual air shower, i.e. the mean muon pseudorapidity. The present analysis could have been performed also with the muon-production heights. However, the uncertainty in reconstruction of the distance to the shower axis introduces an additional uncertainty to the production height. Thus, muon pseudorapidities can be measured with a higher precision, and thus are used here. To minimize further systematic effects disturbing the analysis, we applied several quality cuts. In particular, we considered only events whose shower center falls within the fiducial area of the Grande array, and which have a distance from the MTD to the shower axis between 160 m and 320 m (for further quality cuts see Ref. [4]). Moreover, we considered only with events with a reconstructed energy above $5 \cdot 10^{16}$ eV, since this is the approximate threshold for high quality LOPES measurements (though LOPES is by far not fully efficient at this energy).

For some of the events fulfilling these conditions, we have in addition a LOPES measurement of the radio signal with at least 15 east-west aligned antennas in the frequency band 43 – 74 MHz. From these LOPES measurements, we reconstructed the lateral distribution of the radio amplitude, and fitted an exponential function with an amplitude parameter and a slope parameter (Fig. 2) [12, 4]. The amplitude parameter mainly depends on the energy of the air shower and its angle to the geomagnetic field. The slope parameter depends not only on the shower inclination and the axis distance where it is measured, but also on the longitudinal shower development and thus implicitly on the mass of the primary particle (cf. also Refs. [13, 14]). In total, we have 59 air showers for which we have in addition to the mean

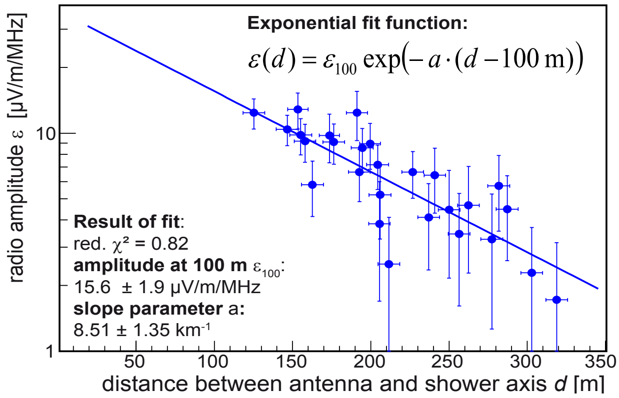

Figure 2: Lateral distribution of the radio signal of one event measured with LOPES.

muon pseudorapidity a reconstruction of the radio-lateral distribution.

2 Results

There is a clear and significant correlation between the slope parameter and the mean muon pseudorapidity for these 59 events (Fig. 3). This correlation is expected, since both observables depend in a similar way on the shower geometry and the longitudinal shower development. The strength of the correlation can be estimated by calculating the correlation coefficient r which is (-)1 in case of a perfect (i.e. in the absence of measurement uncertainties), linear (anti-)correlation, and 0 in case of no correlation. Counting by how many sigmas the slope of the line is different from 0 results in a significance of 7.1 σ. The found correlation is probably a combination of the causal link (the common sensitivity of both observables to the shower development) searched for, or due to common systematic effects and biases of the measurement devices.

To extract the part of the correlation which is only due to the shower development, we fitted the dependencies of both observables on the axis distance and the zenith angle (Fig. 4). Then, we corrected both observables for the determined dependencies and plotted the remaining correlation (Fig. 5), which is not as strong as the uncorrected correlation, but still significant at 3.7 σ.

The distribution of the individual points in Figs. 3 and 5 is compatible with what we expect for a linear correlation and a spread originating only from the individual uncertainties. Still, this does not mean that the correlation is necessarily truly linear, but with the sensitivity of our measurements we are not able to detect a possible slight deviation from a perfect linear correlation.

The fact that the observed correlation is partially due to a dependence on the shower inclination is consistent with the assumption that the radio signal is primarily sensitive to the distance between the shower maximum and radio detector, and only as a consequence to the atmospheric depth of the shower maximum. This is a difference to other detectors, e.g., fluorescence light detectors, which primarily are sensitive to the atmospheric depth of the shower maximum. Still, to compare the radio measurements to other techniques, it is possible to estimate corresponding $X_{\max}$ uncertainties. For the present data set, the typical uncertainties of the slope parameters of the radio lateral distributions correspond to $X_{\max}$ uncertainties of approximately 115 g/cm^2. This is in

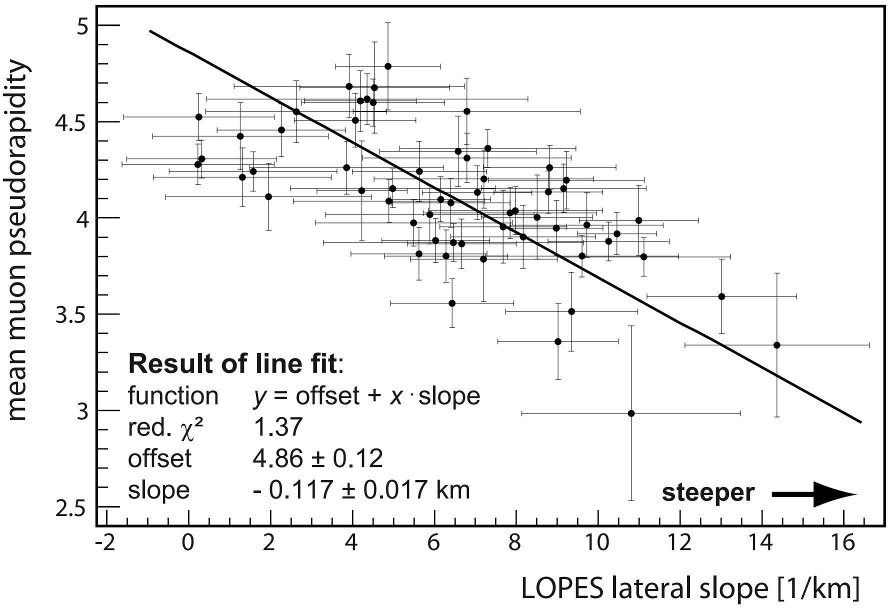

Figure 3: Correlation of the slope parameter of the radio-lateral distribution and the mean muon pseudorapidity for the 59 events.

the order of the typical difference between air showers initiated by protons or initiated by iron nuclei. Still, one has to keep in mind that the quality cuts for the present analysis have not been chosen with the aim to maximize the precision, but with the aim to minimize systematic effects on the correlation analysis. Thus, with a different set of LOPES events, a higher precision can be achieved [13], which, however, is still limited by the high background level at LOPES.

3 Conclusion

We observe a correlation between the mean pseudorapidity of high-energy muons and the slope of the lateral distribution of the radio signal emitted by the same air-showers. This correlation is partially, but not totally because of systematic effects (shower inclination and axis distance of the detectors). Thus, we conclude that it is also partially due to the shower development, especially since the mean muon pseudorapidity is already known to be sensitive to the longitudinal shower development. Consequently, this is the experimental proof that also the radio-lateral distribution is. Young showers which have a shower maximum at a closer distance to the detector have a steeper radio-lateral distribution than old showers. This feature can be exploited to reconstruct $X_{\max}$ and – on a statistical basis – the mass composition of the cosmic rays. However, the sensitivity of LOPES is limited. In near future, next-generation radio arrays, like AERA [15] or Tunka-Rex [16] will explore, which precision on $X_{\max}$ can be achieved in environments with lower radio background.

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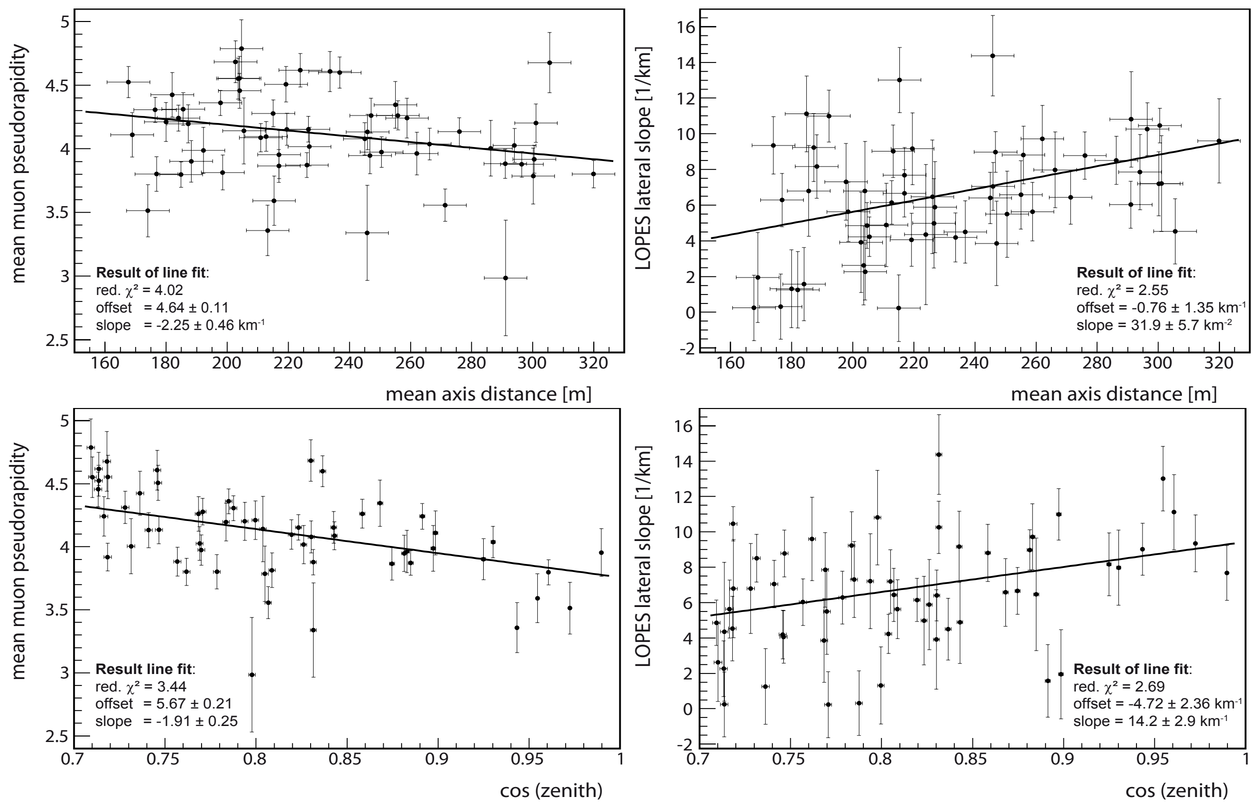

Figure 4: Dependencies of the mean muon pseudorapidity (left) and radio slope parameter (right), on the axis distance (top) and the zenith angle (bottom).

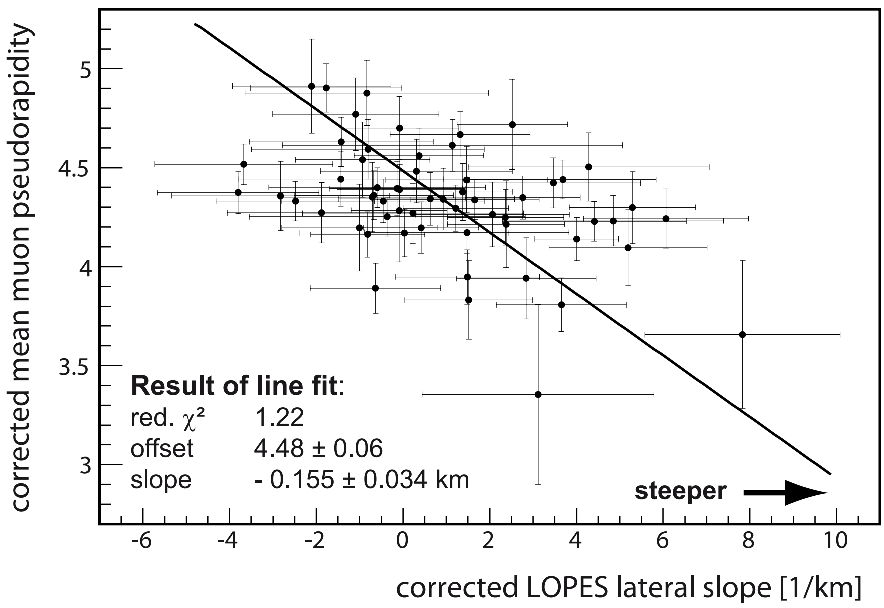

Figure 5: Correlation of the slope parameter of the radio-lateral distribution and the mean muon pseudorapidity after the corrections for the dependencies determined in Fig. 4.