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Update on radio detection of inclined air showers with LOPES-10

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Abstract: Inclined air showers are a particularly interesting target for observation with the radio technique. They are expected to be well detectable and allow analyses of angular correlations over a much broader range in geomagnetic angle than near-vertical events. We present an updated analysis of highly inclined ($> 50^\circ$ zenith angle), high energy ($N_\mu > 10^5$) air showers measured with LOPES-10 in coincidence with KASCADE-Grande. Data from the Grande rather than the KASCADE array are used for the reconstruction of the air shower events, giving us access to a broader range of core distances for an independent cross-check with the earlier analysis.

Introduction

It is a known fact that air showers generate radio waves while propagating through the atmosphere. Since the 1960s various mechanisms have been proposed. The last of them, dating back only to 2003, explains the radio emission from air showers as a coherent geosynchrotron emission due to the deflection of charged particles, electrons and positrons, in the Earth's magnetic field [1, 2]. In order to shed more light on the features of the radio emission and confirm dominant mechanisms responsible for the emission, we must investigate in detail correlations of the measured field strength with shower parameters. For this purpose we use the LOPES set-up, placed within the KASCADE-Grande array (KArlsruhe Shower Core and Array Detector and Grande array), which is a good tool to investigate shower radio emission in coincidence with shower parameters obtained from independent particle detectors in the energy range of $10^{16} - 10^{18}$ eV [3].

An air showers develops in the atmosphere and evolves due to multiple interactions. The electromagnetic component reaches a maximum high above the ground and afterwards decreases rapidly. Consequently, only a small number of electrons (comparing with the electron number at the shower maximum) reach the ground. But the number of electrons and positrons in the shower maximum is expected to be approximately proportional to the strength of the radio pulse detected by the antennas. Therefore, better knowledge of radio emission parameters may give extra information on shower development.

Also the radio detection technique is proposed as a tool for neutrino detection. High energy vertical neutrinos most likely pass through the Earth's atmosphere without any interaction, but as the zenith angle increases the probability that a neutrino may generate an electromagnetic shower increases. Radio emission can be observed for vertical, slightly inclined as well as highly inclined air showers with no principle limitations from the radio detection point of view. The antenna sensitivity poses much smaller problems when zenith angle increases in comparison with flat particle detectors for which the reconstruction becomes unreliable for zenith angles larger than $60°$.

Data analysis

For the present study we have analyzed data recorded in 2004 by LOPES-10 which consists of 10 East-West polarization antennas placed inside the KASCADE array. The LOPES-10 data sets have been submitted to several selections in order to investigate different aspects. For this work we have selected only inclined events, zenith angle $> 50°$, and high energy events, $N_\mu > 10^5$. By analyzing inclined events we are able to investigate angular correlations over a much broader geomagnetic angle than vertical or near-vertical events. The geomagnetic angle is the angle between the shower axis and Earth's magnetic field.

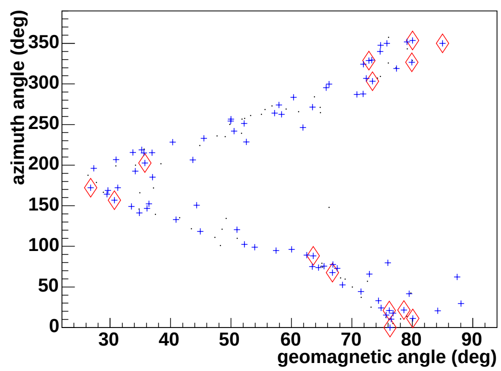

Figure 1: Azimuth angle as a function of geomagnetic angle for the 139 selected events with available radio data. Red rhombs - clear radio signal detected; blue crosses - reliable reconstruction with Grande, processed with optimized beam forming procedure; black dots - Grande reconstruction unreliable.

A previous work on inclined showers [4] has reported correlations between measured field strength and shower parameters considering data in coincidence with the KASCADE array which covers an area of 200x200 m^2. The LOPES-10 antennas are also situated inside the KASCADE array, therefore only close events were processed. Now we extend the study and investigate events in coincidence with Grande data, keeping the zenith angle and energy cuts. This gives us the opportunity to investigate distant events of up to 800 m from the LOPES antennas that have been detected by the Grande stations on an area of $\sim$0.5 km^2. For large showers triggering KASCADE with at least 10/16 clusters fired, data readout of both the LOPES antennas and the Grande array is triggered. In total, for 139 out of 149 selected high energy inclined events ($N_\mu > 10^5$ and zenith angle $> 50°$) with Grande data, radio data was recorded with the LOPES array. The following analysis is performed with these 139 events.

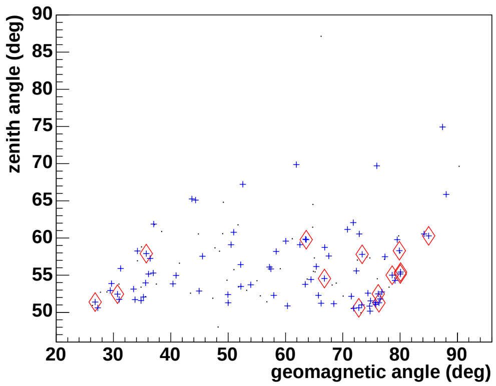

Figure 2: Zenith angle as a function of geomagnetic angle. Symbols are the same as in figure 1.

Because we use KASCADE-Grande data as a starting point in the digital beam-forming of radio data we have to establish which of the detected radio events have reliable reconstructed parameters (core coordinates, azimuth and zenith angles). Figure 1 shows the azimuth angle as a function of geomagnetic angle. Azimuth origin point ($0°$) is North. There are clear coherent events detected from North and South because the LOPES-10 antennas are more sensitive to the East-West polarization. For a shower coming from the East or West the emission is expected to be North-South polarized, therefore such a shower would not be detected with the LOPES-10 set-up. Also there are more events with azimuth angle corresponding to a northward direction than those coming from a southward direction. This effect is due to the fact that events coming from the North have larger geomagnetic angles, considering the orientation of the Northern Europe magnetic field.

Figure 2 shows the zenith angle as a function of geomagnetic angle for the same set of data as figure 1. Most detected events are in the range of $50° - 60°$. Above this limit, radio detection is possible but the shower parameters reconstruction becomes uncertain.

Optimized beam forming

The optimized beam forming procedure consists of varying the direction and core coordinates re-

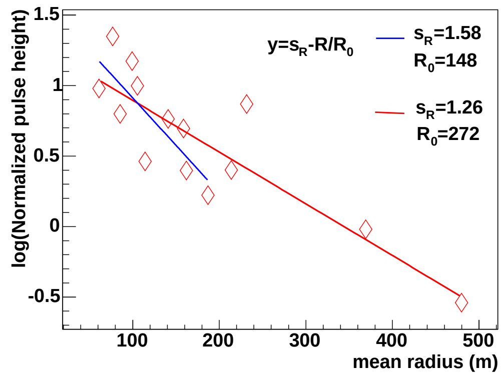

Figure 3: Dependence of radio pulse height (normalized by geomagnetic angle and muon number) on the mean distance from the shower axis to the antennas. The lines show results of a linear fit with a two parameter function: red line - parameter R_0=272 m, blue line - fit only for close events, mean distance$<$200 m, parameter R_0=148 m.

constructed for each event in the error range of Grande, $1.5°$ for the angle reconstruction and 20 m for the core coordinates reconstruction in order to improve beam parameters. All the events marked with blue crosses in figures 1 and 2 were submitted to the optimized beam forming procedure. For each of these events sets of 50 randomly varied parameters were generated in the Grande error range. For events with visible strong coherent signal the optimization lead to an important increase in the cross-correlation beam amplitude. For other 15 event the optimization improved the parameters only slightly, and did not clear the radio signal.

Correlations

The dependence of the radio pulse height on different parameters can be separated into: a dependence on the geomagnetic angle, a dependence on the distance to the shower axis and a dependence on the primary energy ($\sim$muon number) [5, 1, 2, 4]. To separate these parameters they are fitted separately in three iteration steps starting from the raw pulse height. In each fit the other dependencies are removed by dividing by the results of the fit from the previous iteration step. The correlations were made after optimized beam forming.

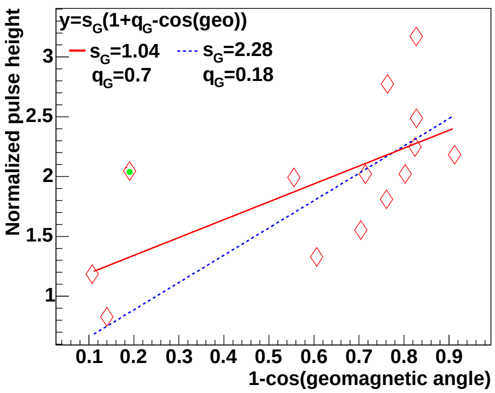

Figure 4: Dependence of the pulse height (normalized by muon number and distance) on the geomagnetic angle. Two linear fits were performed: red line - fit for all the clear radio events, blue dashed line without the event marked with the green dot. Parameters are shown in the plot.

Figure 3 shows the dependence of the pulse height, obtained after two iterations, corrected for muon number and geomagnetic angle, on the mean distance from the shower axis to the antenna set-up. There is a clear decrease with distance.

As shown in figure 4, there is a clear correlation of the pulse height, corrected for muon number and distance, with the geomagnetic angle which suggests that the emission is caused by the interaction of the shower with the Earth's magnetic field. The increase of the pulse height with geomagnetic angle supports the geosynchrotron theory. There is one event, marked with the green dot, which is still under investigation and therefore two fits were performed, one with the outlier and one without it.

Figure 5 shows a clear dependence of the pulse height, corrected for the geomagnetic angle and distance, on the muon number which is an approximate estimator of the primary particle energy. The dependence is fitted with a power law.

Conclusions

In this work we have extended previous studies of radio emission from inclined air showers to larger distances by analyzing LOPES-10 data in coincidence with data recorded by the Grande array of the KASCADE-Grande experiment. The predicted features, increase of the pulse height with the primary energy, decrease of the pulse height with distance and the geomagnetic influence are confirmed. In addition, the data proves that very inclined events can be detected in the radio domain at large distances showing the capabilities of the radio technique for measuring very inclined air showers.

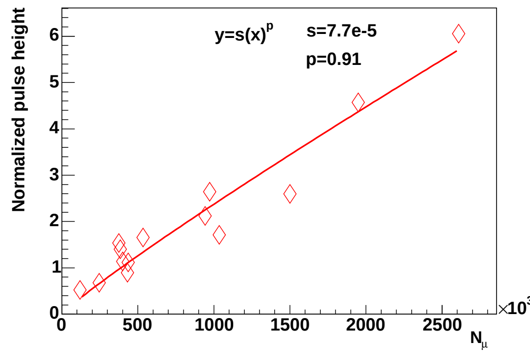

Figure 5: Dependence of the pulse height (normalized by geomagnetic angle and distance) on muon number, fitted with a power law.

Acknowledgements

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