Restoring Azimuthal Symmetry of Lateral Density Distributions of EAS Particles

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***Abstract.* The lateral distributions of EAS particles are affected by various kinds of azimuthal asymmetries, which arise from different effects: Geometric effects of mapping the horizontal plane observations onto the shower plane, different attenuation of particles on different sides of inclined EAS and the influence of the geomagnetic field on the particle movement. A procedure is described of minimizing the effects of azimuthal asymmetries of lateral density distributions. It is demonstrated and discussed in context of practical cases of data reconstruction by KASCADE-Grande.**

***Keywords*: Extensive air showers; lateral density distribution; azimuthal asymmetry**

I. Introduction

A crucial observable for the reconstruction and analysis of Extensive Air Showers (EAS) [1] is represented by the lateral distribution of the EAS particles evaluated in the intrinsic shower plane, hereafter called normal plane. In the case of ground arrays like KASCADE-Grande [2] this observable is obtained first by converting (by the use of appropriate Lateral Energy Correction Functions, LECF) the detector signals in particle densities evaluated in the horizontal plane. In a second step the density in the horizontal plane is mapped into the normal plane by applying specific projection techniques. Typically the detectors sample only a small fraction of the EAS particles; information concerning the complete distribution is obtained by using lateral distribution functions (LDFs) fitted to the measured data. The commonly used LDFs assume that the particle density possesses axial symmetry in the normal plane. This assumption greatly simplifies the problem of fitting the LDFs, but its validity should be investigated, especially in the case of arrays which only sample a limited part of the azimuthal dependence of the particle density. The bias is more important for inclined showers and in the case of observables evaluated far from the core, e.g. the density at 500 m, which can be used as an energy estimator [3]. In this context the purpose of this work is to study the asymmetry of the reconstructed particle density in the range of the KASCADE-Grande experiment and to propose practical methods to restore the symmetry in the intrinsic shower plane.

II. Basic origin of asymmetry

In the absence of the Earth's magnetic field the LDF of shower particles would possess symmetry around the shower axis. Consider an inclined shower and assume for the moment that shower evolution in the vicinity of the ground is negligible. Then in the simplified description of shower particles coming on the surface of a cylinder centered on the shower axis elementary geometrical effects would distort the LDF in the horizontal plane; a simple orthogonal projection of the observed densities

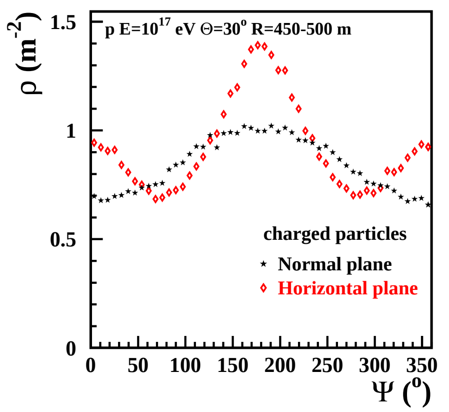

Fig. 1: Charged particle density in the horizontal plane (CORSIKA) and in the normal plane (by orthogonal projection). Coordinate system: $\Psi = 0°$ in the late region, $\Psi = 90°$ along the intersection of the horizontal plane with the normal plane.

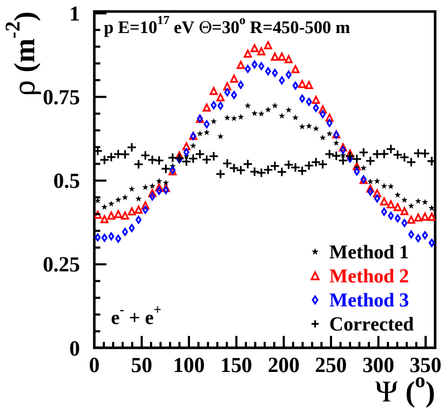

Fig. 2: Electron density reconstructed in the normal plane using the three projection methods, together with the density corrected as detailed in Section IV.

from the horizontal plane to the normal plane would restore the symmetry. If the shower particles would come on a surface of a cone, then the simple orthogonal projection would not completely restore the symmetry, because the particles would be projected outwards from the core with respect to their real trajectory in the region above the shower axis and towards the core in the opposite region. In the normal plane in a given radial bin the error of the reconstructed number of particles depends on the balance between the number of particles that are artificially projected into that bin and the number of particles that are artificially removed from the bin due to this imperfection of the orthogonal projection. As a result, close to the core, the reconstructed density in the region above the shower core is artificially decreased and it is artificially increased in the opposite region. Far from the core the effect is reversed.

In fact shower evolution should also be taken into account. Due to shower development, the particles hitting the ground below the shower axis (the early region) represent an earlier stage of shower development with respect to the shower particles coming above the shower axis (the late region). This evolution additionally distorts the symmetry around the shower core, for e.g. the particles from the late region have traveled longer paths than the particles from the early region and are more attenuated [4], [5], [6]. The magnetic field of the Earth, producing asymmetry also for vertical showers, is especially important when the densities of particles of opposite charge are compared [7], [8].

III. Projection in the intrinsic shower plane

In this work we analyzed proton and Fe induced showers with energy E=10^{17}, 1.78$\cdot 10^{17}$, 3.16$\cdot 10^{17}$ and 5.62$\cdot 10^{17}$ eV and incidence angle Θ=22, 30 and 45°; proton showers with an extended range of angles (Θ=22, 30, 45, 55 and 65°) were also studied for E=10^{15} eV. The showers were produced by CORSIKA version 6.01 [9] in the absence of the magnetic field of the Earth.

Clearly the simple model of shower particles coming on cylindrical surfaces with negligible shower development in the vicinity of ground is contradicted by shower simulations. Indeed, the orthogonal projection of the densities from the horizontal plane into the normal plane does not restore axial symmetry (Figure 1).

To investigate further the role played by the imperfection of the method of orthogonal projection (Method 1) and of the shower evolution we applied two other methods of mapping the particle impact point from the horizontal plane to the normal plane: projection along the particle momentum when it reaches the ground (Method 2) and a method based on triangulation using particle arrival time and assuming that the particles have been produced close to the shower axis (Method 3) [10]. Method 2 would be rigorous if the interactions in the space between the horizontal plane and the normal plane would be negligible, while Method 3 requires negligible interactions along the complete trajectory of the particle. The results demonstrate that shower evolution has an important contribution to the asymmetry of LDF, especially in the case of the electron component (Fig. 2). In the case of the muon component the three methods give almost similar results between each other and the amplitude of the early-late variation is smaller, e.g. it is 14% while for electrons it is 72% in the same conditions (Fig. 2).

IV. Correction function

Along the intersection of the horizontal plane with the normal plane ($\Psi = 90°$ and $\Psi = 270°$) the imperfections of the projection method have minimal effects; also shower development between the two planes is negligible. The density $\rho(r, \Psi)$ in the normal plane at other azimuth angles differs from the density $\rho_{ref}(r)$ at the same radial distance and $\Psi = 90°$ or $\Psi = 270°$ due to the imperfections of the projection method and to shower evolution. The magnitude of the effects should

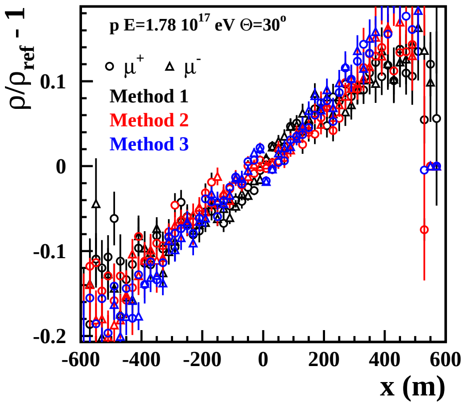

Fig. 3: The dependence of $\rho(r, \Psi)/\rho_{ref}(r) - 1$ on the distance x between the corresponding points in the normal and horizontal planes ($x > 0$ in the early region).

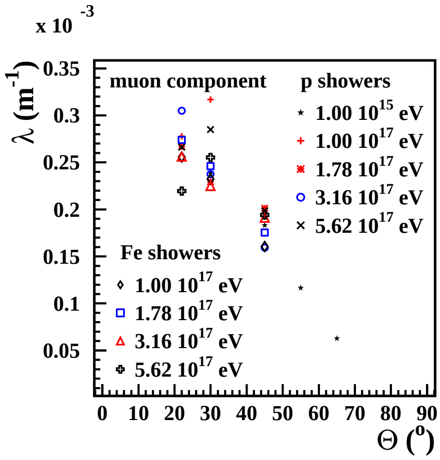

Fig. 5: Attenuation coefficient for the muon component. Note the scale difference between Fig. 4 and Fig. 5.

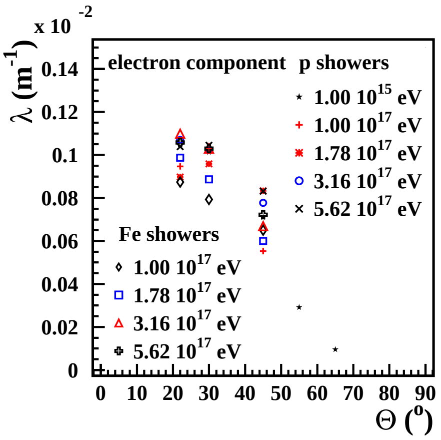

Fig. 4: Attenuation coefficient for the electron component

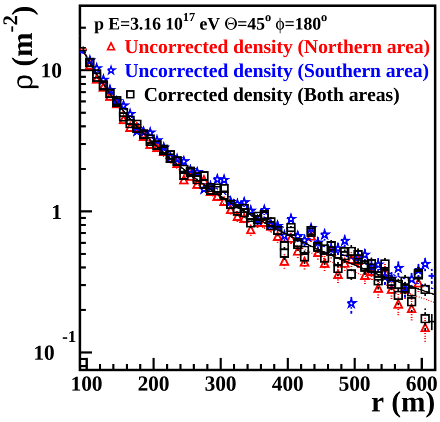

Fig. 6: Comparison of the reconstructed density in the case of showers with the core in the Northern area of Grande with the reconstructed density in the case of showers with the core in the Southern area of Grande

depend on the distance x between the corresponding points in the normal and horizontal planes. The dependence of the average density on x is approximated by an exponential function, $\exp(-\lambda x)$. In Fig. 3 this dependence is represented for the case of muons.

The values of λ incorporate both the attenuation by shower development and the distortions due to the projection method. The results show that λ depends mainly on the angle of the shower axis. The systematic dependence on the primary energy or composition is less obvious; certainly the sensitivity to these parameters is small. A more refined study [11], [12] shows that the imperfections of Method 1 induce a slight dependence of λ on the radial distance from the core: it decreases when the radial coordinate increases from 0 to about 200 m and then remains practically constant. In Figs. 4 and 5 this asymptotic value of λ in each set of simulated showers is represented for the case when Method 1 was applied for projection.

V. RESULTS

The application of the correction procedure greatly removes the asymmetry of lateral distribution (Fig. 2). In order to test the applicability to the KASCADE-Grande experiment, a proton induced shower with E=3.16 $\cdot 10^{17}$ eV, $\Theta = 45°$ incident from North, was repeatedly positioned with the core in various points in the Northern part of KASCADE-Grande, so that most of the Grande detectors were located in the late region of the shower development. The energy deposition in the detectors was realistically simulated, then the density in the observation plane was obtained by applying an appropriate LECF. The density in the normal plane was reconstructed using the Method 1 of projection. The same procedure was applied for a second set of results, obtained in the case when the same shower was repeatedly positioned with the core in various points in the Southern part of the KASCADE-Grande, so that now

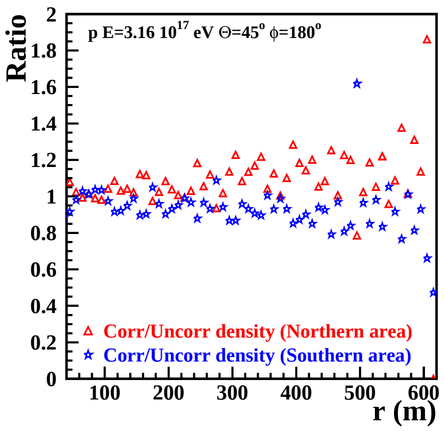

Fig. 7: The ratios of the corrected to the uncorrected densities (proton induced EAS)

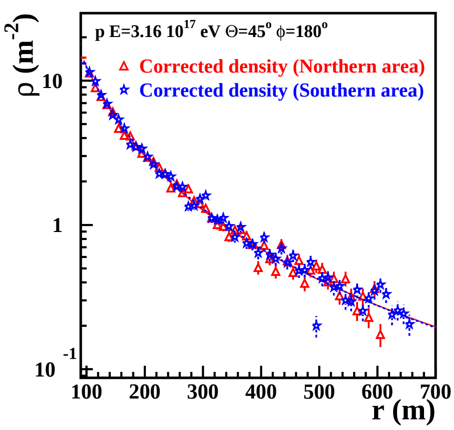

Fig. 8: Corrected lateral density distributions for p induced showers. Linsley fits of the density for showers with the core in the northern area (full line) and southern area (dashed line), respectively

most of the detectors were located in the early region. The reconstructed density in the case of the first set of showers is lower than the reconstructed density in the case of the second set of showers if no correction procedure is applied (Fig. 6).

As can be seen in Fig. 7 the corrections are important, especially at large radial distances. The difference between the mean density at 500 m in the two cases was 23% when the corrections were not applied and negligible when the corrections were applied [11]. After applying the correction method proposed the reconstructed density in the case of the set of showers with the core located in the Northern part of the Grande array does not differ significantly from the reconstructed density in the case of the set of showers with the core located in the Southern part of the array (Fig. 8).

Similar results were obtained in the case of a Fe shower with E=5.62 $\cdot 10^{17}$ eV, $\Theta = 45°$.

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