The electromagnetic component of inclined air showers at the Pierre Auger Observatory

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***Abstract*. Muons, accompanied by secondary electrons, dominate the characteristics of inclined air showers above $60°$. The characteristics of the signal induced by the electromagnetic component in the water-Cherenkov detectors of the Pierre Auger Observatory are studied using Monte Carlo simulations. The relative contributions of the electromagnetic component to the total signal in a detector are characterised as a function of the primary energy, for different assumptions about mass composition of the primary cosmic rays and for different hadronic models.**

***Keywords*: electromagnetic component, muonic component, Pierre Auger Observatory**

I. INTRODUCTION

Inclined air showers are conventionally defined as those arriving at ground with zenith angles θ above $60°$. At large zenith angles the electromagnetic (EM) component in air showers, mainly produced by the decay of π^0s, is largely absorbed in the vastly enhanced atmospheric depth crossed by the shower before reaching ground, so in a first approximation only the more penetrating particles such as muons survive to ground. Muons are accompanied by an EM component produced mainly by muon decay in flight and muon interactions such as bremsstrahlung, pair production and nuclear interactions, which amount to $\sim 20\%$ of the muonic component [1]. This is the so-called electromagnetic "halo".

The Surface Detector Array (SD) of the Pierre Auger Observatory [2] is well suited to detect very inclined showers at energies above about 5×10^{18} eV, with high efficiency and unprecedented statistical accuracy. The cosmic ray energy spectrum obtained with inclined events is given in these proceedings [3].

The distribution of the detector signals produced by shower particles is used to estimate shower observables such as the primary energy. The specific characteristics of inclined showers, such as the absorption of the EM component and the deviations suffered by muons in the geomagnetic field, entail that their analysis requires a different approach from the standard one for showers of $\theta < 60°$. The study of the signal distributions of the electromagnetic and muonic components at ground level becomes essential in the reconstruction [3], [4] and analysis of events at large angles.

In this work we have performed a comprehensive characterisation of the electromagnetic component with respect to the well-known behaviour of the muonic component. We have studied the ratio of the EM to muonic contributions to the signal in the water-Cherenkov detector as a function of several parameters. We have examined the effect of the shower evolution, shower geometry and geomagnetic field on the ratio. The dependences of this ratio on the primary energy, mass composition and hadronic model assumed in the simulations are addressed. The resulting parameterisations are used for the reconstruction of inclined events measured with the SD of the Pierre Auger Observatory [3].

The study described here is based on Monte Carlo simulations. A library of proton and iron-induced showers with energies from 10^{18} to 10^{20} eV, zenith angles between $60°$ and $88°$ and random azimuthal angle were generated with AIRES 2.6.0 [5] and the hadronic interaction models QGSJET01 [6] and Sibyll 2.1 [7]. The showers were simulated with and without geomagnetic field at the site of the SD of the Pierre Auger Observatory. The detector response is calculated here using a simple method based on parameterisations of the detector response to the passage of shower particles.

II. THE RATIO OF ELECTROMAGNETIC TO MUONIC DETECTOR SIGNALS

The electromagnetic and muonic particle components have a characteristic behaviour with distance to the shower axis, shower zenith angle and azimuth angle (ζ) of the detector position with respect to the incoming shower direction projected onto the plane transverse to the shower axis (shower plane). Also the different contributions to the electromagnetic component differ from each other as shown below. This is reflected by the ratio of the EM to muonic contributions to the detector signal

$$R_{\mathrm{EM}/\mu} = S_{\mathrm{EM}}/S_{\mu} \quad (1)$$

In Fig. 1, we show the average signal distributions of the EM and muonic components (left panel) and their corresponding ratio $R_{\mathrm{EM}/\mu}$ (right panel) as a function of the distance to the core r for different θ. Near the core, the ratio decreases with zenith angle from $\theta = 60°$ to $\sim 70°$ because the remnant of the EM shower due to

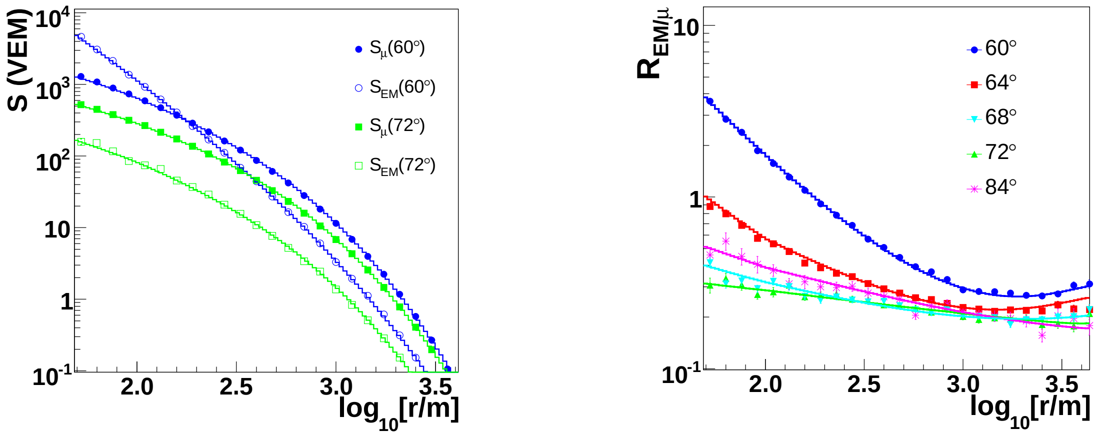

Fig. 1. Left plane: Lateral distribution of the electromagnetic and muonic contributions to the signal in the shower plane. Right panel: The ratio of the electromagnetic to muonic contributions to the detector signal as a function of the distance from the shower axis. Simulations were performed for 10 EeV proton showers at different zenith angles and in absence of geomagnetic field.

cascading processes (π^0 decay) is increasingly absorbed, until it practically disappears at $\theta \sim 70°$. Then the ratio increases again with θ, mainly due to muon hard interaction processes (bremsstrahlung, pair production and nuclear interactions) that are expected to dominate near the core in very inclined showers. Far from the core the lateral distribution of the ratio tends to flatten due to the dominant contribution of the EM halo produced by muon decay in flight. The larger the zenith angle, the ratio levels off closer to shower core. The slight increase of the ratio for $\theta \lesssim 68°$ and far from the core ($r \gtrsim 2$ km) is attributed to the combination of two effects, one is that the number of low energy muons decreases more rapidly at large distances because they decay before reaching the ground, and only energetic muons survive, and on the other hand the presence of the contribution to the EM component due to π^0 decay, particularly in the early region of the shower (the portion of the shower front that hits the ground before the shower axis).

A. Azimuthal asymmetry of the ratio $R_{\mathrm{EM}/\mu}$

There is an azimuthal asymmetry in the ratio of the EM to muonic contributions due to the combination of the geometrical and shower evolution effects [8]. As illustrated in the left panel of Fig. 2 shower particles do not travel parallel to the shower axis in general and therefore they cross different amounts of atmosphere depending on ζ. In particular, particles arrive at ground in the early region of the shower ($\zeta = 0°$) with a smaller local zenith angle than those in the late region ($\zeta = 180°$). This is essentially the basis for the geometrical effect. In inclined showers, the asymmetry induced by the geometrical effect is typically small and the main source of azimuthal asymmetry is the shower evolution effect which can be understood as follows. Particles at the same distance from the shower axis in the shower plane, but arriving with different ζ, travel along different paths and belong to different stages in the evolution of the shower. The importance of this effect depends on the depth-dependent evolution of the lateral particle distribution and on the attenuation of the total number of particles. The asymmetry induced by the shower evolution affects more the remnant of the EM shower than the muonic component or its associated EM halo. As a consequence, the shower evolution is expected to induce a negligible asymmetry in the ratio in showers with $\theta \gtrsim 70°$, because the EM remnant is practically suppressed, and the EM halo approximately has the same asymmetry than the muonic component.

To study further the azimutal dependence of the asymmetry we divide the shower plane in ζ bins, and we calculate the lateral distributions of the ratio in each bin for a fixed zenith angle: $R_{\mathrm{EM}/\mu}(r, \theta, \zeta)$, and we compare these distributions to the distribution obtained averaging over ζ: $\langle R_{em/\mu}\rangle(r, \theta)$. For this purpose we define the asymmetry parameter Δ_ζ as

$$R_{\mathrm{EM}/\mu}(r, \theta, \zeta) = \langle R_{\mathrm{EM}/\mu}\rangle(r, \theta) \times (1 + \Delta_\zeta) \quad (2)$$

In Fig. 2, we show the lateral distribution of $R_{\mathrm{EM}/\mu}$ in different ζ bins compared to the mean value (middle panel) and their corresponding asymmetry parameter Δ_ζ (right panel) for showers at $\theta = 60°$. $|\Delta_\zeta|$ increases with distance to the core and it is larger in the early region than in the late region as expected. Moreover, $|\Delta_\zeta|$ decreases as the zenith angle increases for the reasons explained above, becoming negligible for $\theta > 68°$. This plot illustrates the importance of accounting for the asymmetry in the ratio when dealing with inclined showers with $60° < \theta < 70°$.

B. Geomagnetic field effect on $R_{\mathrm{EM}/\mu}$

Muons in inclined showers travel along sufficiently long paths in the atmosphere to be affected by the Earth's magnetic field (GF). Positive and negative muons are deviated in opposite directions and as a consequence the muonic patterns in the shower plane are distorted in elliptical or even 2-lobed patterns [9], [10]. This

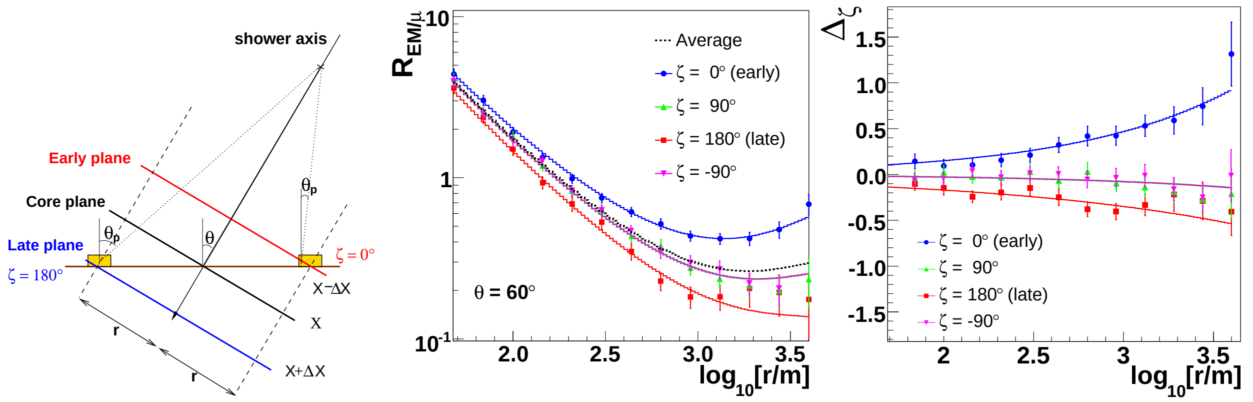

Fig. 2. Azimuthal asymmetry in the ratio $R_{\mathrm{EM}/\mu}$. Left panel: Schematic picture of an inclined shower reaching the ground. Middle panel: The ratio $R_{\mathrm{EM}/\mu}$ as a function of the distance from the shower axis in the shower plane in different bins of ζ for 10 EeV proton showers with $\theta = 60°$. Right panel: Asymmetry of the lateral distribution of the ratio $R_{\mathrm{EM}/\mu}$ in different ζ bins. The size of the bins is $\Delta\zeta = 30°$ centered at ζ.

effect on the muonic distributions is only significant for $\theta \geq 75°$. At these angles, the dominant contribution to the EM signal at ground is due to the EM halo, which inherits the muon spatial distribution and is proportional to the muonic signal distribution. For this reason, the ratio of the EM to muonic signals maintains the symmetry in the azimuthal angle ζ. However, the GF increases the $\langle R_{\mathrm{EM}/\mu}\rangle$ with respect to the value in its absence. The effect depends on the shower zenith (θ) and azimuth (ϕ) angles, and is more important near the core. After studying all these dependences, we have concluded that the effect on the ratio is important for showers at $\theta \gtrsim 86°$. It should be noted that the rate of events at such high zenith angles detected at ground level is small due to the reduced solid angle and the $\cos\theta$ factor needed to project the array area onto the shower plane. Very inclined events are also subject to other uncertainties [3] and we therefore choose to ignore them at this stage without losing much on statistical grounds.

C. Systematic uncertainties

The lateral distributions of the electromagnetic signal due to cascading processes and muonic signal exhibit a different behaviour as a function of the energy and of the depth of the shower maximum, while the contribution to the EM signal due to muon decay in flight mimics the energy dependence of the muonic one. Combining all the results, we expect $R_{\mathrm{EM}/\mu}$ to have a different behaviour depending on whether the EM remnant or the EM halo contributes more to the total signal. We study the energy dependence of $R_{\mathrm{EM}/\mu}$ performing the relative difference Δ_E between the ratio at a given energy with respect to that obtained for 10 EeV proton-induced showers, $\langle R_{\mathrm{EM}/\mu}\rangle$:

$$\Delta_E = \frac{R_{\mathrm{EM}/\mu}(E) - \langle R_{\mathrm{EM}/\mu}\rangle(10\mathrm{EeV})}{\langle R_{\mathrm{EM}/\mu}\rangle(10\mathrm{EeV})} \qquad (3)$$

The dependence of Δ_E on the zenith angle and distance from the shower axis is studied as in the example of Fig. 3 (left panel), where we plot Δ_E in different bins of r, as a function of the zenith angle for 1 EeV proton showers. We find that either for $\theta \gtrsim 68°$ at all the distances to the shower core or for distances beyond 1 km at all the zenith angles the ratio $R_{\mathrm{EM}/\mu}$ remains constant at the same level with energy because only the EM halo contributes to the EM signal. Otherwise, there is a dependence on energy that increases as the distance to the shower axis decreases, and therefore the dependences must be taken into account as systematic uncertainties. We obtain the same general result studying Δ_E for other shower energies.

At present, the chemical composition of the cosmic rays at the highest energies (> 1 EeV) remains unknown. For this reason we have studied the dependence of the ratio on the mass of the primary particle initiating the shower accounting for protons and iron nuclei in our simulations. Following the same procedure as in the case of the energy, we calculate the relative difference Δ_{mass} between the ratio in iron-induced showers at 10 EeV with respect to that obtained for 10 EeV proton shower simulations:

$$\Delta_{\mathrm{mass}} = \frac{R_{\mathrm{EM}/\mu}(\mathrm{Fe}) - \langle R_{\mathrm{EM}/\mu}\rangle(\mathrm{p})}{\langle R_{\mathrm{EM}/\mu}\rangle(\mathrm{p})} \qquad (4)$$

For reasons very similar to those that explain the energy dependence studied before, we conclude that either for $\theta \gtrsim 68°$ at all the distances to the shower core or for distances beyond 1 km at all θ the ratio $R_{\mathrm{EM}/\mu}$ remains constant at the same level with primary mass as shown in Fig. 3 (middle panel).

At the highest energies, there is lack of knowledge about the hadronic interactions which determine the shower development of MC simulations [11]. This fact leads to discrepancies between the different hadronic models on predictions such as the densities of the EM and muonic components at ground.

In this work, we compare two high energy interaction models widely used in cosmic ray physics: QGSJET01

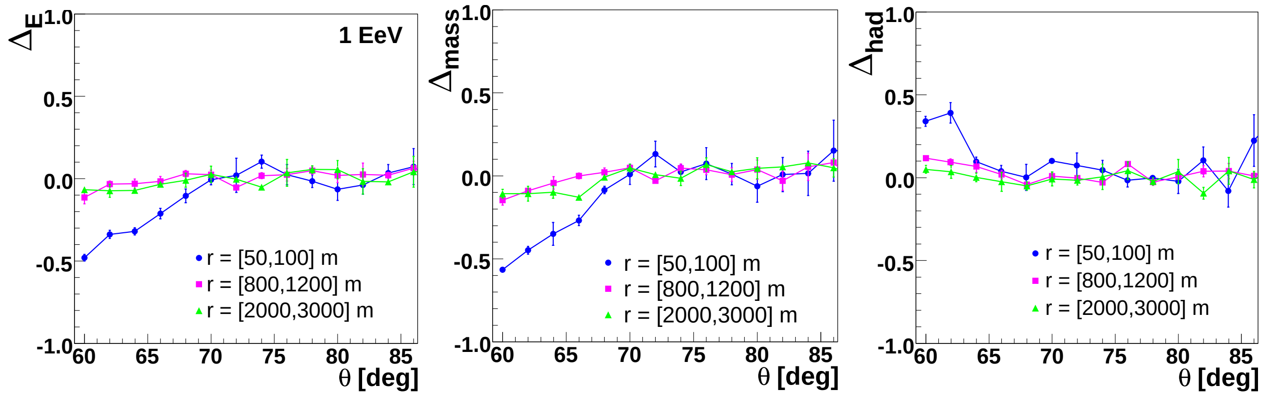

Fig. 3. Left plane: The relative difference $\Delta_{\rm E}$ between the ratio $R_{{\rm EM}/\mu}$ obtained in 1 EeV proton-induced showers with respect to the reference ratio $\langle R_{{\rm EM}/\mu}\rangle$ obtained in 10 EeV proton-induced showers simulated with QGSJET01 (Eq. 3). Middle panel: The relative difference $\Delta_{\rm mass}$ between the ratio $R_{{\rm EM}/\mu}$ obtained in 10 EeV iron-induced showers simulations with respect to $\langle R_{{\rm EM}/\mu}\rangle$ (Eq. 4). Right panel: The relative difference $\Delta_{\rm had}$ between the ratio $R_{{\rm EM}/\mu}$ obtained in 10 EeV proton-induced showers simulated with Sibyll 2.1 with respect to $\langle R_{{\rm EM}/\mu}\rangle$ (Eq. 5). The relative differences are shown as a function of the shower zenith angle in different bins of distance to the shower axis r.

and Sibyll 2.1. For proton primaries at 10 EeV, the QGSJET model predicts showers that on average develop higher in the atmosphere and have 40% more muons than showers simulated with Sibyll.

We calculate the relative difference $\Delta_{\rm had}$ between the ratio for 10 EeV proton showers simulated with Sibyll 2.1 with respect that obtained in showers simulated with QGSJET01:

$$\Delta_{\rm had} = \frac{R_{{\rm EM}/\mu}({\rm Sibyll}) - \langle R_{{\rm EM}/\mu}\rangle({\rm QGSJET})}{\langle R_{{\rm EM}/\mu}\rangle({\rm QGSJET})} \quad (5)$$

In Fig. 3 (right panel) we show $\Delta_{\rm had}$ as a function of the zenith angle in different bins of r. The differences between both models are more apparent near the shower axis as expected from the dominance of the EM component due to cascading processes near the core. We obtain a similar result to the case of energy and mass dependences, which is that either for $\theta \gtrsim 64^\circ$ at all the distances to the shower axis or for distances beyond 1 km at all zenith angles the ratio $R_{{\rm EM}/\mu}$ remains constant at the same level independently of the model used.

III. Conclusions

We have characterised the signal distributions of the electromagnetic and muonic components of inclined showers at the ground level on the shower plane [12]. We have accounted for the different sources of azimuthal asymmetry and the effect of the geomagnetic field. As a result, we have obtained a parameterisation of the ratio $S_{\rm EM}/S_\mu$ as a function of the shower zenith angle and the detector position that is used in the reconstruction of inclined events measured with the Surface Detector Array of the Pierre Auger Observatory.

We have studied the dependence of this ratio with the primary energy, mass composition and the hadronic interaction model used in the simulations. The general result is that either for zenith angles exceeding $\theta \gtrsim 68^\circ$ or for distances to the shower core beyond 1 km at all the zenith angles $> 60^\circ$, the ratio remains constant because only the electromagnetic halo contributes to the EM signal. Otherwise, the dependences are important and must be taken into account as systematic uncertainties within the event reconstruction.

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