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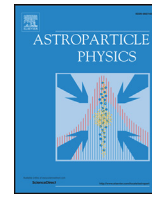

A new observable in extensive air showers

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ABSTRACT

We find that the ratio $r_{\mu e}$ of the muon to the electromagnetic component of an extended air shower at the ground level provides an indirect measure of the depth $X_{\max}$ of the shower maximum. This result, obtained with the air-shower code AIRES, is independent of the hadronic model used in the simulation. We show that the value of $r_{\mu e}$ in a particular shower discriminates its proton or iron nature with a 98% efficiency. We also show that the eventual production of *forward* heavy quarks inside the shower may introduce anomalous values of $r_{\mu e}$ in isolated events.

1. Introduction

Ultrahigh energy comic rays (CRs) enter the atmosphere with energies above 10^9 GeV = 1 EeV. The precise determination of their composition, direction of arrival and energy provides valuable information about their astrophysical sources and about the medium that they have traveled through on their way to the Earth. In addition, their collisions with air nuclei probe QCD in a regime never tested at colliders. The center of mass energy $\sqrt{2Em_N}$ when the primary CR or the leading hadron inside an extensive air shower (EAS) hits an atmospheric nucleon is 14 TeV for $E = 10^8$ GeV, the nominal energy at the LHC. Beyond that point collisions occur in uncharted territory.

The complementarity between air-shower and collider observations does not refer only to the energy involved in the collisions, but also to the kinematic regions that are accessible in each type of experiments. At colliders the detectors capable of particle identification do not cover the ultraforward region, too close to the beampipe. This region includes the *spectator* degrees of freedom in the projectile, which carry a large fraction of the incident energy after the collision. It turns out that the details there can be relevant to the longitudinal development of EASs. The production of forward heavy hadrons [1], for example, is a possibility frequently entertained in the literature that is difficult to test at colliders [2].

Air-shower observatories with surface detectors able to separate the muon from the electromagnetic (EM) signals, like the Pierre Auger Observatory [3] will after its projected upgrade [4], offer new oportunities in the characterization of EASs. In this paper we show that the ratio of these two signals at the ground level defines a model-independent observable very strongly correlated with the atmospheric slant depth of the shower maximum and sensitive to possible anomalies introduced by forward heavy quarks.

2. Muons versus electrons in the atmosphere

An EAS can be understood as the addition of a very energetic (*leading*) baryon defining the core of the shower plus lower energy pions produced in each collision of this baryon in the air. After just four interaction lengths (around 300 g/cm^2) 99% of the initial energy has already been transferred to pions. Neutral pions will decay almost instantly into photon pairs, generating the EM component of the shower, whereas most charged pions of $E_{\pi^\pm} \geq 100$ GeV will hit an air nucleus giving softer pions. Although in hadronic collisions the three pion species are created with similar frequency, the high-energy $\pi^\pm$s are a source of π^0s but not the other way around. As a result, most of the energy in the EAS will be processed through photons and electrons instead of muons and neutrinos.

At large atmospheric depths the number and the spectrum of each component in the shower are determined by its very different propagation through the air. While electrons and photons basically double their number and halve their energy every 37 g/cm^2, muons lose just a small fraction of energy through ionization, bremsstrahlung and pair production as they cross the whole atmosphere. Most muons created with $E_\mu > 3$ GeV inside the EAS reach the ground. As a consequence, at the depth $X_{\max}$ of the shower maximum electrons dominate over muons 100 to 1, but in inclined showers of zenith angle $\theta \geq 60^\circ$ the dominant signal at

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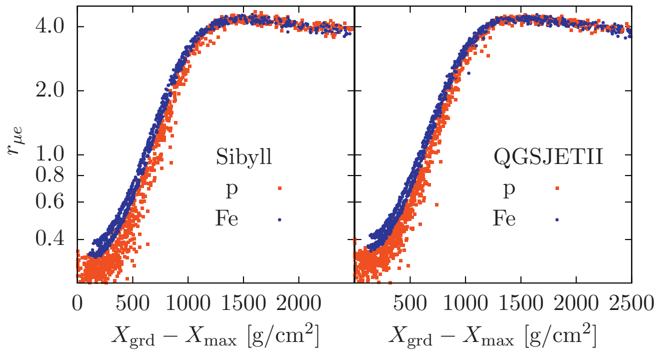

Fig. 1. $r_{\mu e} = \frac{n_\mu}{E_{em}/(0.5\ \text{GeV})}$ versus $X_{grd} - X_{max}$ for proton and iron showers of 10 and 50 EeV (500 events of each type) simulated with AIRES using SIBYLL21 (left) and QGSjetII-04 (right). The ground is at 1400 m of altitude, and we have taken only the particles at transverse distances larger than 200 m from the shower axis.

the ground level is provided by muons. To understand this signal, two observations are in order.

1. In inclined events the EM component at the ground level does not go to zero. Although any EM energy deposition high in the atmosphere will be exponentially attenuated by the air, there is a continuous production of photons by high-energy muons: muons do not come alone but together with an EM *cloud* that is proportional to their number.
2. While the position of X_{max} is dictated by the inelasticity in the first interactions of the leading hadron and can vary by 200 g/cm^2 among events with identical primaries, we expect that the evolution beyond the shower maximum is much less *fluctuating*. In particular, the ratio of the muon to the EM component should depend very mildly on the energy or the nature of the CR primary.

Fig. 1 fully confirms these two points. We have used the Monte Carlo code AIRES [5] to simulate 2000 showers of mixed composition (50% proton and 50% iron), different energy (50% 10 EeV and 50% 50 EeV) and random inclination up to 75°. We have assumed a ground altitude of 1400 m, typical in EAS observatories. The minimum kinetic energy of muons, electrons and photons in our simulation is 70 MeV, 90 keV and 90 keV, respectively. In the figure we plot the ratio $r_{\mu e}$ between the number of muons and the EM energy (photons plus electrons) divided by 500 MeV at ground level in terms of the distance (slant depth) from the ground to the shower maximum, $X_{grd} - X_{max}$. In our analysis we do not include the particles at transverse distances from the shower core less than 200 m, as they tend to saturate the detectors even in inclined events. The depth $X_{grd}(\theta)$ varies between 800 and 3000 g/cm^2 depending on the inclination of each shower, whereas X_{max} takes typical values between 700 and 900 g/cm^2. We observe that $r_{\mu e}$ is a shower observable with relatively small dispersion with the energy and the nature of the primary that, for zenith angles below 60°, could be used as an indirect measure of X_{max}. For values between 0.5 and 3 it can be approximated by the function

$$r_{\mu e} \approx A\, e^{B\,(X_{grd} - X_{max})}\,, \tag{1}$$

whereas at higher inclinations $r_{\mu e} \approx C$ does not depend on the energy nor the composition of the CR primary. In Fig. 1 we have used the hadronic models SIBYLL21 [6] and QGSjetII-04 [7]; it is most remarkable that this observable is clearly independent from the hadronic model that we used in the simulation.

The analysis of the longitudinal development of EASs by a number of authors [9–14] shows that the evolution with the atmospheric depth of the EM and the muon components of the shower

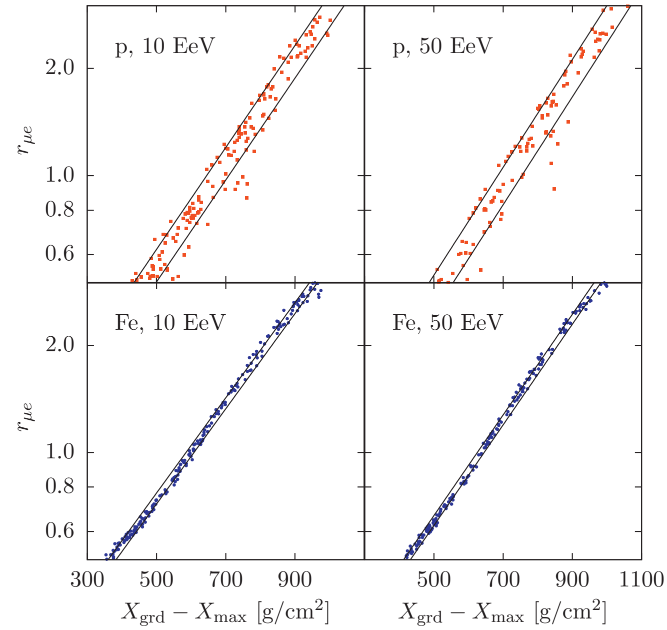

Fig. 2. Correlation between $r_{\mu e}$ and $X_{grd} - X_{max}$ for $0.5 < r_{\mu e} < 3$ and different CR primaries obtained with SIBYLL21.

can be understood numerically or with approximate analytical expressions. The average number of muons and of electrons, however, have large fluctuations from shower to shower and also a strong dependence on the hadronic model assumed in each analysis. Our result in Figs. 1 and 2 reflect, basically, that the fluctuations in the two components of the shower are correlated, so that the ratio $r_{\mu e}$ is more stable than the two quantities that define it. We will show that this stability can be used to discriminate very efficiently the nature of a CR primary.

3. Composition analyses

In Fig. 2 we plot the correlation between $r_{\mu e}$ and $X_{grd} - X_{max}$ for $0.5 < r_{\mu e} < 3$ and different primaries. These values of $r_{\mu e}$ include zenith inclinations $33° < \theta < 63°$. For example, a fit with Eq. (1) for 50 EeV iron primaries gives (see Fig. 2)

$$A = 0.126 \qquad B = 3.25 \times 10^{-3}\ \text{cm}^2/\text{g}\,, \tag{2}$$

with a dispersion (one standard deviation)

$$\frac{\Delta r_{\mu e}}{r_{\mu e}} \approx 0.032\,. \tag{3}$$

The correlation between $r_{\mu e}$ and the shower maximum is then

$$X_{max}^{\mu e} = X_{grd} - \frac{\ln\left(r_{\mu e}/A\right)}{B} \pm \frac{\Delta r_{\mu e}/r_{\mu e}}{B}\,, \tag{4}$$

where the superscript indicates that X_{max} has been deduced from $r_{\mu e}$ and the uncertainty, around 10 g/cm^2, corresponds to one standard deviation. Notice that this uncertainty reflects only the dispersion in the correlation deduced from our simulation, it does not include the experimental error in the determination of $r_{\mu e}$. For a 50 EeV proton shower the value of $X_{max}^{\mu e}$ obtained this way would have a larger uncertainty: our simulation gives $(A,\ B,\ \Delta r_{\mu e}/r_{\mu e}) = (0.081,\ 0.0035\,\text{cm}^2/\text{g},\ 0.12)$, implying a $\pm$ 34 g/cm^2 dispersion.

Let us discuss with a particular example how $r_{\mu e}$ may be used in composition analyses. We simulate a 50 EeV shower of random inclination and unknown proton or iron composition and obtain $r_{\mu e} = 0.648$ and $X_{grd} = 1367$ g/cm^2 $(\theta = 50.2°)$. From Eq. (4) and