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.

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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 $\theta \geq 60°$ the dominant signal at

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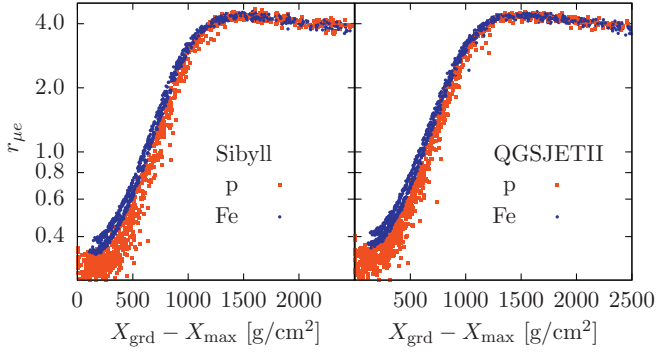
Fig. 1. $r_{\mu e} = \frac{n_\mu}{E_{em}/(0.5\,\text{GeV})}$ versus $X_{grd} - X_{max}$ for proton and iron showers of 10 and 50 EeV (500 events of each type) simulated with AIRES using SIBYLL21 (left) and QGSjetII-04 (right). The ground is at 1400 m of altitude, and we have taken only the particles 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
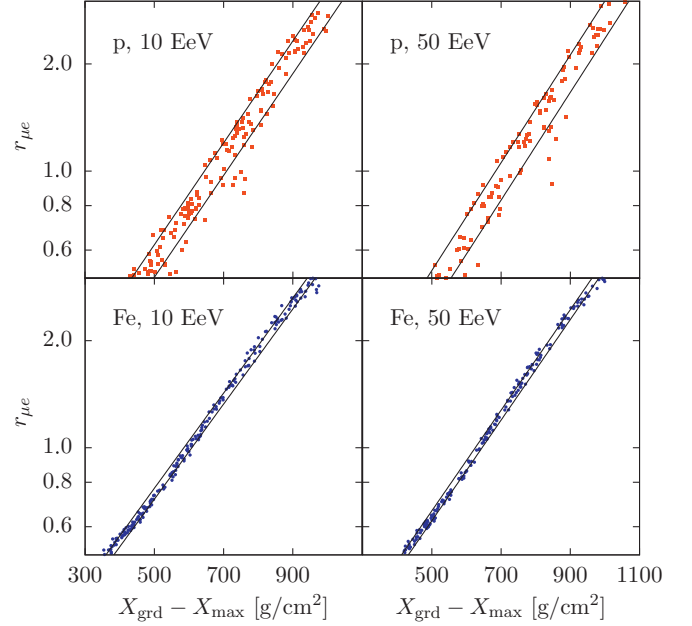
Fig. 2. Correlation between $r_{\mu e}$ and $X_{grd} - X_{max}$ for $0.5 < r_{\mu e} < 3$ and different CR primaries obtained with SIBYLL21.

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 ± 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

this value of $r_{\mu e}$ we know that if the primary were an iron nucleus the shower maximum would be at $X_{\max}^{\mu e} = 863 \pm 10$ g/cm^2, whereas if it corresponded to a proton it should be at $X_{\max}^{\mu e} = 773 \pm 34$ g/cm^2. The average values of $X_{\max}$ and $\Delta X_{\max}$ in 50 EeV showers are

Fe : $X_{\max} = 742$ g/cm^2, $\Delta X_{\max} = 18$ g/cm^2

H : $X_{\max} = 838$ g/cm^2, $\Delta X_{\max} = 52$ g/cm^2. (5)

Adding the uncertainties in quadrature we see that (863 ± 10) g/cm^2 is 5.8σ away from iron $[(742 \pm 18)$ g/cm$^2]$, while (773 ± 34) g/cm^2 is just -1.0σ away from proton $[(838 \pm 52)$ g/cm$^2]$. This clearly reveals the proton nature of the shower.

The actual value of $X_{\max}$ in the previous event was 774 g/cm^2. If measured with some fluorescence detectors, $X_{\max}$ would also signal the proton nature of the primary: it is 1.7σ away from iron and just -1.2σ from proton. However, the statistical significance would have been much lower than the one obtained from $X_{\max}^{\mu e}$. Applying the discriminant deduced from $r_{\mu e}$ to the 290 events in Fig. 2 (50 EeV events with $r_{\mu e}$ between 0.5 and 3) we find that it gives the right answer in 284 of them (98%), while $X_{\max}$ indicates the true proton or iron nature in 262 events (92%). Notice that two events with similar values of $r_{\mu e}$ and $(X_{\text{grd}} - X_{\max})$ may have quite different inclination (i.e., different X_{grd}), especially if their composition is different. As a consequence, the value of $X_{\max}^{\mu e}$ deduced from $r_{\mu e}$ depends on whether the primary is a proton or an iron nucleus, *separating* both possibilities from each other further than the direct observation of $X_{\max}$. Of course, there could be an experimental error in $r_{\mu e}$ (measured at the surface detectors) larger than the one in $X_{\max}$ (at the fluorescence detectors), but the use of this observable in composition analyses [8] seems very promising.

Notice also that in our previous analysis we have assumed a given value for the energy of the EAS. The shower energy could in principle be deduced from other observables, like the total signal at the surface detectors, its lateral distribution, etc. If a particular observatory is able to determine $E \pm \Delta E$ with a certain precision, then the correlation between $r_{\mu e}$ and $X_{\max}$ (the specific values of A and B for this event) should be established from a fit of showers within the same energy interval. As for the range of distances to the shower axis to be included in the definition of $r_{\mu e}$ (we have taken all transverse distances beyond 200 m), the optimal one should be decided after a simulation of the surface detectors in the particular observatory.

4. Forward charm and bottom hadrons

Our results above show that, while the position of $X_{\max}$ may have large fluctuations related to the inelasticity in the first few interactions of the leading hadron, the longitudinal evolution of an EAS from that point to the ground is very stable, and the ratio $r_{\mu e}$ appears always strongly correlated with $X_{\text{grd}} - X_{\max}$. The obvious question would then concern the possibility to break this correlation: what physical process could explain an anomalous value of $r_{\mu e}$?

As we have mentioned before, the production of forward heavy hadrons carrying a large fraction of the incident energy is a possibility often discussed in the literature. Analogous processes $(p \to K^+ \Lambda)$ [15] have been observed for strange particles. Indeed, the asymmetry detected in charm production at large Feynman x [16] indicates a soft contribution that may be explained with an *intrinsic charm* hypothesis [1,2] or through the *coalescence* of perturbative charm with the valence quarks present in the projectile [17,18] (this has also been the approach in SIBYLL 2.3 [19]).

Charm or bottom hadrons produced inside an EAS with energy above 10^9 GeV would be long lived (their decay length becomes larger than 100 km) and very penetrating: a D or a B meson would keep 60% [20] or 80% [21] of its energy in each collision with the

air, respectively. One of these mesons could experience 10 (D) to 20 (B) collisions before its energy has been reduced to $\approx 10^7$ GeV and it decays. It would be a small fraction of the total energy in the shower, but if the deposition takes place near the ground it may reduce significantly the value of $r_{\mu e}$. This observable could then open new possibilities in the search for heavy quark effects in EASs [22].

We have used AIRES [5] for a first look at this issue. Although AIRES includes the production of *central* (perturbative) heavy hadrons as well as their propagation in the atmosphere [23], we find that these hadrons do not carry enough energy to have any influence on $r_{\mu e}$. Therefore, we have simulated events where the leading hadron may create a forward charmed or bottom hadron that takes a large fraction of its energy (to be definite, we have used the x distribution in [24]). We have run events with 10 and 50 EeV of energy, arbitrary inclination and a proton or iron primary (in the second case the heavy hadron will take a fraction of the energy per nucleon in the projectile). Although the average value of $r_{\mu e}$ is not changed significantly by the forward heavy hadrons, we are able to identify two types of isolated events that are clearly anomalous.

- The first anomaly may appear in proton showers when the leading hadron creates a B meson or a Λ_b baryon of energy above 1 EeV. These hadrons are then able to penetrate very deep in the atmosphere and decay near the ground, starting a *minishower* of 10^6–10^8 GeV that reduces the value of $r_{\mu e}$. The anomaly only appears in showers with $50° < \theta < 60°$: at lower zenith angles the relative effect of the minishower is too small (the attenuation of the rest of the shower at the ground level is insufficient), whereas in showers with a larger inclination the heavy hadron tends to decay too far from the ground. We find events where the actual $X_{\max}$ is 400 g/cm^2 smaller than the depth $X_{\max}^{\mu e}$ deduced from $r_{\mu e}$, a 12σ deviation.
- The second anomaly is an indirect effect of the heavy quarks: it appears in very inclined EASs when a muon of $E_\mu \geq 10^7$ GeV experiences a relatively hard radiative process (bremsstrahlung or pair production) near the ground. At such high energies pions and kaons are very long lived, and the main source of muons is the decay of charm and bottom hadrons (see [25] for other sources of atmospheric muons). We find that the effect may only appear at zenith angles $\theta > 65°$. These inclinations favor the decay of the heavy hadrons high in the atmosphere, before they lose energy. We identify events where a high-energy muon crosses 2000–3000 g/cm^2 of air and deposits 10^6–10^7 GeV at 100–500 g/cm^2 from the ground, changing the muon-to-EM ratio $r_{\mu e}$ from the asymptotic value $C \approx 4$ to a value around 1. Since the muon comes from a forward heavy hadron, in these events the anomaly is larger near the shower core, and it disappears as we increase the lateral distance.

5. Summary and discussion

The possibility to separate the muon and the EM components in the surface detectors at CR observatories seems essential both to fully characterize the shower and also to *tune* the Monte Carlo codes used to simulate ultrahigh-energy events. Here we have discussed a new observable, the ratio $r_{\mu e}$ between the two components, that correlates with $X_{\max}$ with an uncertainty of around ± 10 g/cm^2 for iron nuclei or ± 40 g/cm^2 for protons. A precise analysis of the spectrum and the composition of ultrahigh energy CRs relies very strongly on simulations, and this observable could provide a crucial consistency check. In particular, it could give a surprisingly effective discriminant in composition analyses.

One important issue currently being discussed [26] is the possible under-prediction of the muon signal by basically all hadronic simulators. This would suggest a correction towards a higher multiplicity in hadron collisions: a larger number of less energetic pions inside the shower implies a stronger muon signal (number of muons) with the same EM signal (energy in electrons and photons). Obviously, if the *muon problem* is confirmed after the upgrade of the Auger observatory and the hadronic models are modified, their prediction for $r_{\mu e}$ will change accordingly. The analysis with the *wrong* simulators presented here would then be biased, and our determination of $X_{\max}$ from $r_{\mu e}$ would have a *systematic* error. The only way to identify and correct this bias would be to compare $X_{\max}^{\mu e}$ with the $X_{\max}$ provided by the fluorescence detectors in hybrid events. It is then interesting that such comparison can be used to quantify the suspected muon problem of current simulations.

Our analyses based on SIBYLL and QGSjetII show that the relation between $X_{\max}$ and $r_{\mu e}$ is very stable and model independent. It is crucial that we compare showers at the same distance depth from the maximum (*i.e.*, same value of $X_{\mathrm{grd}} - X_{\max}$), which minimizes the shower to shower fluctuations. Our results also reflect that the fluctuations and the model dependencies in the muon and the EM components of a shower are correlated, *i.e.*, if $r_{\mu e} = x/y$ with $x = n_\mu$ and $y = E_{\mathrm{em}}/(0.5\ \mathrm{GeV})$, then $\Delta r_{\mu e} \ll \sqrt{(\Delta x/y)^2 + (\Delta y\, x/y^2)^2}$.

We have argued that only the production of very energetic *forward* heavy hadrons could introduce anomalies. In particular, we have identified reductions in the value of $r_{\mu e}$ caused *(i)* by the decay of these hadrons deep in the atmosphere in proton showers of intermediate inclination ($50° < \theta < 60°$), and *(ii)* by stochastic energy depositions near the ground coming from very energetic muons in inclined showers ($\theta > 65°$). These muons would be created high in the atmosphere through semileptonic decays of charm and bottom hadrons. Therefore, we conclude that $r_{\mu e}$ may be a key observable to characterize EASs, determine the nature of the CR primary, and even in the search for the elusive forward heavy hadrons.

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