SF2A 2014
J. Ballet, F. Bournaud, F. Martins, R. Monier and C. Reylé (eds)

THE MASS COMPOSITION OF ULTRA-HIGH ENERGY COSMIC RAYS WITH THE PIERRE AUGER OBSERVATORY

D. Martraire[1] and the Pierre Auger Collaboration[2]

Abstract. Ultra-high energy cosmic rays are the most energetic particles known in nature. The Pierre Auger Observatory was built to study these amazing particles to determine their origin. The study of their mass composition can help to constrain the models concerning their origins and their production mechanisms in the astrophysical sources. To this aim, several methods have been developed to infer the composition using the Auger surface detector array data. The main difficulty is to isolate the muonic component in the signal measured by the surface detector. We present the results of the composition parameters derived from the ground level component and compare them to the predictions for different nuclear masses of the primary particles and hadronic interaction models.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, composition, muons, hadronic interaction models

1 Introduction

The composition of the UHECRs (Ultra High Energy Cosmic Rays) is one of the challenging questions. Improving our knowledge about the composition of cosmic rays allows us to constrain the models concerning their origins and their production mechanisms in the astrophysical sources.

When a cosmic-ray particle reaches Earth, it collides with a nucleus high in the atmosphere, producing many secondary particles, which share the energy of the original primary particle. The secondary particles subsequently collide with other nuclei in the atmosphere, creating a new generation of energetic particles that continue the process. The resulting particle cascade, called an extensive air shower, arrives at ground level with billions of hadrons and electromagnetic (EM) particles extending over tens of km^2.

The Pierre Auger Observatory, located on the Pampa Amarilla at 1400 m a.s.l., is the largest cosmic-ray observatory ever built. Its hybrid design allows us to collect the shower particles with a surface detector array (SD) and to observe the longitudinal development of EM profiles by collecting the UV light with the fluorescence detector (FD). The SD consists of 1660 water Cherenkov detectors in a 1.5 km triangular grid over 3000 km^2, whereas the FD is composed of 24 telescopes distributed over four sites overlooking the array. More details on the observatory can be found in Abraham et al. (2004); Allekotte et al. (2008); Abraham et al. (2010).

One way to determine the mass is to study the longitudinal development of the electromagnetic component of a shower. The depth of the shower maximum, X_{max}, is sensitive to the primary particle (Baltrusaitis et al. 1998). However X_{max} measurements suffer from low statistics due to the duty cycle of only 13% of the fluorescence detector and the cuts imposed to avoid a biased datasets (de Souza 2013).

The Pierre Auger Collaboration has proposed different methods to assess the muon content of the extensive air shower taking advantage of the large statistical sample provided by the almost 100% duty cycle of the surface detector array. Estimating the muon content in atmospheric showers was recognized a long time ago as an essential tool for primary identification, and the Auger surface detector array was designed to have an enhanced sensitivity to muons compared to photons and electrons. However the signals due to the muonic and electromagnetic components overlap, and it is not straightforward to measure them separately.

---

[1] Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3, Orsay, France

[2] Pierre Auger Observatory, Av. San Martín Norte 304, 5613 Malargüe, Argentina
(Full author list: `http://www.auger.org/archive/authors_2014_06.html`)

When a charged particle of sufficient energy passes through the water in a SD station, it produces Cherenkov photons. After a few reflections on the liner enclosing the water, their distribution is isotropized. Their distribution is sampled by the FADCs from three photomultiplier tubes at the top of the detector. The observed signal is proportional to the geometric path of the particle in water, and therefore there is not a difference between signals produced by muons compared to those produced by electrons or positrons. The main difference between incident EM particles and muons is their energy spectrum. Usually, the muons have enough energy to go through the detector and give a signal of the order of 1 Vertical Equivalent Muon (VEM) or more if they are inclined. On the contrary, most of electromagnetic particles have an energy below a few tens of MeV, and generally they deposit their whole energy within the water, giving a signal well below 1 VEM. However, the muons are much less abundant, so that their contribution is overlapped by the tail of the EM component.

The techniques developed by the Auger Collaboration are based on the time profile and spectral characteristics of the Cherenkov light signal generated by shower particles in the water of the detectors. The main difficulty is to identify the muonic component overlaped by the EM one. We present two types of methods: the analysis of the muon fraction with the temporal structure of the SD signals in vertical showers and the analysis of the muon content in inclined showers.

2 Muon fraction from the temporal structure of the SD signals

The number of muons can be used as an observable to study the composition of the primary particle. Two different methods are used to assess the fraction of the signal attributed to muons with respect to the total signal, $f_\mu = S_\mu/S$: a multivariate method and a smoothing method.

The basic idea of the multivariate method relies on using the characteristics of the muon signal in the FADC signal to reconstruct the muon fraction f_μ :

$$f_\mu = a + b\theta + c f_{0.5}^2 + d\theta P_0 + er$$

where θ is the reconstructed zenith angle of the shower and r is the distance of the detector from the reconstructed shower axis. $f_{0.5}$ is the proportion of the signal in FADC bins larger than 0.5 VEM, and P_0 is the normalized zero-frequency component of the power spectrum (Kégl 2013).

Both $f_{0.5}$ and P_0 are sensitive to large relative fluctuations and short signal, which are the signatures of high muon content. The parameters of the fit (a, b, c, d, e) are estimated using simulations described in Kégl (2013).

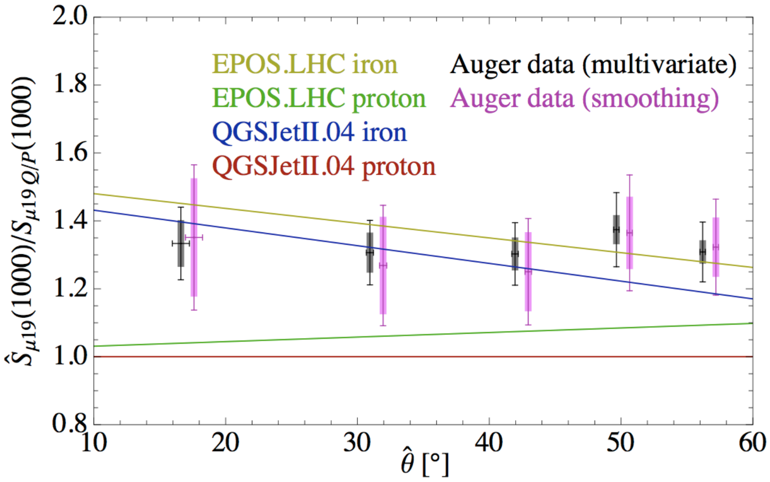

Fig. 1. The measured muon signal rescaling to $E = 10^{19}$ eV and at 1000 m from the shower axis vs. zenith angle, with respect to QSGJetII-04 proton simulations as a baseline. The rectangles represent the systematic uncertainties, and the error bars represent the statistical uncertainties added to the systematic uncertainties. See Kégl (2013) for details.

The smoothing method consists in running a low-pass filter a few times on the signal to gradually separate the low-frequency EM component from the high-frequency one which is assigned to muons. For the first run, the signal is smoothed by a moving average of size L over the FADC. The window size L is tuned using simulations to follow the low frequencies corresponding to the EM signal. At large angles (above 50°) a wider window is needed whereas to extract the EM component in vertical showers a narrower window is more suitable, since the EM component is more similar to the muonic signal. So, the window size L increases with the zenith angle as $L = 7.83 + 0.09\,\theta/\text{deg}$. The procedure is repeated four times, re-smoothing each time the smoothed signal obtained at the previous iteration. The final muon signal is the sum of the non-smoothed positive differences.

The muon fraction is estimated only for the detectors at 1000 m from the shower core and for an energy $E = 10^{19}$ eV. The muon signal can be retrieved by multiplying the muon fraction by the total signal. The results with respect to QSGJetII.04 with proton primaries as baseline are shown in figure 1. The results of the two methods are in very good agreement with a value between 1.3 and 1.4 as a function of the zenithal angle. While the measured angular dependence of the muonic signal is found to be similar to the prediction obtained for proton showers and QSGJetII.04, the magnitude of the muonic signal is comparable to the predictions for iron showers.

It is interesting to note that depending on the hadronic interaction models, especially at larger angle (above 50°), the composition favours particles heavier than iron. This observation shows the limit of these methods. Moreover, the distribution of the depth of shower maximum at 10^{19} eV observed by the fluorescence detector is not compatible with a composition dominated by iron or heavier elements. So, we conclude that the muonic signal is not well reproduced by the shower simulations. More details on this analysis can be found in Kégl (2013).

3 Muon Production Depth (MPD)

The arrival times of the muons reaching the water-Cherenkov detectors can be used to obtain the distribution of the muon production distances along the shower axis. As a first approximation, we assume that the muons travel in straight lines at the speed of the light, c, with trajectories not parallel to the shower axis. The muon time of flight relative to the arrival time of the shower-front plane for each position at ground (r,ζ) is given by: $ct_g = \sqrt{r^2 + (z-\Delta)^2} - (z-\Delta)$, where Δ is the distance from the point at ground to the shower plane.

The muon production point along the shower axis z, taking into account the muon delay as the kinematic time t_ϵ (due to the finite energy of the muons), is approximated as

$$z \simeq \frac{1}{2}\,\frac{r^2}{ct - < ct_\epsilon >} + \Delta$$

From the muon production distance, the MPD X^μ is reconstructed as an integration of the atmospheric density, ρ, over the range of production distance:

$$X^\mu = \int_z^\infty \rho(z')dz'$$

The shape of the MPD distribution is fitted by a Gaisser-Hillas function and the maximum of the muon profile, X^μ_{max}, varies as a function of the mass of the primary particle. So, this parameter is an efficient observable for composition studies.

Like the previous methods, we are only concerned about the muonic component to build the MPD. The EM component is a contamination that must be eliminated. The approach chosen is to use only the inclined events with a zenithal angle range from 55° to 65°. In order to have a good time resolution of the single muons only stations at a distance of $r > 1700$ m are selected. For these data, most of the EM particles are absorbed by the atmosphere. The behaviour of the $\langle X^\mu_{\text{max}}\rangle$ as a function of $\log_{10}(E)$ is shown in figure 2. The uncertainties represent the standard error on the mean and the parentheses represent the systematic uncertainty which is $17\ \text{g}\,\text{cm}^{-2}$.

The data are compared to air shower simulations using different hadronic interaction models for proton and iron primaries. Both models have the same muonic elongation rate but with considerable differences in the absolute value of $\langle X^\mu_{\text{max}}\rangle$ which can completely change the interpretation of the composition. Indeed, the QSGJetII.04 model suggests a change in composition, from proton to iron, as the energy increases, whereas the EPOS-LHC model shows a composition heavier than iron. This provides evidence of the limitations of the current hadronic interaction models in inferences about the mass composition of UHECRs. However, the MPD suffers of low statistics due to the different cuts applied for the selection of the data to eliminate the EM component. So, with the actual method we cannot really conclude about mass composition. Several studies are trying to extend the MPD to lower zenithal angles.

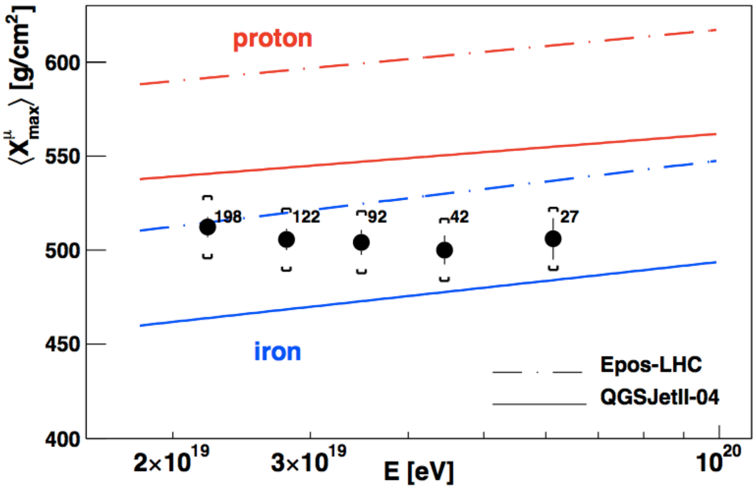

Fig. 2. $\langle X^{\mu}_{\max} \rangle$ as a function of energy. The straight lines represent the predictions of two hadronic interaction models for proton and iron primaries. The number of events in each energy bin is indicated and the parentheses represent the systematic uncertainties. See Garcia-Gamez (2013) for details.

4 Conclusion

The Pierre Auger Observatory offers the possibility to study the mass composition of UHECRs with the surface detector array. Different methods are used to identify the muonic component through the characteristics of the muon signal or using inclined events. Although the muon content at ground is sensitive to the masses of the primary particles, the interpretation is obtained comparing the data to the predictions of high-energy interaction models. The MPD is a promising method but more statistics is needed to understand the mass composition at ultra-high energies.

The results of the different methods show the necessity to achieve a clean separation of the electromagnetic and muonic components of the shower. With the present design, the Auger Observatory measures the muonic component with poor precision through indirect methods. A precise measurement of the number of muons is the key to estimate the primary mass on a shower-by-shower basis to study fundamental interactions at the highest energy. There are several ideas for the upgrade of the Auger Observatory to measure muons with the required precision (Bueno 2014).

References

Abraham, J. et al. [Pierre Auger Collaboration], Nucl. Instrum. Meth. A 523, 50 (2004)

Abraham, J. et al. [Pierre Auger Collaboration], Nucl. Instrum. Meth. A 620, 227 (2010) [arXiv:0907.4282[astro-ph.IM]]

Allekotte, I. et al. [Pierre Auger Collaboration], Nucl. Instrum. Meth. A 586, 409 (2008) [arXiv:0712.2832[astro-ph]]

Baltrusaitis, R. M. et al. [Fly's Eye Collaboration], Proceedings of the 19th International Cosmic Ray Conference, La Joya, USA, 30 (1998) 166

Bueno, A. [Pierre Auger Collaboration], Proceedings of the 26th Rencontres de Blois (2014)

Garcia-Gamez, D. [Pierre Auger Collaboration], Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro, Brazil (2013) [arXiv:1307.5059 [astro-ph.HE]]

Kégl, B. [Pierre Auger Collaboration], Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro, Brazil (2013) [arXiv:1307.5059 [astro-ph.HE]]

de Souza, V. [Pierre Auger Collaboration], Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro, Brazil (2013) [arXiv:1307.5059 [astro-ph.HE]]