Parameters Sensitive to the Mass Composition of Cosmic Rays and Their Application at the Pierre Auger Observatory

J. Vícha

Institute of Physics of the Academy of Sciences of the Czech Republic.

Abstract. The Pierre Auger Observatory studies extensive cosmic ray showers of energy above $10^{18}$ eV. The mass composition of the shower-inducing primary particles plays an important role in the search for an anisotropy of their arrival directions and in considerations about the possible mechanisms of their acceleration. Several air shower parameters carrying information about the mass of primary cosmic ray are introduced and their applications to data of the Pierre Auger Observatory are discussed.

Introduction

The Pierre Auger Observatory studies cosmic rays of ultra-high energy (UHECR, energy above $10^{18}$ eV) since 2004 and is fully operational since 2008. This largest astroparticle experiment in the world is located in Argentine pampa (see Fig. 1) at altitude about 1400 m a.s.l. (vertical atmospheric depth equivalent to $\approx 880$ g/cm$^2$). Since the flux of UHECR is so low that it is impossible to detect them directly, the atmosphere is used as a huge calorimeter for their indirect detection. Primary UHECR particle induces extensive air shower of secondary particles propagating up to the ground. About 90% of the shower energy is carried by the electromagnetic component (electrons, positrons and photons) and the rest energy by muons and neutrinos reaching the ground. There are two independent detection techniques used for the detection of cosmic ray showers at the Observatory. On the area of $3000$ km$^2$ more than 1650 water Cherenkov tanks (shown in the left panel of Fig. 2) are deployed in the regular triangular grid with 1.5 km spacing. This Surface Detector (SD) is sensitive to the electromagnetic and muonic component of the shower. During the propagation of the shower through the air, nitrogen molecules are excited and ionised by the electromagnetic component of the shower. The fluorescence light (300–400 nm) emitted isotropically during the deexcitations of the nitrogen molecules is very faint, what consequently lowers the duty cycle (13%) of the fluorescence measurement due to dark sky demand. There are 4 Fluorescence Detector (FD) buildings comprising 6 fluorescence telescopes (shown in the right panel of Fig. 2) each. A typical event detected by the Pierre Auger Observatory is shown in the left panel of Fig. 3.

It is assumed that the shower-inducing particles are predominantly protons or heavier nuclei\(^1\). It is therefore needed to compare the observed data with Monte Carlo (MC) predictions to reveal the mass composition of UHECR. The weak point of this method is in the fact that interactions at energies far beyond the accelerator abilities are described by interaction models extrapolated from the accelerator data. There are still quite huge differences between the predictions of the individual hadronic models used. The knowledge of the UHECR mass composition is crucial for understanding the mechanisms of their acceleration, the size of distortion effects on their propagation in galactic and extragalactic magnetic fields and for tuning of the hadronic interaction models themselves.

\(^1\) As extreme cases of their composition, protons and iron nuclei are considered in Monte Carlo simulations according to the elements’ occurrence in the possible astrophysical sources.
Figure 1. The view of the Pierre Auger Observatory configuration. Red spots represent stations of the surface detector array, yellow labels are the names of 4 hills on which 4 fluorescence detector buildings are installed. The green lines demonstrate schematically the azimuthal field of view of the individual fluorescence telescopes. For reference see [1].

Figure 2. Left panel: Cross-section of one water Cherenkov tank with the description of its parts. Picture is obtained from [2]. Right panel: Cross-section of one fluorescence telescope with the description of main parts. Picture is taken from [3].

Parameters Sensitive to Mass Composition

The cross section of few first interactions and their particle multiplicity influence differently the speed of shower evolution according to the mass of the primary particle. Therefore, the position where the number of secondary particles of electromagnetic component reaches its maximum is a very good FD observable sensitive to the mass composition of primary particle. In the FD, a longitudinal profile (dependence of the deposited energy on the atmospheric depth\(^2\)) can be reconstructed and the depth where the fluorescence light production is highest is denoted as \(X_{\text{max}}\). An example of the reconstructed profile is shown in the right panel of Fig. 3. Moreover, considering the so called Superposition Model, the shower induced by a nucleus composed of \(A\) nucleons is described as \(A\) independent subs showers of \(A\)-times lower energy. Then, the shower induced by heavier nucleus has its maximum higher in the atmosphere and set of showers is statistically more ordered and thus the fluctuations of the position of shower maximum \(\sigma(X_{\text{max}})\) are smaller.

As another consequence of the Superposition model, the average energy of secondary

\(^2\)The atmospheric depth corresponds to the mass of air that shower penetrates in the atmosphere.
hadrons in the first interactions is much lower for showers induced by heavier primaries than in the case of proton-induced showers. Thus, in the former case, there are less generations of particles produced before the critical energy is reached and the particles start to decay rather then interact. In each generation, approximately one third of energy is transformed to the electromagnetic component via neutral pions, leaving less energy for muon production. The lower number of generations implies the higher number of muons. The number of muons ($N_\mu$) is a parameter with a good ability to differentiate between proton- and iron-induced showers. Nevertheless, water Cherenkov tanks are more or less equally sensitive to the electromagnetic and muonic component. Moreover, FD is insensitive to the muonic component. Therefore, $N_\mu$ can be measured in inclined showers (zenith angle $\gtrsim 60^\circ$) only where the electromagnetic component at the ground level is already so much suppressed that the signal in the SD comes predominantly from the muonic component. As a side note, referring to [5], large inconsistencies between the observed $N_\mu$ and MC predictions by a factor $\approx 2$ have been reported.

Using an approximation that muons propagate along straight paths with speed of light before they reach the array and after the shower axis is reconstructed, apparent production heights of muons can be inferred for inclined showers. After a conversion of the distance in the
atmosphere to the matter transversed, the profile of muon production depth (see the left panel of Fig. 4) is reconstructed. The position of its maximum \(X_{\mu_{\text{max}}}\) is also sensitive to the mass composition of primary particle.

**Pierre Auger Observatory Results**

Since the distribution of \(X_{\text{max}}\) for simulated proton-initiated showers extends even over the distribution of showers induced by iron nuclei, it is almost impossible to infer the mass composition of primary particle just from the \(X_{\text{max}}\) value on event-by-event basis. Therefore, studies of the \(X_{\text{max}}\) distribution can provide us some information about the mass composition for a larger set of events only. The energy dependence of mean (RMS) of the \(X_{\text{max}}\) distribution for the Pierre Auger Observatory data is shown in the left (right) panel of Fig. 5. MC predictions for showers induced by protons (in red) and iron nuclei (in blue) are shown for different hadronic models used. There is a reversal in the observed data at energy \(\approx 2.4 \text{ EeV}\) indicating a change in composition from lighter to heavier primaries. Although it seems that the averaged mass composition is getting heavier with increasing energy, it is needed to mention that the differences between individual hadronic model predictions themselves are quite large. It comes from the fact that the interaction models are extrapolated from accelerator energies to energies at least one order of magnitude higher in the central of mass system. It is worth to note that such a break could be also caused by a different interaction mechanism working at the highest energies.

In the right panel of Fig. 4 the quantity \(X^\mu_{\text{max}}\) is plotted with respect to shower energy. According to MC predictions, it indicates heavier composition at higher energies again. It is important to note that this quantity is inferred from SD data only and it is thus an independent measurement indicating also heavier composition at higher energies.

**Conclusions**

Selected parameters sensitive to the mass composition of primary particles were introduced and their application to the Pierre Auger Observatory data were discussed. The muonic shower component seems to be very appropriate for a combined study of mass composition together with the \(X_{\text{max}}\) quantity inferred from the electromagnetic shower component. An upgrade of the Pierre Auger Observatory providing better opportunities for muonic component detection would be very beneficial in the future for UHECR mass composition considerations.
VÍCHA: SHOWER PARAMETERS SENSITIVE TO PRIMARY COMPOSITION

Acknowledgments. The presented work was supported by MSMT CR LA08016.

References