Energy reconstruction of primary cosmic rays in air shower studies

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Introduction

The astrophysical models on the origin, acceleration and propagation of primary cosmic rays (PCRs) beyond 100 TeV gain impetus constantly from two important sources of information. These are the energy spectrum and mass composition of PCRs obtained from various air shower experiments. Hence, the mass composition and energy spectrum of cosmic rays (CRs) are crucial for understanding the origin of the PCRs including their acceleration and propagation mechanisms.

The basic strategy of the present analysis is to search for some energy sensitive air shower observable by exploiting different characteristics of extensive air showers (EASs) initiated by charged primaries *e.g.* protons and irons, and electromagnetic component *i.e.* gamma rays, around the *knee* region from a detailed Monte Carlo simulation. Air shower experiments, *viz.* KASCADE [1], GRAPES-3 [2], ARGO-YBJ [3] have (or are being) contributed tremendously to the current knowledge on the energy spectrum around the *knee* region. This was mainly done from the comparison between the measured properties of EASs initiated by the energetic particle and the detailed simulations of these particle cascades.

Beyond 100 TeV, the information about PCRs is achievable through the study of EAS which are cascades of mainly secondary electrons ($e^{+}+e^{-}$), muons ($\mu^{+}+\mu^{-}$) and hadrons ($h\bar{h}$) produced when PCR particles interact with atmospheric nuclei during their advancement towards the ground. The ground based air-shower experiments equipped with scintillation detectors seed their measurements with two basic EAS data which are known to be densities and arrival times of electrons and/or muons. The crucial EAS parameters such as the shower size (N_{e}), the EAS core (x_{o}, y_{o}) and the shower age (s), are obtained by applying the shower reconstruction to the electron density data using the Nishimura-Kamata-Greisen (NKG) type lateral density function (LDF). The shower direction, i.e. the zenith angle (Θ) and the azimuth angle (Φ) are obtained using the shower front plane fitting with arrival time information of electrons from timing detectors.

Results and discussion

Among the several observables introduced in the present work, the N_{μ} is found reasonably a good primary energy estimator in the concerned energy region. From the longitudinal data sub-block of CORSIKA [4] output for proton, helium and iron simulated showers, it is noticed that the number of total muons remains nearly the same in an EAS after reaching the shower maximum. However, for gamma ray induced showers, attenuation of muons after the shower maximum becomes little faster than the case for protons or nuclei induced showers. These attenuation features of showers irrespective of their primaries lead to consider the N_{μ} as a primary energy estimator at any observable level beyond the point of shower size or muon size maximum. As N_{μ} is considered to be an energy estimator here, therefore a more reliable and updated high-energy hadronic model has to be selected in simulations. simulations.

The PCR energy estimation in the present analysis ultimately requires quite a few EAS observables from an experiment *viz.* N_{μ}, Θ and N_{e}. The N_{μ}^{Max} parameter however can only be obtained from the simulation employed in an EAS experiment.

We will now discuss how the information on N_{μ} or N_{μ}^{Max} and Θ can be utilized to obtain

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the PCR energy ($E_{\rm o}$). The available muon data in the longitudinal sub-block of CORSIKA for simulated showers give the variation of N_μ with atmospheric depth, which in turn provides the $N_\mu^{\rm Max}$. Moreover, the important correlation of N_μ on the slant depth ($sec\ \Theta$) is also necessary to determine $E_{\rm o}$.

First, we will now proceed for correlations between reconstructed energy ($E_0^{\rm REC}$) and the prime energy estimator i.e. the $N_\mu^{\rm Max}$. Later, by introducing a size-dependent scale factor, say β, the $N_\mu^{\rm Max}$ is converted into N_μ in the energy reconstruction formula of $E_0^{\rm REC}$. When attenuation characteristics of muons in air are considered then $E_0^{\rm REC}$ can be expressed by the formula as follows,

$$E_0^{\rm REC} \ = \ \delta_E A(\Theta)(N_\mu^{\rm Max})^\beta, \qquad (1)$$

where δ_E is the overall energy conversion factor of $N_\mu^{\rm Max}$ obtained from simulation. The Θ-dependent scale factor $\rm A(\Theta)$ appeared due to attenuation of N_μ for showers with $\Theta \neq 0^{\rm o}$. The factor $\rm A(\Theta)$ has been found to be proportional to $e^{\frac{X_{\rm o}}{\Lambda_\mu}(sec\ \Theta-1)}$, where Λ_μ takes different values due to in-congruent development processes of cascades induced by different primaries.

The $N_{\rm e}$ range needed for estimating Λ_μ from generated showers with 200–800 TeV energy values is selected as 2×10^3–4×10^3. The corresponding selected N_μ bins for proton, iron and gamma ray showers are 1.0×10^3–1.6×10^3, 2.8×10^3–4.0×10^3 and 75–100 respectively. We have then estimated mean values of the ratio $\rm g = \langle\frac{N_\mu^{\rm Max}}{N_\mu}\rangle$ taking into account all the generated events for proton, iron and gamma ray primaries separately. We have obtained these values for g close to 1.59, 1.61 and 4.55 from the frequency distributions.

We substitute δ_E (after absorbing g into it) and also β, and $\rm A(\Theta)$ obtained from simulation into the eqn. (2). Finally, the relations between $E_0^{\rm REC}$ (in TeV) and the pair N_μ and $sec\ \Theta$ for proton, iron and gamma ray primaries are as follows:

$$E_0^{\rm REC} \ = \ {\rm a}(N_\mu)^{\rm b}e^{{\rm c}(sec\ \Theta-1)} \qquad (2)$$

The values of Λ_μ appear in $\rm A(\Theta)$ due to attenuation of muons in air are borrowed from KASCADE simulation using the constant $N_{\rm e}$–N_μ method. These numbers are 982, 1028 and 901 gm-cm^{-2}, with an average error of nearly ±91 gm-cm^{-2} that resulted from intrinsic fluctuations present in EAS development [5]. The set $\rm (a, b, c)$ takes various values, as obtained from simulation, and those are; $(0.075, 1.01, 1.03)$, $(0.055, 1.02, 0.98)$ and $(0.75, 1.34, 1.12)$ for proton, iron and gamma ray primaries in the concerned energy region.

Finally, we evaluate performances of the relation (2) by establishing correlations of $E_0^{\rm REC}$ and $E_0^{\rm SIM}$ with N_μ. We study the correlations between N_μ–$E_0^{\rm SIM}$ and N_μ–$E_0^{\rm REC}$ separately for proton initiated showers in the $E_0^{\rm SIM}$-range; 200–800 TeV. These studies show that the PCR energy might be estimated from the muon size and its attenuation properties in the atmosphere.

Acknowledgments

The author thanks the SERB, DST for financial support under the Grant no. EMR/2015/001390.

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