On the primary particle type of the most energetic Fly’s Eye event

M. Risse\textsuperscript{a, b, c}, P. Homola\textsuperscript{a}, R. Engel\textsuperscript{b}, D. Góra\textsuperscript{a}, D. Heck\textsuperscript{b}, J. Pękala\textsuperscript{a}, B. Wilczyńska\textsuperscript{a} and H. Wilczyński\textsuperscript{a}

\textsuperscript{a}Institute of Nuclear Physics PAN, ul. Radzikowskiego 152, 31-342 Kraków, Poland
\textsuperscript{b}Forschungszentrum Karlsruhe, Institut für Kernphysik, 76021 Karlsruhe, Germany
\textsuperscript{c}Electronic address: markus.risse@ik.fzk.de

The longitudinal profile of the 320 EeV event observed by the Fly’s Eye experiment is analysed. A method of testing the hypothesis of a specific primary particle type is described. Results for different particle types are summarized. For hadronic primaries between proton and iron nuclei, the discrepancy between observed and simulated profiles is in the range of 0.6-1.0σ for two different hadronic interaction models investigated. For primary photons, the discrepancy is 1.5σ assuming a standard extrapolation of the photonuclear cross-section with energy. Larger values of the cross-section at highest energies make primary photon showers more similar to hadron-initiated events. The influence of varying the extrapolation of the photonuclear cross-section is studied.

1. Introduction

Deciphering the primary particle type of the most-energetic cosmic rays would be an important step towards understanding their origin. Due to the stochastic process of air shower development, it is in general not possible to unambiguously identify the nature of the primary. However, if the expectation for a specific primary type were found to be inconsistent with the data, an exclusion of such a primary particle hypothesis might be possible.

In this work, we summarize an analysis method developed for this purpose: By comparing large statistics simulations to the data of an individual event, the level of consistency between data and the showers simulated for a given primary particle type is evaluated. Results of applying this method to the 320 EeV Fly’s Eye event \footnote{1} are presented. A detailed discussion is given in \footnote{2}.

Of particular interest is the primary photon hypothesis. For the simulation of primary photon showers, the photonuclear cross-section \( \sigma_{\gamma-\text{air}} \) has to be extrapolated to highest energies. It is quantified in this work, how the uncertainty in extrapolating \( \sigma_{\gamma-\text{air}} \) influences shower features of primary photons.

2. Method and application

Given the reconstructed primary energy, direction, and depth of shower maximum \( X_{\text{max}} \) of the 320 EeV Fly’s Eye event \footnote{1}, for each assumption on the primary particle type a large set of detailed Monte Carlo simulations is generated. The simulations are performed adopting the primary energy, direction, and local geomagnetic field conditions as for the observed event.

The simulated \( X_{\text{max}} \) distribution is then compared to the measured \( X_{\text{max}} \) value. The probability of each primary particle hypothesis to be consistent with the data is determined, taking the uncertainty in the measured \( X_{\text{max}} \) into account. In this way, i.e. by directly comparing each simulated \( X_{\text{max}} \) to the data, also non-Gaussian shower fluctuations are preserved and naturally considered in the probability evaluation.

As an example, in Fig. \footnote{1} \( X_{\text{max}} \) values for the primary photon assumption are shown together with the measurement of \( X_{\text{max}} = 815 \pm 60 \text{~g~cm}^{-2} \). The simulations are performed with the PRESHER\footnote{3}OWER code \footnote{4} linked to CORSIKA 6.16 \footnote{4}. The discrepancy between primary photons and data obtained this way from comparing \( X_{\text{max}} \) is below the 2σ level. The average values \( \langle X_{\text{max}} \rangle \) also for hadronic primaries are listed in Tab.\footnote{1}.
Table 1
Average depth of shower maximum $X_{\text{max}}$ and RMS (both in g cm$^{-2}$) for the simulated profiles. The reconstructed depth of shower maximum of the 320 EeV Fly’s Eye event is 815 g cm$^{-2}$ with a combined uncertainty of 60 g cm$^{-2}$.

|          | QGSJET 01 photon | P C Fe | SIBYLL 2.1 photon | P C Fe |
|----------|------------------|--------|-------------------|--------|
| $X_{\text{max}}$ | 937              | 848    | 808 733           | 882    |
| RMS      | 26               | 54     | 30 22             | 47 27 19 |

For the Fly’s Eye event, not only $X_{\text{max}}$, but the complete observed profile can be compared to the simulations, see Fig. 2. The statistical method for evaluating the consistency of simulations and data based on the profile information was developed in [2]. An important issue in this comparison is to take the correlation of the reconstructed profile points in atmospheric depth $X$ into account, since otherwise a too large discrepancy between simulation and data might erroneously lead to the conclusion that the considered primary hypothesis could be rejected. The results in case of the Fly’s Eye event for primary photons and different hadronic primaries, simulated with the hadronic interaction models QGSJET 01 [5] and SIBYLL 2.1 [6], are listed in Tab. 2. The discrepancy of photon shower profiles to data is 1.5$\sigma$, and the values for primaries between proton and iron nuclei range between 0.6-1.0$\sigma$. Thus, no considered primary particle hypothesis can be rejected for the Fly’s Eye event.

3. Uncertainty of photonuclear cross-section

The photonuclear cross-section must be extrapolated to highest energies, i.e. several orders of magnitude beyond the range of cross-section data, see Fig. 3. Increased values of $\sigma_{\gamma-\text{air}}$ will result in a larger energy flow from the electromagnetic to the hadronic shower component. Correspondingly, features of primary photon showers are expected to change. More specifically,

Figure 1. Shower maximum distribution of primary photons compared to the reconstructed value of the Fly’s Eye event. The measured depth is shown with the 1$\sigma$- and 2$\sigma$- uncertainty. In addition to the simulations with standard photonuclear cross-section, results when assuming the extrapolation $\sigma^{\text{extr}}$ (see Fig. 3) are given.

Table 2
Probability $P$ of a given primary particle hypothesis to be consistent with the observed Fly’s Eye event profile and corresponding discrepancy $\Delta$ in units of standard deviations.

|        | QGSJET 01 photon | P C Fe | SIBYLL 2.1 photon | P C Fe |
|--------|------------------|--------|-------------------|--------|
| $P$ [%] | 13               | 43     | 54 53             | 31 52 54 |
| $\Delta$ $\sigma$ | 1.5           | 0.8    | 0.6 0.6           | 1.0 0.6 0.6 |

$<X_{\text{max}}>$ becomes smaller and the average number of muons $<N_\mu>$ larger when assuming larger values of $\sigma_{\gamma-\text{air}}$ for primary photon simulations at highest energies.

This has been verified by adopting an extreme parametrization of the photonuclear cross-section [9], denoted $\sigma^{\text{extr}}$ in Fig. 3. In that case, $<X_{\text{max}}>$ for the Fly’s Eye event simulations is decreased by $\pm 30$ g cm$^{-2}$ (see Fig. 3). This corresponds to a smaller discrepancy of the primary photon hypothesis to data, reduced from 1.5$\sigma$ to about 1.2$\sigma$. The shift in $<X_{\text{max}}>$ is relatively
modest here, since for the conditions of the Fly’s Eye event, strong precascading of the initial photon in the geomagnetic field occurs. The shift is found to be much larger (up to 100-200 g cm$^{-2}$) for highest-energy photons that enter the atmosphere without precascading.

Although the muon content of the shower was not measured by the Fly’s Eye experiment, it is interesting to check for the effect in $<N_{\mu}>$. Applying the extrapolation $\sigma^{extr}$, the muon number on ground is increased by $\simeq$75%, thus reducing considerably the difference in muon content between primary photon and proton showers. Therefore, the uncertainty in extrapolating the photnuclear cross-section to highest energies must be seriously considered when conclusions on primary photons are to be drawn.

4. Conclusion

Both primary photons and any hadron between proton and iron nuclei can not be excluded as primary particle of the 320 EeV Fly’s Eye event. The method developed for this analysis is further exploited in an investigation of the most energetic AGASA events as presented at this conference [10]. The large uncertainty in extrapolating the photnuclear cross-section can considerably influence the predictions of features of primary photon events and deserves a further careful study.

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