Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 4 (HE part 1), pages 597–600

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Cosmic-Ray Events as Background in Imaging Atmospheric Cherenkov Telescopes

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Abstract: The dominant background for observations of gamma-rays in the energy region above 50 GeV with Imaging Atmospheric Cherenkov telescopes are cosmic-ray events. The images of most of the cosmic-ray showers look significantly different from those of gamma-rays and are therefore easily discriminated. However, a small fraction of events seems to be indistinguishable from gamma-rays. This constitutes an irreducible background to the observation of high-energy gamma-ray sources, and limits the sensitivity achievable with a given instrument. Here, a Monte Carlo study of gamma-like cosmic-ray events is presented. The nature of gamma-like cosmic-ray events, the shower particles that are responsible for the gamma-like appearance, and the dependence of these results on the choice of the hadronic interaction model are investigated. Most of the gamma-like cosmic-ray events are characterised by the production of high-energy π^0 early in the shower development which dump most of the shower energy into electromagnetic sub-showers. Also Cherenkov light from single muons can mimic gamma-rays in close-by pairs of telescopes. Differences of up to 25% in the collection area for gamma-like proton showers between QGSJet/FLUKA and Sibyll/FLUKA simulations have been found.

Introduction

The study of the non-thermal universe at energies above 80 GeV by means of ground-based γ-ray astronomy has evolved substantially in the past few years. About 40 sources of high-energy γ-rays are now known and several new classes of γ-bright objects (e.g. microquasars or young stellar clusters) have been discovered. This progress is due to the large increase in sensitivity of new instruments, which consist of arrays of large imaging atmospheric Cherenkov telescopes (IACT). These systems detect Cherenkov light from air showers simultaneously in several telescopes. The sensitivity increase is primarily due to the much improved suppression of the background of hadronic cosmic rays, which are more than a thousand times more numerous than the γ-rays.

Arrays of imaging atmospheric Cherenkov telescopes reject a significant number of cosmic rays already at the trigger level. Further suppression is achieved by applying cuts to the shape parameters describing the images (i.e. the Cherenkov light distribution) in the focal plane. For point-like or slightly extended sources the reconstructed arrival direction can also be used to distinguish between γ-rays and the isotropic cosmic-rays. The combination of all selection cuts leads to the elimination of the major part of the background events. Even so, after all γ-hadron separation cuts, a small but significant fraction of the remaining events are of hadronic origin. The large ratio of cosmic rays to γ-rays and the substantial fluctuations in the shower development of hadronic showers lead in general to a considerable overlap of the distributions of shower parameters, which are used for the separation. Observations are therefore still background limited and most of the weaker known sources require observation times in the range of 10-80 hours for a significant detection. In this paper we study background events in IACTs to understand the origin of γ-like cosmic-ray showers and perhaps to improve the γ-hadron separation in the data analysis (see [1] for more details of this analysis).

Simulation and Analysis

Extensive air showers induced by primary protons with energies following a power law with a differential spectral index of -2.7 between 50 GeV and 10 TeV are simulated with the CORSIKA code v.6.2 [2]. Two different combinations of low and high-energy interaction models are used: QGSJet (version 01c) [3] and FLUKA (version 2003.1) [4] with a transition energy of 500 GeV, and Sibyll (version 2.1) [5] and FLUKA (version 2003.1) with a transition energy of 80 GeV. Calculation of all electromagnetic interactions are performed with EGS4 [6] which is well tested and has small uncertainties, even up to 100 TeV.

The array of IACTs consists of four telescopes arranged in a quadrangle with different sides, very similar to the temporary VERITAS layout at the Fred Lawrence Whipple Observatory in southern Arizona [7]. All telescopes are at the same altitude of 1270 m above sea level. The telescopes have Davies-Cotton reflectors of 12 m diameter with a focal length of 12 m. The cameras are equipped with 499 PMTs. The field of view is 3.5°. The simulated trigger system consists of three levels (pixel above threshold, pattern of pixels above threshold, array trigger). The telescope simulation [8] consists of two parts, the propagation of Cherenkov photons through the optical system and the response of the camera and electronics (see [9, 7, 10] for more details).

The event reconstruction procedure consists of image cleaning, second-moment image analysis for each camera, and reconstruction of shower direction and impact parameter on the ground, using all available images. Shape cuts (generally known as mean scaled with and length cuts [11]) and direction cuts (θ^2-cut) are used for hadron suppression.

γ-ray like proton showers

The Cherenkov light of proton showers is mainly a superposition of contributions of electromagnetic sub-showers from π^o decays and of muons from $\pi^\pm$ decays. Usually the resulting Cherenkov pattern on the ground is easily distinguishable from that of γ-ray showers, but a very small fraction of events passes all suppression cuts and end up in the γ-ray sample. This study shows that hadron showers with γ-ray-like appearance can be classified into two categories: events where most of the energy is dumped into one electromagnetic sub-shower by the decay of high energy π^o's early in the shower development and events where the

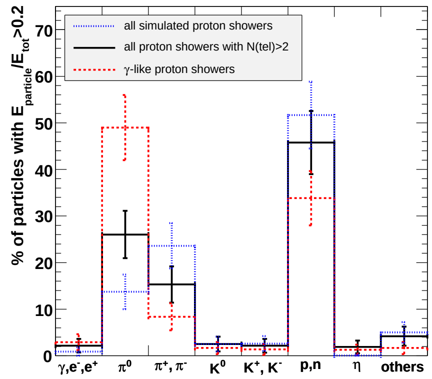

Figure 1: Distribution of secondary particles from the first interaction in proton showers. Only particles with energies larger than 20% of the primary energy are counted (QGSJet/FLUKA simulations).

light of nearby single high-energy muons illuminates two telescopes. Here we concentrate on the first class, see [1] for a detailed description of γ-like events from high-energy muons.

Figure 1 shows the distribution of secondary particles in the first interaction in proton showers. While the distribution for all simulated events shows the expected ratio of charged to neutral pions of 2 to 1, this ratio approximately reverses for particles in events with a 3-fold array trigger. Well above-average Cherenkov light emission is needed to trigger three or more telescopes. As the large number of π^0's indicates, the light originates in electromagnetic subshowers initiated by π^0 decay. About 50% of all secondaries in the first interactions of γ-like proton showers are neutral pions.

The importance of the production of high-energy π^0's is highlighted in Figures 2 and 3. The fraction of events with a π^0 energy sum above 80 GeV in all simulated proton showers is very small, while the majority of events with a 3-fold array trigger exceed this threshold. γ-like events are even more likely to contain high-energy π^0's. The dominance of electromagnetic subshowers in γ-like proton events can be seen in clearly in Figure 3. These events are 4-10 times more likely to have an electromagnetic energy share of 40% or more of the primary energy. Both findings suggest that, firstly, the electromagnetic part in the proton initiated shower has to be energetic enough to trigger

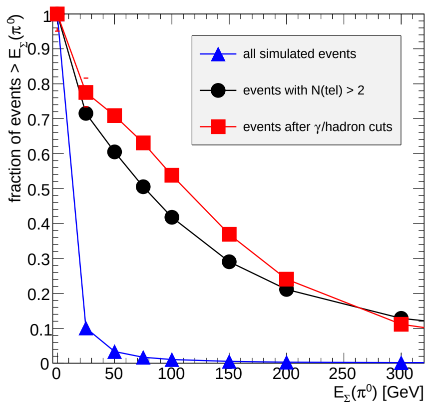

Figure 2: Fraction of events with $E_\Sigma(\pi^0)$ larger than the value on the abscissa in, or close to, the first interaction. (Sibyll/FLUKA simulations).

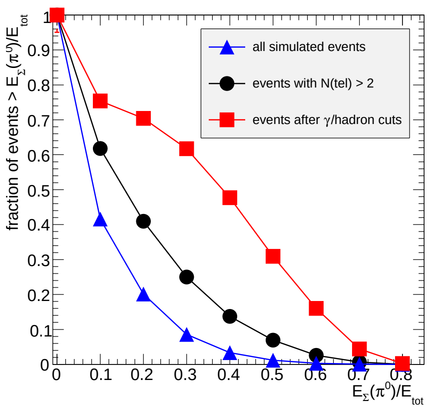

Figure 3: Fraction of events with $E_\Sigma(\pi^0)/E_{tot}$ larger than the value on the abscissa in, or close to, the first interaction. (Sibyll/FLUKA simulations).

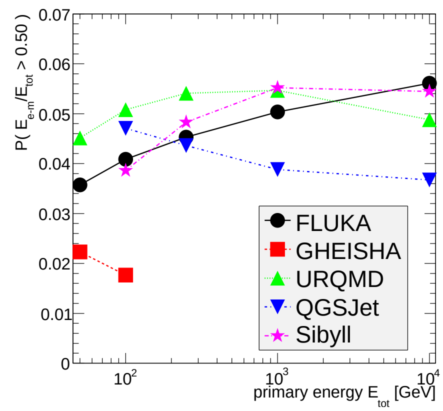

Figure 4: Probability that more than 50% of the primary energy is deposited in the electromagnetic part in proton-nitrogen collisions for different interaction models and primary energies.

the array and, secondly, this part must carry a significant part of the primary energy to prevent the occurrence of other large subshowers that would disturb the γ-like appearance of the Cherenkov image in the cameras.

Influence of interaction models

Results from simulations depend in general on the choice of the nuclear and hadronic interaction model, which rely on phenomenological descriptions of interactions and extrapolations to the energy and angular ranges required. The CORSIKA package allows the systematic study of these differences since several low- and high-energy interaction models are available in the same framework. Here we examine the models FLUKA (version 2003.1) [4], GHEISHA (version 2002) [12], URQMD (version 1.3.1) [13] for low energies, and QGSJet (version 01c) [3] and Sibyll (version 2.1) [5] for high-energy interactions.

Simulations of the interaction of protons with nitrogen nuclei (i.e. the first interaction in a proton-induced air shower) are used to study the amount of energy deposited in the electromagnetic part right at the start of the shower development. Figure 4 displays the probability that more than 50% of the primary energy is are deposited in the electromagnetic component, as a function of primary energy. GHEISHA gives a very different prediction compared to other models: events with large E_{e-m}/E_{tot} are less than half as probable. According to ref. [14], GHEISHA does not reproduce well the available experimental data of pion production and generates in general too few pions. Differences between the other models are in the range of 20-40%. URQMD, Sibyll, and FLUKA tend to deposit more energy in the electromagnetic part, QGSJet systematically less.

What is the effect of these differences on the Cherenkov photon part of the air shower and on the simulated performance of arrays of IACTs? Energy dependent measures like the collection area should give a good description of the per-

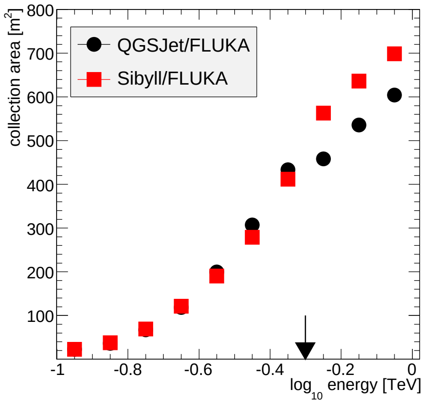

Figure 5: Collection area of the considered array of four telescopes for proton showers for QGSJet/FLUKA (transition energy 500 GeV) and Sibyll/FLUKA (transition energy 80 GeV) simulations. The arrow indicates a primary energy of 500 GeV.

formance of IACTs. Figure 5 shows the collection areas after all γ-hadron separation cuts for QGSJet/FLUKA and Sibyll/FLUKA simulations[1]. The collection areas are very similar in the energy range from 100 GeV to 500 GeV, where the figure shows essentially a comparison of pure FLUKA with Sibyll/FLUKA simulations. However, the QGSJet/FLUKA collection area ($>$ 500 GeV) shows a discontinuity exactly at the transition energy between QGSJet and FLUKA, with a smaller collection area at higher energies. As shown in Figure 4, the difference in the amount of energy between QGSJet, and FLUKA at 500 GeV deposited into the electromagnetic part of the shower is about 15-30%, while the difference between Sibyll and FLUKA is below 5%. This QGSJet version, in contrast to Sibyll and FLUKA, cannot reproduce the experimental values of pion multiplicity in proton-proton interactions at energies of about 500 GeV [14]. The systematic differences of about 25% in the predictions of Sibyll/FLUKA and QGSJet/FLUKA at energies above 500 GeV for the collection area translate directly into an uncertainty of about 10% for any sensitivity estimate. QGSJet/FLUKA predicts a lower background, and therefore a higher sensitivity to γ-ray sources. Both findings, the different collection area of QGSJet at energies above 500 GeV and the shortcomings of GHEISHA indicate that a careful choice of both, interaction models and transition energies, is necessary to obtain reliable results.[2]

Acknowledgments

G.M. acknowledges the support as a Feodor Lynen Fellow of the Alexander von Humboldt foundation. He would also like to thank the High Energy Astrophysics Group of the University of Leeds for hospitality during the main phase of this work.

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1. Note that the transition energy for the QGSJet/FLUKA simulations is at 500 GeV, for Sibyll/FLUKA it is at 80 GeV.

2. During completion of this paper a new version of QGSJet has been released, with marked improvements in the sub TeV range. [15].