Influence of uncertainty in hadronic interaction models on the sensitivity estimation of Cherenkov Telescope Array

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Abstract. Very-high-energy (VHE) interaction between cosmic-ray proton and nuclei in the atmosphere is still not perfectly understood and efforts to improve interaction models used in simulations are ongoing, with feedback from various collider and air shower experiments. Imaging Atmospheric Cherenkov Telescopes (IACTs) are indirect VHE gamma-ray detectors on the ground and cosmic-ray proton is a major background to gamma-ray measurements in these systems. Rejection power of background protons determines most part of the gamma-ray sensitivity curve of IACTs. As for an IACT system in design phase, simulated proton events are used to estimate the residual background level. We investigated the influence of the uncertainty in the current hadronic interaction models on the estimated gamma-ray sensitivity of Cherenkov Telescope Array, using several interaction models available in CORSIKA.

1. Introduction

Imaging Atmospheric Cherenkov Telescopes (IACTs) are the most powerful cosmic gamma-ray detectors in the very-high-energy (VHE) region. Along with their large collection area ($\sim 10^4$ m^2 for current systems), efficient gamma-hadron separation achieved by imaging method enables IACTs to function as gamma-ray observatories, since at the hardware trigger level majority of the events ($>99\%$) are cosmic ray (CR) backgrounds.

Gamma-ray sensitivity of an IACT system strongly depends upon its background rejection efficiency, not only on signal event statistics. As for the case of Cherenkov Telescope Array (CTA), a next-generation large-scale IACT project, gamma-ray sensitivity in E<10 TeV region is determined by signal significance to the residual background fluctuation (5σ detection criteria, significance definition in Li & Ma [1]) and signal-to-background ratio ($\geq 5\%$). Thus it is essential

to understand the nature of those CR backgrounds which mainly consist of proton and electron, for the precise estimation of the gamma-ray sensitivity.

As for the existing IACT systems, residual CR background level is estimated using real CR data (OFF-source data). The current IACT analyses seldom require proton Monte Carlo (MC) simulation as far as gamma-ray sources are studied.

As for the systems in design/construction phase such as CTA, MC simulation of background cosmic rays is inevitable. At the same time, high energy interaction between cosmic-ray proton and nuclei is not perfectly understood currently and several interaction models are proposed and commonly in use in very- and ultra-high-energy cosmic-ray field. Differences on the analysis results originated from the uncertainty in the interaction are regarded as systematic errors.

IACTs can possibly observe differences in hadronic interactions, in Cherenkov photon density on the ground [2], flux of muons from $\pi^{\pm}$ [3], and rate of sub-electromagnetic (EM) showers from π^0 and so on. Previous studies ([4], [5]) show that proton-induced sub-EM showers from a single high energy (close to primary proton energy) π^0 are observed as very gamma-ray-like events and are a major source of background in the gamma-ray analysis. Thus spectral shape of π^0 at high-energy edge in the interaction model can affect the estimation of gamma-ray sensitivity of an IACT system when we use MC simulation data. In this paper, we investigate the effect of this uncertainty in hadronic interaction on the estimation of gamma-ray sensitivity of CTA using four interaction models, QGSJET-II-03 (currently used in the sensitivity derivation in CTA), QGSJET-II-04, Sibyll2.3c, EPOS-LHC ([6],[7],[8],[9],[10]) available in air shower simulation tool CORSIKA[11].
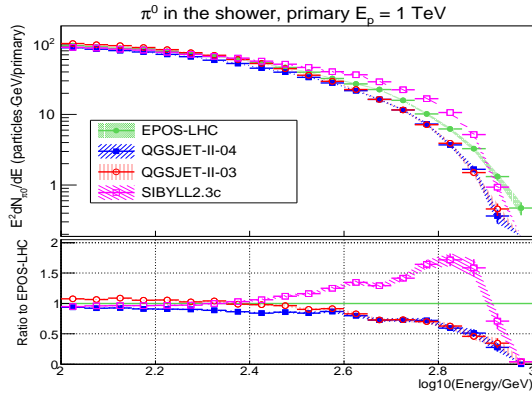
2. Simulation and analysis

In order to investigate the difference in interaction models, two types of simulations were performed and both used CORSIKA version 6.99 and 7.69. In high energy region (above 80 GeV/nucleon) four models mentioned above were used (QGSJET-II-03 in CORSIKA 6.99 and others in CORSIKA 7.69) and in low energy region a fixed model UrQMD was used for all cases.
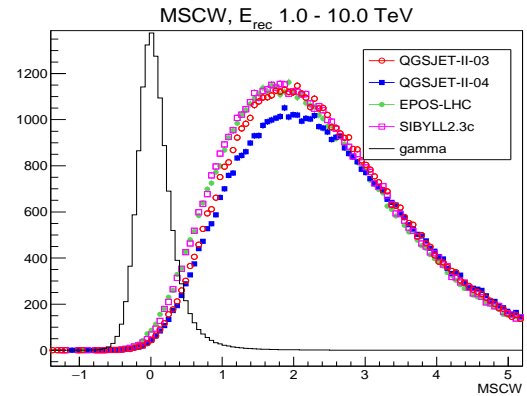
Simulation without detector response: The first simulation aims at investigating the difference of particles in the shower and was performed without detector response or Cherenkov emission and particle track information were extracted as outputs. Mono-energetic protons (0.1 to 10 TeV in 5 steps) were simulated and target nuclei was fixed as nitrogen. From the track outputs π^0 spectrum near primary energy which is expected to correlate with gamma-ray-like event rate was extracted as shown in Fig. 1. Spectral shape at high energy edge shows different feature from model to model and we expect EPOS-LHC and Sibyll2.3c will produce more gamma-ray-like background events than two QGSJET-II models considering the hardness of their π^0 spectra. Energy fraction consumed in γ, e^- and e^+ (E_{EM}) was calculated from the track outputs and probability of high ($> 80\%$ for CTA case) $E_{\mathrm{EM}}/E_{\mathrm{primary}}$ was also estimated for the four interaction models. As expected from π^0 spectra, EPOS-LHC and Sibyll2.3c produce more events with a high EM fraction, and EPOS-LHC seems to have an energy dependence of this probability which is decreasing towards low energy.

Simulation with CTA array configuration and detector response: The second simulation was performed with Cherenkov photon emission and detector response of CTA with sim_telarray tool [12]. The South site array which consists of 99 telescopes was chosen to cover full energy range. To estimate the influence on the gamma-ray sensitivity, MC datasets of gamma-rays and electrons with the identical detector setup were also used. The MC data of gamma, electron, and proton with QGSJETII-03 correspond to the so-called Prod3b simulation[1] produced on the EGI computing grid. The other three proton productions with post-LHC models were run on a Japanese computer center. These MC data were processed with an analysis pipeline [13]

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[1] https://www.cta-observatory.org/science/cta-performance

Figure 1. Energy spectra of π^0 produced in the showers for different interaction models. One decade from the energy of primary proton is shown. Difference in high energy edge affects the rate of gamma-ray-like background events.

Figure 2. Distribution of mean reduced scaled width (MSCW) which reflects lateral size of the shower. Proton histograms are normalized by the number of simulated event, gamma histogram is scaled with an arbitrary factor.
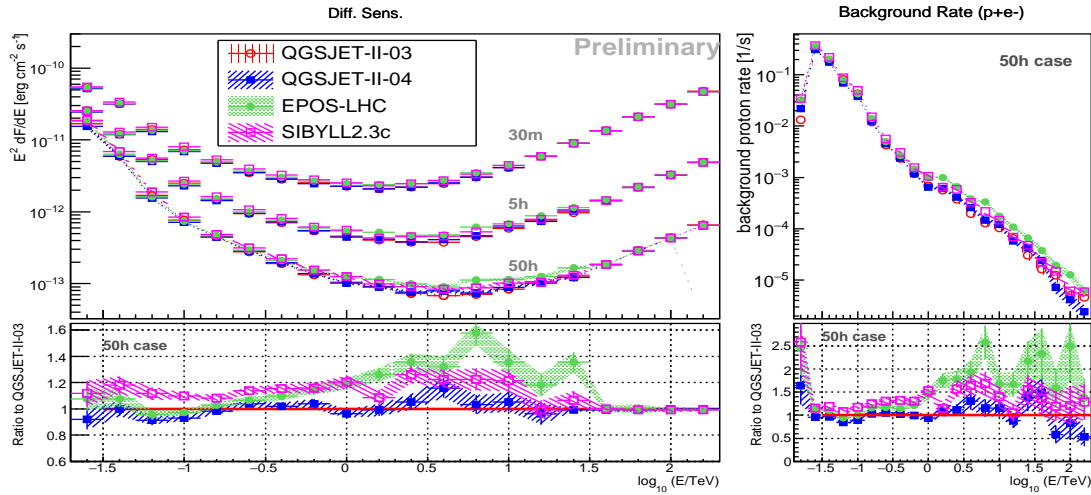
used in the derivation of CTA Instrument response functions (IRFs). Fig. 2 shows one of the intermediate analysis outputs, a shower characteristics parameter (lateral size of the shower) which is most important in the gamma-hadron separation in TeV region. There is a difference at the left of the distributions, EPOS-LHC and Sibyll2.3c show more events in gamma-ray-like region than two QGSJET models as expected.

3. Effect on the estimation of CTA gamma-ray sensitivity

Difference of the shower characteristics leads to differences in the number of residual background events after gamma-ray-like event selection cuts, and will affect the gamma-ray sensitivity as mentioned before. Fig. 3 shows the resulting differential gamma-ray sensitivity of the CTA South site array for the four interaction models. Difference in the sensitivity from the interaction models is mainly seen in the 1 - 30 TeV region and reaches up to $\sim 30 \pm 10\%$ level, still with large statistical errors from statistics of MC datasets. In the E > 30 TeV region sensitivity is determined by signal event statistics and uncertainty of the hadronic interaction model has almost no effect, and in the low energy region we used a fixed low-energy interaction model UrQMD (below 80 GeV/nucleon), thus sensitivity curves naturally converge towards low energy. As for 100 GeV - 1 TeV region CR electrons significantly contribute as background and uncertainty of interaction has a weaker effect. EPOS-LHC and Sibyll2.3c show limited sensitivity value because of their higher gamma-ray-like residual background rates (shown in the right panel of fig. 3) as expected and their curves cross at ~ 1 TeV, which is also expected from the analysis of energy fraction in EM with MC data without detector response.

4. Possibility of interaction model verification using CTA

Since the frequency of gamma-ray-like background events is sensitive to the π^0 spectrum at high-energy edge, in principle this relation can be utilized to verify the interaction models by comparing real cosmic-ray and Monte Carlo data. A series of observables (event rate of cosmic-ray shower, shower shape parameter distributions, multivariate analysis parameter distributions, muon event rate etc.) can be used in the comparison for the verification. At the same time we have to consider the contribution from heavy nuclei for some of them, and the verification accuracy is affected by the uncertainty in cosmic-ray nuclei composition. A merit of using gamma-ray-like event rate among them is that it is almost free from the uncertainty of the

Figure 3. (Left) Differential gamma-ray sensitivity curves of the CTA south site array for different interaction models (z=20 deg, average of North and South pointing). Ratios to QGSJET-II-03 (currently used in CTA) are also shown in the bottom. (Right) Residual background rates as a sum of proton and electron.

CR composition, since it is known that gamma-ray-like events of hadronic origin are almost pure protons and contribution from heavier nuclei is negligibly small. This fact was already mentioned in the previous studies on CR electron spectrum by H.E.S.S. and VERITAS([14], [15]) and also confirmed with CTA simulation in this work. Along with its relatively large (factor $\sim$2) difference between current models, gamma-ray-like event rate can be a relatively good verification measure of interaction models as a consequence. Development of analysis methods dedicated to discriminate the interaction models will possibly improve the verification accuracy further.

Acknowledgments

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