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Analysis of extensive air showers with the hybrid code SENECA

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The ultrahigh energy tail of the cosmic ray spectrum has been explored with unprecedented detail. For this reason, new experiments are exerting a severe pressure on extensive air shower modelling. Detailed fast codes are in need in order to extract and understand the richness of information now available. In this sense we explore the potential of SENECA, an efficient hybrid tridimensional simulation code, as a valid practical alternative to full Monte Carlo simulations of extensive air showers generated by ultrahigh energy cosmic rays. We discuss the influence of this approach on the main longitudinal characteristics of proton and gamma induced air showers for different hadronic interaction models. We also show the comparisons of our predictions with those of CORSIKA code.

1. Introduction

Since the very first observations, ultra-high energy cosmic rays (UHECR) have been an open question and a priority in astroparticle physics. Their origin, nature and possible acceleration mechanisms are still a mystery.

Due to the very low flux of high energy cosmic rays, measuring extensive air showers (EAS) is the only possible technique to learn about the shape of the UHECR spectrum and their chemical composition. Two different ways have been historically applied to observe and analyze EAS's: ground array of detectors and optical detectors. Surface detectors measure a lateral density sample and trigger in coincidence when charged particles pass through them while optical detectors (i.e., fluorescence detectors) observe the longitudinal profile evolution by measuring the fluorescence light from atmospheric nitrogen excitation produced by the ionization of the secondary charged particles (essentially electrons and positrons).

The combination of shower observables (such as lateral density, the depth of maximum shower development ($X_{\rm max}$), the number of charged particles at shower maximum ($S_{\rm max}$) and number of muons (N_μ) at detector observation level) and simulation techniques is the current way to obtain information about the primary energy, composition and arrival direction. For this purpose the shower simulation should provide all possible, and ideally the necessary, information to interpret measurements of shower parameters.

Many shower simulation packages have been developed over the years. Most of them are based on the Monte Carlo method and simulate complete high energy showers with well described fluctuations in the first particle interactions and realistic distributions of energy of shower particles. Recently, different ways of calculating the air shower development have been proposed [1, 2, 3]. Most of them combine the traditional Monte Carlo scheme with a system of electromagnetic and hadronic cascade equations or pre-simulated showers, described with parameterizations.

In the present contribution we analyze the results obtained by the SENECA [4] code which is based on the Monte Carlo calculation of the first and final stages of the air shower development, and on a cascade equation system that connects both stages reproducing the longitudinal shower development. We explore the main longitudinal shower characteristics of proton and gamma initiated air showers at ultra-high energy, as predicted by the QGSJET [5] and SIBYLL [6] hadronic interaction models. The SENECA predictions are compared with the well tested CORSIKA (COsmic Ray SImulations for KAscade) simulation code [7].

2. Air Shower Modelling

The main goal of this approach is the generation of EAS's in a fast manner, obtaining the correct description of the fluctuations in showers and giving the average values for the shower characteristics. Even though the SENECA code describes both longitudinal and lateral air shower developments, the simulation scheme is used here to generate large statistics of longitudinal shower profiles applicable mainly to the present fluorescence detectors, such as Pierre Auger Observatory [8] and HiRes [9], as well to the future telescope EUSO [10].

For the present work we track explicitly every particle with energy above the fraction $f = E_0/1.000$, where E_0 is the primary shower energy, studying in detail the initial part of the shower. All secondary particles with energy below the mentioned fraction are taken as initial conditions to initialize a system of hadronic and electromagnetic cascade equations [4]. We use the cascade equations with the minimum electromagnetic energy thresholds of 1 GeV for the electromagnetic component ($E^{\rm em}_{\rm min}$) and $E^{\rm had}_{\rm min}=10^4$ GeV for the hadronic component. The hadronic interactions at high energies are calculated with both QGSJET01 [5] and SIBYLL2.1 [6] models. The adopted kinetic energy cutoffs for all simulations were 50 MeV (0.3 MeV) for hadrons and muons (electrons and positrons).

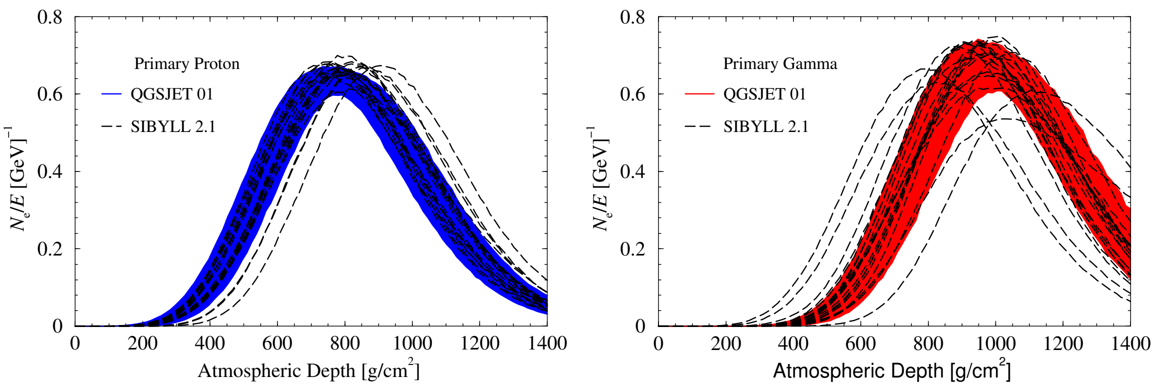

Figure 1. Longitudinal profiles of $e^{\pm}$ illustrates the upper limit of 68% of confidence level for 1000 QGSJET01 shower profiles (dashed area) with 20 random SIBYLL2.1 showers (dashed lines) simulated with SENECA scheme, for proton (left panel) and gamma (right panel) induced showers at primary energy of 10^{19} eV.

3. Results and Comparisons

Although the simulation of showers at fixed energies is not a very realistic application we intend in the present contribution to compare quantitatively SENECA predictions for both hadronic interaction models, providing few comparisons with CORSIKA results. Such study can be useful to many experiments which use the fluorescence technique.

In order to make a simple comparison Figure. 1 illustrates the upper limit of 68% of confidence level for 1000 QGSJET01 shower profiles (dashed area) with 20 random SIBYLL2.1 showers (dashed lines) simulated with SENECA scheme, for proton (left panel) and gamma (right panel) induced showers at primary energy of 10^{19} eV. It is possible to verify a reasonable difference between the longitudinal profiles obtained for both hadronic interaction models. Such predictions reveal distinct descriptions of the $X_{\rm max}$ fluctuations. Moreover, the evolution of hadron-induced showers depends on the elasticity of the interaction defined as the fraction of energy carried by the leading secondary particle. The hadronic model SIBYLL2.1 predicts a larger elasticity than QGSJET01 and by this reason the showers penetrate more in the atmosphere, as can be seen in the left panel of Figure. 1.

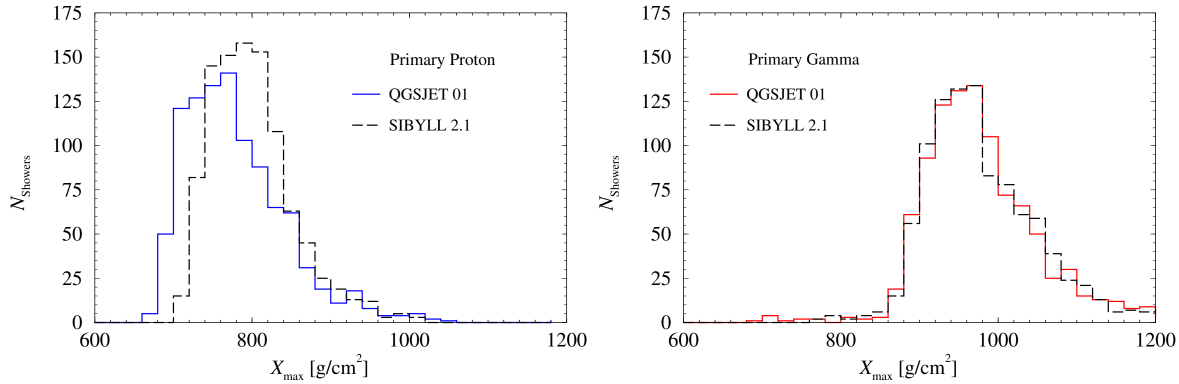

Figure 2. Distributions of the depth of maximum air shower development shown for 1000 proton (left panel) and gamma (right panel) showers at a particular primary energy of 10^{19} eV, with incident zenith angle of 45°, generated by the hybrid technique with QGSJET01 and SIBYLL2.1 hadronic interaction models.

Figure. 2 illustrates the potential of the $X_{\rm max}$ distribution, generated with the hybrid scheme, to distinguish possible primary signatures. In principle, obtaining the values of $X_{\rm max}$ and/or $S_{\rm max}$, by the fluorescence technique, and their respective fluctuations, by Monte Carlo, one should be able to reconstruct the shower energy and infer the identity of the primary cosmic ray [11]. The $X_{\rm max}$ distributions are obtained for proton (left panel) and gamma (right panel) induced showers, at a particular energy of 10^{19} eV, with incident zenith angle of 45°, calculated with the hybrid technique for both QGSJET01 and SIBYLL2.1 hadronic models. Once more we can clearly see the differences between the predicted average values for hadronic shower observables calculated with QGSJET01 and SIBYLL2.1 hadronic interaction models. Such differences can be understood if we analyze the multiplicity. The charged particle multiplicity is an important observable that measures how fast the primary energy is dissipated into low energy sub-showers. The QGSJET model predict a much higher multiplicity at high energies when related with SIBYLL. For this reason, the $X_{\rm max}$ distribution obtained with the QGSJET model is shifted to lower values and presents a wider distribution. For gamma showers, the $X_{\rm max}$ distribution are almost identical.

As a final verification we show the correlation between $S_{\rm max}$ and $X_{\rm max}$, which are important longitudinal shower quantities on event reconstruction. We compared SENECA results with CORSIKA predictions for gamma and proton induced air showers, calculated with QGSJET01 hadronic interaction model. Figure. 3 shows the correlation between these parameters for both simulation schemes. We simulated 500 proton (left panel) and gamma (right panel) showers for each code, of energy 10^{19} eV, incident zenith angle θ=45° and free first interaction point. The full circles (squares) denote the values for CORSIKA (SENECA). It is possible to verify the existence of large fluctuations in gamma (right panel) ray showers at this particular primary energy. The small box in the figure encloses, approximately, the highest density of correlation points for both codes, showing very similar predictions: 61% of the total number of events simulated by SENECA, and 64% of the total showers generated with CORSIKA. For the proton showers (left panel), it is quite visible that the hybrid approach generates a more scattered distribution of showers, with wider tales, than CORSIKA does. This is confirmed by counting the number of events inside the small box shown in the figure. SENECA expectation amounts to 80% of the proton showers falling inside the box while CORSIKA expectation is 85%. The differences mentioned here are most, in principle, due to the air shower fluctuations and are visibly model dependent.

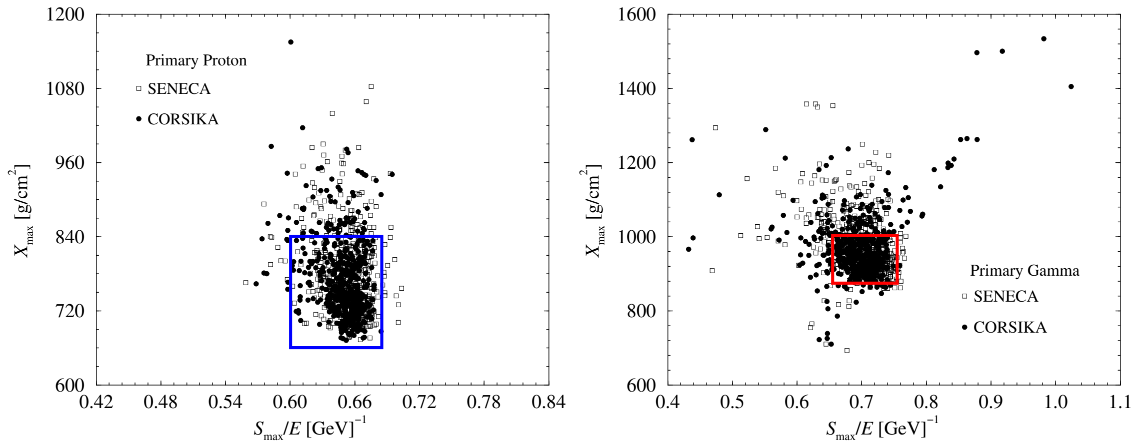

Figure 3. The correlation between $X_{\max}$ and $S_{\max}/E$ for proton (left) and gamma (right) induced showers at primary energy 10^{19} eV, at zenith angle $\theta = 45°$, obtained with SENECA and CORSIKA codes. The full circles represent 500 showers simulated with CORSIKA, while the squares correspond to 500 showers generated with the hybrid method

4. Conclusions

In the present work we analyzed the practical potential of SENECA, a very fast hybrid tri-dimensional code, for the simulation of the longitudinal development of extensive air showers at high energies. The consistency of the SENECA scheme was tested and it proved to be very stable for energies above 10^{18} eV. The results obtained by both codes agree well for the analyzed quantities. Our careful analysis shows that many shower quantities discussed here are strongly model depended. The undisputable bounty of SENECA is velocity which (see [12]), to say the least, is impressive over the primary shower energy simulated for this contribution.

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