Secondary Cosmic Ray particles due to GCR interactions in the Earth's atmosphere

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Abstract

Primary GCR interact with the Earth's atmosphere originating atmospheric showers, thus giving rise to fluxes of secondary particles in the atmosphere. Electromagnetic and hadronic interactions interplay in the production of these particles, whose detection is performed by means of complementary techniques in different energy ranges and at different depths in the atmosphere, down to the Earth's surface.

Monte Carlo codes are essential calculation tools which can describe the complexity of the physics of these phenomena, thus allowing the analysis of experimental data. However, these codes are affected by important uncertainties, concerning, in particular, hadronic physics at high energy. In this paper we shall report some results concerning inclusive particle fluxes and atmospheric shower properties as obtained using the FLUKA transport and interaction code. Some emphasis will also be given to the validation of the physics models of FLUKA involved in these calculations.

Keywords: GCR EAS, inclusive fluxes of secondary particles, Monte Carlo models and codes
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1 Introduction: EAS development and detection

GCR interactions in the Earth's atmosphere, induced by particles with energies high enough (E $\gtrsim 10^{14} - 10^{15}$ eV), may originate Extended Air Showers (EAS). Both the EM and the μ component of EAS can be detected and used to infer properties concerning GCR primary spectrum energy and composition. At present, a special emphasis is put in the investigation of Very High and Ultra High Energy Cosmic Rays (VHECR and UHECR), through dedicated experiments devoted to the detection of EAS originated by these particles, due to the still open questions concerning the shape of the spectrum (2^{nd} knee, ankle), the composition (γ, p, heavy ions), and the origin of cosmic rays (galactic / extragalactic), their transport, acceleration and the GZK cut-off.

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Information on GCR primary flux and composition are inferred from the experimental observables by using Monte Carlo (MC) simulations. In particular, while the fluorescence technique, used by many experiments, allows with some uncertainties to estimate the EM energy deposited in the atmosphere, the total primary energies can be obtained only after estimating the missing energy carried by other shower components (μ, nucleons...), and this requires indeed MC simulations. Even the search for particular estimators, such as the S variable, allows to obtain primary energy information in a way nearly independent of composition [1], but needs MC for calibrations.

In particular, in the AUGER experiment [2] information on primary energies are inferred by hybrid measurements and the fluorescence technique as far as the EM sector is concerned (with an uncertainty amounting to $\sim$ 20%), whereas the number of μs at the Earth's surface, N_μ, is still related to total primary energies by means of MC simulations. On the other hand, in the KASCADE and KASCADE-Grande experiments [3] information on primary energies are inferred from measures of μ and e with the aid of MC shower simulations. Both in AUGER and in KASCADE / KASCADE-Grande, as well as in many other EAS experiments, MCs are heavily needed to analyse data in terms of GCR mass composition. At present there are however still important uncertainties, since different MC models produce important differences on the interpretation of the same data. The critical ingredients in these MC codes are the physical models for hadronic and nuclear interaction, and their implementation.

In this work we summarize some of the results which can be obtained by MC simulation of EAS, giving examples taken from the use of the FLUKA code.

2 MC simulation of EAS

EAS simulations can be performed by means of MC codes, which include hadronic and EM modules. This method leads, in a straightforward way, to account for fluctuations in the evolution of different showers initiated by primaries of the same type and energy.

The GCR primary spectrum covers a wide energy range, extending on many orders of magnitude. This fact implies that it is very difficult to have in a MC code a single hadronic model able to describe primary and secondary hadron interactions in the Earth's atmosphere. Therefore in many cases different models, differing according to the energy range under study, have to be merged together.

At present the most diffused MC package for GCR induced shower simulation is CORSIKA [4]. As far as its hadronic sector is concerned, it distinguishes between high energy (E $\gtrsim$ 100 - 200 GeV) and low energy (E $\lesssim$ 100 - 200 GeV) hadronic models. In the present version, CORSIKA offers the choice, at high energy, among models like QGSJET, QGSJET-II, SIBYLL, DPMJET-2.55, NEXUS, EPOS, whereas, at low energy, GHEISHA, UrQMD, FLUKA are available. Other packages for GCR EAS simulation also exist. We just mention, among the others, the AIRES [5] and the Cosmos [6] codes.

In this paper, we focus instead on the performances of the FLUKA multipurpose code [7]. FLUKA is a fully integrated, high precision, transport and interaction code, without the need of invoking other external packages. Besides its use in the CORSIKA package at energies $\lesssim$ 100 - 200 GeV, FLUKA has recently been used also as a standalone code, complemented by the DPMJET-III code [8], for the simulation of EAS at energies

$< 10^{16}$ eV. FLUKA simulations can, in principle, lead to results different from the ones made by FLUKA+CORSIKA, due to the implementation of different EM and hadronic models. FLUKA contains a highly accurate EM interaction model [9, 10], not included in CORSIKA. As far as the hadronic sector is concerned, the following models are available in FLUKA:

- low energy (E < 20 TeV) h + A reactions can be simulated by means of the PEANUT (PreEquilibrium Approach to NUclear Thermalization) module, originally worked out for energies < tens of GeV [11], and recently improved and extended to higher energies [12]. This extension has superseded a previously existing DPM + INC model, working at E > 5 GeV.
- high energy (E > 20 TeV) h + A reactions can be described by means of the interface to the DPMJET-2.5 or III codes.
- A + A reactions can be simulated by means of an interface to the RQMD2.4 code, written in Frankfurt and modified for insertion in FLUKA [13], for E < 5 GeV/A, and by means of the interface to the DPMJET-2.5 or III codes for E > 5 GeV/A. Alternatively, the superposition model is also available to roughly describe heavy-ion interactions.

Constraints on theoretical models for particle interactions can (or will) be obtained by data collected at collider experiments, but, unfortunately, diffractive cross-sections are difficult to be measured at colliders. Furthermore, present and near future accelerators do not and will not allow to test the physics of particles at the highest GCR energies (E > 1.5 10^{18} eV, GCR spectrum tail). Thus, MC models used in the analysis of EAS data are still affected by important uncertainties, concerning in particular the hadronic sector. Other constraints/checks on low-energy models, besides the ones from accelerator data, can come from astrophysical measurements of inclusive particle fluxes at different atmospheric depths, as performed by balloon-borne experiments and satellites. We emphasize that for an accurate description of VHECR and UHECR EAS also low-energy physics is important, e.g. the larger is the distance from the shower core and the shower inclination, the stronger is the required accuracy of the adopted low energy models.

2.1 Validation of the FLUKA models at low energies

Validation of the FLUKA models at low energies has been performed by means of comparisons of their theoretical predictions with data collected at the accelerators. Data concerning inclusive particle fluxes in the atmosphere down to the Earth's surface, have been then used to assess the FLUKA performance on cosmic ray physics.

While the first issue can be addressed by using the version of the code officially distributed and available on the web, the second one requires the inclusion of further (geometrical, geomagnetical, astrophysical) assumptions and information. These elements have been inserted by means of the FLUKA user routines.

Validation of FLUKA using accelerator data Data recently collected by the HARP and the NA49 experiments have been nicely reproduced by means of FLUKA [10], Many others validations of the code, referred to previously published data, can be found in literature. Furthermore, data from the SPS collider, Tevatron and RHIC have been used to successfully validate the DPMJET2.5 and III codes [14].

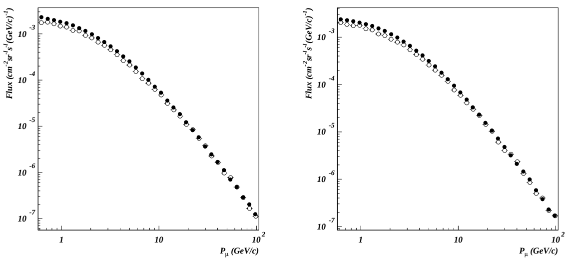

Figure 1: Calculated inclusive fluxes of μ^- (*left panel*) and μ^+ (*right panel*) at the top of Mt. Norikura ($\sim$ 2700 m a.s.l.) as obtained by FLUKA simulations (open symbols) vs. exp. data [15] from BESS'99 (full symbols). Other examples of FLUKA benchmarks in GCR physics can be found in [16].

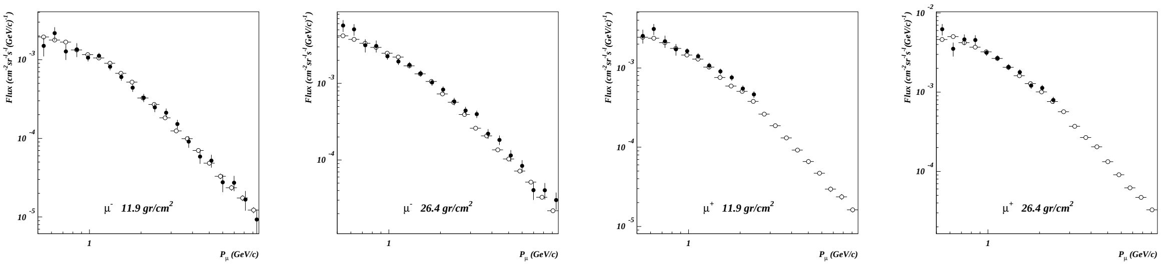

Figure 2: Calculated inclusive fluxes of μ^- (*left panels*) and μ^+ (*right panels*) at atmospheric depths of 11.9 g/cm^2 (*odd panels*) and 26.4 g/cm^2 (*even panels*), respectively, as obtained by FLUKA simulations (open symbols) vs. exp. data [17] from BESS 2001 (full symbols).

Validation of FLUKA using astrophysical data from satellites and balloon-borne experiments Inclusive particle fluxes in the Earth's upper and lower atmosphere, induced by GCR propagation and interactions, have been measured by means of satellites and balloon-borne experiments such as BESS. Different sets of data, taken in different atmospheric and geomagnetic conditions, have been analyzed and reproduced by FLUKA, under proper assumptions concerning GCR primary spectrum, solar modulation, atmospheric and geomagnetic models. As examples, data concerning μ collected at the top ($\sim$ 2700 m a.s.l.) of Mt. Norikura (geomagnetic cut-off $\sim$ 11.2 GV) in 1999, and at two different atmospheric depths (11.9 and 26.4 g/cm^2) in a balloon flight campaign over Ft. Sumner (geomagnetic cut-off $\sim$ 4.2 GV) in 2001, are presented in fig. 1 and 2, respectively, and compared to the theoretical fluxes expected on the basis of FLUKA simulations. The agreement between the experimental and theoretical results is quite nice and increases at increasing energies. Furthermore, atmospheric μ charge ratios in the energy range from $\sim$ 20 GeV up to $\sim$ 3 TeV have been detected by the L3+C experiment at CERN ($\sim$ 450 m a.s.l.), that has provided also μ arrival directions. FLUKA has successfully reproduced also these data [18].

Proton and heavier ion inclusive fluxes have also been obtained by FLUKA theoretical simulations and compared to experimental data available from BESS. In these cases, the results of the simulations turn out to be very sensitive to a correct treatment of the geomagnetic cut-off, of the transport of particles in the upper layers of the atmosphere (trapping of particles and their recirculation), and to the accuracy of the theoretical modelling of low-energy A-A interactions.

2.2 Predictions of the FLUKA models at high energies: EAS

In the following we shall report about some tests of EAS simulation at energies 10^{14} - 10^{15} eV, performed by means of FLUKA, complemented by DPMJET-III for the description of A-A reactions at E $>$ 5 GeV/A and h-A reactions at E $>$ 20 TeV. Vertical showers, induced by primaries of different mass (p and Fe ions), have been considered.

The X_{max} position, i.e. the atmospheric depth where the shower reaches its maximum development (in terms of EM energy deposition), is a good probe of GCR composition. In fact, since the inelastic scattering cross-section for p-Air interactions is lower than the A-Air ones, EAS induced by Fe primaries have, on the average, vertical profile maxima shifted towards lower atmospheric depths than p induced showers. e and μ fluences as a function of the atmospheric depth ρ for p and Fe induced showers at 10^{14} and 10^{15} eV, as calculated with FLUKA + DPMJET-III, are shown in ref. [10]. In general, different codes, based on different models, due to different modelings of hadronic and EM processes, give different results for X_{max}. Anyway, to disentangle the effects of different models and different primary composition, also more specific variables can be considered. Among the others, the study of X_{max} fluctuations [19] for primaries at a fixed energy has been proposed for this purpose. As an example, X_{max} fluctuations for Fe induced showers have been computed from our simulations, considering the e, μ, charged hadron and neutral hadron vertical shower profiles, and are shown in the central and right panels of fig. 3. In general, the average muon X_{max} is located at larger ρs with respect to the electron one, since μs penetrate more deeply. The charged hadrons undergo strong absorption effects, thus their X_{max} are located at lower ρs with respect to the ones of neutral hadrons.

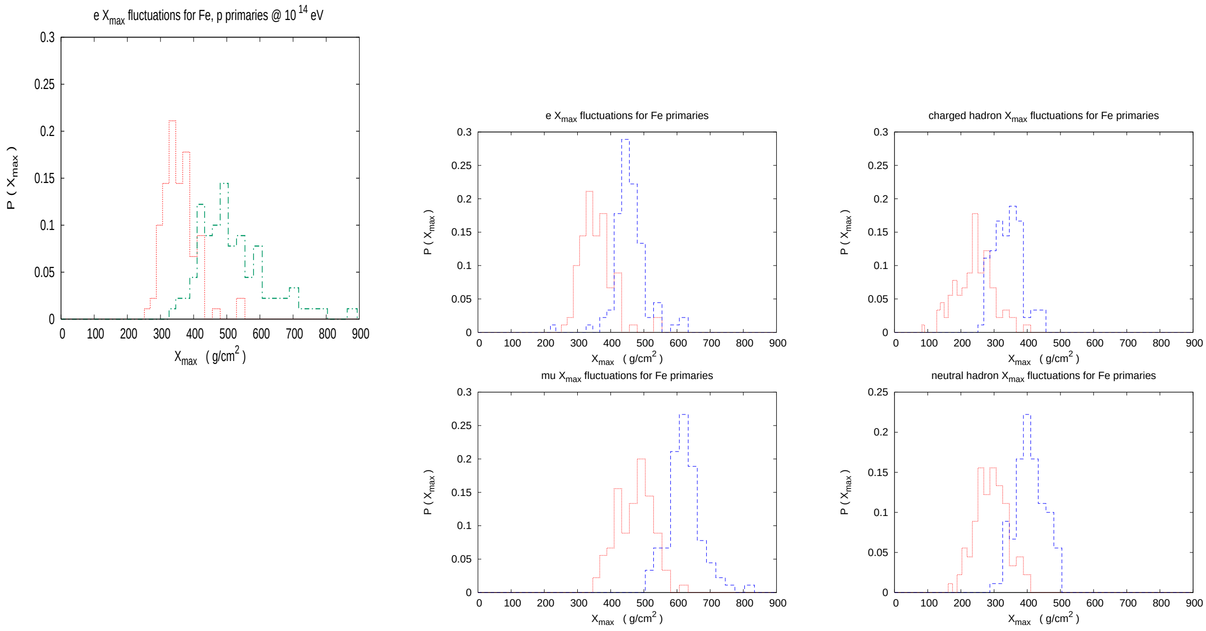

Figure 3: *Left panel*: fluctuations in the distribution of e $X_{\max}$ for a few hundred vertical showers induced by p (*dot-dashed green line*) and Fe ions (*dotted red line*) at 10^{14} eV energy. *Central and Right panels*: fluctuations in the distribution of e $X_{\max}$ (*central upper panel*), μ $X_{\max}$ (*central lower panel*), charged hadron $X_{\max}$ (*right upper panel*) and neutral hadron $X_{\max}$ (*right lower panel*) for a few hundred vertical showers induced by Fe ions at 10^{14} eV (*dotted red line*) and 10^{15} eV (*dashed blue line*) energies.

Increasing energies lead, in general, to a shift of $X_{\max}$ to higher ρs for all considered profiles, even if, in all cases, the fluctuation profiles at 10^{14} and 10^{15} eV overlap. That means that reconstructing the energy of GCR primaries out of this method is not possible, since showers of energies that differ even by a factor 10 can give rise, in some cases, to the same position of $X_{\max}$. An example from our simulations of the sensitivity of $X_{\max}$ fluctuations to the GCR primary composition is shown in the left panel of fig. 3. Not only the position of maxima but also the shape and broadness of the fluctuation profiles change according to the GCR masses, as can be seen by comparing the cases of p and Fe induced EAS at a fixed energy (10^{14} eV for the cases considered in the figure).

Besides the vertical spreads of particle distribution, also lateral spreads can be calculated. In particular, in case of EM particles, the lateral spread is due to the effect of multiple Coulomb scattering, while, in case of μs, the lateral spread is mainly correlated with the p_T distribution of charged π and K, from the decay of whom μs originate (we are not mentioning here μs from the decay of short-lived charmed particles, which are also considered in FLUKA and other codes). Detailed maps of e and μ fluences in the atmosphere, down to the Earth's surface, which allow to appreciate both the average vertical profile and the lateral spread of each component, as calculated by FLUKA for Fe induced showers, can be found in [10].

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