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Investigation of soft component in cosmic ray detection

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ABSTRACT

Cosmic ray detection is a research area which finds various applications in tomographic imaging of large size objects. In such applications, the background sources which contaminate cosmic muon signal require a good understanding of the creation processes, as well as reliable simulation frameworks with high predictive power are needed. One of the main background source is the “soft component”, that is electrons and positrons. In this paper a simulation framework based on GEANT4 has been established to pin down the key features of the soft component. We have found that the electron and positron flux shows a remarkable invariance against various model parameters including the muon emission altitude or primary particle energy distribution. The correlation between simultaneously arriving particles have been quantitatively investigated, demonstrating that electrons and positrons tend to arrive within a close distance and with low relative angle. This feature, which is highly relevant for counting detectors, has been experimentally verified under open sky and at shallow depth underground. The simulation results have been compared to existing other measurements as well as other simulation programs.

1. Introduction

The primary cosmic rays (mostly hadrons) originating from astrophysical sources enter to our atmosphere isotropically, from which hadronic interactions produce secondary mesons, mostly pions and kaons. The competition of energy dependent processes, decays and interactions produce three different components, namely the hadronic-, muonic- and soft component. Out of these the muons are prominent at sea level due to their high penetrating power, however the most energetic primary particles with the energy of several TeV create Extensive Air Showers (EAS) which spread a high number of particles over a large area [1].

The motivation for the study to be presented was to find a computation efficient approach fully relevant for time resolved, ground based cosmic muon imaging systems. Some of the key findings are intuitive, however background estimation with a good predictive power required quantitative understanding as well. The aim of the study was to clarify the origins and pin down key features of spectra, ratios and correlations, and to pin down the creation altitudes and involved production processes of electrons, positrons and muons.

From the practical point of view, this study can provide an important impact on background estimation for muography measurements (imaging with cosmic muons), where the suppression of the soft particles in case of tracking detectors is an important issue [2,3].

The soft (electron, positron, photon) component creation is initiated either via the decay of neutral pions into a pair of photons, $\pi^0 \rightarrow \gamma + \gamma$, or via the muon decay. Subsequent steps of the electromagnetic shower development produces electrons and positrons via pair production and creates photons via Bremsstrahlung. Knock-on electrons (delta rays), being part of the ionization process, are relevant mostly for energetic muons. The mean energy of the created electrons is close to the critical energy (at which the Bremsstrahlung and the energy loss by ionization are equal, 90 MeV in air), that is, considerably lower than the GeV-range of the mean muon energy.

The nature of the soft particles is not easy to understand. The atmosphere of Earth can be seen as a large “calorimeter”, in which the hadronic shower develops. The electrons and positrons are mostly created by the electromagnetic sub-showers, which is expected to determine their local structure. In the present paper, the applied strategy was that in the first place muon induced reactions (decay, electromagnetic shower) were studied, and once the key systematic features were understood, other circumstances (proton induced air shower, or underground measurements) were considered.

For the simulation of secondary particles, including eventually the primary particles as well, different approaches exist. The COsmic Ray SImulations for KAscade (CORSIKA) [4] provides a de-

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Table 1
The main parameters of the simulations: the type of primary particles injected into the simulation, the altitude of the primary emission and in case of CRY the emission altitude of muons, electrons and gammas, the exponent of the power function of energy, the zenith angle and in case of CRY the range of emission angle (θ), the strength of the magnetic field, the detector level relatively to sea level (0 m), as well as the number of generated events.

Simulation primaries	Altitude km	Exponent n	θ deg	Mag. field µT	Det. level m	Events $\times\ 10^6$
$\mu^\pm$	15	−2.7	0	0	0	0.5
$\mu^\pm$	10	−2.7	0	0	0	0.5
$\mu^\pm$	6	−2.7	0	0	0	0.5
$\mu^\pm$	6	−2.2	0	0	0	0.15
$\mu^\pm$	6	−3.2	0	0	0	0.15
$\mu^\pm$	6	−2.7	60	0	0	0.5
$\mu^\pm$	6	−2.7	0	28.3	0	0.4
$\mu^\pm$	6	−2.7	0	63.6	0	0.4
$\mu^\pm$	3	−2.7	0	0	0	0.25
p	30	−2.7	0	0	0	0.5
CRY	0	–	0–90	0	0	1
CRY	0	–	0–90	0	−7.5	3.3
CRY	0	–	0–90	0	−10	0.5
CRY	0	–	0–90	0	−50	0.2

tailed simulation of extensive air showers with the possibility to apply different primaries (such as photons, muons, protons or iron nuclei), to include different hadronic interaction models (such as Dual parton Model DPMJET [5] or HDPM [6] at high energies and FLUKA [7] or GEISHA [8] at low energies), and to include the interactions of the soft component as well as providing all the decay branches. Another example is the Cosmic-ray shower generator (CRY) [9] simulation which is based on precomputed tables derived from MCNPX simulations [10]. Evidently, CRY is expected to require considerably less computational time, whereas may lack reliability on the shower development geometry.

The structure of the paper is as follows. In Section 2 the used Monte Carlo framework is outlined. In Section 3 the basic observations on the simulation results on the soft component in terms of spectra, ratios and correlations are discussed. In Section 4 consistency tests, comparisons to CRY and to measurement data is presented. In Section 5 a study in case of a shallow depth underground setting is presented. In Section 6 a summary is presented.

2. Description of the simulation framework

To simulate the penetration of particles across the atmosphere a code based on GEANT4.9.4.p01 release [11] has been developed. In the simulation, the atmosphere is represented by a rectangular volume with the area of 5 km × 5 km and the height of 10 km. The air column has been horizontally divided into 20 layers with thickness of 0.5 km, and with the pressure set according to the 1976 US atmosphere model [12]. The atmosphere layers have been composed of N_2, O_2, and Ar with the volume fractions of 78.1%, 21.0% and 0.9% respectively.

The simulation incorporates all of the relevant electromagnetic physics process [13,14] for muons, electrons, positrons and gammas (decay, multiple scattering, ionization, Bremsstrahlung, pair production, annihilation, gamma conversion, Compton scattering and photo-electric effect). The Earth's magnetic and electric fields has not been taken into account.

The simulations and the main parameters, including type of primary particles, altitude of production, exponent of energy distribution, zenith angle and the number of generated primaries are summarized in Table 1. In the context of the simulation, the "primary" refers to the emitted particle in the simulation, and not the true primary cosmic ray. The energy distribution of the emitted particles (muons or protons) was assumed to always follow a power law for simplicity, $N(E) \propto E^n$. Primaries have been generated from different altitudes. The passage of primaries and secondary electrons and gammas have been simulated across the atmosphere. For charged particles, the identification numbers (PDG, track and mother), the momentum direction vector, position vector and energy have been recorded in their creation and at sea level. To simulate the detector effects (such as energy cut) a low material budget tracking has been deployed. The tracking layers are assumed to be standard printed circuit board (Oxygen, Carbon, Silicon, Hydrogen and Nitrogen in the portion of 40:28:18:7:7) layers with thickness of 2 mm, the density of 1.7 gcm^{-3} and the size of 5 km × 5 km and have been placed parallel under each other with the equivalent distance of 5 cm. The energy, momentum and position vectors of charged particles have been recorded in the tracking layers as well.

Most of the simulations were run with muon primaries. To provide complete air shower simulation and explore the limits of our model, protons induced simulations has also been developed. Proton primaries have been generated at the altitude of 30 km with the power law energy distribution with the exponent value of $n = -2.7$. To provide both electromagnetic and hadronic interaction as well as reliable particle production, the QGSP_BERT physics list [15] has been applied in the simulation framework. The atmosphere model and detector configuration was the same as in the muon induced simulation.

In order to verify our results against a widely used simulation framework, comparison to the CRY simulation was also performed. In case of CRY, the primary protons are generated by MCNPX simulations at the altitude of 31 km with energy from 1 GeV up to 100 TeV and tracking of the particles across the atmosphere based on 1976 US atmosphere model down to sea level was performed. Muons, electrons and gammas are generated from precomputed tables at various altitudes via GEANT4 output which allowed us to set up the same detector configuration.

3. Results of the simulations

In this section, the results of the simulation framework are presented: details on production conditions, sources, energy spectra and ratios as well as spatial and angular correlations of secondary electrons/positrons are detailed.

3.1. Sources of soft component at sea level

The soft component of cosmic rays originates from well understood particle physics processes, whereas the quantitative proper-