PROCEEDINGS OF SCIENCE

Development of a hybrid air shower simulation tool COSMOS X

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Extended COSMOS, COSMOS X, is a major upgrade of the air shower simulation tool COSMOS, which has been developed since 1970's. COSMOS X allows particle tracking not only in the atmosphere of the earth but in the arbitrary spherical media such as water, ice, scintillator, soil and concrete with a common center. This hybrid feature of COSMOS X extends the possibility of shower simulations in the atmosphere of stars and planets. In this contribution basic functions and some interesting applications of COSMOS X are presented. Recent samples include a simulation in the atmosphere of the Sun and an implementation of arbitrary interaction vertex, which allows a simulation of neutrino-initiated showers through external interaction generators.

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1. Introduction

The importance of the air shower simulation is increasing according to the developments of observation technic and the applications of the secondary cosmic-ray detection in the various cases. CORSIKA [1] is leading the community as the standard tool, but COSMOS is also capable of satisfying most of the applications [3]. At the same time, a major update of CORSIKA version 8 is now undergoing [2]. Not only proposing COSMOS as an alternative of COSMOS, it is also important to compare three tools to test the validity and uncertainty of air shower simulations. A major update of COSMOS to the extended COSMOS, COSMOS X, is now capable of simulating particle tracking not only in the earth's atmosphere but also various material such as water, concrete, soil. Such hybrid feature opens window for various applications of cosmic-ray physics and helps designing new future experiments. In this paper, an overview of COSMOS X is described.

2. COSMOS X

COSMOS X [4] means the extended COSMOS, which is born as a combination of the air shower simulation tool COSMOS and the detector simulation tool EPICS [5]. Thanks to the inclusion of the detector simulation tool, COSMOS X enables a seamless particle tracking from the atmosphere to, for example, soil, water, ice and concrete materials. The shape of the material is not arbitrary, but it is restricted to a spherical shell with the common center. Practically this means a layer of infinite size. If a user defines gas layers with radius different from the radius of the earth, one can simulate air shower development at non-earth planet or Sun. Some existing applications are introduced in Sec.4.

3. Structure of COSMOS X

COSMOS X is an open source tool and available from webpage [1]. Main codes are composed of Fortran language and gfortran compiler is supported. Major hadronic interaction models such as QGSJET, EPOS and Sibyll are in the package and their latest versions are included at a reasonable pace. Users are not requested to install any external tools. Once the compilation of the main code is completed, users are requested to edit following parameter files and one main code.

- **primary file** contains information of the primary particles. It is not only single mono-energetic particle, but users can define a list of multiple particles with their energy spectra (relative fluxes). An example of cosmic-ray mixed mass composition spectra is available in the package. It is useful when one wants to simulate secondary cosmic-ray flux in a room of a students' laboratory course.

- **param file** contains condition of simulation such as observation longitude, latitude and hight. Ranges of the zenith and azimuthal angle are also specified here. A list of heights to sample particle information is also defined in this file. When one wants to define non-standard atmosphere or non-air material layers, an optional external material list file is defined here.

[1] https://www.icrr.u-tokyo.ac.jp/cosmos/

- **chook.f file** is a Fortran code which user defines. Some predefined subroutines, which are called from the main routine at certain condition, are contained in this code. *chookBgRun* is called at the beginning of the simulation sequence where users can output simulation conditions. *chookObs* is called when a particle passes a predefined height level. *chookEnEvent* is called at the end of each event where users can output summary of this event. Users can find appropriate subroutines and edit them to customize their simulations.

Depending on the application, users are requested to edit files to define material layers, Fortran code to define the electromagnetic field, and response to the ionization energy loss.

4. Examples

Some interesting applications of the secondary cosmic-ray simulation are already found in the publications of geophysics research [6][7].

Depending on the users' demand, various patterns of example code are prepared in the package.

- **FirstKiss** is the first example to know how COSMOS X works. Mono energetic single particle is injected and particles arriving at a height defined in *param* are output. At the same time, information of all track (file) is damped. Together with a visualization code using ROOT, user can easily visualize the air shower a shown in Fig.1. Of course, *trace* file is a large file, it is recommended to use in a small number of showers.

- **PrimaryHowTo** outputs information of incident particle and kills the tracking immediately so that the user can easily confirm if the spectum of primary cosmic ray is correctly defined. An example of spectra defined in a mixed-mass spectra *primary* file is shown in Fig.2.

- **MyField** allows to define arbitrary electromagnetic field in the medium. Figure 3 shows an example of air shower development in a uniform horizontal electric field. Separation of electrons (yellow) and positrons (red) is clearly seen.

- **UnderGround** calculates response of plastic scintillators located at the sea level ground and underground below 1 m soil and 2 m air layers as shown in Fig.4 (left) for a vertical 100 TeV proton shower. Figure 4 (top) shows the energy deposit of 1 m$times$1 m scintillators. Instead of the smooth lateral distribution at the ground level, underground distribution exhibits a clustering structures representing some local hadronic cascades developped in the 1 m soil layer. A $\sim$10 nsec timing difference between the ground and underground (bottom) is consistent with the 3 m vertical difference between two scintillator layers.

More samples to guide to draw lateral distribution, longitudinal distribution, tracking in the Solar atmosphere, neutrino interaction in the atmosphere are included.

5. Summary

COSMOS X is a new type of air shower simulation tool kit convenient for the design of new experiments not only for the cosmic-ray physics and calculations of cosmic-ray interactions in the non-earth environments. The release version is available in the web page.

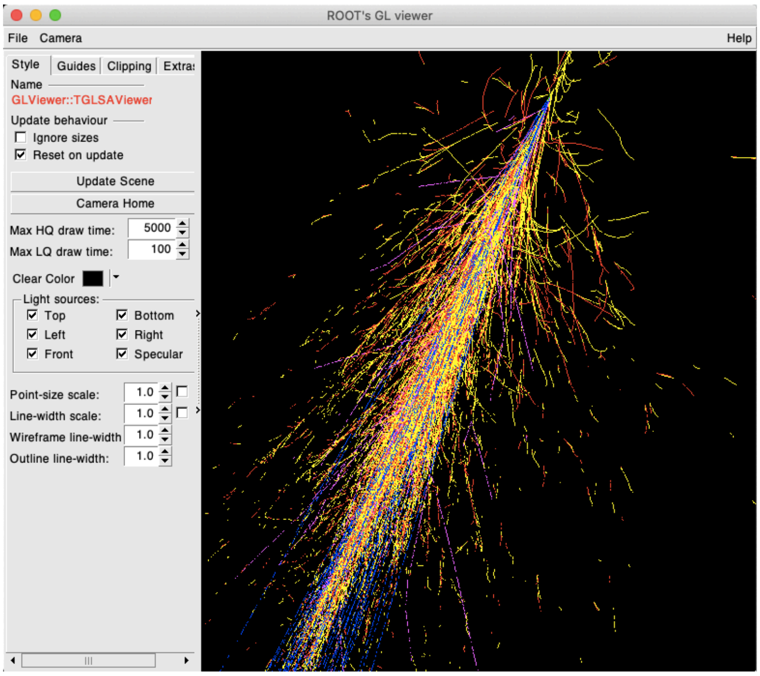

Figure 1: Visualization of a trace output.

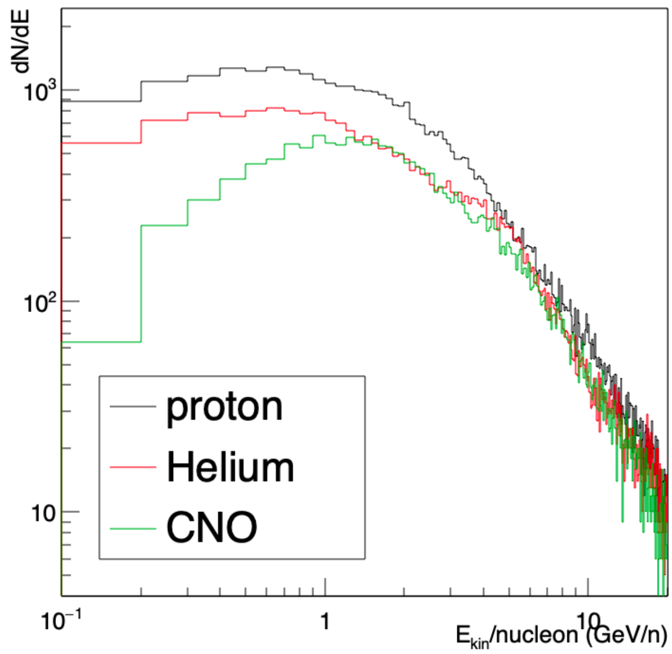

Figure 2: Energy spectra of mixed mass primary file.

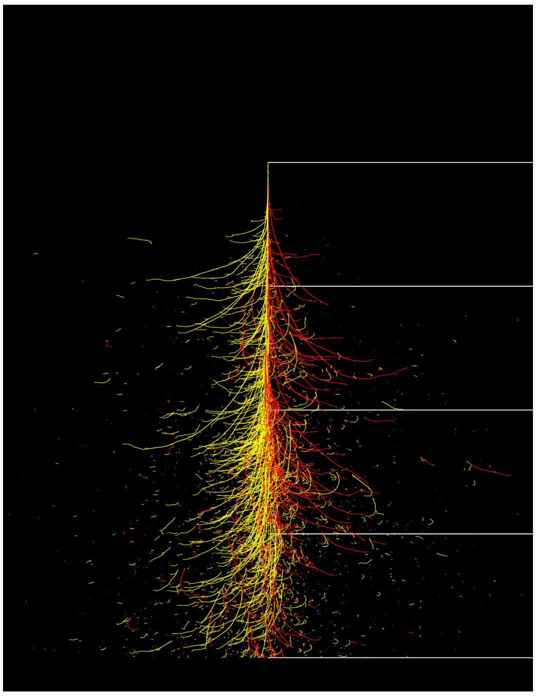

Figure 3: An air shower development in a horizontal electric field. Yellow and red lines indicate tracks of electrons and positrons, respectively.

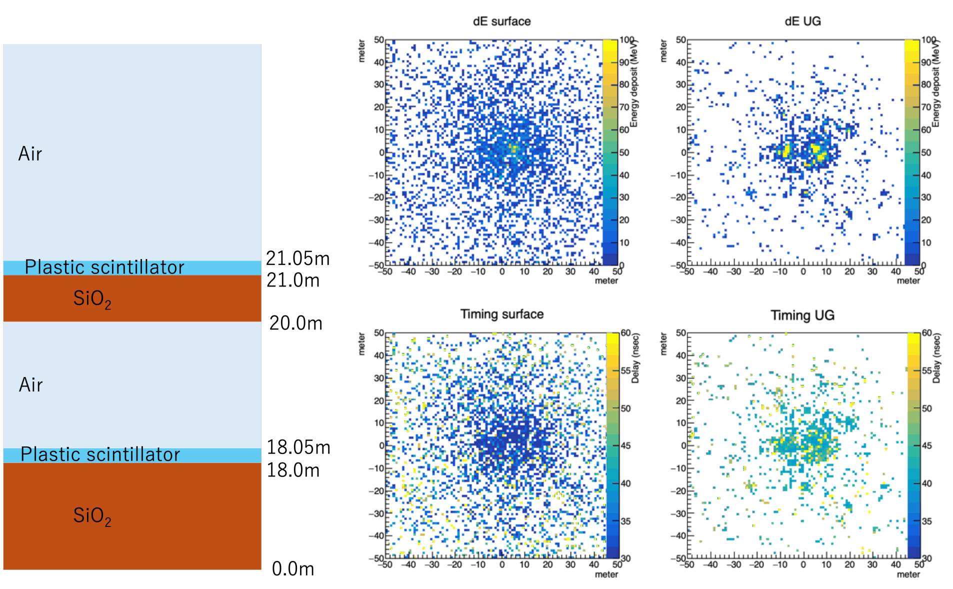

Figure 4: (Left) Setup of the *UnderGroud* sample. (Right) Energy deposit (top) and signal timing (bottom) of the scintillator tile at the ground level (middle) and underground (right).

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