



## Comparison Study of Extensive Air Shower Simulations with COSMOS and CORSIKA

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**Abstract:** COSMOS and CORSIKA are Monte Carlo codes for extensive air shower (EAS) simulations, which are currently being used to analyze the data of the Telescope Array experiment. Using the two codes, we have generated a library of about 10,000 simulated EASs with the primary energy ranging from  $10^{18.5}$  eV to  $10^{20.25}$  eV and the zenith angle of primary particles ranging from  $0^\circ$  to  $45^\circ$  for proton and iron primaries. We have compared simulations from CORSIKA and COSMOS, which were obtained under the same condition. Our comparison has shown differences in the longitudinal particle distribution, the  $X_{max}$  value, the calorimetric energy, the energy distribution at the ground, and the lateral distribution function. The results are presented and the implications are discussed.

**Keywords:** Ultra-high energy cosmic ray, Air shower simulation, CORSIKA, COSMOS

## 1 Introduction

Cosmic rays with energy larger than  $10^{18}$  eV are referred to as ultra-high energy cosmic rays (UHECRs). When they enter the atmosphere, they generate extensive air showers (EASs), which can be observed by ground arrays and fluorescence telescopes. The Auger [1] and Telescope Array (TA) [2] experiments perform hybrid observations of UHECRs with ground arrays and fluorescence telescopes.

In an EAS, the cascade of interactions induced by an UHECR in the upper atmosphere, results in a very large number of secondary particles: of order  $10^{12}$  particles for a primary particle with energy  $10^{19}$  eV. Experiments detecting UHECRs utilize EAS simulations to evaluate their energy, composition and arrival direction. So EAS simulations need to provide us with the information on the momentum, energy, time, and direction of secondary particles. In order to reproduce EASs, detailed Monte Carlo codes are required; they follow the development of interactions produced by UHECRs. COSMOS [3] and CORSIKA [4] are among such the Monte Carlo codes. The TA experiment employs both CORSIKA and COSMOS to cross-check EAS simulations.

In this paper, we present a comparison between CORSIKA and COSMOS simulations, concerning the differences in the longitudinal particle distribution, the  $X_{max}$  value, the calorimetric energy, the energy distribution at the ground, and the lateral distribution function (LDF) in EAS.

## 2 Simulations

The results in this paper are based on simulations from the COSMOS version 7.54 and the CORSIKA version 6960. Most widely used hadronic interaction models in each codes have been employed. At high energies, the QGSJET II-03 [5] model has been chosen for both COSMOS and CORSIKA. At low energies, the FLUKA version 2008 model has been used for CORSIKA, while the PHITS [6] and JAM [7] models have been used for COSMOS. For electromagnetic interactions, the EGS4 code was chosen for CORSIKA, while the Tasi's and Nelson's formula was used for COSMOS. Both CORSIKA and COSMOS use 80 GeV as the transition value between the high and low energies.

In order to reduce the computing time, a "thinning" has been turned on; it works below  $10^{-7}$  times the primary energy in both COSMOS and CORSIKA. The cut energies have been set to be 500 KeV, 500 KeV, 50 MeV, and 50 MeV for photons, electrons/positrons, muons, and hadrons, respectively, in the both codes. We have set 1430m above sea level as the observation site of TA; the level corresponds to an atmospheric depth, 875 g/cm<sup>2</sup>.

EASs with the primary energy,  $E = 10^{18.5}, 10^{18.75}, 10^{19}, 10^{19.25}, 10^{19.5}, 10^{19.75}, 10^{20}$  and  $10^{20.25}$  eV, and the zenith angle,  $\theta = 0^\circ, 31.75^\circ$ , and  $45^\circ$ , for proton and iron primaries (about 30 EASs for each  $E$ ,  $\theta$ , and primary with COSMOS and CORSIKA) have been used for this paper.

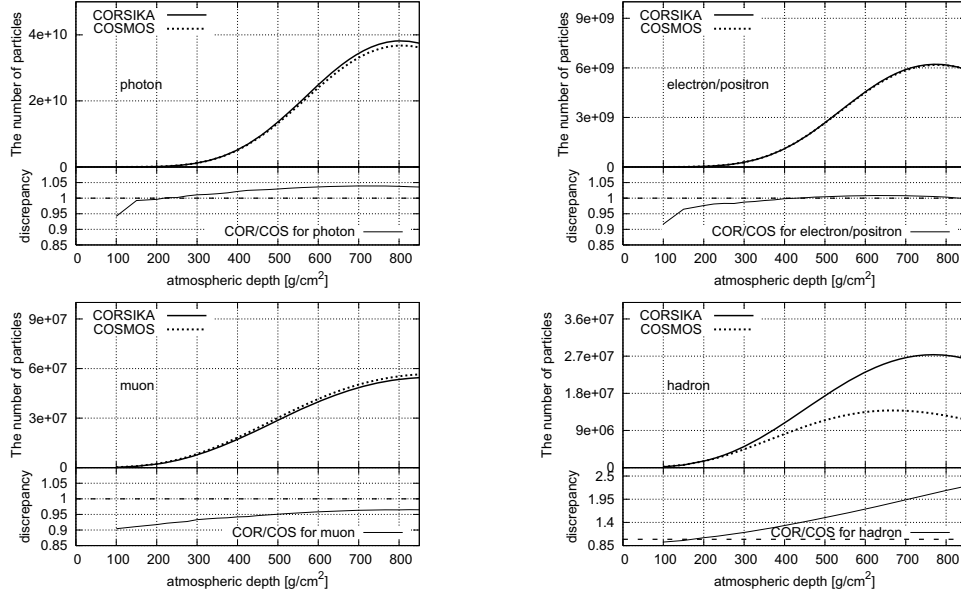


Figure 1: Longitudinal profiles of photons, electrons/positrons, muons and hadrons for an EAS of proton primary at  $E = 10^{19}$  eV and  $\theta = 0^\circ$ . The bottom panel shows the ratio of the number of particles from CORSIKA and COSMOS.

### 3 Results

#### 3.1 Longitudinal particle distribution

We first present the longitudinal profiles of particles from COSMOS and CORSIKA simulations. Figure 1 shows as a function of atmospheric depth, the longitudinal particles distribution of photons, electrons/positrons, muons, and hadrons for an EAS of proton primary with  $E = 10^{19}$  eV and  $\theta = 0^\circ$  (vertical shower). The agreement in the electron number is very good. On the other hand, the photon number is predicted to be larger with CORSIKA, while the muon number is expected to be larger with COSMOS. The maximum difference in the photons and muons numbers is  $\sim 5\%$ . However, the difference in the hadron number is much larger, although the number itself is much smaller than those of other particles.

#### 3.2 $X_{max}$ value

$X_{max}$  is the atmospheric depth of the shower maximum. It is known to be effective in determining the composition of primary particles. We have employed the following function for the electron distribution,  $N(x)$ ,

$$N(x) = a \left( \frac{x}{x_{max}} \right)^b \exp \left[ -c \left( \frac{x}{x_{max}} \right)^d \right]$$

where  $a$  is the number of particles at the shower maximum and  $b$ ,  $c$ , and  $d$  are free parameters, to evaluate  $X_{max}$ . The resulting  $X_{max}$  from COSMOS and CORSIKA for both proton and iron primaries is shown in Figure 2. The agreement between COSMOS and CORSIKA is quite good; the difference is within  $\sim 10$  g/cm<sup>2</sup> for most cases.

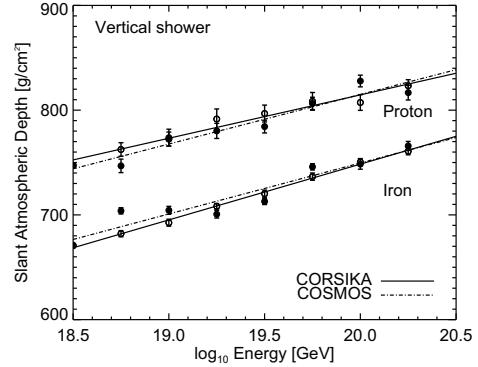


Figure 2:  $X_{max}$  as a function of the primary energy. Filled circles (•) indicate the COSMOS data. Open circles (○) indicate the CORSIKA data. Line are the chi-square fittings.

#### 3.3 Calorimetric energy

As an EAS develops, a part of the primary particle energy ( $E_0$ ) is deposited into air molecules and eventually radiated as fluorescence light. But a fraction of the energy is carried away by secondary particles, not contributing to fluorescence light. A correction for the so-called missing energy must be applied to the measurement of the calorimetric energy ( $E_{cal}$ ), in order to correctly determine the primary energy,  $E_0$ , from observation of fluorescence light. We have calculated the calorimetric energy by following the prescription described by [8]. Table 1 and Table 2 show  $E_{cal}/E_0$  for a few primary energies and  $\theta = 0^\circ$  and  $45^\circ$ .

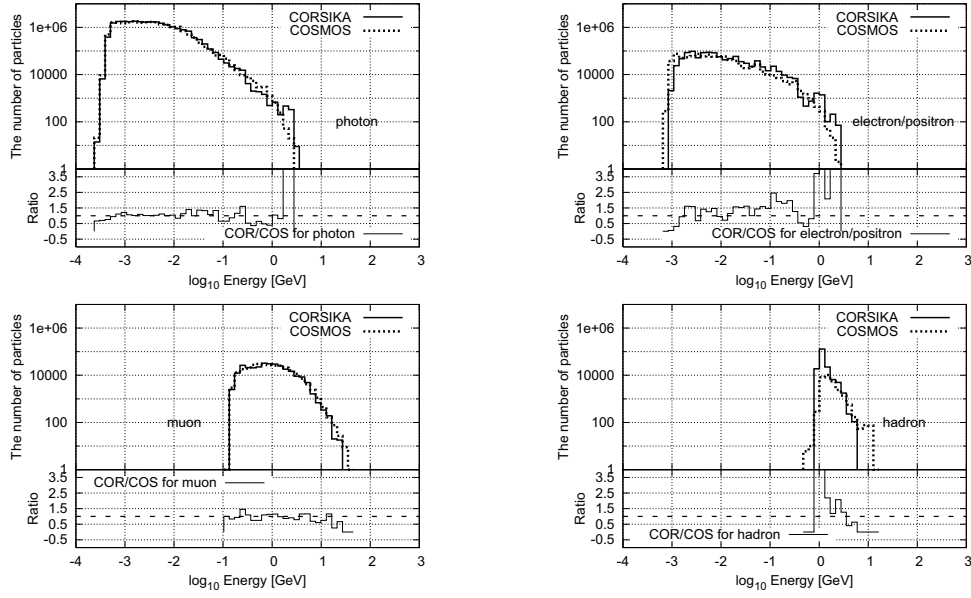


Figure 3: Energy spectrum at the ground for photons, electrons/positrons, muons and hadrons for an EAS of proton primary with  $E = 10^{19}$  eV and  $\theta = 0^\circ$ . Solid and dashed lines represent the CORSIKA and COSMOS data, respectively. The bottom panel shows the ratio of CORSIKA to COSMOS.

energy[eV]	$10^{18.5}$	$10^{19}$	$10^{19.5}$	$10^{20}$
CORSIKA	0.931	0.936	0.939	0.942
COSMOS	0.948	0.951	0.956	0.959

Table 1: Calorimetric energy for EASs of proton primary with  $E = 10^{18.5}$ ,  $10^{19}$ ,  $10^{19.5}$ , and  $10^{20}$  eV and  $\theta = 0^\circ$ .

energy[eV]	$10^{18.5}$	$10^{19}$	$10^{19.5}$	$10^{20}$
CORSIKA	0.929	0.951	0.955	0.958
COSMOS	0.949	0.952	0.959	0.955

Table 2: Calorimetric energy for EASs of proton primary with  $E = 10^{18.5}$ ,  $10^{19}$ ,  $10^{19.5}$ , and  $10^{20}$  eV and  $45^\circ$ .

The agreement between COSMOS and CORSIKA is good; the difference is less than 2% in the cases shown.

### 3.4 Energy distribution at the ground

A fraction of the secondary particles produced through interactions in atmosphere come down to the ground. Ground arrays in UHECR experiments utilize these particles to estimate the energy and arrival direction of primary particles. Figure 3 shows the energy distribution of photons, electrons/positrons, muons, and hadrons arriving at 800m from the shower core for an EAS of proton primary with  $E = 10^{19}$  eV and  $\theta = 0^\circ$ . Table 3 shows the integrated energies and numbers of those particles. The difference in the energy between COSMOS and CORSIKA is quite large; the difference in the total energy has been found to be 32%.

The difference in the integrated number between COSMOS and CORSIKA is smaller and around 10%.

### 3.5 Lateral distribution function (LDF)

We have also computed the particle density at several distances from the shower core. We have chosen circular rings with thickness of  $\pm 10$  m at 500, 600, 800, 900, 1000, and 2000m. By randomly sampling particles hitting on the circular rings, we have evaluated the energy deposition at ground detectors using GEANT4 simulations. The energy deposition has been used to build the LDF as a function of radial distance from the shower core [9]. In Figure 4, we compare the resulting LDF from COSMOS and CORSIKA for an EAS of proton primary with  $E = 10^{19.75}$  eV and  $\theta = 0^\circ$  and  $45^\circ$ . There is a noticeable difference for a zenith angle of  $\theta = 0^\circ$ , while the agreement is better for  $\theta = 45^\circ$ .

## 4 Discussion

The TA experiment employs EAS simulations from COSMOS and CORSIKA. In this paper, we compare the simulations with COSMOS and CORSIKA and quantify the differences. For the longitudinal distribution of photons, electrons/positrons, and muons, we have found the maximum difference of  $\sim 5\%$ . The difference in the hadron number is much larger than other particles, although the number of hadrons is much smaller than others. For  $X_{max}$  and the calorimetric energy, the difference is typically a few percent. The difference in the total energy of particles

particles	Total energy			Total number of particle		
	CORSIKA(A)	COSMOS(B)	A/B	CORSIKA(A)	COSMOS(B)	A/B
$\gamma$	1.76E+05	1.57E+05	12%	2.45E+07	2.30E+07	7%
$e^+/e^-$	2.38E+04	2.03E+04	17%	9.84E+05	1.00E+06	2%
$\mu^+/\mu^-$	3.95E+05	3.94E+05	$\ll 1\%$	2.93E+05	2.84E+05	3%
hadron	2.23E+05	4.72E+04	large	1.78E+05	2.74E+04	large
Total	8.18E+05	6.18E+05	32%	2.59E+07	2.44E+07	6%

Table 3: Integrated energy and number of photons, electrons/positrons, muons, and hadrons for an EAS of proton primary with  $E = 10^{19.75}\text{eV}$  and  $\theta = 0^\circ$ .

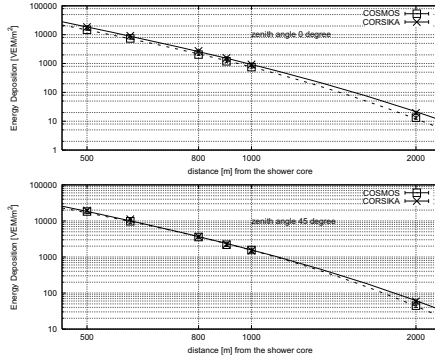


Figure 4: Lateral distribution for EASs of proton primary with  $E = 10^{19.75}\text{eV}$  and  $\theta = 0^\circ$  and  $45^\circ$ . Solid lines are the fittings of the CORSIKA data and dash lines are the fittings of the COSMOS data.

arriving the ground around 800m from the shower core is quite large, a few tens %, in the case we have examined, while the difference in the total number of particles is less, several %. About the lateral distribution, the agreement between COSMOS and CORSIKA is fairly good for the inclined shower we have examined, while the difference is larger for the vertical shower.

Our results suggest that we should expect an uncertainty of a few percent in the estimation of the primary energy in UHECR experiments including the TA experiment, simply due to the uncertainty in EAS simulations.

Finally, it is worthwhile to mention that there is a large difference in the production of secondary hadrons in the CORSIKA and COSMOS codes. We have found that the production is rather sensitive to the low-energy (below 80 GeV) hadronic interaction model. This may indicate that low-energy hadronic interaction models in Monte Carlo codes for EAS need to be further investigated.

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