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First results of the CORSIKA 8 air shower simulation framework

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CORSIKA 8 is a novel C++ framework for Monte Carlo simulations of particle cascades in air and other media. It is the designated successor of the well-known, long-standing Fortran version (CORSIKA 7), prepared to serve the astroparticle physics community over the next decades. Designed as a modular and open framework, the possible domains of applicability of CORSIKA 8 reach beyond its predecessor. In this contribution we give a status report of the project and outline some of the first capabilities of CORSIKA 8. We present the particle interaction and physics models already implemented and compare first results obtained from simulations of vertical proton-initiated showers to other codes, CORSIKA 7 and AIRES, focusing on energy spectra of hadrons and muons as well as their lateral and longitudinal distributions.

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PoS(ICRC2019)399

1. Introduction

30 years after the development of the original version of the Monte Carlo air shower simulation code CORSIKA [1] begun, the *CORSIKA 8 Project* aims to provide a modern replacement, suited for current and future challenges in the simulation of particle cascades in astroparticle physics [2]. The current state of the project – being a completely new and independent implementation rather than a continuation based on existing code – is still far from being feature-complete. Nevertheless, first physics modules, comprising hadronic event generation and the propagation of hadrons and muons, are already implemented and can be used for limited applications.

In this work, we demonstrate the current capabilities of CORSIKA 8, present first results concerning the hadronic and muonic components of extensive air showers initiated by very high energy cosmic rays, and show first comparisons with two up-to-date air shower simulation codes.

2. Current capabilities

The development of CORSIKA 8 is ongoing work since April 2018. The fundamental building blocks, allowing for the propagation of particles in arbitrary media while undergoing continuous and stochastic processes, are available and now in the course of being complemented with accurate physical models. The most prominent, already implemented improvements with respect to CORSIKA 7 are

- The ability to simulate particle cascades in environments composed by the user. Users are able to not only define custom atmospheric models according to their needs but also simulate in environments which consist completely or in parts of different media like water or rock by defining a world composed out of multiple simple geometric shapes with different physical properties [3].
- The capability to define a custom selection of physical processes to be considered in the simulation. Furthermore, it is possible with little effort to customize the selection of processes depending on the phase space, therefore going beyond the traditional simple switch between low- and high-energy hadronic models at a certain energy.

For more detailed overviews of the guiding principles of the design and its implementation we refer the reader to Refs. [2–4].

At the moment, CORSIKA 8 is able to handle the hadronic and muonic components of showers, i.e., propagate these types of particles while taking into account decays, inelastic interactions with the medium, and continuous energy losses. Hadronic event generation is supported with SIBYLL 2.3c [5, 6] at high energies and UrQMD 1.3cr [7, 8] at low energies, though, the support for the latter should still be considered preliminary for reasons discussed below. PYTHIA v8.235 [9] is interfaced mainly for its decay routines but can also be used for event generation in limited cases.

Muons, produced in decays of unstable hadrons, are mainly subject to decays. The energy losses of charged particles are modeled after a fully parametric formulation of the Bethe-Bloch theory with Sternheimer correction. This is equivalent to what is done in CORSIKA 7 (for air only). Furthermore, the radiative losses in air are parametrized as

$$-\left.\frac{\mathrm{d}E}{\mathrm{d}X}\right|_{\mathrm{rad}} = 3 \cdot 10^{-6}\,\mathrm{cm}^2\,\mathrm{g}^{-1} \times E, \tag{2.1}$$

PoS(ICRC2019)399

however, no new particles are generated so far. Additionally, energy losses dictate a maximum loss of 1 % per step, thereby limiting the maximum step-length of each charged particle.

Electromagnetic interactions are currently not supported. Hence, electromagnetic particles ($\gamma, e^{\pm}$) are discarded together with neutrinos directly after their production.

As medium properties we currently model local mass density and fractional nuclear composition, nevertheless keeping the design flexible enough to extend this list later based on the requirements of selected physics modules. The implemented density models comprise

- a homogeneous density distribution,
- a flat exponential density distribution in which the density changes exponentially in a fixed direction and is constant in directions orthogonal to it,
- a radially-symmetric exponential density distribution in which the density changes exponentially as a function of the distance to a specific central point. For the integration of grammages in this model an analytical solution is not available and we make use of the sliding planar approximation [10].

All of them can be combined with in principle any arbitrary nuclear composition. In SIBYLL, however, we are limited to nuclei with $A \leq 18$ as targets. Moreover, for simplicity the material constants for energy losses are currently provided for air only.

3. First comparison to CORSIKA 7 and AIRES

We perform a simulation study to compare CORSIKA 8-generated showers to those of CORSIKA 7 as well as AIRES [11] with basic settings as equal as possible among the different codes. For an earlier comparison of previous versions of AIRES and CORSIKA, see Ref. [12].

We use AIRES v19.04, CORSIKA v7.64 and CORSIKA 8-ICRC2019[1]. In all three codes we use SIBYLL 2.3c as high-energy hadronic interaction model. With CORSIKA 7 and 8 we use UrQMD v1.3cr as low-energy model, whereas AIRES employs a custom version of the Hillas Splitting Algorithm [13]. To have a phase space as large as possible covered by the common high-energy model we set the energy threshold to the lowest value still allowed by SIBYLL, which is 55 GeV. Since in interactions energy of high-energy particles is distributed to low-energy particles, we expect in principle equal results for all observables that take into account only particles with energies greater than 55 GeV.

In CORSIKA 8 and AIRES we employ a flat, single-layer exponential atmospheric model with a density at sea level of $1.20\,\mathrm{kg\,m^{-3}}$ and a scale height of 8.634 km. The heights of the observation level and the top of the atmosphere are set to 1.452 km a.s.l. and 112.8 km a.s.l., respectively, resulting in a total vertical grammage of $878\,\mathrm{g\,cm^{-2}}$. In CORSIKA 7 only Linsley's atmospheric model composed of four exponential and one linear layer can be used. Here we mimic the single-layer setup by setting the threshold heights and the height of injection of the primary particle in such a way that particles effectively only propagate in the uppermost exponential layer which features

[1] available at https://gitlab.ikp.kit.edu/AirShowerPhysics/corsika

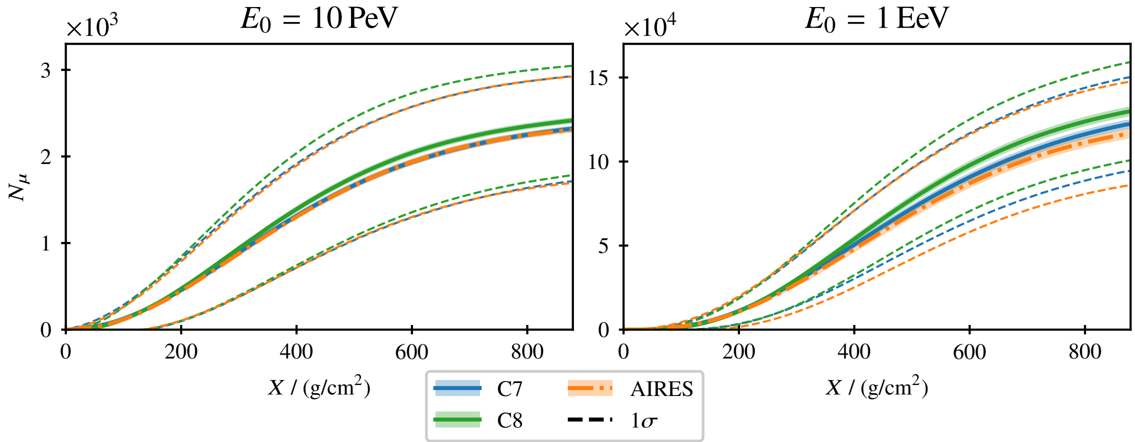

Figure 1: Average muon longitudinal profile with $E_\mu > 55$ GeV. Filled bands around the average curves show the standard error of the mean of 300 (left) and 100 showers (right). The dashed lines limit the $\pm 1\sigma$ bands of shower-to-shower-fluctuations.

the same parameters as the AIRES/CORSIKA 8 setups. The geomagnetic field is disabled in all three codes. No thinning is employed.

In the CORSIKA 7 setup we disable electromagnetic interactions, reducing the runtime of a shower simulation from typically weeks to less than an hour at $E = 1$ EeV. In the AIRES simulations we cannot easily disable electromagnetic interactions completely. Instead, we set the electron and photon cutoff energies to 99.9 % of the primary energy. We furthermore disable muon bremsstrahlung and muonic pair production in AIRES, resulting in reduced energy losses [14], after we found this to cause substantial disagreement between CORSIKA 7 and AIRES regarding the number of high-energy muons.

Longitudinal profiles are calculated along the shower axis integrated from the outer boundary of the atmosphere in intervals of 10 g cm^{-2}. Proton primary particles are simulated. Averages and spreads are determined from sets of 300 showers at $E_0 = 10$ PeV and 100 showers at $E_0 = 1$ EeV.

4. Results

The average muon longitudinal profiles of showers of primary energies of 10 PeV and 1 EeV are shown in Fig. 1. To exclude any differences caused by the different treatments of low-energy interactions, only muons with energies above 55 GeV are counted. We note that on average CORSIKA 8 produces a few percent more muons than the other codes, notably at depths deeper than 200 g cm^{-2}. Compared to the shower-to-shower fluctuations, however, the discrepancy is rather small. This is already noteworthy and requires further scrutiny to better understand the cause of this systematic difference.

In Fig. 2 we show muon energy spectra at ground. Here, we additionally include sets of CORSIKA 8-showers simulated with all energy losses deactivated in order to estimate their influence. We find good agreement between AIRES and CORSIKA 7 at all energies despite the different low-energy models used. With CORSIKA 8 (including energy losses) we note that the shape of the spectrum agrees well with the other codes above the model transition energy and the small

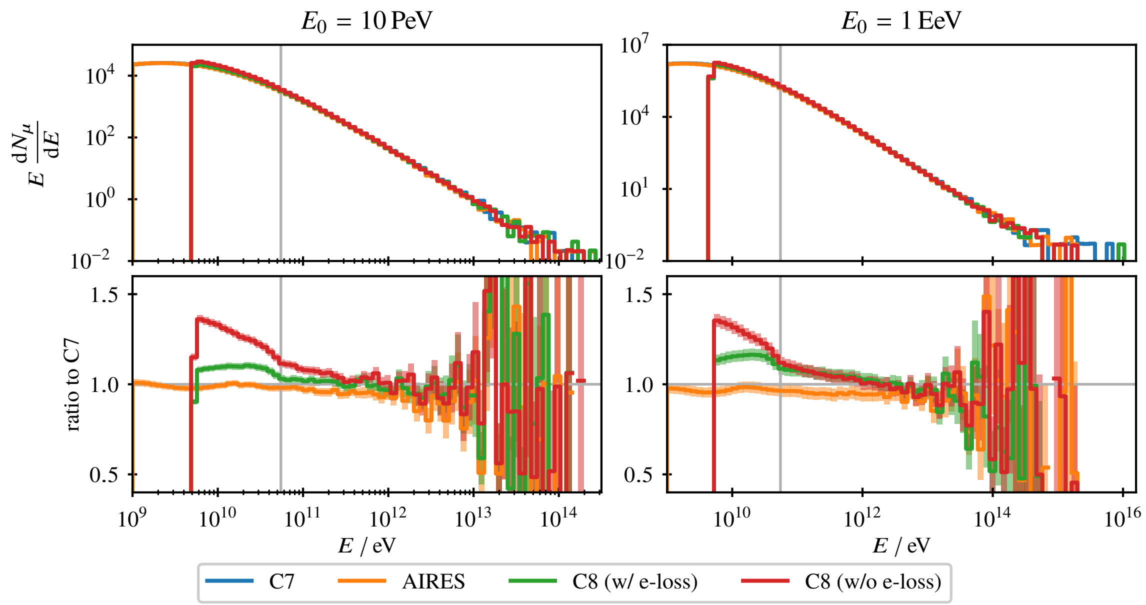

Figure 2: Average muon energy spectra at ground. The lower plots display the ratios to CORSIKA 7. The grey vertical line indicates the low-/high-energy model transition energy.

muon excess visible in the longitudinal profiles is present at energies up to 1 TeV (Fig. 2 right-hand side). In the regime of the low-energy model the influence of different treatments of inelastic cross-sections in the respective UrQMD interfaces of CORSIKA 7 and 8 becomes visible: While CORSIKA 7 uses tabulated hadron-air cross-sections, in CORSIKA 8 we currently determine them directly from UrQMD, which yields purely geometrical and energy-independent cross-sections for hadron-nucleus interactions determined from the nuclear radius.

Furthermore, comparing the spectra including and excluding energy losses we observe only very minor differences in the high-energy regime with a slightly softer spectrum. On the other hand, the inclusion of energy losses reduces the number of muons significantly starting below around 100 GeV.

In our setup, muons are only produced through the decays of hadrons. A discrepancy in the muon energy spectrum is therefore likely to be present in the hadron spectra as well. Hence, we show the energy spectra of charged pions, kaons, as well as neutrons at the height of 7 km a.s.l., corresponding to a depth of 460 g cm^{-2}, where mesons are still abundant in Fig. 3. We find that the spectra produced with CORSIKA 8 in the high-energy regime are in general softer compared to CORSIKA 7. Interestingly, the meson spectra of CORSIKA 7 and 8 cross at 1 TeV, while the neutron spectra cross at an energy of about a factor of ten higher. Above these crossing points we notice good agreement between CORSIKA 8 and AIRES.

Additionally, we observe that the different implementations of the links to UrQMD cause an enormous discrepancy in the number of low-energy neutrons and, due to further interactions subsequent to their production, they also leave an imprint on the spectra of the other species.

As additional result we include in Fig. 3 the spectra when neutrons are not propagated at all in CORSIKA 8 and removed after their production. This means neutrons do not further participate

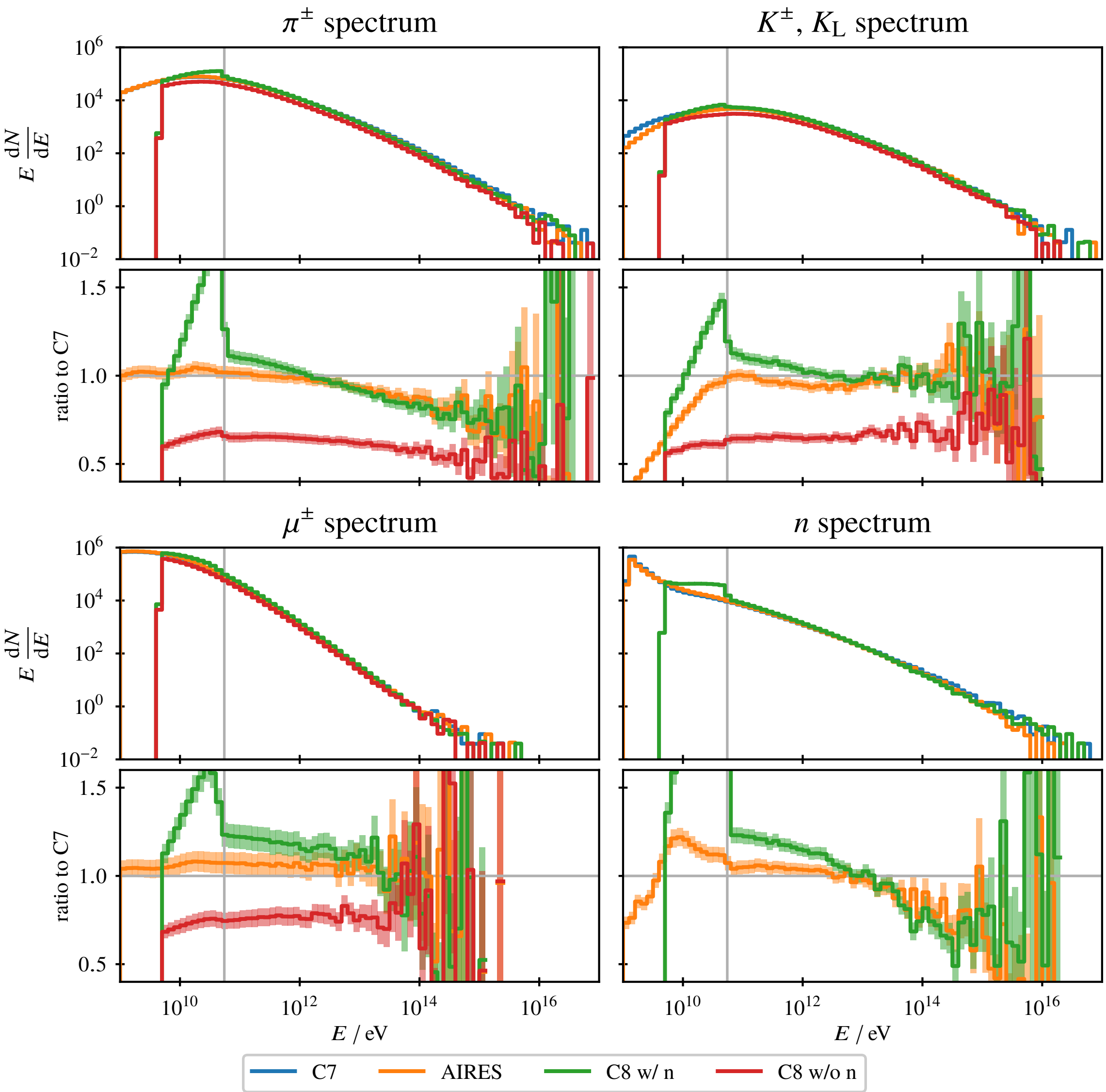

Figure 3: Average energy spectra of several hadron species and muons at 7 km a.s.l. (corresponding to 460 g cm^{-2}) of a 1 EeV primary proton. The red and green curves correspond to simulations with and without imposing a cut on all (anti-)neutrons, respectively.

in the hadron cascade and their energy content lost with their removal effectively contributes to invisible energy in a similar way as neutrinos. The impact on all hadron spectra as a result of this additional invisible energy is significant and the bumps in the range 10 GeV to 50 GeV are greatly reduced after the removal. This is also visible in the muon energy spectrum, which is softer in CORSIKA 8 than in CORSIKA 7, with a crossing point around 10 TeV. The discrepancies among high- and low-energy hadron spectra between CORSIKA 8 and CORSIKA 7 still need to be studied further and understood in detail and will likely contain relevant information about the mechanism of muon production in air showers.

As last observable included in the comparison we consider the lateral distribution, i.e. the

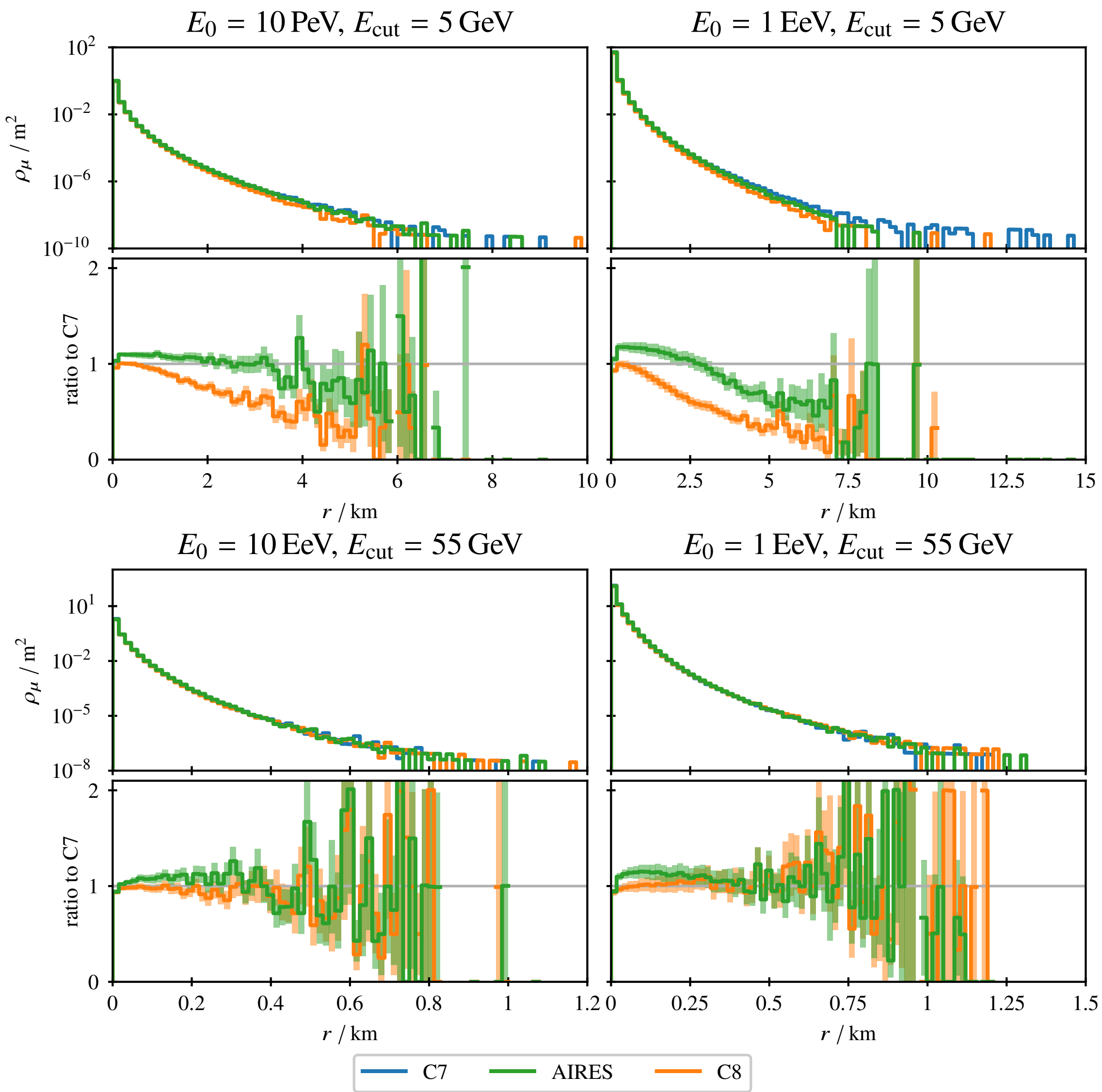

Figure 4: Average muon lateral distributions for $E_\mu \geq 5\,\text{GeV}$ (top) and $E_\mu \geq 55\,\text{GeV}$ (bottom).

particle density at ground ϱ_μ as a function of the distance r to the shower core, of the muons as shown in Fig. 4. Here, we distinguish between two lower energy cuts for the muons: 5 GeV and 55 GeV. The latter is chosen to reflect the result just after the common high-energy model and hadronic cascade, while the former are heavily affected by the different low-energy models. It is intruiging that the shape of the distribution for the 55 GeV cut (shown in lower plots) for both primary energies agree very well with CORSIKA 7, while there is a visible small offset in the overall normalization. At the lower threshold value of 5 GeV the agreement is not as good, also indicating a slightly steeper distribution in CORSIKA 8 compared to CORSIKA 7. In general, the level of agreement of CORSIKA 8 with AIRES and CORSIKA 7 is similar. This is remarkable insofar as multiple scattering is not modeled in CORSIKA 8 yet.

5. Summary

A brief overview of the status of the CORSIKA 8 air shower simulation framework is given. The current capabilities are outlined and a first basic air shower setup allowing us to make detailed comparisons between CORSIKA 8, CORSIKA 7, and AIRES simulations has been configured. We present average results derived from proton induced showers at 10 PeV and 1 EeV. The electromagnetic part of the cascade is switched off in order to put a focus on hadrons and muons. In important distributions the differences between CORSIKA 8 and the other codes are on the percent level and typically better than 10 %.

There are, however, clear and unexpected systematic differences in the hadronic and muonic energy spectra which yet need to be fully understood. The conclusion will shed some more light on muon production mechanisms in air showers.

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