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Status and prospects of the CORSIKA 8 air shower simulation framework

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The Fortran-versions of the CORSIKA air shower simulation code have been at the core of simulations for many astroparticle physics experiments for the last 30 years. Having grown over decades into an ever more complex software, maintainability of CORSIKA has become increasingly difficult, though its performance is still excellent. In 2018, therefore a complete rewrite of CORSIKA has begun in modern modular C++. Today, CORSIKA 8 has reached important milestones with a full-fledged implementation of both the hadronic and electromagnetic cascades, the ability to simulate radio and Cherenkov-light emission from air showers and an unprecedented flexibility to configure simulation media and their geometries.

This presentation will discuss the current status of CORSIKA 8, highlight the new possibilities already available, and future prospects of this new air shower simulation framework.

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[*] Speaker

[†] The full author list can be found at `https://tinyurl.com/corsika8-202210`

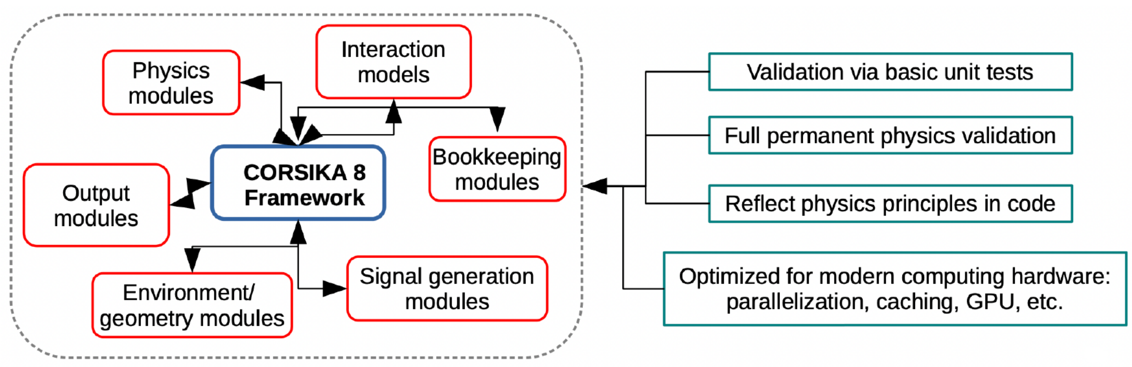

Figure 1: Overall structure of the CORSIKA 8 air shower simulation framework. From [4].

1. Introduction

The air shower simulation code CORSIKA was originally developed for the KASCADE experiment in the 1980s and has become a common reference frame for the community [1]. Thanks to decades of careful maintenance and development, CORSIKA is at the core of air shower simulations in many astroparticle physics experiments today.

As a hand-optimized code, CORSIKA shows an excellent performance, however, it is also subject to some limitations. Maintenance of a monolithic Fortran code, with program options heavily intertwined in the source code, is becoming increasingly difficult. In addition, the possibilities of parallelization of the Fortran version of CORSIKA are limited: MPI parallelization is available, but no multi-threading or GPU parallelization are possible.

To address these issues, in 2018 a rewrite of CORSIKA in modern C++ (currently C++17) has begun, focussing on modularity and the needs and possibilities of modern supercomputing environments [2, 3]. This effort is coordinated by KIT, but has a strong community integration. The overall structure of this new version, called CORSIKA 8, is shown in Figure 1.

2. Status of CORSIKA 8

Both hadronic and electromagnetic cascades are available, so CORSIKA 8 is now capable of simulating complete air showers. Extensive validation by comparison to CORSIKA 7 and other codes accompanies the development. Currently, CORSIKA 8 offers most of the possibilites of previous CORSIKA versions and already has several capabilities, which were not available in the Fortran version, such as full genealogy of particles, cross-media showers, and more flexible medium definitions.

2.1 Hadronic cascades

Currently, the available hadronic interaction models in CORSIKA 8 are QGSjet-II-04, EPOS-LHC, and Sibyll 2.3d at high energies, UrQMD at low energies, and decays are treated either with Sibyll 2.3d or PYTHIA 8. Comparisons of particle spectra between CORSIKA 8, CORSIKA 7, and MCEq have been presented in [5], and show a good agreement between the different codes (cf. Figure 2).

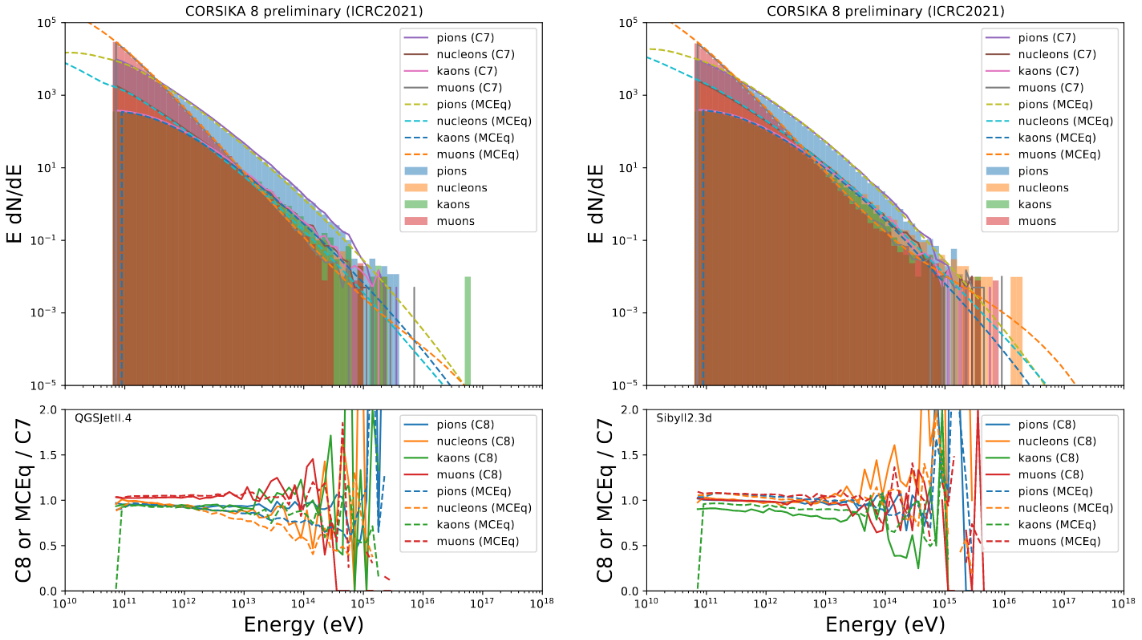

Figure 2: Comparison of particle spectra at observation level (1400 m a. s. l.) in a vertical proton shower at 10^{18} eV between CORSIKA 8, CORSIKA 7, and MCEq. From [5].

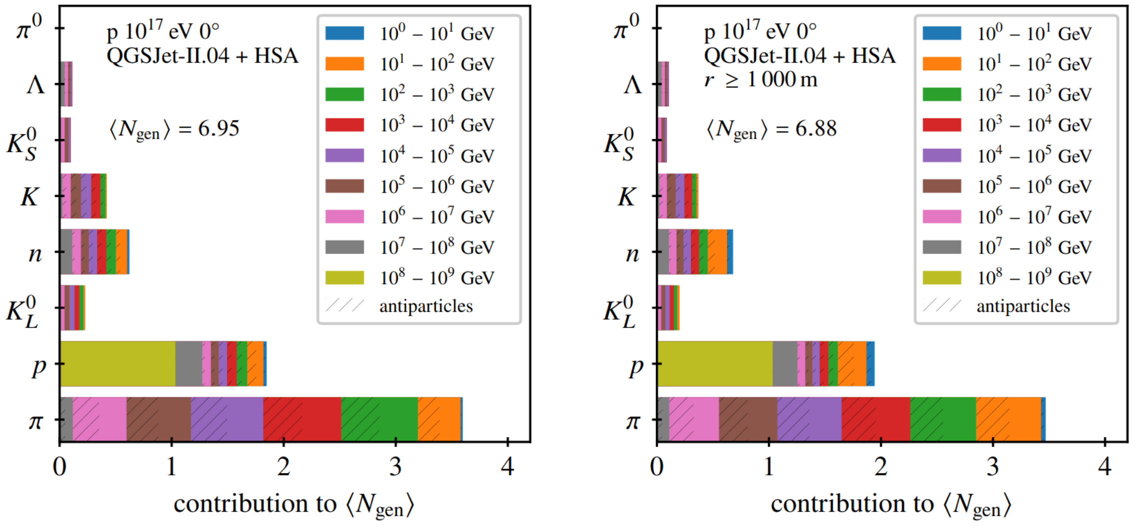

Figure 3: Muon ancestor particle distributions by species and energy. From [6].

A new possibility of CORSIKA 8 is the genealogy of particles. While current air shower simulation codes have only the possibility to identify the mother and grandmother particle, in CORSIKA 8 the complete genealogy of particles is available (cf. Figure 3). A detailed report on muon genealogy has been published in [6].

Another novelty is the possibility to consistently treat cross-media showers, e. g. cosmic ray showers transitioning from air to water or ice, inside a common framework. As an example, the longitudinal profile of a vertical 10^{16} eV proton shower transitioning from air to water is shown in

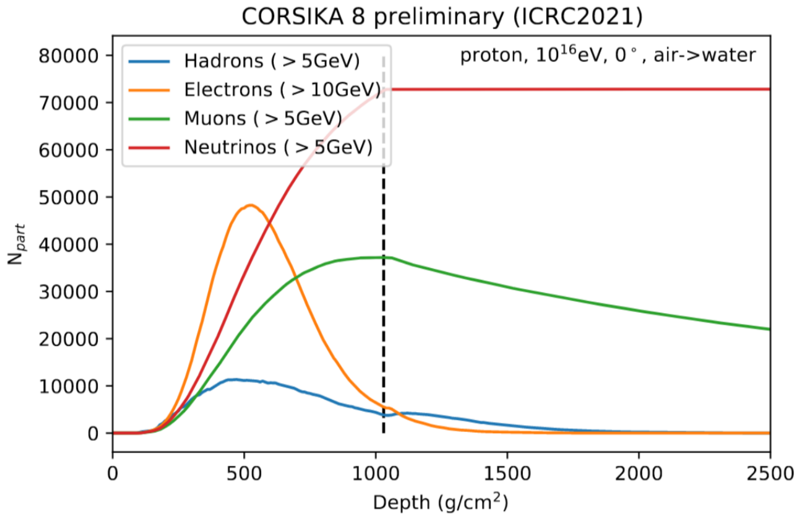

Figure 4: Vertical 10^{16} eV proton shower transitioning from air to water. From [5].

Figure 4.

2.2 Electromagnetic cascades

In CORSIKA 7, electromagnetic cascades are treated using a modified version of EGS 4 [7], a Mortran code that was deeply integrated into the CORSIKA source code; beside the processes contained in the original EGS 4, the muon pair production process $\gamma \to \mu\mu$, the photohadronic interaction $\gamma N \to X$, and (optionally) the Landau-Pomeranchuk-Migdal effect have been added. Alternatively, the analytic NKG treatment of electromagnetic cascades is available.

In CORSIKA 8, electromagnetic cascades are simulated using the lepton propagator PROPOSAL [8–10], a modular C++14 library with Python bindings, which can propagate electrons, positrons, photons as well as muons and tau-leptons. The LPM effect is currently available only in media with homogeneous density; for inhomogeneous media, this is currently under development. The rather good agreement between CORSIKA 7, CORSIKA 8, AIRES, and the ZHS air shower Monte Carlo code is shown for the longitudinal profile and the charge excess of 1 TeV electromagnetic showers in Figures 5 and 6.

2.3 Radio and Cherenkov emission

The aim of the CORSIKA 8 radio module is to overcome limitations of previous CORSIKA versions, in particular to be able to simulate the reflected radio signal of downwards-going showers, to consider the ray curvature in the atmosphere, and to simulate showers crossing from air to dense media.

To calculate the radio emission, two algorithms have been implemented, the CoREAS algorithm as in CORSIKA 7, and the ZHS algorithm as in ZHAireS; the radio emission calculated according to both formalisms is in good agreement. The radio emission is fully implemented as a process, with particle filtering, the used formalism, the radio wave propagator, and the antenna configuration configurable by the user. A schematic of the radio emission calculation is shown in Figure 7. A

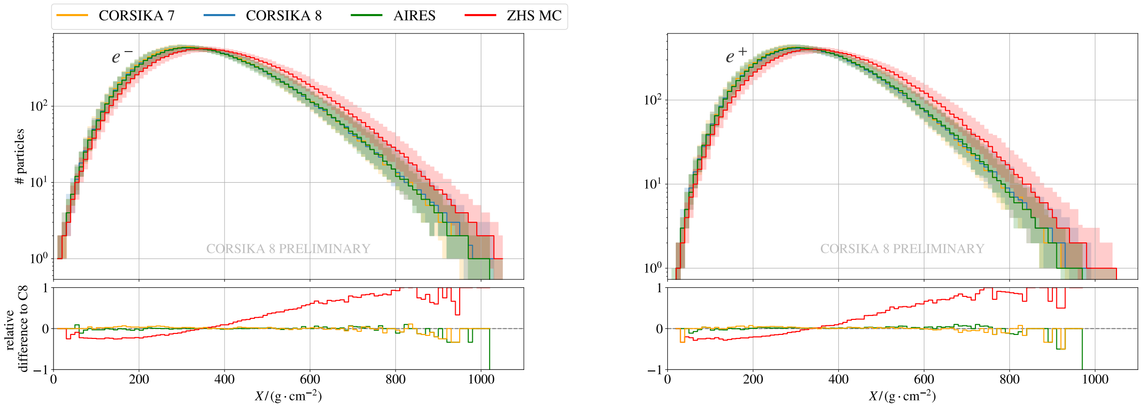

Figure 5: Longitudinal profile of 1 TeV electromagnetic showers in C7, C8, AIRES, and ZHS MC. From [11].

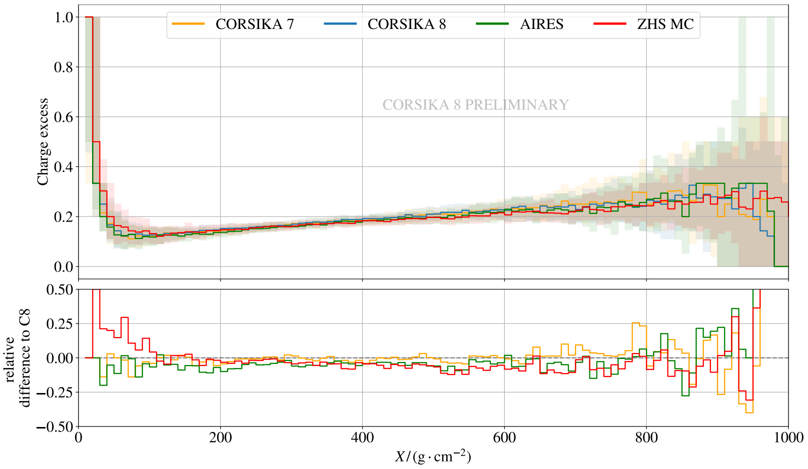

Figure 6: Charge excess of 1 TeV electromagnetic showers in C7, C8, AIRES, and ZHS MC. From [11].

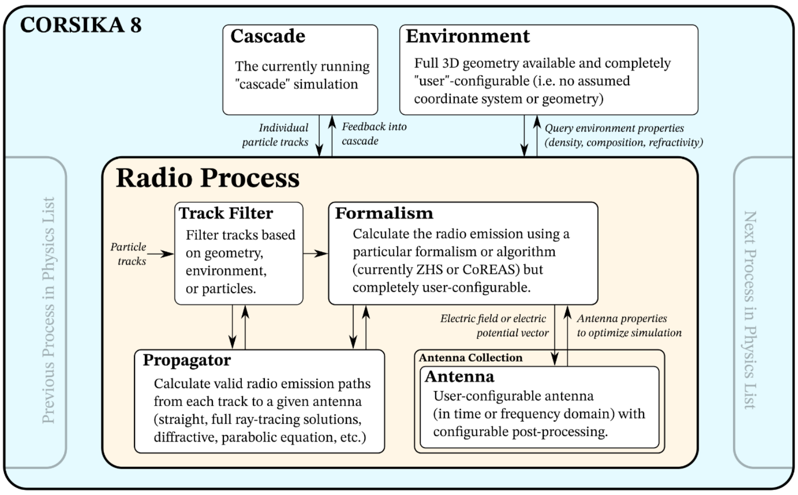

Figure 7: Schema of radio emission calculation in CORSIKA 8. From [12].

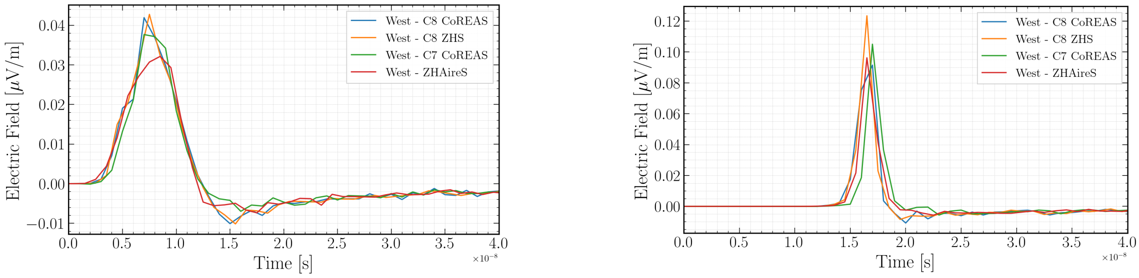

Figure 8: Radio pulses from a 10 TeV electromagnetic shower at 50 m (left) and 200 m (right) distance from shower core, west polarization. From [13].

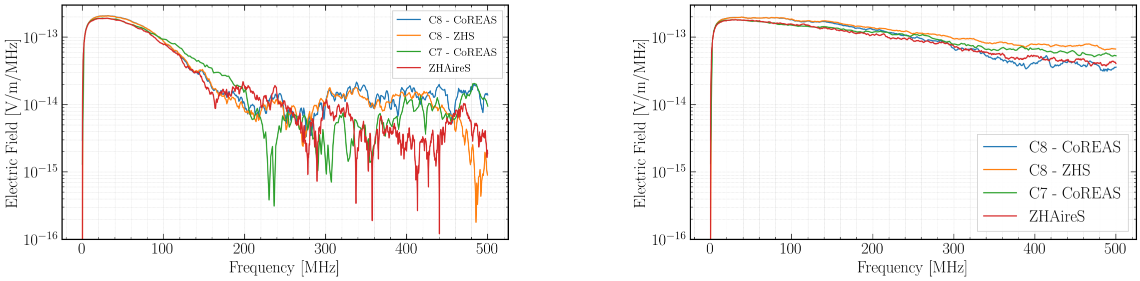

Figure 9: Radio frequency spectra of a 10 TeV electromagnetic shower at 50 m (left) and 200 m (right) distance from shower core, west polarization. From [13].

detailed account of the radio implementation in CORSIKA 8 was given in [12]. The agreement of the radio emission between CORSIKA 7, ZHAireS and the two formalisms in CORSIKA 8 is illustrated in Figures 8 and 9, which provide update results to [12].

The Cherenkov module of CORSIKA 8 provides two implementations for the calculation of Cherenkov emission. The calculations of these are in good agreement with each other and CORSIKA 7. One of the implementations is vectorized, the other uses GPU parallelization. The ground level distribution of Cherenkov light from a 1 TeV shower is shown in Figure 10. A detailed account of the Cherenkov modules was given in [14, 15].

3. Conclusion

CORSIKA 8 is an open source project, with the source code available on the KIT gitlab server[1]. Current directions of development for CORSIKA 8 are the performance optimization of the code, an improved treatment of multiple scattering, the implementation of the Landau-Pomeranchuk-Migdal effect in inhomogeneous media, the development of interfaces to PYTHIA 8[2], FLUKA, and SOPHIA, and the implementation of photohadronic interactions at low energies.

CORSIKA 8 is now capable of simulating all components of extensive air showers, provides most possibilities of CORSIKA 7 and already has features going beyond earlier versions. Now is a great time for developers to join; the first release for end users is tentatively planned for mid-2023.

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[1] `https://gitlab.iap.kit.edu/AirShowerPhysics/corsika/`

[2] First results with the interface to PYTHIA 8 were presented after the symposium at UHECR2022 [16].

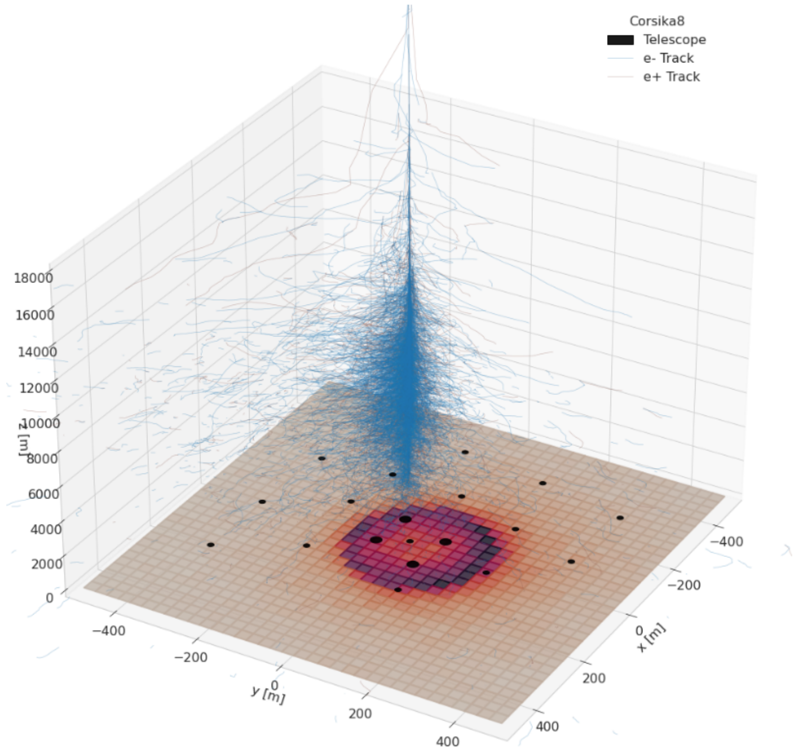

Figure 10: 1 TeV shower with ground level distribution of Cherenkov light. From [14].

Acknowledgments

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