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Electromagnetic Shower Simulation for CORSIKA 8

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Extensive air showers in astroparticle physics experiments are commonly simulated using CORSIKA. The electromagnetic shower component has been treated using EGS4 in the Fortran 77-based versions, which have been developed in the last thirty years. Currently, CORSIKA is being restructured and rewritten in C++, leading to the new version CORSIKA 8. In this process, the electromagnetic component is now being treated by the high-energy lepton and photon propagator PROPOSAL. Originally designed for the efficient simulation of high-energy muons and tau-leptons in large volume neutrino telescopes, the Monte Carlo library PROPOSAL has been extended to also treat electrons, positrons, and high-energy photons. Validating this new implementation of the electromagnetic shower model is very important. In this talk, the electromagnetic shower component simulated with PROPOSAL is compared to previous versions of CORSIKA, the air shower simulator AIRES as well as the electromagnetic shower tool ZHS, which is optimized for the radio signal. This includes comparisons of the underlying theoretical models, the runtime performance as well as lateral and longitudinal shower characteristics, especially of parameters relevant for the radio component such as the charge excess.

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1. Introduction

For decades, many astroparticle experiments have simulated extended air showers using CORSIKA [1]. In recent years, a major effort has started to rewrite CORSIKA in modern C++, resulting in the new version CORSIKA 8. In the course of this undertaking, the propagation of electromagnetic particles has been transferred from a modified version of EGS4 [2] to the PROPOSAL library [3–5]. This contribution is dedicated to the systematic comparison of electromagnetic showers simulated in the current version of CORSIKA 8 to the established frameworks in CORSIKA 7 and also the air shower simulation program AIRES [6] and the electromagnetic cascade simulation code ZHS [7], having compared already in the past these two last codes against GEANT4 [8] and found in agreement for an homogeneous ice atmosphere.

The proceeding is divided in two main parts. In section 2 we compare the theoretical description of the electromagnetic interaction processes in the different codes. Section 3 describes the results of our simulations and compares the longitudinal and lateral shower development and the runtime of the simulated showers.

2. Comparison of theoretical description of EM processes

The comparison of the theoretical models used in the different shower frameworks considers the energy loss cross sections as well as the scattering models. Also, the different treatments of energy thresholds to cut low energetic particles as well as energy cuts, that divide interactions into stochastic and continuous interactions, are discussed.

In all frameworks but AIRES, the electromagnetic model is similar to the Electron Gamma Shower code system EGS4 [2]. While in ZHS and PROPOSAL, the models are mainly based on EGS4, CORSIKA 7 uses EGS4 directly in a modified version. For AIRES, electromagnetic processes are based on several parametrizations different from EGS, which will be described in more detail later in this chapter. Since EGS4 is a built-in system producing the showers with limited access for external frameworks, the lepton propagator PROPOSAL is being used in CORSIKA 8. Thereby, PROPOSAL is used as an external library by CORSIKA 8, proposing propagation steps, while the overall task of the shower generation remains in the CORSIKA framework.

The two dominating processes in an electromagnetic shower are electron-positron pair production by photons and bremsstrahlung losses of electrons and positrons. In CORSIKA 7, the bremsstrahlung parametrization of Koch and Motz is used for energies above 50 MeV, while for lower energies, tabulated empirical corrections are applied. The same bremsstrahlung parametrization has been implemented in PROPOSAL. In ZHS, the parametrization of [9] is used, which is based on [10, 11]. The framework AIRES uses a cross section based on the parametrization by [12], with the LPM effect being added following Migdal's theory. In all frameworks, the LPM effect is included, although it can currently not be used in CORSIKA 8.

Is Rossi & Greisen (1941) the correct reference?

In ZHS, the cross section based on the calcuations by [9] is used for the pair production of photons, whch is consistent with the used parametrization of bremsstrahlung. The pair production cross sections used in AIRES is, similar to the used bremsstrahlung cross section, based on the cross section by [12], with an LPM correction from Migdal's theory. In CORSIKA 7, the pair production cross section by Koch and Motz is used, while in CORSIKA 8, a parametrization by Tsai is used.

needs double check with article

This is not completely consistent with the bremsstrahlung parametrization, however, replacing the cross section showed negligible differences compared to other uncertainties.

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Regarding ionization and the production of knock-on electrons, CORSIKA 7, CORSIKA 8 and ZHS all use the Berger and Seltzer parametrization [13] of the Bhabha and Møller scattering for electrons and positrons, respectively. In AIRES, a fit to GEANT3 data with a distinction between continuous and discrete losses at an energy of 1 MeV is made. In order to be consistent with the simulation parameters in the other frameworks, this energy loss has been substituted by the the Berger and Seltzer parametrization for this work, which has already been done in [8]. All frameworks also include density correction effects.

Further interactions implemented in all frameworks are the annihilation of positrons with atomic electrons and the Compton scattering of photons. Ionization, annihilation and Compton scattering are in particular relevant for the charge excess of an air shower and therefore the radio signal.

Only in CORSIKA 7 and AIRES, the photohadronic and the photoelectric effects are implemented. For this work, the photohadronic interaction has been deactivated in AIRES to be more comparable. In CORSIKA 7, the photoelectric effect also includes the fluorescence loss. Further processes that are only taken into account by CORSIKA 7 are coherent Rayleigh scattering and the production of muon pairs induced by photons.

In PROPOSAL, the production of electron-positron pairs induced by ingoing electrons and positrons is implemented as well as inelastic nuclear interactions. The latter, however, is only included as an energy loss process, but not yet as a source of hadronic secondary particles.

For the description of multiple scattering, the Highland approximation of Molière theory is used in all frameworks. Stochastic deflections, i.e. the deflection of particles in stochastic interactions, are included in CORSIKA 7. These effects are in principle also available in PROPOSAL, but not yet implemented in the interface to CORSIKA 8. In AIRES, Coulomb scattering is implemented as a deflection process.

Besides the physical models, the implementation and treatment of energy cuts are important to compare the simulations. The cuts can be divided into two kinds of cuts: Firstly a particle energy cut, below which particles are not further propagated. Secondly, there are energy loss cuts, describing the energy of losses above which losses are treated stochastically. All losses below the energy loss cut are treated as a continuous energy loss between two interactions.

In AIRES, the user can define particle cuts, which need to be above 80 keV for the particles in an electromagnetic shower. Energy loss cuts are set in the code and can not be changed externally. For this work, the AIRES code has been modified in such a way that the energy loss cuts match the cuts used in the other simulation programs.

In ZHS, particle cuts are carefully linked to the cut between discrete and continuous losses, without the option to set them individually. For comparison reasons, a different particle cut has been superimposed in order to calculate the cross sections with the same integration limits as the other programs.

Since the particles cuts in AIRES and ZHS have been modified from their initial values, these routines may not perform with their optimal accuracy.

In CORSIKA 7, the particle cut can be set, where the cuts for electrons and positrons need to be above 10 keV and above 1 keV for photons. Energy loss cut can not be set in CORSIKA 7.

Table 1: List of frameworks used for this contribution.

Framework	Version	Reference
CORSIKA 8	`ICRC-2021`	[14]
CORSIKA 7	`7.7410`	[1]
AIRES	`19.04.00`	[6]
ZHS	-	[7]

In CORSIKA 8, both the energy loss cut and the particle cut can be set for the different particle types. For the comparisons in this work, the particle cuts has been set to 4 MeV, since CORSIKA 8 is known to produce stable results for these settings. Per default, the energy loss cut is set to half of the particle cut, which is also used for this analysis.

3. Comparison of simulated shower parameters and runtimes

To validate the current status of the simulations of the electromagnetic shower component in CORSIKA 8 using PROPOSAL, relevant shower parameters are analyzed and compared to the results from simulations created by other shower simulation codes. These comparisons are vital to understand the current possibilities, but also to highlight the remaining restrictions when interpreting the physical results which are provided by CORSIKA 8.

To create the results presented in this contribution, the frameworks listed in Table 3 with their corresponding versions have been used. Any comparisons that are presented have been obtained by simulating an electromagnetic shower induced by an electron with an initial energy of 1 TeV. The particle threshold has been set to 4 MeV, i.e. shower particles with a kinematic energy below this threshold are discarded.

3.1 Longitudinal shower development

The longitudinal shower development is analyzed by observing the number of particles in vertical steps along the shower axis. This is shown for the different particle types in Figure 1, where the longitudinal profile averaged over 200 showers has been simulated. Here, the solid lines indicate the mean, while the error bands display the standard deviation of the particle number.

While the general shapes of the longitudinal shower distribution tend to agree, a displacement of the showers simulated by CORSIKA 8 towards larger depths is cleary visible. This may be attributed to differences in the cross sections, especially to the fact that some interaction processes are not yet considered by PROPOSAL, for example the photohadronic interactions relevant for high-energy photons.

Figure 2 shows the longitudinal development of the difference between the electron and positron number, called charge excess. This effect is caused by the ionization of atomic electrons either by charged leptons or by compton scattering as well as the annihilation of positrons. The resulting charge excess is, next to the geomagnetic contribution, the cause of radio emission in air showers.

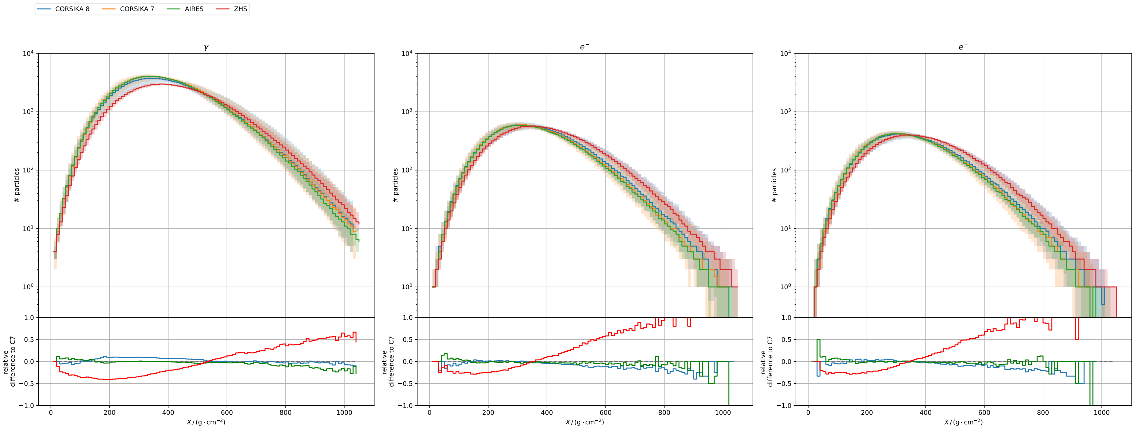

Figure 1: Average longitudinal profile of 200 showers.

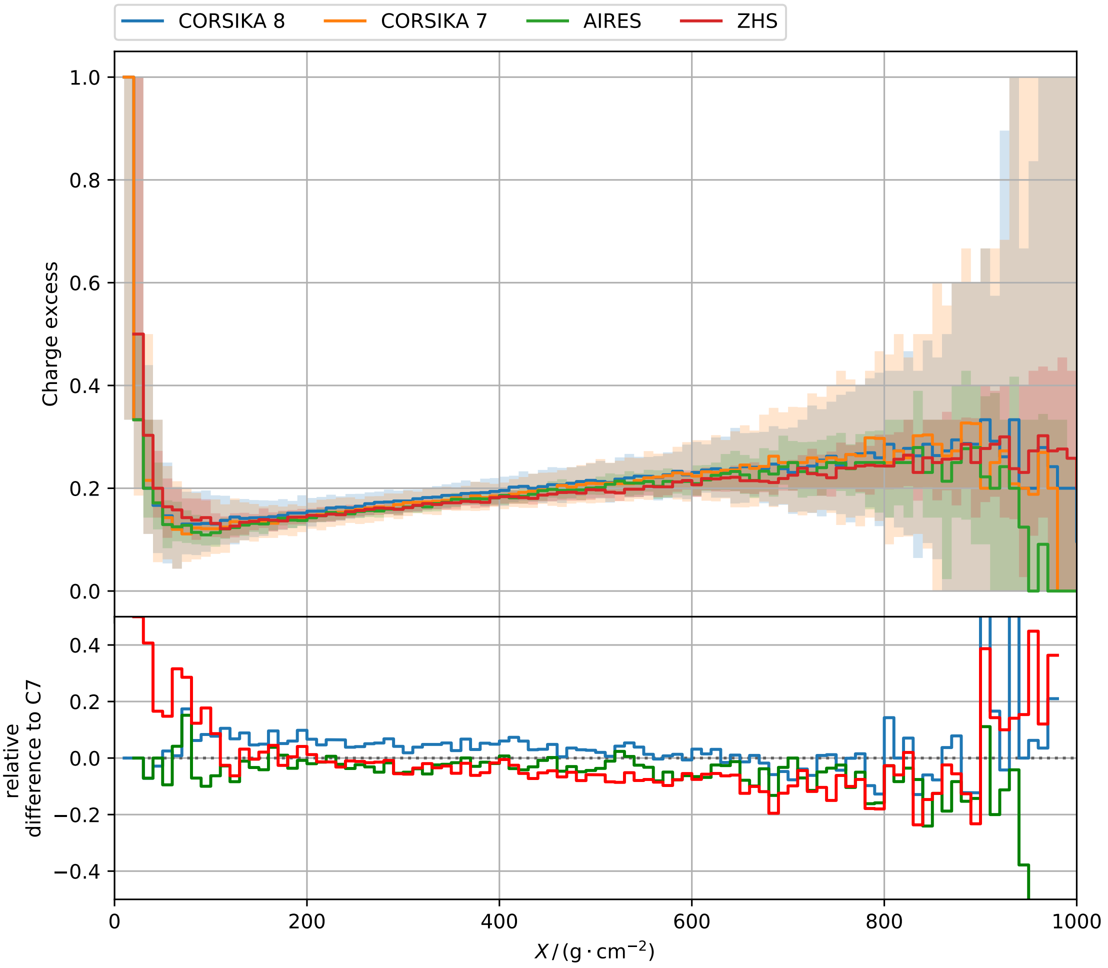

Figure 2: Charge excess.

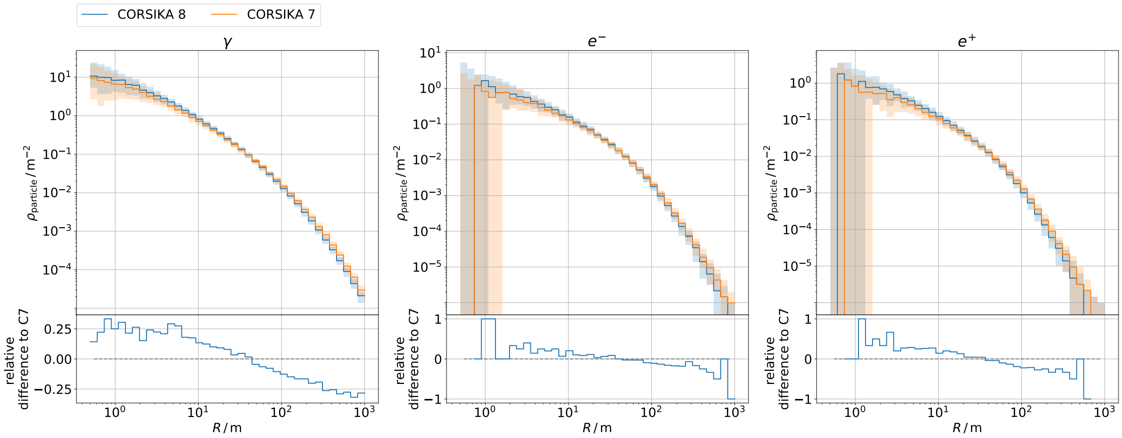

Figure 3: Lateral particle distribution, averaged over 200 showers, for an observation height of 8600 m.

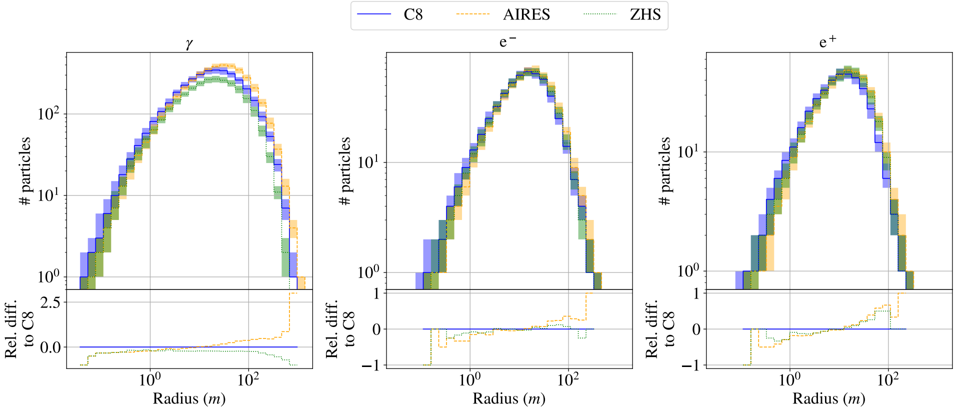

Figure 4: Lateral profile in homogeneous atmosphere.

3.2 Lateral shower development

The lateral shower development, i.e. the evolution of the shower perpendicular to the shower axis, is analyzed by observing all particles passing a fixed observation level and calculating their distance to the shower axis. In Figure 3, the lateral particle density is shown for the different particle types, averaged over simulations of 200 showers, with an obervation level set at 8600 m. The mean of the particle density is depicted by the solid lines, the error bands indicate the standard deviation of the particle density.

The comparisons show that the lateral profiles from the CORSIKA 8 simulations are shifted slightly closer to the shower axis compared to the simulations from the other frameworks. This indicates that showers produced by CORSIKA 8 have a smaller lateral spread, which can be understood since not all contributing processes are already implemented in CORSIKA 8. For example, bremsstrahlung photons produced by electrons and positrons inherit the direction of the initial lepton, neglecting the photon emission angle.

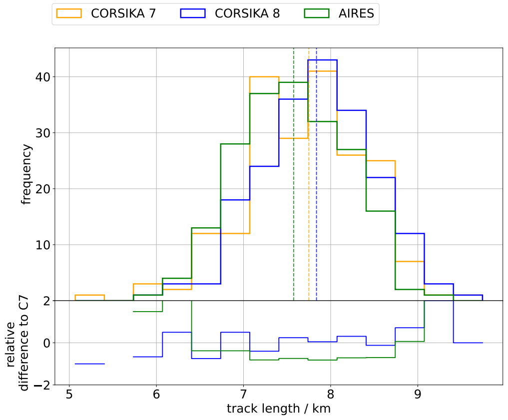

Figure 5: Distribution of the charged track length, i.e. the sum of all electron and positron track lengths projected onto the shower axis, for 200 showers. The dashed lines indicate the medians of the corresponding distributions.

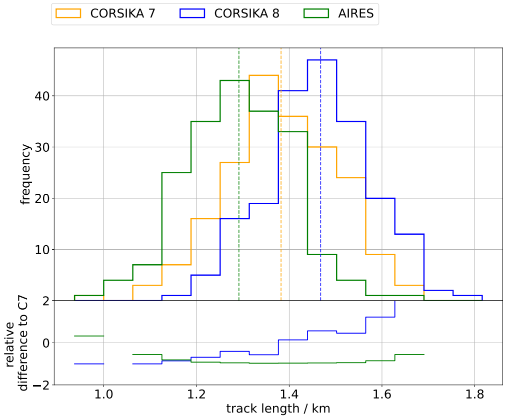

Figure 6: Distribution of the excess charged track length, i.e. the difference between the sum of all electron track lengths projected onto the shower axis and the sum of all positron track lengths projected onto the shower axis, for 200 showers. The dashed lines indicate the medians of the corresponding distributions.

Table 2: Track length medians in km for 200 showers in homogeneous atmosphere.

	C8	AIRES	ZHS
Total	2891.16	2915.575	3126.18
Total proj.	2775.97	2770.50	2924.50
Excess	549.06	519.81	573.92
Excess proj.	503.66	477.61	504.43
Excess proj / Total	0.1742	0.1638	0.1614

3.3 Shower track lengths

The charged track length is defined as the sum of the lengths of all electron and positron tracks, with the projected charged track length being defined as the sum of all charged tracks projected onto the shower axis. These quantities are calculated for 200 showers, and their distributions are shown in Figures **??** and 7.

In addition, the excess track length is calculated, which is the sum of all electron track lenghts in the shower minus the sum of all positron track lengths, while the projected excess track length is defined analogously to the projected charged track length. Especially the projected excess track length is an imporant quantity in simulating the radio emission of air showers, as it is crucial for the normalization of the electric field spectrum. The distributions of both quantities are shown in Figures **??** and 8.

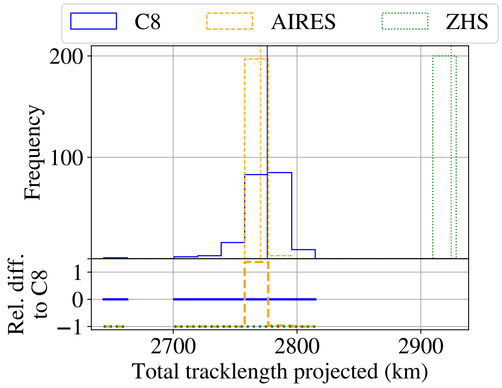

Figure 7: Distribution of the charged track length in homogeneous atmosphere, i.e. the sum of all electron and positron track lengths projected onto the shower axis, for 200 showers. The dashed lines indicate the medians of the corresponding distributions.One event of C8 has been taken out of the histogram due to having very low track length in comparison with the other caused by a photonuclear interaction.

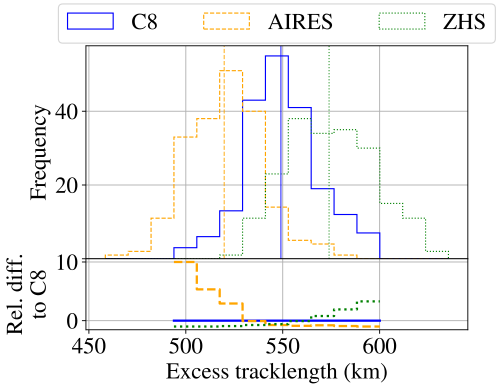

Figure 8: Distribution of the excess charged track length in homogeneous atmosphere, i.e. the difference between the sum of all electron track lengths projected onto the shower axis and the sum of all positron track lengths projected onto the shower axis, for 200 showers. The dashed lines indicate the medians of the corresponding distributions. One event of C8 has been taken out of the histogram due to having very low track length in comparison with the other caused by a photonuclear interaction.

Table 3: Run time of 1000 showers with each program.

C7	C8	AIRES	ZHS
5m53,697s	107m40,171s	1m55,376s	2m35,752s

3.4 Run time comparison

AIRES once cross sections were calculated only took 1.95 s. Showers were done only with longitudinal profiles as data output.

4. Outlook

In this work, the results of the first simulations of electromagnetic showers within the framework CORSIKA 8, using PROPOSAL as an electromagnetic model, have been presented and compared to other shower simulation tools. Although these comparisons revealed several differences, the general results are promising.

Further work on both PROPOSAL and the interface to CORSIKA 8 are necessary in the future. In order to improve the longitudinal distribution, the photohadronic interaction of photons will be implemented. Furthermore, a correct treatment of the LPM effect in inhomogeneous media needs to be applied. Both additions will be especially relevant for the simulation of higher-energetic showers.

With regard to the lateral distribution, the stochastic deflection of primary particles during stochastic interactions as well as the deflection of bremsstrahlung photons will be added in the near future. Including these effects may solve the deviations currently observed in the lateral profile of CORSIKA 8.

Parallel to these improvements, further comparisions to other simulation frameworks are going to be necessary.

Acknowledgments

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