The CORSIKA 8 air shower simulation framework

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Workshop on the tuning of hadronic interaction models, Wuppertal 2024

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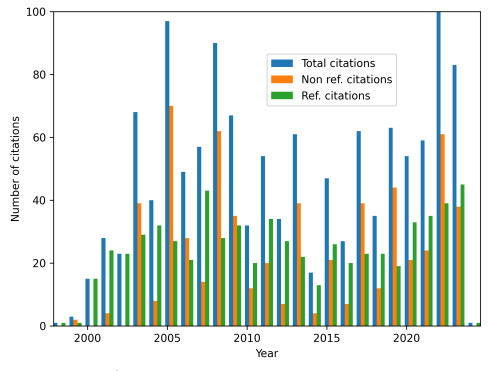
- originally developed for the KASCADE experiment in the 1980s
- at the core of air shower simulations in many astroparticle physics experiments over the last 30 years
- dedicated maintenance from KIT (D. Heck, T. Pierog, . . .)
- common reference frame for the community
- latest version: 7.75



ADS citation metrics of FZKA-6019

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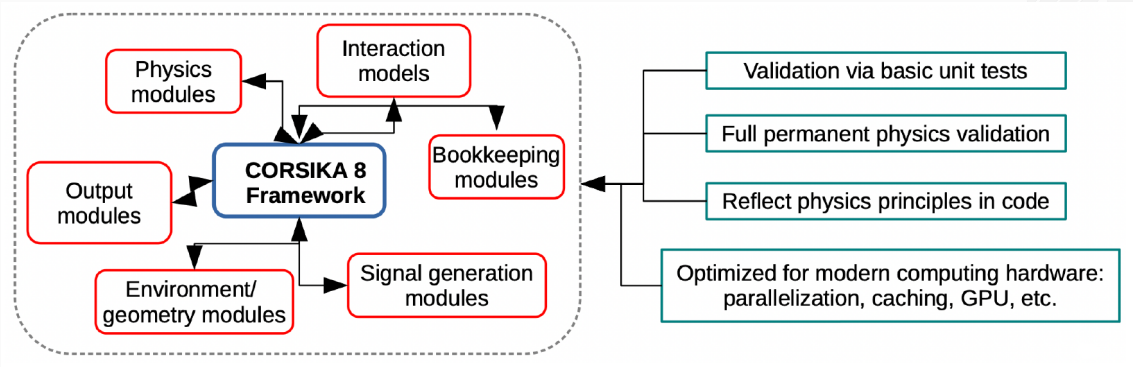
Limitations of CORSIKA 7

- hand-optimized code: excellent performance, but incurs limitations
- monolithic Fortran code
- program options heavily intertwined in source code
- maintenance increasingly difficult
- parallelization possibilities limited (MPI parallelized, but no multi-threading, no GPU parallelization, . . .)

- since 2018: rewrite of CORSIKA in modern C++17
- focus on modularity and the needs and possibilities of modern supercomputing
- coordinated by KIT, strong community integration



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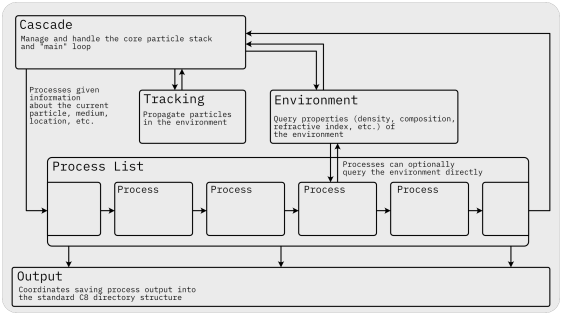
Architecture

- calculation of the particle cascade
  - tracking: propagation of particles under influence of energy losses and electromagnetic fields
  - stochastic events: creation of new particles in decays and interaction, sampling from interaction models
- environment provides media and fields
  - environment can be constructed from spheres and cuboids of different media
  - flexibility unparalleled by other simulation codes
- processes calculated can be customized
  - hadronic interactions
  - electromagnetic interactions
  - decays
  - radio emission
  - Cherenkov light calculation
  - ...



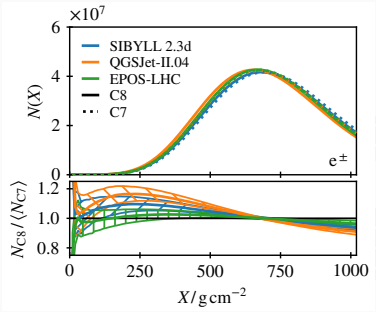
General structure of the CORSIKA 8 framework.

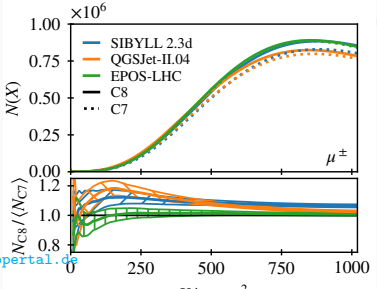
Status of CORSIKA 8

- full hadronic and electromagnetic cascades are available
- extensive validation with CORSIKA 7 and other codes → actually found and fixed bugs in CORSIKA 7 this way
- already some possibilities go beyond what was possible in CORSIKA 7
- performance (work in progress!)
  - particle-only showers and radio showers about a factor of 3—5 slower
  - showers with Cherenkov emission about as fast as CORSIKA 7

Hadronic cascades

- available hadronic interaction models
  - high energy: EPOS-LHC, QGSjet-II-04, Sibyll 2.3d
  - low energy: UrQMD, FLUKA, SOPHIA (for γp)
  - decay: Sibyll 2.3d
  - work in progress: Pythia 8
- comparison of particle spectra in showers calculated with CORSIKA 7, CORSIKA 8 and with a numerical solution of cascade equations MCEq
  - vertical proton shower at 10^{18} eV
  - good agreement with other codes





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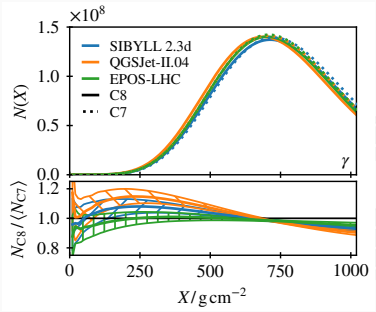

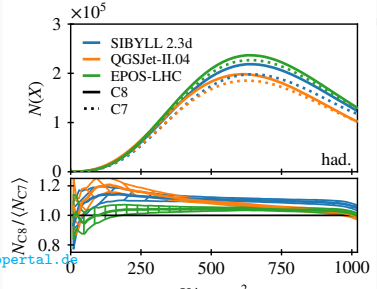

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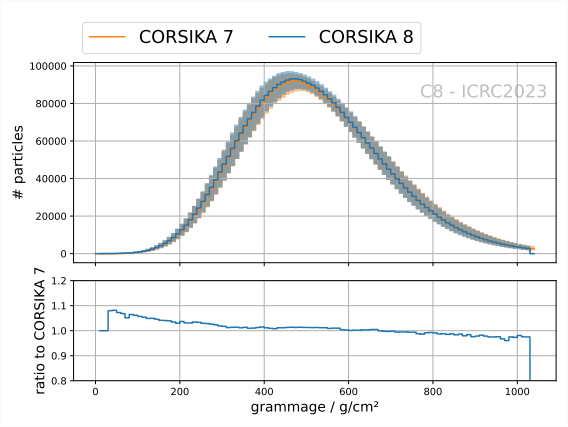
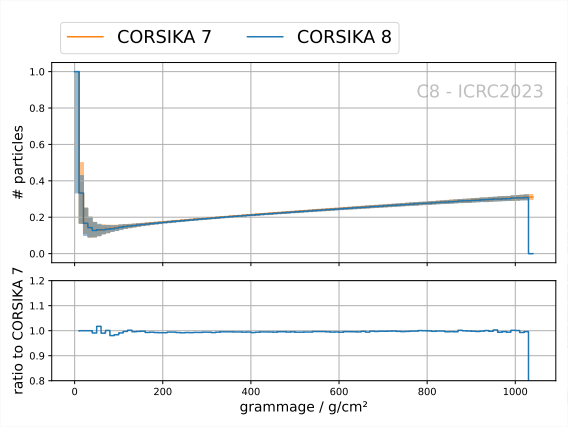
Electromagnetic cascades

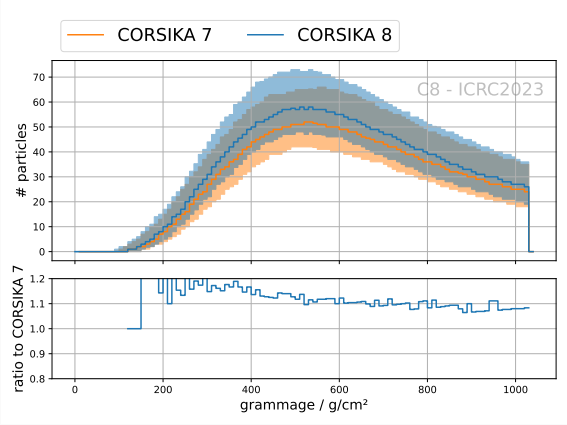
- in CORSIKA 7: modified version of EGS 4
  - Mortran code
  - deeply integrated into the CORSIKA source code
  - added $\gamma \to \mu\mu$, $\gamma N \to X$ and (optionally) Landau-Pomeranchuk-Migdal (LPM) effect
- in CORSIKA 8: lepton propagator PROPOSAL
  - modular C++14 library with Python bindings
  - propagation of electrons, positrons, and photons as well as muons (and taus)
  - LPM effect available in media with homogeneous density (for inhomogeneous density validation of a recent implementation is in progress)
- good agreement to C7 and AIRES



Longitudinal profile of 100 TeV electromagnetic showers in C7 and C8.



Charge excess of 100 TeV electromagnetic showers in C7 and C8.



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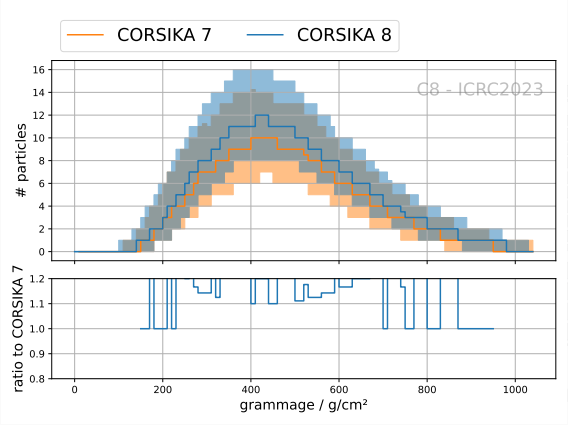

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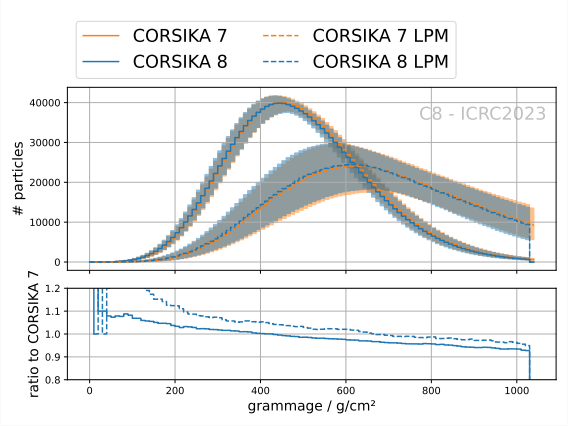
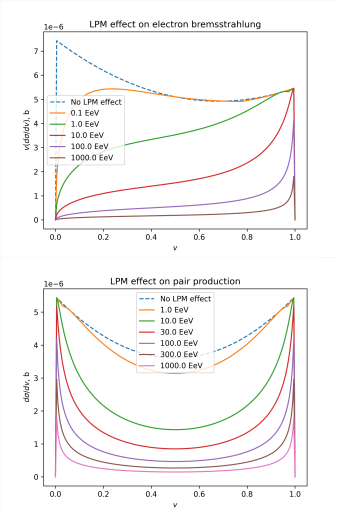


Longitudinal profile of 10^{20} eV electromagnetic showers in air with and without the LPM effect in C7 and C8. The energy cut is at 100 PeV.



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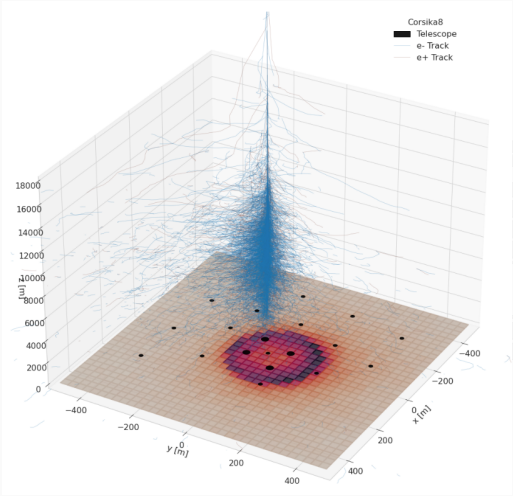
- Two implementations of Cherenkov emission available
- in good agreement with each other and CORSIKA 7
- one vectorized, the other uses GPU parallelization



1 TeV EM shower with ground level distribution of Cherenkov light.

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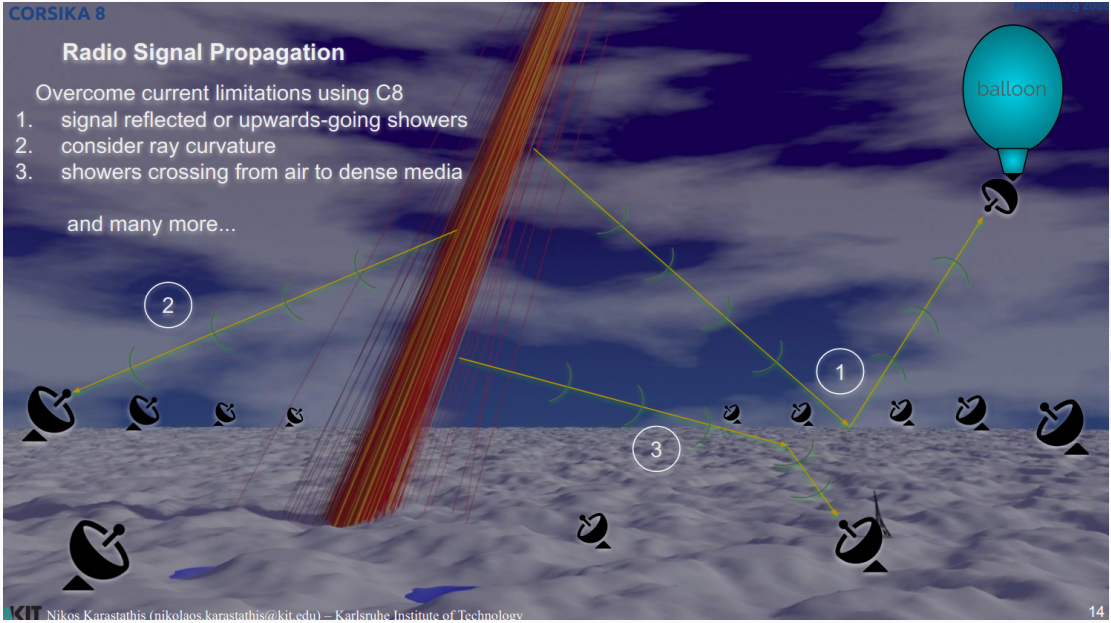
Radio Signal Propagation
Overcome current limitations using C8
1. signal reflected or upwards-going showers
2. consider ray curvature
3. showers crossing from air to dense media
and many more...
balloon
1
2
3
KIT Nikos Karastathis (nikolaos.karastathis@kit.edu) – Karlsruhe Institute of Technology
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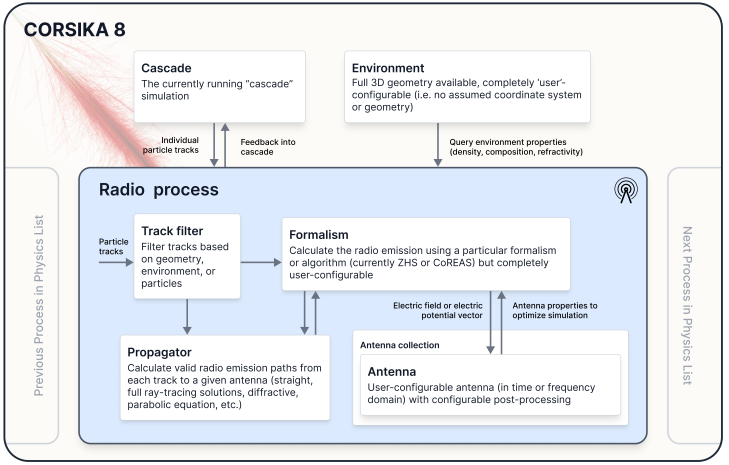
- fully implemented as process
- filter, formalism, propagator, and antenna configurable by user
- two algorithms for radio emission calculation
  - CoREAS as in CORSIKA 7
  - ZHS as in ZHAires
  - both formalisms in good agreement
- generation and processing of radio signals in antenna arrays parallelized (multi-threading with Gyges)



Schema of radio emission calculation.

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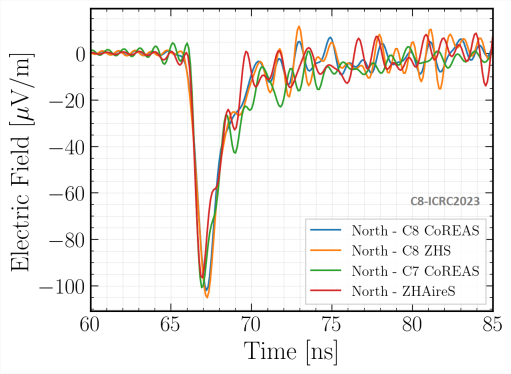
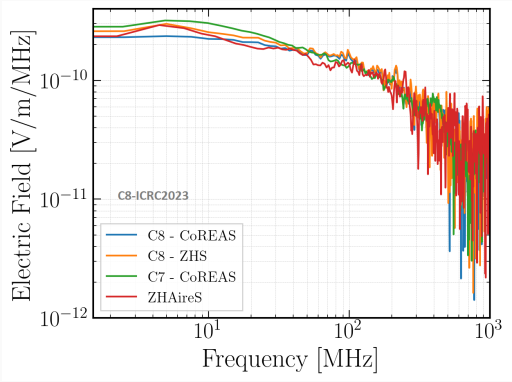
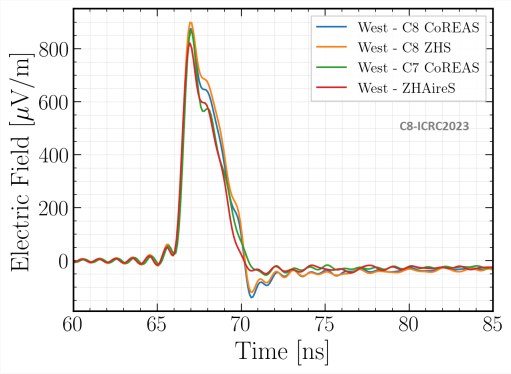
Comparison of radio pulses and frequency spectra

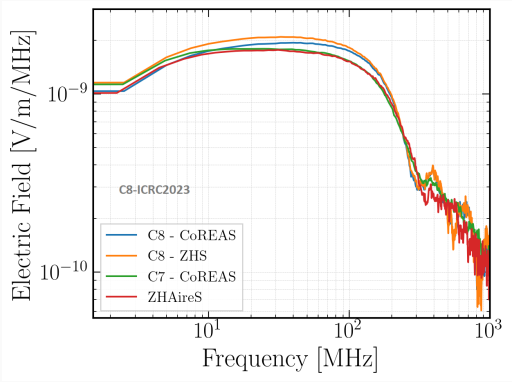




100 PeV iron-induced shower at 50 m distance from shower core. Geomagnetic contribution.

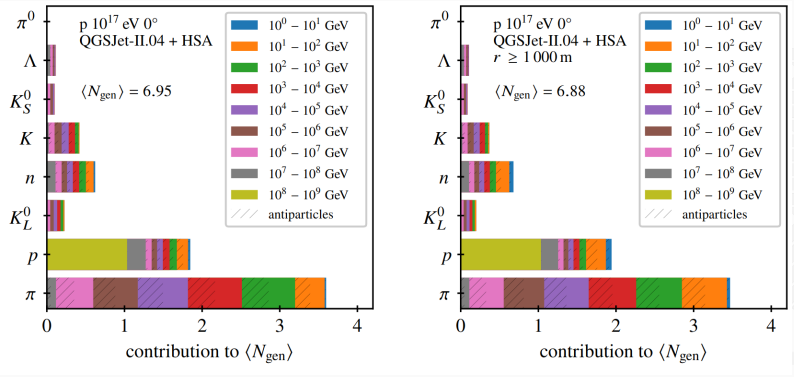
Comparison of radio pulses and frequency spectra





100 PeV iron-induced shower at 50 m distance from shower core. Charge-excess contribution.

- ancestry of particles (beyond mother and grandmother particle)
- here: muon ancestor particle distributions by species and energy
- left: total shower, right: outer particles ($r \geq 1000\,\mathrm{m}$)
- more details later in this workshop (M. Reininghaus)



From PoS(ICRC2021)463.

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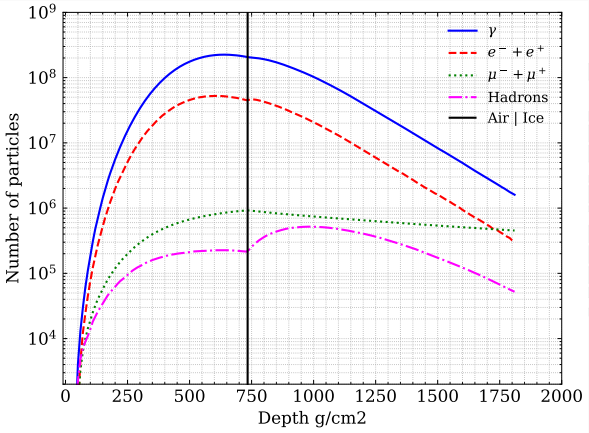
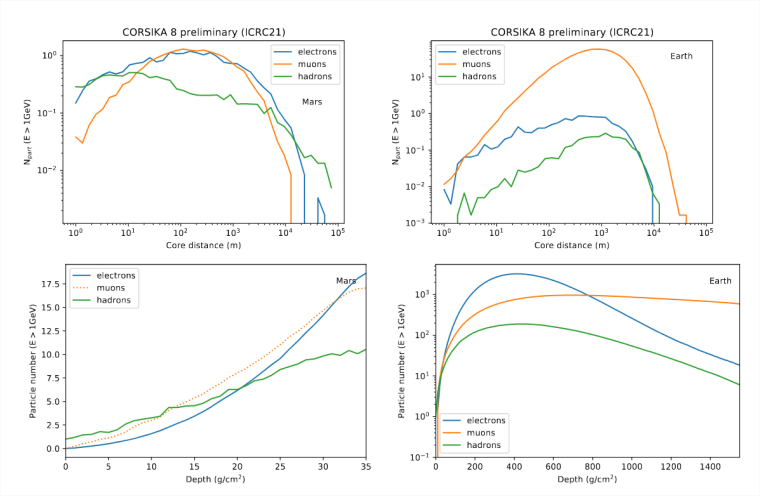
Cross-media shower

- vertical 100 PeV proton shower transitioning from air to ice at 2.4 km altitude (at dashed line)
- previously only possible by combining several simulation tools, now consistently inside one framework



Air showers on Earth and on Mars



100 TeV proton showers at 60° zenith angle. From PoS(ICRC2021)474.

Agreement with other codes

- good agreement to CORSIKA 7 for longitudinal profiles and lateral distributions for hadronic and electromagnetic showers
- number of muons in hadronic showers is systematically higher in C8 than C7, dependent on the high-energy hadronic interaction model
- number of muons in electromagnetic showers is about 10% higher in C8 than C7 (small component in hadronic showers)
- radio and Cherenkov emission agree well with ZHAires/CoREAS and CORSIKA 7, respectively

New possibilities

- full genealogy of shower particles
- much more flexible geometry setup (cross-media showers, neutrino-induced showers coming from mountain range, Mars atmosphere, . . .)
- multithreaded radio emission calculation
- GPU-parallelized Cherenkov emission

Conclusion

- CORSIKA 8 is physics-complete
- already some capabilities go beyond what is possible with CORSIKA 7
- first release planned in the first half of the year