

CORSIKA 8

A modern and universal framework for particle cascade simulations

Marvin Gottowik

for the CORSIKA8 Collaboration,
Karlsruhe Institute of Technology (KIT)

UHECR2024
20.11.2024



Current CORSIKA 7

- Monte Carlo simulations essential for interpretation of measured air-shower data
- CORSIKA 7 has monolithic FORTRAN code, key developers retired. Challenging to navigate, maintain, and extend by physicists today.
- Hand-optimized code: fast, but incurs limitations, e.g. exp. atmospheric models
- Difficult to adapt to modern computing environments: MPI-parallelized, but no multi-threading, no GPU parallelization

- More flexible simulation tool is needed:
 - In-ice showers, cross-media showers, ...
 - complex radio-signal propagation in ice, ...

CORSIKA 8 simulation framework

- a modern reimplementation in C++, with focus on modularity
- designed with the needs of modern computing in mind
- coordinated by KIT, but as a true community effort
- First commit:
Mon Apr 9 14:55:03 2018



CORSIKA 8 workshop, July 2023 at KIT

CORSIKA 8 simulation framework

- a modern reimplementation in C++, with focus on modularity
- designed with the needs of modern computing in mind
- coordinated by KIT, but as a true community effort
- More information / Get in contact:
 - <https://www.iap.kit.edu/corsika/88.php>
 - <https://gitlab.iap.kit.edu/AirShowerPhysics/corsika/>
 - <https://mattermost.hzdr.de/corsika8/channels/town-square>



CORSIKA 8 workshop, September 2024 at KIT

Status of CORSIKA 8

- code can be considered „physics-complete“ and is openly available
- Many crucial improvements over the last two years
 - FLUKA as low-energy interaction mode
 - Sibyll 2.3d, QGSJETII-04, EPOS-LHC as high-energy interaction models. Also Pythia 8.3 (preliminary version) available for the first time, cf. poster by Chloé Gaudu,
 - EM: Photohadronic interactions, LPM effect, Particle thinning
 - Fully integrated Cherenkov-light calculation
 - Fully realistic radio emission calculation with two formalisms
- extensive validation versus CORSIKA 7 and other codes
- still polishing user-level aspects (simulation steering, documentation, ...)

Implementing Pythia 8 for EAS Studies: Another Piece to the Muon Puzzle
 Chloé Gaudu, Bergische Universität Wuppertal, Germany
 Poster ID

Motivation
 To gain insights into the 'Muon puzzle' – a persistent muon deficit observed in air shower simulations compared to measurements, e.g. from the Pierre Auger Observatory – several studies took place: from ad hoc modification of cross-section, multiplicity, and elasticity of hadronic interactions model, or by altering directly particle, to perform a multi-parameter fit of model predictions against Auger data. This work introduces another hadronic interaction model, Pythia 8, into the landscape of air showers, for which all above-mentioned study can be applied to.

CORSIKA 8

- new C++ based particle shower simulation code, successor of CORSIKA 7
- wide range of state-of-the-art hadronic interaction models available:
 - high energies: Sibyll 2.3d, EPOS-LHC, QGSJET-II.04.
 - Pythia 8 (preliminary), low energies: FLUKA
 - decays handled by Sibyll 2.3d and Pythia 8
 - hadronic interaction results agree at the ~10% level with CORSIKA 7
- new features: enhanced thinning, shower genealogy, cross-media showers
- code can be considered "physics-complete"

Pythia 8

- general purpose hadronic interaction model
- well-tailored for LHC experiments: e^+e^- , pp, pp, pPb, PbPb interactions
- Angularity model
- nuclear geometry given by Glauber model
- stack individual nucleon-nucleon subcollisions and hadronize them
- new feature in 8.3.12: variable energy and beam on an event-by-event basis

Lateral profile*

Energy spectrum*

Cross-sections

- tabulate total and partial σ , including σ^{had} for several (projectile, target, $P_{\text{had}} \leftrightarrow \nu_{\text{had}}$) with Pythia 8.3.12, using Angularty for nuclear interactions

Energy loss*

- X_{max} shift between models
- Pythia 8/QGSJET-II.04: ~660 g cm⁻²
- EPOS-LHC ~ 670 g cm⁻²
- Sibyll 2.3d ~ 690 g cm⁻²

Longitudinal profile*

Conclusion

- need to compute σ^{had} with Pythia 8 for use in CORSIKA 8
- successful CORSIKA 8 implementation of Pythia 8 for proton primaries
 - comparable outputs with state-of-the-art models
 - fewer muons observed at ground
 - interesting tuning playground available for Pythia 8
- obstacles for nuclear shower primaries
 - long Angularty initialization to be reduced thanks to reuse file feature
 - missing data in tables for AA interactions to be filled using semi-superposition model (as done with Sibyll 2.3d)
 - target fragments reaching ground to be dealt with

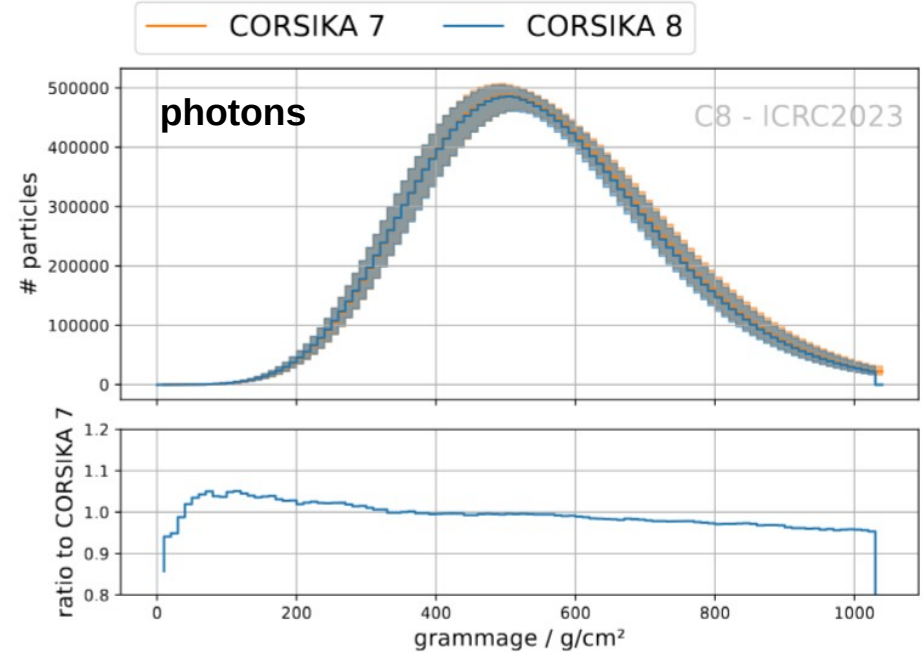
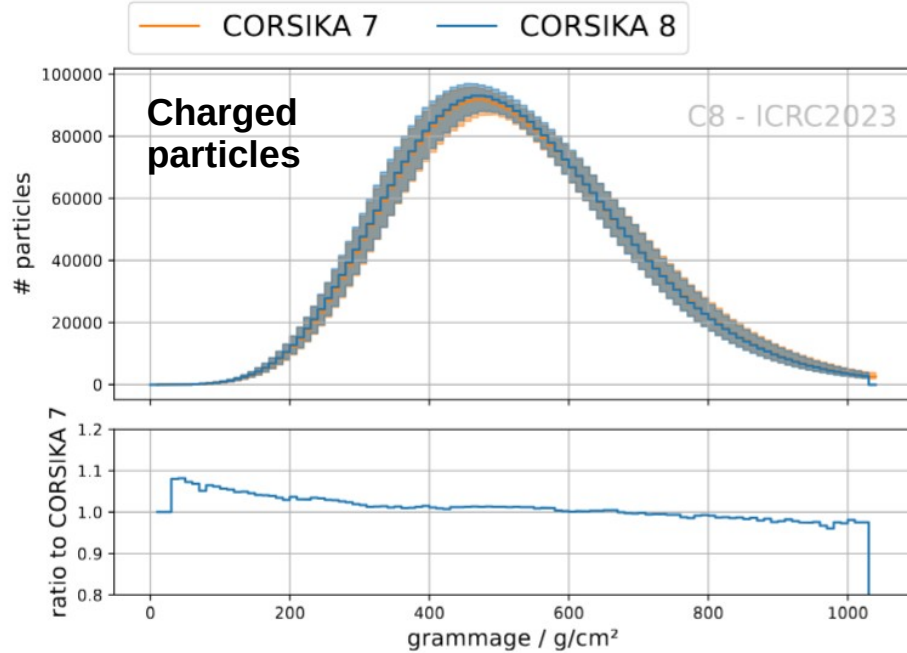
KEY REFERENCES

ACKNOWLEDGEMENT

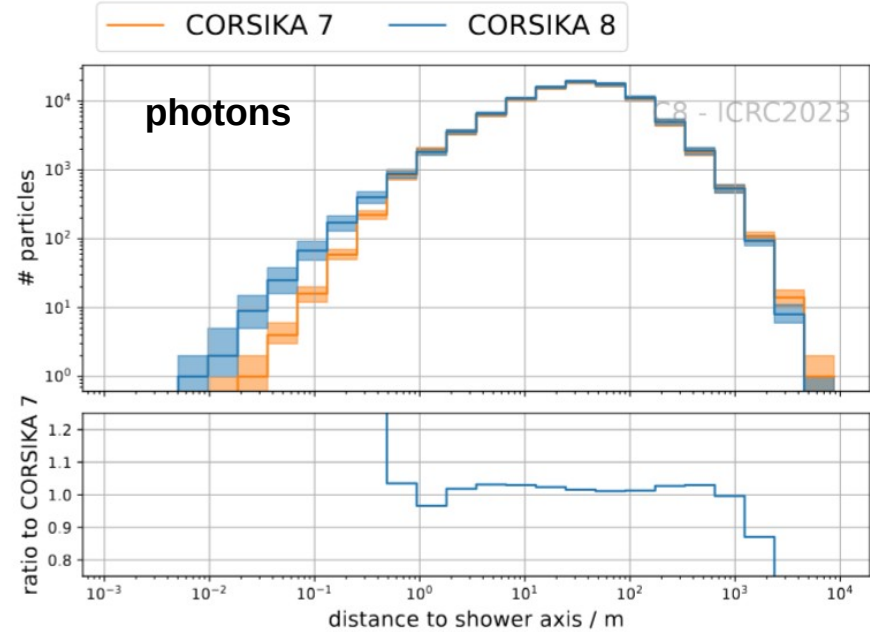
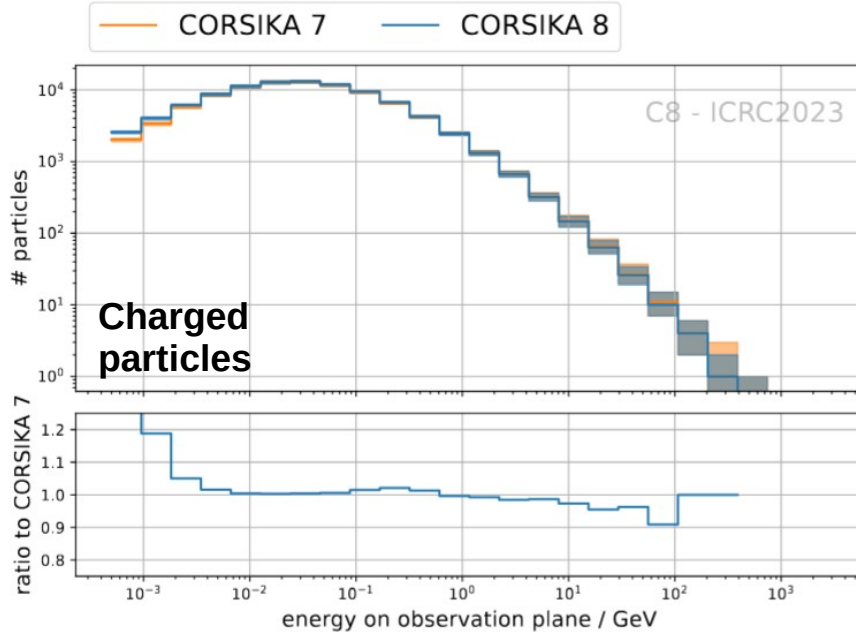
MORE INFORMATION

CORSIKA 8 Collaboration
 Get in contact with us:
 corsika_dev@lists.kit.edu
 https://mailman.hep.fsu.edu/list/corsika
 Join the effort!
 https://github.com/kit-edu/AirShowerPhysicsCORSIKA

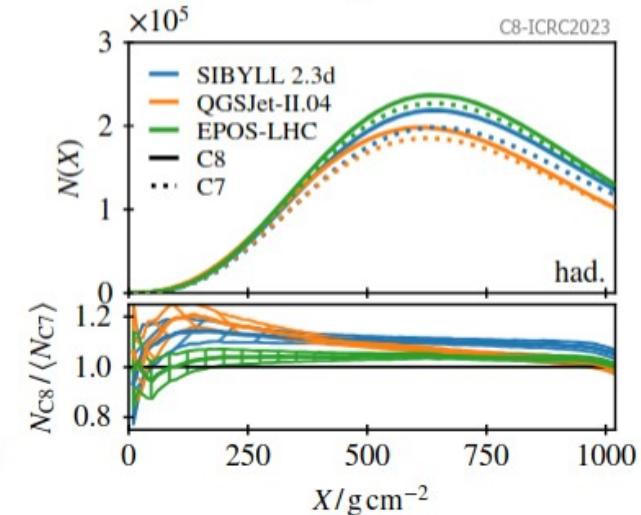
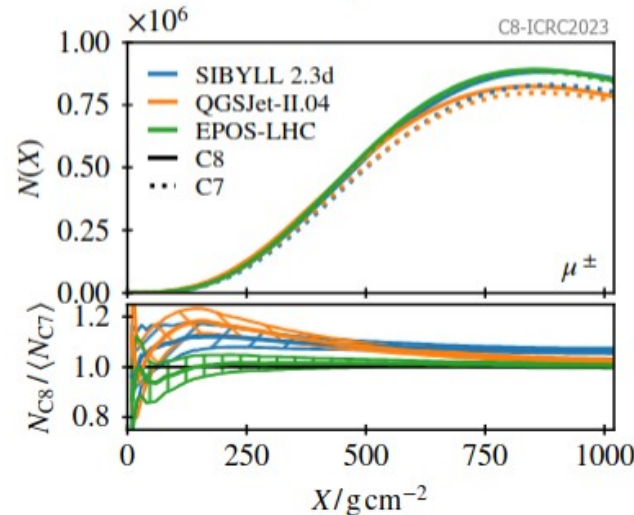
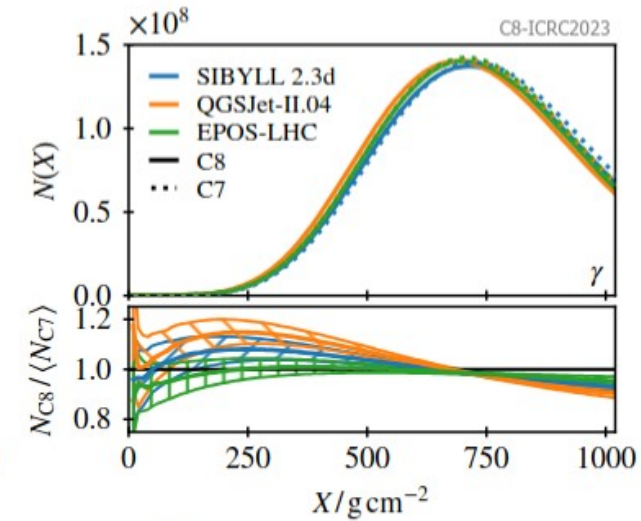
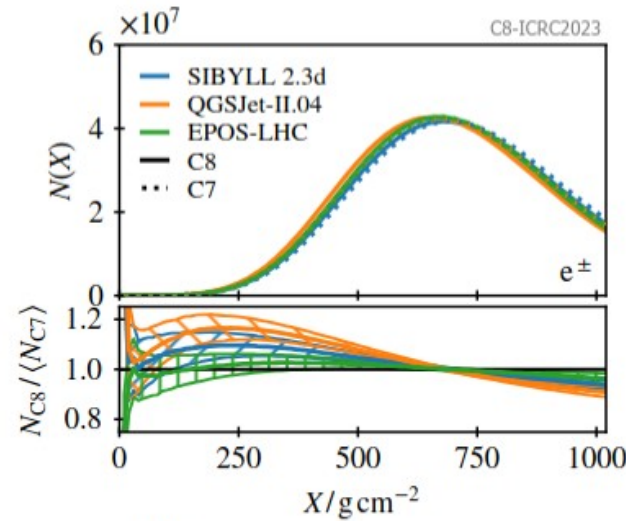
- New code for electromagnetic component
 - Corsika 8: PROPOSAL 7.6.2
 - Corsika 7: customized version of EGS4
- Comparing a 100 TeV primary
 - General agreement on the <10% level for longitudinal and lateral profile, energy distribution
 - Likely due to particle tracking & multiple scattering treatment



- New code for electromagnetic component
 - Corsika 8: PROPOSAL 7.6.2
 - Corsika 7: customized version of EGS4
- Comparing a 100 TeV primary
 - General agreement on the <10% level for longitudinal and lateral profile, energy distribution
 - Likely due to particle tracking & multiple scattering treatment

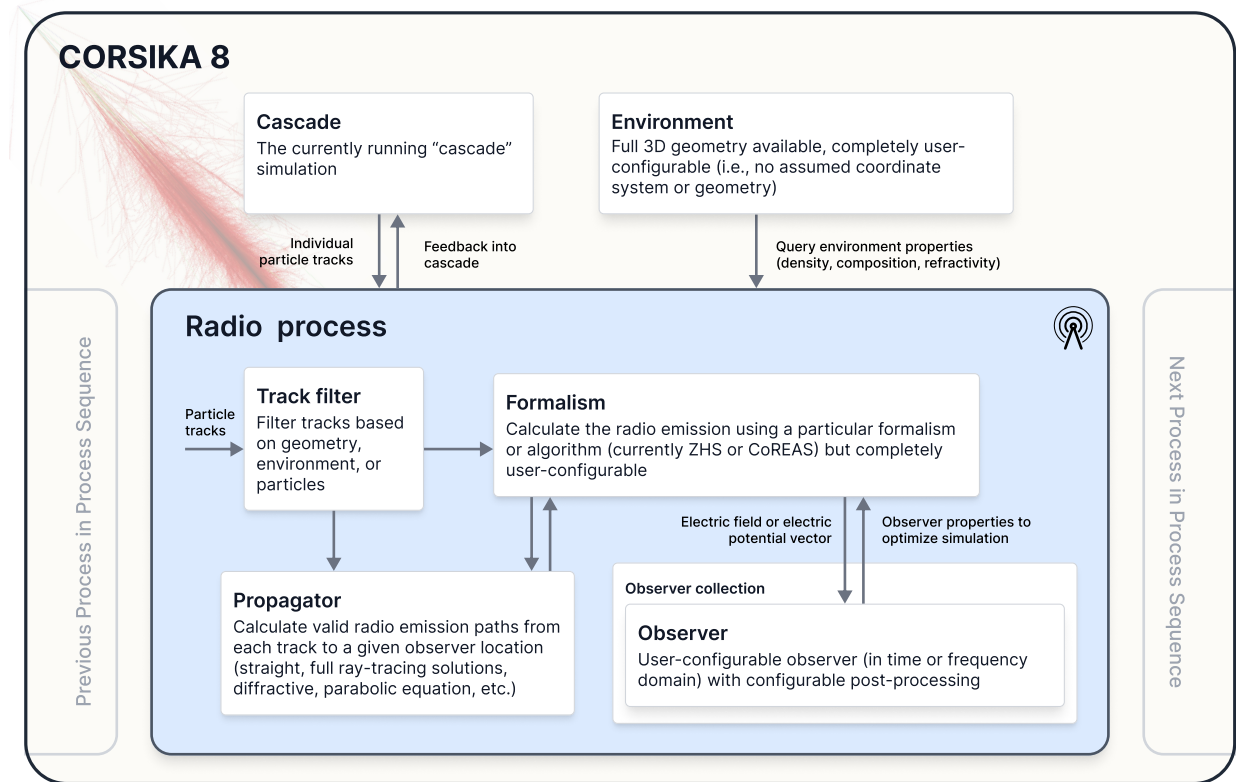


- Longitudinal distributions for the averages of 300 vertical proton-induced 100 PeV air showers
- Dependence on interaction model
- Will be investigated in more detail
- Agreement for electrons/positrons, photons, muons and hadrons within $\sim 10\%$

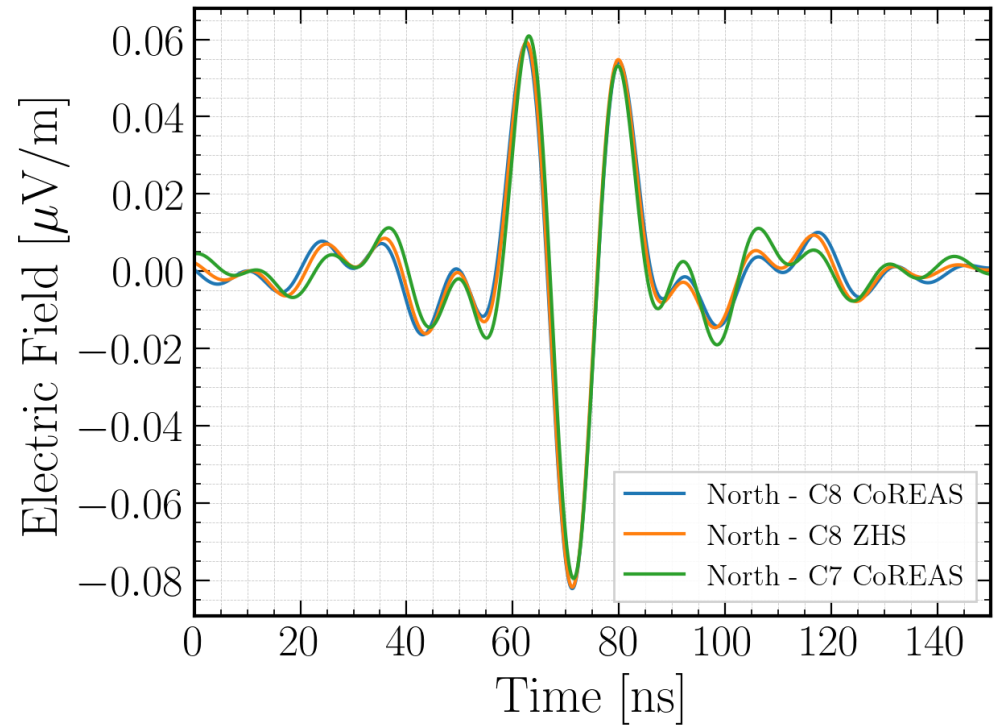
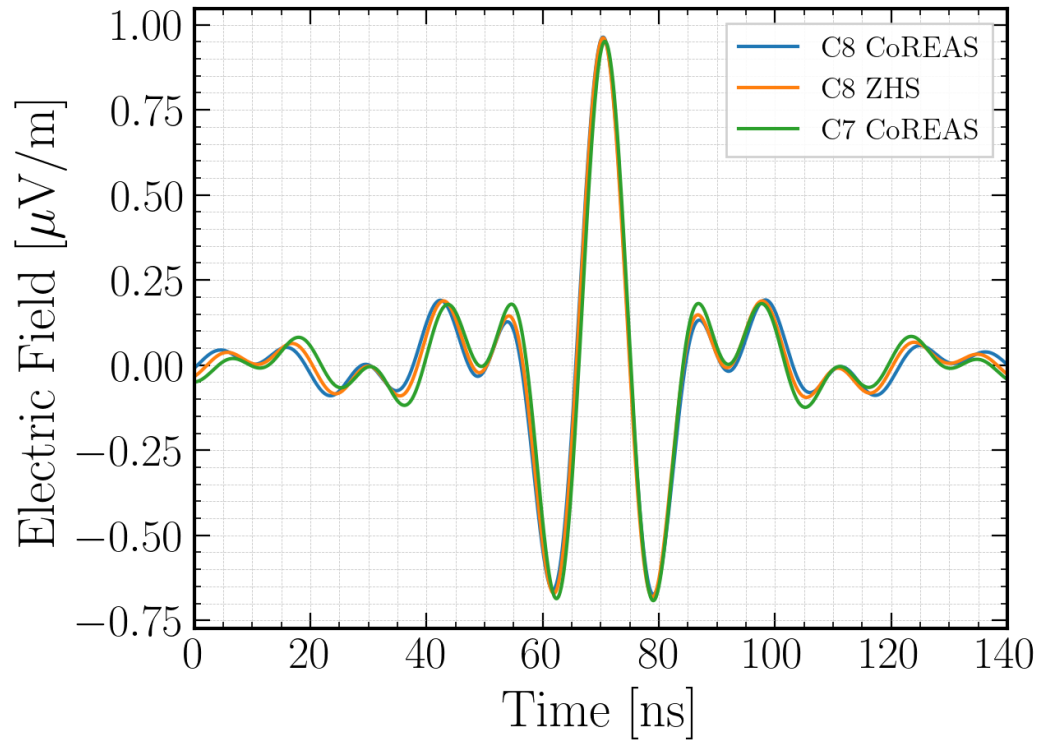


Radio emission

- Calculation of radio emission from particle cascades fully implemented
 - „CoREAS“ (endpoints) à la C7
 - „ZHS“ à la ZHAireS
- Both formalism in same code, can compare for exact same air shower
- Generic structure: filter, formalism, and propagator can be configured separately
- Paper submitted to Astroparticle Physics, very positive review



Radio pulses



- Pulse for 1 PeV vertical shower at 100 m distance from core
- Pulses agree nicely for high-precision simulations

Here: 30-80 MHz,
same for 50-350 MHz

Radio emission components

- Patterns and polarizations match predictions of CoREAS and ZHAireS

- C8 produces slightly more signal with default setting of technical parameters

- Radiation energy converges to within 1-2% for high-precision simulations

modulus

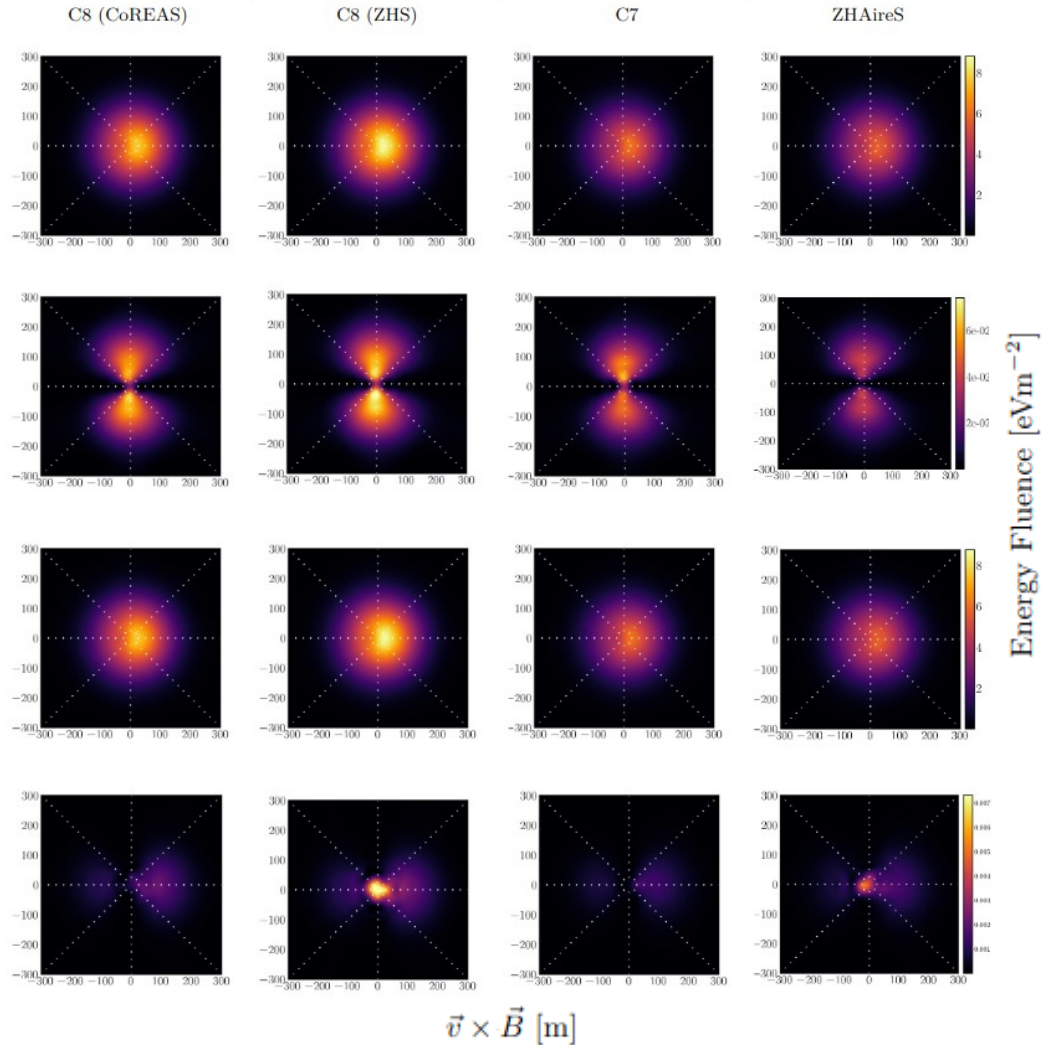
$$\vec{v} \times (\vec{v} \times \vec{B})$$

$$\vec{v} \times \vec{B}$$

$$\vec{v}$$

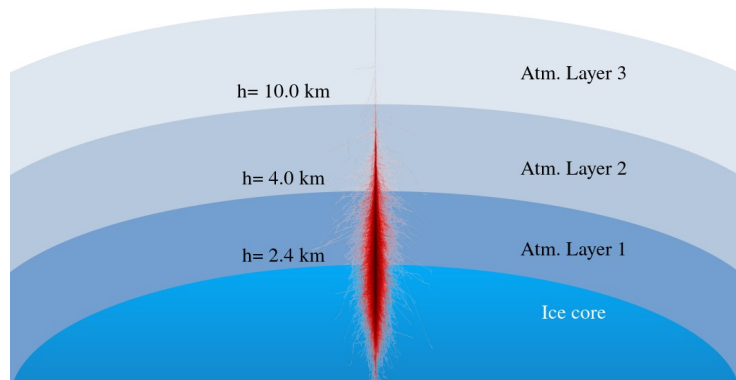
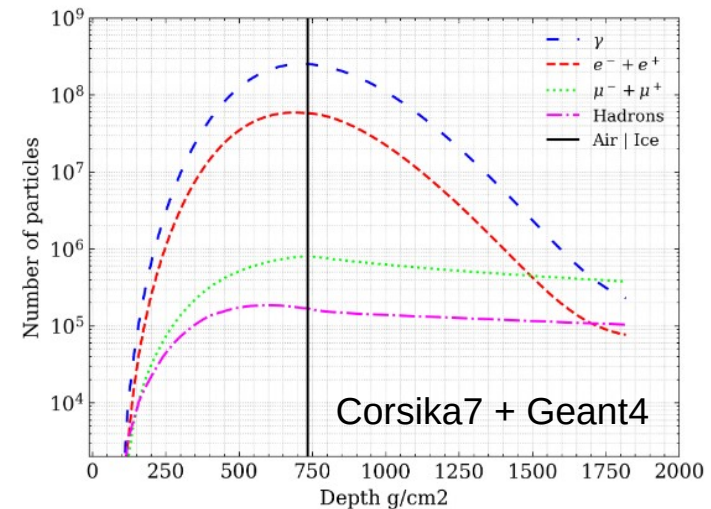
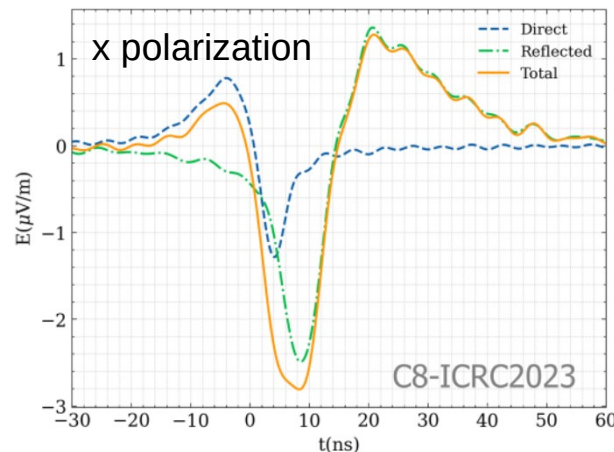
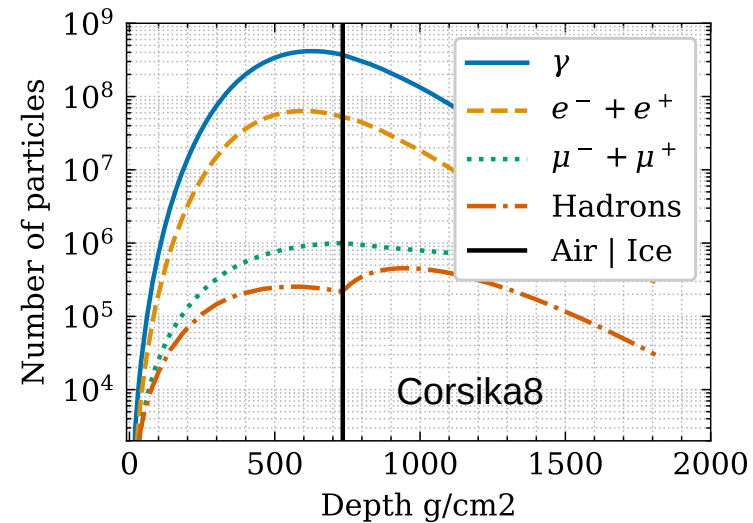
$\vec{v} \times (\vec{v} \times \vec{B})$ [m]

Energy Fluence [eVm^{-2}]



Cross media showers

- Example: particle showers penetrating from air in to ice.
- Comparing Corsika8 with combination of Corsika7 + Geant4
- Rehadronization when the showers intersects the ice due to the dominance of the hadronic interaction. Missing in Geant4 due to absence of hadronic interaction models in-ice.
- Medium-specific propagators for radio emission.
In ice: direct and reflected path



Expert release

- We will have an expert release for Christmas to gather broader feedback from the community
- Basic steering available, advanced one using config file under development
- Python library to read corsika8 output, examples scripts are provided

```
c8_air_shower --pdg 2212 --energy 1e5 --zenith 35 --azimuth 0
--filename test_shower
```

```
config.yaml  energyloss      interactions  primary      summary.yaml
CoREAS      interaction_hist  particles    profile      ZHS
```

```
energyloss:
config.yaml  dEdX.parquet  summary.yaml
```

```
particles:
config.yaml  particles.parquet  summary.yaml
```

Summary

- Tremendous progress in the development of CORSIKA 8, considered “physics-complete”.
- Expert release for Christmas, feedback from the community very much appreciated.
- Only single tool for simulation of cross-media showers.

- Validation against CORSIKA 7 results shows agreement generally on a $\approx 10\%$ level.
- CORSIKA 8 radio implementation successfully validated. ZHS and CoREAS formalisms converge at the same result within 1-2%.
- Already successfully used by community working on radio emission in ice, excellent agreement with previous results

The CORSIKA8 Collaboration

J.M. Alameddine^{a,b}, J. Albrecht^{a,b}, J. Ammerman-Yebra^c, L. Arrabito^d, A.A. Alves Jr.^{e,f}, D. Baack^{a,b}, A. Coleman^g, H. Dembinski^{a,b}, D. Elsässer^{a,b}, R. Engel^e, A. Faure^d, A. Ferrari^e, C. Gaudu^h, C. Glaser^g, M. Gottowik^e, D. Heck^e, T. Huege^{e,i}, K.H. Kampert^h, N. Karastathis^e, L. Nellen^j, T. Pierog^e, R. Prechelt^k, M. Reininghaus^l, W. Rhode^{a,b}, F. Riehn^{m,c}, M. Sackel^{a,b}, P. Sampathkumar^e, A. Sandrock^h, J. Soedingrekso^{a,b}, R. Ulrich^e

