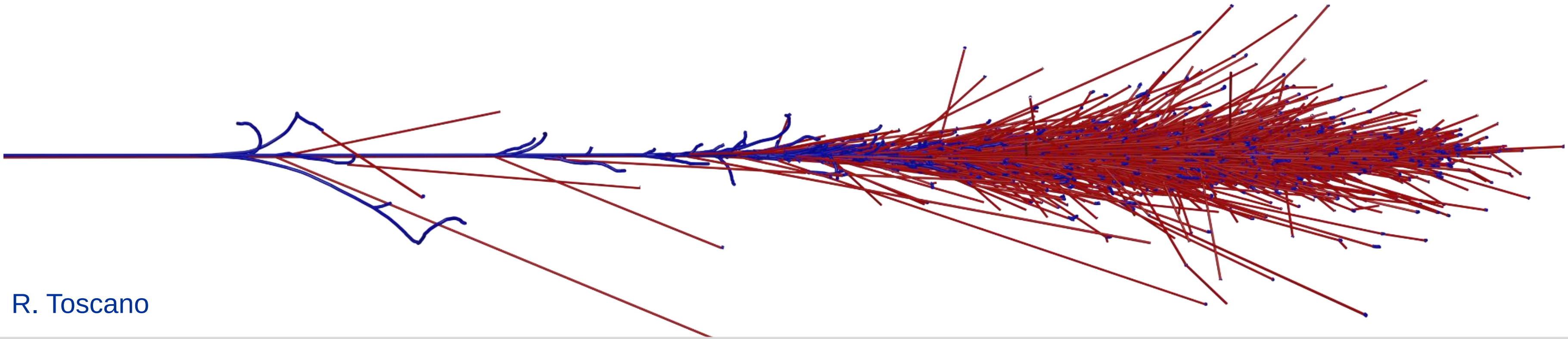
Simulating and validating air-shower radio emission with CORSIKA 8

T. Huege, **N. Karastathis**, R. Prechelt, J. Ammerman-Yebra, M. Reininghaus for the CORSIKA 8 Collaboration



R. Toscano

CORSIKA

The CORSIKA code in astroparticle physics

CORSIKA: A Monte Carlo code to simulate extensive air showers

D. Heck (Karlsruhe, Forschungszentrum), J. Knapp (Karlsruhe U., EKP), J.N. Capdevielle (College de France), G. Schatz (Karlsruhe, Forschungszentrum), T. Thouw (Karlsruhe, Forschungszentrum)

Feb, 1998

90 pages

Report number: FZKA-6019

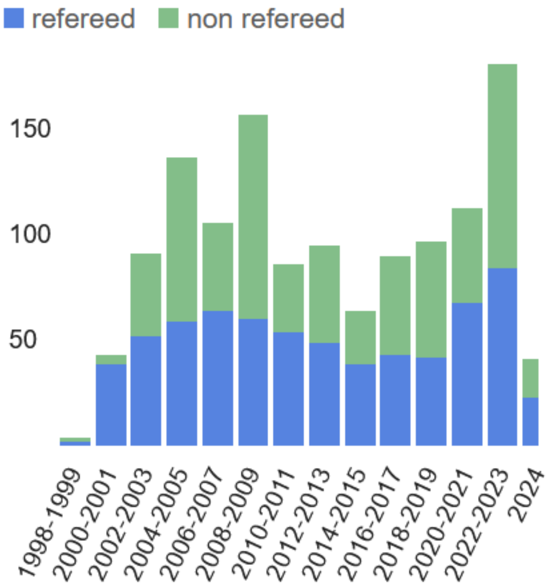
pdf links cite claim reference search 1,116 citations

[PDF] CORSIKA: A Monte Carlo code to simulate extensive air showers

JN Capdevielle, G Schatz, T Thouw - digbib.bibliothek.kit.edu

CORSIKA is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other …

☆ Speichern 99 Zitieren Zitiert von: 2288 Ähnliche Artikel »



NASA ADS:
1305 citations on 04-06-2024

The need for a CORSIKA 7 successor

Karlsruhe Institute of Technology

- CORSIKA 7 has monolithic FORTRAN code (several dialects mixed), key developers retired, hard to navigate by physicists today
- program „options“ heavily intertwined in the source code
- hand-optimized: fast, but incurs limitations, for example: atmospheric model based on strictly exponential density profiles
- especially the radio community needs more flexibility: in-ice showers, cross-media showers, complex signal propagation, …
- the astroparticle physics community needs a worthy, well-supported and realiably maintained successor – for *decades* to come

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

The CORSIKA 8 project is coordinated by the steering committee consisting of the following members (deputies):

- Tim Huege <tim.huege@kit.edu>: project coordination
- Dominik Baack (Alexander Sandrock): electromagnetic interactions
- Tanguy Pierog (Felix Riehn): hadronic interactions
- Alan Coleman (Max Reininghaus): software development
- Augusto Alves jr.: performance, parallelization
- Lukas Nellen: deployment, continuous integration

CORSIKA 8 workshop, July 2023 at KIT

https://gitlab.iap.kit.edu/AirShowerPhysics/corsika/

Status of CORSIKA 8

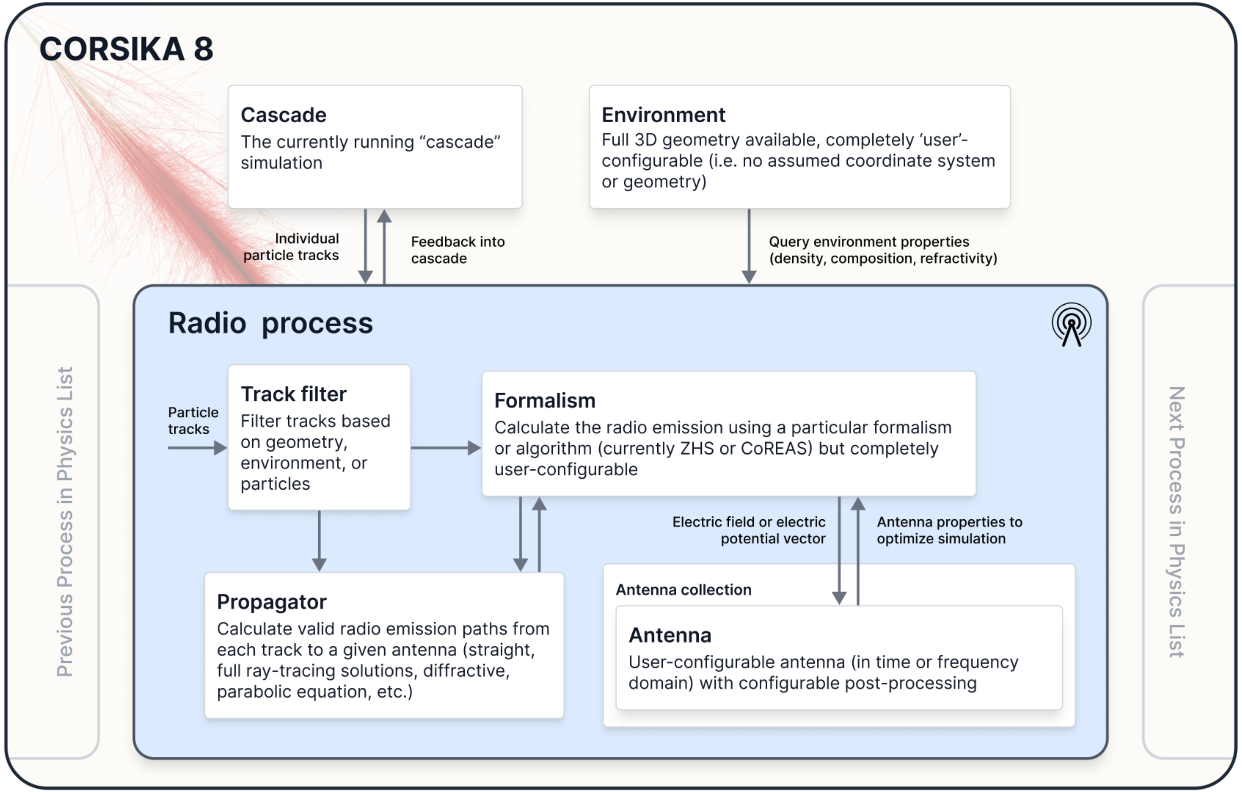
Karlsruhe Institute of Technology

- code can be considered „physics-complete“ and is openly available
- Started in 2018, *many* crucial improvements over the last two years
  - FLUKA as low-energy interaction model
  - Sibyll 2.3d, QGSJETII-04, EPOS-LHC as high-energy interaction models, also Pythia 8.3 (testing version) available for the first time
  - 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 (sim. steering, documentation, …)
- already very useful for the in-ice radio endeavors!

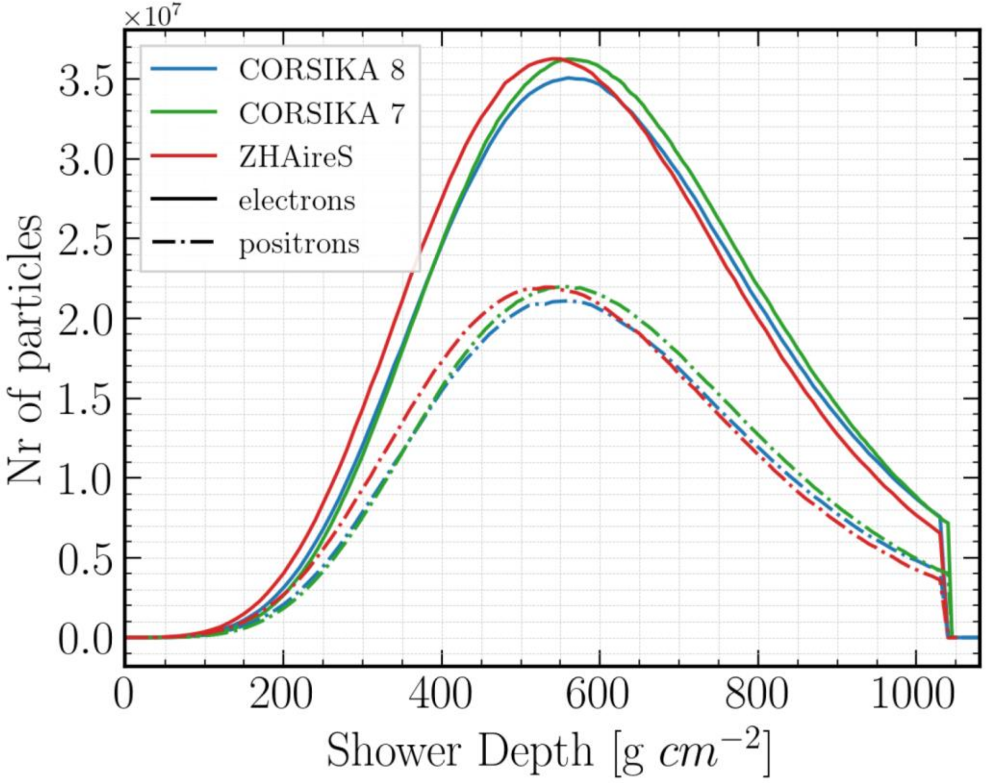
Radio in CORSIKA 8

Radio-emission simulations

- radio emission from particle cascades fully implemented
- two formalisms: „CoREAS“ (endpoints) à la C7 and „ZHS“ à la ZHAireS
- generic structure
- powerful diagnostic



Comparison C8 vs C7 vs ZHAireS



- Select „similar“ showers
- Standard settings for particle tracking
  - C8 max geomagnetic deflection angle 0.2 rad
  - C7 STEPFC 1.0 and max deflection 0.2 rad
- Vertical 10^{17} eV, 50 μT horizontal B-field, Sybill 2.3d & FLUKA, 0.5 MeV em particle cut, 10^{-6} opt. thinning, US standard atmo with n_0=1.000327

Radio-emission 30-80 MHz

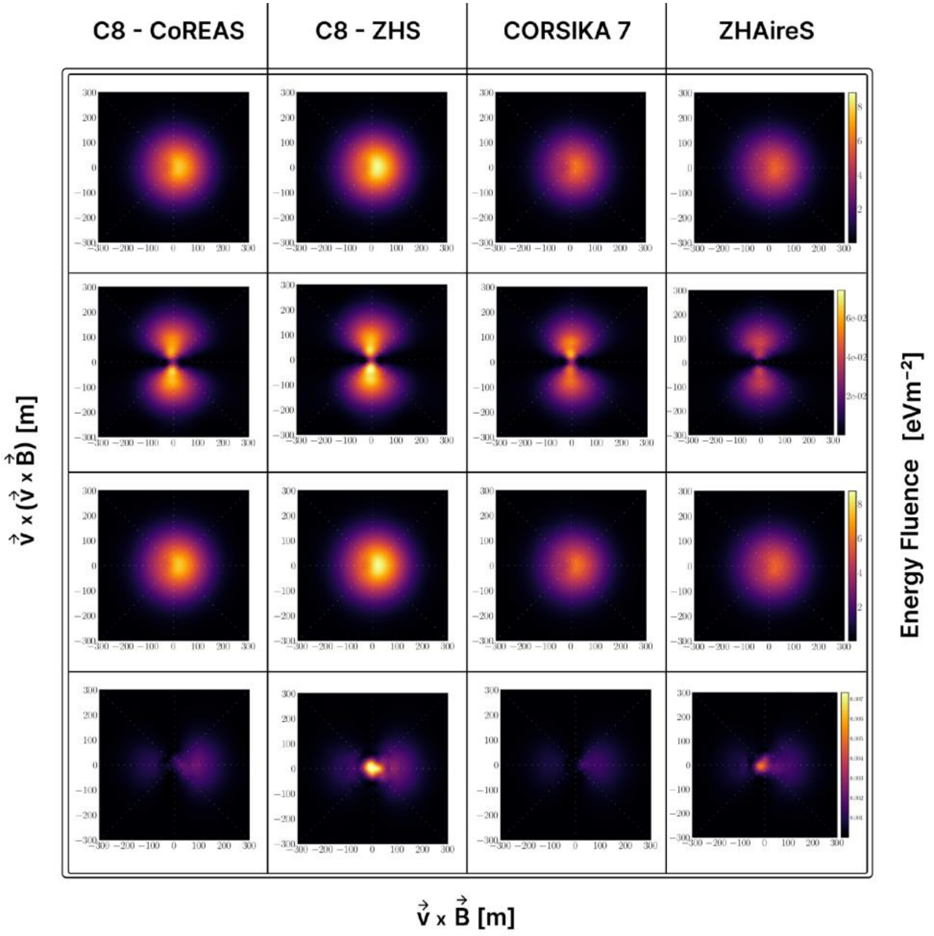
- state at ICRC2023
- patterns and polarizations match
- C8 produces slightly more signal!?

modulus

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

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

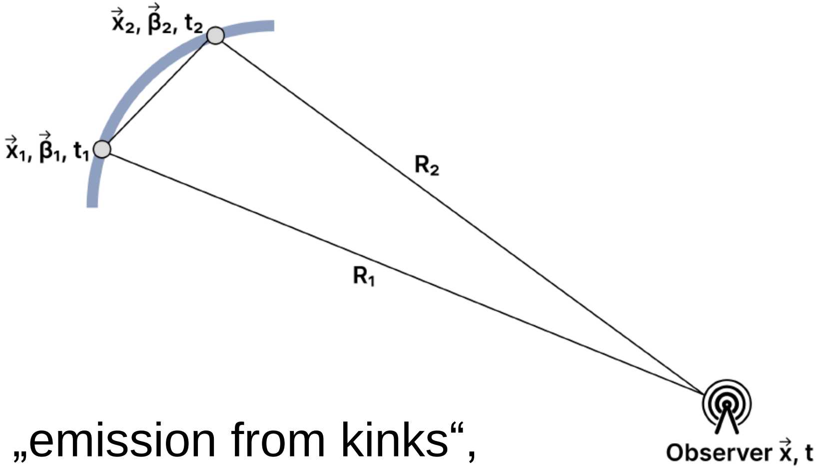
$$\vec{v}$$



Both codes at 0.2 rad maxRadians!

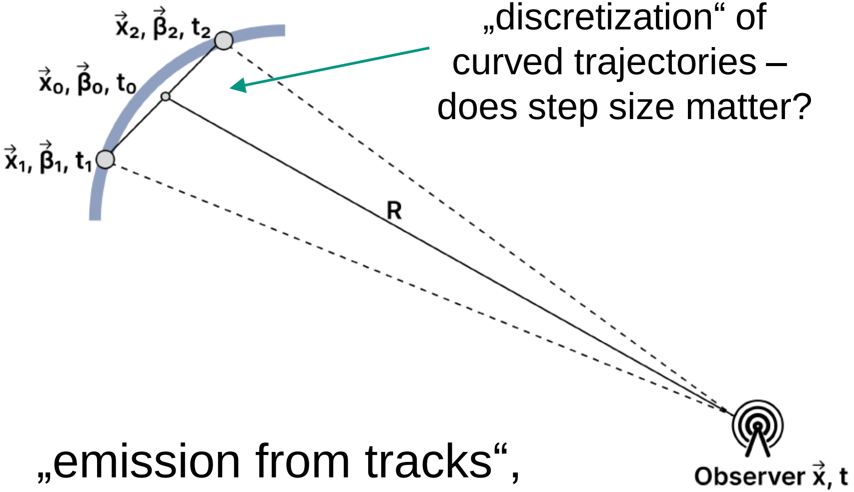
Comparing the formalisms

„Endpoints“ (CoREAS) and ZHS formalisms



„emission from kinks“,
E-fields in the time domain

James, Falcke, Huege, Ludwig, PRE (2011)



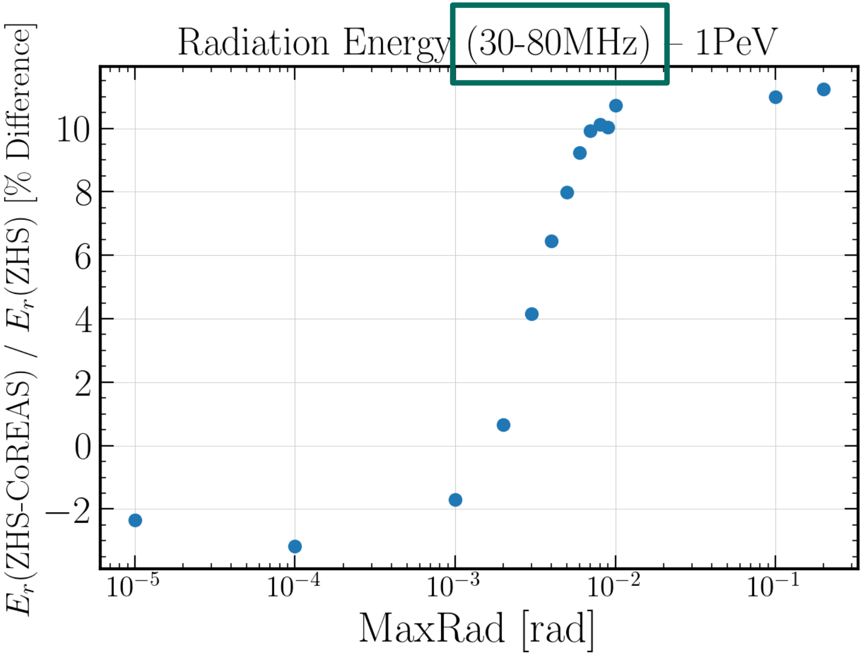
„discretization“ of curved trajectories – does step size matter?

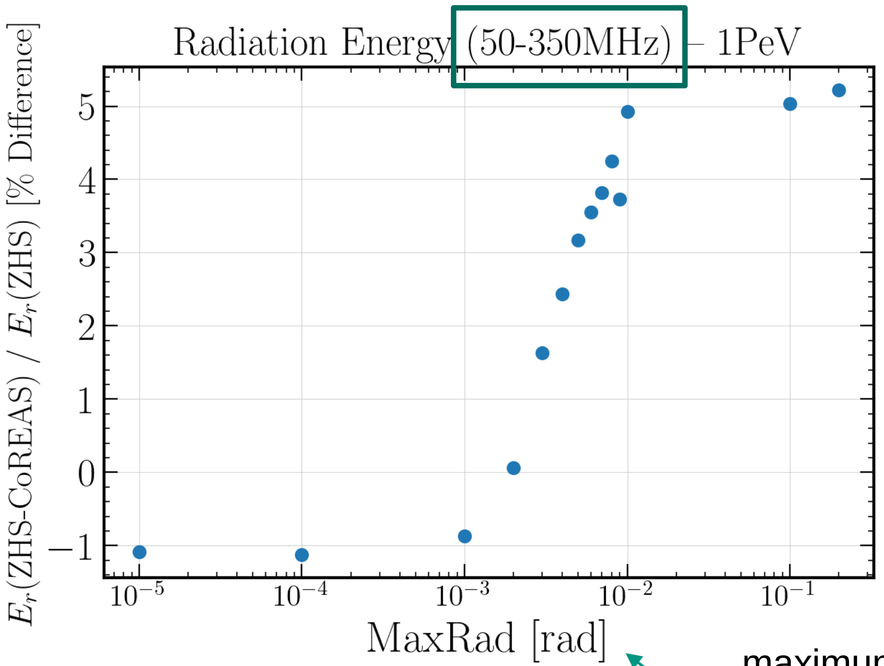
„emission from tracks“,
vector potential in the time domain

Alvarez-Muniz, Carvalho, Zas, Astropart. Phys. (2012)

- previously „endpoints“ in CORSIKA 7 & ZHS in AireS – hard to compare
- now both in same code, can compare for exact same air shower!

ZHS and endpoints comparison varying step size

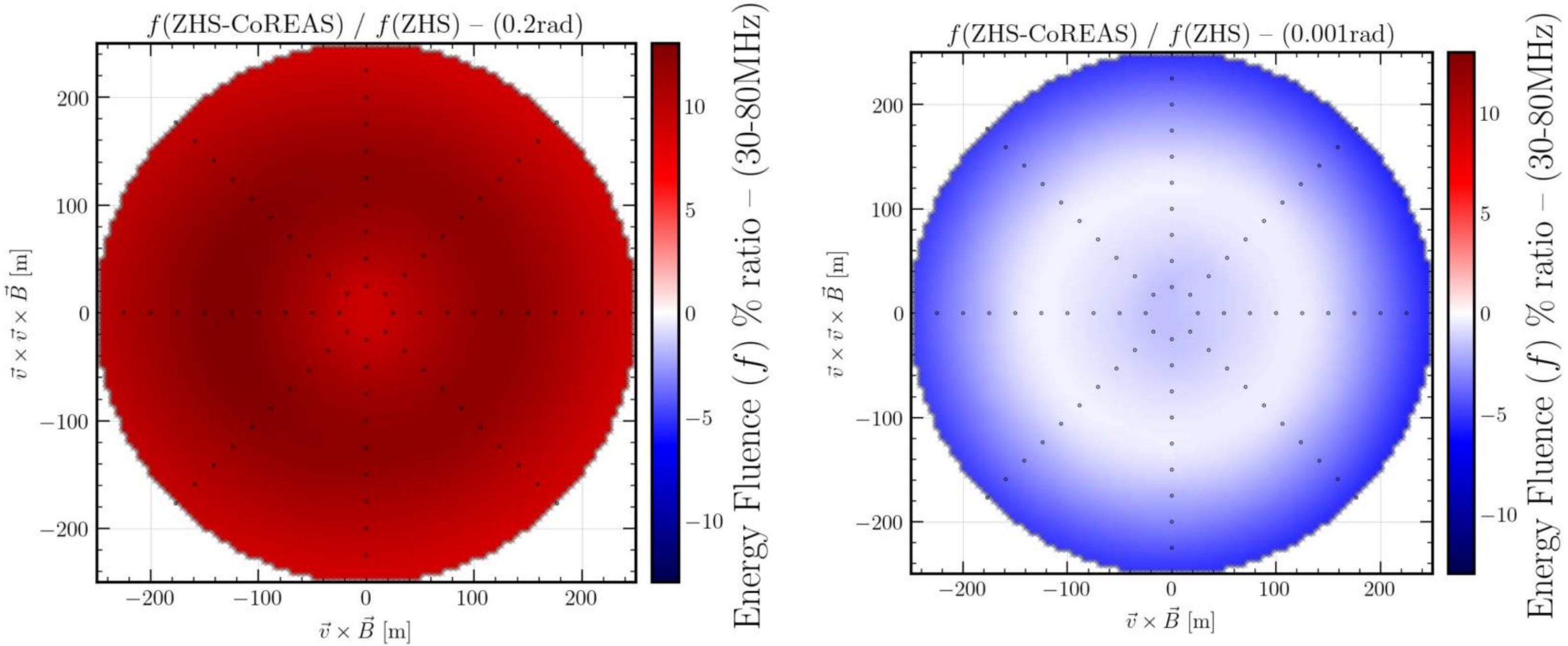




maximum deflection angle in B-field

- Radiation energy converges to within 1-2% for small tracks!
- Same behavior for different particle energies and types

Fluence distribution ZHS/endpoints (CoREAS)



- Very good agreement where signal is significant with small steps

Comparing C8 and C7

Reason for C8 radio-emission overestimation

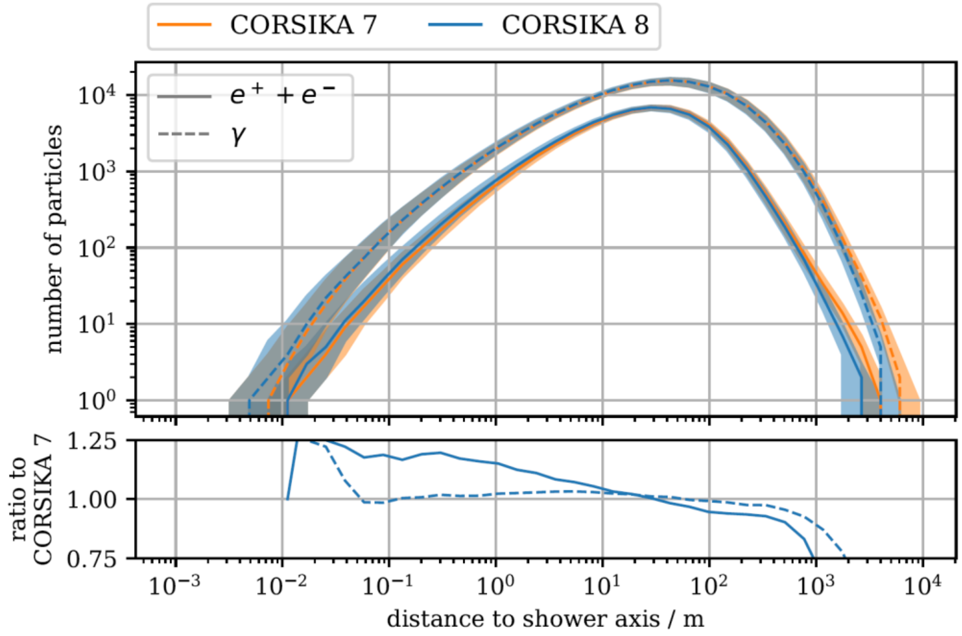
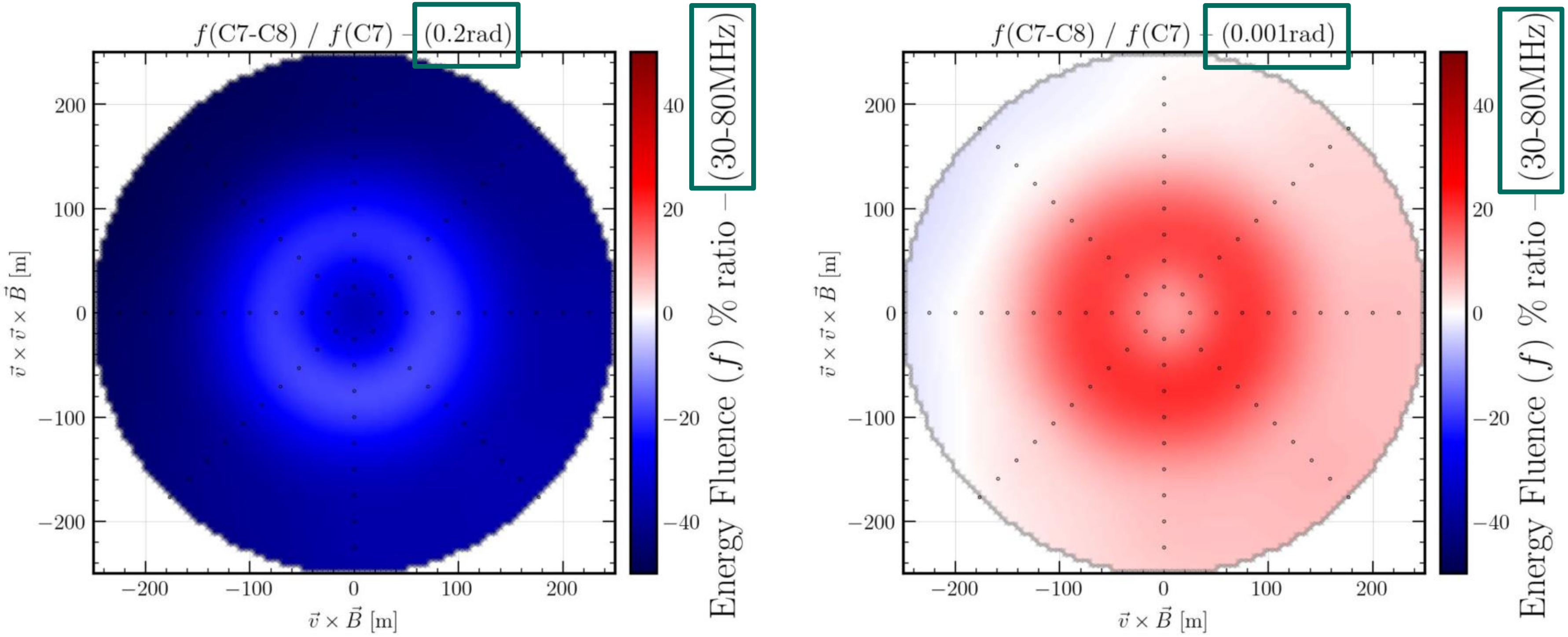


Figure 47: Median values of lateral profiles of electrons, positrons and photons for 100 TeV photon induced showers. Observation height for the evaluation is set to 5800 m, corresponding to $X_{\max} = 497\,\mathrm{g\,cm^{-2}}$.

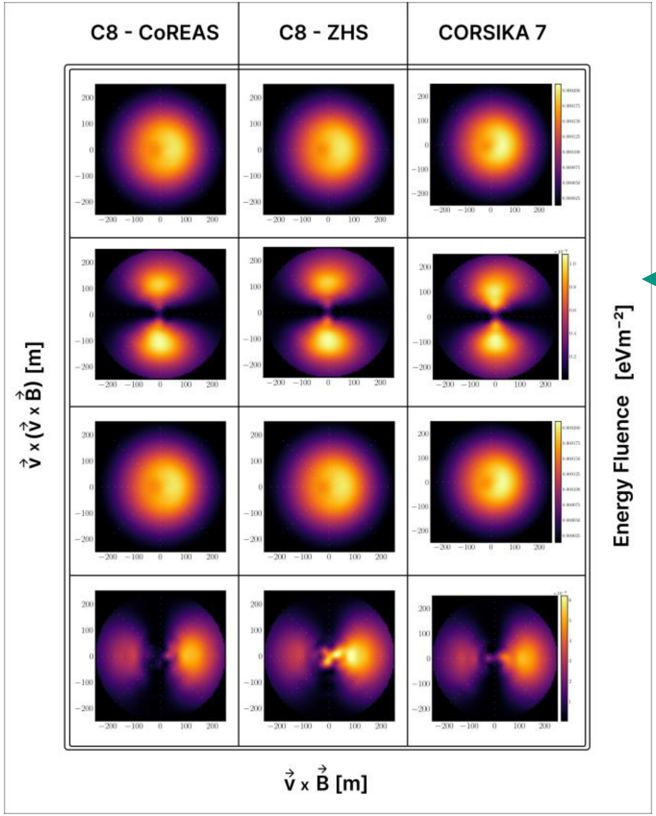
- EM cascade in C8 based on PROPOSAL 7.6.2 (CORSIKA 7 uses modified EGS)
- EM lateral distri-butions differ, more coherence in C8
- Likely due to particle tracking & multiple scattering treatment

At small stepsize: C8 and C7 agree well



- At 30-80 MHz improvement from +30% to -10% difference in radiation energy

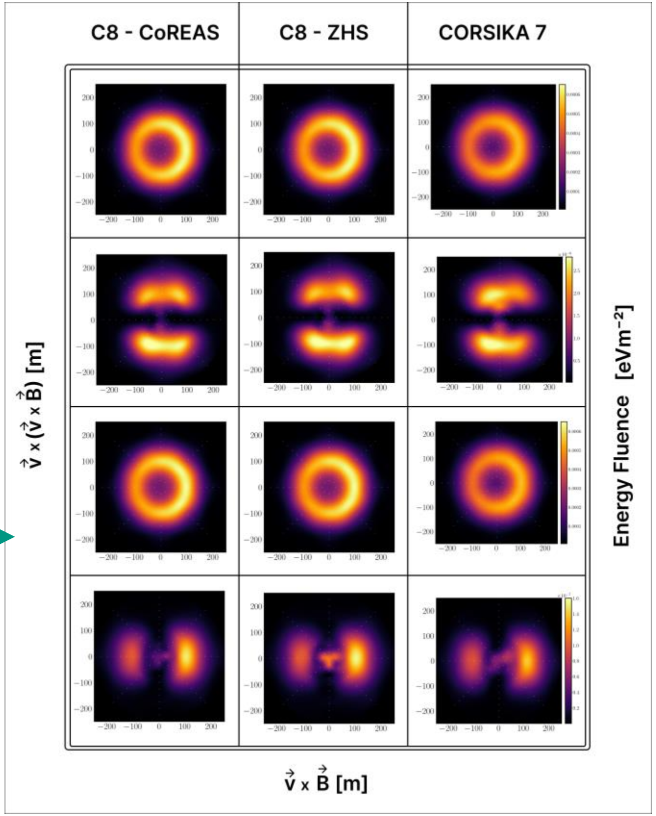
Fluence maps comparison for small steps



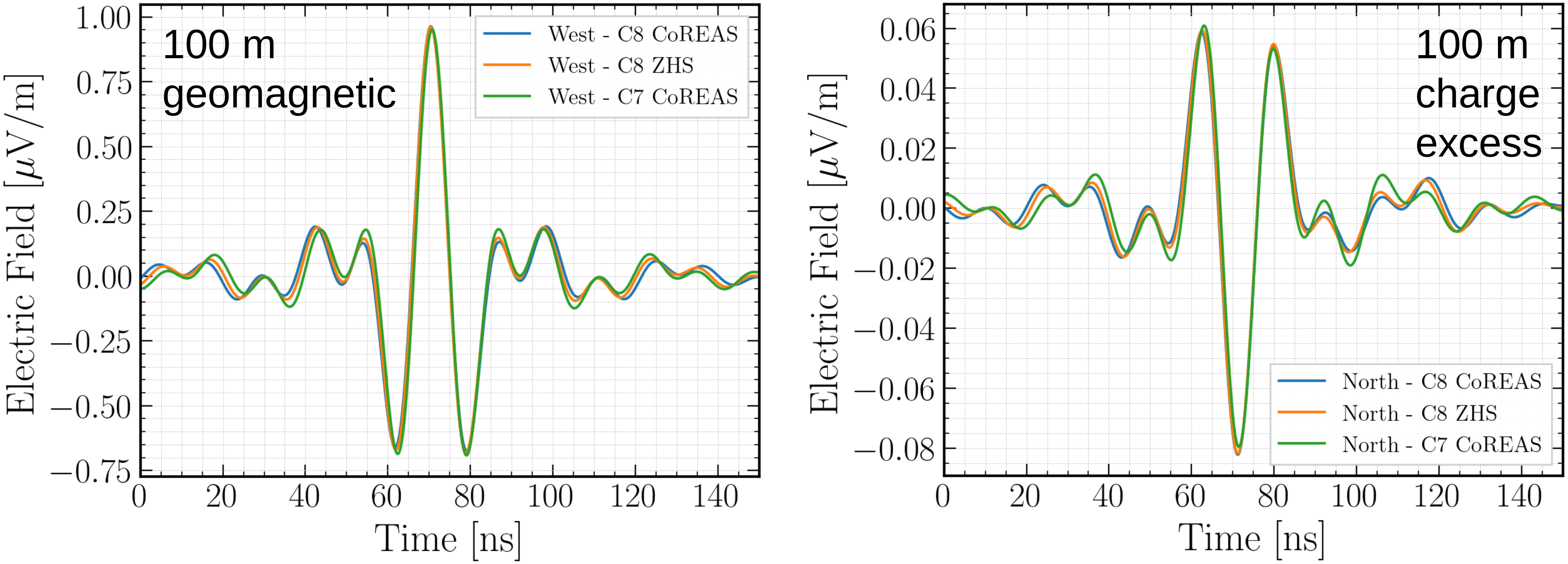
- Improved agreement on absolute scale

30-80 MHz

50-350 MHz

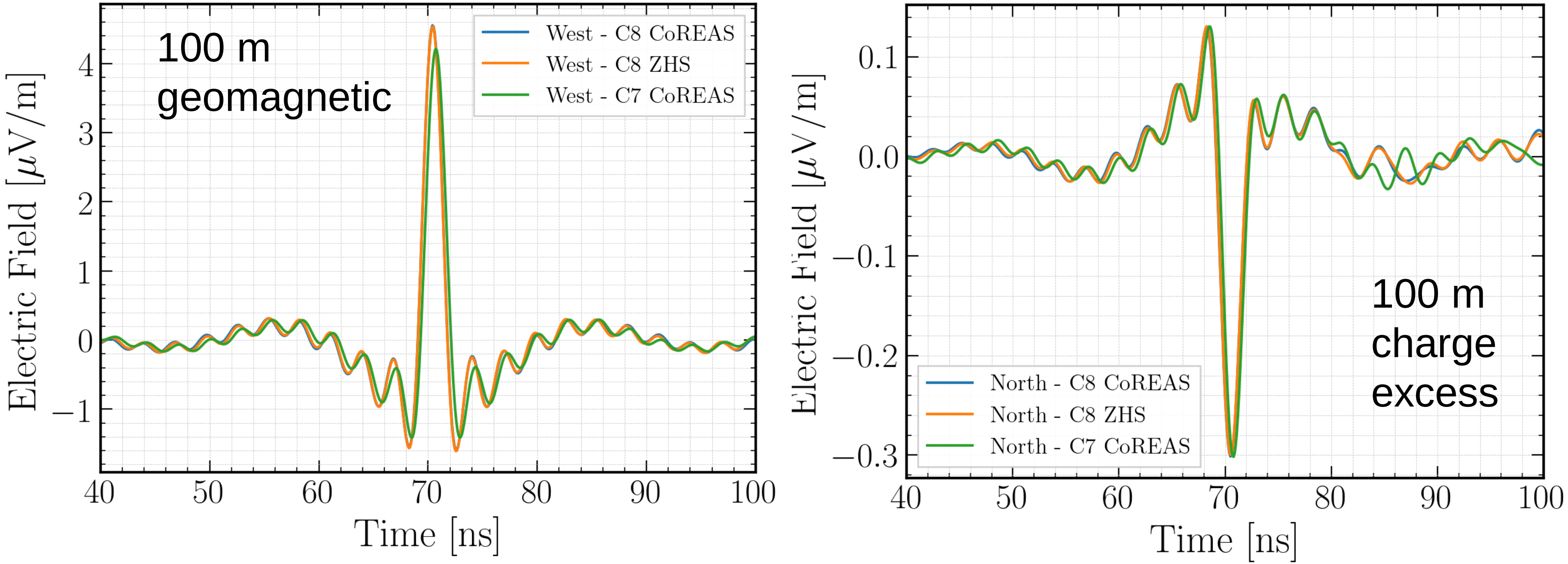


Pulses C8 vs. C7 for small steps, 30-80 MHz



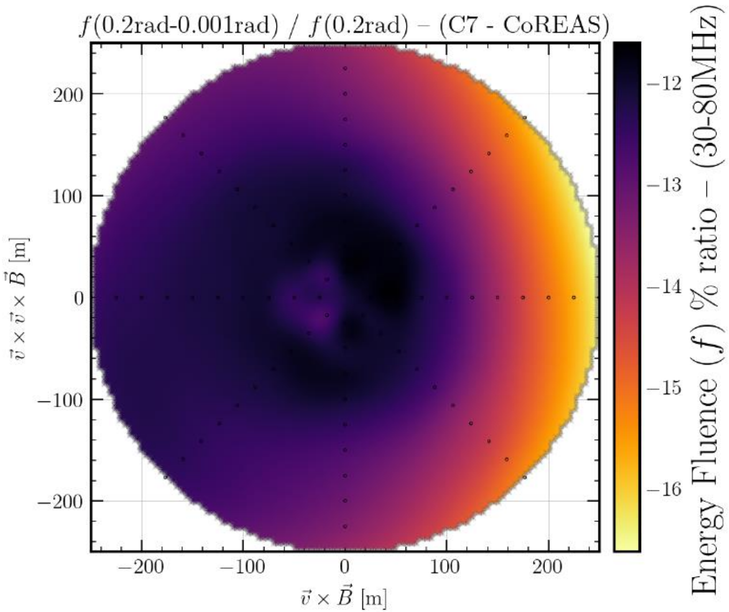
- 1PeV vertical shower: pulses agree nicely for small steps

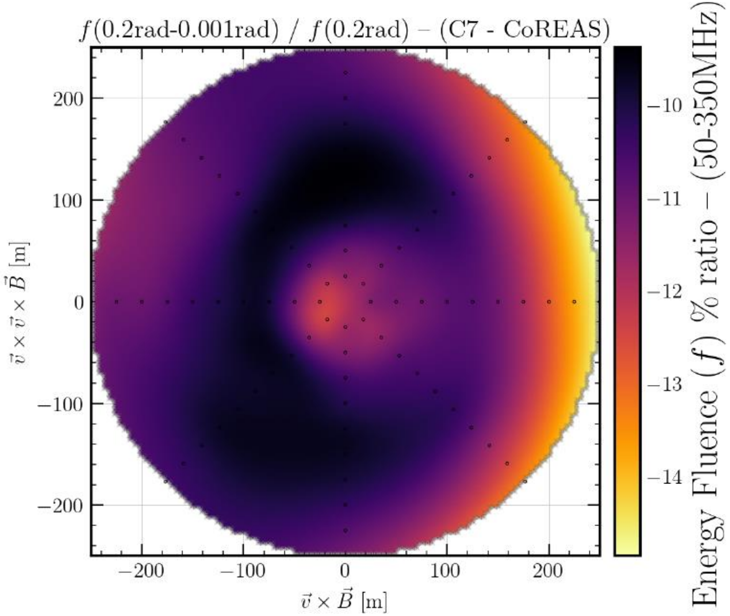
Pulses C8 vs. C7 for small steps, 50-350 MHz



- 1PeV vertical shower: pulses agree nicely for small steps

CORSIKA 7 fluence evolution with smaller steps





- Smaller tracks lead to ~12% more radiation energy, known before, cf. Gottowik et al., *Astropart. Phys.* 103 (2018) 87-93
- Fluence distribution in footprint (Xmax) changes only on „few %“ level

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In-ice radio sims with C8

In-ice Showers and Verification of NuRadioMC

work by Alan Coleman, Maria Duran, Christian Glaser (Uppsala University)

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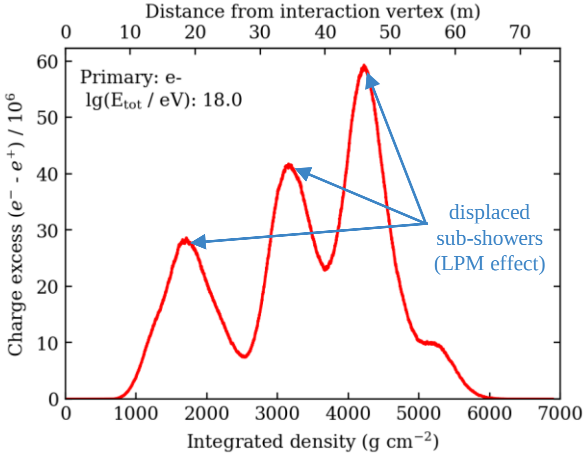
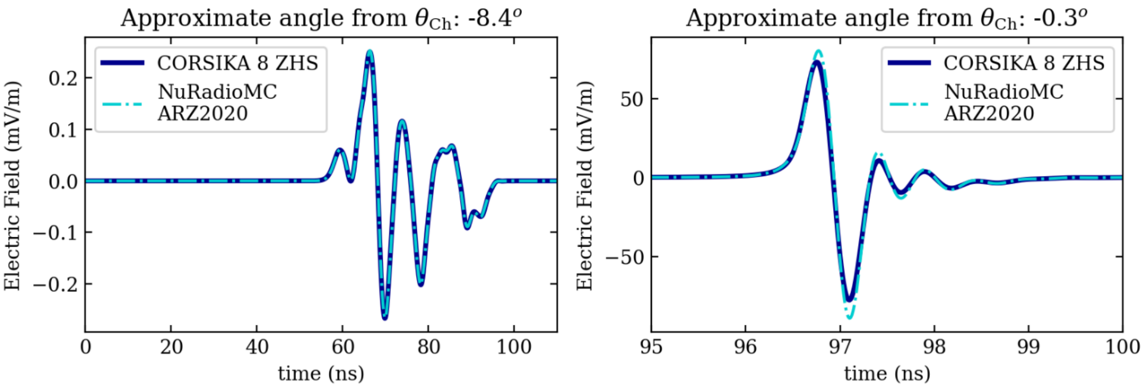
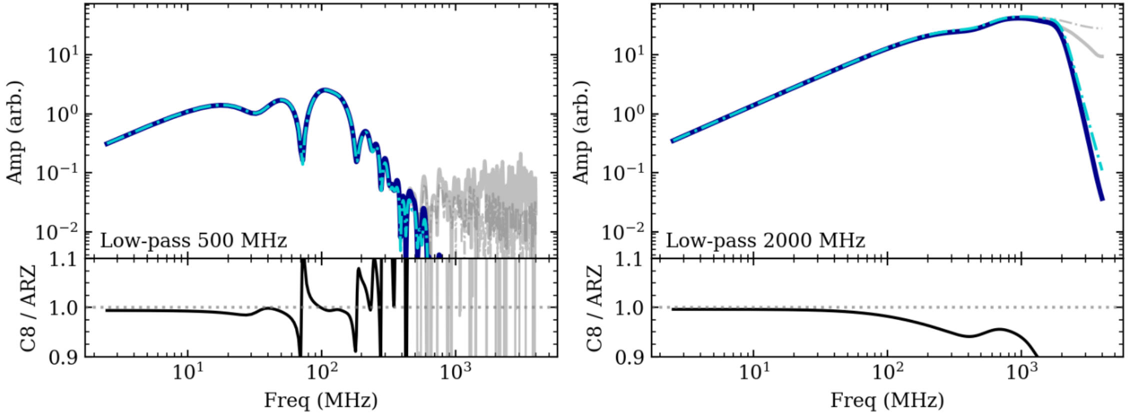
CORSIKA 8 can be used in dense media (ice)
Here: homogeneous ice with n=1.78 with antennas 1km from interaction vertex

CORSIKA 8 prediction reproduces previous results (ARZ model parameterized from ZHAireS simulations)

Next step: Study effect of inhomogeneous media (now enabled by CORSIKA8)







Cross-media Showers (Air-Shower Core impacting Ice)

work by Alan Coleman, Maria Duran, Christian Glaser (Uppsala University)

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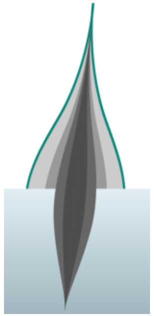
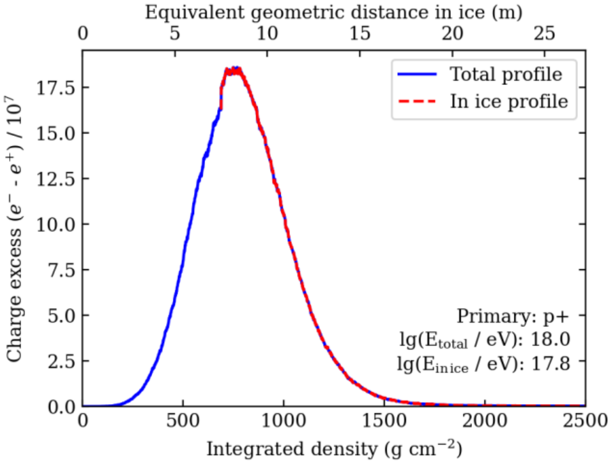


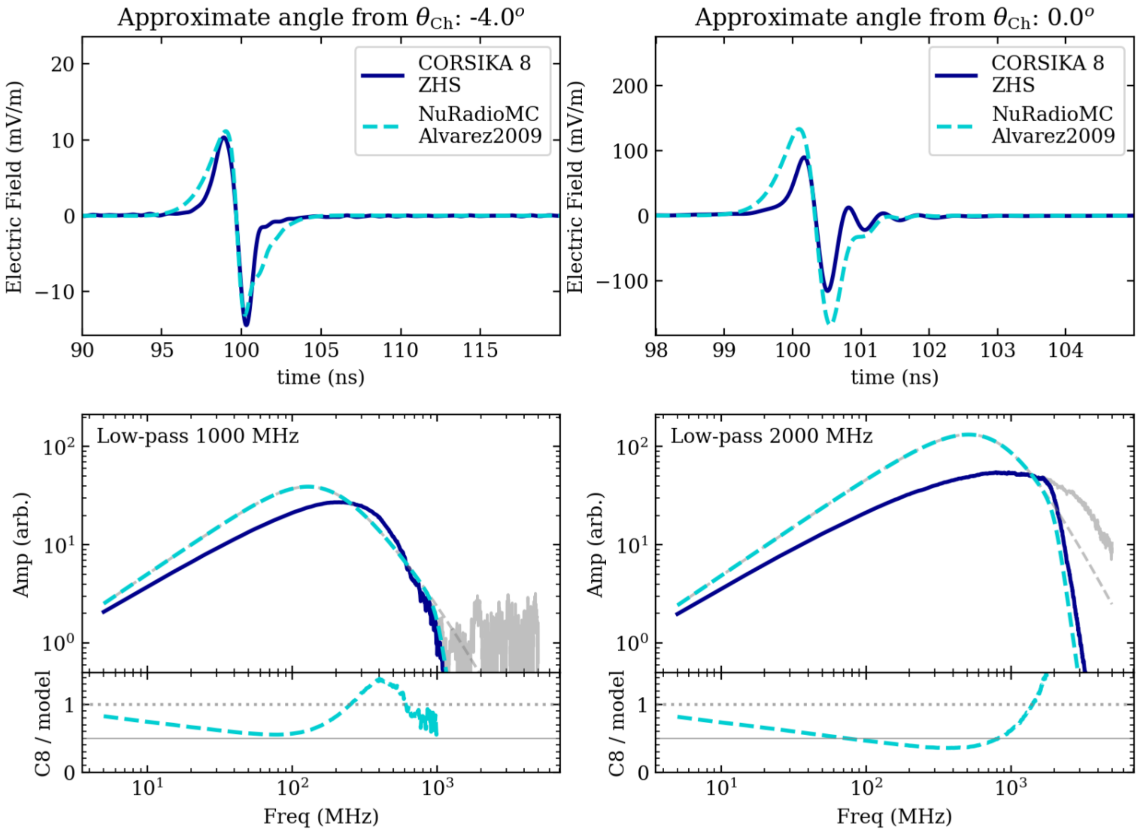
Plots show in-ice Askaryan emission only

Comparison with Askaryan emission models of neutrino-induced showers show (very) coherent emission
(Askaryan model evaluated for deposited in-ice energy as shower energy)

Next step: create a fast emission model of shower cores hitting the ice based on C8 simulations!



1EeV vertical Air Shower at South Pole



Conclusions

- CORSIKA 8 radio implementation successfully validated
- C8 results sensitive to simulation step size (tracking/scattering details)
- ZHS and CoREAS formalisms converge at the *same* result within 1-2%
- C8 and C7 agree within 10% in radiation energy for small steps
- For C7, changes in stepsize have small (and known) effect, changes to footprint (for Xmax reconstruction) are very minor
- **Microscopic radio simulations continue to be robust and trustable**

- In-ice radio-emission sims in C8 work well and show excellent agreement with previous results!

Backup

A random look inside the CORSIKA 7 code

```
     *          ' IS NOT IMPLEMENTED'
#if __PARALLELIB__
        call printstatusstop(NRRUN,MPIID,
     * 'COMBINATION OF VIEWCONE AND VOLUMECORR IS NOT IMPLEMENTED')
#endif
            STOP
#else
   46       CALL RMMARD( RD,3,1 )
#endif
            CT1 = COS( VUECON(1) )
            CT2 = COS( VUECON(2) )
            CTT = RD(2) * ( CT2 - CT1 ) + CT1
            THETAP = ACOS( CTT )
            PHIP = RD(1) * PI2
C  TEMPORARY CARTESIAN COORDINATES
            XVC1 = COS( PHIP )*SIN( THETAP )
            YVC1 = SIN( PHIP )*SIN( THETAP )
            ZVC1 = COS( THETAP )
C  ROTATE AROUND Y AXIS
            XVC2 = XVC1*COS( THETPR(1) ) + ZVC1*SIN( THETPR(1) )
            YVC2 = YVC1
            ZVC2 = ZVC1*COS( THETPR(1) ) - XVC1*SIN( THETPR(1) )
#if !__VOLUMEDET__
C  FOR A HORIZONTAL TARGET, THE COS(THETA) WEIGHT IS OBTAINED BY
C  THROWING THE DICE ANOTHER TIME.
            IF ( RD(3) .GT. ZVC2 ) GOTO 46
#endif
            THETAP = ACOS( ZVC2 )
#if __CURVED__
#if __CERENKOV__
            IF ( THETAP .GT. 88.D0*(PI/180.D0) ) GOTO 46
#else
            IF ( THETAP .GE. 90.D0*(PI/180.D0) ) GOTO 46
#endif
#else
            IF ( THETAP .GT. 70.D0*(PI/180.D0) ) GOTO 46
#endif
            IF ( XVC2 .NE. 0.D0  .OR.  YVC2 .NE. 0.D0 ) THEN
              PHIP = ATAN2(YVC2,XVC2) + PHIPR(1)
            ELSE
              PHIP = PHIPR(1)
            ENDIF
            IF ( PHIP .GT. PI2  ) PHIP = PHIP - PI2
            IF ( PHIP .LT. 0.D0 ) PHIP = PHIP + PI2
          ENDIF
#endif
#if __IACT__
          CALL EXTPRM(PRMPAR(0), PRMPAR(1), THETAP, PHIP)
          CTT = COS( THETAP )
#endif
#if __CURVED__
C  COSINE OF APPARENT ZENIT ANGLE IS PUT IN PRMPAR(15)
C  (COSINE OF LOCAL ZENIT ANGLE IS IN PRMPAR(2))
          PRMPAR(15) = COS( THETAP )
#else
          PRMPAR(2) = COS( THETAP )
#endif
        ELSE
#if __CURVED__ && __UPWARD__
          IF ( FIMPCT ) THEN
C  SKIMMING INCIDENCE, COSTAP AT DETECOR IS 0
            THETAP = 0.5D0 * PI
            CTT    = 0.D0
C  CHOOSE IMPACT PARAMETER AT RANDOM
            CALL RMMARD( RD,1,1 )
```

- 83,000 lines plus interaction models

Radio-emission 50-350 MHz

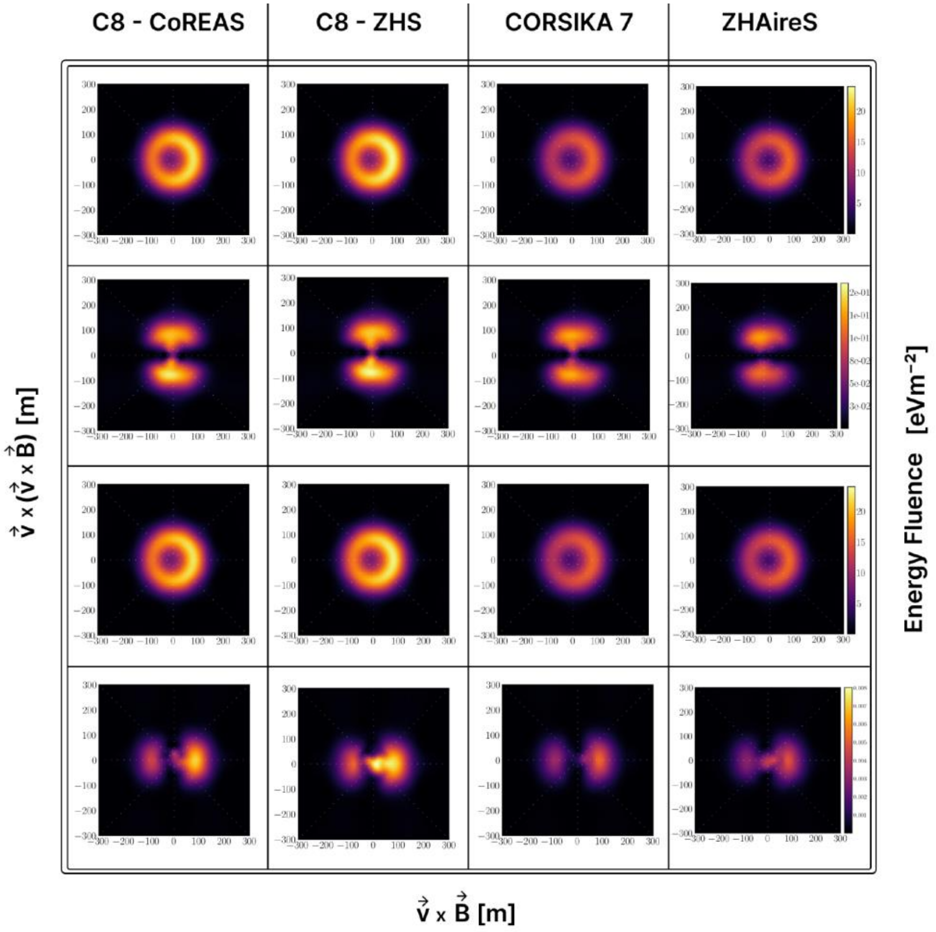
- patterns and polarizations match
- C8 produces slightly more signal

modulus

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

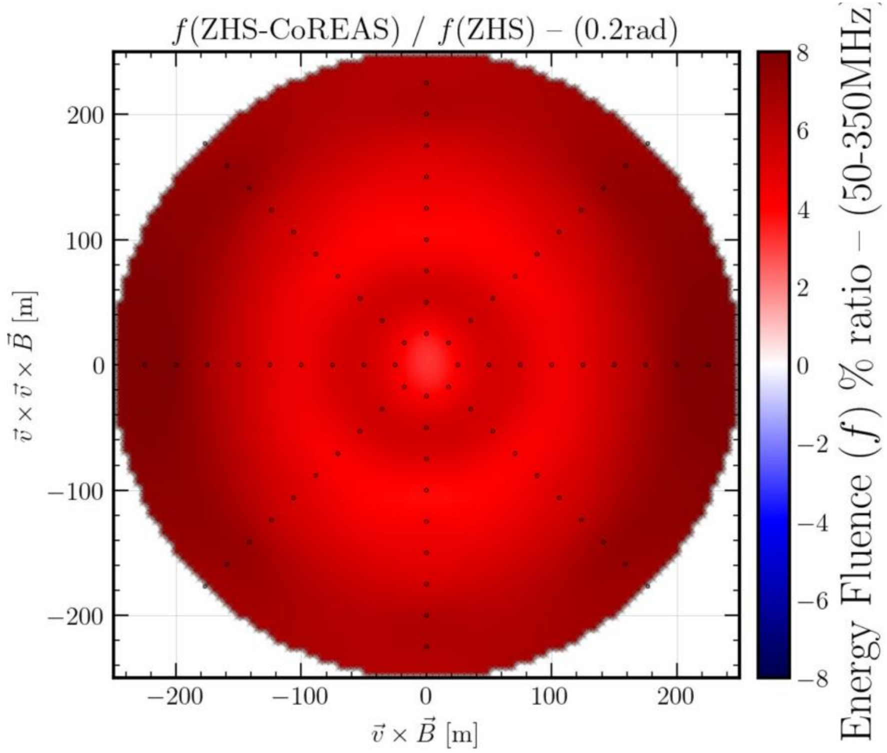
$\vec{v} \times \vec{B}$

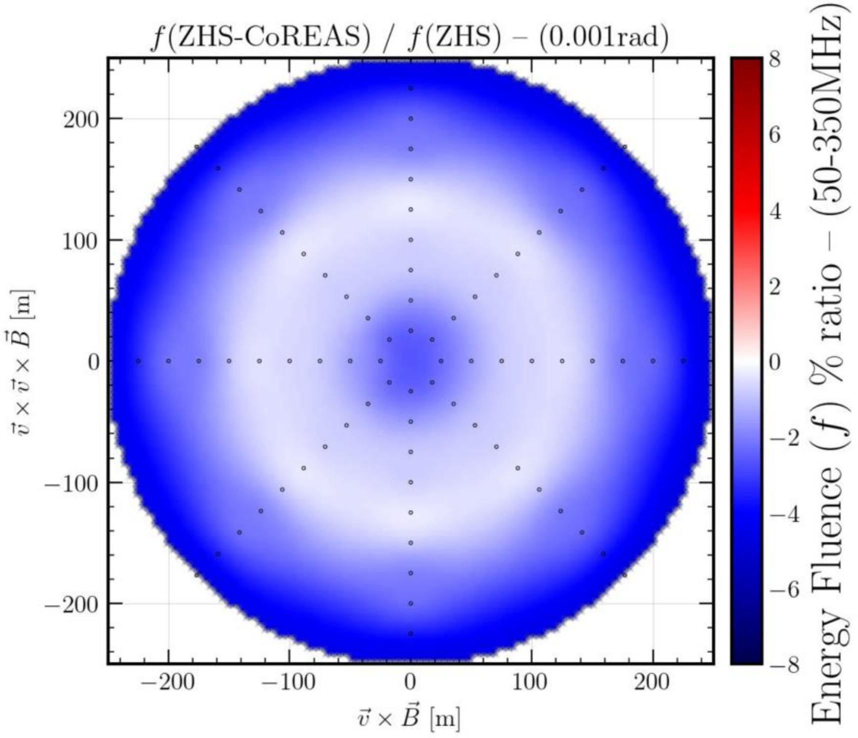
$\vec{v}$



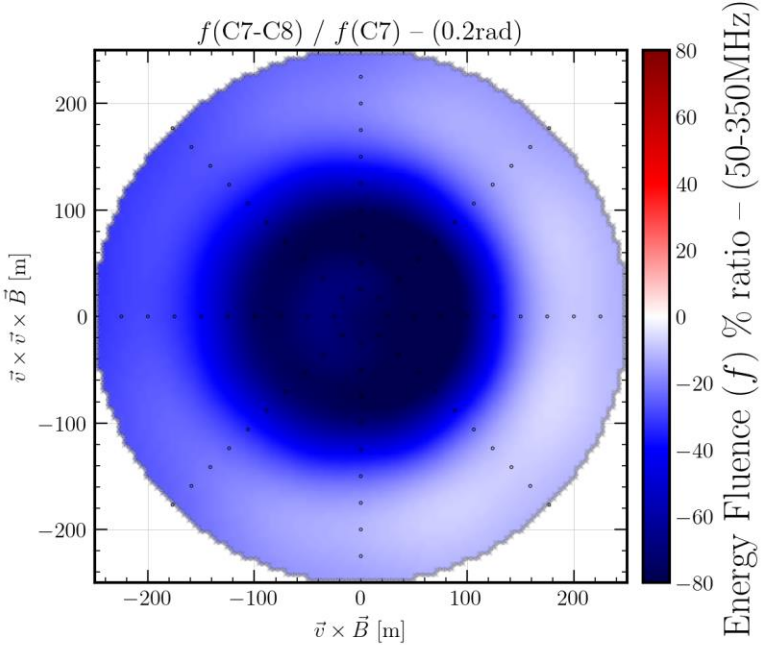
Both codes at 0.2 rad maxRadians!

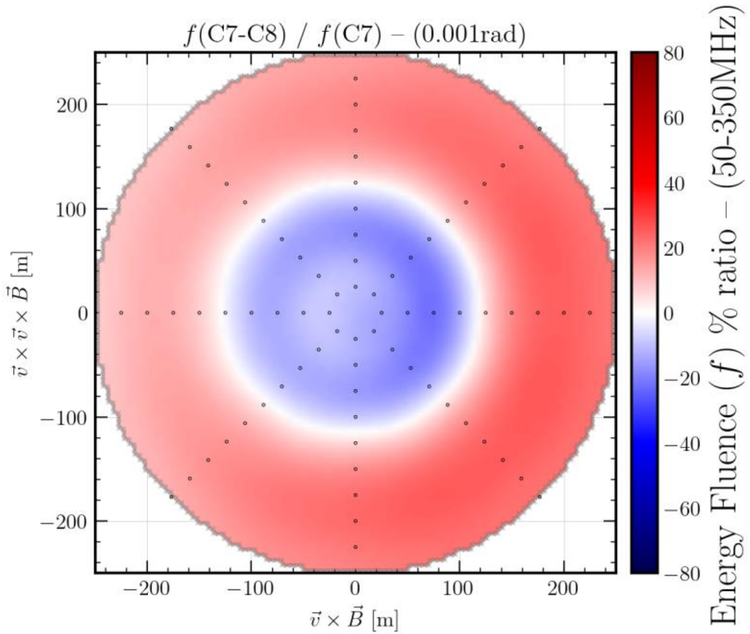
Comparison of formalisms at 50-350 MHz





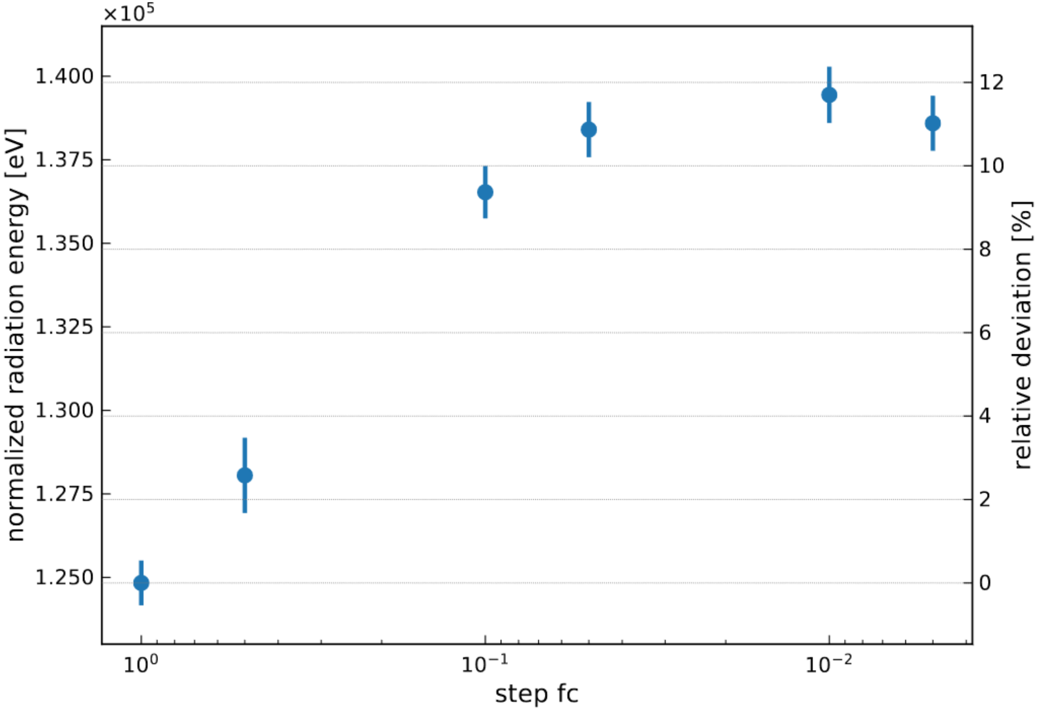
Comparison of C8 vs C7 at 50-350 MHz





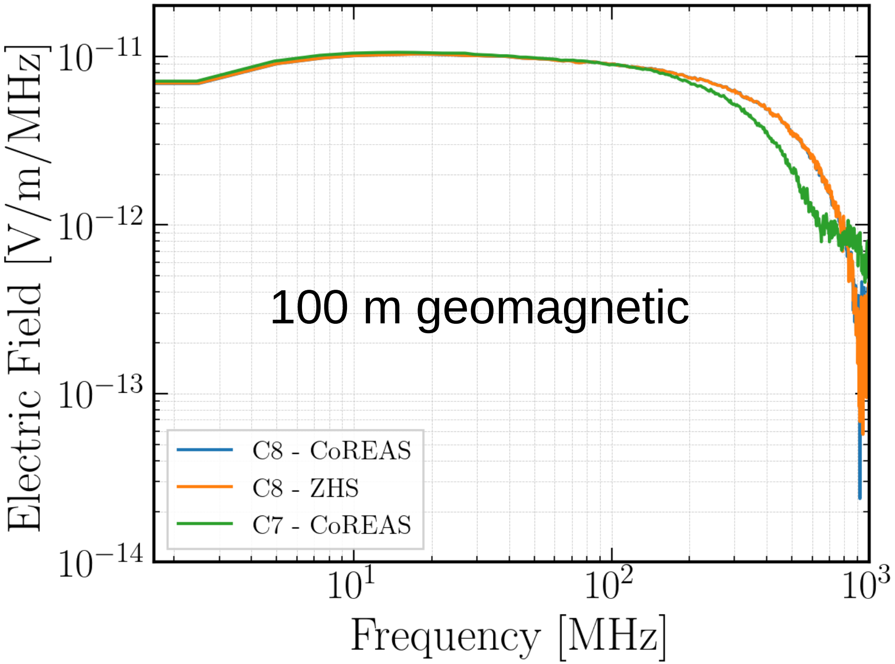
- Slightly more strucutre than at 30-80 MHz, to be checked further?

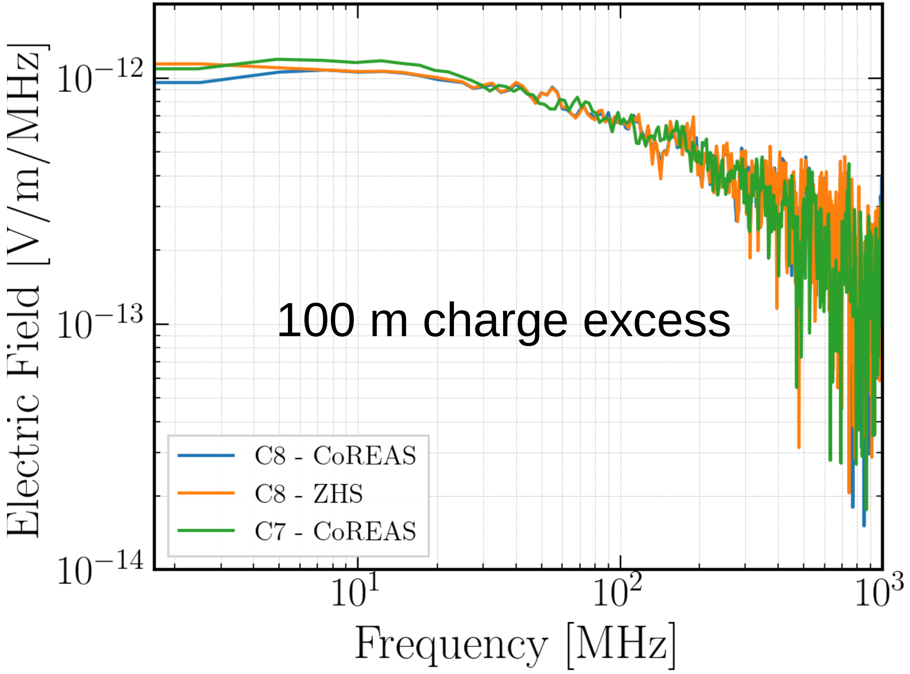
Known radiation energy scaling for C7 stepsize



- See Gottowik et al., *Astropart.Phys.* 103 (2018) 87-93, yielding a 11% increase of radiation energy
- Effect much smaller than in CORSIKA 8
- We (independently) find again a +12% effect at 30-80 MHz

Spectra C8 vs. C7 for small steps



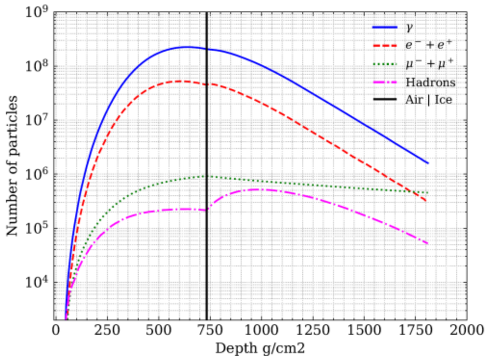


- 1PeV vertical shower: spectra agree mostly well

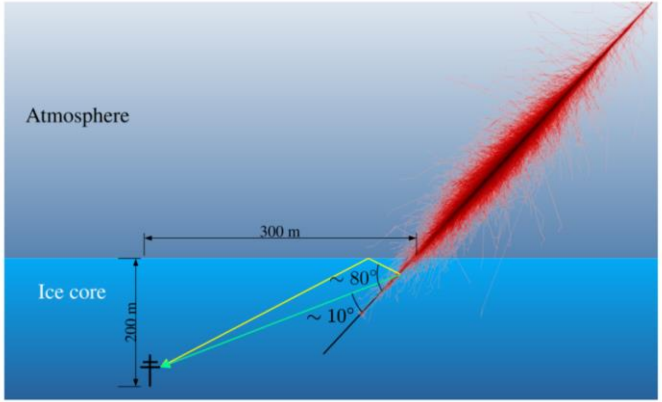
Cross-media showers for in-ice radio detection

J. Ammerman-Yebra for C8
PoS(ICRC2023)442

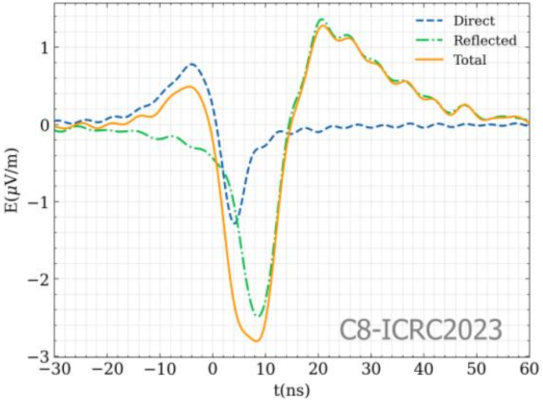
Vertical shower



- C8 environment setup is very flexible
- cross-media particle showers natural
- very relevant for in-ice radio-detection community, first glimpse below



x polarization



z polarization