Simulation of radio signals from air showers measured by in-ice radio antennas

Simon De Kockere

simon.de.kockere@vub.be

Krijn de Vries, Nick van Eijndhoven, Tim Huege, Uzair Latif

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Cosmic-ray air showers moving into high-altitude ice layers

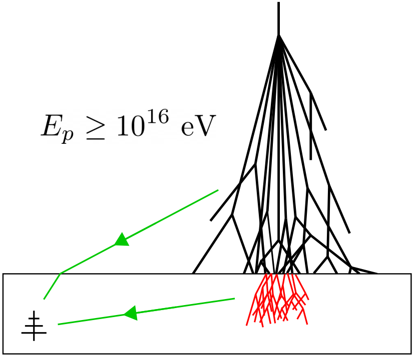
In-air radio emission (geomagnetic, Askaryan)

- Well understood (e.g. CoREAS in Corsika)
- Problem: propagation into ice

In-ice radio emission (Askaryan)

- Important for low zenith angles

Useful as **in-situ calibration source**



In-air radio emission (Uzair Latif, Tim Huege)

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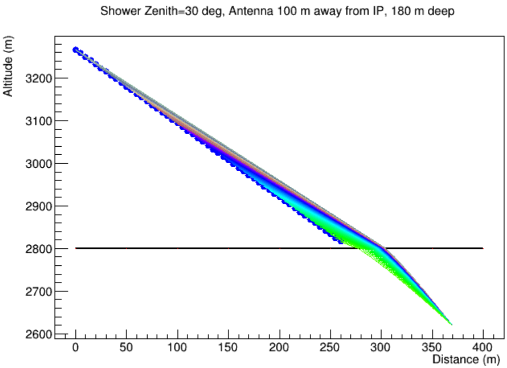
- In-air and in-ice raytracing implemented in CoREAS but still in testing phase
- Ray paths and times are calculated analytically for multiple transmitter (tx) and receiver (rx) positions.
  - The positions are spread over a grid.
  - The times and paths are used to make a interpolation tables which is then used by CoREAS.
- An exponential refractive index profile is used for air and ice.



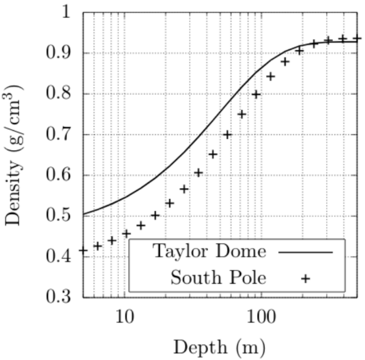
Ice Layer at 2800 m
Antenna 180 m deep

Summary: working prototype in Corsika 7

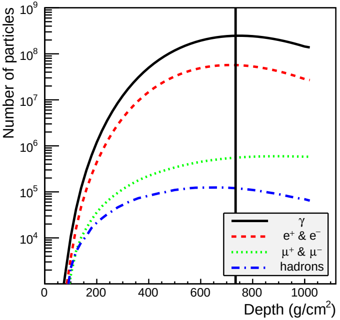
In-ice core radio emission - strategy

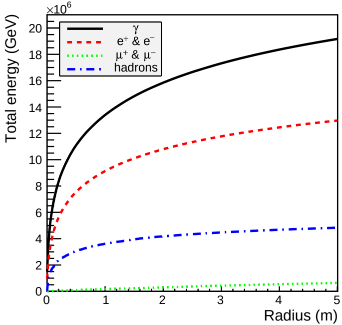
Setup:

- **Corsika 7.7100** for the in-air particle cascade simulation
  - QGSJETII-04, GHEISHA 2002d, thining for $E_p \geq 10^{17}$ eV
  - Read out at altitude of 2.4 km
- **Geant4** for the propagation of the cascade through ice
  - Block of ice with density gradient
  - Propagate all Corsika particles within **5** m from point of impact



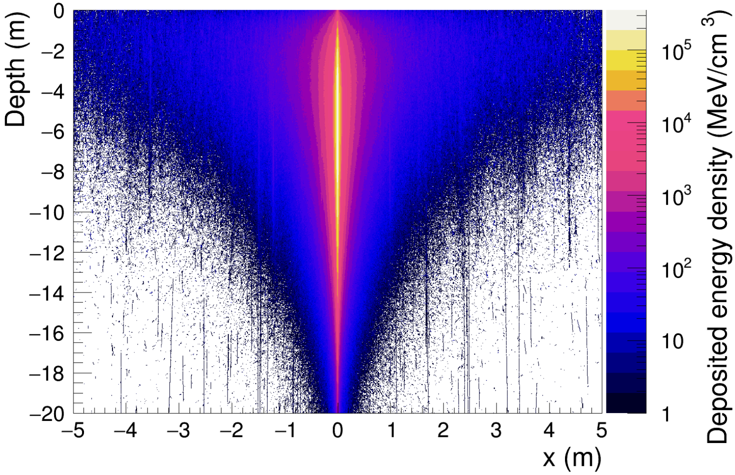
What to expect?





proton, $E_p = 10^{17}$ eV, $\theta = 0$

In-ice core radio emission - particle distributions



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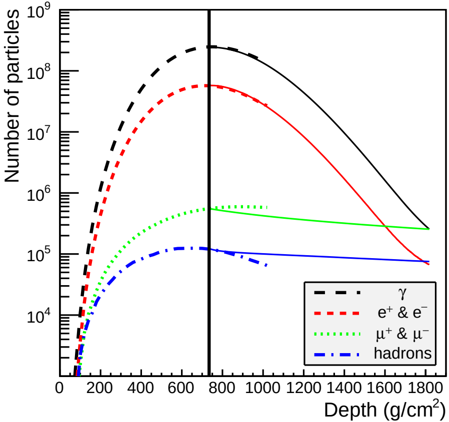
Longitudinal distribution



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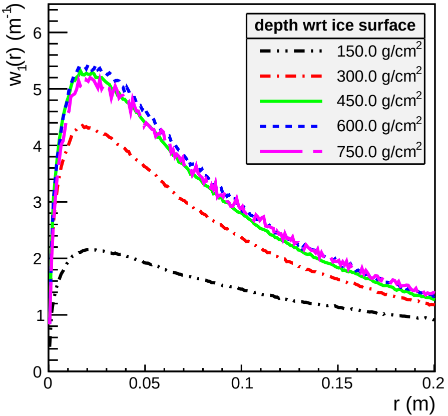
Lateral distributions at given time values (translated to depth values of the cascade front with respect to ice surface)

$w_1(r)dr$ = number of charges in $[r, r + dr[$ (normalized)



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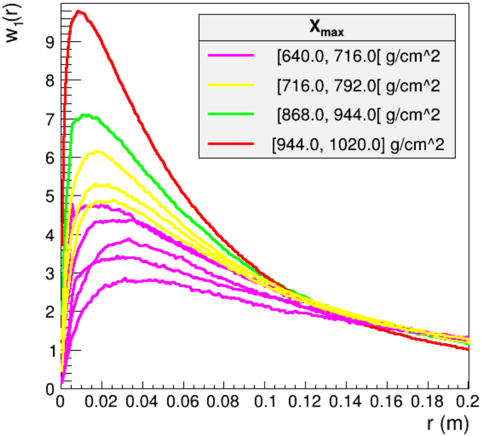
Lateral distributions for 450 g/cm^2, 10 different showers

$w_1(r)dr$ = number of charges in $[r, r+dr[$ (normalized)



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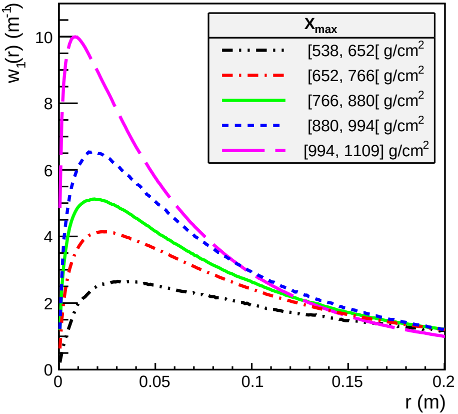
In-ice core radio emission - particle distributions

Average lateral distributions for 450 g/cm^2, sorted by X_{max}



proton, $E_p = 10^{16} - 10^{18}$ eV, $\theta = 0° - 30°$, 150 in total

In-ice core radio emission - endpoint formalism

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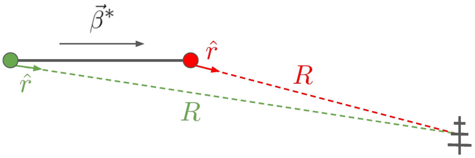
Code based on Anne Zilles' work (SLAC T-510 experiment)



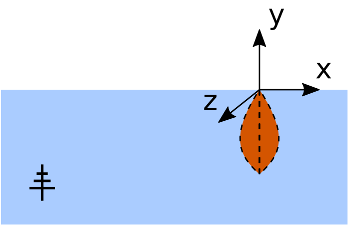
Contribution to the electric field in the antenna at $t = R/(c/n)$ for starting point (+) and end point (-) (arXiv:1007.4146v3):

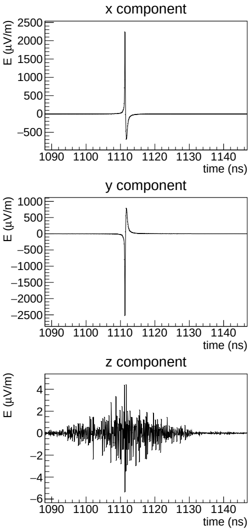
$$\vec{E}_{\pm}(\vec{x},t) = \pm \frac{1}{\Delta t}\frac{q}{c}\left(\frac{\hat{r}\times[\hat{r}\times\vec{\beta}^*]}{|1-n\vec{\beta}^*\cdot\hat{r}|R}\right)$$

Exception:
If $(1 - n\vec{\beta}^* \cdot \hat{r})$ gets too small: Evaluate formula both for start and end point in **the middle** of the step and redistribute contributions over time scale defined by sampling rate (ZHS formalism)

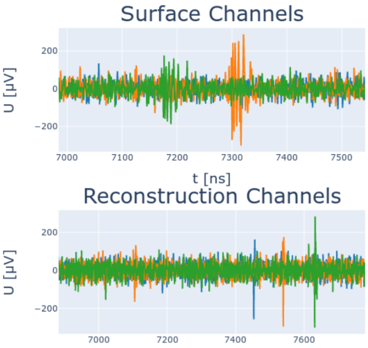
Care has to be taken with non-constant *n*

Antenna at
[-160 m, -150 m, 0 m]
(close to Cherenkov angle)

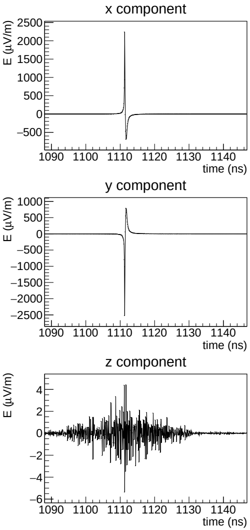




In-ice core radio emission - first results



Simulated RNO-G neutrino event
(arXiv:2010.12279)



CORSIKA 8 – why and what? (Tim Huege)

- complete rewrite of air-shower simulation in modern C++ framework
- exploit modern computing concepts
  - vectorization, multi-core and multi-node calculations, GPU parallelization, …
- modular design, in contrast to monolithic CORSIKA 7 Fortran code
  - air, dense media, complex geometries, possibility to interchange modules, …
  - consistent simulations of air showers and their radio emission for cascades transitioning from air into ice!
- radio emission calculation is being implemented right from the start: Nikos Karastathis (KIT), Remy Prechelt (U. Hawaii), Tim Huege (KIT, VUB)

CORSIKA 8 – state of things

- air-shower cascade working, similar performance as C7
- several hadronic interaction models included and validated
- electromagnetic interactions included (PROPOSAL), being validated
- magnetic field deflection included
- atmospheric refractive index model included
- structure/interface for radio emission calculations established
- ZHS and endpoint formalisms being implemented in parallel
- „first radio pulses“ expected within the next weeks

Back-up

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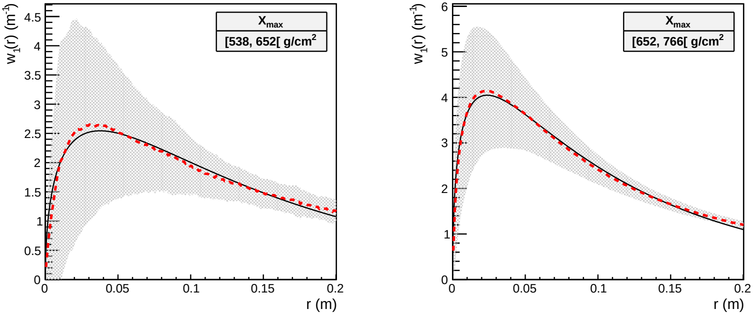
In-ice core radio emission - particle distributions

Average lateral distributions for 450 g/cm^2, sorted by X_{max}

Solid line: fit function of the form $W(r) = a\sqrt{r}e^{-(r/b)^c}$



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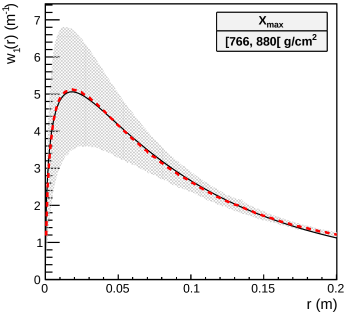

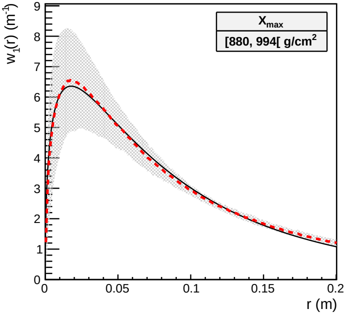

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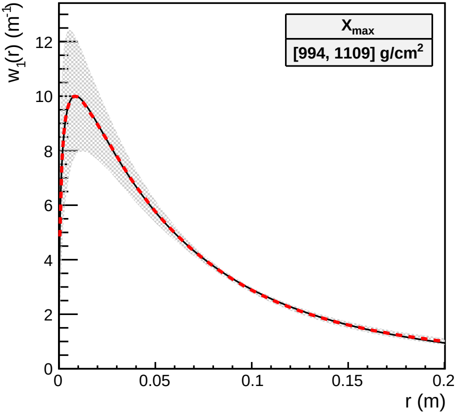

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