Simulation of the propagation of CR air shower cores in ice

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Introduction

- Development of radio neutrino observatories to extend flux measurements to higher energies

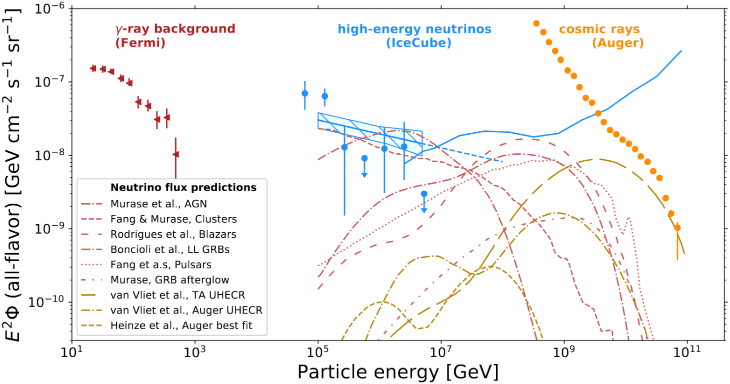
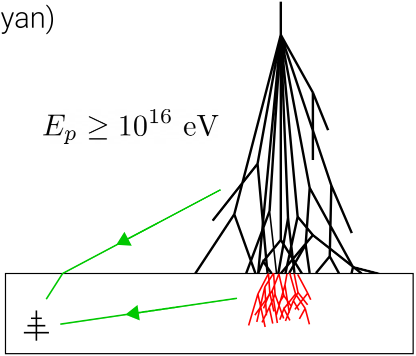


Figure: RNO-G collaboration, JINST **16**, P03025 (2021)

Introduction

- Important **background** signal: cosmic ray air showers
  - **In-air** radio emission (geomagnetic, Askaryan)
  - **In-ice** radio emission (Askaryan)
- Useful as **in-situ calibration** source
- Detailed study of in-ice propagation and radio emission is needed



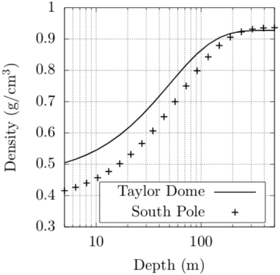
Overview

- Simulation setup
- Simulation results
    - Deposited energy
    - Shower development
    - Charge distribution
- Applications
    - Askaryan radio emission
    - RADAR reflection techniques

Simulation setup

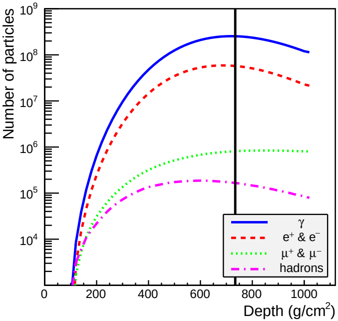
Simulation setup

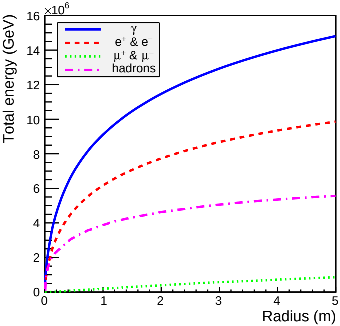
- Simulation of in-air particle development using **CORSIKA**
  - QGSJETII-04, GHEISHA 2002d
  - Minor amount of thinning ($E_p \geq 10^{17}$ eV)
  - Particle read-out at altitude of 2.4 km
- Simulation of in-ice propagation using **Geant4**
  - Propagation of all CORSIKA output particles ($\vec{p}$, $\vec{r}$, t, w) within 5 m of core position
  - Using realistic ice density gradient



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

- Showers with $E_p \geq 10^{16}$ eV typically reach Polar ice sheets close to shower max
- Have very energy dense core, which will propagate through ice
- Example shower (proton, $E_p = 10^{17}$ eV, $\theta = 0$, $X_{max} = 680$ g/cm^2)

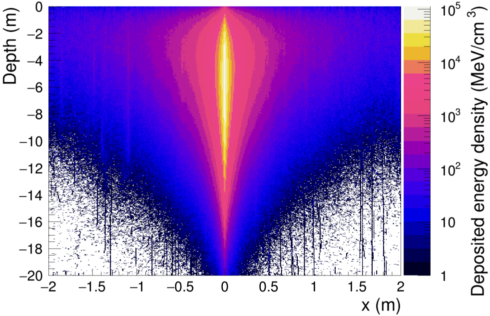




Simulation results

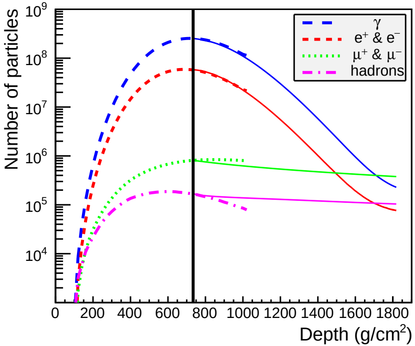
Deposited energy density

- Energy highly concentrated around core ($\sim$ 10 cm), resembling neutrino induced particle cascade
- Shower core is still developing



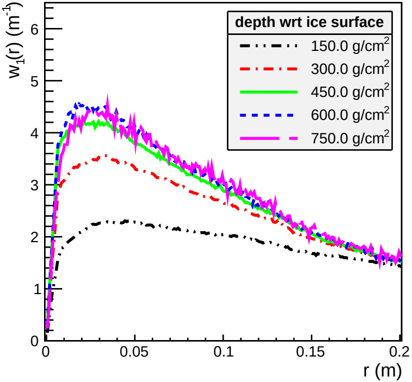
Shower development

- Propagation through ice does not influence development of electromagnetic part
- Standard air shower parameterizations (e.g. Gaisser-Hillas) can be used



Charge distribution

- Thin disk ($\sim$ 1—10 mm)
- Lateral dimension is relevant dimension when studying radio emission
- $w_1(r)dr$ = number of charges in $[r, r + dr[$ (normalized)



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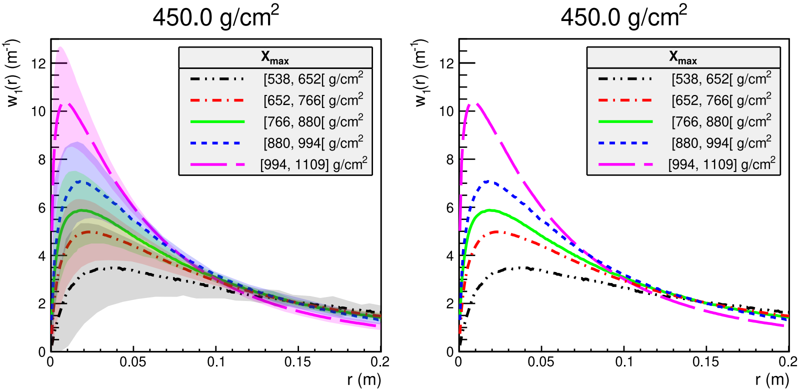
Charge distribution

- 10 different shower sets, 10^{16} eV - 10^{18} eV, 0° - 30°
- Group showers based on X_{max} and calculate average $w_1(r)$ distribution for each group
- Higher X_{max} value results in sharper peak in $w_1(r)$ distribution

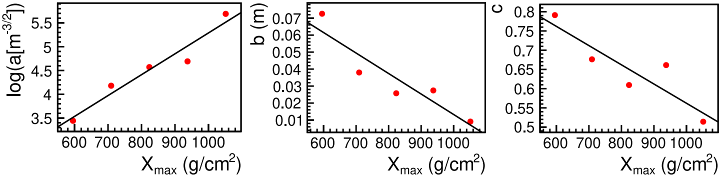


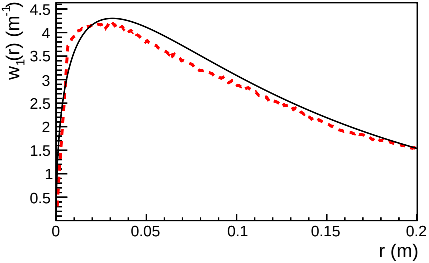
Charge distribution

- Distributions can be well described by analytical expression:

$$W(r) = a\sqrt{r}e^{-(r/b)^c}$$

450.0 g/cm^2

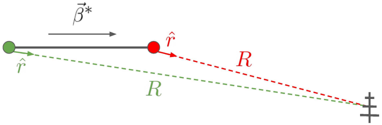




Applications

Radio emission

- Using end-point formalism to get first estimate of in-ice radio emission

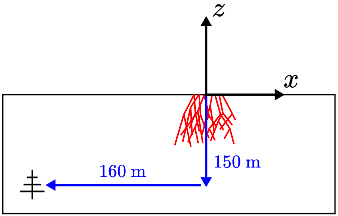


Contribution to the electric field in the antenna at $t = R/(c/n)$ for starting point (+) and end point (-):

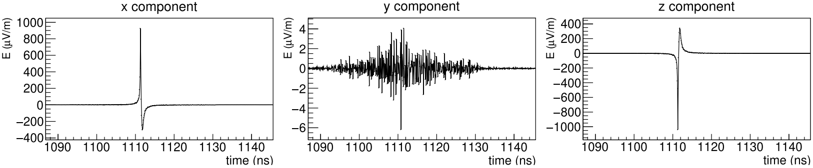
$$\vec{E}_{\pm}(\vec{x}, t) = \pm \frac{1}{\Delta t} \frac{q}{c} \left(\frac{\hat{r} \times [\hat{r} \times \vec{\beta}^*]}{|1 - n\vec{\beta}^* \cdot \hat{r}|R} \right)$$

- Same formalism also used in CoREAS (radio extension of CORSIKA), and PhD thesis of Anne Zilles (ISBN 978-3-319-63411-1)
- Assumes constant index of refraction n, which might be oversimplification for top layer of natural ice

Radio emission



- Antenna 150 m deep in the ice (*z* = -150 m), at horizontal distance of 160 m from point of impact (*x* = -160 m)
- Bipolar, radial polarized signal (Askaryan)
- Well above typical detection thresholds of 10-100 μV/m (antenna convolution forseen for future work)

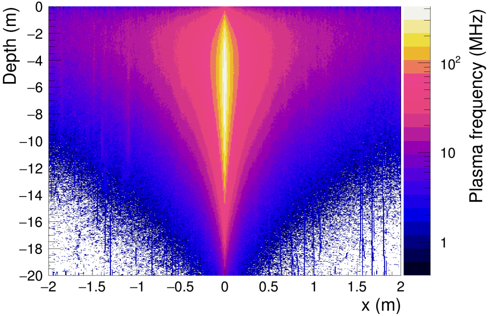


Plasma properties

- Shower core creates dense plasma in the ice
- Plasma can be detected using RADAR reflection techniques (see also RET contributions 102154, 101376 and others)
- Estimation of plasma frequency ω_p:

$$\omega_p = 8980\sqrt{n_q[\mathrm{cm}^{-3}]}\ \mathrm{Hz}; \quad n_q = \rho_E/(50\ \mathrm{eV})$$

- Rule of thumb: signals with $\omega < \omega_p$ will be reflected



Summary

- Cosmic-ray air showers with $E_p \geq 10^{16}$ eV have very energy dense cores at typical altitudes of polar ice sheets
- Shower development: electromagnetic depth profile does not change when propagating through ice
- Charge distribution: thin disk, radial charge distribution can be parameterized in function of X_{max}
- Expect Askaryan radio emission to be detectable
- Plasma in ice sufficiently dense for a realistic RADAR setup