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

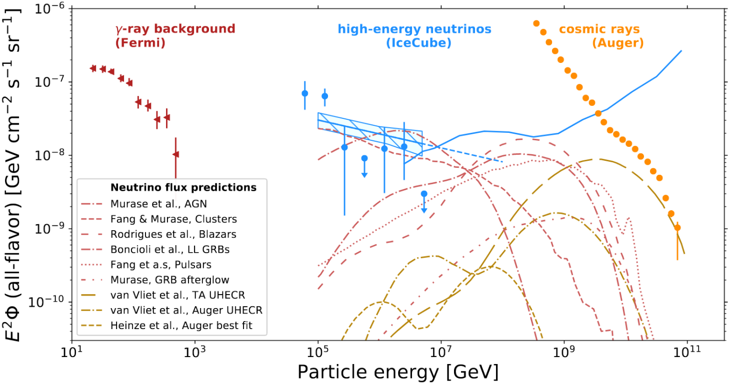


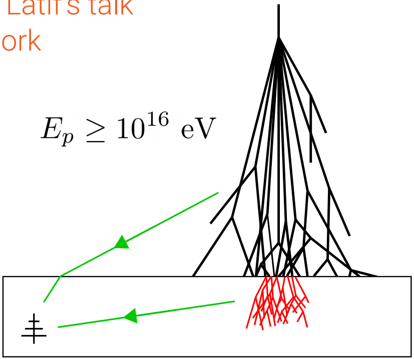
Figure: RNO-G collaboration, JINST **16**, P03025 (2021)

Introduction

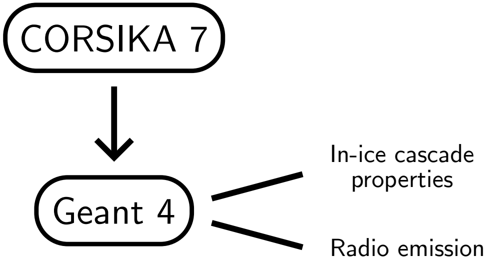
- Radio emission from HE cosmic ray air showers for in-ice radio detectors:
  - In-air radio emission - see U. Latif's talk
  - In-ice radio emission - this work

- Important **background** signal

- Useful as **in-situ calibration** source



- Detailed simulations of in-ice propagation and radio emission is needed (as well as other media)
- Upgrade to **CORSIKA 8** is perfect opportunity to include this extension
- This work:



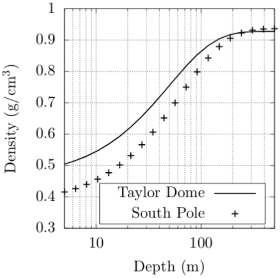
Overview

- Simulation setup
- Simulation results
  - Deposited energy
  - Shower development
  - Charge distribution
  - Askaryan radio emission

More details: `arXiv:2202.09211`

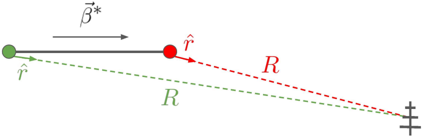
Simulation setup

- Simulation of in-air particle development using **CORSIKA 7.7100**
  - Proton
  - QGSJETII-04 (HE), GHEISHA 2002d (LE)
  - Minor amount of thinning
  - Particle read-out at altitude of 2.4 km above sea-level
- Simulation of in-ice propagation using **Geant4 10.5**
  - Propagation of all CORSIKA output particles $(\vec{p}, \vec{r}, t, w)$ within 5 m of core position
  - Using realistic ice density gradient (Taylor Dome)



Simulation setup

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



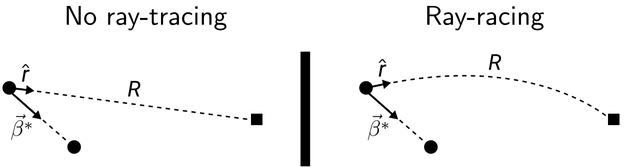
Contribution to the electric field in the antenna at $t = R/(c/n)$ for starting point (+) and end point (-):

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

- Also used in CoREAS (radio extension of CORSIKA), and T-510 experiment (Anne Zilles, ISBN 978-3-319-63411-1)
- Assumes constant index of refraction n, which might be oversimplification for top layer of natural ice (**NOT: constant density**) $\rightarrow$ Work in progress

Simulation setup

Ray tracing NOT included in results shown this presentation



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

- U. Latif: Analytical ray tracer
- D. Van den Broeck: Using launch direction and n at emission point works well
- Rotation so $\vec{E}$ is perpendicular to ray path
- $R = \int ds$ (geometric) or $R = \int n(z) ds$ (optical)?

Simulation results

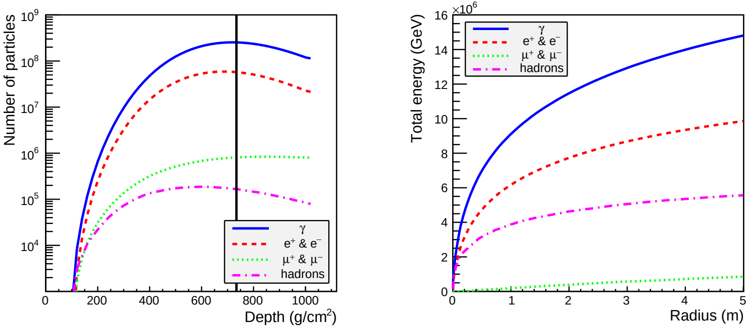
QGSJETII-04, GHEISHA 2002d

Altitude at 2.4 km

Taylor Dome density gradient

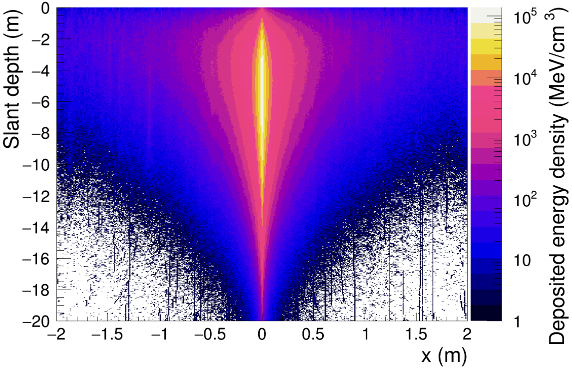
On the surface

- 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)

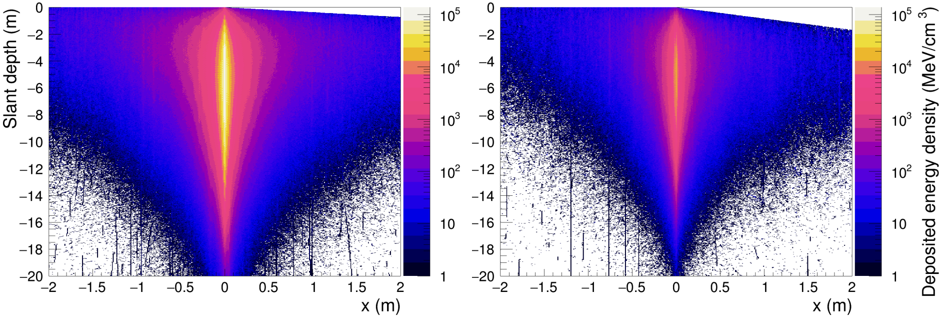


Deposited energy density

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



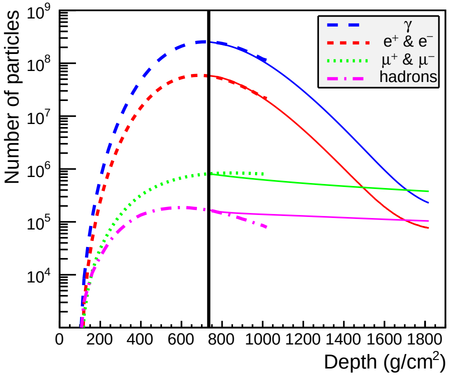
Deposited energy density



$\theta = 20^\circ$ and $\theta = 40^\circ$

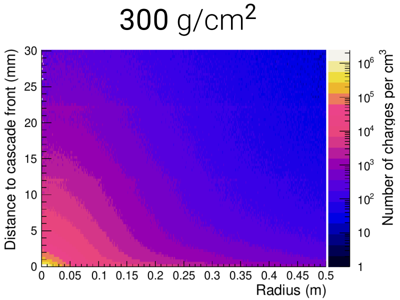
Shower development

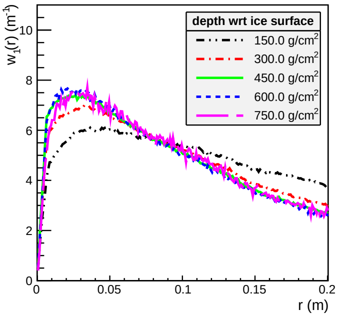
- Propagation through ice does not influence development of electromagnetic part
- Standard air shower parameterizations (e.g. Gaisser-Hillas) can be used



Charge distribution

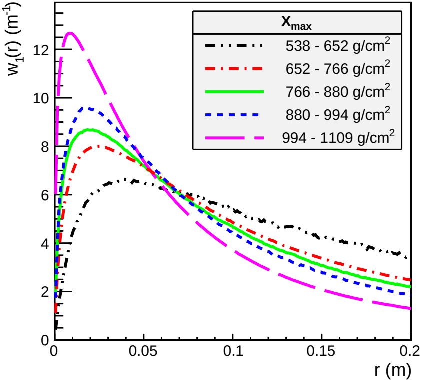
- Thin disk (∼ 1–10 mm)
- Lateral dimension is relevant dimension when studying radio emission
- $w_1(r)dr$ = number of charges in $[r, r + dr[$ (normalized)





Charge distribution

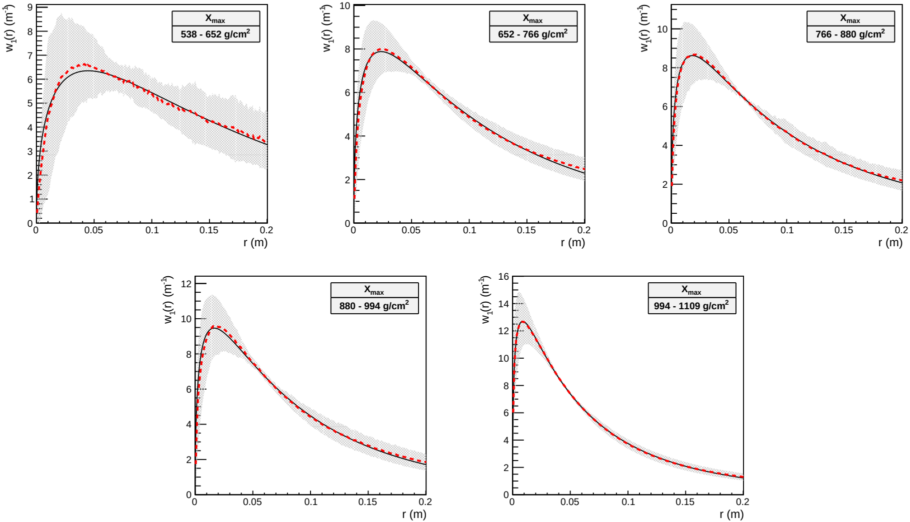
- 10 different shower sets, 10^{16} eV - 10^{18} eV, 0° - 30°
- Group showers based on X_{max} and calculate average $w_1(r)$ distribution for each group
- Result at depth of 450 g/cm^2 wrt ice surface:



Fits to parameterisation

$$W(r) = \frac{1}{A}\sqrt{r}e^{-(r/b)^c}$$

Charge distribution

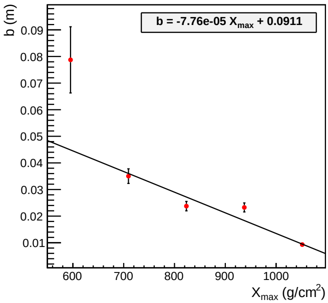


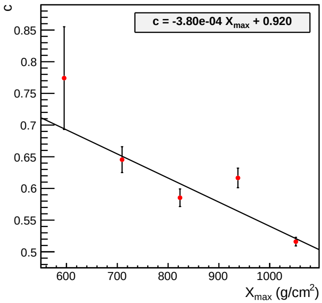
Charge distribution

$$W(r) = \frac{1}{A}\sqrt{r}e^{-(r/b)^c}$$

with

$$A = \frac{b^{3/2}}{c}\left\{\Gamma\left(\frac{3}{2c}\right) - \Gamma\left(\frac{3}{2c}, \left(\frac{R_0}{b}\right)^c\right)\right\},$$





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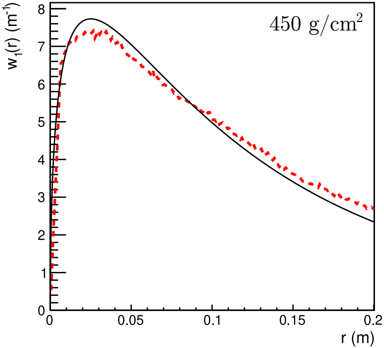
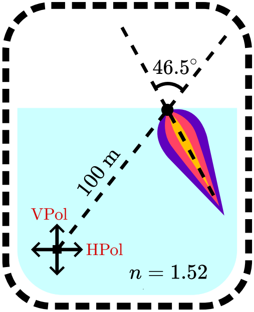
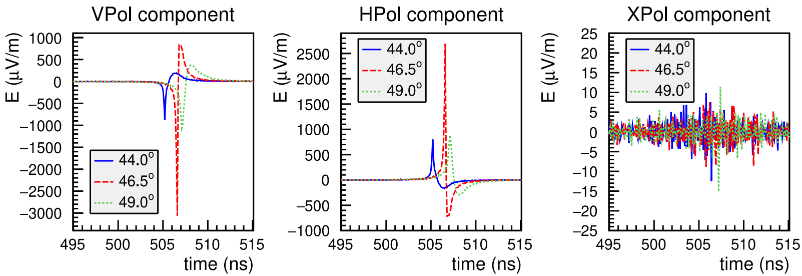


Radio emission

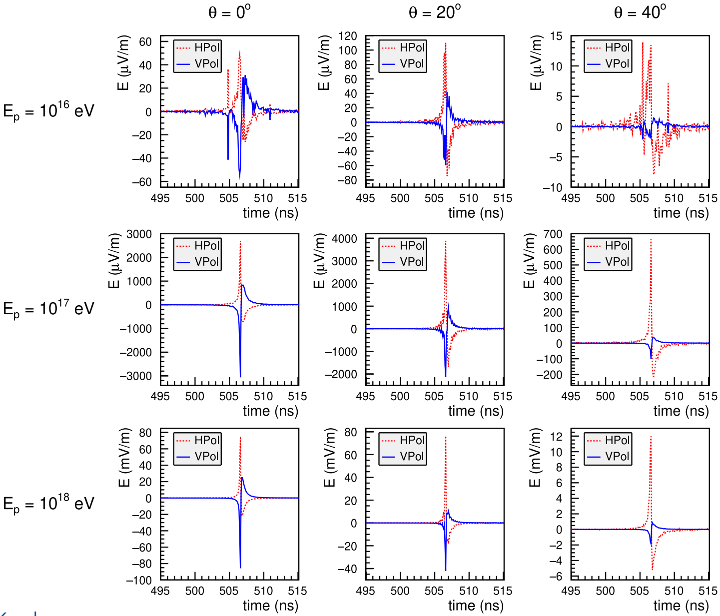
- Bipolar, radial polarized signal (Askaryan)
- Well above typical detection thresholds of 10-100 μV/m (antenna convolution forseen for future work)



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



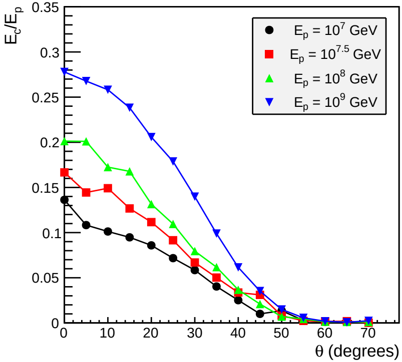
Radio emission



Backup

Deposited energy density

- Energy E_c within radius of **100** cm on surface (average over 10 showers for each point)
- Correlates with primary energy E_p and zenith angle θ



Deposited energy density