Particle content of very inclined air showers for radio signal modeling

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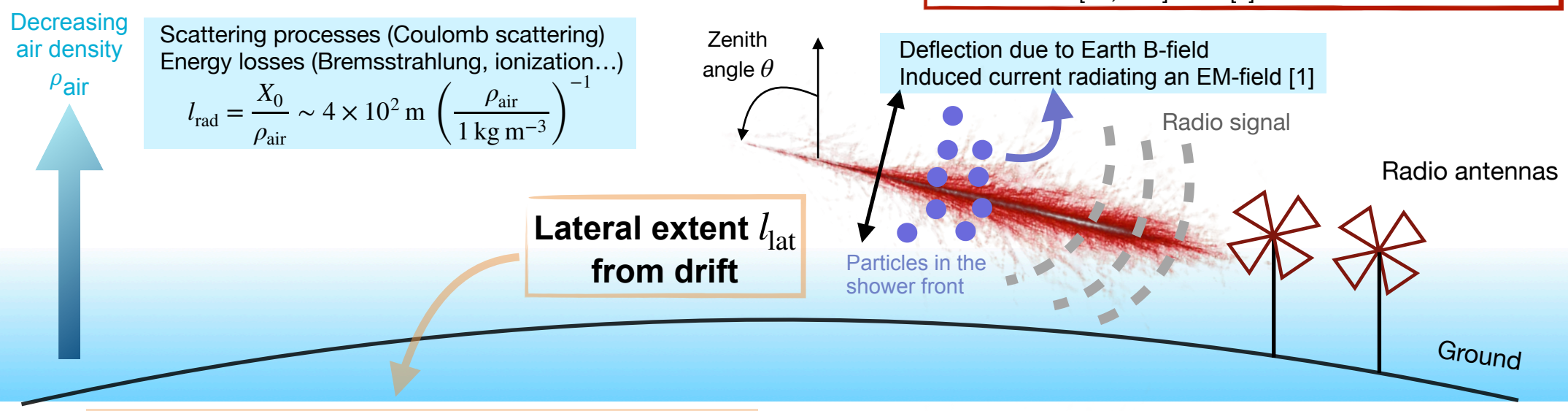
- Reconstruction of very inclined air showers: new challenge for next-generation radio experiments (AugerPrime radio upgrade, BEACON, GRAND) which focus on detection of ultra-high-energy particles.
- Radio signals emitted by very inclined air showers different from those of vertical ones: drastic drop of geomagnetic emission amplitude.

Goals:

- **Study the electromagnetic particle content of very inclined EAS**
- Explore energy range of the particles that contribute most to radio emission
- Estimate the atmospheric depth at which radio emission is strongest
- Quantify their lateral extent to be linked with features of radio signal

Very inclined air showers

Develop higher in atmosphere: lower air density
➡ Larger mean free path for collisions and radiation losses
➡ Stronger impact of geomagnetic field B
➡ **Larger lateral extent**
➡ Loss of coherence for radio signal at frequencies between [30, 200] MHz [2]

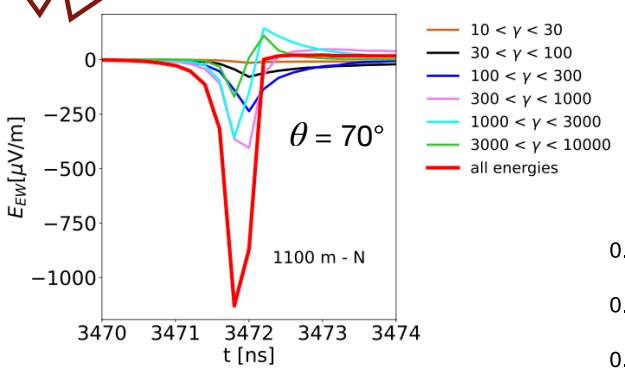


$$l_{lat} \sim 3 \times 10^1\,\mathrm{m} \left(\frac{\rho_{air}}{1\,\mathrm{kg\,m^{-3}}}\right)^{-2} \left(\frac{B}{50\,\mu\mathrm{T}}\right) \left(\frac{\epsilon_0}{100\,\mathrm{MeV}}\right)^{-1}$$

Particle energy

[1] O. Scholten, K. Werner and F. Rusydi, AstroPart. Physi.29 (2008) 94
[2] Chiche et al., PRL accepted, arXiv:2404.14541

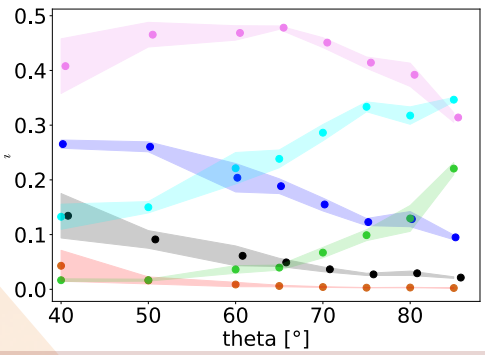
Contribution of air-shower particles to radio emission

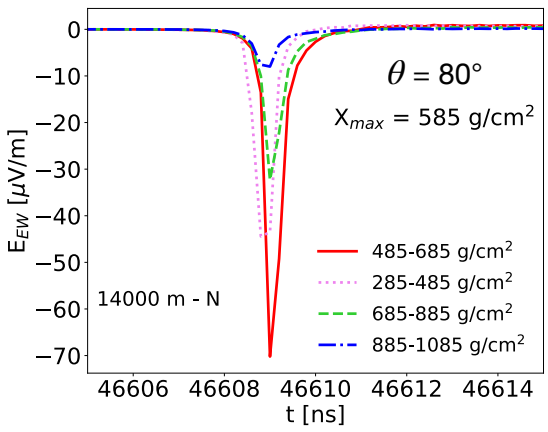


Energy fluence: energy emitted by electrons and positrons of the air shower in form of radio waves

$$f = \epsilon_0 c \Delta t \sum_i (E_{\mathrm{EW}}^2 + E_{\mathrm{NS}}^2 + E_{\mathrm{vertical}}^2)(\mathbf{r}, t_i)$$

Normalized energy fluences according to the inclination for different particle energy ranges





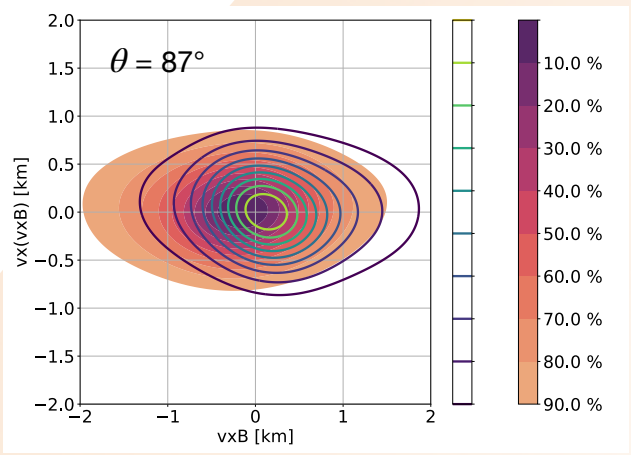
Traces of the radio signal at different stages of the shower development
Traces are at the position of the Cherenkov cone obtained from simulations

Radio signal dominant in two different energy regimes: [10, 500] MeV for vertical air showers and [50, 1500] MeV for very inclined ones
Bulk of the radio signal originates from the X_{max} region

Monte Carlo simulations

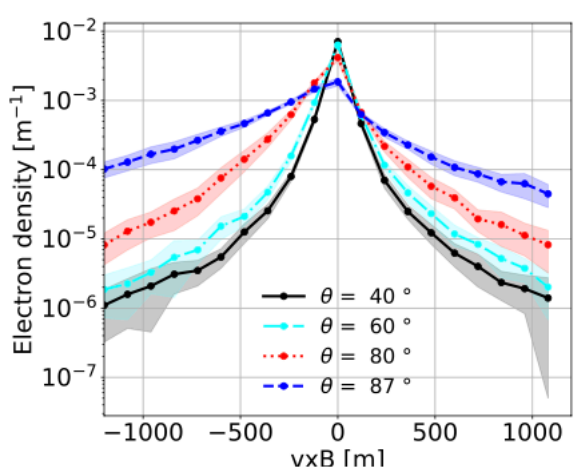
- CORSIKA 7.7500
- CoREAS V1.4 (radio extension)
- Primary: proton with energy $10^{17} - 10^{18}$ eV
- Zenith angle between 30° and 85°
- Azimuth angle: 0° or 45°
- Site elevation and magnetic field: Dunhuang (China) (h = 1100 m a.s.l. and $B = 50\,\mu\mathrm{T}$)

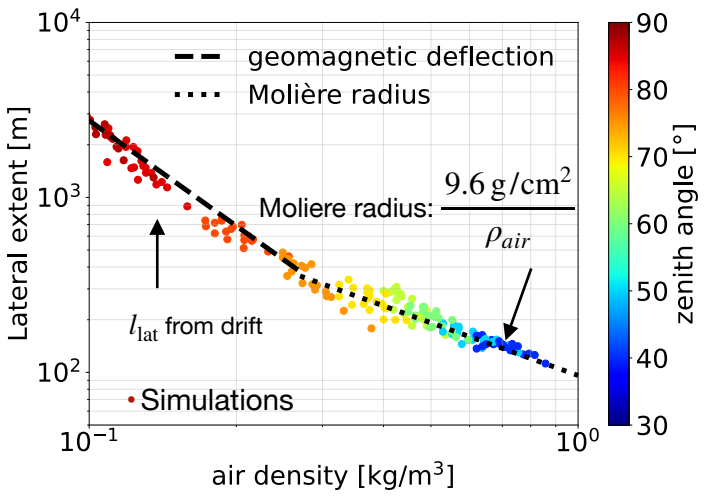
Lateral extent estimation from simulations



Particle density in the shower plane at X_{max}

Electron distributions projected on the (v × B) axis at X_{max} for various inclinations





- Two distinct regimes at high and low density
- Drastic lateral extent increase for very inclined air-showers
- Loss of coherence and drop of the radio signal [2]
- **Will strongly impact reconstruction strategies of next generation of extended radio arrays**
- **Could allow to discriminate between cosmic-ray air showers and neutrinos (also have very inclined trajectories but develop in very dense atmosphere)**