Particle density fluctuations and correlations in low energy Cosmic-Ray showers simulated with CORSIKA

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1. Introduction

The current studies of cosmic rays are focused on most energetic particles entering the atmosphere and producing a single Extensive Air Shower (EAS). There are, however, models predicting that interactions of high energy particles may result in Cosmic-Ray Ensembles (CRE) created far from the Earth. They could be observed as some number of correlated air showers of relatively low energies spread over a large area. The objective of the Cosmic Ray Extremely Distributed Observatory (CREDO) is to search for CRE using all available data from different detectors and observatories including even small but numerous detectors spread over large areas.

In this study 18 sets of cascades were simulated using CORSIKA (COsmic Ray SImulations for KAscade - a commonly used program for simulations of EAS with different possible parameters [2]). The primary particles were protons, with energy set to a particular value from the range 1 TeV - 4 000 TeV. Zenith angle in every case is set to 0. The energy cut for EM particles is 0.3 GeV and 1 GeV for muons.

2. Basic energy dependences

The first part of the analysis included calculation of the average number of muons, electrons and photons contributing to an EAS with a specific energy as well as calculation of radii of a cascade in which a selected fraction of muons, electrons and photons are contained. The results are shown in Fig. 1.

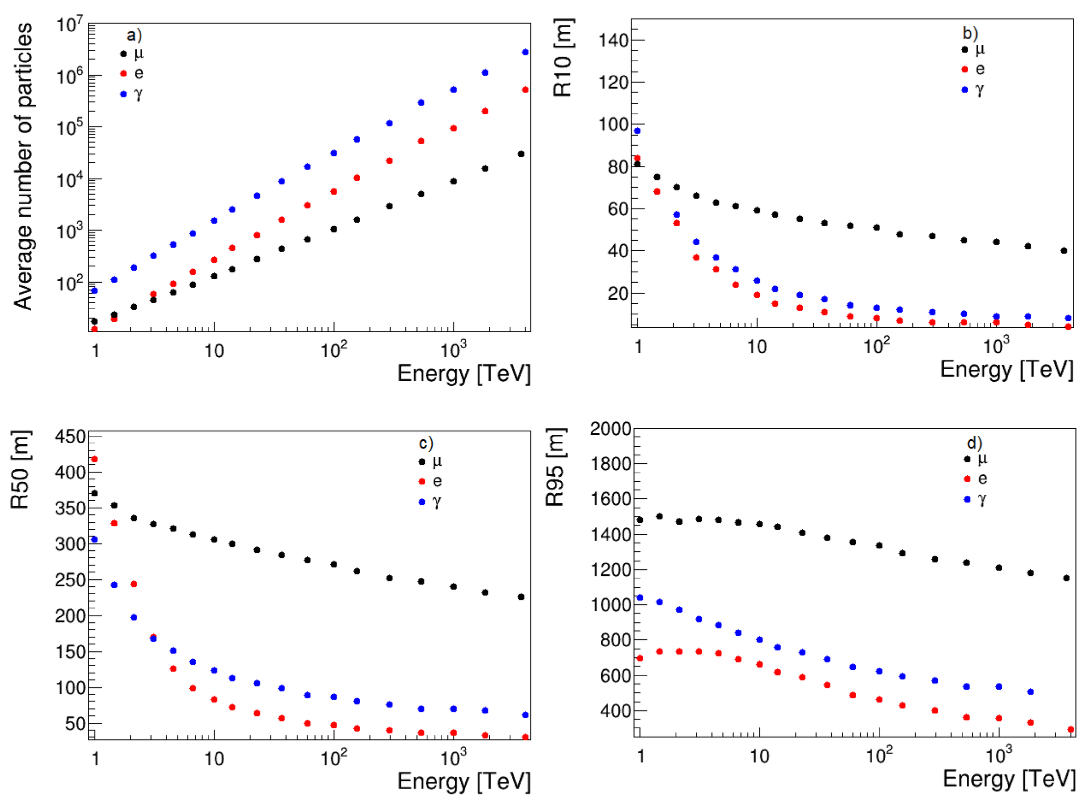

Figure 1: (a): Average number of particles as a function of energy of the primary particle; (b)-(d): Average radius in which 10% (denoted as $R10$), 50% ($R50$) and 95% ($R95$) of particles are contained.

The number of particles of each type increases approximately linearly in a $log - log$ scale (Fig. 1(a)). Average number of μ increases more rapidly than the number of e or γ. Muons are also spread over larger distances than e or γ (Fig. 1(b)-(d)). Interestingly, in every case the radii decrease with the primary energy, while the number of particles becomes larger. It clearly indicates that more particles are emmited closer to the cascade axis, as it may be expected from the kinematics of interactions in the cascade.

3. Two particles correlations in location

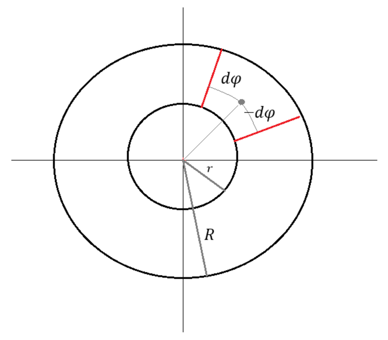

Figure 2: Definition of the neighborhood of a selected particle.

The method used in correlation analysis is based on counting particles in the neighborhood of a selected particle. The general procedure is the following:

- The surface covered by a cascade is divided into rings, ΔR = 2 m, 5 m or 20 m wide.
- For each particle with coordinates (r_0, φ_0) the neighborhood is defined as a part of the ring (inner and outer radius, $r \leq r_0 < R$, respectively) with azimuthal angles in the range $(\varphi_0 - d\varphi;\ \varphi_0 + d\varphi)$, $d\varphi = (R-r)/2r$, with the area approximately $\Delta R \times \Delta R$, as shown in Fig. 2.
- Particle density (without that selected) is calculated in such neighborhood area as well as in the whole ring, together for e and γ and separately for μ.

Electrons and photons: Calculations were performed for five primary proton energies: 4.544 TeV, 10 TeV, 60.12 TeV, 100 TeV and 291.888 TeV. The maximum radius of cascades was set to 750 m, in order to include 95% of particles, as indicated by Fig. 1(d). Three sizes of ring widths, ΔR, were used: 2 m, 5 m and 20 m (Fig. 3).

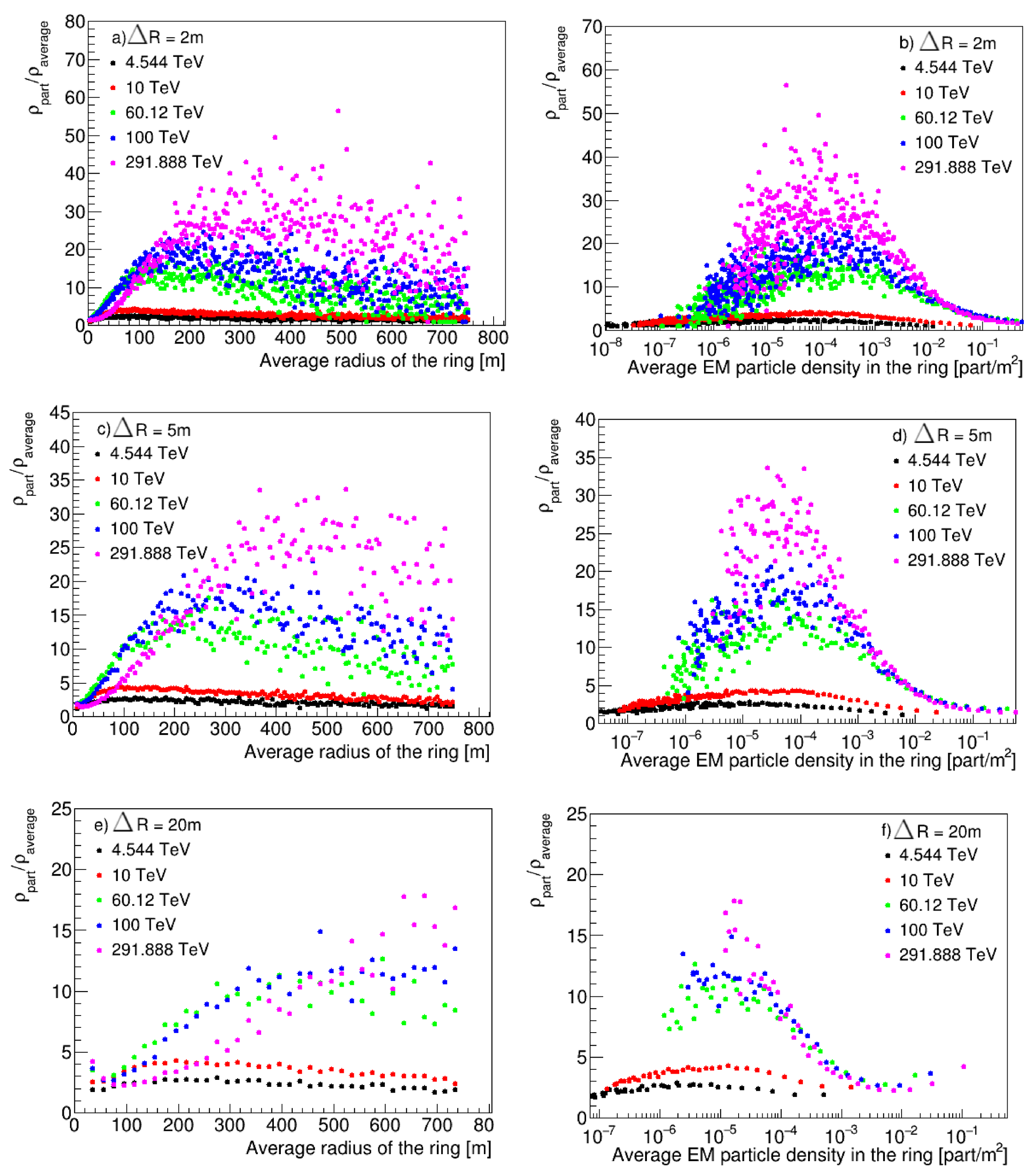

Figure 3: Ratio of density of EM particles in the neighborhood of a selected particle (e or γ) and the average density in the ring for rings with different values of ΔR.

In Fig. 3(a)-(c) the clustering effect becomes pronounced at larger distances from the centre, where the particle density decreases. Each energetic electron or photon created somewhere in the atmosphere is able to produce a small "subshower" with an axis which may deviate from the direction of the primary particle. Far from the centre of the cascade such "subshowers" are sparse and clustering effect is strong. Contrary, near the centre of the cascade "subshowers" are overlaping and thus the local particle density becomes less sensitive to correlations within a single "subshower".

Muons: The analogous analysis only for muons is presented below. The calculation in this section was carried out for six primary particle energies. The maximum radius was set to 1500 m. Results are shown in Fig. 4.

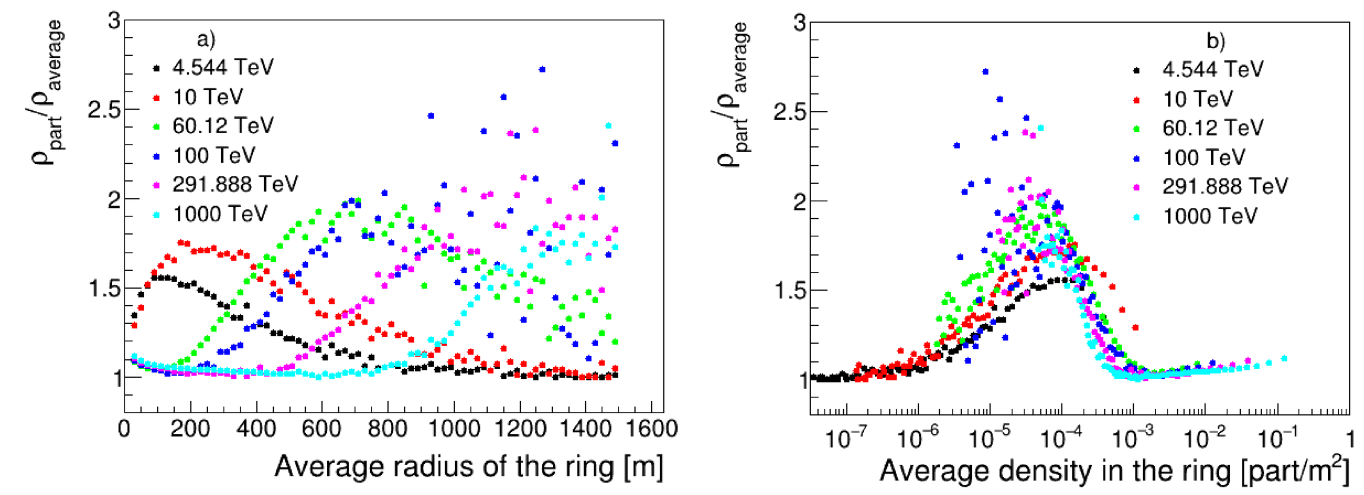

Figure 4: Ratio of density of muons in the neighborhood of a selected muon and the average density in the ring for rings with ΔR = 20 m.

For lower energies (4.544 TeV, 10 TeV) the density ratio reaches the maximum value significantly closer to the centre (at $\sim$100 m and $\sim$200 m, respectively). The probability of finding an additional muon near the selected one is there 1.6–1.8 times larger than probability of finding a muon in randomly selected place at the same radius (Fig. 4(a)). In Fig. 4(b), there is a peak at the density close to 10^{-4} m^{-2}. For smaller densities there are no clusters or they are much larger than the area used in the analysis. For rings with large densities which contain a lot of muons, the correlations become negligible.

4. Conclusions

- In the $log - log$ scale the number of electrons, photons and muons increases linearly with energy.
- Radii in which 10%, 50%, 95% of EM particles and muons are included decrease with cascade energy because of kinematics of interactions.
- Results obtained during correlation analysis confirm that the density increases around a selected particle.
- Clustering effect is very strong for electrons and photons but it is also visible for muons.

References

[1] Homola P. *et al*, *Cosmic-Ray Extremely Distributed Observatory*, 2020, Symmetry 2020, 12(11), 1835

[2] Heck D., Pierog T., *Extensive Air Shower Simulation with CORSIKA: A User's Guide*, Version 7.7100 from October 1, 2019), Forschungszentrum Karlsruhe; available from https://www.iap.kit.edu/corsika/70.php