Numerical study of the electron and muon lateral distribution in atmospheric showers of high energy cosmic rays

XIIth Quark Confinement and the Hadron Spectrum

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The simulation

The Monte Carlo technique is used for the simulation of the lateral growth of an extensive air shower which has a specified primary particle type and energy corresponding to a specific interaction model.
The CORSIKA (COsmic Ray SImulations for KAscade) is a Monte Carlo simulation program for the physics of cosmic rays, used by many cosmic ray experiments for various actions. It can be used to simulate interactions and decays of nuclei, hadrons, muons, electrons, and photons in the atmosphere up to energies of some 10^{20} eV. It gives details for all secondary particles that are created in an air shower and pass a selected observation level.
In this paper, for each entry angle we ran 100 simulations with fixed primary particle energy and of zenith angles varying from 0 to 75 degrees. The results obtained as the mean value of all simulations for each particle. The corresponding errors are due to the limited number of events in the Monte Carlo simulation.

magnitude	value
Shower sets	10
Shower/set	100
Primary particle	Proton, Helium, Gamma, Iron
Primary energy	10^{13}eV – 10^{16} eV
Zenith angle	0^o, to 75^o
Azimuth angle	-180^o to 180^o
Energy cut (hadrons, muons)	0.3 GeV
Energy cut (electrons, photons)	0.003 GeV
Starting height	0 g/cm^2
Earth's magnetic field Thessaloniki	B_x=25.005μT, B_z= 39.488μT
Observation level	110 m

The NKG function

The atmospheric cascade is a superposition of individual cascades generating electrons (those that concern our work), and muons at different depths and with different energies.
The NKG (Nishimura-Kamata-Greisen) function is a good theoretical approach to the lateral distribution of electrons and muons.

The NKG function for electrons

The function which is adapted to the electrons, is given by the formula below.

$$\rho(r) = N_e C(s)\left(\frac{r}{r_M}\right)^{s-2}\left(1+\frac{r}{r_M}\right)^{s-4.5}$$

Where C(s) is normalization constant, r_M is the Moliere radius (for electrons the Moliere radius is 80m in the atmosphere) and s is the time slope parameter (age parameter).
The constant C(s) is given by the relation below.

$$C(s) = \frac{\Gamma(4,5-s)}{2\pi r_M^2\Gamma(s)\Gamma(4,5-2s)}$$

The above function is analytically derived for the case of electromagnetic cascade but is also used in the description of the lateral distribution of electrons in a hadronic cascade. However, based on knowledge of previews studies, it seems that the NKG functions have shortcomings in the implementation of the measured lateral distribution of electrons, becoming more evident in the large distances from the axis of the cascade.

This deficit is usually caused by the fact that the NKG function has occurred for electromagnetic cascades while hadronic cascades are a superposition of a large number of independent electromagnetic cascades. For typical cascade, detectors extend in approximately 200m from the axis of the cascade.

In the case of large cascades with over 10^6 electrons with primary energy 10^{16}eV, detectors near the axis of the cascade are saturated and must be removed from the analysis.

The NKG function for muons

The function which is adapted to the muons, is given by the formula below.

$$\rho(r) = N_e C(s)\left(\frac{r}{r_M}\right)^{s-2}\left(1+\frac{r}{r_M}\right)^{s-4}$$

Where C(s) is normalization constant, r_M is the Moliere radius (for muons the Moliere radius is 420m in the atmosphere) and s is the time slope parameter (age parameter).
The constant C(s) is given by the relation below.

$$C(s) = \frac{\Gamma(4-s)}{2\pi r_M^2\Gamma(s)\Gamma(4-2s)}$$

Reconstruction of Cosmic Rays for the Determination of their Mass

The results obtained from the simulation of atmospheric cascades with CORSIKA lead us to the modification of the NKG function by varying the exponent values. The new function which fits better the results of the simulation than the original NKG function is:

For electrons

$$\rho = C\left(\frac{r}{r_o}\right)^{s-1,8}\left(1+\frac{r}{r_o}\right)^{2s-3,8} \quad \text{and} \quad C = \frac{N_e}{2\pi r_o^2}\frac{\Gamma(3,8-s)}{\Gamma(s+0,2)\Gamma(3,6-2s)}$$

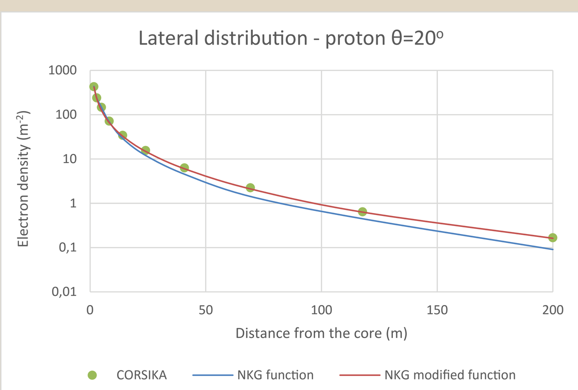

Figure 8. Lateral distribution of electrons for cascades with a primary particle proton having primary energy 10^7 GeV and entry angle 20 degrees. The red line represents the fitted function while the blue represents the original.

For muons

$$\rho = C\left(\frac{r}{r_o}\right)^{s-1,6}\left(1+\frac{r}{r_o}\right)^{s-3,8} \quad \text{and} \quad C = \frac{N_e}{2\pi r_o^2}\frac{\Gamma(3,8-s)}{\Gamma(s+0,4)\Gamma(3,4-2s)}$$

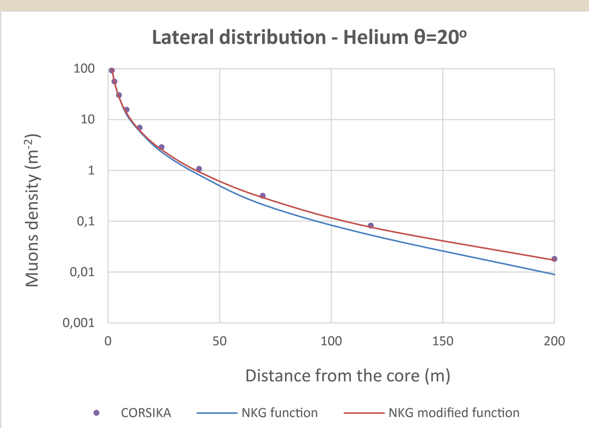

Figure 9. Muon lateral distribution for atmospheric showers with primary particle helium nucleus. The blue line is the NKG function. The red line is the modified NKG function.

Lateral Distribution of Electrons

Compare of the lateral distribution of electrons for different primary particles and at different angles.

When the entry angle θ is small 0^o<θ<20^o the differences of lateral distribution (of electrons arriving at the observation plane and the electrons arriving at the plane perpendicular to the axis of the cascade) are small. But when the entry angle increases, some electrons arrive at the observation level (Earth's surface) by the shortest path (point C in Figure 1), while others arrive from the longest path (point A in Figure 1).
The cascade development on the short path is faster. In the long path we have greater absorption of electrons, thus the larger the entry angle; the fewer electrons reach at point A.

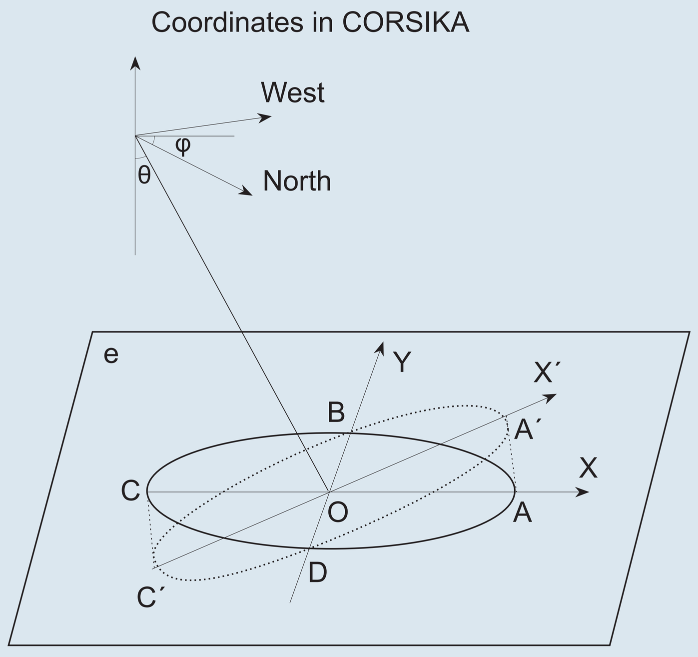

Figure 1. The plane e is the level of observation. The lateral distribution of electrons is symmetrical to the dashed plane which is perpendicular to the axis of the cascade.

The lateral distribution of electrons for primary particle proton, photon and iron nuclei, for 0 degrees entry angle is shown in Figure 2. Respective Figures derived (according to the simulation) for small entry angles 0^o <θ<20^o.
But in all the scenarios of the simulation where the primary particle is photon (electromagnetic cascade), the density of electrons is greater.The diagram of Figure 2 shows that there is symmetry around the center of the cascade (in a plane perpendicular to the axis of the cascade).When the entry angle is small θ<20 degrees, the plane which is perpendicular to the axis of the cascade and the observation plane are almost identical. But as the entry angle increases, the angle of the two planes (Figure 1) increases respectively. Thus there is no longer symmetry on both sides of the axis of the cascade at the level of observation.
The variation in the number of lateral electron explained by the difference of the two roads d = AA´ + CC´ = 2CC´ = 2xtanθ (for angle θ=60 degrees), followed by the electrons in the cascade. Thus, the lateral distribution of electrons is not symmetrical (Figure 3).

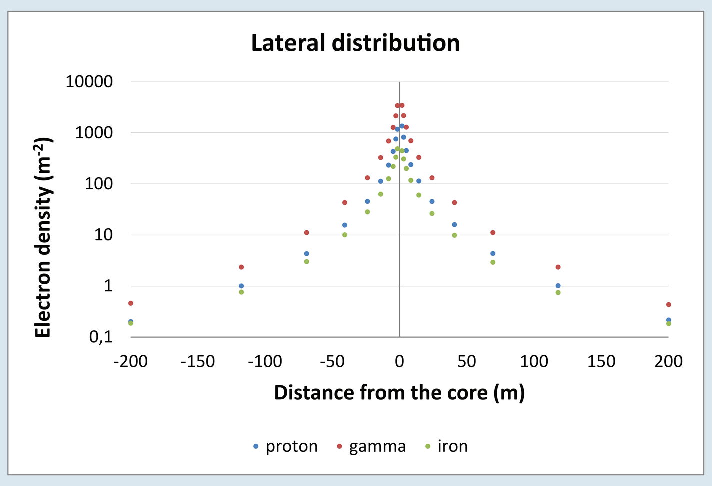

Figure 2. Lateral distribution of electrons for cascades of primary particles proton, photon and iron nuclei with primary energy 10^7 GeV and entry angle 0 degrees.

What causes this?
When increasing the entry angle, the cascade develops into greater heights, since we have more lateral route to the higher layers of the atmosphere. So the electrons arriving at observation level are significantly less. But over 40 degrees and apparently over 60 degrees the data differ in the symmetry of the lateral distribution. The electrons that reach the observation level from the long path are less than those arriving from the small path (Figure 3).
In very large zenith angles θ~90 degrees, cosmic rays develop their own cascades in the upper atmosphere, with a similar mechanism as that in the vertical cascades. Their electromagnetic component almost completely absorbed by the increased atmospheric side depth and cannot reach the ground. A few electrons with irregular distribution reach the Earth's surface from only one side of the cascade.
In contrast, the high energy neutrinos can cause the creation of horizontal cascades at a larger depth in the atmosphere and therefore likened to vertical atmospheric cascades as to the particles that reach the ground.
So the assumption that we can detect high energy neutrinos by horizontal cascades takes on a consistent basis.

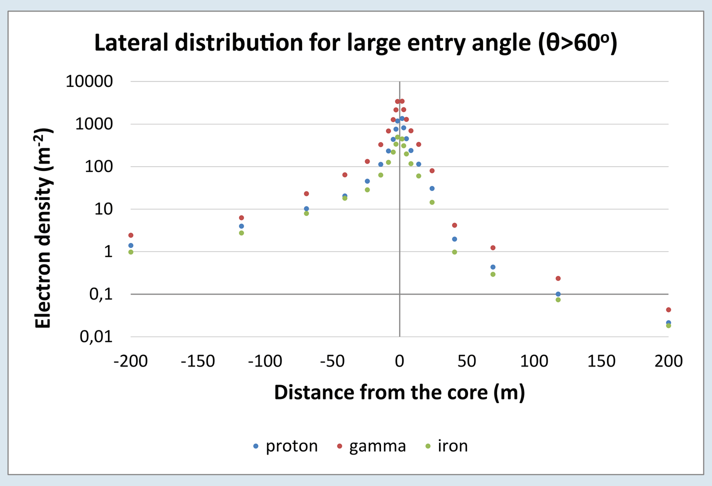

Figure 3. In large entry angles θ>60° for electrons arriving at observation level there is no symmetry. The cascade develops differently in the lateral plane.

Compare of the lateral distribution of electrons on the same original particle and at different angles.

We applied the simulation for a proton primary particle with energy 10^7GeV and for different entry angles. By increasing the entry angle, the number of electrons that reach the ground decreased, accordingly to the reasons mentioned above.

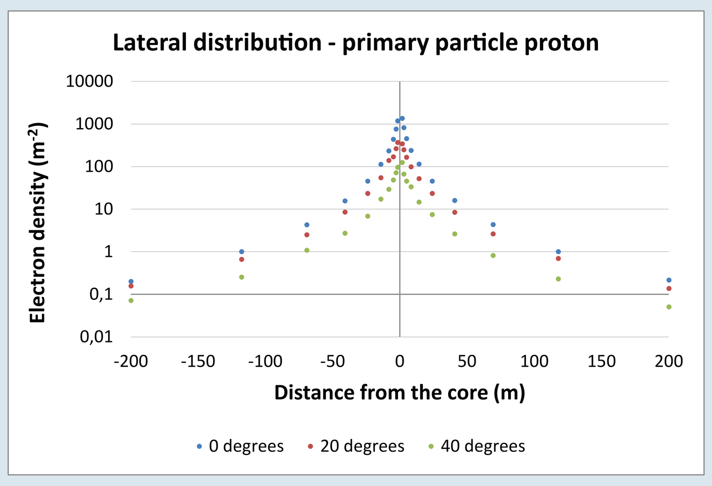

Figure 4. Lateral distribution of electrons for cascades with a proton primary particle with primary energy 10^7 GeV and entry angles 0, 20 and 40 degrees.

Another reason for the reduction of the lateral electron is the height of the first interaction. Obviously in large entry angles that height increases since the initial particle travels deep side to first interaction.

Lateral Distribution of muons

The number of muons arriving at the observation level is growing by the energy of the primary particle. This increase is almost linear as shown in Figure 5.

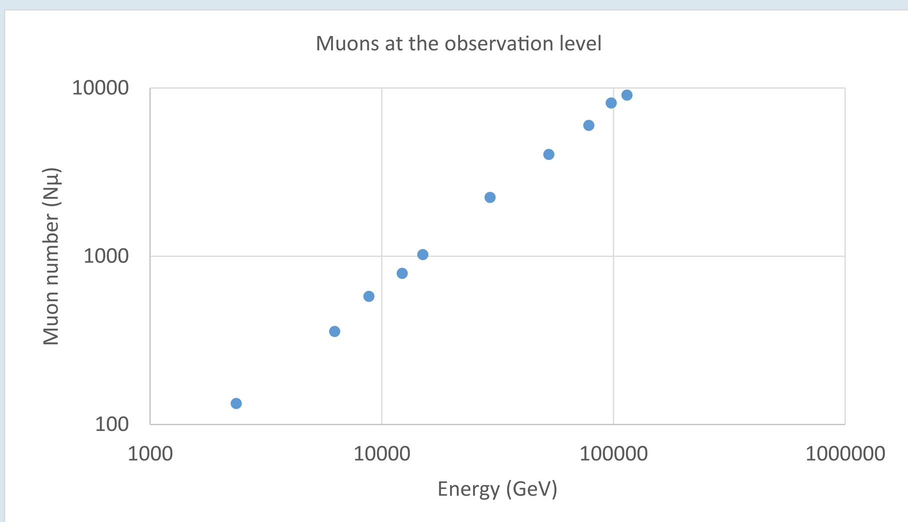

Figure 5. The number of muons arriving at the observation level increases with the energy of the original particle.

Figure 6 shows the comparison of the lateral distribution of electron and muon at an atmospheric shower with primary particle a proton with energy 10^7 GeV. In the same picture is also shown the lateral distribution of muons from the data of the KASKADE experiment.
As it is known, the lateral distribution of muons at the sea level and in the region of energy considered in this work is much more flat and typically one order of magnitude lower than the lateral distribution of electrons in our own scale distance from the core.
The number of muons that arrive at the observation plane does not only depend on the primary energy of the particle but of the type also. Figure 7 shows this dependence for three different primary particles (proton, helium, iron).

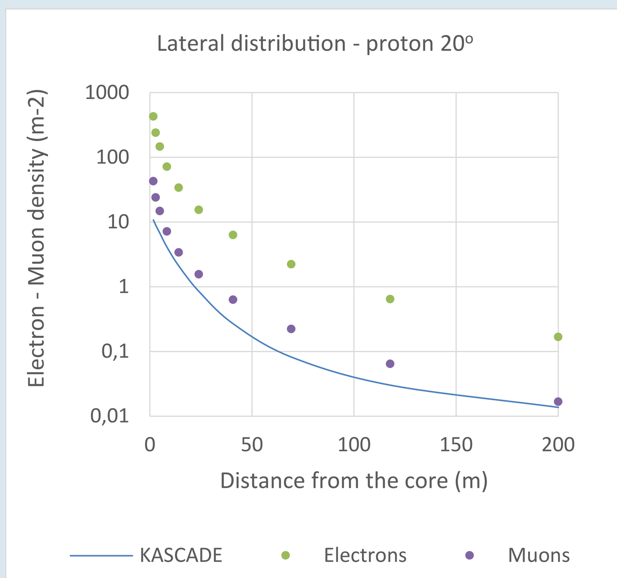

Figure 6. Lateral electron and muon distribution for atmospheric shower with a primary particle proton with energy 10^7 GeV.

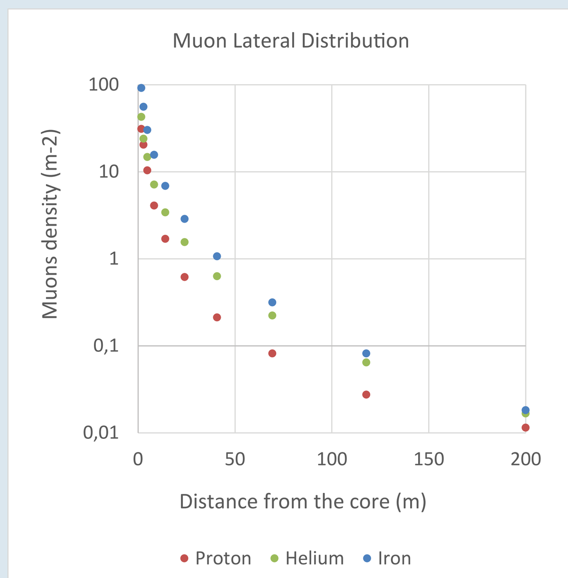

Figure 7. Lateral muon distribution for atmospheric showers with a primary particle proton, helium and iron nucleus. The primary energy is 10^7 GeV.

The following tables give the exponent s obtained as the mean value of all simulations for each particle. The corresponding errors are due to the limited number of events in the Monte Carlo simulation.

Exponent s for electrons

Particle - Nucleus	exponent s
proton	0,75±0,06
helium	0,63±0,06
oxygen	0,79±0,06
silicon	0,85±0,06
calcium	0,89±0,06
iron	0,90±0,06

Exponent s for muons

Particle - Nucleus	exponent s
proton	0,724±0,062
helium	0,616±0,061
oxygen	0,757±0,063
silicon	0,828±0,061
calcium	0,874±0,065
iron	0,896±0,067

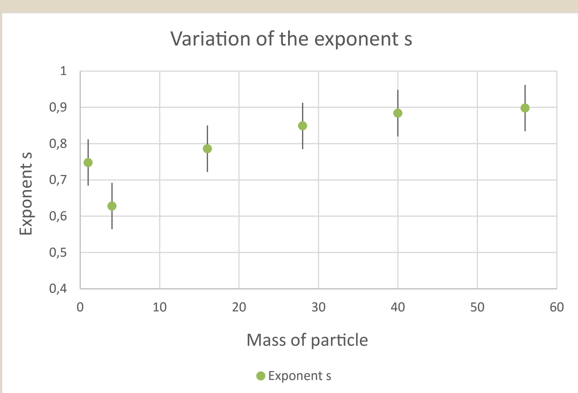

Figure 10. Variation of the exponent s, in relation to the mass of the primary particle.

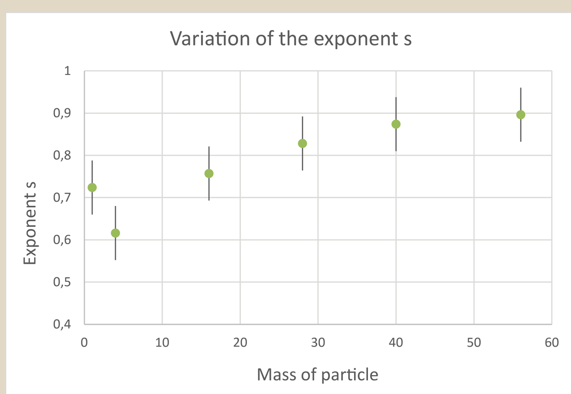

Figure 11. Variation of the exponent s, in relation to the mass of the primary particle.

Conclusions

Studying the data of our simulation we can reach the following conclusions.
There is symmetry in the density of the lateral distribution of the electrons and muons in relation to the axis of the cascade, as shown in Figure 2.
For heavier primary nuclei the electron density decreases but the symmetry remains.
But as the entry angle increases, the symmetry on a plane perpendicular to the axis of the cascade remains, while on the observation plane there is no longer symmetry on both sides of the axis of the cascade (Fig. 3).
The lateral electron density decreases for larger entry angles as shown in Figure 4. This is due to the higher absorption of electrons because of the lateral distance traveled until they reach the ground as well as the greatest height of the first interaction.
The initial NKG function describes well the lateral distribution of electrons and muons in smaller distances from the core of the cascade. For larger distances we propose a modified NKG function. With this modified function we can achieve better fit also at the greater distances from the core of the cascade.
Finding the parameter s of the modified NKG function that adjusts the simulation data better, we can make conclusions for the primary mass of the particle. It appears that the exponent s varies with the mass of the primary particle up to Z ≈ 18, remaining nearly constant for heavier nuclei.
Our aim is to extend this study for larger primary energies and larger entry angles, where the lateral distribution of electrons and muons seems to be completely asymmetrical in relation to the core of the cascade.