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Investigating the lateral distribution distortions of air showers at different observation levels

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Abstract

The comprehension of the basic properties of ultrahigh energy Extensive Air Showers (EAS) is affected by the description of hadronic interactions beyond the LHC energy range. Diffractive interactions with a 20 – 30 percent occurrence probability of all inelastic hadronic collisions lead to high elasticity and large transverse momentum. These interactions are expected to modify the lateral shower development, as well as the measurable observable of the longitudinal profile. This study provides a new approach exploring the impact of diffractive hadronic interactions on lateral development patterns by investigating the fluctuations of simulated lateral distributions. In particular, this research interprets the influence of the observation level and primary energy on fluctuations of lateral electron density. Eventually, an optimized observation level with the maximum fluctuation is introduced as the most probable level to see unconventional EAS.

Keywords: extensive air showers, lateral distribution function, diffractive hadronic interaction, observation level

1. Introduction

In the realm of high-energy astrophysics, the measurement of air showers is a key to understanding the mysteries surrounding Cosmic Ray (CR) interactions with the Earth's atmosphere [1]. The collision between primary cosmic rays and atmospheric nuclei produces cascades of secondary particles. This creates extensive air showers carrying invaluable information about the underlying physical processes. The properties of primary cosmic rays are deduced from the development of the shower in the atmosphere, and from the characteristics of the secondaries detected at different observation levels [2-4]. The CR spectrum extends to more than 10^{20} eV, which corresponds, for proton primaries, to a center-of-mass energy for nucleon-nucleon interactions of $\sqrt{s}$ = 433 TeV. This is about 50 times higher than the maximum collision energy of $\sqrt{s}$ ≅14 TeV, obtained at the Large Hadron Collider (LHC) at CERN. Therefore, the study of cosmic rays supplies equipment to investigate hadronic interactions beyond man-made accelerators. Hadronic interaction models play a key role in understanding the physics driving the production of extended air showers induced by Ultra High Energy Cosmic Rays in the atmosphere, which are continuously confirmed by new accelerator data.

This research delves into the realm of multicore EAS and the nuanced aspects of diffractive hadronic interactions, employing advanced simulations conducted through the Cosmic Ray Simulations for cascades (CORSIKA) [5]. The choice of simulation parameters, specifically altering observation levels, offers a unique lens through which the characteristics of EAS at varying altitudes are scrutinized. Moderate and high altitudes are significantly more favorable conditions for hadron studies than the sea level because of reduced atmospheric attenuation. Our simulations span observation levels ranging from 1420 to 8420 meters above the sea level, capturing the intricacies of showers at energy levels spanning orders from 10^{17} to 10^{19} eV.

The manuscript is organized as follows: in Section 2, as the main points of our approach, the influence of diffractive hadronic interactions on lateral development of EAS at the observation level is discussed. A brief description is provided about the circumstance of displaying unusual behavior and large transverse momentum creation of secondary particle lateral distributions which is inflicted by diffraction events. In section 3, a parametrization factor for EAS Lateral Distribution Fluctuations (LDF) is introduced. The unusual spanning of simulated lateral electron density curves is analyzed at different observation levels. After that, the optimal height for observing the maximum distortion in LDFs is explored for each initial energy value. This provides predictions to find the most probable detection level for multicore observation. In addition, the fluctuation parameter increase is depicted via primary energy. The conclusion is discussed at the end of the paper.

2. Effect of diffractive hadronic interactions on multicore air showers

From a theoretical point of view, diffractive collisions are defined as events exchanging a virtual particle without any quantum numbers called a pomeron [6]. Although the mechanism of diffraction is not well known, diffractive events occur about 20-30 percent of the time in the case of proton-proton collisions at the LHC, which increases with the center-of-mass energy [7]. Experimentally, these collisions are characterized by a leading hadron with high elasticity, and by a large rapidity gap of the produced particles from the dissociation of the incident particles [8]. These events produce final states with high energy leading particles, providing high elasticity which is defined as $K_{el} = E_{lead}/E_{proj}$. Here, E_{lead} is the energy of the most energetic hadron and E_{proj} represents the energy of the projectile particle.

Diffractive interactions are expected to affect the development of air showers as they supply a way of transporting substantial amounts of energy deep in the atmosphere through the leading particles. In particular, showers which develop very deep in the atmosphere are typically those with a diffractive first interaction. Enhancing the collision center-of-mass energy leads to more diffraction that causes a higher elasticity and consequently more penetrating air showers.

Diffractive Deep Inelastic Scattering (DDIS) can lead to the formation of a large angular separation between regions with hadronic activity. This separation is usually expressed in terms of a rapidity gap, meaning a region in the rapidity observable where no particles are produced. Rapidity describes the angle of a particle relative to the axis of the colliding beams. In the limit where the particle is traveling close to the speed of light, or equivalently in the approximation that the particle's mass is negligible, the rapidity is substituted with pseudorapidity η. Large rapidity gap occurrence in DDIS interactions produces large transverse momentum for the products of the incident dissociation [6]. Transverse momenta of secondaries are important properties of hadronic interactions and carry crucial information about the dynamics of the interaction. The transverse momentum acquired by secondaries in the corresponding interactions is intimately linked to the lateral distribution of air showers. The average transverse momentum of charged hadrons in Deep Inelastic Scattering (DIS) is an ascending function of the center-of-mass energy [9]. The growth of the average transverse momentum with the center-of-mass energy is confirmed according to the results of the CDF experiment at the Tevatron, UA1, and the ISR at CERN [10-12]. As diffractive process occurrence grows asymptotically with the energy increase [13], it is expected that the primary energy enhancement has a visible impact on the lateral distribution of air shower secondaries [14]. Thereafter, it is desirable to study the influence of transverse momentum of hadronic interactions in the atmosphere depth on the lateral distribution of secondary particles, to investigate the diffraction effect on cascade transverse development.

3. Parametrization of lateral distribution fluctuations

In this study, the EAS events are simulated by the CORSIKA version 77420, which is a detailed Monte Carlo program to analyze the evolution and properties of extensive air showers in the atmosphere. To describe high and low-energy hadronic interactions, QGSJET [15] and gheisha [16] are selected, respectively.

Proton is selected as an incident particle with primary energies 10^{17}, 10^{18}, and 10^{19} eV. Zenith angle which is defined as the angle between the direction of the primary particle colliding the atmosphere and the perpendicular line of the earth's surface, is considered 10 degrees. 11 different observation levels, from 1420 to 8420 meters above the sea level, are chosen. More than 1700 events and 50 simulated showers per primary energy at each detection level are generated. It is noteworthy to mention that the maximum distance from the shower core to count the secondary particles is considered RADNKG =2000 (m). The lateral distribution of secondary particles versus core distance at the specified observation levels is given by DAT files in CORSIKA outputs. The number of electrons has been counted via a Python program to produce a lateral electron density diagram for each simulated shower, separately. The lateral distribution of particle densities is fitted using two exponential decay functions in order to have a reliable fitting

$$f(r) = a_1 e^{-b_1 r} + a_2 e^{-b_2 r} + f_0 \ . \tag{1}$$

The distance distribution of lateral secondary electron data N_i (1/m2) from the fitted average value f_i (1/m2) introducing distortion parameter $D = N_i - f_i$ follows the Gaussian behavior for each simulated event. The Gaussian function is compatible with a standard deviation σ and a zero mean value. The relevant frequency and the Gaussian function fitted to LDF fluctuation N_i-F_i for a specific event given in the Appendix are shown in figure 1. It is expected that the value of D quantity as a function of the distance from the core shows the amount of distortion in LDF.

Therefore, to investigate the influence of incident particle energy and also the secondary detection level on the amount of LDF fluctuations, the absolute value of $N_i - f_i$ is demonstrated in figure 2 versus the distance from the core. Figure 2(a) compares the D parameter for a typical shower at a height of 1420 (m) with another at a height of 3000 (m) for the primary energy of 10^{19} eV. This expresses that a higher detection level causes more distortion in LDF. In figure 2(b), the D quantity for a typical shower at the energy of 1017 eV is depicted against the case of 10^{19} eV at the height of 1420 (m). The effect of energy raising on the lateral case of 10^{19} eV at the height of 1420 (m). spreading fluctuation enhancement is clearly visible. This can be inspiring to explore an optimum observation level including characteristics of the most distortion in LDF spreading.

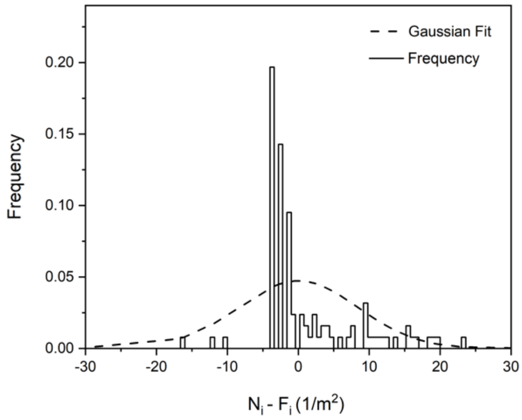


Figure 1. The fluctuation density distribution D for a specific event (E_0=10^{19} eV at observation level of 3420 m). The mean value is compatible with 0 and the standard deviation is 8.3894.

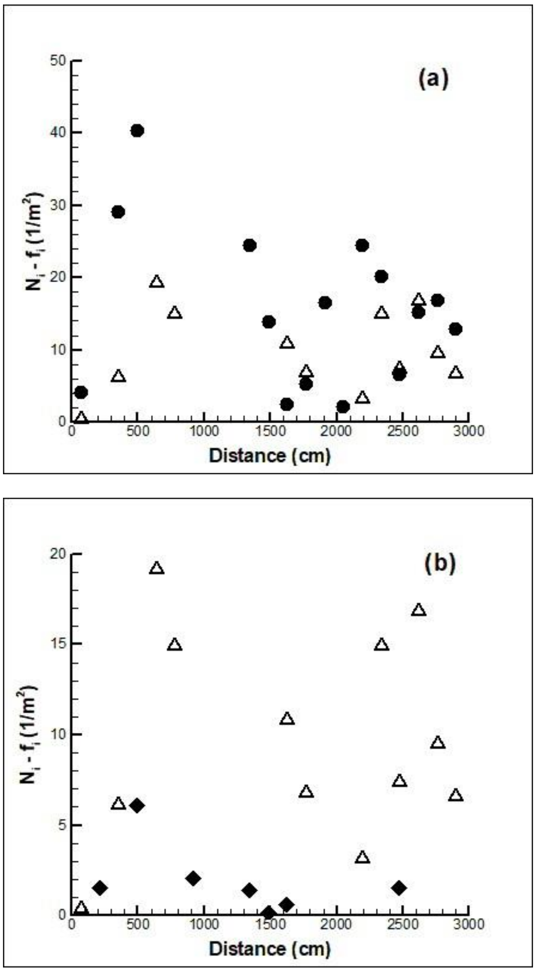


Figure 2. The absolute value of Ni -fi in the case of (a) E_0 =10^{19} eV at observation level of 1420 meters (triangle) and 3000 meters (circle) and (b) observation level of 1420 meter for E_0 =1017 eV (diamond) and E_0 =10^{19} eV (triangle).

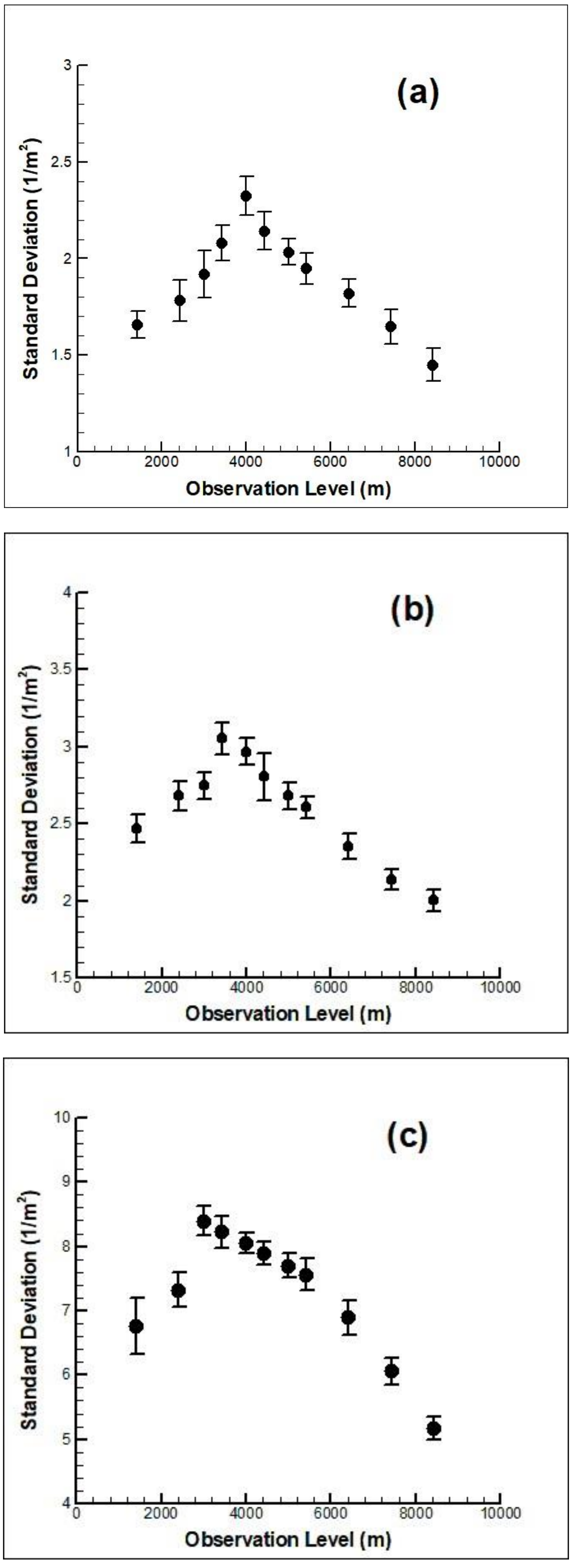


Figure 3. The mean Standard Deviation of electron density lateral distribution versus the Observation Level height for a proton as a primary particle with energies: (a) 10^{17}, (b) 10^{18} and (c) 10^{19}.

Table 1. Density and depth of the atmosphere at given altitude.

Height(m)	Density(kg/m^3)	Depth(gr/m^2)
1000	1.112	920
2000	1.007	820
3000	0.909	720
4000	0.819	640
5000	0.736	560
6000	0.660	485
7000	0.590	425
8000	0.525	370

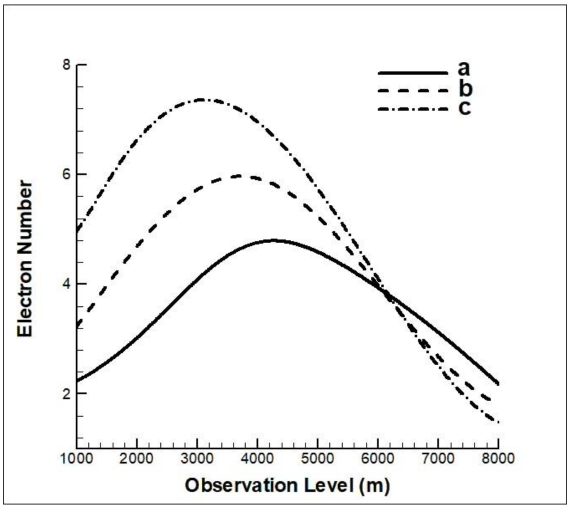


Figure 4. Electron numbers versus observation level, (a): $\times 8 \times 10^{-7}$ for E_0 $=10^{17}$ eV (solid), (b): $\times 10^{-7}$ for $E_0=10^{18}$ eV (dashed) and (c): $\times 0.125 \times 10^{-7}$ for $E_0=10^{19}$ eV (dash-dotted).

Studying the optimal detection level is beneficial to avoid the unwilling effect of subsequent interactions in covering the rapidity gap of diffractive events. The standard deviation quantity σ as a measure for lateral distribution fluctuations in the proposed approach, is calculated in each particular observation level, per event. The average σ for all 50 events at each observation level, is depicted in figure 3 for each primary energy. On average, the standard deviation has a rising behavior as a function of the observation level until it reaches a maximum value. This behavior supplies an optimum value of observation level with maximum distortion as a preferred candidate for exploring unusual EAS with unconventional lateral electron density.

The atmosphere density decreases versus the altitude from the earth as shown in table 1. The probability of hadronic interaction occurrence decreases while going up in the atmosphere. Consequently, the probability of diffractive interaction occurrence is facing a reduction.

On the other hand, advancement in the depth of the atmosphere and the decrease in altitude, increase the number of interactions as well as the number of secondary particles. This causes covering the rapidity gap produced in diffractive events. Therefore, the destructive effects of the subsequent interactions' secondary particles in covering the rapidity gap, fall and result in a greater amount of LDF fluctuation by increasing the height. Substantially, the points get away from the average fit in the lateral distribution function. So, the average standard deviation rises with height. Whereas, with a further increase in height, the probability of hadronic interaction occurrence decreases after a while, as it penetrates the atmosphere.

This originates from the atmosphere density descending. So the effect of reducing the diffraction interactions becomes more apparent. Since the diffractive interactions probability depends on primary energy E0, for different altitudes it is observed that from one height onwards the effect of reducing the number of diffraction interactions dominates and LDF distortion reduces. Lateral electron density fluctuations show descending treatment. Therefore, the possibility of detecting jet production with large transverse momentum and seeing unusual EAS growth, and then falling against the observation level altitude. This leads to an optimum behavior of standard deviation versus the observation level as it is illustrated in figure 3. In addition, figure 3 demonstrates a shift in standard deviation peak to the left (lower observation level altitude) for higher incident energy. This is because more energetic primary particles interact less and can go deeper into the atmosphere. This means that the impact of diffractive interactions with more E_0 manifests at lower altitudes. The same process is predicted in the longitudinal development of simulated showers. This can be seen in the form of a shift of the maximum value of the number of detected electrons to lower heights by increasing the initial energy, as shown in figure 4, the distribution of average electron number at the observation level is a good witness to this claim.

The quantity σ as a measure for fluctuations of lateral density distribution, can be a good parameter to assess the unusual behavior of air showers. However, searching for EAS with a multicore structure needs significant distortion compatible with σ in one or more points of LDF.

Therefore, it is desirable to compare the average of LDF points distance from the fitted value at each altitude $\overline{D}$ (h) with the average standard deviation $\overline{\sigma}$ (h). Using 50 showers of each observation level, the average number of cases where $\overline{D}$ is larger than $3\overline{\sigma}$, $5\overline{\sigma}$, and $7\overline{\sigma}$ is evaluated. The average operation is done for more than 550 simulated LDFs, at 11 observation levels for each primary energy.

Summarized in table 2, one can see an increase in $\overline{D}/\overline{\sigma}$ with larger E_0. This implies that the probability of multicore EAS detection grows with primary energy at high energy regions. It is worthwhile to mention that a sub-core structure is found when the logarithmic D factor, defined as DLog = Log N_i - Log f_i, is significantly larger than the Gaussian distribution standard deviation of DLog and does not coincide with the main EAS core [17].

If one or more significant distances are found, the EAS is tagged as multicore. While we do not seek to find multicores, we propose an approach that predicts the most probable detection level for the multicore observation. It is achieved via searching the optimal height for the maximum distortion in LDF at every value of E_0.

4. Discussion and summary

This study investigates the amount of lateral distributions and their dependence on different factors such as primary energy and detection level above the sea level. The phenomenon of diffraction and the presence of a large rapidity gap of the products of the incident dissociation plays an important role in revealing secondary particles with large transverse momentum and observing more distortion in LDFs.

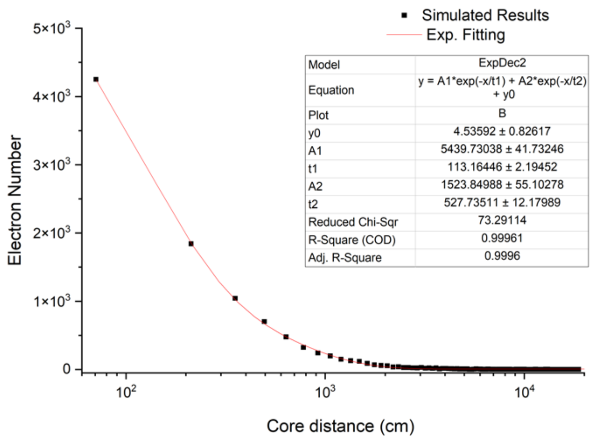
In this study, instead of nucleons, protons are considered as incident particles so the energy is carried by a single particle and is not divided between different constituents. This way, the probability of diffractive interactions is enhanced for a given incident energy. In addition, compared with heavier particles such as iron atoms, protons provide higher elasticity and lead to less secondary.

This facilitates the occurrence of diffractive interactions and provides conditions for investigating large transverse momenta in LDFs. Also, to increase the accuracy of studying the distortions of lateral distribution, a low incident angle has been adopted. This leads to the fact that the slant depth traveled in the atmosphere, and consequently, the number of subsequent interactions and the large rapidity gap covering effects are less. Air shower simulation models are based on accelerator data with energies 30 times less than cosmic rays. Comparing the results of these simulations with the cosmic ray measurements significantly contributes to a better understanding of the mechanism of hadronic interactions at higher energies. The possibility of investigating unusual showers by studying the lateral distributions at optimal heights provides a better comprehension of diffractive interactions; Also, this makes the mechanism of transverse momentum generation at energies higher than the human-made range apprehensible.

Table 2. The average number of data points in lateral distribution with distance factor $\bar{D}$ larger than $3\bar{\sigma}$, $5\bar{\sigma}$ and $7\bar{\sigma}$.

$E_0(eV)$	$\bar{D} \geq 3\bar{\sigma}$	$\bar{D} \geq 5\bar{\sigma}$	$\bar{D} \geq 7\bar{\sigma}$
10^{17}	13.09	0	0
10^{18}	37.64	1.82	0
10^{19}	79.91	19.1	1.64

Appendix



Lateral distribution of electrons versus core distance for a specific event with $E_0=10^{19}$ eV at an observation level of 3420 m. An exponential function is fitted.

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