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Arrival time distributions of air shower particles measured by LHAASO-KM2A

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The arrival time distributions of air shower particles provide critical insights into the longitudinal development of extensive air showers and the properties of primary cosmic rays. This study analyses the temporal characteristics of secondary particles detected by the KM2A detectors of the Large High Altitude Air Shower Observatory (LHAASO). We propose a novel parameterized function to describe the temporal profiles of secondary electromagnetic and muon components, significantly improving the modeling accuracy of the shape and thickness of the shower disk. These findings provide a crucial tool for enhancing the accuracy of angular reconstruction algorithms, testing the predictions of high-energy hadronic interaction models, and improving the primary mass composition discrimination capabilities of the ground-based cosmic ray experiments.

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1. Introduction

When high energy cosmic rays arriving at earth, they interact with the atmosphere and generate cascades of secondary particles known as extensive air showers (EAS). The swarm of secondary particles traveling at nearly the speed of light, form a curved thin disk. The spatio-temporal structure of its front is a particularly powerful probe of shower development. The curvature of this front, the lateral density of particles, and the distribution of their arrival times are all sensitive to the primary mass and the underlying physics of high-energy hadronic interactions[1].

Early experiments established the fundamental concept of a shower disk with a finite thickness. Over the decades, increasingly sophisticated ground-based arrays have performed detailed measurements of this structure. The KASCADE-Grande experiment, for instance, provided comprehensive data on the arrival times of both electrons and muons, demonstrating that muons arrive systematically earlier and that the time spread for both components increases with distance from the shower core[2]. At higher energies, the Pierre Auger Observatory has effectively used observables derived from the temporal structure of detector signals, such as the signal risetime ($t_{1/2}$), as a proxy for X_{max} to perform mass composition studies[3].

Phenomenological models used to describe the arrival time distributions have also evolved. While simple geometric models of a plane or curved front were sufficient initially, the need to describe the spread of arrival times led to the adoption of statistical functions. The Gamma probability density function (Γ-p.d.f.) has been a popular choice[4, 5]. However, this function is known to be inadequate for describing the full distribution, particularly the long tail of very late-arriving particles that result from processes like extensive multiple scattering or the decay of high-altitude pions. An accurate characterization of this tail is crucial, as it contains valuable information about the shower's development and composition.

The Large High Altitude Air Shower Observatory (LHAASO) is uniquely positioned to advance these studies[6]. Located at an altitude of 4410 m (a.s.l.), corresponding to a vertical atmospheric depth of approximately 600 g/cm^2, LHAASO is situated near the average depth of shower maximum for cosmic rays in the knee region. This vantage point allows for the detection of showers with significantly less atmospheric attenuation, providing a clearer view of the cascade development. The Kilometer-Square Array (KM2A), a key component of LHAASO, combines a dense array of Electromagnetic Particle Detectors (EDs) with an unprecedentedly large array of Muon Detectors (MDs), covering a total area of over 40,000 m^2. This hybrid design enables simultaneous, high-precision measurements of both the electromagnetic and muonic components of the shower front with high statistics.

2. Methods

2.1 Event Selection and Quality Cuts

The dataset used in this study was collected by the full LHAASO-KM2A array during the period from September 2021 to August 2022. This corresponds to a total effective observation time of approximately 8600 hours, during which 7.4×10^{10} shower events were recorded.

The temporal structure of the shower disk is known to depend on several factors, including the primary particle's energy and mass, zenith angle, and the observation altitude. To minimize

Table 1: Event Selection Criteria

Variable	Description	Cut
θ	Zenith angle of primary	<18°
R_{core}	Distance from reconstructed core to array center	320 m - 420 m
N_e	Number of EM particles	>80
N_μ	Number of muons	>15
N_{trigE}	Number of triggered EDs	>50

confounding variables and ensure a sample of high-quality, well-reconstructed events, a series of stringent selection criteria were applied to both the experimental and simulated data. The primary goals of these cuts are to: (1) select near-vertical showers to reduce the effects of atmospheric attenuation and asymmetries in shower development; (2) ensure the shower core is located within a well-instrumented fiducial region of the array to guarantee high-quality reconstruction of the core position and arrival direction; and (3) select events well above the energy threshold of the array where the trigger efficiency is saturated and the shower is well-sampled by a large number of detectors. The specific cuts used in this analysis are summarized in Table 1. After applying these criteria, a total of 1.2×10^8 events were selected for the final analysis.

2.2 Definition of Particle Arrival Delay

Figure 1 shows the structure of an EAS shower front. A precise measurement of the particle arrival time distribution requires a robust and unbiased definition of the reference time, or $t = 0$, for each shower. The time delay measured between detectors can be attributed to three main contributions: 1) the geometrical delay (T_t), which is a function of the shower axis direction; 2) a correction arising from the curvature of the shower front (T_d); and 3) variations arising from the shower front thickness and particle density. (τ). In general practice, the arrival time of the first detected particle (typically near the core) serves as a reference. This approach is susceptible to sampling fluctuations, which introduce a bias that depends on the local particle density and thus on the core distance.

To circumvent this issue, we firstly employ a standard direction reconstruction described in Ref. [7]. The reconstruction parameters include $l = \sin\theta\cos\phi$, $m = \sin\theta\sin\phi$, $n = \cos\theta$, and T_0. Here, θ, ϕ are the zenith angle and azimuth angle respectively, and T_0 is the time the shower core passes through the origin of the coordinate system. The expected arrival time of a particle in the reference plane is

$$T_t = \frac{1}{c}\mathbf{r}_i \cdot (l, m, n) + T_0, \tag{1}$$

where $\mathbf{r}_i = (x_i, y_i, z_i)$ is the coordinates of each detector. The arrival delay, T_d, for each individual particle hit (in both EDs and MDs) is then calculated as the difference between its calibrated measured time, $T_{measured}$, and the expected arrival time of the fitted front at that detector's location:

$$T_d = T_{measured} - T_t. \tag{2}$$

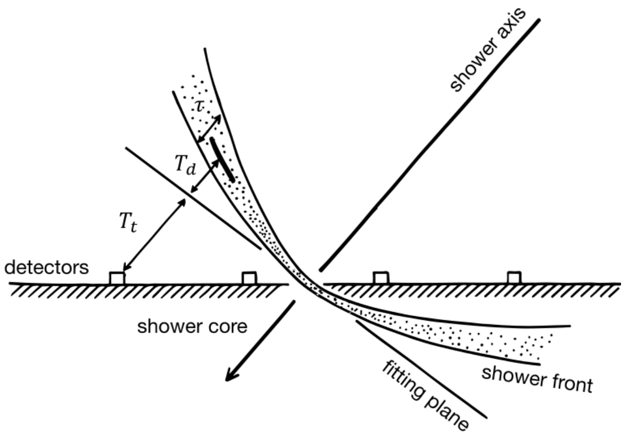

Figure 1: The structure of EAS shower front

The analysis is performed separately for the electromagnetic (EM) and muonic components. The EM component consists of all valid hits in the EDs. The muonic component consists of all valid hits in the MDs.

3. Results

The analysis of the selected data provides a detailed picture of the temporal structure of the shower front. The distributions of measured arrival delays, T_d, are constructed for both the EM and muonic components in several bins of core distance R. Figure 2 shows a distribution of EM particle delay at a core distance 95-105 m. Within a shower event, only the first pulse measured by an ED or MD are taken into consideration. To better estimate the geometry of the shower front, the delay time is multiplied by the speed of light to represent it as a spatial distance. This conversion is also applied to the other figures in this paper. It can be seen that this distribution shows a 'fast rising, slow falling' feature. When fitting this distribution with traditional $\Gamma-$function, it can adequately describe the rising part of the distribution, but poorly fits the peak and falling parts, especially failing to describe the "long tail" structure exhibited in the distribution. To address this, we propose a new function form-the inverse gamma function, which is the reciprocal of a generalized gamma-distributed random variable.

$$f(x) = \frac{A}{\Gamma(\alpha)}\beta^{\alpha} \exp\left(-\frac{\beta}{x-d}\right)(x-d)^{(-\alpha+1)} \tag{3}$$

The inverse Gamma function contains two effective parameters α and β, which determine the shape and scale of the distribution. We add a constant parameter d in the fitting to adjust the shift of the zero time point.

As can be seen from the Figure 2, the inverse gamma function well match the shape of the time difference distribution over the entire range. Within a distance ranging from several tenth to 800 meters to the shower core, this functional form can effectively describe the distribution of time residuals (Figure 3). For even closer distances, since the significantly higher particle density, the

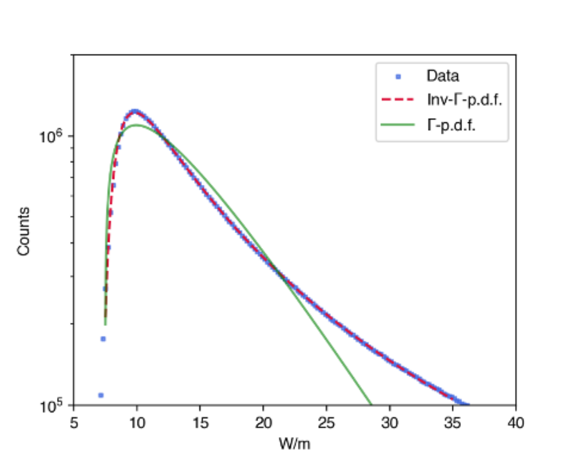

Figure 2: The shape of delay time distribution and fitting results

actual distribution deviates from the expectation and require additional treatment. In addition, this functional form can not only describe the time distribution of electromagnetic particles, but also be well applied to muons. For the muon component, attention should be paid to the impact of the "punch through" effect in region of $D < 40$ m.

The most probable value (MPV) for a inverse-gamma distribution (Eq. 3) is $\frac{\beta}{1+\alpha} + d$. Figure 4(a) shows the variation of the MPV of the time delay distributions of EM and muon components with respect to the core distance, which directly reflect the shape of the shower front. It can be observed that within approximately 150 meters, the EM particles and muons have almost the same slope, but as the distance increases, the two components gradually separate. On average, EM particles in the shower arrive at the detector later than muons, meaning that the leading front formed by the EM component has a greater curvature compared to the muon component. This conclusion is consistent with some previous studies[2, 8]. We also found that for either of the component, the curvature increases as the primary energy goes higher (shown in Figure 4(b) for EM component).

4. Discussion

The large coverage area and high temporal resolution of the LHAASO detectors enable this more precise study of the spatiotemporal distribution of EAS particles. Although the inverse-gamma function has been found to effectively describe the temporal distribution of these particles, this description remains empirical and lacks an adequate physical interpretation. In future work, we will attempt to characterize the shape of the shower front using a specific functional form. This will facilitate further investigation into how the shape parameters vary with energy, zenith angle, and particle type. Furthermore, a comparison with results from similar analysis on simulation data will provide valuable insights for evaluating the different hadronic interaction models (EPOS, QGSJET-II, SIBYLL, etc.) used in these simulation codes.

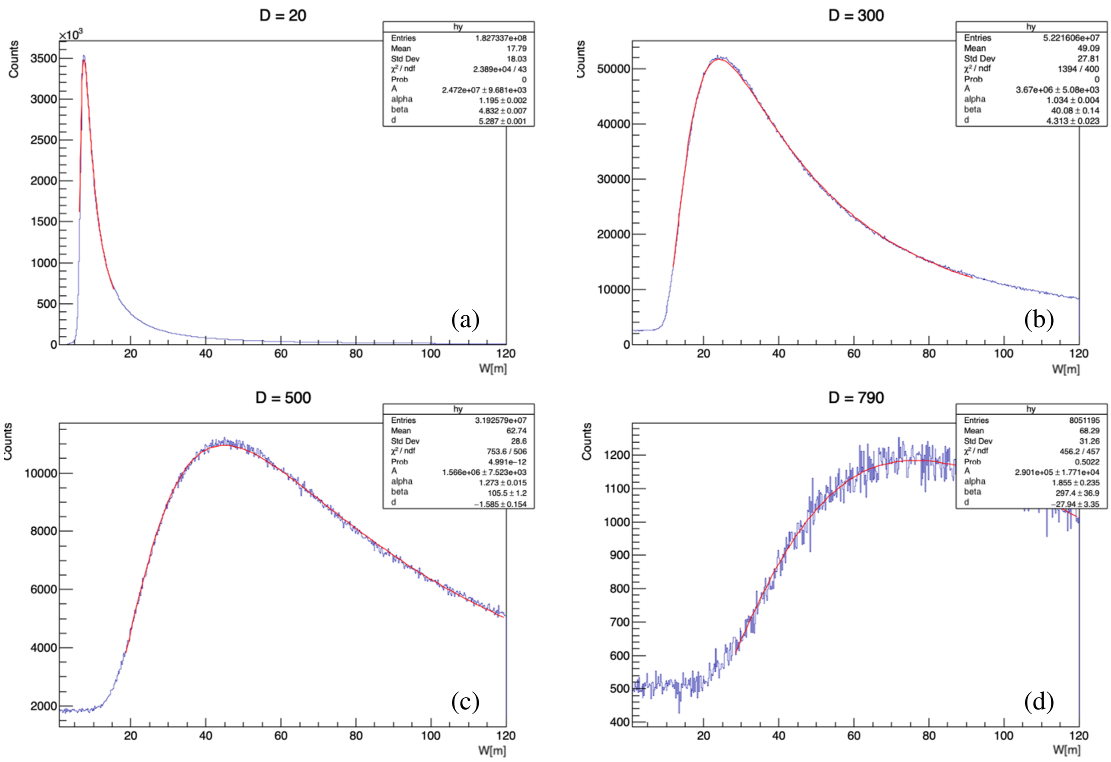

Figure 3: Delay time distributions and fitting results at difference distances to the core (a) 20 m, (b) 300 m, (c) 500 m, (d) 790 m

5. Summary

In this proceeding, we present a high-statistics analysis of the arrival time distributions of EAS particles measured by LHAASO-KM2A. We leverage the high quality of the experimental data to critically evaluate the performance of the standard Gamma distribution model. We then propose and validate a new function that provides a superior description of the observed temporal profiles, including the late-time tail. Using this new parameterization, we precisely characterize the mean delay and thickness of the electromagnetic and muonic shower disks as a function of core distance. These results provide knowledge that can be integrated into reconstruction algorithms to enhance the pointing accuracy and core resolution of the array. Besides, the newly introduced parameters characterize the shape and thickness of the shower front, might complement traditional methods and improving the separation power between different primary nuclei, or between the gamma-ray-induced showers from the hadronic background.

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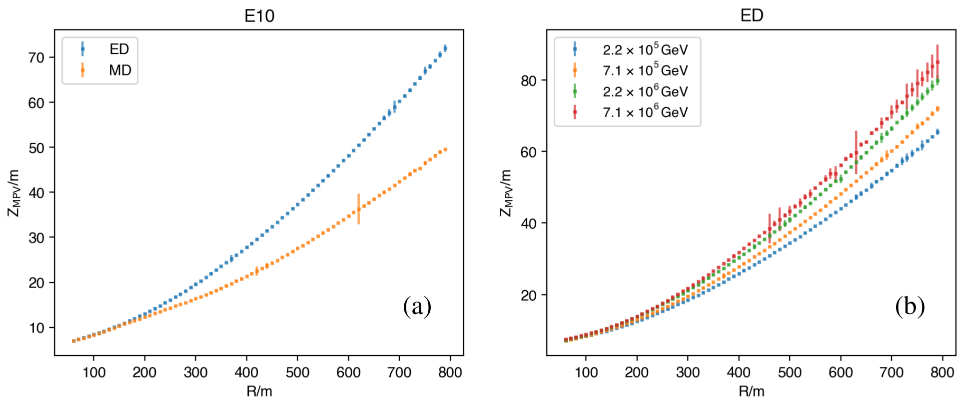

Figure 4: Shower front profiles of (a) EM particles and muons, (b) EM particles from different primary energies.

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