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

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Abstract

The arrival time distribution of extensive air shower (EAS) particles is a key observable for understanding shower development and primary cosmic ray properties. Using high-statistics data from LHAASO-KM2A, we analyze the temporal profiles of secondary particles. We find that the traditional Gamma function inadequately models the observed distributions. We propose a novel parameterized function based on the inverse-gamma distribution that accurately describes the shower front's shape and thickness for both electromagnetic and muonic components. This provides a powerful tool for improving angular reconstruction, testing hadronic interaction models, and enhancing mass composition studies.

1. Introduction

- **Physics Backgroud:** A better description of the spatio-temporal structure of an EAS front (curvature, thickness) provides valuable hits to the discriminate the primary particle's mass and constrain high-energy hadronic interaction physics[1–3].
- **LHAASO's Advantage:** Located at 4410 m a.s.l., LHAASO-KM2A observes showers near their maximum development, with large-area, high-precision electromagnetic (ED) and muon (MD) detectors[4].
- **The Problem:** Widely-used models, like the Gamma p.d.f., fail to accurately describe the full arrival time distribution, especially the long tail of late-arriving particles[5, 6].
- **Our Goal:** Find a better empirical function to model the arrival time profiles and use it to precisely characterize the shower front.

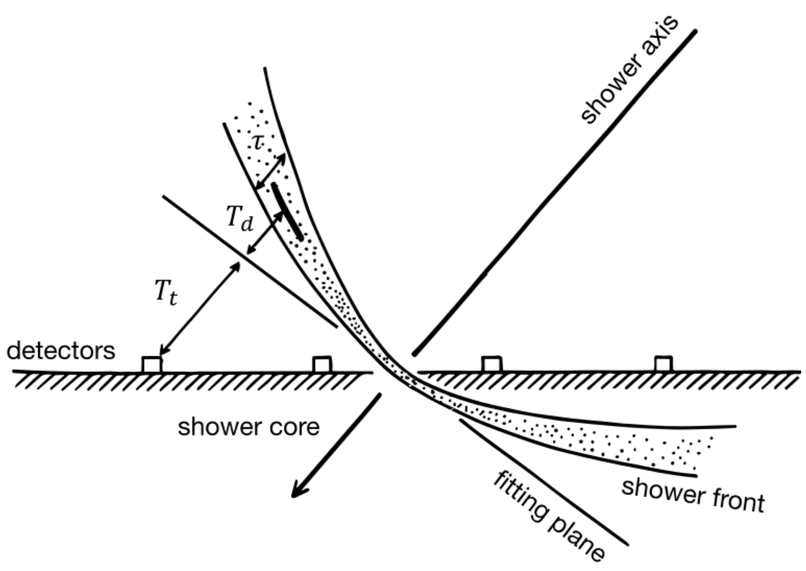

Figure 1: Illustration of an extensive air shower front, showing the geometrical delay (T_t), curvature delay (T_d), and shower thickness (τ).

2. Methodology

- **Data:** 8600 hours of LHAASO-KM2A data (Sept 2021 - Aug 2022).
- **Final Sample:** 1.2×10^8 well-reconstructed events after cuts.

Table 1: Main 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

The arrival time delay T_d for each particle is calculated relative to a fitted planar front:

$$T_d = T_{\text{measured}} - T_t, \tag{1}$$

where T_{measured} is the calibrated hit time and T_t is the expected arrival time of the plane at the detector's location.
The standard Gamma function fails to describe the peak and long tail of the observed arrival delay distribution.
We propose a new function based on the inverse-gamma distribution, which provides an excellent fit over the entire range.

$$f(x) = \frac{A}{\Gamma(\alpha)}\beta^\alpha \exp\left(-\frac{\beta}{x-d}\right)(x-d)^{(-\alpha+1)}, \tag{2}$$

where α and β are parameters determine the shape and scale of the distribution, along with d the shift of the zero time reference point.

3. Results

The Inverse-Gamma function successfully models the time profiles for both EM and muon components across a wide range of core distances (up to 800 m).

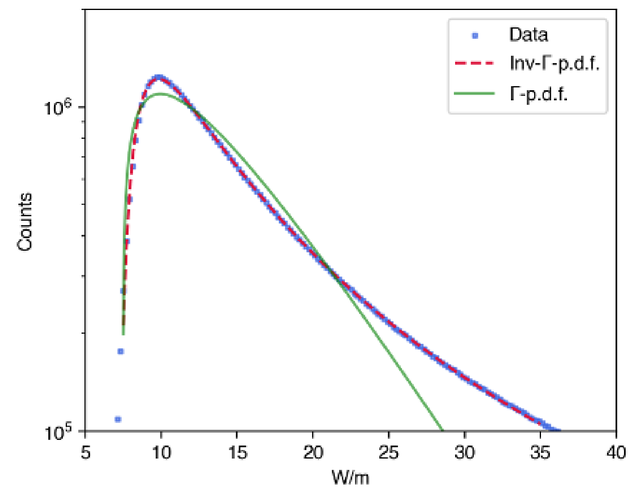

Figure 2: The observed arrival delay distribution (black points) with fittings by standard Gamma function (dashed red) and Inverse-Gamma function (solid blue).

Using the most probable value (MPV) from the fits, we can map the shower front curvature.

- Muons (detected by MDs) arrive systematically earlier than EM particles (detected by EDs), indicating a flatter front.
- The curvature of the EM front increases with primary energy.

These findings consist with previous studies described in Refs. [2, 7].

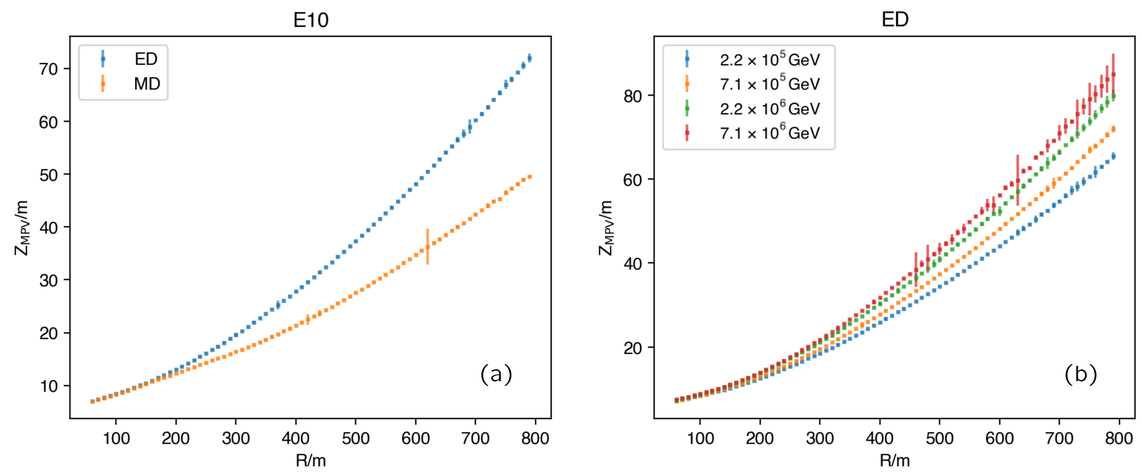

Figure 3: Shower front profiles (delay vs. core distance) for: (a) EM vs. Muon components, and (b) EM component at different primary energies.

4. Summary & Outlook

- We have performed a high-statistics analysis of EAS particle arrival times with LHAASO-KM2A.
- A new **Inverse-Gamma function** is proposed, which provides a superior description of the temporal profiles compared to standard models.
- This new parameterization precisely characterizes the shower front **shape (curvature) and thickness** for both EM and muon components.
- **Impact & Future Work:**
  - The model can be integrated into reconstruction algorithms to **improve pointing accuracy** (see poster #449).
  - The shape parameters provide new observables for **primary mass discrimination**.
  - Comparison with simulations will allow for stringent **tests of hadronic interaction models**.

References

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