

A Study of the Shower Front in Inclined Showers at the Pierre Auger Observatory

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Abstract. Using a sub-sample of high quality events at zenith angles above 60 degrees the delays in the start-time of the signals detected with water-Cherenkov detectors of the Pierre Auger Observatory with respect to a plane front are compared to those from a model for the arrival time distribution of muons. Good agreement is found and the model correctly accounts for the start-time dependence on the number of particles on each water-Cherenkov detector and on the asymmetries of the shower front. The arrival direction of inclined showers reconstructed by using this model are in good agreement with those obtained with the standard Auger reconstruction.

Keywords: shower front, muons, inclined showers

I. INTRODUCTION

The southern site of the Pierre Auger Observatory [1] uses 1600 water-Cherenkov detectors, each with an area of 10 m², and spread over 3000 km² to collect the secondary particles of extensive air showers. The Cherenkov light is detected by three photomultipliers (PMTs) and the signal is digitalized and recorded as a function of time in 25 ns bins by means of Flash Analog Digital Converters (FADC) whereas conventional GPS receivers are used to synchronize the detectors across the array. The total signal in each detector is measured in Vertical Equivalent Muons (VEM). The time distributions of the signal contain valuable information concerning the arrival direction of the cosmic ray, the longitudinal evolution of the shower and the composition of the primary.

The shower front, defined as the surface containing the first particles to arrive at ground, is estimated by using the onset of the signal in the surface-detector stations, the so called start-time. By fitting a model of the shower front to the experimental start-time, the arrival direction of the air shower can be obtained. The precision achieved in the arrival direction depends on the precision of the detectors clock, the uncertainty in the GPS synchronization, and on the fluctuations in the arrival time of the first detected particles. The standard angular reconstruction uses a model [2] to obtain the start-time variance which is parametrized as a function of the width of the FADC trace and total signal at each triggered station.

A model published elsewhere [3] and updated in [4] describes the arrival time distribution of muons in

extensive air showers. Applications of this model span from fast Monte-Carlo simulations used on the Hybrid reconstruction [5] to the reconstruction of longitudinal development of muons based on the surface-detector data only [6]. In this article we use this model to estimate a shower front and compare it to the measured shower front for showers with zenith angles above 60 degrees, which are dominated by muons.

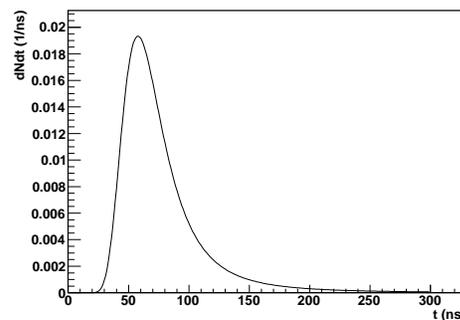


Fig. 1. Example of the probability distribution of the muon arrival times for showers of 70 degrees, at 1000 m from the core.

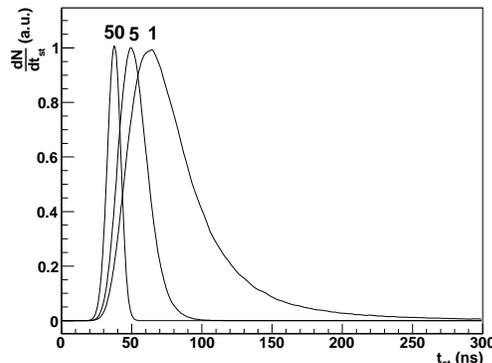


Fig. 2. Example of probability distribution of the start-time for showers of 70 degrees and observed at 1000 m from the core and for $n=1$, $n=5$, $n=50$ muons as labeled.

The model assumes that muons are produced in a narrow cylinder of a few tens of meters around the shower axis. Muons travel practically in straight lines from the production site to the observation point. The effect of multiple scattering and bremsstrahlung on their

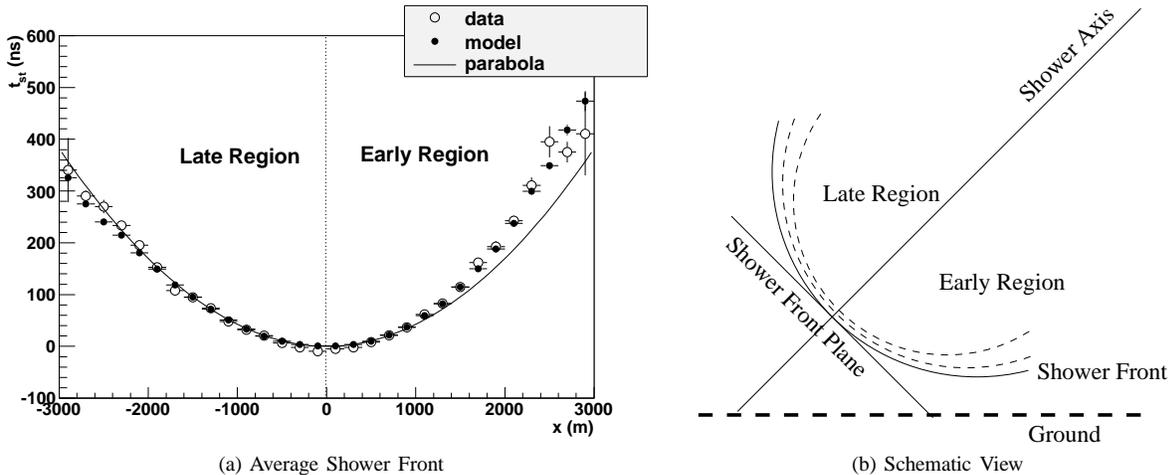


Fig. 3. (a) Average start-times for showers at 70 degrees for data (open circles) and model (solid circles). Also shown a parabola. (b) Schematic view of the geometry of the shower pancake. The shower front is just the surface containing the first particles arriving to ground. Also labeled the early and late regions.

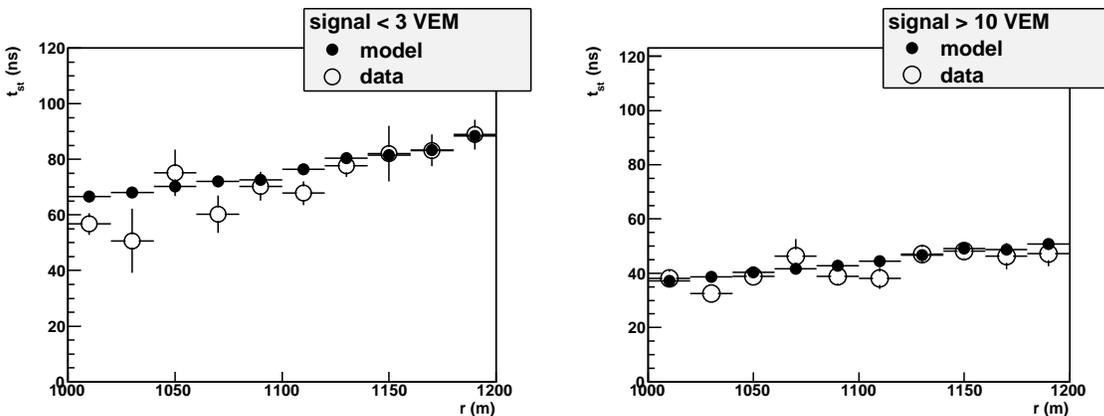


Fig. 4. Comparison of average start-times for showers at 70 degrees at a given range of distances to the shower core in two very different conditions of signal at the station, namely less than 3 VEM (left panel), and more than 10 VEM (right panel).

time delay is negligible compared to other effects. From pure geometry, the time delay with respect to a plane front can be easily calculated. This *geometrical delay* establishes a one-to-one correspondence between the production distance z , measured along the shower axis from the ground up to the production site, and the arrival time delay t , which is the time elapsed from the arrival time of the shower front plane and the arrival time of the particle. This one-to-one correspondence is different for each relative position with respect to the shower axis. If the muons are produced at distances z with a distribution $\frac{dN}{dz}$, the corresponding arrival time distribution is simply¹ $\frac{dN}{dt} = \frac{dN}{dz} \frac{dz}{dt}$. The distribution $\frac{dN}{dz}$ depends on

¹There is an additional source of delay coming from the fact that muons have finite energies and they do not travel at the speed of light. This is the so called *kinematic delay* and it is accounted for by modeling the energy spectrum of muons at the observation point. At large distances from the core the *geometrical delay* dominates, and the *kinematic delay* is just a small correction. Besides, the effects the geomagnetic field are negligible, and only for showers with $\theta > 85$ deg the arrival time distributions start to show some visible effect due to the extra path of the bent muon trajectories.

composition, zenith angle, energy of the primary and it is affected by shower-to-shower fluctuations. The model for this article uses a parametrization of the average $\frac{dN}{dz}$ of 10^{19} eV proton showers simulated with AIRES 2.6.0 [7] QGSJET01 [8].

The description provided by this model has been verified with detailed Monte Carlo simulations [3][4]. Figure 1 displays an example of the muon arrival time distribution predicted by this model, $\frac{dN}{dt}$, for showers of 70 degrees at 1000 m from the core.

II. THE START-TIME

The expected start-time is calculated from the model at each station in the following way:

- First, the signal produced solely by muons is estimated by taking the VEM content at the detector and subtracting a parametrized EM component [9]. Muons arrive earlier than the electromagnetic component, which is affected by multiple scattering, and is of the order of 15%-20% of the total signal in inclined showers.

- The number of muons n is calculated dividing the remaining signal by the average signal produced by muons, which is proportional² to the average tracklength of the muon in the detector: $n \simeq S \frac{h}{L_\alpha}$, where S is the VEM content of the station, h is the height of water in the the detector, and L_α is the average tracklength at a given incident angle to the station α , which can be approximated by the zenith angle of the shower, becoming $\alpha = \theta$.
- Once the $\frac{dN}{dt}$ distribution is calculated for a given zenith angle and the relative position of the station respect to the core, (see Figure 1 for an example of $\theta = 70$ deg and $r = 1000$ m), it is sampled n times simulating the physical realisation of n muons arriving at ground. The first or earliest muon out of n is kept, and its time t_{st} becomes a possible start-time realisation. Figure 2 displays the distribution of the start-times, $\frac{dN}{dt_{st}}$, for $n=1$, $n=5$, and $n=50$ muons.

Note that we cannot predict t_{st} in each single realisation of real data, but only its distribution. The average $\langle t_{st} \rangle$ becomes the expected start-time predicted by the model, and the RMS of this distribution, σ_{st} , corresponds to the expected typical fluctuation or uncertainty of any t_{st} . The value of σ_{st} can be extremely small because the arrival time distribution of particles can be very narrow when the station is near the core, or when the number of muons n is large. To account for the finite resolution of the detection device in the final start-time uncertainty, a constant term b has been introduced. The total uncertainty therefore becomes

$$\sigma_{det} = \sqrt{\sigma_{st}^2 + b^2} \quad (1)$$

Pairs of adjacent stations separated by 11 m were used to adjust the value of b and make σ_{det} equal to the average start-time fluctuations of data. The value that best meets this requirement for a broad range of signal at each station and distance to the core is $b = 20$ ns. The GPS time resolution [10] (~ 10 ns) and the procedure of signal digitization in the 25 ns bins accounts for 12 ns, which is not enough to explain the value of b . A possible explanation is that b absorbs a mismatch of the model with respect to data. The model for the start-times uncertainties described in [2] which is used in the standard reconstruction, finds a value for b in better agreement to the expectations by not attempting to describe the details of the shower front itself and using an estimation of the overall length of the arrival time distribution of the particles from the data recorded in each station.

III. VALIDATION

Data collected from January 2004 through December 2008 were reconstructed using the horizontal reconstruc-

²A more sophisticated approach that takes into account the distribution of signal S for each number of muons n is currently under study. Note that S is affected by the muon energy spectrum and the distribution of tracklengths L_α .

tion chain [11], and events satisfying the T5 quality trigger were selected [12]. The described time model needs the incoming direction of the shower and also the core position, which are obtained from an iterative angular-core reconstruction [12].

Figure 3a displays the average of the predicted and observed start-times for a subset of showers of 70 degrees as a function of the perpendicular distance to the shower core. The overall curvature features are well described by the model, although data tend to show slightly more curvature than the model. A parabola is shown, to illustrate the asymmetries on the arrival times between the early and late region, which are depicted in Figure 3b. This asymmetry is naturally accounted for by the model through the different distances to the production site along the shower axis.

Figure 4 displays a comparison of the average start-times at a given range of distances to the shower core in two very different conditions of signal at the station, namely less than 3 VEM (left panel), and more than 10 VEM (right panel). One can see that the effect on the start-time produced by the different sampling of the number of muons is to bring the start-time to earlier times when n is larger.

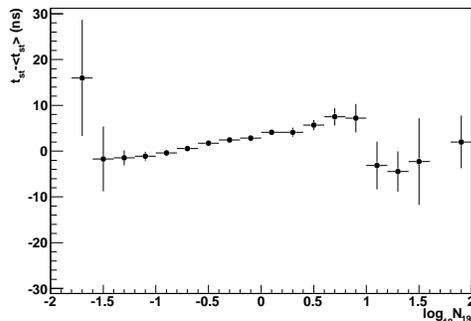


Fig. 5. Average value of the difference between t_{st} (data) and $\langle t_{st} \rangle$ (model) as a function of the shower size parameter N_{19} .

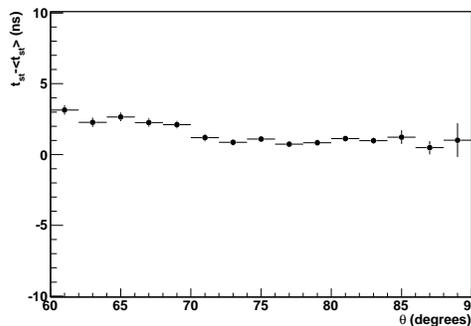


Fig. 6. Average value of the difference between t_{st} (data) and $\langle t_{st} \rangle$ (model) as a function of the zenith angle θ .

Figure 5 and 6 display the average value of $t_{st} - \langle t_{st} \rangle$ as a function of the zenith angle and of

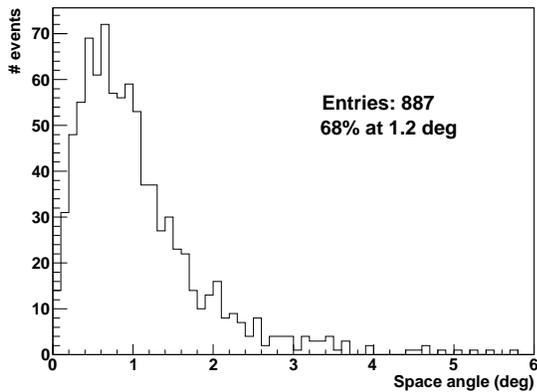


Fig. 7. Comparison of the angular reconstruction using the present model to the Hybrid Auger reconstruction.

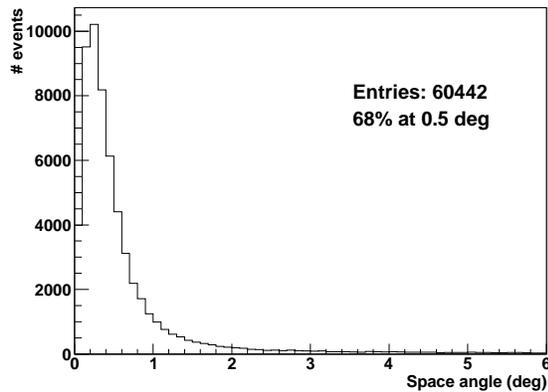


Fig. 8. Comparison of the angular reconstruction using the present model to the one currently used in the Auger reconstruction chain.

the shower size parameter N_{19} , which is approximately proportional to the energy of the primary and it is used in the inclined showers reconstruction [11]. The average typical differences between the start-time given by the model and data are below 10 ns within this range of N_{19} and zenith angles.

It is expected that further refinements of the model, like a parametrization of the average $\frac{dN}{dz}$ distribution from real data [6], or accounting for the shower to shower fluctuations may further improve the results.

An independent indication that the model is describing the data reasonably well comes from a comparison of the angular reconstruction that uses the current prediction shower front to that coming from the hybrid reconstruction, which is shown in Figure 7. 68% of events have a space angle difference less than 1.2 degrees, which result in an angular resolution of ~ 1 degrees. (The hybrid resolution is ~ 0.6 degrees). Figure 8 displays the comparison between the angular reconstruction that uses the current model with the standard Auger reconstruction: 68% of the events have a space angle difference less than 0.5 degrees, which is compatible with the angular resolution of Auger [13].

IV. CONCLUSIONS

A model for the arrival time distribution of muons has been used to predict the shower front. This model uses as input a parametrization of the muon production distance distribution $\frac{dN}{dz}$. The model accounts for the different curvatures due to the early-late asymmetries of the shower front, and the number of particles detected at the station. The results from the model have been compared to data coming from real events above 60 degrees showing good agreement. When the predicted shower front is used to reconstruct the arrival directions, results are consistent with those coming from the standard reconstruction and hybrid reconstruction. Future improvements of the model include the use of $\frac{dN}{dz}$ distributions deduced from data.

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