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Lowering the ARGO-YBJ Energy Threshold to a Few Tens of GeV by Using the Double Front Shower Events

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Abstract.ARGO-YBJ, located at the YangBaJing Cosmic Ray Observatory (4300m a.s.l., Tibet, China), is a full coverage air shower array, with an energy threshold of about 300 GeV for gamma ray astronomy. Most of the recorded events are single front showers, satisfying the trigger requirement of at least 20 particles detected in a given time window. However, in about 13% of the events, two randomly arriving showers may be recorded in the same time window, and the second one, in generally smaller, does not need to satisfy the trigger condition. These events are called double front shower events. By using these small showers, well under the trigger threshold, the detector primary energy threshold can be lowered to a few tens of GeV. In this paper, the angular resolution that can be achieved with these events is evaluated by simulations, and the capabilities of this technique in the search for GRBs are discussed. The double front shower events have some advantages in detecting GRBs at $E<30$ GeV.

Keywords: double front shower events, GRBs, sensitivity, ARGO-YBJ

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1. Introduction

Gamma-ray burst (GRB), an energetic form of energy released from cosmic unpredictable locations, is one of the most captivating astronomical phenomena since its first discovery. Though thousands of GRBs detected by satellite experiments such as Swift [1], HETE [2] and Fermi-GBM [3] concentrate in the keV-MeV energy range, EGRET [4] and Fermi-LAT [5] observed photons in the MeV-GeV range. Until May in 2015, EGRET and Fermi-LAT detected photons above 1 GeV from more than 50 GRBs, including 13 GRBs with energies above 10 GeV [6, 7]. Particularly, Fermi-LAT announced the detection of the highest photon energy (95 GeV) from GRB130427A [8]. So far the redshifts of about 400 GRBs have been observed. The maximal redshift of GRBs observed by Swift satellite is 8.1 from GRB090423 [9].

In fact, the search of high energy emission above GeV from GRBs has been done by ground-based experiments including extensive air shower arrays [10, 11] and imaging atmospheric Cherenkov telescopes [12]. No significant detection of high energy (above 10 GeV) emission from GRBs has been observed up to now, while some positive indications were reported [13]. Now, some ground-based experiments attempt to improve the sensitivity in detecting GRBs by reducing the energy threshold. In this paper, we use double front shower events to lower the energy threshold of ARGO-YBJ.

The paper is organized as follows: The ARGO-YBJ experiment and double front shower events are introduced in Section 2. The angular resolution of double front shower events is shown in Section 3. The sensitivity for GRBs is presented in Section 4. Discussion and conclusion are given in Section 5.

2. Double Front Shower Events in the ARGO-YBJ Experiment

The ARGO-YBJ detector is connected to two independent data acquisition systems, corresponding to two operation modes [14]. One is the scaler mode which counts the single particle rate. The other is the shower mode that ARGO-YBJ detector is triggered when at least 20 pads in the entire carpet detector are registered within 420 ns. For each triggered event (SF Event) [15], all the hits registered within a time window of 2134 ns are recorded. During this time, another randomly arriving shower, with a possibility of about 13% (from ARGO-YBJ data), may be recorded. These coincident events are called double front shower events (DF Events) in this paper. Fig.1(a) and (b) show the TDC time distribution of a normal triggered event and a double front shower event. A large TDC value means early registered hit. The TDC times of a triggered event are distributed from 1150 ns to 1450 ns. The double front shower event, recorded in other times within the 2134 ns, is normally the smaller shower event. The double front shower event is selected with following steps: According to the TDC time, find the triggered event which arrives firstly and satisfies the trigger requirement of at least 20 particles. Beyond about 200 ns from the triggered event, the event whose multiplicity is more than 5 within 100 ns is considered as a double front shower event.

Fig.2 shows the pad-multiplicity (N_{pad}) distribution of triggered events and double front shower events. Since there is no need for the smaller shower to satisfy the trigger requirement, the energy threshold can be lowered by using double front shower events.

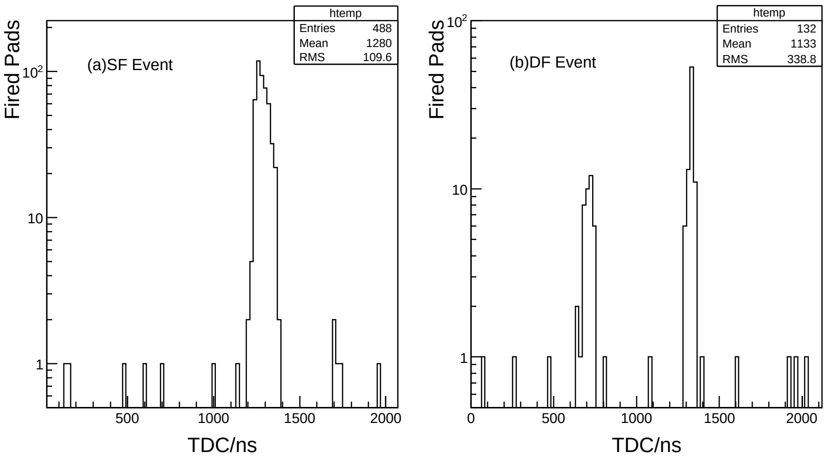

Fig. 1: TDC time distribution of secondary particles in ARGO-YBJ arrays for a normal triggered event (a) and a double front shower event (b)

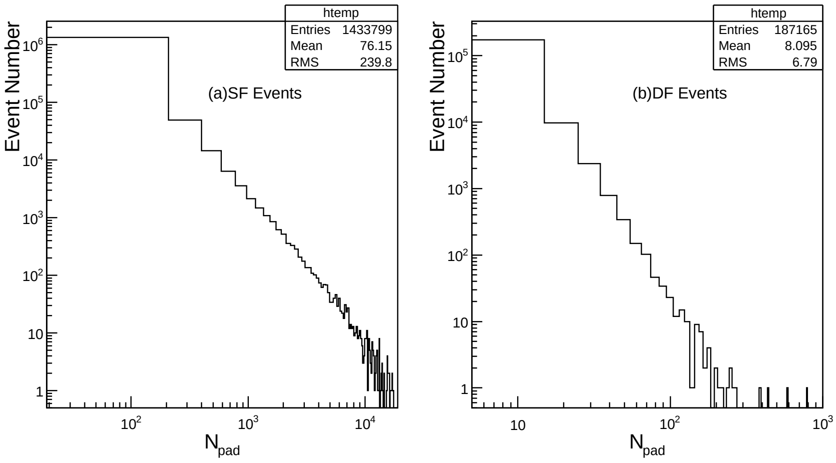

Fig. 2: N_{pad} distribution for triggered events (a) and double front shower events (b)

3. Simulation of Double Front Shower Events and the Angular Resolution

In this work, CORSIKA7.3700 is used to simulate the evolution and properties of extensive air showers in the atmosphere. Because double front shower events can not be simulated by using the normal G4argo, the data which is generated by CORSIKA should be mixed according to the following principles:

(1)The average number of events (λ) within 2134 ns is estimated through the fluence of cosmic ray.

(2)The event number is subject to Poisson distribution based on the parameter λ, and the time interval between two events is sampled on the basis of the exponential distribution.

(3)Rank the time of secondary particles produced by CORSIKA in accordance with the mid arriving time of intensive events.

(4)Put another photon at random into the time window (2134 ns) in the simulation of photons.

Next, mixed data is input to the G4argo which is based on GEANT4 and used to simulate the response of the ARGO-YBJ detector. Here, the form of input and output in the normal G4argo is modified to be available for double front shower events. Lastly, double front shower events are selected using the procedure presented in the last section, and then reconstructed using the least square method with conical fit [16]. The sampling area is 200 m×200 m around the carpet center.

Ψ_{72} (the angular resolution) is the angular aperture with respect to the simulated shower direction containing 72% of the reconstructed tracks. The zenith angle is chosen from 0° to 60°, the angular resolution of double front shower events as a function of pad-multiplicity for photons and protons is compared in Fig.3. It is obvious that the value of the angular resolution for photon-induced shower is slightly better than that for proton-induced shower. The angular resolution of double front shower events is not so good, one reason of which is that some hits in triggered events are blended in double front shower events.

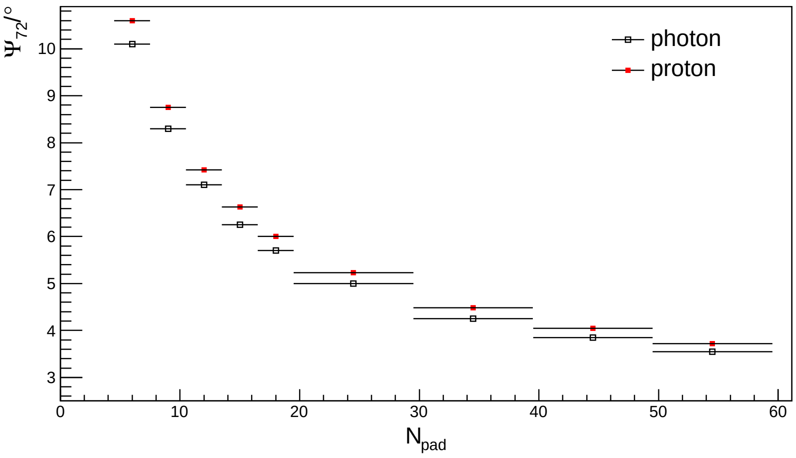

Fig. 3: The angular resolution of double front shower events as a function of pad-multiplicity for photons and protons (The horizontal bars refer to the width of the pad-multiplicity bins.)

4. ARGO-YBJ Sensitivity to Detect GRBs

4.1 Effective Area of ARGO-YBJ Apparatus in Observing GRBs

The ARGO-YBJ sensitivity in detecting a GRB is determined by the effective area and the angular resolution. The effective area, A_{eff}, is calculated by means of Monte Carlo simulation which is identical to the simulation of the angular resolution. A_{eff} depends on the gamma-ray energy E and the zenith angle θ. We calculate A_{eff} at $E = 10^1, 10^{1.2}, 10^{1.4}, 10^{1.6}, 10^{1.8}$ and 10^2 GeV, for $\theta = 0°, 10°, 20°$and 30°. By definition, A_{eff} can be calculated as:

$$A_{eff}(E,\theta) = \frac{n_s}{N} \cdot A_s \cdot \cos\theta \tag{4.1}$$

Here, n_s is the number of successfully reconstructed double front shower events, N is the total number of events which are generated by CORSIKA, A_s is the sampling area (200 m×200 m). Fig.4 is the primary result about A_{eff} of photons for SF events ($\theta = 10°$) and DF events at different zenith angles as a function of the primary energy. The SF points have been simulated with the trigger requirement and are plotted just for comparison with DF points. The effective area enlarges with the decrease of the zenith angle. We find that the effective area for DF events is about 0.024 m^2 with the primary energy of 10 GeV at $\theta = 10°$, and that for SF events is about 0.008 m^2.

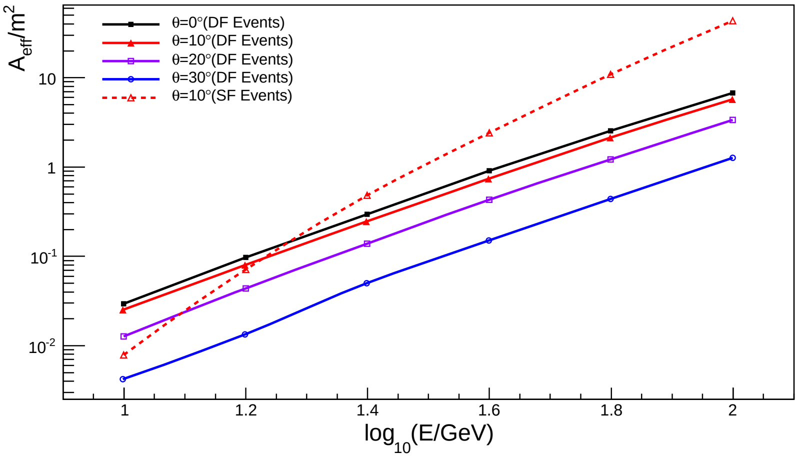

Fig. 4: The A_{eff} of photons for SF events ($\theta = 10°$) and DF events at different zenith angles as a function of the primary energy (The SF points have been simulated with the trigger requirement and are plotted just for comparison with DF points.)

4.2 Sensitivity of ARGO-YBJ to Search for GRBs

In ARGO-YBJ experiment, a GRB appears to be a shower cluster in a given small sky window and a time interval with an appropriate significance [17]. In this work 5σ is taken as the necessary significance to specify a new discovery of GRB from the background fluctuation. From above Monte Carlo simulation of double front shower events we know that, the angular resolution (Ψ_{72}) is about 7.9° for photons with $E \geq$10 GeV. In this work, the GRB search is performed in an angular window with radius 7.9°. Within the time duration of 1 second, the background events $<N_b>$ can be estimated from ARGO-YBJ data as a function of zenith angles. N_{on}, which is the number of events falling within the given sky window and a time interval, can be calculated under a 5σ observation by following Eq.(4.2) and Eq.(4.3):

A probability (P_b) of this candidate being due to a background fluctuation can be calculated as [18]:

$$P_b = \sum_{i=N_{on}+1}^{\infty} P(i) + \frac{1}{2} P(N_{on}) \tag{4.2}$$

Where $P(i)$ is the Poisson probability for the multiplicity i and a given $<N_b>$. A small value of P_b means a high possibility of GRBs. P_b can be transformed into the significance of Gauss distribution (S) as follows:

$$P_b = \int_S^{\infty} \frac{1}{\sqrt{2\pi}} \cdot e^{-\frac{1}{2}x^2} dx \tag{4.3}$$

Considering the angular resolution, the minimum signal events N_s within 1 second can be calculated as: $N_{on} = N_s \times 72\%+$<$N_b$>. <$N_b$> and N_s are shown in Fig.5 for double front shower events. After obtaining A_{eff} from Eq.(4.1), the coefficient K can be calculated by

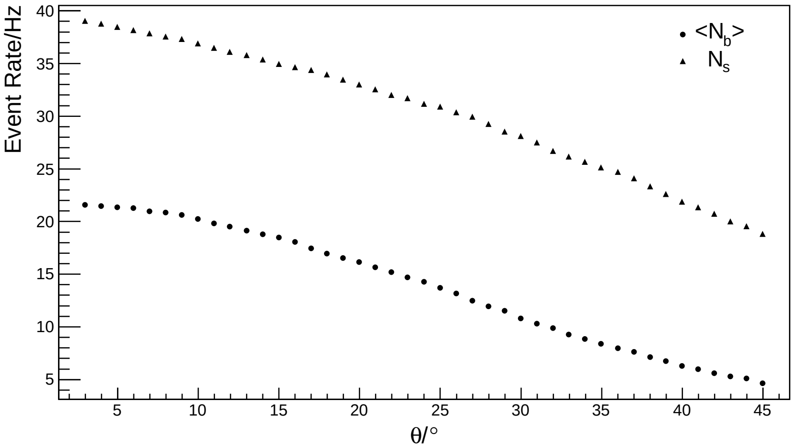

Fig. 5: The background event rate <N_b> and the minimum signal event rate N_s as a function of zenith angles for double front shower events (A GRB signal with a rate equal or higher than N_s is observed with a significance at least of 5σ.)

$$N_s(\theta,\Delta t) = K\int_{E_{min}}^{E_{max}} A_{eff}(E,\theta)\cdot E^{-\alpha}\cdot e^{-\tau(E,z)}dE \tag{4.4}$$

Where, N_s, depending on θ and the time duration Δt, is the minimum number of signals. $\tau(E,z)$ as the function of E and redshift z is the optical depth due to the EBL absorption. We use the value of $\tau(E,z)$ from Gilmore Model(2012) [19, 20]. E_{min} is 10 GeV in this paper. E_{max} is the energy cutoff. The power law index α of primary gamma is assumed to -2.0.

The sensitivity is related to the zenith angle of GRBs in the ARGO-YBJ′s field of view. $\theta = 10^\circ$ is set in the following. The fluence F (from 10 GeV to E_{max}) required for a 5σ observation can be calculated as follows:

$$F = K\int_{10GeV}^{E_{max}} E\cdot E^{-\alpha}\cdot dE \tag{4.5}$$

Here, K is from Eq.(4.4). Assuming $\alpha = -2.0$, $\theta = 10^\circ$, and $\Delta t = 0.1$s, 1s, 10s respectively, nine curves can be drawn in Fig.6, showing for double front shower events, the 5σ minimum fluence as a function of E_{max} for $z = 0, 0.5, 1$. It can be seen from Fig.6 that the ARGO-YBJ sensitivity is better in case of a high energy cutoff and short time duration. With energy increasing, the EBL effect for gamma-rays strengthens. Therefore, the decrease in the energy threshold can contribute to detect GRBs.

For triggered events, the angular window with radius 2.6° [21] is used to search for a GRB, and with the time duration of 1 second , the background events from ARGO-YBJ data are 20.1 at $\theta = 10^\circ$ and the minimum signal events useful for the GRB signal discovery are 36.7. The SF points have been simulated with the trigger requirement and are plotted just for comparison with

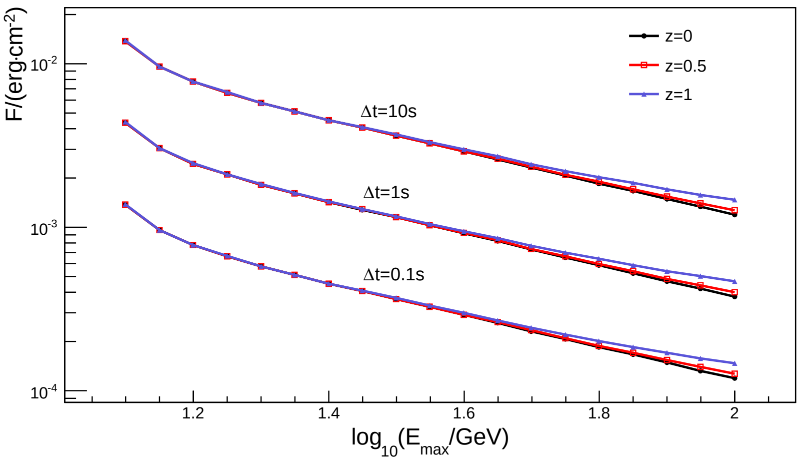

Fig. 6: The discovery fluence F as a function of E_{max} in different redshift and time duration for double front shower events

DF points. Fig.7 shows the discovery fluence F for SF events ($\theta = 10^\circ$) and DF events as a function of E_{max} for $\theta = 0^\circ, 10^\circ, 20^\circ$ and 30° at $z = 0$ and $\Delta t = 1$s.

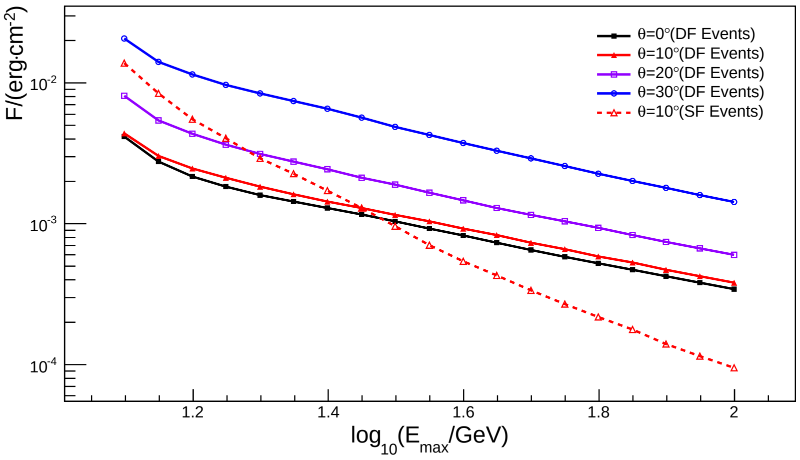

Fig. 7: The discovery fluence F for SF events ($\theta = 10^\circ$) and DF events at different zenith angles as a function of E_{max} (The SF points have been simulated with the trigger requirement and are plotted just for comparison with DF points.)

According to Fig.7, we can see that the 5σ minimum fluence of double front shower events, which characterizes the sensitivity to detect GRBs, varies from 10^{-4} erg/cm^2 to 10^{-3} erg/cm^2 with the time duration of 1s at $\theta = 10^\circ$. Compared with triggered events, the sensitivity of double front shower events is higher at E_{max}<30 GeV.

5. Discussion and Conclusions

The result from Monte Carlo simulation shows that the energy threshold of ARGO-YBJ can be decreased to a few tens of GeV by using double front shower events. The angular resolution and effective area of double front shower events are also investigated by a full Monte Carlo simulation which is driven by the program of CORSIKA and G4argo. Meanwhile, in this paper it is shown that for a GRB with a zenith angle around 10°, the power law index around -2.0, and the energy cutoff less than 100 GeV, and if the time duration lasts 1s, the required minimum signal fluence of double front shower events is about $10^{-4} - 10^{-3}$ erg/cm^2. Under the same condition, the sensitivity of triggered events to detect GRB is worse than that of double front shower events at E_{max}<30 GeV.

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