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Study on the separation of 100 TeV γ-rays from cosmic rays for the Tibet ASγ experiment *

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Abstract: A γ/hadron separation analysis is described for the observed air shower events with primary energy above 100 TeV based on the Tibet ASγ detector configuration. The shower age and size parameters are fitted from the measured lateral density distribution and used as discrimination variables. According to the MC simulation while taking into account the systematic uncertainty estimated from data and MC comparison, it is found that 70% of the cosmic ray (CR) background can be rejected while more than 78% of the γ-rays can be retained. Sensitivity for 100 TeV γ-rays observation can thus be improved by at least 40%.

Key words: origin of cosmic rays, 100 TeV γ-rays emission, Tibet ASγ experiment, NKG-function

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1 Introduction

Studies of CRs have greatly helped us understand many fundamental physics problems in particle and astrophysics in the past century. However, the fundamental questions such as “how and where do the cosmic accelerators work” [1] remain unresolved up to today. Though a few unidentified TeV γ-rays sources [2, 3] have been observed recently, shedding light on the origin problem of the galactic cosmic rays (GCRs), people tend to believe that decisive and unambiguous evidence will rely on the positive detection of 100 TeV γ-rays sources. The reason for the 100 TeV γ-rays detection being a smoking-gun of the acceleration of CRs is that the electron contribution to the 100 TeV γ-rays emission is largely suppressed due to the synchrotron cooling and KN effect of the inverse Compton scattering and the dominant contribution of 100 TeV γ-rays should come from the decay of secondary π^0-mesons produced in the interaction of very high energy CRs with ambient gas particles [4].

In order to improve the sensitivity of 100 TeV γ-rays observation, an upgrading plan is proposed by the Tibet ASγ collaboration recently to add a 10000 m^2 underground muon detector (TibetMD) to the current existing TibetIII array [5]. With the TibetMD, CR background is expected to be rejected almost completely as CR showers contain many more muon particles than those in γ-rays showers. Nevertheless, considering the Tibet ASγ experiment has accumulated a very large data sample through the past 20 years, to develop a γ/hadron separation method with the lateral distribution information using surface detectors would be very useful for the exploration of the 100 TeV γ-rays with the already existing data sample [6]. On the other hand, with the independent information, the method will be an important complement to the muon number information measured by the TibetMD in the near future.

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2 Experiment

The Tibet ASγ experiment is located at Yangbajing in Tibet, China (90.522°E, 30.102°N, 4300 m a.s.l., 606 g/cm^2). The Tibet I array was constructed in 1990 [7], with 49 scintillation counters of 0.5 m^2 each, deployed in a 7×7 matrix form with a separation of 15 m. Another 16 scintillator counters of 0.25 m^2 each surround the detector matrix to select showers whose core falls in the array. This array had been gradually expanded and densified to Tibet II in 1994 [8, 9], Tibet II-HD in 1996 [10], TibetIII in 1999 [11] and finalized to today's configuration in 2003 [12].

In the late fall of 1999, Tibet-III consisted of 533 fast timing scintillation counters (denoted as FT counters, measuring up to 15 particles) with 7.5 m spacing for inner array and 15m spacing for outer array covering an area of 36900 m^2, among which 52 were also equipped with a wide dynamic range PMT (denoted as FT-w/D counters, measuring up to 500 particles) and had a 30 m spacing. In addition, 36 density scintillation counters (D counters, measuring up to 500 particles) were allocated on the edge of the array in a 30 m spacing. After October 2000, the number of FT-w/D counters was increased to 185 and the spacing was reduced to 15 m. From December 2003 up to today, the Tibet array has 761 FT counters with 7.5 m spacing and covers 36900 m^2 in an area surrounded by 28 D counters, while 249 out of 761 FT-counters are FT-w/D and with a 15 m spacing. Each counter has a plastic scintillator plate of 0.5 m^2 in area and 3 cm in thickness. Each counter is in an inverted pyramidal shape as shown in the top panel of Fig. 1. A 0.5 cm thick lead plate is put on the top of each counter to increase the detection efficiency by converting secondary γ-rays into electron-positron pairs.

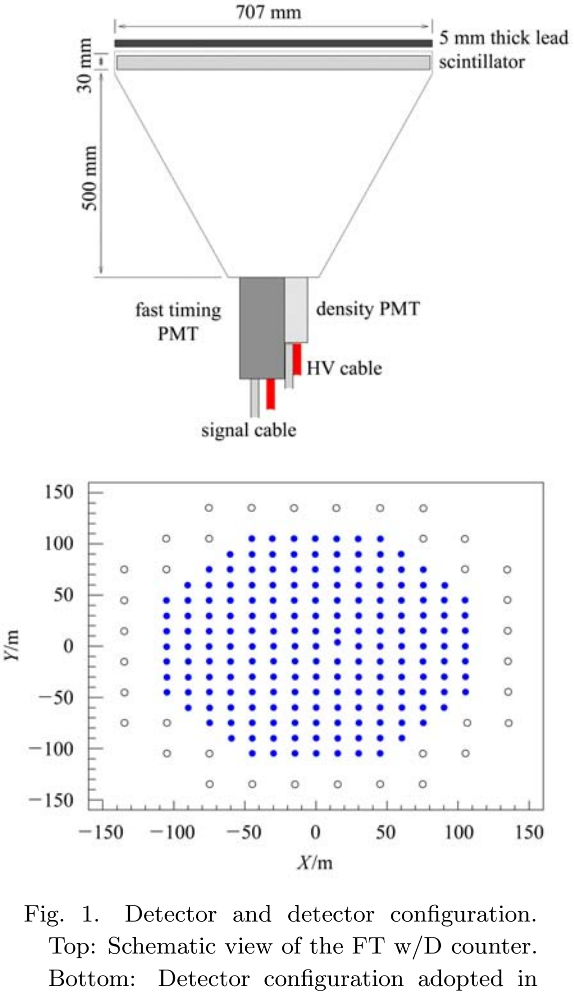

Fig. 1. Detector and detector configuration. Top: Schematic view of the FT w/D counter. Bottom: Detector configuration adopted in this work. The solid dots indicate 185 FT w/D detectors located on a 15 m grid, the circles indicate 36 D detectors located on a 30 m grid. Origin of the axis is at the center of the array.

To properly record the secondary particle density in the shower core area for primary energy above 100 TeV (between a few hundred to a few thousand particles per m^2 on average) for the purpose of shower age and size reconstruction, FT-w/D and D counters which have a wide dynamic range are used in this analysis. And for simplicity, the Tibet III configuration in 2000 (see the bottom panel of Fig. 1) is taken as an example to demonstrate the analysis method.

3 Lateral distribution reconstruction

Being an empirical formula, the NKG-function [13] serves perfectly as the solution to the cascading equation [14] for an electromagnetic shower process. The shower age parameter is sensitive to the longitudinal shower development and is determined by the lateral distribution of the shower. On the other hand, the shower size parameter is sensitive to the primary energy. With a given primary energy, a γ-ray shower on average has a younger age (smaller age parameter) than that for a CR shower, and light elements of CR have younger ages than those for heavy elements. And thus statistically, γ-ray showers and CRs showers can be separated.

Particle number density measured by the Tibet ASγ experiment is defined as the number density of "MIP" (in an area of 1 m^2) after passing through a 0.5 cm thick lead plate [12]. Though it is different from the particle number density defined in the NKG function, the two variables are positively correlated. In this work, the measured particle number densities from the FT w/D and D detector are used as an estimator for the NKG shower density (see Eq. (1) in the following) in fitting the shower parameters.

$$\mu(r) = \frac{N_{\mathrm{e}}}{2\pi r_0^2}\frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)}\left(\frac{r}{r_0}\right)^{(s-2)}\left(1+\frac{r}{r_0}\right)^{(s-4.5)}. \tag{1}$$

Here N_{e} is the shower size, s is the shower age, r_0 is the Moliere radii (130 m at Yangbajing), Γ is the gamma function. $\mu(r)$ gives the number of particles seen by a 1 m^2 counter at a distance r to the core in the plane perpendicular to the shower axis. For the i-th counter at a distance of r to the shower core in the plane perpendicular to the shower axis, the probability for it to see m_i particles can be calculated by the Poisson Eq. (2).

$$P(m_i) = \frac{\mu(r)^{m_i}}{m_i!}\mathrm{e}^{-\mu(r)} = \frac{\mu(r)^{m_i}}{\Gamma(m_i+1)}\mathrm{e}^{-\mu(r)}. \tag{2}$$

Then the likelihood function can be constructed as Eq. (3).

$$\mathrm{LF} = \prod_{i=1}^{N} P(m_i). \tag{3}$$

The corresponding log-likelihood function is as Eq. (4).

$$\mathrm{LLF} = \sum_{i=1}^{N} m_i \ln(\mu(r)) - \sum_{i=1}^{N}\mu(r) - \sum_{i=1}^{N}\ln(\Gamma(m_i+1)). \tag{4}$$

In Eqs. (3) and (4), N is the total number of detectors that are normally working and are not saturated.

Minimizing-LLF by TMinuit of ROOT package [15], size N_{e} and age s can be obtained.

4 Data quality check and the performance of γ/hadron separation

To optimize the analysis, a full Monte Carlo (MC) simulation is performed for the air shower development in the atmosphere by Corsika (version 6.204) [16] with QGSJET01c being chosen as the hadronic interaction model and for the detector response by Epics (version 8.65) [17]. All shower particles in the atmosphere are traced down to the minimized energy of 1 MeV without using a thinning method. CR events are generated with the zenith angle between 0° to 60°, and the azimuthal angle from 0° to 360°. The heavy dominant (HD) composition model [12] is adopted. The γ-ray events are generated with the zenith angle less than 60° along the Crab's orbit with a differential energy spectrum $E^{-2.62}$. Energies for both CRs and γ-rays are distributed between 50 TeV to 10 PeV. All events are thrown uniformly within 300 m distance to the center of the array and repeatedly 10 times in order to increase the data statistics. In total, about 1.4×10^6 CRs MC events are generated, while there are about 5.4×10^5 γ-rays MC events.

To test the MC performance, data collected by the Tibet ASγ experiment from October 2000 to December 2008 are used to compare with the MC distributions.

Event reconstruction is done by three steps. First, the shower core position and direction are reconstructed by the traditional method [12]. Then the lateral particle density distribution is calculated in the inclined plane perpendicular to the shower axis direction and with which the size, age and shower core position are fitted jointly. At last, the shower direction is reconstructed again with the new core position to further improve the angular resolution.

To ensure the quality of the event reconstruction and to select the event with primary energy greater than 100 TeV, the following criteria are applied for all these data sets: MC γ-rays, MC CRs and experimental data.

On air shower core location: among the three hottest counters in each event, two should be contained in the inner 22500 m^2.

On energy estimator: $\sum\rho_{\mathrm{FT}}$, which is the sum of the particle number density by all the FT-PMTs, should be larger than 400.

On Zenith angle: the zenith angle of the arrival direction should be less than 50°.

In total, 146 million experimental events can pass the selection criteria and from which the moon shadow can be clearly seen. Fig. 2 shows the moon shadow with 0.4 degree smoothing radius using analysis method in Ref. [18]. The maximum deficit point has 13.9 standard deviations and locates right at the center of the moon, demonstrating that the reconstruction data are of good quality.

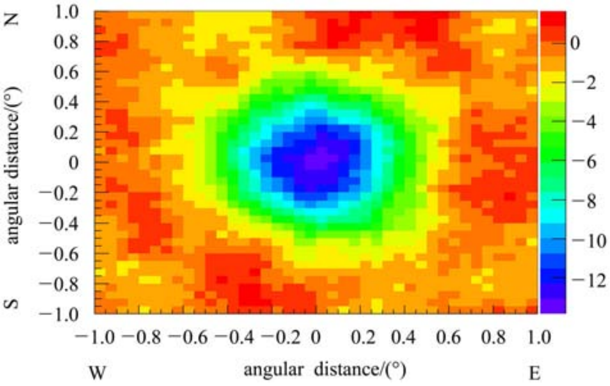

Fig. 2. The moon shadow of events passing the three selection criteria. The center of the map is the position of moon.

As an example, Fig. 3 shows the lateral density distribution and its fitted curve for one typical data event. The NKG function describes the lateral density distribution very well with a reduced chi-square value of 1.06.

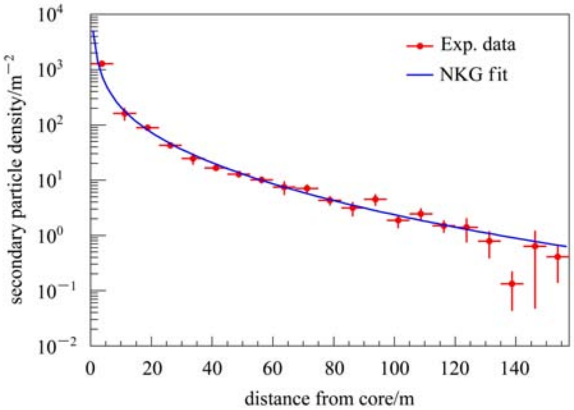

Fig. 3. Lateral distribution of one typical event recorded by the Tibet ASγ experiment. The red points are data and the blue line is the fitted curve.

Statistical difference of discrimination variables between γ-rays and CRs can be found in Fig. 4. The sample size of MC γ-rays, MC CRs and experimental data are 15652, 7749 and 100000 events respectively. Fig. 4(a), Fig. 4(b) and Fig. 4(c) show the scatter diagram of age against lg(size) of MC γ-rays, MC CRs and experimental data respectively. The pink line indicates γ/hadron cut(see discussion below). From these three figures we can find that MC CRs and experimental data are consistent quite well while MC γ-rays have younger age than MC CRs and the experimental data with the same size. On average, the γ-rays showers have an age parameter of about 0.65 and CR showers of about 0.85.

Figure 4(d) and e show good agreement between data and MC for the shower size and age distribution. However, small difference in the two lowest bins can be found in Fig. 4(d). On average, the age parameter in the data is about 0.03 older than that in MC. We think these small differences are coming from the uncertainty related with the composition model and hadronic interaction model. And similar differences have been reported by other experiments as well [19]. Nevertheless, such differences have no effect on the estimation of the background rejection rate as we estimate it from real data anyway.

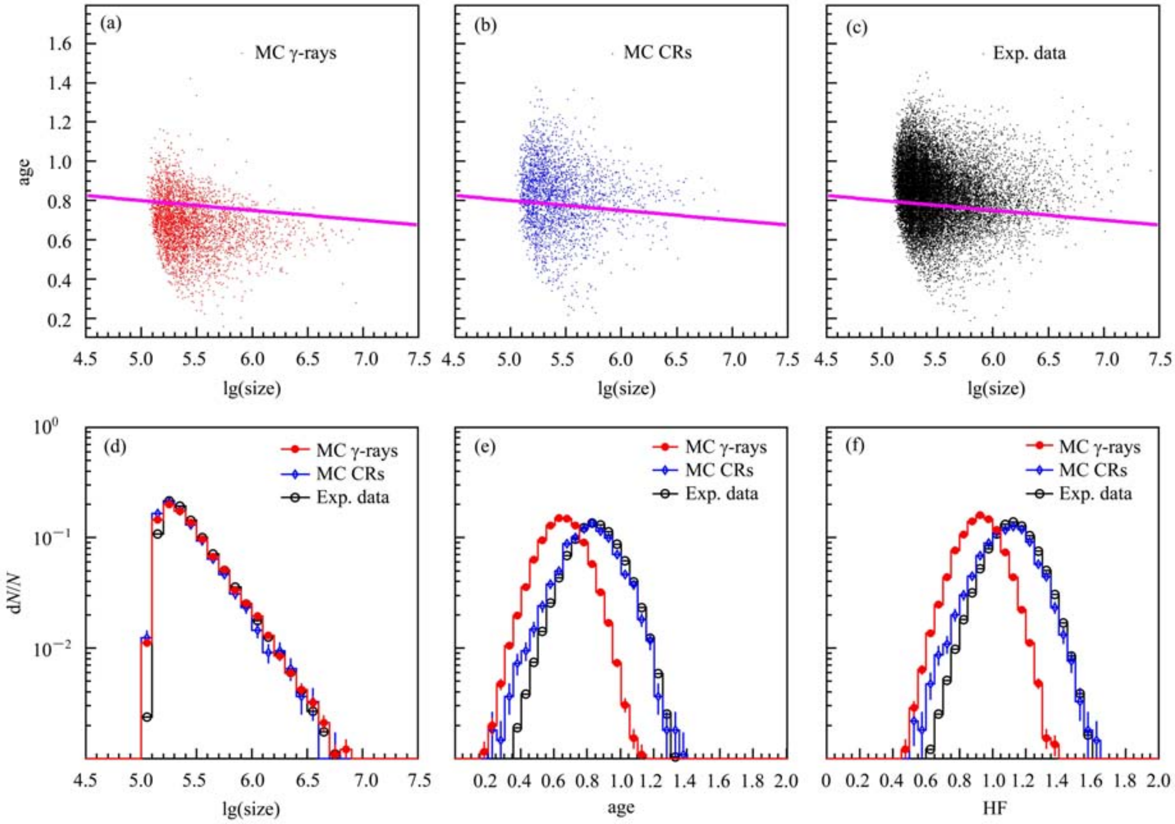

Fig. 4. Experimental data are compared with MC CRs and MC γ-rays. (a), (b), (c) are the age VS lg(size) plot of MC γ-rays, MC CRs and Experimental data respectively. (d), (e), (f) are the size, age and γ/Hadron variable HF distribution of MC γ-rays, MC CRs and experimental data respectively. Detailed discussion about this figure can be found in the text.

To have an optimal discrimination power between CRs and γ-rays, we actually apply a cut on a linear combination of the age and shower size parameters. As defined by Eq. (5), this variable (HF) is highly correlated with shower age parameter. Fig. 4(f) shows the HF distribution for MC γ-rays, MC CRs and data respectively, which are very similar to the distribution of shower age parameter in Fig. 4(e). The optimal cut value on HF variable is obtained as 1.05 by requiring a largest Q factor (a ratio between signal efficiency and root square of background efficiency), the location of the cut is indicated by the pink lines in Fig. 4(a), 4(b), 4(c).

$$\mathrm{HF} = \mathrm{age} + 0.05 \times \lg(\mathrm{size}). \tag{5}$$

On the γ/hardon separation: an event is identified as a γ-event if HF<1.05, otherwise it is treated as a cosmic ray event. As shown in Fig. 1(e), this cut is effectively equivalent to a cut on shower age parameter at a value of about 0.8 when the shower size is not a huge one.

The experimental data sample is therefore divided into two samples by the γ/hardon separation criterion. 30% of the events are identified as γ-ray events while the other 70% of the events are identified as CR events and can be rejected. According to the MC simulation, 84% γ-rays are retained as γ-events. As discussed earlier, the average shower age parameter for CRs is about 0.03 larger in data than in MC. As a conservative consideration, we can suppose the average shower age for γ-rays in data is also 0.03 larger than that in MC, a more accurate efficiency can be obtained by shifting the age parameter distribution for MC γ-rays sample before applying all the cuts. With such a consideration, the γ-rays efficiency is found to be 78%. In this case, the sensitivity for 100 TeV γ-rays astronomy is improved by at least 40% ($78\%/\sqrt{30\%}$).

With the simple number counting method and the Bootstrapping method [20], consistent results are obtained for the statistic error on the rejection rate of CRs and the efficiency of γ-rays: 0.1% for CRs rejection rate and 0.3% for γ-rays efficiency.

5 Summary

A γ/hadron separation analysis is described for the observed air shower events with primary energy above 100 TeV based on the Tibet ASγ detector configuration. The shower age and size parameters are fitted from the measured lateral density distribution and used as discrimination variables. According to the MC simulation and by taking into account the small difference observed in data and MC comparison, we conservatively conclude that more than 78% of the γ-rays events can survive the selection criteria while 70% of the cosmic rays background can be rejected. Sensitivity for 100 TeV γ-rays observation can thus be improved by at least 40%.

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