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Simulation Study On High Energy Electron and Gamma-ray Detection With the Newly Upgraded Tibet ASgamma Experiment

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The rapidly decreasing electron flux with the power index of -3.3 makes it difficult to measure directly with instruments on board balloons and satellites at energies higher than about 1 TeV. However, the large-area and wide-field EAS arrays could be used to extend cosmic-ray (CR) *electrons* spectrum ($e^+ + e^-$, in the following *electrons* refer to both electrons and positrons) measurements up to several tens of TeV or more. The newly upgraded Tibet hybrid AS experiment (Tibet-III+MD) may become one of the world's most sensitive observatories of gamma rays or maybe *electrons* above $\sim$10 TeV due to its high separation ability of γ-rays and hadrons. In this paper, using a full Monte Carlo simulation, we examine its ability for measuring CR *electrons* in the high galactic latitude area above $\sim$10 TeV.

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1. Introduction

The AMS-02 have reported their observations of CR *electrons* with the unprecedented accuracy [1]. Below 1 TeV, the energy spectrum of *electrons* can be well described with a single power law. Above 1 TeV, the lifetime and propagation distance of *electrons* in the Galaxy are severely limited by rapid energy losses via synchrotron radiation and inverse Compton scattering. Since the H.E.S.S. data[2] show a much steeper *electrons* spectrum at multi TeV, it may be suggested that the spectrum breaks at about 2 TeV. However, Chen et al., [3] show that CR *electrons* favored by AMS-02 and H.E.S.S. data may not need TeV breaks. There are many uncertainties for TeV observations, and the tens of TeV sepectrum observations may give a better understanding of whether the cut off really exists.

2. Current Observations

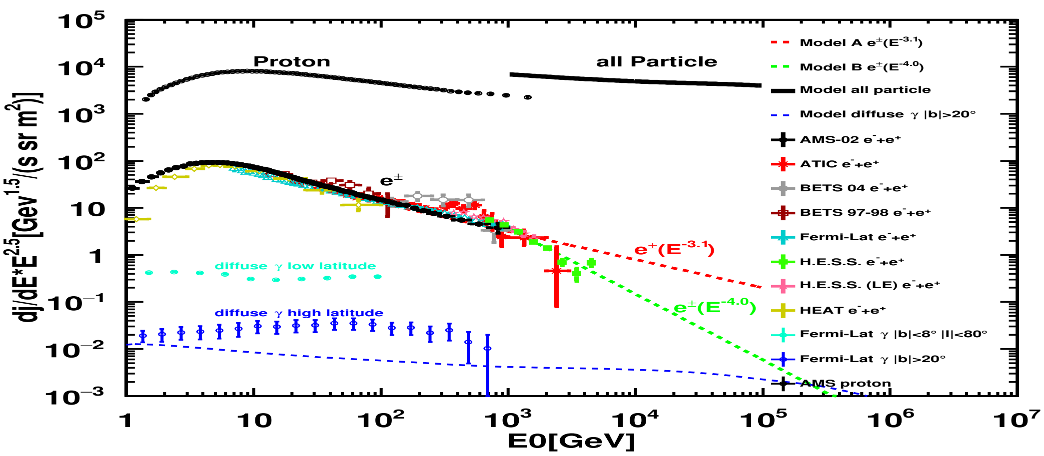

Figure 1: Primary energy spectra of protons[12], *electrons*[1, 2, 14, 15, 16, 17, 18] and diffuse γ-rays at different galactic latitude[4, 5]. The black solid line is the sum of cosmic-ray hadrons used in simulation. The blue dash line is the average predicted diffuse γ spectrum with galactic latitude larger than 20°. The red dash line is a fit of AMS-02 data with the power index -3.1. The green dash line is a fit of H.E.S.S. data with the power index -4.0. Details of how to predict the flux of diffuse γ-rays will be found in the paper [3].

Fig.1 shows the energy spectra of all particles, protons, *electrons* and diffuse gamma rays observed by various experiments. We have examined the characteristic features of CR *electrons* and diffuse gamma rays using a GALRPOP package. At tens of TeV, the absolute flux of *electrons* is about 0.01% of that of cosmic rays. The red dash line is a predicted *electrons*. Much more background of hadronic cosmic rays makes the hadron-rejection power very important. No TeV diffuse γ-ray data except upper bound limits makes it difficult to give the γ-ray background. However, it might be possible to estimate the diffuse γ-ray spectrum in the high galactic latitude using the 100 GeV data by Fermi/LAT [4]. At high-latitude area, γ-ray flux is at least several times smaller than *electrons* around ~10 TeV as seen in Fig.1. The reasons is as follows: since in high latitude, observed γ-ray are mostly produced by AGNs distributing uniformly in the sky. Because of their cosmological distance, high energy γ-rays are strongly absorbed by IR and FIR CMB. Therefore, we can choose this area with galactic latitude larger than 20° to separate *electrons*/γ for EAS arrays, and then we may obtain primary spectrum of *electrons* since *electrons* are expected to distribute isotropically in the Galactic disk.

3. (Tibet-III + MD + YAC-II) Experiment

The new Tibet hybrid experiment (Tibet-III+MD) has been operated at Yangbajing (E90°31′, N30°06′, 4300 m above sea level) in Tibet, China, and data taking started from February 2014. This hybrid experiment currently consists of three types of detector array, including the Tibet AS array (Tibet-III), an underground water-Cherenkov muon-detector array (MD) and the Yangbajing AS core-detector array (YAC-II) as shown in Fig. 2. This hybrid-array system is used to observe air showers of high energy celestial gamma-ray origin and those of nuclear-component origin with considerable accuracy.

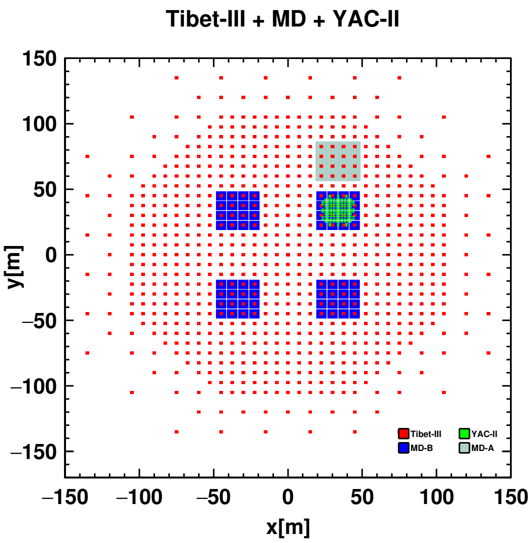

Figure 2: Schematic view of (Tibet-III+YAC-II+MD) array.

Here, the Tibet-III AS array consists of 789 plastic scintillation detectors of each 0.5 m^2 which are placed on a lattice with 7.5 m spacing, covering the area of 50,000 m^2. This array can observe air showers induced by primary particles in the atmosphere. The arrival direction and energy of each primary particle can be estimated with the accuracy of 0.5° and 70% at 10 TeV for γ-rays and 0.2° and 40% at 100 TeV for γ-rays, respectively.

The MD array consists of 5 water pools of each 800 m^2 and set up 2.5 m underground of the Tibet-III array, covering the area of 4,500 m^2 as shown in Fig. 2. Muons in excess of 1 GeV associated with air showers are observed by detecting Cherenkov lights with 20-inch-diameter PMTs mounted downward on the ceiling of each pool. Since γ-ray induced air showers are muon poor, while hadron induced showers are accompanied by many muons. This enables us to separate γ-rays from cosmic rays. In this work, our current MC simulation predicts that the cosmic-ray background events will be rejected by approximately 99.99% at around 50 TeV using this MD array.

The YAC-II array consists of 124 core detectors of each 0.4 m^2 being a sandwich of a 3.5cm thick lead plate and a plastic scintillator, covering the area of 500 m^2. This array aims to select high-energy components such as Proton, Helium and Iron in CRs from others nuclei.

4. Simulations

Air shower events observed with our detector system have been generated by a full Monte Carlo method using a code CORSIKA (version 7.400) [6]. For the hadronic interacton models, we use EPOS-LHC[7] and FLUKA[8], and MC events generated are observed under the same detector configurations and observation conditions as the experiment using Geant4.10 [9]. The chemical composition of primary cosmic rays is modeled based on the recent direct observational data[10, 12] and Tibet-EC [11] experiment. For the primary *electrons* model, we examined two different models (shown in Fig.1), namely, "Model A" and "Model B" are used to examine its ability for measuring CR *electrons* in this work. The "Model A" is fitted to the newest AMS-02 result [1], and the "Model B" is fitted to the H.E.S.S result [2]. The "Model A" and "Model B" are assumed to be the power-law spectra with index -3.1 and -4.0, respectively. The minimum sampled primary energy is set to be 3 TeV for both CRs and *electrons*. Air shower event selection was made by imposing the following conditions; 1) shower events hit more than 20 surface detectors with the number of each detector is larger than 0.8; 2) sum number of particles of all hit detectors should be larger than 50 detectors; 3) the zenith angle of events is smaller than 25°, resulting in covering about 1/4 times high galactic area (latitude$>$ 20°). For better energy resolution, only the core events (core position less than 60 m from the center of the AS array) are selected.

In this work, only the four middle MD pools are simulated and the number 0.4 μ is chosen as MD trigger threshold, just a conservative estimate. Finally, we got the cosmic-ray hadron events with the mode energy of about 20 TeV and *electron*-like events with the mode energy of about 10 TeV as shown in Table1

Table 1: Statistics of M.C. events

CR component	mode energy	events
Model A($e^+ + e^-$)	~10 TeV	2.74×10^6
Model B($e^+ + e^-$)	~10 TeV	6.38×10^5
Hadrons	~20 TeV	2.03×10^6

5. Results and Discussions

5.1 Trigger efficiency

In this work, our simulation confirmed that the air showers induced by primary *electrons* with $E_0 \geq 20$ TeV can be fully detected without any bias under the above-mentioned criteria. Fig.3 shows that the trigger efficiency is about 10% at 10 TeV while reaches 100% above 20 TeV for *electron*-induced events.

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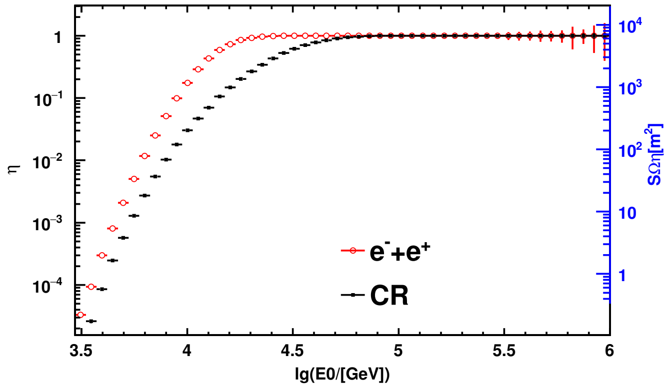

Figure 3: Trigger efficiency for different components. The trigger efficiency is about 10% at 10 TeV, while reaches 100% above 20 TeV for *electron*-induced events.

5.2 Selection of *electron*-induced events

The separation of the primary *electrons* and hadrons is realized as follows. Since $\sum \mu$ is the most sensitive parameter for primary *electrons*/hadrons separation above 10 TeV. We use it to select *electrons* and γ events from hadron events. Fig.4 shows the number of true-*electron*-induced events based on "Model A" and "Model B" model and background cosmic-ray events respectively for 1 year observation.

When we set $(\sum \mu)_{cut} = c$, then we can calculate the *electron*-induced events by the following equation

$$N_{e^\pm} = \left(N_{all}(\sum \mu \leq c) - N_{all}(\sum \mu > c) \times \frac{N_{M.C.,CR}(\sum \mu \leq c)}{N_{M.C.,CR}(\sum \mu > c)} \right) \times \frac{N_{M.C,e^\pm}}{N_{M.C.,e^\pm}(\sum \mu \leq c)}$$

Here, $N_{e^\pm}$ is the number of *electron*-induced events. N_{all} is the number of observed events. N_{CR} is the number of hadron-induced events. $N_{M.C.}$ means number of MC events.

From Fig.4, we found if we set $(\sum \mu)_{cut} = 0$ (see the first bin), we are then able to get Table.2, we found we could reject more than 99.99% of cosmic rays and save 37% of *electrons*. The ratio of primary *electrons* observed to that cosmic rays reach almost (50% : 50%) at about 60 TeV by using "Model A" with spectrum index of -3.1. It means if there exists no cut off before tens of TeV or suppose there exist heavy dark matter [19] or local-*electron* sources above tens of TeV, the Tibet AS+MD array would be able to search for possible nearby sources emitting high-energy *electrons* and search for heavy dark matter in both the *electrons* and gamma-ray spectra.

5.3 Model dependence of the muons distribution

We also checked the difference of both model in the distribution of the sum of muons of all MD detectors at different energy region as shown in Fig.5. Fig.5 shows the distribution of $\sum \mu$ for two primary-*electron* models with power indices of -3.1 and -4.0, and we found the shape of this muon distribution is almost same, and there is a difference less than 2% for both model at $(\sum \mu) < 1$ below 100 TeV.

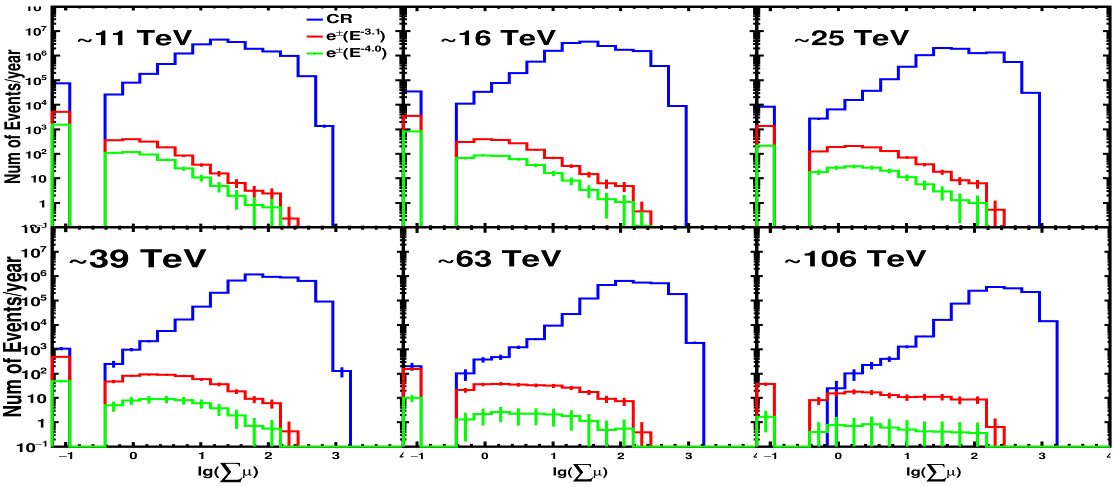

Figure 4: Predicted distribution of the sum of muons ($\sum\mu$) at different energy for one year observation. The blue markers is for cosmic-ray-induced events, the red marker is for true-*electron*-induced events based on "Model A" with spectrum index of -3.1 and the green markers is for true-*electron*-induced events based on "Model B" with spectrum index of -4.0. The first bin is $\sum\mu = 0$.

Table 2: Hadron-rejection power. One year events at different energy. For each component, the left column is trigger events, the right is events after selected condition with $\sum\mu = 0$. If we set $(\sum\mu)_{cut} = 0$, we could reject more than 99.99% of cosmic rays and save 37% of *electrons*. The ratio of primary *electrons* observed to that cosmic rays reaches almost (50% : 50%) at about 60 TeV by using "Model A" with spectrum index of -3.1.

$\sum\rho$	energy	"Model B"		"Model A"		cosmic rays	
$[m^{-2}]$	[TeV]	trigger	$\sum\mu = 0$	trigger	$\sum\mu = 0$	trigger	$\sum\mu = 0$
271-446	25	359	212	2.34×10^3	1.36×10^3	8.76×10^6	8.22×10^3
446-735	40	101	49.3	1.00×10^3	483	4.66×10^6	1.06×10^3
735-1210	64	26.9	10.0	410	**152**	2.49×10^6	**202**
1210-2000	107	7.11	1.68	160	**37**	1.26×10^6	**0**

5.4 Determination of primary energy of *electrons*

We are then able to obtain the correlation between the sum of particle densities of all hit detectors($\sum\rho$) and primary energy of *electrons* (E_0 in unit of GeV) as shown in Fig.6. In this analysis, the function

$$log(E) = a + b \times log(\sum\rho) + c \times (log(\sum\rho))^2$$

was used for primary energy reconstruction. The primary energy resolution is about 40% at 100 TeV. We also checked the model dependence in the correlation of $\sum\rho$ and E_0, and we found there is less than 2% difference for the determination of the primary-energy of *electrons* based on "Model A" and "Model B".

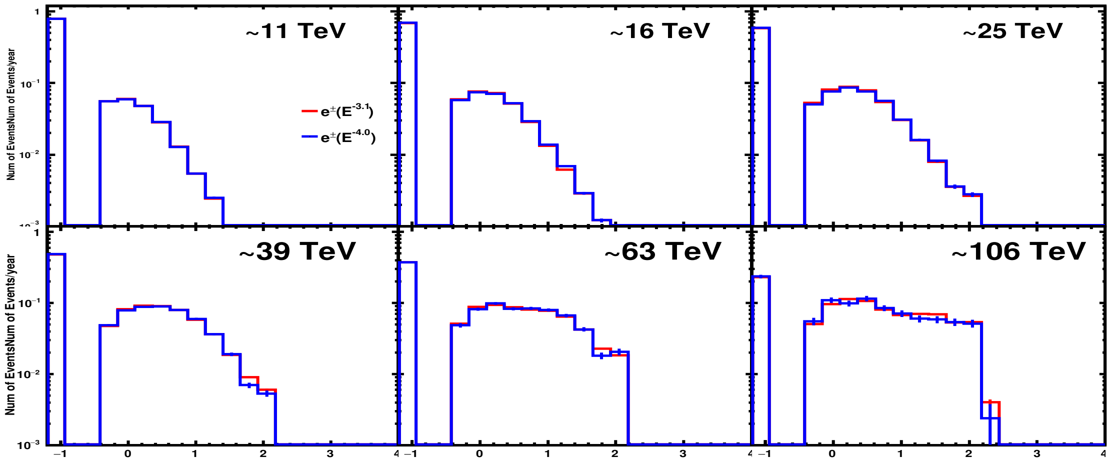

Figure 5: Normalized distribution of the sum of muons of all MD detectors $\sum\mu$ at different energy. The red line is for *electrons* based on "Model A" with spectrum index of -3.1 and the blue line is for *electrons* based on "Model B" with spectrum index of -4.0. The first bin is for $\sum\mu = 0$.

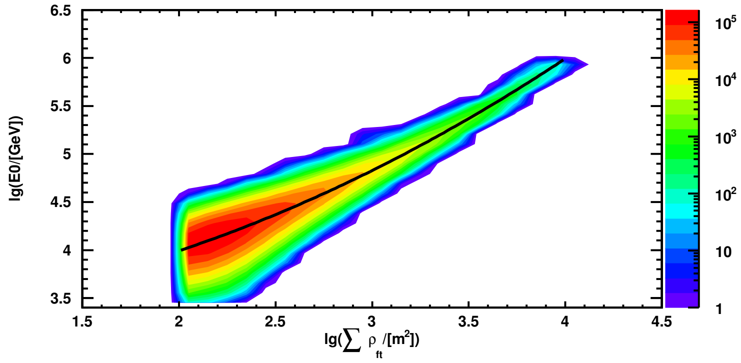

Figure 6: Scatter plot of primary energy and the sum of particle densities of all detectors($\sum\rho$), the black line is the function which used to reconstruct the primary energy from $\sum\rho$.

6. Summary

In this work, using a full Monte Carlo simulation, we examine (Tibet-III+MD) experiment's ability for measuring the energy spectrum of primary *electrons* in the high galactic latitude area above ∼10 TeV. We found if the primary-*electron* spectrum has a cut off at 2 TeV, and above the spectrum index is -4.0, the primary-*electron* flux will be 10 times smaller than background cosmic rays. It would be then required to reduce as much as possible systematic errors caused from simulation or to increase hadron-rejection power as well. However, if there exists no cut off before tens of TeV or suppose there exist heavy dark matter [19] or local-*electron* sources above tens of TeV, the (Tibet-III+MD) array would be able to search for possible nearby sources emitting high-energy *electrons* and search for heavy dark matter signature in both the *electrons* and gamma-ray spectra.

Acknowledgments

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