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Measurement of cosmic-ray electrons with LHAASO KM2A-WCDA synergy

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Cosmic-Ray Electrons (CREs) lose energy rapidly during their propagation and constraint themselves in local galactic space. Hence, a detailed measurement of the spectra extending to tens of TeV is a probe to CRE origin, from sources or from more exotic production mechanisms. Ground-based imaging atmospheric Cherenkov telescopes have measured CREs up to 20 TeV. However, measurements of CREs spectrum above 20 TeV with ground-based arrays are still challenging due to the difficulty in rejection of hadronic background. The LHAASO with a large effective area and strong background rejection power is very suitable for investigating the CREs. Combining KM2A and WCDA, we can get a more efficient rejection of the hadronic background. In this proceeding, we'll discuss the status of the CRE spectrum measured with LHAASO.

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1. Introduction

The cosmic-ray electrons (CREs)[1] flux is of great importance for High Energy Astrophysics because it can be a probe to investigate the nearby astrophysical sources, processes of cosmic-ray secondary production/diffusion, and acceleration mechanisms.

Seriously constrained by energy losses via synchrotron radiation and inverse Compton scattering, the lifetime and propagation distance of CREs around TeV are confined within the local volume (the surrounding $\sim 10^2$ pc) of the Milky Way on a time scale of 10^5 yr. Thus, the anisotropy and spectral features of CREs are associated with the spatial distribution and properties of nearby sources. The spectral shape of CREs could further provide evidence for the possible existence of Galactic dark matter in the form of weakly interacting massive Pparticles and astrophysical antimatter accelerators.

In recent years, an unexpected positron excess at tens of GeV range aroused wide attention and discussion on possible interpretations of the observations [1]. At present, the only consensus view is that the suppression of spectral features above TeV energies may provide valuable information to clarify the physical mechanisms that generate the CREs spectra [2]. Hence, it is crucial to settle this issue based on precision measurements on the CREs spectrum in TeV and multi-TeV energy range.

Measurements of CREs spectrum using space and ground-based detectors are currently available up to 10 TeV energy range. Space-borne detectors, like Fermi/LAT [3], AMS-02 [1], CALET [4], DAMPE [5], have reported the measurement of CREs spectrum up to 4 TeV. At multi-TeV energy range, ground-based measurements have been done with H.E.S.S. [6], MAGIC [7] and VERITAS [8] up to approximately 5 TeV, and possibly to higher, $\sim$ 20 TeV, energy by H.E.S.S. [9]. However, space-based detectors will run out of statistics due to the combined effect of the steep CREs spectrum and their relatively small acceptances at higher energies. Measurement of CREs in ground-based experiments always suffers from the limited discrimination power between electron and hadronic components. A detailed measurement of the spectra of CREs from 10 TeV to 100 TeV is a crucial but inevitable process to figure out the electronic origin.

The LHAASO experiment is a ground-based EAS observatory with a hybrid technique at 4,410 m above sea level where the measured atmospheric depth is around 600 g/cm^2. With its wide aperture and its almost 100% duty cycle, LHAASO is expected to gather significantly larger electron event statistics than Imaging Atmospheric Cherenkov Telescopes, which may help in extending the electron spectrum further and potentially reveal more details of the local source distribution. However, measurements of CREs spectrum above 20 TeV with ground-based arrays is still challenging because of the difficulty of rejection of hadronic extensive air shower background. In this proceeding, we'll discuss the status of the CRE spectrum measured with LHAASO and possible improvements on background rejection power.

2. Simulation and Experiment Data

Air showers were generated with CORSIKA (v77410)[10]. This work generates five components (Proton, helium, nitrogen, aluminum, and iron) to simulate cosmic rays. Cosmic-ray showers following an E^{-2} energy spectrum in a wide energy range from 10^{12} to 10^{16} eV and an isotropic

[1]Hereafter, electrons are generally referred to as electron and positron.

angular distribution are simulated with a zenith angle range of 0-40° and an azimuth range of 0-360° in a 1000m sample radius. While cosmic-ray electrons following an E^{-2} energy spectrum in a different energy range from 10^{12} to 10^{16} eV are generated with a zenith angle range of 0-70° and an azimuth range of 0-360° in a 1000m sample radius. The total simulated events number for cosmic rays and electrons is approximately 5.555×10^8 and 2.222×10^8, respectively.

The secondary particles reaching ground level are treated in detector response simulations G4KM2A, which was developed in the framework of the Geant4 package[11]. To guarantee a good measurement by KM2A, these event selection criteria are applied corresponding to the full array simulation:

- the reconstructed shower core is located within the radius [320m, 420m] from the LHAASO center;
- the reconstructed zenith angle is less than 30°;
- the reconstructed energy is greater than 4 TeV;
- the event triggered at least 10 KM2A-EDs within 200m after noise-filtering.

The KM2A experiment data is collected from July 20^{th}, 2021, to August 18^{th}, 2022, 383 days in total. Additional cut on galactic latitude (|b|>7°) is applied to discard the gamma astrophysical sources. However, the presence of the isotropic diffuse gamma-ray background (IGRB) in the extra-galactic field of view cannot be rejected, but it contributes less than 1% over TeV according to Fermi/LAT observation [12].

3. The status of the background rejection power

The LHAASO-KM2A utilizes the ratio between the measured number of muons and electrons to discriminate gamma-like events from cosmic rays, which is defined as,

$$R = \log\left(\frac{N_\mu + 0.0001}{N_e}\right) , \tag{1}$$

where N_μ and N_e denote the number of muons and electromagnetic particles measured by MDs and EDs, respectively. The discrimination parameter is optimized to get the maximum significance of cosmic-ray electrons. The expected significance of cosmic-ray electron could be formulated as,

$$\mathrm{Sig} = \frac{\mathrm{N_{CRE,sur}}}{\sqrt{\mathrm{N_{CRE,sur}} + \mathrm{N_{CR,sur}} + (\delta \mathrm{N_{CR,sur}})^2}} , \tag{2}$$

where $N_{\mathrm{CRE,sur}}$ and $N_{\mathrm{CR,sur}}$ is the number of survival events of simulated CRE and CR showers after KM2A discrimination by the R parameter. In this situation, residual background events affect much to the result. Thus, the absolute CR flux uncertainty should be considered [13], and δ takes 0.2 at a conservative estimate. According to Fig. 1, the distribution of R for cosmic-ray electrons and cosmic rays partly overlap at low energies due to wide N_μ and N_e fluctuations. As the energy increases, the distinction becomes more evident. The discrimination cut is optimized to achieve maximum significance while keeping the survival fraction of CRE over 25%.

Figure 2 shows that the simulated CR-induced showers have run out of statistics in $N_\mu = 0$ over 40 TeV due to insufficient survival simulated CR events. According to Fig.3, the expected flux of CRE is still lower than CR by two orders of magnitude; thus, the discrepancy between data and CR is not due to CRE contamination. Even though the simulation has tested for its validity by comparing the distributions of several shower parameters with the measured in the observation, the $N_\mu = 0$ events induced by the CR sample would consume large computing resources due to its tiny proportion. Thus, this insufficient Monte Carlo CR-background sample will overestimate the background rejection power of cosmic-ray background. Hence, using the experimental data (subtracting the CRE MC sample) as the cosmic-ray background is reasonable to get the conservative number of survival CR background events $N_{\mathrm{CR,sur,1year}}$ and signal events $N_{\mathrm{CRE,sur,1year}}$ in one year from simulation. Next, the number of survival signal events in 3σ significance $N_{\mathrm{CRE,sur,3\sigma}}$ could be derived from Eq.2. Then, the sensitivity of LHAASO-KM2A can be formulated as follows,

$$F_{\mathrm{CRE,3\sigma}} = \frac{N_{\mathrm{CRE,sur,3\sigma}}}{N_{\mathrm{CRE,sur,1year}}} \cdot f_{\mathrm{H.E.S.S.}}\,, \tag{3}$$

where $f_{\mathrm{H.E.S.S.}}$ is the extrapolation of H.E.S.S.'s fit result, and $N_{\mathrm{CRE,sur,1year}}$ is the event number after the same event cut in simulation. One can see that the 3σ sensitivity limit of LHAASO-KM2A is still over the extrapolated electron spectrum measured by H.E.S.S. in Fig.4. The early stage of LHAASO sensitivity on cosmic-ray electron flux is insufficient for detecting and mapping the anisotropy of cosmic-ray electrons.

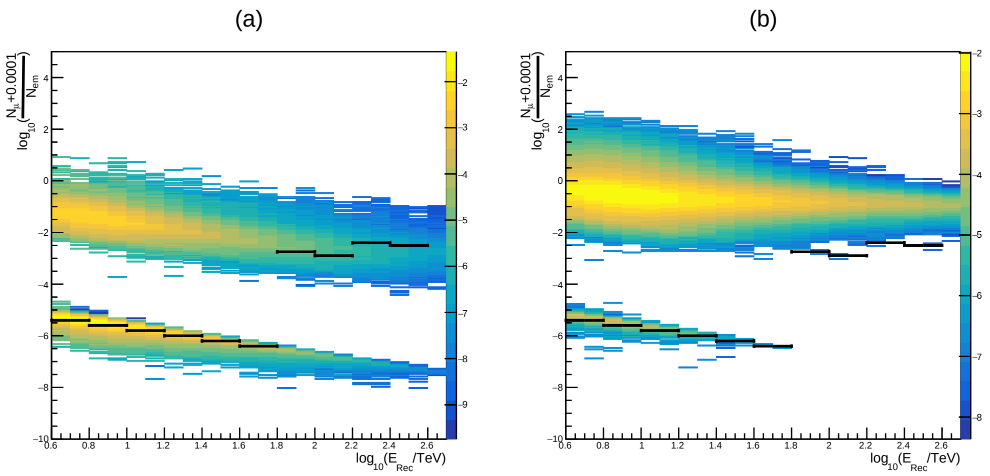

Figure 1: (a) Scatter plot of R as defined in equation vs. reconstructed energy using simulated CRE-induced (a) and CR-induced (b) air showers, respectively. The color represents the log probability density within each reconstructed energy bin. The solid lines indicate the CRE/CR discrimination cuts according to the simulation result. The separated population with R<-4 is the $N_\mu = 0$ events measured by LHAASO-KM2A.

4. The derivation of upper limits

Based on the experimental data (subtracting the CRE MC sample), we optimized the discrimination cut for cosmic-ray electrons again. However, the significance of cosmic-ray electrons has

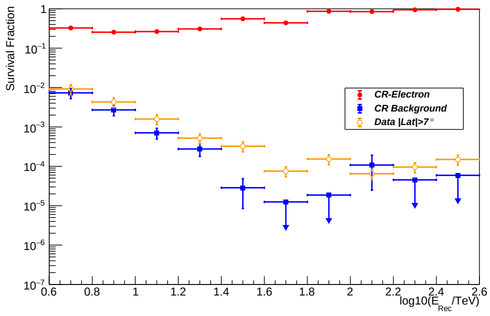

Figure 2: The survival fraction of simulated CRE, CR-background, and observed events in different energy bins after the discrimination cuts optimized from the CR MC sample.

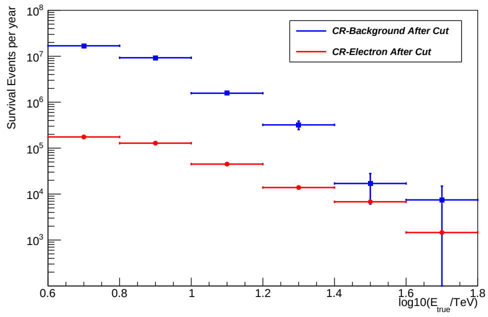

Figure 3: The survival events of CRE and CR-background events (according to simulation) in different energy bins after the discrimination cuts optimized from the CR MC sample.

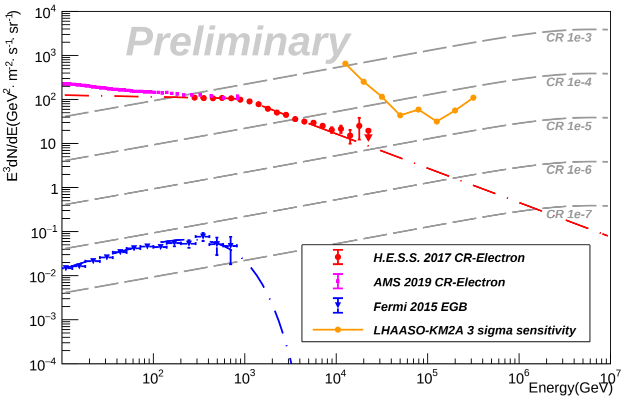

Figure 4: The LHAASO-KM2A 3σ sensitivity on cosmic-ray electron according to simulation. The measurement of cosmic-ray electrons by H.E.S.S. and the required rejection power for the cosmic-ray background are plotted.

not markedly improved in its current state. To estimate the upper limit of cosmic-ray electrons at a 90% confidence level, we utilize the hypothesis testing analysis based on the observation events and simulation. Overwhelmed by cosmic ray background events, we treated the cosmic-ray background events and observed events after discrimination cut for each energy bin as two independent Gaussian-like distributions. Thus, the cosmic-ray electron signals in our observed events after discrimination cut obey normal distribution approximately. The expectation and variance of the survival cosmic-ray electron signals ξ could be formulated as follows,

$$\begin{aligned} \hat{\xi} &= N_{\text{obs}} - N_{\text{CR}} \,, \\ \sigma_{\xi}^2 &= \sigma_{N_{\text{obs}}}^2 + \sigma_{N_{\text{CR}}}^2 + (\delta \cdot N_{\text{CR}})^2 \,, \end{aligned} \tag{4}$$

where the N_{obs}, N_{CR} denote the survival observed events, and simulated cosmic-ray background events after discrimination cut for each energy bin. In order to calculate an upper limit on the cosmic-ray electron flux, we need to calculate the one-side confidence interval. Considering that $\xi < 0$ is a non-physical situation[14, 15], it should be rid of this effect, then we have,

$$\alpha = \frac{\Phi(\xi_{\text{limit}})}{\Phi(0)}, \tag{5}$$

where α equal 0.1 in 90% confidence level and $\Phi(\xi)$ is the complementary cumulative distribution function (CCDF) of the normal distribution from ξ. The solution of ξ_{limit} is presented in the right panel of Fig.5. Thus, the 90% C.L. upper limit flux of cosmic-ray electrons based on the early stage of KM2A measurement can be calculated as,

$$F_{\text{CRE,limit}} = \frac{\xi_{\text{limit}}}{N_{\text{CRE,sur,1year}}} \cdot f_{\text{H.E.S.S.}}, \tag{6}$$

where ξ_{limit} is 90% upper limit of cosmic-ray electron event number derived from the observed data.

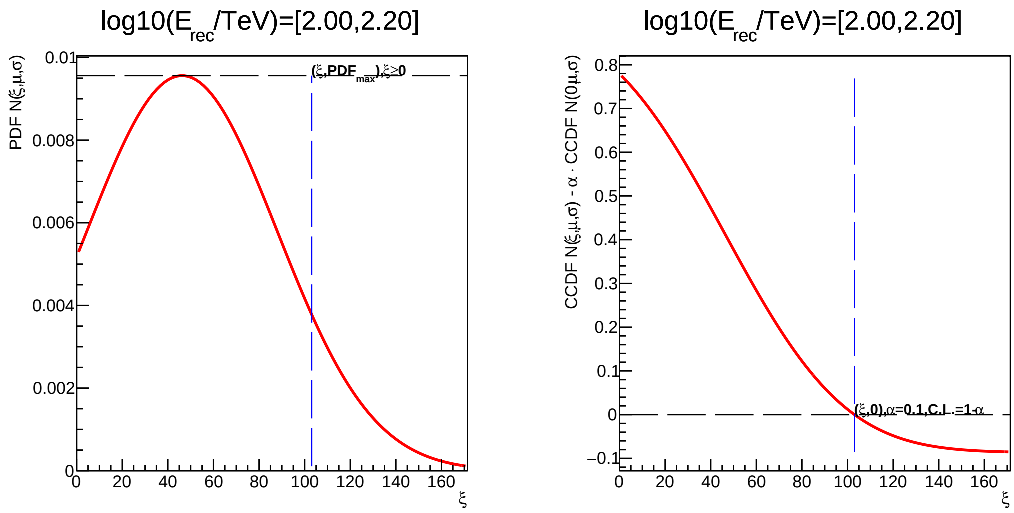

Figure 5: In the energy range from 100 TeV to 160 TeV, the probability density function (PDF) is a function of ξ ($\xi \geq 0$) where the black dash line denotes the maximum value in the left; The residual of $\Phi(\xi_{limit})$ to $\alpha \cdot \Phi(0)$ where the black dash line denotes the root of the residual when $\alpha = 0$ in the right. The blue dash lines in both plots denote the solution of ξ_{limit} in 90% upper limit.

5. Discussion

The full KM2A and WCDA became operational in July 2021 and March 2021, respectively. The LHAASO observatory has achieved the simultaneous measurement of the same shower with the help of data-acquire-system calibration. The simulation of the KM2A-WCDA synergy is under development at the same time as presented in Fig.7. The comparison between the experiment and simulation will be implemented in the future. The optimization selection adapted for the full KM2A in gamma/hadron separation is about to release, which will contribute to further depress the background of cosmic-ray events. In addition, a method to utilize WCDA as a muon counter to measure the muon content in EAS with LHAASO KM2A-WCDA synergy released in this conference did help to improve the background rejection power of LHAASO above 20 TeV.

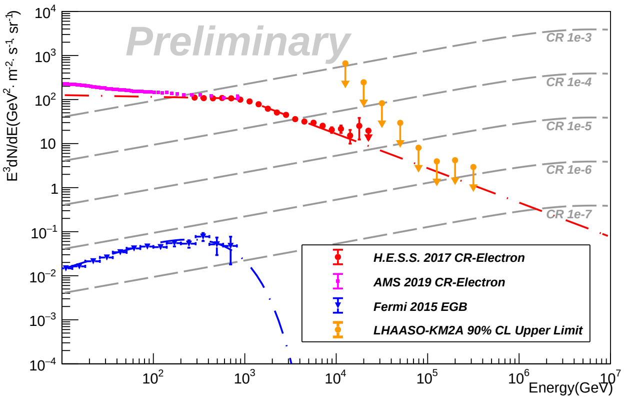

Figure 6: The LHAASO-KM2A 90% C.L. upper limit for cosmic-ray electron spectrum.

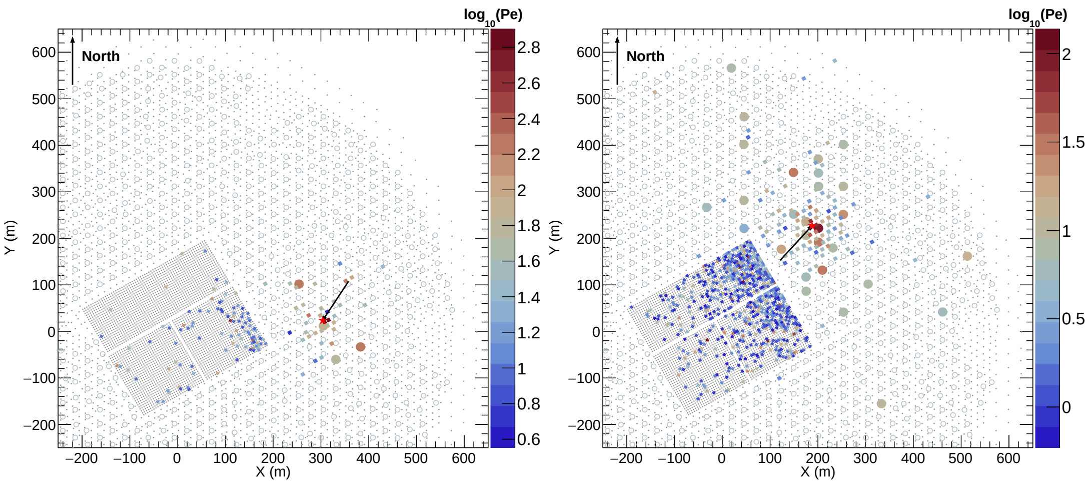

Figure 7: A simulated shower event with reconstructed energy of 14.8 TeV with primary energy of 26.1 TeV in the left pattern; An observed shower event with reconstructed energy of 46.0 TeV in the right pattern. They show the triggered pattern of KM2A and WCDA hits after the noise-filtering process colored by $\log_{10}(N_{pe})$.

The present work attempt to set the reference for a simple method to give the upper limit of cosmic-ray electron flux above 20 TeV. Due to the insufficient simulation events, KM2A could only give an upper limit of flux for cosmic-ray electrons based on the early stage of KM2A measurement. As it was discussed, LHAASO has the potential to measure the flux of cosmic-ray electrons with the KM2A-WCDA synergy.

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