論文の内容の要旨

Study of muons from ultra-high energy cosmic ray air showers measured with the Telescope Array experiment

(テレスコープアレイ実験による極高エネルギー宇宙線空気シャワー中のミューオンの研究)

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Cosmic rays with energies above about 10^{18} eV are called ultra-high energy cosmic rays (UHECRs). The origin of UHECR is a long-standing mystery. When UHECRs enter in the atmosphere, they interact with atmospheric nuclei and generate the particle cascade, which are called air showers. The Telescope Array (TA) experiment is designed to measure air shower secondary particles on the ground with the surface detector (SD) and fluorescence light induced from the air shower with the fluorescence detector (FD). The experiment aims to reveal the origin of UHECR by measuring the spectrum, the anisotropy and the mass composition of UHECR. The TA SD array is located in western Utah, USA and consists of 507 scintillation counters, placed on a square grid with 1.2 km spacing, covering 700 km^2. The three TA FD is located around the SD array, looking towards the sky above the array.

One of the uncertainties of the UHECR observation derives from the hadronic interaction model used for the air shower Monte Carlo (MC) simulation. The testing of hadronic models using air shower data and MC enables us not only to understand hadron interactions in the energy above 10^{18} eV, but also to identify the correct cosmic ray composition.

The number of muons from the UHECR on the ground depends on the composition of primary cosmic rays. Its MC prediction also depends on hadronic interaction models. By comparing the measured number of muons with the MC prediction, hadronic models can be tested. The Pierre Auger Observatory reported that the average ratio of observed number of muons to MC prediction value is $1.841 \pm 0.029(\text{stat.}) \pm 0.324(\text{syst.})$ using QGSJET II-03 model for proton[1]. The same issue occurs for QGSJET II-04 and EPOS-LHC models, in which the discrepancy in the number of muons is about 30% for proton. The present hadronic models do not reproduce the data.

[1] A. Aab *et al.*, *Phys. Rev. D.* **91**, 032003 (2015).

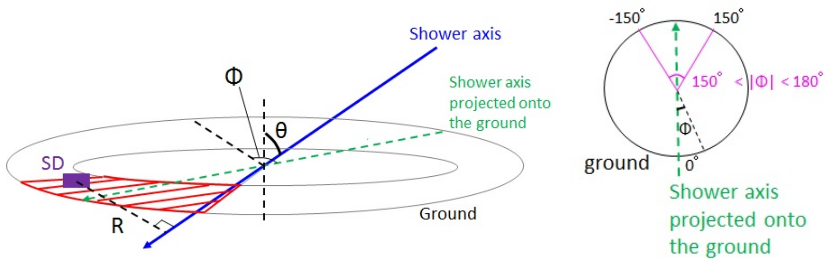

Figure 1: (left) Geometry definition in the muon analysis. The ground is separated by (ϕ, R) to reduce EM background. The muon purity in the SD signal is calculated in each (ϕ, R) bin. The red region in the figure shows the largest distance bin from the particle generation points on the shower axis, which is expected to be the least EM background bin. (right) ϕ definition. There are six bins for the analysis and the region for $150° < |\phi| < 180°$ is shown.

The TA experiment uses the SD made of plastic scintillator. It is sensitive to the electromagnetic (EM) component that is the major part of secondary cosmic rays from UHECR air showers. An analysis approach to increasing muon purity is necessary to calculate the number of muons in the TA SD data. This work aims to develop an analysis of muons from the UHECR air showers by using TA SD and study the difference of the number of muons between the data and the MC.

For the analysis, we use the events reconstructed by the same method as the TA spectrum analysis[2] with energy range $10^{18.8}$ eV $< E <$ $10^{19.2}$ eV following the analysis of the Auger experiment[3]. In the energy range, the composition of the primary cosmic ray can be proton by $X_{\max}$ measured using the TA FD, thus we use the MC for proton primaries. The hadronic model QGSJET II-03 is used for the MC, which is the basic model of making the TA SD MC.

The EM components (electron and gamma) from air showers are more attenuated than muon component because average energy of EM components is smaller than that of muons. Hence the ratio of the number of air shower muons to that of all charged particles in the same SDs (hereafter this ratio is described as the muon purity) is expected to be larger as the SDs are more distant from secondary particle generation points on the shower axis. We divide the air shower events of the dataset in θ, the zenith angle, ϕ, the azimuth angle relative to the shower arrival direction projected onto the ground, and R, the distance from shower axis. The geometry definition is described in figure 1. If $\theta, |\phi|$ or R value is larger, the pass length of air shower particles increases, then the muon purity in the signal of SDs is expected to become high.

For each event, SDs which have air shower signals are picked up and the integrated FADC values of the waveforms are calculated. The value by the unit of VEM (Vertical Equivalent Muon) is filled in corresponding (θ, ϕ, R) bin of the histogram. One detector signal deserves one entry in the histogram. If there is a SD in a (ϕ, R) bin but it does not have any signal, then one statistics is filled to the corresponding bin of the histogram as 0 VEM. Figure 2 shows the lateral distributions of the average integrated FADC values and the muon purity in each R bin. For the condition $(30° < \theta < 45°, 150° < |\phi| < 180°$, 2000 m $< R <$ 4000 m), the muon purity

[2] T. Abu-Zayyad *et al.*, *ApJ*, **768**, L1 (2013).
[3] A. Aab *et al.*, *Phys. Rev. Lett.*, **117**, 192001 (2016).

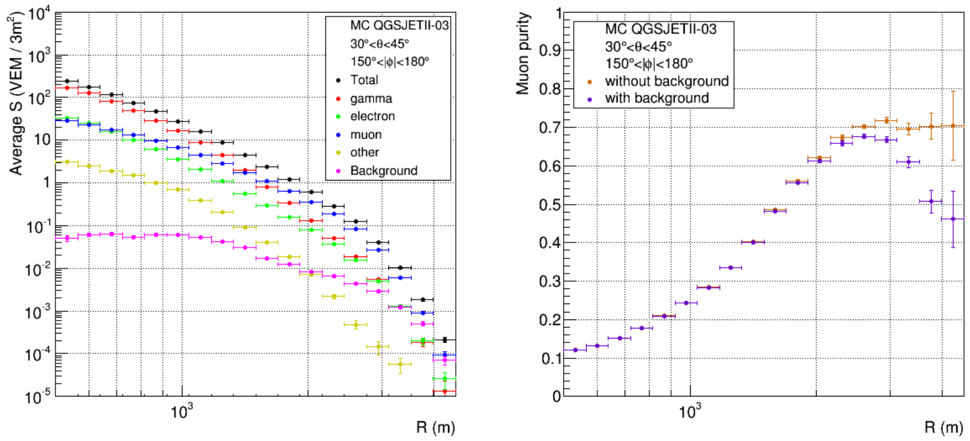

Figure 2: Lateral distributions for $30^\circ < \theta < 45^\circ, 150^\circ < |\phi| < 180^\circ$. The vertical error bar shows the standard deviation. (left) The average lateral distributions of the integrated FADC values, denoted as S in the figure. The red, green, blue, yellow, magenta and black represent gamma, electron, muon, other shower components, atmospheric muon background and the total of them, respectively. (right) The muon purity. The violet and orange show the calculation with and without atmospheric muon background, respectively.

is 60 - 70%, and we use this condition for the comparison of the number of particles from air showers of the data with that of the MC.

We use the TA SD 7 year dataset recorded from 11 May 2008 through 11 May 2015. The lower error of the histogram of the integrated FADC values cannot be calculated properly for $R >\sim 1.5$ km because the fraction of SDs with 0 VEM is too large to take 68% of the whole statistics of the histogram within the lower and upper errors. Hence we assume Poisson distribution for the histogram and calculated the average value of them as the signal size. Figure 3 shows the lateral distributions of the average number of particles per SD and its ratio to various MC hadronic interaction models; QGSJET II-03, QGSJET II-04, Epos 1.99 and Sibyll 2.1. For all the models described here, the distribution falls down slower in the data than the MC, causing larger difference of the signal size at larger $|\phi|$ and R values.

The systematic error of the signal size of the data is dominated by the systematic uncertainty of FD energy measurement, which is 21%, The lateral distributions of the ratio of the number of particles of the data to that of the MC are presented in figure 4 (left). The typical ratios are $1.72 \pm 0.10(\text{stat.}) \pm 0.40(\text{syst.})$ at 1910 m $< R <$ 2160 m and $3.14 \pm 0.36(\text{stat.}) \pm 0.72(\text{syst.})$ at 2760 m $< R <$ 3120m. The significance of the discrepancy between the data and the MC is about 1.6 - 2.7 σ, depending on R. Figure 4 (right) is the correlation of the muon purity expected from the MC with the ratio of the signal size of the data to that of the MC. The figure shows larger difference in the signal size between the data and the MC at the larger muon purity. This result indicates that part of the discrepancy in the signal size between the data and the MC is caused by the muon excess in the data. The significance of the discrepancy obtained in this work is consistent with the muon excess detected with Auger SD.

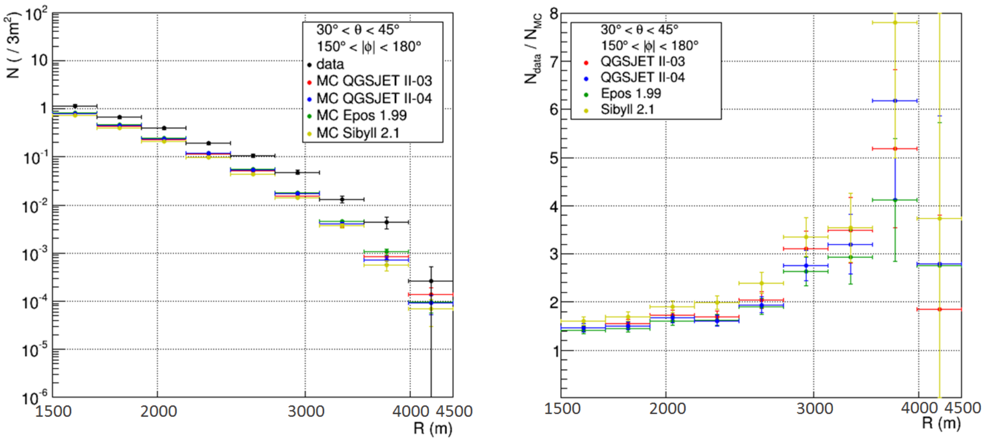

Figure 3: Lateral distributions for $30° < \theta < 45°, 150° < |\phi| < 180°$ and 1500 m $< R <$ 4500 m with various hadronic models. (left) The average lateral distribution of the signal size per detector assuming Poisson distribution, denoted by N in the figure. The black, red, blue, green and yellow represent data, QGSJET II-03, QGSJET II-04, Epos 1.99 and Sibyll 2.1, respectively. (right) The average ratio of the data to the MC. The color corresponds to MC hadronic models described in the left figure.

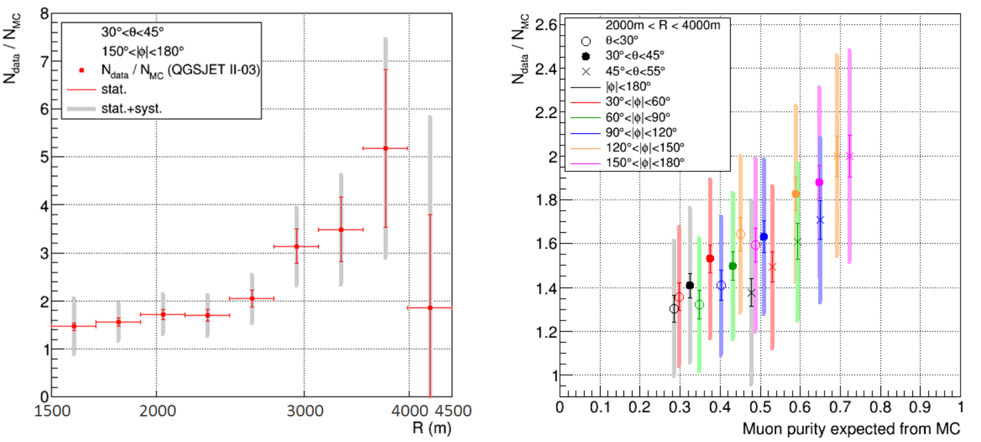

Figure 4: (left) Same as the right panel of figure 3 but including systematic errors, for only QGSJET II-03 model. The error bars is statistical error and the bands include statistical and systematic errors. (right) The correlation between the muon purity and the ratio of the signal size $N_{\rm data}/N_{\rm MC}$ for 2000 m $< R <$ 4000 m using QGSJET II-03. The black, red, green, blue, yellow and magenta represent $|\phi| < 30°$, $30° < |\phi| < 60°$, $60° < |\phi| < 90°$, $90° < |\phi| < 120°$, $120° < |\phi| < 150°$ and $150° < |\phi| < 180°$, respectively. The open circle, filled circle and cross represent $\theta < 30°$, $30° < \theta < 45°$ and $45° < \theta < 55°$, respectively. The error bars is statistical error and the bands include statistical and systematic errors.