Mass Composition of UHECRs Measured Stereoscopically by the Telescope Array Fluorescence Detectors

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Abstract: The Telescope Array (TA) is a hybrid detector consisting of Fluorescence Detectors (FDs) and Surface Detectors (SDs) to observe Ultra High Energy Cosmic Rays (UHECRs). FDs can measure longitudinal developments of cosmic ray air showers directly. $X_{\max}$ is the maximum depth of the air shower development which depends on cosmic ray primary particle type. In this presentation, the most recent $X_{\max}$ analysis of UHECR mass composition measured by TA FD stereo will be reported.

Keywords: icrc2013, latex, template, example.

1 Introduction

The Telescope Array (TA) experiment is the largest observatory of cosmic rays in the northern hemisphere. TA consists of tree fluorescence detector (FD) stations and a 507 surface detector (SD) array to achieve the hybrid detection of air showers generated by UHECRs. FDs can measure air shower developments directly. Shower development depends strongly on the primary particle. This is an advantage over SD measurements for the determination of the primary particle. Moreover, TA FD can measure air showers stereoscopically to improve geometry reconstruction. FD measurement of shower development is a superior s-trategy for determination of the mass composition.

The mass composition of ultra-high energy cosmic rays (UHECRs) is very important in the understanding of their sources. High Resolution Fly's Eye (HiRes) reported that the mass composition is dominated by proton componen-t [1], on the other hand Pierre Auger Observatory (PAO) suggested that the composition is getting heavier as the energy increasees [2]. The energy spectra reported by HiRes and PAO show the suppression at the GZK energy region. If this suppression is caused by the GZK mechanism, the composition should be purely protonic [3].

2 $X_{\max}$ Analysis

Since the shower developments have large fluctuation, it is not easy to determine the primary particle of an air shower, individually. Thus, the mass composition is determined statistically, by comparing average, RMS or distribution of $X_{\max}$ of Data with a monte carlo (MC) simulation. However, it should be noted that the uncertainty of the MC depends strongly on hadron interaction models that have been extrapolated from measured cross sections at much lower energies.

As energy increases, the $X_{\max}$ of air showers increase. And at a given energy, the $X_{\max}$ of a light primary particle will be deeper than that of a heavier primary particle. Since the FDs only can see showers in limited geometric region-s, the $X_{\max}$ might be either above the field of view (FOV) or below it, or it may be inside the FOV but the FD cannot reconstruct the shower (for instance, the shower may be coming nearly directly toward the FD). In these cases $X_{\max}$ can not be determined. This means that the distribution of $X_{\max}$ will be different from the expected distribution unless the FD configuration is taken into account in the simulation. In this analysis, the $X_{\max}$ distribution affected by the detector configuration and shower reconstruction biases will be estimated and compared with data to determine UHECR mass composition.

2.1 Air Shower Simulation

The distribution of $X_{\max}$ is estimated by the MC shower simulation code of CORSIKA (ver 6.972) [4]. To reduce computation time, thinning is applied with a thinning factor $\varepsilon = 10^4$ and weighting limitations of $w(e.g.) = \varepsilon \times E_0(\mathrm{GeV})$ for electrons and gammas, and $w(m.h.) = w(e.g.)/100$ for muons and hadrons, where E0 is the primary energy. The thinning factor and weighting limitations were chosen to produce smooth shower development. The energy below which the simulation no longer follows particles is 100keV for the hadronic component and 100MeV for the electromagnetic component.

The shower library used for the expected distributions is generated using a primary energy between 10^{18}eV and 10^{20}eV. Primary particle type is taken to be protons or iron nuclei. QGSJET-I, QGSJET-II and SYBILL are used for the hadronic interaction models. The zenith angle is randomly chosen between 0 and 65 degree. The shower development is only followed to the median elevation of the TA site of 1400 m asl. The left side of Fig. 1 shows the average $X_{\max}$ for each energy bin based on the shower MC simulation. This $X_{\max}$ distribution cannot be compared directly with the observed data because the simulation at this point still does not reflect the detector response or reconstruction procedure used for the data.

2.2 Detector Simulation

The expected distributions of the energy and $X_{\max}$ to be observed by TA FD should be estimated by the detector simulation with the generated air shower profiles by CORSIKA. $X_{\max}$ and energy distribution is affected by the detection and reconstruction bias. The detector simulation proceeds in the following way. First the amount of fluorescence light and Cherenkov emission along the shower axis is estimated from the energy deposited and number of

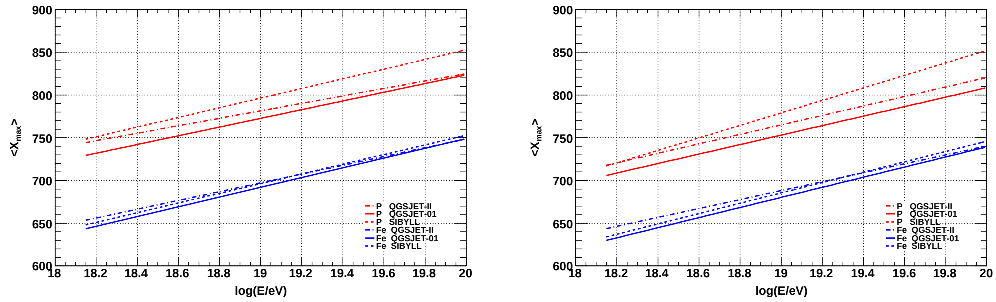

Fig. 1: Left: Averaged X_{max} by CORSIKA. Right: (under calculating) Expected averaged X_{max} observed by TA FD. Primary particles are protons (red) or iron nuclei (blue). Hadronic interaction models are QGSJET-01 (Solid line) or SIGYLL (dotted line).

shower particles at various depths along the shower. Although the ratio of Cherenkov light to total light that hits the FDs directly is very small due to the directionality of the Cherenkov photons, the contribution of scattered (Rayleigh and aerosol) Cherenkov light becomes larger around the depth of shower maximum. Thus we should take scattered Cherenkov light into account. Otherwise we overestimate X_{max} and energy. Next, for each shower geometry, the shower core is placed randomly within a large enough area to cover the detectable region. Then the expected FADC counts produced by photons from a shower axis are estimated when atmospheric attenuation, actual detector configuration, mirror reflectivity, gains of PMTs, etc. are take into account. Finally, the energy and X_{max} distribution is estimated from the simulated showers that pass the same reconstruction cuts as used in the observed data. Fig. 1 (right) shows the average X_{max} that is expected to be observed by TA FD for either proton or iron primaries. This averaged X_{max} includes biases due to both the detector's acceptance and shower reconstruction.

The reconstruction accuracy is estimated by detector simulation by comparing the reconstructed values with simulation truth. The determination of arrival directions and positions of the shower core at $10^{19.0} \sim 10^{19.2}$eV are ± 2.0 deg and ± 0.3km respectively. The energy determination is $1.6 \pm 8\%$ for protons. The X_{max} accuracy $6.2 \pm 22\mathrm{g/cm^2}$ for protons. The total energy deposit which is calculated by integration of the Gaisser-Hillas function along the shower axis is 93 % for protons and 89 % for iron.

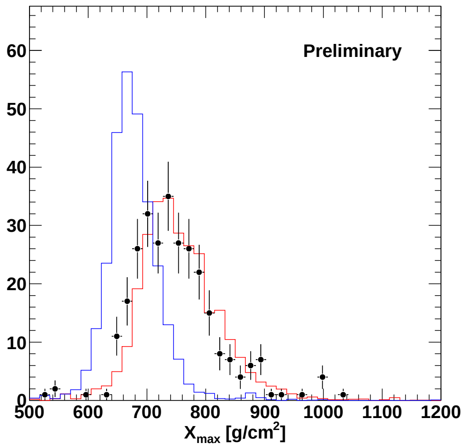

Fig. 2: X_{max} distribution above $10^{18.2}$eV. Black points are data. Red and blue histograms are MC for proton and iron primary, respectively. These MC are based on the hadronic interaction model of QGSJET-II.

3 Results

Fig. 2 shows the distribution of X_{max} above the energy of $10^{18.2}$eV. Red and blue histograms are the prediction of X_{max} distributions by MC simulation for proton and iron primary with the hadronic interaction model of QGSJET-II. Fig. 3 shows the averaged X_{max} with the prediction rails for proton (red) and iron (blue) primary and several hadronic interaction models. In order to estimate the agreement of X_{max} distribution with the MC predictions, Kolmogorov-Smirnov (KS) test is applied to these X_{max} distributions. The result of KS test is shown in Fig. 4. For any hadron interaction models, X_{max} distributions of proton primary model are compatible with data.

Here we present the TA FD stereo result on the UHECR mass composition using data from Nov. 2007 to Sept. 2011. At this conference, the data will be updated to 2012 Nov. Mass composition analysis derived from X_{max} technique is affected by acceptance or reconstruction bias which is well understood by comparison of data and MC. The X_{max} distribution is consistent with proton primary model with QGSJET model above $10^{18.2}$eV. X_{max} distributions for each energy are tested by KS test and P values show that proton model is compatible with proton model for whole energy region. On the other hand, iron model can be excluded below $10^{19.4}$eV. Averaged X_{max} shows that data is consistent with proton model, especially QGSJET model.

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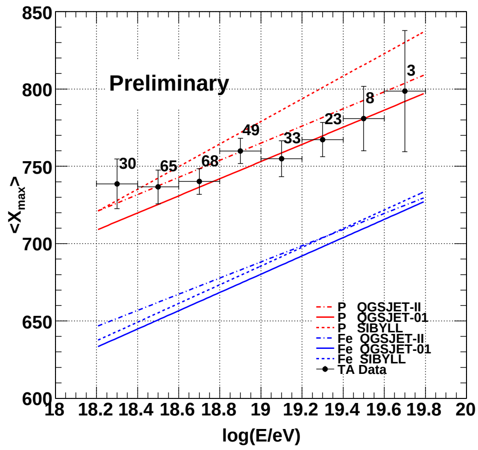

Fig. 3: Averaged $X_{\max}$ of MC and Data measured by TA FD stereoscopically.

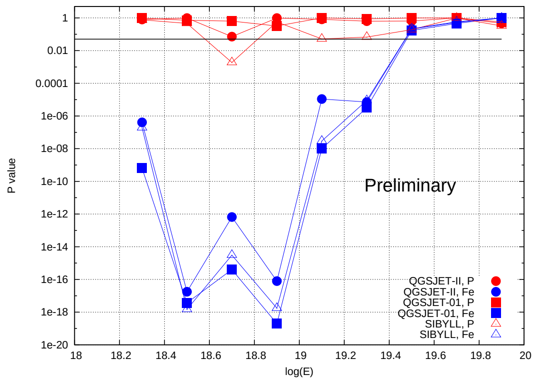

Fig. 4: P-values estimated by KS test applied to $X_{\max}$ distribution for each primary particle type, hadronic interaction model and each energy region.

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