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Measurement of the knees of proton and H&He spectra below 1 PeV

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Abstract. Galactic Cosmic ray (CR) origin is still a mystery. Measuring the knees of the CR spectra for individual species is a very important approach to solve the problem. ARGO-YBJ and LHAASO-WFCTA[1] combined experiment made the first step by measuring the spectrum of hydrogen plus helium nuclei and finding the knee around 0.7 PeV[2]. A significant boost is expected by using LHAASO experiment[3] to measure the spectra and their knees for pure proton and other species in few years. The key is to separate the specific species from all CR samples. In this paper, a multi variate analysis (MVA) approach for the CR composition analysis in LHAASO experiment is discussed. Preliminary results of the analysis and expectations are presented.

1. Introduction

In order to discover the origin of galactic cosmic ray (CR), tremendous efforts have been made in the passed 100 years. Many experiments had been carried out on both space borne and ground based platforms. The most significant feature of the power-law-like spectrum of CRs with all species mixed is the “knee”, i.e. a significant bending of the spectrum from the power-law index of approximately -2.7 to -3.1 around few PeV. Solving the mystery of the mechanism of the knee would be a significant progress in the approach. Measuring the knees for every single species is a straightforward route. Since the space borne detectors in the latest experiments such as DAMPE and ISS-CREAM are designed to reach the upper limits of few hundred TeV, the measurements of CR spectrum at higher energies in which the knee was found have been carried out by using ground based extensive air shower (EAS) technique. Because of the lack of the way to identify the type of CR particles before they entering the atmosphere, the identification of the primary CR particles troubles the EAS measurements since it was invented in last century. In principle, the EAS technique is a calorimeter-like detection of showers in the air generated by the incident CR particles at the top of the atmosphere. The way to identify the primary particles is to measure as many as possible the shower parameters that characterize the differences, even if they are insignificant sometimes, between the showers caused by specific types of particles. Finding primary species sensitive parameters is the most important step and building the corresponding detectors with sufficient sensitivities is the other. After all, the real difficulty to the high precision measurements of the parameters is the intrinsical fluctuation of the shower development in the



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atmosphere. Selecting a right altitude to carry out the multi-parameter detection experiment is very crucial as well. All of those key criteria are met by the experiment of ARGO-YBJ at 4300 m above sea level (a.s.l.) with the combination of the air Cherenkov telescopes, namely LHAASO-WFCTA prototype detectors. As a unique design with the full coverage on the ground, ARGO-YBJ detectors measures every single secondary particles in a shower. The advantages are that the core can be located with a precision better than 2 meters, and the particle density in the core, e.g. within 3 meters from the core, is well measured. Plus the well measured direction of the shower, the former enables the Cherenkov telescopes which watch the same shower to measure the shower energy as a function of the total number of photons in the shower image with a resolution of approximately 25% and accuracy better than 3% over the energy range from 100 TeV to 10 PeV for selected rather pure samples (93%) of protons and helium nuclei. The later combining with the shape information carried by the Cherenkov image of the shower, provides a tool of identifying primary protons and α 's out of other species with a contamination of few percent. All of those result a clean measurement of the spectrum of CR protons and α 's over the range from 100 TeV to 3 PeV and a discovery of the knee of the spectrum at 0.7 PeV, which is well below the knee of the spectrum of all particles[2]. Along the way established by this experiment, LHAASO with much larger exposure and more parameters being measured, is planned to achieve the goals of measuring more spectra for more species with much higher statistics. In this paper, the measurement of the spectra for mixed $H&He$ are discussed as an example of the Multi Variate Analysis (MVA).

2. Composition sensitive parameters and their measurements in LHAASO

LHAASO is a multipurpose complex of EAS detection consisting of four major detector arrays[3], ie. 5195 scintillation counters and 1171 muon detectors covering a area of 1.3 km², 78,000 m² water Cherenkov detector (WCD) with 3150 gap-less detecting units, similar to the ARGO-YBJ carpet detector array, and 18 wide field of view Cherenkov telescopes watching over the sky above the whole complex with a coverage of 5200 square degree. The measurements of pure proton and $H&He$ spectra needs only 1/4 of the whole array which is expected to be turned on for operation by the end of 2018. In ref.[4], the apparatus has been described in details including following 3 pieces.

1) 900 WCD units, 25 m² each equipped by a large (9") PMT for timing and a small (1.5") PMT for pulse size, measure shower directions with a resolution better than 0.3 degree, core locations with a resolution of 3 m and the energy flux near the core within the unit which the core hits in. The last parameter is sensitive to the type of primary particle because it is a measure of the energy carried by hadrons near the core. Number of hadrons remaining in a shower depends on the shower development rather sensitively.

2) about 200 muon detectors, 36 m² each surrounding the WCD, measure the muon content for every shower that triggered the complex of detector arrays. Since the muon content in a shower is a function of the shower energy following a power law, so $N_{\mu}^A/N_{\mu}^p \approx A^{(1-\eta)}$, where η is the index of the power law. This indicates that the muon content is a sensitive parameter to the composition unless the index is very close to 1.

3) 6 telescopes take the shower Cherenkov images with a pixel size of 0.5 degree. Given the shower distance by WCDs, the total number of photons in the image measures the shower energy with a resolution of $\sim 20\%$ as a constant over a wide energy range. The angular offset of the shower image from the arrival direction measures the distance from the shower maximum to the telescopes with a resolution of ~ 40 g/cm². Some Hillas parameters of the shower image is also sensitive to the composition, e.g. the angular length reduced by the width that was used in the ARGO-YBJ/WFCTA experiment.

A set of parameters is well defined as follows in Table 1 in which, $\log_{10}N_0^{pe} = \log_{10}N^{pe} + 0.0092(R_p/1m) + 1.05\tan\alpha$ is the total number of photoelectrons in the Cherenkov image N^{pe}

Table 1. The parameters sensitive to the shower composition.

parameter	definition	explanation
p_F	$\log_{10} S_{max} - 1.39 \log_{10} N_0^{pe}$	reduced energy flux in shower core
p_μ	$\log_{10} N_\mu - 0.982 \log_{10} N_0^{pe}$	reduced muon content
p_X	$\Delta\theta - 0.0097 R_p - 0.47 \log_{10} N_0^{pe}$	reduced angular off-set of shoer image
p_C	$L/W - 0.0139 R_p + 0.267 \log_{10} N_0^{pe}$	reduced image length

normalized to $R_p = 0$ and $\alpha = 0$, where R_p is the impact parameter of the shower axis to the Cherenkov telescope and α is the space angle between the shower direction and the optical axis of the telescope, as a good shower energy estimator as mentioned above. S_{max} is the total number of equivalent photoelectrons recorded by the small PMT in the water Cherenkov detector unit hit by the shower core. $\Delta\theta$ is the angular distance between the shower arrival direction and the centroid of shower image. L and W are length and width of the shower Cherenkov image as two Hillas parameters.

All parameters are well defined with the corresponding measurements using relevant apparatus in LHAASO elsewhere[4]. The typical distributions of the parameters and the separation between proton showers and iron showers are discussed also there. One-to-one correlation between the parameters had been checked and find quite independent between them. According to this, to achieve the selection of the pure proton out of all well constructed CR samples is straightforward by using any two of the parameters with required purity and sufficient efficiency. A more sophisticated analysis based on standard multi variate analysis (MVA) procedures are discussed in following section.

3. Multi Variate Analysis for selection of pure proton and $H&He$ showers

There are methods in the market of MVA in high energy physics, such as artificial neural network and boost decision tree with gradient boosting(BDTG). The later has been well developed as an algorithm available in toolkit TMVA[5] analysis kit and used in this paper for the analysis. Results reported here are based on a set of parameters similar to that was listed in Table 1, except the parameter p_X being replaced by the parameter $p_E = \log_{10} N^{pe} + 0.0084 R_p$ without the correction on the space angel between the shower axis and the telescope optical axis, α . The exact definitions of the parameters can be found elsewhere [6]. By including p_E in, the energy dependence of those parameters used in the analysis will be taken into account.

To train the BDTG based classifier with four tuned parameters, namely p_F , p_M , p_C and p_E , about 250k showers have been found triggered the both detectors, ie. WCDA and WFCTA, among 1.83M generated showers at energies between 100 TeV and 1 PeV using LHAASO simulation programs. The showers are assumed to be generated by a composition model with five components of proton, Helium, CNO, MgAlSi and iron nuclei. The population ratio between the components is 1:1:1:1:1. A half of the data set has been used to train the classifier for the separation of proton and Helium events from all heavier nuclei than Helium. A weight, defined as $1/\Delta N_C(E)$, is applied in the training, where $\Delta N_C(E)$ is the the number of events of C -th component between the energy E and $E + \Delta E$, where ΔE is the width of the energy bin in the analysis. The response of the classifier can be normalized to a variable with values from -1 to 1, while the value -1 indicate signal-like events and 1 for background events. The other half of the simulated events has been used to test the trained classifier. Figure 1. shows how the classifier reacts to the sample events which we have known what primaries of them are. Colors of the curves indicate the species of the primary CR particles as illustrated in the figure

legends. It is clearly shown that the classifier has a high efficiency to separate protons from irons, while the CNO component has a nearly constant distribution over the whole range from -1 to 1 indicating the classifier can not find clearly differences of them from either light or heavy components as they should be. The Helium showers are less efficiently selected out by the classifier than protons'. Nevertheless, the classifier works very efficiently to pick out proton plus Helium showers by setting a cut around -0.8 with a small contamination mainly due to CNO.

Figure 2. shows that the efficiency maintained to be a constant around 85% for p+He, with a constant contamination of about 15%, over the whole energy range from 100 TeV to 1 PeV. Given the size of the WCDA, the event rate is very large. With one year operation, one should

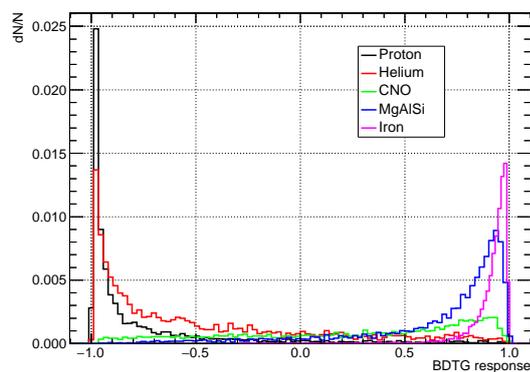


Figure 1. The responses of the trained classifier to the sample events generated using LHAASO simulation tools between energies from 630 to 707 TeV. Colors of curves indicate species as explained in the legends.

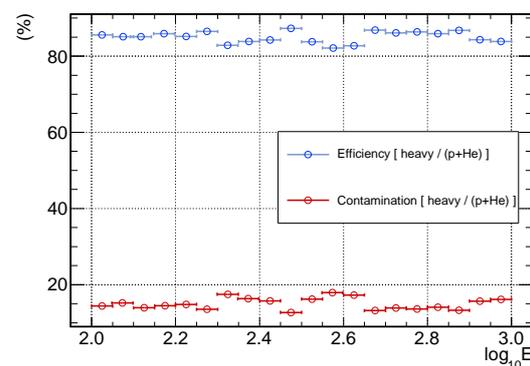


Figure 2. The efficiency of the selection of $p+He$ showers from the samples that have 5 components with the population ratio of 1:1:1:1:1 over an energy range from 0.1 to 1 PeV.

have enough statistics to complete a quite clean measurement of the energy spectrum of the protons plus Helium nuclei. As an example, one estimated the $p+He$ event rate by using the composition model by J.Horandel[7] and assuming a duty cycle of 15% for WFCTA of LHAASO as presented in Figure 3. About 150,000 events are expected above 100 TeV that allow us to measure the knee of proton spectrum around 700 TeV with high significance, while about 7000 events above 700 TeV allow us to measure the features of the spectrum above the knee with sufficient statistics as well. This is the missing puzzle in the previous measurement[2].

Given a sample of CRs with a purity of 85% or better, the energy reconstruction of the shower is rather straightforward by using the total number of Cherenkov photons in the shower image minimized the uncertainty due to the composition. It has been proved to be a good energy estimator because of both the bias less the 3% and the consistent resolution as a function of energy less than 20% as shown in Figure 4.

In summary, the LHAASO experiment will enable an effective way to identify CR primary by measuring at least 4 independent parameters of the induced air shower and applying the MVA algorithm. As an example, the selection of $p+He$ samples with the purity better than 85% has been achieved using the simulation tools developed for LHAASO experiment. With such a pure sample, the CR shower energy measurement using the total number of Cherenkov photons in the shower image is much certain and precise, i.e. the energy bias is under control within 3% and the resolution is maintained to be nearly a constant of below 20% over the energies at which the knees of the spectra are for all species. MVA has great potential to be developed to select even pure samples such as pure proton or pure iron samples. Thus, one would expect to have a clear

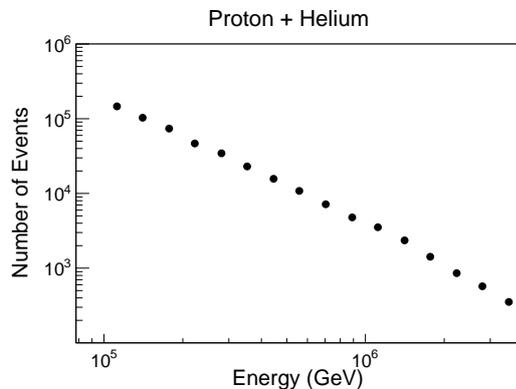


Figure 3. The expected number of events per year for $p+He$ showers based on the model of composition by J.Horandel[7].

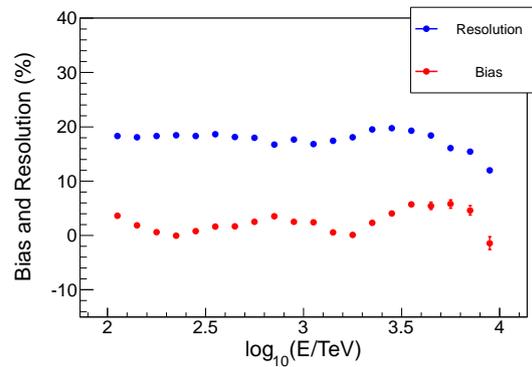


Figure 4. The energy resolution (blue) and systematic offset (red) of pure $p+He$ events using the total numbers of Cherenkov photons in the shower images. It is noticed that the resolution is nearly a constant over the whole energy range.

picture of the phenomena associated with the knees or even more detailed structures of the CR spectra. It will enable a much deeper understanding on the mechanism of knees, propagation and the production of the galactic CRs.

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