Measuring the attenuation length of muon number in the air shower with muon detectors of 3/4 LHAASO array

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Abstract

LHAASO KM2A consists of 5915 scintillation detectors and 1188 muon detectors, and the muon detectors cover 4% area of the whole array with 30 m spacing. The muon number of air shower events, with very high energy, is investigated with the data recorded by muon detector of the 3/4 LHAASO array in 2021. The attenuation length of muon number in the air shower is measured by fitting the muon number with constant flux in various zenith angles, based on the constant intensity cut method. The variation of the attenuation length as shower energy from hundreds TeV to tens PeV is presented. The results of simulation also is presented for comparing.

1 Introduction

Muons are produced in decay of baryons and mesons generated in hadronic collisions during the early processes of the EAS (extensive air shower). They are very penetrating particles and suffer less attenuation in the atmosphere than electromagnetic and hadronic components of showers. Thus, shower muons keep the original information of hadronic interaction at very high energies, the mean number of muons in a shower could be used to validate hadronic interaction models by comparing EAS predictions with experiment data. On the other hand, the muon number is also sensitive to the mass composition of the cosmic ray, since the mean number of muons produced at one and the same interaction energy grows in accordance with the atomic mass *A* of interacting particles [1].

The HiRes/MIA collaboration already reported a discrepancy in simulated and measured muon number in air showers between 10^{17} to 10^{18} eV in the year 2000 [2]. A combined analysis of eight experiments (EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk) shows that the muon deficit in simulation increasing with the energy [3]. Recently experiment results also found that, the muon deficit is greater at larger distances to the shower axis [4], and the attenuation of the muon content of measured is lower than that of predicted [5].

LHAASO (Large High Altitude Air Shower Observatory) experiment built 1178 buried water Cherenkov detectors over one square kilometer area with 30 m spacing. It provides one new facility to measure the muon content in air shower around knee region of cosmic ray. In this paper, we will present the preliminary results on the attenuation length of muon number in the EAS measured with the muon detectors in the 3/4 LHAASO KM2A.

2 LHAASO muon detector and muon number measurement

LHAASO is a ground-based air shower observatory located at 4410 m above sea level in Daocheng, China [6]. It is a hybrid detectors array that consists of an EAS array covering an area of 1.3 km^2 (KM2A), 78,000 m^2 water Cherenkov detector array (WCDA) and 18 wide-field air Cherenkov/fluorescence telescopes (WFCTA). The KM2A consists of muon detectors (MDs) with a spacing of 30 m and electromagnetic detectors (EDs) with a spacing of 15 m which will record the muon and electromagnetic particles respectively.

In this paper, the analysis is based on the data sample collected from Jan to June of 2021 with the 3/4 LHAASO KM2A, which includes 3978 EDs and 917 MDs as shown in the left plot of Figure 1.

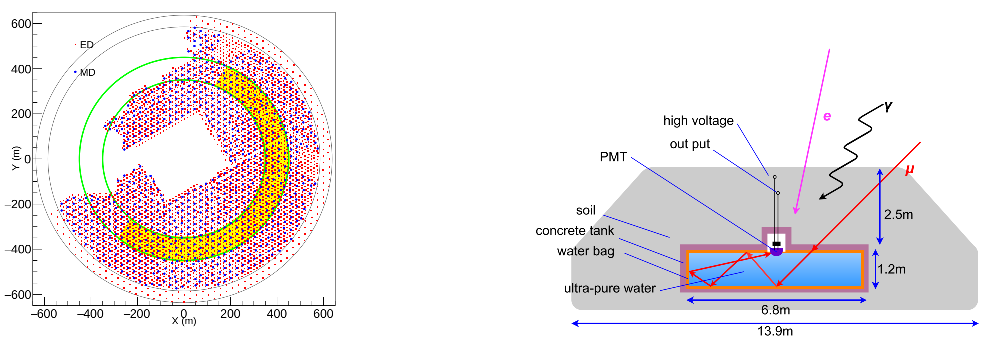

Figure 1: Left: Layout of 3/4 LHAASO KM2A. The yellow area show the core distribution of events after selection. Right: Schematic of LHAASO muon detector.

2.1 Muon detector and muon measurement

The effective area of one MD is 36 m^2. The total muon sensitive area in LHAASO is more than 40,000 m^2. The MD has a wide dynamic range up to 10,000 particles, which enables to measure the muon content in a large energy range without saturation [6]. The right plot of Figure 1 shows the schematic of MD. The housing of unit MD is a concrete tank which diameter is 6.8 m and depth is 1.2 m. Tank internal is a water bag with reflectivity higher than 95%, and ultra-pure water is enclosed by tank. The thickness of the overburden soil above MD is 2.5 m that absorb electromagnetic and other charged particles in the shower, the muons with the energy above 1 GeV can pass through the overburden soil. At the top of the water is an 8-inch photo-multiplier tube (PMT), PMT collects the Cherenkov light which yield by high speed muons.

The PMT signals are digitized by flash analog-to-digital converters (FADCs) [6]. When signals of one FADC channel amplitude exceeds the preset threshold, the signal is recorded as one 'hit' and this MD is recorded as fired detector. A time stamp of the hit is generated by a time-to-digital converter (TDC). Hits from MDs and EDs in a time window of ± 5 μs around the event trigger time are collected and built into one event. Only the ED and MD hits within [-30,50] ns of the shower front plane are selected for further analysis work. An event trigger is generated if the hit multiplicity in the time window of 200 ns exceeds a preset multiplicity threshold.

The number of muon for one triggered event is equal to the integral charge of all the hits divided by the VEM (vertical equivalent muon). In order to reduce the punch-through effect of the high energy particles near the shower core, all the hits within 40 m from the shower axis will not be counted. On the other hand, the hits 200 m far from the shower core isn't counted also due to the limited geometry of the KM2A. So, in this paper, the number of muon N_μ in one shower event is defined as the total muons by counting the MD within the 40—200 m ring from the shower axis. For the inclined shower with zenith angle θ, the number of muon N_μ will be corrected.

2.2 Simulation

The COsmic Ray SImulations for KAscade (CORSIKA) code (version7.6400) [7] software package is used to simulate EAS of cosmic ray with primary energy from 100 TeV to 10 PeV. The zenith angle of incident cosmic ray were sampled within $0° - 70°$. In CORSIKA simulation, both hadronic interaction models QGSJET-II-04 and EPOS-LHC are applied for model checking. Primary particle components contained in simulation include hydrogen (H), helium (He), nitrogen (N), aluminum (Al) and iron (Fe) nuclei. The detector response of ED and MD were simulated by G4KM2A [8] package which developed in the framework of GEANT4. The random noise in single ED and MD is also considered in the simulation.

After the simulation data normalized according to the H3a model spectrum of [9], the rate of hits for one single MD is shown in the left plot of Figure 2 together with the experiment data. The hit rate is matched well between simulation and data except below the 0.2 muons. So only the hit larger than 0.2 muons will be counted for the number of muon N_μ in the shower event. The hit rate distribution for various zenith interval is shown in the right plot of Figure 2. It's clear to find that, the single muon peak is equal for various zenith angle after this correction.

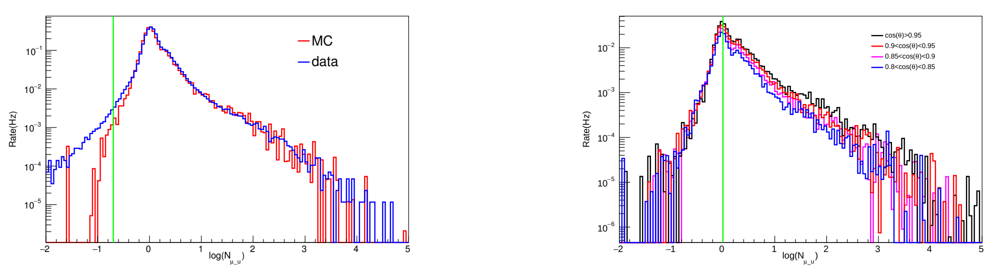

Figure 2: The hit rate distribution of one single MD with the muon number of the hit N_{μ_u}. Left plot shows the simulation result together with the data, which match well above 0.2 muons as the green line indication. Right plot shows the hit rate for various zenith angle, the single muon peak is same as the green line indication.

2.3 Event selection

The following event selection criteria are applied in this work: (1) NfiltE $\geq$ 50 (NfiltE: the hit number of EDs after filter out noise); (2) NfiltM $\geq$ 15 (NfiltM: the hit number of MDs after filter out noise); (3) NtrigE $\geq$ 50 (NtrigE: the EDs number after filter out noise); (4) 350 m $\leq R_p \leq$ 450 m (R_p: distance from shower axis to array center); (5) zenith angel $\theta \leq 45°$.

After application the above event selection criteria, more than 5×10^8 events left and the shower core distribution is shown in left plot of Figure 1. More than 3.7×10^5 simulation events pass the selection criteria. The event rate distribution is shown in Figure 3 for the simulation sample of two interaction models after the selection, the event rate of the data is also plotted together with simulation. The bottom ratio plot indicates the data matched well with the simulation.

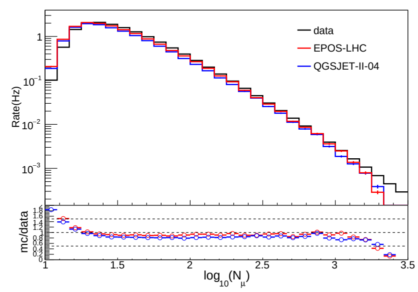

Figure 3: The event rate distribution with the number of muon N_μ after event selection. The ratio between the simulation and data (black) for both hadronic interaction models EPOS-LHC (red)and QGSJET-II-04 (blue) are shown at the bottom plot.

3 Attenuation length of muon number

According the the isotropic assumption of cosmic ray, the same intensity corresponds to the same primary energy for showers at various zenith angle. The muon number at the same intensity varies with zenith angle θ, because the showers travel through different path for different zenith angle and the evolution of muon number in the atmosphere is different. For the shower with same primary energy, the relationship of muon number and zenith angle follows formula (1):

$$N_\mu(\theta) = N_\mu^0 e^{\frac{-X_0 sec\theta}{\Lambda_\mu}} \tag{1}$$

Where $N_\mu(\theta)$ is the muon number of the shower with the zenith angle at θ. N_μ^0 is the normalization parameter. X_0 is the vertical atmospheric depth, it is $600g/cm^2$ at LHHASO, and the Λ_μ is attenuation length of muon number.

After event selection according above critira, the events within the zenith angle from $0° - 45°$ were grouped into 5 zenith angle intervals with the same aperture. The integral flux of cosmic ray in each zenith angle interval should be same for the same constant primary energy. The integral flux number for shower with more muon than N_μ for each angle interval is plot in the left of Figure 4.

As shown in the left plot of Figure 4, one constant intensity dotted line will cross with these five integral spectrum. The corresponding N_μ for these five intersection points is plotted in the

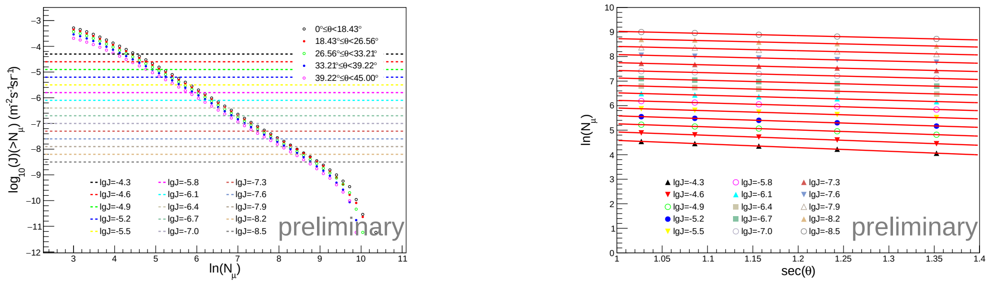

Figure 4: Left: The integral flux spectrum of the muon number N_μ of the shower, only statistic error bar shown. Each type of the mark represents one interval as the legend in the right up corner. Each dotted line represents one constant intensity as the legend at the bottom. Right: The muon number N_μ of the shower various as the zenith angle θ. Each type of the mark represents one constant intensity as the legend shown at the bottom.

right plot of Figure 4 with same type of mark. Total 15 constant intensity dotted lines produce 15 group intersection points as shown in right plot of Figure 4. Each group is fitted with the formula (1) as the line in the plot. The slope of the fitted line is equal to $\frac{X_0}{\Lambda_\mu}$.

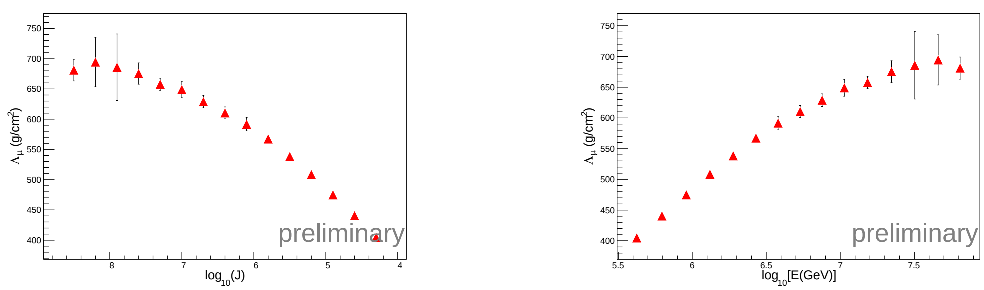

Figure 5: Left: The attenuation length various as the intensity of the shower. The error bar from the fitting results, the longest due to its worst fitting. Right: The attenuation length various as the reconstruction shower energy.

According the fitting result, the attenuation length of muon number is different under different cutting integral intensity, as plotted in the left panel of Figure 5. The attenuation length decrease as the intensity increase. The intensity corresponds to shower energy, which can be reconstructed from N_μ of vertical shower. After the transition from intensity to energy, the attenuation length increases as the reconstruction energy during hundreds TeV to Tens PeV, as shown in the right plot.

The attenuation length of muon number is also measured with same method for simulation data. As shown in Figure 6, the simulation result for both hadronic models QGSJET-II-04 and EPOS-LHC are consistent well with LHAASO experiment predicted with the energy below 1 PeV. The attenuation length of simulation also increases with shower energy. The statistic of the simulation for shower with energy above PeV is very limited, it shoud be improved in the future full LHAASO array analysis work.

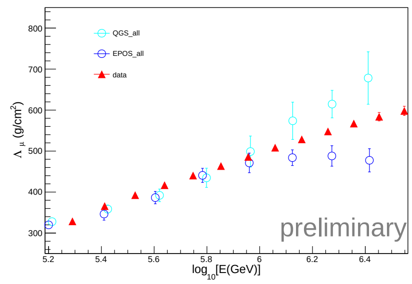

Figure 6: The Λ_μ of Data and MC. The red triangle indicts the data result, the pale blue circle and the blue circle indict the result of QGSGET-II-04 and EPOS-LHC. Error bar indicts statistical error.

4 Conclusion

This work is based on the data collected during January to June of 2021 with the 3/4 LHAASO-KM2A operation. By comparing with the simulation results, the muon number measured by LHAASO muon detector is agreed well with expected results for various zenith angle shower. The event rate distribution is matched with the expected results also.

The attenuation length of muon number in the air shower is measured with 3/4 LHAASO-KM2A based on the CIC method. The preliminary results of attenuation length are presented for shower energy above hundreds TeV to tens PeV, the increasing trend as the shower energy is clear. This trend also is found in the simulation results for both hadronic interaction model EPOS-LHC and QGSJET-II-04.

Acknowledgements

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