Test of the hadronic interaction model EPOS-LHC and QGSJETII-04 with Tibet EAS core data

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Abstract: A hybrid experiment has been started by The Tibet ASγ collaboration at Tibet, China. It consists of a burst-detector-grid (YAC, Yangbajing Air Shower Core array) and the Tibet air-shower array (Tibet-III). The Tibet-III array is used to measure the total energy and the arrival direction of the air-showers, and YAC-I observes high energy electromagnetic particles in air-shower cores. By comparing the MC data with our experimental data, we examine hadronic interaction models currently used for air-shower simulation code CORSIKA(ver.7.3500), especially EPOS-LHC(ver.3400) and QGSJETII-04. In this paper, the preliminary results on the interaction model check at *10 TeV energy region is reported using YAC-I data taken from May 1st 2009 through February 23rd 2010 with the effective live time 152.16 days.

Keywords: air shower core, hadronic interaction model, cosmic ray.

1 Introduction

The Monte Carlo simulations are widely used in the extensive air showers (EAS), which are based on some hadronic interaction models and primary cosmic ray composition models. In our previous work, we have reported the results to check the hadronic interaction models SIBYLL2.1 and QGSJET2 at an energy region of *10 TeV using the data obtained by the YAC-I (Yangbajing Air Show Core detector, the first stage)[1]. After the LHC experiments have provided a number of very interesting data sets comprising minimum bias p-$\bar{p}$, p-Pb and Pb-Pb interactions, the new hadronic interaction models EPOS-LHC(ver.3400)[2] and

QGSJETII-04 [3]have been reported. It need to be checked and further improved.

In this paper, we check the hadronic interaction models EPOS-LHC and QGSJETII-04 at an energy region of *10 TeV using the data obtained by the YAC-I. The energy region of *10TeV is chosen because the primary composition at this energy region has been better measured by direct measurements and the uncertainty is smaller.[4][11] Therefore, we could avoid the confusion coming from the uncertain primary composition, as always appeared in higher energy region.

2 A New Tibet Hybrid Experiment

A new hybrid experiment has been started by The Tibet ASγ collaboration at Tibet,China(4300m above sea level; 606 g/cm^2) from May 2009 to February 23rd, 2010 . It consists of a burst-detector-grid (YAC, Yangbajing Air Shower Core array) and the Tibet air-shower array (Tibet-III). The Tibet-III array consists of 789 detectors is used to measure the total energy and the arrival direction of the air-showers, and YAC-I consisting of 16 scintillation detectors, observes high energy electromagnetic particles in air-shower cores. Each unit of YAC-I is composed by a lead layer of 3.5 cm thickness ($\sim$ 7 r.l.) and a plastic scintillator of size 40cm$\times$50cm$\times$1cm. It covered $\sim$ 10m^2 by 4$\times$4 detectors which is used to record the electromagnetic showers induced by high energy electrons and/or photons in the EAS cores. To measure the EAS-core-burst under the lead layer, we use two photomultipliers(PMT) to achieve a wide dynamic range from 1 MIP (Minimum Ionization Particle) to 10^6 MIPs, i.e. a high-gain PMT and low-gain PMT for the range of $1 \sim 3 \times 10^3 and 10^3 \sim 10^6$ MIPs, respectively. The response linearity of each YAC-I detector was calibrated by cosmic-ray single muons and by the accelerator beam (BEPC-LINAC)[5][6]. YAC-I is triggered when any one of 16 detectors records a local shower with the size of at least 20 MIPs. The event rate is about 30 Hz. The total live time of our data set in present analysis is 152.16 days.

3 Simulations

A Monte Carlo simulation code CORSIKA (ver.7.3500) has been carried including SIBYLL2.1, EPOS-LHC(ver.3400) and QGSJETII-04 hadronic interaction models are used to generate air shower events. In this work, we first use Monte Carlo simulation of SIBYLL2.1, with two primary composition models, the heavy dominant model (HD)[7] and the non-linear acceleration model (NLA)[1][8]. The proton spectrum of two models is connected with the direct experiment at the low energy side and the Tibet AS+EC experiment at the high energy side. But the He spectrum of two models is different. HD model coincides with the results from RUNJOB and ATIC-I, but the NLA coincides with the results from JACEE, ATIC-II, CREAM3. The fractions of the component of two composition models in different energy regions are listed in Table 1.

In the simulation, the primary energy is sampled from 1 TeV to infinite with zenith angles from 0 to 60 degrees incident isotropically. The axis of each EAS event is randomly dropped onto an area of 32.84 m$\times$32.14 m with YAC-I at its central part. The Monte carlo air-shower events are randomly dropped onto the YAC-I detector array plane, 15m wider in each side of the YAC-I array. We choose the value 15m because the area of 32.84 m$\times$32.14 m is checked to be wide enough to contain 99.5% EAS events under our event selection conditions (see below in the text).When high energy electrons or photons hit a YAC-I detector, the Geant4 (9.5) code[9] is used to generate the cascade showers in the Pb layer and in the detector. To identify an AS core event we use following quantities:

N_b: number of shower particles recorded by a YAC-I detector;

N_{hit}: number of YAC-I detector with N_b higher than a threshold value N_{bmin} (If $N_b \geq N_{bmin}$ for a YAC detector, it is called that this detector is fired);

$\sum N_b$: the sum of all N_b from 1 to N_{hit} ;

N_{btop}: the maximum of all N_b;

$< R >$: the mean lateral distance from the center of a fired detector to the N_b weighted center of all fired detectors;

$< N_b \times R >$: the mean N_b weighted lateral distance from the center of a fired detector to the N_b weighted center.

By choosing a N_{bmin} value and setting some event selection conditions we can obtain different event samples for that primary energies range at different region. For the present work using N_{bmin} =200 and the conditions of 1) N_{hit}=3, $\sum N_b \geq 3500$, 2)N_{hit} =4, $\sum N_b \geq 1700$,3)N_{hit} =5, $\sum N_b \geq 2200$, three Monte Carlo samples with the mode energy at $\sim$35 TeV,$\sim$70 TeV and $\sim$90 TeV are obtained, respectively. Their sample sizes are seen from Table 3. In all 12 cases Monte Carlo shows that the core resolution is better than 2 m if the Nb weighted center is taken as the AS core.

4 Data analysis

The data used in the analysis was collected in the period from May 1st 2009 to February 23rd, 2010 with the effective live time 152.16 days. We first check some noises appeared in our data set due to the hardware and the environment conditions. It is found that most noises appear as smaller 'signals'. Taking N_{bmin}=200, we can remove them and achieve a biggest available data sample. In addition, we found some gain drift for some YAC-I detectors during the operating process, by checking N_b spectrum of each YAC-I detector. By an 'off-line self-calibration' method this effect is carefully treated and corrected. Then the fit between high-gain signals and low-gain signals in their overlapping region is executed and N_b (or MIPs) is obtained for each fired YAC-I detector.

After the off-line calibration, we get $\sim$150000 events with $N_b \geq 200$ and $N_{hit} \geq 1$.With the same selection condition, three experimental data samples are obtained. They are also listed in Table3.

5 Results and Discussion

1) Check the primary composition model dependence. The comparison of Monte Carlo simulation of SIBYLL2.1 with two primary composition models are shown in Table 1 and Table 2. Table 1 shows, the fractional contents of the assumed primary cosmic-ray flux models, together with those for making air showers accompanied by high-energy bust events as shown in Table 2. The selection conditions which have been introduced in the above section. One can see from Table 2 that:

(a) more than 83% of events we selected are induced by protons and heliums below 100 TeV.

Composition model	Component	1 – 10 TeV	10 – 100 TeV	10^2-10^3 TeV
HD model	P	38.6%	32.0%	24.2%
	He	24.7%	22.4%	19.1%
	M	24.7%	27.1%	27.3%
	Fe	10.4%	18.5%	29.4%
NLA model	P	47.3%	31.1%	26.3%
	He	30.2%	25.1%	28.9%
	M	30.3%	32.4%	34.4%
	Fe	12.8%	11.3%	10.6%

Table 1: The fractions of the components of the HD model and the NLA model.Fraction of the proton (P),helium (He), medium (M) and iron (Fe) components in the assumed primary cosmic-ray spectrum of the HD[5] and NLA[6] models are listed.

Mode energy	Component	$\sim$ 35 TeV	$\sim$ 70 TeV	$\sim$ 90 TeV
SIBYLL2.1+HD	P+He / ALL	91.1% $\pm$ 2.4%	85.0% $\pm$ 1.3%	84.3% $\pm$ 1.7%
SIBYLL2.1+NLA	P+He / ALL	90.7% $\pm$ 2.1%	85.3% $\pm$ 1.1%	83.6% $\pm$ 1.4%

Table 2: After the core event selection, the fractions of the P+He in all components of the SIBYLL2.1+HD model and the SIBYLL2.1+NLA model are listed.

(b) We found the composition models dependence is less than 5% in our result. Therefore, we check the EPOS-LHC(ver.3400) and QGSJETII-04 hadronic interaction models only with the primary composition HD model.

2) Check the absolute intensity. Since our Monte Carlo simulation is started from 1 TeV, in order to normalize MC data and experimental data, we need to know the integral intensity of all particles of cosmic rays at E_0 = 1 TeV. Starting from Hörandal's spectra of each composition[10], we improve the major 8 ones (p, He, C, O, Ne, Mg, Si , and Fe) by the newest measurements [5][11][12]. The resultant integral intensity: I($E_0 \geq$1 TeV) = 0.139 $m^{-2}s^{-1}sr^{-1}$ with the error +0.0013, -0.0012 coming from the error of the index of each of the 8 spectra.

The comparison of our data with Monte Carlo simulations of EPOS-LHC +HD, QGSJETII-04 +HD , SIBYLL2.1+ NLA and SIBYLL2.1+ HD is seen from Fig.1 and Fig.2:

(i)The shape of the distributions of $N_b/\sum N_b$ are consistent between the YAC-I data and simulation data in all four cases, indicating that in the *10 TeV energy region the particle production spectrum of EPOS-LHC, QGSJETII-04 and SIBYLL2.1 may correctly reflect the reality within our experimental systematic uncertainty of a level about 10%.

(ii)The comparison of event absolute intensities in all cases, as seen from Fig.2, show some discrepancies between experimental data with Monte Carlo simulation. The smallest one is SIBYLL2.1+ NLA and the most obvious one is QGSJETII-04+HD.

A further analysis is going on. We will check QGSJETII-04 and EPOS-LHC with NLA, and we also want to check other hadronic interaction models used in corsika simulation code(ver 7.3500).

6 Summary

We examine hadronic interaction models currently used for air-shower simulation code CORSIKA(ver.7.3500), especially EPOS-LHC(ver.3400) and QGSJETII-04. The shape of the distributions of $N_b/\sum N_b$ are consistent between the YAC-I data and simulation data in all four cases, EPOS-LHC +HD, QGSJETII-04 +HD , SIBYLL2.1+ NLA and SIBYLL2.1+ HD, and in this *10 TeV energy region with YAC-I experiment, Compared with QGSJETII-04, EPOS-LHC is more close with Monte Carlo simulation. Some other quantities, such as N_b, $N_b{}^{top}$, Rw, Rw$\times N_b$ have the same behavior as well, though we did not show them in this paper due to the limit of the space.

Some discrepancies in the absolute intensities are seen. Data normally shows a higher intensity than Monte Carlo. Taking a more hard He spectrum as given by CREAM at the 1-100 TeV region can improve this situation. A further study is going on.

7 Acknowledgement

The collaborative experiment of the Tibet Air Shower Arrays has been performed under the auspices of the Ministry of Science and Technology of China and the Ministry of Foreign Affairs of Japan. This work was supported in part by a Grant-in-Aid for Scientific Research on Priority Areas from the Ministry of Education, Culture, Sports, Science and Technology, by Grants-in-Aid for Science Research from the Japan Society for the Promotion of Science in Japan, and by the Grants from the National Natural Science Foundation of China (Y11122005B, Y31136005C and Y0293900TF) and the Chinese Academy of Sciences (H9291450S3) and the Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS. The Knowledge Innovation Fund (H95451D0U2 and H8515530U1) of IHEP, China also provide support to this study.

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Mode energy	∼ 35 TeV	∼ 70 TeV	∼ 90 TeV
EPOS-LHC+HD	5072	16350	9983
QGSJETII-04+HD	4087	15781	9415
SIBYLL2.1+HD	2921	9239	5495
SIBYLL2.1+NLA	3941	12568	7492
YAC-I data	1609	5243	2990

Table 3: The numbers of core events of three samples selected by conditions 1), 2), 3) (see Section 3)in Monte Carlo simulation and YAC-I data.

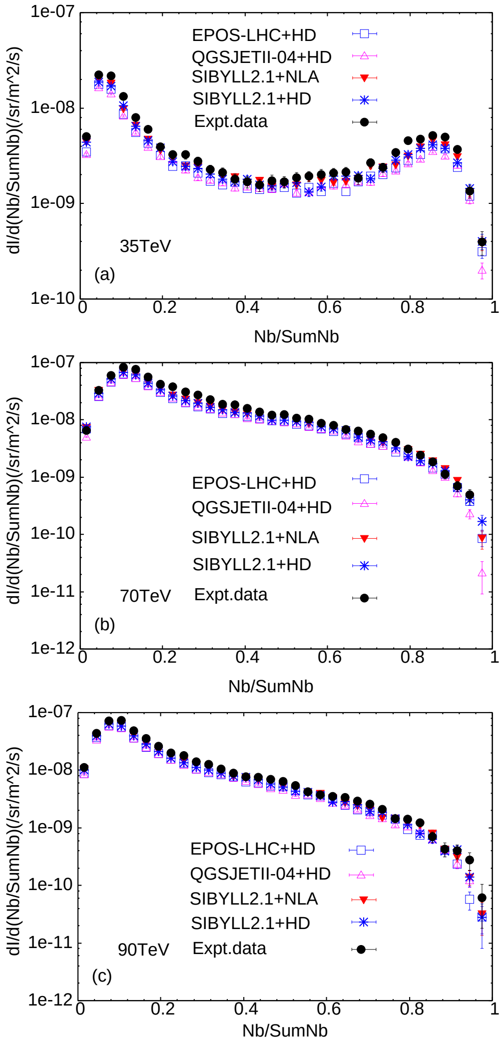

Fig. 1: The absolute intensity of $N_b/\sum N_b$ distribution of the three samples for EPOS-LHC+HD model, QGSJETII-04+HD, SIBYLL2.1+NLA model, SIBYLL2.1+HD model and the experimental data.

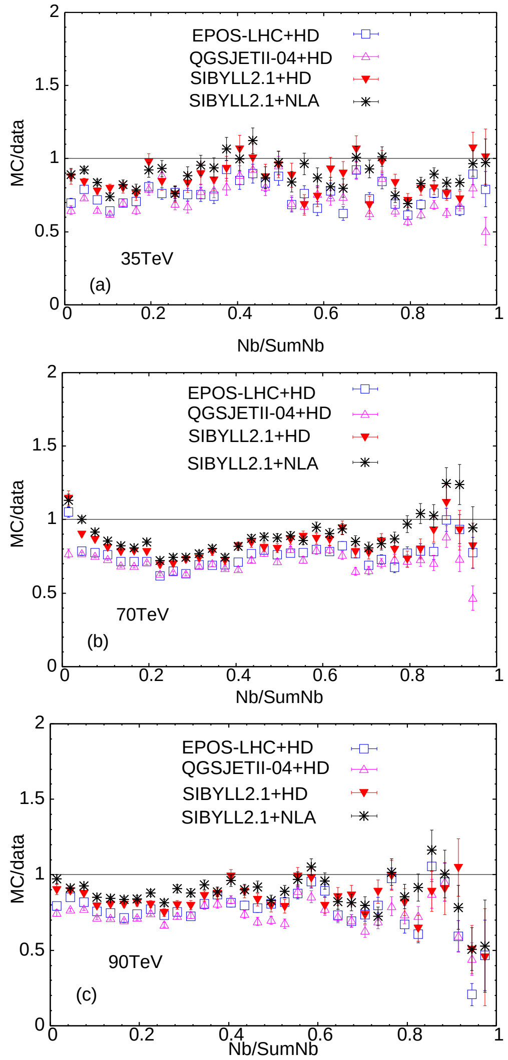

Fig. 2: The ratio of absolute intensity between MC and Expt. data.

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