European Organization for Nuclear Research

CERN Summer Student 2015 work report: Charm and Bottom Contributions to Muon Production in Ultra-high Energy Cosmic-ray Showers

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1 Introduction

Current Models for cosmic ray shower suffer a deficiency in muon numbers as compared with the observations made by Pierre Auger Observatory. One of the possible reasons is the lack of heavy quarks in the simulations. Since heavy quarks were produced in the LHC experiments, it is highly possible that cosmic ray showers, with an energy level high above those of all current collider experiments, generate heavy quarks which would further decay into muons[1]. Compared with Monte Carlos like EPOS, SIBYLL, QGSJET-1 and QGSJET-II, PYTHIA takes heavy quark production into consideration[2][3][4][5][6][7][8][9][10][11], which would futher decay into muons, raising the muon number to the level that is close to the observed value. This project is thus dedicated to the comparison of the features between PYTHIA and other models, especially those concerning muon production at ultra-high energy.

2 Comparison in 2D

During the first phase of the project, simulations were generated using CORNEX for a hydrogen atmosphere with proton being the primary particle, due to the fact that PYTHIA deals merely with proton-proton collision[2]. EPOS, SIBYLL, QGSJET-1 and QGSJET-II were all involved in the simulation, as well as tune 350, 371, 372, 380, 381 and 382 of PYTHIA. The composition of the atmosphere is an important factor affecting the behaviors of the plots and some of the effects will be discussed in the following sections. For each point in the plots, 1000 collisions were generated. With the statistics being high, the values of the dots were calculated by simply taking the mean of all events. By modifying the code relating CONEX and PYTHIA, a line can be printed out if a heavy quark is produced, thus charm and bottom quark production were tested and confirmed.

2.1 Muon and Electron number

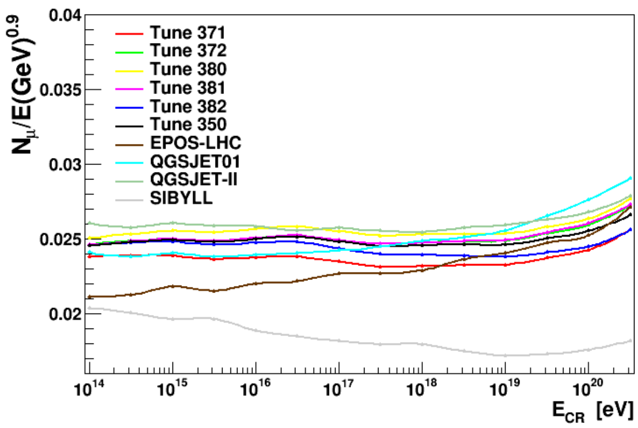

Figure 1: Muon number at $\chi = 1010\ g/cm^2$ with respect to E_{CR}. QGSJET-II has the largest muon number, while PYTHIA does not show a particularly high value.

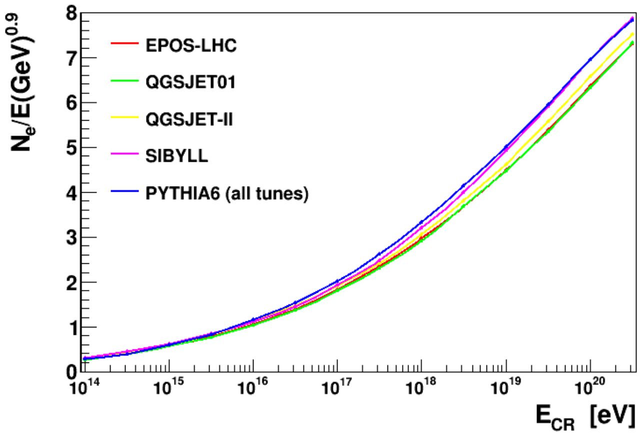

Figure 2: Electron number at $\chi = 1010\ g/cm^2$. All tunes of PYTHIA behave the same in the plot, therefore one PYTHIA6 curve is used to represent all the tunes.

Plots for muon (figure 1) and electron (figure 2) number were obtained at $\chi = 1010$ g/cm^2, which corresponds to h = 1500m, the height of Pierre Auger Observatory. The numbers are normalized with respect to $E_{CR}^{0.9}$ with GeV being the unit. It is obvious in the muon number plot that QGSJETII produces more muons than other Monte Carlos, which disagrees with the expectation that PYTHIA would give more muon number and the former result that EPOS produces the most muons among the other models. This might be due to a nuclear effect which is absent in the case of running with a hydrogen air, and further investigations of some spectra is needed to better understand the situation.

2.2 χ_{max} and $\sigma_{\chi_{max}}$

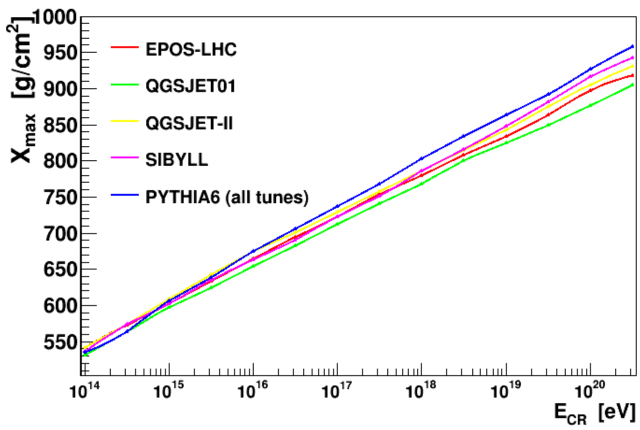

Figure 3: χ_{max} with respect to E_{CR}. PYTHIA has the largest χ_{max}.

χ_{max} is plotted (figure 3) as well as $\sigma_{\chi_{max}}$ (figure 4). The $\sigma_{\chi_{max}}$ plot was calculated by first taking the mean of all the values and then fitting the graph using

$$y = a(bx^2 + cx)^d \tag{2.1}$$

Here a, b, c and d are the fitting parameters. The fitting is not satisfying enough and further attempts should be taken, though the major features can be seen currently. The

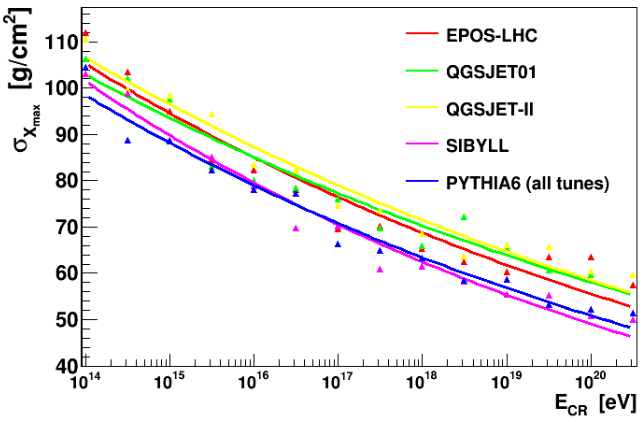

Figure 4: Preliminary plot of $\sigma_{\chi_{max}}$ obtained using fit as described in the text.

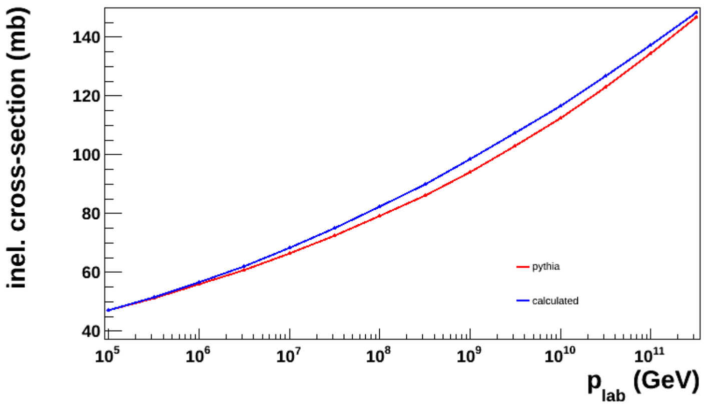

Figure 5: Comparison of cross section between PYTHIA and COMPETE. PYTHIA has a smaller cross section, which serves as a source for a larger χ_{max} value.

χ_{max} plot shows that PYTHIA has the largest χ_{max} value among all the models, and the sigma plot shows that it is less divergent than other models. This could be explained by a comparison of cross section between PYTHIA and COMPETE (figure 5). The cross section for PYTHIA was obtained by outputting the value during run time, different tunes giving the same value, and that of COMPETE was calculated. Since COMPETE fits the LHC data and its cross section is similar to those of EPOS-LHC and QGSJET-II, but lower than the QGSJET-1 predictions, it makes sense to compare these two models' cross section. The plot shows that PYTHIA has a smaller cross section than that of COMPETE, which leads to a lower interaction rate, causing the χ_{max} to be larger.

Another explanation could be found in the XFirstIn plot (figure 6), which presents the inelasticity of the first interaction calculated by 1-(the fraction of the primary energy carried by the leading particle). The plot has strong fluctuation and a fitting is necessary. However, presently no satisfacotry equations has been found, yet since the major trends can be identified, the plot is nevertheless shown here. It is interesting that Pythia is lower in XFirstIn than other CR models. Inelasticity being lower, χ_{max} should be larger, which is in agreement with the χ_{max} behavior obtained.

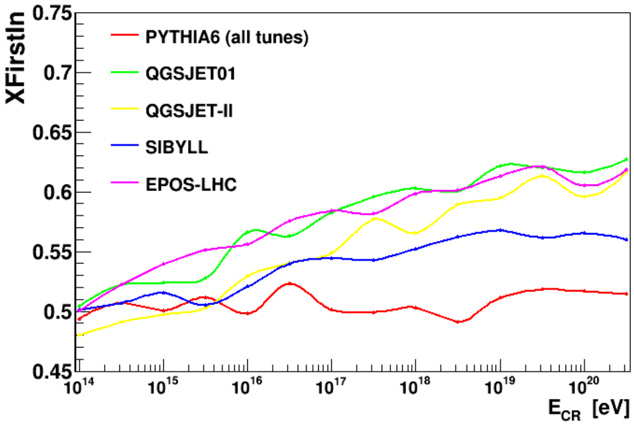

Figure 6: XFirstIn value with respect to center of mass energy. PYTHIA has a lower value compared with other models, which partly accounts for a larger χ_{max} value for PYTHIA.

3 Comparison in 3D

The second phase of the project makes use of simulations in 3D, with the same group of Monte Carlos implemented. The plots will be done with respect to zenith angle instead of energy. Since Auger is not able to measure muons directly, in best case it is "muon signal" which is the Cherenkov light emitted in a tank that was detected. The plotted values are the signal left by all particles for S1000 or only by the muons for SDmu in a water Cherenkov tank like the one used by the Pierre Auger Observatory at 1000m for the shower core. So the unit is in VEM (Vertical Muon Equivalent) which is more or less like an MIP in a scintillator. It is used as an energy estimator for Auger and to test the muon content. The ratio of SDmu can be used to compare with what is measured by Auger or at least compare to the other models. For instance it is interesting to see that Pythia as less muons than QGSJETII (in the previous plot when they were all counted) but more at 1000m. It means that the lateral distribution is probably different. To make sure that it is not coming from the electrons and photons the ratio of SDmu should be plotted. Plots can also be made concerning the ratio of MuMIA which is the muon density at 600m and the ratio of MuTr which the number of muons between 40m and 200m) to see the difference with 1000m. MuMIA, MuTr and SDmu are different quantities but all based on pure muons, so if the ratio to the same model is used they are comparable to see the evolution as function of the distance.

Due to the fact that the simulation takes significantly longer time compared with those in 2D, and that the jobs were submitted lately, the files for plotting are still under calculation, and currently no significative plots has been made. This section will be further discussed in the future.

4 Conclusion

Though PYTHIA does produce heavy quarks, present analysis shows that there is no excessive muon production compared with other models in a hydrogen atmosphere. Actual reason for such a behavior requires further investigations into the models and Monte

Carlos in 3D, yet comparisons in 2D simulations has confirmed a smaller cross section and XFirstIn, and a larger χ_{max} value for PYTHIA, which are in consistency with each other. Generation for the 3D files will be finished and new analysis will be carried out in the future. A new version of Monte Carlo which can deal with real atmosphere with heavy quarks taken into consideration may also help resolve the puzzle.

References

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