Muon Yields from Heavy-Quark Production in Ultra-High-Energy Cosmic Rays

Awadallah Mekki

African Institute for Mathematical Science (AIMS-Cameroon)
University of Khartoum
ASP2012 & 2014 CERN Summer Student Alumni

Objectives

1. The aim is to study the properties of extended air showers generated by ultra-high energy cosmic rays colliding with the nuclei (N, O) in the upper Earth atmosphere.
2. A simulation is generated for an air shower which is initiated by high energetic proton or nucleus (primary particle), which interacts with air by producing many secondary hadrons that interact again, and again and so on.
3. The main idea is to compare the characteristics of the air-showers using different hadronic Monte Carlos (MC) models and compare the result with others.

Introduction

- The work is a summer school project at the CMS experiment, CERN-Geneva.
- The purpose is to compare the characteristics of the air-showers using different hadronic MC models
- We used high-energy hadronic interactions models
- The models are $EPOSLHC$, $QGSJETII-04$, $SIBYLL2.1$ & $PYTHIA-6$

Materials

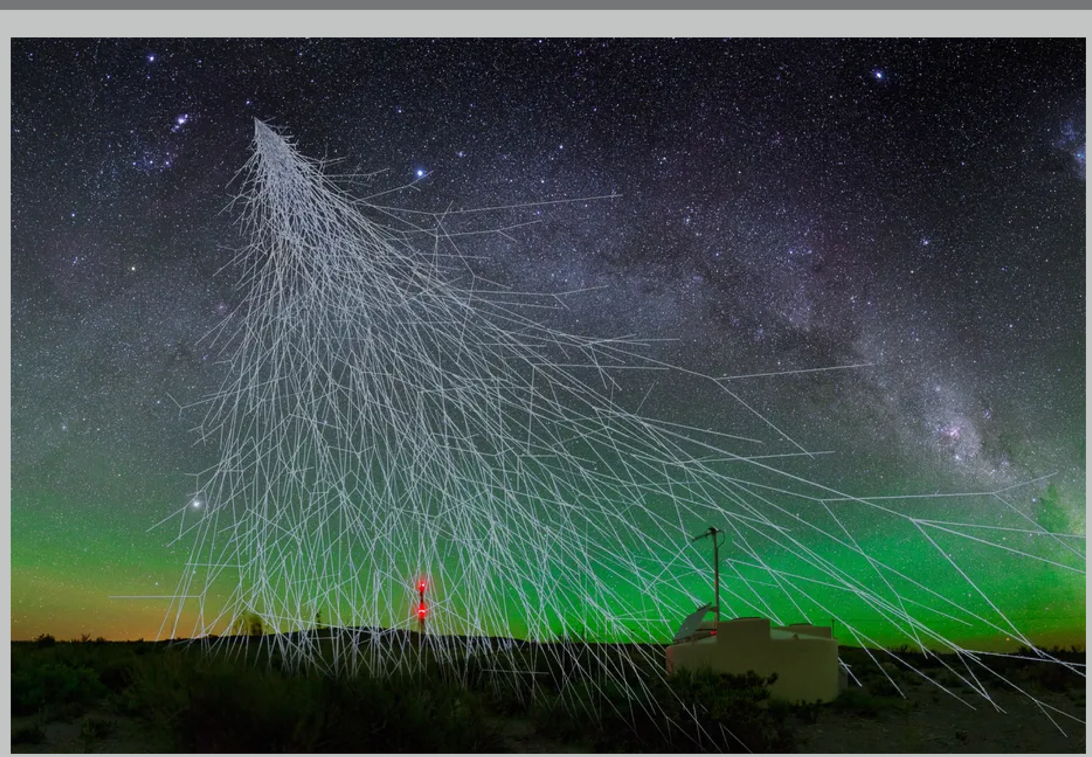

Figure 1:Illustration showing cosmic rays showering particles into Earth by A. Chantelauze, S. Staffi, and L. Bret

- We used the hybrid simulation code CONEX which interfaced to ROOT with Pythia-6 that is the only MC mode that contains heavy-quark production, and a proton atmosphere that is suited for fast one-dimensional simulations of shower profiles, including fluctuations. and a proton atmosphere that is suited for fast one-dimensional simulations of shower profiles, including fluctuations.
- CONEX combines Monte Carlo simulation of high energy interactions with a fast numerical solution of cascade equations for the resulting distributions of secondary particles.
- For a given primary mass, energy, and zenith angle, the energy deposit profile as well as charged particle and muon longitudinal profiles are calculated
- The simulation run for each model for different energies on lxplus. We used Linux, C++ and ROOT.

Procedures

- Two schemes were chosen for the calculations:
  i. Explicit MC simulation of the cascade for particles with energies above some chosen threshold as a free parameter.
  ii. Solution of nuclear-electro-magnetic cascade equations for sub-cascades of smaller energies.
- Using the same physical content.
- Only Bremsstrahlung, pair production and muon-nuclear interaction are taken into account in the MC part but are neglected in the cascade equations.
- The equation of the hadron-initiated extensive air shower is the hadronic cascade which develops via particle propagation, decay, and interaction with air nuclei of the initial particle and produced hadrons.
- The results written to ROOT files and presented.

The Main Cascade Equation:

- The hadronic cascade equation for propagation, decay, and interaction with air nuclei for initial and produced secondary particle is:

$$\frac{\partial\, h_a(E,X)|_T}{\partial X} = -\frac{h_a(E,X)|_T}{\lambda_a(E)} - h_a(E,X)|_T \frac{\left|\frac{dL}{dX}\right|_T}{\tau_a(E)\,c} + \frac{\partial}{\partial E}\left(\beta_a^{\rm ion}(E)\, h_a(E,X)|_T\right)$$
$$+\sum_d \int_E^{E_{\max}} dE'\;\; h_d(E',X)|_T \left[\frac{W_{d\to a}(E',E)}{\lambda_d(E')} + D_{d\to a}(E',E)\frac{\left|\frac{dL}{dX}\right|_T}{\tau_d(E')\,c}\right]$$
$$+ S_a^{\rm had}(E,X)\big|_T\,,$$

- The calculations do not require any pre-tabulation of particle cascades, they are characterized here by high efficiency and large flexibility.
- Applicable to wide range of energies and angles of incidence of a primary particle, and arbitrary parametrization of earth atmosphere

Results:

- We run the MC simulation for each of these models with different energies on lxplus and got following result:

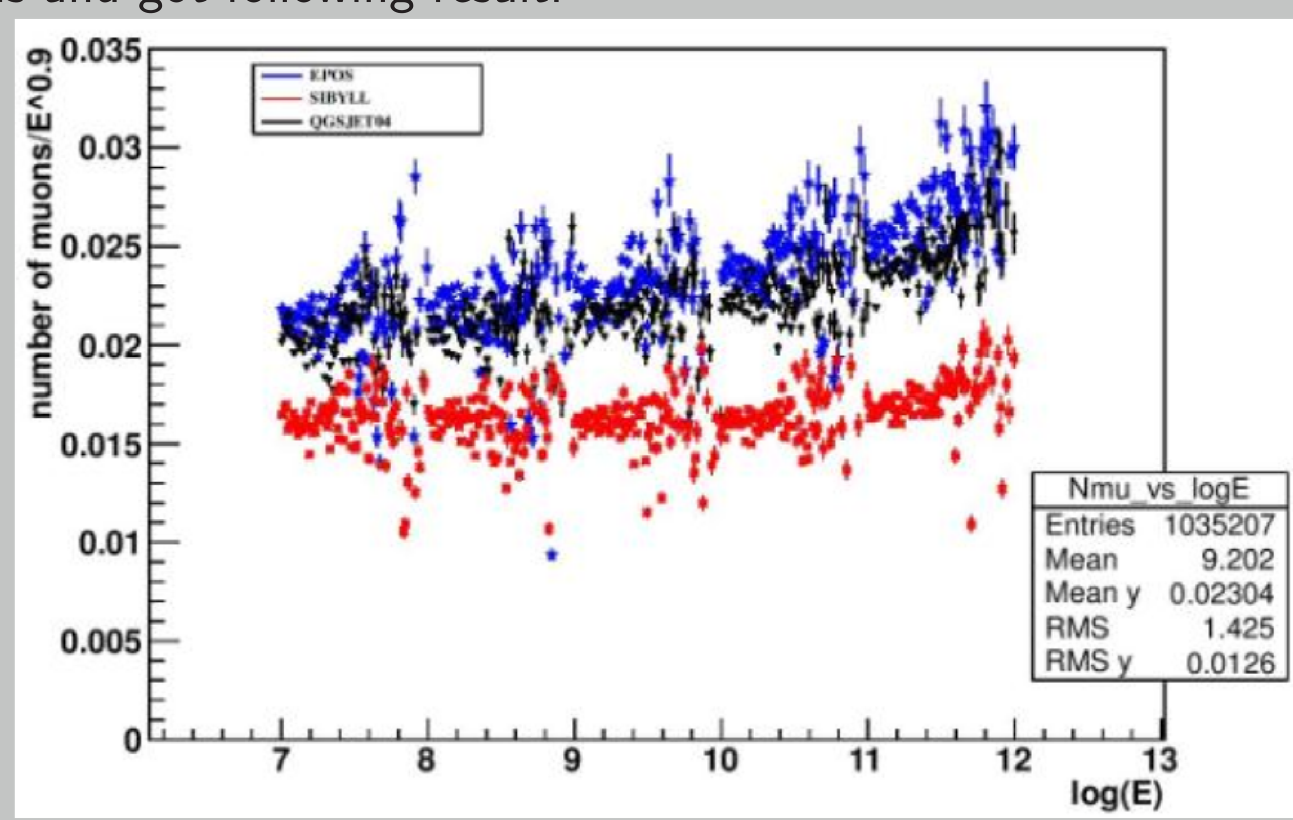

Figure 2:The number of muons $E^{(0.9)}$ vs $log(E)$ in GeV for the incident proton for each of the EPOS LHC, QGSJETII-04 and SIBYLL 2.1.

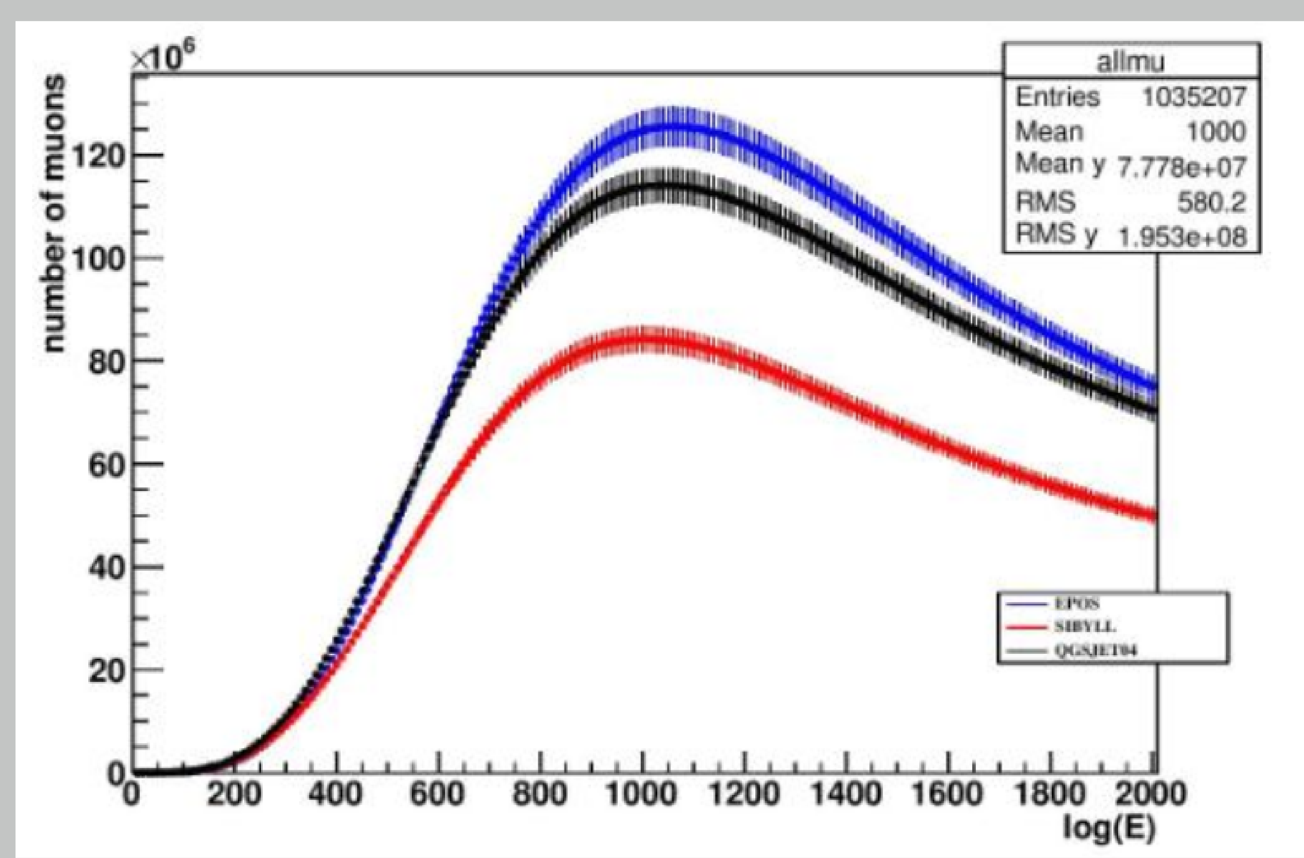

Figure 3:The profile for muons vs energy of the incident particle for each of the EPOS LHC, QGSJETII-04 and SIBYLL 2.1.

Conclusion

- In this project, we used a hybrid simulation code to understand the properties of extended air showers generated by ultra-high energy cosmic-rays colliding with the nuclei at the top of atmosphere.
- We run four MC simulations models separately to study in particular muons produced from these interactions.
- We found that different MC models predict a different number (and spectrum) of muons produced in very high-energy cosmic-ray collisions, but still below the experimental measurements of the Auger Observatory, thereby confirming the existence of a "muon puzzle" in the data.

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We refer back to all referenced used at the report resources.

 mekki@aims-cameroon.org