Testing Hadronic Interaction Models with Cosmic Ray Measurements at the IceCube Neutrino Observatory

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Introduction

The flux of cosmic rays above 100 TeV is so small that they can only be observed indirectly via extensive air showers. To infer the energy and mass of the primary nucleus from indirect measurements one needs to rely on air-shower simulations. Several hadronic interaction models, tuned to accelerator data, exist to describe the hadronic physics in these simulations. The predictions of measurable observables however show a strong model-dependence. Large uncertainties are especially present in the muon component of air showers [1].

The IceCube Neutrino Observatory is able to provide unique input to this problem by measuring different components of an air shower: the electromagnetic (EM), TeV muon, and GeV muon component [2]. In this work, we compare data and simulation for different composition-sensitive observables. These measurements should be consistent with one another, and thus provide a strong test of hadronic interaction models. The models included in this study are Sibyll 2.1 [3], QGSJet-II.04 [4], and EPOS-LHC [5].

The IceCube Neutrino Observatory

The IceCube Neutrino Observatory is a multi-purpose detector located at the geographical South Pole. It consists of a surface air-shower array, IceTop [6], and a deep detector, IceCube [7]. Using the two detectors in coincidence, we are able to perform detailed measurements of cosmic-ray air showers in the 1 PeV - 1 EeV range.

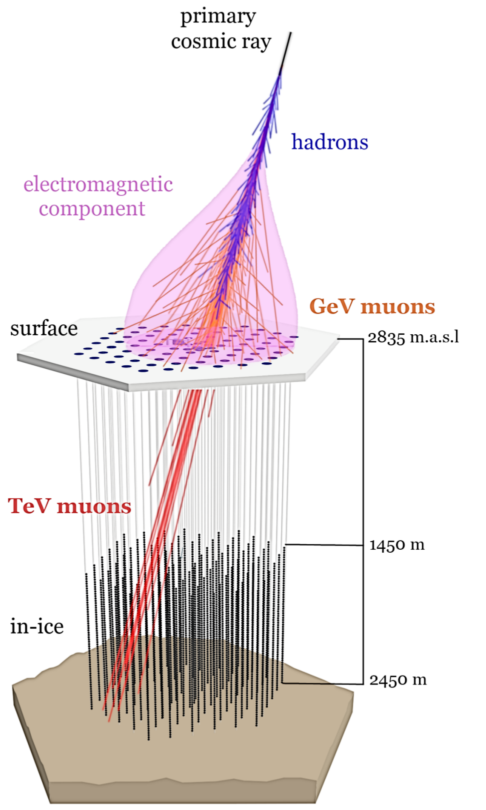

Figure 1: Schematic overview of an air shower developing over the IceCube Neutrino Observatory

IceTop:

- 81 stations of 2 ice-Cherenkov tanks on ~triangular grid over 1 km^2
- Elevation of 2835 m a.s.l., close to shower maximum
- Detects EM particles and GeV muons
- Signal charge expressed in 'vertical equivalent muons' (VEM)

IceCube:

- Installed in the ice between depths of 1450 m and 2450 m
- 5160 Digital Optical Modules detect Cherenkov light of charged particles
- Detects bundle of muons with energy $\gtrsim$ 400 GeV resulting from the first interactions in the shower

Observables

This work uses several air-shower observables that result from different reconstructions applied to the data.

Energy estimator

- S_{125}: Expected signal strength at 125 m from the shower axis, obtained from the lateral distribution function (LDF) fit to the signals in the standard IceTop air-shower reconstruction [6]. Accurately estimates primary energy with minimal model dependence [8].

Composition-sensitive observables

- β: Slope parameter of the IceTop LDF, influenced by both EM and muon component.
- $\ln \mathrm{d}E/\mathrm{d}X_{1500}$: Reconstructed muon bundle energy loss in IceCube at depth of 1500 m, sensitive to high-energy muons [9].
- $\ln \rho_\mu$: Measurement of the GeV muon density in IceTop at lateral distances of 600 m and 800 m based on Ref. [10].

Method

We compare the distribution of the composition-sensitive variables in data with the distribution in pure proton and iron simulation produced with CORSIKA [11]. We do this by calculating the 'z-values' [1, 2] defined as

$$z = \frac{x_{\mathrm{data}} - x_{\mathrm{p}}}{x_{\mathrm{Fe}} - x_{\mathrm{p}}}, \quad (1)$$

where x represents the different observables under consideration as derived from data and proton and iron simulation. For observables $x \propto \ln A$, this reduces to

$$z = \frac{\ln A_{\mathrm{data}}}{\ln 56}. \quad (2)$$

Simulations show that this holds approximately for the composition-sensitive observables considered in this work. Therefore, if the data is well described by simulations, the composition interpretation as represented by the z-values should be consistent for all observables.

Results

We calculate the z-value using 10% of data from May 2012 to May 2013. This is done in bins with width 0.2 in $\log_{10} S_{125}/\mathrm{VEM}$. Cuts are applied to ensure that all events are contained in IceTop and IceCube, have succesful reconstructions, and have zenith angle limited to $\cos\theta > 0.95$. The S_{125} lower limit corresponds roughly to a primary energy of $10^{6.4}$ GeV, the upper limit to about $10^{8.8}$ GeV for Sibyll 2.1 and $10^{7.9}$ GeV for QGSJet-II.04 and EPOS-LHC.

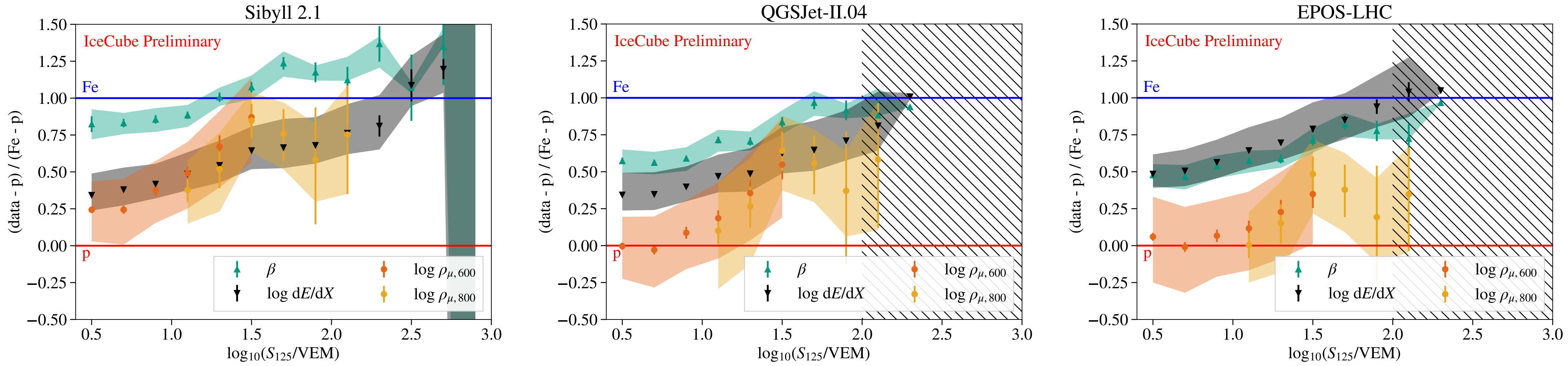

Figure 2: z-values versus primary energy estimator S_{125}, calculated for the IceTop LDF slope β, the high-energy muon bundle energy loss $\ln \mathrm{d}E/\mathrm{d}X_{1500}$, and the density of GeV surface muons $\ln \rho_\mu$ derived at 600 and 800 m lateral distance. The error bars give statistical uncertainties, the shaded bands represent systematic uncertainties. Results in the different plots are based on simulations using Sibyll 2.1, QGSJet-II.04, and EPOS-LHC.

We observe consistent behaviour for the low- and high-energy muons in Sibyll 2.1, while the results for β are inconsistent and extend beyond iron, which is unphysical. For QGSJet-II.04 we see little overlap between the variables, with most notably an inconsistency between β and ρ_μ. For EPOS-LHC, there is a strong disagreement between the low-energy muons and the other observables.

Conclusion

We performed a measurement of composition-sensitive observables based on different air-shower components. Inconsistencies are observed between several observables for the models Sibyll 2.1, QGSJet-II.04, and EPOS-LHC, which suggests these models don't adequately describe the experimental data. The inconsistencies between the models and in the models internally make it challenging to determine the composition of cosmic rays beyond the modest conclusion that all models indicate that the composition becomes heavier between 2.5 and 80 PeV.

References

[1] H. P. Dembinski *et al.* *EPJ Web Conf.* **210** (2019) 02004.
[2] S. De Ridder, E. Dvorak, and T. Gaisser *PoS* **ICRC2017** (2017) 319.
[3] E.-J. Ahn, R. Engel, T. K. Gaisser, P. Lipari, and T. Stanev *Phys. Rev. D* **80** (2009) 094003.
[4] S. Ostapchenko *Phys. Rev. D* **83** (2011) 014018.
[5] T. Pierog, I. Karpenko, J. M. Katzy, E. Yatsenko, and K. Werner *Phys. Rev. C* **92** no. 3, (2015) 034906.
[6] **IceCube** Collaboration, R. Abbasi *et al.* *Nucl. Instrum. Meth. A* **700** (2013) 188--220.
[7] **IceCube** Collaboration, M. G. Aartsen *et al.* *JINST* **12** no. 03, (2017) P03012.
[8] **IceCube** Collaboration, M. G. Aartsen *et al.* *Phys. Rev. D* **88** no. 4, (2013) 042004.
[9] **IceCube** Collaboration, M. G. Aartsen *et al.* *Phys. Rev. D* **100** no. 8, (2019) 082002.
[10] **IceCube** Collaboration, J. G. Gonzalez *EPJ Web Conf.* **208** (2019) 03003.
[11] D. Heck *et al.*, *CORSIKA: A Monte Carlo code to simulate extensive air showers, Report FZKA 6019, Forschungszentrum Karlsruhe*, 1998.

More info

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