Probing hadronic interaction models with the hybrid data of the Pierre Auger Observatory

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Abstract

Presently large systematic uncertainties remain in the description of hadronic interactions at ultra-high energies and a fully consistent description of air-shower experimental data is yet to be reached. The amount of data collected by the Pierre Auger Observatory using simultaneously the fluorescence and surface detectors in the energy range $10^{18.5} - 10^{19.0}$ eV has provided opportunity to perform a multi-parameter test of model predictions. We apply a global method to simultaneously fit the mass composition of cosmic rays and adjustments to the simulated depth of shower maximum, and hadronic signal at ground level. The best description of the hybrid data is obtained for a deeper scale of simulated depth of shower maximum than predicted by hadronic interaction models tuned to the LHC data. Consequently, the deficit of the simulated hadronic signal at ground level, dominated by muons, is alleviated with respect to the unmodified hadronic interaction models. Because of the size of the adjustments to simulated depth of shower maximum and hadronic signal and the large number of events in the sample, the statistical significance of these assumed adjustments is large, greater than $5\sigma_{\text{stat}}$, even for the combination of the systematic experimental shifts within $1\sigma_{\text{sys}}$ that are the most favorable for the models.

1 Problems of models of hadronic interaction

The current models of hadronic interactions (HI models) are known to have problems consistently describing both the ground signals and the longitudinal shower development [1–3] using the hybrid data of the surface detectors (SD) and fluorescence detectors (FD) at the Pierre

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‡ https://www.auger.org/archive/authors_2022_05.html
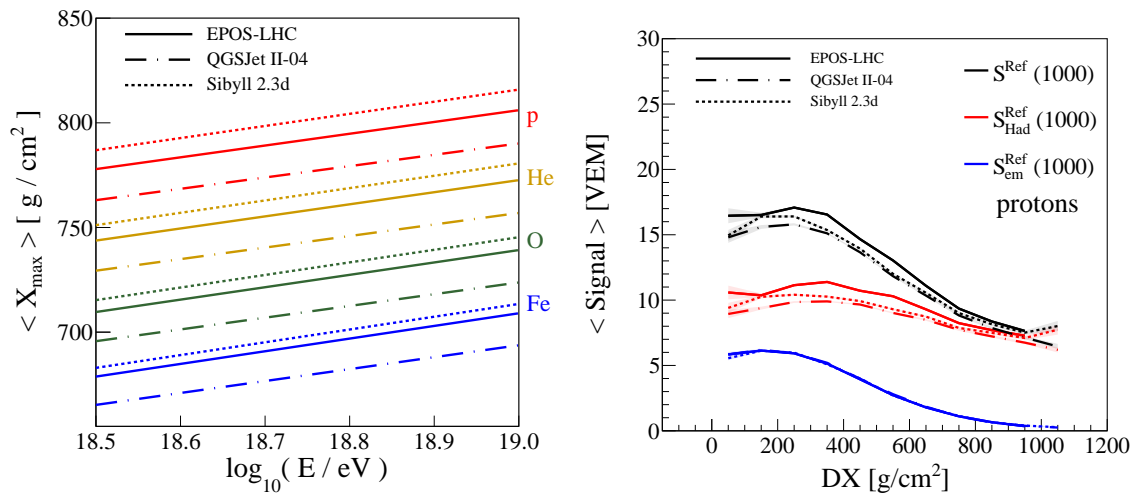
Figure 1: Left: the energy evolution of the mean of the X_{max} distribution predicted for three models of hadronic interactions and four primary species. Right: the dependence of average signal at the Pierre Auger Observatory induced in SD at 1000 m from the shower core (black) on the distance of X_{max} to the ground ($DX = 880 \text{ g/cm}^2 / \cos(\theta) - X_{max}$) for proton showers of energy $10^{18.5} - 10^{19.0}$ eV. The hadronic (S_{Had}^{Ref}) and electromagnetic (S_{em}^{Ref}) parts of the signal are shown in red and blue, respectively. The signals are corrected to the reference energy $10^{18.7}$ eV. From [10].

Auger Observatory [4]. The ground signal predicted by Monte Carlo (MC) simulation is found lower than measured, with an indication of increasing with energy when the results of more experiments are combined [5]. All these tests of HI models are based on the assumption that the scale of depth of shower maximum (X_{max}) predicted by a given HI model is correct. However, at the energy $10^{18.7}$ eV, the uncertainties on the predicted X_{max} scale, $\langle X_{max} \rangle$, are larger than about one third of the difference between the two extremes - protons and iron nuclei, see the differences between the three HI models, EPOS-LHC [6], QGSJET II-04 [7], SIBYLL 2.3d [8] on the left panel of Fig. 1, see also [9].

2 Extended testing of hadronic interaction models

In this work, we consider a more complex test of the HI models in the energy range $10^{18.5-19.0}$ eV. This test is motivated by the differences observed in the predictions obtained with HI models for $\langle X_{max} \rangle$ and hadronic part S_{Had} of the total ground signal $S(1000)$ at 1000 m from the shower core at the Pierre Auger Observatory, see Fig. 1. These differences are approximately primary and energy independent. The differences in the hadronic signals are DX (zenith-angle) dependent. These features suggest to leave both X_{max} and $S_{Had}(\theta)$ free in the fitting procedure.

We fit simultaneously five two-dimensional distributions of measured $S(1000)$ and X_{max}, see Fig. 2, that are corrected for their energy evolution to a reference energy $10^{18.7}$ eV, see [10] for more details. The influence of changing X_{max} scale on $S(1000)$ is incorporated in the method. Implicitly, the nearly model-independent information on mass composition from the correlation between $S(1000)$ and X_{max}, see [11], is naturally incorporated in the method.
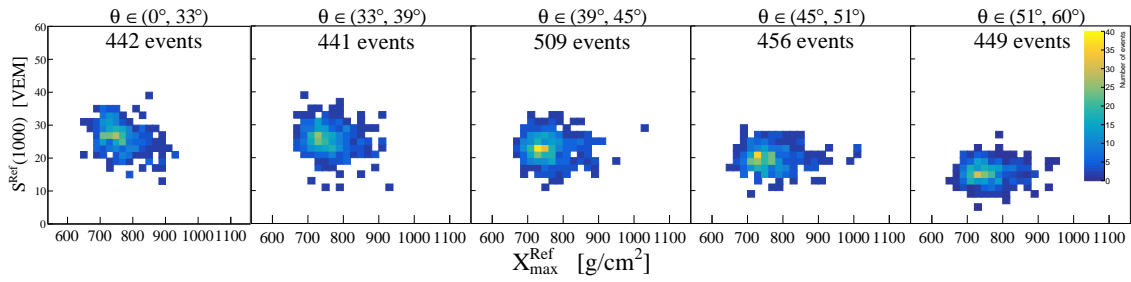
Figure 2: Two-dimensional distributions of $S(1000)^{\text{Ref}}$ and $X_{\text{max}}^{\text{Ref}}$ measured by the Pierre Auger Observatory in the energy range $10^{18.5} - 10^{19.0}$ eV in five zenith-angle (θ) intervals. From [10].

3 Results of the test

The best description of the hybrid data of the Pierre Auger Observatory is obtained modifying the MC templates by shifting X_{max} by a parameter ΔX_{max} and rescaling the hadronic component at two extreme zenith angles by factors $R_{\text{Had}}(\theta_{\text{min}})$ and $R_{\text{Had}}(\theta_{\text{max}})$ as shown in Fig. 3 with statistical and systematic errors. The overall description of the five two-dimensional distributions by the fits is achieved with p-value $\simeq 2.6\%$ for EPOS-LHC, $\simeq 3.6\%$ for QGSJET II-04, and $\simeq 18.0\%$ for SIBYLL 2.3d based on detailed MC-MC tests.

The optimum description of the data is achieved for a deeper X_{max} scale than predicted by HI models, see also left panel of Fig. 4. Consequently, heavier mass composition and smaller rescaling of the hadronic component is obtained than using previous tests [1] and mass composition fits [12].

Systematic Uncertainties   We have identified four dominant sources of systematic uncertainties influencing our results. Three are related to the experimental uncertainties on the measurement of energy ($\pm 14\%$), of X_{max} ($^{+8}_{-9}$ g/cm^2) and of $S(1000)$ ($\pm 5\%$). We consider also the uncertainty stemming from the MC-MC tests of the method. The total uncertainty is summed in quadrature and is plotted in Fig. 3 with shaded boxes. The individual systematic contributions to ΔX_{max} and differences in the two fitted R_{Had} are shown in the right panel of Fig. 4. The size of systematic uncertainty on the energy scale does not allow us to draw any conclusion about the muon spectrum from the R_{Had} differences.

Significance of Data/MC Inconsistency   We perform a scan in all possible combinations of the 1σ experimental systematic uncertainties and calculate the statistical significance as

$$\sigma_{\text{STAT}} = \sqrt{\left(\frac{R_{\text{Had}}(\theta_{\text{min}})-1}{\sigma_{\text{STAT}}(R_{\text{Had}}(\theta_{\text{min}}))}\right)^2 + \left(\frac{R_{\text{Had}}(\theta_{\text{max}})-1}{\sigma_{\text{STAT}}(R_{\text{Had}}(\theta_{\text{max}}))}\right)^2 + \left(\frac{\Delta X_{\text{max}}}{\sigma_{\text{STAT}}(\Delta X_{\text{max}})}\right)^2}, \quad (1)$$

where $\sigma_{\text{STAT}}(R_{\text{Had}}(\theta_{\text{min}}))$, $\sigma_{\text{STAT}}(R_{\text{Had}}(\theta_{\text{max}}))$ and $\sigma_{\text{STAT}}(\Delta X_{\text{max}})$ are the statistical uncertainties of the fit for $R_{\text{Had}}(\theta_{\text{min}})$, $R_{\text{Had}}(\theta_{\text{max}})$ and ΔX_{max}, respectively.

Even for the most favourable combination of the systematic uncertainties that minimizes σ_{STAT} the significance value is still above 5σ. This example is shown in Fig. 5.
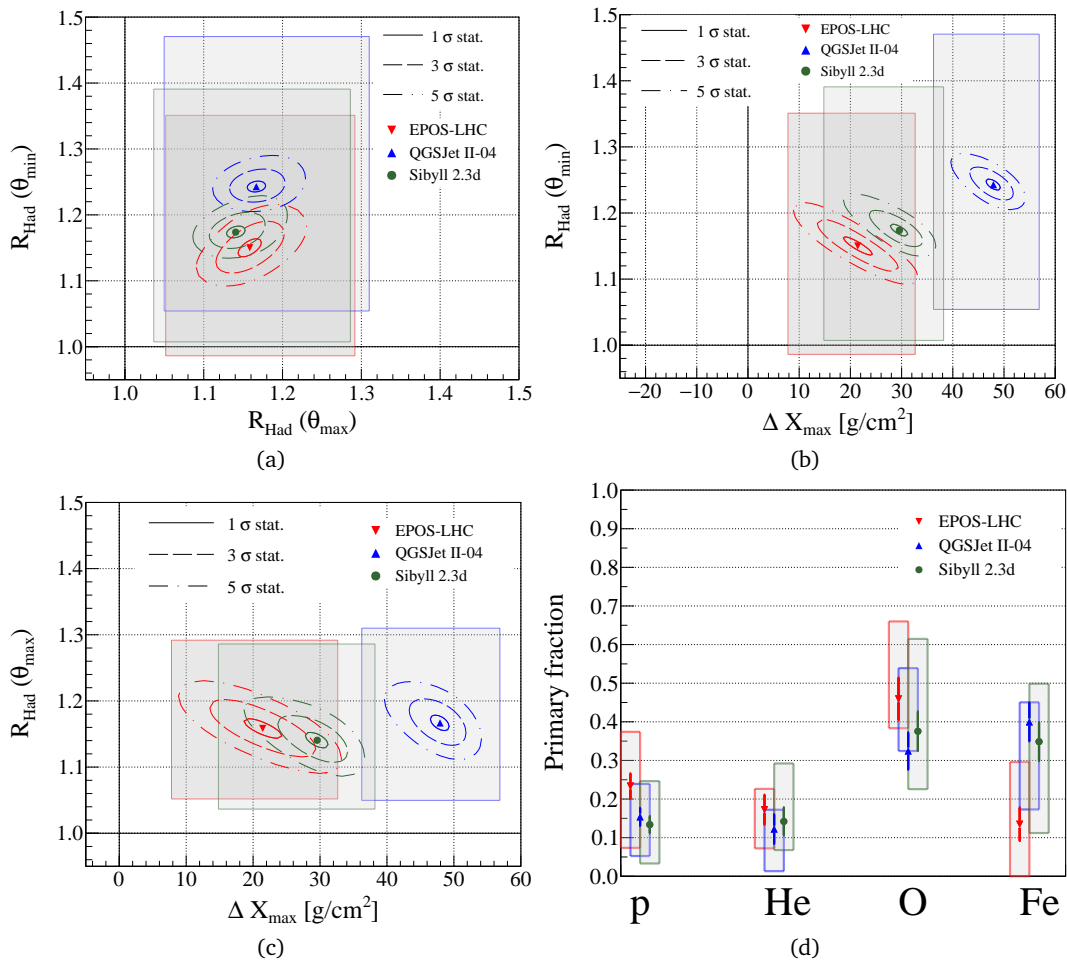
Figure 3: Results of the fits to $[X_{\text{max}}^{\text{Ref}}, S^{\text{Ref}}(1000)]$ distributions with MC templates for EPOS-LHC, QGSJET II-04 and SIBYLL 2.3d. The relations between the fit parameters $R_{\text{Had}}(\theta_{\text{min}})$, $R_{\text{Had}}(\theta_{\text{max}})$ and ΔX_{max} are shown in (a), (b), (c) panels and the fitted primary fractions in panel (d). The contours denote regions with 1σ, 3σ and 5σ statistical uncertainties. The gray bands indicate the size of the total systematic uncertainties. From [10].

4 Conclusions

The combined measurements of cosmic-rays with energies between $10^{18.5}$ eV and $10^{19.0}$ eV using the SD and FD of the Pierre Auger Observatory provide event statistics large enough to apply a novel method to test HI models. This method introduces three adjustments to the air-shower observables predicted by the HI models and simultaneously fits the fractions of four primary particles. The results of the method are in tension with the HI models EPOS-LHC, SIBYLL 2.3d and QGSJET II-04 by more than 5σ with much higher significance in case of the QGSJET II-04. The best description of the data is obtained when the X_{max} scale of the MC predictions is deeper by about 20 g/cm², 30 g/cm² and 50 g/cm² for EPOS-LHC, SIBYLL 2.3d and QGSJET II-04, respectively. Consequently, the differences between the HI models in the fitted mass composition fractions are decreased and the mass composition is heavier than obtained using the unmodified predictions of the three HI models. For such heavier mass composition, the "muon problem" of the HI models is alleviated with respect to the previous studies, observing 15-25% deficit of the hadronic component of simulated ground signal for all the three studied HI models.
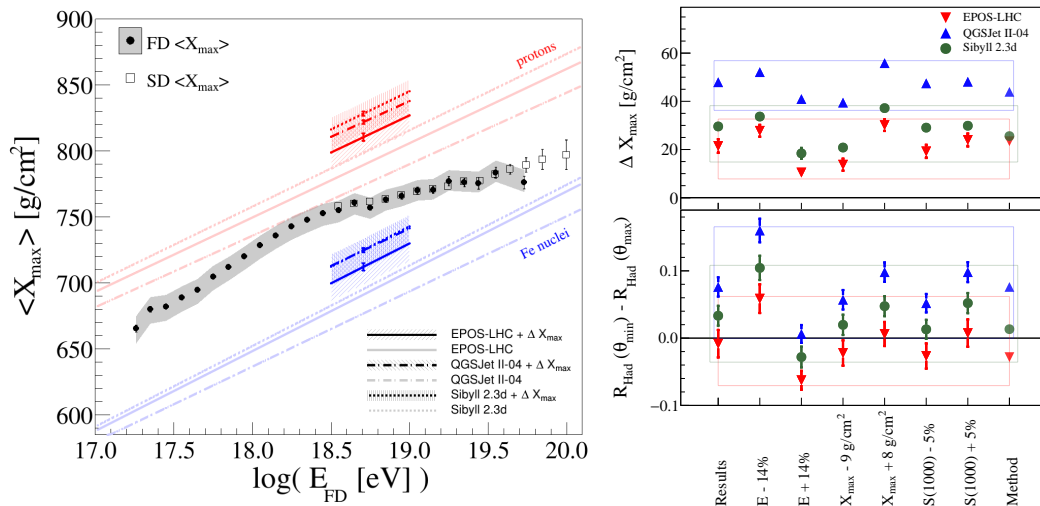
Figure 4: Left: the energy evolution of the mean $X_{\max}$ measured at the Pierre Auger Observatory (black) using FD [13] and SD [14]. The adjusted MC predictions on $\langle X_{\max} \rangle$ obtained in this work to improve the description of hybrid data (SD and FD) are shown in red and blue for protons and iron nuclei, respectively. The bands correspond to the systematic uncertainties of $\Delta X_{\max}$. The lighter color lines indicate the unmodified MC predictions. Right: the best fit results on the $\Delta X_{\max}$ and the adjustment to the S_{Had} attenuation for the individual systematic effects. The bands illustrate the total systematic uncertainty summed in quadrature. From [10].
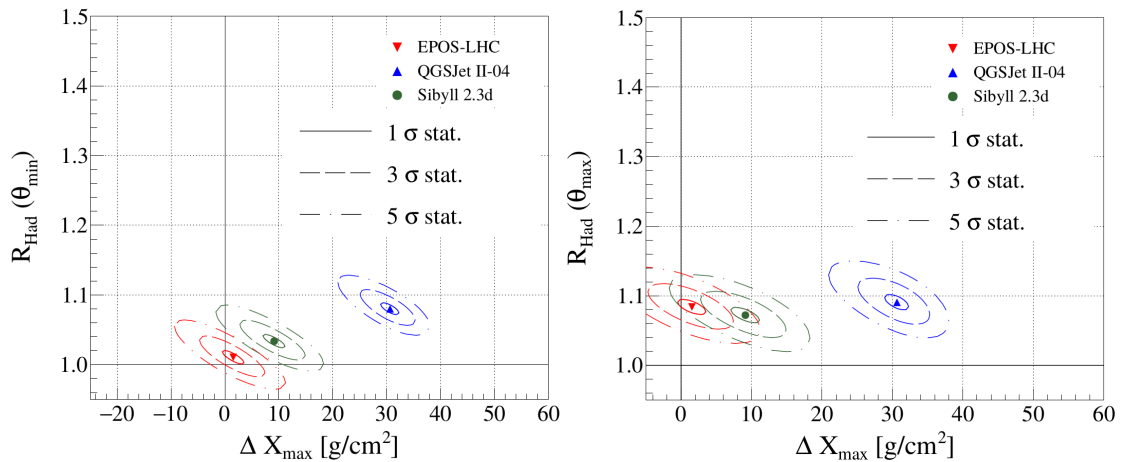
Figure 5: The MC adjustments obtained by fits to the measured data that are systematically corrected for energy +14% and $X_{\max}$- 9 g/cm² to minimize the total statistical significance from Eq. (1). The contours denote regions with 1σ, 3σ and 5σ statistical uncertainties.

Acknowledgements

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References

[1] A. Aab et al., *Testing hadronic interactions at ultrahigh energies with air showers measured by the Pierre Auger observatory*, Phys. Rev. Lett. **117**, 192001 (2016), doi:10.1103/PhysRevLett.117.192001.

[2] A. Aab et al., *Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events*, Phys. Rev. D **91**, 032003 (2015), doi:10.1103/PhysRevD.91.032003.

[3] A. Aab et al., *Direct measurement of the muonic content of extensive air showers between* 2×10^{17} *and* 2×10^{18} *eV at the Pierre Auger Observatory*, Eur. Phys. J. C **80**, 751 (2020), doi:10.1140/epjc/s10052-020-8055-y.

[4] A. Aab et al., *The Pierre Auger cosmic ray observatory*, Nucl. Instrum. Methods Phys. Res. A **798**, 172 (2015), doi:10.1016/j.nima.2015.06.058.

[5] J. Albrecht et al., *The muon puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider*, Astrophys. Space Sci. **367**, 27 (2022), doi:10.1007/s10509-022-04054-5.

[6] T. Pierog, I. Karpenko, J. M. Katzy, E. Yatsenko and K. Werner, *EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider*, Phys. Rev. C **92**, 034906 (2015), doi:10.1103/PhysRevC.92.034906.

[7] S. Ostapchenko, *Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: QGSJET-II model*, Phys. Rev. D **83**, 014018 (2011), doi:10.1103/PhysRevD.83.014018.

[8] F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser and T. Stanev, *Hadronic interaction model sibyll 2.3d and extensive air showers*, Phys. Rev. D **102**, 063002 (2020), doi:10.1103/PhysRevD.102.063002.

[9] R. Abbasi and G. Thomson, $\langle X_{max} \rangle$ *Uncertainty from extrapolation of cosmic ray air shower parameters*, JPS Conf. Proc. **19**, 011015 (2018), doi:10.7566/JPSCP.19.011015.

[10] J. Vícha et al., *Adjustments to model predictions of depth of shower maximum and signals at ground level using hybrid events of the Pierre Auger observatory*, Proc. Sci. **395**, 310 (2021), doi:10.22323/1.395.0310.

[11] A. Aab et al., *Evidence for a mixed mass composition at the 'ankle' in the cosmic-ray spectrum*, Phys. Lett. B **762**, 288 (2016), doi:10.1016/j.physletb.2016.09.039.

[12] J. Bellido et al., *Depth of maximum of air-shower profiles at the Pierre Auger Observatory: Measurements above* $10^{17.2}$ *eV and composition implications*, Proc. Sci. **301**, 506 (2017), doi:10.22323/1.301.0506.

[13] A. Yushkov et al., *Mass Composition of cosmic rays with energies above* $10^{17.2}$ *eV from the hybrid data of the Pierre Auger observatory*, Proc. Sci. **358**, 482 (2019), doi:10.22323/1.358.0482.

[14] C. J. T. Peixoto et al., *Estimating the depth of shower maximum using the surface detectors of the Pierre Auger observatory*, Proc. Sci. **358**, 440 (2019), doi:10.22323/1.358.0440.