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COSMIC RAYS AND HADRONIC INTERACTIONS*

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The interpretation of cosmic ray measurements at the highest energies is fundamentally linked with the understanding of hadronic interactions. The dependence of the air shower observables $X_{\max}$ and N_{μ} on certain features of hadronic interactions is discussed and the effect of some of the LHC measurements is demonstrated. The uncertainty due to the lack of accelerator data on meson interactions is stressed.

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1. Introduction

The question of the origin of ultra-high energy cosmic rays remains unsolved to this day. One of the pieces still missing is the mass composition at the highest energies. The determination of the primary masses from air shower measurements is one of the main goals of the Pierre Auger Observatory. Currently, however, the question cannot be answered because the measurement of different air shower observables that are sensitive to the composition seem to give conflicting results. One example [1] is shown in Fig. 1 (left). Here, the measurement of two observables for air showers with an inclination of 67° and a primary energy of 10 EeV are compared with the predictions from simulations. It seems that the data lie in a nonphysical region. One way to resolve the contradiction is to admit that the models for hadronic interactions that are used in the air shower simulations are incomplete or wrong. In what follows, the performance of the models compared to accelerator data will be discussed and the effect of uncertainties due to the incompleteness of accelerator data will be demonstrated to argue the case that the models are, in part at least, responsible for the discrepancy.

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1.1. Extensive air shower development

To understand how the models affect the interpretation of the CR measurements, it is helpful to understand how extensive air showers develop.

The most abundantly produced particles in hadronic interactions are pions. The different lifetimes and decay products of charged and neutral pions result in the development of a hadronic and an electromagnetic cascade.

The electromagnetic cascade develops much more rapidly ($\lambda_{\rm rad} = 36$ g/cm^2 *vs.* $\lambda_{\rm int} = \mathcal{O}(100\ {\rm g/cm^2})$) and produces much more particles. When the electromagnetic particles in the cascade interact with the nitrogen molecules in the air, the latter can be left in an excited state. The light that is emitted in the subsequent de-excitation can be measured and is used to reconstruct the profile of the air shower ($X_{\rm max}$ in Fig. 1). This measurement mostly depends on the properties of the first few hadronic interactions, since the energy that can be transferred to the electromagnetic cascade and produce fluorescence light, is reduced with each hadronic generation.

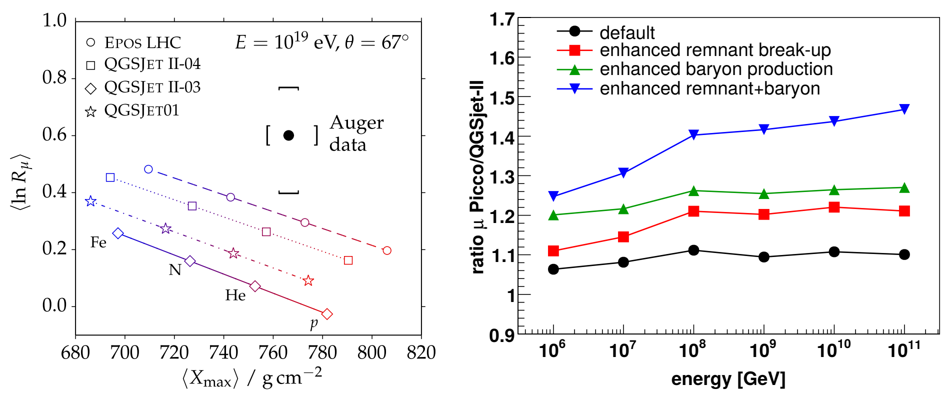

Fig. 1. Left: Comparison of two mass composition measurements based on different shower properties [1]. Right: Effect of baryon production and remnant break-up (related to leading neutral pion production) in hadronic interactions on the number of muons in air showers [2].

The hadronic cascade typically produces much less particles. It terminates when particles have such low energy that decay is more likely than interaction. Among the decay products of charged pions are muons, which are very penetrating and can propagate all the way to the ground. In highly inclined air showers, like the ones studied in Fig. 1, the path through the atmosphere is so long that only muons can be measured at ground ($\ln(R_\mu)$ in Fig. 1). Since the muons are produced at the end of the cascade, this observable depends on the properties of all the interactions in the cascade. In particular, the interactions of pions with air.

Figure 1 (right) shows the result of a study of the effects of baryon production and the so-called remnant break-up on the number of muons in air showers [2]. Both significantly increase N_μ, predominantly through the formation of additional subshowers. Similar results for the role of baryons were found by Pierog *et al.* [3].

2. Interaction models compared to LHC data

One of the measurements with the highest impact on CR interaction models from the LHC is the cross section measurement. The previous Tevatron measurements were conflicting with each other, so models predict a higher or lower cross section depending on which measurement they chose to trust (Fig. 2). Hence, the very different predictions at high energy. The new measurements do not have this ambiguity and the retuned models give comparable predictions for high energies.

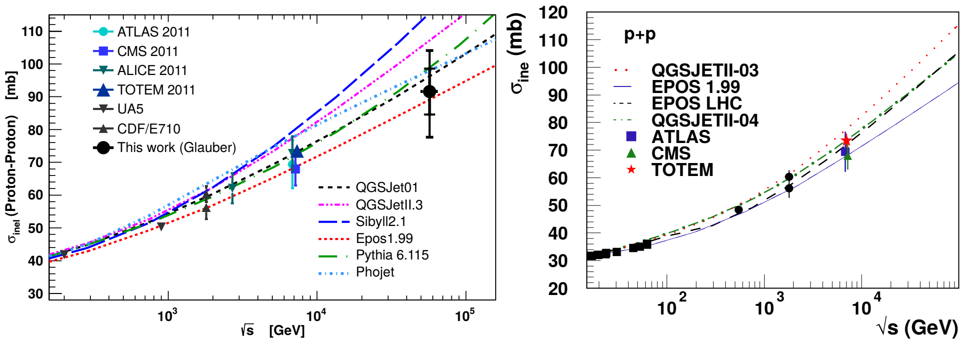

Fig. 2. Left: Proton–proton inelastic cross section in hadronic interaction models before LHC measurements. The air shower measurement [4] at 57 TeV already excludes some of the older models. Right: Proton–proton inelastic cross section in interaction models before (EPOS 1.99, QGSJETII-03) and after (EPOS-LHC, QGSJET II-04) LHC measurements.

A good measure of overall particle production is given by the number of charged particles produced in the central region, the so-called rapidity plateau (see Fig. 3). Particle production in the models depends on all stages of the interaction, from the initial parton structure that determines the number of parton interactions to the fragmentation function. The pre-LHC models bracket these data, which means the models give a good description of *pp* interactions and the predictions for higher energy can be trusted. In post-LHC models, the predictions have converged.

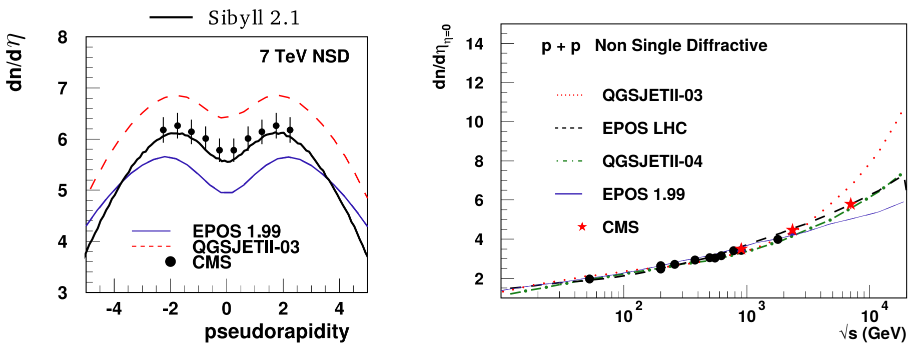

Fig. 3. Left: Pseudorapidity distribution of charged particles in the CMS [5] and pre-LHC CR models SIBYLL, EPOS and QGSJET. Right: Evolution of the plateau with energy. Post-LHC models EPOS-LHC and QGSJET II-04 agree very well in their prediction for particle production at high energy.

3. Model predictions for EAS

3.1. $X_{\max}$

As it has been said before, $X_{\max}$ mostly depends on the first few high energy interactions. These are predominantly proton interactions, so the LHC measurements can be expected to reduce the difference between model predictions for this observable.

Figure 4 (left) shows the $\langle X_{\max}\rangle$ predicted by the latest models for proton and iron induced air showers. Post-LHC models QGSJET II-04 and EPOS-LHC give now very similar results to SIBYLL 2.1 which is a model from the

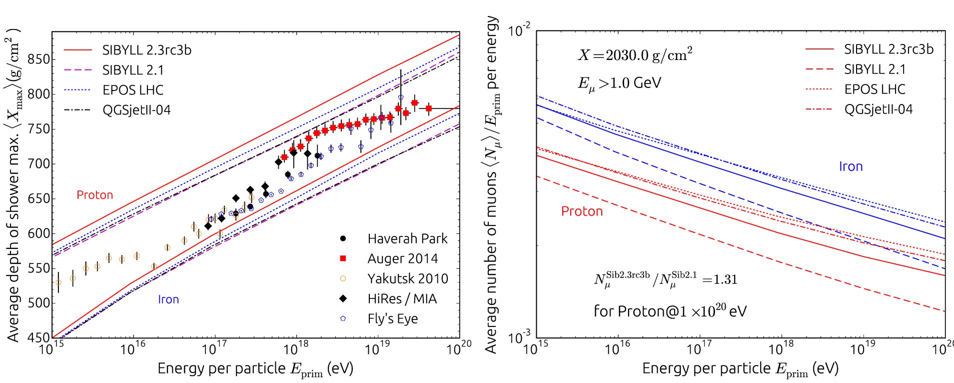

Fig. 4. Left: Comparison of model predictions for the $\langle X_{\max}\rangle$ of proton and iron induced air showers and measurements. Right: Prediction of the number of muons at ground for the different models in proton and iron air showers with an inclination of 60°.

TeVatron era. Comparing to the previous predictions they have converged quite a bit (see *e.g.* review by Engel *et al.* [6]). SIBYLL 2.3rc3b is currently under development, so the large predicted $X_{\max}$ is still subject to change.

3.2. N_μ

The number of muons at ground shown in Fig. 4 (right) paints a far darker picture. Here, the predictions have converged but they also have shifted towards larger number of muons as a whole. This development was triggered by experimental observations as the one shown before in Fig. 1, which could be explained in terms of an underestimation of the number of muons in simulations.

Such a dramatic shift is possible due to the dependence of N_μ on the production of pions in the whole hadronic cascade. Seemingly small effects can thereby add up to a noticeable change in the number of muons.

4. Model modifications

The effect of some of the properties of hadronic interactions on air shower observables can be demonstrated by changing that property *ad hoc* and comparing the results obtained in simulations.

4.1. Proton and meson cross sections

The proton-air cross section enters multiple times in air shower development. First in that it determines the average distance between interactions in the cascade and then, again, in each interaction since it is determined by the microscopic features of the interaction which also determine particle production.

Using the CONEX [7] cascade calculation, one can show the effect of the retuned cross section by replacing the interaction length used in the calculation with the one given by the pre-LHC cross section.

In Fig. 5 (left), the difference between the interaction lengths in SIBYLL before and after the LHC are shown. Although the *pp* cross sections differ a lot, the difference in interaction length amounts to only 5 g/cm^2 at 1 PeV. On the right, the effect on $X_{\max}$ is shown. Not surprisingly, it is only of the order of a few g/cm^2.

The same game can be played for the meson-air cross sections using the COMPETE cross section model [8] and SIBYLL. The difference between these cross sections is that the SIBYLL cross section is smaller at c.m. energies below 5 TeV ($E_{\mathrm{Lab}} \simeq 10^{16}$ eV) and larger at higher energy.

Meson interactions are important in later stages of the air shower so the difference at the lower energies counts.

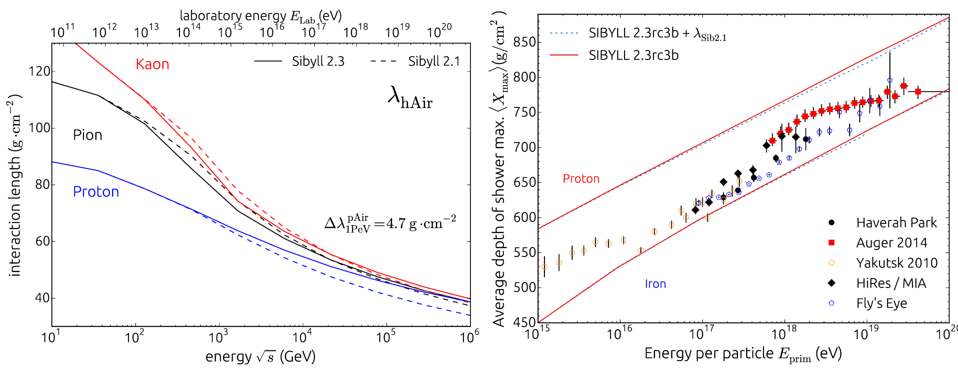

Fig. 5. Left: Interaction length using the pre- and post-LHC p-air cross sections. Right: $X_{\rm max}$ predictions from cascade calculations using the pre- (dashed) and post-LHC (solid) interactions lengths in the model SIBYLL.

The effect of the meson interaction length was found to mostly appear in the so-called muon production profile (Fig. 6 (right)). It shows how the longer meson interaction length in SIBYLL at the energies, where meson interactions take place, moves muon production deeper into the atmosphere. The total number of muons at ground is left unchanged from the modification (Fig. 6 (left)).

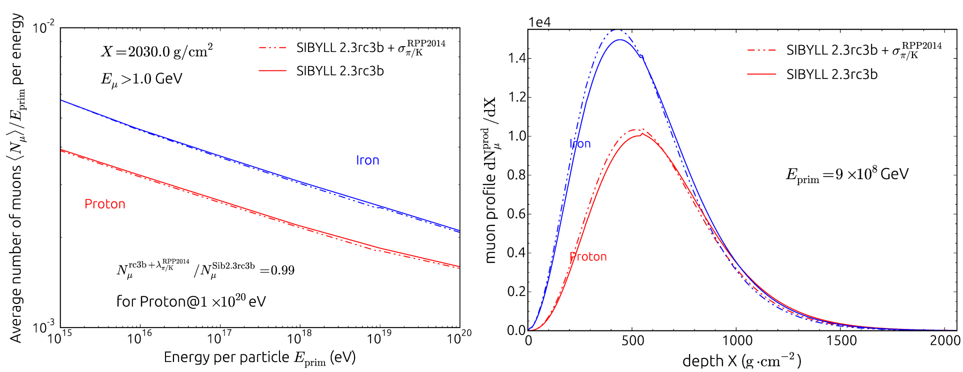

Fig. 6. Comparison between the predictions of the model using different interaction lengths for mesons in the cascade calculation. Left: Number of muons at ground. Right: Muon production profile. An effect is mostly visible in the production profile. $X^\mu_{\rm max}$ is slightly smaller with the RPP'14 cross section [8].

It should be added that the models for meson interactions are relatively unconstrained, since there are only few measurements available. The largest constraint comes from within the models, that microscopically link the meson and proton interactions.

4.2. Neutral pion production

It has been mentioned before that the muon content of an air shower depends on the size of the hadronic cascade. This can be shown by modifying the production of neutral pions. Decreasing production means less energy is transferred from the hadronic to the electromagnetic cascade. If this change occurs in the later stages of the air shower, then X_{max} will not be affected much.

Fixed target data [9,10] show that the production of π^0 is overestimated in the SIBYLL 2.3rc3b model by a large amount (see Fig. 7). Adding an *ad hoc* correction after event generation that replaces the additional π^0 with ρ^0 or $\pi^{\pm}$, the model can be forced to agree with these data.

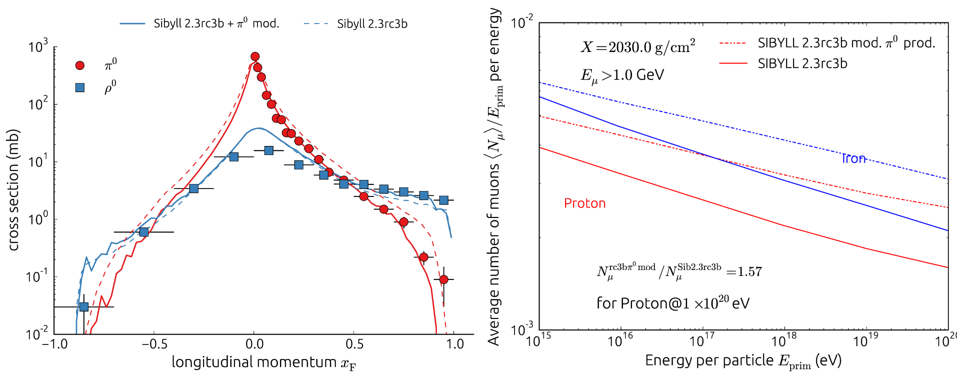

Fig. 7. Effect of forward neutral pion production in meson interactions with air. Left: x_{F}-spectra of ρ^0 and π^0 measured in $\pi^+ p$ interactions. Models shown are a development version of SIBYLL with leading ρ^0 production accounted for and an *ad hoc* tune of the same model to the π^0 data. Right: The prediction for the number of muons at ground for the two models is shown.

The effect on the number of muons at ground is dramatic. For proton showers with 100 EeV primary energy, the number of muons increases by almost 60%. For primary energies beyond 10^{17} eV, proton showers in the *ad hoc* model have more muons than iron showers previously.

This takes out some of the tension in the comparison of X_{max} and N_μ sensitive measurements, like the one in Fig. 1. However, it also shows that the uncertainty in the predictions by the models in the number of muons is quite large.

It should be noted that the measurement used here was done using a proton target. Preliminary measurements of ρ^0 production in pion–carbon interactions with the NA61 detector [11] indicate that the effect could be even stronger with nuclear targets.

5. Conclusion

A general conclusion to be drawn from the presented discussion is that it seems that the question of the composition of UHECR cannot be solved without a better understanding of hadronic interactions. In particular, the interactions of mesons, which are poorly known experimentally but make up the largest part of the air shower, were shown to have a large impact on the interpretation of CR measurements. In terms of progress, the LHC measurements were shown to have a positive result on the range of the model predictions and seem to confirm the general picture of hadron interactions underlying the CR models.

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