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Review of Model Predictions for Extensive Air Showers

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In detailed air shower simulations, the uncertainty in the prediction of shower observable for different primary particles and energies is currently dominated by differences between hadronic interaction models. With the results of the first run of the LHC, the difference between post-LHC model predictions has been reduced at the same level as experimental uncertainties of cosmic ray experiments. At the same time new types of air shower observables, like the muon production depth, have been measured, adding new constraints on hadronic models. Currently no model is able to reproduce consistently all mass composition measurements possible with the Pierre Auger Observatory for instance. We review the current model predictions for various particle production observables and their link with air shower observables and discuss the future possible improvements.

KEYWORDS: air shower, hadronic interaction models

1. Introduction

Knowing the elemental composition of cosmic ray particles arriving at Earth is of crucial importance to understand their production and propagation. Unfortunately, cosmic rays can be measured only indirectly above an energy of 10^{14} eV, through the cascades of secondary particles, called extensive air showers (EAS), that they produce in the atmosphere (for a recent review, see [1]). Only by simulating the generation of EAS and comparing the predictions with measurements can one draw conclusions on the primary mass composition of the arriving particles [2]. With the operation of modern large-scale experiments, the reliability of air shower simulations has become the source of the largest systematic uncertainty in the interpretation of cosmic ray data [3–7, 9, 10]. While the electroweak interaction processes are reasonably well understood, modeling of hadronic multi-particle production is subject to large theoretical uncertainties that are, moreover, difficult to estimate [11–13].

The Large Hadron Collider (LHC) at the CERN laboratory allows us to access, for the first time, the energy region above the cosmic ray spectral knee with about 10^{17} eV in the laboratory frame. Therefore an analysis of inclusive particle data taken at the LHC is particularly interesting for constraining existing hadronic interaction models and for testing possible new mechanisms of hadron production [14]. The first published data from LHC experiments have mostly been taken with detectors covering the central phase space region in pseudorapidity ($|\eta| < 2.5$). This region is most easily accessible in collider experiments and is also the region of the highest rapidity-density of produced particles. The first data have been compared to cosmic ray models in [15]. On the other hand, since the number of particles in an air shower is roughly proportional to the energy of the primary particle, the most energetic outgoing particles of an interaction, emitted in the very forward region of a collider experiment – such as in diffractive interactions – are the most important ones for understanding air showers. For the first time at the LHC, collider experiments include a large variety of forward detectors to study forward particle and energy spectra which have a direct impact on air shower development [16]. These latest measurements are not yet taken into account in the available hadronic interactions models, but are very important to understand the open issues in these models and for their future developments.

At the same time, a new generation of hybrid cosmic ray detectors such as the Pierre Auger Observatory [8] (surface and fluorescence detectors), the IceCube/IceTop experiments [17, 18] (low energy muons at the surface and high energy muons deep underground) or the KASCADE/KASCADE Grande experiment [19,20] (muons of different energies and at different distances) gives access to various precise measurements of the mean logarithmic mass of cosmic rays within the same experiment. By definition the mean logarithmic mass should be independent of the measurement technique. If the physics is well described by a given hadronic model, the masses obtained from different observables should be consistent. This constraint is much stronger than the traditional test limiting the results to the range between proton and iron induced showers. This is now satisfied in most of the cases, but none of the current models is able to give a fully consistent picture of the different observables within a given experiment [21–23].

In this paper, we will compare the latest hadronic model predictions after LHC data and their consequences on air shower observables. In the first section, we will compare their results for the observables important for the air shower development. The main source of remaining uncertainties will be then identified. Using detailed Monte Carlo simulations done with CONEX [24], the new predictions for X_{max} will be shown. Finally we will take the example of the muon production depth (MPD) measured by the Pierre Auger Observatory [21] to see how air shower measurements can constrain hadronic interaction physics and can be used to solve the remaining open issues.

2. Model comparison

A toy-model, as described in [25], gives only a very much over-simplified account of air shower physics. However, the model allows us to qualitatively understand the dependence of many air shower observables on the characteristics of hadronic particle production. Accordingly the parameters of hadron production which are most important for air shower development are the cross section (or mean free path), the multiplicity of secondary particles of high energy, the elasticity and the production ratio of neutral to charged particles. Until the start of LHC operations, these parameters were not well constrained by particle production measurements at accelerators. As a consequence, depending on the assumptions of how to extrapolate existing accelerator data, the predictions of hadronic interaction models were very different [26]. We will show that the extrapolation to high energy is not really the issue anymore.

There are several hadronic interaction models commonly used to simulate air showers. Here we will focus on the three high energy models which were updated to take into account LHC data at 7 TeV: QGSJETII-03 [27, 28] changed into QGSJETII-04 [29], EPOS 1.99 [30, 31] replaced by EPOS LHC (v3400) [32], and Sibyll 2.1 [33–35] updated to Sibyll 2.3 [36] all available since CORSIKA v7.5600 [37]. There is no major change in these models but in addition to some technical improvements, some parameters were changed to reproduce TOTEM [38] cross sections. They all are based on Gribov-Regge multiple scattering, perturbative QCD and string fragmentation.

2.1 Inelastic cross section

As shown in [25], the inelastic nuclear cross section is very important for the development of air showers and in particular for the depth of shower maximum. As a consequence, the number of electromagnetic particles at ground level is strongly correlated to this observable (if the shower maximum is closer to ground, the number of particles is higher).

The inelastic cross section of proton-proton scattering is usually used as an input to fix basic parameters in all hadronic interaction models. Therefore it is very well described by all the models up to the LHC energies, where data exist [39]. As shown in Fig. 1 left-hand side, thanks to the measurements at the LHC even the extrapolations up to the highest energy are now very similar. In all the figures EPOS LHC is represented by a full (blue) line, QGSJETII-04 by a dashed (red) line and Sibyll 2.3 by a dashed-dotted (green) line.

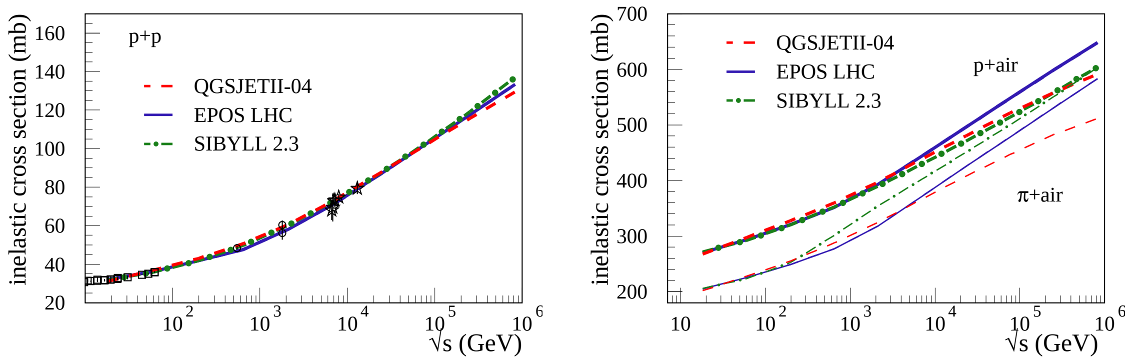

Fig. 1. Inelastic p-p cross sections (left-hand side) and p-air (thick lines) and π-air (thin lines) cross sections (right-hand side) calculated with EPOS LHC (full line), QGSJETII-04 (dashed line), and Sibyll 2.3 (dashed-dotted line). Points are data from [40] and the stars are the LHC measurements [41–45].

However plotting the prediction of these models for the proton-air and pion-air inelastic cross-sections as shown in Fig. 1 right-hand side, one can notice that significant differences appear which will have direct consequences on air shower development. Not only do the evolutions diverge at high energy, but for Sibyll 2.3 the relative behavior of the proton and pion-air cross-section is different from the other models (faster increase of the pion-air cross-section).

2.2 Multiplicity

According to [25], the multiplicity plays a similar kind of role as the inelastic cross section, but with a weaker dependency (log). On the other hand the predictions from the models have larger differences for the multiplicity compared to the cross section. As shown in [46], the average multiplicity is well reproduced by all the models up to 1 TeV and even up to 13 TeV for EPOS LHC and QGSJETII-04 [47] and a difference appears between these two models only at the highest energy (beyond 100 TeV).

In Fig. 2 left-hand side it can be seen on the pseudorapidity distribution of charged particles at 7 TeV that even if the central density of particles is well reproduced by all models, the width of the distribution is too narrow in the case of Sibyll 2.3 which leads to a reduced total multiplicity. Furthermore on the right-hand side of Fig. 2, we can observe that the fluctuations are very similar for QGSJETII-04 and EPOS LHC but again Sibyll 2.3 seems to have problems to reproduce the shape of the distribution. This can be important when extrapolating from p-p to p-air interactions and for the fluctuations of the air shower maximum.

So, for both cross section and multiplicity, when the models are constrained by LHC data up to 7 TeV, the extrapolations to the highest energy in p-p are very similar but differences remain in nuclear and pion interactions because of the lack of data at high energy and with light ions (only heavy ion data available from RHIC and LHC at high energy).

2.3 Elasticity

Another important observable determining air shower development is the elasticity [25] defined as the largest energy fraction carried by a secondary particle (the leading particle). The model pre-

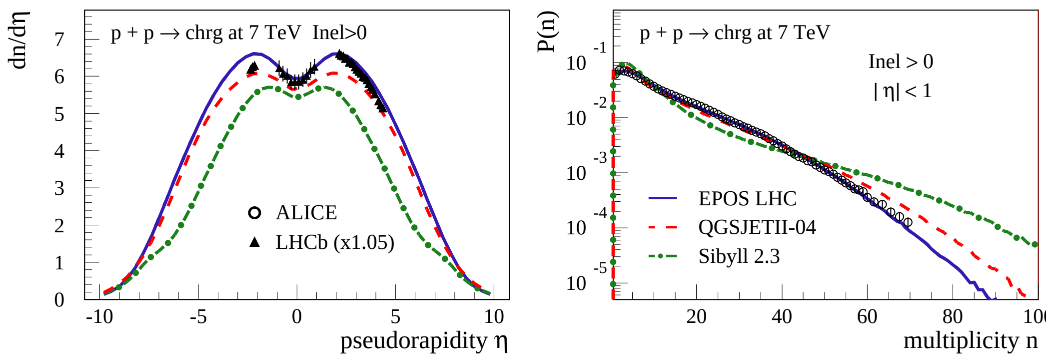

Fig. 2. Pseudorapidity distribution $dN/d\eta$ for events with at least one charged particle with $|\eta| < 1$ (left-hand side) and corresponding multiplicity distribution (right-hand side) for p-p interactions at 7 TeV. Simulations with EPOS LHC (full line), QGSJETII-04 (dashed line) and Sibyll 2.3 (dashed-dotted line) are compared to data points from the ALICE and LHCb experiments (rescaled by 5% to take into account the different trigger in ALICE) [48, 49].

dictions are shown in Fig. 3 for p-p, π-air and p-air (as inelasticity=1-elasticity) as a function of center of mass energy. Sibyll 2.3 has the largest elasticity which is probably related to the fact that the multiplicity is lower (less energy taken from the leading particle). In the cases of EPOS LHC and QGSJETII-04 the difference is smaller for an air target compared to p-p interactions. This opposite behavior compared to the other observables can be explained by the fact that this quantity is very difficult to measure in collider experiments since the latter cannot cover 100% of the phase space. As a consequence there are only indirect constraints on the different contributions to the elasticity leading to a larger uncertainty in the models.

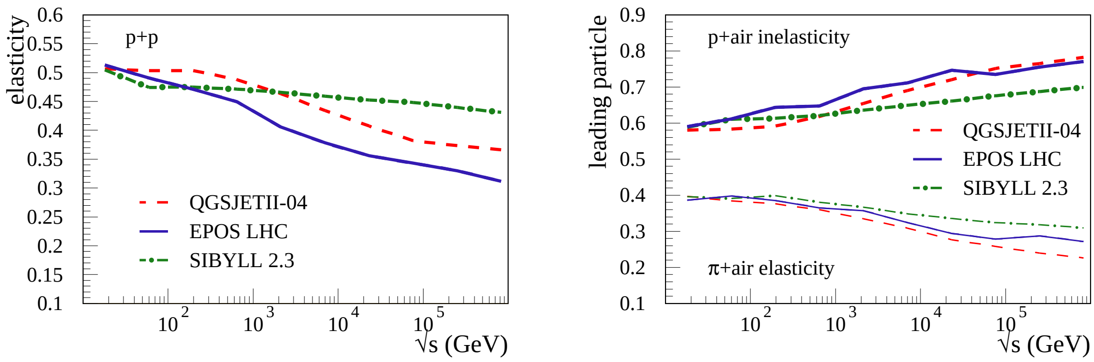

Fig. 3. Elasticity (energy fraction of the leading particle) for p-p interactions (left-hand side) and for π-air (thin lines on the right-hand side) and inelasticity (1-elasticity) for p-air (thick lines on the right-hand side) as a function of center of mass energy. Simulations are done with EPOS LHC (full line), QGSJETII-04 (dashed line) and Sibyll 2.3 (dashed-dotted line).

3. EAS Simulations

3.1 Depth of shower maximum

As shown in Fig. 4 left-hand side, the mean depth of shower maximum, $\langle X_{\rm max}\rangle$, for proton and iron induced showers simulated with CONEX is different for EPOS LHC, QGSJETII-04 and Sibyll 2.3 as a direct consequence of the differences shown in section 2. However the elongation rate (the slope of the $\langle X_{\rm max}\rangle$ as function of the primary energy) is almost the same for all models since the difference between models is now much lower than it was in the past [26]. The difference between the models is a constant shift of about +/-20 g/cm^2 around the value given by EPOS LHC. From the results shown in section 2 it is likely that Sibyll 2.3 predicts too large values of the $\langle X_{\rm max}\rangle$ since the multiplicity is already too low and the elasticity too high at the LHC.

Nevertheless the very similar elongation rate is very important for the study of the primary cosmic ray composition. If the models converge to a similar elongation rate, it will allow us to have a more precise idea on possible changes in composition at the “ankle” for instance where the Pierre Auger Observatory measures a break in the elongation rate of the data [50].

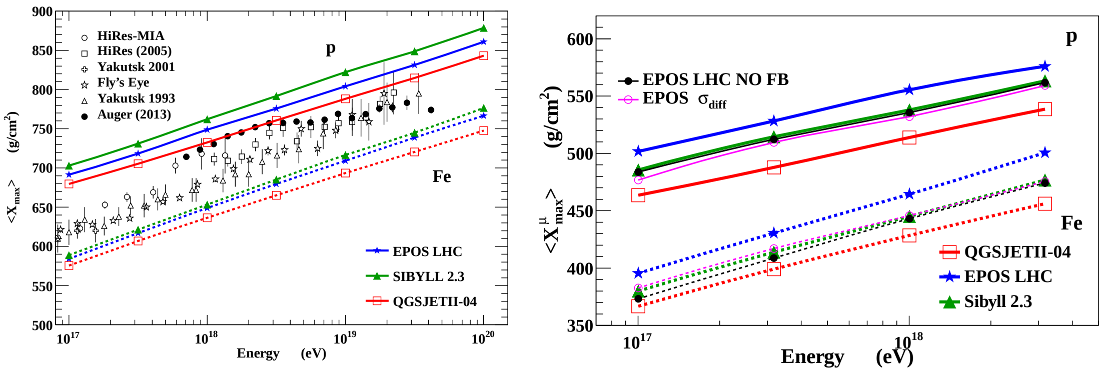

Fig. 4. $\langle X_{\rm max}\rangle$ (left-hand side) and $\langle X^{\mu}_{\rm max}\rangle$ (right-hand side) for proton and iron induced showers as a function of the primary energy . Predictions of different high energy hadronic interaction models are presented with full lines for proton and dashed lines for iron with full triangles for Sibyll 2.3, open squares for QGSJETII-04, full stars for EPOS LHC, full circles for EPOS LHC without forward baryon production (NO FB) and open circles for EPOS LHC with a reduced elasticity in pion-air interactions ($\sigma_{\rm diff}$). Refs. to the data can be found in [1] and [50].

In fact, further study using the fluctuations of $X_{\rm max}$ around the mean can be used to test model consistency. Indeed both $\langle X_{\rm max}\rangle$ and $X_{\rm max}$ fluctuations depend on the mass composition and since fluctuations are less dependent on the details of hadronic interactions (superposition model [25]) than the mean value, it can be checked that the composition corresponding to a given $\langle X_{\rm max}\rangle$ is consistent with the observed fluctuations. In [50] the Pierre Auger Collaboration shows that while it is possible to describe the observed data with EPOS LHC, QGSJETII-04 is in tension with data at a 1 sigma level ($\langle X_{\rm max}\rangle$ too shallow by $\sim$15g/cm^2).

3.2 Muon production depth (MPD)

We have seen in the previous section how LHC data could improve the description of EAS using updated hadronic interaction models. In fact, in one particular case, the update of EPOS leads to inconsistent results: the muon production depth measured by the Pierre Auger Observatory [21]. In that paper the mean logarithmic mass $\langle \ln A\rangle$ calculated from $\langle X^{\mu}_{\rm max}\rangle$ is incompatible with the one extracted from $\langle X_{\rm max}\rangle$ and even out of the range defined by the proton and iron primary mass when

EPOS LHC is used for the simulation. With QGSJETII-04 the resulting $\langle \ln A \rangle$ from $\langle X^{\mu}_{\max} \rangle$ is below the iron line but not consistent with the one from $\langle X_{\max} \rangle$. In a previous analysis [51], EPOS 1.99 was giving a mean composition lighter than iron, so the important shift observed in the MPD simulated with EPOS LHC can partially be explained by the change in elasticity due to the corrections in diffractive interactions needed to reproduce the rapidity gap distributions measured by the ATLAS collaboration [52].

The change of the parameters needed to describe the rapidity gap correctly (the diffractive cross-section and the diffractive mass distribution) affected both proton and pion interactions because the same parameters were used for both types of projectile. While the change of diffraction and thus of elasticity in proton interactions has very little impact on $\langle X^{\mu}_{\max} \rangle$, it appears that the MPD is extremely sensitive to the elasticity of pion interactions. This can be understood by the fact that muons are produced at the end of the hadronic cascade after many generations of mainly pion-air interactions. As a consequence of this cumulative effect, even a small increase of only about 10% of the elasticity of pion-air interactions can lead to a large shift in $\langle X^{\mu}_{\max} \rangle$.

To check this hypothesis, the diffractive cross-section for pion interactions has been reduced in EPOS LHC to get a reduction of about 10% of the elasticity of the pion-air interactions. As a result $\langle X^{\mu}_{\max} \rangle$ is reduced by about 20 g/cm^2 as shown in Fig. 4 right-hand side with the pink line with open circles. The diffraction has not been changed for proton interactions to keep full compatibility with LHC data and then the change in $\langle X_{\max} \rangle$ is limited to less than 5-10 g/cm^2. Another consequence is the increase of the number of muons at the ground by a few percent.

Such a small change is compatible with all pion-nucleus data that are available at low energy and thus these two versions of EPOS cannot be discriminated from accelerator data. But the effect on the MPD is so strong that data from the Pierre Auger Observatory can be used to constrain diffraction in pion interactions to get consistent results between the mean logarithmic mass which can be extracted from $\langle X^{\mu}_{\max} \rangle$ and the one deduced from $\langle X_{\max} \rangle$ which has very little dependence on pion hadronic interaction [53]. From the EAS development we can thus say that the elasticity of pion-air interactions should be lower than the elasticity of proton-air interactions.

The second factor explaining the large shift in MPD was identified in [53] as the too large production of forward baryons in pion interactions (which was indeed extended from low energy only in EPOS 1.99 to all energies in EPOS LHC to improve model consistency). Simply suppressing the production of diquark in string ends and thus the forward baryon pair production, the resulting $\langle X^{\mu}_{\max} \rangle$ is shown in Fig. 4 right-hand side as a thin black line (on top of Sibyll 2.3 predictions) which is again about 20 g/cm^2 lower than the original EPOS LHC predictions. The electromagnetic $\langle X_{\max} \rangle$ is increased by less than 5 g/cm^2 by the change of forward baryon production (more energy in the π^0). The muon production is reduced at the level of QGSJETII-04.

Since these two effects are cumulative, changing both diffraction and forward baryon production leads to a value of $\langle X^{\mu}_{\max} \rangle$ very similar to the one from QGSJETII-04 and thus compatible with Auger $X^{\mu}_{\max}$ [21] with a $\langle X_{\max} \rangle$ reduced by only 5 g/cm^2 still compatible with the Auger $X_{\max}$ [50]. The decrease of the muon production could be compensated by a larger ρ^0 production which is in fact related to the increase of diffractive dissociation in pion-nucleus interactions. This is the way to follow for future model development.

4. Summary

In [53] the uncertainty in the first proton(nucleus)-air interaction has been identified as the source of 70% of the uncertainty in the simulated $\langle X_{\max} \rangle$. The remaining 30% is linked to the pion-air interactions. Concerning the muon production, 90% is coming from the pion interactions and only 10% from the first interaction. In section 2 we have shown that for the first interaction the uncertainty is not in the basic p-p interaction anymore, very well constrained by LHC data, but by the nuclear effects which cannot be tested properly with current model and data combinations (data with heavy ion only at high energy and only EPOS LHC can treat heavy ion collisions properly). These nuclear effects being important both for the air target and in case of heavier primary, they are the main source of the systematic shift in X_{max} of about 20 g/cm^2 around EPOS LHC predictions. This uncertainty is comparable to the experimental uncertainty in the measurement of X_{max} and the elongation rate is now the same for all models for a constant composition. As a consequence the interpretation of the data using a post-LHC model will be more reliable, especially concerning the possible change in mass composition with energy as summarized in [54].

To further reduce these uncertainties and improve the description of air shower by hadronic interaction models, in particular the observables based on muons, it is crucial to improve the description of pion-nucleus interactions in general and the diffractive dissociation in particular which is likely to be different than in proton interactions. Upcoming studies of diffraction at the LHC, including those with a nuclear target [16, 55], will reduce the model uncertainty for the first interaction to its minimum. To further improve the models it is important to take into account that the air shower measurements, such as the muon production depth, can also give very strong constraints on hadronic interactions in particular for pion interactions [53] for which cumulative effects due to the hadronic cascade are observed. This should give qualitative input to improve the models which then can be quantitatively tested against past and future NA61 measurements for instance [56].

To conclude, we can say that LHC data contribute a lot to reducing the uncertainties in air shower simulations, providing better tools to analyze cosmic ray data. The differences between the hadronic models have been reduced but one should keep in mind that there are still uncertainties in the models themselves which have to be better quantified and transferred to the calculation of the systematic errors in EAS analysis. Consistency of different EAS observables can and should be used to test the hadronic interaction models. The open issues concern now mainly the treatment of pion interactions which have a direct influence on the geometry and energy of the muons in air showers. The next generation of models taking into account more detailed LHC data and what has been learned from the MPD study should improve significantly their description of air showers.

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